QCD@Work - International Workshop on QCD Theory and Experiment

27-30 June 2016 *Martina Franca, Italy*

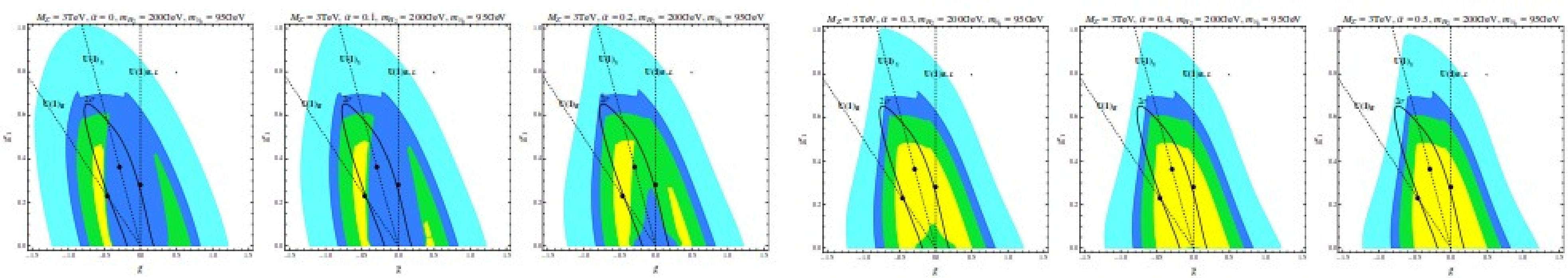
Europe/Rome timezone

8th Edition of the International Workshop on Quantum Chromodynamics

Search for Z-prime.

Vacuum (in)stability and hints of high energy structure.

28-06-2016 --- Martina Franca, Italy



Carlo Marzo

Physics Department, Salento University and INFN, Lecce

Dipartimento di Matematica e Fisica "Ennio De Giorgi"

Based on:

C. Coriano, L. Delle Rose and C. M.,
"Vacuum Stability in U(1)-Prime Extensions of the Standard Model with TeV Scale Right Handed Neutrinos" *arXiv:1407.8539 [hep-ph].*

C. Coriano, L. Delle Rose and C. M.,
"Constraints on abelian extensions of the Standard Model from two-loop vacuum stability and U(1)$_{B-L}$" *arXiv:1510.02379 [hep-ph]*

E. Accomando, C. Coriano, L. Delle Rose, J. Fiaschi, C. M. and S. Moretti,
"Z', Higgses and heavy neutrinos in U(1)' models: from the LHC to the GUT scale" *arXiv:1605.02910 [hep-ph].*

Proton decay and new contribution to $0\nu 2\beta$ decay in SO(10) with low-mass Z' boson, observable $n-\bar{n}$ oscillation, lepton flavor violation, and rare kaon decay

Z' SEARCHES: FROM TEVATRON TO LHC

J. ERLER[a], P. LANGACKER[b], S. MUNIR[a], E. ROJAS[a]

Kinetic Mixing of the Photon with Hidden $U(1)$s in String Phenomenology

Z' Bosons from E_6: Collider and Electrowe... Constraints

Implications of Abelian Extended Gauge Structures From String Mo...

Some Z' and W' Models facing current LHC Searches

Ennio Salvioni[1,2]

Neutrino Masses, Neutral Vector Bosons and the scale of $B-L$ Breaki...

The 750 GeV di-... excess and Extra Z's in Heteroti... ...ring Derived Models

DISCOVERY AND IDENTIFICATION OF EXTRA GAUGE BOSONS [1]

Mirjam Cvetič
Department of Physics, University of Pennsylvania
Philadelphia, PA 19104-6396
and
Stephen Godfrey
Department of Physics, Carleton University
Ottawa, ON K1S 5B6

Embedding Z' models in SO(10) GUTs

Paweł Pachołek

Z' Gauge Bosons at the Tevatron

Marcela Carena[1], Alejandro Daleo[1,2] Bogdan A. Dobrescu[1], Tim M.P. Tait[1]

An extra Abelian gauge factor is an almost inevitable low-energy fate for many different UV-completions of the SM.

$$SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)_{Y'}$$

They naturally arise in grand and partial unifications, extra-dimensions, string theory compactifications...

From our low-energy perspective we recognize the SM x $U(1)_{Y'}$ as having a large UV universality class .

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From our low-energy perspective we recognize the SM x $U(1)_{Y'}$ as having a large UV universality class .

Is there a recipe to discriminate among different UV-completions from an (assumed observed) low-energy $U(1)_{Y'}$?

YES! **A minimal Z' class** **(see Luigi's Talk)**

- ***No Susy***
- ***The $U(1)_{Y'}$ class under this investigation is made anomaly free with a 3-generation family of extra-fermions (ν_R).***
- ***No exotic fermions (other than ν_R) in the model.***
- ***A Z' (of course!)***
- ***A new scalar H_2, breaking $U(1)_{Y'}$ and responsible for Z' mass***
- ***Z' visibility***

YES!

A minimal Z' class

(see Luigi's Talk)

- The $U(1)_{Y'}$ class under this investigation is made anomaly free with a 3-generation family of extra-fermions (ν_R).
- No exotic fermions (other than ν_R) in the model.

Cancellation of gauge and mixed gravitational-U(1) anomaly strongly constrain the Abelian sector.

$$D_\mu^{Abelian} \sim \begin{pmatrix} I_a, & I_b \end{pmatrix} \begin{pmatrix} g_a & 0 \\ 0 & g_b \end{pmatrix} \begin{pmatrix} A_{a\,\mu} \\ A_{b\,\mu} \end{pmatrix}$$

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After an appropriate change of basis

$$D_\mu^{Abelian} \sim \begin{pmatrix} Y, & Y' \end{pmatrix} \begin{pmatrix} g_Y & 0 \\ 0 & g_1' \end{pmatrix} \begin{pmatrix} A_{Y\,\mu} \\ A_{Y'\,\mu} \end{pmatrix}$$

all the new charge assignments are spanned by the ratio of just two new couplings

$$Y' = I_{B-L} + \frac{\tilde{g}}{g_1'} Y$$

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$$Y' = I_{B-L} + \frac{\tilde{g}}{g_1'} Y$$

In the basis of Hypercharge and the Baryon-Lepton number (B-L) we meet a non diagonal gauge coupling matrix.

$$D_\mu^{Abelian} \sim \begin{pmatrix} Y, & I_{B-L} \end{pmatrix} \begin{pmatrix} g_Y & \tilde{g} \\ 0 & g_1' \end{pmatrix} \begin{pmatrix} A_{Y\,\mu} \\ A_{I_{B-L}\,\mu} \end{pmatrix}$$

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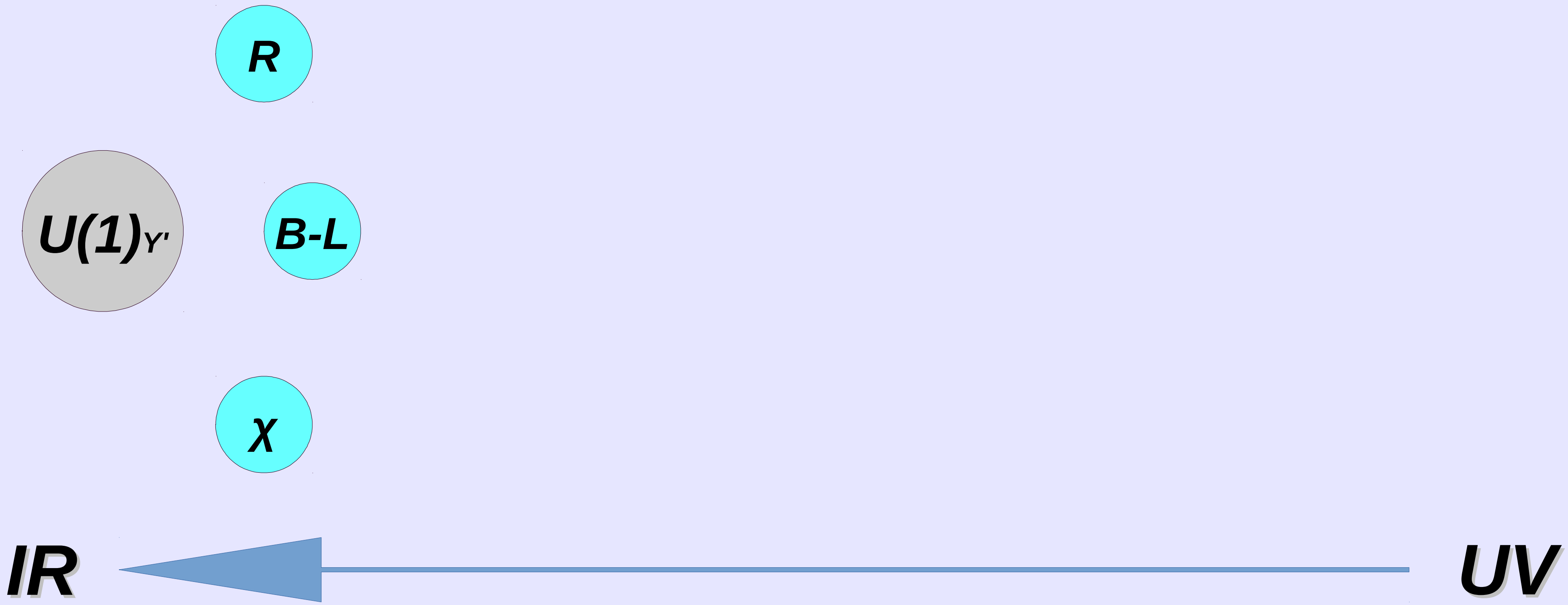

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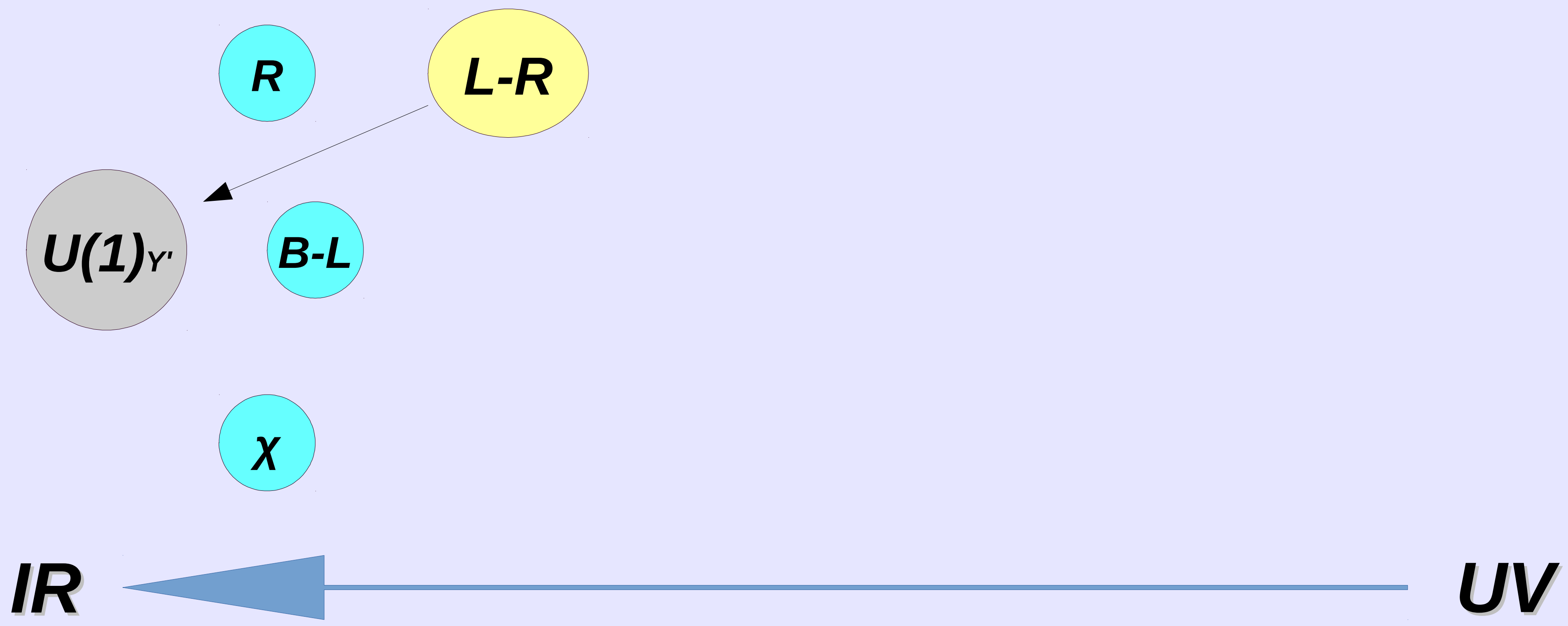

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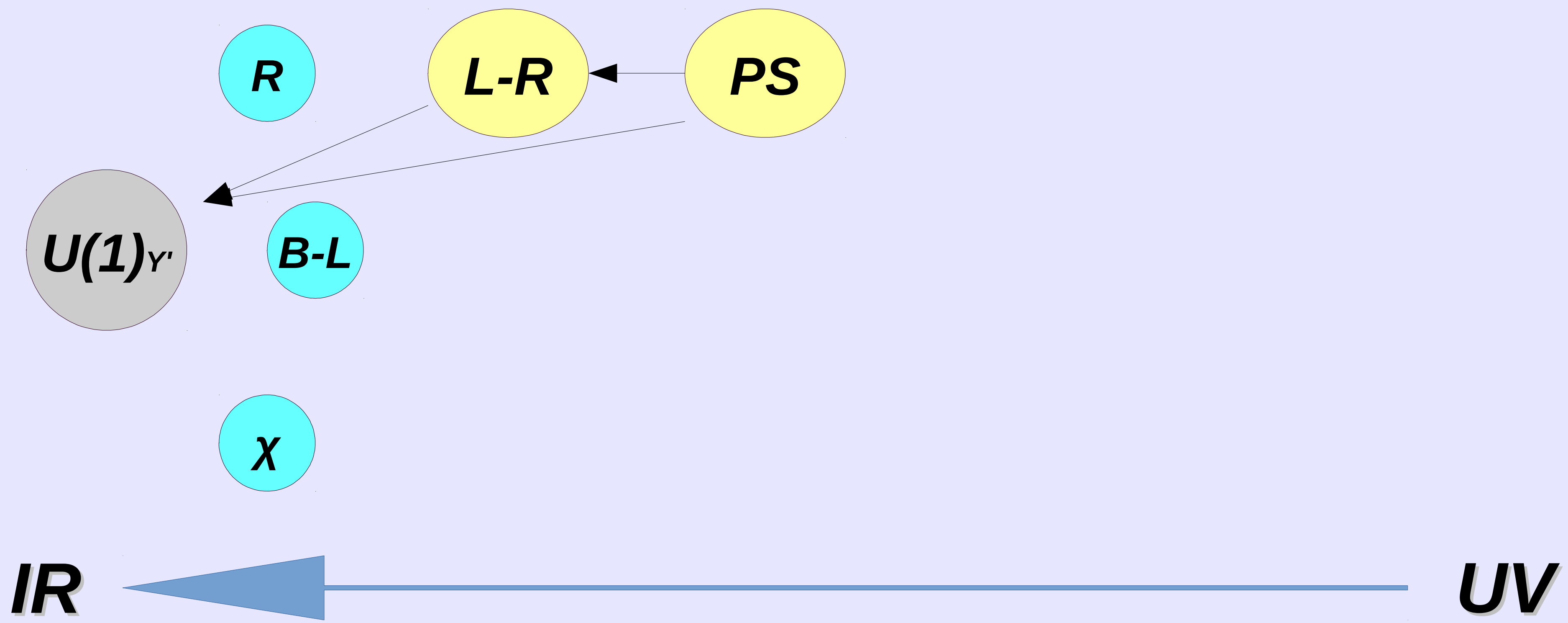

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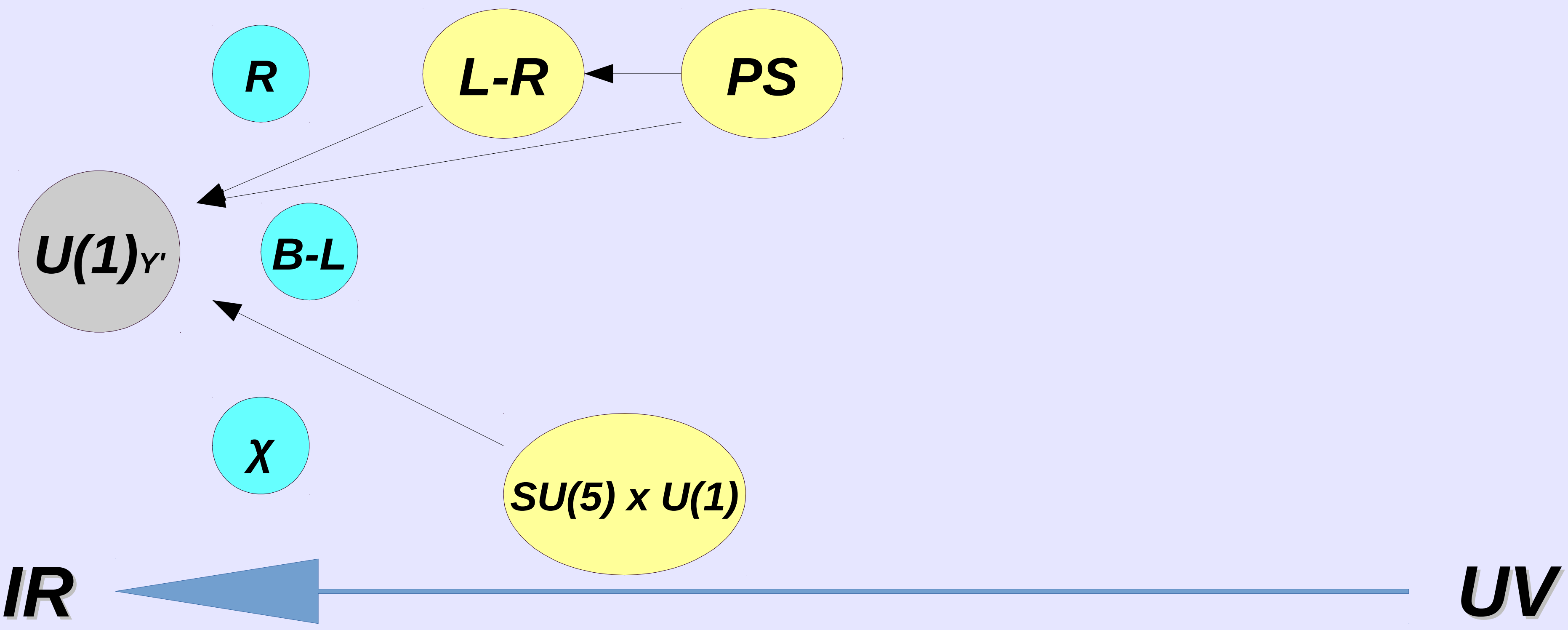

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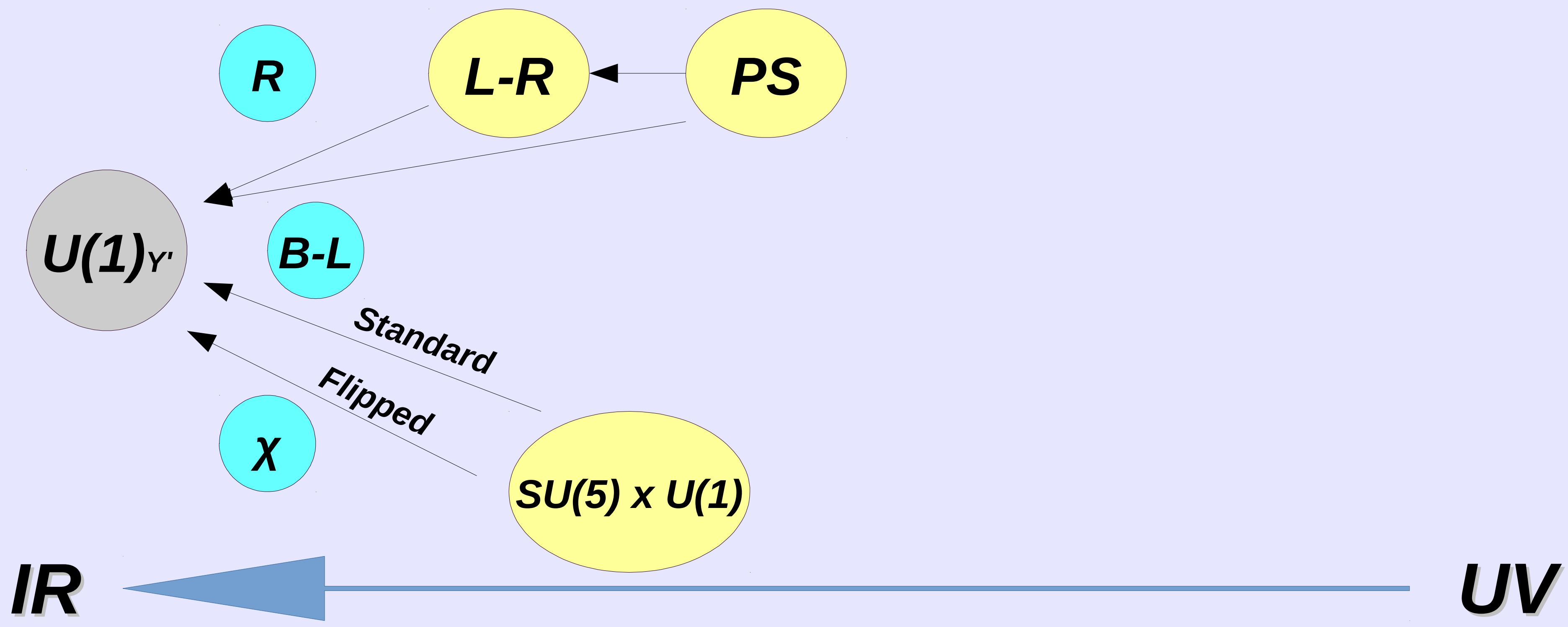

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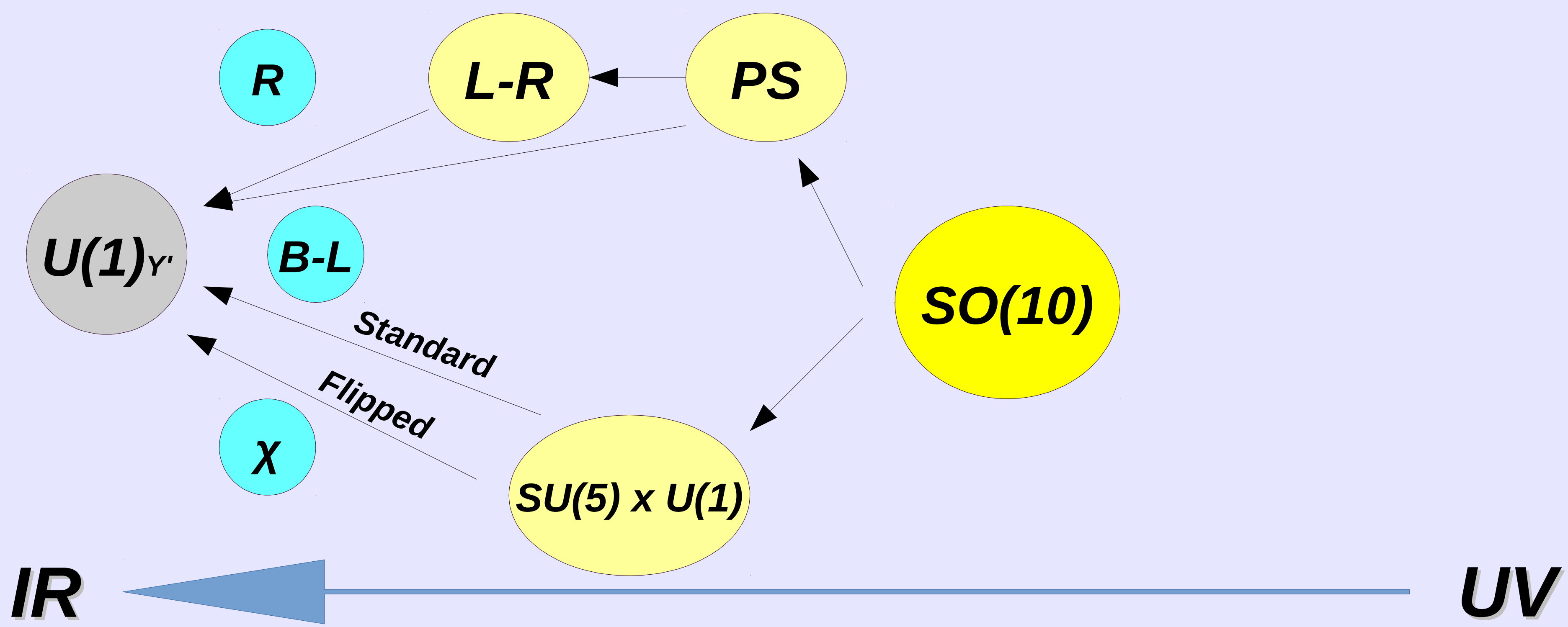

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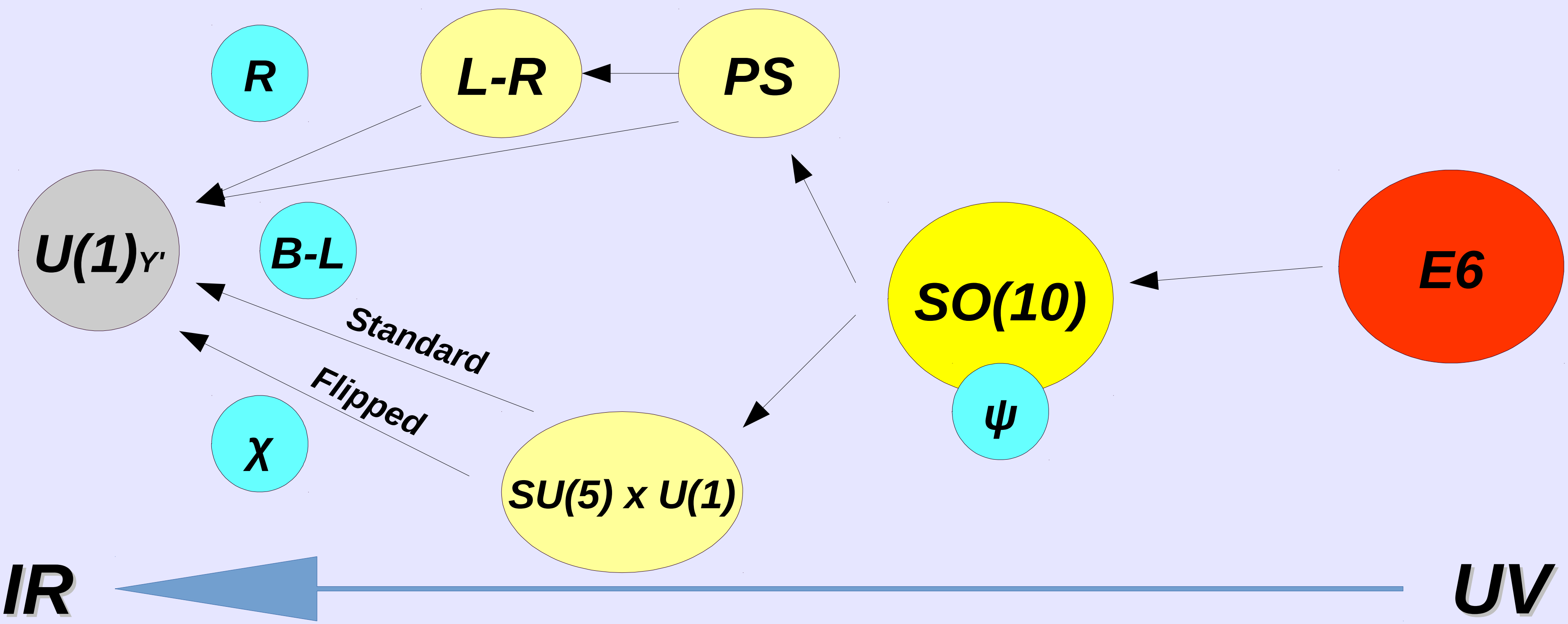

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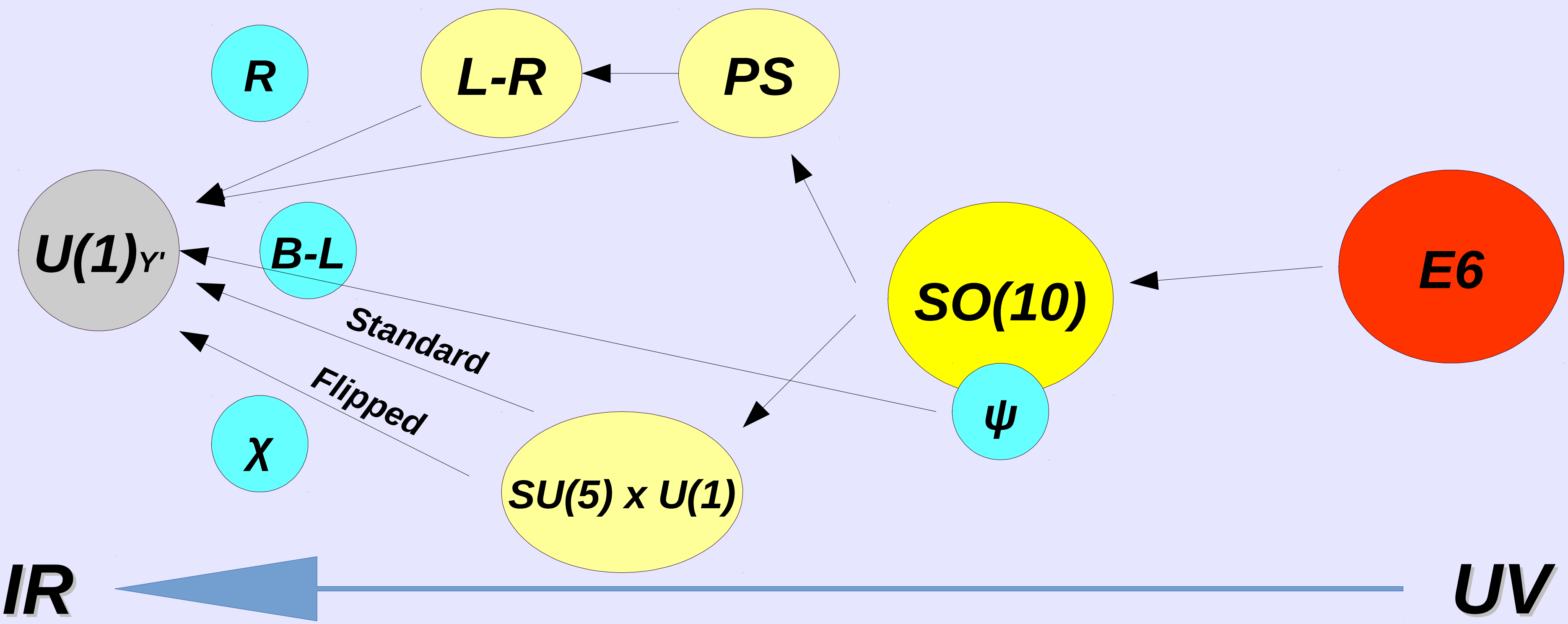

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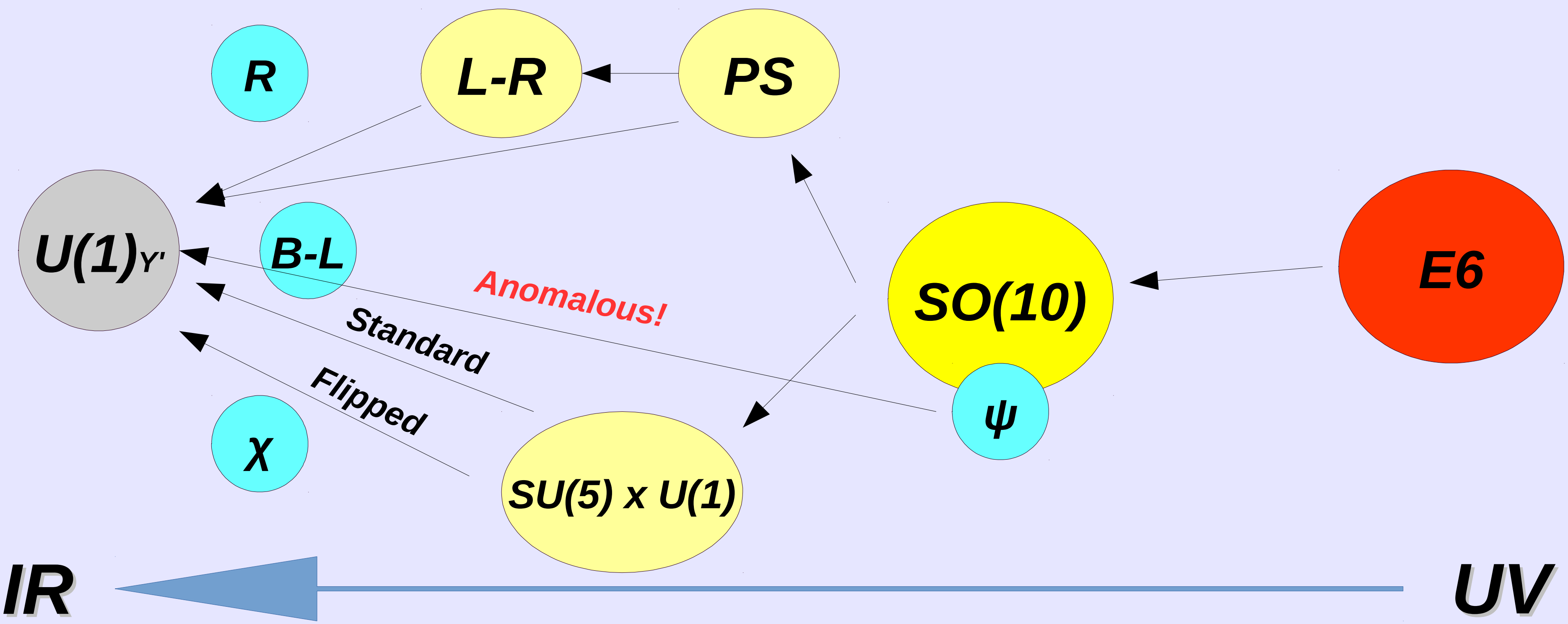

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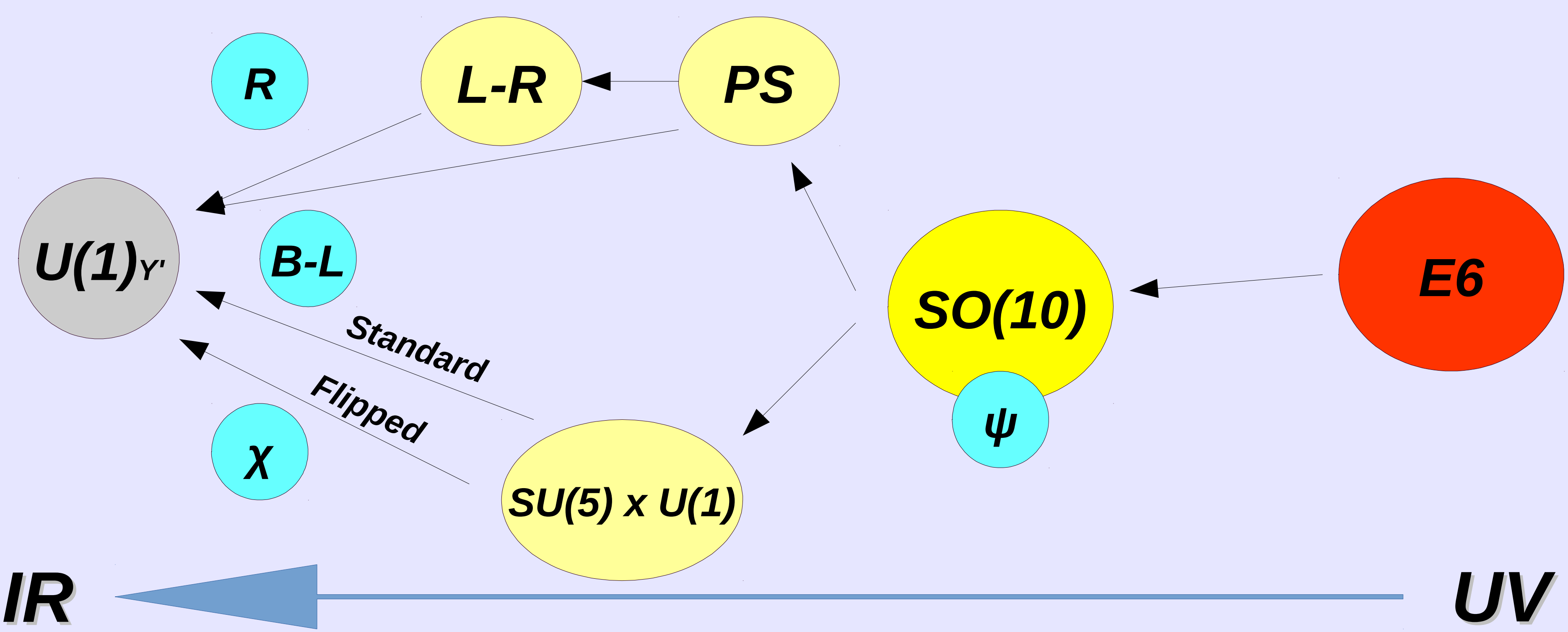


A minimal Z' class: LHC visibility

We set our parameter space at the verge of LHC collider probe.

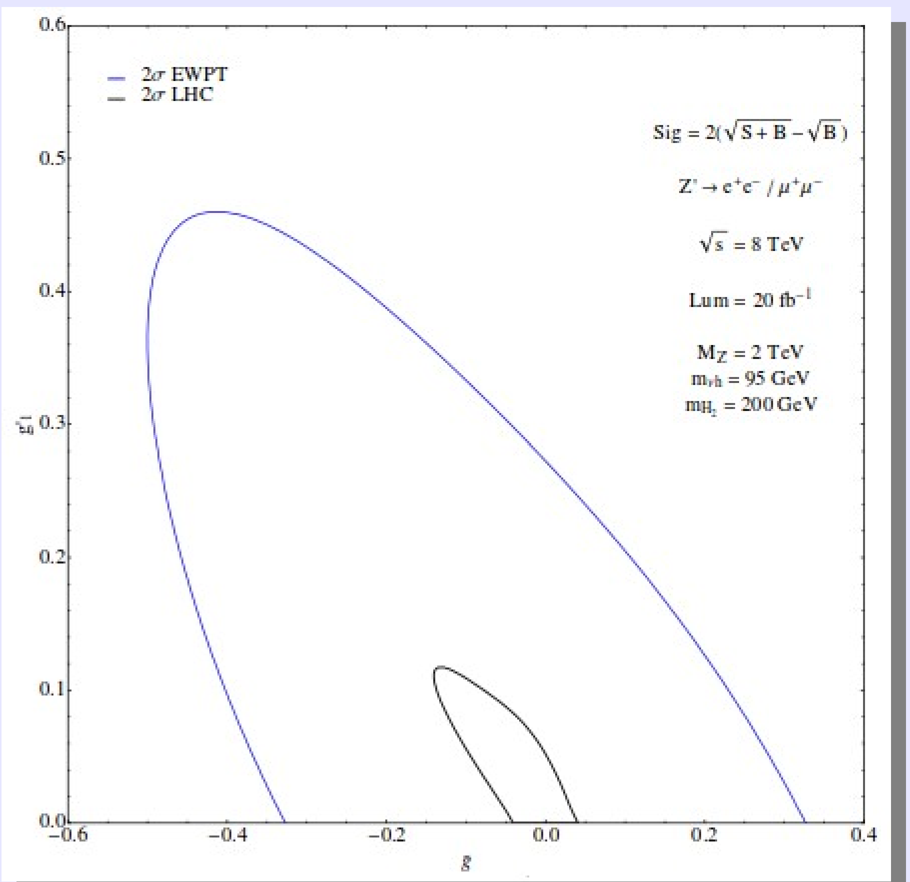
- *A TeV scale Z' .*
- *A sufficiently heavy scalar H_2 to open decay channels in SM vectors.*
- *Heavy neutrinos to be produced with characteristic signatures by Z' decay (displaced vertices).*

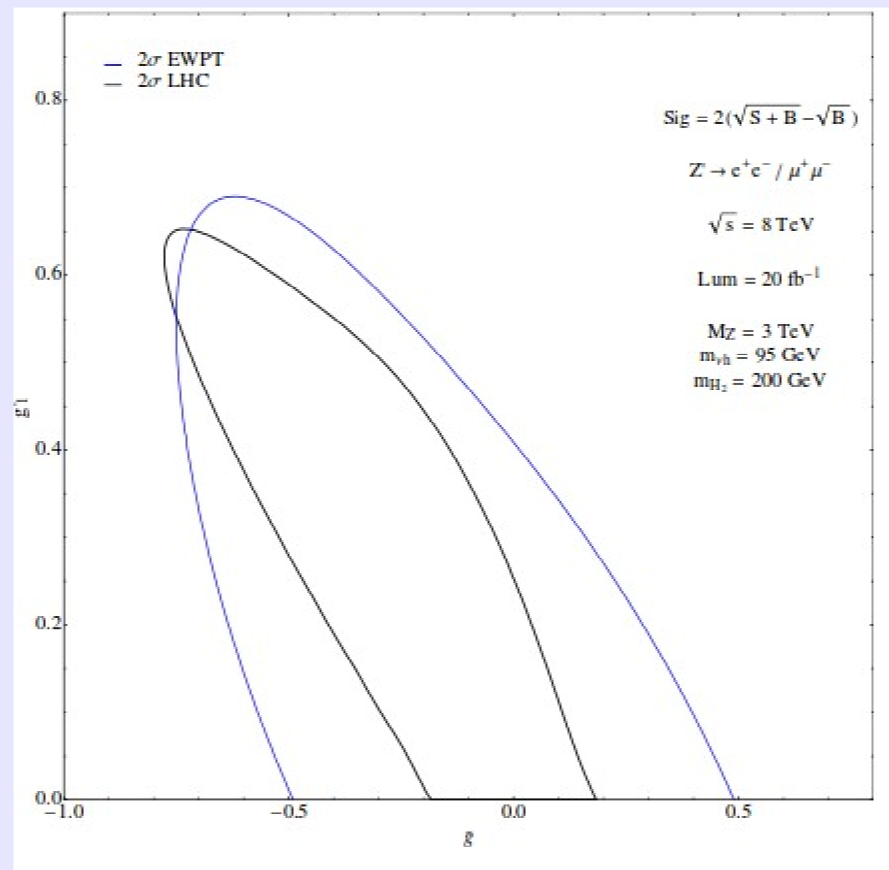
I will rely on the Z' visibility and stability analysis of:
E. Accomando, C. Coriano, L. Delle Rose, J. Fiaschi, C. M., and S. Moretti, (2016), “Z', Higgses and heavy neutrinos in U(1)' models: from the LHC to the GUT scale” arXiv:1605.02910 [hep-ph].

See Luigi's Talk for details on the collider signatures of the model.

A minimal Z' class: LHC visibility

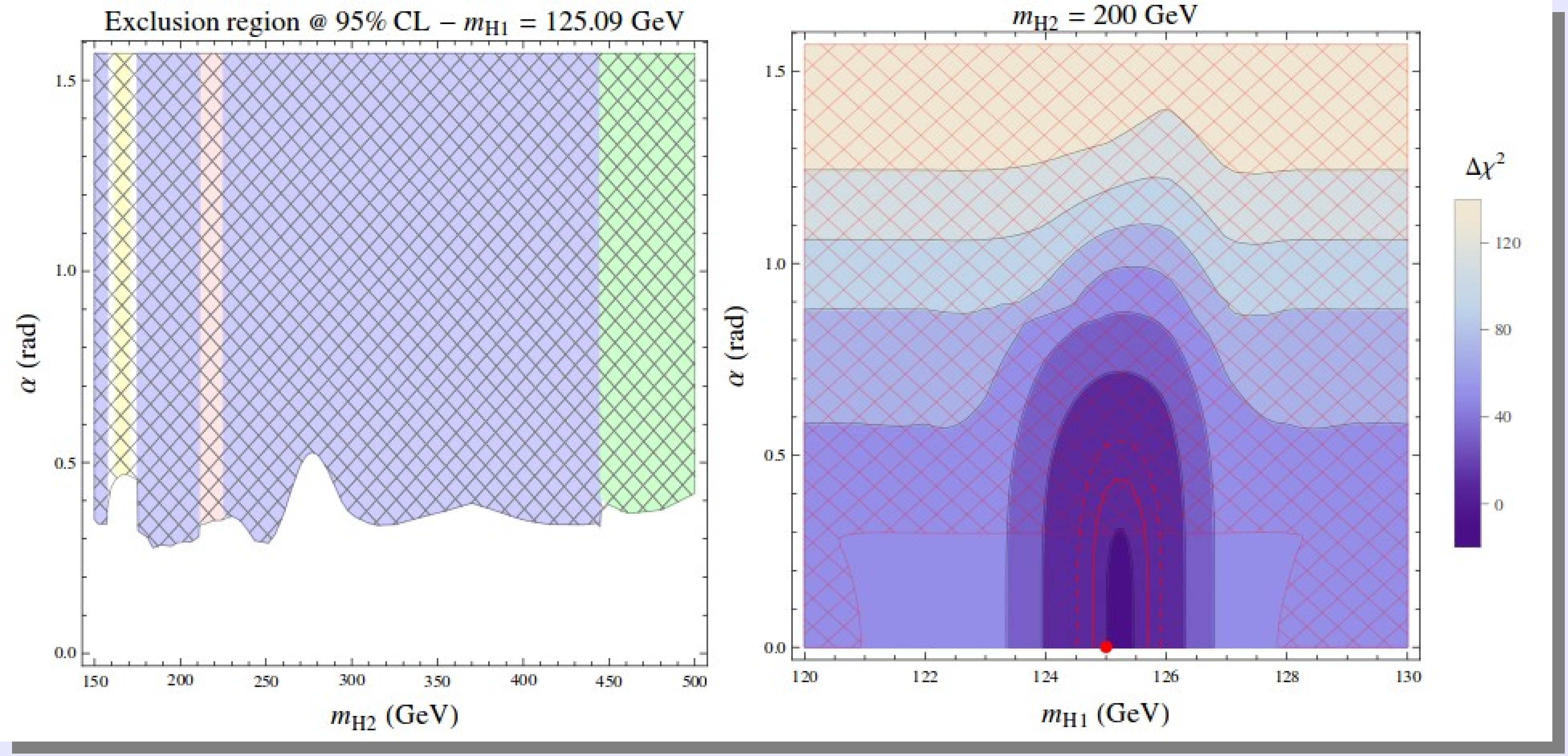
The extended <u>gauge sector</u> for a low-scale Z' has strong bounds coming from EWPTs (LEP2-data).
To these we add the more recent one drawn from data of the first Run of LHC at 8 TeV and L = 20 fb^{-1} based on a signal-to-background analysis for the di-lepton (electrons and muons) channel.





A minimal Z' class: LHC visibility

Excluded region by LEP + Tevatron + LHC in (mH_2, α) plane via HiggsBounds.
Fit result using HiggsSignals with mH_2 = 200 GeV $m\nu_H$ = 95 GeV (see arxiv:1605.02910 for details).



A minimal Z' class: hints from the UV

The basis to parametrize the Abelian sector is typically low-energy related:

$$D_\mu^{Abelian} \sim \begin{pmatrix} Y, & I_{B-L} \end{pmatrix} \begin{pmatrix} g_Y & \tilde{g} \\ 0 & g_1' \end{pmatrix} \begin{pmatrix} A_{Y\,\mu} \\ A_{I_{B-L}\,\mu} \end{pmatrix}$$

Clearly different from the one we would choose living, for example, close to a Left-Right world just after the breaking

$$SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$$

$$\downarrow$$

$$SU(3)_c \times SU(2)_L \times U(1)_R \times U(1)_{B-L}$$

A minimal Z' class: hints from the UV

Our high-energy experimental outcomes would be described by an Abelian sector with diagonal coupling matrix

$$D_\mu^{Abelian} \sim \begin{pmatrix} I_R, & I_{B-L} \end{pmatrix} \begin{pmatrix} g_R & 0 \\ 0 & g_{B-L} \end{pmatrix} \begin{pmatrix} A_{R\,\mu} \\ A_{B-L\,\mu} \end{pmatrix}$$

And the kinetic remnant of the L-R breaking:

$$\mathcal{L}_K^{Abelian} = -\frac{1}{4} F_R^2 - \frac{1}{4} F_{B-L}^2$$

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Not a gauge-invariant Lagrangian! Field-strength tensors are invariants.

This is a PROTECTED form in the $SU(2)_R$ non abelian embedding. Renormalization require a kinetic mixing...

A minimal Z' class: hints from the UV

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Renormalization require a kinetic mixing...

$$\mathcal{L}_K^{Abelian} = -\frac{1}{4} F_R^2 - \frac{1}{4} F_{B-L}^2 + \frac{k}{2} F_R F_{B-L}$$

...the mixing is a new running parameter.

A minimal Z' class: hints from the UV

The kinetic mixing can always be rotated out so to reach a canonical form.

The three Abelian running parameters (g_R, g_{B-L}, k) can be traded for a non-diagonal coupling matrix.

$$D_\mu^{Abelian} \sim \begin{pmatrix} I_R, & I_{B-L} \end{pmatrix} \begin{pmatrix} g_R & g_{R/B-L} \\ 0 & g_{B-L} \end{pmatrix} \begin{pmatrix} A_{R\,\mu} \\ A_{B-L\,\mu} \end{pmatrix}$$

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UV

We have a UV-IR map:
by this map we can check
when the R/B-L mixing
becomes zero via RG:
Hints of Left-Right
symmetry restoration

$$\begin{pmatrix} g_Y & \tilde{g} \\ 0 & g_1' \end{pmatrix}$$

IR

A minimal Z' class: hints from the UV

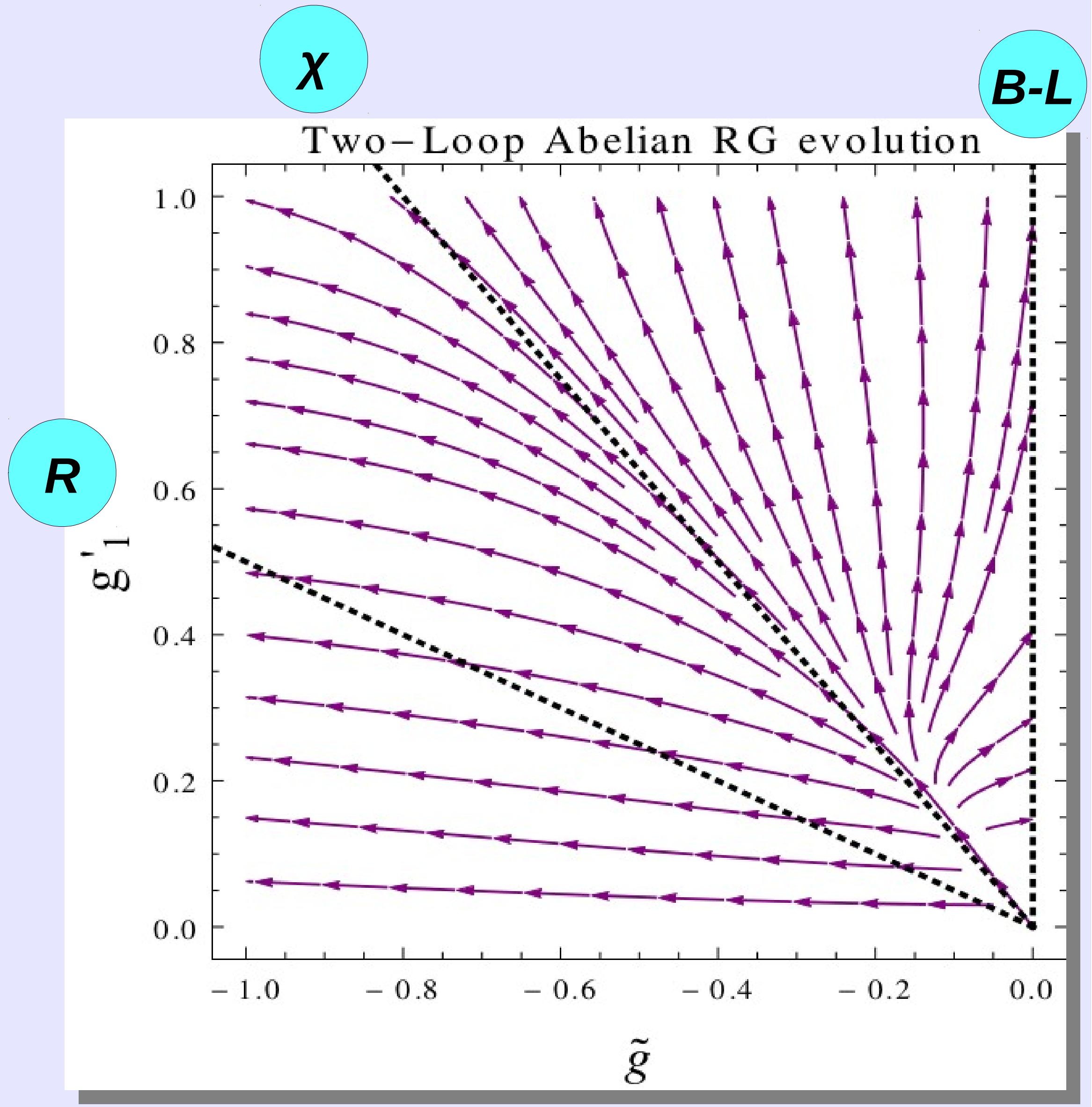
Evolution of charge assigments:

- *The non-diagonal Abelian coupling runs with the RG scale.*
- *Mixing encodes information of high-energy structures.*
- *The measured charge assignment evolve.*

$U(1)_R$ $U(1)_\chi$ $U(1)_{B\text{-}L}$
are commonly under scrutiny.

$U(1)_\chi$ *the only UV-stable*

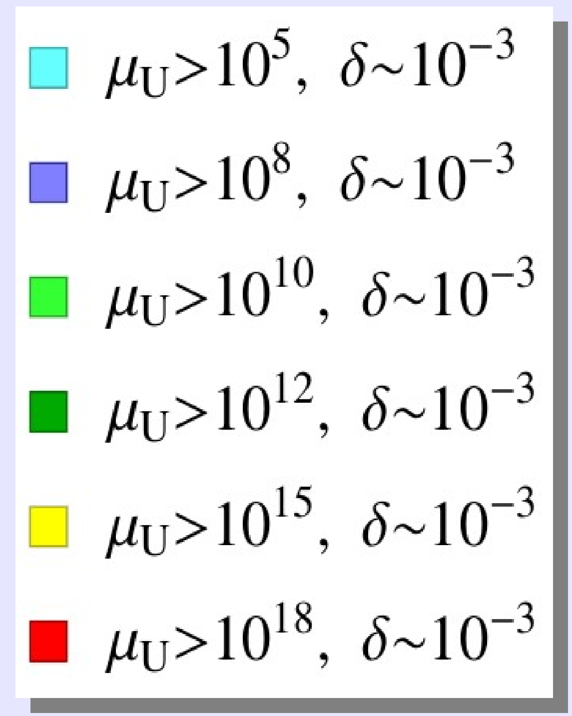
$$g_{\chi/B-L} = 0 \rightarrow \frac{\tilde{g}}{g'_1} = -\frac{4}{5}$$



A minimal Z' class: hints from the UV

Evolution of charge assigments:

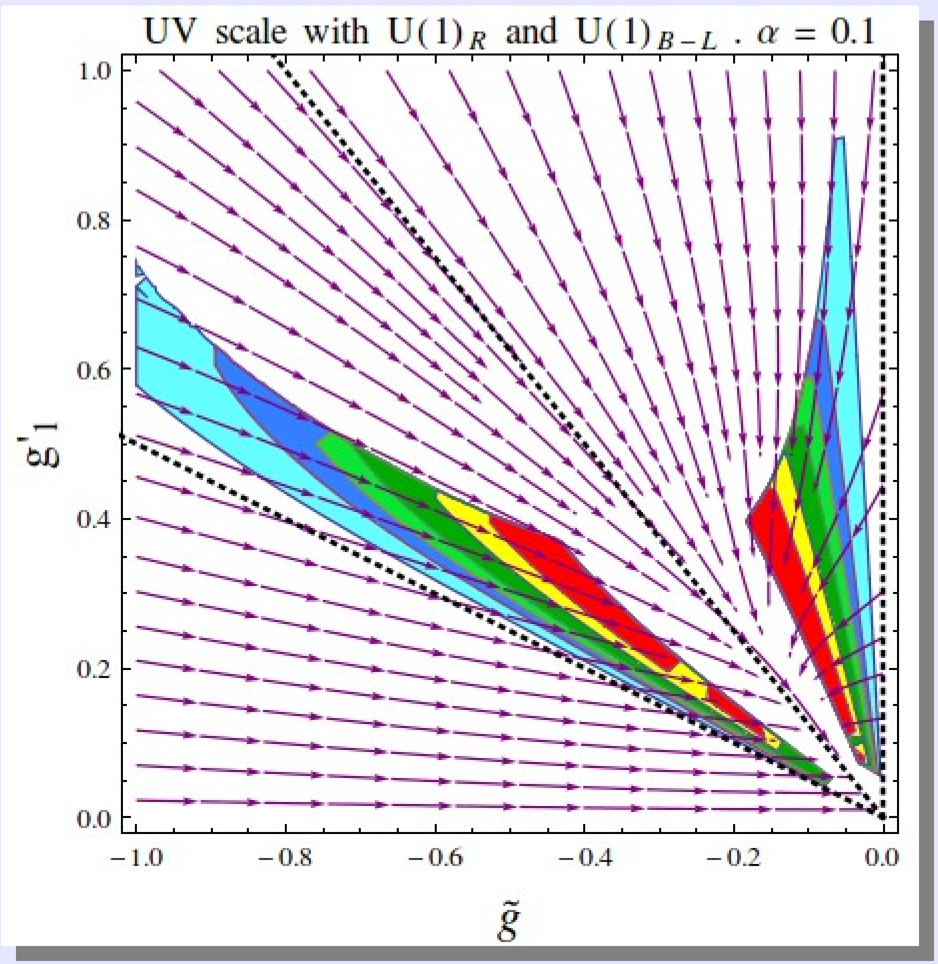
To visualize the moving $U(1)_{Y'}$ assignment we ask for a ~ 0.001 tolerance in the ratio comparison. When the condition is met we stop the bottom-up running at the scale μ_U (GeV) .

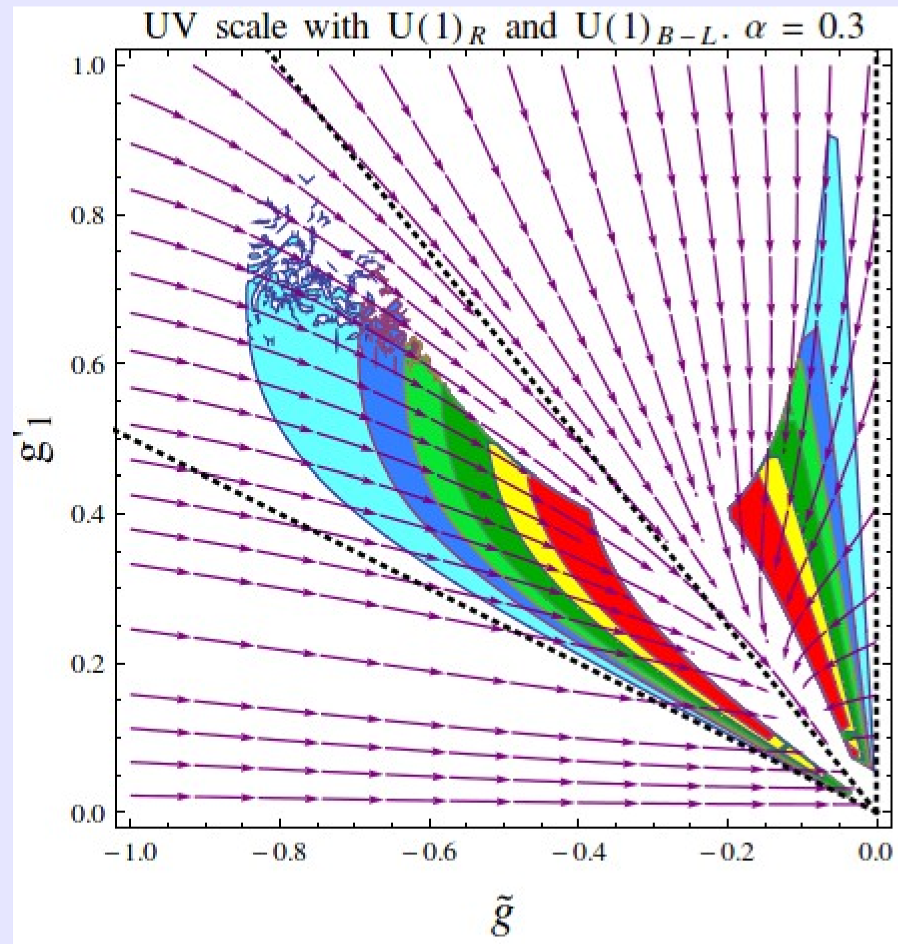


The emerging pattern of UV-charges:

A minimal Z' class: hints from the UV

Evolution of charge assigments: (reversed flow)





A minimal Z' class: hints from the UV

SO(10)-induced thresholds:

- ***No assumptions on the breaking mechanism are done.***
- ***We assume the SM x $U(1)_{Y'}$ matter content to belong to the 16 of SO(10).***
- ***We set our benchmark with Z' mass at 3 TeV, heavy Higgs mass at 200 GeV and heavy neutrino at 95 GeV to investigate the <u>interplay among the Abelian gauge sector and the scalar mixing</u>.***

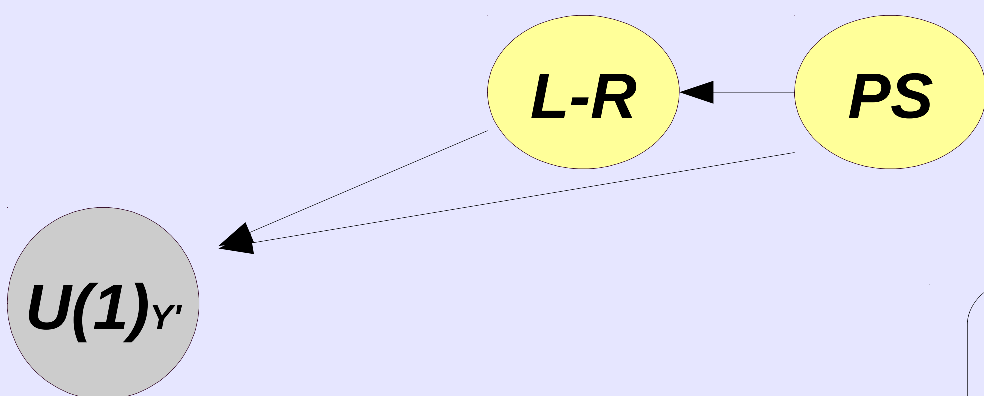
A minimal Z' class: hints from the UV

SO(10)-induced thresholds:

Chains:

- ***Pati-Salam L-R way***

$$U(1)_a \times U(1)_b = U(1)_R \times U(1)_{B-L}$$



$$I_R = Y - \frac{I_{B-L}}{2}$$

- ***(Flipped) SU(5) way***

PS

L-R

No R/B-L mixing

$g_R = g_2$

$g_3 = g_{B-L}$

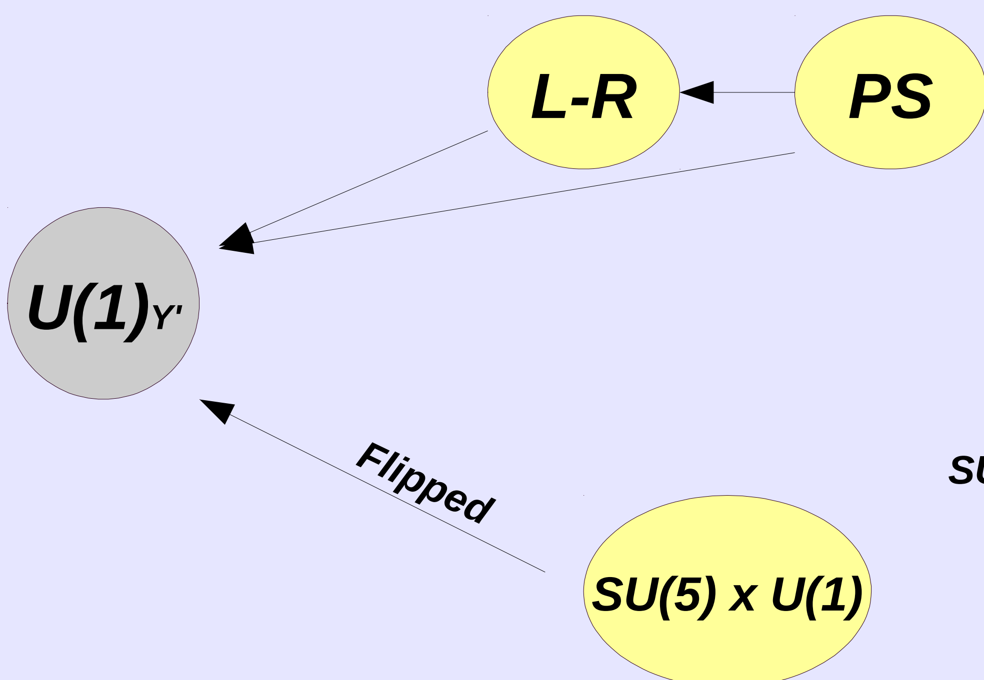
A minimal Z' class: hints from the UV

SO(10)-induced thresholds:

Chains:

- ***Pati-Salam L-R way***

$$U(1)_a \times U(1)_b = U(1)_{Y'} \times U(1)_{Z'}$$



$$Y' = -I_R + \frac{I_{B-L}}{2}$$
$$Z' = 4I_R + 3I_{B-L}$$

SU(5)

No Y'/Z' mixing

$g_3 = g_2 = g_{Y'}$

- ***(Flipped) SU(5) way***

A minimal Z' class: hints from the UV

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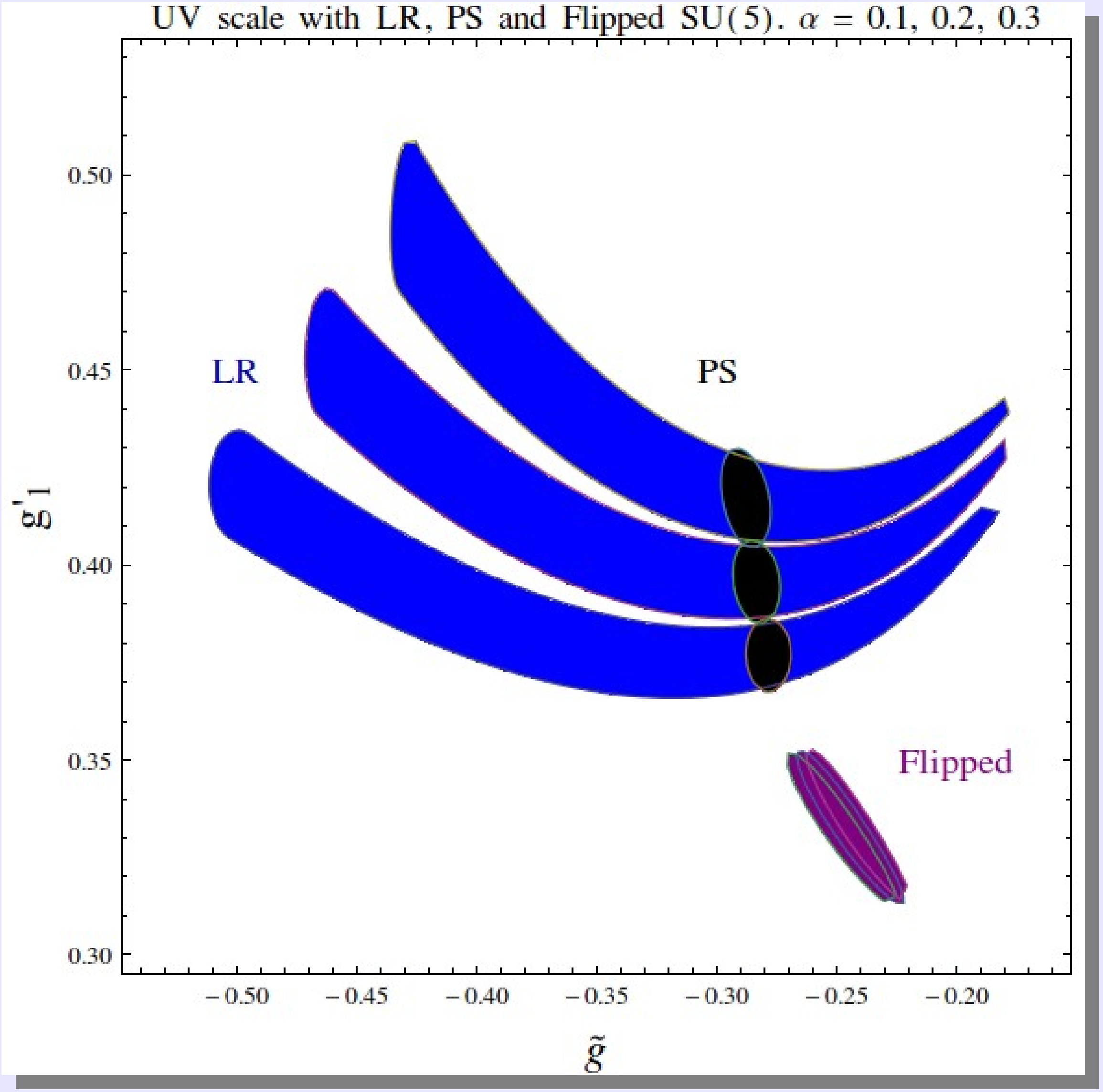

"Rough unification" plot

A minimal Z' class: hints from the UV

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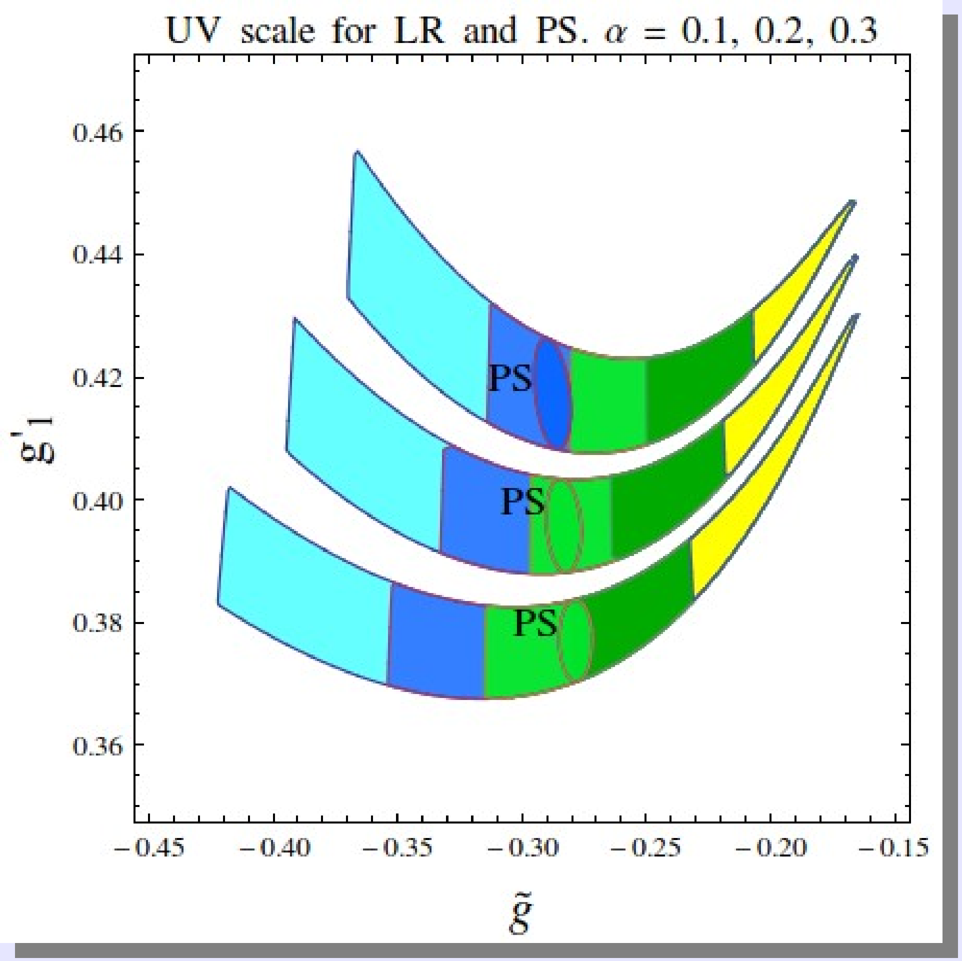
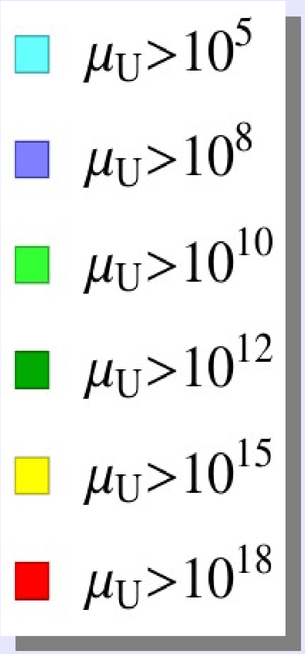


Left-Right and Pati-Salam



A minimal Z' class: hints from the UV

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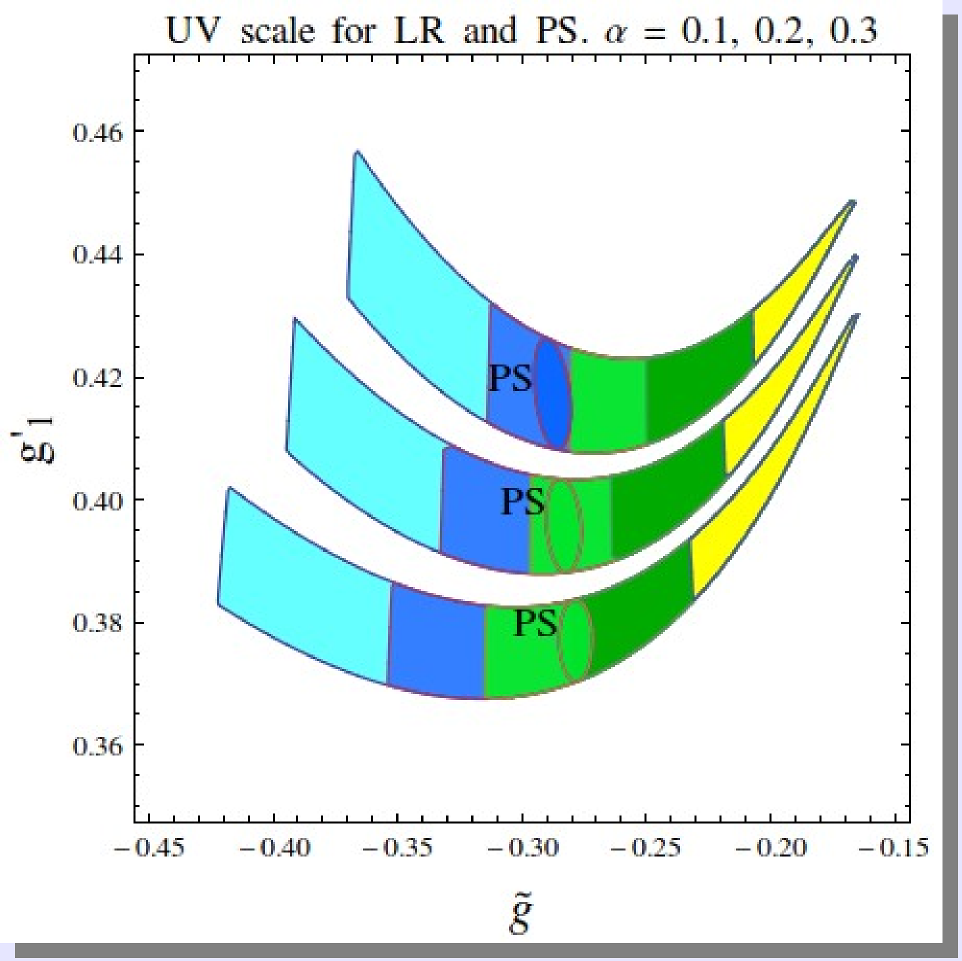

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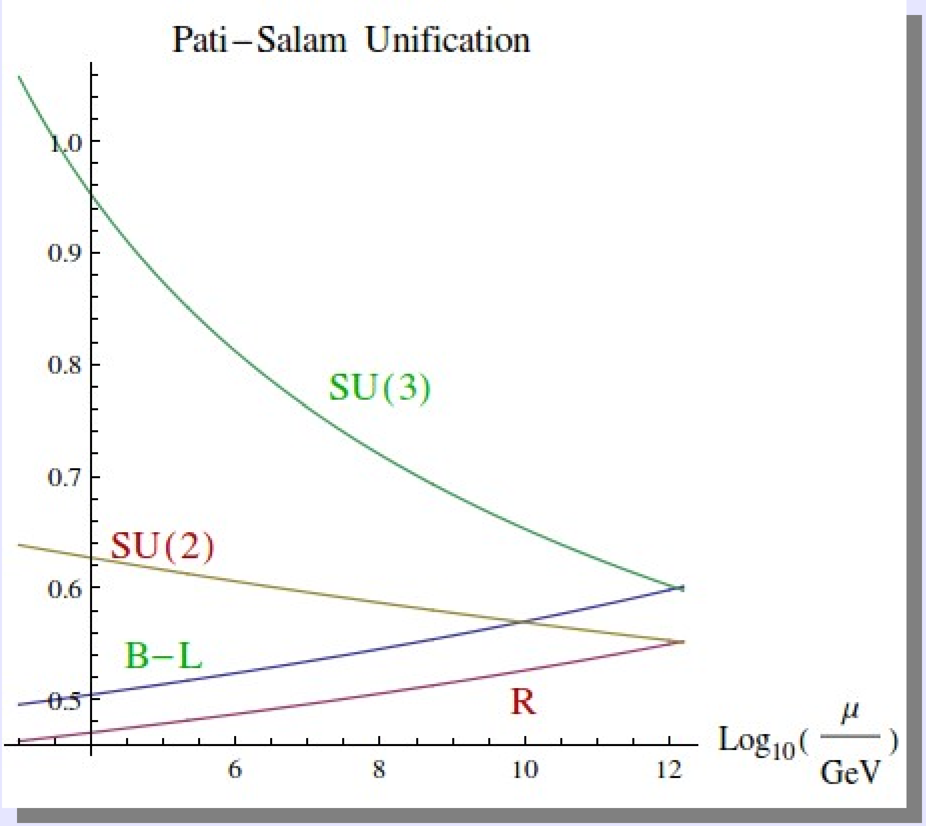

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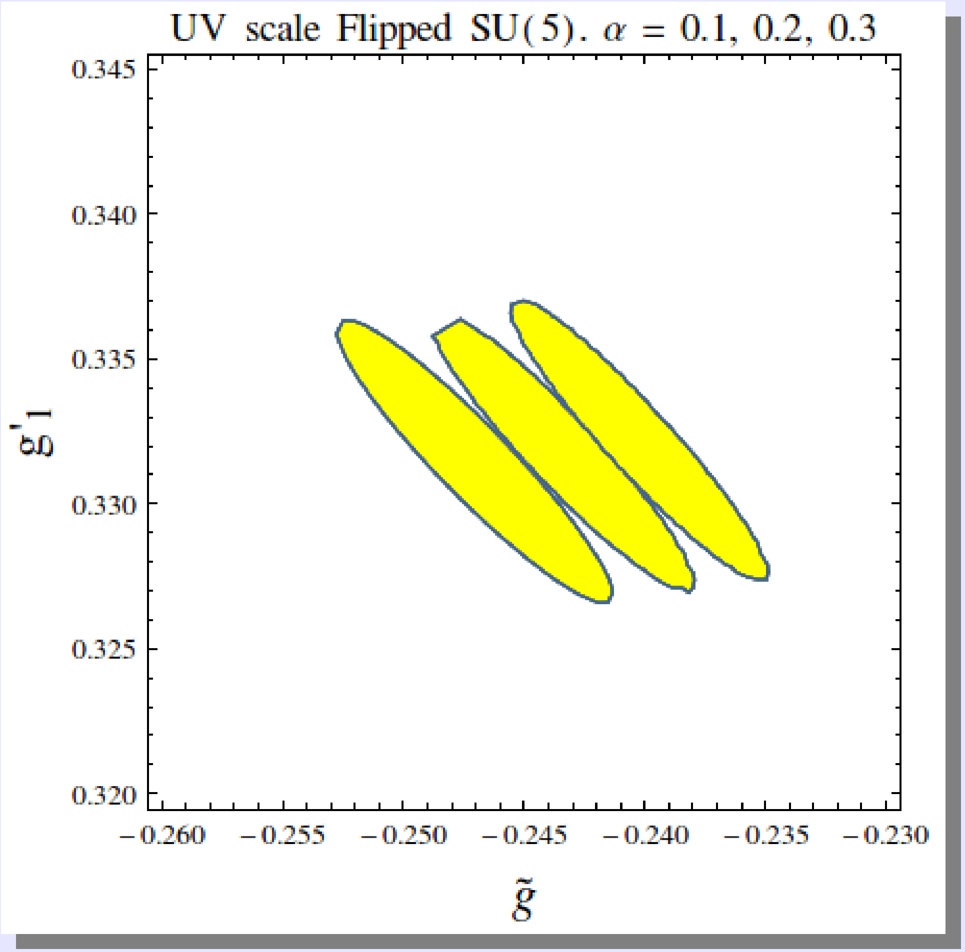

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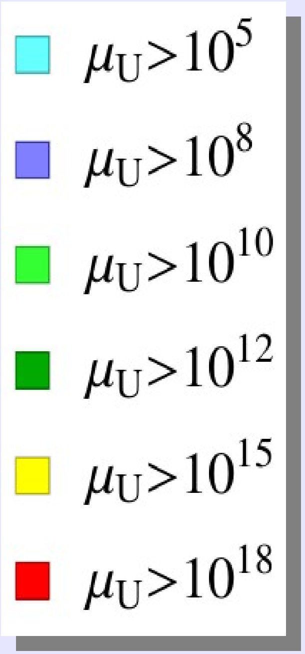

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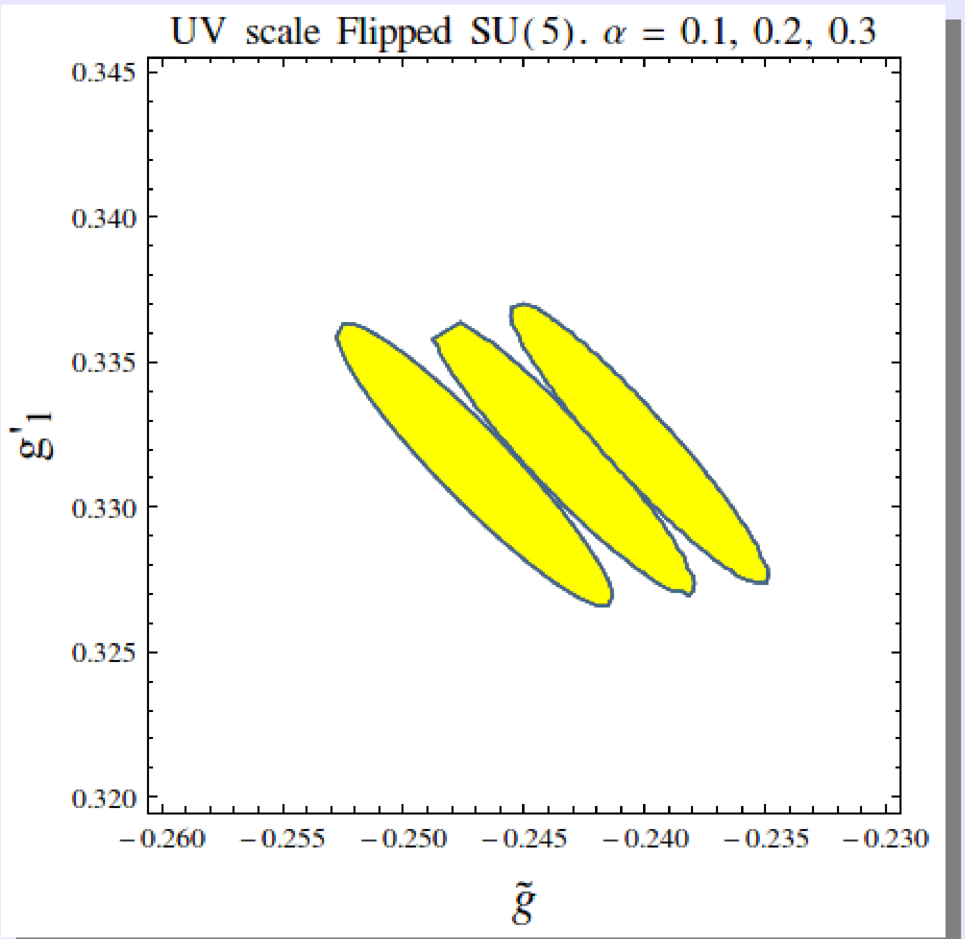

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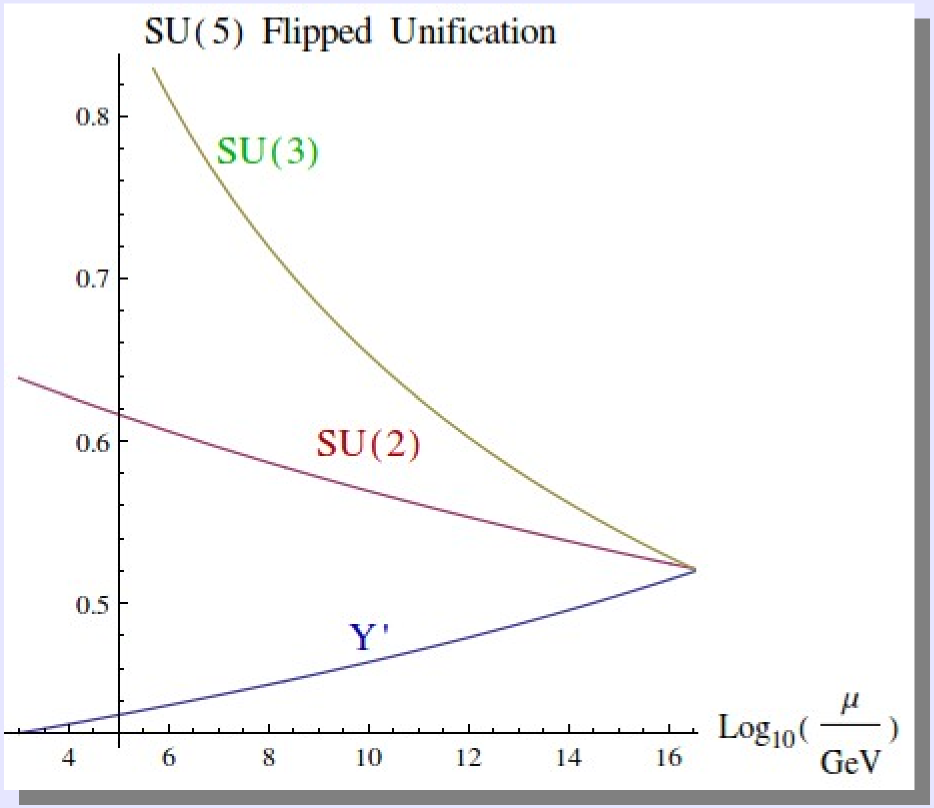

A minimal Z' class: Instability scale

Our analysis found the <u>“unification” scale</u>.

Not the only scale needed to read the model extrapolation to UV.

Radiative corrections can destabilize the EW vacuum.

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Radiative corrections can destabilize the EW vacuum.

The true vacuum of the model is at perturbative reach via Renormalization Group Improvement of the Effective Potential.

A minimal Z' class: Instability scale

The true vacuum of the model is at perturbative reach via Renormalization Group Improvement of the Effective Potential.

For our purposes we must exploit the condition for the improved potential

$$V(H,\phi) = m_1^2 H^\dagger H + m_2^2 \phi^\dagger \phi + \lambda_1 (H^\dagger H)^2 + \lambda_2 (\phi^\dagger \phi)^2 + \lambda_3 (H^\dagger H)(\phi^\dagger \phi)$$

to be bounded from below.

For high-energy values of the field configurations we reduce to the positivity requirement on the quartic terms:

$$\lambda_1(\phi) > 0 \,, \lambda_2(\phi) > 0 \,, 4\, \lambda_1(\phi)\, \lambda_2(\phi) - \lambda_3^2(\phi) > 0$$

A minimal Z' class: Instability scale

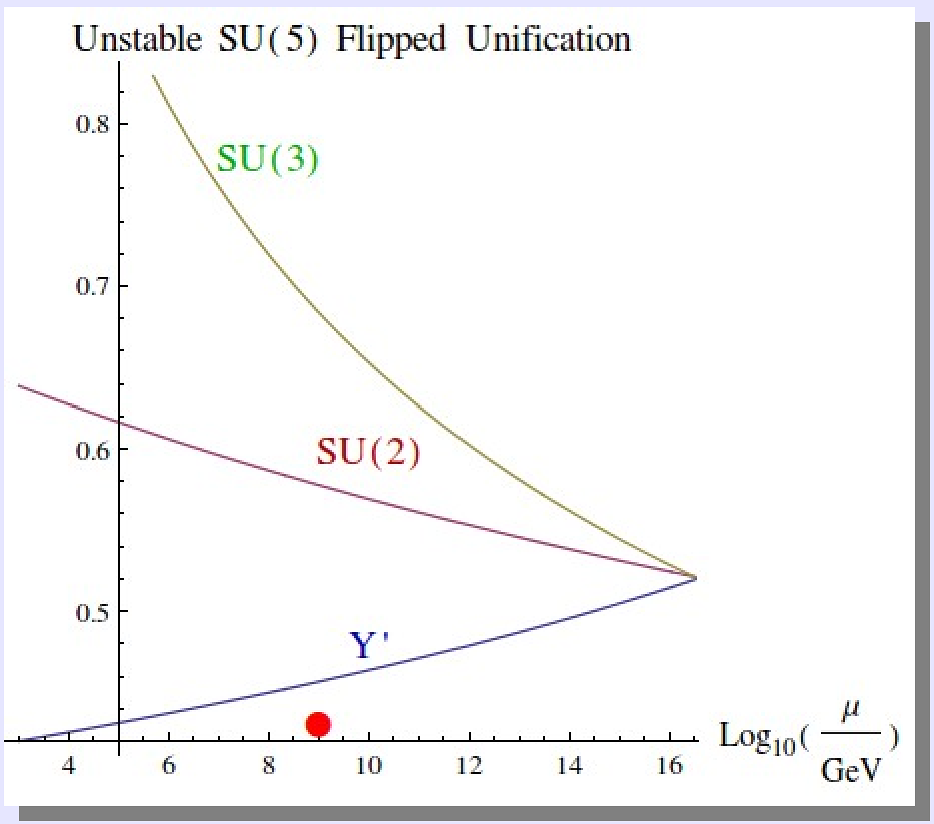
The true vacuum of the model is at perturbative reach via Renormalization Group Improvement of the Effective Potential.

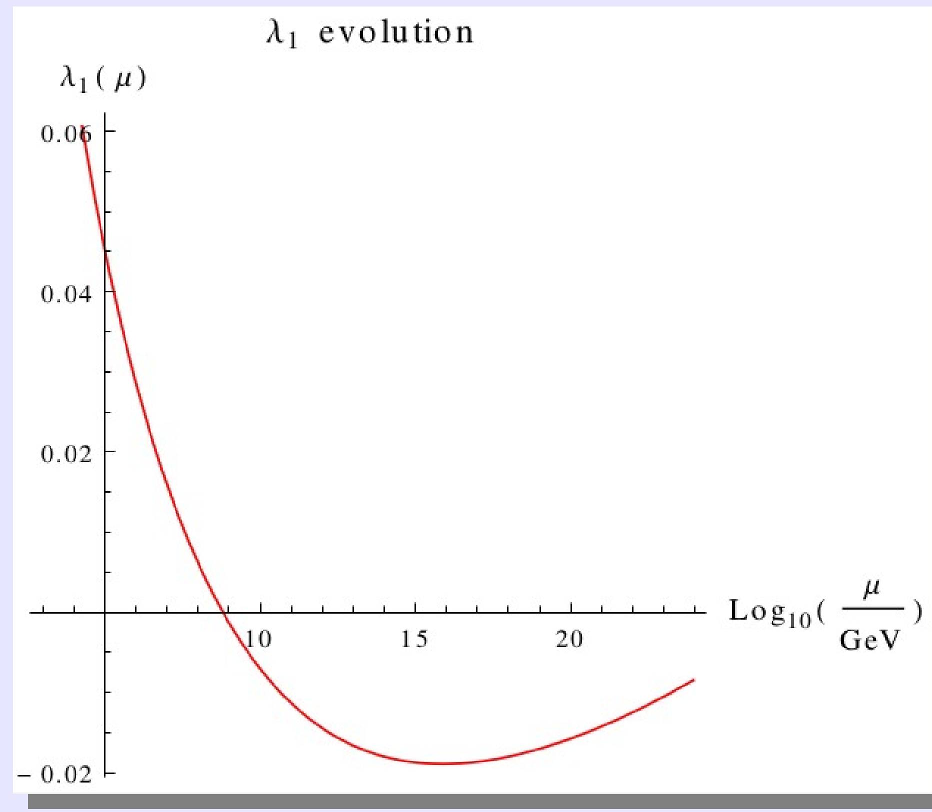
- ***Two-Loop beta functions***
  (coupled dimensionless sector)

- ***One-Loop matching of SM observables to MS parameters via Chankowski-Pokorski-Wagner scheme***
  (crucial to avoid spurious instability)

A minimal Z' class: Instability scale

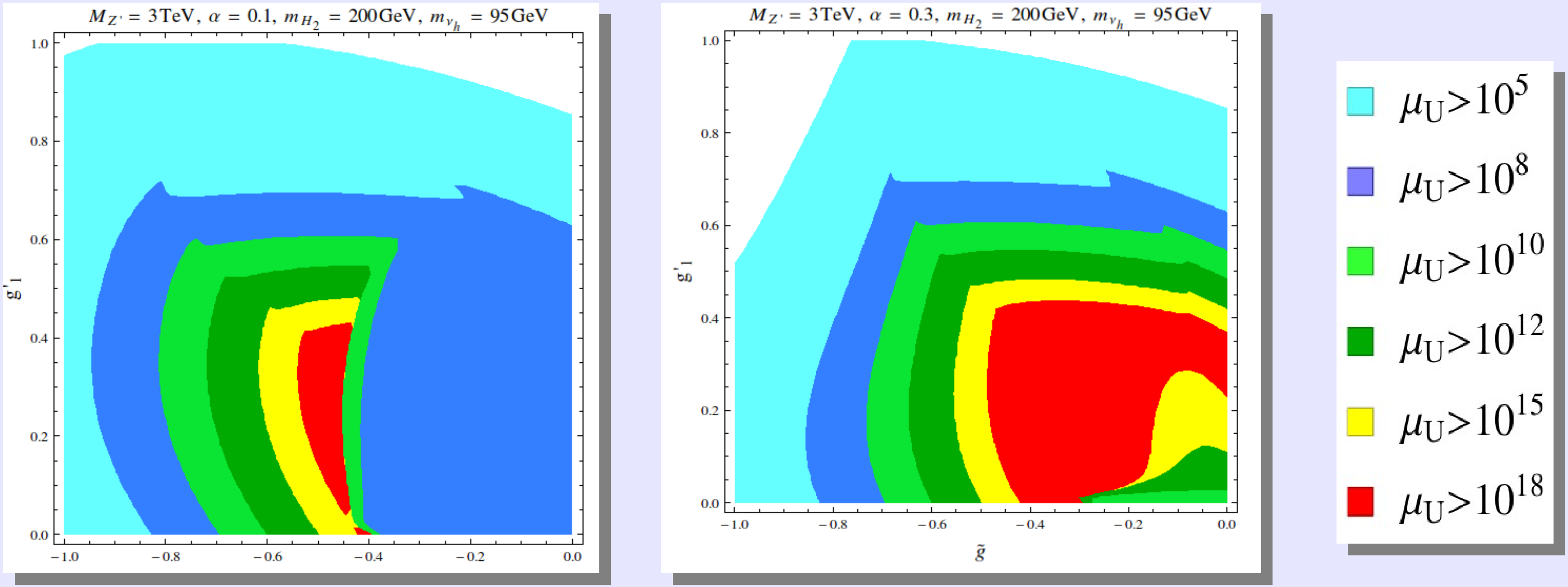
Scale of Instability vs Scale of Unification.
A mismatch:





A minimal Z' class: Instability scale

Scale of Instability vs Scale of Unification.
A coherent UV extrapolation <u>require a comparison</u>.



What happen when we compare the scales?
Back to the $U(1)_R$ and $U(1)_{B-L}$ case:

A minimal Z' class: Instability scale

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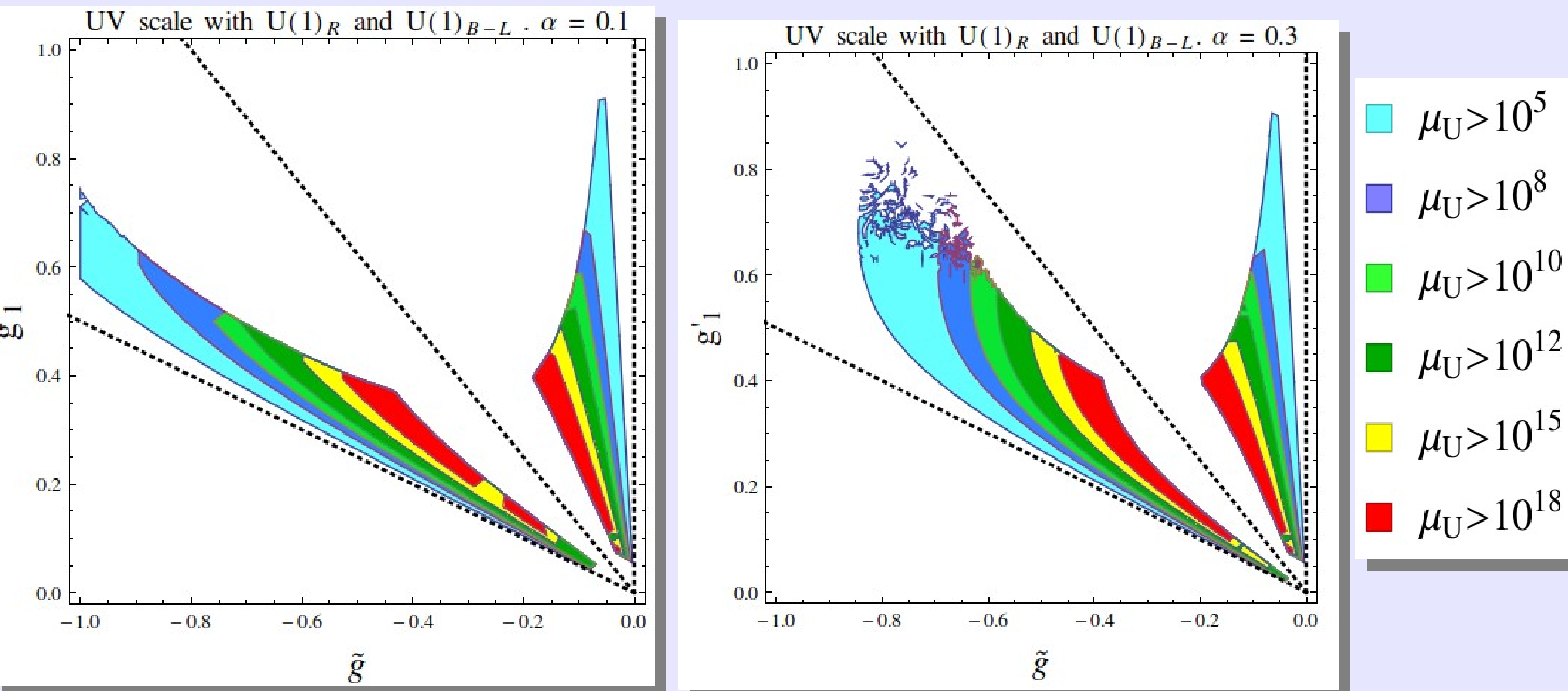

A minimal Z' class: Instability scale

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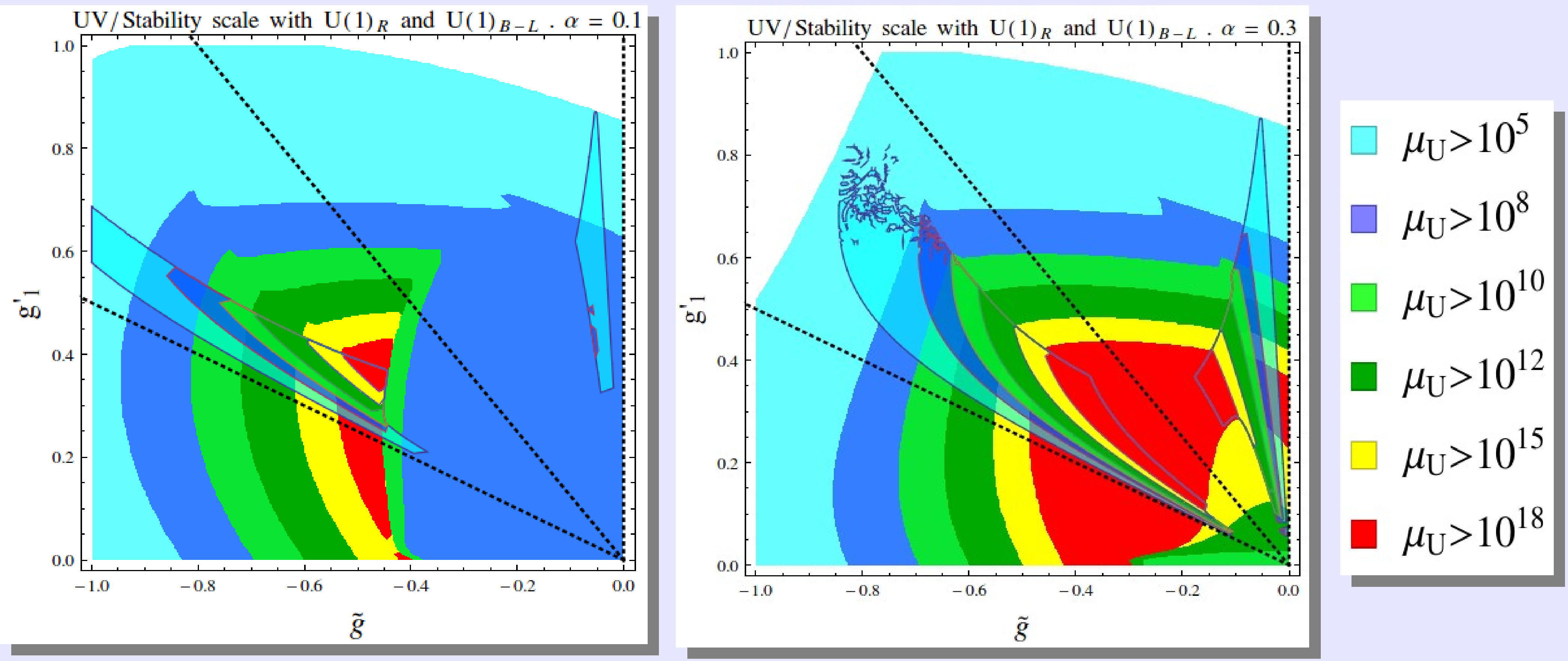
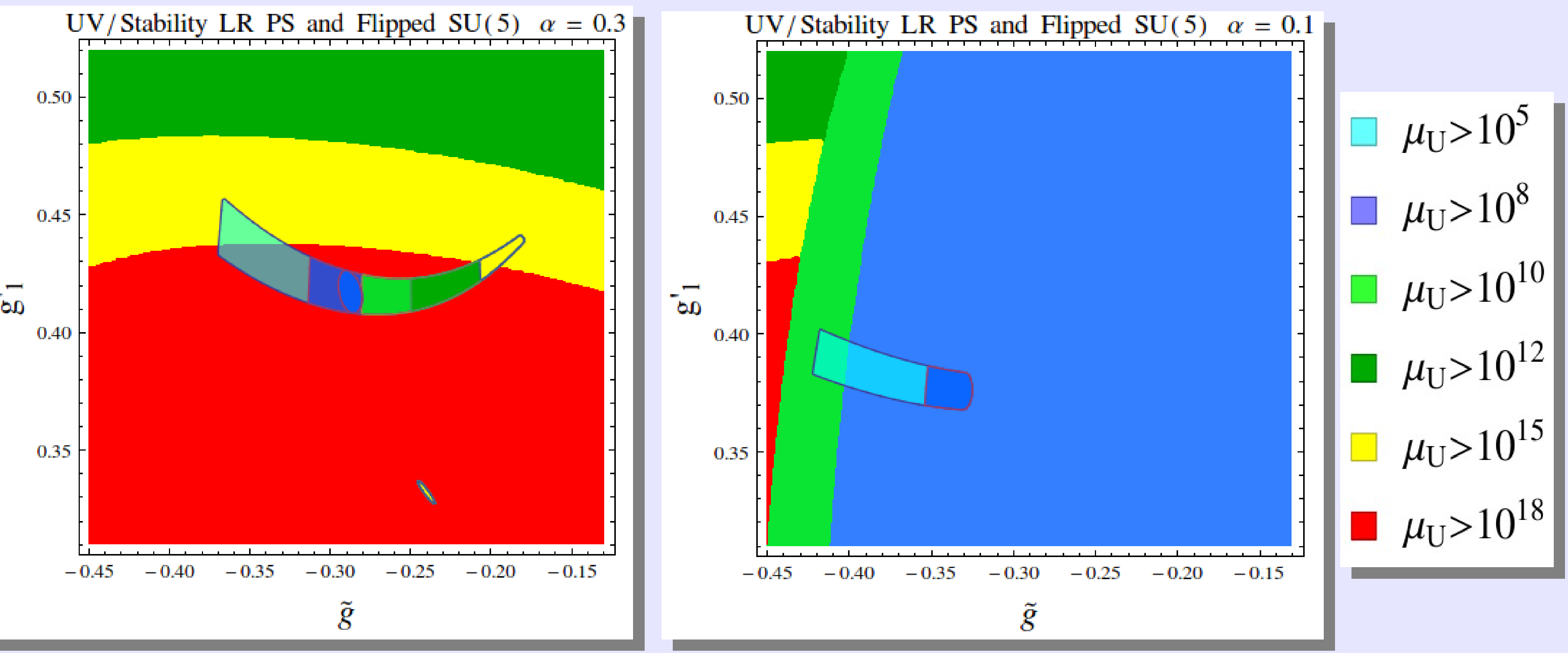


A minimal Z' class: Instability scale

What happen when we compare the scales?
Left-Right, Pati-Salam and SU(5) unification:



A minimal Z' class: Instability scale

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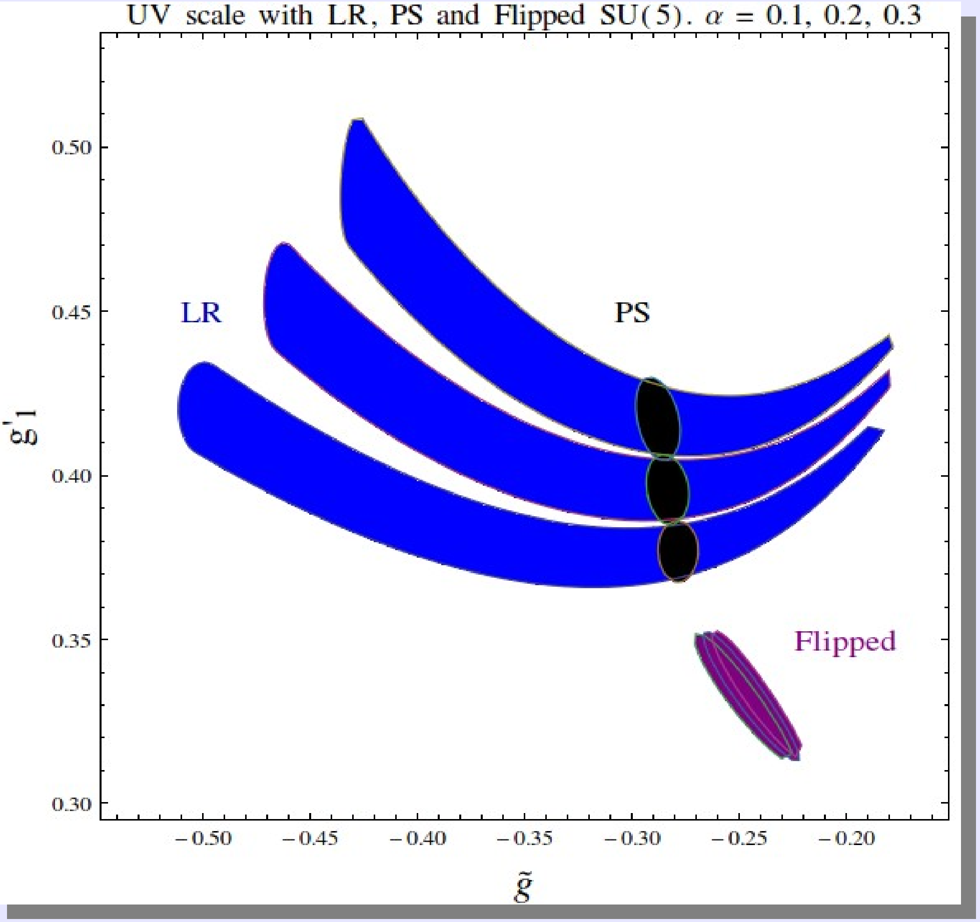

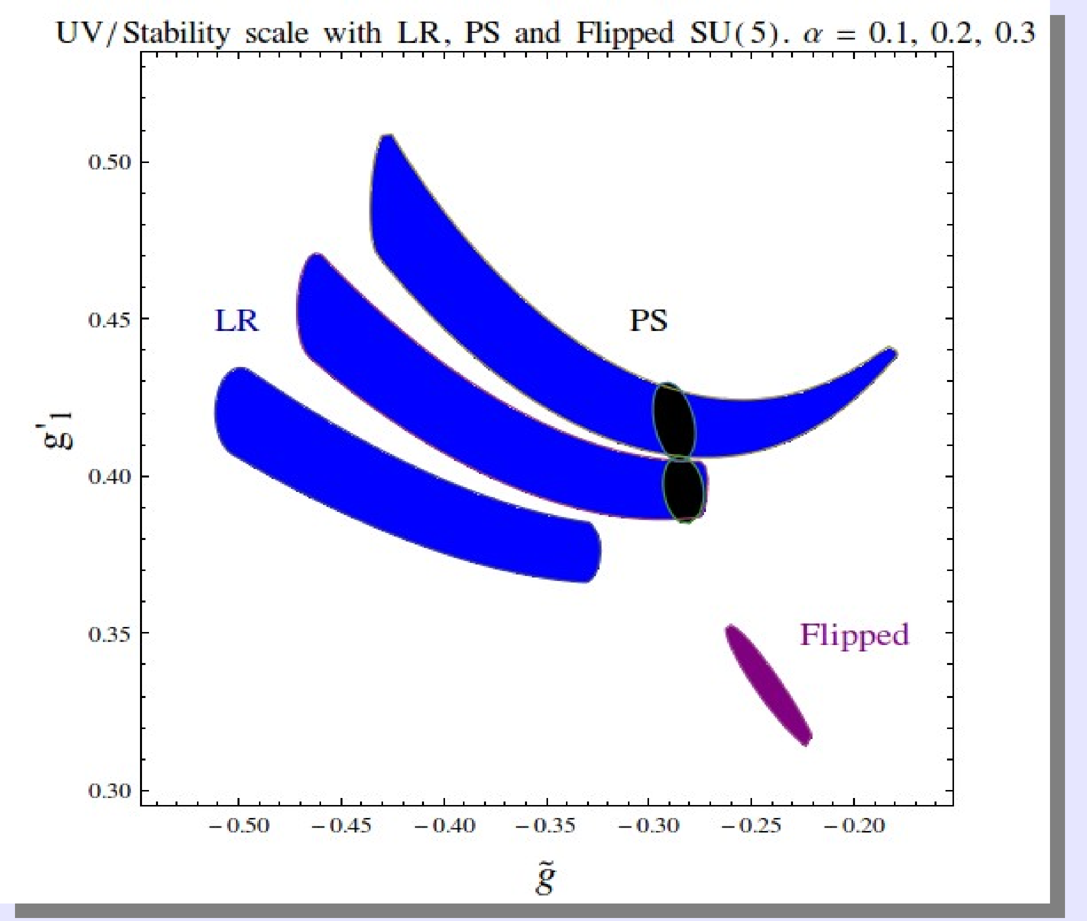

Summarizing:

- *The Abelian sector conceals footprints of possible UV-completions.*

- *A revelation of a Z' at LHC would shape the SM x $U(1)_{Y'}$ regime of a possible high-energy theory. The more we discover the more effective the renormalization group analysis can be.*

- *The unification scale and the stability scale can then emerge in the UV extrapolation of the model. These two scales must be compared in order to clarify the high-energy status of the model.*

- *<u>In case of tension among the scales</u> (instability before unification) two roads are in front of us:*

  a) Trust the unification. Then new degrees of freedom are required to stabilize the vacuum (New Scalars?)

  b) Trust the model. If no room is left for new degrees of freedom we must abandon the candidate UV-theory.

Thank you!