University of Zurich[UZH]

Physik-Institut

Lepton Flavor Violation in Composite Higgs Models with Partial Compositeness

Andrea Pattori

Joint ETH-PSI-UZH PhD Seminar

PSI, 27.08.2015

F. Feruglio, P. Paradisi, A.P. (in preparation)

Outline

- Composite Higgs Models and Partial Compositeness scenario
- A model independent approach: the spurionic analysis
- An explicit dynamical model and its predictions
- Conclusions

The hierarchy problem and its possible solutions

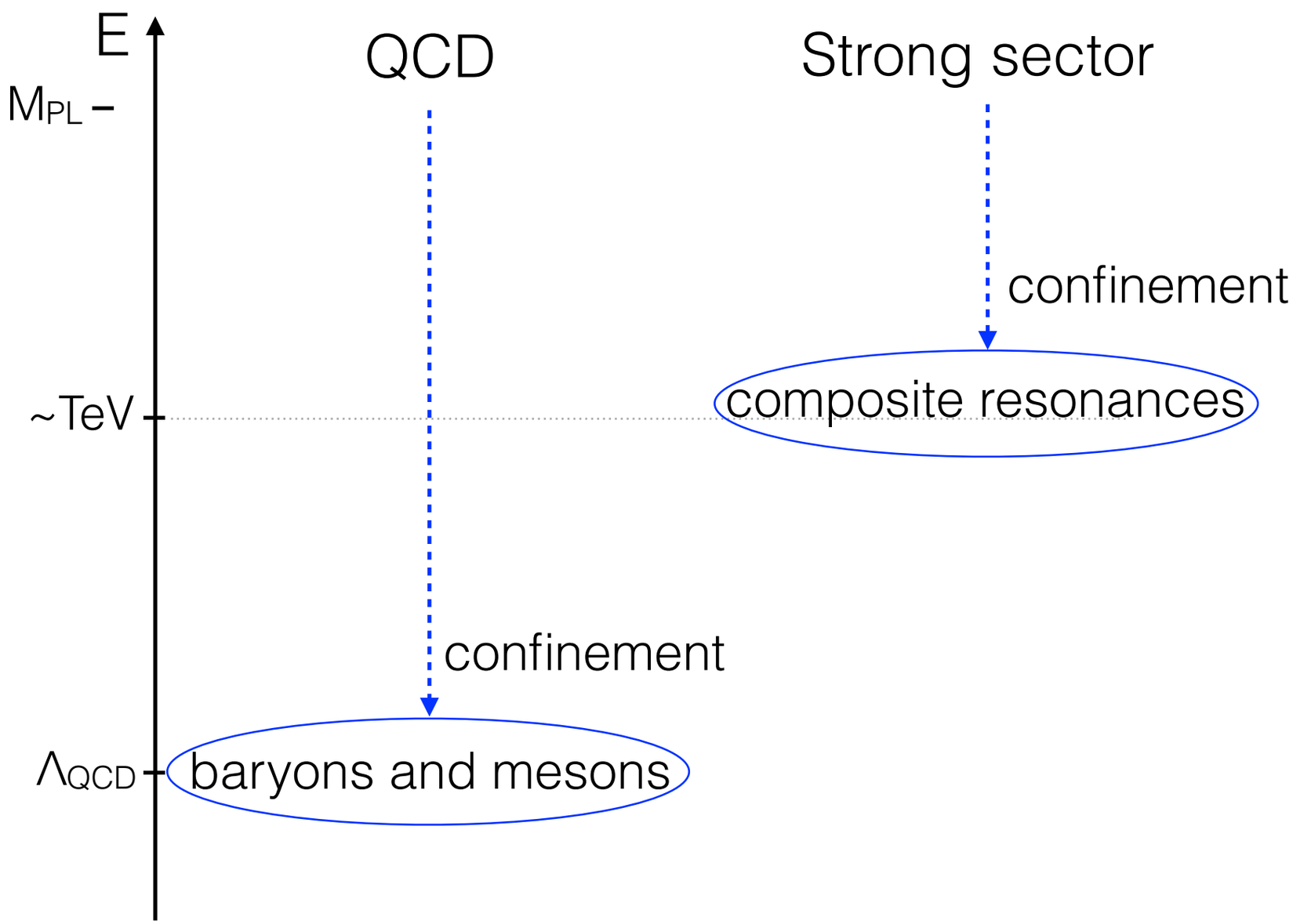
Hierarchy Problem: Huge mass gap between Planck scale (~10^{18} GeV) and EW scale (~100 GeV).

Possible solutions:

- Disregard for naturalness argumentations
- Multiverse reformulation of the problem
  - Anthropic selection
  - Likelihood of SM vacuum in the multiverse scenario
- New physics at the TeV scale
  - Supersymmetry
  - Composite Higgs models
  - “Large” compactified extra dimension(s)

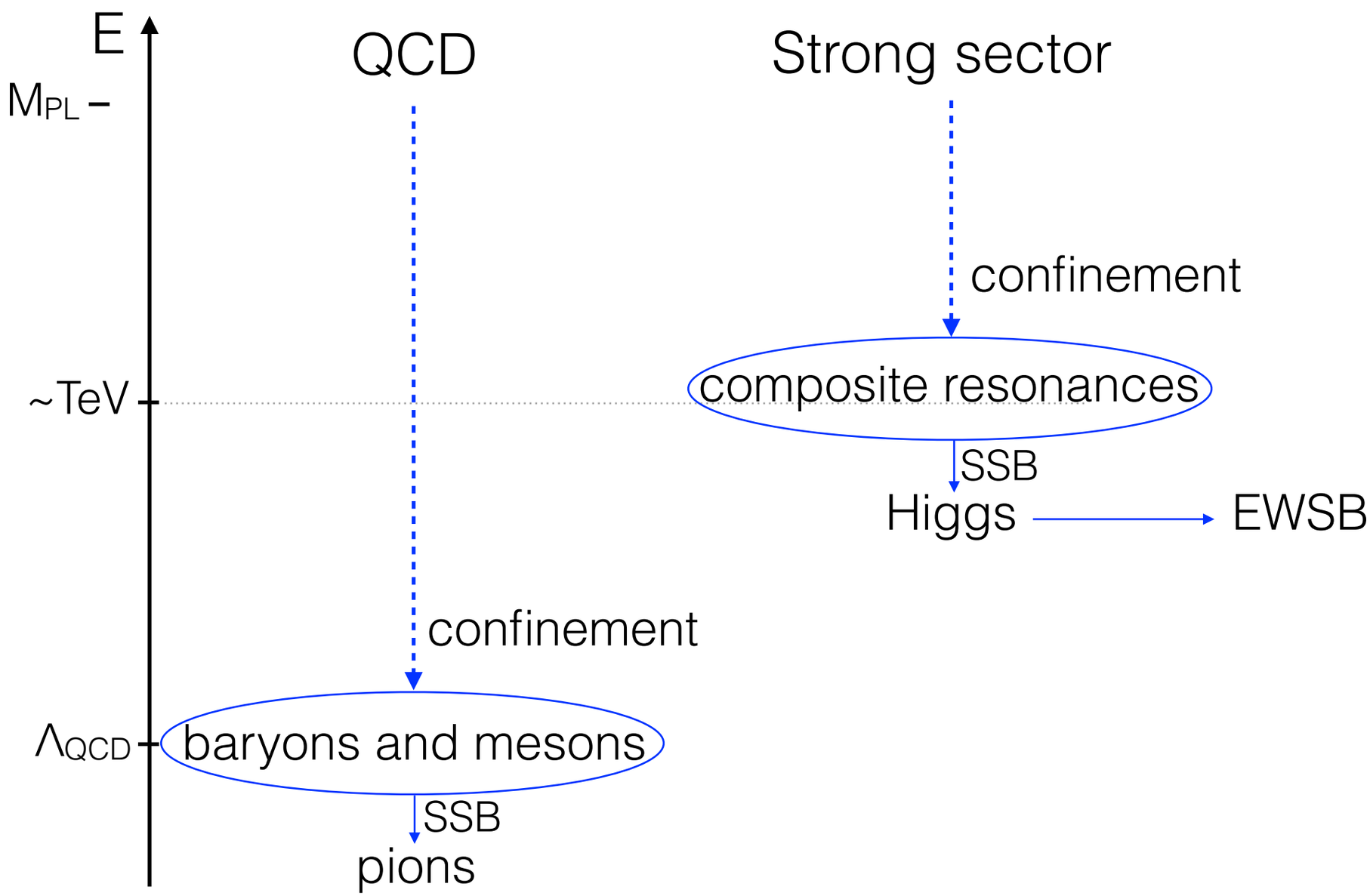
Composite Higgs models with Partial Compositeness

The Higgs as a resonance of a strong interacting sector:



Composite Higgs models with Partial Compositeness

The Higgs as a resonance of a strong interacting sector:



Composite Higgs models with Partial Compositeness

New gauge group: $\mathcal{G} = G_{SM} \times G_{ST}$

Particles charged only under G_{SM}

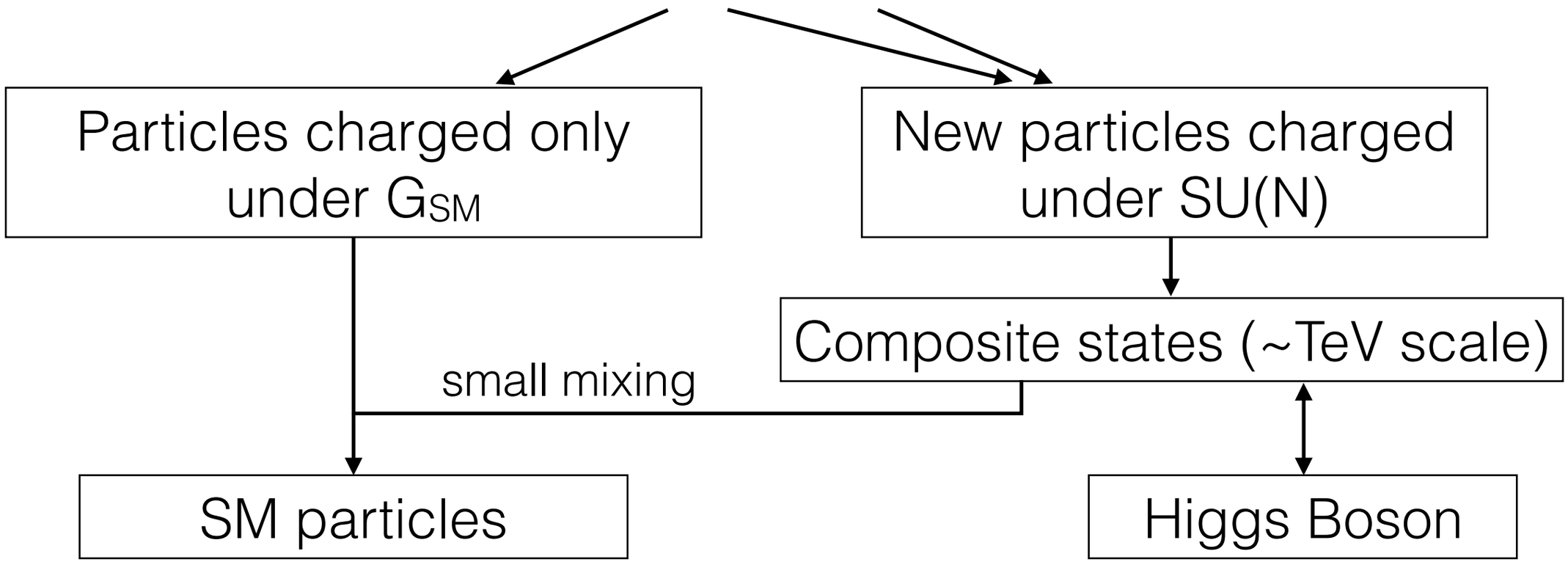
New particles charged under SU(N)

Composite states (~TeV scale)

Higgs Boson

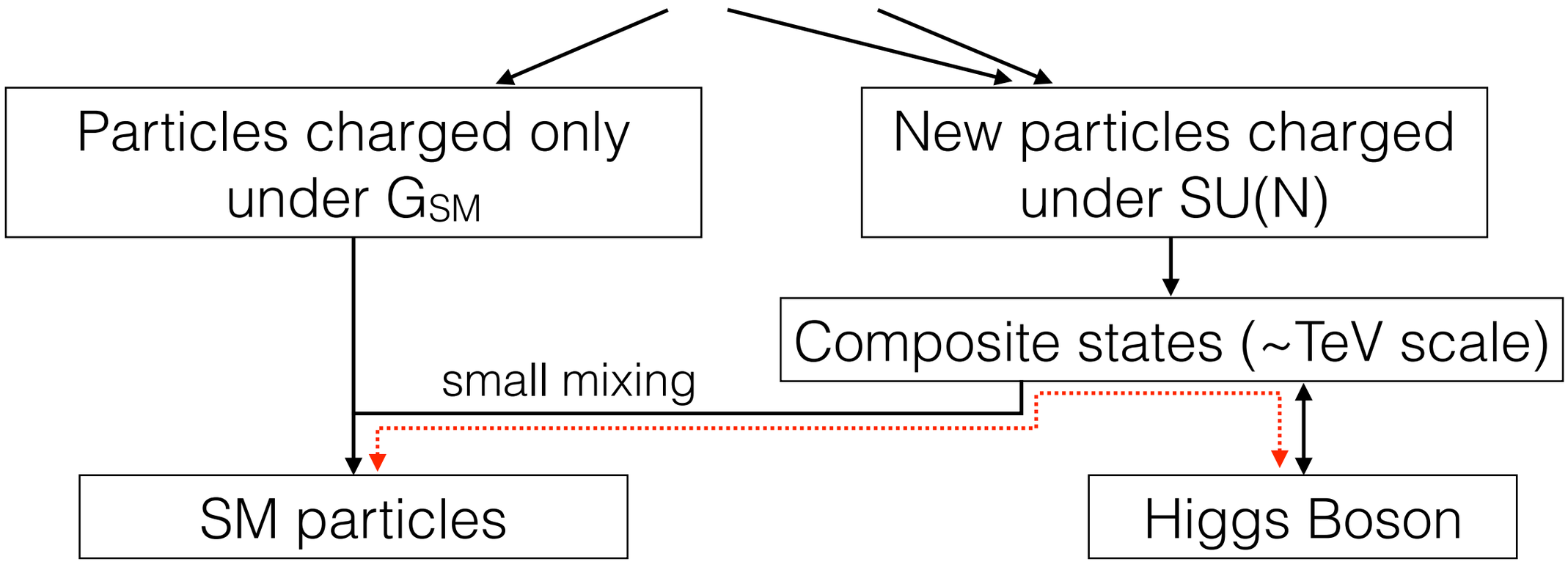
Composite Higgs models with Partial Compositeness

New gauge group: $\mathcal{G} = G_{SM} \times G_{ST}$



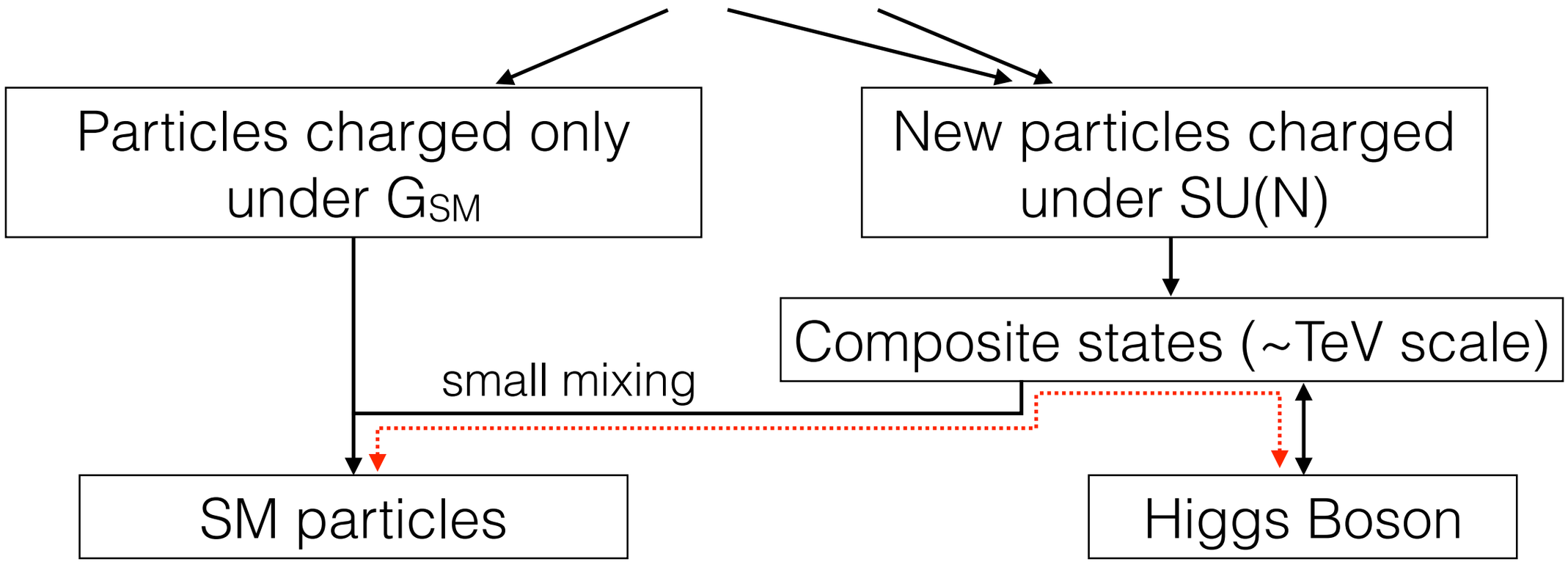
Composite Higgs models with Partial Compositeness

New gauge group: $\mathcal{G} = G_{SM} \times G_{ST}$



Composite Higgs models with Partial Compositeness

New gauge group: $\mathcal{G} = G_{SM} \times G_{ST}$



Pros:

- Solving the hierarchy problem
- Addressing the SM flavor puzzle

Cons:

- New flavor violating interactions

The spurionic approach

New set of vector-like heavy fermions.

<u>Extend the lepton flavor group:</u>

$$G_f = SU(3)^6 = \underbrace{SU(3)_\ell \times SU(3)_{\tilde{e}}}_{\text{SM flavor group}} \times \underbrace{SU(3)_{L_L} \times SU(3)_{L_R} \times SU(3)_{\tilde{E}_L} \times SU(3)_{\tilde{E}_R}}_{\text{extension}}$$

The spurionic approach

New set of vector-like heavy fermions.

<u>Extend the lepton flavor group:</u>

$$G_f = SU(3)^6 = \underbrace{SU(3)_\ell \times SU(3)_{\tilde{e}}}_{\text{SM flavor group}} \times \underbrace{SU(3)_{L_L} \times SU(3)_{L_R} \times SU(3)_{\tilde{E}_L} \times SU(3)_{\tilde{E}_R}}_{\text{extension}}$$

The most general set of **spurions**:

$$m \to V_{L_L} m V^\dagger_{L_R} \,, \qquad \Delta \to V_\ell \Delta V^\dagger_{L_R} \,, \qquad Y^*_R \to V_{L_L} Y^*_R V^\dagger_{\tilde{E}_R}$$

$$\tilde{m} \to V_{\tilde{E}_L} \tilde{m} V^\dagger_{\tilde{E}_R} \,, \qquad \tilde{\Delta} \to V_{\tilde{e}} \tilde{\Delta} V^\dagger_{\tilde{E}_L} \,, \qquad Y^*_L \to V_{L_R} Y^*_L V^\dagger_{\tilde{E}_L}$$

The spurionic approach

New set of vector-like heavy fermions.

<u>Extend the lepton flavor group:</u>

$$G_f = SU(3)^6 = \underbrace{SU(3)_\ell \times SU(3)_{\tilde{e}}}_{\text{SM flavor group}} \times \underbrace{SU(3)_{L_L} \times SU(3)_{L_R} \times SU(3)_{\tilde{E}_L} \times SU(3)_{\tilde{E}_R}}_{\text{extension}}$$

The most general set of **spurions**:

$$m \to V_{L_L} m V^\dagger_{L_R} \,, \qquad \Delta \to V_\ell \Delta V^\dagger_{L_R} \,, \qquad Y^*_R \to V_{L_L} Y^*_R V^\dagger_{\tilde{E}_R}$$

$$\tilde{m} \to V_{\tilde{E}_L} \tilde{m} V^\dagger_{\tilde{E}_R} \,, \qquad \tilde{\Delta} \to V_{\tilde{e}} \tilde{\Delta} V^\dagger_{\tilde{E}_L} \,, \qquad \cancel{Y^*_L \to V_{L_R} Y^*_L V^\dagger_{\tilde{E}_L}}$$

too dangerous:
is set to 0

The spurionic approach

Flavor violating observables for charged leptons.

EFT approach:

$$(Q_{\varphi l}^{(1)})_{ij} = (\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{\ell}_{Li}\gamma^\mu \ell_{Lj})$$

$$(Q_{\varphi l}^{(3)})_{ij} = (\varphi^\dagger i \overleftrightarrow{D}^I_\mu \varphi)(\bar{\ell}_{Li}\tau^I\gamma^\mu \ell_{Lj})$$

$$(Q_{\varphi e})_{ij} = (\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{e}_{Ri}\gamma^\mu e_{Rj})$$

$$(Q_{e\gamma})_{ij} = (\bar{\ell}_{Li}\sigma^{\mu\nu} e_{Rj})\varphi F_{\mu\nu}$$

$$(Q_{e\varphi})_{ij} = (\varphi^\dagger\varphi)(\bar{\ell}_{Li} e_{Rj}\varphi)$$

$$(Q_{ll})_{ijmn} = (\bar{\ell}_{Li}\gamma_\mu \ell_{Lj})(\bar{\ell}_{Lm}\gamma^\mu \ell_{Ln})$$

$$(Q_{ee})_{ijmn} = (\bar{e}_{Ri}\gamma_\mu e_{Rj})(\bar{e}_{Rm}\gamma^\mu e_{Rn})$$

$$(Q_{le})_{ijmn} = (\bar{\ell}_{Li}\gamma_\mu \ell_{Lj})(\bar{e}_{Rm}\gamma^\mu e_{Rn})$$

The spurionic approach

Flavor violating observables for charged leptons.

EFT approach:

$$(Q_{\varphi l}^{(1)})_{ij} = (\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{\ell}_{Li}\gamma^\mu \ell_{Lj}) \qquad (Q_{e\gamma})_{ij} = (\bar{\ell}_{Li}\sigma^{\mu\nu} e_{Rj})\varphi F_{\mu\nu} \qquad (Q_{ll})_{ijmn} = (\bar{\ell}_{Li}\gamma_\mu \ell_{Lj})(\bar{\ell}_{Lm}\gamma^\mu \ell_{Ln})$$

$$(Q_{\varphi l}^{(3)})_{ij} = (\varphi^\dagger i \overleftrightarrow{D}^I_\mu \varphi)(\bar{\ell}_{Li}\tau^I\gamma^\mu \ell_{Lj}) \qquad (Q_{e\varphi})_{ij} = (\varphi^\dagger\varphi)(\bar{\ell}_{Li} e_{Rj}\varphi) \qquad (Q_{ee})_{ijmn} = (\bar{e}_{Ri}\gamma_\mu e_{Rj})(\bar{e}_{Rm}\gamma^\mu e_{Rn})$$

$$(Q_{\varphi e})_{ij} = (\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{e}_{Ri}\gamma^\mu e_{Rj}) \qquad (Q_{le})_{ijmn} = (\bar{\ell}_{Li}\gamma_\mu \ell_{Lj})(\bar{e}_{Rm}\gamma^\mu e_{Rn})$$

<u>Spurionic analysis</u>. Deriving either:

- Constraints on the mass scale of the CH sector
- Hypothesis on the structure of the spurions

The spurionic approach: results

- Classification of the spurionic structures
- Model independent phenomenological analysis of LFV
- Showed that $Y_L^* = 0$ could be not sufficient
- Identified an <u>Intermediate Flavor Violation (IFV) scenario</u>: $m, \tilde{m}, Y_R^*$ aligned

An explicit model

Considering a <u>specific dynamical model</u> (Contino et al., arXiv:hep-ph/0612180).

An explicit model

Considering a <u>specific dynamical model</u> (Contino et al., arXiv:hep-ph/0612180).

Lagrangian:

The SM Lagrangian

$$\mathcal{L} = -\frac{1}{4}(F^a_{\mu\nu})^2 + \bar{f} i \not{D} f$$

An explicit model

Considering a <u>specific dynamical model</u> (Contino et al., arXiv:hep-ph/0612180).

Lagrangian:

The SM Lagrangian

The Lagrangian for the composite states

$$\mathcal{L} = -\frac{1}{4}(F^a_{\mu\nu})^2 + \bar{f} i \not{D} f - \frac{1}{4}(\rho^a_{\mu\nu})^2 + \frac{M_*^2}{2}(\rho^a_\mu)^2 + \bar{F}(i\not{D} - m)F$$

An explicit model

Considering a <u>specific dynamical model</u> (Contino et al., arXiv:hep-ph/0612180).

Lagrangian:

The SM Lagrangian

The Lagrangian for the composite states

$$\mathcal{L} = -\frac{1}{4}(F^a_{\mu\nu})^2 + \bar{f} i \not{D} f - \frac{1}{4}(\rho^a_{\mu\nu})^2 + \frac{M_*^2}{2}(\rho^a_\mu)^2 + \bar{F}(i\not{D} - m)F$$

$$- M_*^2 A^a_\mu \rho^{\mu\, a} + \frac{M_*^2}{2}(A^a_\mu)^2 - (\Delta \bar{f} F + \text{h.c.})$$

Mass mixing terms

An explicit model

Considering a <u>specific dynamical model</u> (Contino et al., arXiv:hep-ph/0612180).

Lagrangian:

The SM Lagrangian

The Lagrangian for the composite states

$$\mathcal{L} = -\frac{1}{4}(F^a_{\mu\nu})^2 + \bar{f} i \not{D} f - \frac{1}{4}(\rho^a_{\mu\nu})^2 + \frac{M_*^2}{2}(\rho^a_\mu)^2 + \bar{F}(i\not{D} - m)F$$

$$- M_*^2 A^a_\mu \rho^{\mu\, a} + \frac{M_*^2}{2}(A^a_\mu)^2 - (\Delta \bar{f} F + \text{h.c.}) + |D_\mu \varphi|^2 - V(\varphi) - Y \bar{F} \varphi F$$

Mass mixing terms

The Higgs Lagrangian

An explicit model

Lepton content:

- SM leptons: ℓ_L , e_R.
- Heavy leptons: L_L, L_R, E_L, E_R.

$$G_f = SU(3)^6$$

An explicit model

Lepton content:

- SM leptons: ℓ_L , e_R.
- Heavy leptons: L_L, L_R, E_L, E_R.

$$G_f = SU(3)^6$$

Spurions:

- Mass terms: $\mathcal{L}_{\rm mass} = -m\bar{L}L - \tilde{m}\bar{E}E + \text{h.c.}$
- Yukawa: $\mathcal{L}_{\rm yuk} = -Y_R\bar{L}_L\phi E_R - Y_L\bar{L}_R\phi E_L + \text{h.c.}$
- Mass mixing: $\mathcal{L}_{\rm mix} = -\Delta\,\bar{\ell}_L L_R - \tilde{\Delta}\,\bar{e}_R E_L + \text{h.c.}$

An explicit model

Lepton content:

- SM leptons: ℓ_L , e_R.
- Heavy leptons: L_L, L_R, E_L, E_R.

$$G_f = SU(3)^6$$

Spurions:

- Mass terms: $\mathcal{L}_{\rm mass} = -m\bar{L}L - \tilde{m}\bar{E}E + \text{h.c.}$
- Yukawa: $\mathcal{L}_{\rm yuk} = -Y_R\bar{L}_L\phi E_R - \cancel{Y_L\bar{L}_R\phi E_L} + \text{h.c.}$
- Mass mixing: $\mathcal{L}_{\rm mix} = -\Delta\,\bar{\ell}_L L_R - \tilde{\Delta}\,\bar{e}_R E_L + \text{h.c.}$

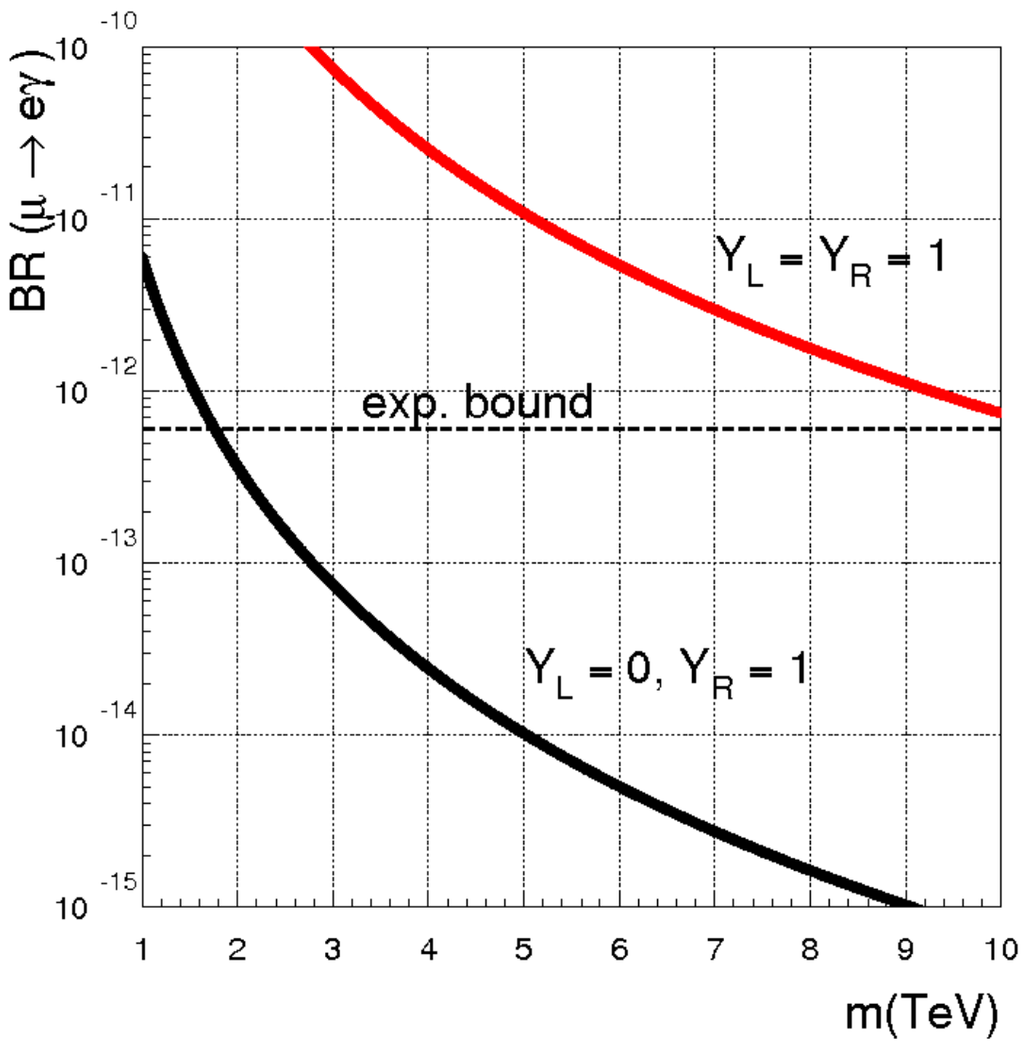
An explicit model

We have performed explicit calculations:

- Confirmed the presence of the predicted spurionic structures
- Explicit one-loop result for the dipole operator $(Q_{e\gamma})_{ij} = (\bar{\ell}_{Li}\sigma^{\mu\nu}e_{Rj})\varphi F_{\mu\nu}$
- Phenomenological predictions for various observables

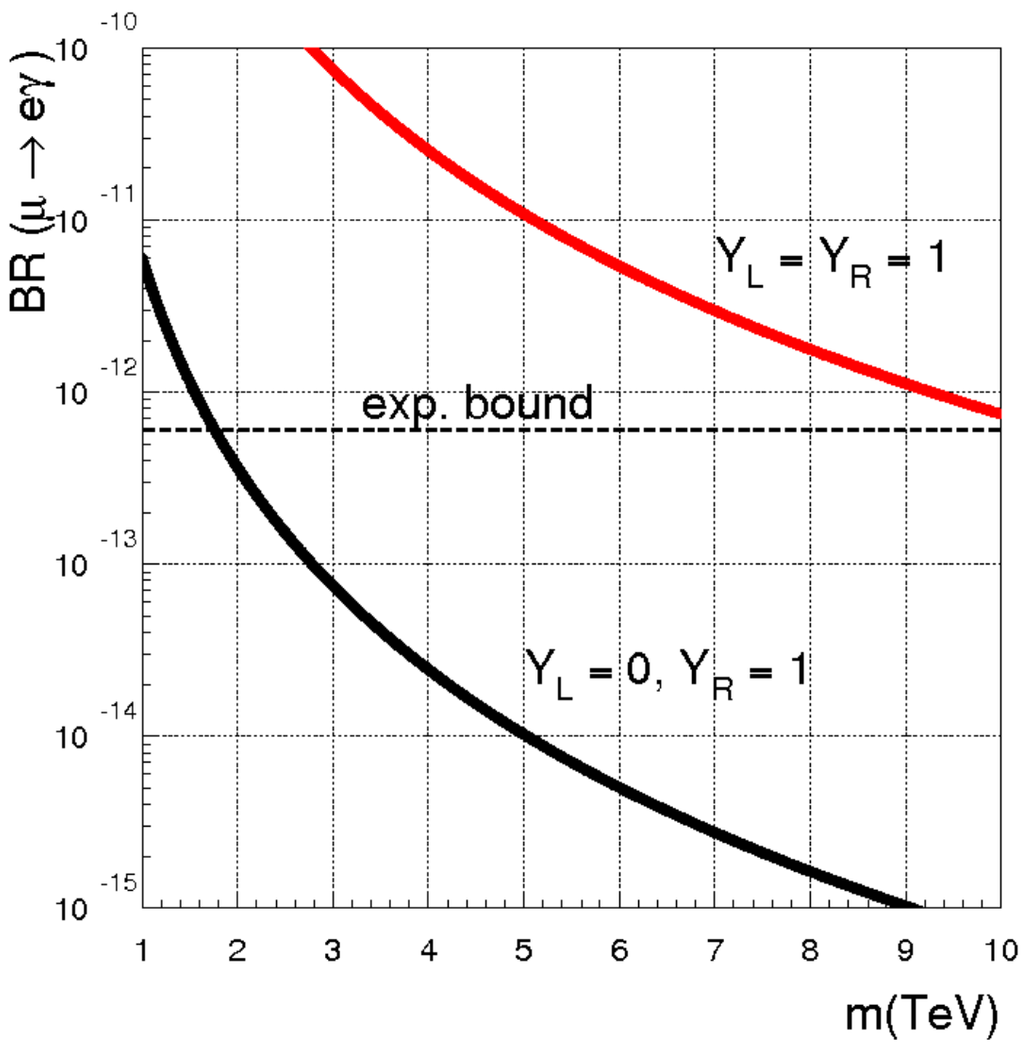
Phenomenological analysis

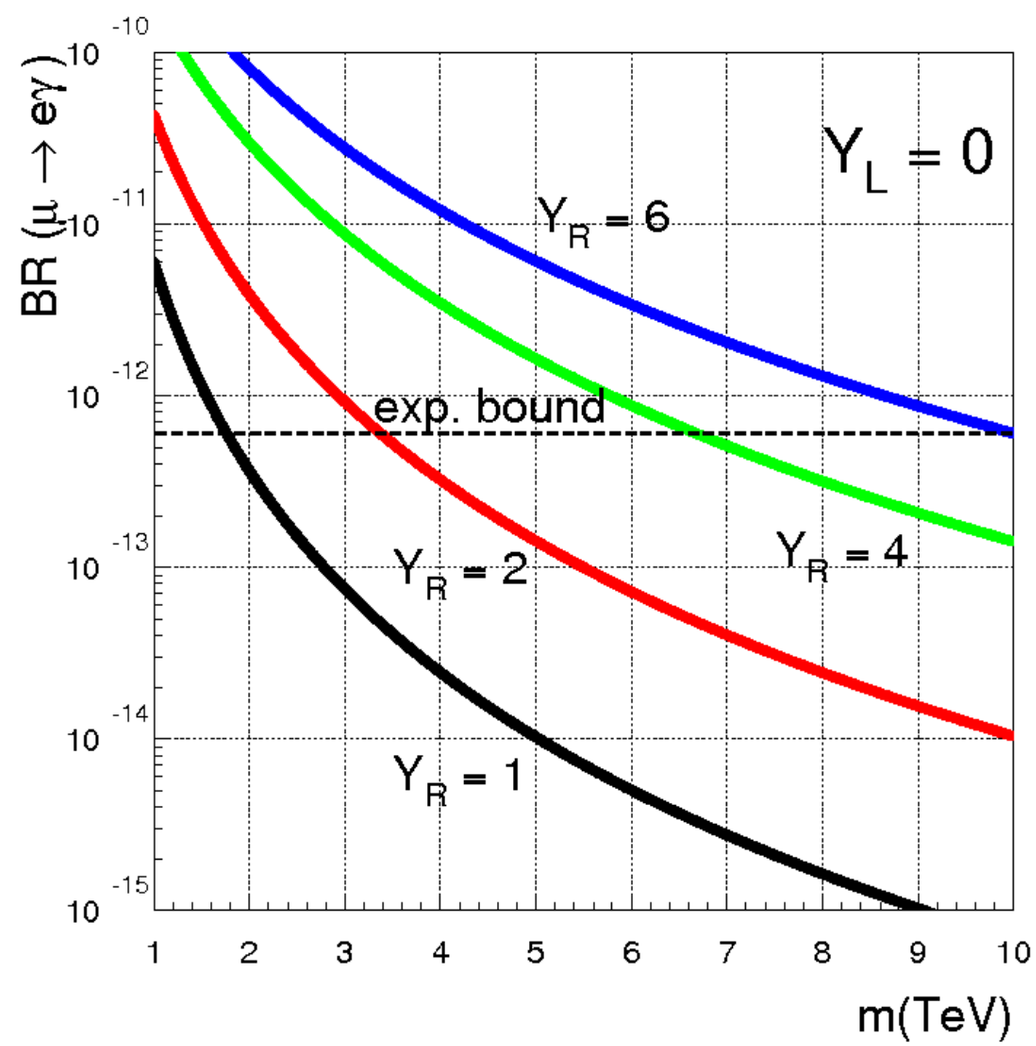
Analysing $BR(\mu \to e\gamma)$



Phenomenological analysis

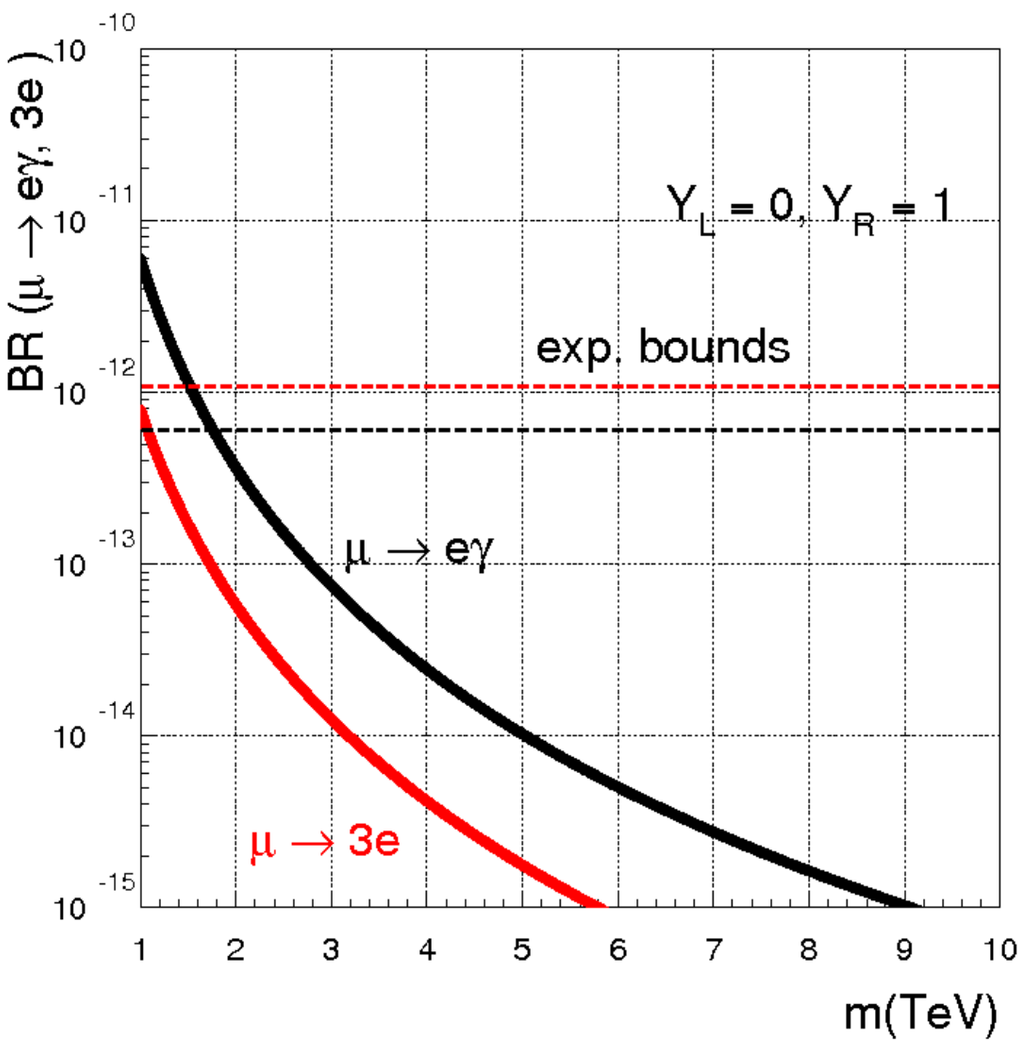
Analysing $BR(\mu \to e\gamma)$





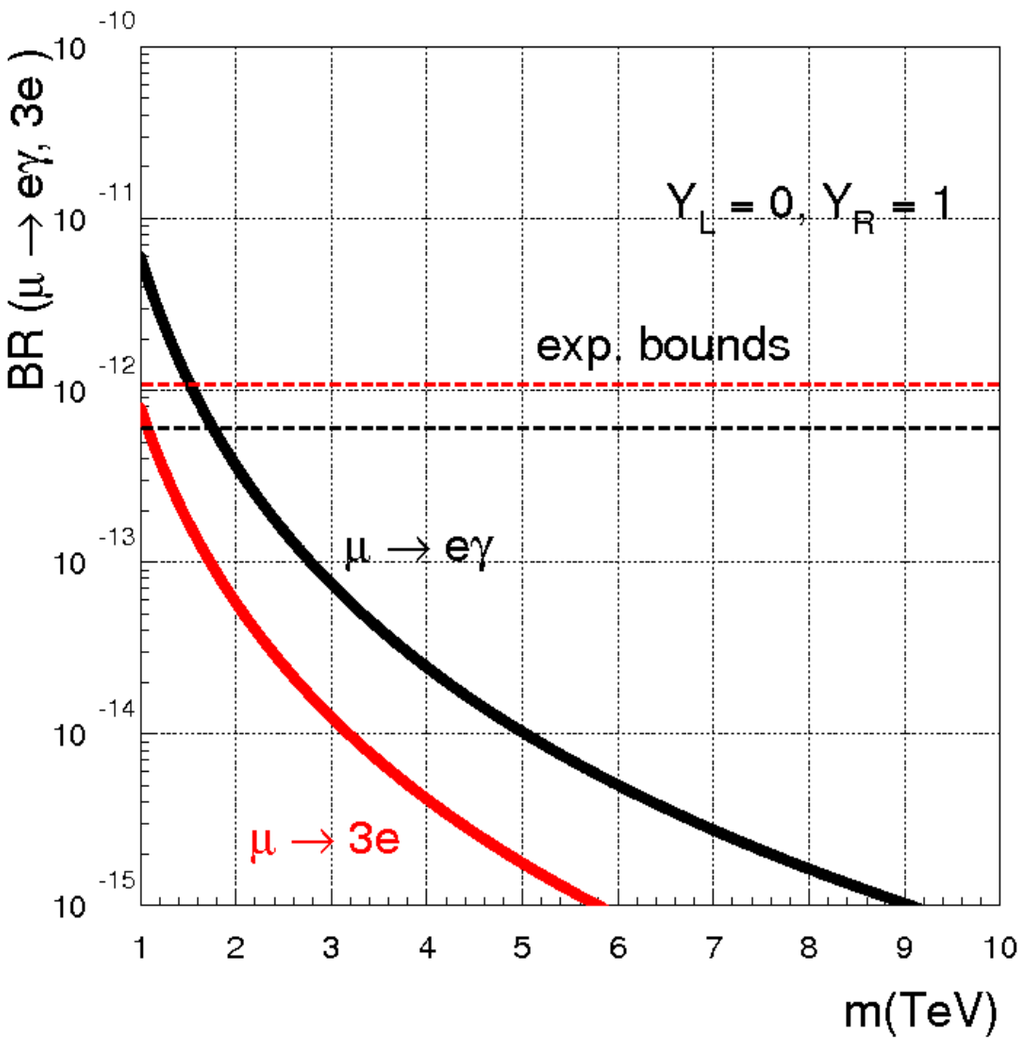
Phenomenological analysis

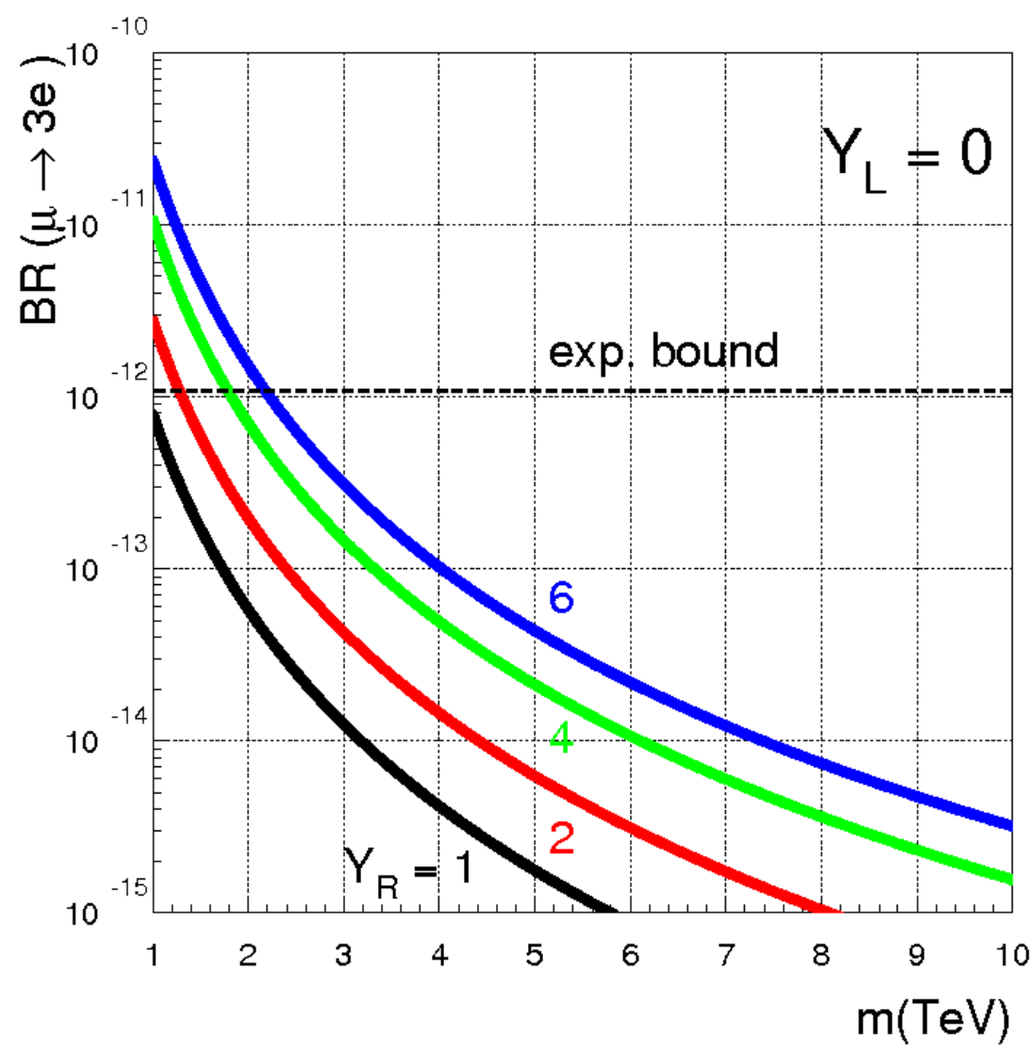
Analysing $BR(\mu \to 3\,e)$



Phenomenological analysis

Analysing $BR(\mu \to 3\,e)$





Conclusions

- From general spurionic approach:
  - Thorough classification of the spurionic structures
  - Prescriptions for viable TeV scale scenarios (IFV)
- From explicit dynamical model:
  - Confirmation of the spurionic analysis
  - Detailed phenomenological analysis

Conclusions

- From general spurionic approach:
  - Thorough classification of the spurionic structures
  - Prescriptions for viable TeV scale scenarios (IFV)
- From explicit dynamical model:
  - Confirmation of the spurionic analysis
  - Detailed phenomenological analysis

Thank You