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Lepton Flavor Violation in Composite Higgs Models

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outline

- Composite Higgs models
    - reasons and features
    - fermion masses
    - possible approaches
- Flavor structure and CLFV
    - overview on the flavor structure
    - anarchic scenarios
    - scenarios with flavor symmetries
- Insights using the simplified approach

why Composite Higgs?

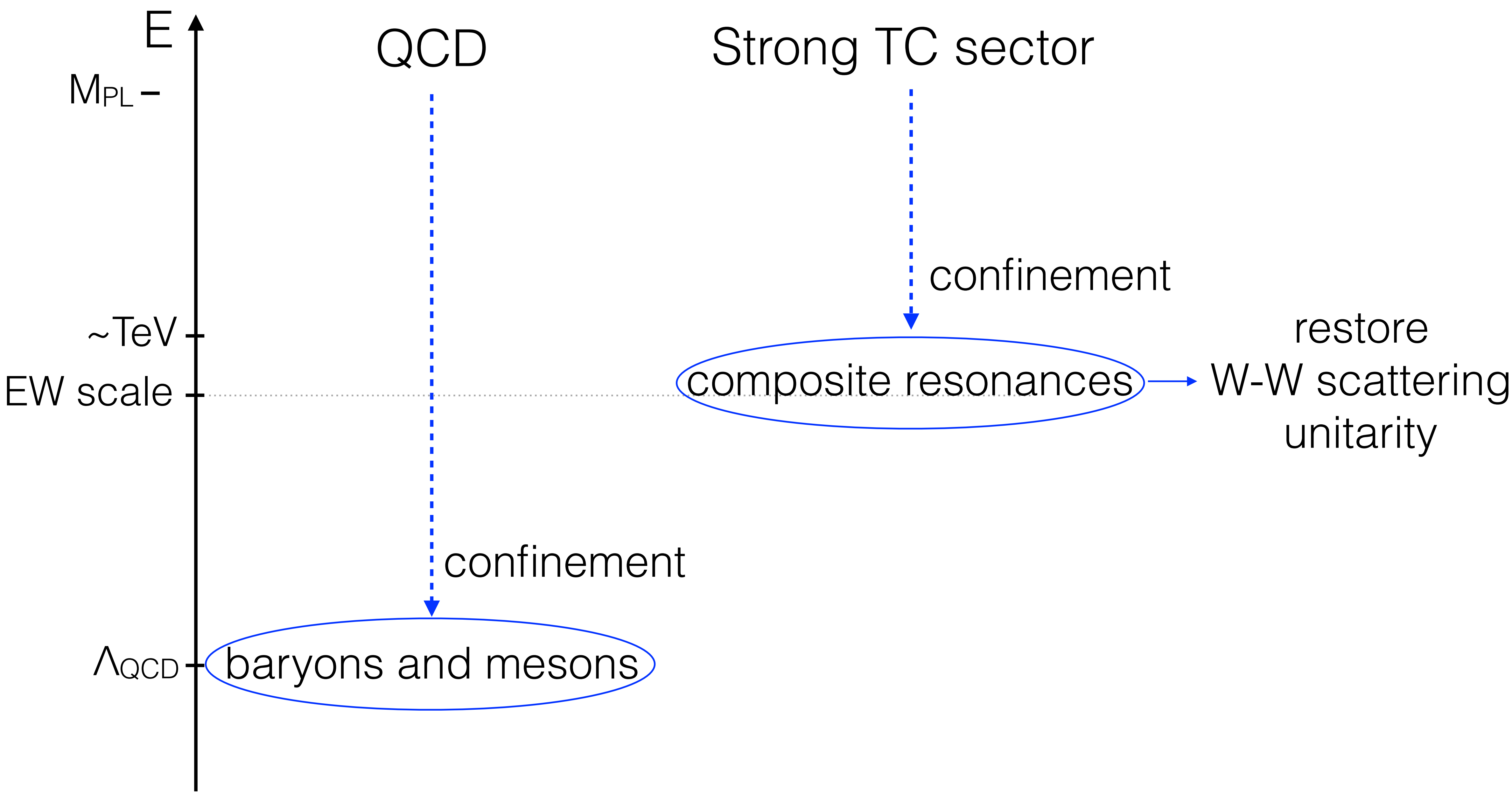
Hierarchy Problem: Huge mass gap between Planck scale (~10^{18} GeV) and EW scale (~100 GeV).

Possible solutions:

- New Physics at the TeV scale
    - Weak interaction (Supersymmetry)
    - Strong interaction (Composite Higgs)
- "Cosmological" explanation
    - Multiverse scenario (anthropic selection, SM likelihood)
    - Relaxion mechanism
- Disregard for naturalness argumentations

- Tecnicolor (TC) theories

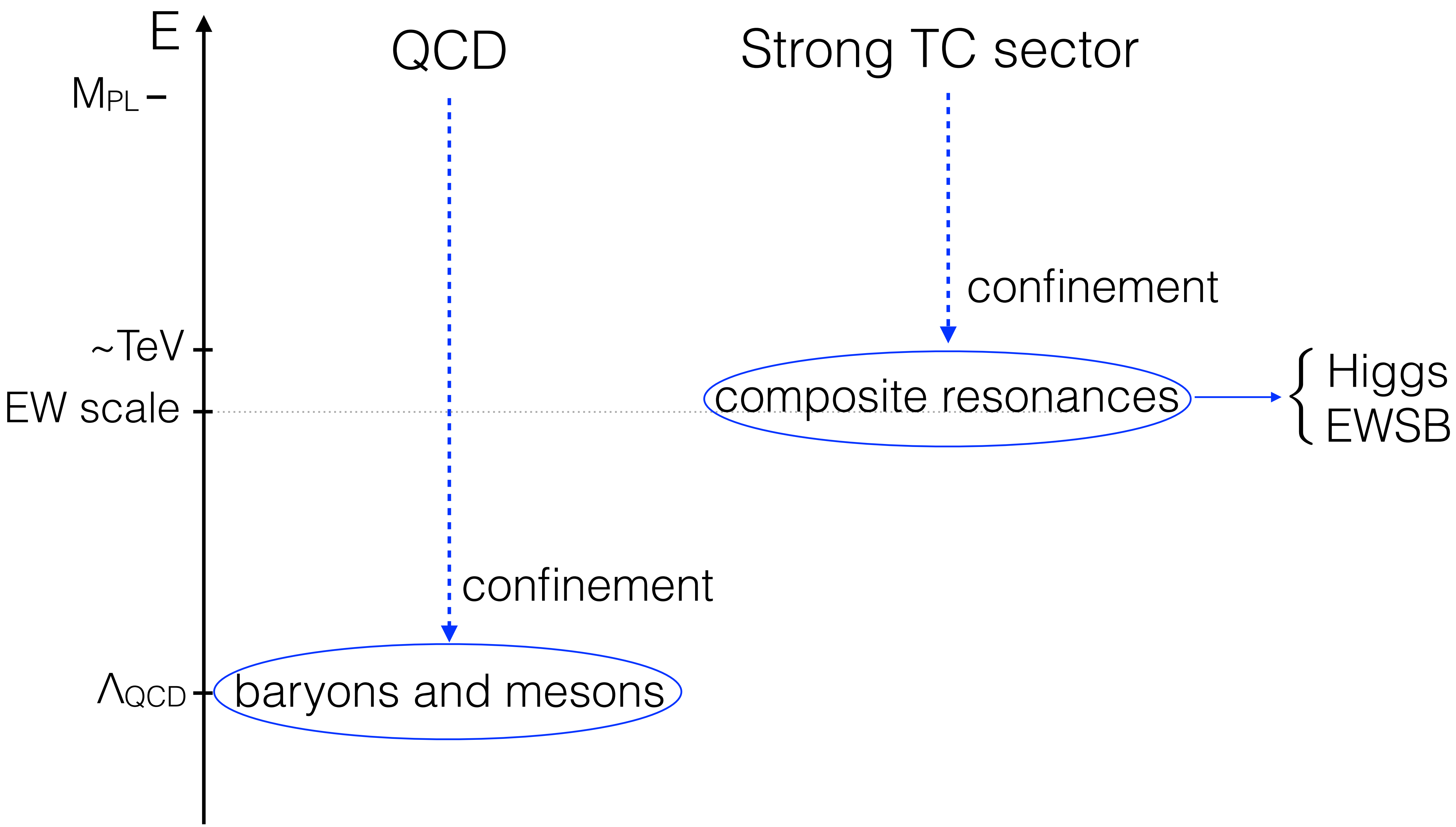
[Weinberg, '76]
[Susskind, '79]



enter the Composite Higgs

- Composite Higgs (CH) models

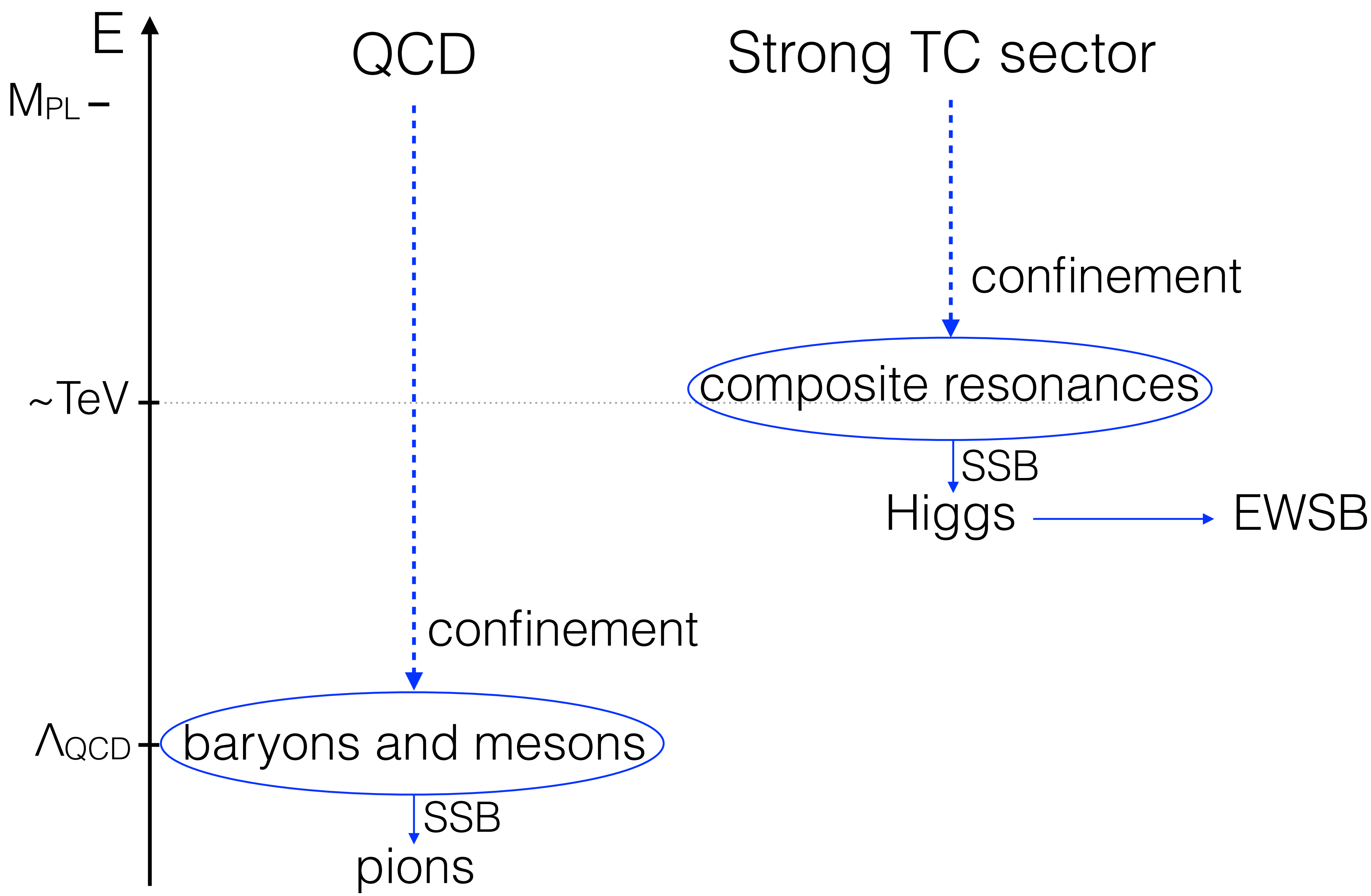
[Dimopoulos, Susskind, ’79]
[’t Hooft, ’80]



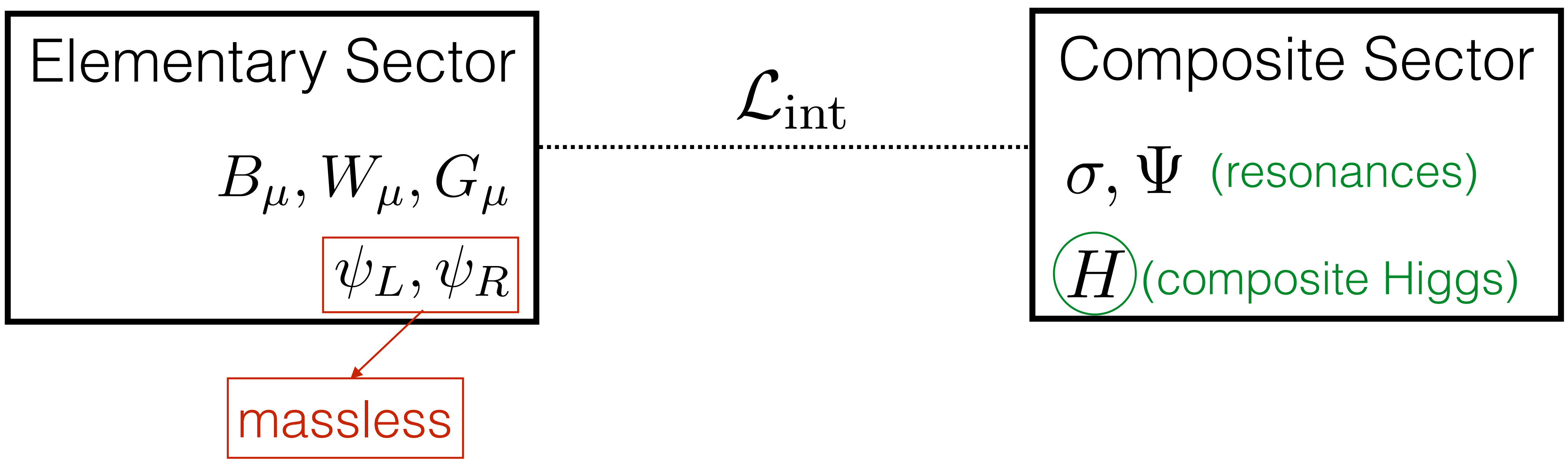
why the Higgs is lighter?

- Higgs as a pseudo-Nambu-Goldstone (pNG)

[Kaplan, Georgi, ’84]
[Kaplan, Georgi, Dimopoulos ’84]
[Dugan, Kaplan, Georgi, ’85]



fermion masses through bilinears



fermion masses through bilinears

Elementary Sector

B_μ, W_μ, G_μ

ψ_L, ψ_R → massless

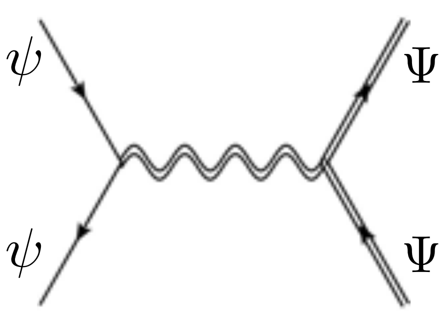
$\mathcal{L}_{\rm int}$

Composite Sector

σ, Ψ (resonances)

H (composite Higgs)

- old TC models: $\mathcal{L}_{\rm int} = \frac{1}{\Lambda_{TC}^2}(\bar{\psi}\psi)(\bar{\Psi}\Psi)$ [Weinberg, '76, '79] [Dimopoulos, Susskind, '79]



$$\sim \frac{1}{\Lambda_{TC}^2}(\bar{\psi}\psi)\,(\bar{\Psi}\Psi) \to \frac{\langle\bar{\Psi}\Psi\rangle}{\Lambda_{TC}^2}\bar{\psi}\psi$$

➤ SM fermion masses

fermion masses through bilinears

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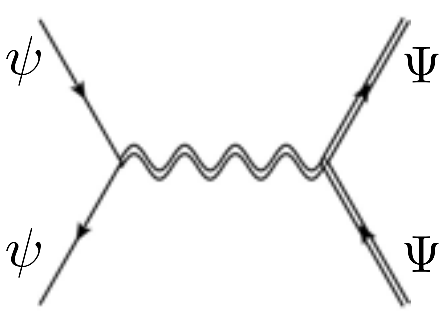

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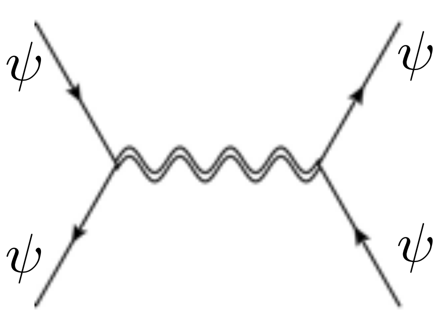
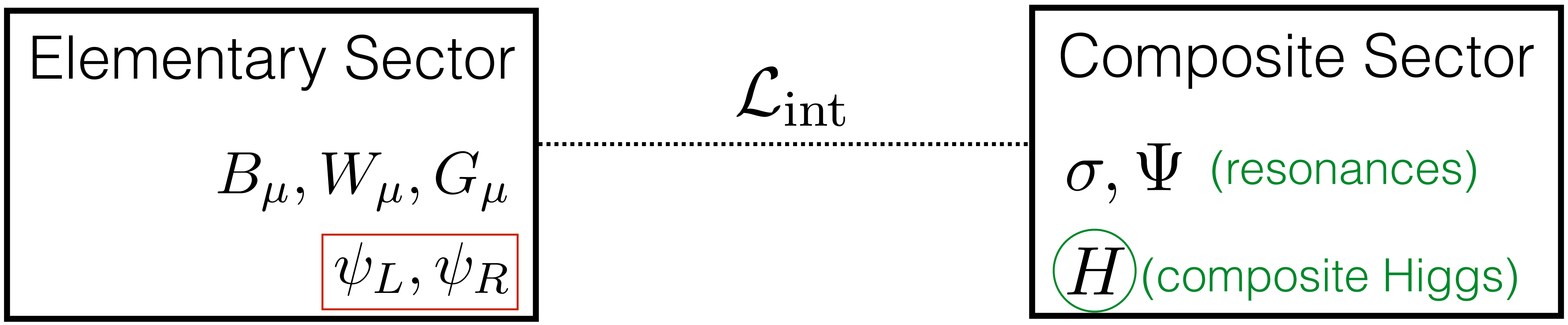


$$\sim \frac{1}{\Lambda^2_{TC}}(\bar{\psi}\psi)(\bar{\psi}\psi)$$

➤ FCNC → **Incompatible**



[Kaplan, '91]

different fields

- Partial Compositeness: $\mathcal{L}_{\text{int}} = \Delta_L \bar{\Psi}^{\mathbf{2}}_R \psi_L + \Delta_R \bar{\Psi}^{\mathbf{1}}_L \psi_R + \text{h.c.} \qquad \frac{\Delta}{m_\Psi} = \epsilon \ll 1$

fermion masses through partial compositeness

Elementary Sector: B_μ, W_μ, G_μ, ψ_L, ψ_R $\cdots\cdots \mathcal{L}_{\text{int}} \cdots\cdots$ **Composite Sector**: σ, Ψ (resonances), H (composite Higgs)

[Kaplan, '91]

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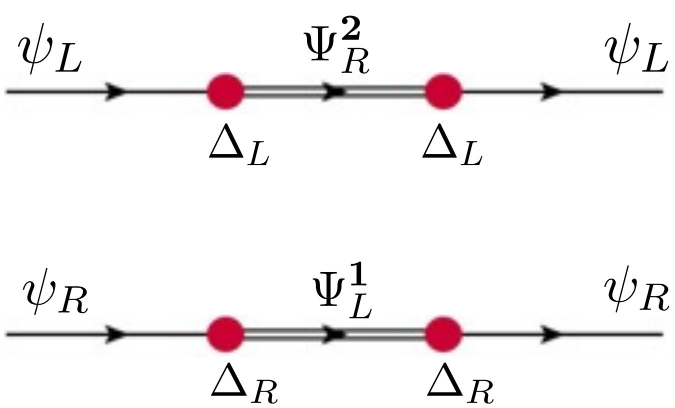
SM sector: <u>admixture</u>
elementary/composite



fermion masses through partial compositeness

Elementary Sector		Composite Sector
B_μ, W_μ, G_μ	$\mathcal{L}_{\text{int}}$	σ, Ψ (resonances)
ψ_L, ψ_R		H (composite Higgs)

[Kaplan, '91]

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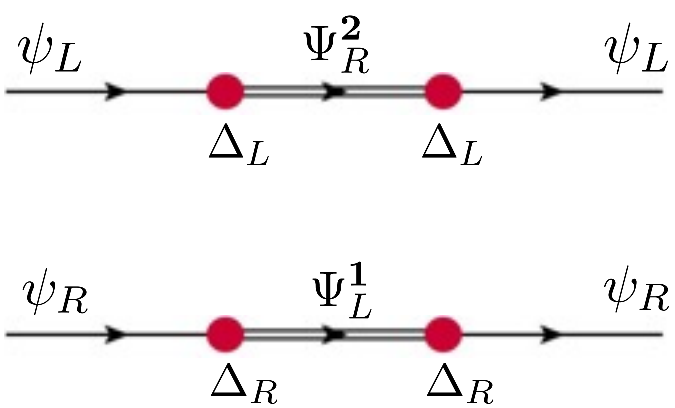
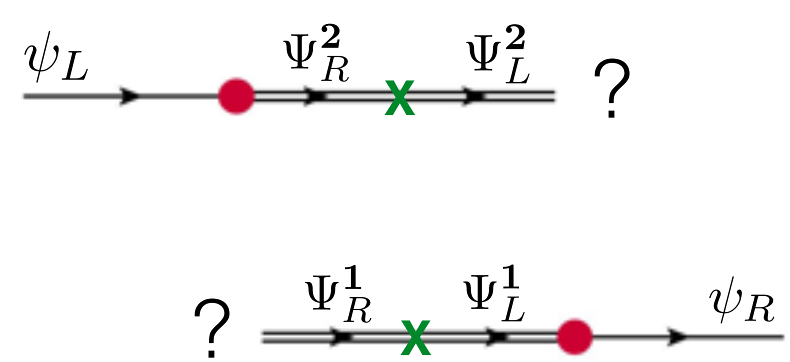
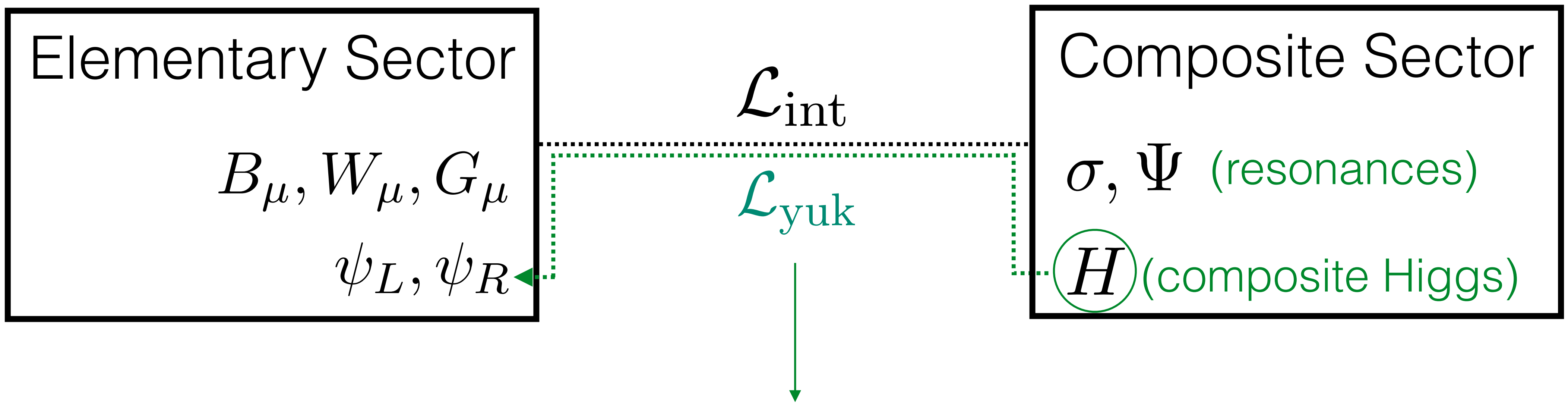
SM sector: admixture elementary/composite

SM fields massless before EWSB

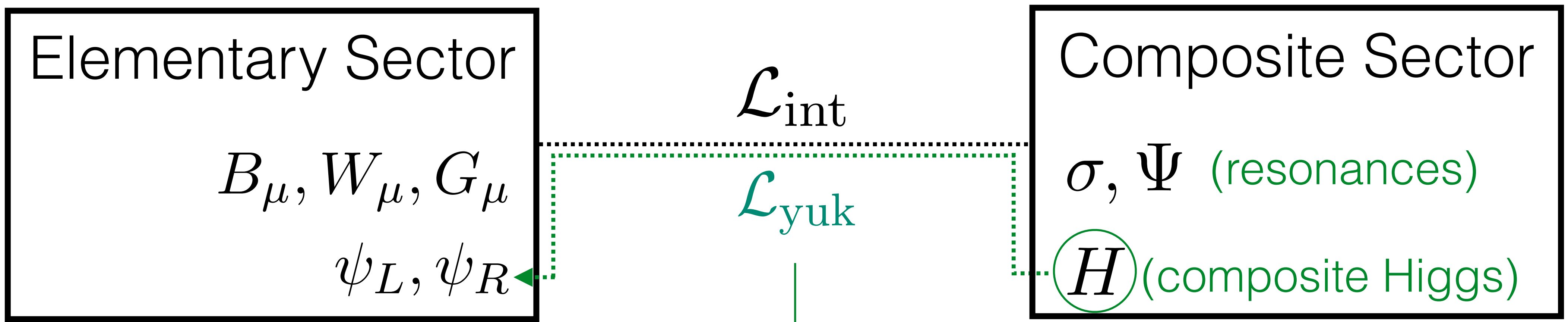




fermion masses through partial compositeness



$$\mathcal{L}_{\rm yuk} = \boxed{Y}\,\bar{\Psi}^{\mathbf{2}}_{L} H \Psi^{\mathbf{1}}_{R} + \boxed{\tilde{Y}}\,\bar{\Psi}^{\mathbf{2}}_{R} H \Psi^{\mathbf{1}}_{L} + \text{h.c.}$$



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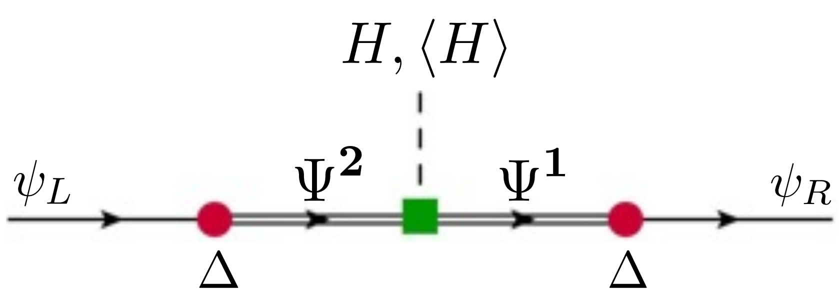


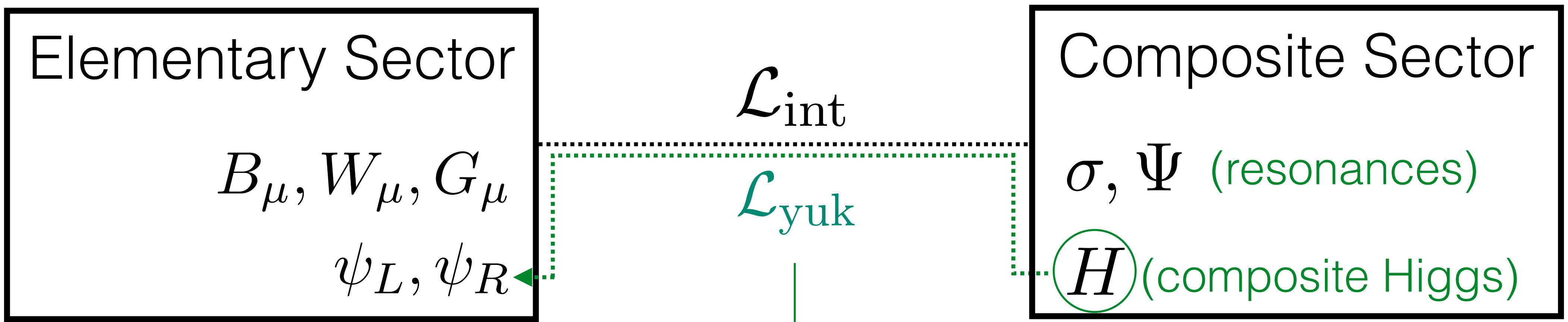
$$\propto \epsilon_L \cdot Y \cdot \epsilon_R$$

- mass term
- SM Yukawa interactions

↓

Aligned at leading order

fermion masses through partial compositeness



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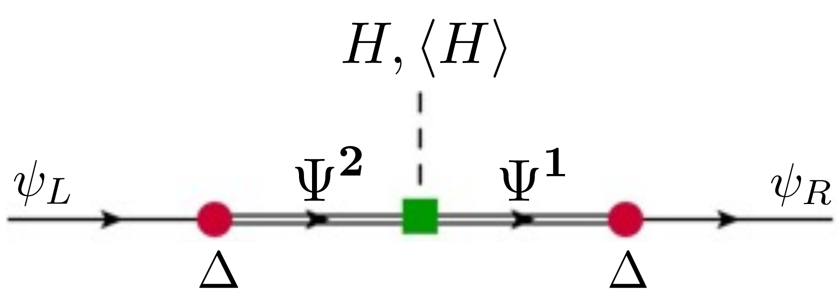


$\propto \epsilon_L \cdot Y \cdot \epsilon_R$

- mass term
- SM Yukawa interactions

↓

Aligned at leading order

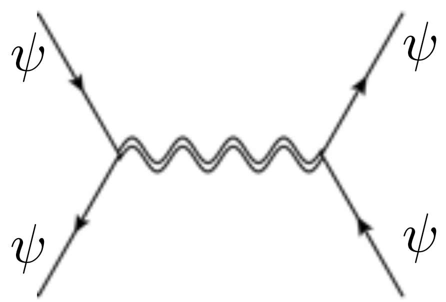
- Yukawa interaction only with Ψ (Vector Meson Dominance, VMD)
- Two different Yukawa couplings $Y, \tilde{Y}$ ("right" and "wrong" Yukawa)

Advantages of PC:

- Under Vector Meson Dominance

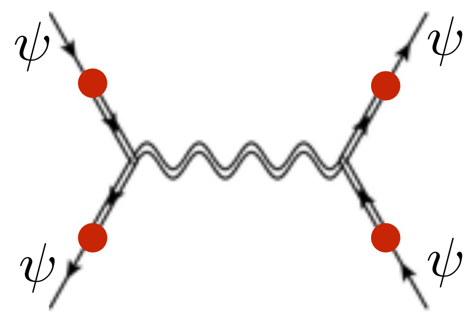
  ➔ effective suppression of NP effects (RS-GIM mechanism)

[Gherghetta, Pomarol, '00]
[Huber, '03]



TC

vs



PC

$\propto \epsilon^4 \qquad \epsilon \ll 1$

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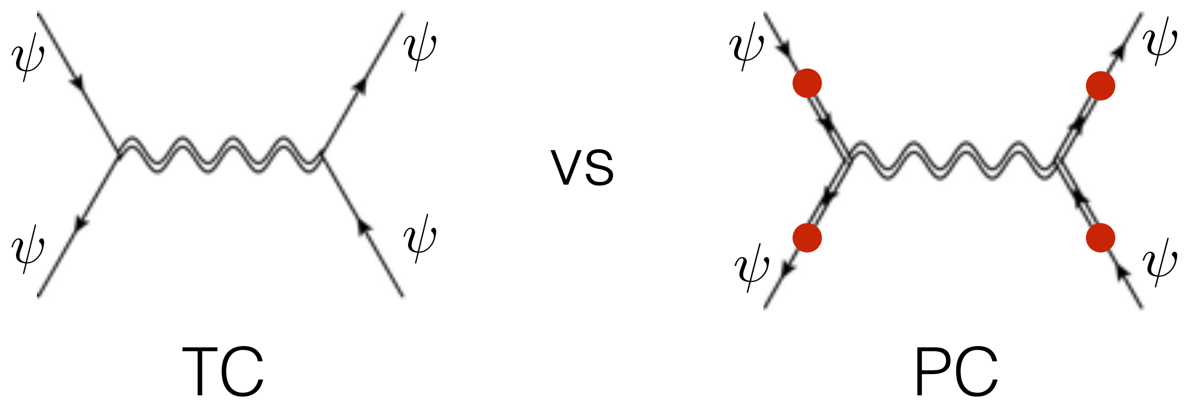

$\propto \epsilon^4 \qquad \epsilon \ll 1$

- Addressing the SM flavor puzzle

  hierarchical *Δ* ➔ hierarchical masses and flavor mixing

is Partial Compositeness better?

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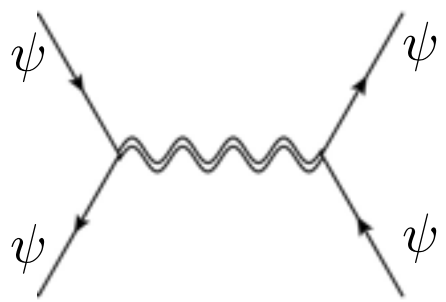

TC

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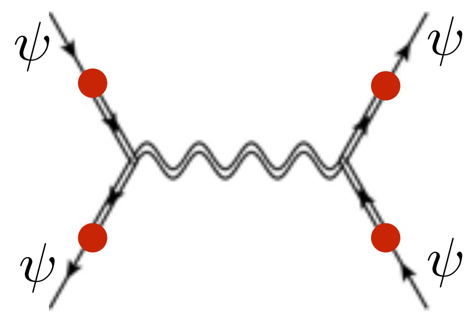


PC

$\propto \epsilon^4 \qquad \epsilon \ll 1$

- Addressing the SM flavor puzzle

  hierarchical Δ ➔ hierarchical masses and flavor mixing

Naturally arise in some concrete realisations

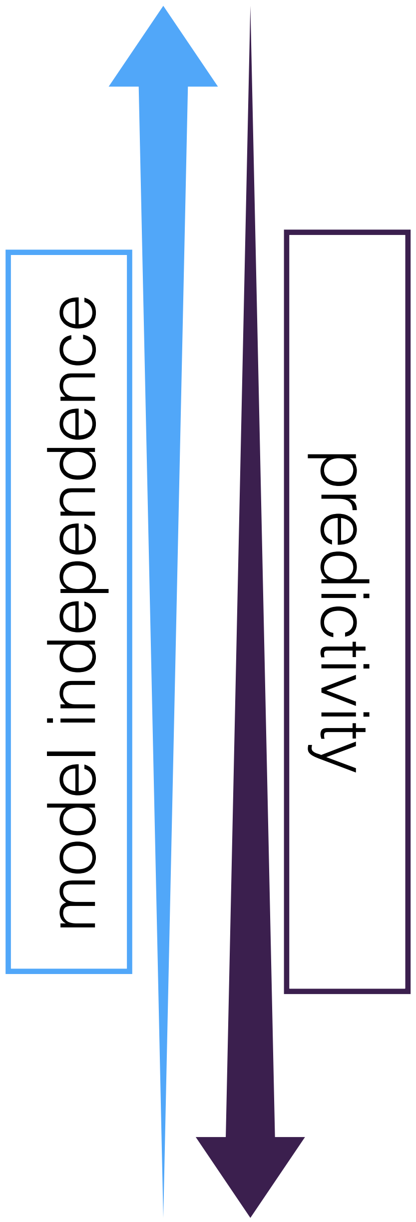
[Contino, Pomarol, ’04]

different model building approaches

starting point:

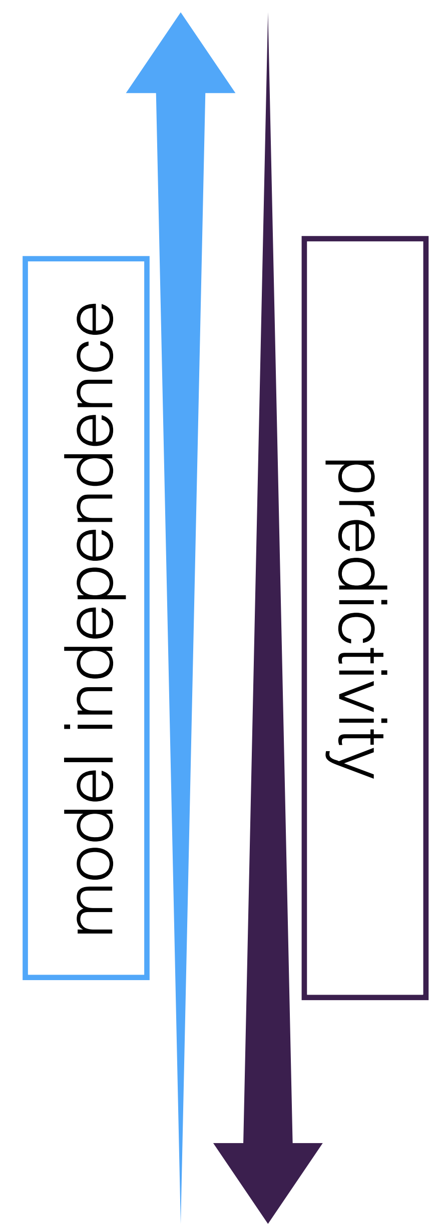
Approach:

implement explicitly
the Higgs as a pNG
$\mathcal{G} \longrightarrow \mathcal{H}$ → CH models in 4D
(CCWZ construction)



different model building approaches

starting point:		Approach:
implement explicitly the Higgs as a pNG $\mathcal{G} \longrightarrow \mathcal{H}$	→	CH models in 4D (CCWZ construction)
build a Lagrangian $\mathcal{L}_{\rm el} + \mathcal{L}_{\rm comp} + \mathcal{L}_{\rm int}$	→	simplified approach ("two-site model")



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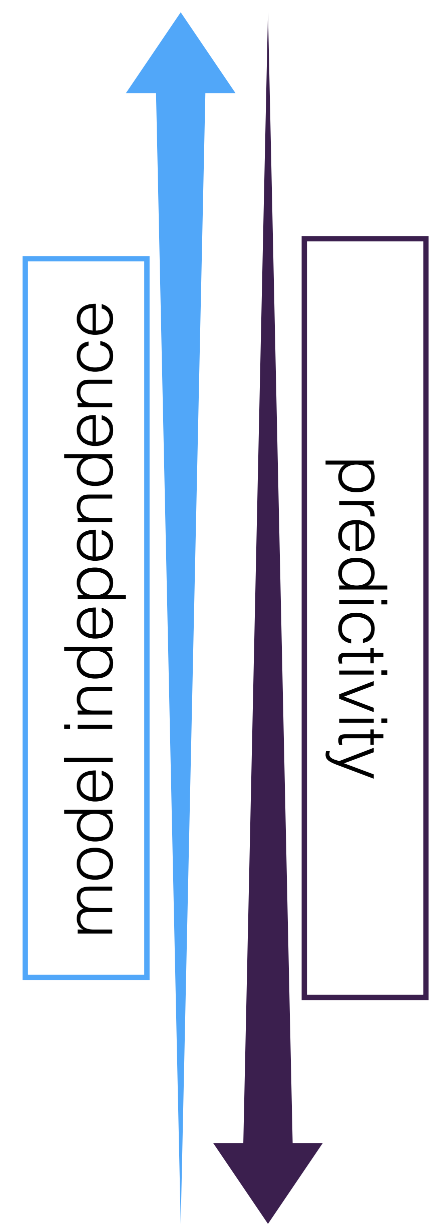
implement explicitly the Higgs as a pNG $\mathcal{G} \longrightarrow \mathcal{H}$ →	CH models in 4D (CCWZ construction)
build a Lagrangian $\mathcal{L}_{\rm el} + \mathcal{L}_{\rm comp} + \mathcal{L}_{\rm int}$ →	simplified approach ("two-site model")
4D strong ↔ 5D weak →	Holographic CH Models (warped 5th dimension)



flavor structure in Partial Compositeness

Realistic 3-generation description:

- Bulk Yukawas $Y, \; \tilde{Y}$
- Mass mixings $\epsilon_L, \; \epsilon_R$

$$\left.\begin{matrix} Y, \; \tilde{Y} \\ \epsilon_L, \; \epsilon_R \end{matrix}\right\} \xrightarrow[\text{basis choice}]{\text{suitable}} \left\{\begin{matrix} Y_{ij}, \; \tilde{Y}_{ij} & \text{3x3 flavor matrices} \\ \epsilon_{L,i}, \; \epsilon_{R,i} & \text{compositeness degree} \end{matrix}\right.$$

Realistic 3-generation description:

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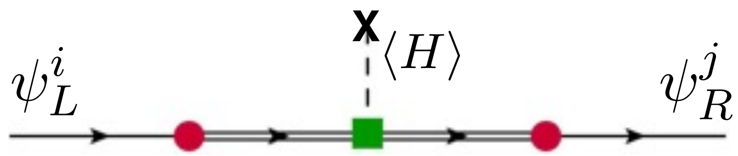
$\longrightarrow$ suitable basis choice

$\begin{cases} Y_{ij},\ \tilde{Y}_{ij} & \text{3x3 flavor matrices} \\ \epsilon_{L,i},\ \epsilon_{R,i} & \text{compositeness degree} \end{cases}$

SM Yukawa ➔ fermion masses:



$$m_i \approx \frac{v}{\sqrt{2}}\, \epsilon_{Li}\, \epsilon_{Ri}\, \langle Y \rangle$$

mass hierarchy?

flavor structure in Partial Compositeness

Realistic 3-generation description:

- Bulk Yukawas $Y,\ \tilde{Y}$
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$\xrightarrow[\text{suitable basis choice}]{}$

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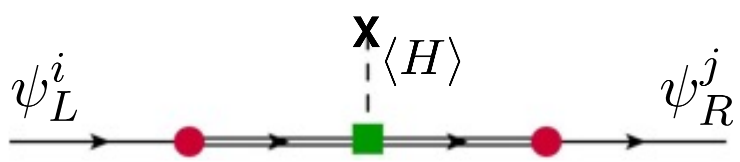

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mass hierarchy?

- Anarchic scenario:
  - $Y_{ij} \sim \mathcal{O}(1)$ and anarchic
  - ϵ_{Li} and ϵ_{Ri} hierarchical
- Flavor symmetries for Y_{ij} (discrete or continuous)

Partial Compositeness and lepton flavor

Flavor structure of the lepton sector:

- Requirements with massless neutrinos:
  - $m_e \ll m_\mu \ll m_\tau$: $\dfrac{\epsilon_{Li}\,\epsilon_{Ri}}{\epsilon_{Lj}\,\epsilon_{Rj}} \approx \dfrac{m_i}{m_j}$

    ✦ democratic: $\dfrac{\epsilon_{Li}}{\epsilon_{Lj}} \sim \dfrac{\epsilon_{Ri}}{\epsilon_{Rj}} \sim \sqrt{\dfrac{m_i}{m_j}} \quad \longrightarrow \quad \epsilon_i \sim \sqrt{\dfrac{m_i}{\langle Y \rangle v}}$

    - likely configuration in anarchic scenarios
    - configuration that minimise LFV

    ✦ LH compositeness: $\epsilon_L \propto \mathbb{1} \;\; \& \;\; \epsilon_{Ri} \approx m_i$

    ✦ RH compositeness: $\epsilon_R \propto \mathbb{1} \;\; \& \;\; \epsilon_{Li} \approx m_i$

    - scenarios with flavor symmetries

Partial Compositeness and lepton flavor

Flavor structure of the lepton sector:

- Requirements with massive neutrinos:
  - $m_e \ll m_\mu \ll m_\tau$
  - $m_\nu \ll m_e$
    - Majorana ν + see-saw mechanism
    - Dirac ν + composite ν_R
  - U_{PMNS} is not hierarchical
    - discrete flavor symmetries ($A_4 x Z_2$, $S_4 x Z_3$, …)
      ➔ troubles with $\theta_{13} \neq 0$
    - possible also in anarchical scenarios [Agashe, '09]

LFV experimental situation

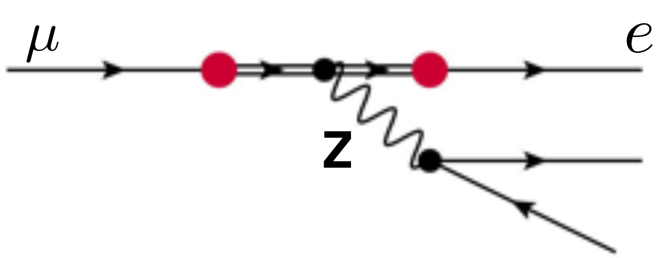
Present bounds and future sensitivity for LFV processes:

LFV Process	Present Bound	Future Sensitivity
$\mu \to e\gamma$	5.7×10^{-13}	$\approx 6 \times 10^{-14}$
$\mu \to 3e$	1.0×10^{-12}	$\approx 10^{-16}$
$\mu^- \mathrm{Au} \to e^- \mathrm{Au}$	7.0×10^{-13}	?
$\mu^- \mathrm{Ti} \to e^- \mathrm{Ti}$	4.3×10^{-12}	?
$\mu^- \mathrm{Al} \to e^- \mathrm{Al}$	–	$\approx 10^{-16}$
$\tau \to e\gamma$	3.3×10^{-8}	$\sim 10^{-8} - 10^{-9}$
$\tau \to \mu\gamma$	4.4×10^{-8}	$\sim 10^{-8} - 10^{-9}$
$\tau \to 3e$	2.7×10^{-8}	$\sim 10^{-9} - 10^{-10}$
$\tau \to 3\mu$	2.1×10^{-8}	$\sim 10^{-9} - 10^{-10}$
Lepton EDM	**Present Bound**	**Future Sensitivity**
d_e(e cm)	8.7×10^{-29}	?
d_μ(e cm)	1.9×10^{-19}	?

- $\mu \to e\gamma$, $\mu \to 3e$, $\mu^-\mathrm{Au} \to e^-\mathrm{Au}$: strongest present challenges for CH scenarios
- τ decays: τ LFV is dangerous in PC scenarios, but present bounds are too mild
- Lepton EDMs: interesting and important correlations with LFV

CLFV: tree vs one loop contributions

- Tree level LFV: $\mathcal{B}(\mu \to 3e),\ \mathcal{B}(\mu\, N \to e\, N)$



$$\mathcal{M} \approx \frac{1}{G_F \Lambda^2} \epsilon_e\, \epsilon_\mu$$

$$\mathcal{B}_{\mu\to e} \approx 4 \cdot 10^{-13} \cdot \boxed{\frac{1}{Y^2}} \left(\frac{2\ \text{TeV}}{\Lambda}\right)^4$$

$$\mathcal{B}(\mu \to 3e) < 1.0 \cdot 10^{-12}$$

$$\mathcal{B}(\mu^- \to e^-)_{\text{Au}} < 4.2 \cdot 10^{-13}$$

CLFV: tree vs one loop contributions

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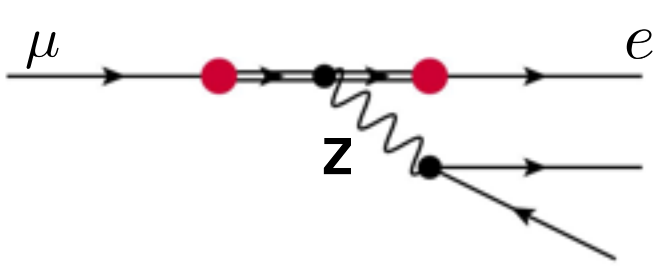

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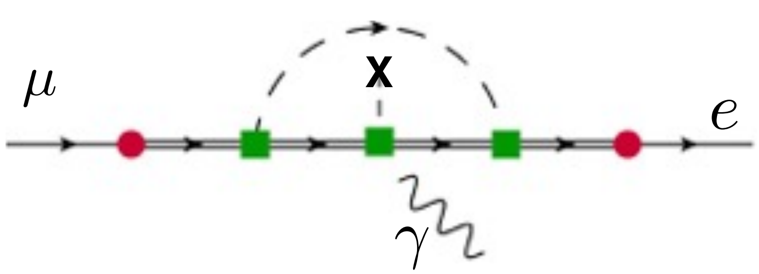
- One loop LFV: $\mathcal{B}(\mu \to e\, \gamma)$

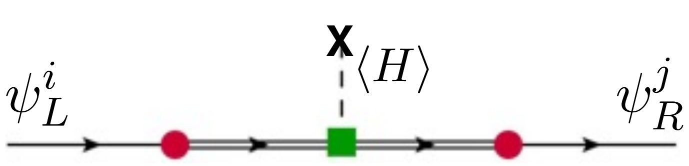


$$\mathcal{M} \approx \sqrt{\frac{\alpha}{\pi}} \frac{v}{G_F \Lambda^2} Y^3\, \epsilon_e\, \epsilon_\mu$$

$$\mathcal{B}_{\mu \to e\gamma} \approx 5 \cdot 10^{-13} \cdot \boxed{Y^4} \left(\frac{20\ \mathrm{TeV}}{\Lambda} \right)^4$$

$\mathcal{B}(\mu \to e\, \gamma) < 5.7 \cdot 10^{-13}$

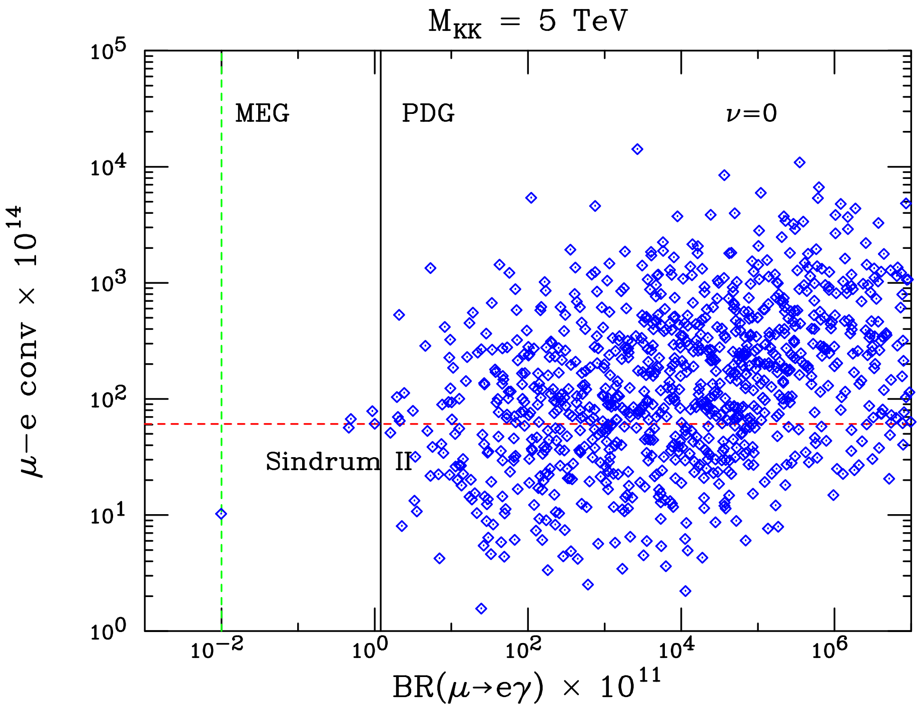
tension



$\propto \boxed{(y_{SM})_{ij}}$

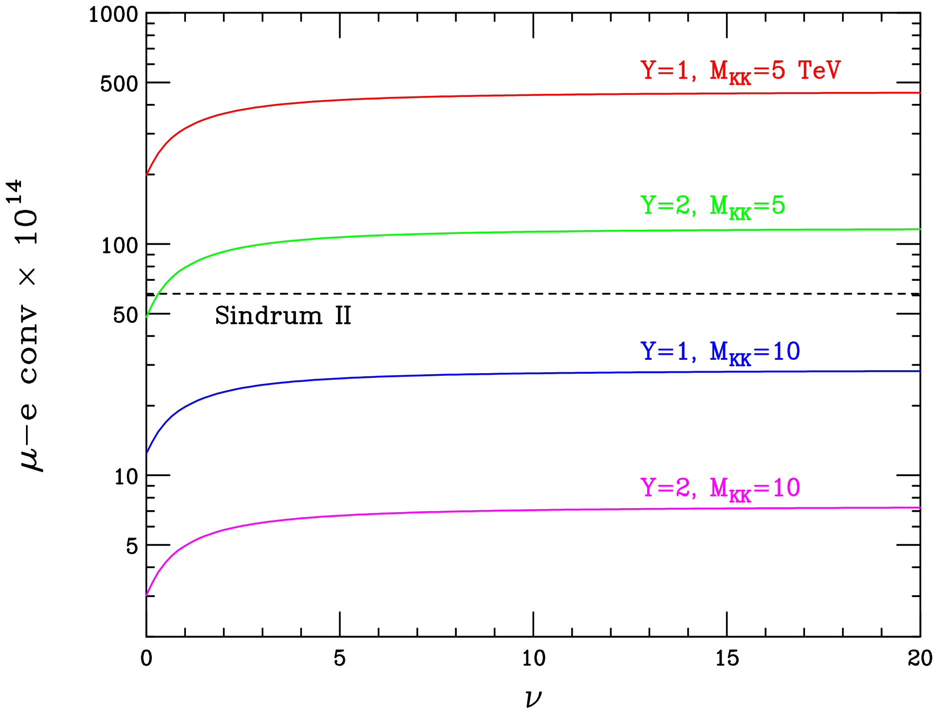
diagonal in mass eigenstate basis

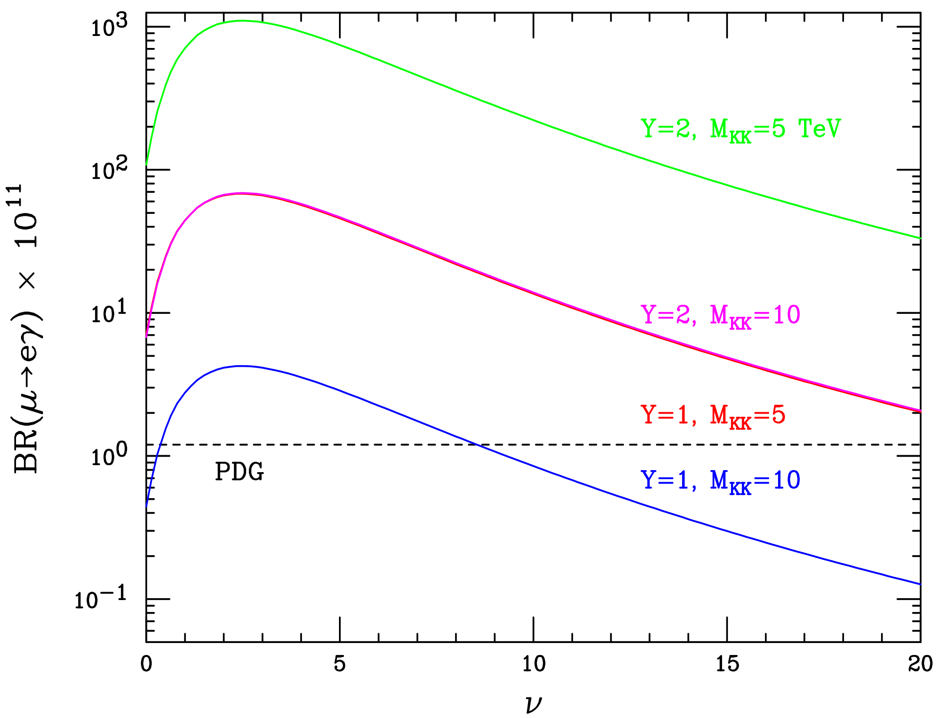
"Tension" between one loop and tree level bounds:



scan of <u>anarchic</u> configurations in a 5D RS model

- $\Lambda \approx 5$ TeV
- $Y \in \left[\frac{1}{2}, 4\right]$

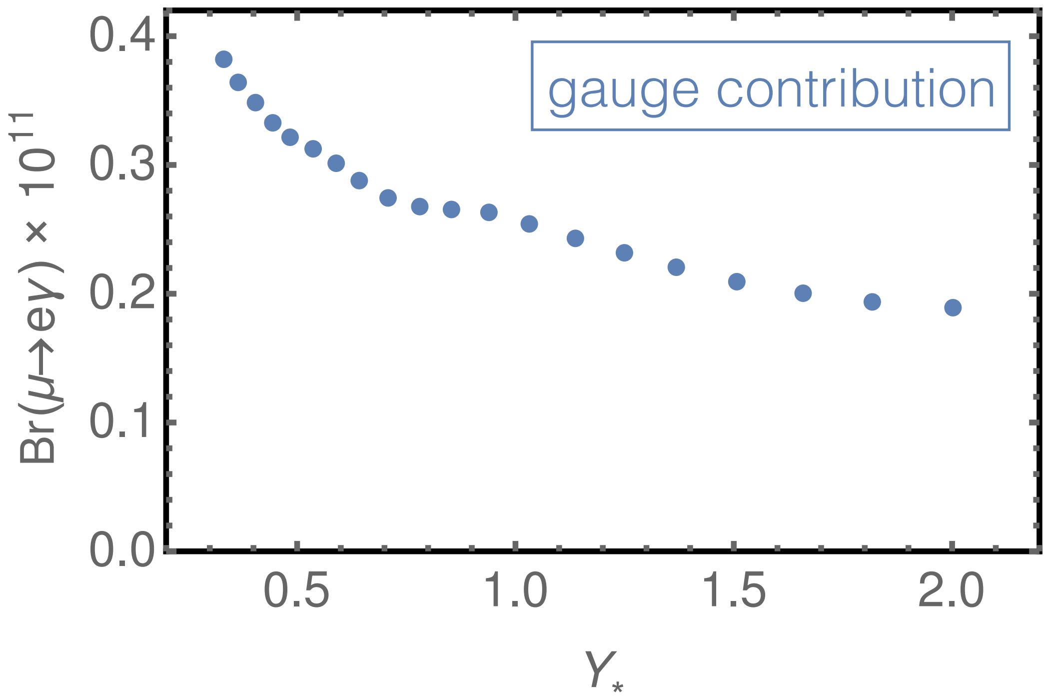


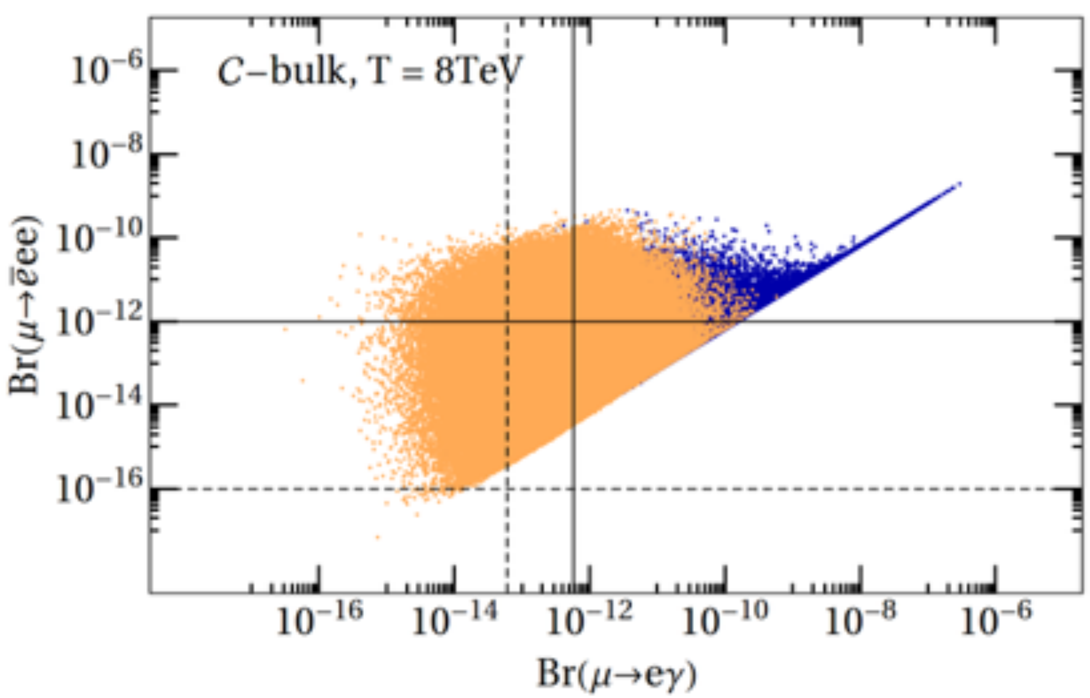


[Agashe, Blechman, Petriello, PRD 74 (2006) 053011]

deeper insights in the anarchic scenario

Spoiling the tension "tree-level vs one-loop":





- There are contributions with different *Y*-dependence in considered processes
- Such contributions are quantitative important for an evaluation of the bounds
- $\mu \to e\gamma \; + \; \mu N \to eN$ provides the most stringent constraints
- Anarchic scenarios are strongly constrained by present experimental bounds

[Beneke, Moch, Rohrwild, Nucl.Phys. B906 (2016) 561-614]

CLFV vs other bounds

Are there strongest challenges for CH models?

- Direct searches: $\gtrsim$ 1 TeV ✘

CLFV vs other bounds

Are there strongest challenges for CH models?

- Direct searches: $\gtrsim$ 1 TeV ✘
- Quark sector: ϵ_K ➔ $\gtrsim$ 7 TeV ≈
  - close to future LFV sensitivity
  - limited theoretical predictions

CLFV vs other bounds

Are there strongest challenges for CH models?

- Direct searches: $\gtrsim$ 1 TeV ✘
- Quark sector: ϵ_K ➔ $\gtrsim$ 7 TeV ≈
  - close to future LFV sensitivity
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- Precision observables: S and T parameter ➔ $\gtrsim$ 4 TeV ≈

with custodial gauge symmetry in 5th dimension ⟶ $\gtrsim$2 TeV

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↓

new dangerous contributions to LFV processes ⟵ with custodial gauge symmetry in 5th dimension ⟶ $\gtrsim$2 TeV

➔ Some kind of "tension" between LFV and EWPT

summary of anarchic scenarios

Conclusions for CH models with anarchic bulk Yukawas:

- Extensively studied for their appealing features, such as dynamical generation of hierarchies
- Despite RG-GIM suppression, bounds from EWPT and CLFV grew bigger in last ~10 years
- Not as appealing as in the past, $\Lambda \gtrsim 8$ TeV (➔ $m_{KK} \gtrsim 20$ TeV)
- These difficulties has increased the interest in models with flavor symmetries

Partial Compositeness with discrete flavor symmetries

Introduce discrete flavor symmetry:

- Originally motivated by conjectures about the U_{PMNS} structure:
  - ✦ explanation of the (nearly) tri-bimaximal lepton mixing
  - ✦ extra-suppression of LFV

Águila, Carmona, Santiago, JHEP 1008 (2010) 127
Hagedorn, Serone, JHEP 1110 (2011) 083

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- After $\theta_{13} \approx 0.1$, too large for old models:
  - ✦ still exist flavor groups that "predict" U_{PMNS}
  - ✦ still suppression of LFV
  - ✦ arguably less appealing models

➔ $m_{KK} \gtrsim 3.5$ TeV

Hagedorn, Serone, JHEP 1202 (2012) 077

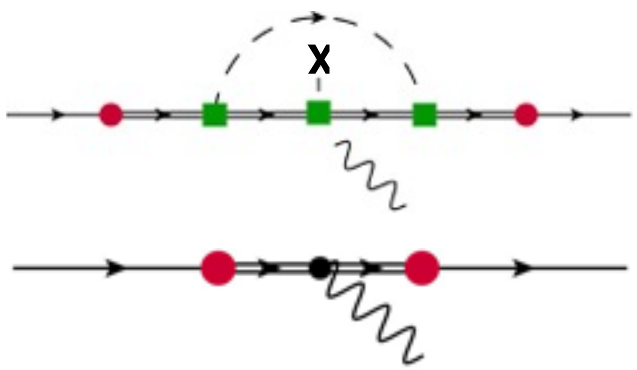
Partial Compositeness with Minimal Flavor Violation

Composite Minimal Flavor Violation:

Redi, EPJC 72 (2012) 2030
Redi, JHEP 1309 (2013) 060

- Only one LFV source in charged lepton sector: y_e

  - Left-handed compositeness: $\epsilon_L \propto \mathbb{1},\ \boxed{\epsilon_R \propto y_e},\ Y \propto \mathbb{1}$
  - Right-handed compositeness: $\boxed{\epsilon_L \propto y_e},\ \epsilon_R \propto \mathbb{1},\ Y \propto \mathbb{1}$
  - Intermediate scenario: $\epsilon_L \propto \mathbb{1},\ \epsilon_R \propto \mathbb{1},\ \boxed{Y \propto y_e}$



$\propto \epsilon_L\, Y^n\, \epsilon_R$

diagonal in mass eigenstate basis
NO CLFV

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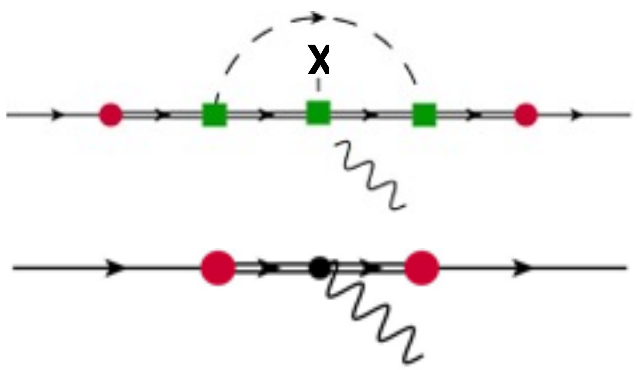

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- Neutrino sector introduce CLFV

➔ effective suppression of CLFV

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➔ way out: different flavor symmetries, e.g. SU(2)

an example of two-site model

Simplified approach starting from an effective Lagrangian:

Contino, Sundrum, JHEP 0705 (2007) 074

The SM Lagrangian

The Lagrangian of the heavy resonances (a "massive version" of the SM Lagrangian)

$$\mathcal{L} = -\frac{1}{4}(F^a_{\mu\nu})^2 + \bar{\psi}\not{D}\psi - \frac{1}{4}(\rho^a_{\mu\nu})^2 + \frac{M_*^2}{2}(\rho^a_\mu)^2 + \bar{\Psi}(i\not{D} - m)\Psi$$
$$- M_*^2 A^a_\mu \rho^{\mu\, a} + \frac{M_*^2}{2}(A^a_\mu)^2 - (\Delta\bar{\psi}\Psi + \text{h.c.}) + |D_\mu\varphi|^2 - V(\varphi) - Y\bar{\Psi}\varphi\Psi$$

Mass mixing terms (for fermions and bosons)

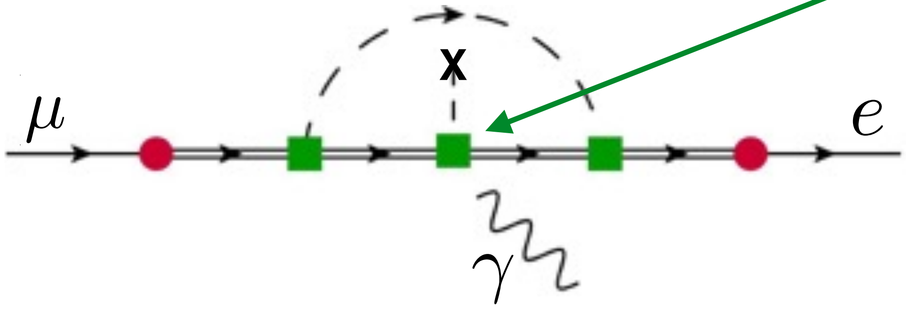
The Higgs Lagrangian (with VMD assumption)

- Partial Compositeness implemented for fermions and bosons
- Vector Meson Dominance assumption
- Focus on the lepton sector

Lepton content:	SU(2)$_L$ doublets	SU(2)$_L$ singlets	
‣ SM leptons:	ℓ_L,	e_R.	chiral fermions
‣ Heavy leptons:	L_L, L_R,	E_L, E_R.	Dirac fermions

Flavor parameters:

- Mass terms: $m \bar{L} L + \tilde{m} \bar{E} E + \text{h.c.}$
- Yukawas: $\Delta_L \, \bar{L}_R \ell_L + \Delta_R \, \bar{R}_R e_L + \text{h.c.}$
- Mass mixings: $Y \bar{L}_L \phi E_R + \tilde{Y} \bar{L}_R \phi E_L + \text{h.c.}$



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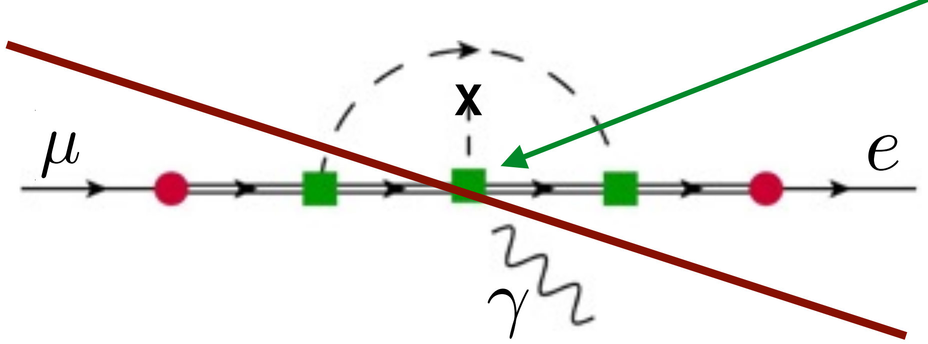
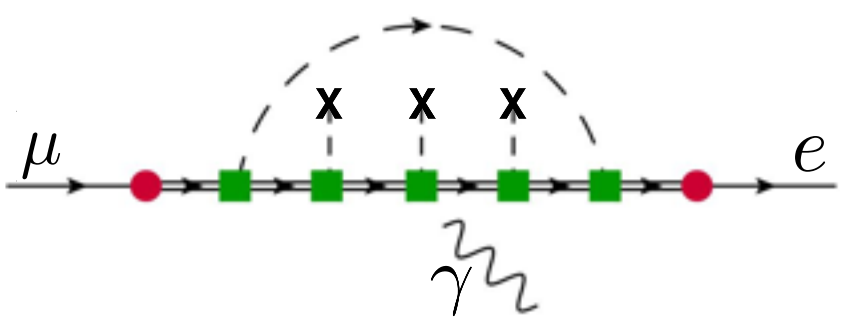
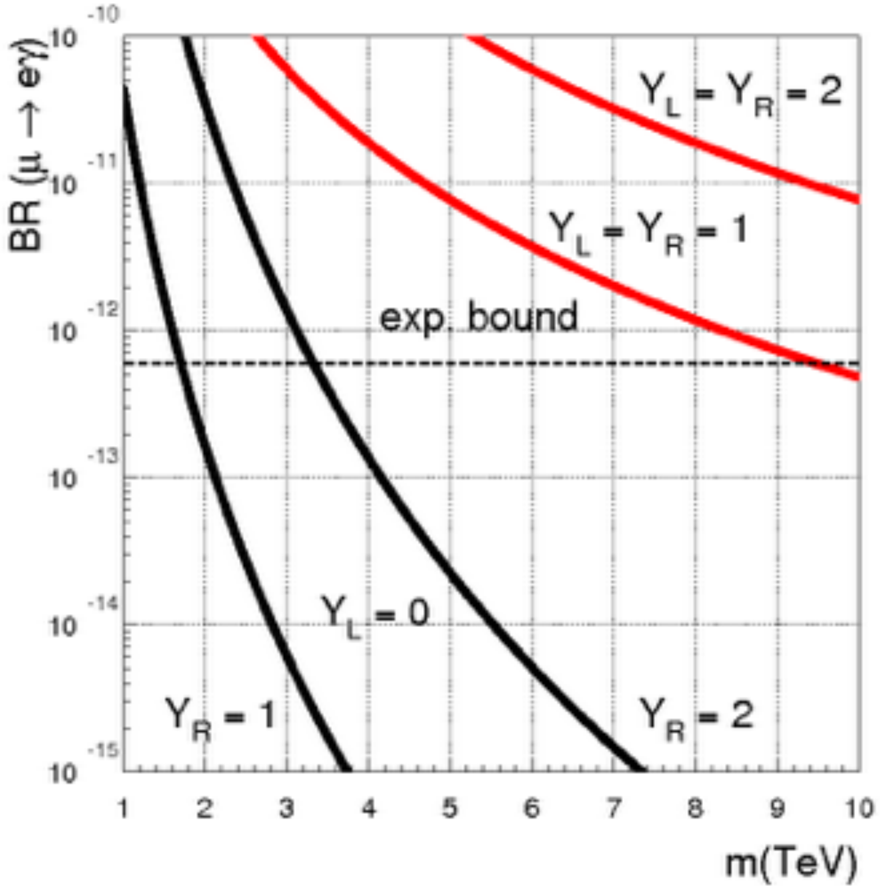


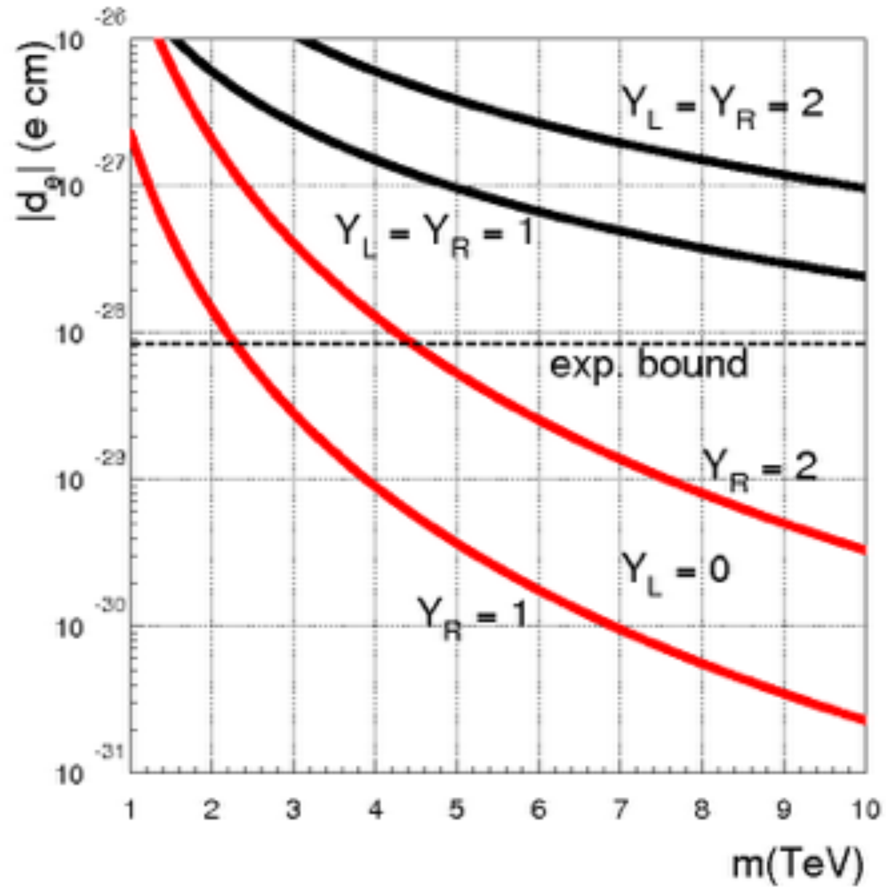
$\Rightarrow$



vanishing wrong Yukawa $\Rightarrow$ suppression of leading LFV one loop contributions

About dipole contributions:





$Y_L = \tilde{Y}$ "wrong"

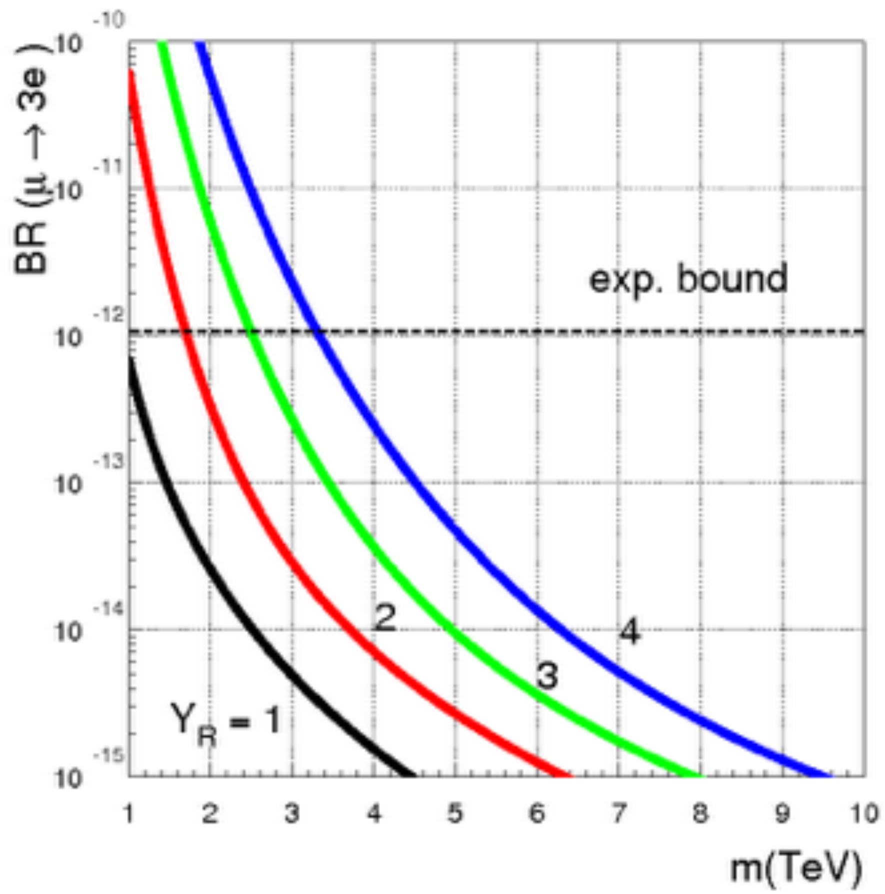
$Y_R = Y$

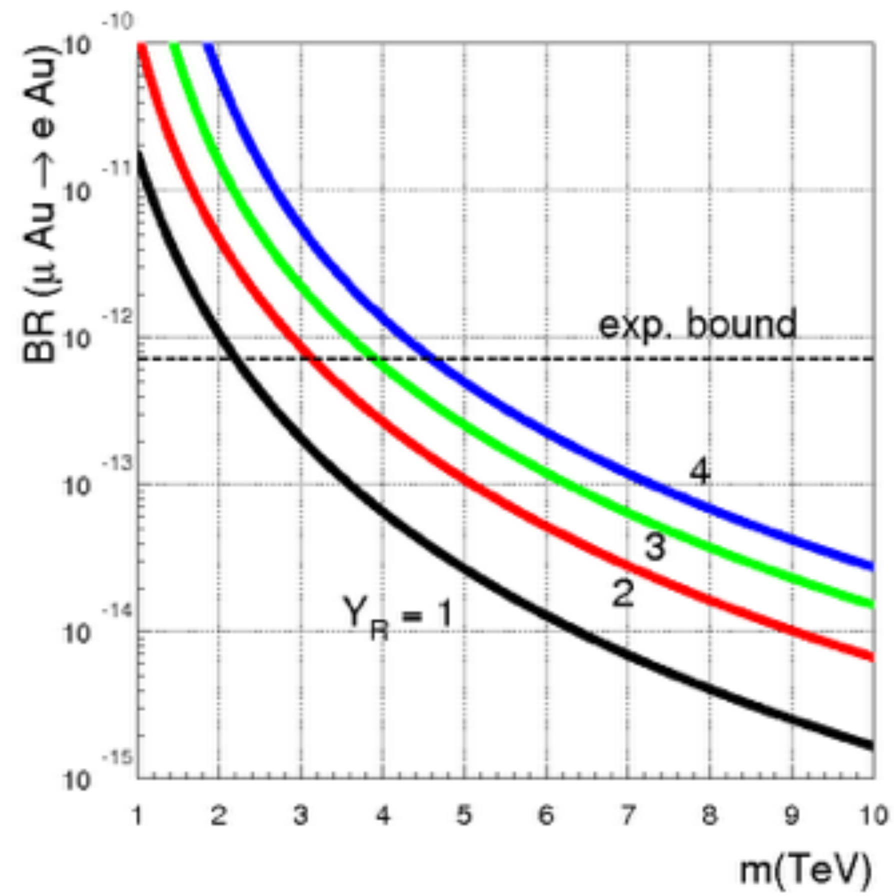
- In this setup LO contributions decouples as $\propto 1/\Lambda^8$
- EDM is an important complementary observable
- Tensions can be reduced

Feruglio, Paradisi, Pattori, EPJC 75 (2015) no.12, 579

effects of a vanishing wrong Yukawa

About tree level LFV:





- Is crucial to consider all kind of contributions
- In this setup the naive $\propto 1/Y^2$ dependence is spoiled by this

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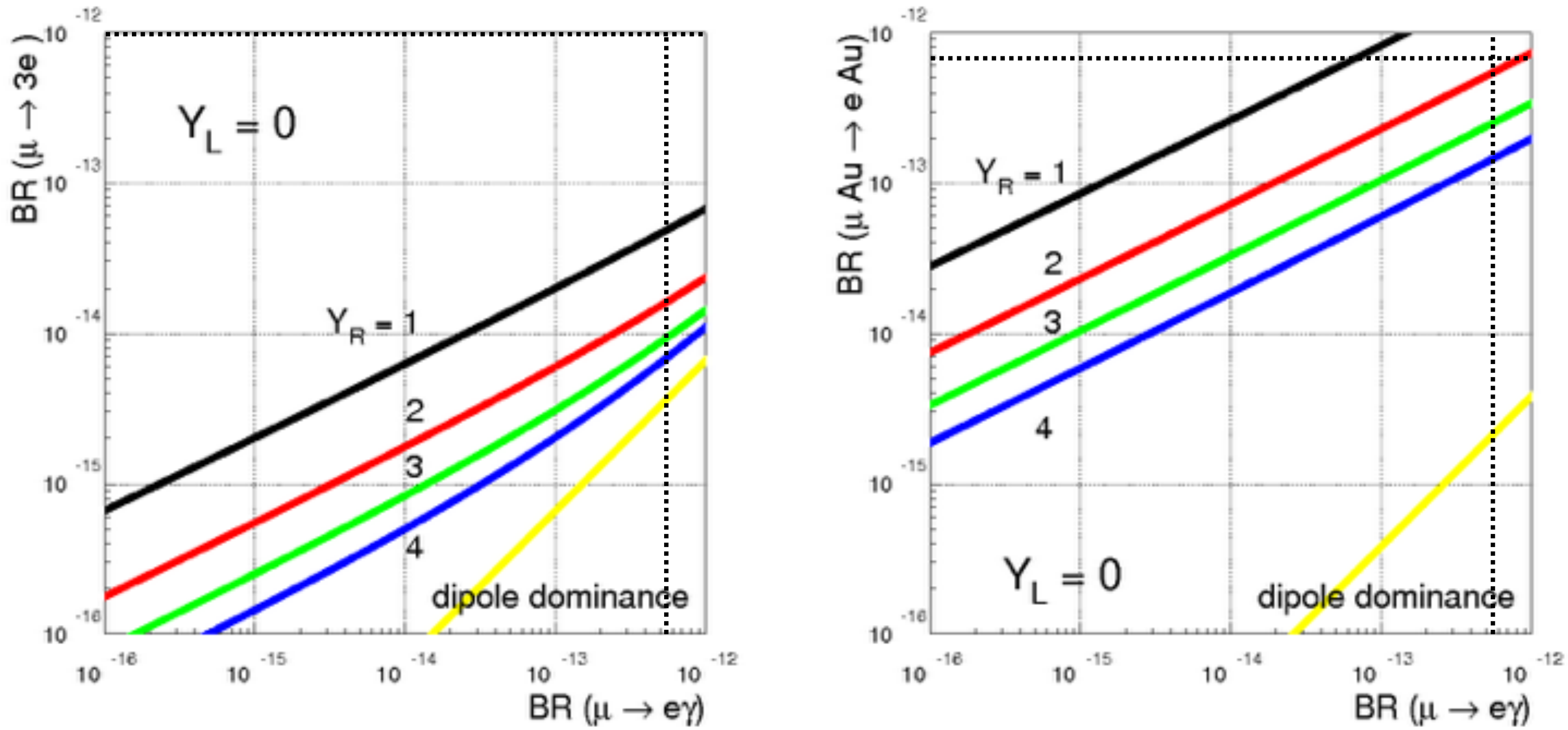
Correlations tree level - one loop:



- Remarkable deviations from the “dipole dominance” case
- distinctive pattern for NP effects correlation

Feruglio, Paradisi, Pattori, EPJC 75 (2015) no.12, 579

conclusions

- Composite Higgs models are appealing proposals
  - natural solution to the hierarchy problem
  - Partial Compositeness address the flavor puzzle(s)
- At present days RS-GIM mechanism is challenged by CLFV
  - Anarchic scenarios gets serious bounds
  - Flavor symmetries are a not-so-easy way out
- The simplified approach gives a different perspective
  - Interesting insights in the flavor structure of these scenarios
  - Viable models have specific LFV patterns