Dealing with new Strong Dynamics at the TeV

Alex Pomarol, UAB & IFAE (Barcelona)

What’s this talk about?

★ Interest from Beyond the SM for Strong dynamics:

☛ provides a solution to the hierarchy problem

★ What are the model-building requirements ?

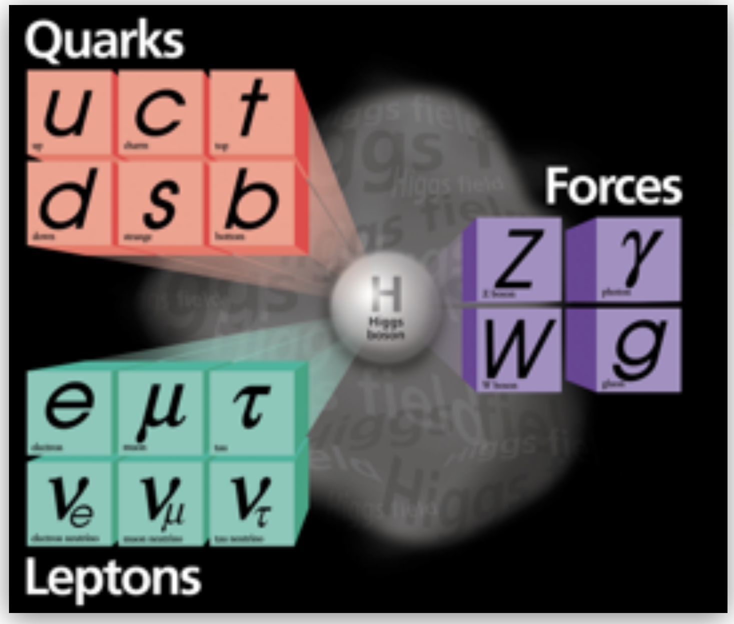
★ What are the special properties of the new strong dynamics ?

(beyond QCD-like theories)

★ How could lattice help ?

★ Which could be potential discoveries at the LHC ?

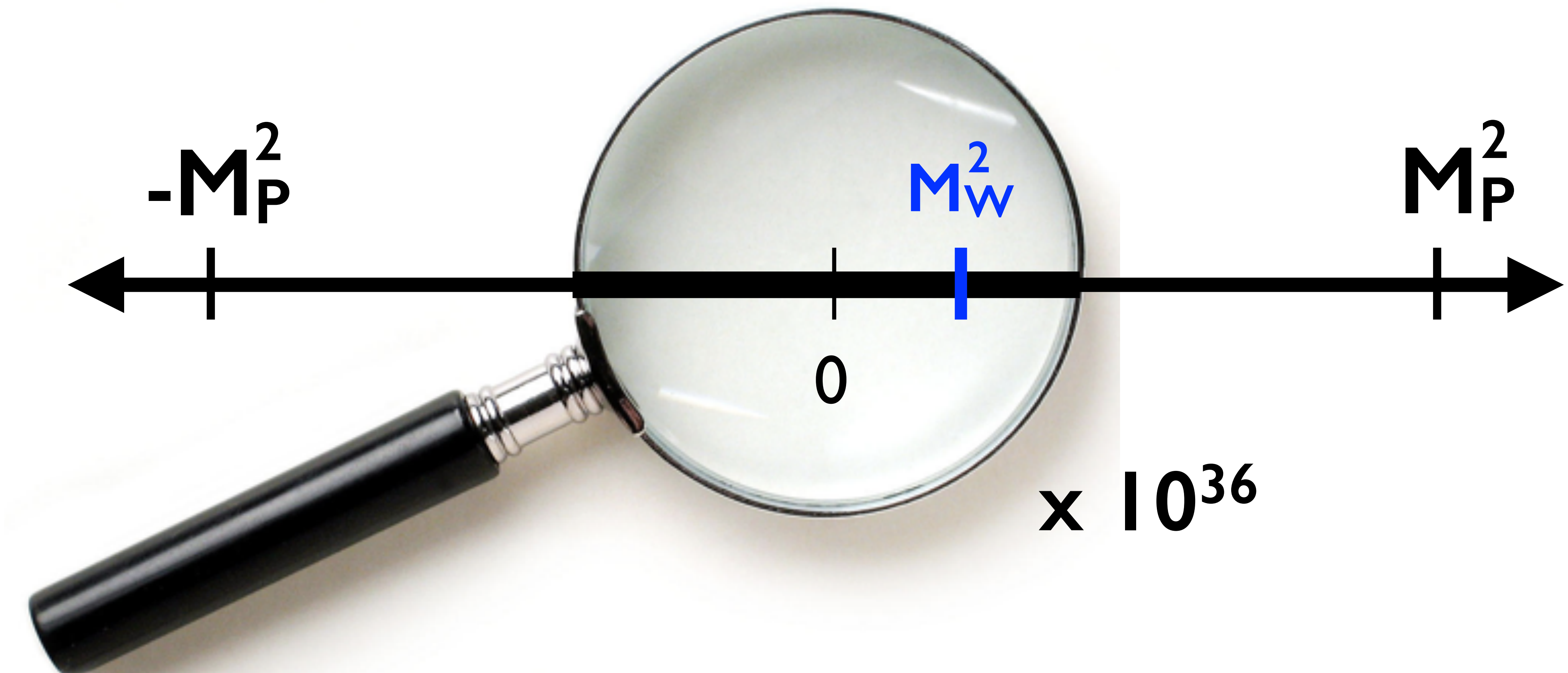
After the Higgs discovery…



… we’ve moved to a new era in particle physics:

We have the theory,
but **now** we’d like to understand **<u>why it is like it is</u>**

In particular, we'd like to understand:



Why the EW-scale is so close to zero ?
(as compared to M_P)

Is it a special point? More symmetrical?

Not in the SM!

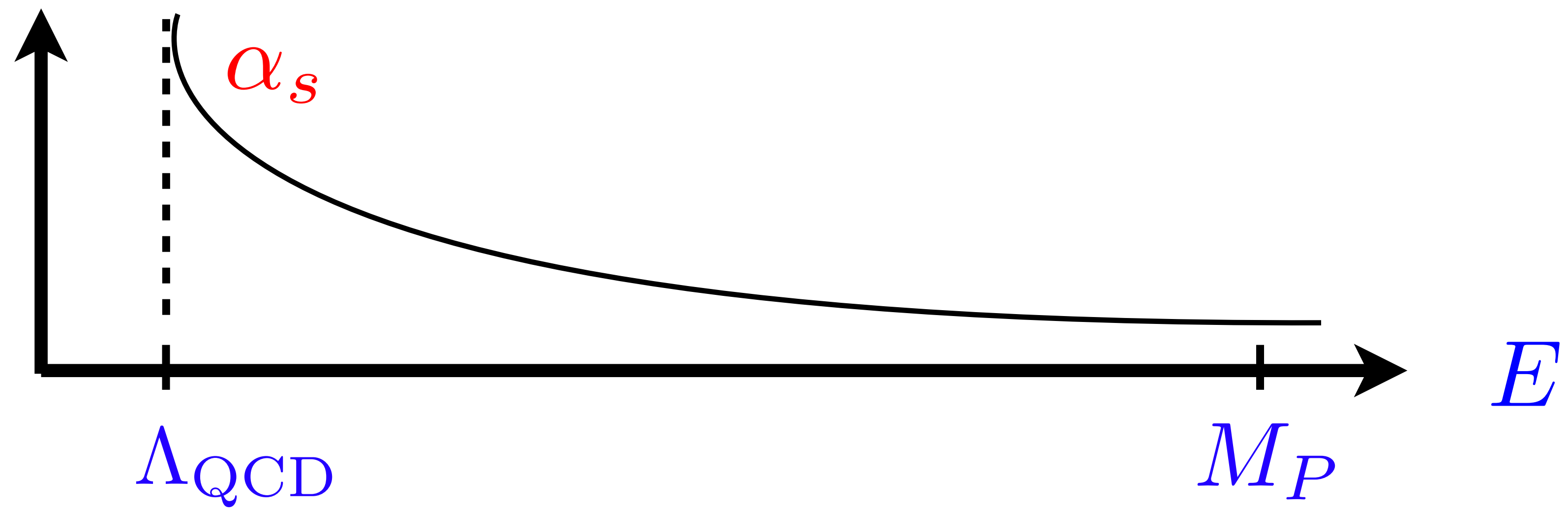
Related to the problem of having massless scalars:

	Massless	Massive	
Vector A_μ	2 *dof* (+,-)	3 *dof* (+,0,-)	$2 \neq 3$ ✔ *Massless vectors are save*
Fermion (charged)	2 *dof* Ψ_L	4 *dof* Ψ_L, Ψ_R	$2 \neq 4$ ✔ *Massless fermions are save*
Scalar	1 *dof*	1 *dof*	*1=1 Problem!*

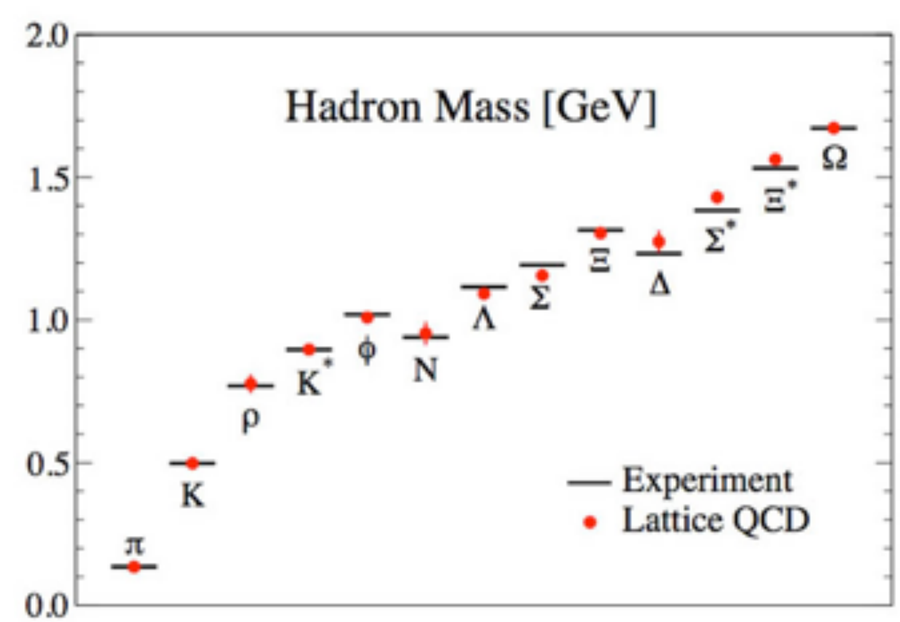
Quantum fluctuations can give mass to scalars

Explanation for the smallness of the EW-scale

QCD as an inspiration: pion mass not a fundamental quantity



Explains why $\Lambda_{\rm QCD} << M_P$ and the origin of most hadron masses



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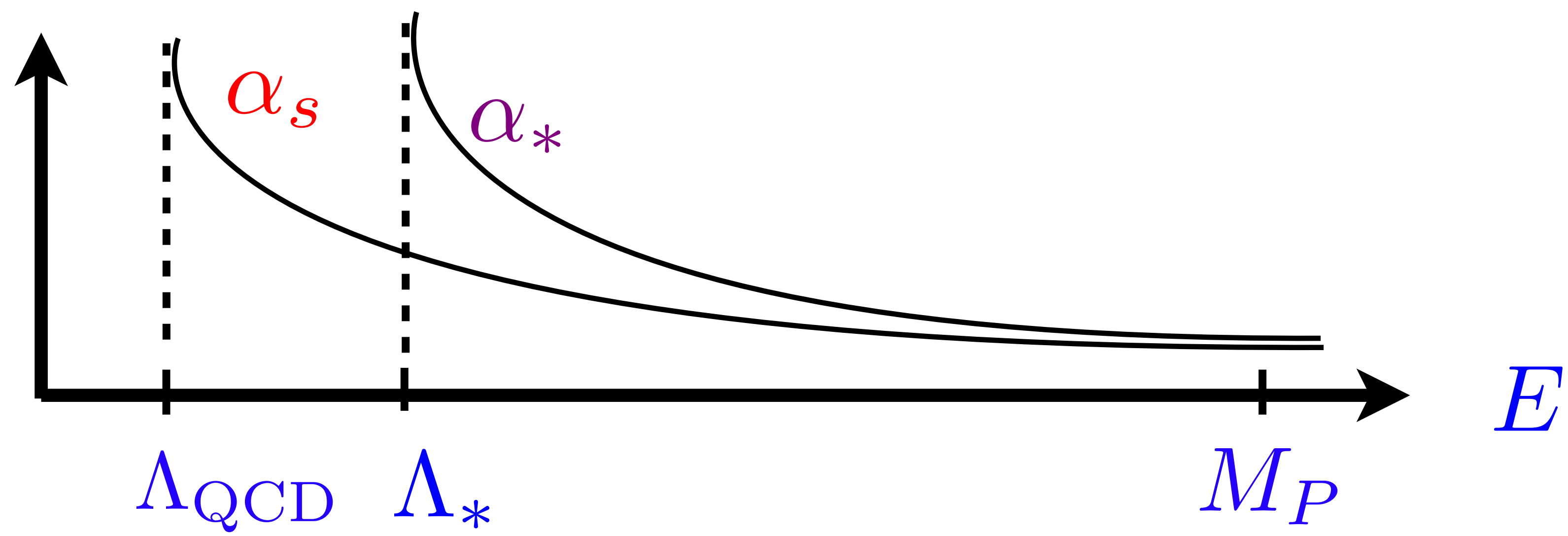


New strong dynamics at TeV

It could explain why $m_H \lesssim \Lambda_* \sim \mathrm{TeV} \ll M_P$

Composite Higgs

Solves the problem in one shot!

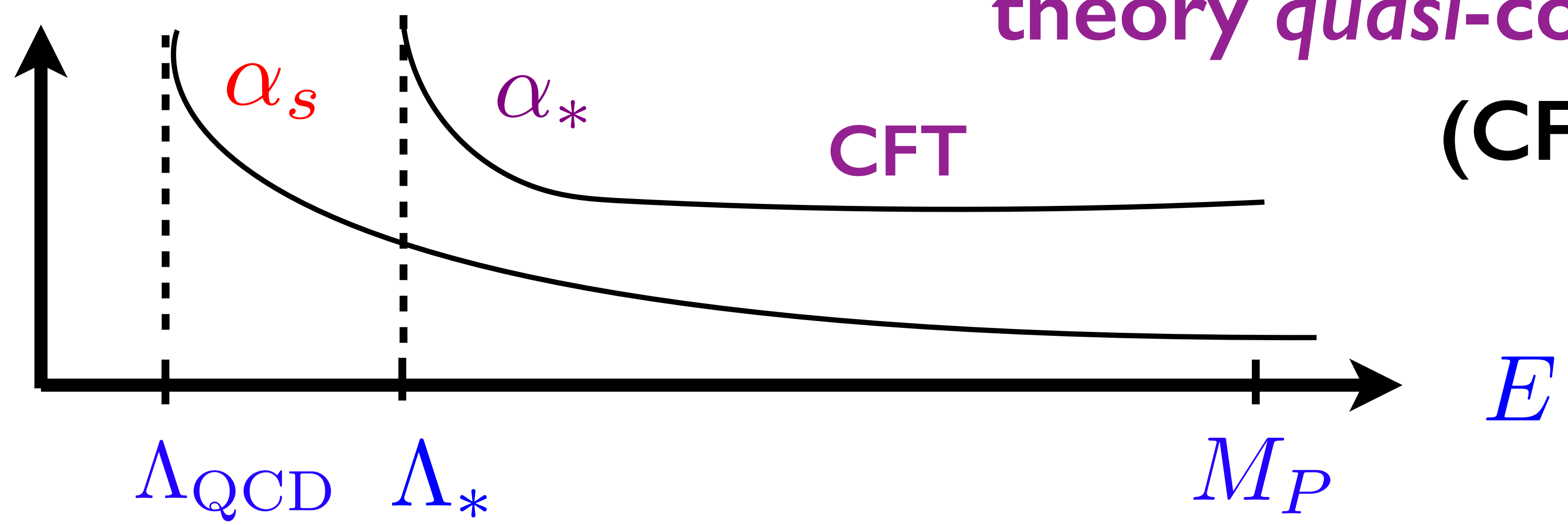
(in supersymmetry we still need strong dynamics to break susy at some low-scale)

Explanation for the smallness of the EW-scale

QCD as an inspiration:

More generically: we need a theory *quasi*-conformal

($CFT_4 \leftrightarrow AdS_5$)



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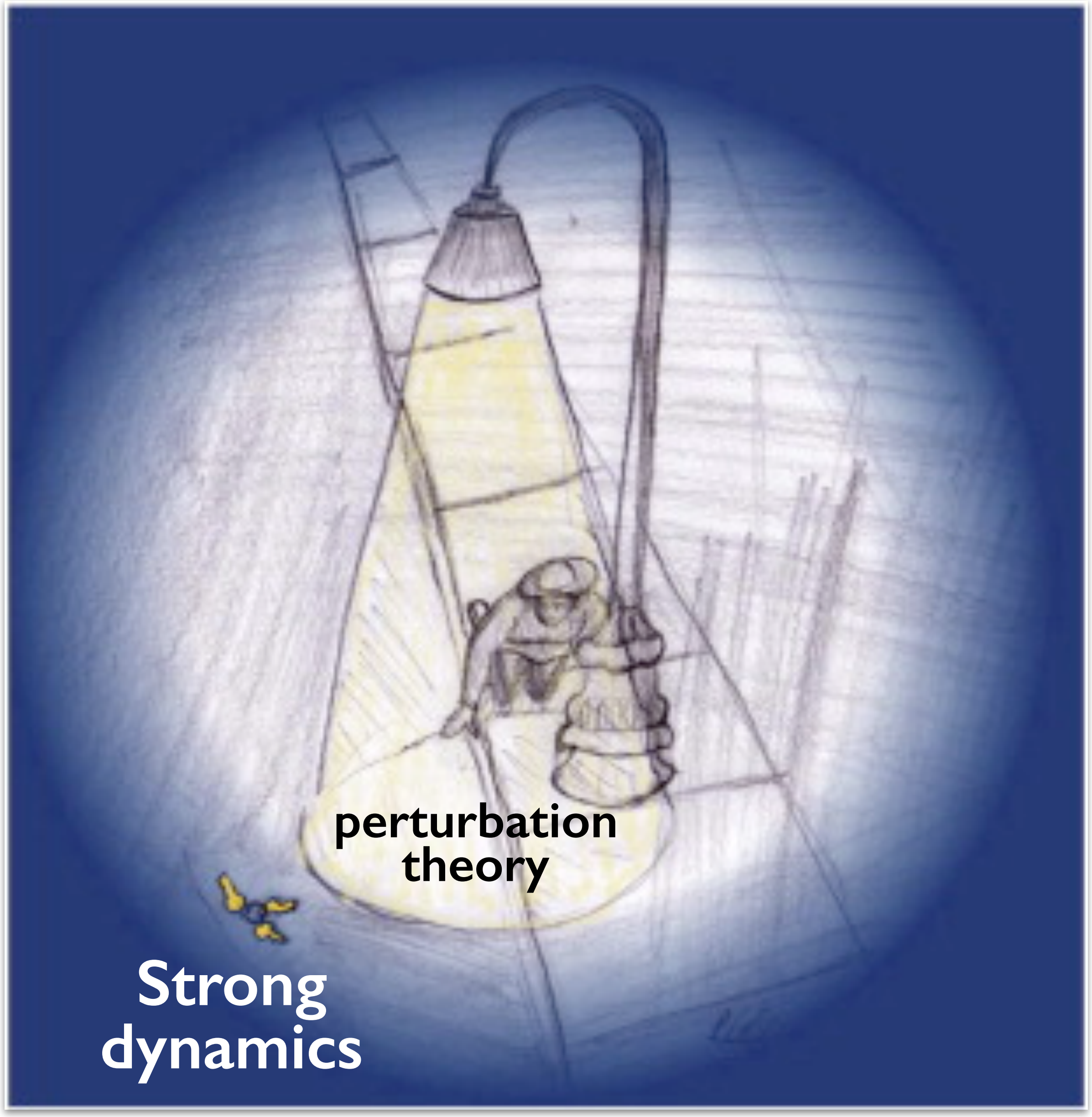
Dealing with strong dynamics….

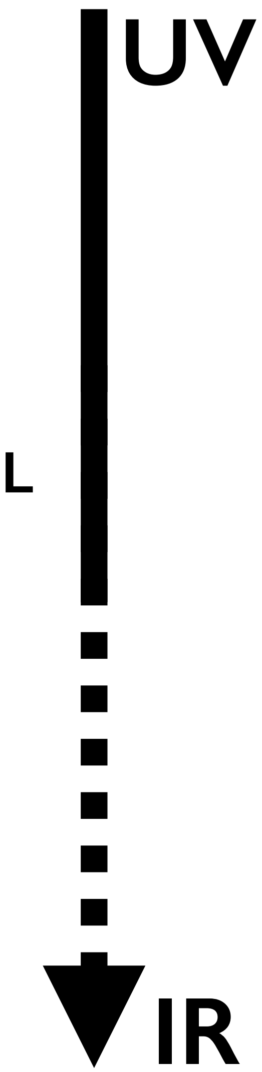
Beyond the lamp-post:



Dealing with strong dynamics….

We can well-define
the UV theory:
gauge-symmetry
+ matter content

e.g. SU(N) + N_F $q_{R,L}$



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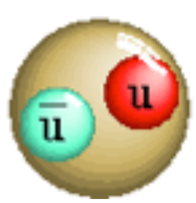
UV

…but we do not know the predictions at the IR



IR

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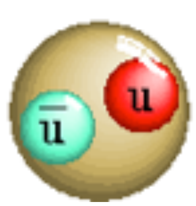
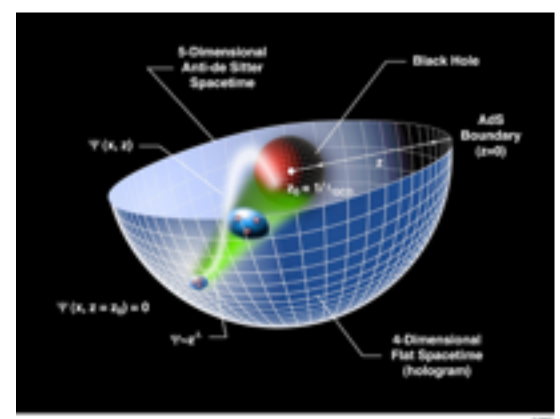


IR

UV

Holography



Questions posed
to strong dynamics
can be addressed
by an **AdS_5**

IR

predictive theories !

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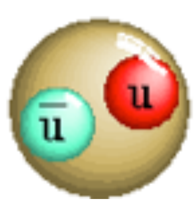

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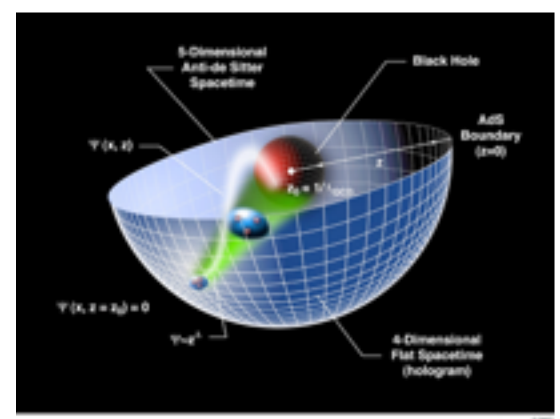

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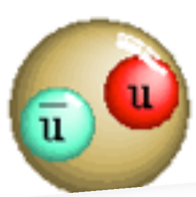
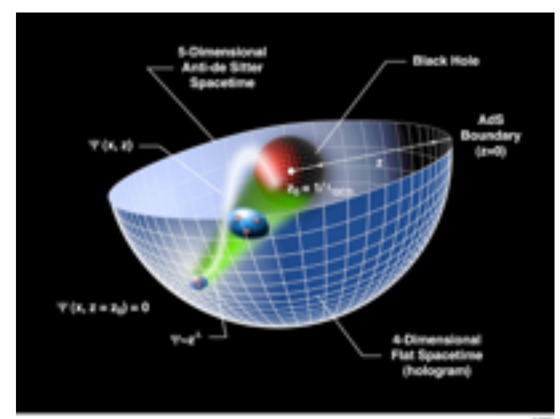


Lattice can help here

UV

…but we do not know the UV theory

Holography



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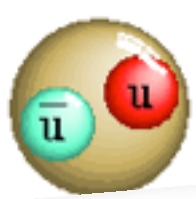


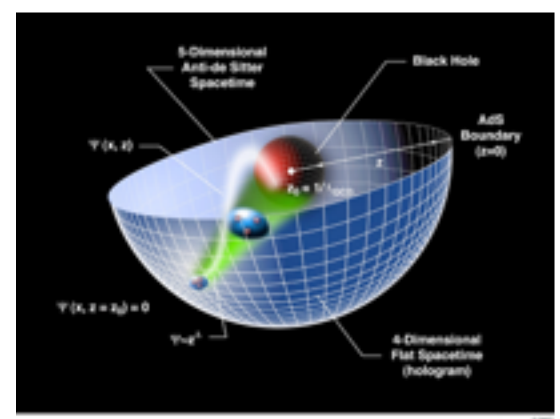
IR

Lattice can help here

string theory can help here

…but we do not know the UV theory

Holography



Questions posed to strong dynamics can be addressed by an **AdS$_5$**

IR

predictive theories !

Inspiration from **QCD** and **holography** has allowed to come up with a **plausible scenario** of **strong dynamics at the TeV**

But not a well-defined & complete model !

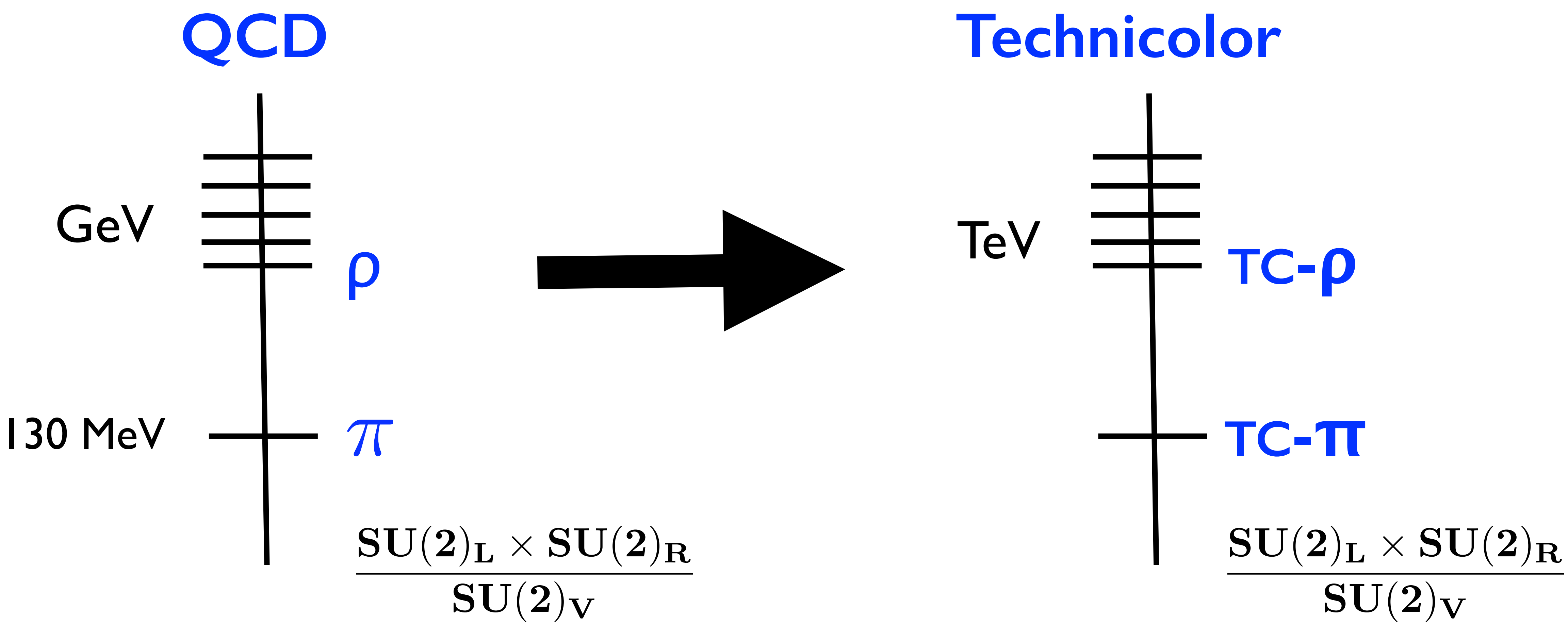
(like the MSSM in the susy approach)

Nevertheless, it has provided a characterization of the expected signals (needed to be searched for)

(as in the 60', experiments must be driving the field)

Attempt 1

The strong dynamics breaks the EW-symmetry



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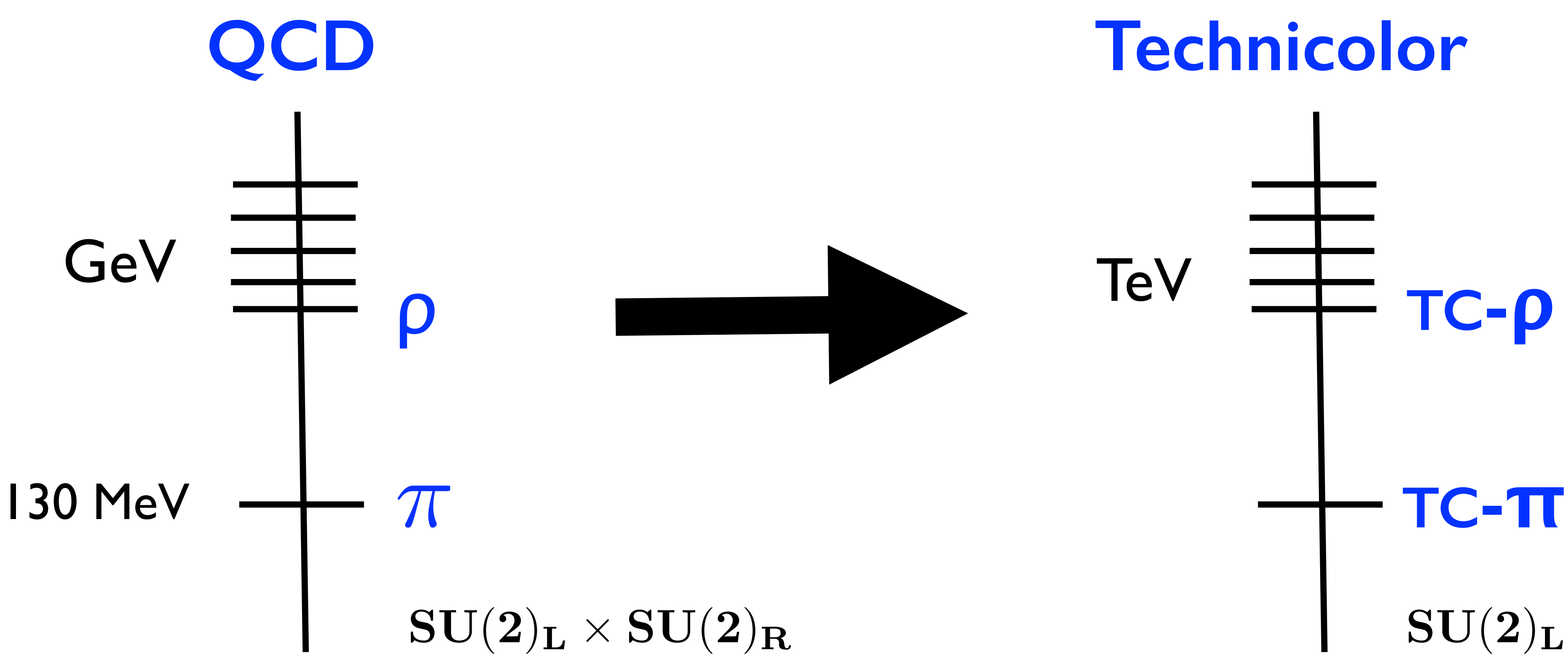
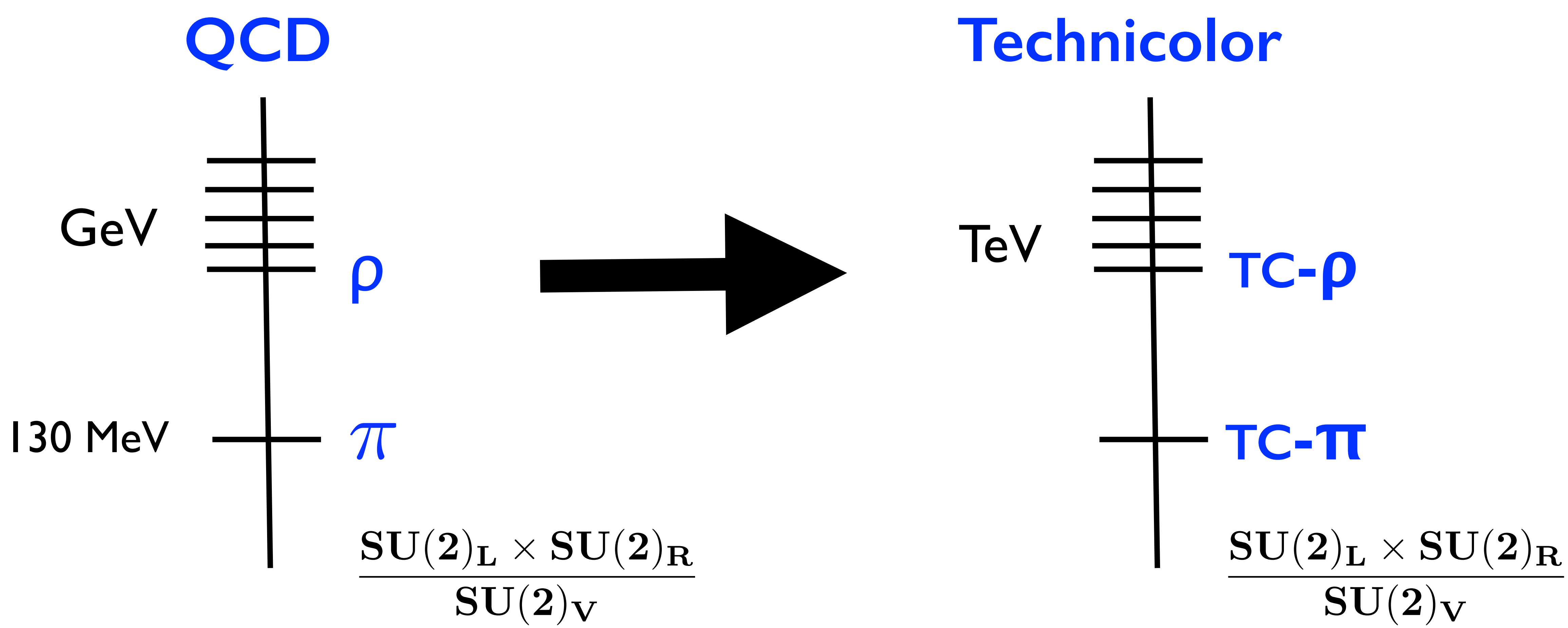


$$\frac{\mathbf{SU(2)_L \times SU(2)_R}}{\mathbf{SU(2)_V}} \qquad\qquad \frac{\mathbf{SU(2)_L \times SU(2)_R}}{\mathbf{SU(2)_V}}$$

But no light "**Higgs**" **predicted!**

(Nature likes to be original!)

The strong dynamics <u>breaks</u> the EW-symmetry



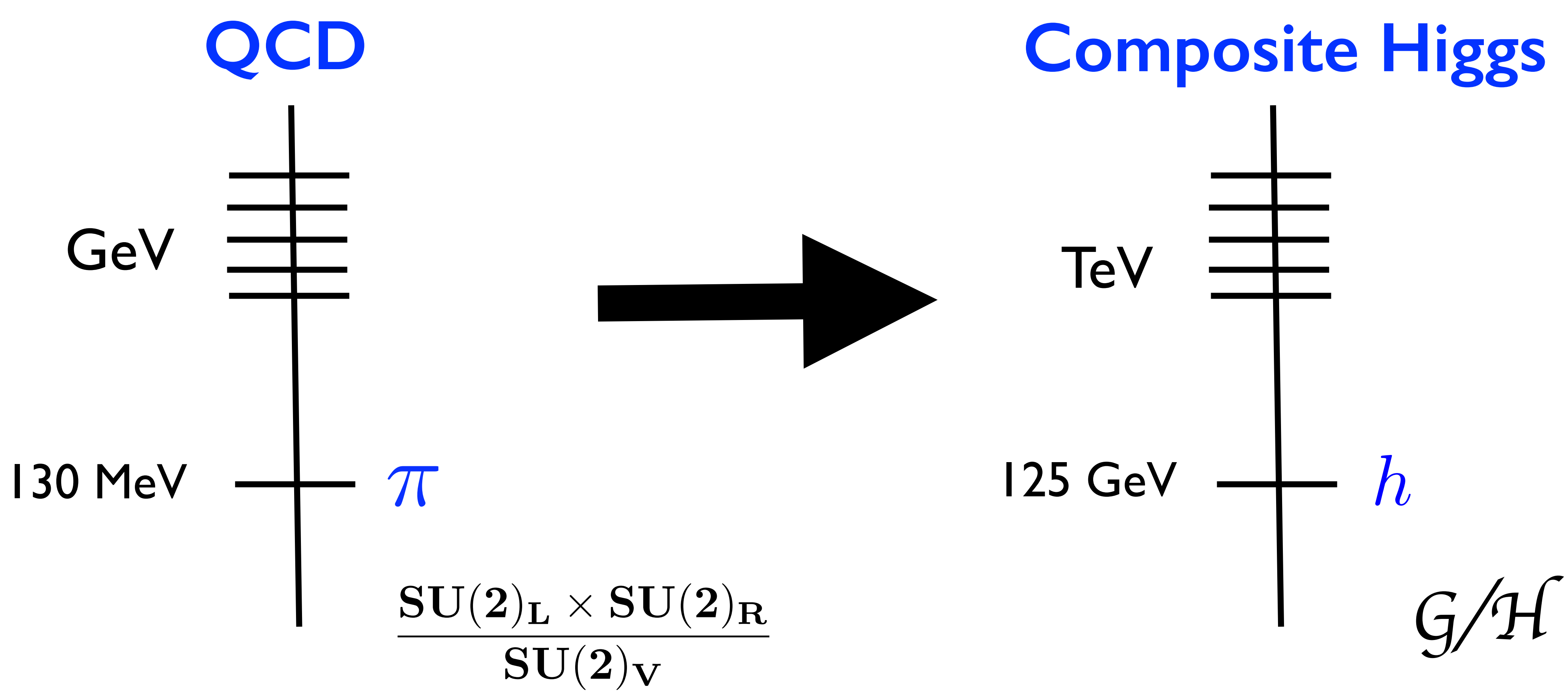
But no light "**Higgs**" **predicted!**

(Nature likes to be original!)

…although recent **lattice** analysis suggest that a light scalar can emerge if more fermions are added

Attempt II

The strong dynamics does not break the EW-symmetry



The **Higgs, the lightest** of the new strong resonances, as pions in QCD: they are Pseudo-Goldstone Bosons (**PGB**)

☛ arising from the symmetry-breaking $\mathcal{G} \rightarrow \mathcal{H}$

Important requirement: $m_W \simeq \cos\theta_W m_Z$

$\mathcal{H}$ must contain the SM group and an extra custodial SU(2)

$\mathcal{G}$	$\mathcal{H}$	C	N_G	$\mathbf{r}_{\mathcal{H}} = \mathbf{r}_{\mathrm{SU}(2)\times\mathrm{SU}(2)}\ (\mathbf{r}_{\mathrm{SU}(2)\times\mathrm{U}(1)})$
$\mathrm{SO}(5)$	$\mathrm{SO}(4)$	$\checkmark$	4	$\mathbf{4} = (\mathbf{2}, \mathbf{2})$
$\mathrm{SU}(3) \times \mathrm{U}(1)$	$\mathrm{SU}(2) \times \mathrm{U}(1)$		5	$\mathbf{2}_{\pm\mathbf{1/2}} + \mathbf{1}_{\mathbf{0}}$
$\mathrm{SU}(4)$	$\mathrm{Sp}(4)$	$\checkmark$	5	$\mathbf{5} = (\mathbf{1}, \mathbf{1}) + (\mathbf{2}, \mathbf{2})$
$\mathrm{SU}(4)$	$[\mathrm{SU}(2)]^2 \times \mathrm{U}(1)$	$\checkmark^*$	8	$(\mathbf{2}, \mathbf{2})_{\pm\mathbf{2}} = 2 \cdot (\mathbf{2}, \mathbf{2})$
$\mathrm{SO}(7)$	$\mathrm{SO}(6)$	$\checkmark$	6	$\mathbf{6} = 2 \cdot (\mathbf{1}, \mathbf{1}) + (\mathbf{2}, \mathbf{2})$
$\mathrm{SO}(7)$	G_2	$\checkmark^*$	7	$\mathbf{7} = (\mathbf{1}, \mathbf{3}) + (\mathbf{2}, \mathbf{2})$
$\mathrm{SO}(7)$	$\mathrm{SO}(5) \times \mathrm{U}(1)$	$\checkmark^*$	10	$\mathbf{10}_{\mathbf{0}} = (\mathbf{3}, \mathbf{1}) + (\mathbf{1}, \mathbf{3}) + (\mathbf{2}, \mathbf{2})$
$\mathrm{SO}(7)$	$[\mathrm{SU}(2)]^3$	$\checkmark^*$	12	$(\mathbf{2}, \mathbf{2}, \mathbf{3}) = 3 \cdot (\mathbf{2}, \mathbf{2})$
$\mathrm{Sp}(6)$	$\mathrm{Sp}(4) \times \mathrm{SU}(2)$	$\checkmark$	8	$(\mathbf{4}, \mathbf{2}) = 2 \cdot (\mathbf{2}, \mathbf{2})$
$\mathrm{SU}(5)$	$\mathrm{SU}(4) \times \mathrm{U}(1)$	$\checkmark^*$	8	$\mathbf{4}_{-5} + \bar{\mathbf{4}}_{+\mathbf{5}} = 2 \cdot (\mathbf{2}, \mathbf{2})$
$\mathrm{SU}(5)$	$\mathrm{SO}(5)$	$\checkmark^*$	14	$\mathbf{14} = (\mathbf{3}, \mathbf{3}) + (\mathbf{2}, \mathbf{2}) + (\mathbf{1}, \mathbf{1})$
$\mathrm{SO}(8)$	$\mathrm{SO}(7)$	$\checkmark$	7	$\mathbf{7} = 3 \cdot (\mathbf{1}, \mathbf{1}) + (\mathbf{2}, \mathbf{2})$
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$\mathrm{SO}(9)$	$\mathrm{SO}(5) \times \mathrm{SO}(4)$	$\checkmark^*$	20	$(\mathbf{5}, \mathbf{4}) = (\mathbf{2}, \mathbf{2}) + (\mathbf{1} + \mathbf{3}, \mathbf{1} + \mathbf{3})$
$[\mathrm{SU}(3)]^2$	$\mathrm{SU}(3)$		8	$\mathbf{8} = \mathbf{1}_{\mathbf{0}} + \mathbf{2}_{\pm\mathbf{1/2}} + \mathbf{3}_{\mathbf{0}}$
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$\mathrm{SU}(6)$	$\mathrm{Sp}(6)$	$\checkmark^*$	14	$\mathbf{14} = 2 \cdot (\mathbf{2}, \mathbf{2}) + (\mathbf{1}, \mathbf{3}) + 3 \cdot (\mathbf{1}, \mathbf{1})$
$[\mathrm{SO}(6)]^2$	$\mathrm{SO}(6)$	$\checkmark^*$	15	$\mathbf{15} = (\mathbf{1}, \mathbf{1}) + 2 \cdot (\mathbf{2}, \mathbf{2}) + (\mathbf{3}, \mathbf{1}) + (\mathbf{1}, \mathbf{3})$

from arXiv:1401.2457

with custodial symmetry

$\mathcal{H} \supset \mathrm{SU}(2) \times \mathrm{SU}(2)$

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from arXiv:1401.2457

Known UV-completion

Galloway, Evans, Luty, Tacchi 10

Example: Just take QCD (with two flavors)
replace **$SU(3)_c$** by **$SU(2)_c$**

	$SU(3)_c$	$SU(2)_c$
Global symmetry:	$SU(2)_L \otimes SU(2)_R$	$SU(4) \sim SO(6)$
	$\langle\psi\psi\rangle \neq 0$ $\downarrow$	$\downarrow$ $\langle\psi\psi\rangle \neq 0$
	$SU(2)_V$	$SP(4) \sim SO(5)$
	3 Golstones = π^0, π^+, π^-	5 Goldstones = **Higgs doublet + singlet**

since $2 \sim \bar{2}$:

$\mathbf{4} = 2_L + 2_R$

ψ_L, ψ_R^c

Fermion masses

Simplest possibility

1) bilinear-mixing:

$$\mathcal{L}_{\rm bil} \sim \bar{f}_i \mathcal{O}_H f_j$$

$$\langle 0|\mathcal{O}_H|H\rangle \neq 0$$

e.g. $\mathcal{O}_H \sim \bar{\psi}\psi$

if dim[$|\mathcal{O}_H|^2$]>4 to avoid a relevant (singlet) operator that would bring back the hierarchy problem,

we expect d_H>2

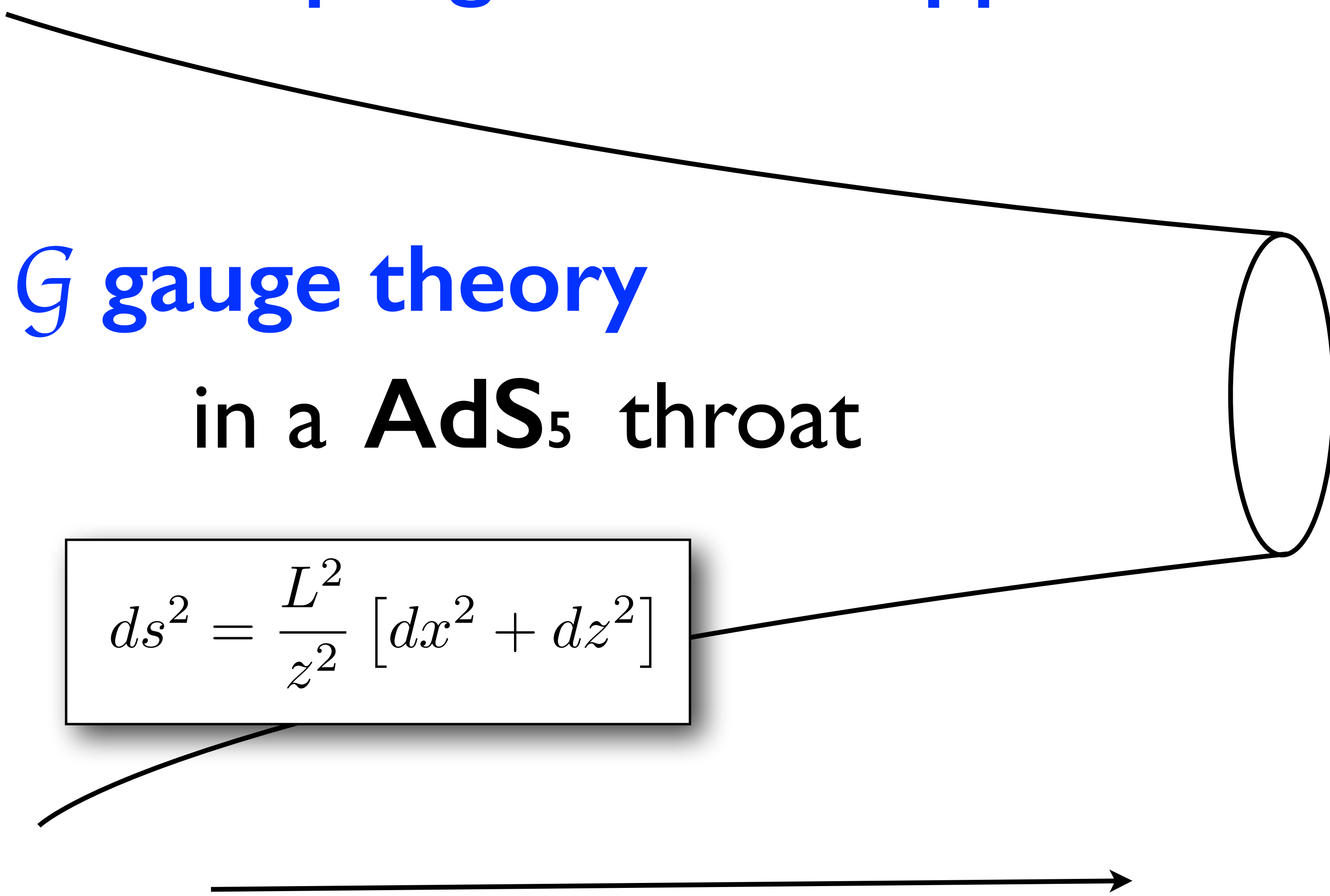
$$Yukawa \sim \left(\frac{\Lambda_{\rm IR}}{\Lambda_{\rm UV}}\right)^{d_H-1}$$

too small for the top!

Inspiration from holography:

Simple geometric approach to fermion masses

Agashe,Contino,A.P.



$\mathcal{G}$ **gauge theory**

in a **AdS5** throat

$$ds^2 = \frac{L^2}{z^2}\left[dx^2 + dz^2\right]$$

Holo. coordinate z ~ 1/E

hard/soft wall

Mass gap ~ TeV

Symmetry : $\mathcal{H}$

Breaking of symmetry by boundary conditions

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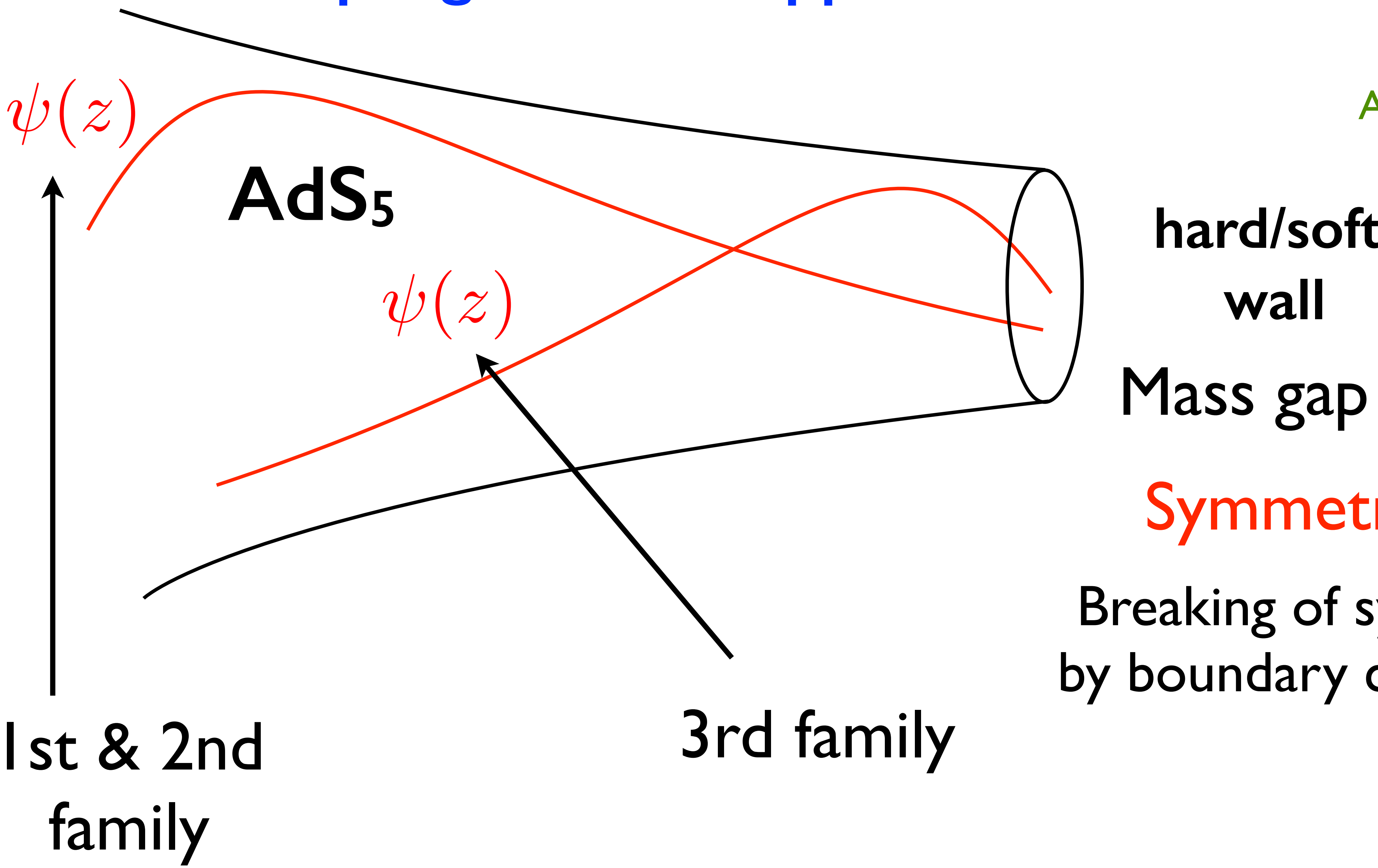

Mass gap ~ TeV

Symmetry : $\mathcal{H}$

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Suggesting an alternative possibility

1) linear-mixing:

$$\mathcal{L}_{\rm lin} = \epsilon_{f_i}\, \bar{f}_i\, \mathcal{O}_{f_i}$$

depending on the dimension of $\mathcal{O}_f$, we can have <u>relevant</u> or <u>irrelevant</u> couplings

☛ large or small mixings ϵ_f depending on the dimension:

$$\epsilon_{f_i} \sim \left(\frac{\Lambda_{\rm IR}}{\Lambda_{\rm UV}}\right)^{\gamma_i} \qquad \gamma_i = {\rm Dim}[\mathcal{O}_{f_i}] - 5/2 > 1$$

For the top, γ ~0 needed: dim[$\mathcal{O}_t$] ~ 5/2

Difficult requirement for gauge theories!

arXiv:1502.00390

e.g. SU(4) strong sector

Fermions:

a) three $\Psi_{L,R} \in \mathbf{4}$ (fundamental)

b) five $\Upsilon \in \mathbf{6}$ (antisym. matrix)

$$\Psi\Upsilon\Psi = \mathcal{O}_{\text{top}}$$

Operator that can be coupled to the top:

$$\mathcal{L}_{\text{mixing}} = t\,\mathcal{O}_{\text{top}}$$

Global sym.

$$G = SU(5) \times SU(3) \times SU(3)' \times U(1)_X \times U(1)'$$

$$\Downarrow$$

$$H = SO(5) \times SU(3)_{\text{color}} \times U(1)_X$$

dimension at weak coupling: 9/2

$$\Downarrow$$

dimension needed at strong coupling: 5/2

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$$\Big\downarrow$$

$$H = SO(5) \times SU(3)_{\rm color} \times U(1)_X$$

Possible?

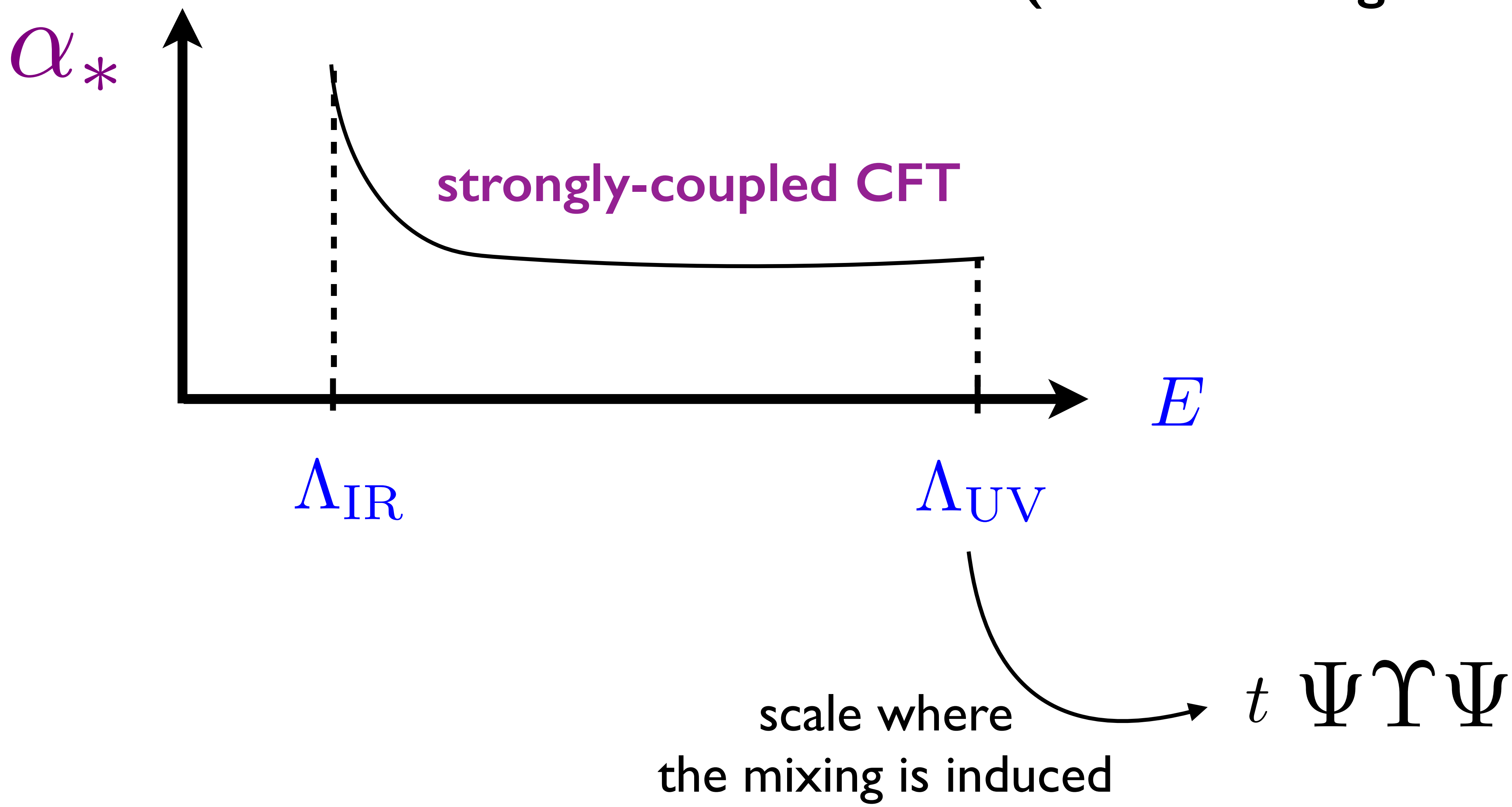
dimension at weak coupling: 9/2

$$\Big\downarrow$$

dimension needed at strong coupling: 5/2

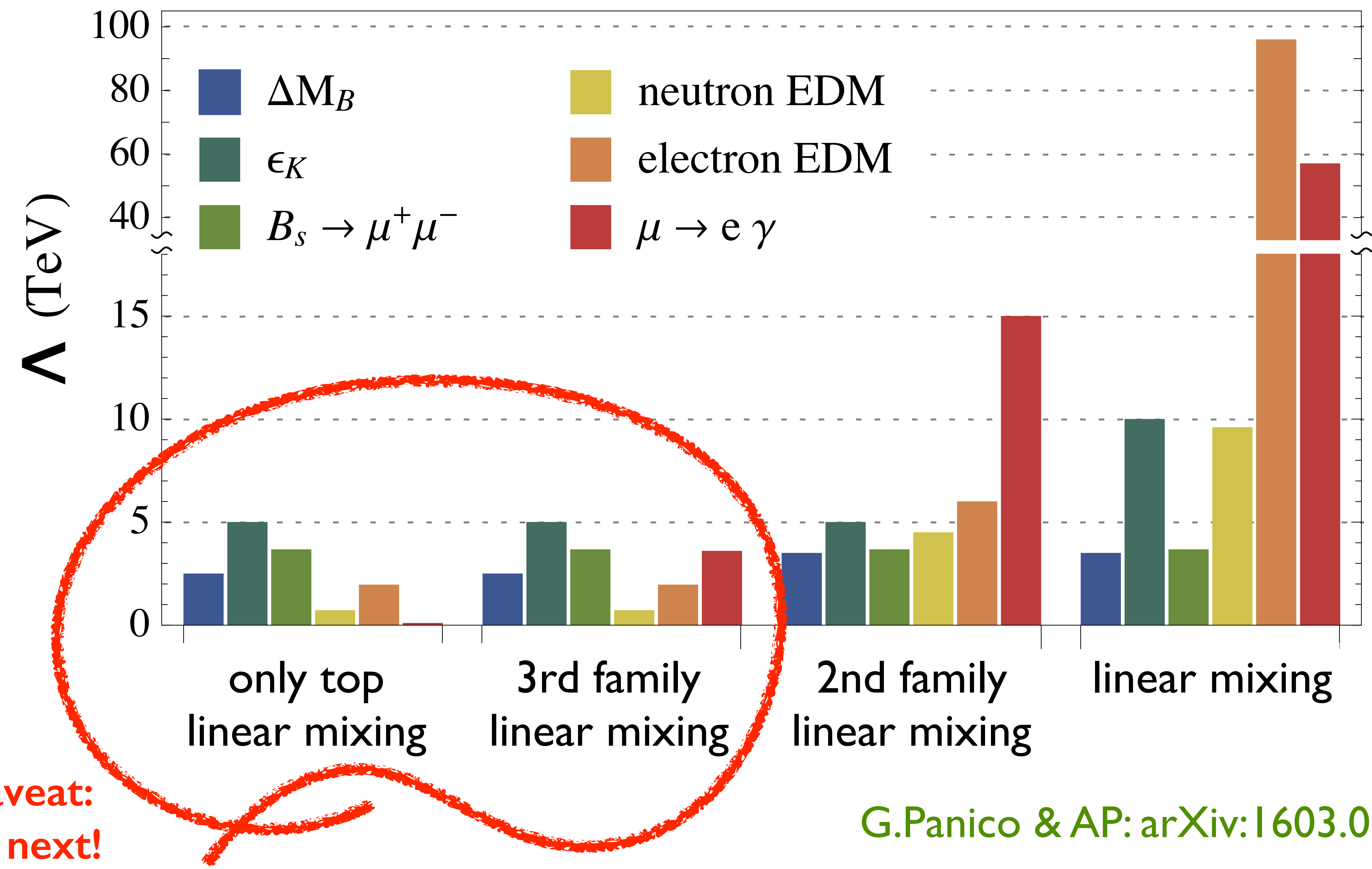
The theory must be a quasi-CFT from the scale where the top-operator is generated

(as in *walking TC*!)



New flavor-violating & CP-violating transitions

Lower bounds on the scale of the strong dynamics Λ



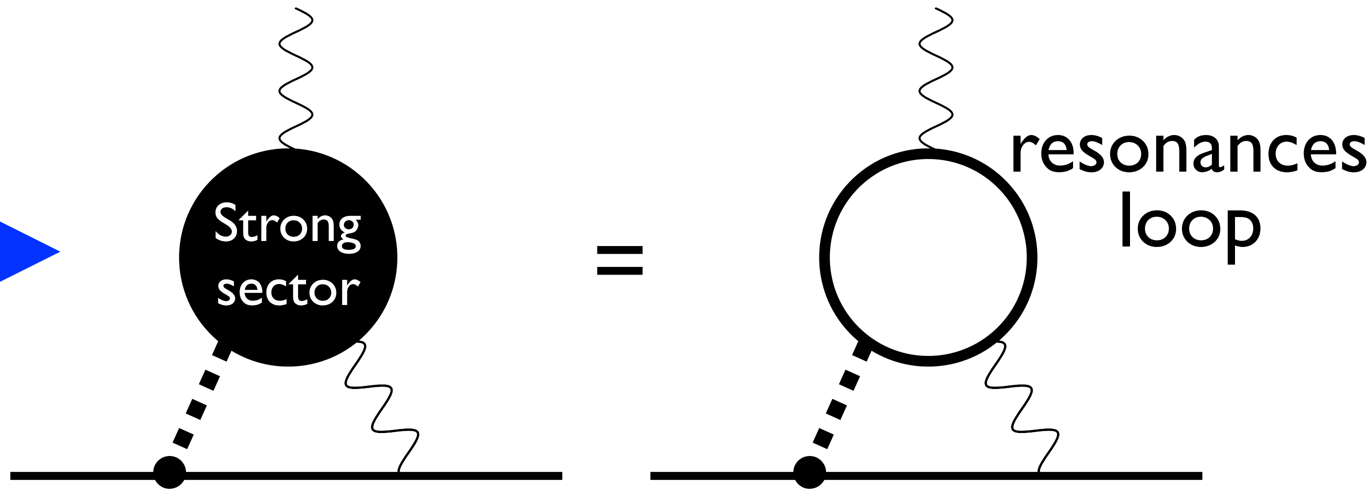
*caveat: see next!

G.Panico & AP: arXiv:1603.06609

Bounds of $\mathcal{O}$(TeV)! Effects visible soon. Hopes for the future!

*Caveat: dipoles in the strong sector assumed to be "loop" suppressed

$$\mathcal{L}_{\rm bil} \sim \bar{f}_i \mathcal{O}_H f_j$$



EDM at most at two-loop!

<u>Property of holographic models</u>

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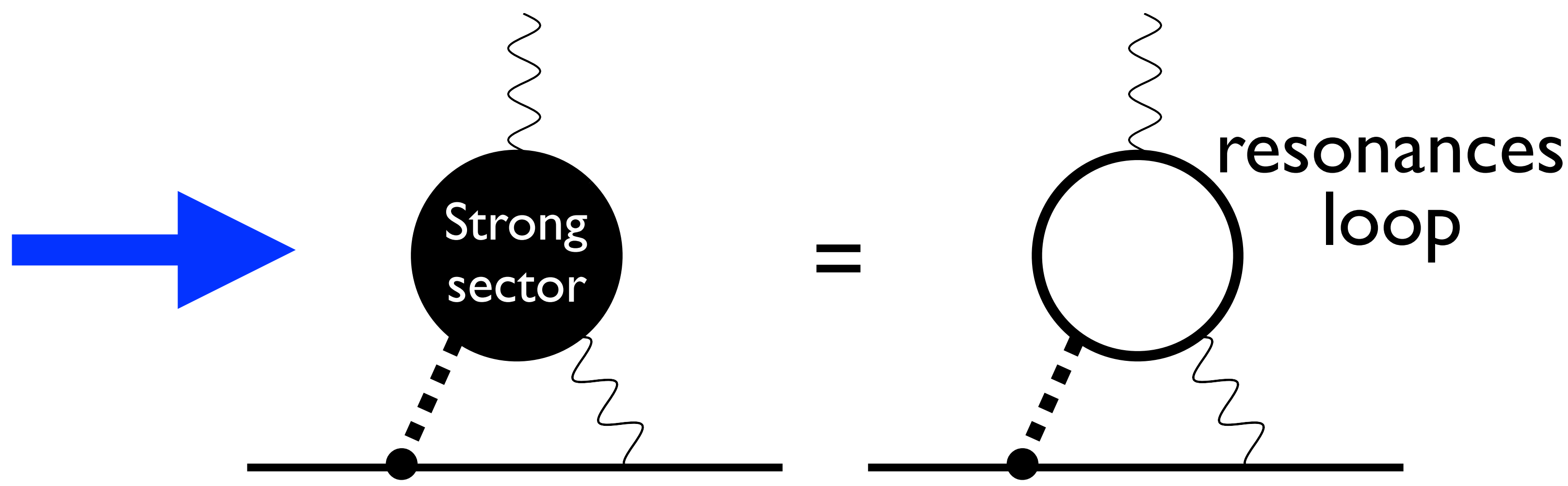


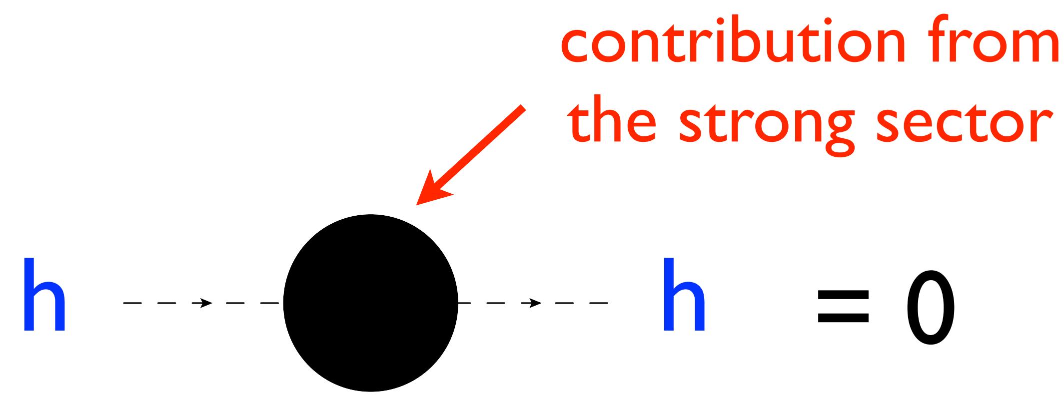
EDM at most at two-loop!

Property of holographic models

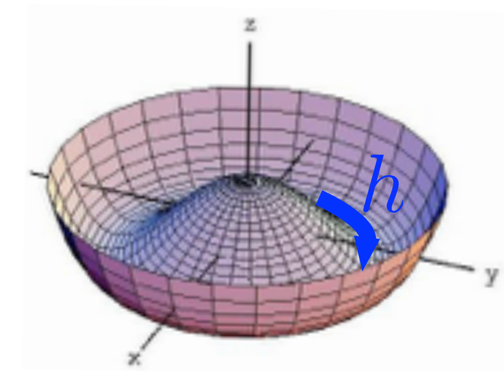
Also in large-N QCD?

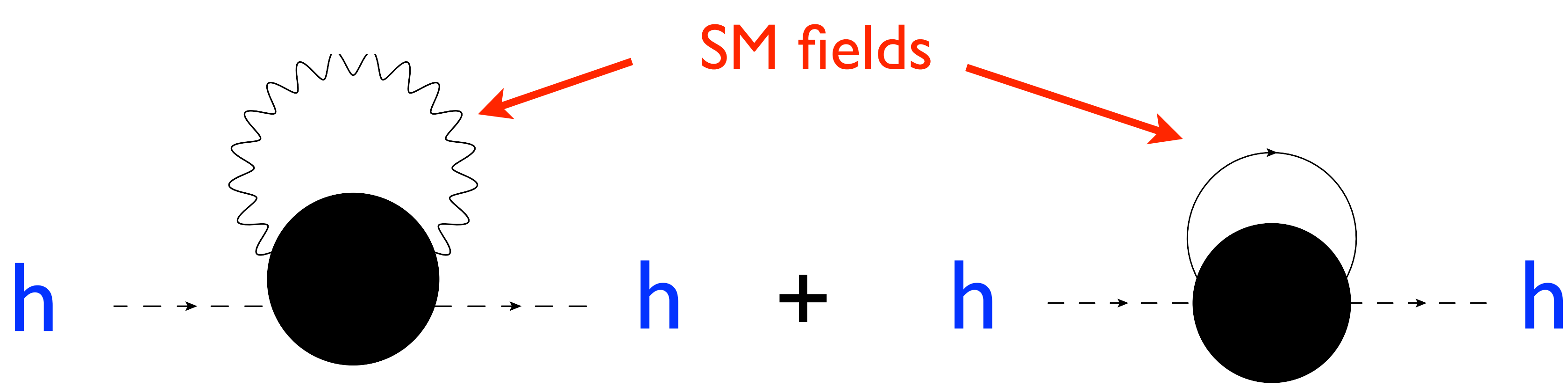
some hints: $\dfrac{L_9 + L_{10}}{L_9 - L_{10}} \simeq \dfrac{6.9 - 5.5}{6.9 + 5.5} \sim 0.1$

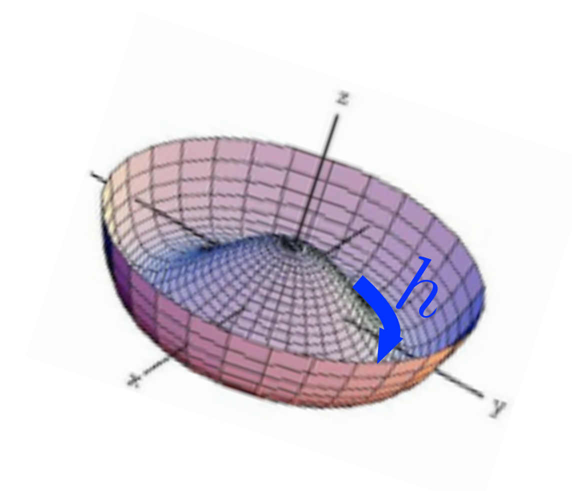
Higgs potential



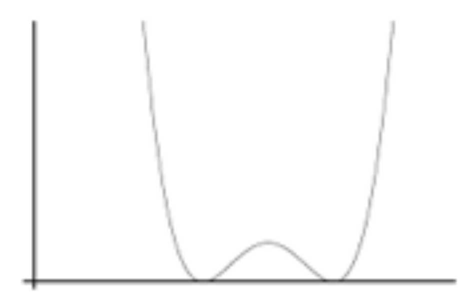
$= 0$ **it's a Goldstone**







- **Top needed to achieve EWSB!**

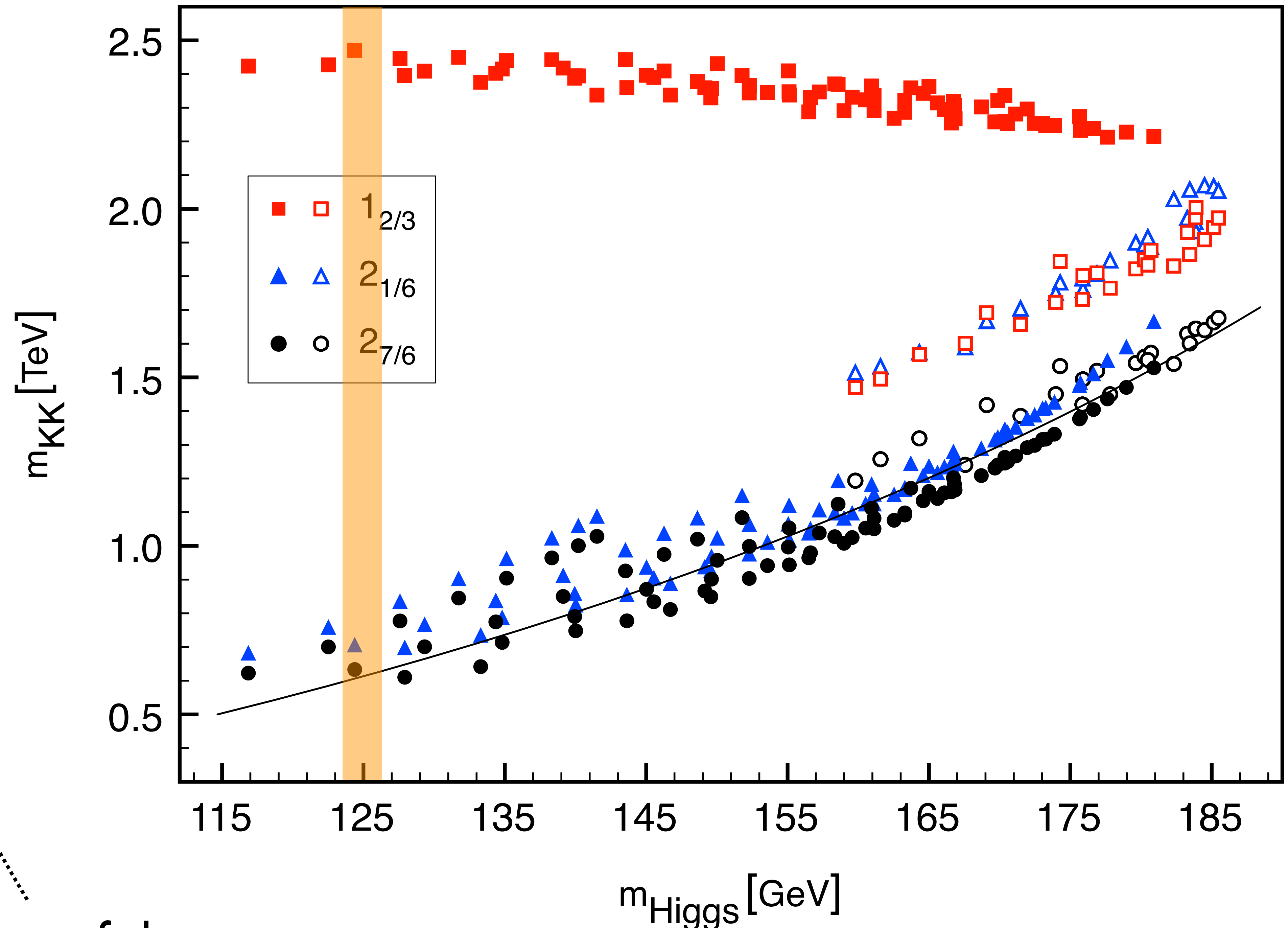


- **Mass at the one-loop level ☛ Light Higgs expected!**

From AdS$_5$ models:

Contino, DaRold, AP 07

$$m_\rho = 2.5 \text{ TeV} \quad , \quad f = 500 \text{ GeV}$$



mass of the fermionic resonances

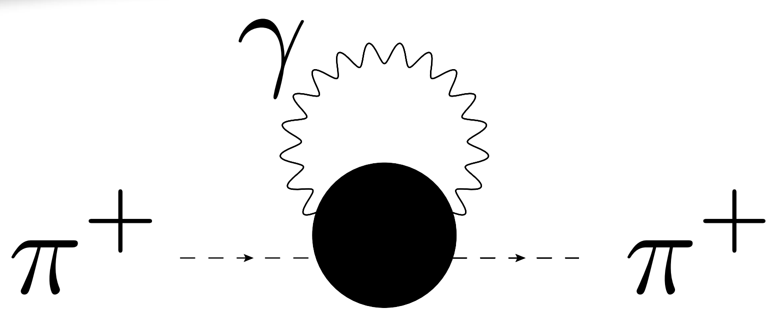
Light Higgs - Light Resonance connection!

Simpler derivation of the connection: Light Higgs - Light Resonance

Marzocca,Serone,Shu; AP, Riva 12

➥ Following Das,Guralnik,Mathur,Low,Young 67 as the charged pion mass:

$$\boxed{m_{\pi^+}^2 - m_{\pi^0}^2 \simeq \frac{3\alpha}{2\pi} m_\rho^2 \log 2 \simeq (37\ \mathrm{MeV})^2}$$



Exp. $(35\ \mathrm{MeV})^2$

quite successful!

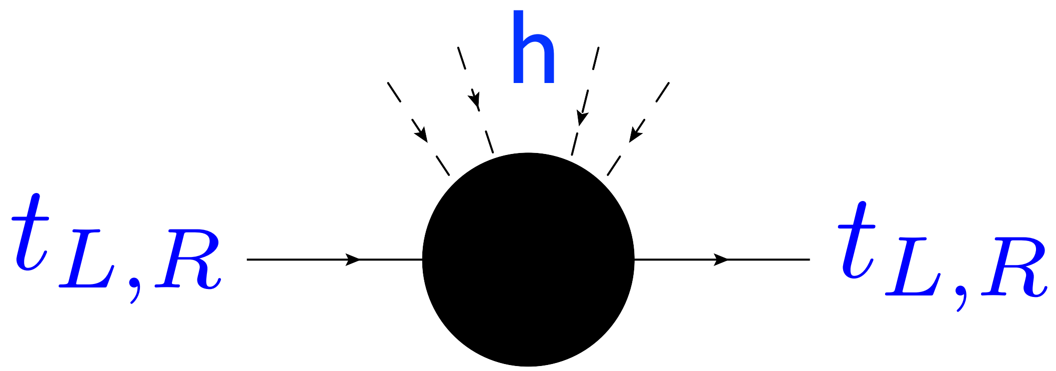
$$\int \frac{d^4p}{(2\pi)^4} \frac{\Pi_{LR}(p)}{p^2} \qquad \Pi_{LR} \equiv \Pi_V - \Pi_A$$

- Assuming Π_{LR} to be dominated by the lowest resonances
- Imposing the Weinberg Sum Rules: $\lim_{p^2\to\infty} \Pi_{LR} = 0 \ , \ \lim_{p^2\to\infty} p^2 \Pi_{LR} = 0$

Top contribution to the Higgs potential:

$$V(h) = -2N_c \int \frac{d^4p}{(2\pi)^4} \log\left[-p^2\left(\Pi^{t_L}\Pi^{t_R}\right) - |\Pi^{t_L t_R}|^2\right]$$

Encode the strong-sector contribution
to the top propagator
in the h-background



related to $\langle \bar{\mathcal{O}}_f \mathcal{O}_f \rangle$

Weinberg Sum Rules
+ Minimal set of resonances
+ proper EWSB

$$m_h^2 \simeq \frac{N_c}{\pi^2}\left[\frac{m_t^2}{f^2}\frac{m_{Q_4}^2 m_{Q_1}^2}{m_{Q_1}^2 - m_{Q_4}^2}\log\left(\frac{m_{Q_1}^2}{m_{Q_4}^2}\right)\right]$$

AP,Riva 12

$$m_Q \lesssim 700\ \text{GeV}\left(\frac{m_h}{125\ \text{GeV}}\right)\left(\frac{160\ \text{GeV}}{m_t}\right)\left(\frac{f}{500\ \text{GeV}}\right)$$

mass of color vector-like fermions
with EM charges 5/3,2/3,-1/3

Wrapping up

Demands on the Strong sector:

- Global symmetry breaking $\mathcal{G} \rightarrow \mathcal{H}$ $\begin{cases} 1) & \text{Higgs in the coset } \mathcal{G}/\mathcal{H} \\ 2) & \mathcal{H} \supset \text{SM} + \text{extra SU(2)c} \end{cases}$

- Fermion operator $\mathcal{O}_{top}$ with the quantum numbers of the top

  of dim~5/2 such that the mixing with the top

  top x $\mathcal{O}_{top}$ is a marginal coupling ~ O(1)

- Lighter fermion resonances seems to be needed for a m_H~125 GeV

- Small dipoles seem to be needed to pass bounds on EDM, $\mu \rightarrow e\gamma$

Where lattice can help ?

Demands on the Strong sector:

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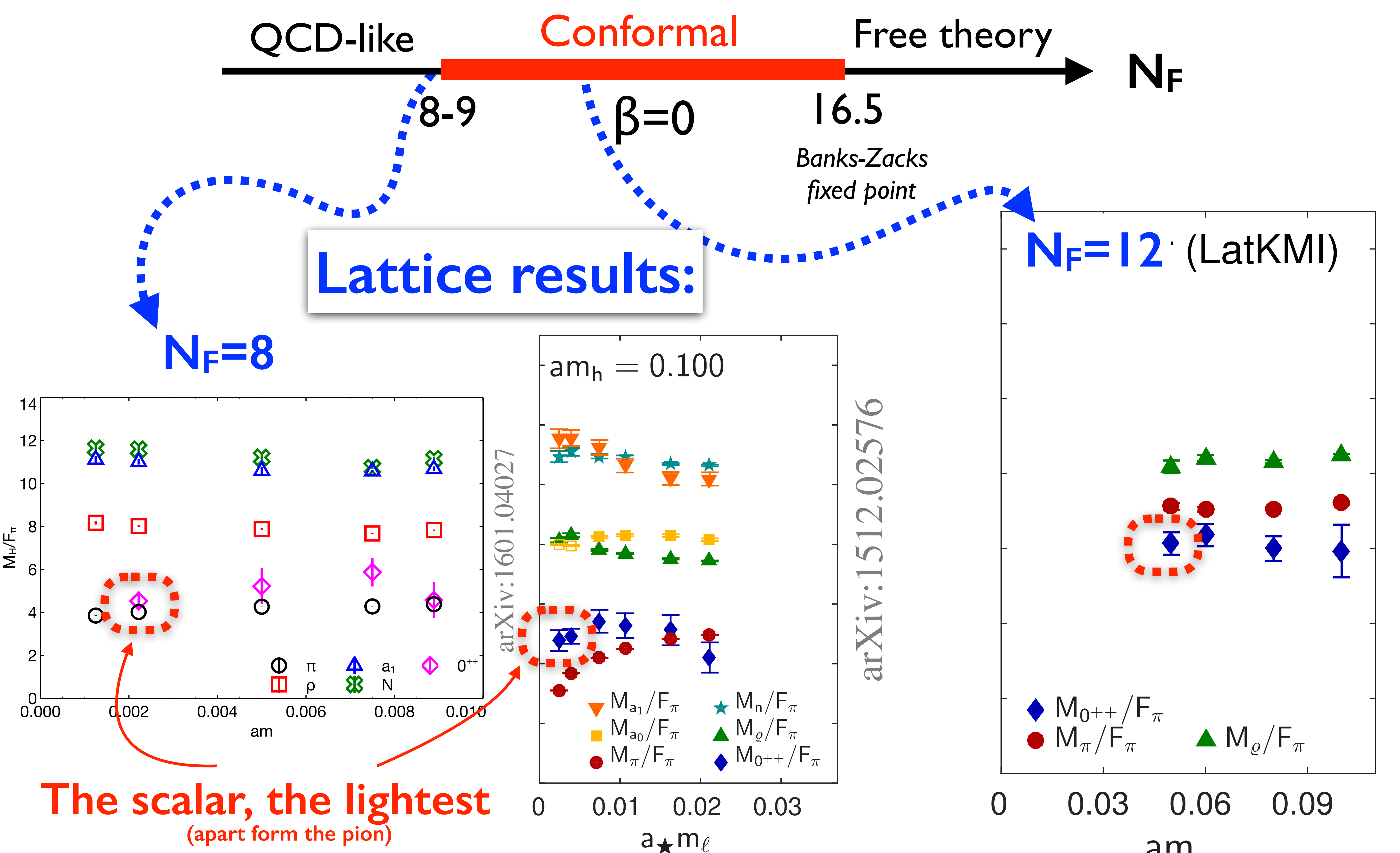
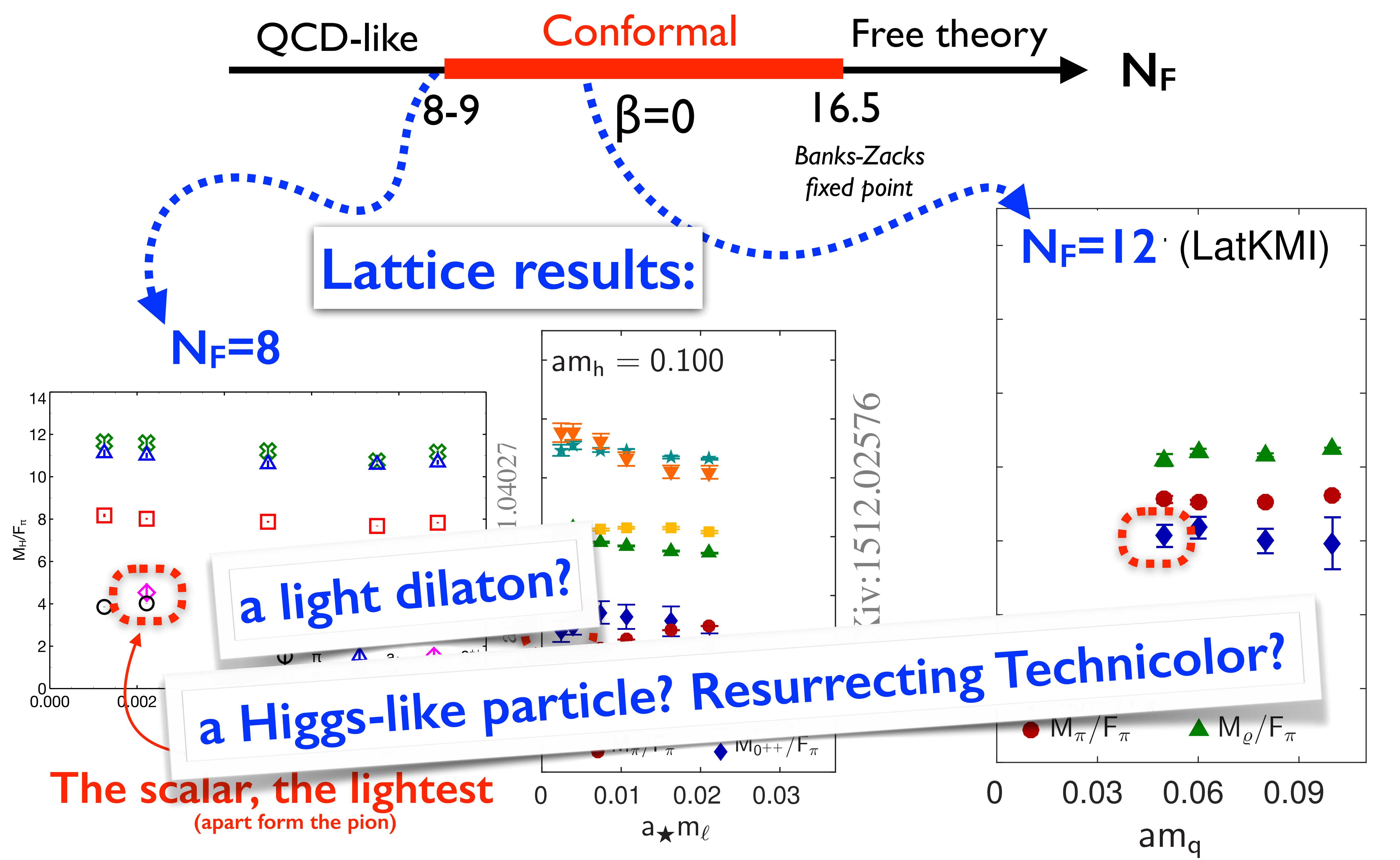
(

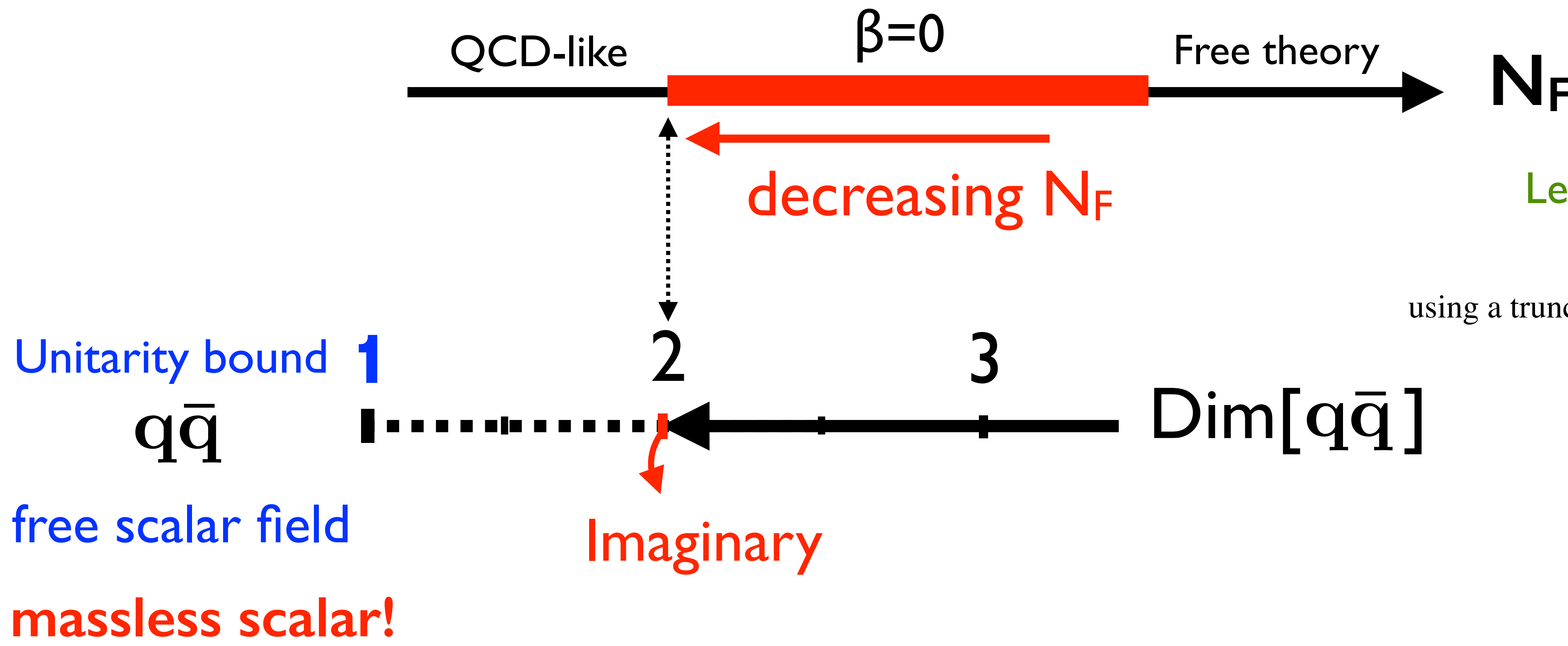
Conformal window in SU(3) with large number of fermions (N_F)



Conformal window in SU(3) with large number of fermions (N_F)



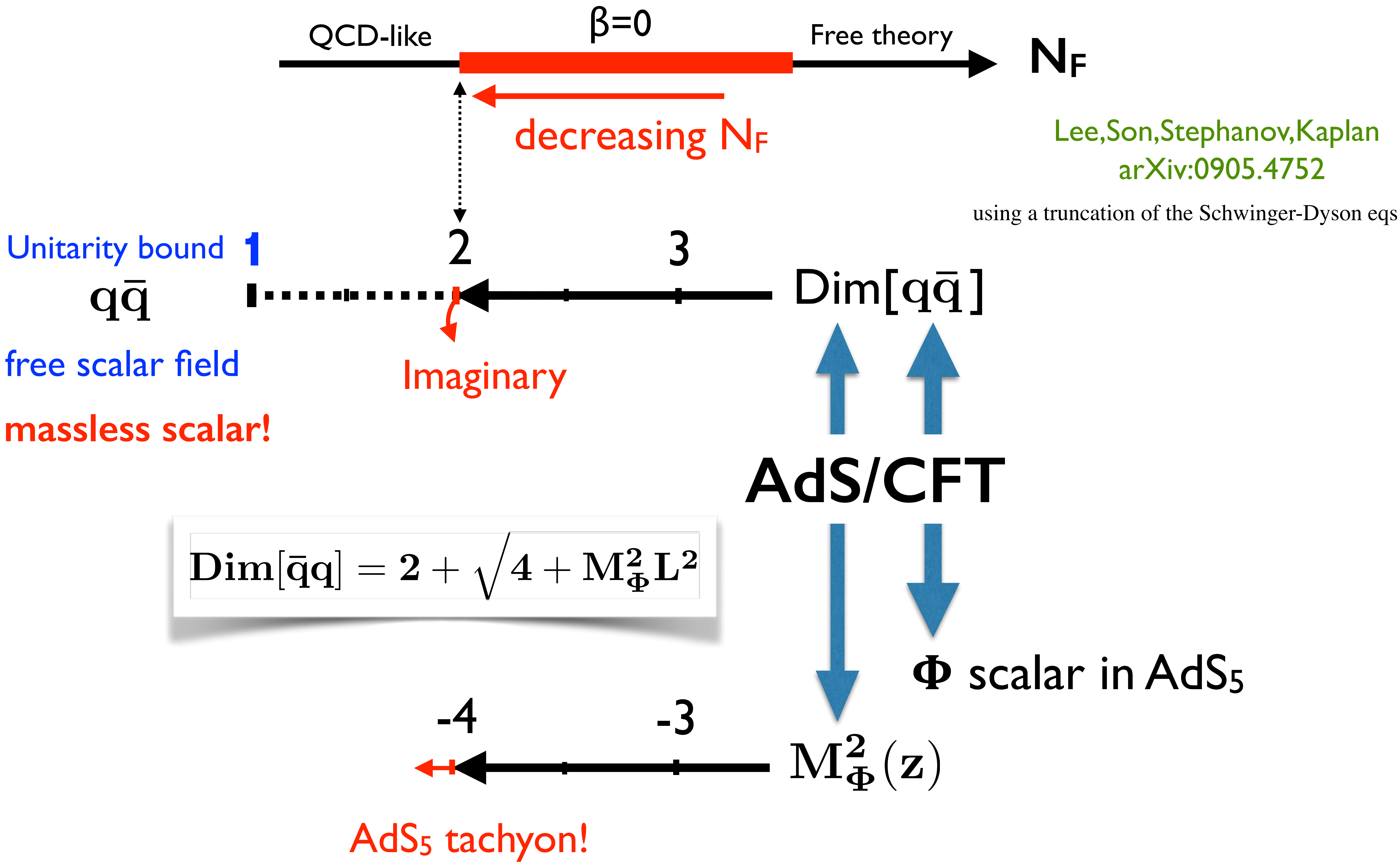
Why a lighter scalar?



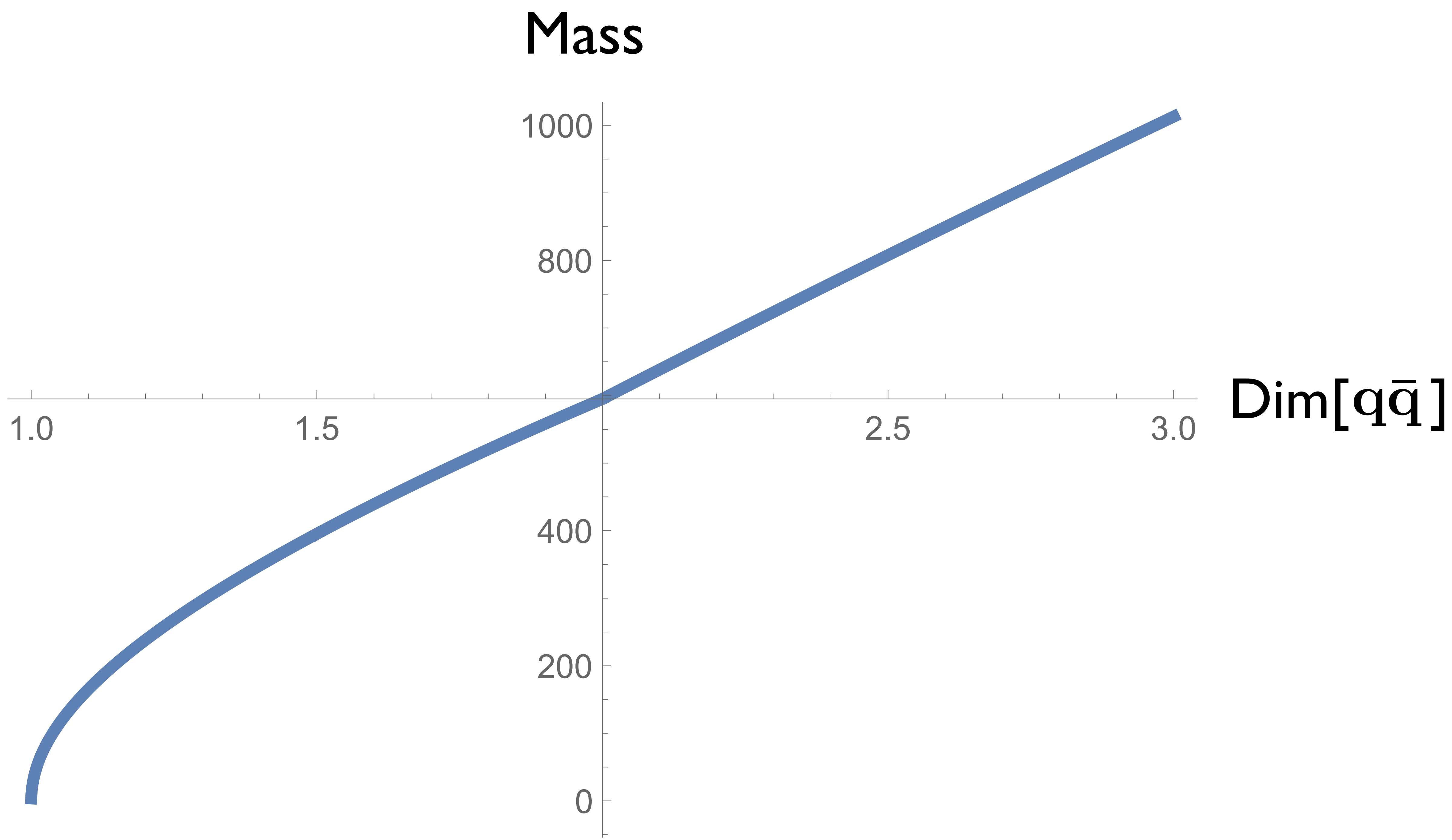
Lee,Son,Stephanov,Kaplan
arXiv:0905.4752

using a truncation of the Schwinger-Dyson eqs.

Why a lighter scalar?



AdS predictions



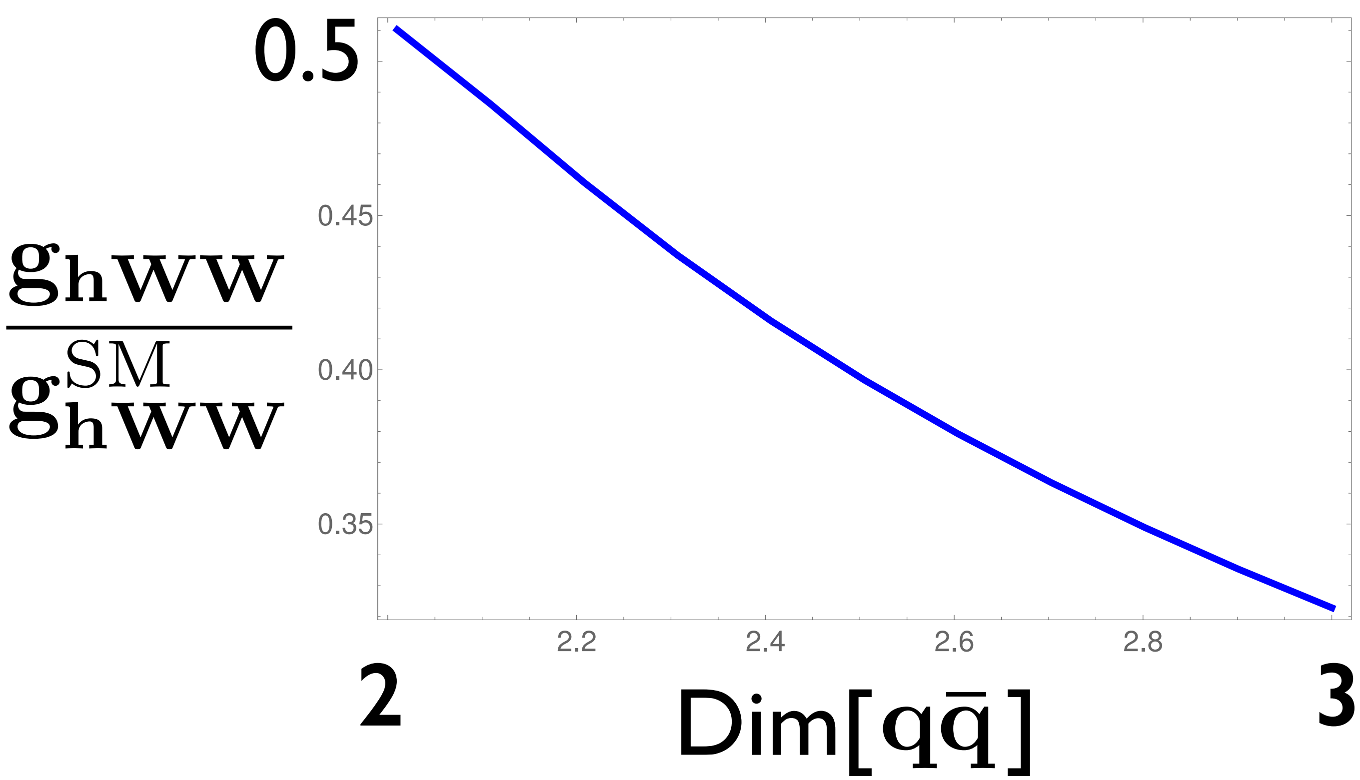
the scalar becomes a factor ~1/2 lighter at dim[qq]=2

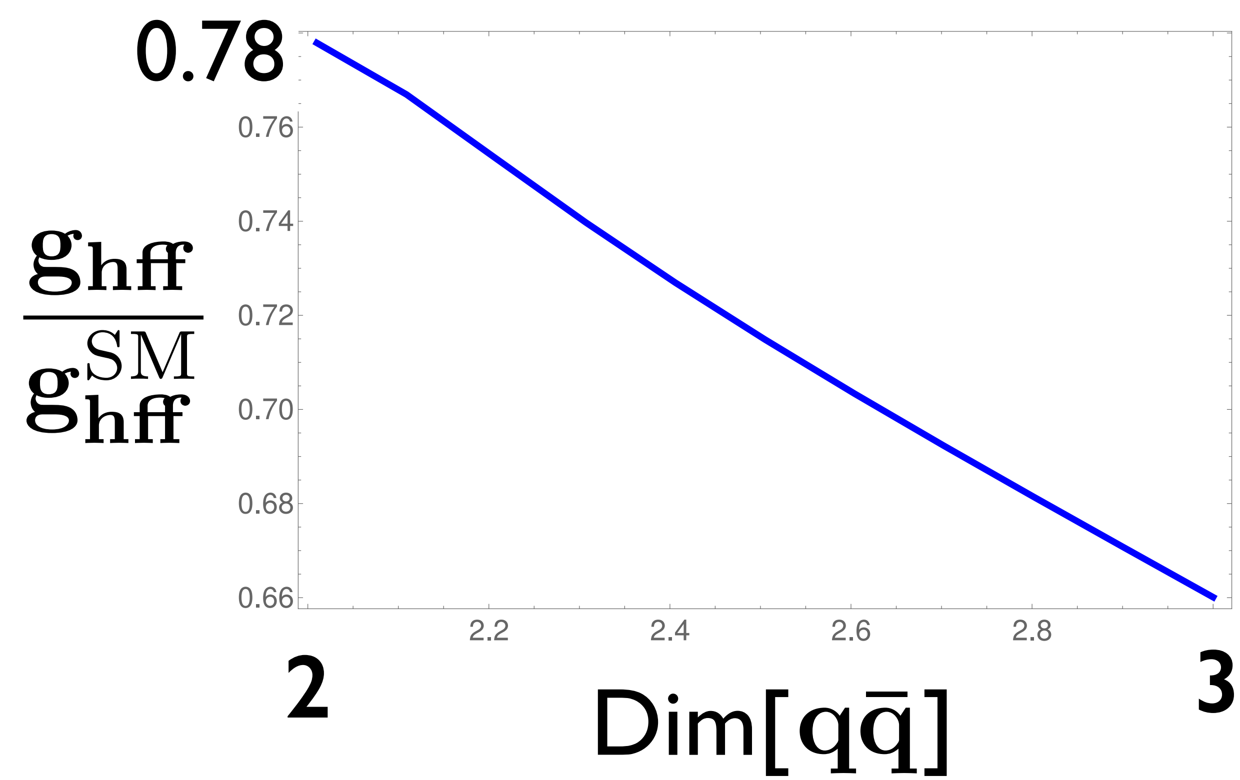
Could this scalar be the Higgs? Resurrecting Technicolor?

Mass? Not light enough

For $M_{TC\text{-}\rho} \sim$ 2-3 TeV we have $M_H \sim M_{TC\text{-}\rho}/2 \sim$ TeV

Higgs-like coupling? Approaching free scalar limit = SM Higgs





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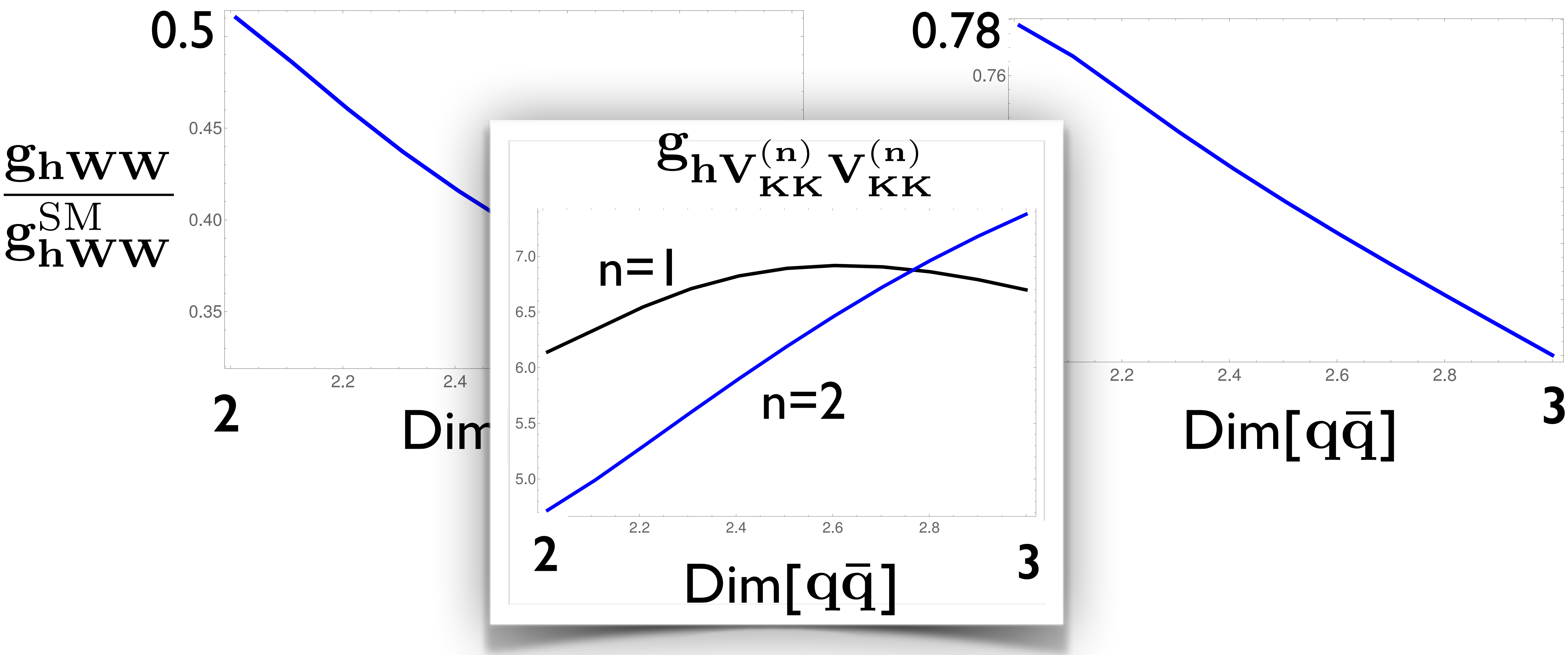
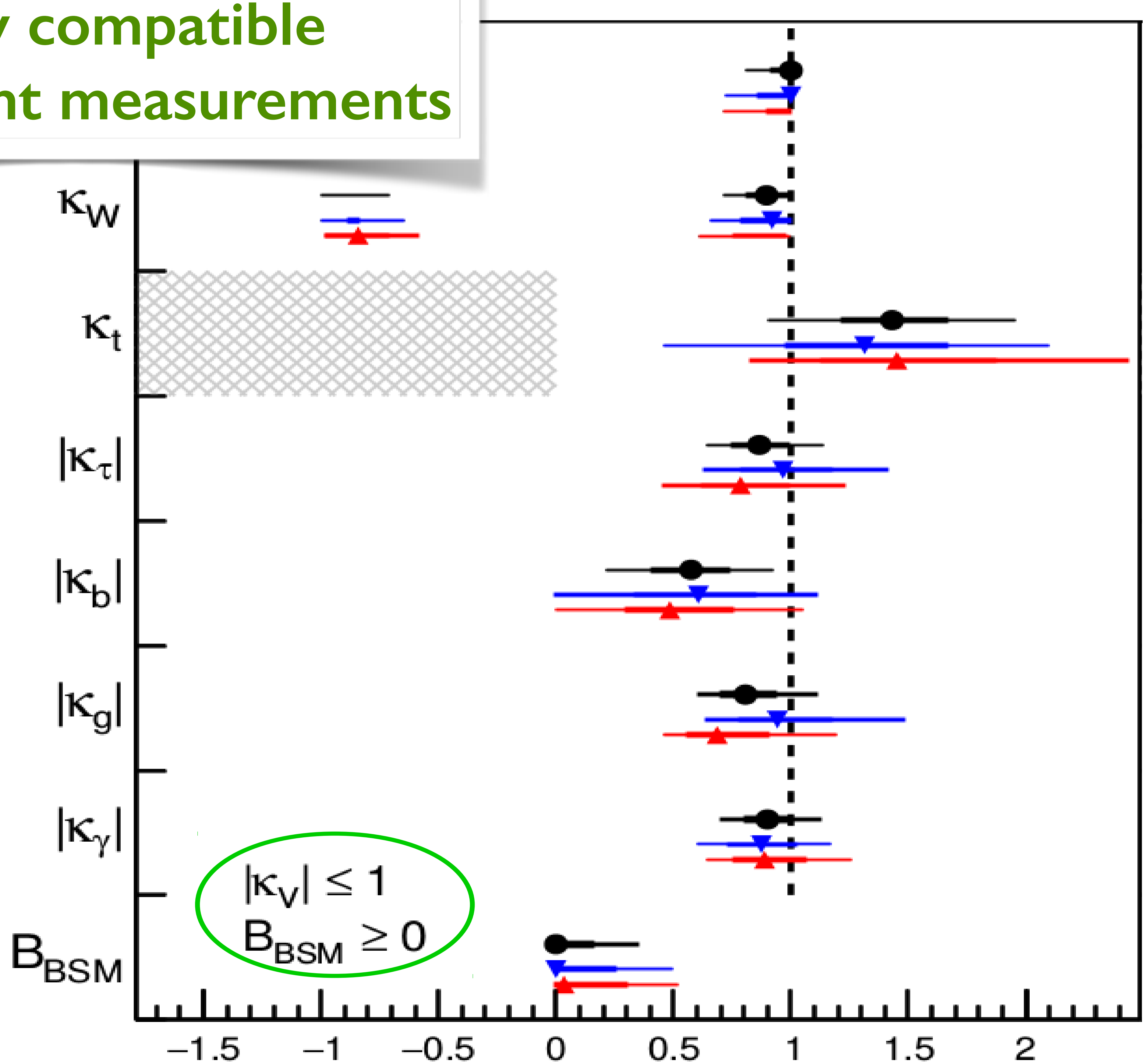


Hardly compatible with present measurements

$$\kappa_i = \frac{g_{Hii}}{g_{Hii}^{\mathrm{SM}}}$$



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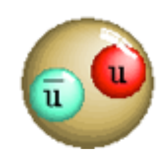
Phenomenology

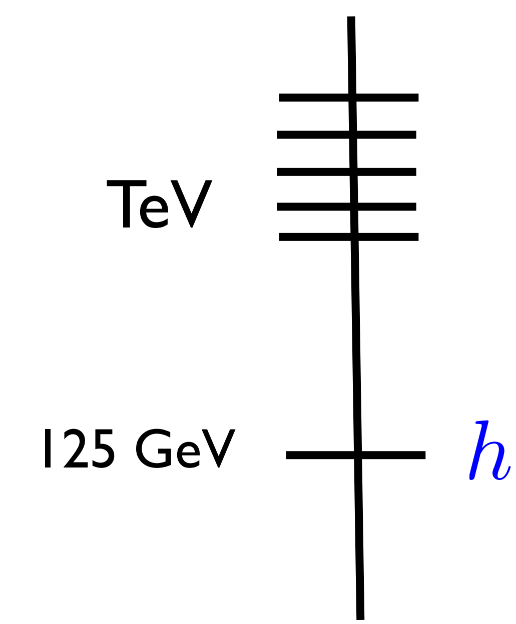
Physical implications of TeV strong-dynamics

New **flavor-violating & CP-violating** transitions

Signs of **compositeness** in the Higgs (and top)



New **resonances**



Signs of compositeness of the Higgs

Well-defined pattern of deviations in Higgs couplings:

Giudice,Grojean,AP,Rattazzi 07

$$\frac{g_{hWW}}{g_{hWW}^{\rm SM}} = \sqrt{1-\frac{v^2}{f^2}}$$

f = Decay-constant of the PGB Higgs related to the compositeness scale

(model dependent but expected f ~ v)

AP,Riva 12

$$\frac{g_{hff}}{g_{hff}^{\rm SM}} = \frac{1-(1+n)\frac{v^2}{f^2}}{\sqrt{1-\frac{v^2}{f^2}}}$$

$$n = \underset{\uparrow \atop \text{MCHM4}}{0},\ \underset{\uparrow \atop \text{MCHM5}}{1},\ 2, \ldots$$

small deviations on the h$\gamma\gamma$(gg)-coupling due to the Goldstone nature of the Higgs

Signs of compositeness of the Higgs

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Giudice,Grojean,AP,Rattazzi 07

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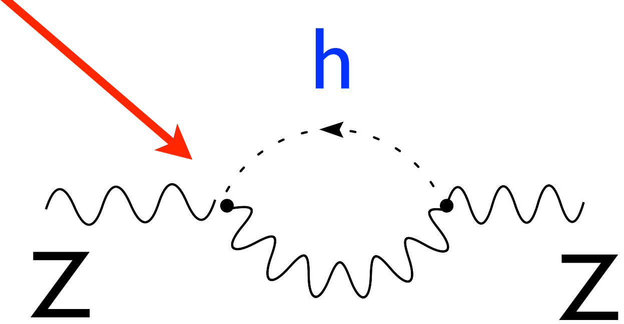
f = Decay-constant of the PGB Higgs related to the compositeness scale

(model dependent but expected f ~ v)

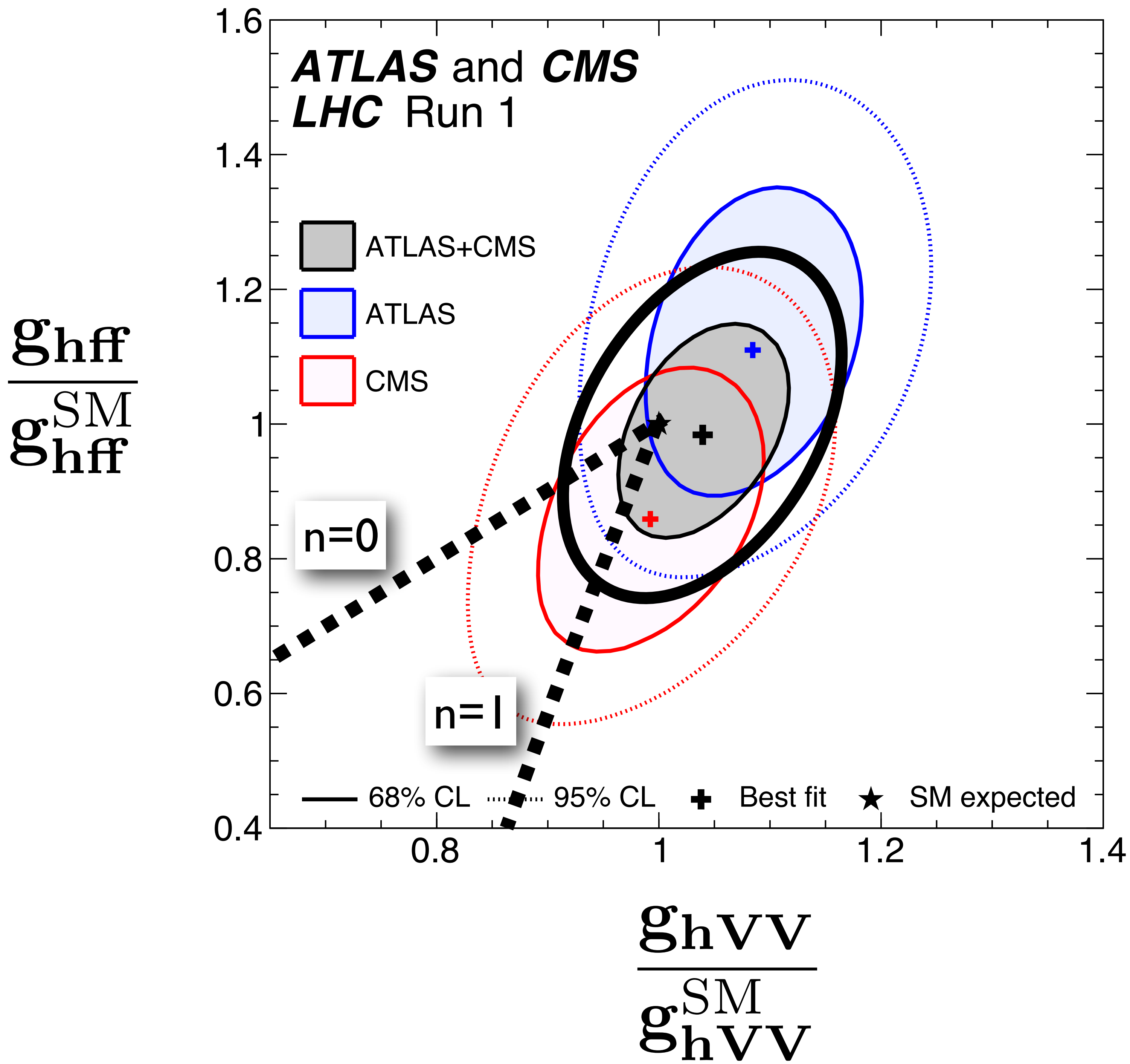
But already constrained at LEP



$$\frac{\delta g_{hWW}}{g_{hWW}} \lesssim 5\%$$

We could not expect large deviations in Higgs coupling measurements

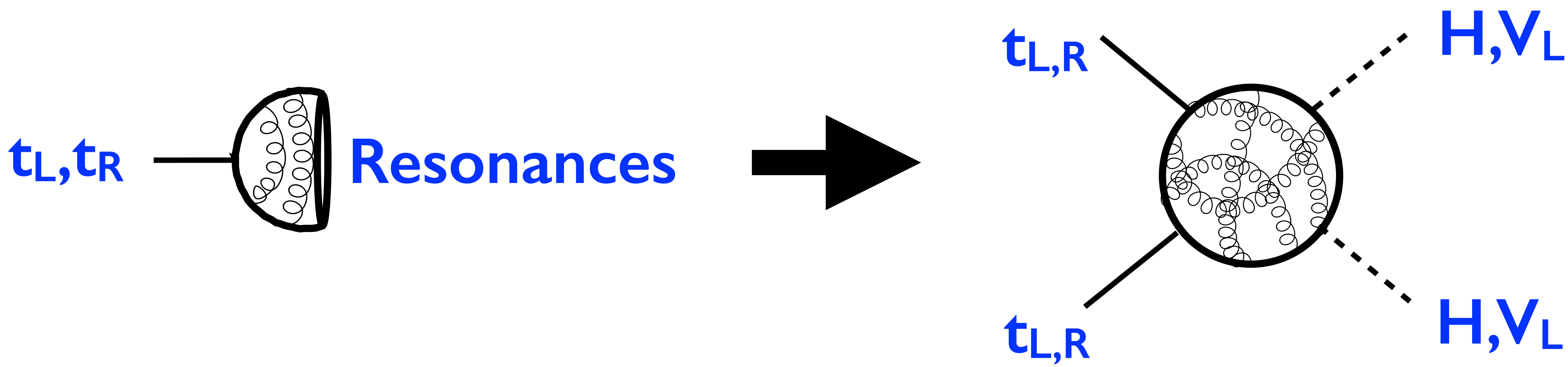
Signs of compositeness of the Higgs



Entering the interesting region: bounds getting below 10%!

Signs of compositeness of the top

Since its mass is large, its mixing with the strong sector must be large:



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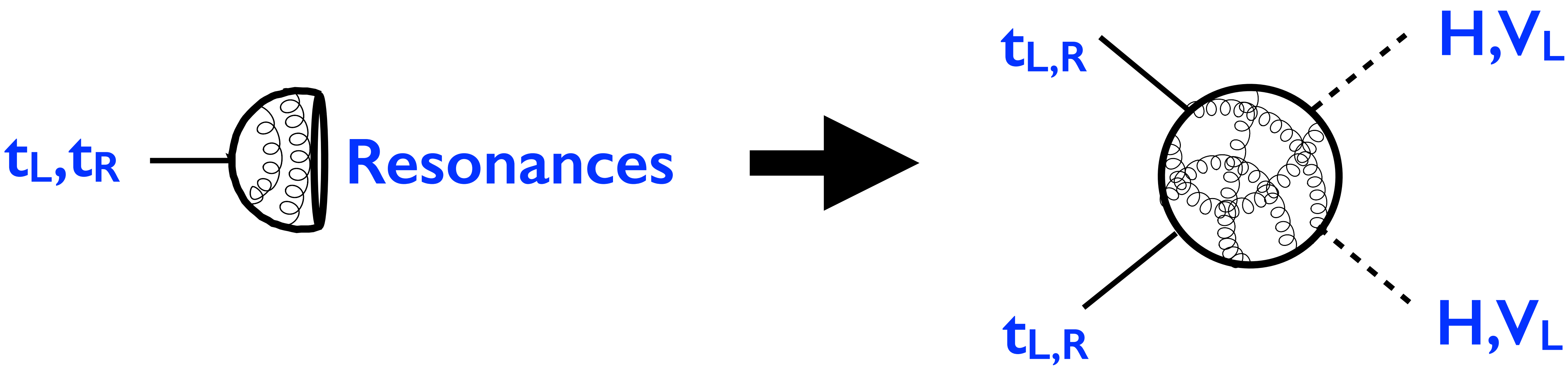
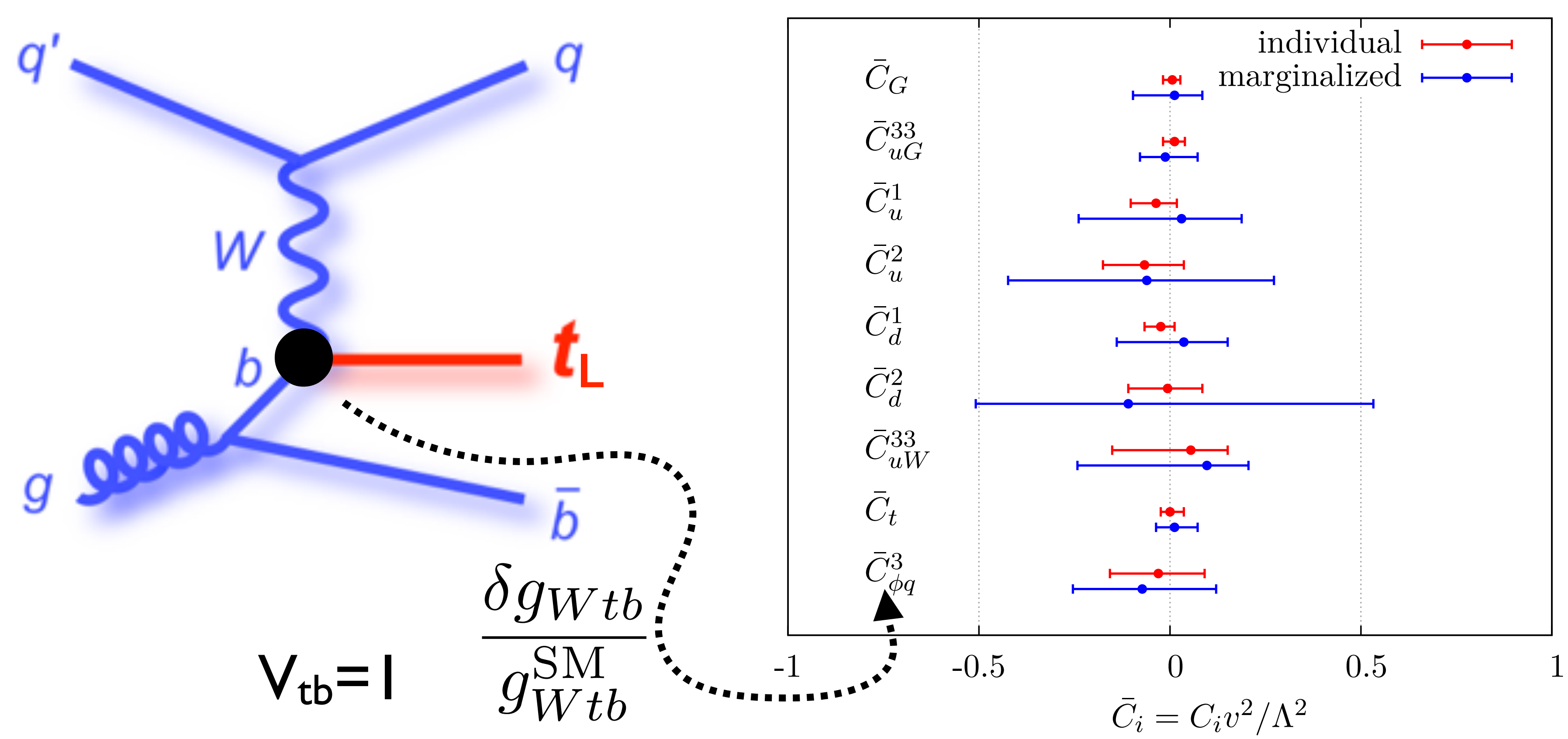


t_L couplings don't show much deviations from SM predictions:



see for example,

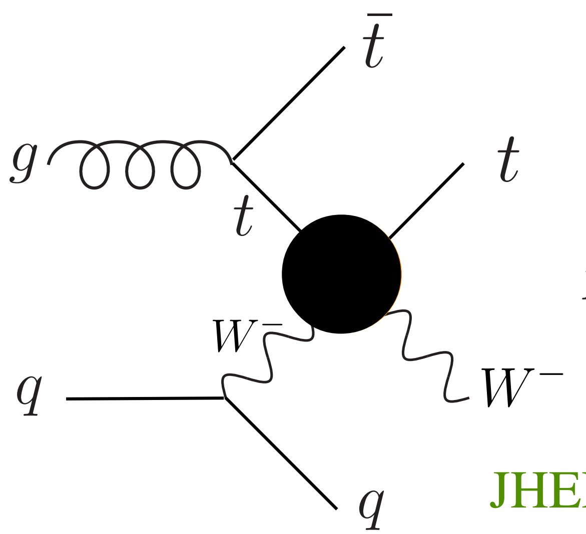
arXiv:1512.03360

arXiv:1504.03785

arXiv:1601.08193

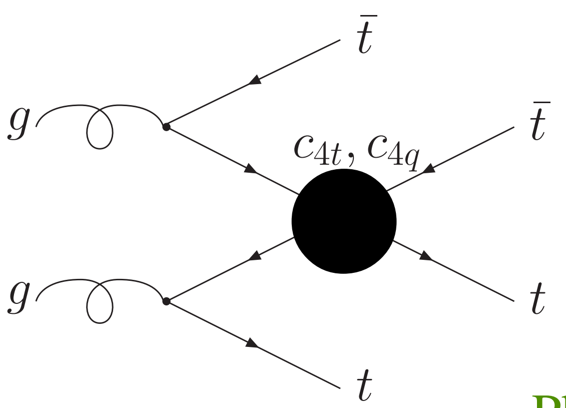
If t_R is highly composite, it will be a challenge to know it!

Best ways to see it in the future:



$pp \to t\bar{t}W^{\pm} + j$

JHEP 1601 (2016) 071



$pp \to t\bar{t}t\bar{t}$

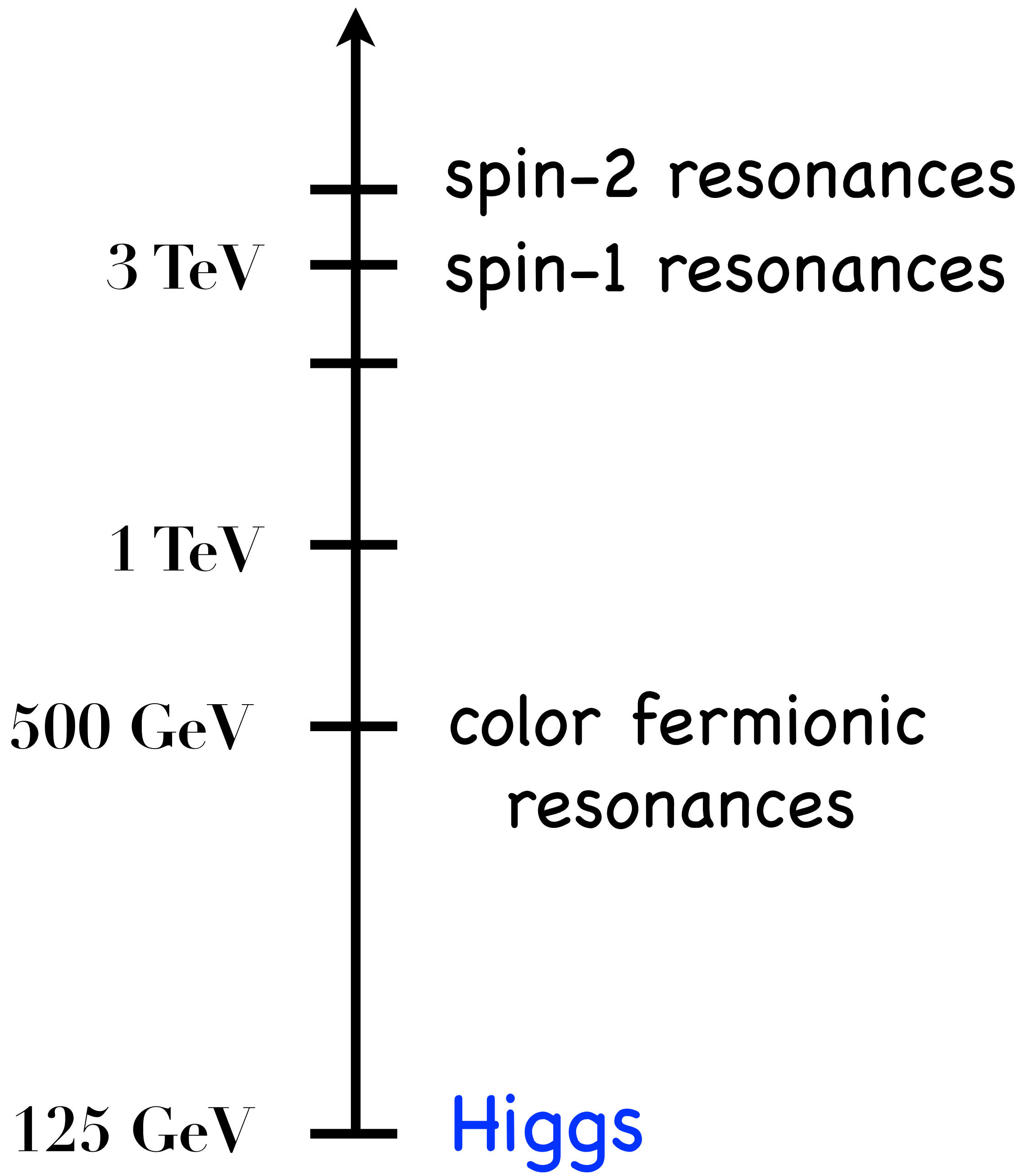
Phys.Rev. D78 (2008) 074026

for a recent analysis, see arXiv:1611.05032

Effects grow with the energy!

New resonances

Expected spectrum of the TeV Composite Sector



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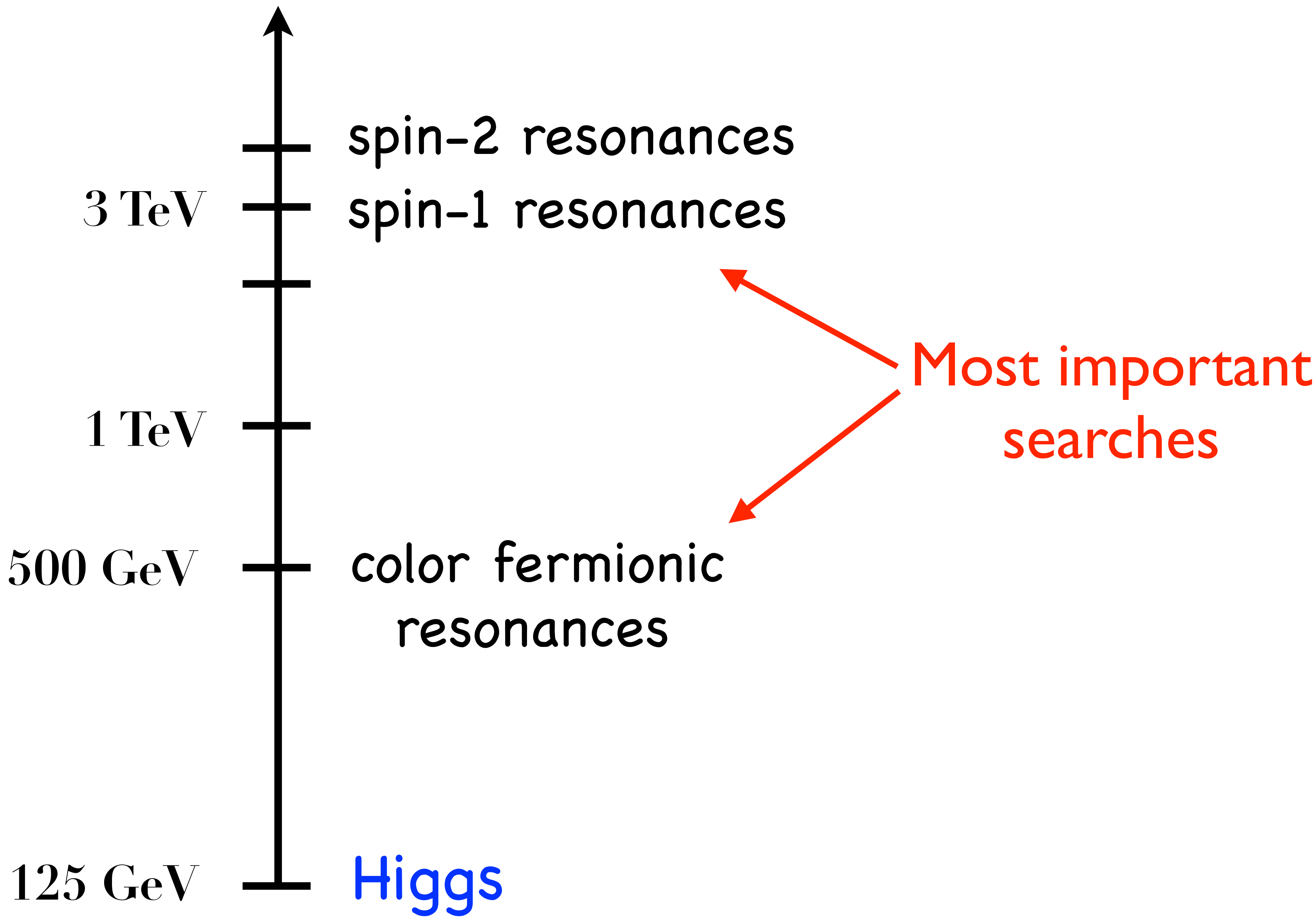

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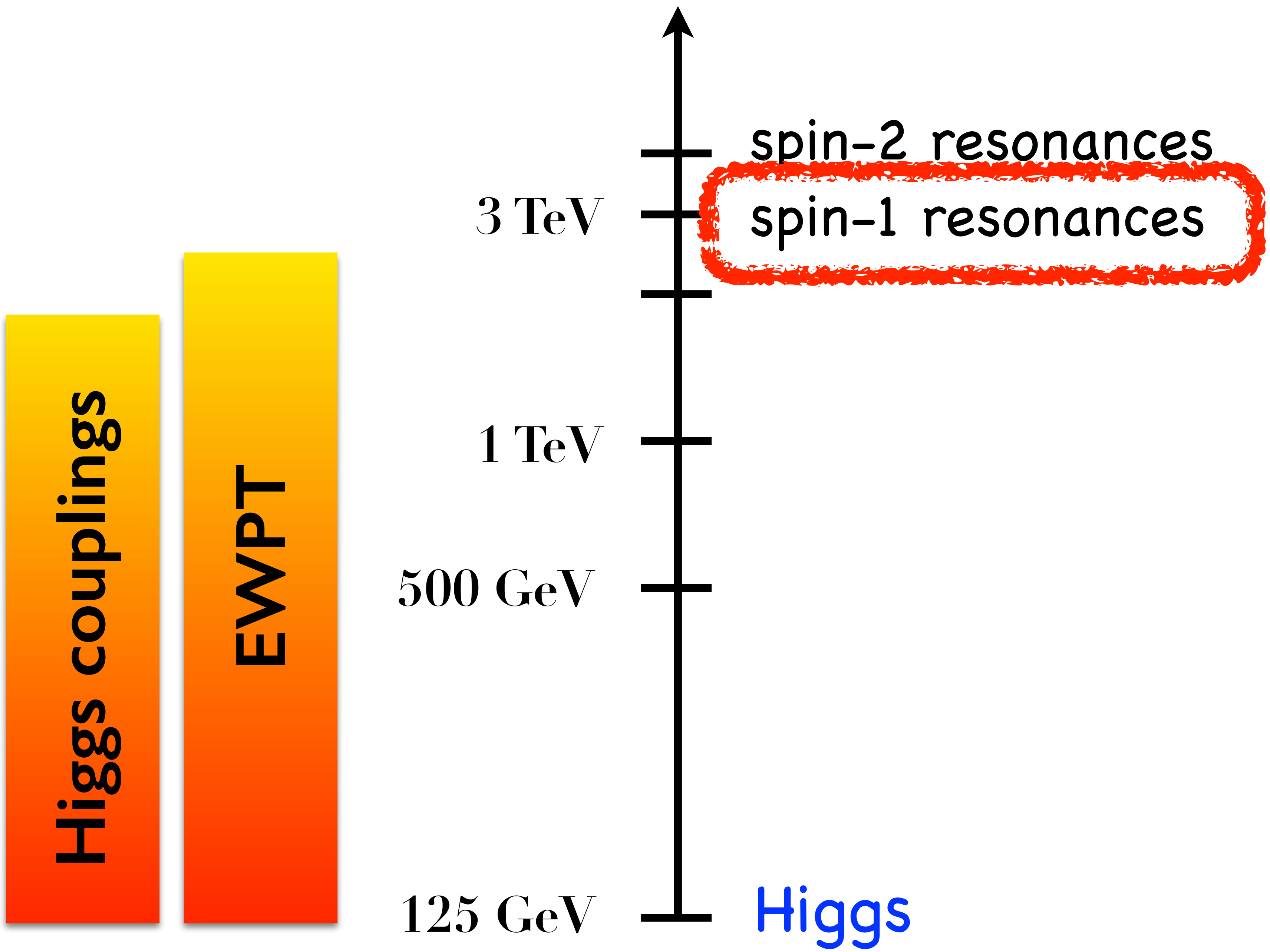
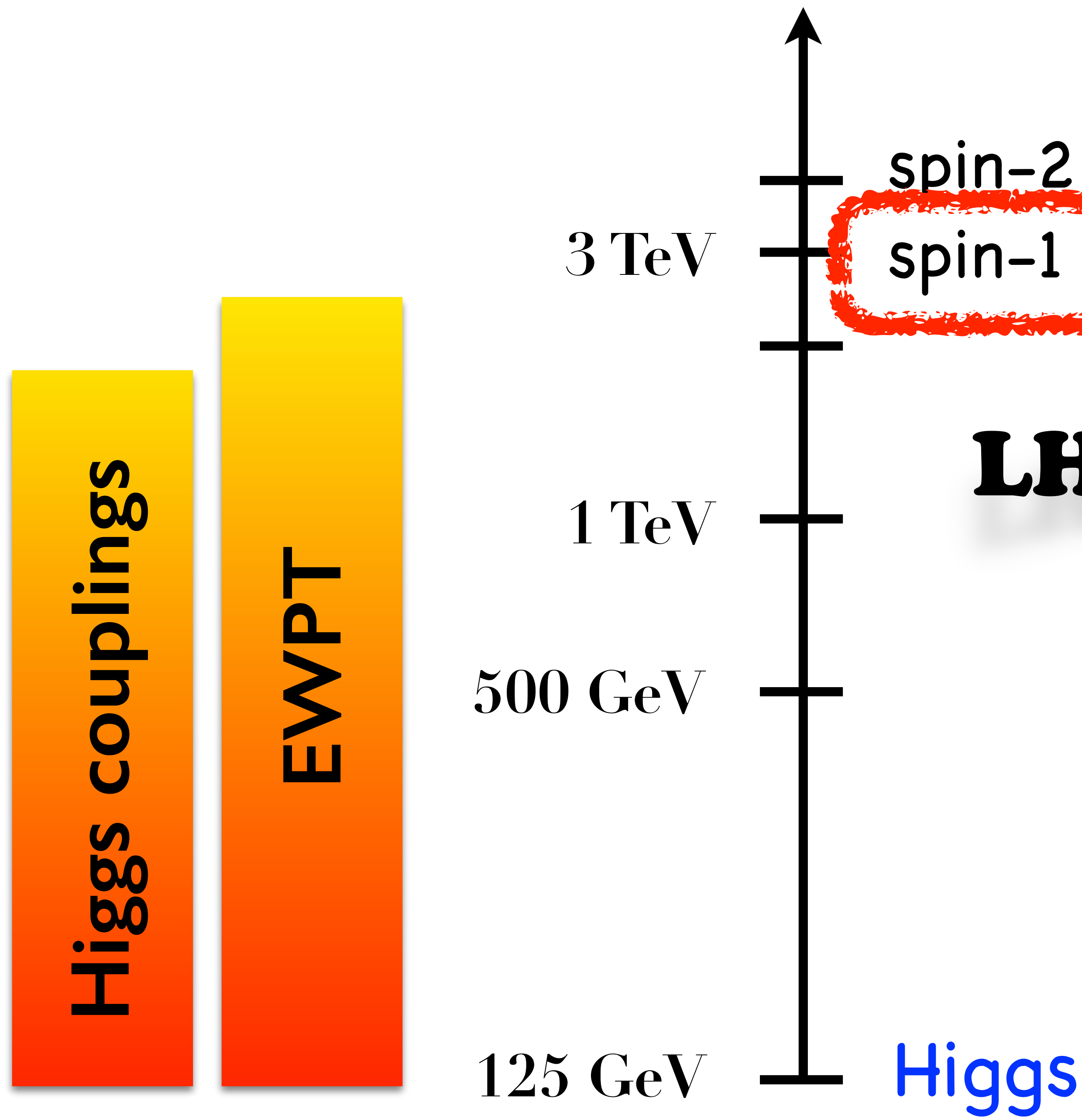


Before 13 TeV LHC bounds
dominated by indirect effects

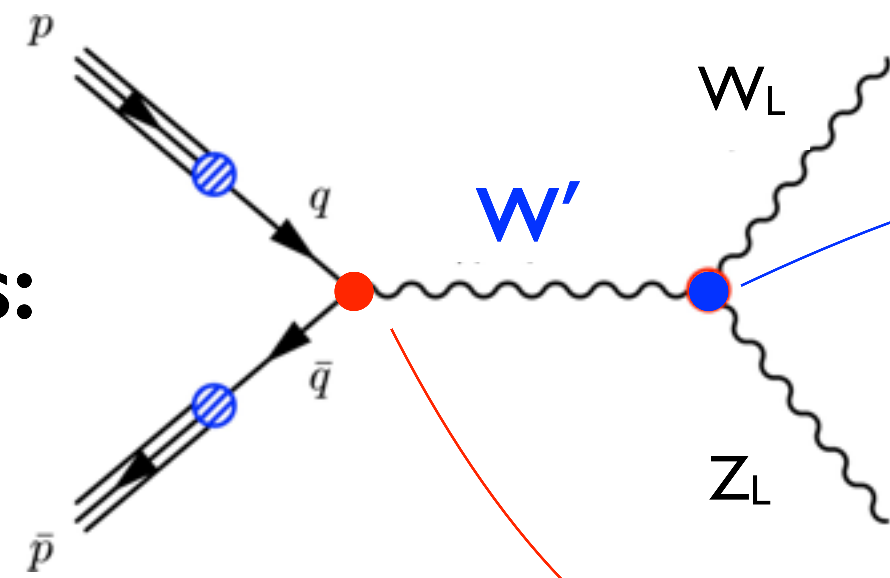
Expected spectrum of the TeV Composite Sector



LHC 7/8 TeV → 13 TeV

Before 13 TeV LHC bounds
dominated by indirect effects

Spin-1 resonance searches:

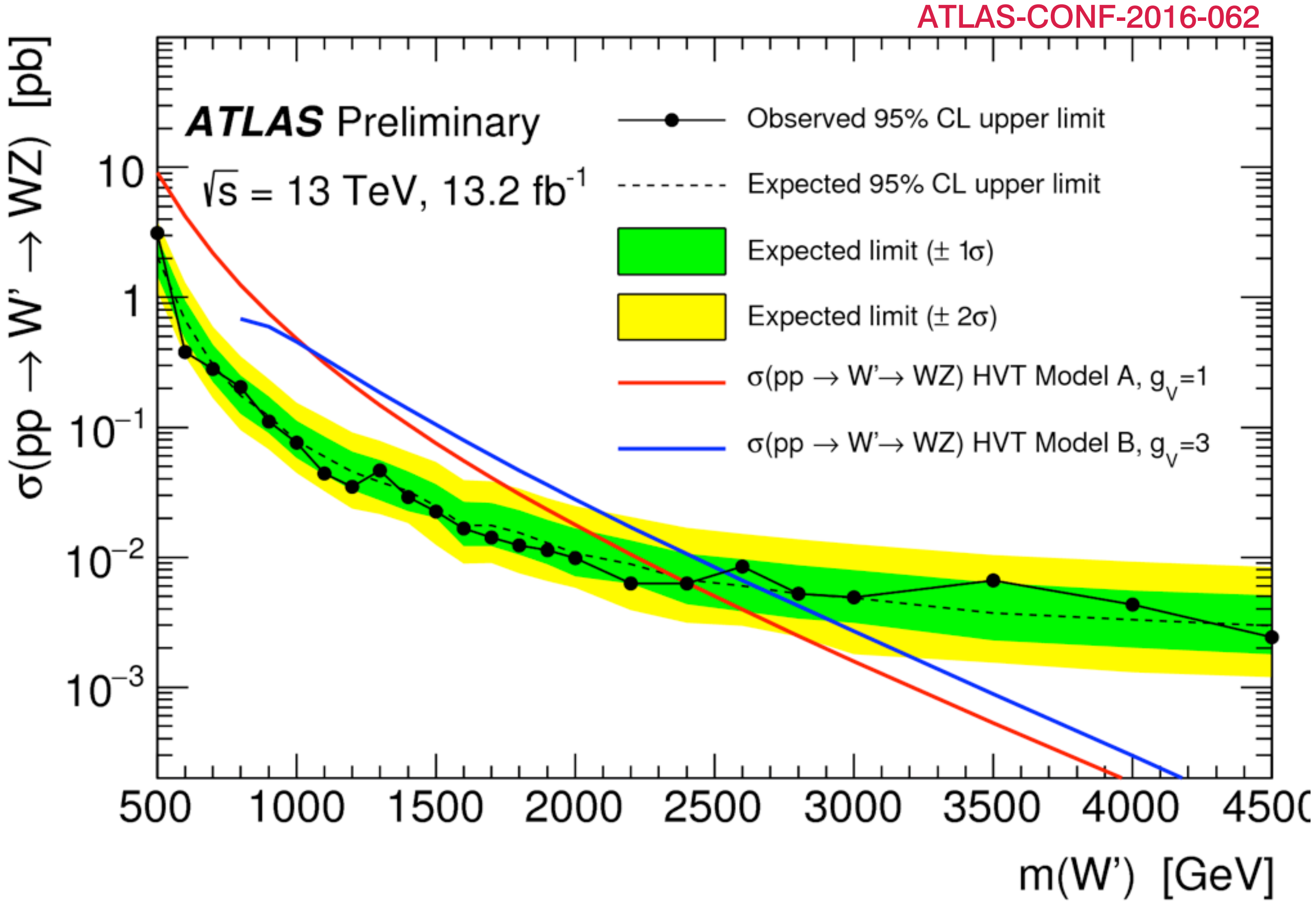


enhanced by large couplings from the composite sector

through mixing with the SM W:
suppressed by large couplings from the composite sector

VV → ℓνqq

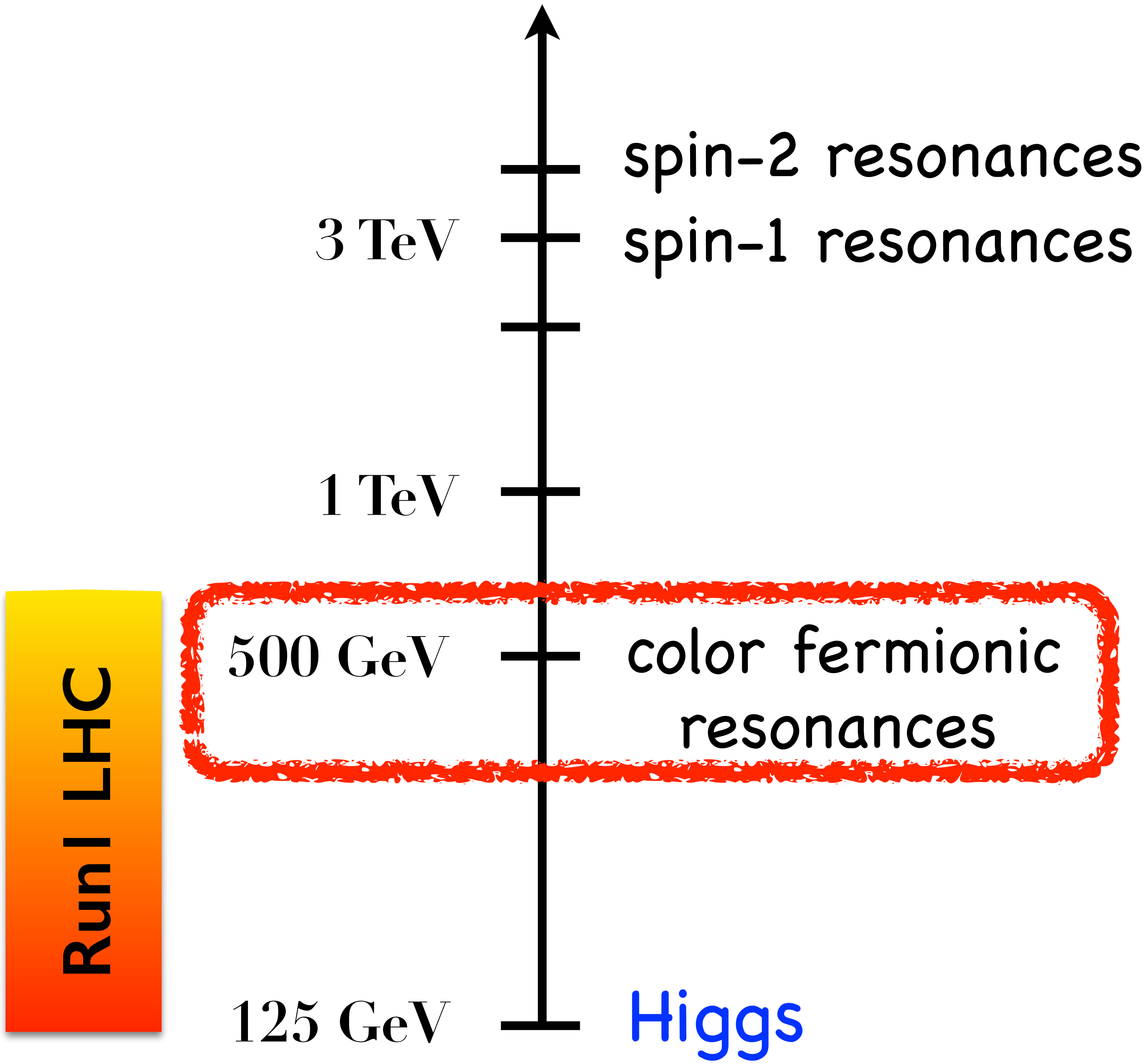
ATLAS-CONF-2016-062



☛ $$\mathbf{m(W') \gtrsim 2.5\ TeV}$$

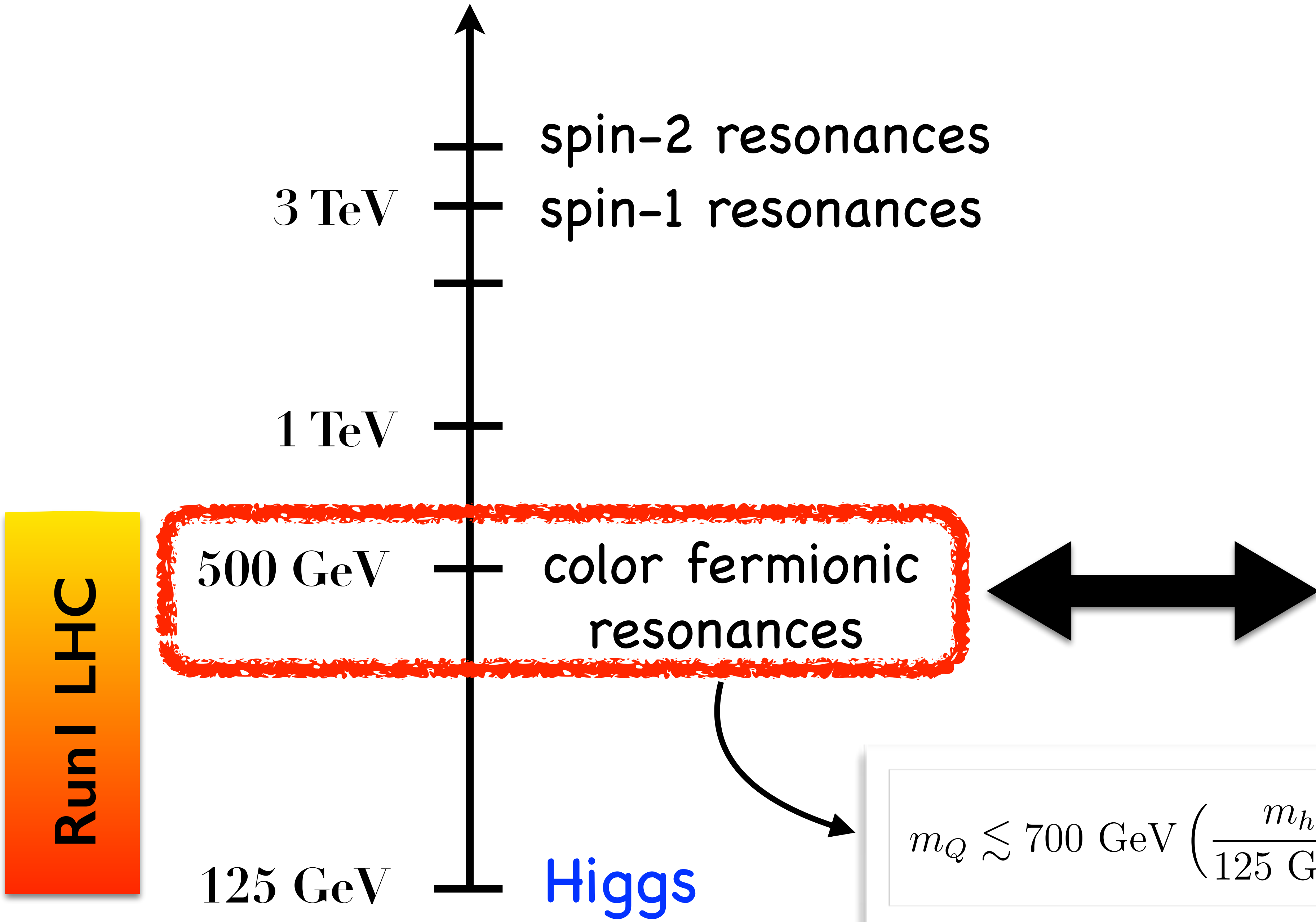
scratching
the interesting regions!

Expected spectrum of the TeV Composite Sector



7/8 TeV LHC searches
"scratching the surface"

Expected spectrum of the TeV Composite Sector



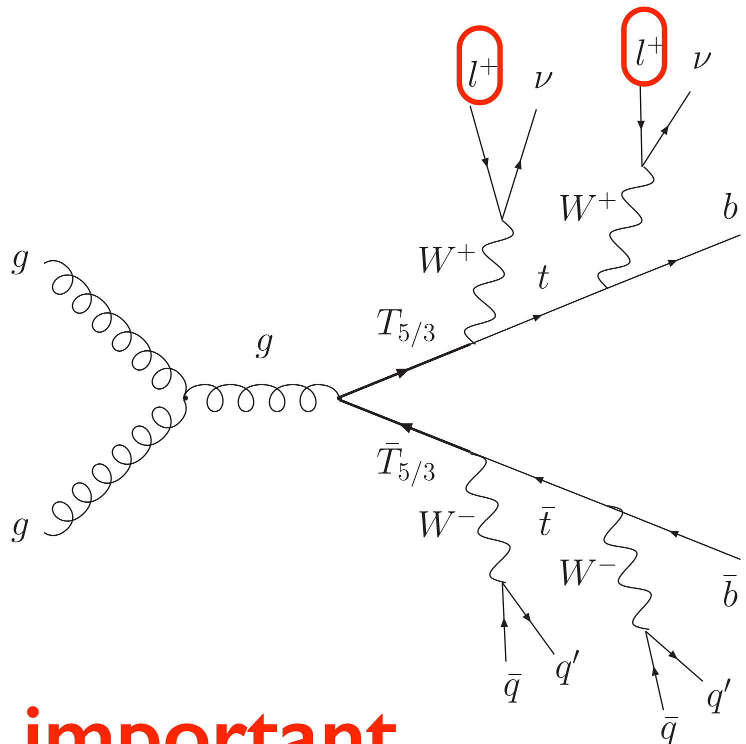
$$m_Q \lesssim 700 \text{ GeV} \left(\frac{m_h}{125 \text{ GeV}}\right) \left(\frac{160 \text{ GeV}}{m_t}\right) \left(\frac{f}{500 \text{ GeV}}\right)$$

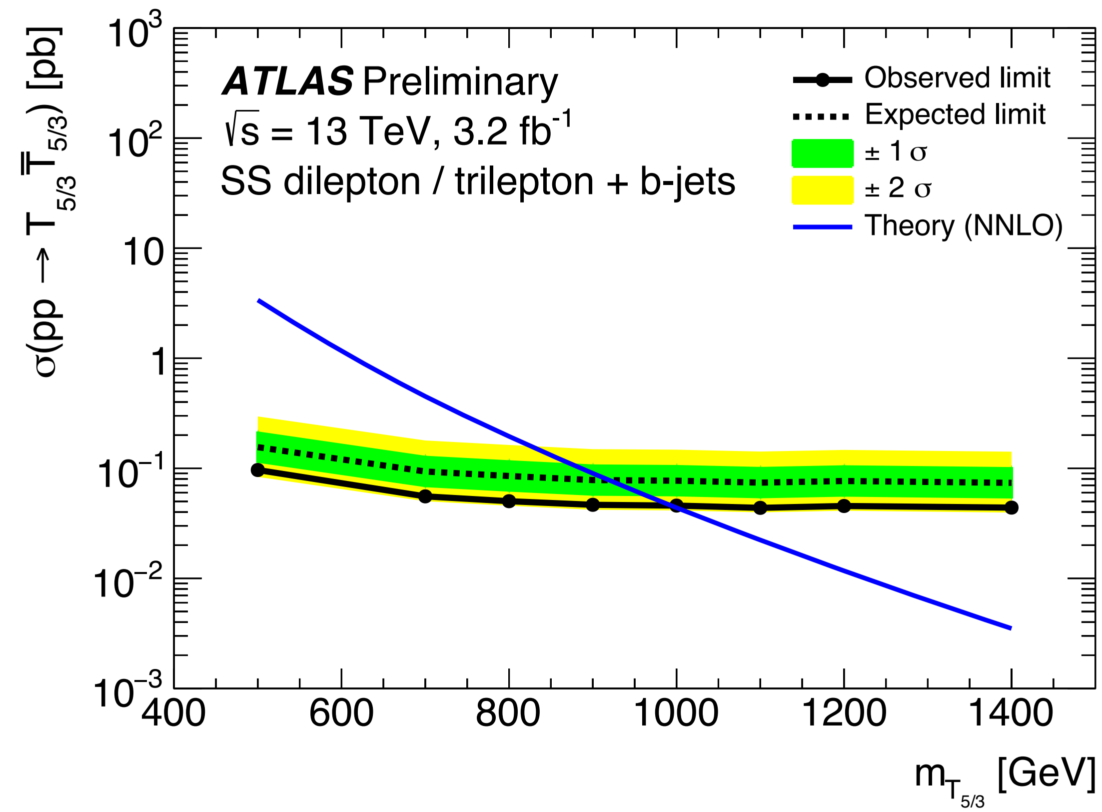
AP, F.Riva JHEP 1208 (2012) 135

7/8 TeV LHC searches

"scratching the surface"

Colored fermion resonances at LHC 13 TeV

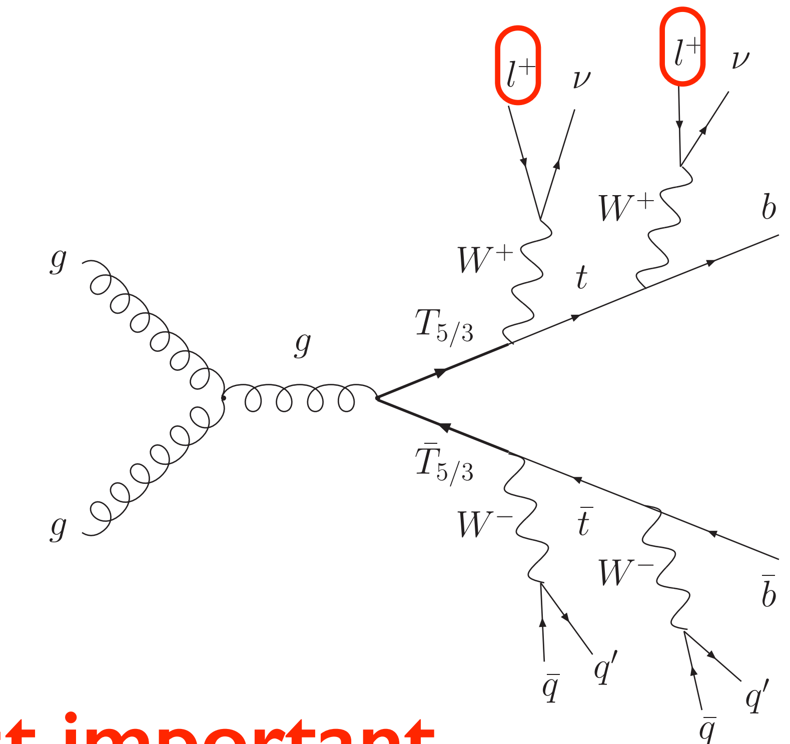


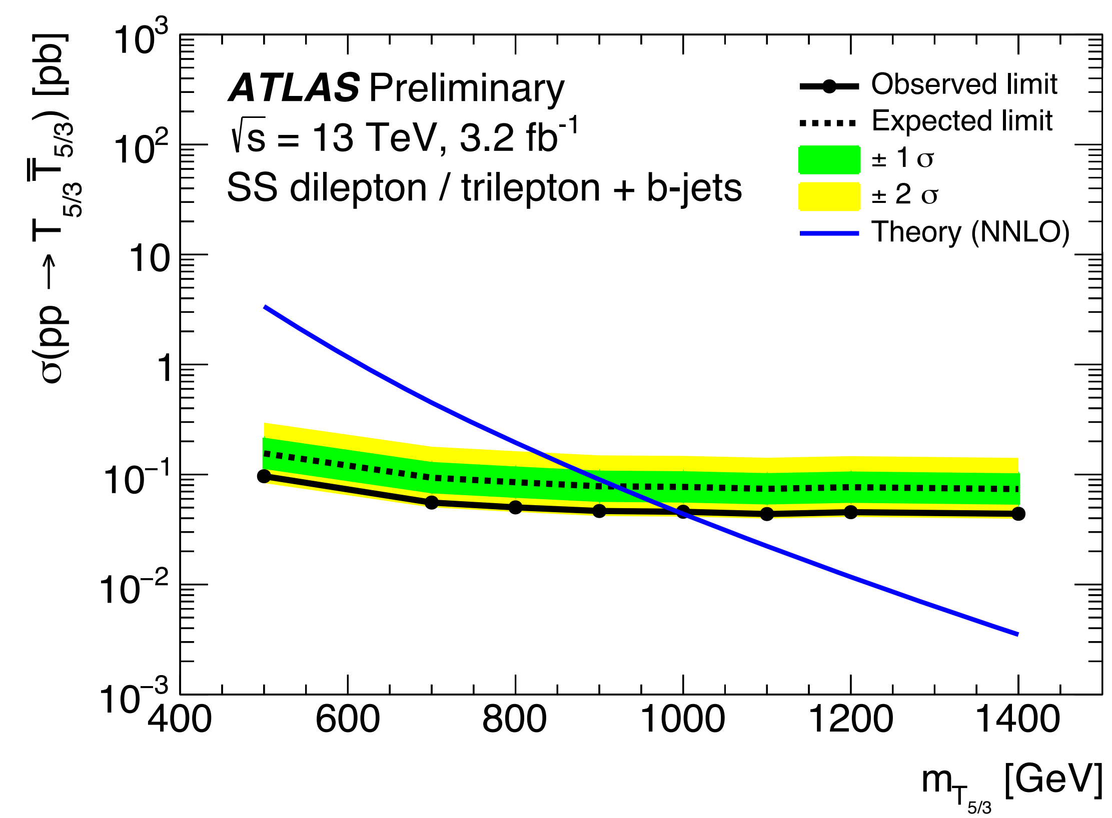


First important constraint from LHC:

$$\mathbf{m(X_{5/3}) \gtrsim 1\ TeV}$$

Colored fermion resonances at LHC 13 TeV





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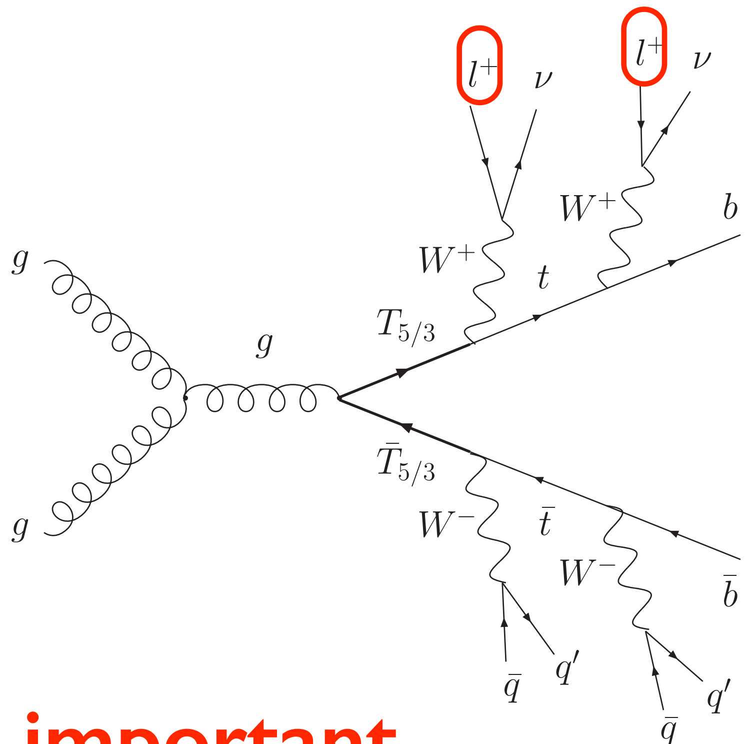
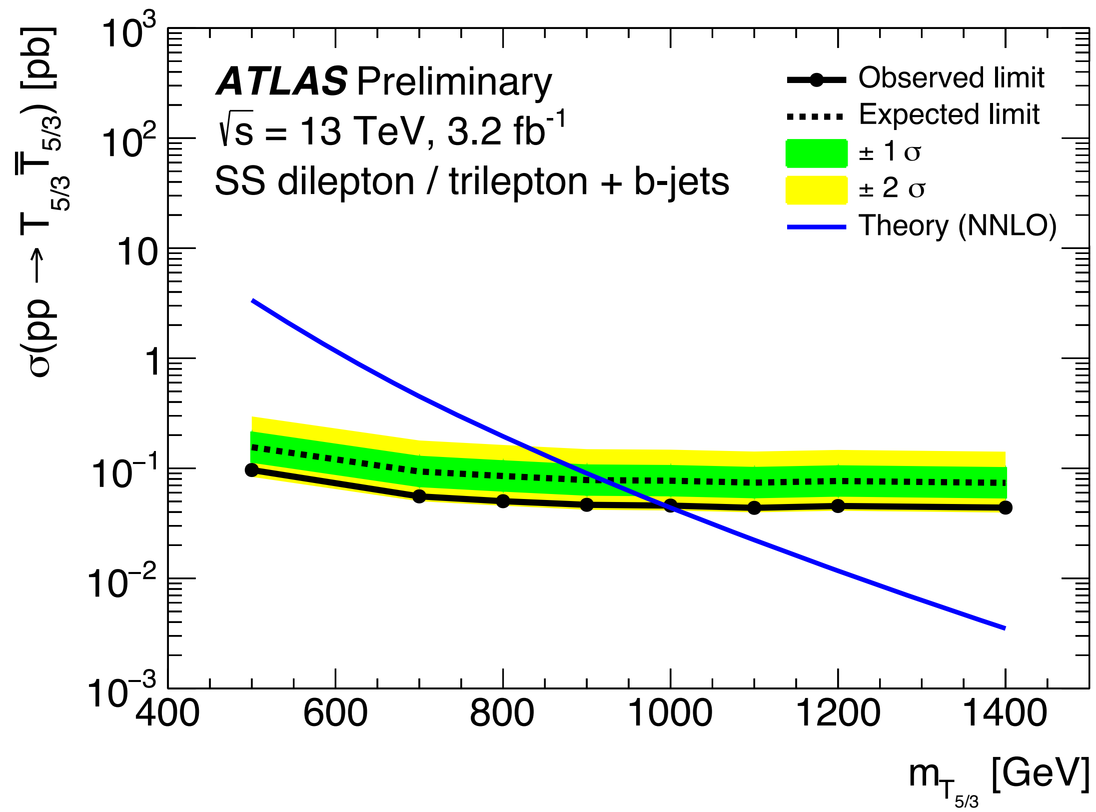
The situation starts being worrisome..

but not yet desperate

Colored fermion resonances at LHC 13 TeV





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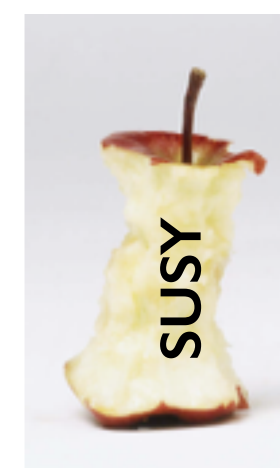
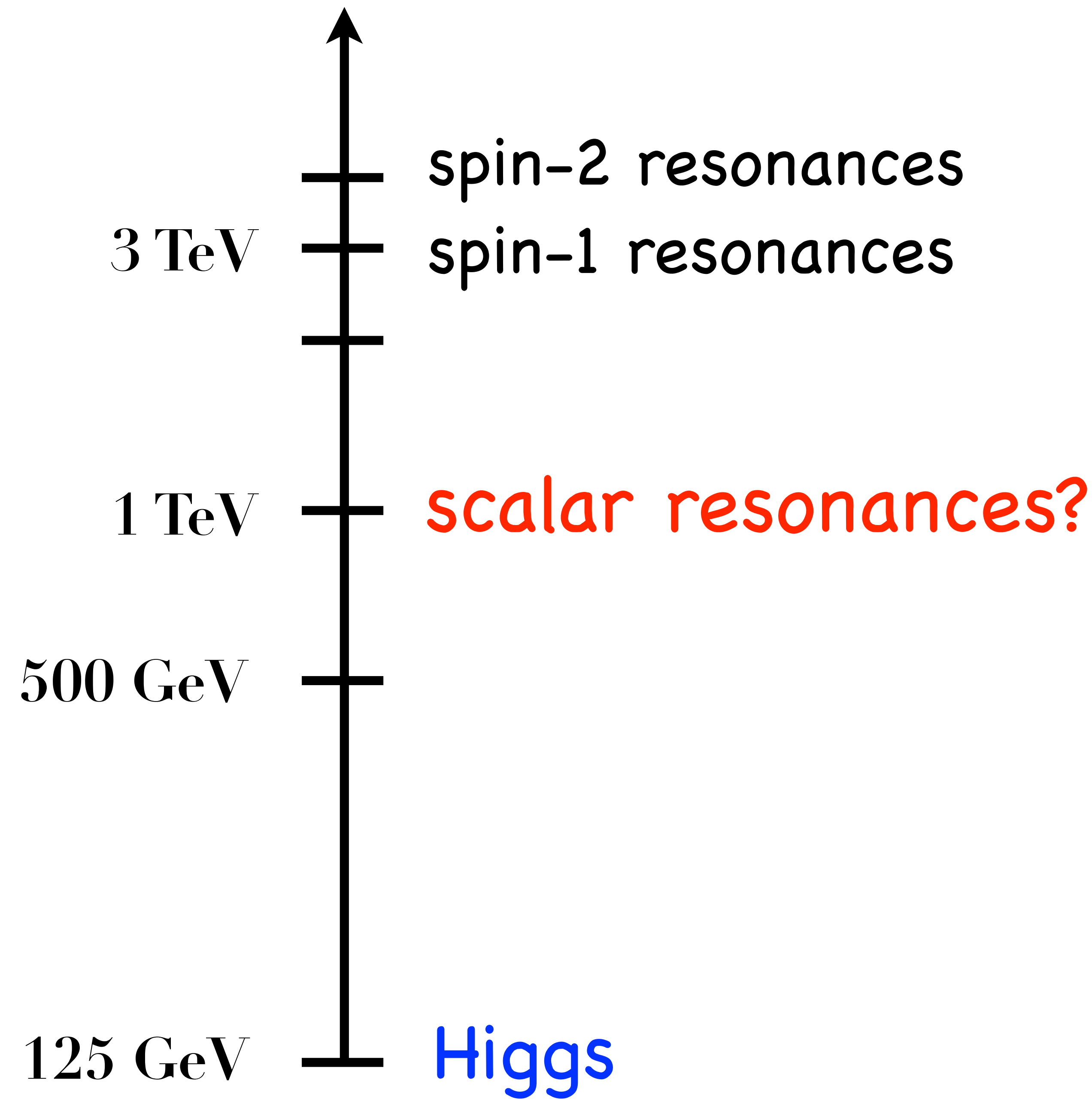


(not as bad as susy)

Expected spectrum of the TeV Composite Sector



Before 13 TeV LHC bounds
dominated by indirect effects

Concluding…

★ Strong dynamics at the TeV is still one of the best ways to tackle the hierarchy problem

Present situation: We can "visualize" **plausible realistic scenarios,** and provide signals to future experiments (LHC)

☛ **top mass, the big challenge!**

but difficult to make progress from here…

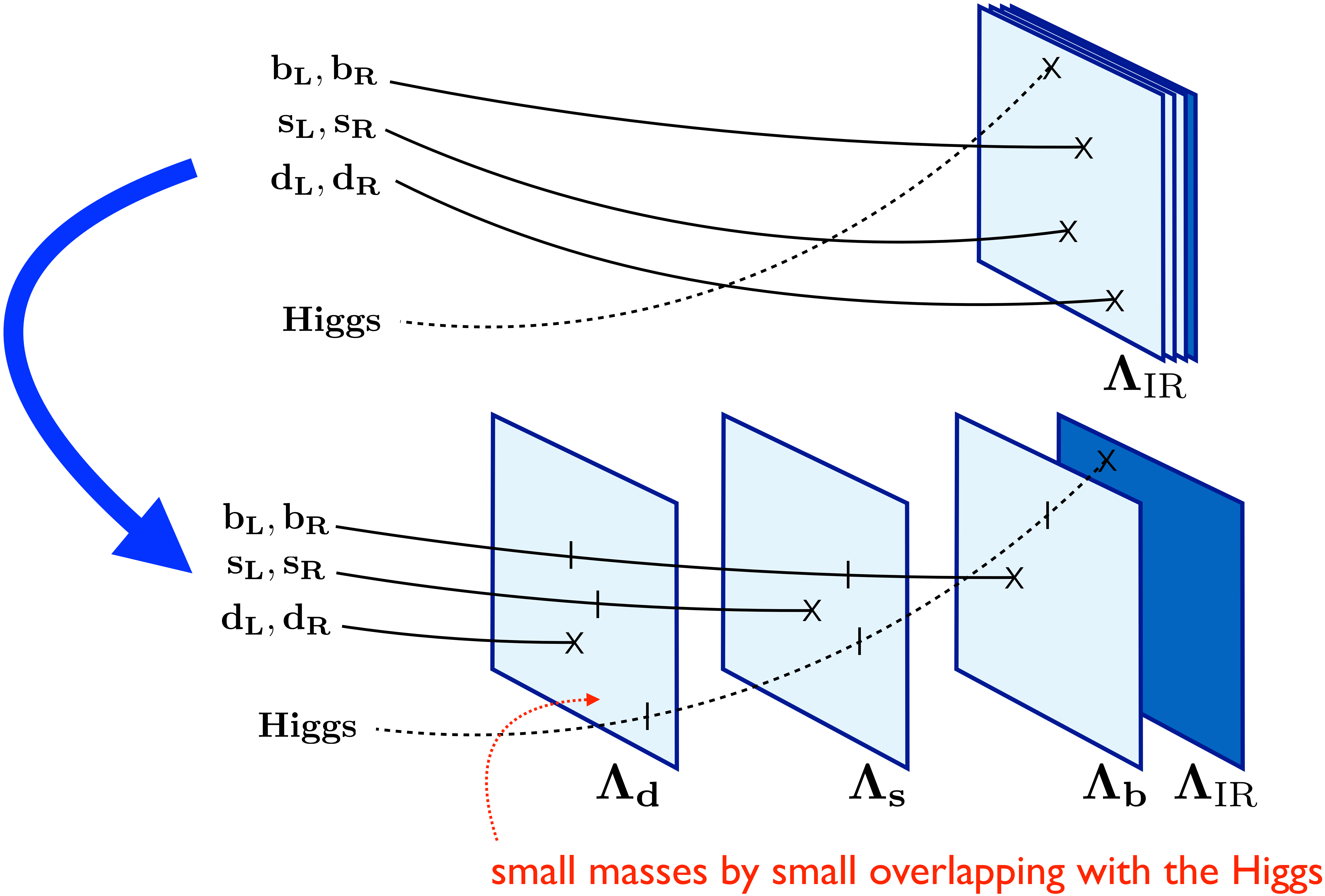
In the future:

- Lattice can shed light on conformal theories (γ of fermionic operators)
- String theory could help to connect realistic 5D models to their 4D duals

★ The *dream situation* would be to have **experimental data** (e.g. LHC), **leading the field** in the future

MORE IF NEEDED

Geometric perspective



Inspiration from QCD: Chiral lagrangian for pions:

Ordinary basis:

$$\mathcal{L}_\chi = \frac{f^2}{4}\langle D^\mu U D_\mu U\rangle + \cdots$$
$$- \; iL_9 \langle F_R^{\mu\nu} D_\mu U D_\nu U^\dagger + F_L^{\mu\nu} D_\mu U^\dagger D_\nu U\rangle \; + \; L_{10}\langle U^\dagger F_R^{\mu\nu} U F_{L\mu\nu}\rangle$$

In a "SILH basis":

"tree" operator: $\langle (U^\dagger \overleftrightarrow{D}_\nu U) D_\mu F_L^{\mu\nu} + (U \overleftrightarrow{D}_\nu U^\dagger) D_\mu F_R^{\mu\nu}\rangle$

"loop" operator: $\langle F_R^{\mu\nu} D_\mu U D_\nu U^\dagger + F_L^{\mu\nu} D_\mu U^\dagger D_\nu U\rangle$

Experiments say: $$\frac{c_{\rm loop}}{c_{\rm tree}} = \frac{L_9 + L_{10}}{L_9 - L_{10}} \simeq \frac{6.9 - 5.5}{6.9 + 5.5} \sim 0.1$$

Smaller by a "loop" ~ 1/Nc ~ 1/3!

Not renormalized by loop of pions: $\gamma_{\rm loop} \propto \gamma_9 + \gamma_{10} = \frac{1}{64\pi^2} - \frac{1}{64\pi^2} = 0$