IS THE HIGGS WE ARE OBSERVING A COMPOSITE HIGGS?

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30 May 2013

based on D. Pappadopulo, A. Thamm and RT, hep-ph/1303.3062
B. Bellazzini, R. Franceschini, L. Martucci and RT, hep-ph/1306.xxxx
M. Montull, F. Riva, E. Salvioni and RT, hep-ph/1306.xxxx

OUTLINE

- The SM Higgs, theorist's and experimentalist's view
- The Higgs as a pseudo-Goldstone boson
  - SB by vacuum misalignment and Partial compositeness
  - The Minimal Composite Higgs Model (MCHM)
- Example of an explicit model (MCHM14)
  - Tuning
  - Spectrum of resonances
- Phenomenology
  - Higgs couplings
  - Top partners
- Conclusion

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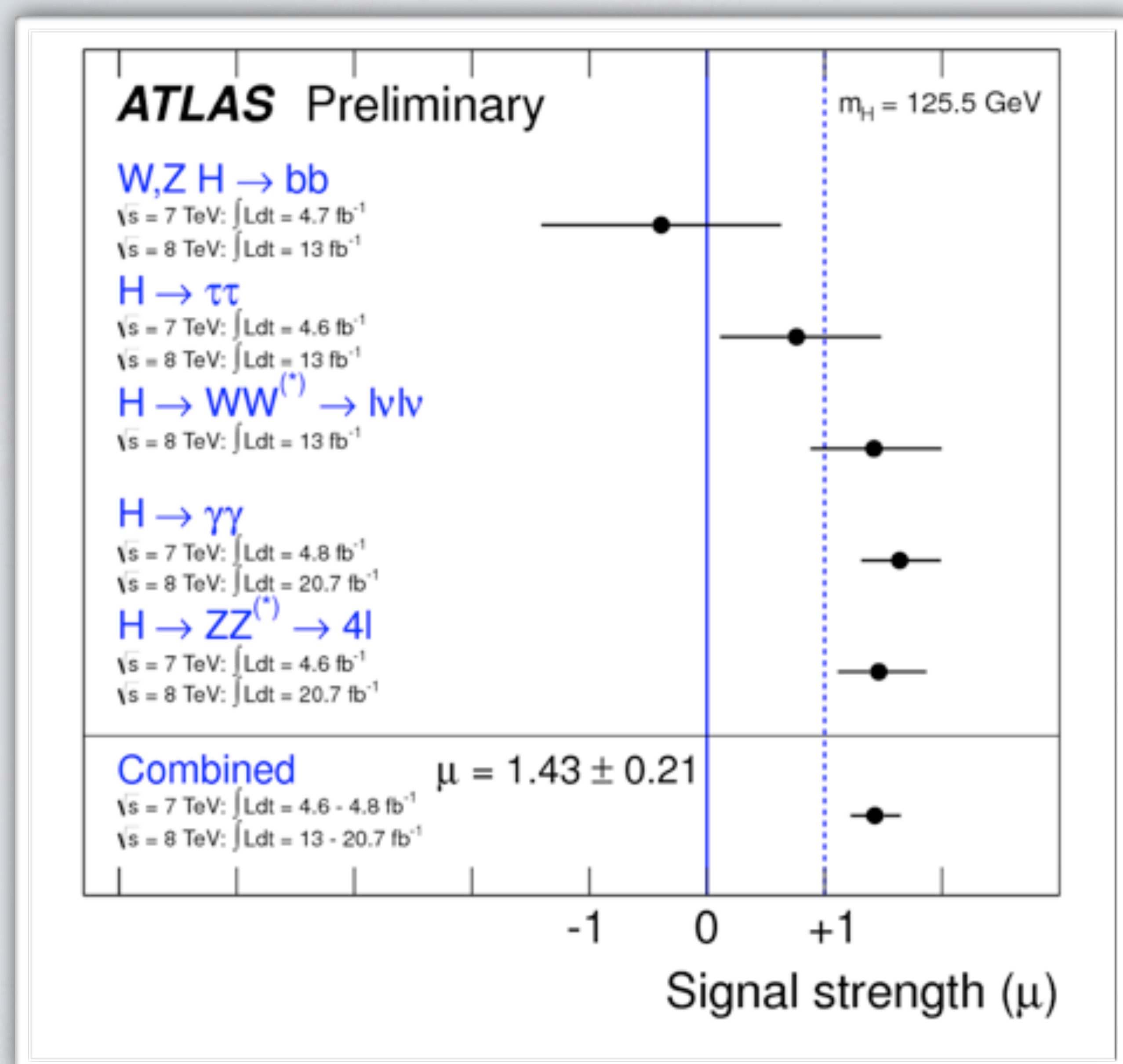
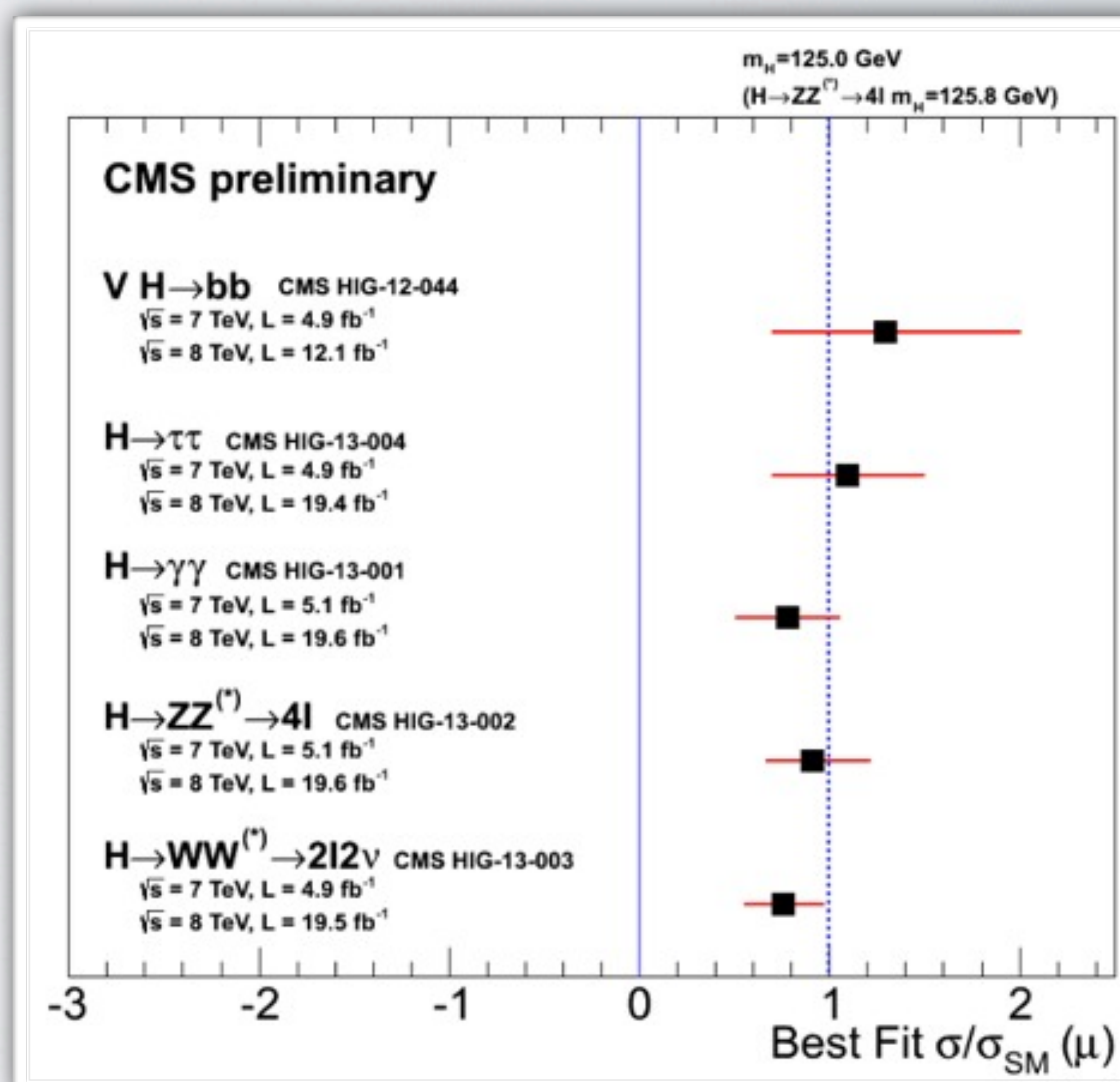
THE SM-LIKE HIGGS

- The Higgs boson is there, has a mass of ~125.5 GeV and is very SM-like (at least for another couple of years!)





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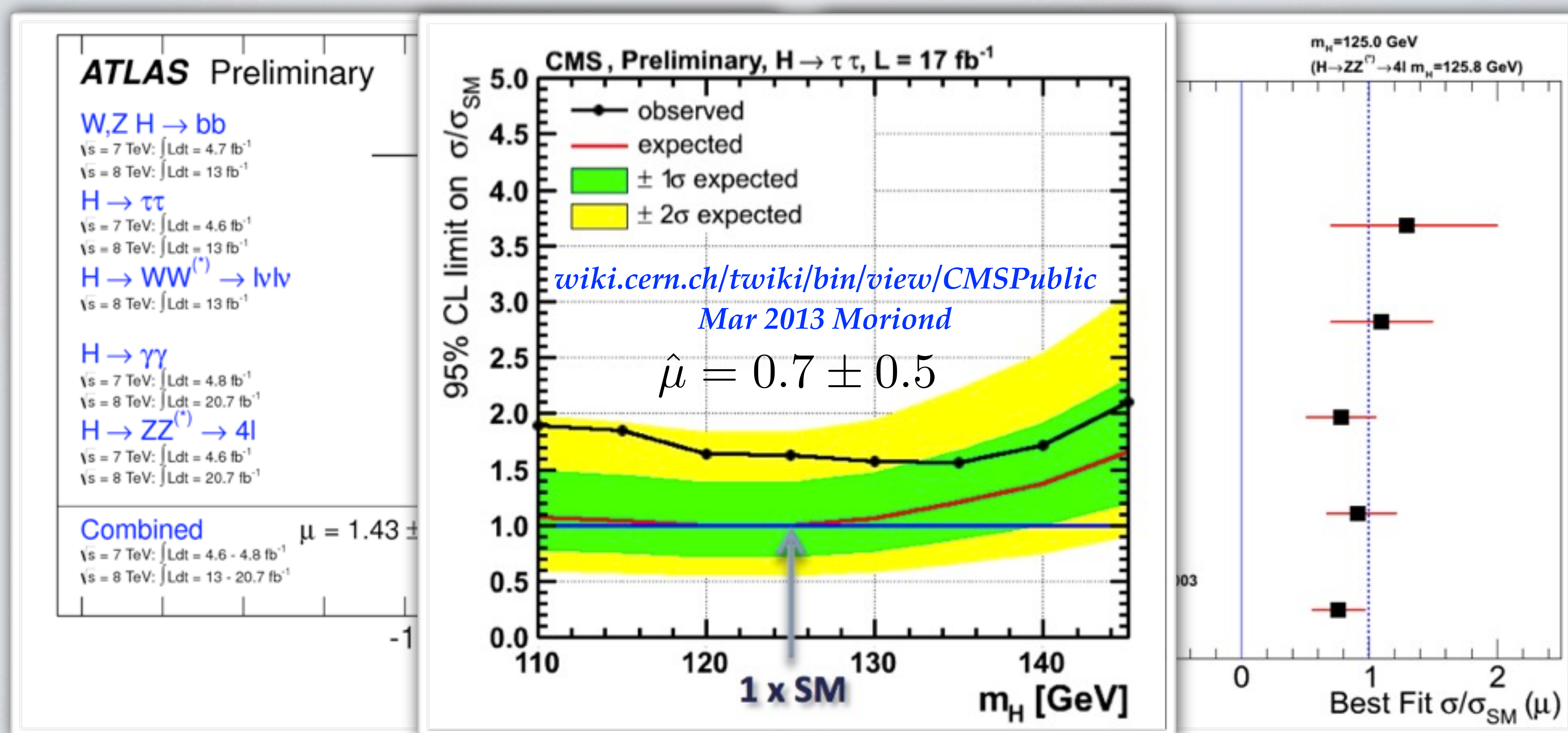

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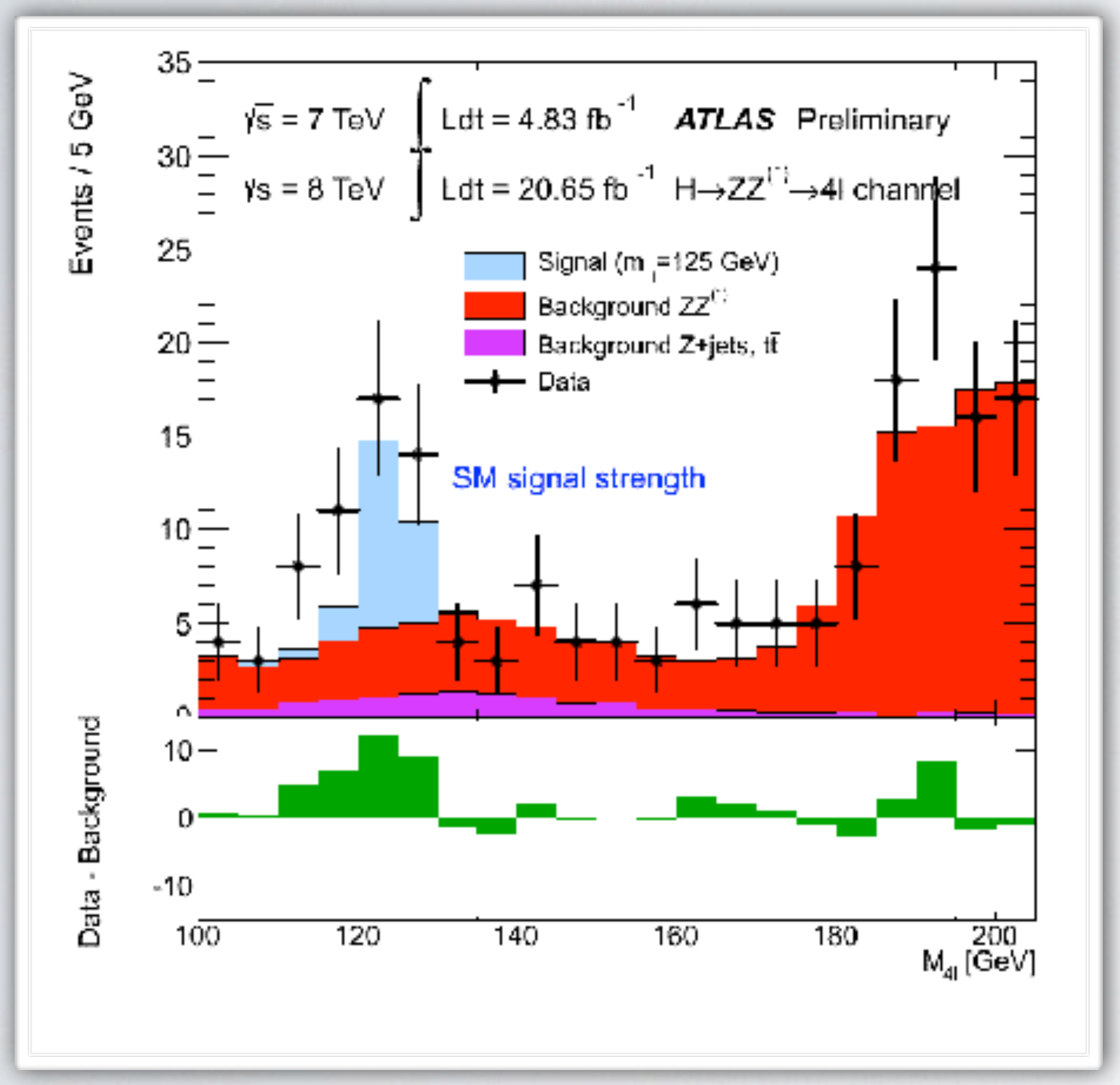

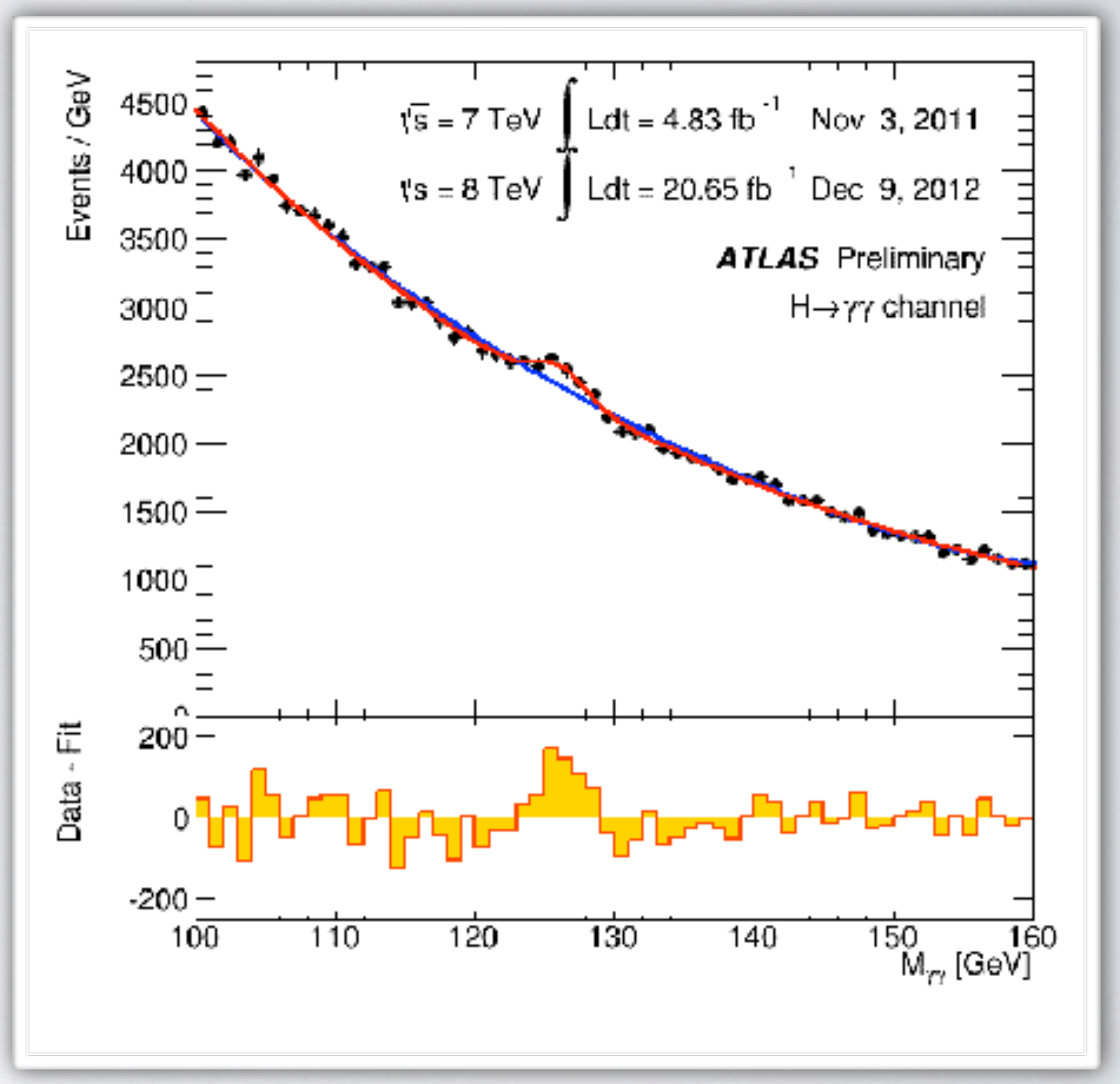

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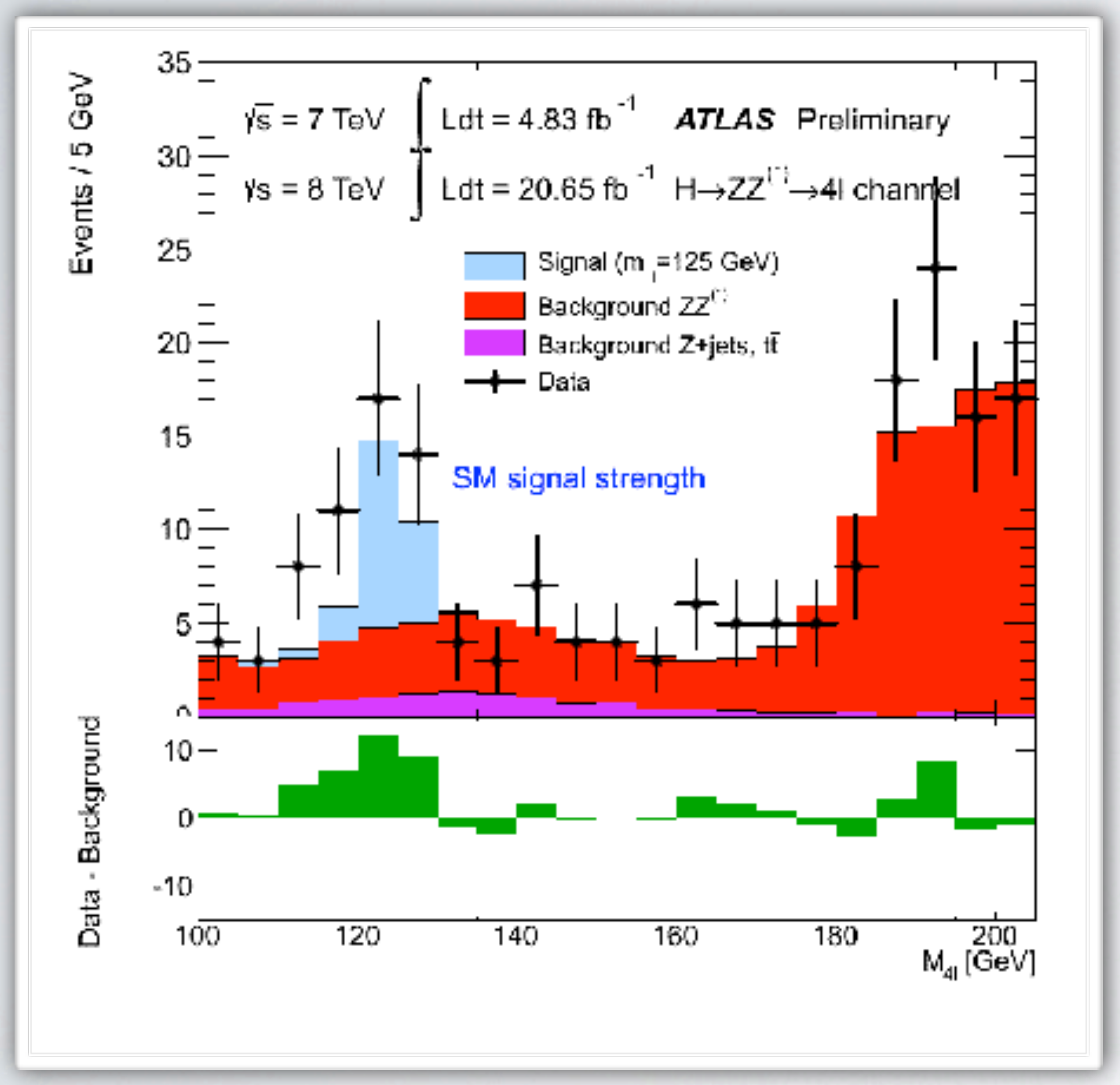

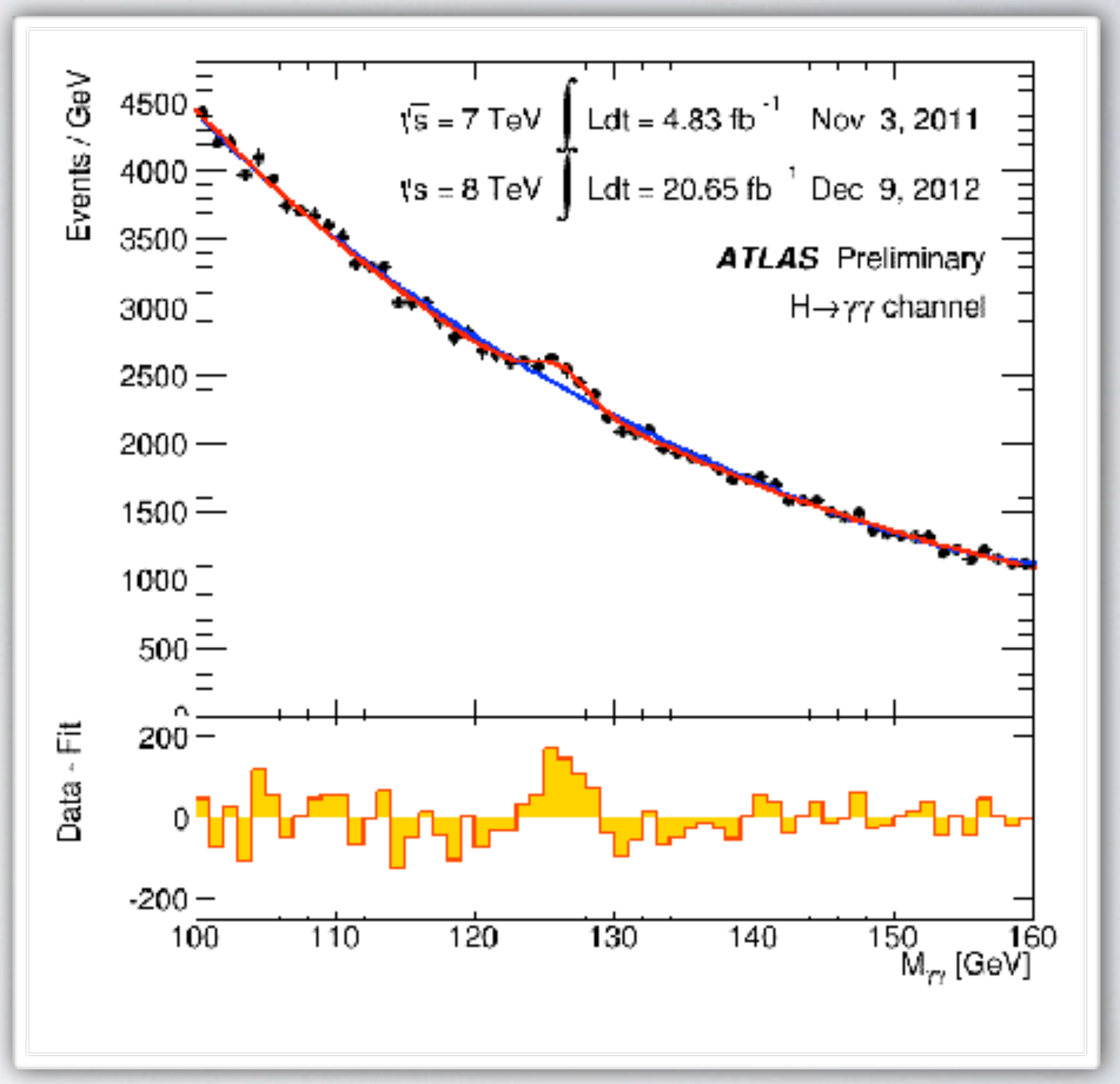

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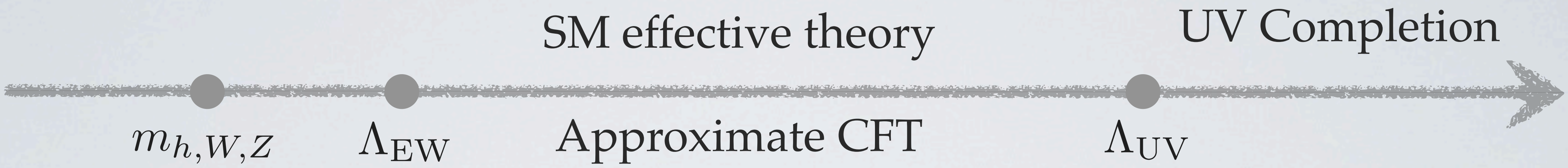
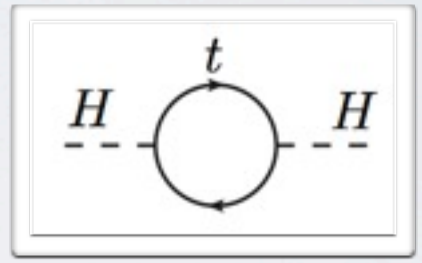
NATURALNESS IN THE SM



1. All deformations of the CFT are either irrelevant, marginal or very close to marginal (e.g. QCD)
2. The relevant deformations can be forbidden by symmetries (e.g. fermion masses forbidden by chiral symmetry)
3. The relevant deformations are tuned to be small

$$\Delta\mathcal{L}_{\rm SM}^{\rm rel} = c\Lambda_t H^\dagger H \qquad c \sim \left(\frac{\Lambda_{\rm EW}}{\Lambda_t}\right)^2$$



$$\delta m_h^2 = -\frac{y_t^2}{16\pi^2}\Lambda_t^2$$

- The sensitivity of the Higgs mass on physics at the scale Λ_t is given by

$$\Delta_t \gtrsim \left(\frac{125\ \text{GeV}}{m_h}\right)^2 \left(\frac{\Lambda_t}{370\ \text{GeV}}\right)^2$$

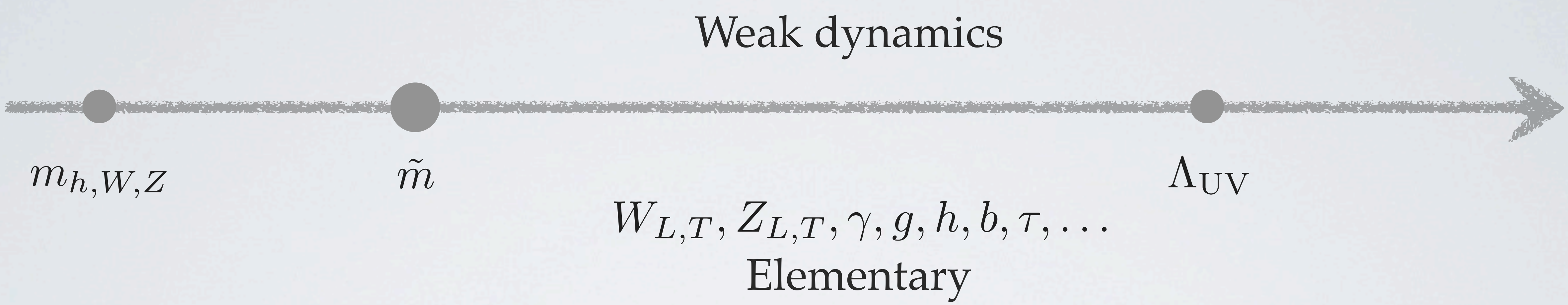
- If we believe in some "naturalness"

$$\Delta_t \lesssim 100 \quad \Longrightarrow \quad \Lambda_t < 3.7\ \text{TeV}$$

- This is the ONLY argument why we can expect new physics related to EWSB at the TeV scale!

THE TWO POSSIBLE SOLUTIONS: THEORIST'S VIEW

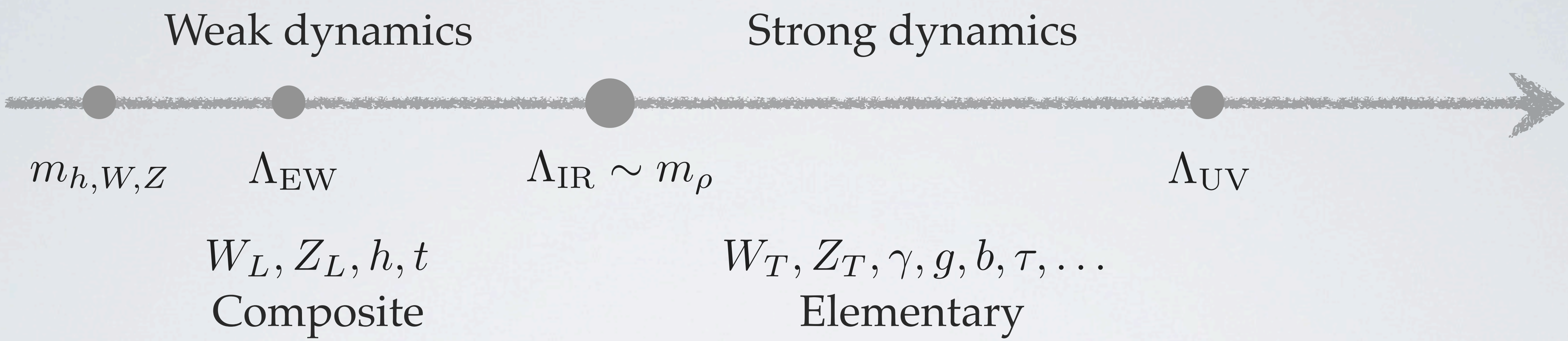
1. Weak dynamics (Supersymmetry)



- The critical point separating the EW broken and unbroken symmetry has an enhanced symmetry, i.e. supersymmetry
- Supersymmetry is broken softly, i.e. only by relevant operators
- The breaking disappears in the UV
- New degrees of freedom, i.e. superpartners of the SM fields are expected to be present close to the EW scale

THE TWO POSSIBLE SOLUTIONS: THEORIST'S VIEW

2. Strong dynamics (Compositeness)



- The IR scale Λ_{IR} is dynamically generated (like in QCD)
- Above the IR scale the Higgs mass term is irrelevant (4 fermion operator) and the big hierarchy is therefore stabilized
- Heavy resonances are expected at the TeV scale
- The dynamical breaking generates the gauge boson masses through a non-linear sigma model
- A light Higgs can be present accidentally (light dilaton) or related to the longitudinal polarizations of the gauge bosons (pGB Higgs)

THE TWO POSSIBLE SOLUTIONS: EXPERIMENTALIST'S VIEW

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Forward and Small-x QCD Physics	Plots and Results	Papers
B Physics and Quarkonia	Plots and Results	Papers
Standard Model Physics (Vector Bosons & Jets)	Plots and Results	Papers
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Supersymmetry (Rimini)

- Very well established
- Very crowded in terms of people and papers
- Experimentalists like very predictive models like CMSSM
- Problem: difficult to find space and not very high quality!!!

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Exotica (Bora Bora)

- Still very unexplored
- Very few people go there
- It looks to experimentalists quite less predictive
- Pros: full of space and amazing quality!!!

JOINING THEORISTS AND EXPERIMENTALISTS

Supersymmetry (Rimini)

Exotica (Bora Bora)

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My Goal:

Compositeness (5 Terre)

- Quite unexplored but well established
- Not too crowded
- Predictive but just a bit more expensive than SUSY
- Still some place and good quality!

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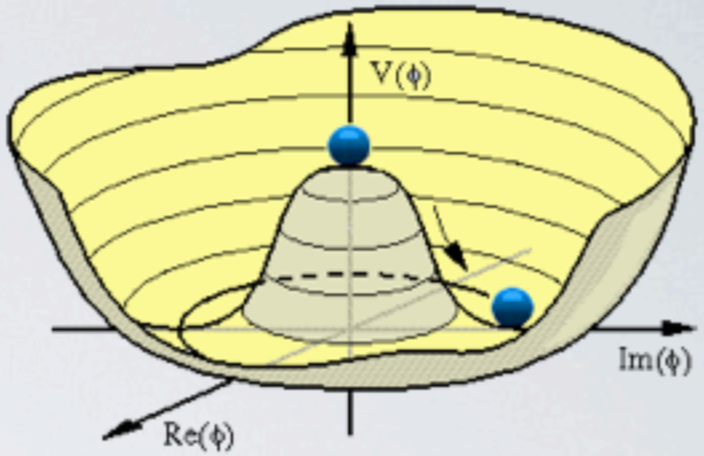
THE (BEH)IGGS PHENOMENON

- The EWSB Lagrangian in the SM is

$$\mathcal{H} = (i\sigma^2 H^*, H) = \begin{pmatrix} H^{0*} & H^+ \\ -H^- & H^0 \end{pmatrix}$$

$$\mathcal{H} \to g_L^\dagger \mathcal{H} g_R \qquad g_{L,R} = \exp(-i\omega^a_{L,R}\sigma^a/2) \in SU(2)_{L,R}$$



$$\mathcal{L}_{\rm SB} = \frac{1}{2}\mathrm{Tr}[(D_\mu\mathcal{H})^\dagger D_\mu\mathcal{H}] - V(\mathcal{H}) \qquad V(\mathcal{H}) = -\frac{\mu^2}{2}\mathrm{Tr}[\mathcal{H}^\dagger\mathcal{H}] + \frac{\lambda}{4}\mathrm{Tr}[\mathcal{H}^\dagger\mathcal{H}]^2$$

$$D_\mu\mathcal{H} = \partial_\mu\mathcal{H} + ig' B_\mu T^3_R\mathcal{H} + igW^a_\mu\mathcal{H}T^a_L$$

- $\mathcal{H}$ is an $SU(2)_L$ doublet of complex scalar fields with hypercharge $Y = 1/2$
- For $\mu^2 > 0$, $\mathcal{H}$ acquires a VEV $v \approx 246$ GeV, and minimizing the potential gives

$$\langle H^\dagger H\rangle = \frac{2\mu^2}{\lambda} \equiv v^2 \quad \Longrightarrow \quad m^2_H \equiv \mu^2 = \frac{1}{2}\lambda v^2$$

- There's no need for the Higgs degree of freedom to break EW symmetry (generate masses) and the lightness of the Higgs is a consequence of weak coupling

$$\lambda \ll 1$$

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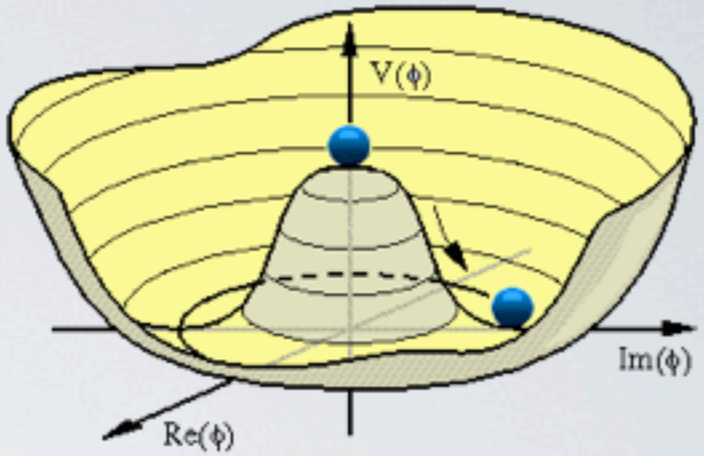

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- The potential has an approx. $SO(4) \sim SU(2)_L \times SU(2)_R$ symmetry that implies

$$\frac{m_W^2}{m_Z^2\cos^2\theta_W} \equiv \rho = 1$$

$$g' \to 0 \quad \Longrightarrow \quad m_W = m_Z$$

- This is a very important phenomenological prediction and we expect BSM corrections to the ρ parameter to be very small (custodial symmetry)

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STRONG EWSB

- A strong sector with a given global symmetry containing the SM gauge group is present
- Dynamical breaking of this symmetry at some scale *f* delivers as many GBs as the broken generators (at least 3 to have EWSB) *Georgi, Kaplan, Galison, Dimopoulos, Dugan, '84-'85*
- Three GBs are eaten by the W/Z providing their longitudinal components and breaking the EW symmetry spontaneously
- Additional GBs can be identified with the Higgs and other scalar particles
- Since the global symmetry of the strong sector is explicitly broken by SM gauge and Yukawa couplings, a potential is radiatively generated for the GBs which acquire a mass and a vev $v \leq f$ (vacuum misalignment) *Coleman, Weinberg PRD7 '73*
- The pseudo-GB nature of these scalars guarantees their lightness
- Notice that the Higgs does not need to be a pGB and can arise from other mechanisms, e.g. it can be a light dilaton or even a mixture of pGB and dilaton

Bellazzini, Csaki, Hubisz, Serra, Terning 1209.3299 [hep-ph]
Bellazzini, Csaki, Hubisz, Serra, Terning 1305.3919 [hep-th]
Bellazzini, Franceschini, Martucci, RT 1306.xxxx [hep-ph]

THE HIGGS AS A PGB

- The old problems of TC can be avoided if the scale of compositeness can be taken parametrically larger than the EW scale

Georgi, Kaplan, Galison, Dimopoulos, Dugan, '84-'85
Contino, Nomura, Pomarol, hep-ph/0306259
Agashe, Contino, Pomarol, hep-ph/0412089
Agashe, Contino, hep-ph/0510164
Contino, Da Rold, Pomarol, hep-ph/0612048
Barbieri, Bellazzini, Rychkov, Varagnolo, 0706.0432 [hep-ph]

$$f > v$$

- This can be achieved using the mechanism of vacuum misalignment
- Since we need custodial symmetry the simplest compact coset is SO(5)/SO(4)

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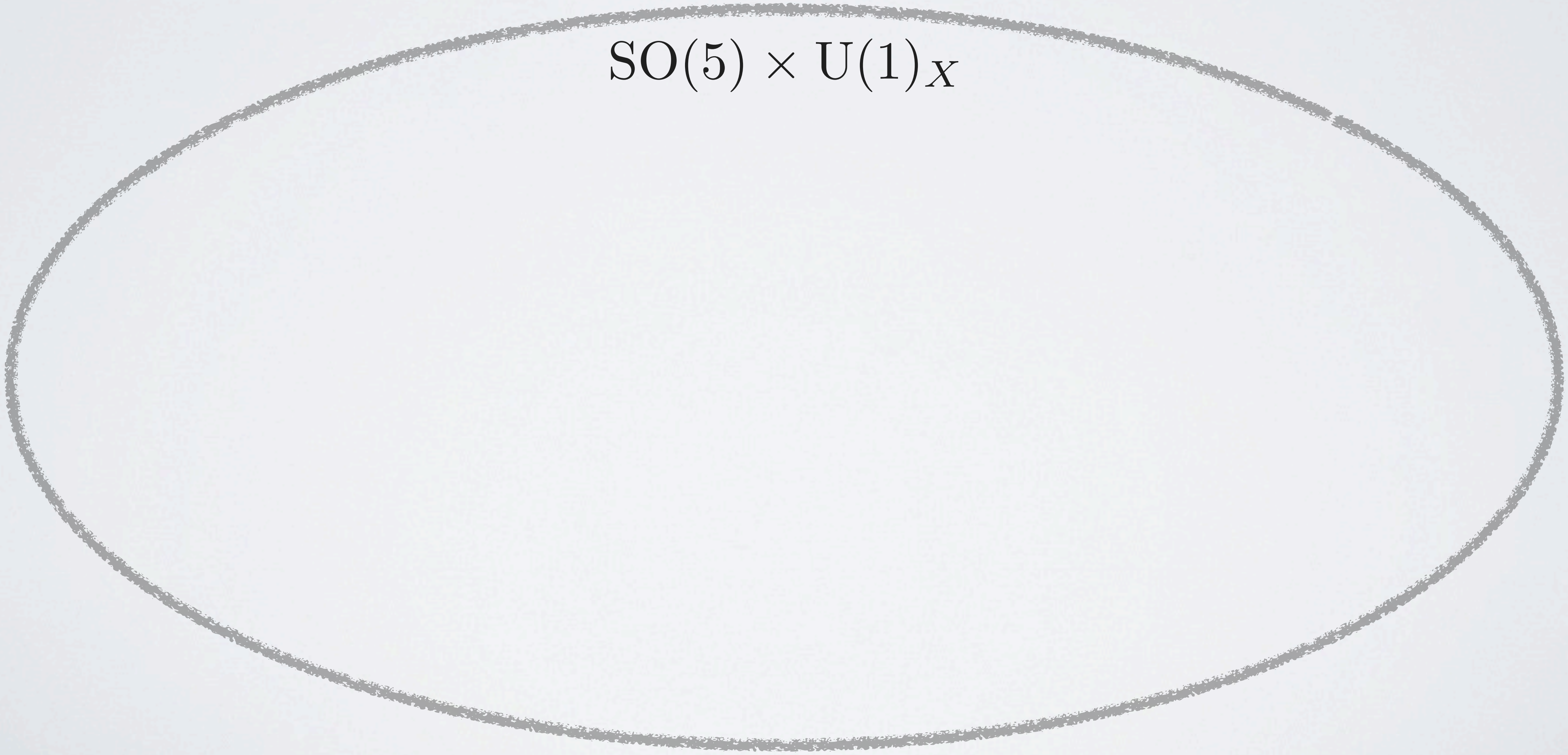

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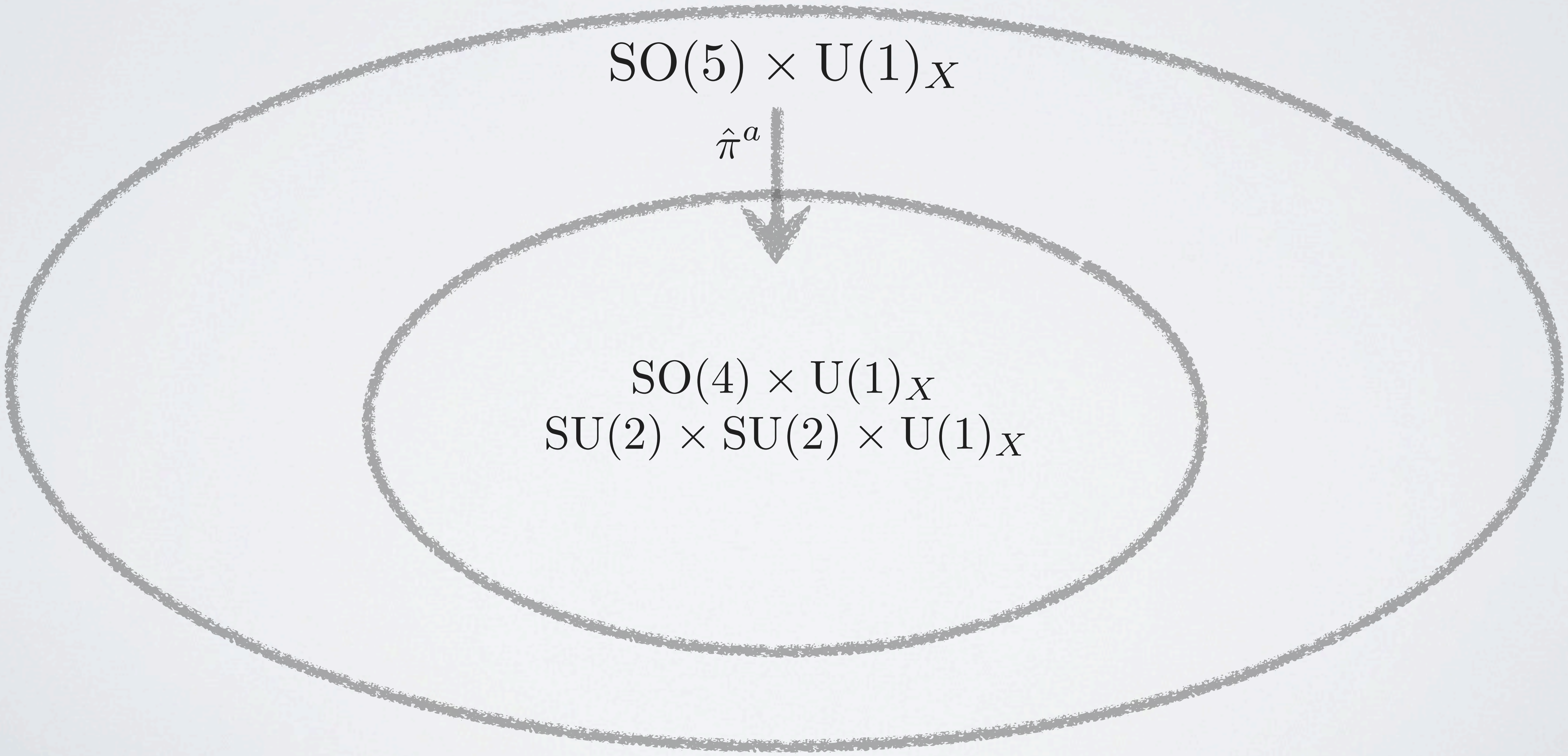

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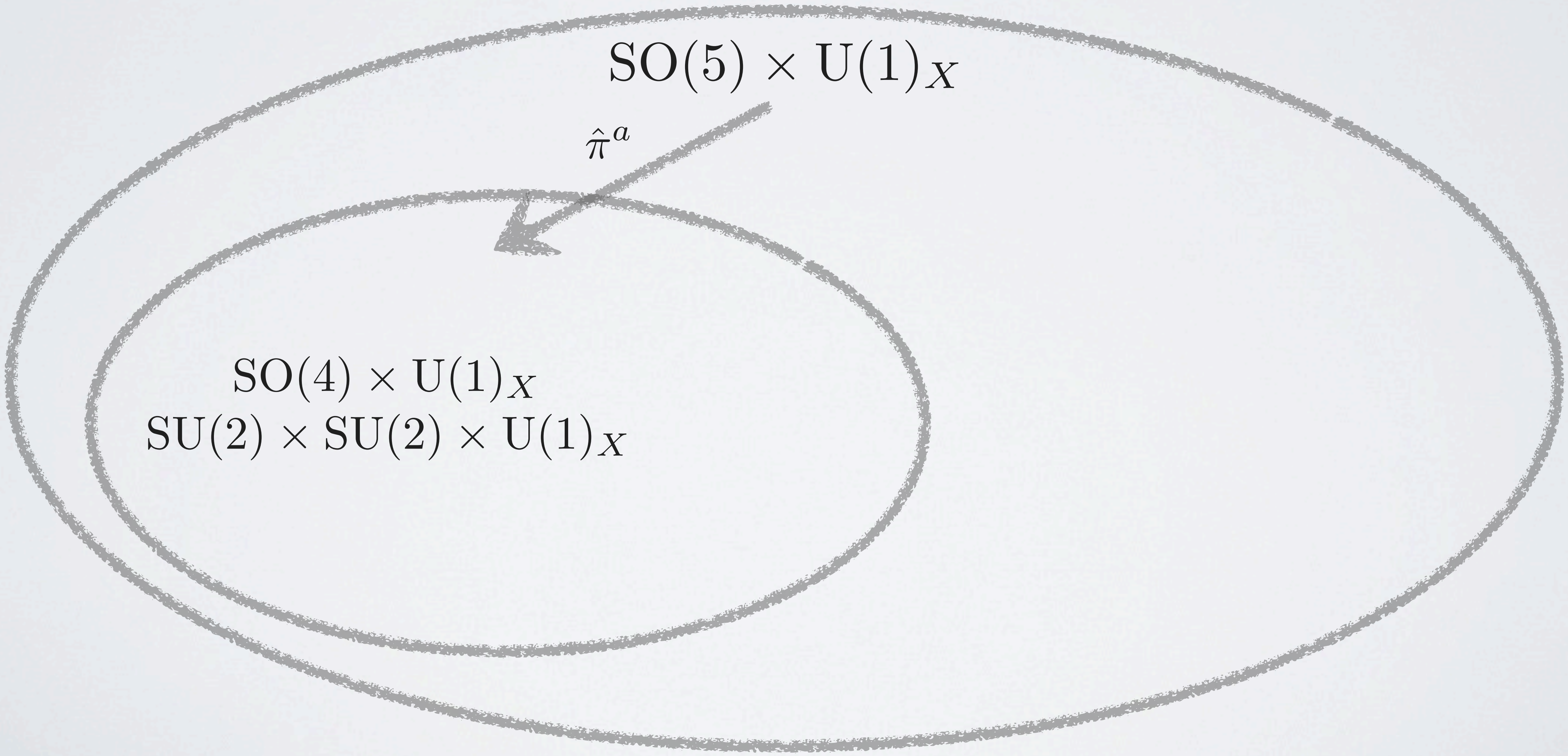

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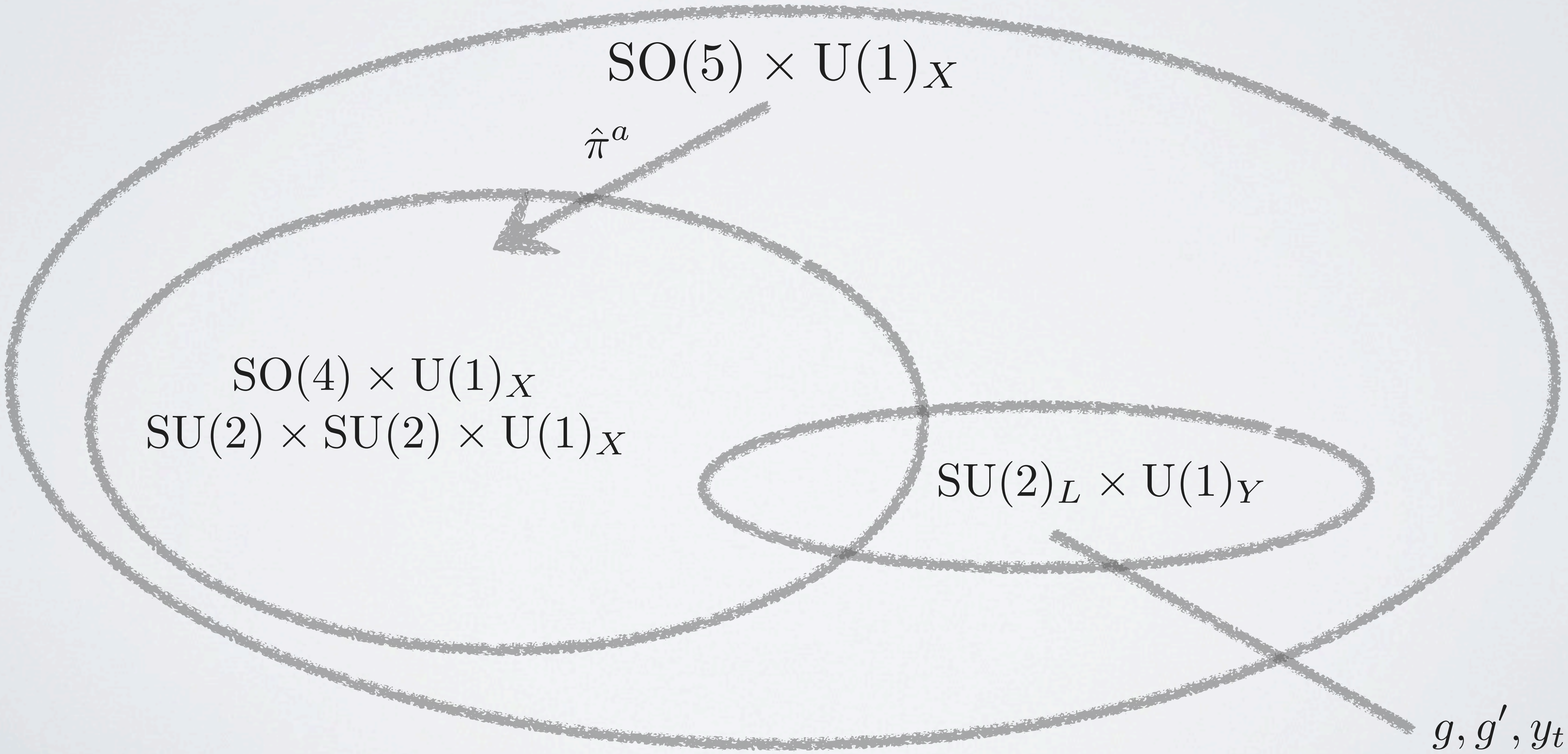

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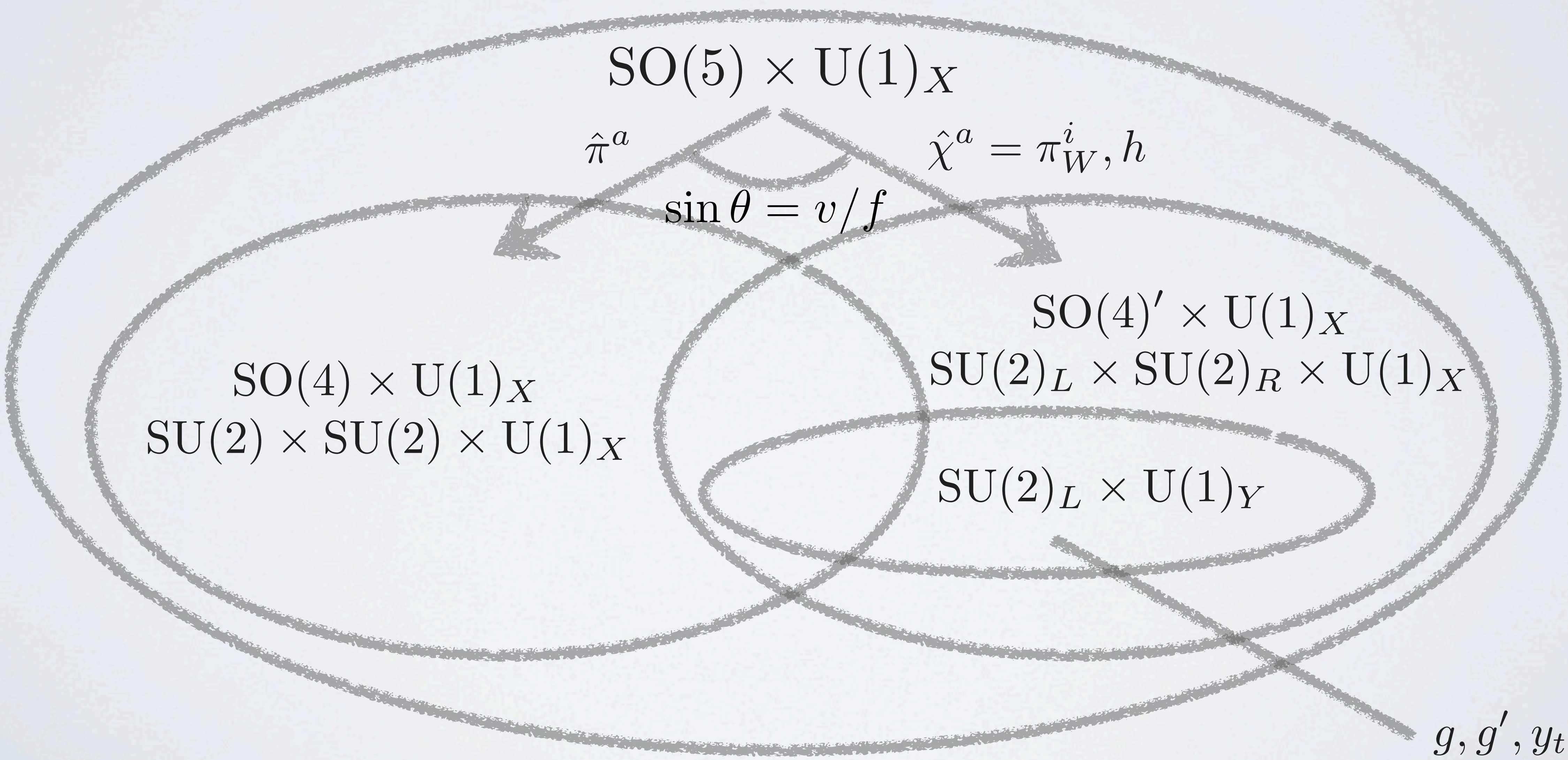

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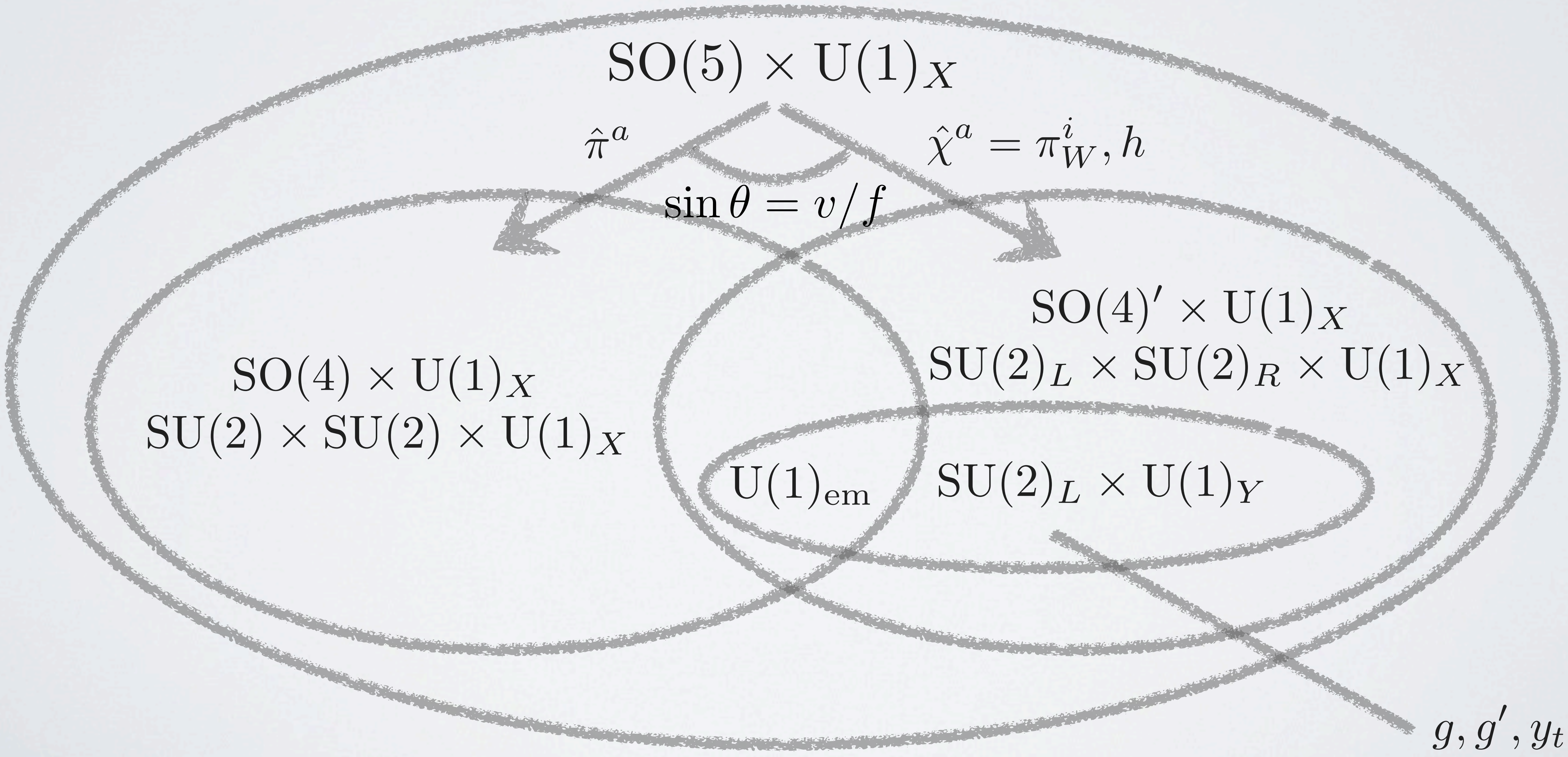


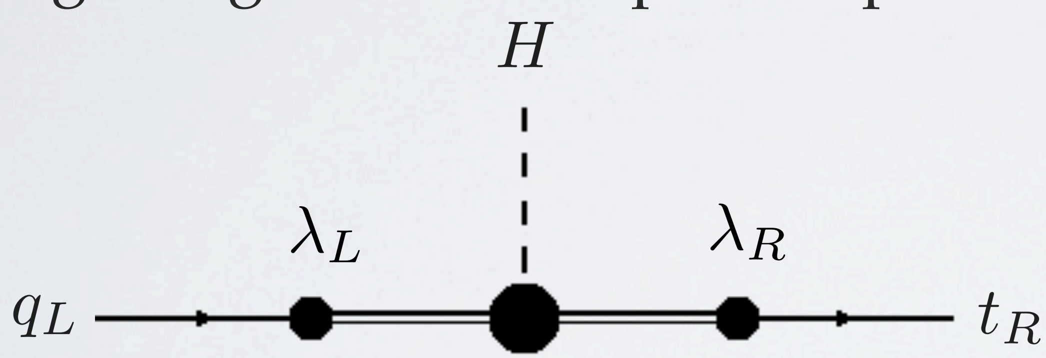
PARTIAL COMPOSITENESS

- The flavor problem of TC theories can be improved if the Yukawa couplings arise through mixings of elementary quarks with fermionic operators of the strong sector
- This idea is called Partial Compositeness

Kaplan, NPB 365 '91
Keren-Zur, Lodone, Nardecchia, Pappadopulo, Rattazzi, Vecchi, 1205.5803 [hep-ph]

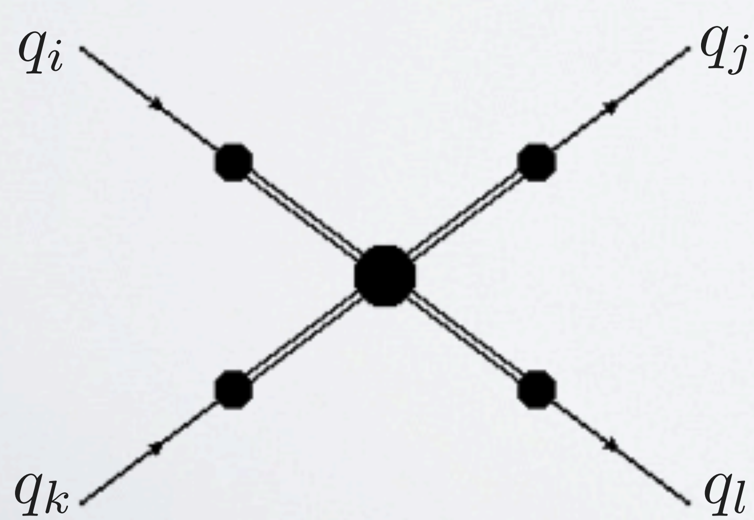
$$\mathcal{L}_{\rm PC} = \lambda_L q_L \mathcal{O}_L^q + \lambda_R t_R \mathcal{O}_R^t + \text{h.c.} + g A_\mu^a \mathcal{J}^{\mu\, a}$$

- Integrating out the composite operators at tree level we get



$$y_t \sim \frac{\lambda_L \lambda_R}{g_\psi} \equiv \epsilon_L \epsilon_R g_\psi$$

- FCNC are suppressed with respect to traditional Technicolor



$$\sim \frac{\lambda_i \lambda_j \lambda_k \lambda_l}{g_\psi^2 f^2} \equiv \frac{\epsilon_i \epsilon_j \epsilon_k \epsilon_l g_\psi^2}{f^2}$$

THE TUNING

- The scalar potential can be written, according to NDA

$$
\begin{aligned}
V(h) &= V^{(1\,\mathrm{loop})}(h/f) + V^{(2\,\mathrm{loop})}(h/f) + \dots \\
&= f^2 m_\Psi^2 \left(\frac{g_\psi}{4\pi}\right)^2 \left(\epsilon^2 \mathcal{F}_1^{(1)}(h/f) + \epsilon^4 \mathcal{F}_2^{(1)}(h/f) + \dots\right) \\
&\quad + f^2 m_\Psi^2 \left(\frac{g_\psi}{4\pi}\right)^4 \left(\epsilon^2 \mathcal{F}_1^{(2)}(h/f) + \dots\right) + \dots
\end{aligned}
$$

- The functions $\mathcal{F}$ are given by linear combinations of non-linear G invariants

$$
\mathcal{F} = \sum_i c_i I_i \left(\frac{h}{f}\right)
$$

- The c_i are expected to be $O(1)$ couplings and some degree of cancellation among them is necessary to get a small enough ratio $\xi = v^2/f^2$
- In absence of additional cancellations ξ provides a measure of the cancellation
- However, when only one invariant is generated at a given order in ϵ an additional cancellation is needed to tune $\xi \ll 1$ and we expect a tuning of the order of $\xi \times \epsilon$ (this is what happens, e.g. in the MCHM5)
- These models are said to be "doubly tuned" ***(Panico, Redi, Tesi, Wulzer 1210.7114)***

AN EXAMPLE: THE MCHM5

- We consider the SO(5)/SO(4) coset with composite operators transforming in the fundamental (5) irrep of SO(5)

(Panico, Redi, Tesi, Wulzer 1210.7114)

- At order ϵ^2 only one invariant is generated

$$V(h) \propto \epsilon^2 \mathcal{F}_1^{(1)} + O(\epsilon^4) \sim c_1 \epsilon^2 s_h^2 + O(\epsilon^4)$$

- At this order the potential has only a discrete set of minima, corresponding to discrete values of ξ
- To properly trigger EWSB with a continuum of values of ξ one is forced to consider the order ϵ^4 subleading contribution

$$V(h) \propto \epsilon^2 \mathcal{F}_1^{(1)} + \epsilon^4 \mathcal{F}_2^{(1)} \sim c_1 \epsilon^2 s_h^2 + \left(c_2 \epsilon^2\right) \epsilon^2 s_h^2 \left(1 - s_h^2\right)$$

- To get EWSB with a small ξ we need to tune $c_1 \approx c_2 \epsilon^2$
- The tuning in this model is therefore expected to be more severe than its NDA estimate $\Delta^{-1} \sim \xi \times \epsilon^2$
- The simplest example of where all the relevant invariants arise at order $O(\epsilon^2)$ corresponds to the choice $\mathcal{O}^q \sim \mathbf{14}_{2/3}$ and $\mathcal{O}^t \sim \mathbf{1}_{2/3}$ of

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THE MCHM: GOLDSTONE SECTOR

- The MCHM is based on the SO(5)/SO(4) coset
- There are 4 GB $h^{\hat{a}}$ that transform as a **4** of $\mathrm{SO}(4)$ (~(**2**,**2**) of $\mathrm{SU}(2) \times \mathrm{SU}(2)$)

$$U(h) = \exp\left(i\frac{\sqrt{2}h^{\hat{a}}T^{\hat{a}}}{f}\right) \qquad \Sigma = U\Sigma_0 = \left(0, 0, 0, \sin\frac{h}{f}, \cos\frac{h}{f}\right)^T$$

- The SM gauge bosons gauge a subgroup $\mathrm{SO}(4)' \sim \mathrm{SU}(2)_L \times \mathrm{SU}(2)_R$
- The Higgs parametrizes the angle between $\mathrm{SO}(4)$ and $\mathrm{SO}(4)'$: $\theta = \frac{\langle h \rangle}{f}$
- For $\theta = 0$ the EW symmetry is unbroken since the EW gauge group is completely contained in the preserved $\mathrm{SO}(4)$
- For $\theta \neq 0$ the SM gauge bosons gauge a combination of the SO(5)/SO(4) broken generators, three of the 4 GB are eaten by the W and the Z and the fourth is identified with the Higgs
- Notice that even if we start at tree level with $\theta = 0$ a value different from zero is generated at loop level due to the explicit SO(5) breaking induced by the SM gauge and Yukawa couplings *(Coleman, Weinberg PRD7 '73)*

THE MCHM: GOLDSTONE SECTOR

- At the lowest order $O(p^2)$ the symmetry breaking Lagrangian simply reads

$$\mathcal{L}_\chi = \frac{f^2}{2} (D_\mu \Sigma)^T D^\mu \Sigma$$

- Expanding this equation we can read the W boson mass, which gives

$$m_W^2 = \frac{g^2 f^2}{4} \sin^2\theta$$

$$\xi \equiv \sin^2\theta = \frac{v^2}{f^2}$$

- The vacuum misalignment generates a separation between the scale of the strong sector f and the EW scale v
- This separation ensures that the usual technicolor tension with the $\hat{S}$ parameter is relaxed in these models

$$\hat{S} \approx \frac{g^2}{3g_\rho^2}\xi \approx 10^{-3}\left(\frac{\xi}{0.1}\right)\left(\frac{4}{g_\rho}\right)^2$$

THE MCHM: GAUGE SECTOR

- The SM gauge bosons gauge a current of the strong sector according to

$$\mathcal{L}_{\text{PC}} \supset g A_\mu \mathcal{J}^\mu$$

- Upon integrating out the strong sector, an effective Lagrangian for the SM gauge bosons is generated
- A simple trick to get the effective action is to gauge the whole $\text{SO}(5) \times \text{U}(1)_X$

$$\mathcal{L}^g_{\text{eff}} = \frac{1}{2} P^{(t)}_{\mu\nu} \left[\Pi^X_0(p) A^{X\,\mu} A^{X\,\nu} + \Pi_0(p) \text{Tr}[A^\mu A^\nu] + \Pi_1(p) \Sigma^T A^\mu A^\nu \Sigma \right]$$

- And then switch off the unphysical gauge d.o.f.

$$\mathcal{L}^g_{\text{eff}} = P^{(t)}_{\mu\nu} \left[\frac{1}{2} W^{a\mu} \Pi_{ab} W^{b\nu} + W^{3\mu} \Pi_{30} B^\nu + \frac{1}{2} B^\mu \Pi_{00} B^\nu \right]$$

$$\Pi_{ab} = \delta_{ab} \left(\Pi_0 + \frac{s_h^2}{4} \Pi_1 \right) \qquad \Pi_{03} = -\frac{s_h^2}{4} \Pi_1 \qquad \Pi_{00} = \Pi_0 + \Pi^X_0 + \frac{s_h^2}{4} \Pi_1$$

OUTLINE

- The SM Higgs, theorist's and experimentalist's view
- The Higgs as a pseudo-Goldstone boson
  - SB by vacuum misalignment and Partial compositeness
  - The Minimal Composite Higgs Model (MCHM)
- Example of an explicit model (MCHM14)
  - Tuning
  - Spectrum of resonances
- Phenomenology
  - Higgs couplings
  - Top partners
- Conclusion

THE MCHM14: FERMIONIC SECTOR

- We consider fermionic composite operators $\mathcal{O}^q \sim \mathbf{14}_{2/3}$ and $\mathcal{O}^t \sim \mathbf{1}_{2/3}$

$$\mathcal{L}_{\text{mix}} = \lambda_L f\, q_L^\alpha \text{Tr}\left[P_L^\alpha \mathcal{O}_L^q\right] + \lambda_R f\, t_R^\alpha P_R^\alpha \mathcal{O}_R^t + \text{h.c.}$$

- The spurion P_L^α transforms in the same representation of $\mathcal{O}^q$ under SO(5)

$$P_L^\alpha = \frac{1}{2}\left(\begin{array}{c|c} & \vec{v}^\alpha \\ \hline \vec{v}^{\alpha\,T} & \end{array}\right) \qquad \begin{aligned} \vec{v}^{1\,T} &= (0,0,i,-1) \\ \vec{v}^{2\,T} &= (i,-1,0,0) \end{aligned}$$

- We can now define the matrices $\psi_q \equiv q_L^\alpha P_L^\alpha$ and $\psi_t \equiv t_R$
- Integrating out the strong sector generates an effective action for q_L and t_R
- In order to respect the full spurionic symmetry only the ψs can enter

$$\begin{aligned} \mathcal{L}_{\text{eff}} \; = \; & \Pi_0^q \text{Tr}\left[\overline{\psi}_q \not{p}\, \psi_q\right] + \Pi_0^t \overline{\psi}_t \not{p}\, \psi_t \\ & + 4\Pi_1^q \Sigma^T \overline{\psi}_q \not{p}\, \psi_q \Sigma + \Pi_2^q \left(\Sigma^T \overline{\psi}_q \Sigma\right) \not{p} \left(\Sigma^T \psi_q \Sigma\right) \\ & + M_1^t \bar{\psi}_t \Sigma^T \psi_q \Sigma + \text{h.c.}\,, \end{aligned}$$

THE MCHM14: FERMIONIC SECTOR

- The effective action can be written in terms of the SM fields as

$$\mathcal{L}^f_{\text{eff}} = \Pi^{b_L}\bar{b}_L \not{p}\, b_L + \Pi^{t_L}\bar{t}_L \not{p}\, t_L + \Pi^{t_R}\bar{t}_R \not{p}\, t_R - \left(\Pi^{t_L t_R}\bar{t}_L t_R + \text{h.c.}\right)$$

$$\begin{array}{lcl} \Pi^{b_L} & = & \Pi^q_0 + 2\Pi^q_1 c^2_h, \\ \Pi^{t_L} & = & \Pi^q_0 + \Pi^q_1\left(1 + c^2_h\right) + \Pi^q_2 s^2_h c^2_h, \\ \Pi^{t_R} & = & \Pi^t_0, \\ \Pi^{t_L t_R} & = & M^t_1 s_h c_h, \end{array}$$

- The approximate top mass is readily computed from the effective Lagrangian

$$m^2_t = \frac{|M^t_1|^2 s^2_h c^2_h}{\Pi^t_0(\Pi^q_0 + \Pi^q_1\,(1 + c^2_h) + \Pi^q_2 s^2_h c^2_h)} \approx \xi\,\frac{|M^t_1|^2}{\Pi^t_0\,\Pi^q_0}$$

- This assumes $\Pi^q_1, \Pi^q_2 \ll \Pi^q_0$ which we will motivate later (it is guaranteed by partial compositeness) and is computed at p=0

THE MCHM14: HIGGS POTENTIAL

- We can compute the 1-loop Coleman-Weinberg potential

$$V(h) = \alpha c_h^2 + \beta s_h^2 c_h^2 = (\beta - \alpha) s_h^2 - \beta s_h^4$$

$$\alpha = -\frac{3}{4}\int \frac{d^4 p_E}{(2\pi)^4}\frac{\Pi_1}{\Pi_0}\left(1 + \frac{2\Pi_0 + \Pi_0^X}{2\left(\Pi_0 + \Pi_0^X\right)}\right) - 6N_c \int \frac{d^4 p_E}{(2\pi)^4}\frac{\Pi_1^q}{\Pi_0^q}$$

$$\beta = -2N_c \int \frac{d^4 p_E}{(2\pi)^4}\left(\frac{\Pi_2^q}{\Pi_0^q} - \frac{|M_1^t|^2}{p_E^2\,\Pi_0^q\,\Pi_0^t}\right)$$

$$\xi = \frac{\beta - \alpha}{2\beta} \qquad m_h^2 = -\frac{8\beta}{f^2}\xi(1-\xi)$$

- The size of the α and β can be estimated using the spurionic symmetry and NDA

$$V(h) \approx N_C \frac{m_\psi^4}{16\pi^2}\frac{\lambda_L^2}{g_\psi^2}\left(a_1 I_1 + a_2 I_2\right) \qquad \hat{S} \approx \frac{g^2}{3g_\rho^2}\xi \approx 10^{-3}\left(\frac{\xi}{0.1}\right)\left(\frac{4}{g_\rho}\right)^2$$

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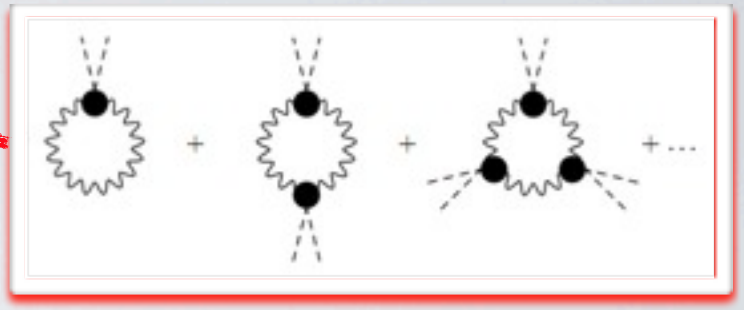

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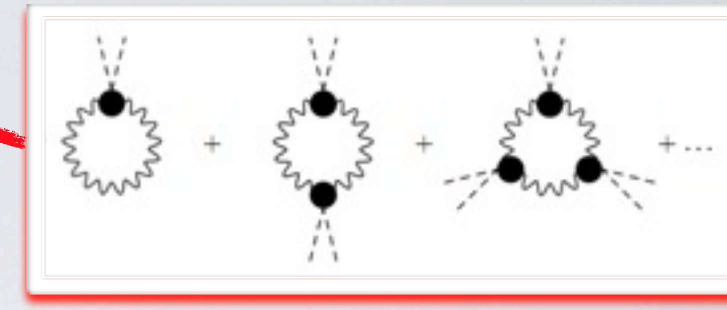

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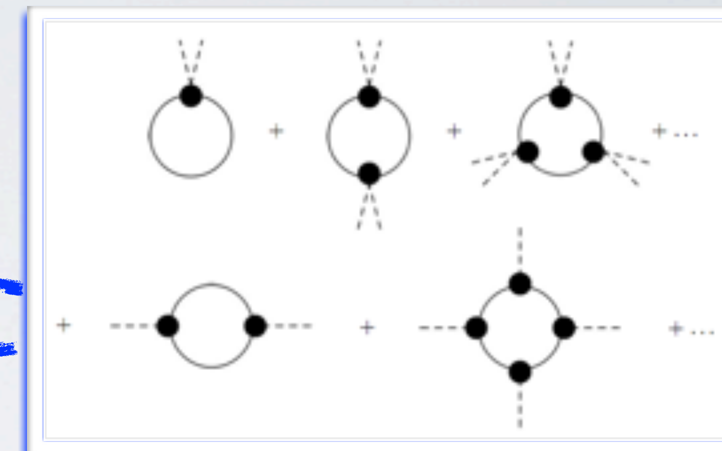

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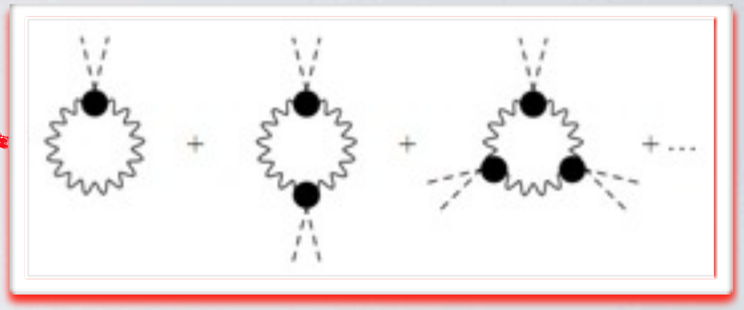

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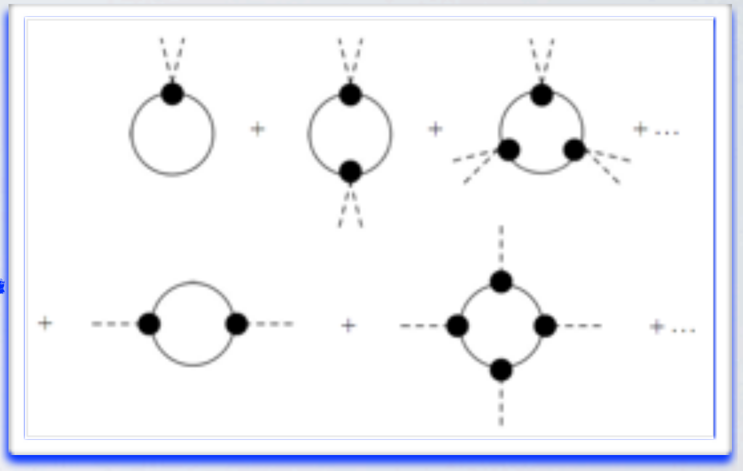

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5D $g_\psi = g_\rho$

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4D $g_\psi \neq g_\rho$

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1. AdS/CFT inspired techniques

The Higgs arises as the 5th component of 5D gauge bosons and the form factors are computed in terms of boundary to boundary 5D propagators

Contino, Nomura, Pomarol hep-ph/0306259
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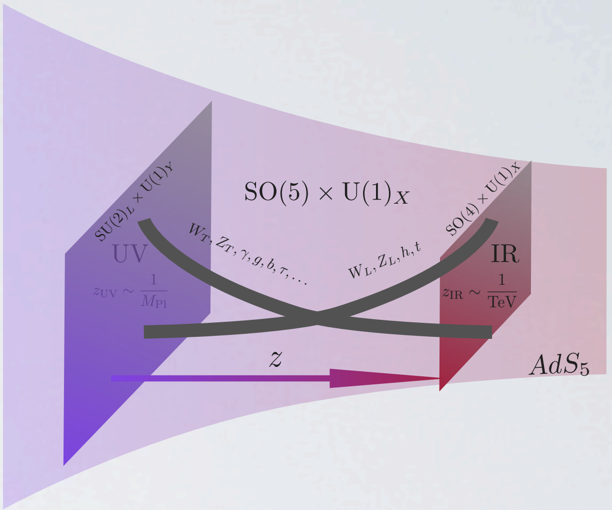
Panico, Wulzer hep-th/0703287
Panico, Safari, Serone 1012.2875
Pappadopulo, Thamm, RT 1303.3062



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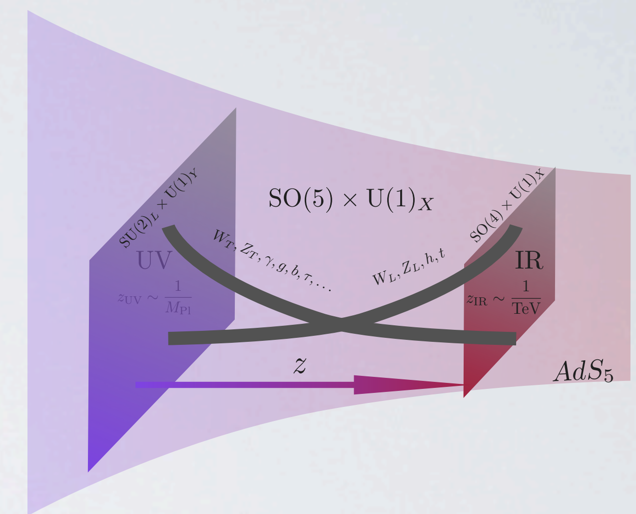
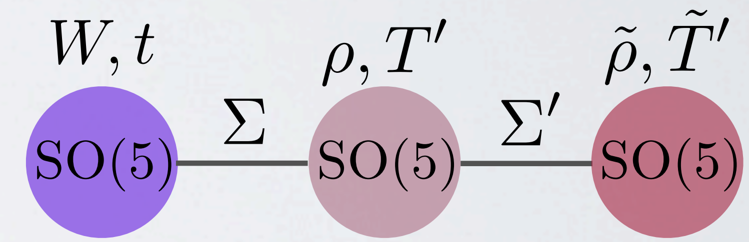
2. Deconstruction

Simple models with 2 or more sites allow to keep the potential finite and calculable

Panico, Wulzer 1106.2719
De Curtis, Redi, Tesi 1110.1613
Redi, Tesi 1205.0232





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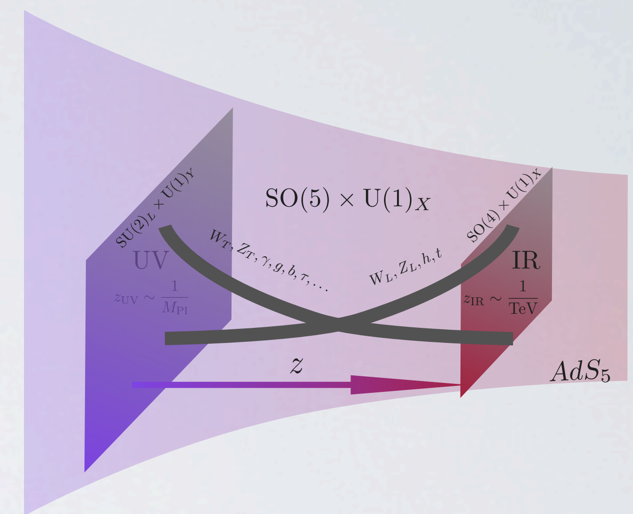
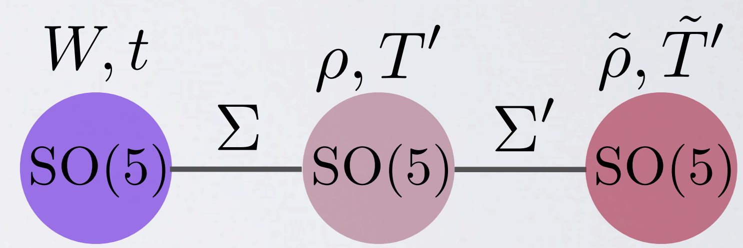
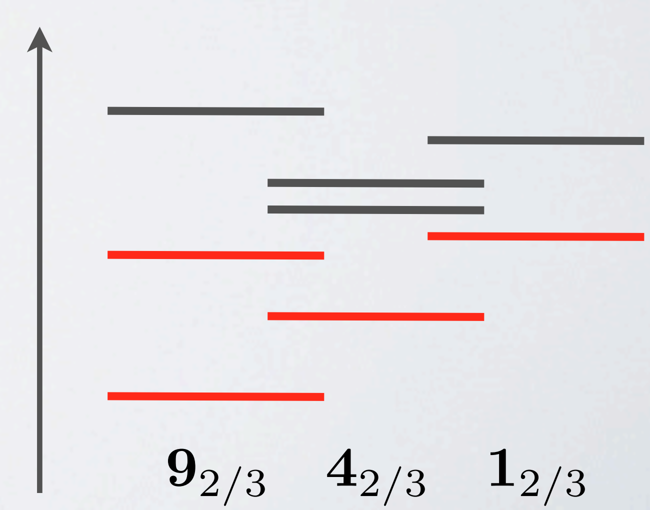
3. **Weinberg sum rules**

   The form factors are expressed in terms of sums of the contributions of towers of resonances and the minimal number of resonances ensuring the convergence of the integrals is retained

   Pomarol, Riva 1205.6434
   Marzocca, Serone, Shu 1205.0770







THE 5D PICTURE

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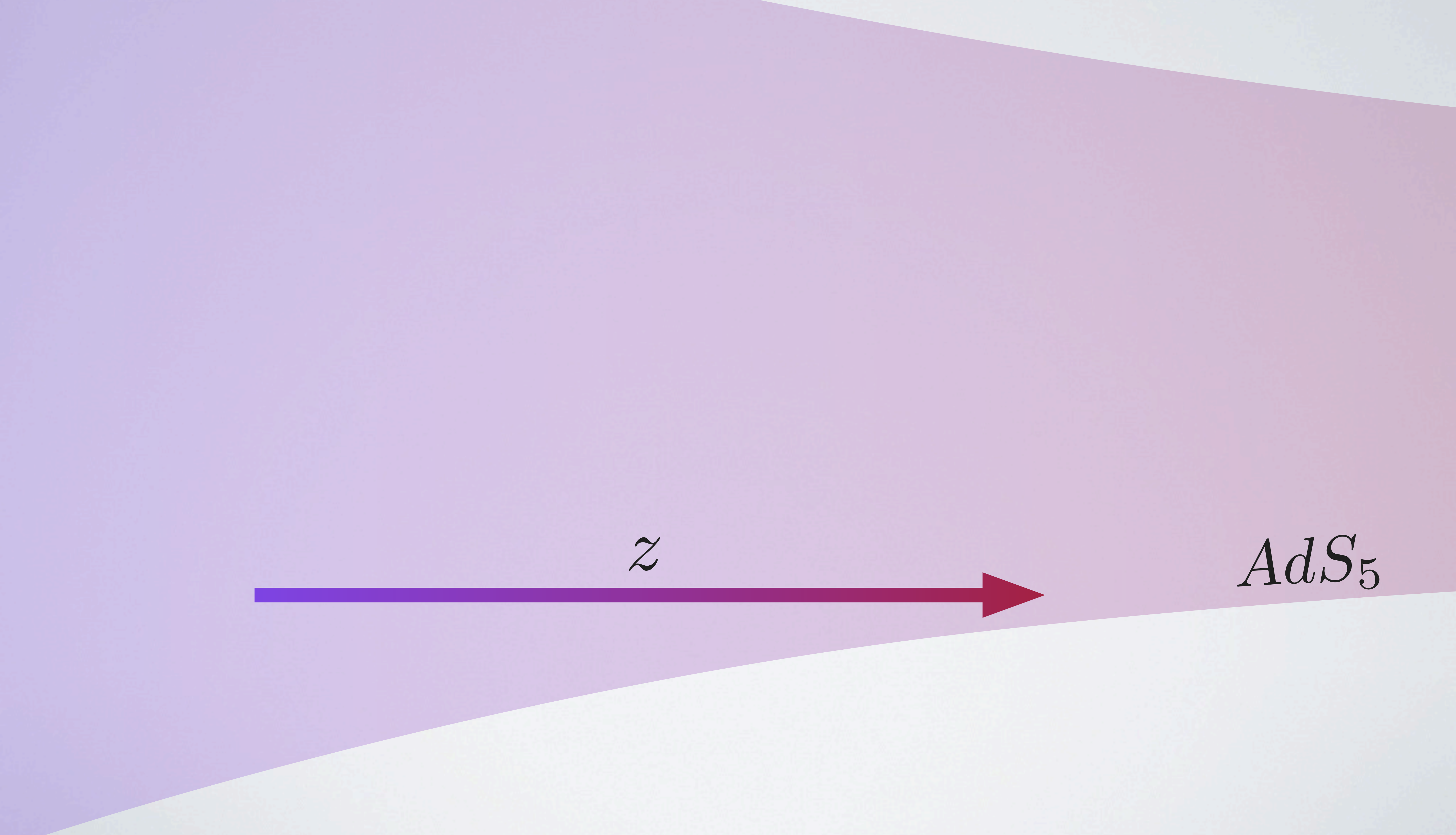

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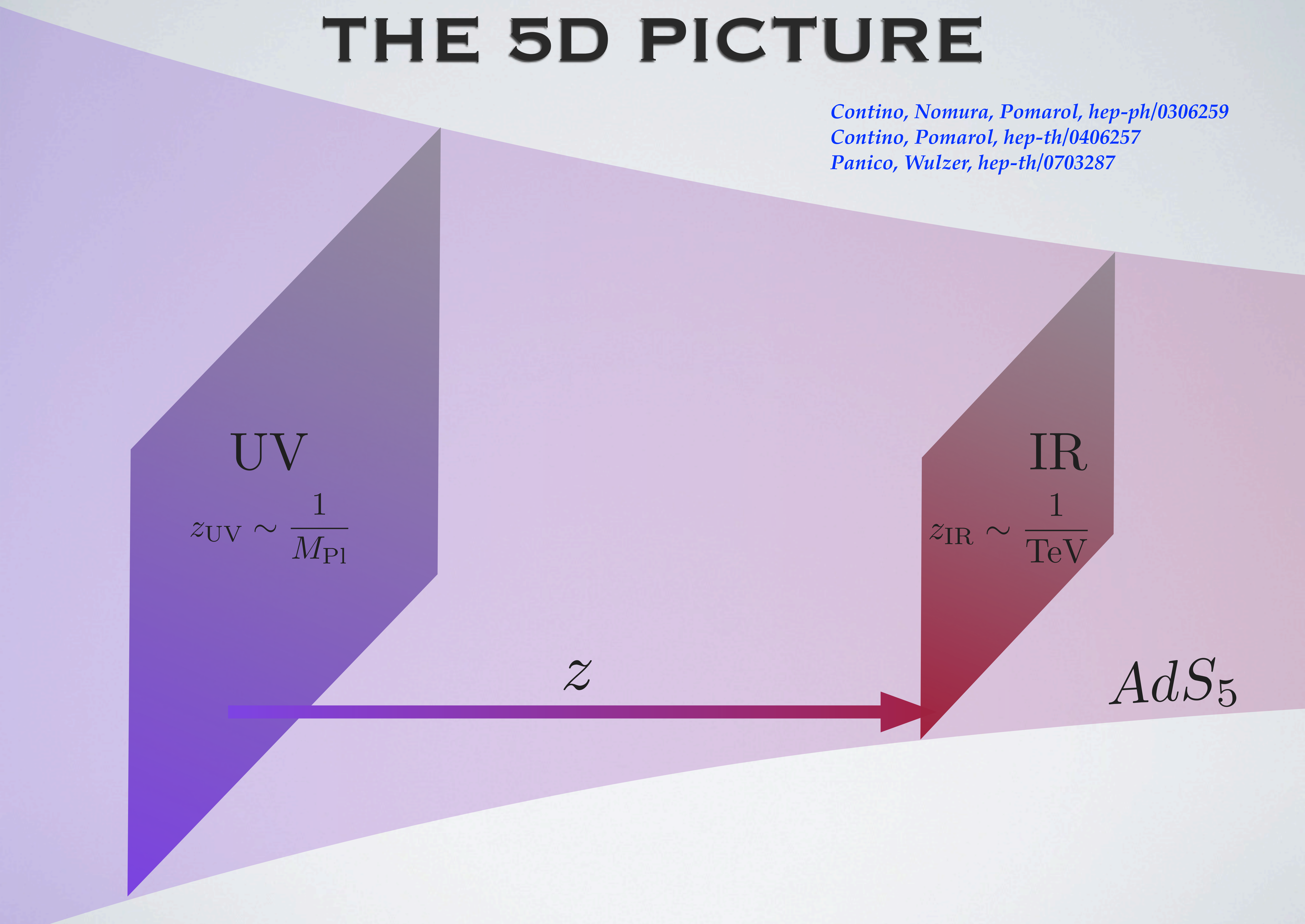
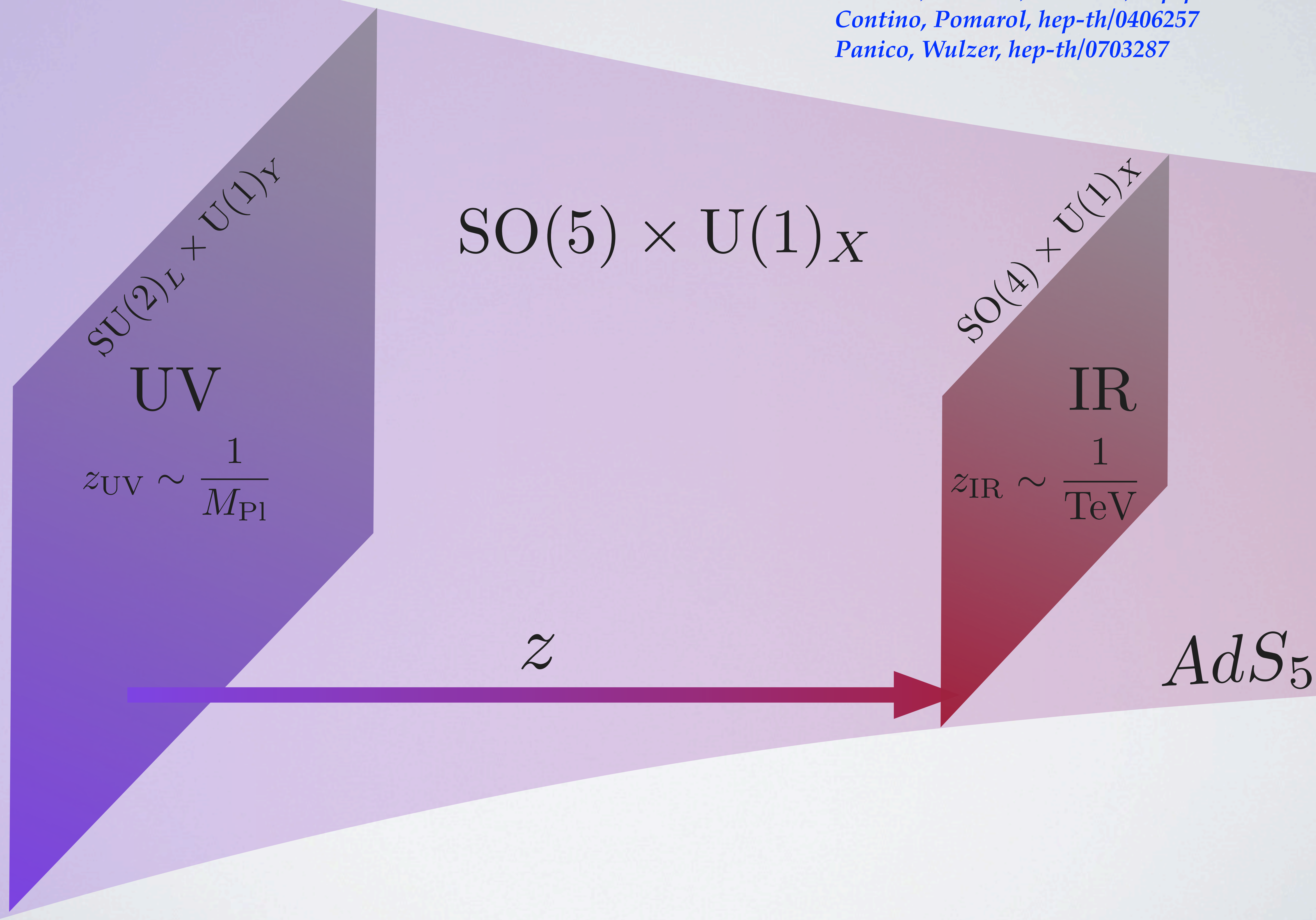


THE 5D PICTURE

Contino, Nomura, Pomarol, hep-ph/0306259
Contino, Pomarol, hep-th/0406257
Panico, Wulzer, hep-th/0703287



THE 5D PICTURE

Contino, Nomura, Pomarol, hep-ph/0306259
Contino, Pomarol, hep-th/0406257
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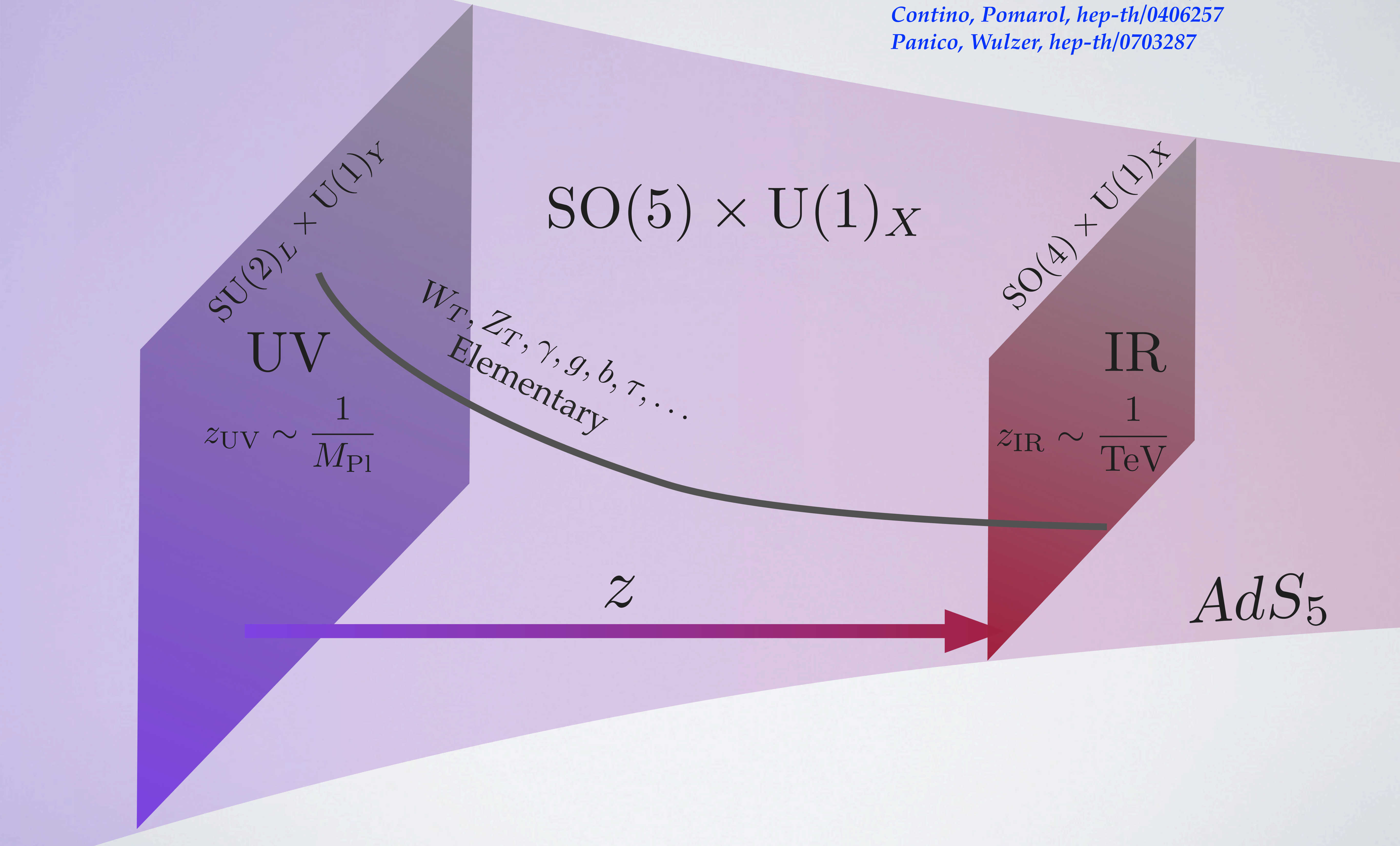

THE 5D PICTURE

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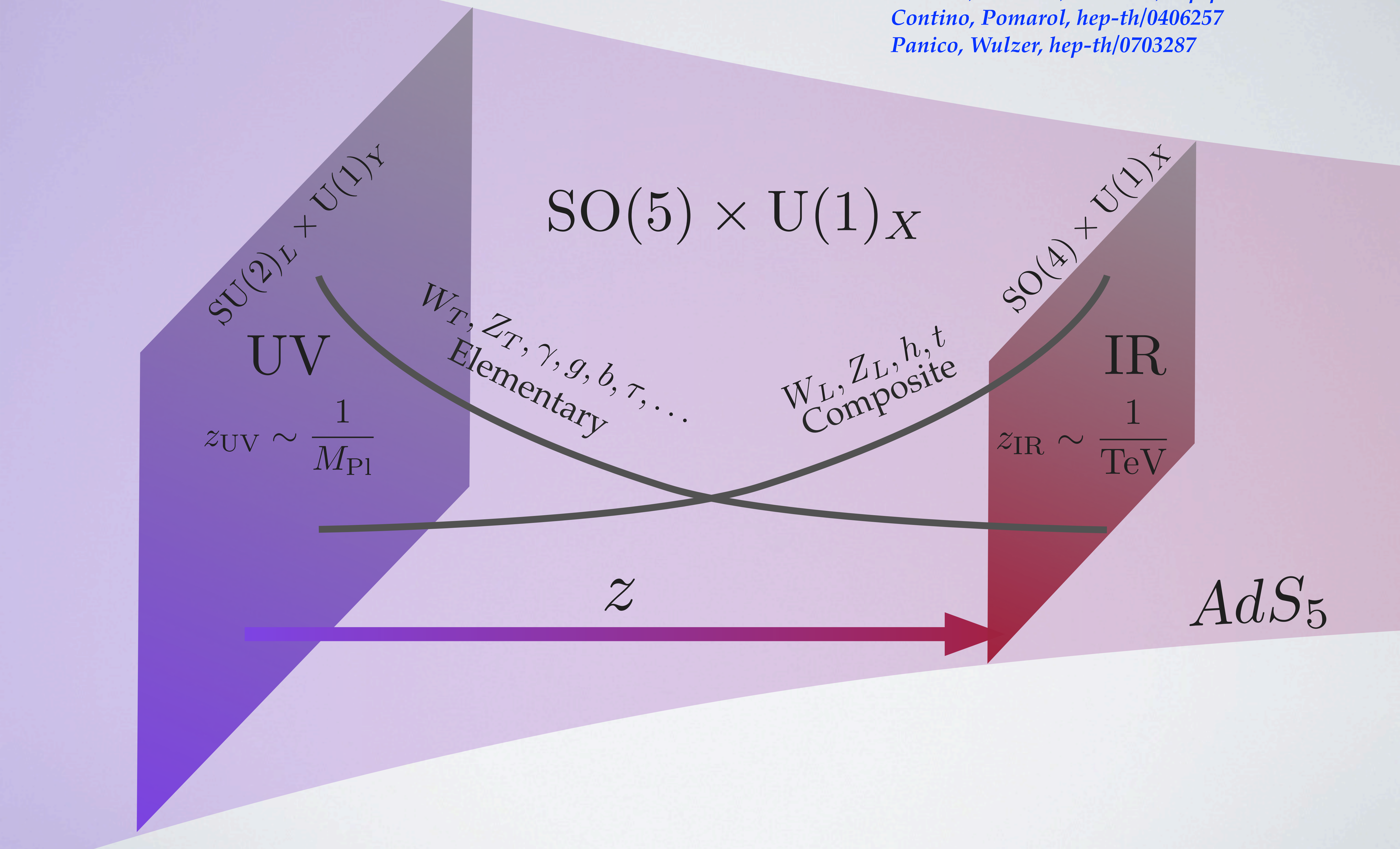
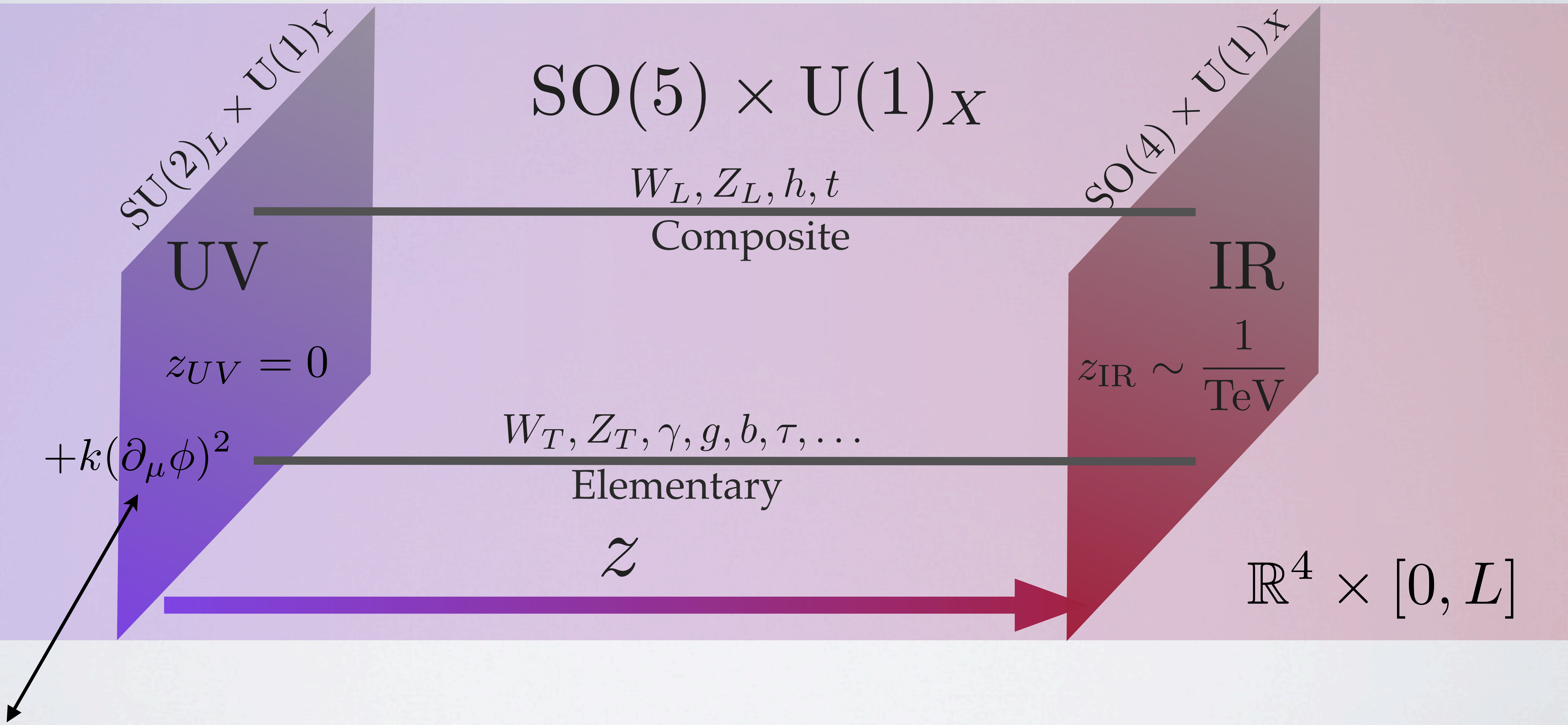
Contino, Pomarol, hep-th/0406257
Panico, Wulzer, hep-th/0703287



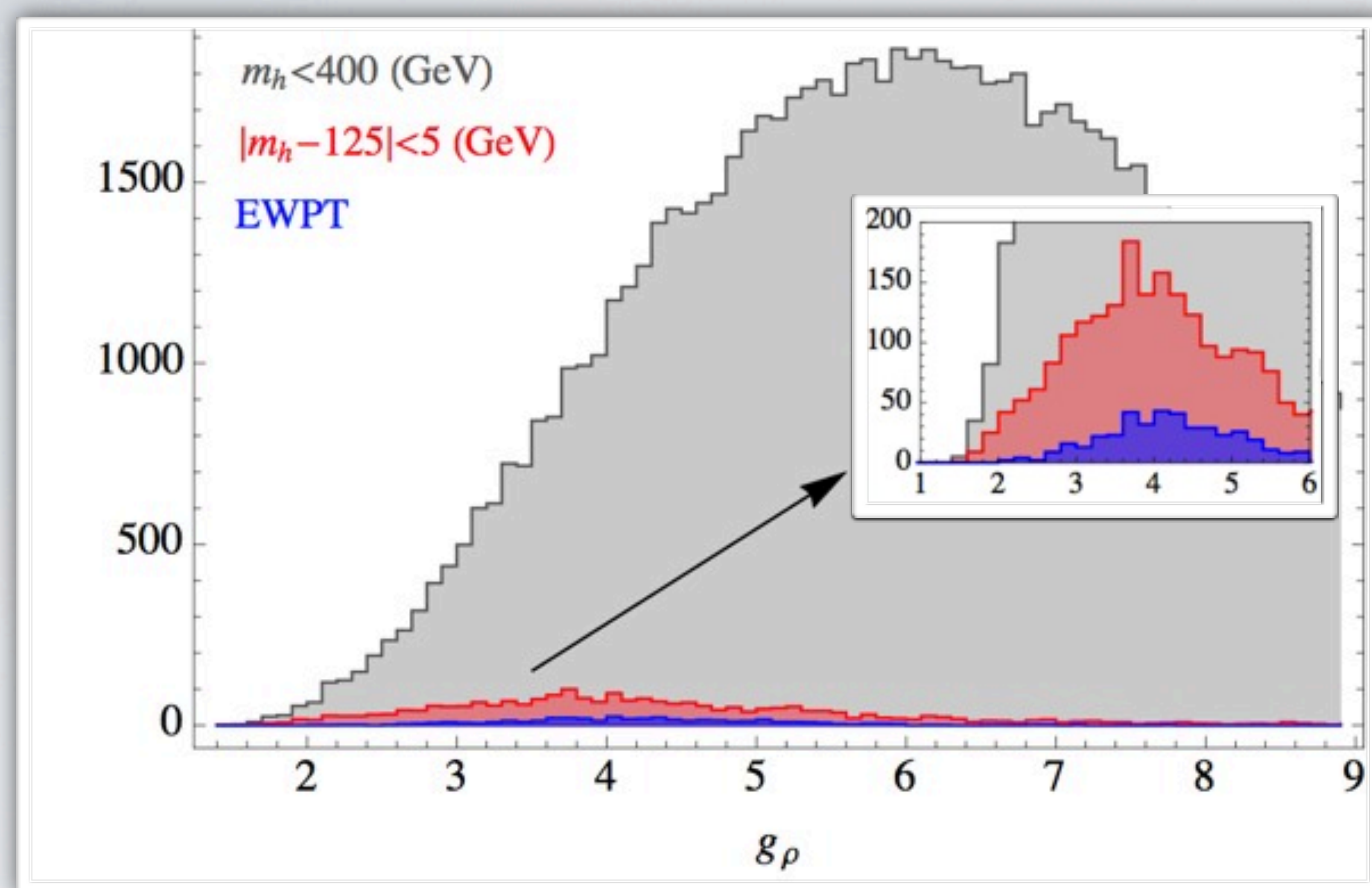
THE 5D PICTURE

Scrucca, Serone, Silvestrini hep-ph/0304220
Barbieri, Pomarol, Rattazzi hep-ph/0310285
Serone 0909.5619
Panico, Safari, Serone 1012.2875
Pappadopulo, Thamm, RT, 1303.3062



Large UV kinetic terms $k \gg 1$ give an overall suppression to the elementary states wave functions, suppressing their interactions and implementing PC: $1/k \sim \epsilon^2$

RESULTS: THE TUNING



$$\Delta = \frac{n_{\mathrm{A}}}{n_{\mathrm{B}}}$$

A

$$\begin{array}{rcl} m_W & = & 81\,\mathrm{GeV} \\ 148\,\mathrm{GeV} \leq & m_t & \leq 154\,\mathrm{GeV} \\ 120\,\mathrm{GeV} \leq & m_h & \leq 130\,\mathrm{GeV} \end{array}$$

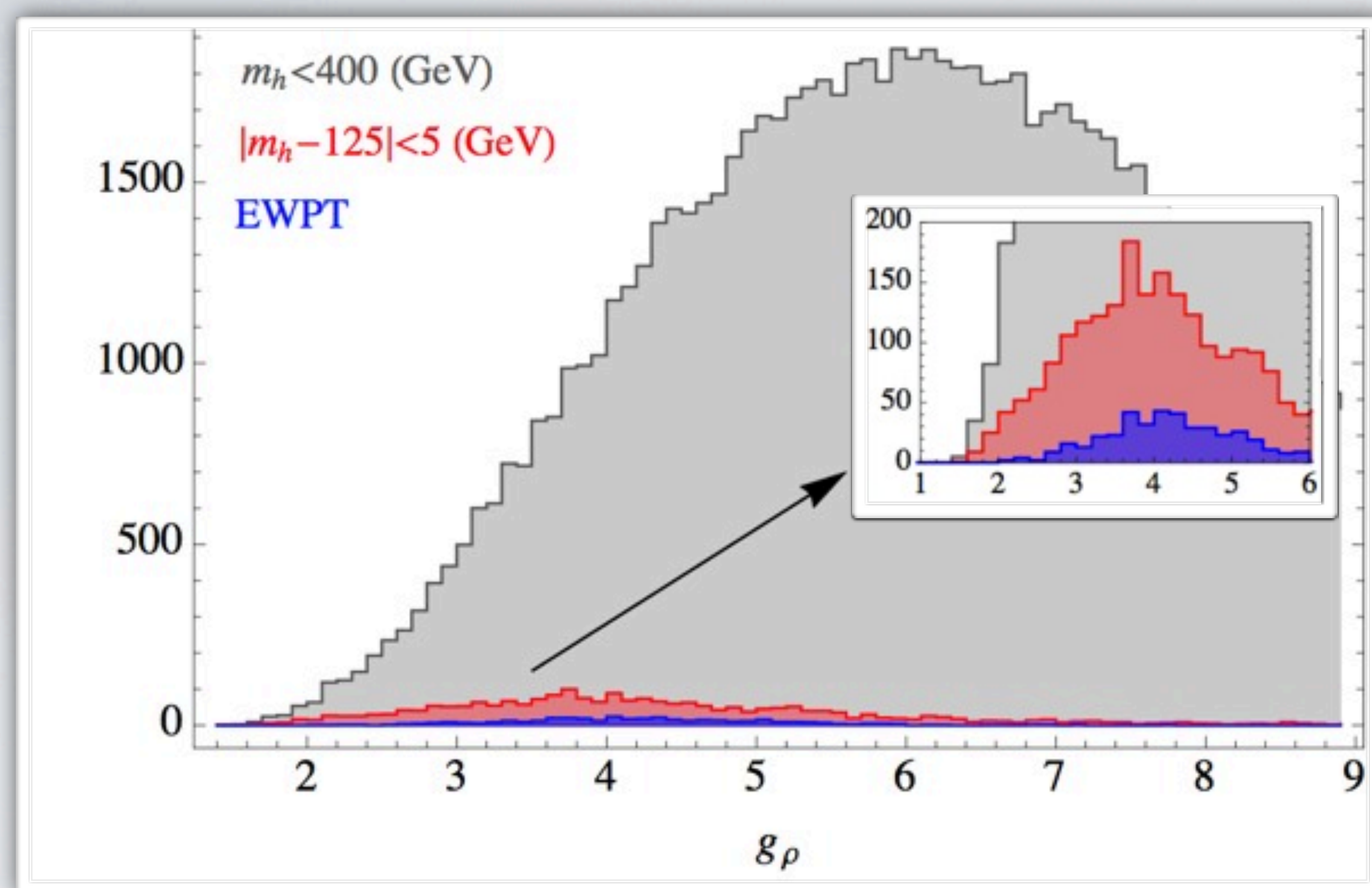
B

$$\begin{array}{rcl} \hat{S} & = & (0.39 \pm 0.70)\,10^{-3} \\ \hat{T} & = & (0.60 \pm 0.56)\,10^{-3} \end{array}$$

$$\rho = \begin{pmatrix} 1 & 0.91 \\ 0.91 & 1 \end{pmatrix}$$

$$\chi^2\left(\hat{S},\hat{T}\right) < 9.21 \quad \Rightarrow \quad 99\% C.L.$$

RESULTS: THE TUNING

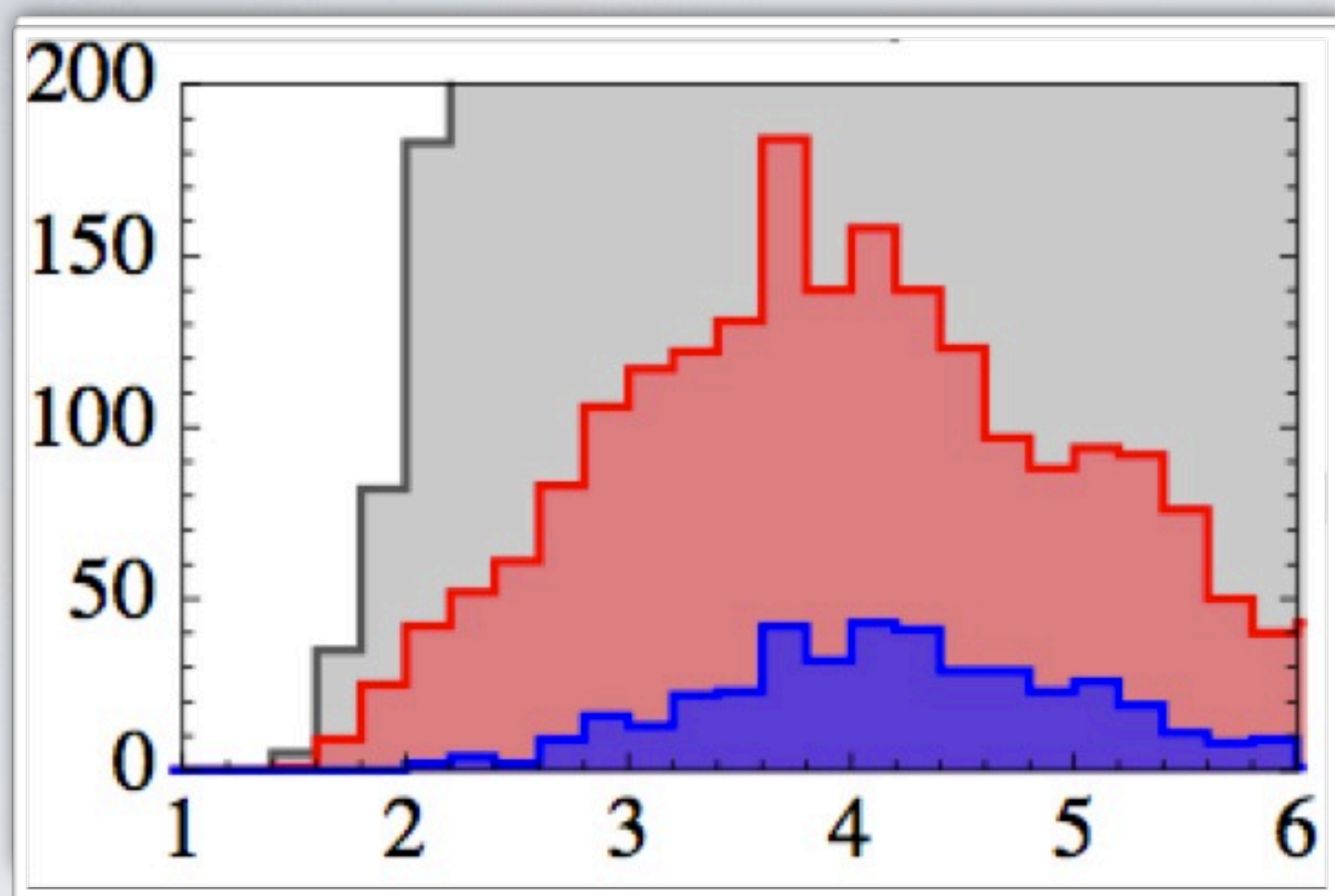


	$1/\Delta$ (%)
EWPT	4.5 ± 0.4
EWPT + $\Delta\hat{T} = 10^{-3}$	18 ± 1

$$m_h^2 \sim N_C \frac{g_\psi^2}{2\pi^2} \frac{g_\psi^2}{\lambda_R^2} y_t^2 v^2 |a_2|(1-\xi) \approx (380 \text{ GeV})^2 \frac{1}{\epsilon_R^2} \left(\frac{g_\psi}{4}\right)^2 |a_2|$$

- It could be argued that we are hiding some tuning in $|a_2| \ll 1$
- To check this we scanned without ANY requirement on the parameter space to find the “naive” expectation for $|a_2|$ in our model

RESULTS: THE TUNING



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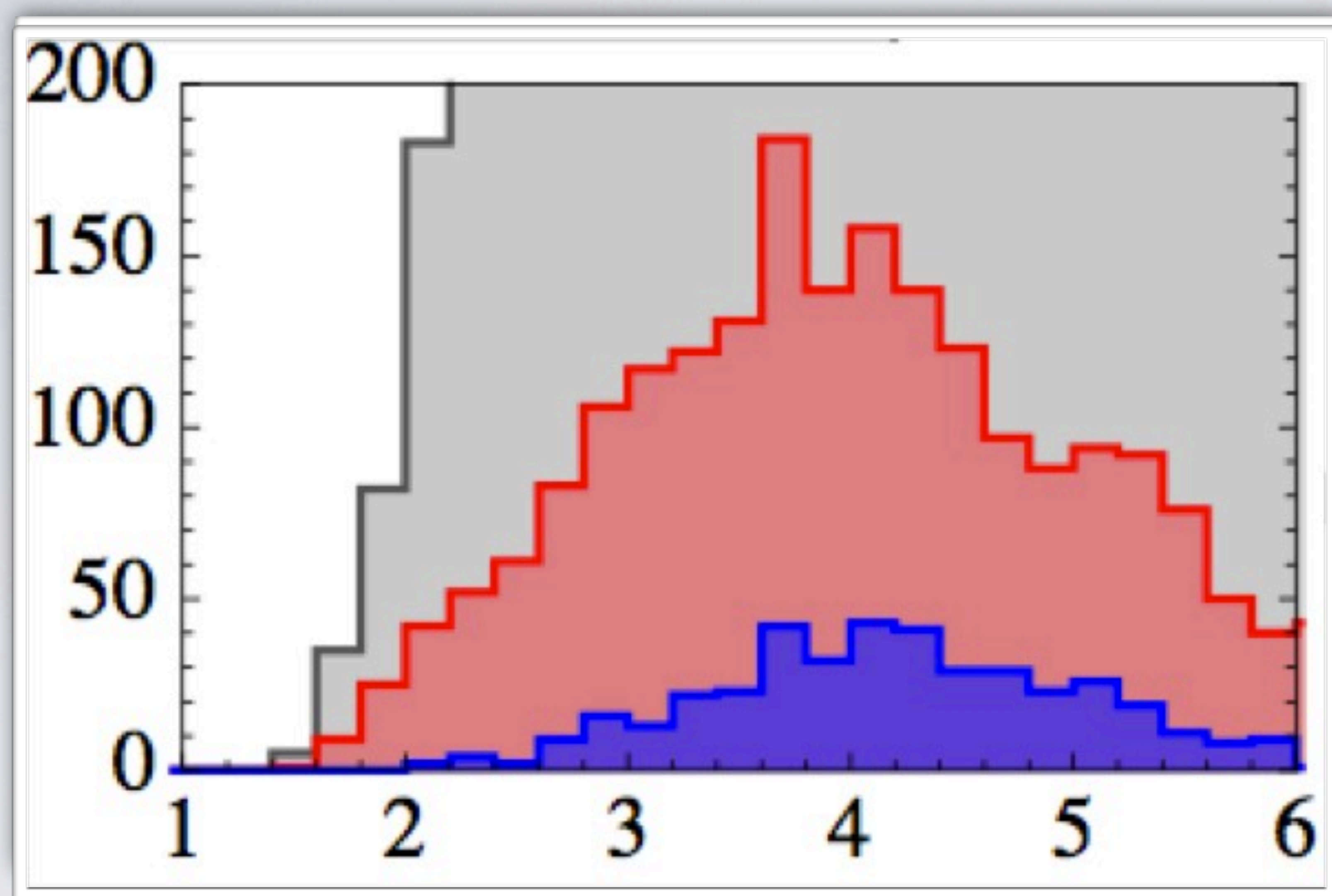

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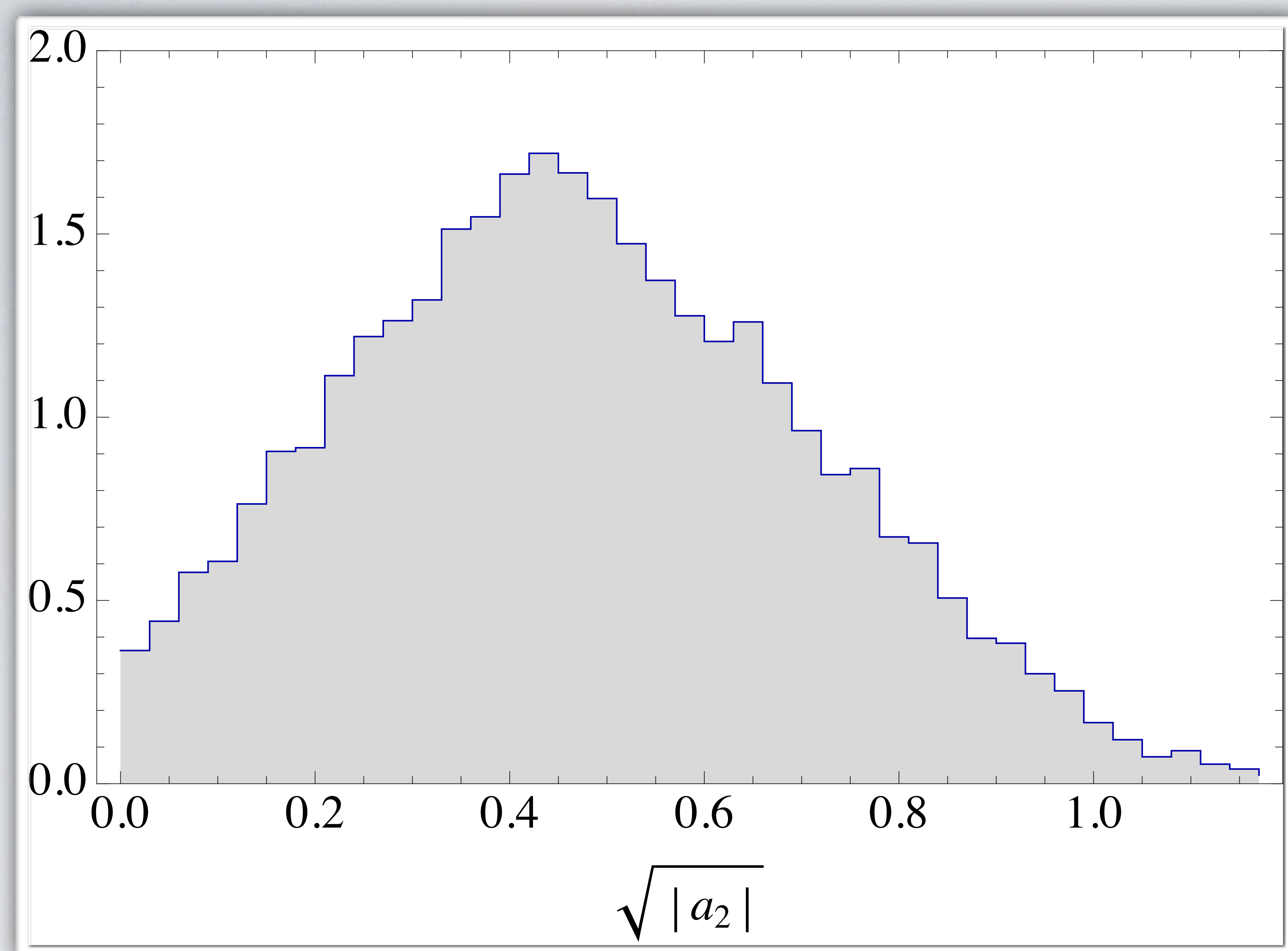

	$1/\Delta$ (%)
EWPT	4.5 ± 0.4
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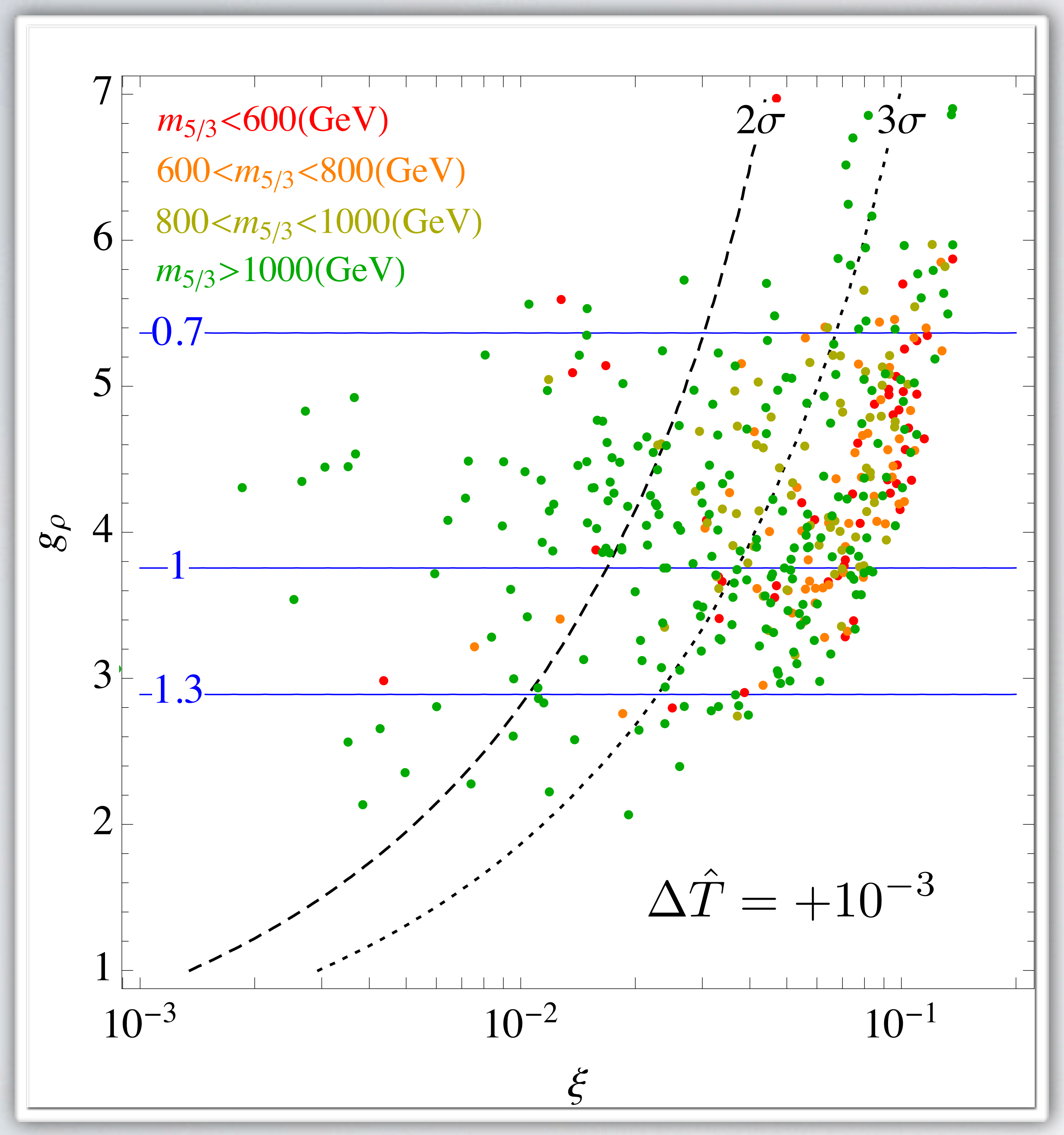
RESULT

$|a_2| \approx 0.2$ is the natural choice of our parameter space and the model, which already shows minimal tuning on the vev ξ, doesn't suffer from additional tuning due to the lightness of the Higgs boson (as it could have been expected)

RESULTS: THE SPECTRUM



- Again the naive expectation

$$m_\psi \sim g_\rho f$$

seem to fail, e.g.

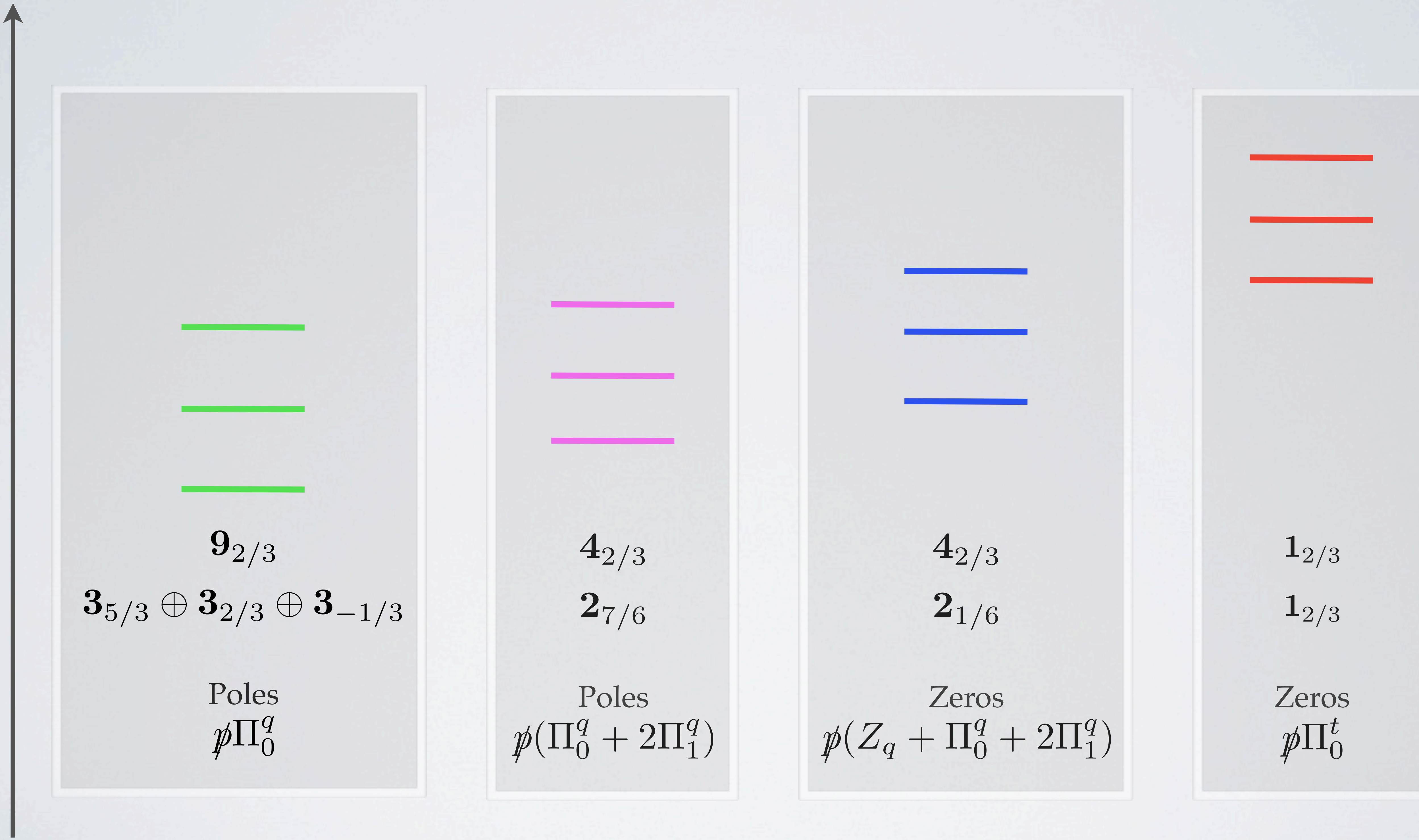
$$g_\rho = 4,\ \xi = 0.1 \quad \Rightarrow \quad m_\psi = 3\ \text{TeV}$$

- This can be explained looking at the whole spectrum and inspecting how it depends on the constraints from the top mass

Matsedonskyi, Panico, Wulzer 1204.6333
Marzocca, Serone, Shu 1205.0770
Pomarol, Riva 1205.6434
Panico, Redi, Tesi, Wulzer 1210.7114
Barbieri, Buttazzo, Sala, Straub, Tesi 1211.5085
Pappadopulo, Thamm, RT 1303.3062

THE FERMIONIC SPECTRUM

- The spectrum of the MCHM14 for unbroken EW symmetry contains



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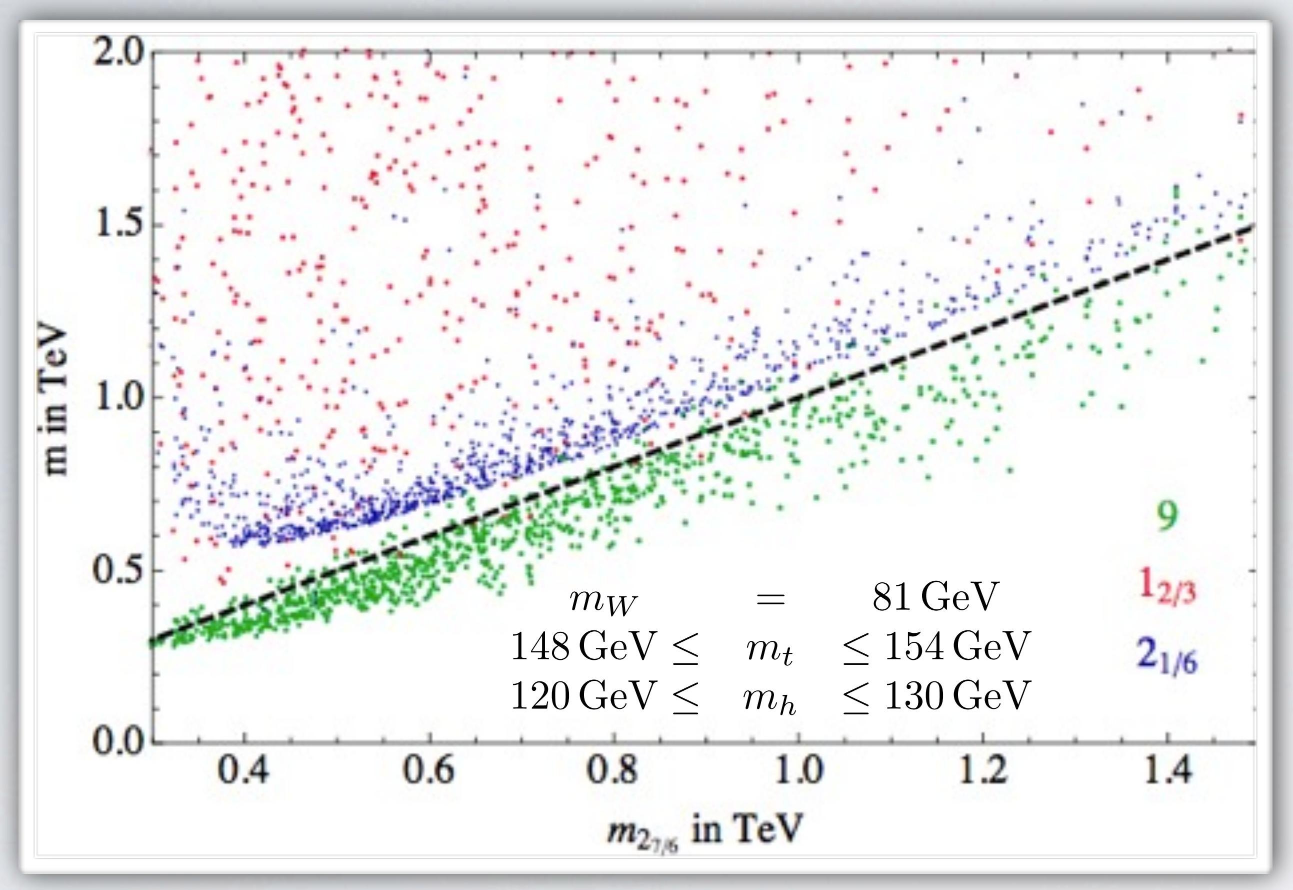


- A definite hierarchy emerges

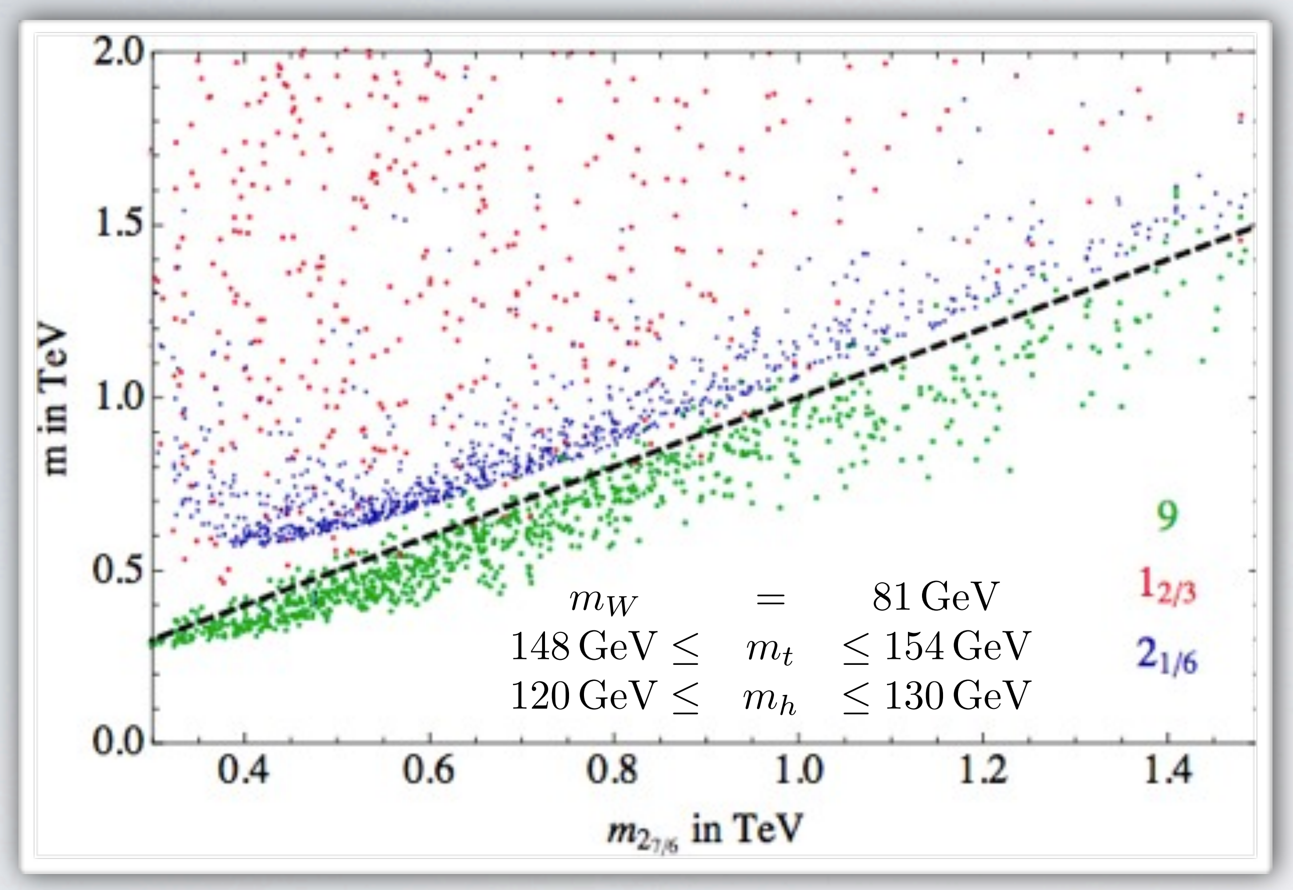
$$m_{\mathbf{9}} < m_{\mathbf{2}_{7/6}} < m_{\mathbf{2}_{1/6}} \ll m_{\mathbf{1}_{2/3}}$$

- For positive M_{Ψ_q} the top mass is exponentially suppressed while for negative M_{Ψ_q}

$$\frac{m_t^2}{m_W^2} = \frac{g_5^2}{g_2^2} \frac{5|M_{\Psi_q} L|}{Z_q + e^{2|M_{\Psi_q} L|} k_9^q}$$

- $m_t = 173 \text{ GeV}$ thus requires $M_{\Psi_q} < 0$

RESULTS: THE SPECTRUM



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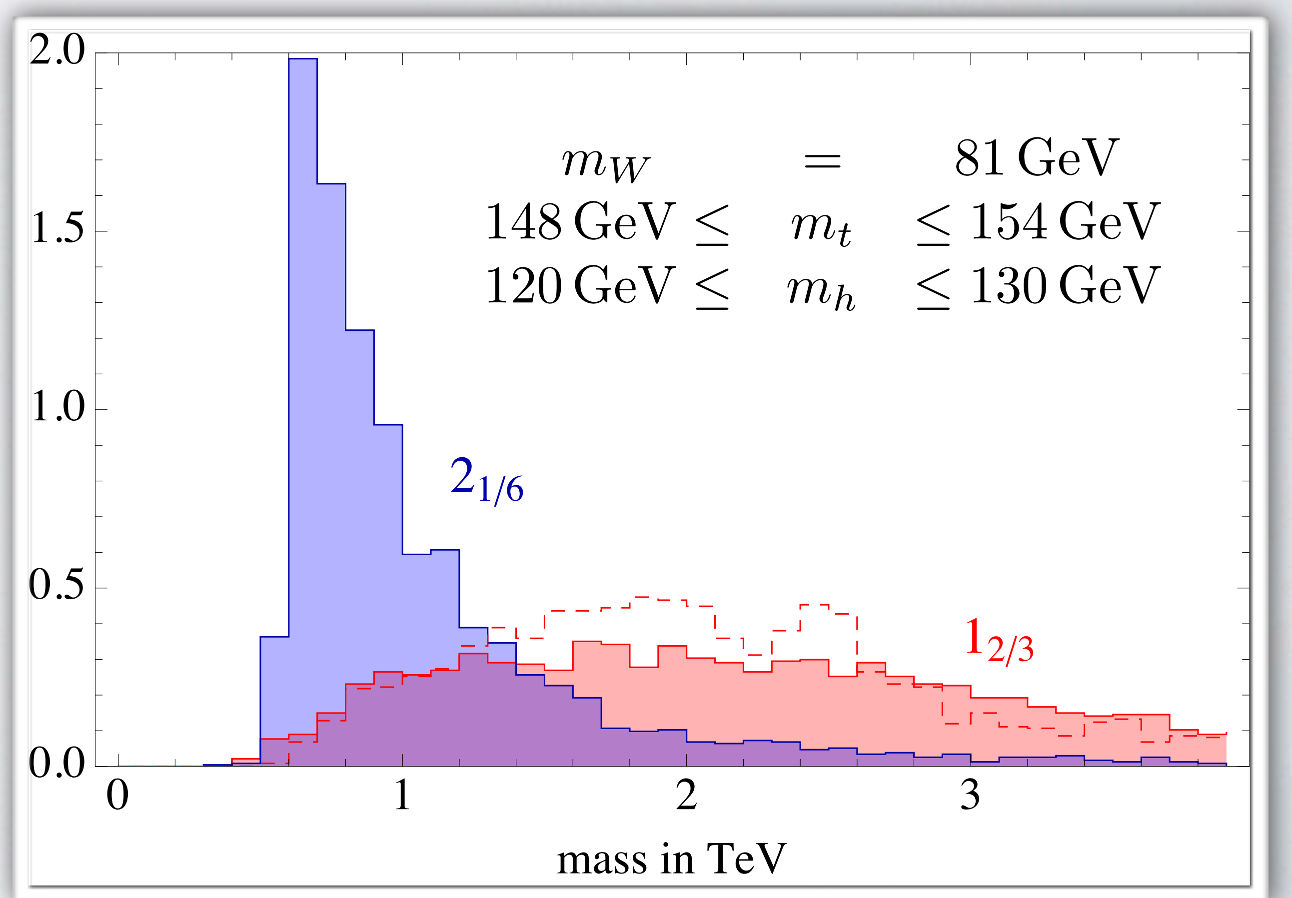


- The masses of the resonances are given by zeros of

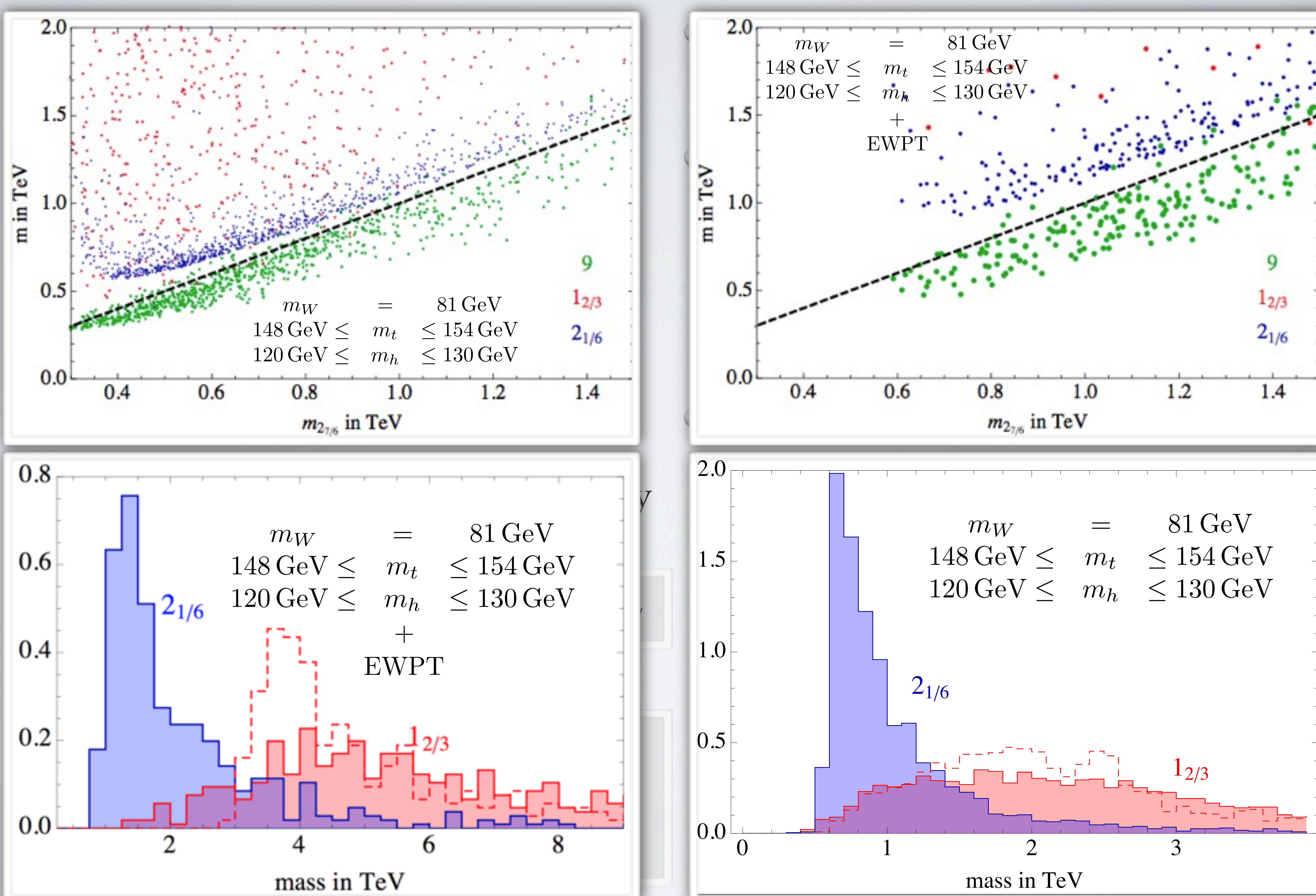
$$M_{\Psi_q} + \omega_q \cot \omega_q L \qquad M_{\Psi_t} + \omega_t \cot \omega_t L$$

- The approximate solution gives

$$p \sim 2|M_{\Psi_i}| e^{-|M_{\Psi_i}|L}, \qquad M_{\Psi_i} L \lesssim 0$$

$$\sqrt{\frac{\pi^2}{4L^2} + M_{\Psi_i}^2} < p < \sqrt{\frac{\pi^2}{L^2} + M_{\Psi_i}^2}, \qquad M_{\Psi_i} L \gtrsim 0$$

RESULTS: THE SPECTRUM



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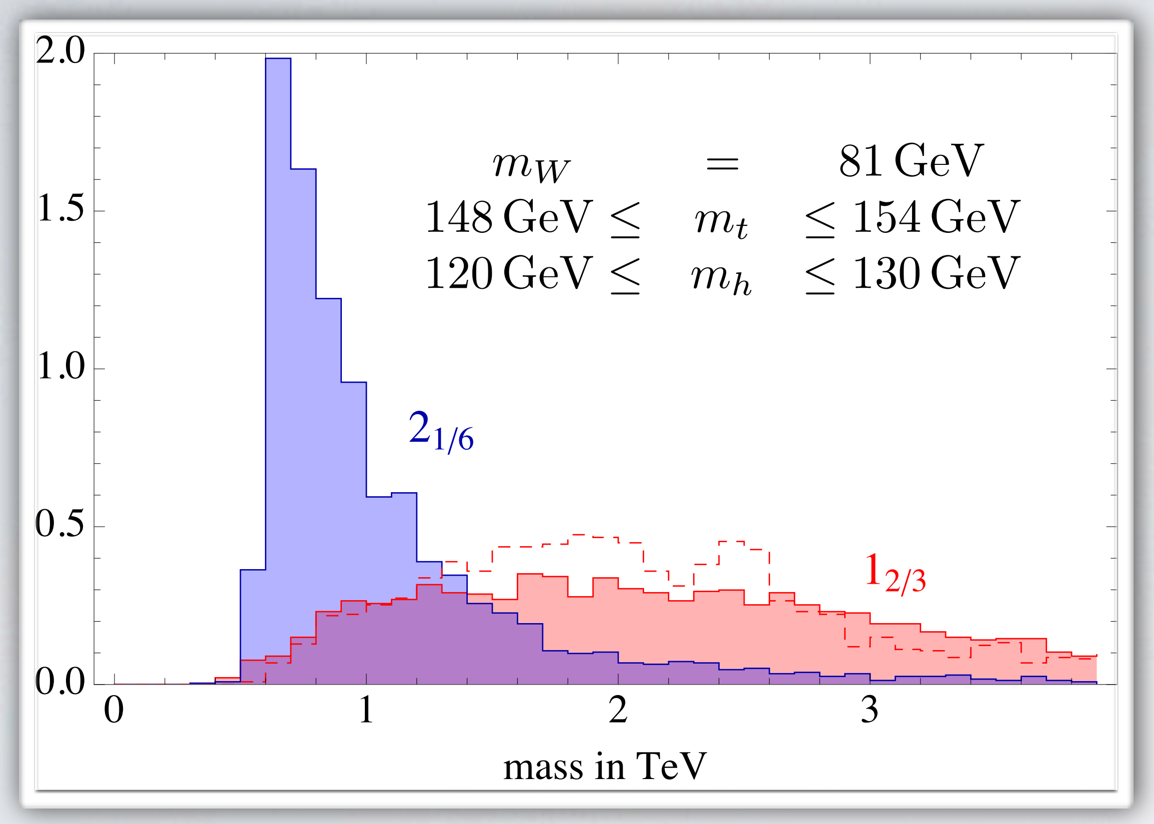
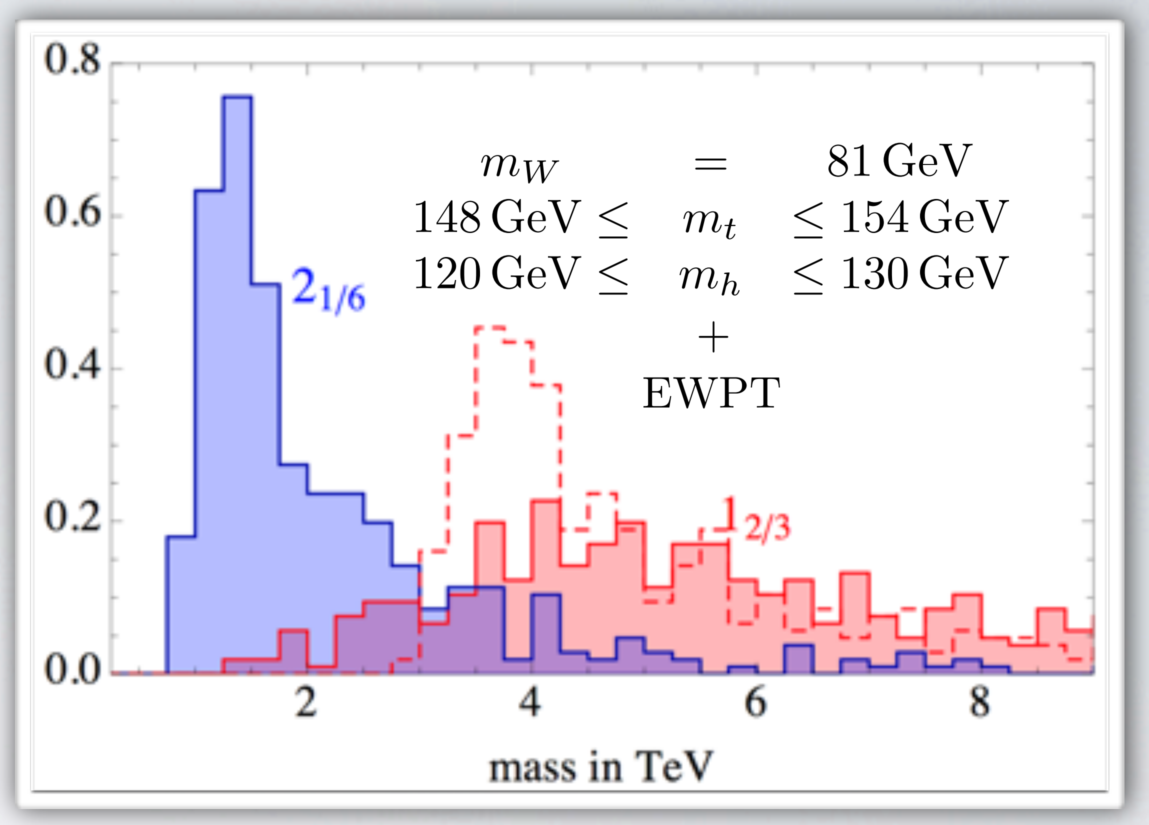




RESULT

Light resonances are expected in 5D composite Higgs models in general

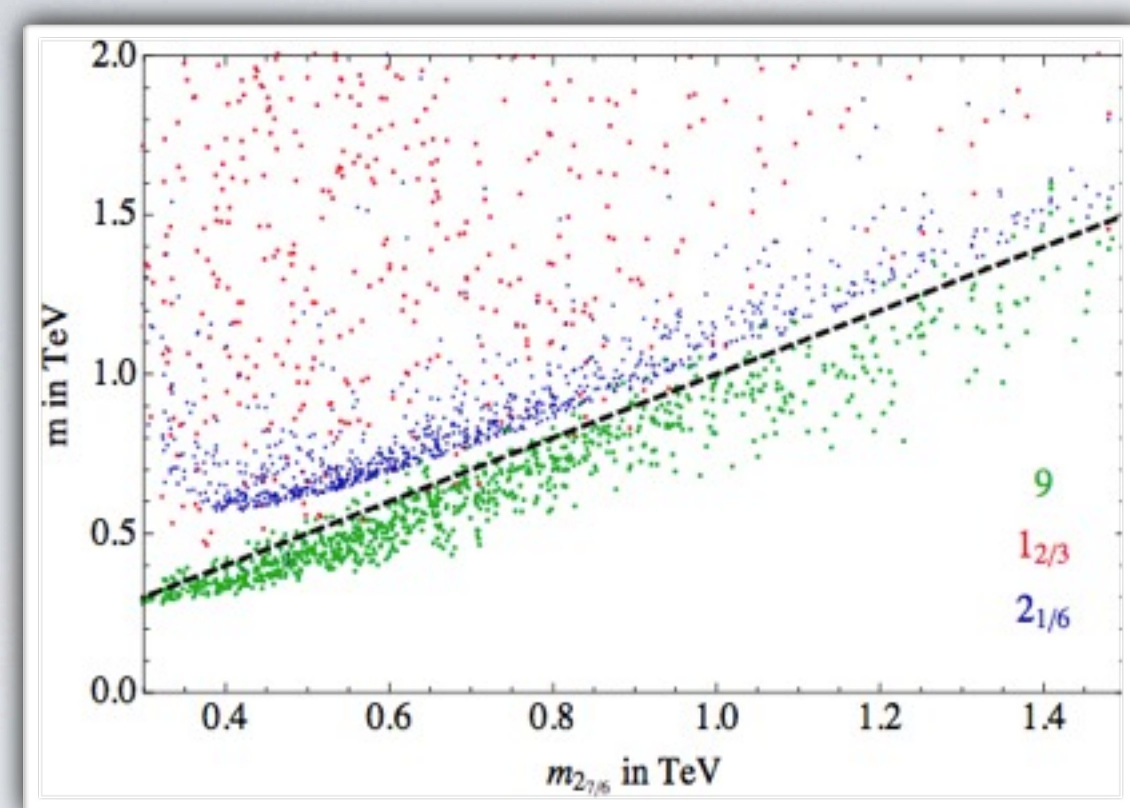
When EWPT are included however the spectrum is pushed toward higher masses

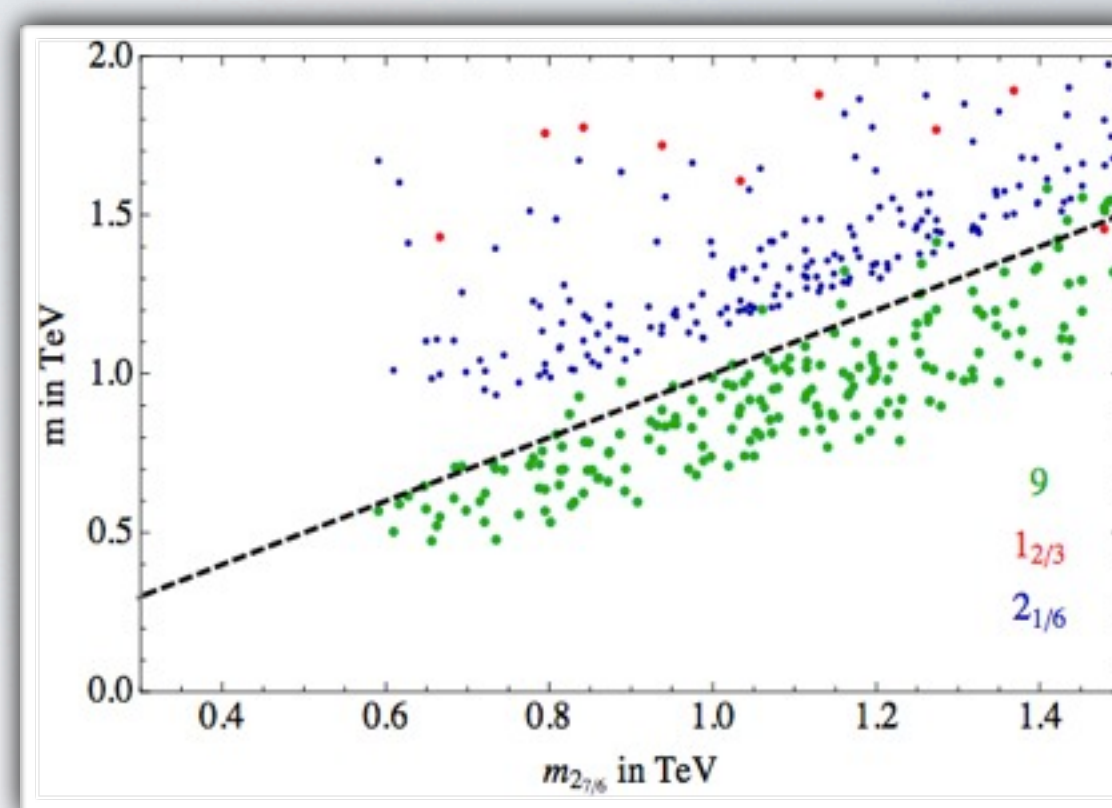
In the case of a fully composite t_R they correspond to the partners of the states contained in the representation which mixes with the q_L (in our case $\mathbf{14}_{2/3}$)

A definite (model depend.) hierarchy between the different representations arises

The presence of light resonances makes the model more testable at the LHC

RESULTS: THE SPECTRUM





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OUTLINE

- The SM Higgs, theorist's and experimentalist's view
- The Higgs as a pseudo-Goldstone boson
  - SB by vacuum misalignment and Partial compositeness
  - The Minimal Composite Higgs Model (MCHM)
- Example of an explicit model (MCHM14)
  - Tuning
  - Spectrum of resonances
- Phenomenology
  - Higgs couplings
  - Top partners
- Conclusion

PARAMETRIZING HIGGS PHYSICS

- The most promising way of studying Higgs physics is to write the most general effective Lagrangian for a scalar singlet h and try to predict (theorists) and measure (experimentalists) its couplings

Giudice, Grojean, Pomarol, Rattazzi hep-ph/0703164
Azatov, Contino, Galloway 1202.3415 [hep-ph] ...

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\not{h}-\text{SM}} + \mathcal{L}_{h-\text{kin}} + \mathcal{L}_{h-\text{pot}} + \mathcal{L}_{h-\text{int}} + \mathcal{L}_{h-\text{loop}}$$

$$\mathcal{L}_{h-\text{pot}} = -\frac{m_h^2}{2}h^2 - \frac{d_3}{6}\left(\frac{3m_h^2}{v}\right)h^3 - \frac{d_4}{24}\left(\frac{3m_h^2}{v^2}\right)h^4 + \dots$$

$$\mathcal{L}_{h-\text{int}} = c_V\frac{2m_W^2}{v}hW_\mu^+W^{\mu\,-} + c_V\frac{m_Z^2}{v}hZ_\mu Z^\mu - c_f\frac{m_f}{v}h\bar{f}f - c_{\text{inv}}h\bar{\chi}\chi$$

$$\mathcal{L}_{h-\text{loop}} = c_g\frac{\alpha_S}{12\pi v}hG_{\mu\nu}^aG^{\mu\nu\,a} + c_\gamma\frac{\alpha}{\pi v}hF_{\mu\nu}F^{\mu\nu}$$

- $c_V = c_f = d_3 = d_4 = 1$, $c_{\text{inv}} = 0$, $c_g \approx 1.03$, $c_\gamma \approx 0.23$ is the SM prediction and h can be embedded with the three EW GBs in a complex doublet transforming linearly under $SU(2)_L \times U(1)_Y$
- Present Higgs measurements already require small deviations (if any) in these couplings with respect to the SM

$$c_V = \sqrt{1-\xi} \qquad c_f^{(\mathbf{4})} = \sqrt{1-\xi} \qquad c_f^{(\mathbf{5})} = \frac{1-2\xi}{\sqrt{1-\xi}} \qquad c_f^{(\mathbf{14})} = f(\xi)f(M_\psi) \qquad \dots$$

HIGGS COUPLINGS (14+14)

- For the smallest representations (**4**, **5**, **10**) the Higgs couplings to fermions get rescaled by universal functions of ξ and there is no sensitivity on the spectrum of resonances

$$c_V = \sqrt{1-\xi} \qquad c_f^{(\mathbf{4})} = \sqrt{1-\xi} \qquad c_f^{(\mathbf{5})} = \frac{1-2\xi}{\sqrt{1-\xi}} \qquad c_f^{(\mathbf{14})} = f(\xi)f(M_\psi) \qquad \ldots$$

$$\frac{c_g}{c_g^{\rm SM}} = c_f \qquad \frac{c_\gamma}{c_\gamma^{\rm SM}} = 1.27c_V - 0.27c_f$$

- In the slightly more complicated case of the **14** (1+4+9 of SO(4)) dimensional irrep of SO(5) the rescaling also depends on the spectrum of resonances and we can get a continuum of values for c_g and c_γ

$$\frac{c_g}{c_g^{\rm SM}} = 1 + \frac{3M_1M_4 - 11M_1M_9 + 8M_4M_9}{2M_9(M_1-M_4)}\xi \qquad \frac{c_\gamma}{c_\gamma^{\rm SM}} = 1.27c_V - 0.27\frac{c_g}{c_g^{\rm SM}}$$

- A clear relation between the top Yukawa coupling and the hgg coupling emerges as a function of the spectrum of resonances

$$c_t \approx \frac{c_g}{c_g^{\rm SM}} + \left[\frac{5\lambda_q^2}{4}\left(\frac{2}{M_4^2} - \frac{1}{M_1^2} - \frac{1}{M_9^2}\right) + \frac{5\lambda_u^2}{2}\left(\frac{1}{M_1^2} - \frac{1}{M_4^2}\right)\right]\xi$$

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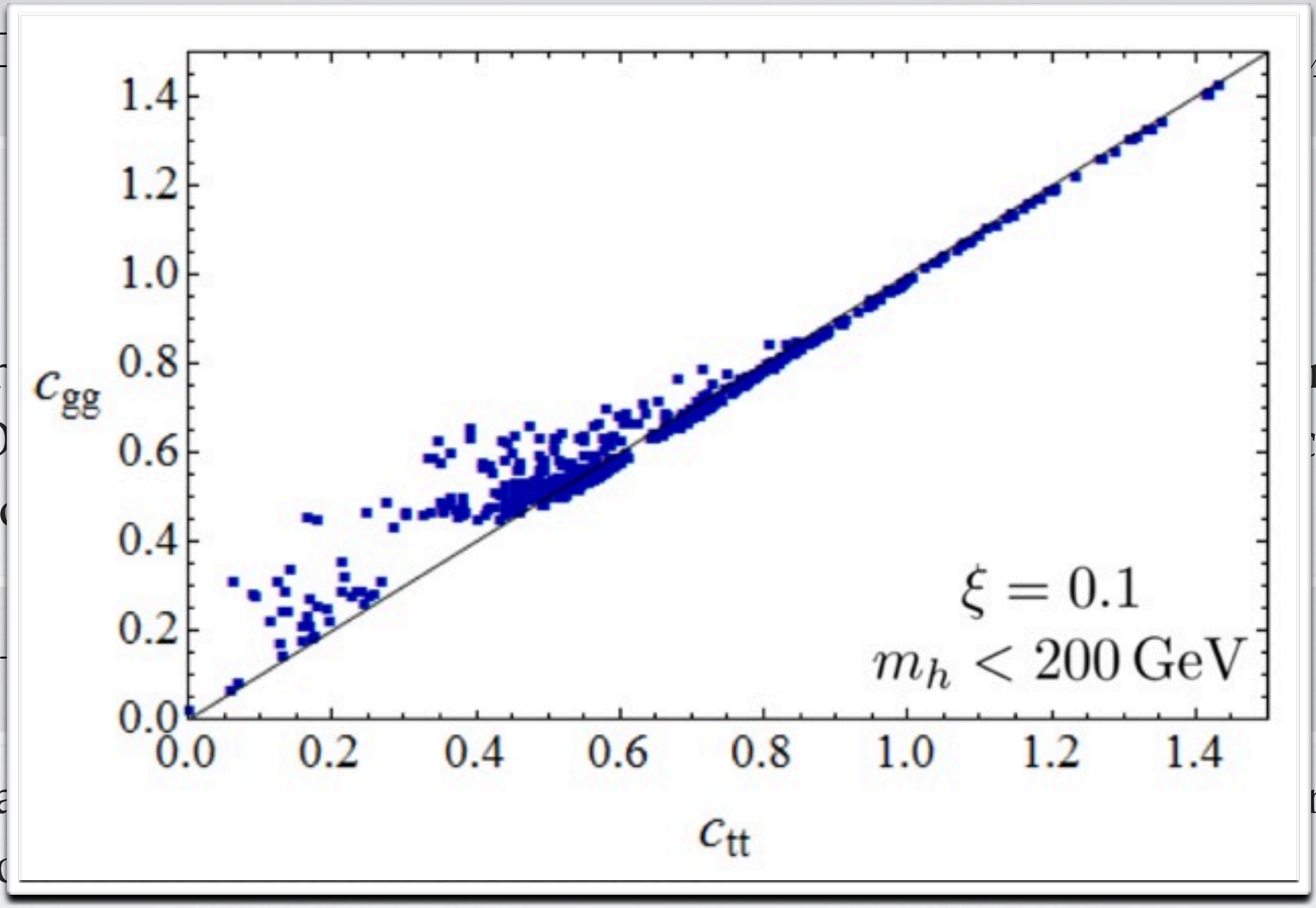
$$c_V = \sqrt{1 - \quad \cdots M_\psi) \quad \ldots$$

- In the sligh… …nsional irrep of SO… …es and we can get a c…

$$\frac{c_g}{c_g^{\rm SM}} = 1 \cdots \quad 0.27\frac{c_g}{c_g^{\rm SM}}$$

- A clear rela… …ng emerges as a functi…



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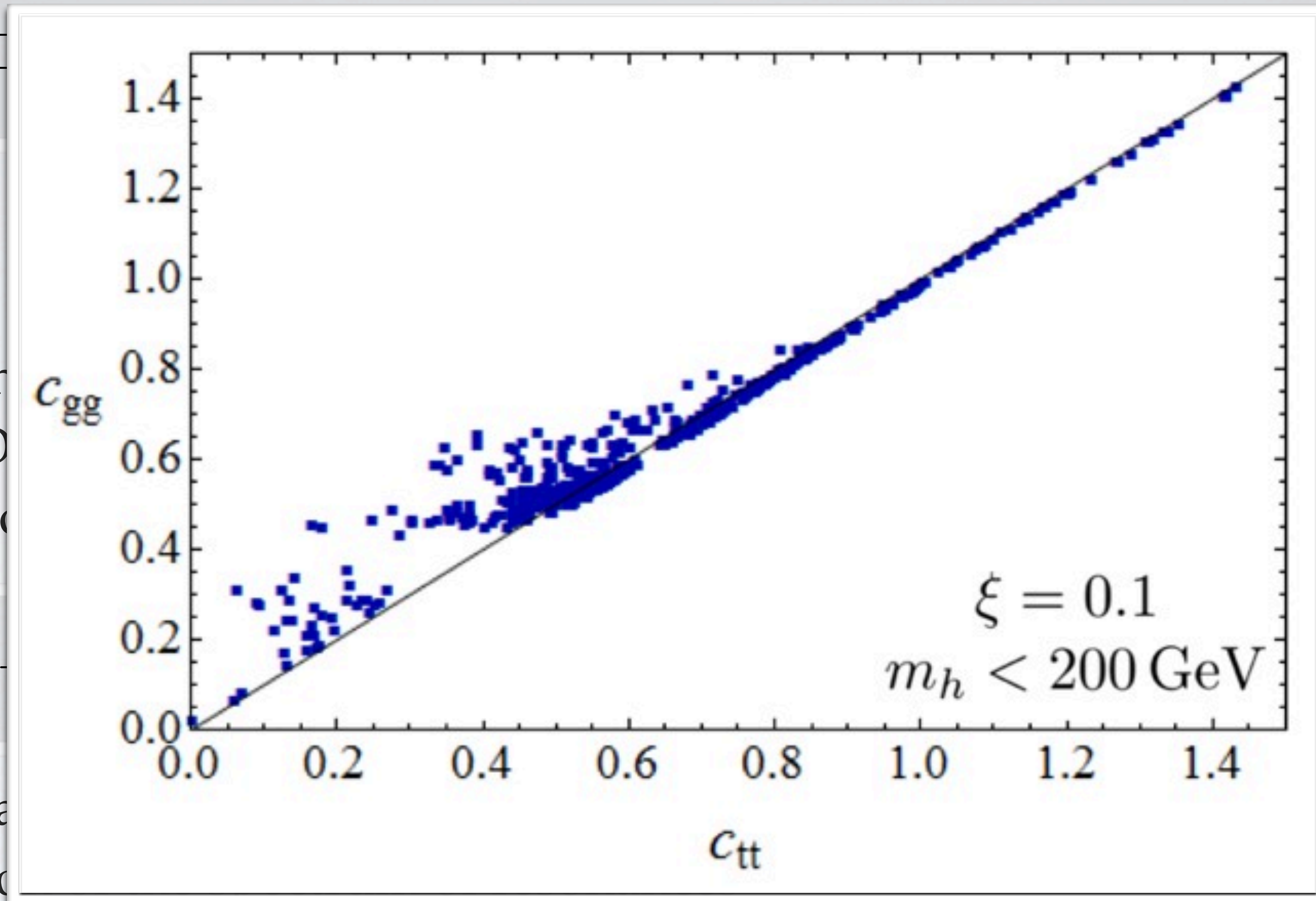
HIGGS COUPLINGS (14+14)

Extremely important to measure independently the Higgs coupling to gluons and to tops (e.g. single production vs tth production)!

$c_V = \sqrt{1 -$ ... $M_\psi) \quad \ldots$



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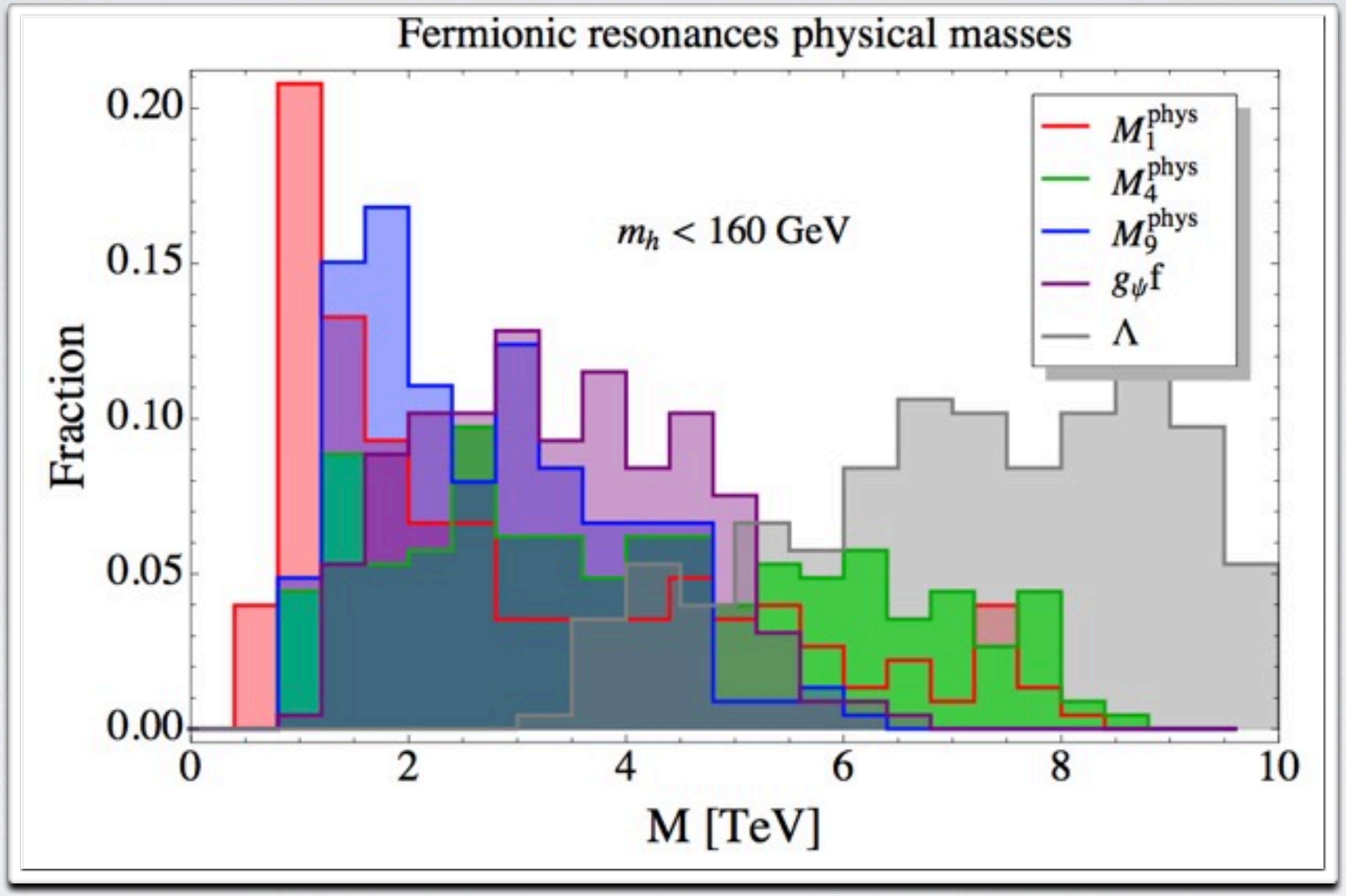
HIGGS COUPLINGS (14+14)

- In a simple model with 2-sites one can compute the typical spectrum given the small value of the Higgs mass

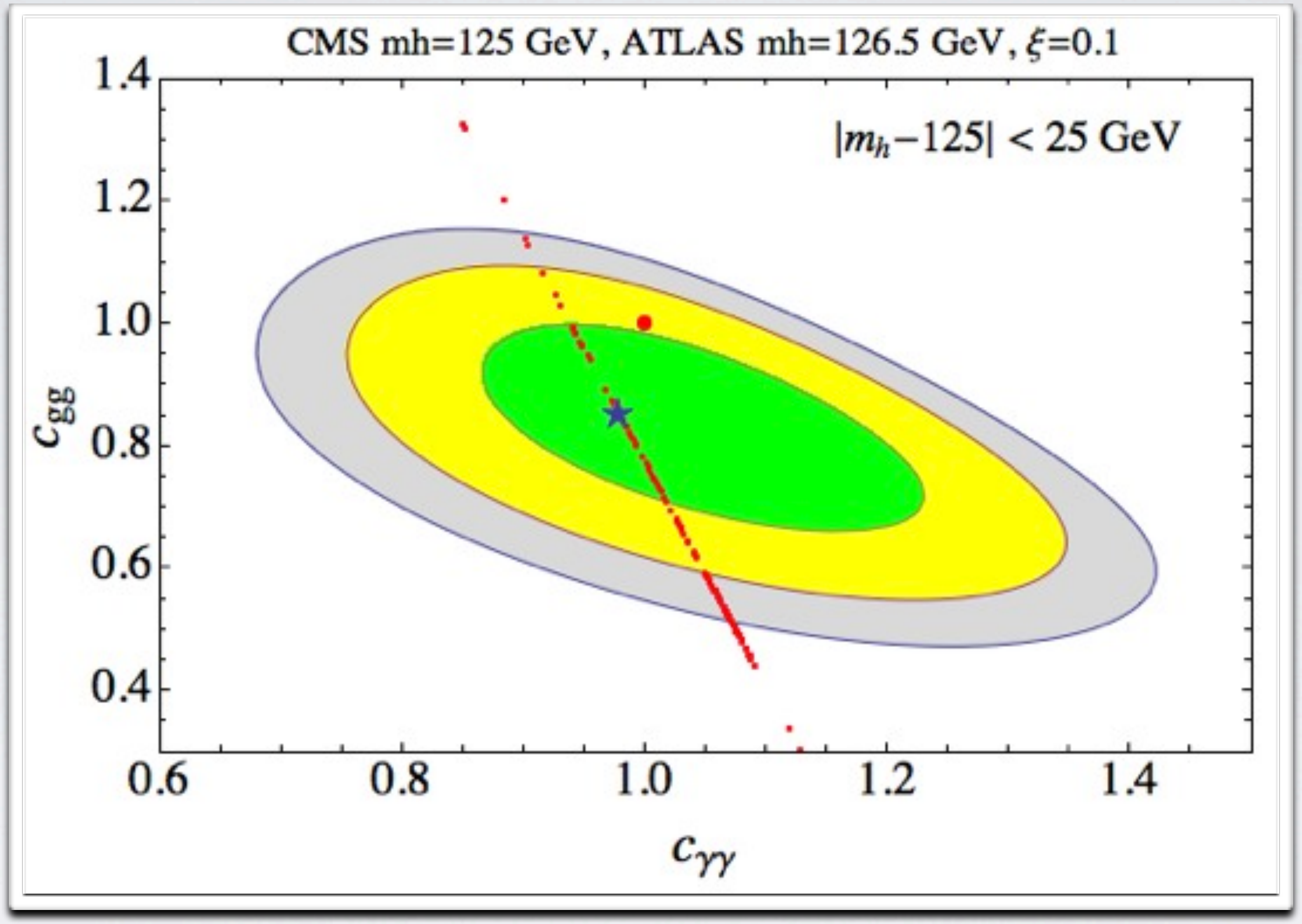


- The main conclusion coming from the lightness of the Higgs is the hierarchy arising between the three SO(4) irreps **1**, **4** and **9**

$$M_1 < M_9 < M_4$$

HIGGS COUPLINGS (14+14)

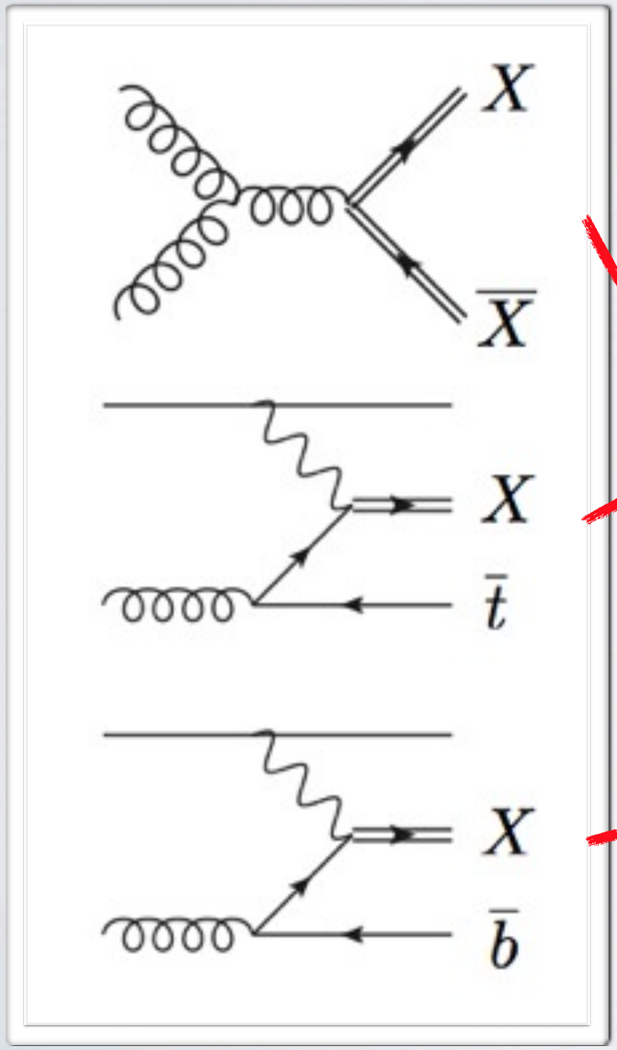
- We can use the available Higgs data to make a fit of the region in the $(c_{\gamma\gamma}, c_{gg})$ plane favored by data

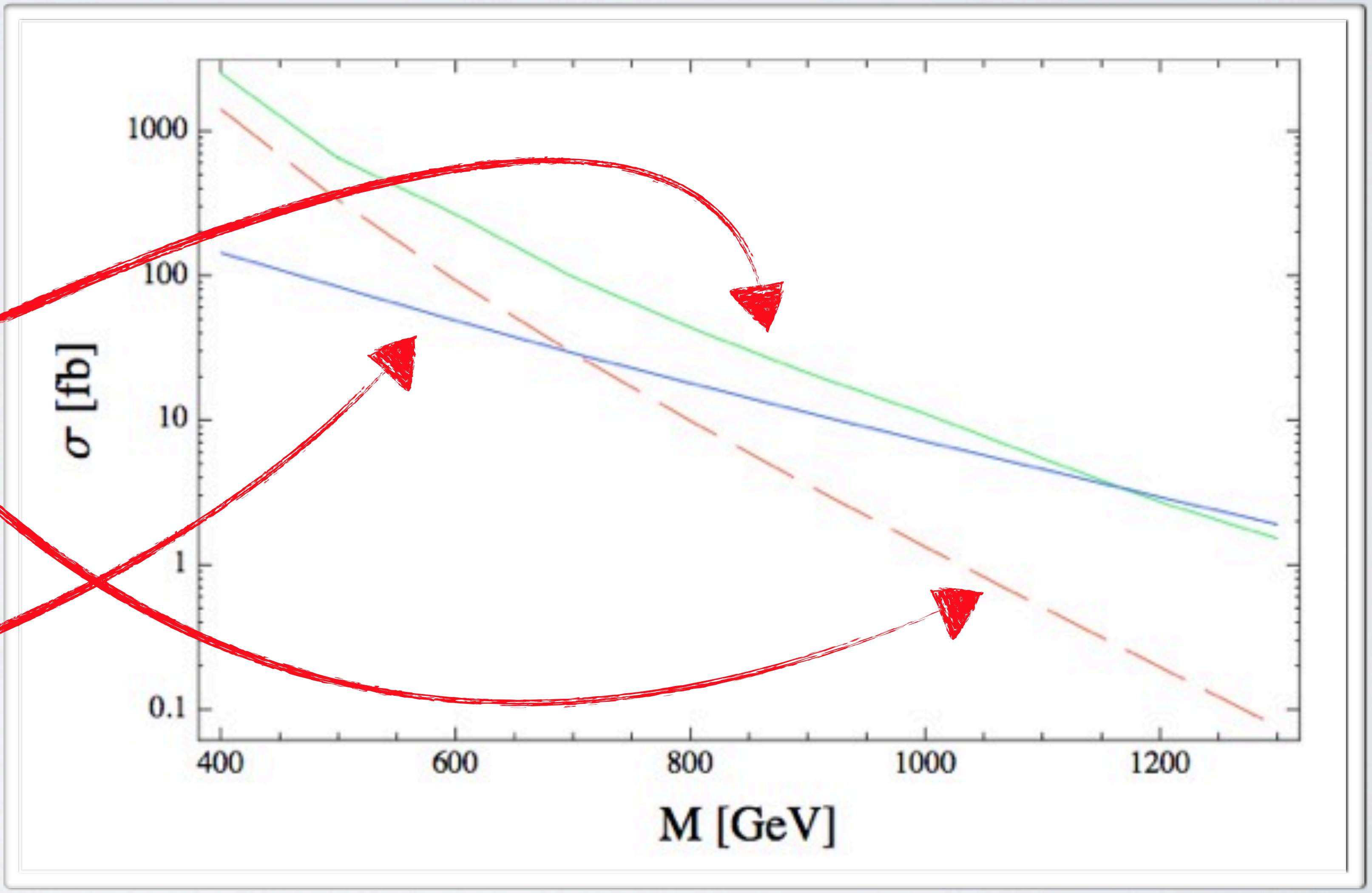


- Main feature of the 14+14 model is the continuum of values with respect to a single point in the case of the 5+5
- Conclusions are of course model dependent, but still plenty of space for deviations
- Difficult at the LHC, probably needs a Linear Collider

TOP PARTNERS

- New fermionic resonances are expected around the TeV scale
- In the minimal case we have an heavy top-like state and an heavy charge 5/3 colored state
- In non-minimal cases (e.g. MCHM14) there are many new states: top and bottom-like states and charge -4/3, 5/3 and 8/3 states



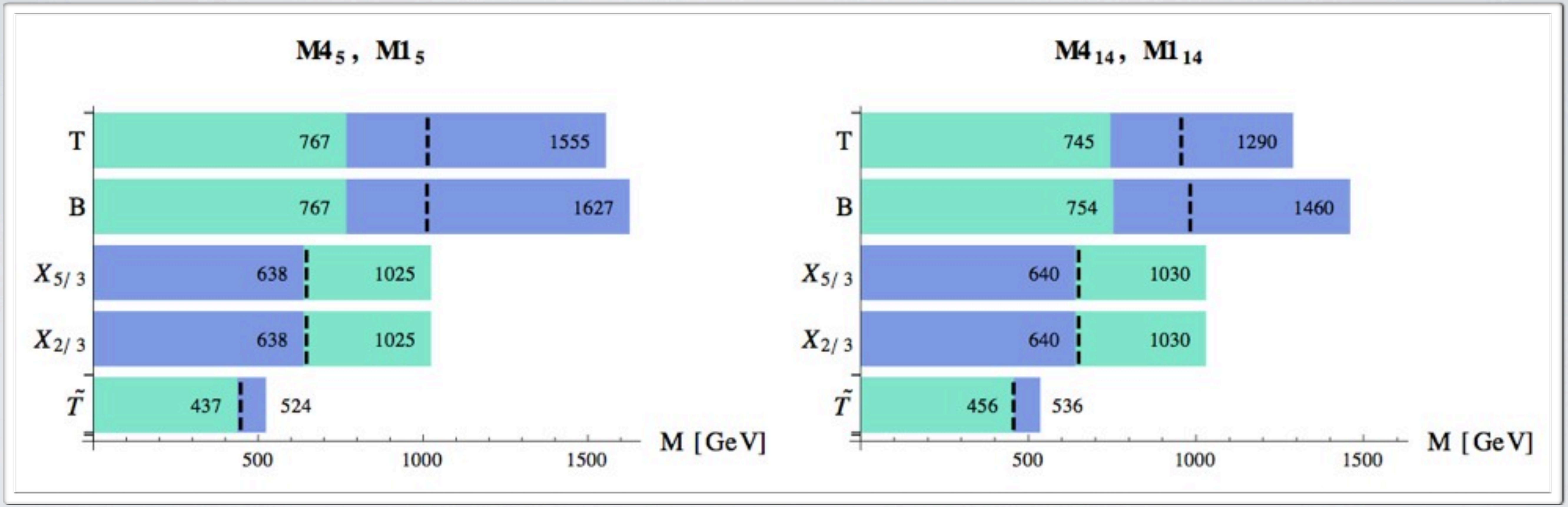


De Simone, Matsedonskyi, Rattazzi, Wulzer 1211.5663 [hep-ph]

TOP PARTNERS

- Searches for heavy quarks and also some SUSY searches with same-sign di-leptons or tri-leptons are already testing the interesting mass region

De Simone, Matsedonskyi, Rattazzi, Wulzer 1211.5663 [hep-ph]



- If nothing is found with a few hundreds of inverse fb at the 14 TeV LHC we expect the level of tuning to decrease much below the 1% level, excluding the model from a naturalness point of view

THE EXOTIC CHARGES

- In the case of the MCHM14 a charge 8/3 exotic quark is expected and is also predicted to be the lightest fermionic resonance in the model
- In can give rise to spectacular decays into 3 Ws and a b quark therefore giving signatures in the same-sign di-lepton and tri-lepton final states with $\mathrm{BR} \sim O(0.1)$
- The pair production of these objects, since colored, is fixed by QCD interactions

Del Nobile, Franceschini, Pappadopulo, Strumia 0908.1567

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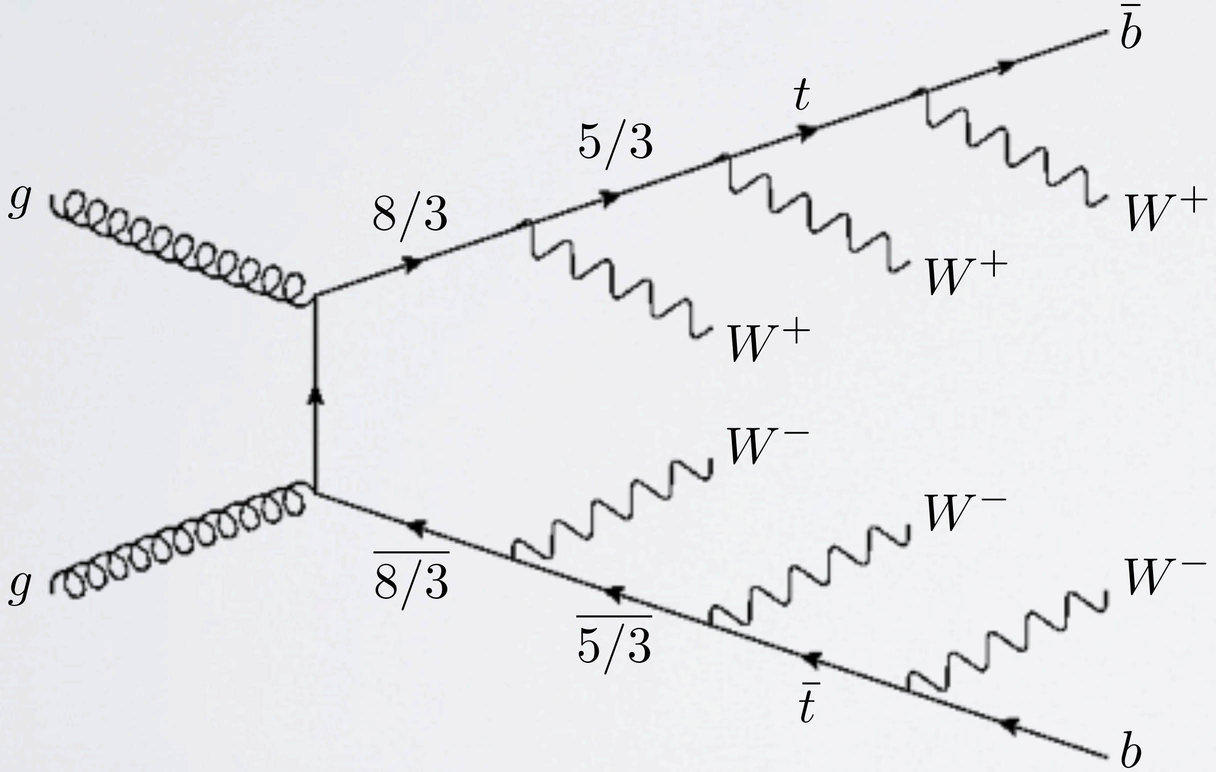

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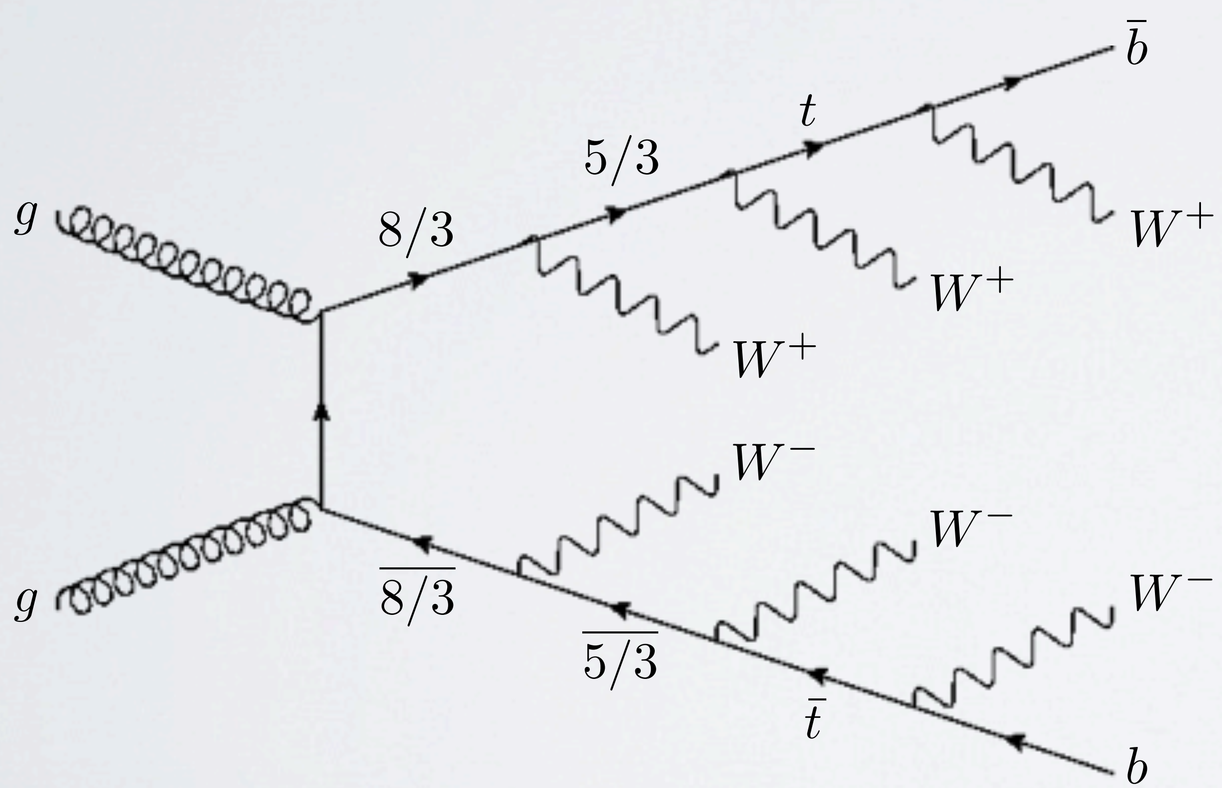

- LHC searches in the final states with leptons already set bounds on these exotic states with masses around $m_{\text{bound}} \gtrsim 700$ GeV

ATLAS-CONF-2012-130
CMS-PAS-SUS-12-027

- Direct searches will be able to test the model in the near future leading either to a confirmation or an exclusion

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CONCLUSION

- Composite Higgs models provide a motivated and well established alternative to weakly coupled BSM theories like SUSY deserving particular attention from the experimental community (what about “Compositeness” in between “Supersymmetry” and “Exotica”)
- These theories still provide a natural solution to the HP: $1/\Delta \sim O(10\%)$
- There are two main predictions: modifications of the Higgs couplings and the existence of fermionic resonances around 1 TeV
- Measuring Higgs couplings at the percent level at LHC is challenging (need a Linear Collider!) and the search for the top partners is therefore the primary task
- Despite some model dependence, the lightness of the Higgs mass implies the presence of the lightest fermionic resonances at or below 1 TeV
- Excluding these new colored fermionic resonances up to a few TeV would rule out the Composite Higgs idea pushing it in a region of unacceptable fine tuning

THANK YOU