UNEXPECTED PHYSICS AT THE LHC

Warsaw, 18 May 2009

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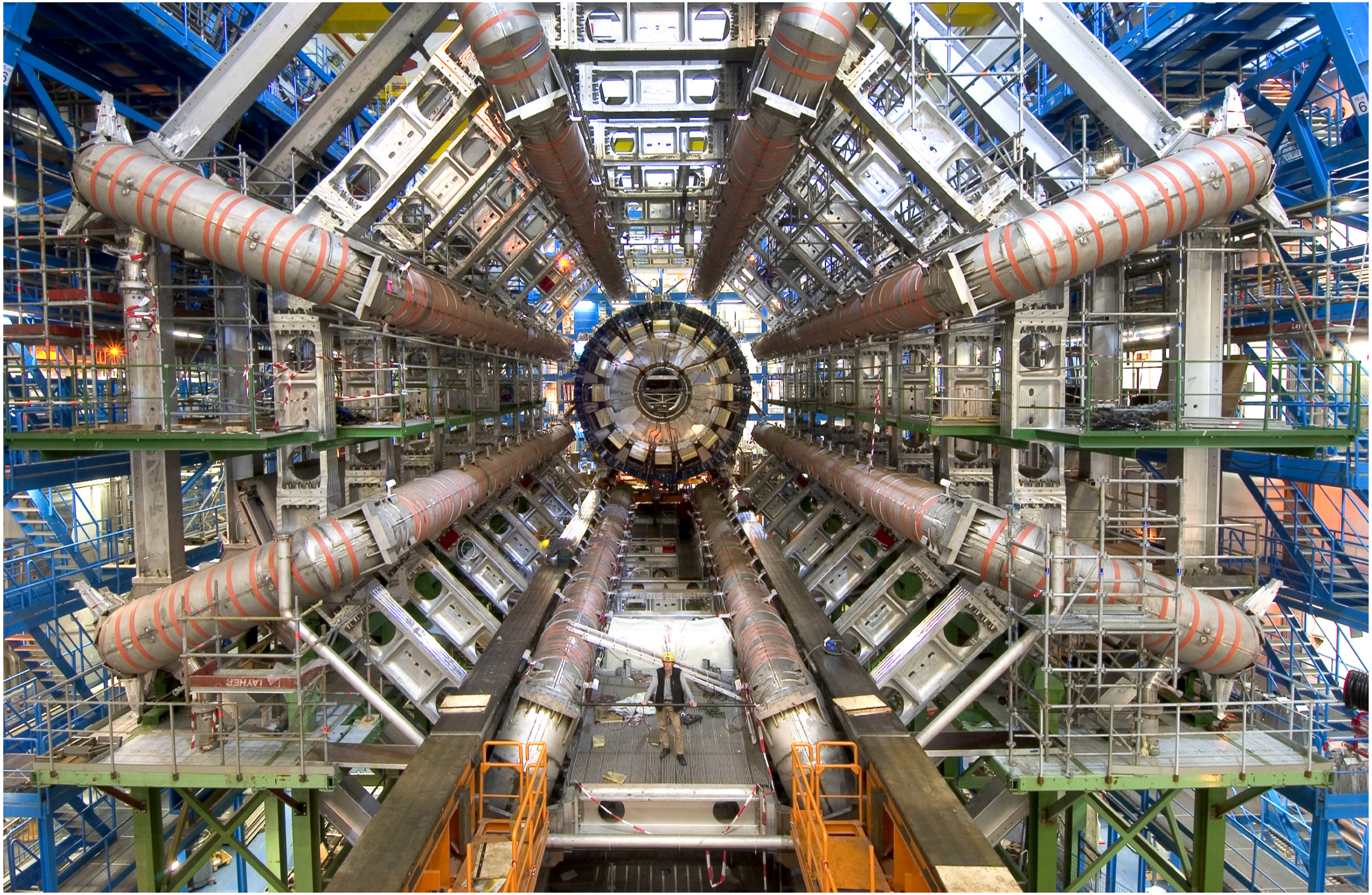
ICREA @ IFAE, Barcelona
& CERN

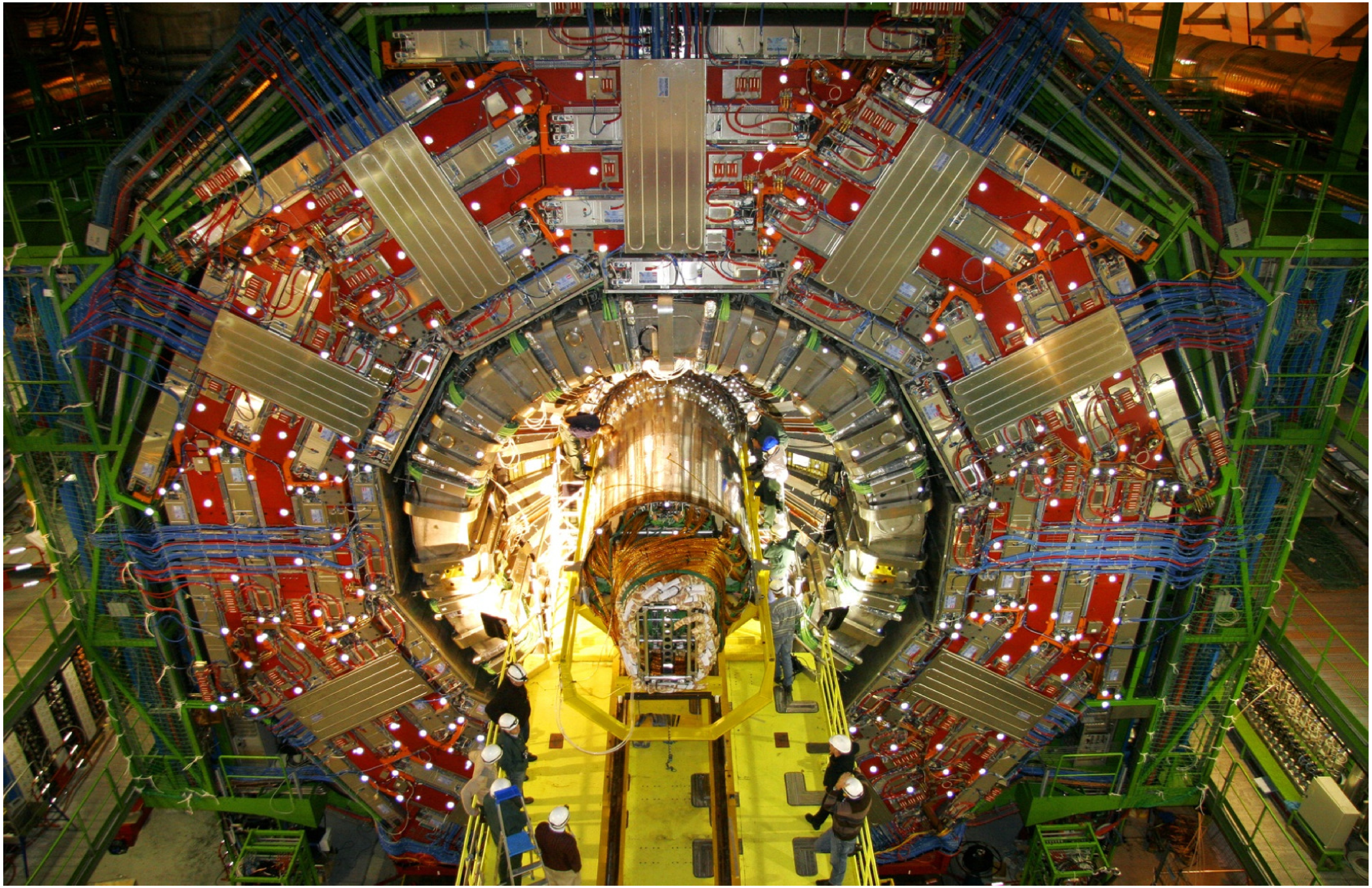
- ★ Most expected : SUSY
- ★ Quite unexpected : Unparticles

MUST BE READY FOR THE UNEXPECTED

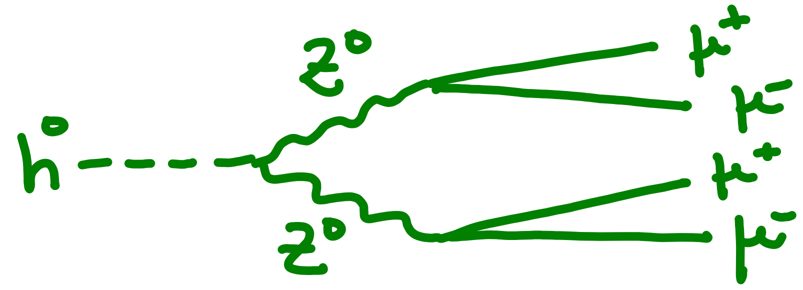
We'll see here stops flying around

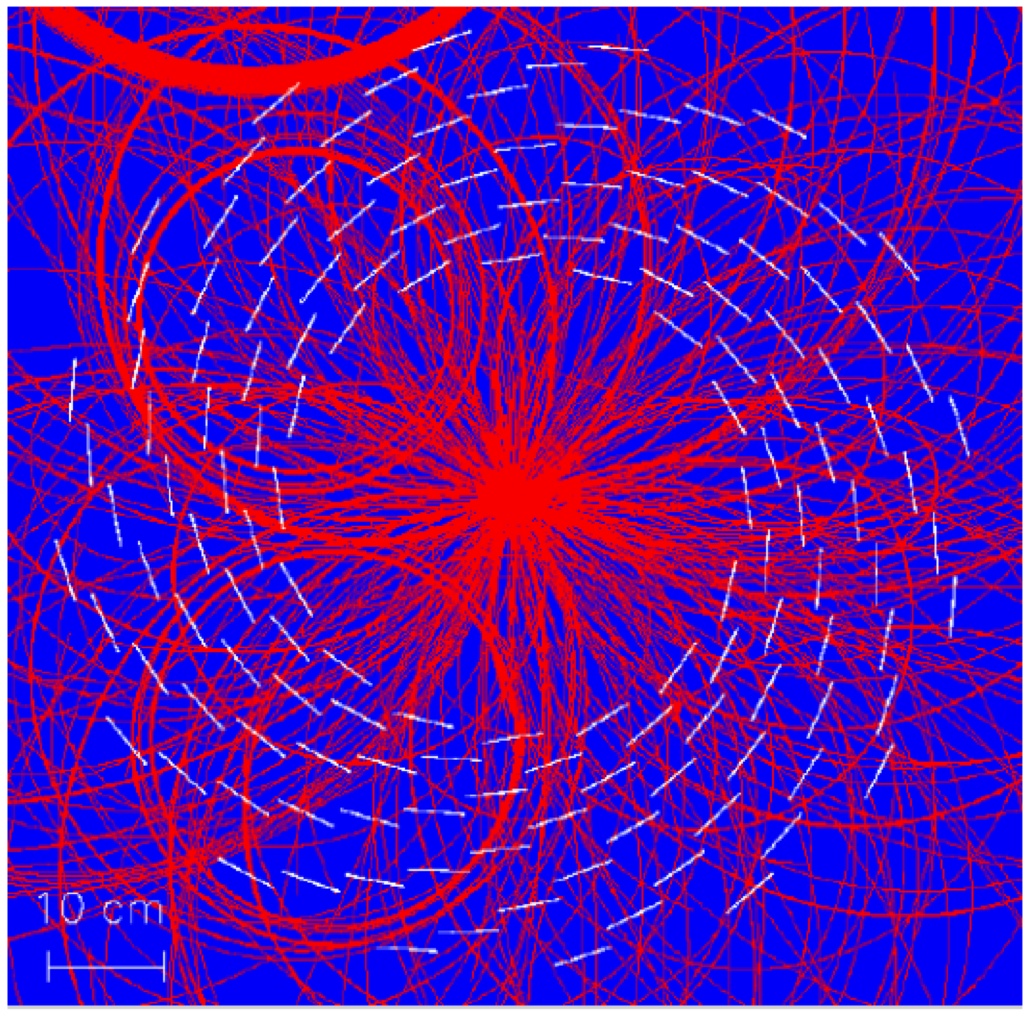


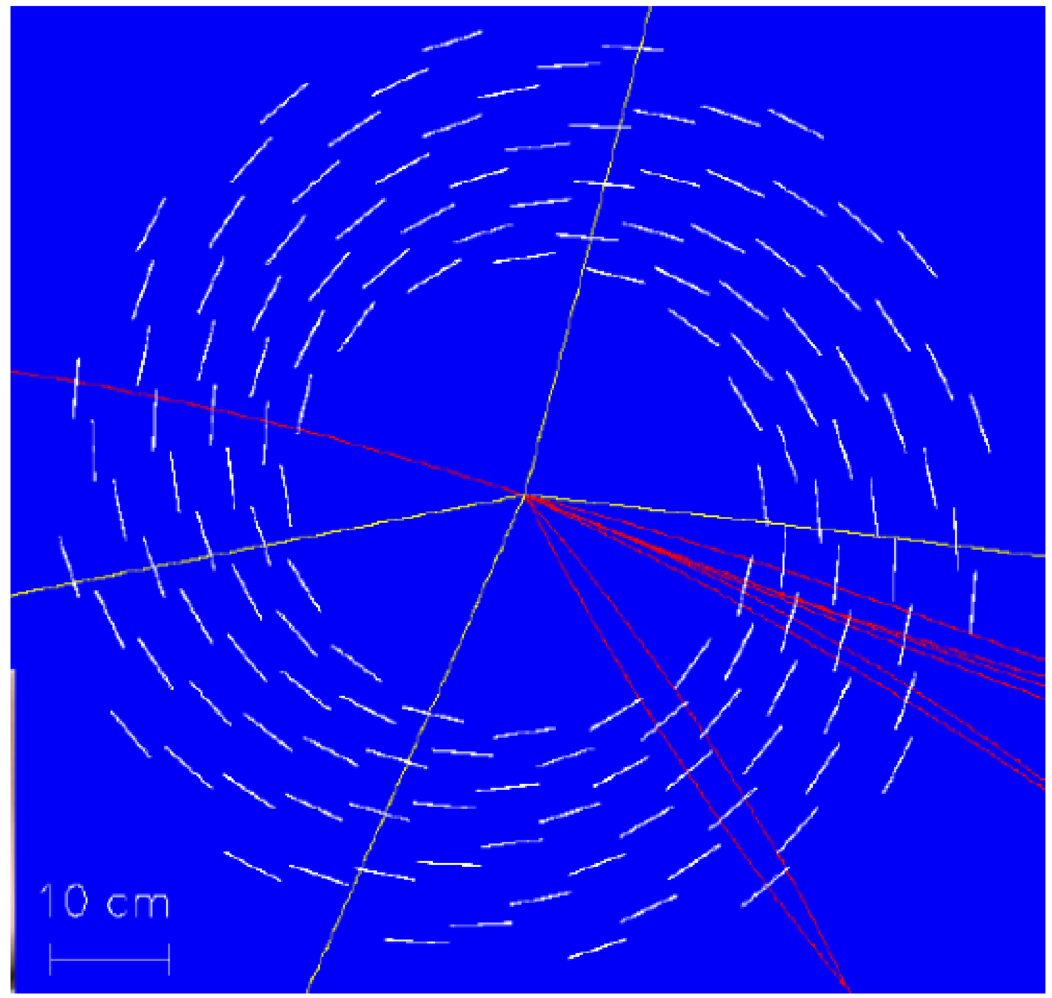
We'll see here gluinos flying around



FINDING A NEEDLE IN A MILLION HAYSTACKS

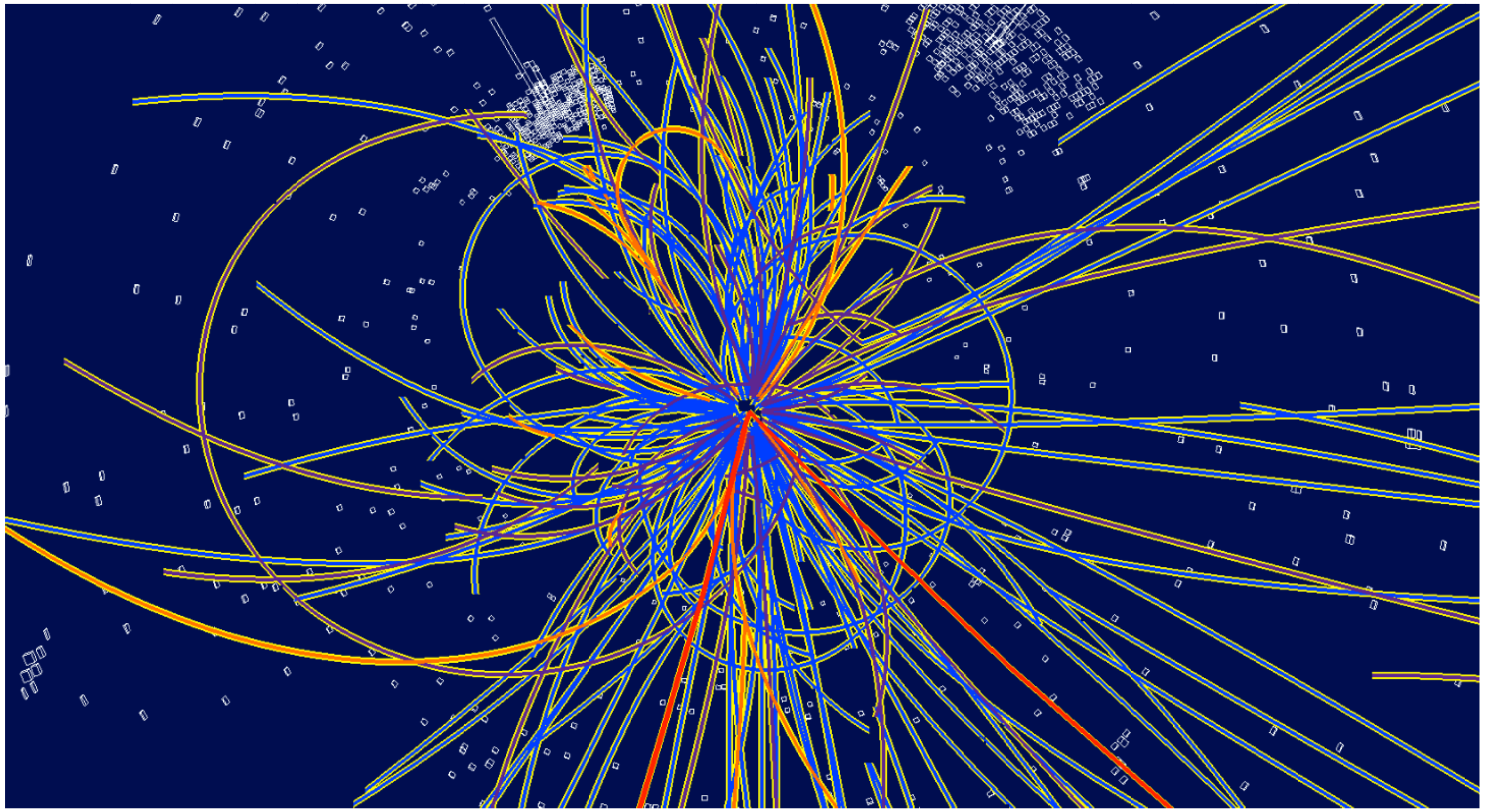






Find 4 energetic muons (straight tracks) Central tracker can do it!

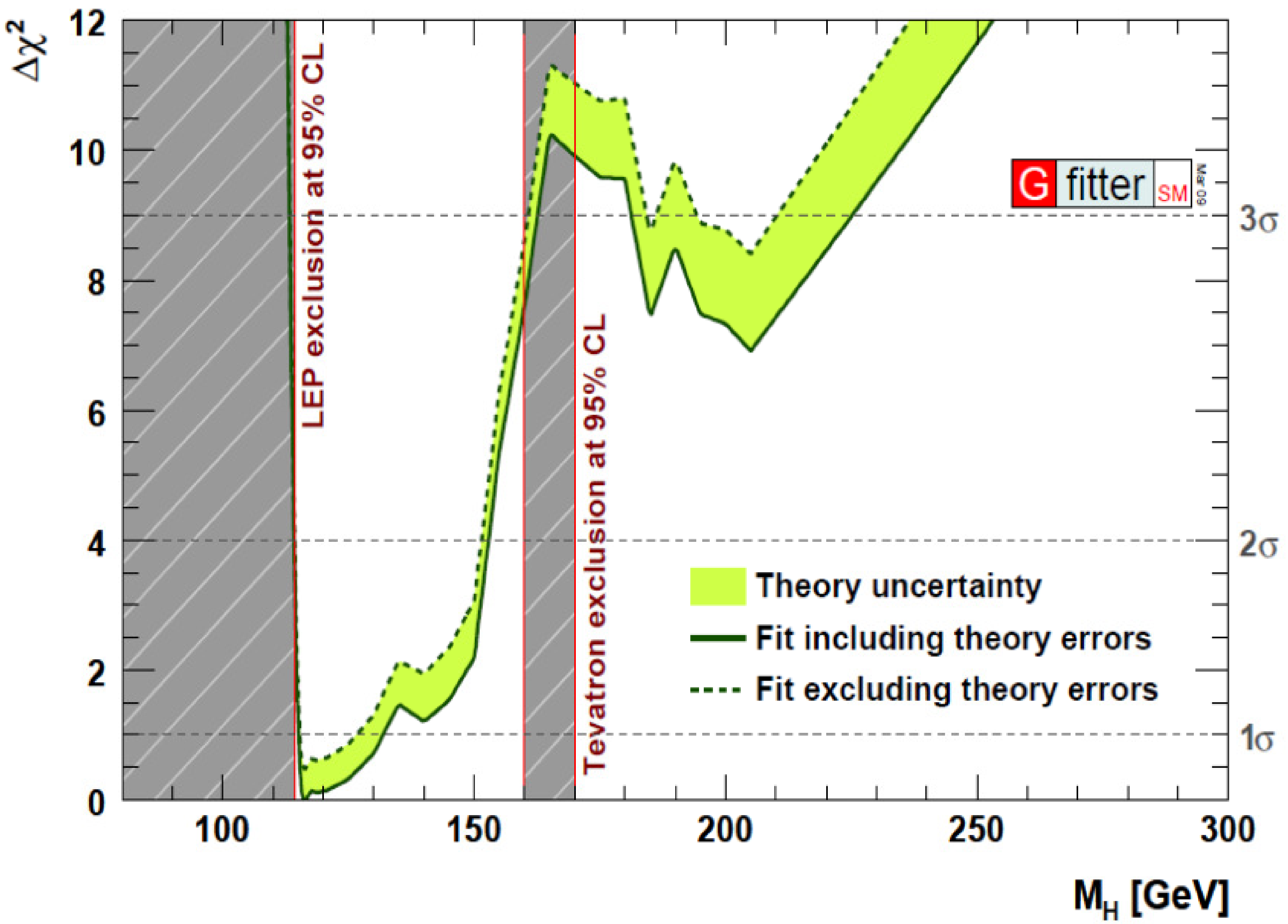
FINDING A NEEDLE IN A MILLION HAYSTACKS



Maybe it's not a needle ...

SM HIGGS IS PROBABLY LIGHT

$m_h < 153$ GeV
at 95% CL



HIERARCHY PROBLEM

It is not natural to have $M_{EW} \ll M_{Pl}$

fixed by $\delta V = \frac{1}{2} m^2 h^2$

and m^2 is very much UV sensitive. Quantum corrections give

$$\delta m^2 \sim \Lambda^2$$

m^2 natural requires new physics beyond the SM at

$\boxed{\Lambda \sim \text{TeV}}$ $\Rightarrow$ LHC !

Many alternatives for such physics have been proposed

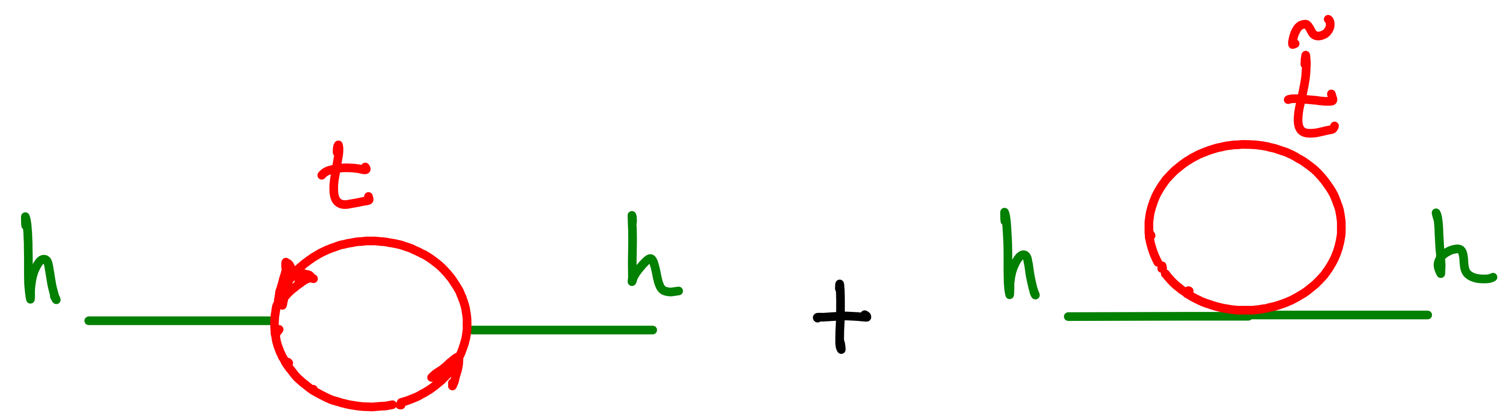
SUPERSYMMETRY

Postulates a very powerful boson $\leftrightarrow$ fermion symmetry with very profound implications.

Predicts a doubling of the particle spectrum.

New particles cancel out the $\delta m^2 \sim \Lambda^2$ behaviour.

But requires "soft" breaking of SUSY symmetry with mass splittings $m_{soft} \lesssim \text{TeV}$ to maintain naturalness.



$$\delta m^2 \sim m_{soft}^2 \log \frac{\Lambda^2}{m_{soft}^2}$$

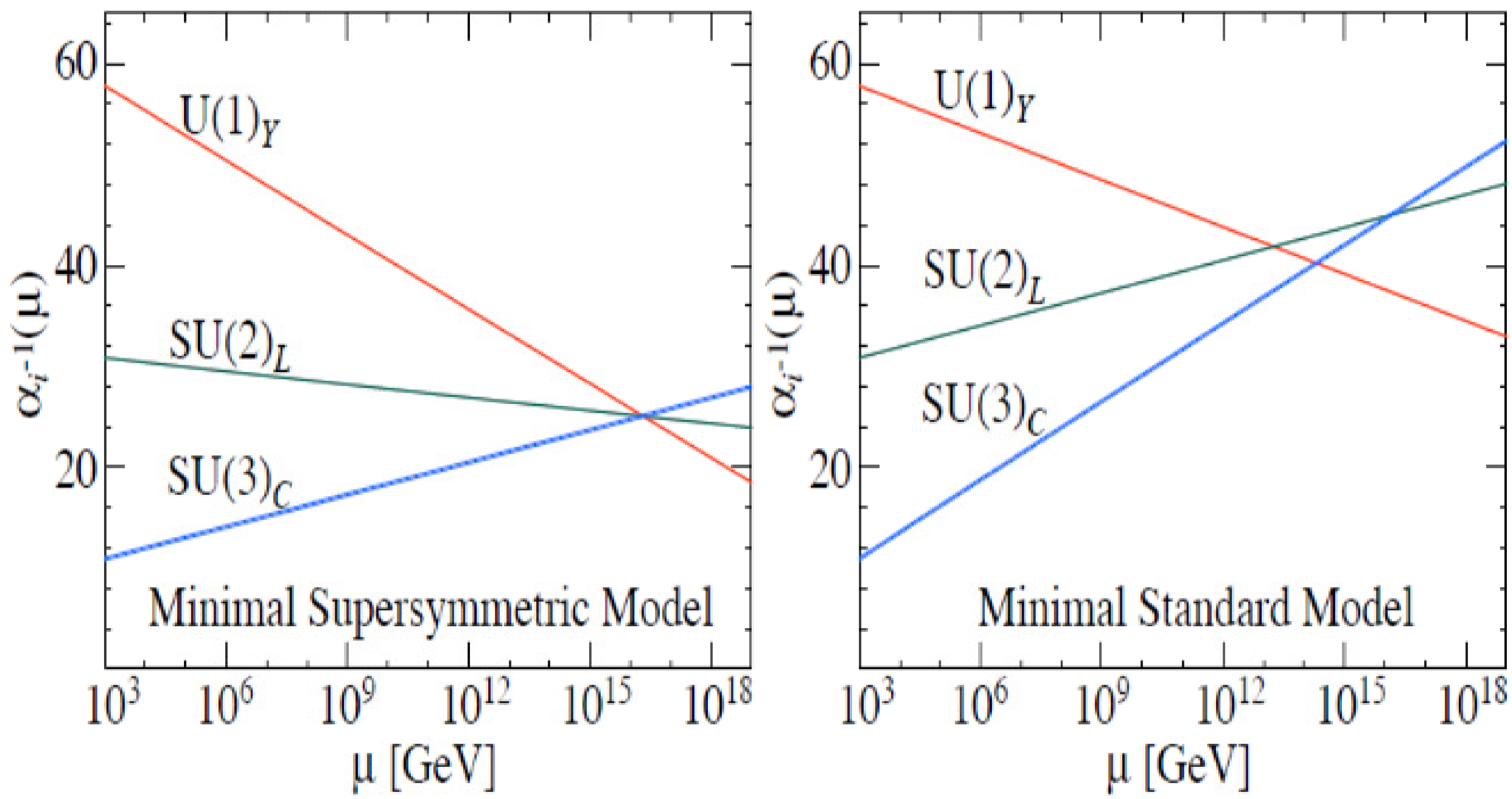
VIRTUES OF SUPERSYMMETRY

- Based on a beautiful and serious symmetry principle (most general sym. of a local relativistic QFT)

$$\boxed{P_\mu = \frac{1}{4i}\bar{Q}\gamma_\mu Q}$$

- Local version fits nicely in string theory
- Extends natural range of the theory up to M_{Pl}
- Perturbative → Calculable
- Simple to get fermion masses
- With R-parity implemented passes easily EW precision tests.
- BONUS: DM candidate
- BONUS: Gauge coupling unification

GAUGE COUPLING UNIFICATION

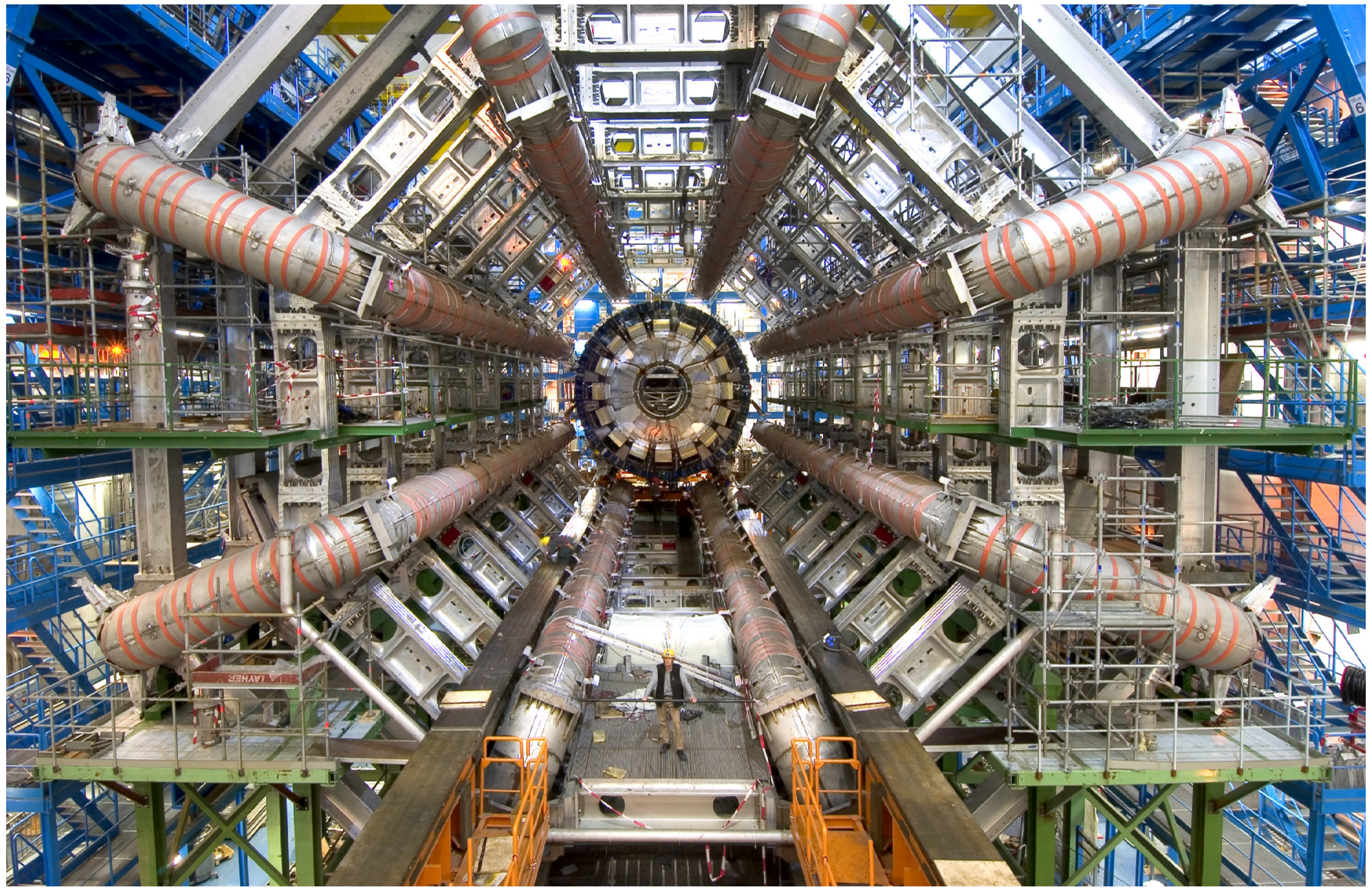


UNPARTICLES

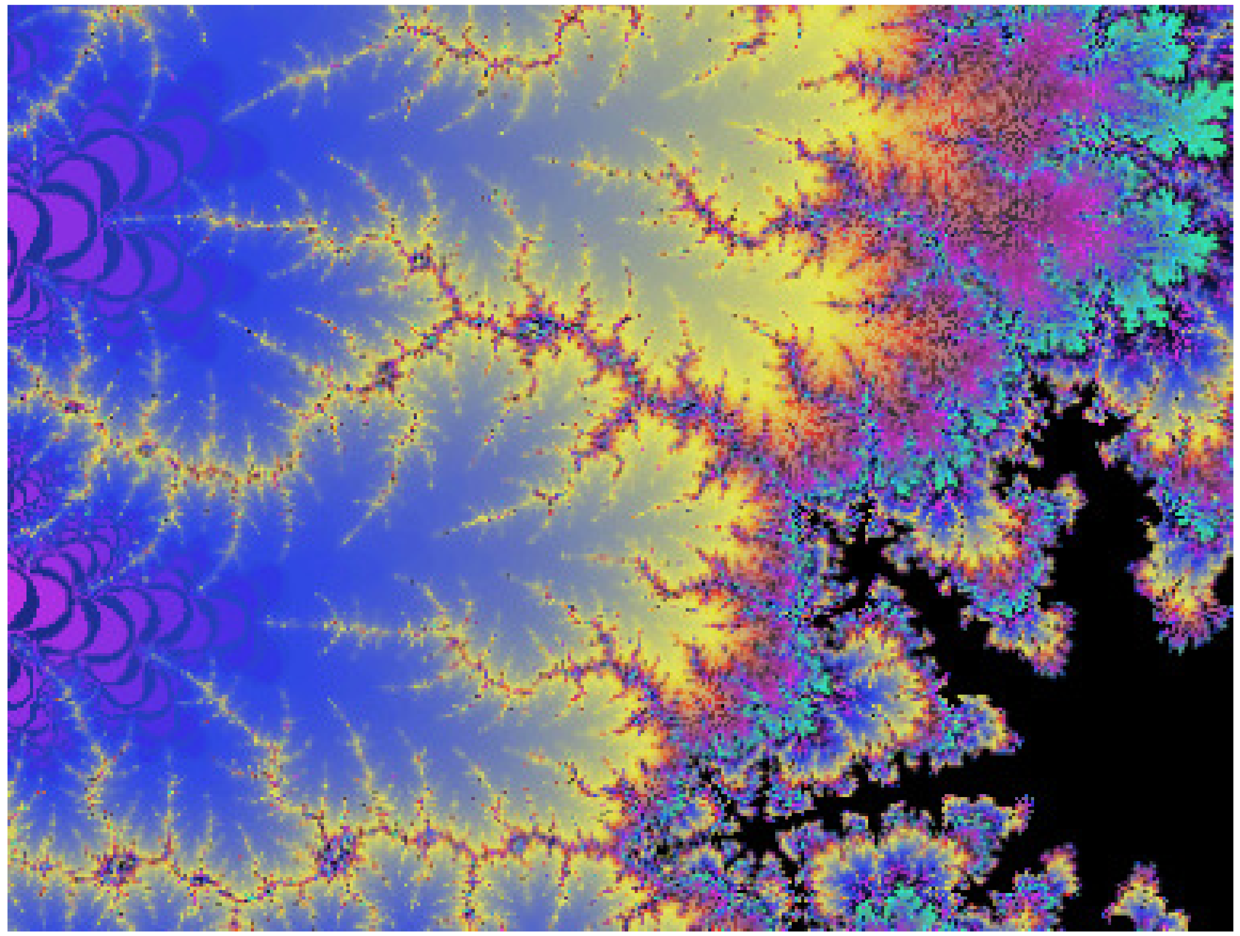
Georgi '07

Assume a scale-invariant sector of the theory

$\Rightarrow$ Very different from our observable sector



Our world



Scale-invariant world

★ SM contains an explicit mass term

$$V(H) = -m^2 |H|^2 + \lambda |H|^4$$

sets the EW scale

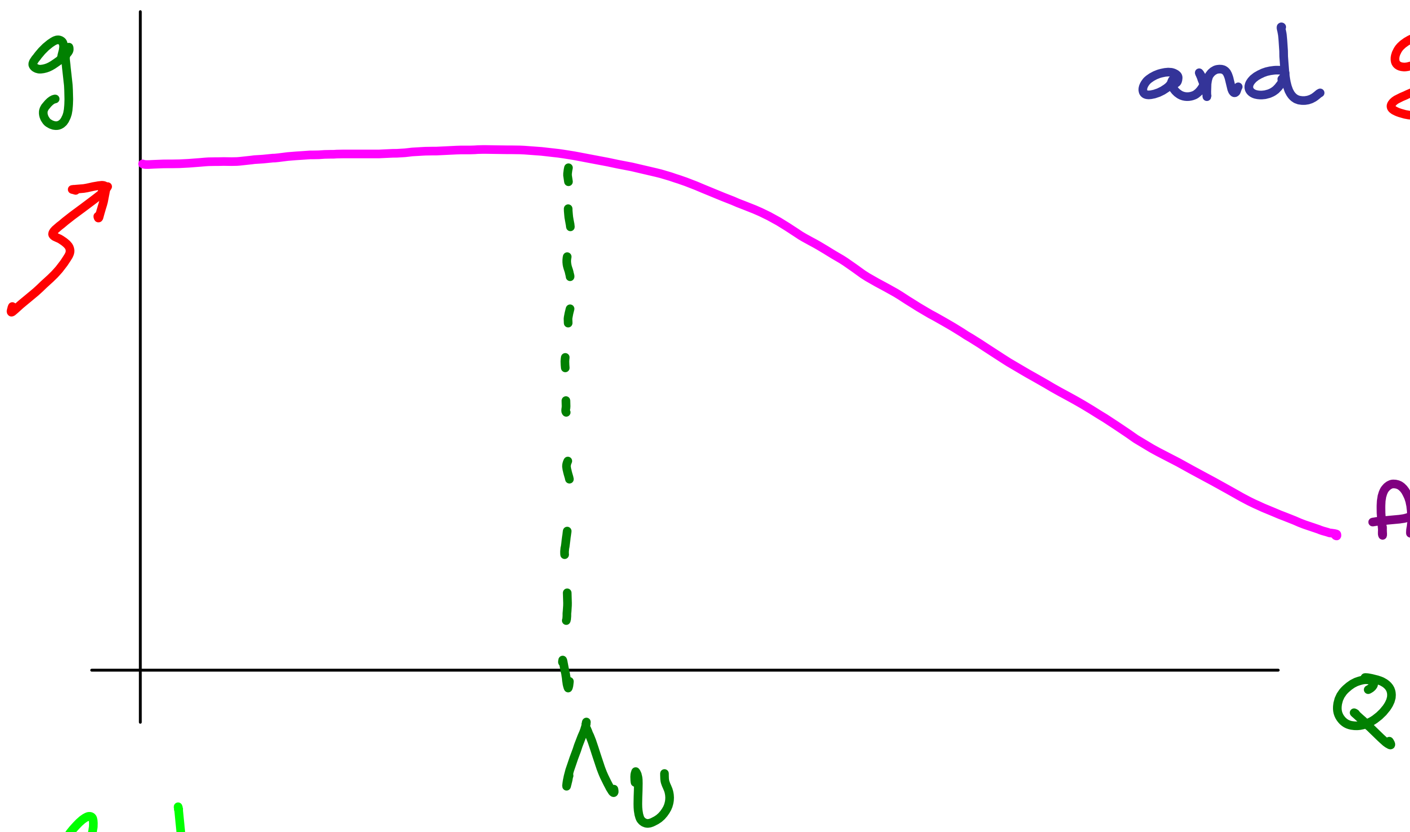
Scale invariant sector

⇘ Massless fields*

★ Quantum corrections can generate a scale (like in QCD)

Scale invariant sector ⇘ $\beta(g) = 0$ required and $g \neq 0$

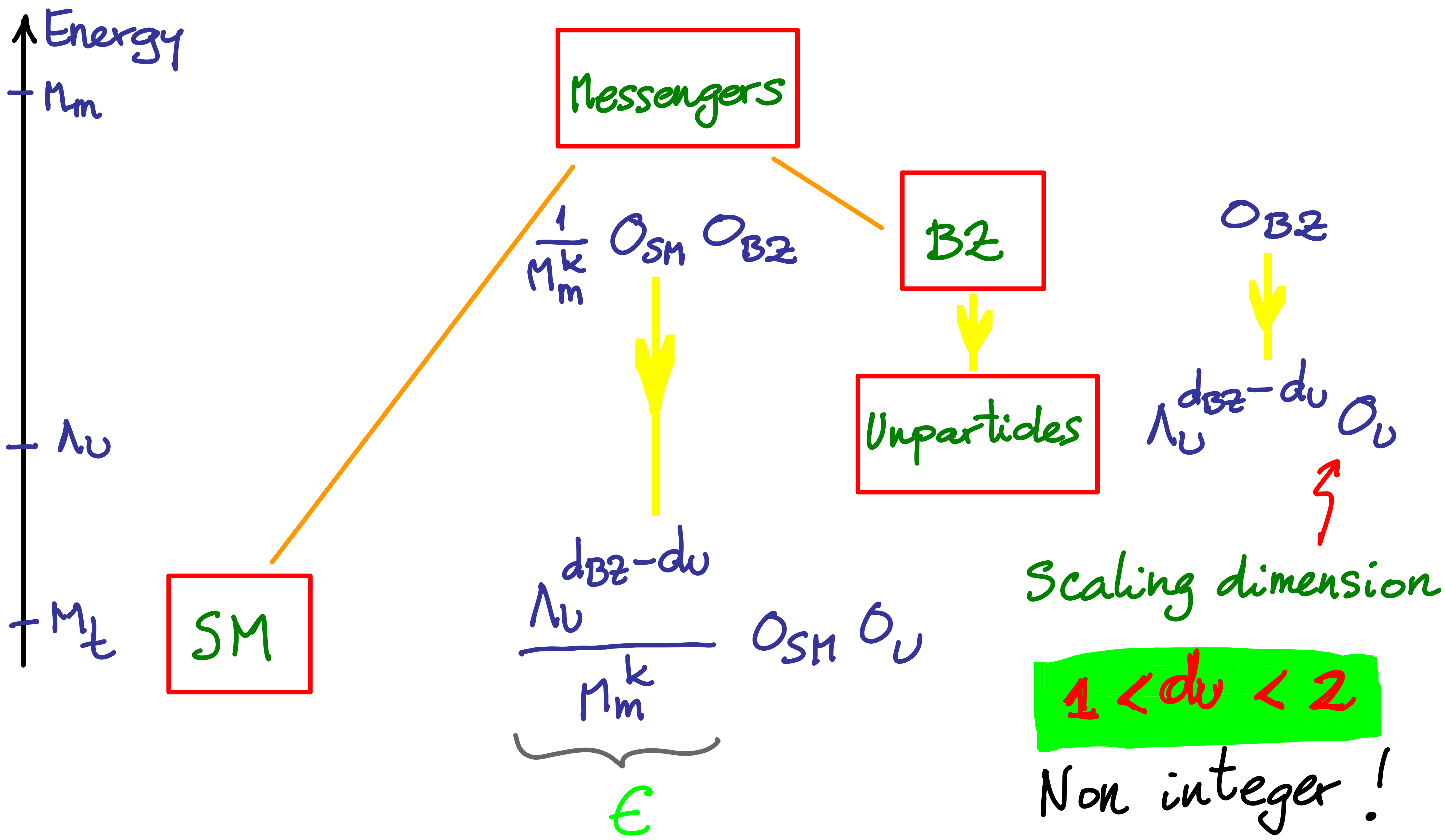
Nontrivial IR fixed point



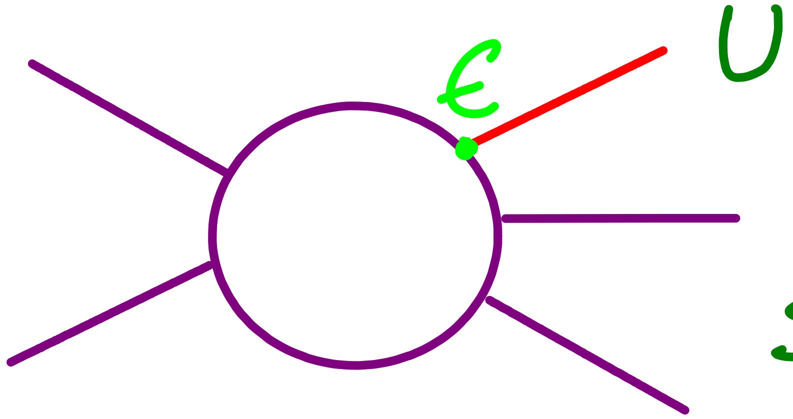
DIMENSIONAL ANTI-TRANSMUTATION

eg. Banks-Zaks $SU(N_c)$ N_f

COUPLE SM TO SCALE INV. SECTOR



UNPARTICLE PRODUCTION

$\epsilon\, O_{SM} O_U \Rightarrow SM_{in}$ 

SM_{out}

Probability $\rightarrow \epsilon^2$

Phase space for unparticles → Determined by scale invariance

$$\langle 0 | O_U(x)\, O_U^{\dagger}(0) | 0 \rangle \sim x^{-2d_U}$$

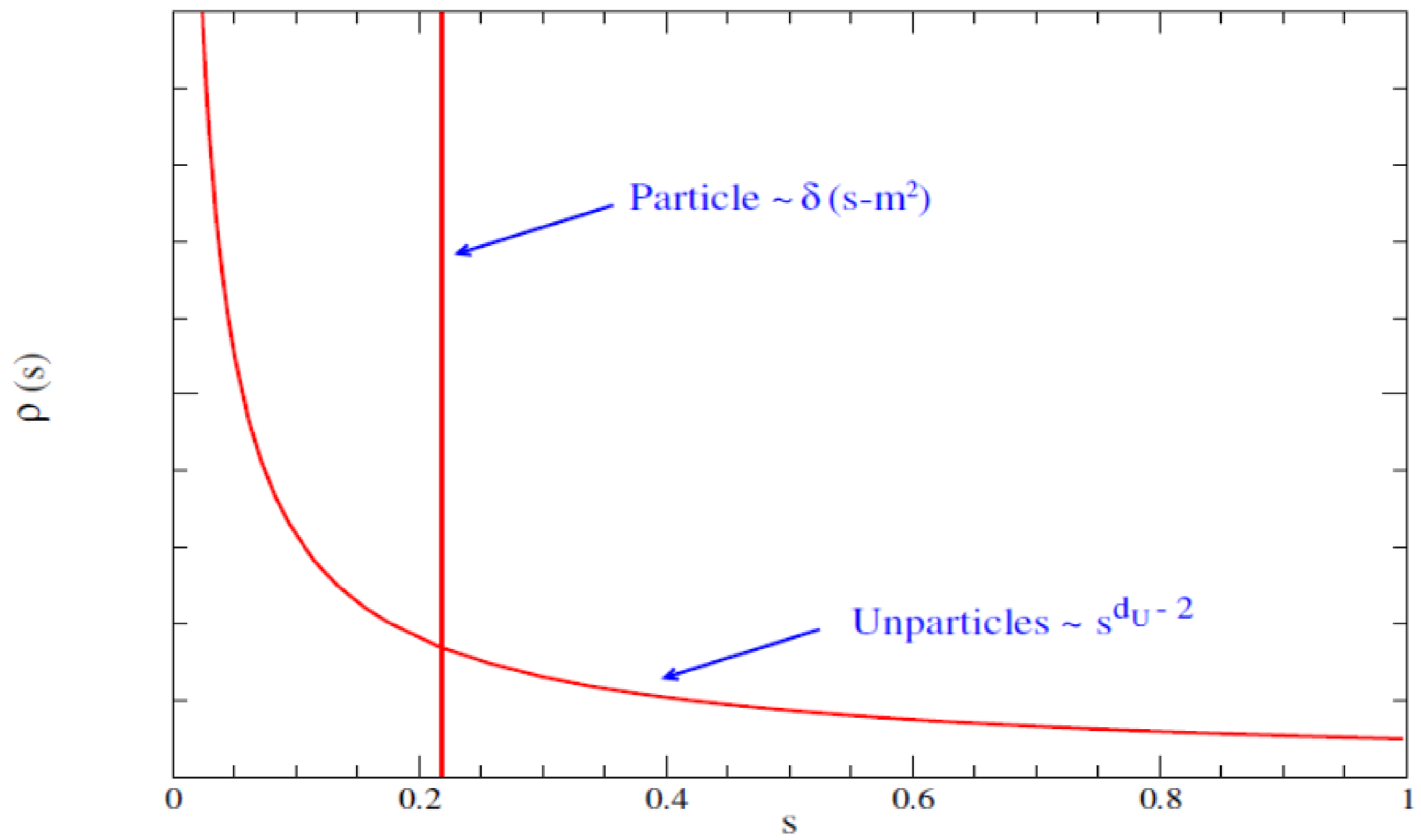
$$P_U(p^2) \sim A_{d_U} (p^2)^{d_U - 2}$$

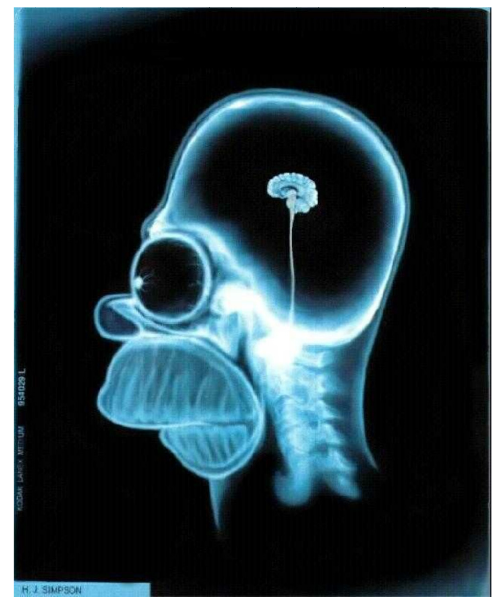
Phase space for n massless particles $dLIPS_n = A_n s^{n-2}$

Unparticles ~ noninteger number of massless particles (!?)

UNPARTICLE SPECTRAL FUNCTION

From $P(p^2) \sim (p^2)^{d_U - 2} \Rightarrow \rho(s) \sim s^{d_U - 2}$



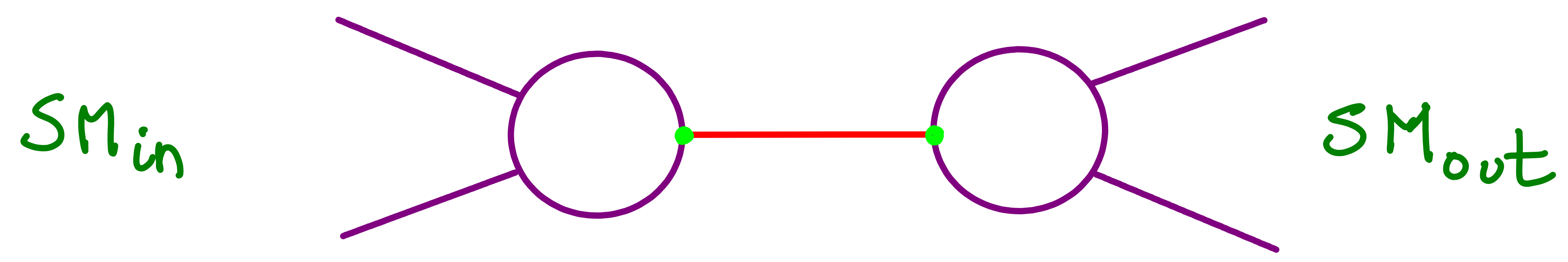


O_U does not create particles out of the vacuum but a non-localized wave over the full range of p^2

Unparticles

Lots of phenomenological implications have been explored

Example :



$$\text{Interference} \sim \epsilon^2 P_U(p^2)$$

Strange phase inside

DECONSTRUCTING UNPARTICLES

Stephanov '07

Unparticles as infinite tower of massive scalars φ_n $(n=1,\dots,\infty)$

$$M_n^2 = \Delta^2 n$$

In the limit of zero mass splitting $M_{n+1}^2 - M_n^2 = \Delta^2 \to 0$

➡ Scale invariant continuous mass spectrum!

$$S = \int d^4x \sum_{n=1}^{\infty} \left[\frac{1}{2}(\partial_\mu \varphi_n)^2 + \frac{1}{2} M_n^2 \varphi_n^2 \right]$$

$\varphi_n(x) \to \lambda \varphi_n(x\lambda)$

$\Delta^2 \to dM^2$

$\varphi_n \to \Delta \cdot u(M^2)$

$$S = \int d^4x \int_0^{\infty} dM^2 \left[\frac{1}{2}(\partial_\mu u)^2 + \frac{1}{2} M^2 u^2 \right]$$

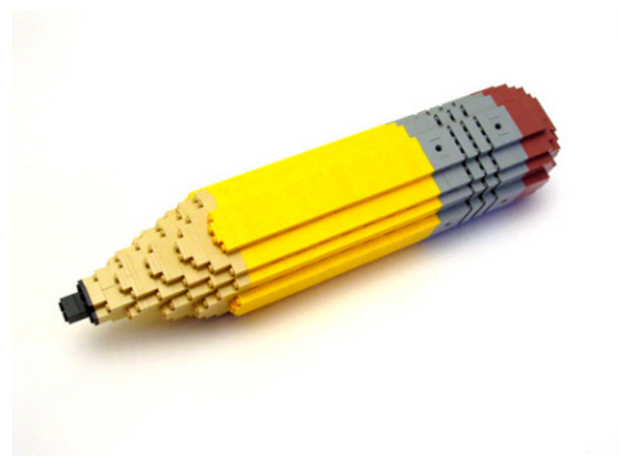
$u(M^2, x) \to u(M^2/\lambda, \lambda x)$

Deconstructed $\mathcal{O}_U$:

$$\mathcal{O} \equiv \sum_{n=1}^{\infty} F_n \varphi_n \longrightarrow \mathcal{O}_U$$

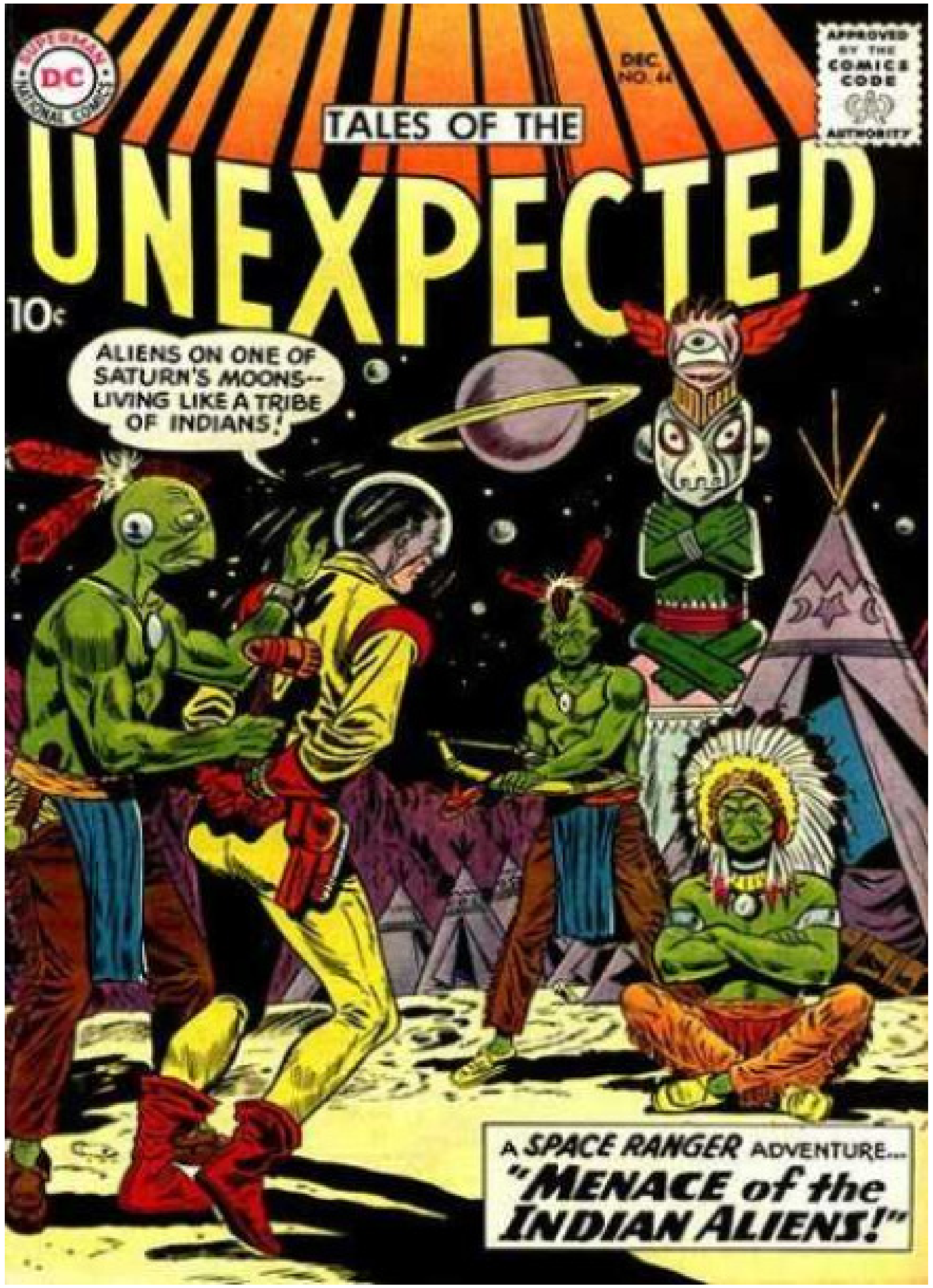
$$F_n^2 = \frac{A_{d_U}}{2\pi} \Delta^2 (M_n^2)^{d_U - 2}$$

$$\Rightarrow \quad \langle \mathcal{O}\mathcal{O}^\dagger \rangle \longrightarrow \langle \mathcal{O}_U \mathcal{O}_U^\dagger \rangle$$



Useful calculational tool. Related to extra-D scenarios: RS 2, soft-wall...

It's difficult to have truly original ideas !



HIGGS AS A PORTAL TO UNPARTICLE WORLD

Fox, Rajaraman, Shirman '07

Delgado, E, Quiros '07

There is room for a relevant operator to H:

$$\kappa_U\, O_{SM}\, O_U \rightarrow \kappa_U |H|^2 O_U$$

dimension $2-d_U > 0$

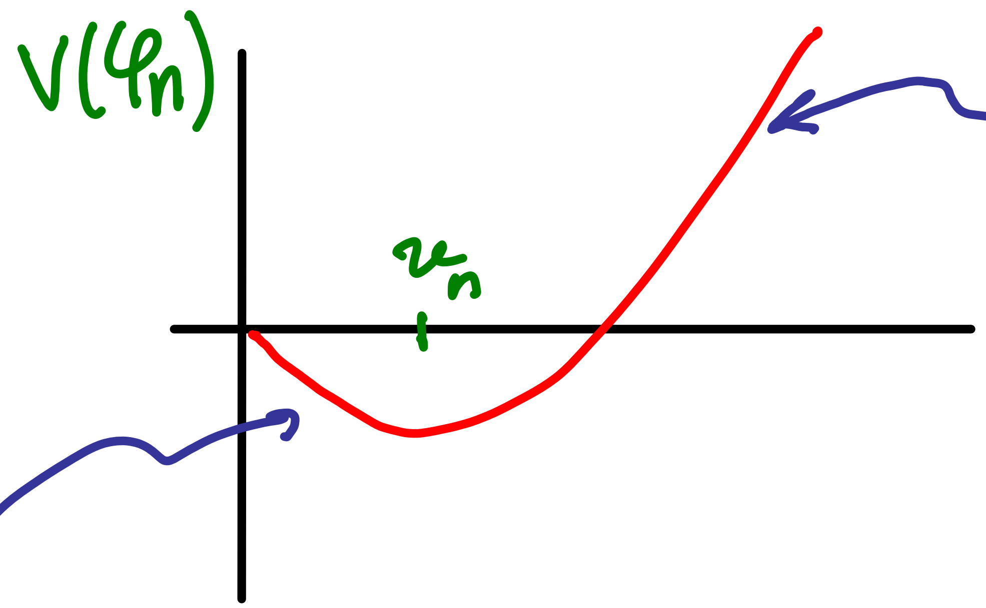
Main source of conformal breaking after EWSB

Difficulty: $\langle H \rangle = \frac{v}{2}$ induces a tadpole for $O_U = \sum_n F_n \varphi_n$

and $\langle O_U \rangle$ has an IR divergence

ORIGIN OF DIVERGENCE

Calculate $\langle O_U \rangle$ through $\langle \varphi_n \rangle = v_n$



$\frac{1}{2} M_n^2 \varphi_n^2 \xrightarrow[M_n \to 0]{} 0$

$\left(\frac{1}{2} K_U v^2 F_n\right) \varphi_n \xrightarrow[M_n \to 0]{} \infty$

$$\langle O_U \rangle \propto v^2 \sum_n v_n \sim \int_0^\infty (M^2)^{d_U - 3} \, dM^2$$

IR div for $d_U < 2$

SIMPLE CURES FOR IR PROBLEM

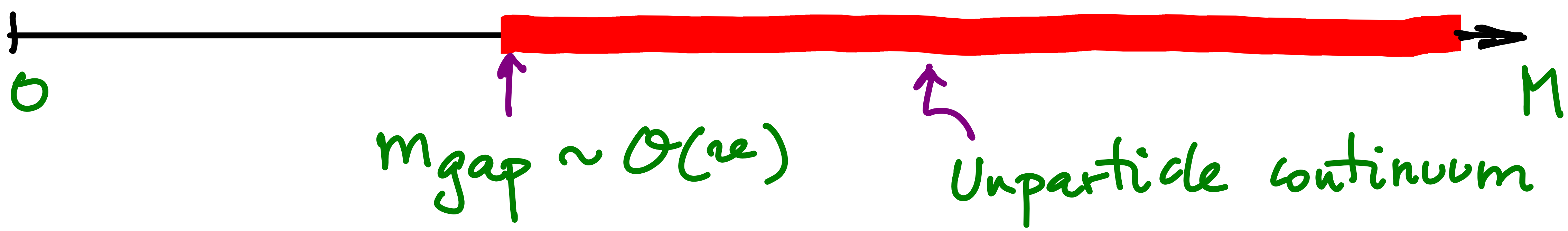
I. Add coupling $\underbrace{\xi |H|^2}_{\text{acts as IR cutoff mass}} \sum_n \varphi_n^2$

II. Add coupling $\frac{1}{4} \lambda_U \left(\sum_n \varphi_n\right)^2$

generates a mass $\sim \lambda_U \left(\sum_n v_n\right)^2$

⇨ A mass gap is generated

MIND THE GAP



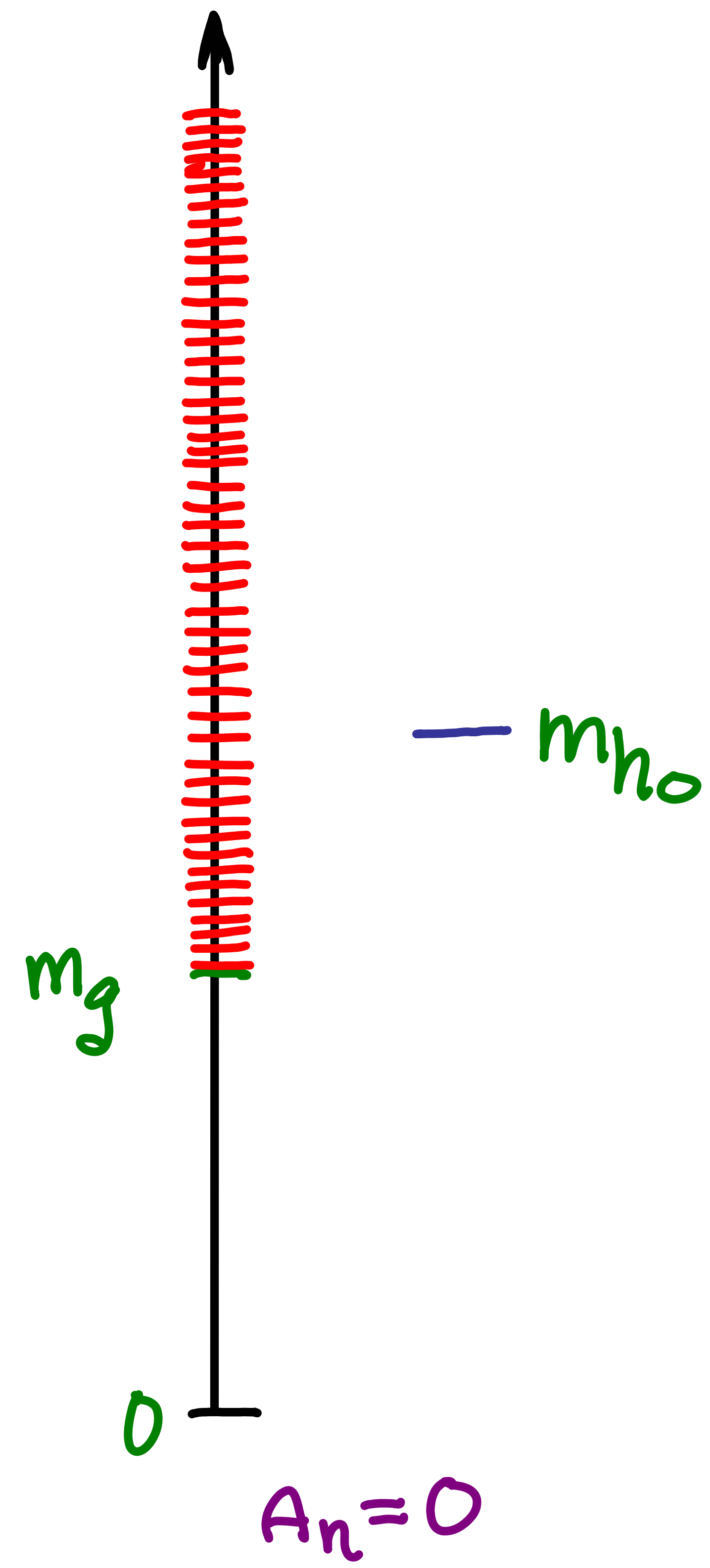
HIGGS-UNPARTICLE INTERPLAY

$$M^2 = \begin{bmatrix} m_{h_0}^2 & A_1 & \cdots & A_n & \cdots \\ A_1 & M_1^2+m_g^2 & & & \\ \vdots & & \ddots & & \\ A_n & & & M_n^2+m_g^2 & \\ \vdots & & & & \ddots \end{bmatrix}$$

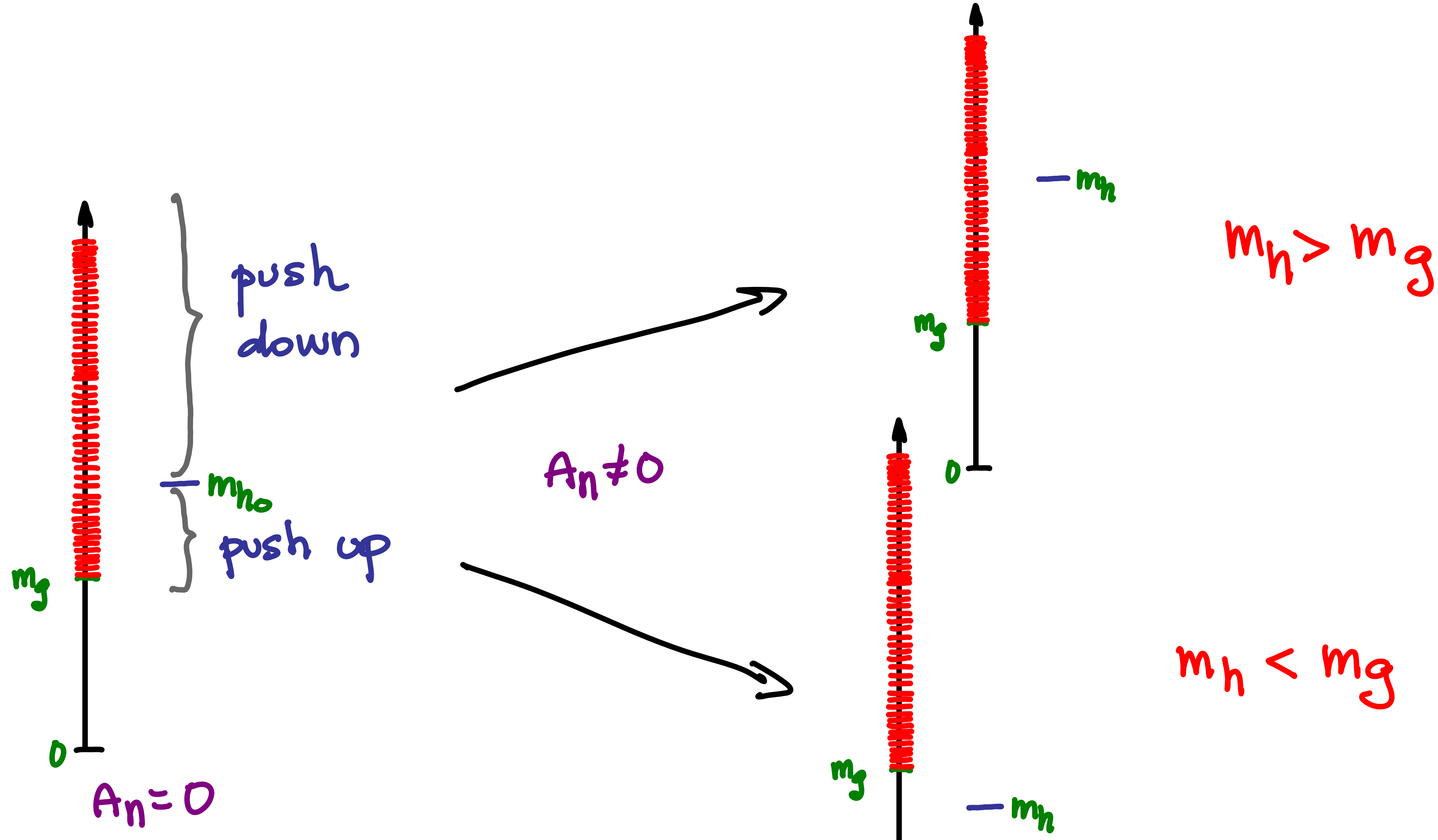
$2\lambda v^2$

$v(\kappa_U F_n + 2\zeta v_n)$

ζv^2



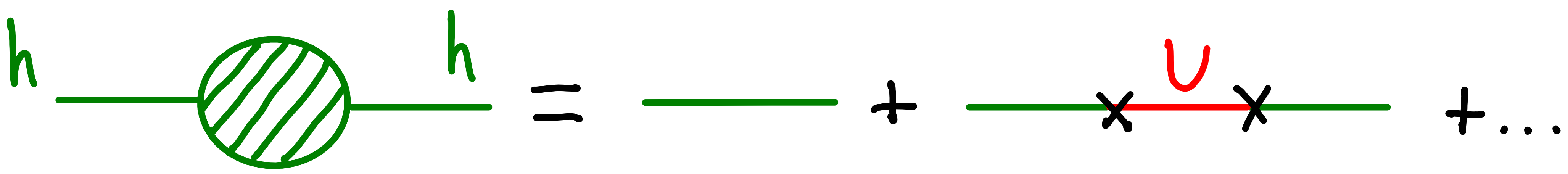
TWO POSSIBLE OUTCOMES:



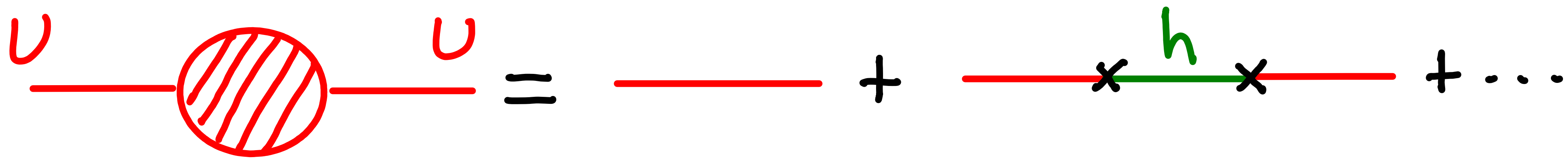
Int. eigenstates $\begin{cases} |h\rangle \\ |u,s\rangle \end{cases}$

Mass eig. $\begin{cases} |H\rangle \\ |U,s\rangle \end{cases}$

MIXED PROPAGATOR



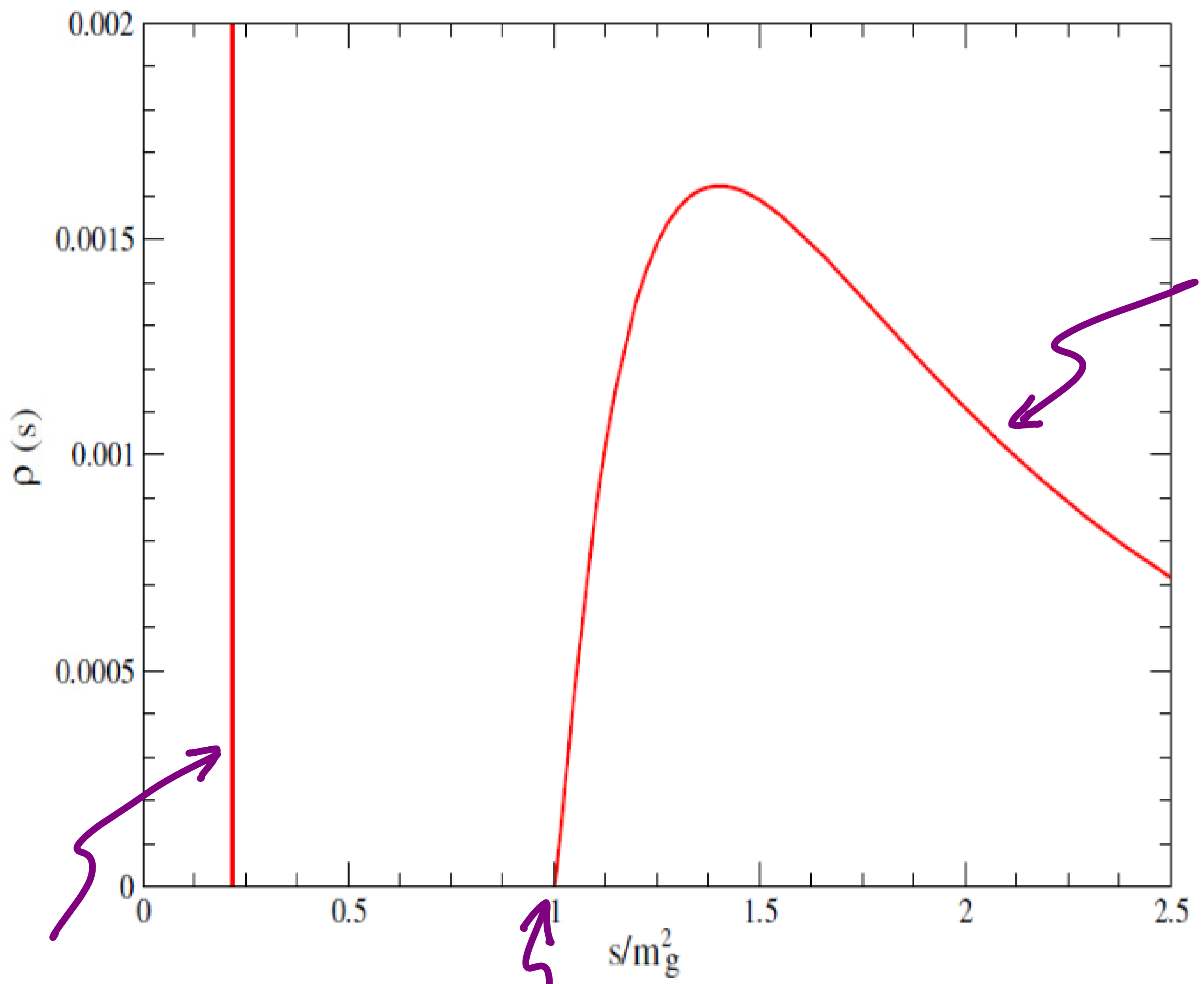
or



$$\Rightarrow iP_{hh}(p^2)^{-1} = p^2 - m_{h_0}^2 + v^2(\mu_U^2)^{2-d_U}\int_0^\infty \frac{(M^2)^{d_U-2}}{(M^2+m_g^2-p^2)}\left(\frac{M^2}{M^2+m_g^2}\right)^2 dM^2$$

We can study its poles or better still obtain the spectral function $\rho_{hh}(s)$

SPECTRAL FUNCTION, $m_h < m_g$



Unparticle continuum above m_g

$\frac{1}{K^2}\delta(s-m_h^2)$

m_g

INTERPRETATION OF $\rho(s)$

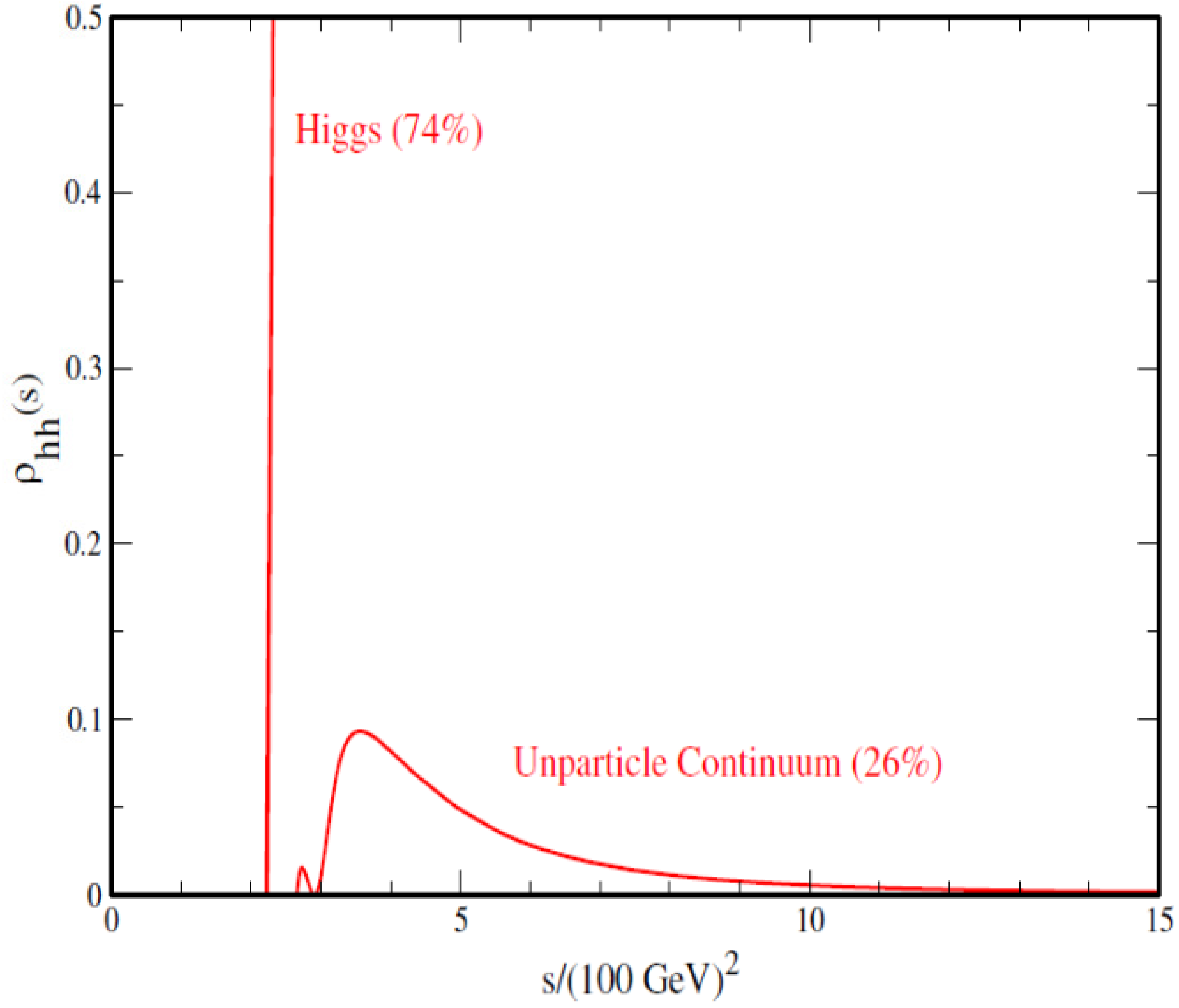
$$\rho_{hh}(s) \equiv \langle h|s\rangle\langle s|h\rangle = |\underbrace{\langle h|H\rangle}_{R_h}|^2\,\delta(s-m_h^2) + \theta(s-m_g^2)\,|\underbrace{\langle h|U,s\rangle}_{R_U(s)}|^2$$

★ HZZ coupling diluted by unparticle contamination of isolated pole. Pure Higgs composition $R_h \equiv \langle h|H\rangle = \frac{1}{K}$

★ UZZ coupling induced by Higgs contamination ~ 'Higgsness' difuses in unparticle continuum

Sum Rule $$R_h^2 + \int_{m_g^2}^{\infty} R_U^2(M^2)\,dM^2 = 1 \qquad = \langle h|h\rangle$$

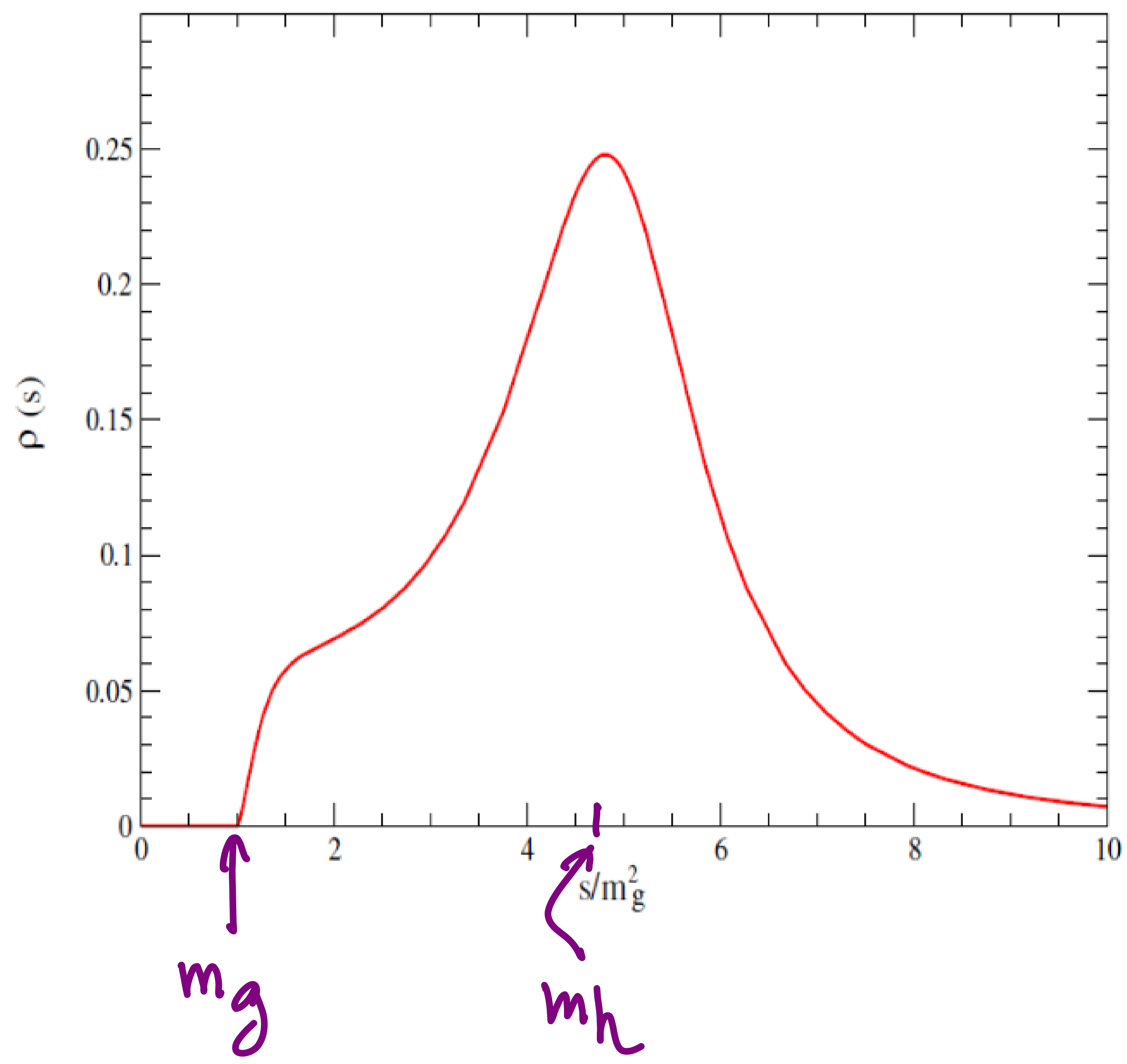
EXAMPLE



Higgs (74%)
Unparticle Continuum (26%)
ρhh(s)
s/(100 GeV)2
0
0.1
0.2
0.3
0.4
0.5
0
5
10
15

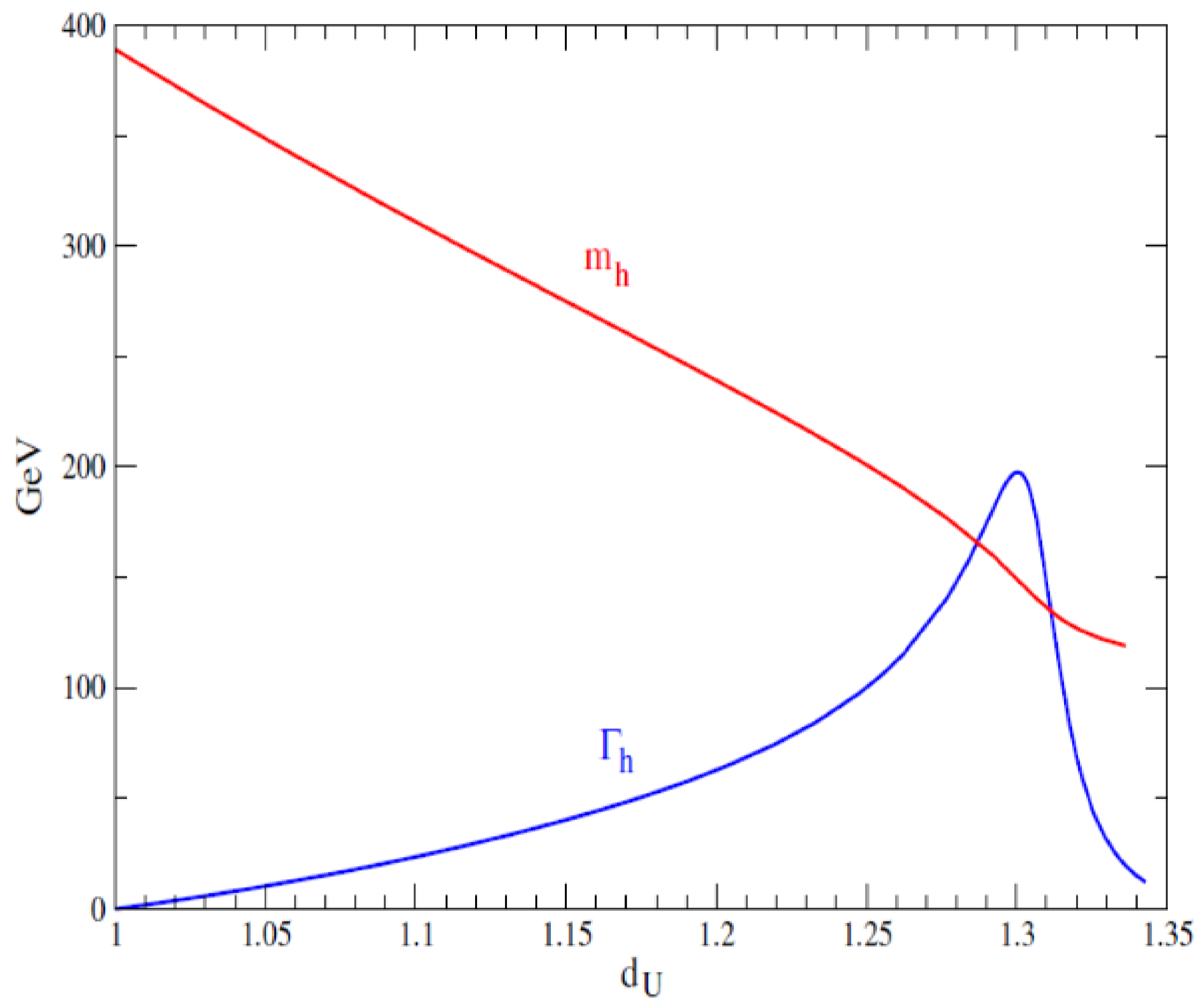
SPECTRAL FUNCTION, $m_h > m_g$

Higgs pole subsumed in unparticle continuum



large
mixing
width

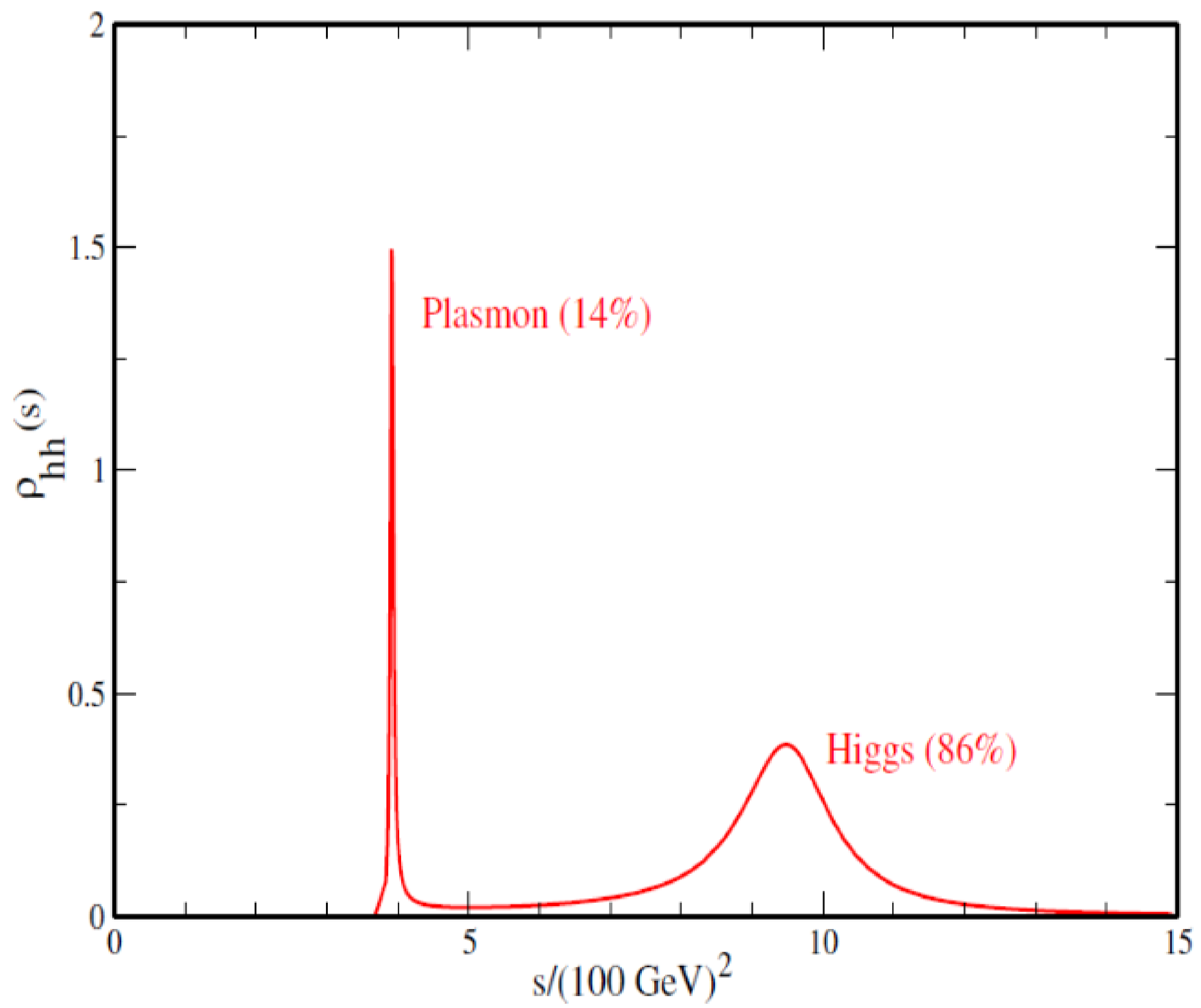
HIGGS WIDTH, $m_h > m_g$



OTHER EFFECTS

Many similarities to effects studied in condensed matter (eg. Anderson-Fano)

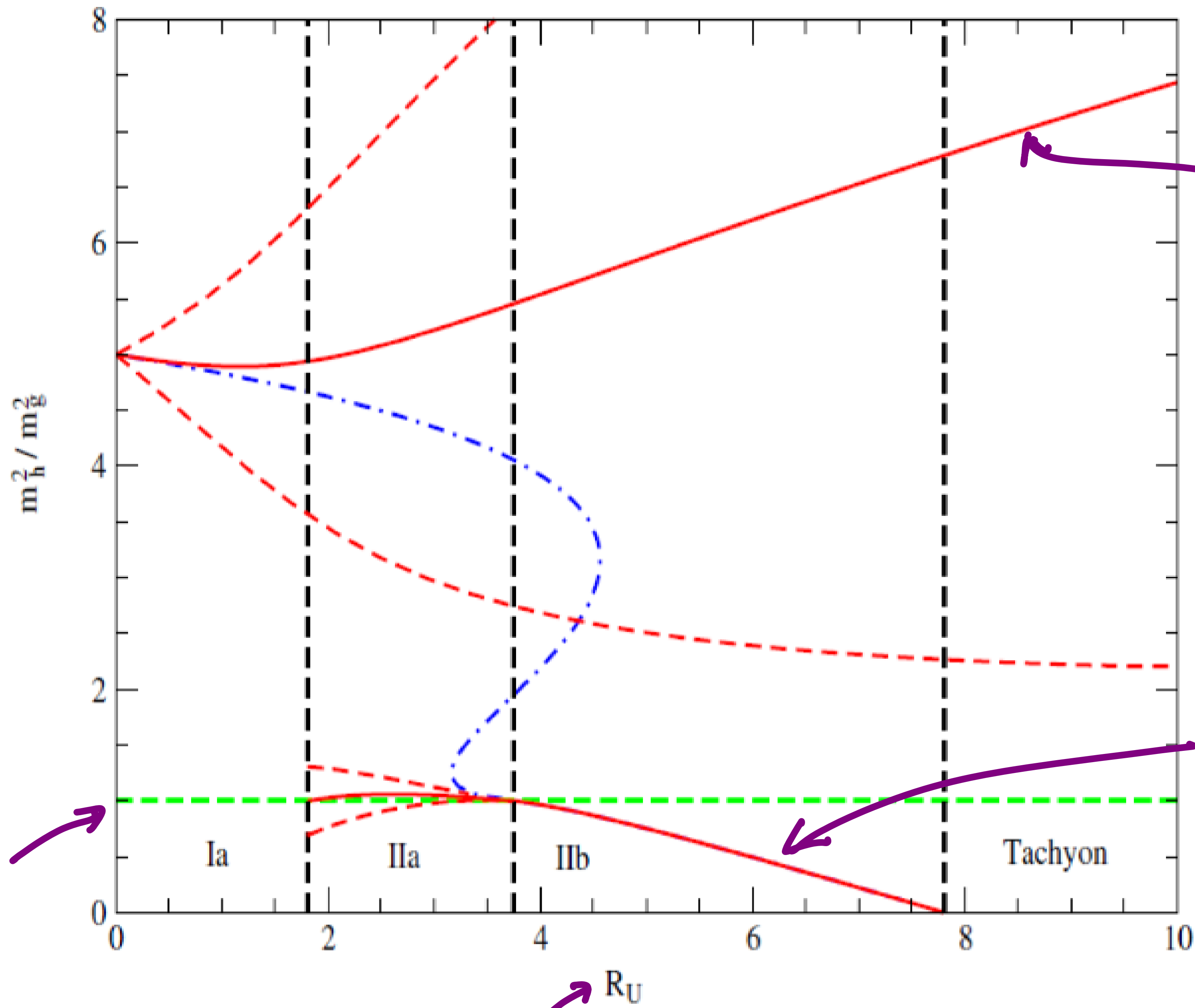
with other solution to IR problem



Higgs can excite "plasmonic" resonances in the unparticle continuum

OTHER EFFECTS, CONT'D

Unexpected "particle" states can pop-out of the unparticle continuum



m_{gap}

Normal Higgs

"Phantom" Higgs

strength of Higgs-Unparticle coupling

CONCLUSIONS

- We don't really know what LHC will find
  that's why it's so exciting !
- We do have good reasons to expect physics beyond the SM at the reach of LHC
- To find Supersymmetry would be a triumph of theoretical imagination and of experimental performance
- To get the most of LHC we have to be prepared for all reasonable alternatives we can imagine
- In any case, we have EXCITING TIMES ahead !

IMPLICATIONS : EFFECTS ON EWSB

Deconstructed potential :

$$V = m^2|H|^2 + \lambda|H|^4 + \frac{1}{2}\sum_n M_n^2 \varphi_n^2 + \kappa_U |H|^2 \underbrace{\sum_n F_n \varphi_n}_{O_U} + \underbrace{\zeta |H|^2}_{\sim m_g^2} \sum_n \varphi_n^2$$

Minimization

$$m^2 + \lambda v^2 + \kappa_U \sum_n F_n v_n + \zeta \sum_n v_n^2 = 0$$

$$\hookrightarrow v_n = -\frac{\kappa_U v^2 F_n}{2(M_n^2 + \zeta v^2)}$$

Continuum $\rightarrow$ $m^2 + \lambda v^2 - \lambda_U (\mu_U^2)^{2-d_U} \underbrace{v^{2(d_U-1)}}_{} = 0$

like coming from $\delta V \sim h^{2d_U}$!

- It's possible to have $v \neq 0$ even for $m^2 > 0$