The Higgs fine-tuning problem

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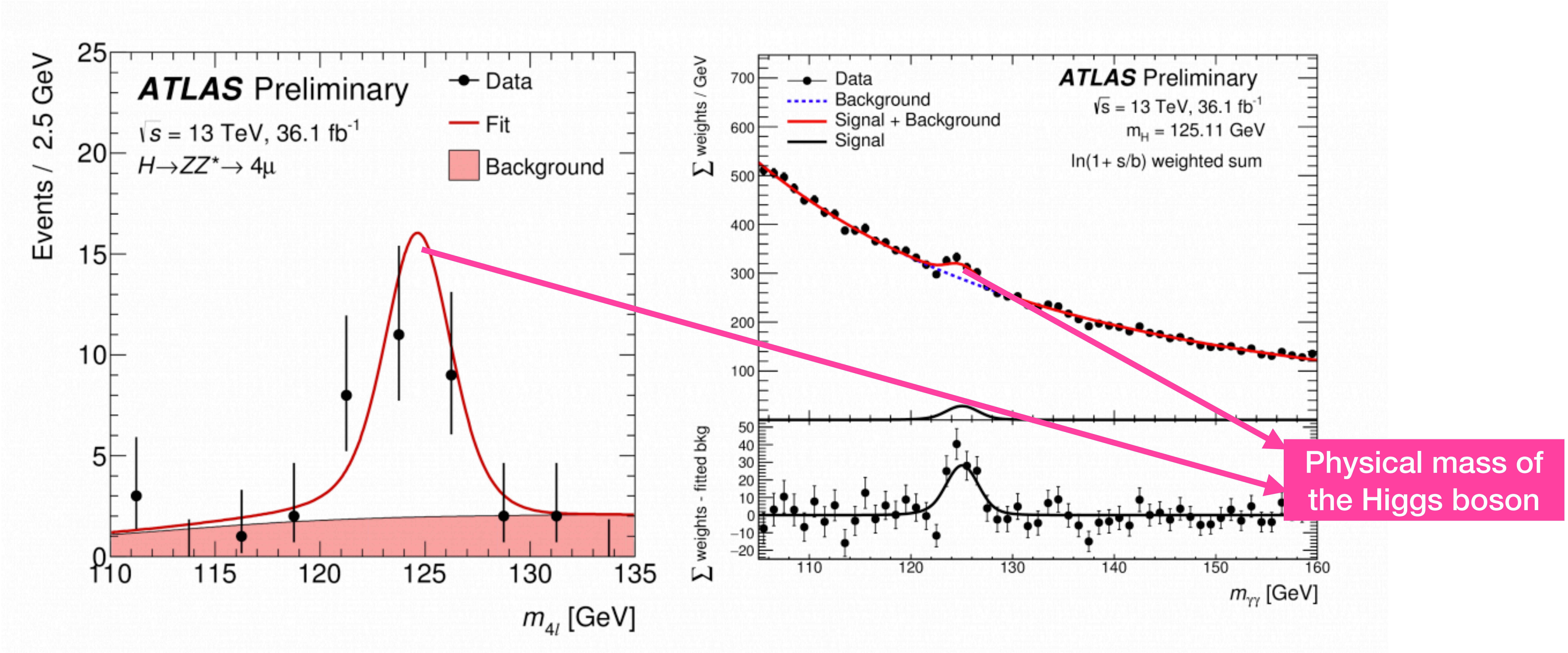
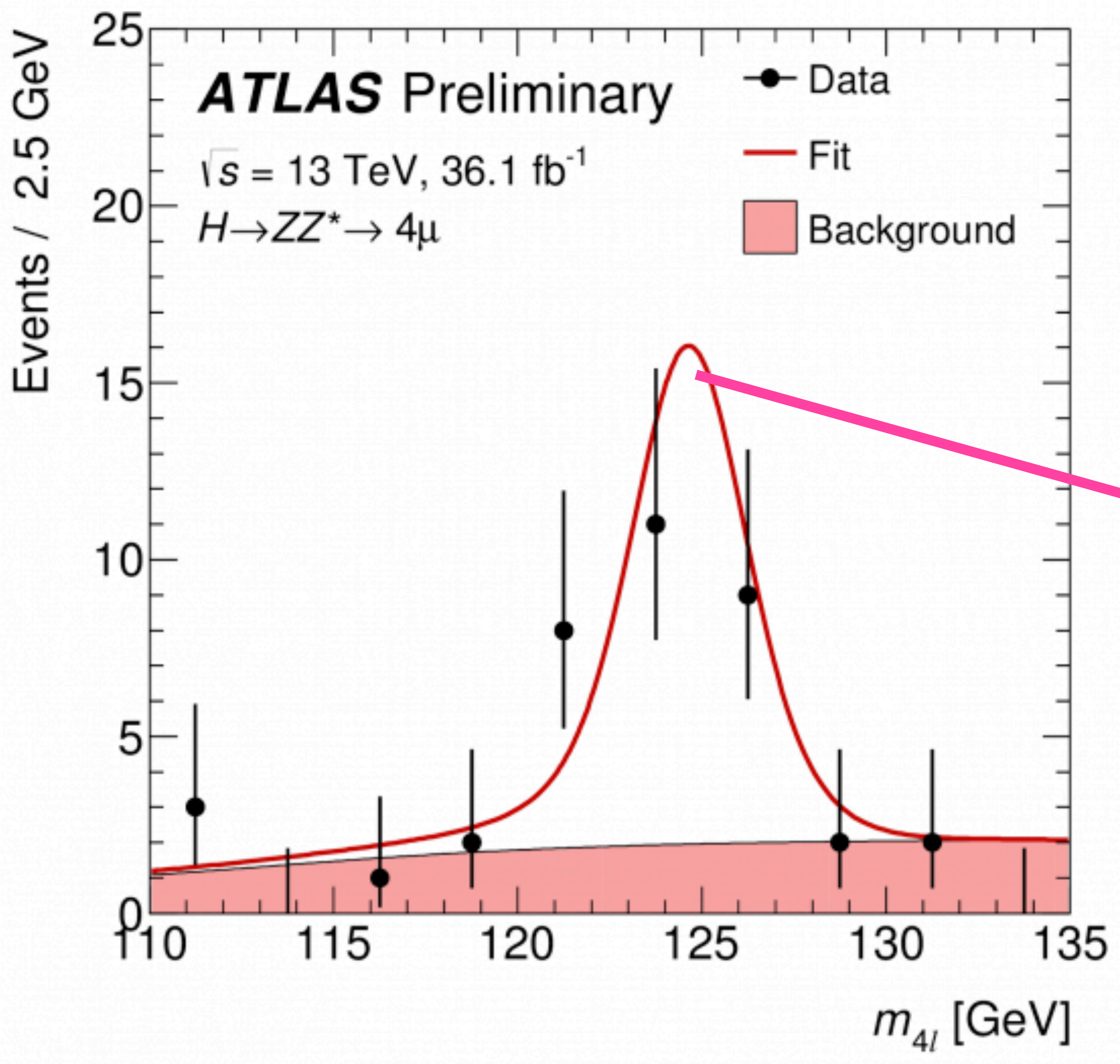
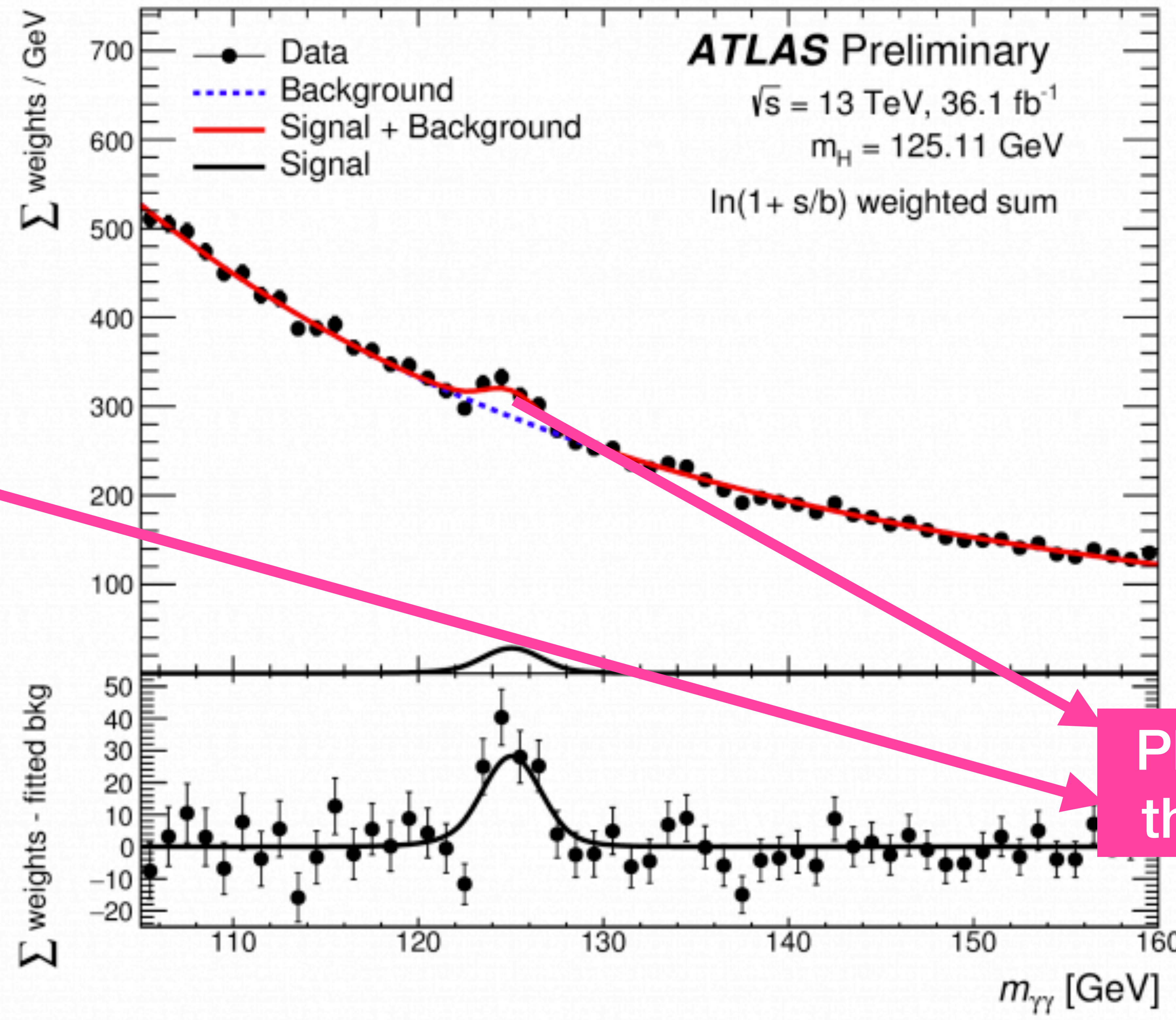
Put my head here



ATLAS Preliminary
$\sqrt{s}$ = 13 TeV, 36.1 fb^{-1}
$H \to ZZ^* \to 4\mu$
Data
Fit
Background
Events / 2.5 GeV
m_{4l} [GeV]
ATLAS Preliminary
$\sqrt{s}$ = 13 TeV, 36.1 fb^{-1}
m_H = 125.11 GeV
ln(1+ s/b) weighted sum
Data
Background
Signal + Background
Signal
$\sum$ weights / GeV
$\sum$ weights - fitted bkg
$m_{\gamma\gamma}$ [GeV]
Physical mass of the Higgs boson





Physical mass of the Higgs boson

Related to theory parameters, but how?

What do you measure?

$$\mathscr{L}_{\rm higgs} = (D_\mu\Phi)^\dagger(D_\mu\Phi) + m_{\rm h}^2\Phi^\dagger\Phi - \lambda\left(\Phi^\dagger\Phi\right)^2 \qquad \left(\lambda = \frac{2m_h^2}{v^2}\right)$$

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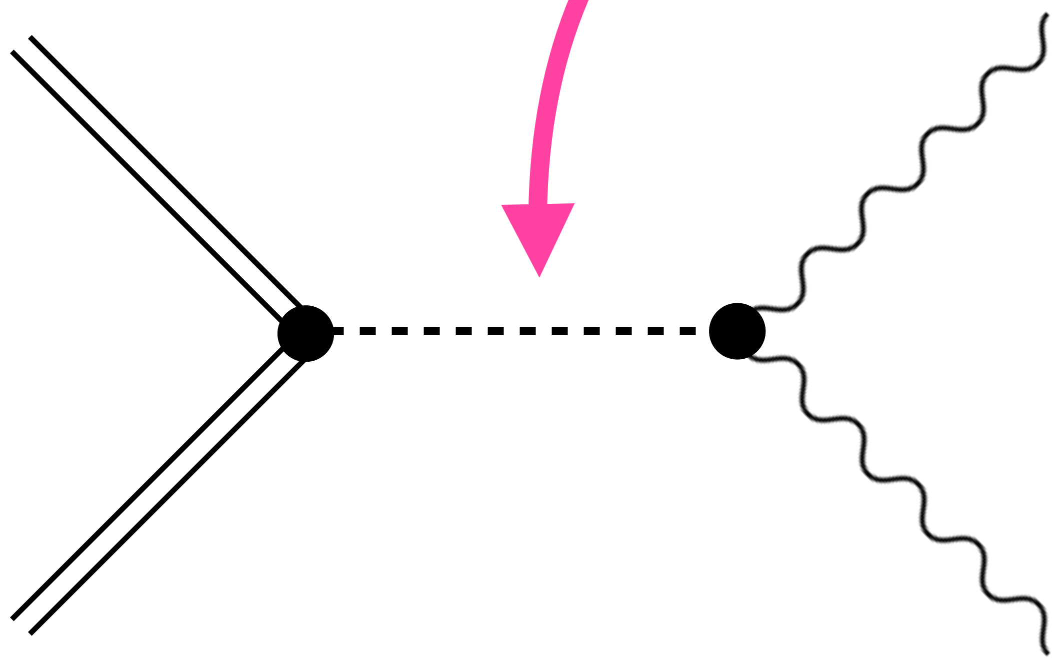
$$\boxed{\frac{1}{p^2 - m_{\text{h}}^2}}$$



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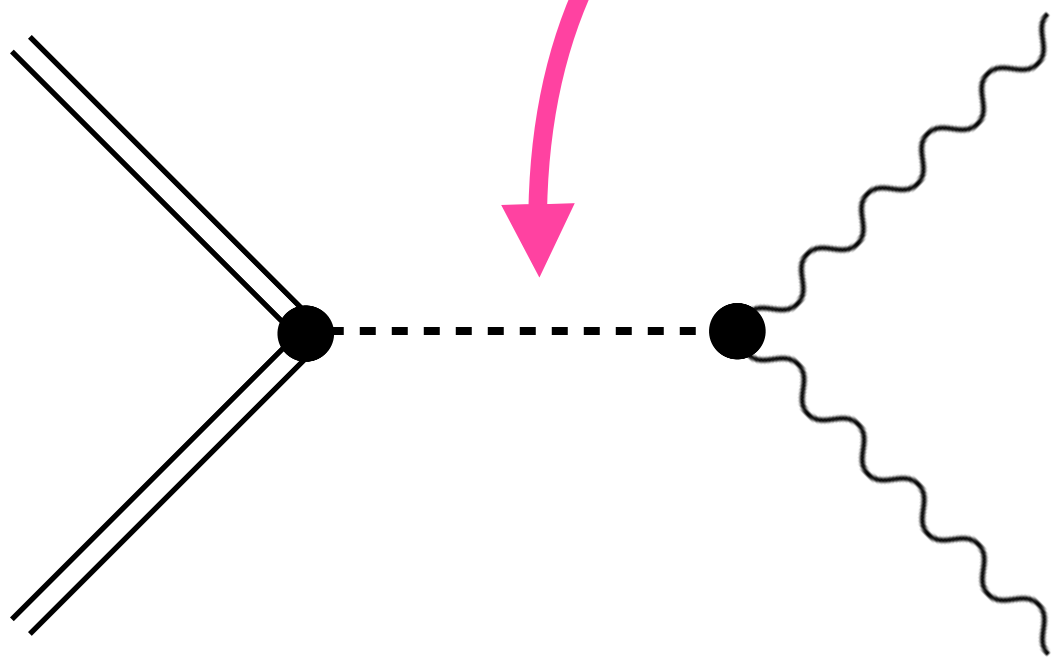

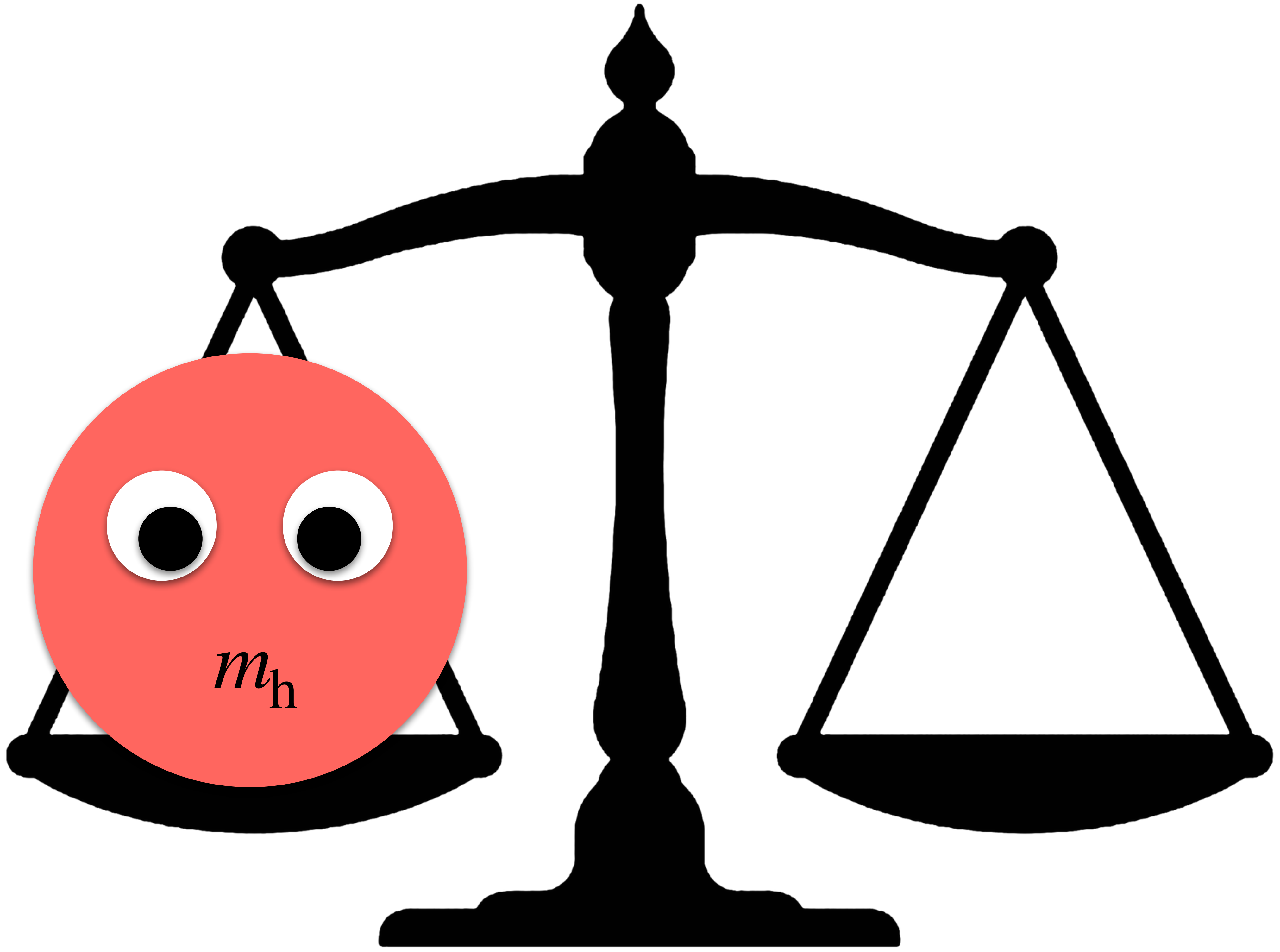

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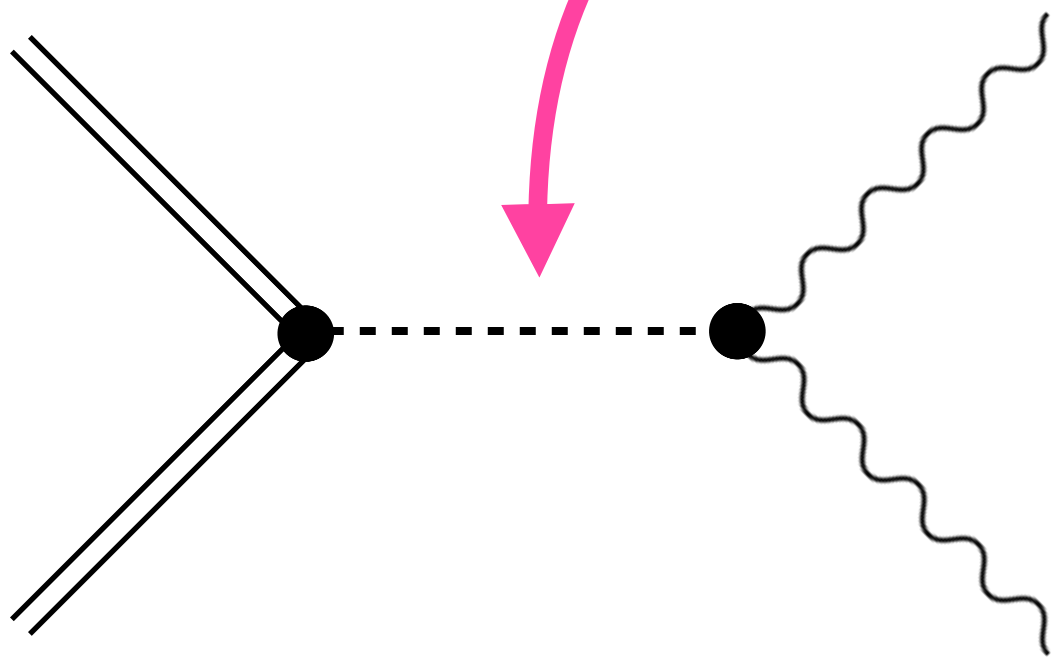

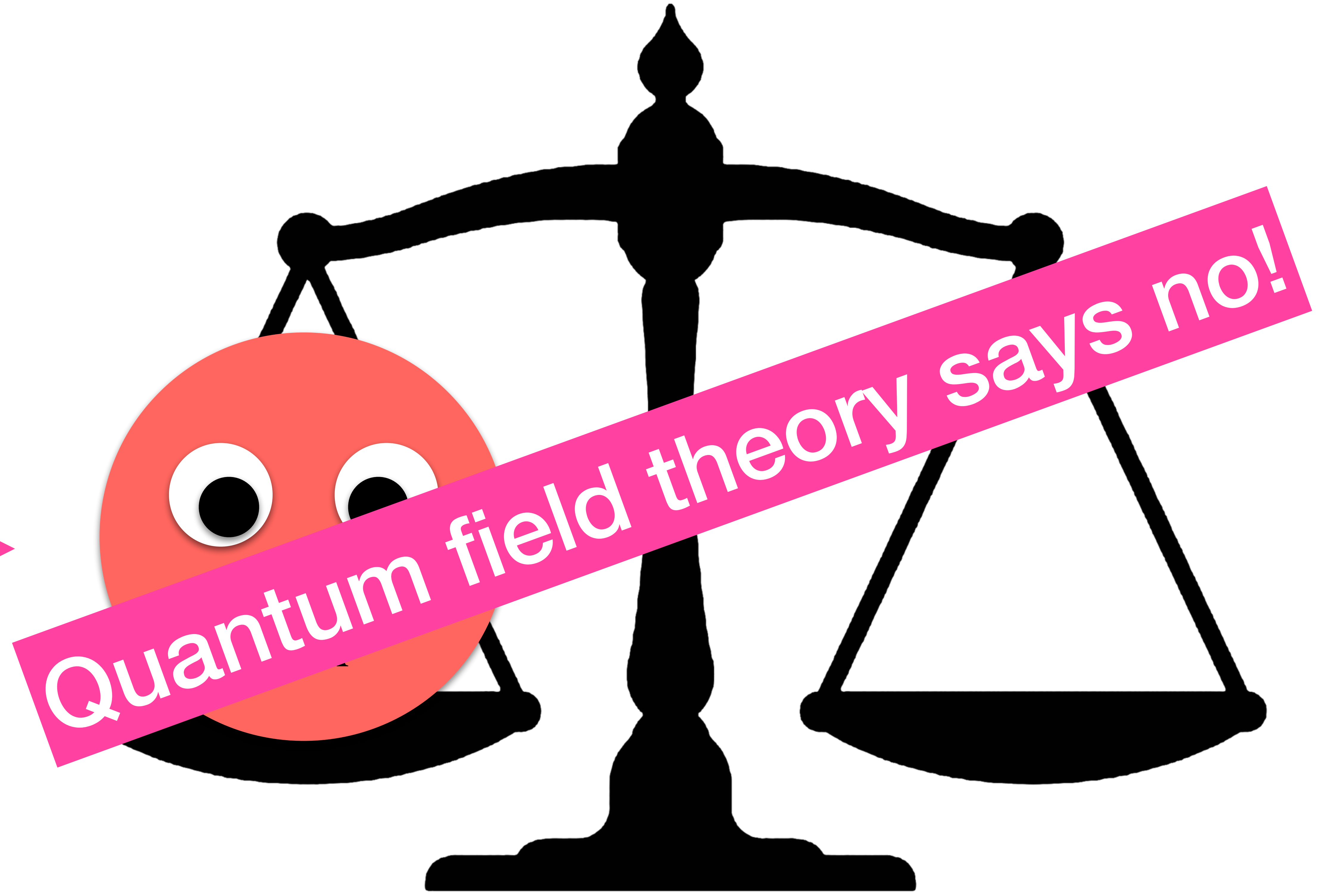

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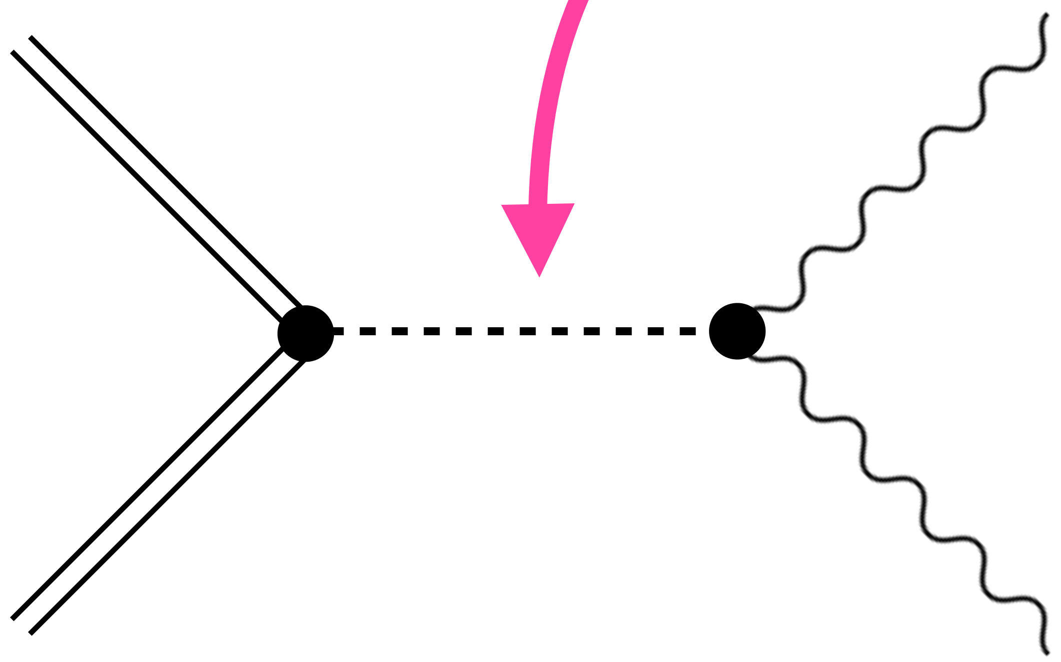
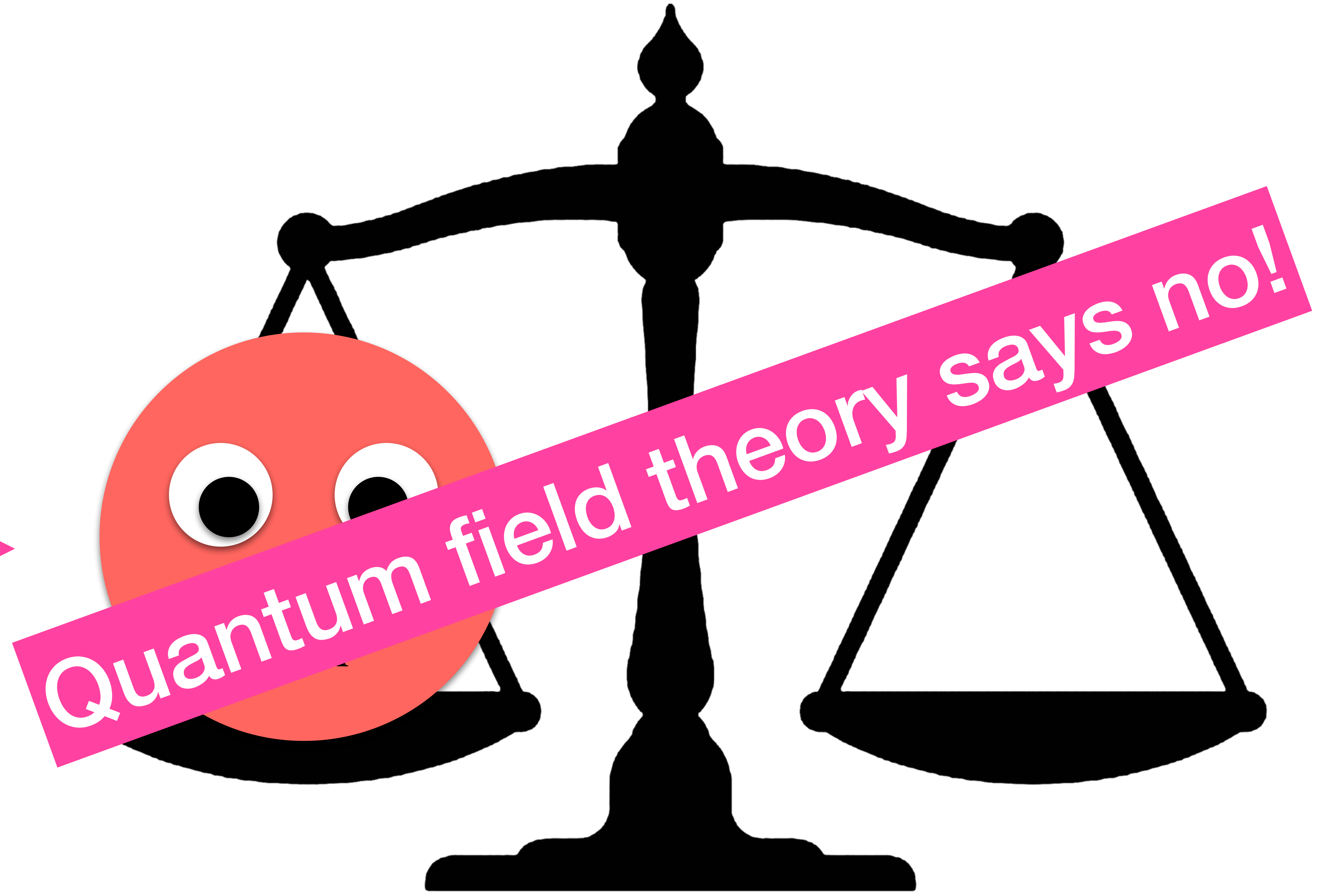


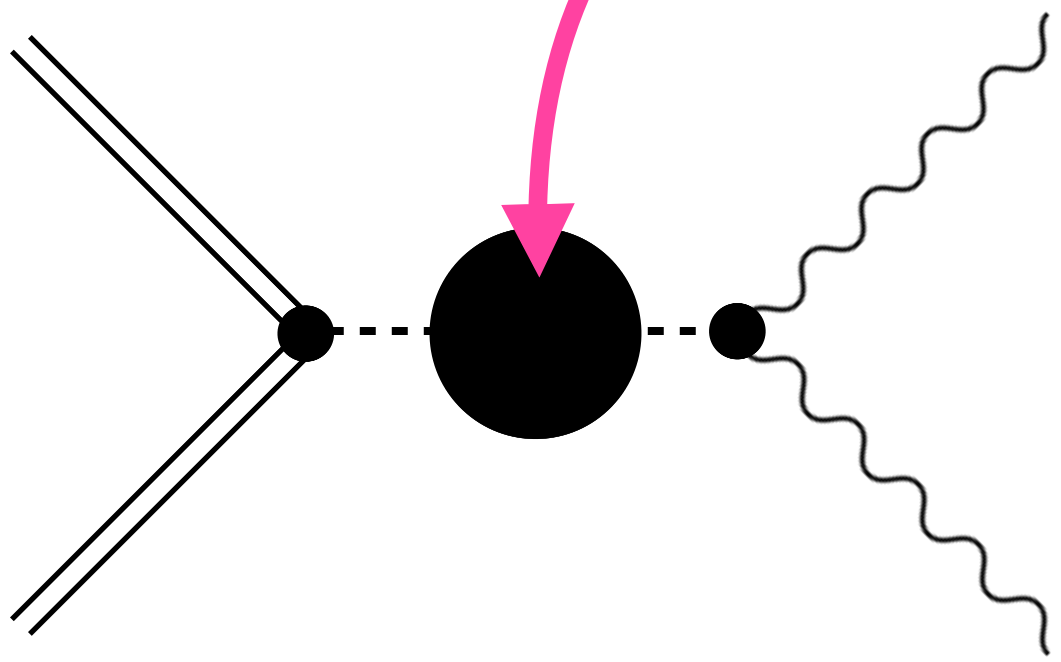


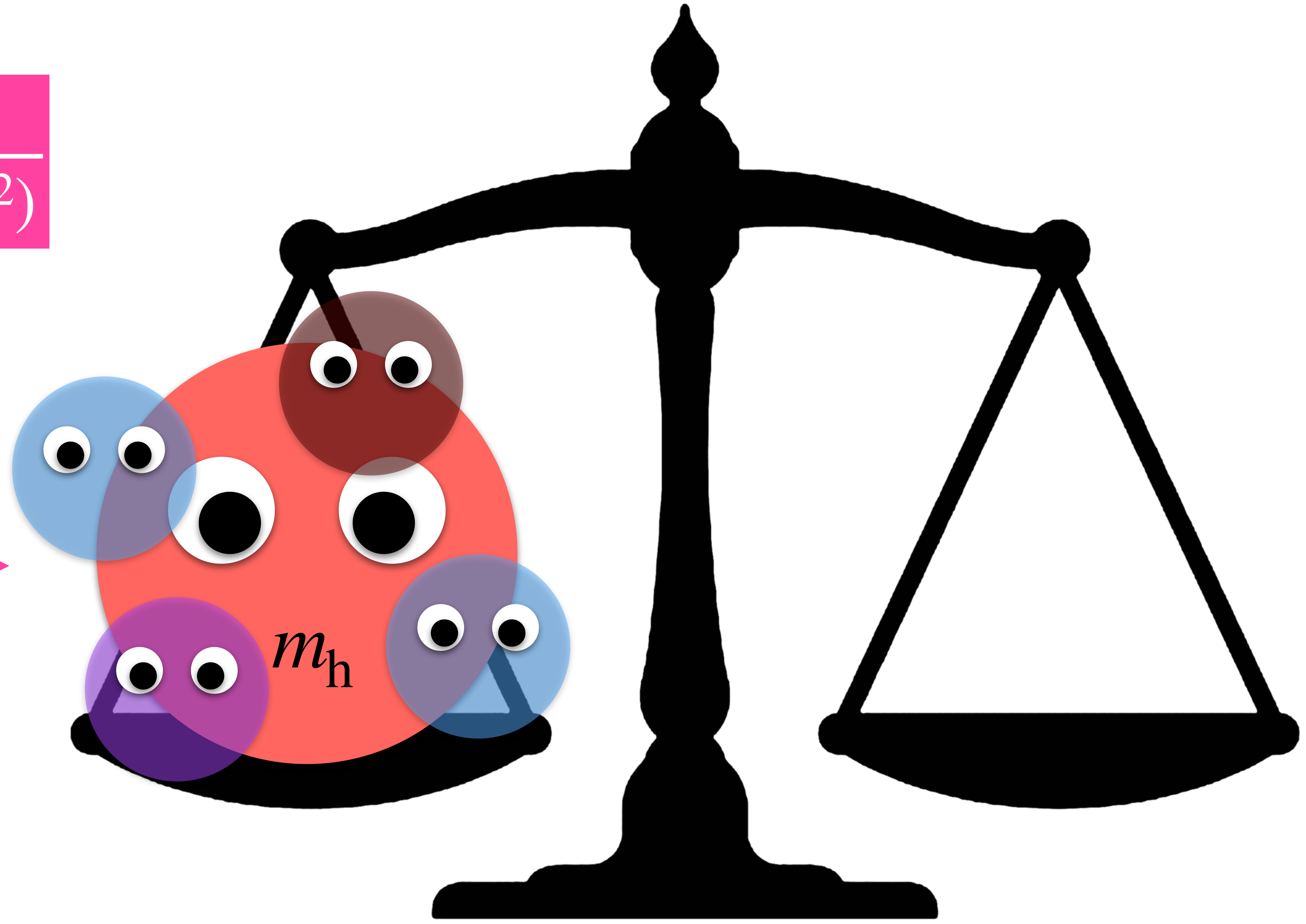
Beyond tree level, this potential receives corrections!

What do you measure?

$$\mathscr{L}_{\text{higgs}} = \underbrace{(D_\mu\Phi)^\dagger(D_\mu\Phi) + m_{\text{h}}^2\Phi^\dagger\Phi + \mathscr{L}_{\text{higgs}}^{\text{corrections}}} - \lambda\left(\Phi^\dagger\Phi\right)^2$$

$$\frac{1}{p^2 - m_{\text{h}}^2 - i\Pi(p^2)}$$





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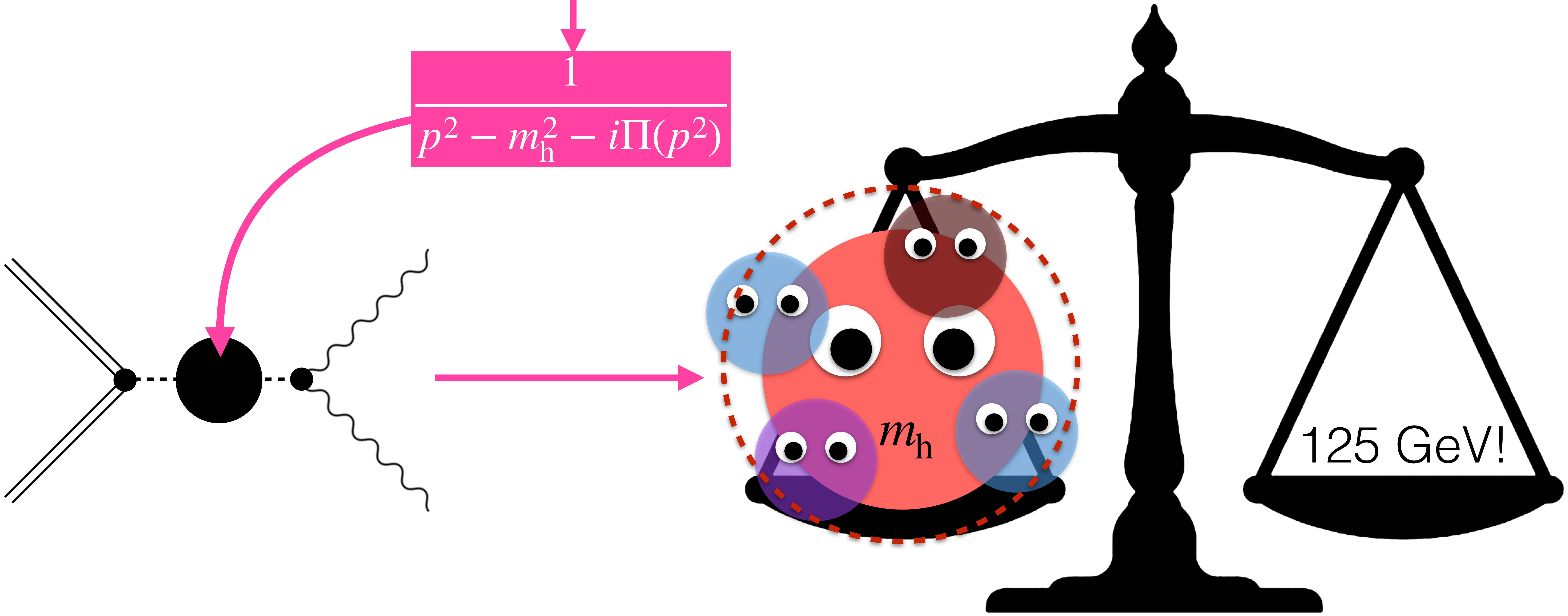

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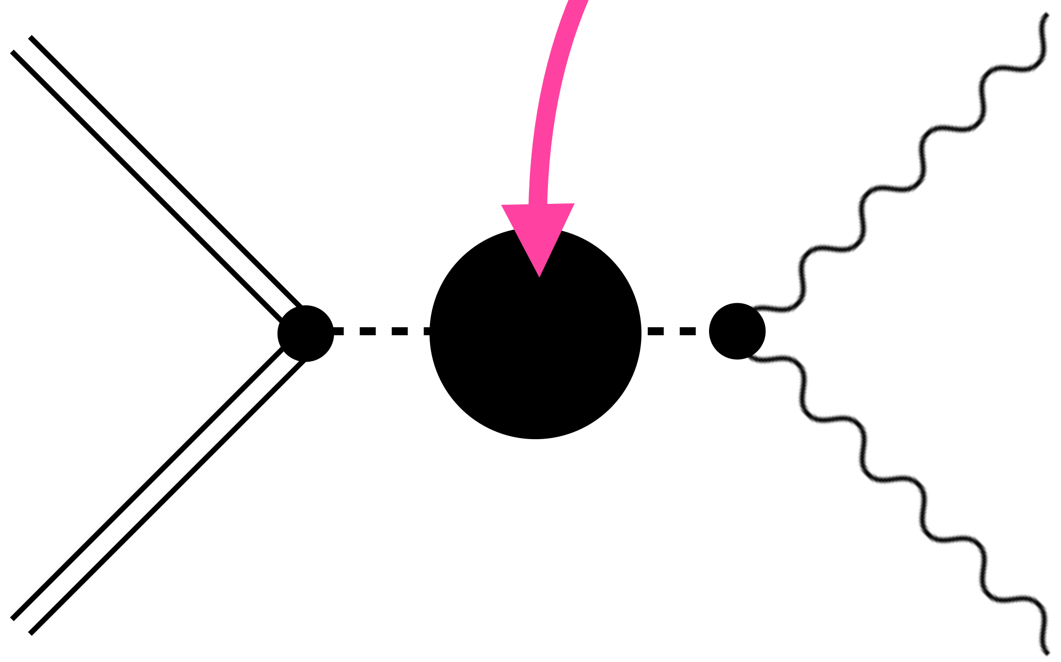
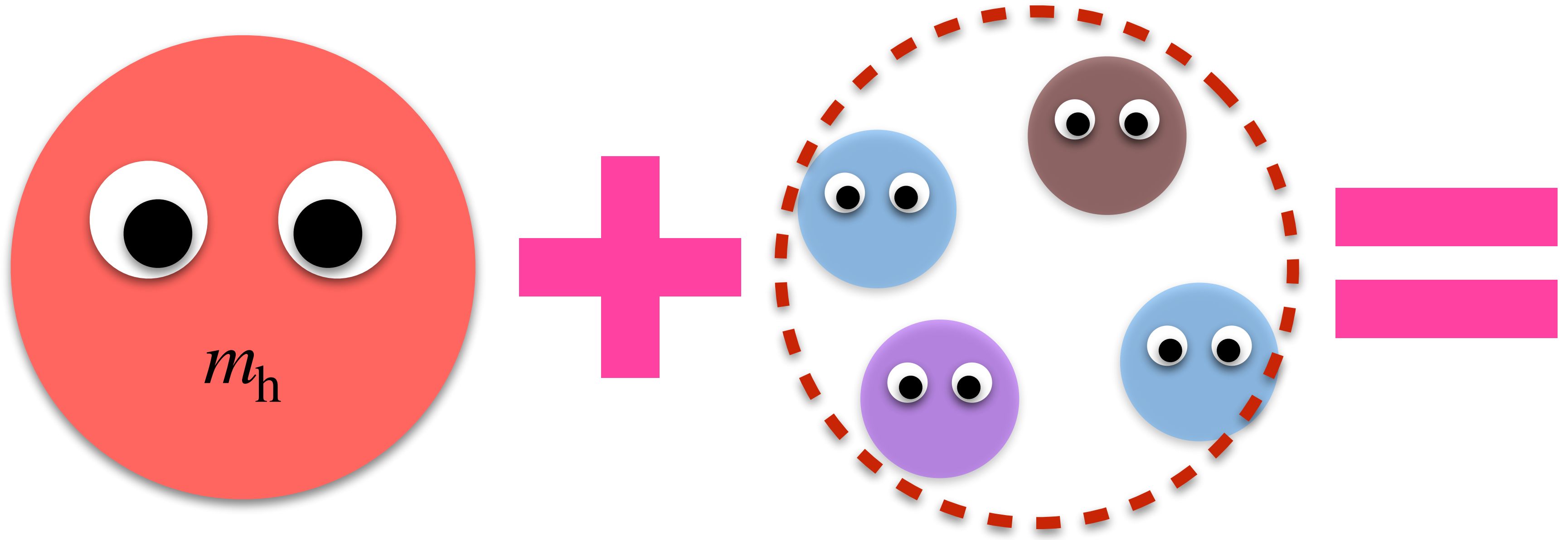




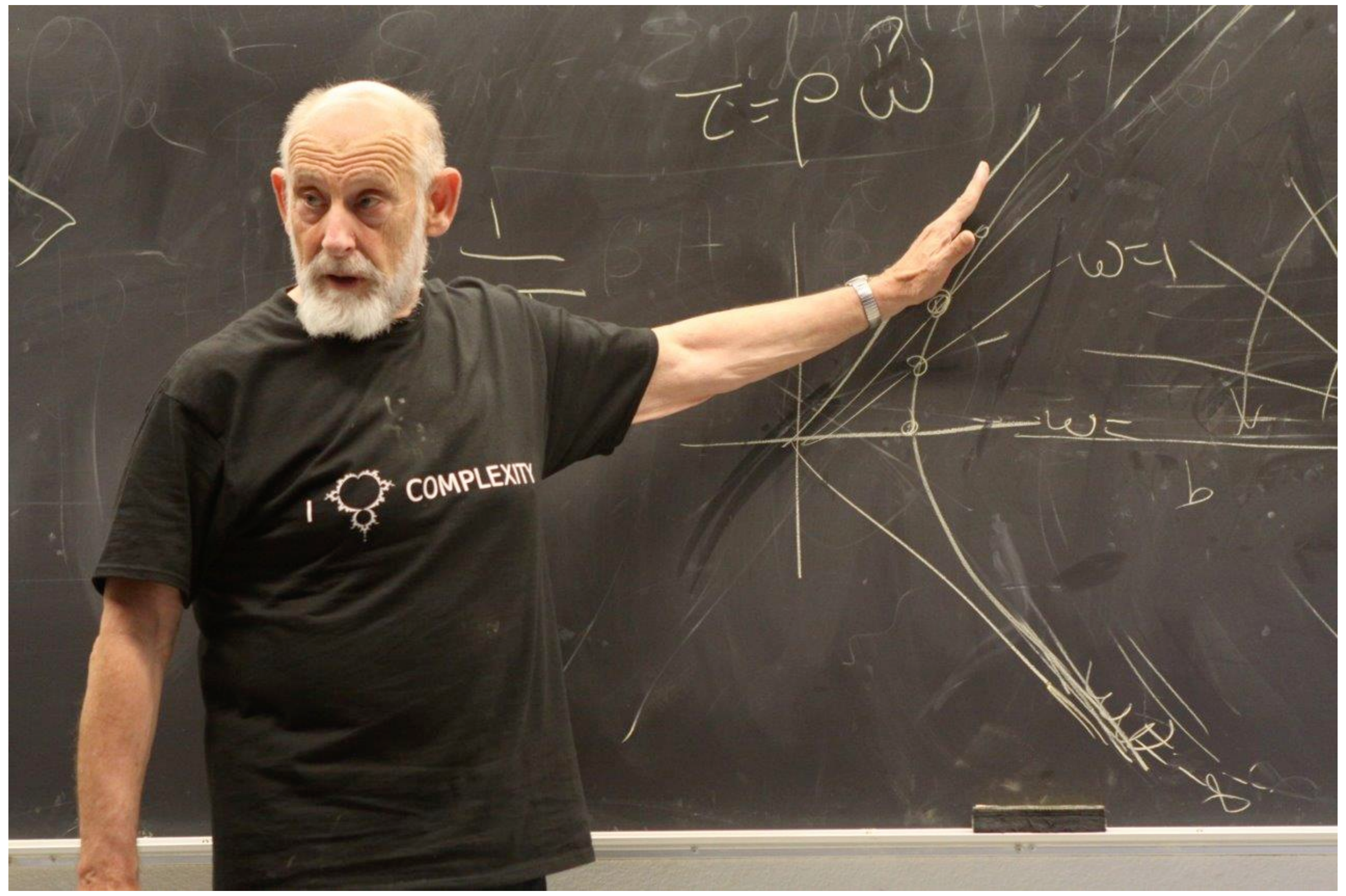
125 GeV

$\boxed{p^2}$

$\boxed{m_{\text{h}}^2 + i\Pi(p^2)}$

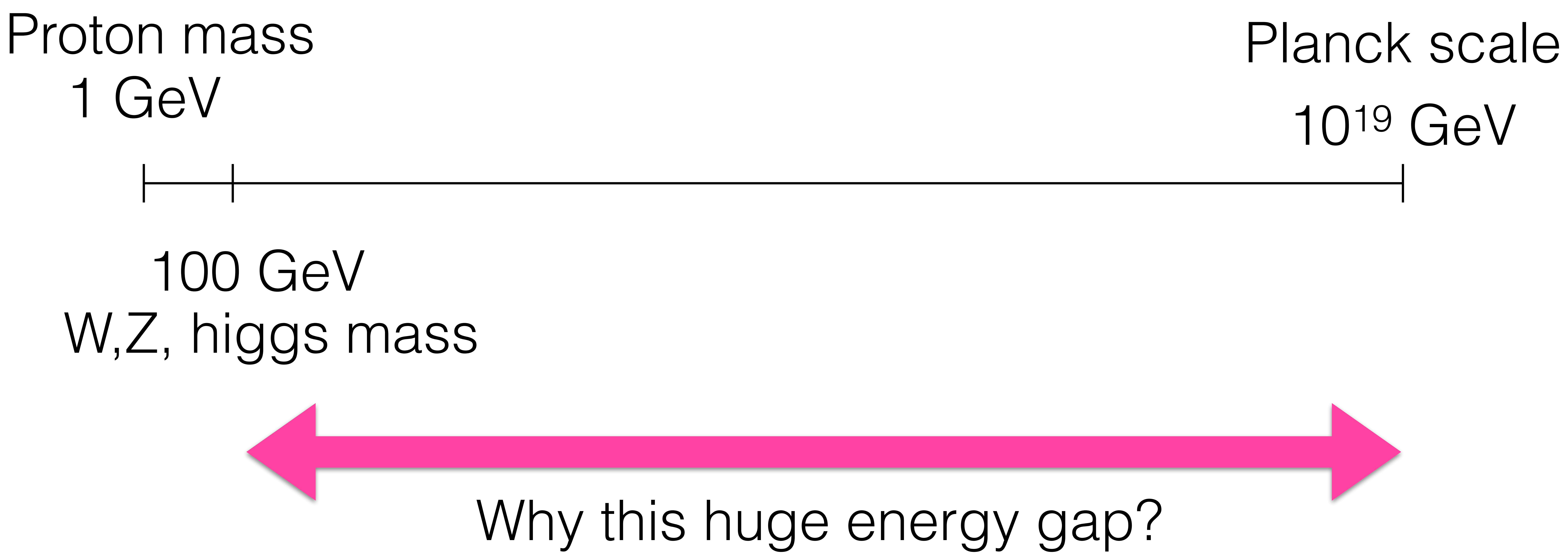
Where the trouble began

L. Susskind - Dynamics of spontaneous symmetry breaking in the Weinberg-Salam theory (1978)



“The need for scalar particles is a *serious flaw*”

The Hierarchy problem



Susskind’s realization

- At the Planck scale our theory breaks down and gravity effects start to play an important role

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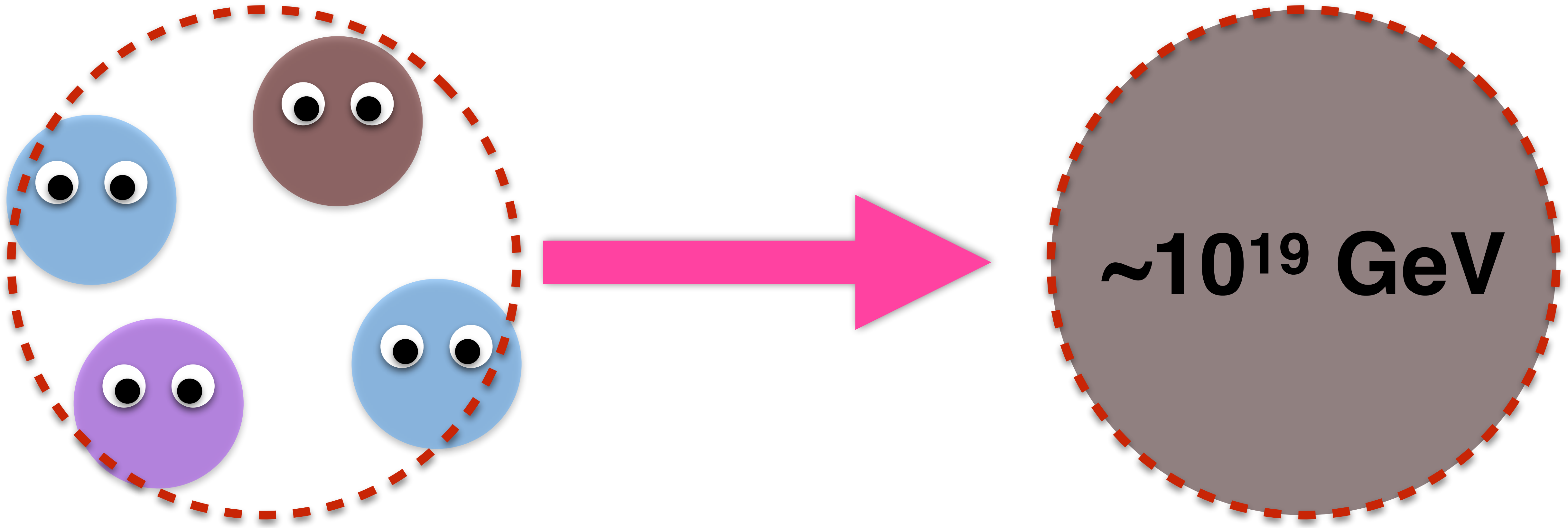
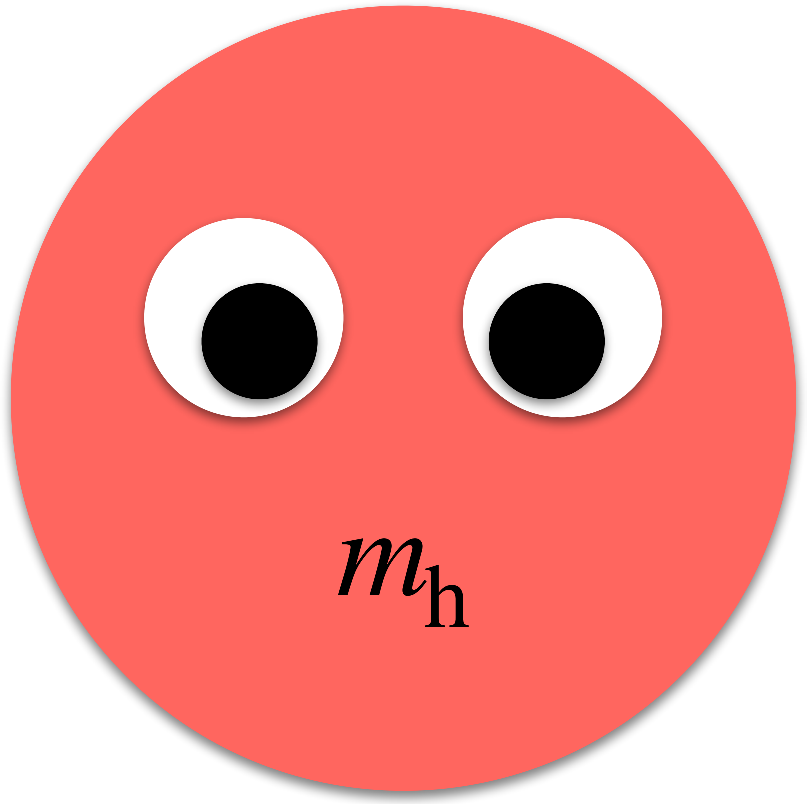
- At the Planck scale our theory breaks down and gravity effects start to play an important role
- Higgs couples all masses, and in particular to the highest mass
- *Therefore QM corrections on the Higgs boson mass become of the order of the Planck scale!*



Fine-tuning

To get this cancellation, one would need to fine-tune 16 digits!

Fine-tuning



$+$ $\sim 10^{19}$ **GeV** $=$ 125 GeV

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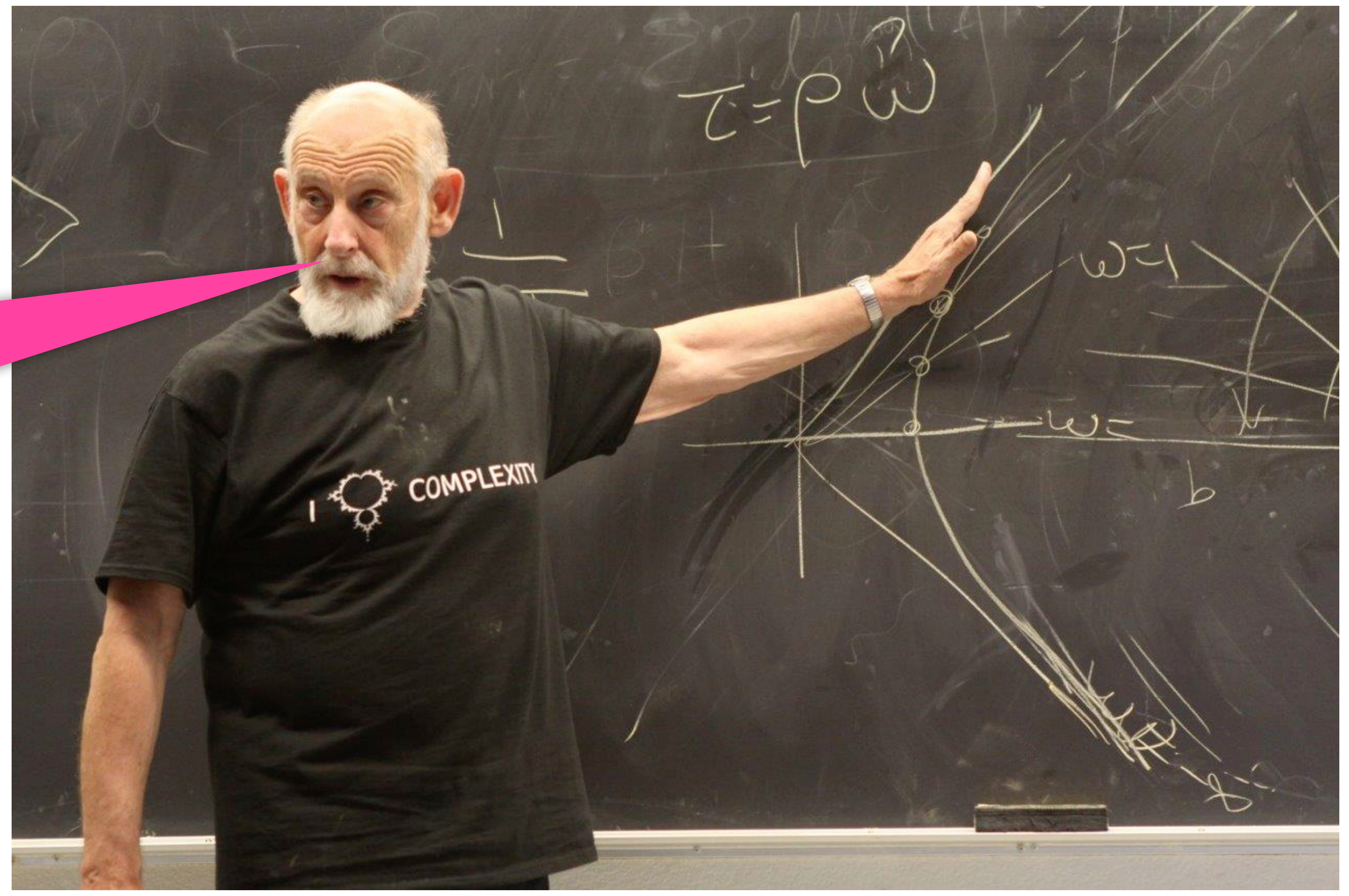
Hierarchy problem = fine-tuning problem!



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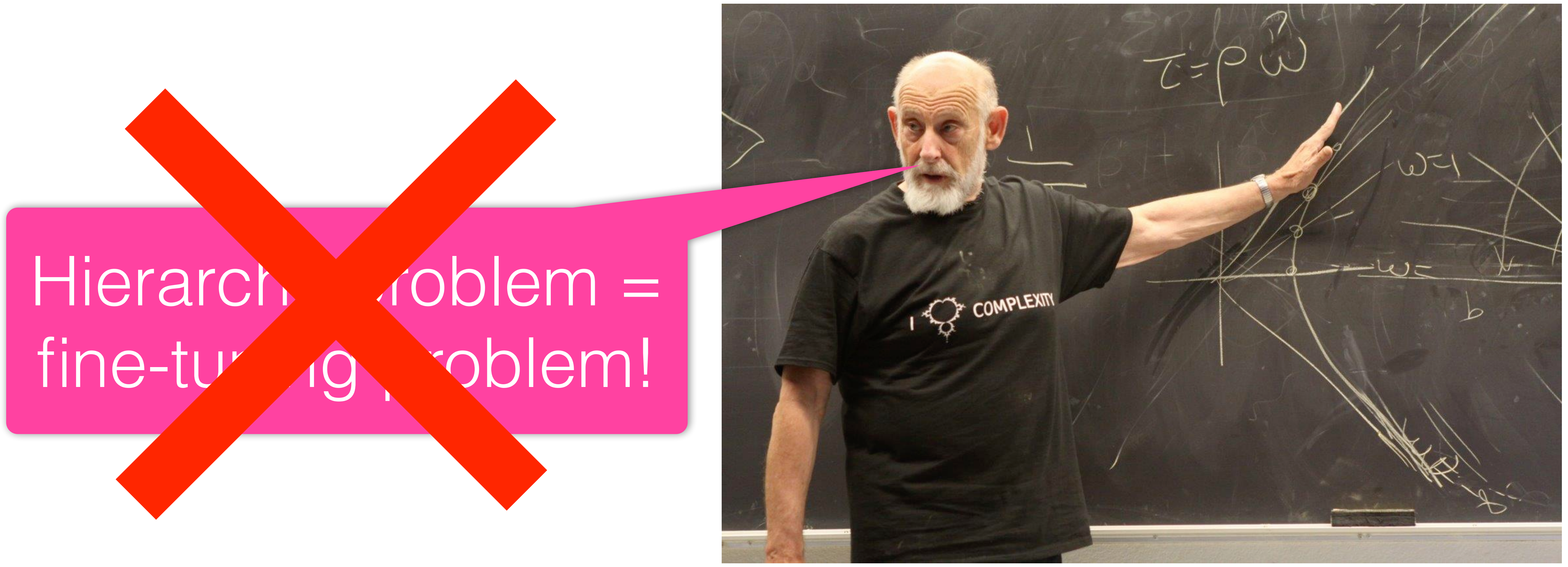
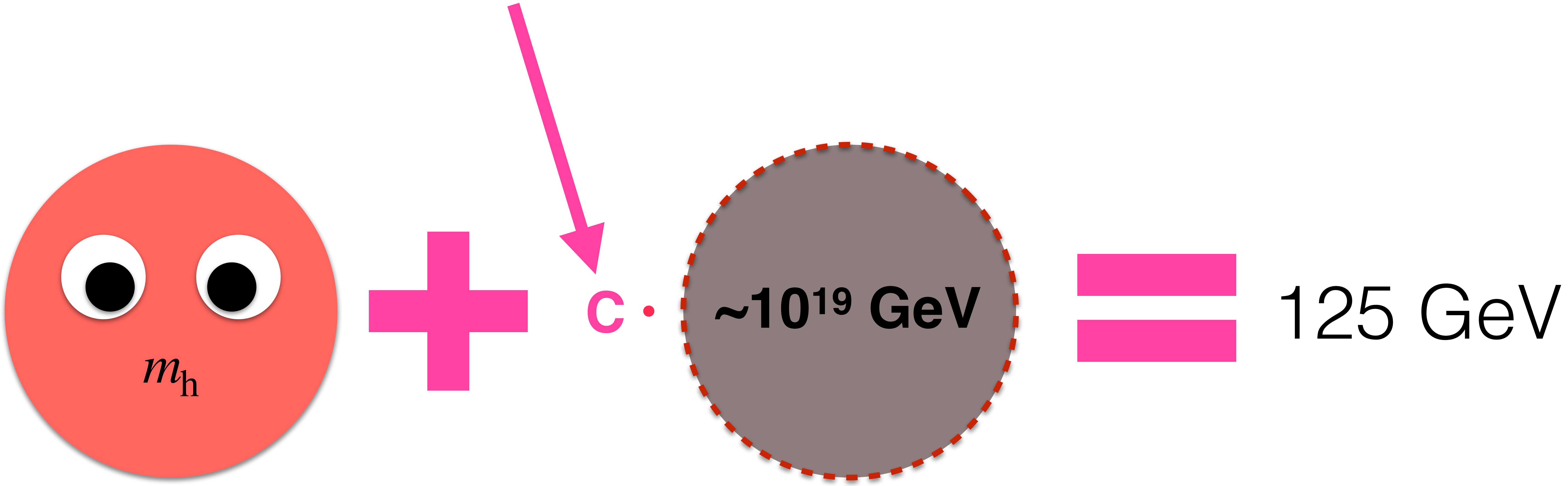


The scale of new physics must **in some way couple** to the Higgs boson!

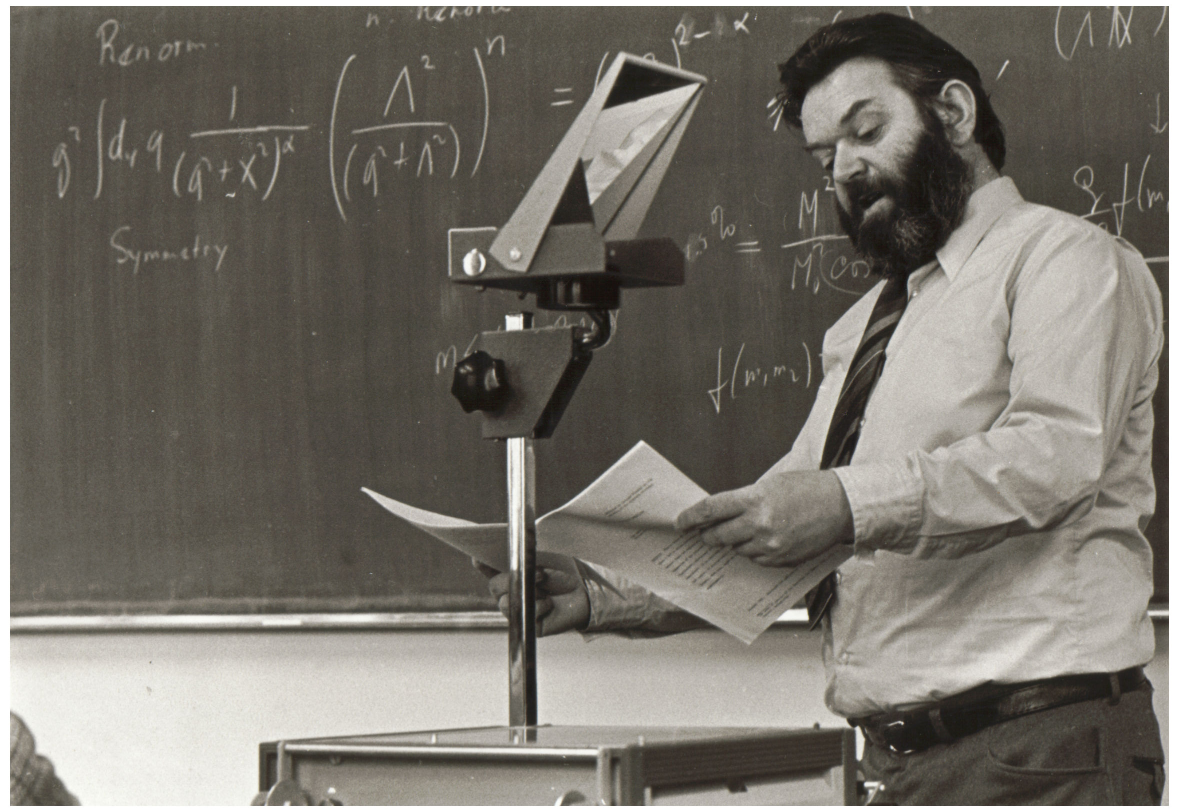


New insight

M. Veltman - *The infrared-ultraviolet connection* (1980)

- Builds on Susskind's paper, but with one small modification:

"One must compare the size of the QM *corrections* to the size of the observed quantity"



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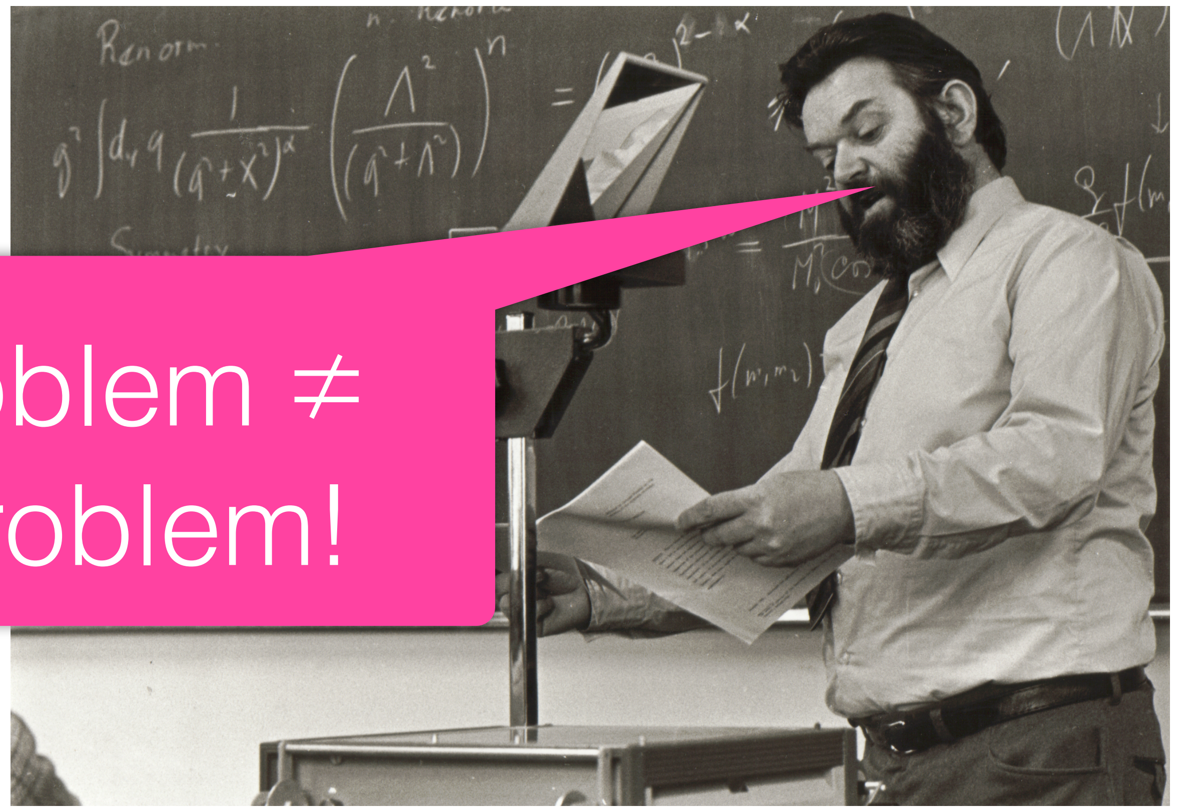

Hierarchy problem ≠ fine-tuning problem!

Large hierarchies are allowed without introducing a fine-tuning problem!

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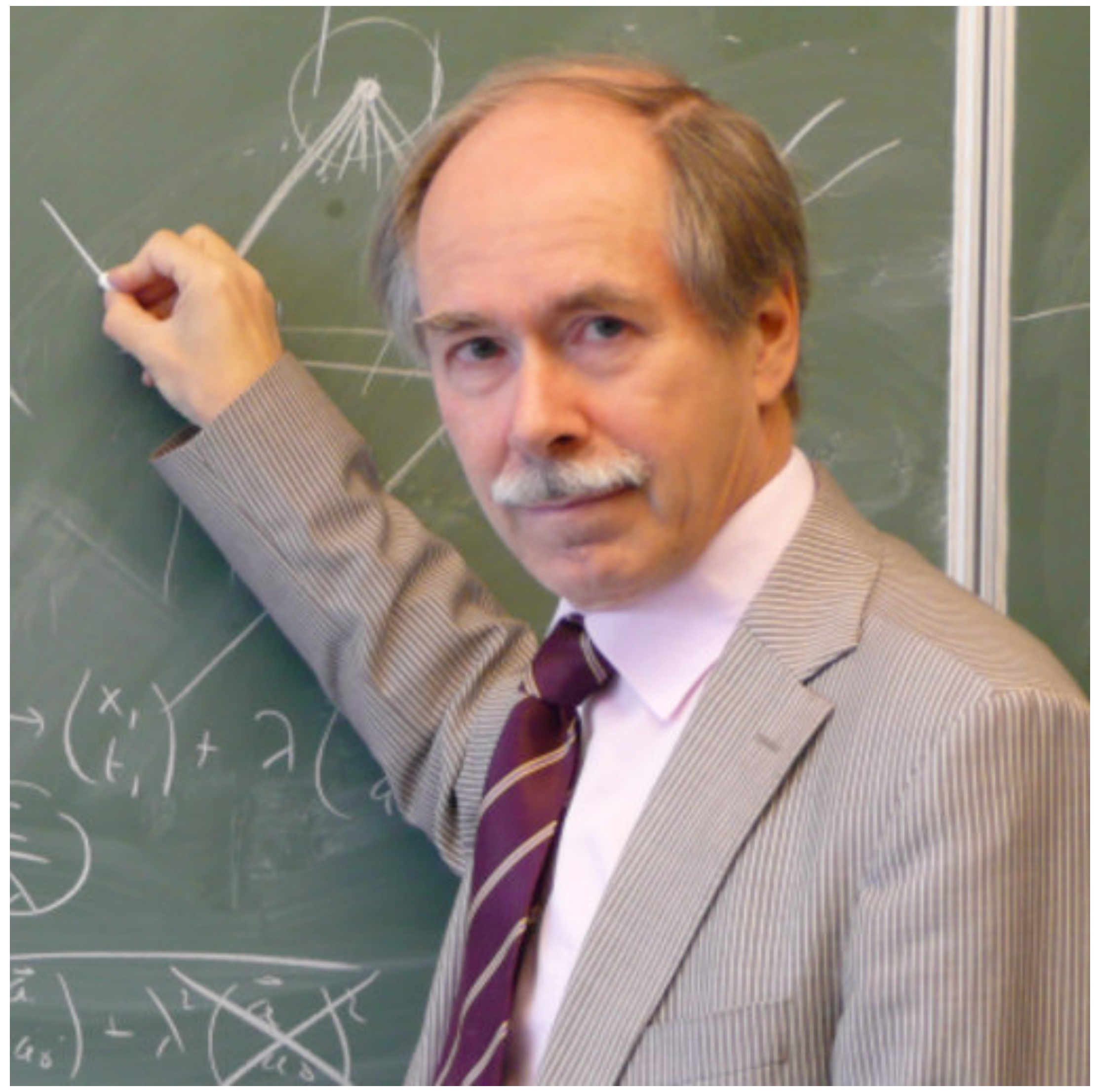
But in which cases does it introduce a fine-tuning problem?

Higgs is special

G. 't Hooft - *Naturalness, Chiral symmetry and spontaneous chiral symmetry breaking* (1979)

"A parameter is only allowed to be small if setting the parameter to 0 increases the symmetry of the system"



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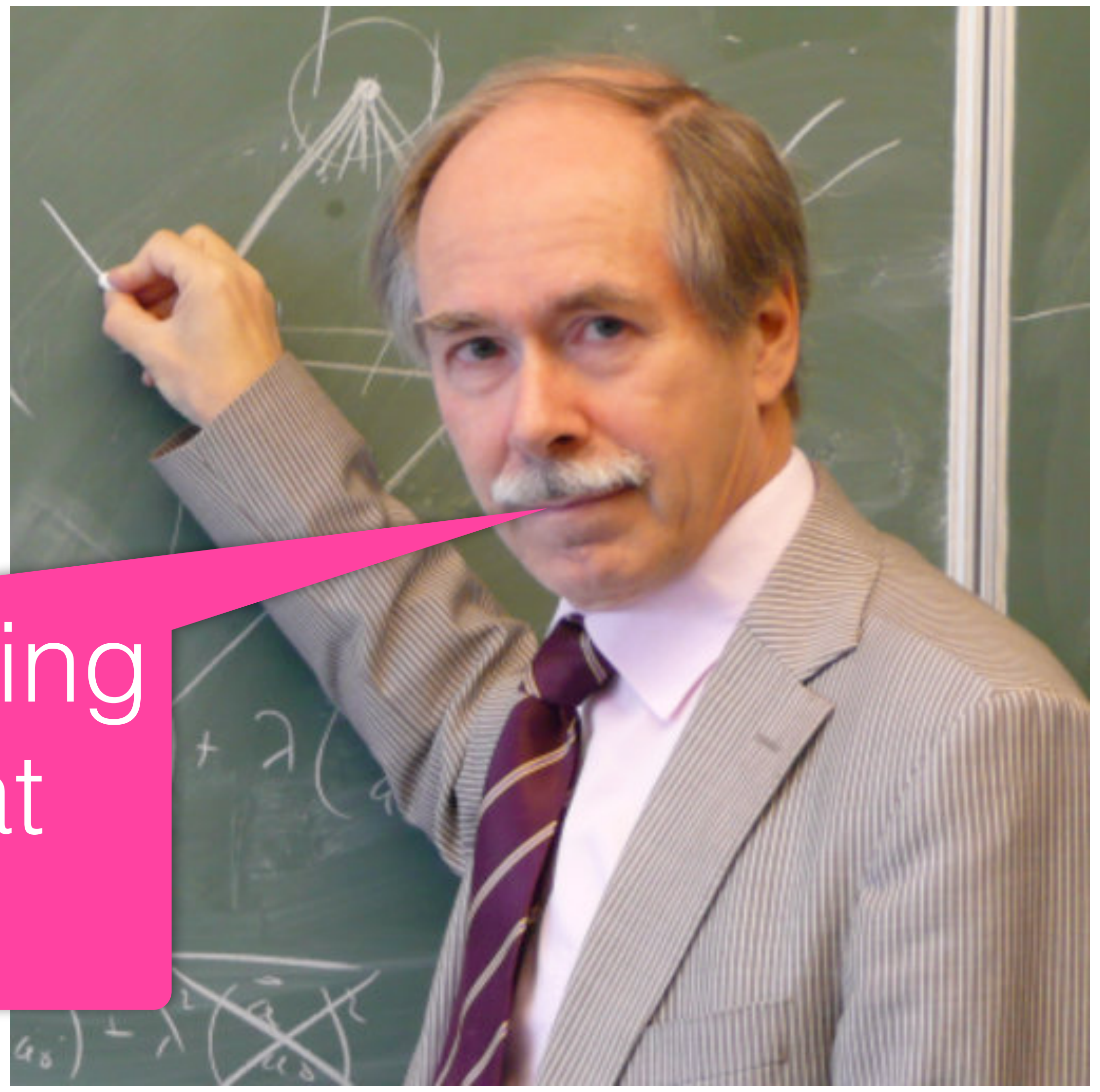

The Higgs has no protecting symmetry, which is what makes it special

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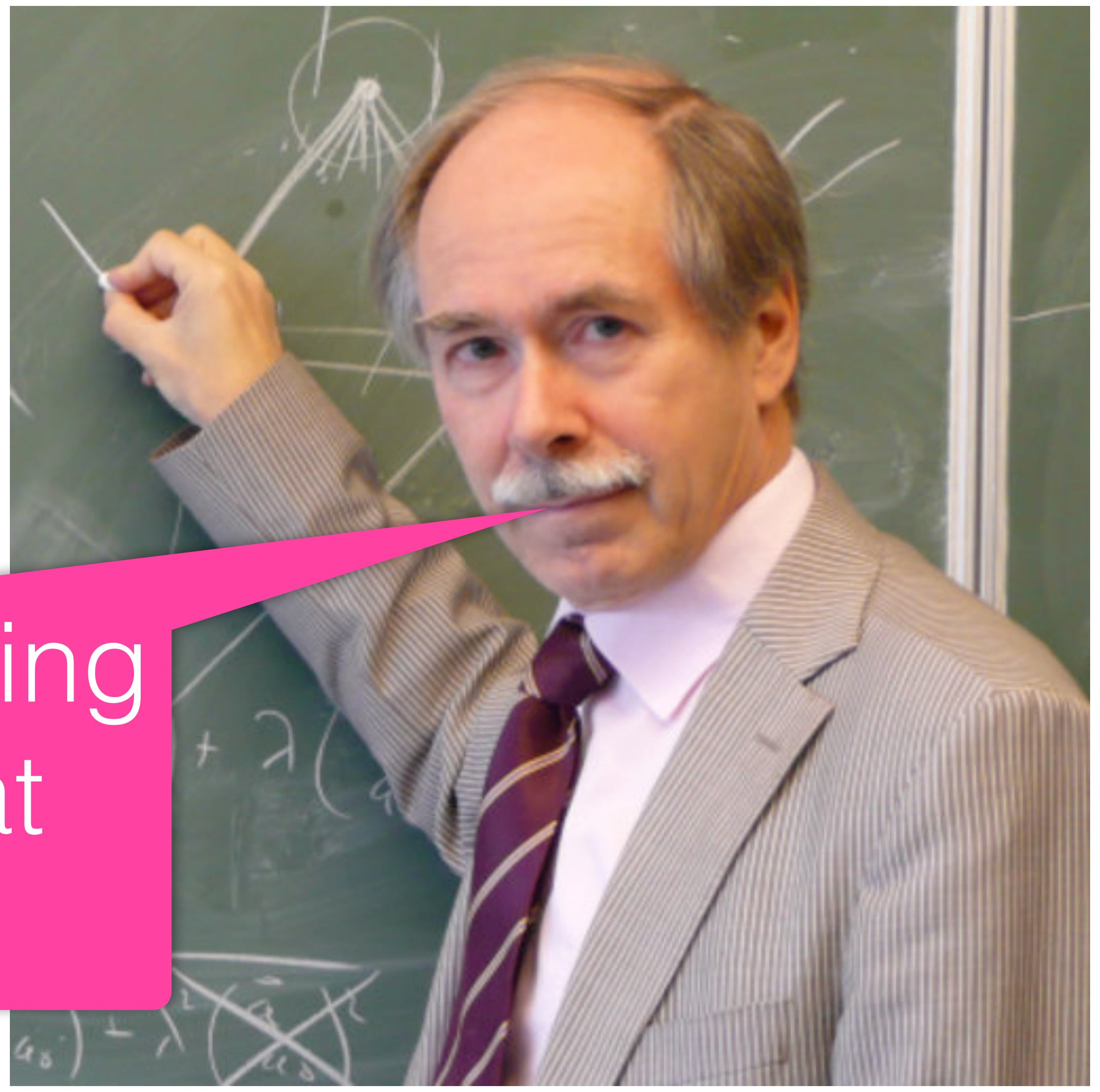

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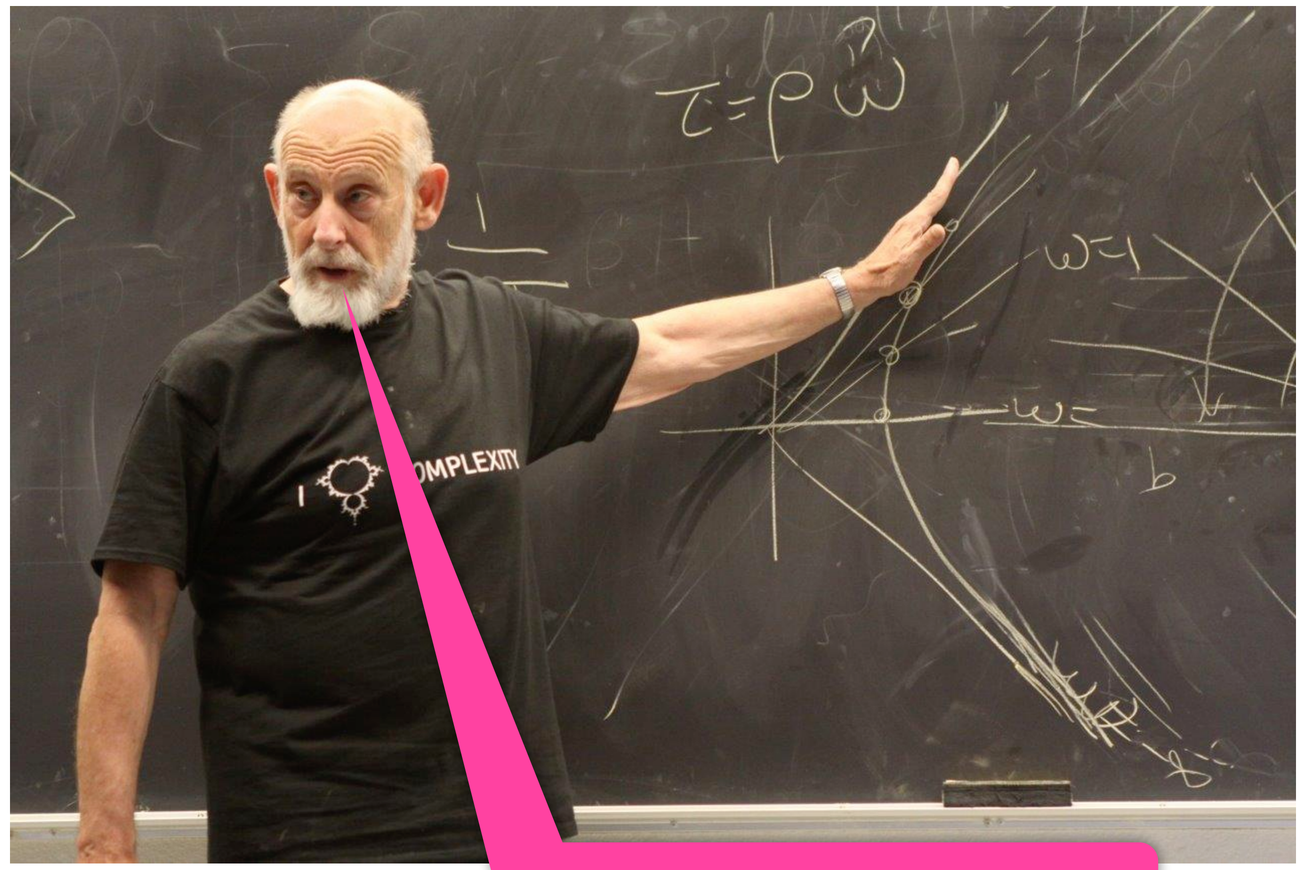
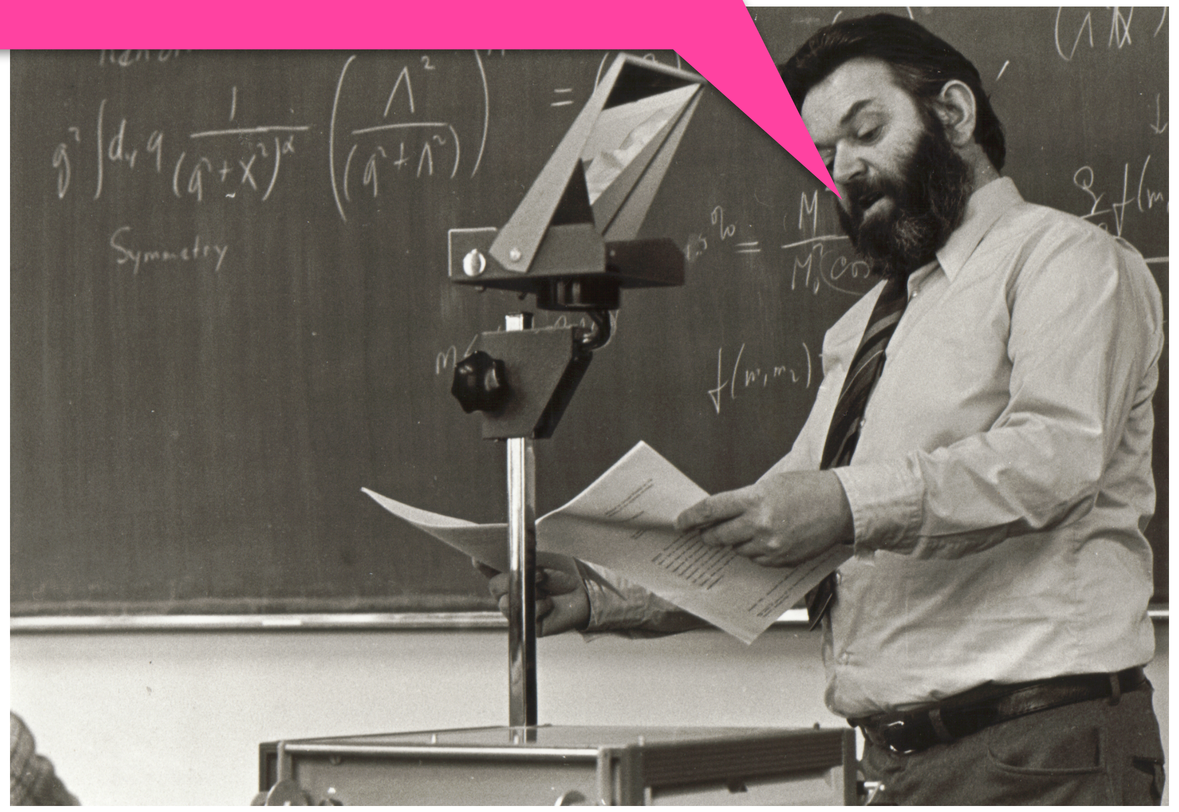
We will come back to this point

Higgs fine-tuning?

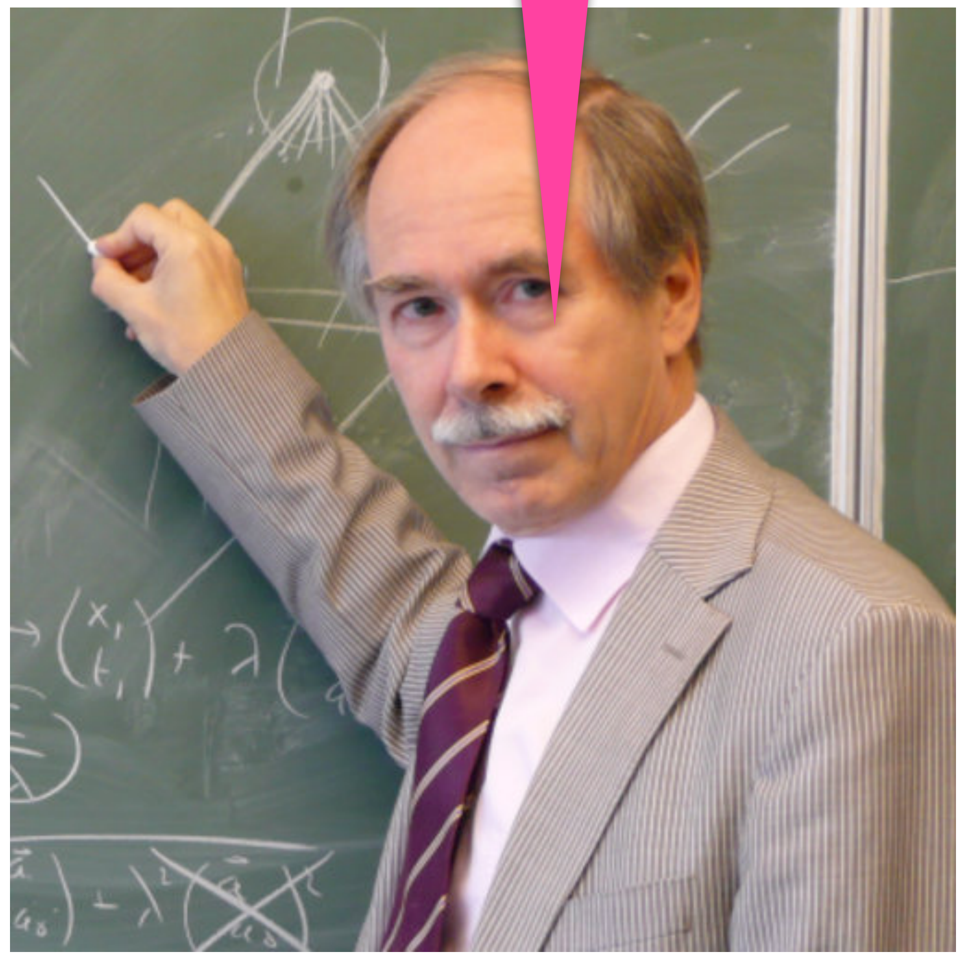


It is about the Planck scale!

No, it is about the QM corrections!



And the lack of symmetries are to blame!



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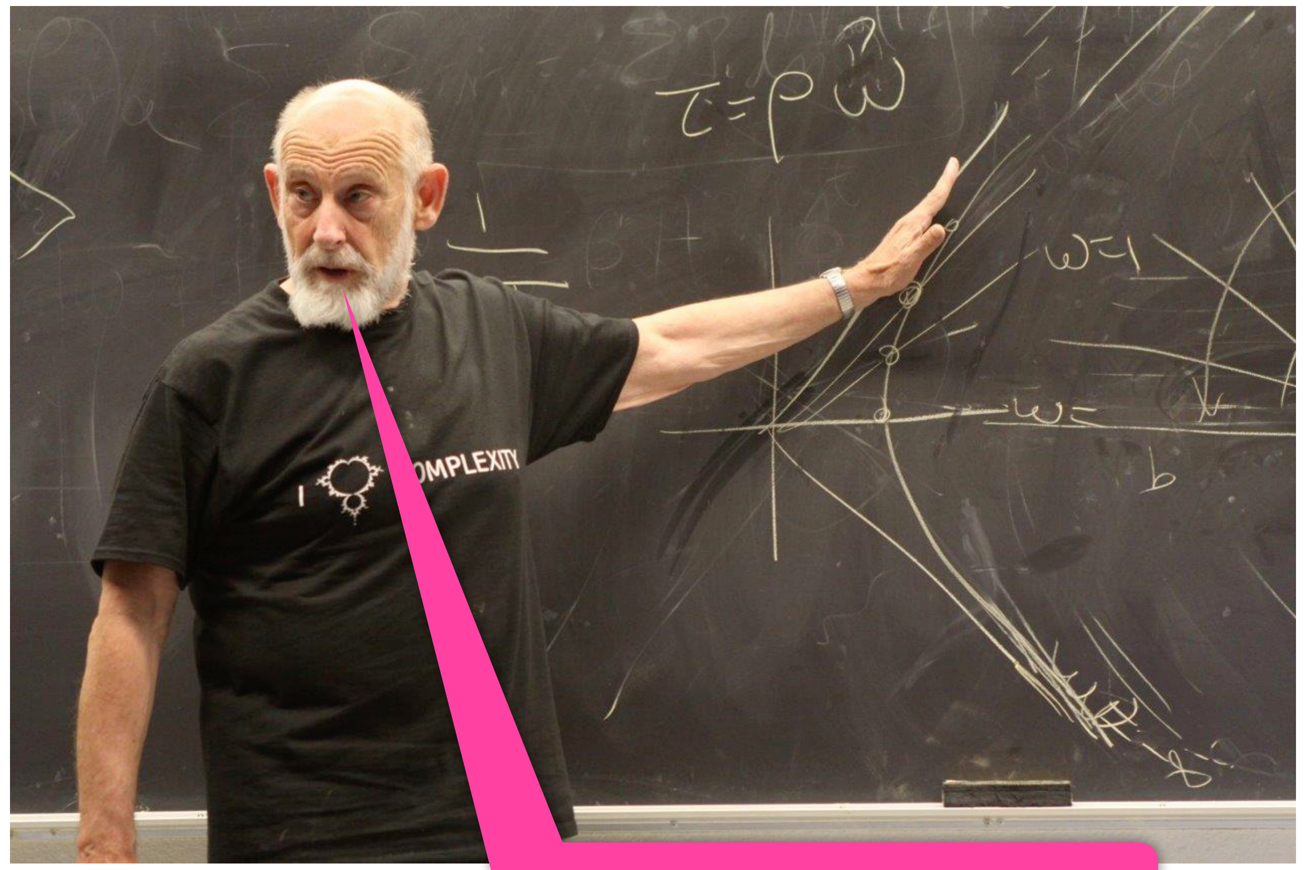

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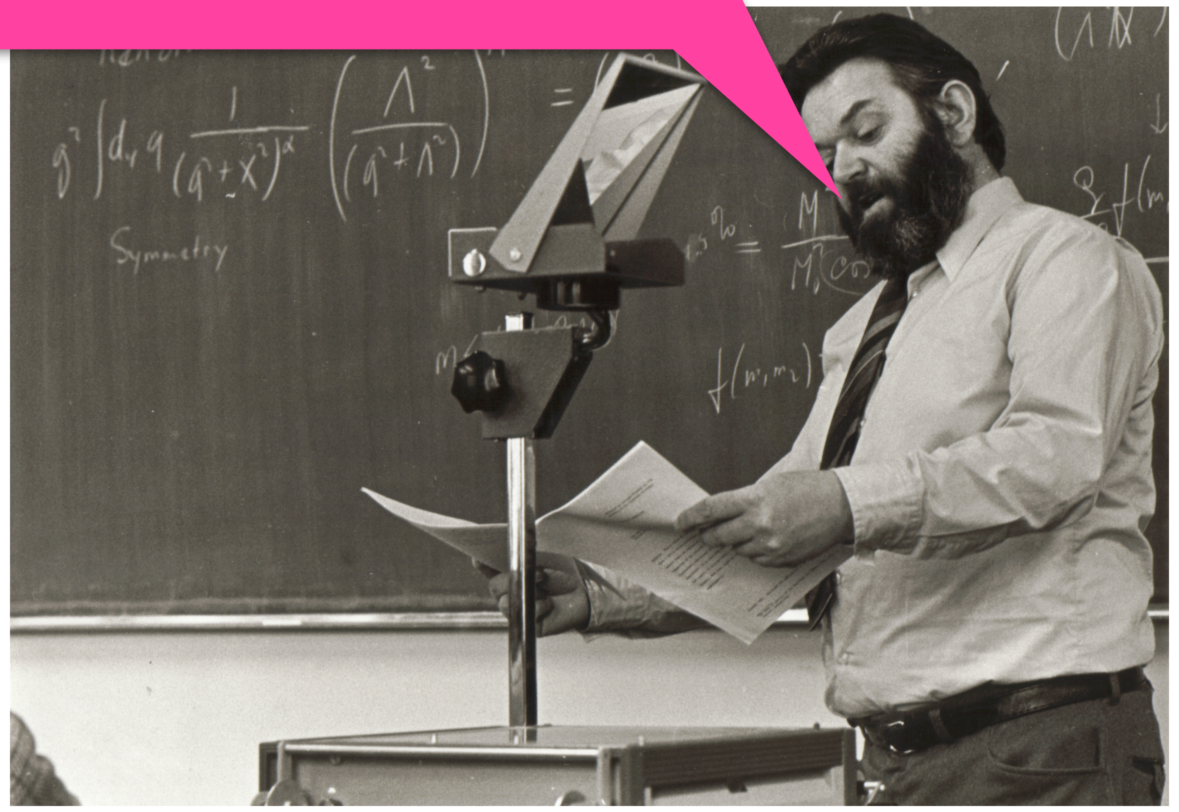

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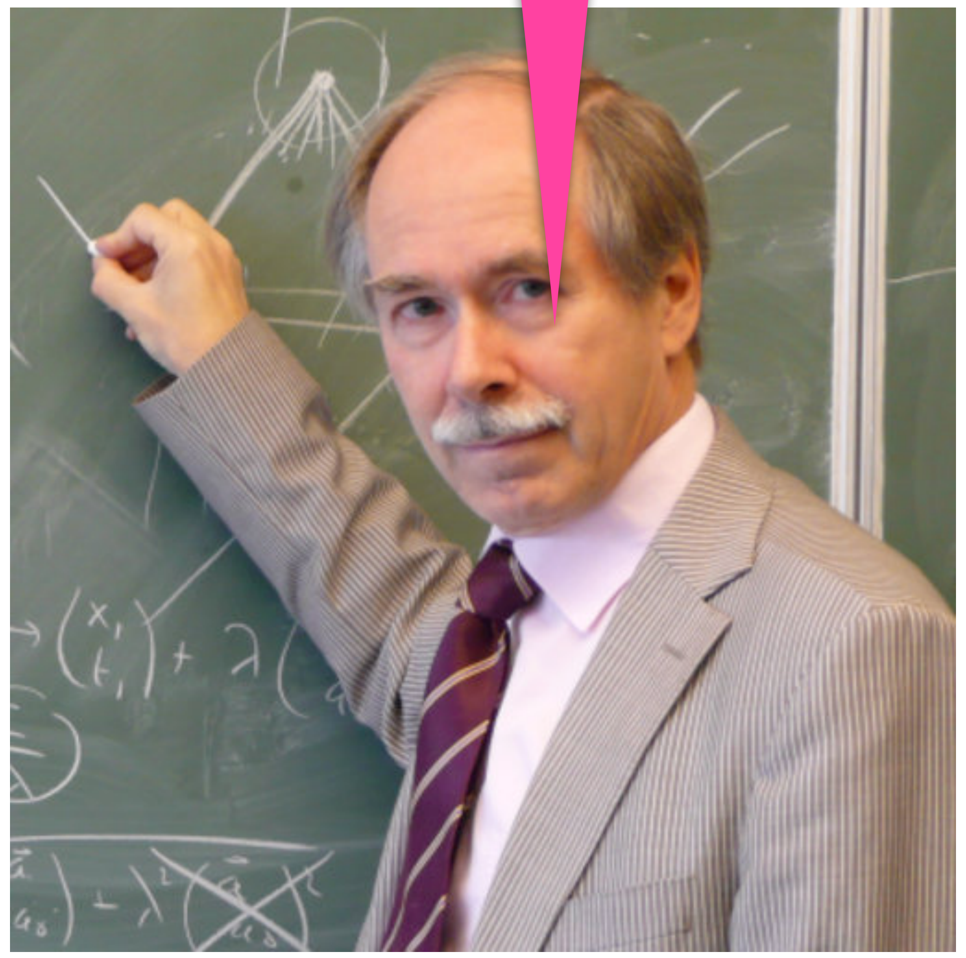

But what is fine-tuning?

Fine-tuning is…

…when an observable (e.g. the Higgs mass) changes a lot as a consequence of a tiny change in other observables of the theory

The Higgs fine-tuning is **not the same as**…

- *The hierarchy problem*
- *(Technical) naturalness, the demand that every parameter should be of $O(1)$*
- *A volume in parameter space that gives rise to the observed quantities*

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- *The hierarchy problem*
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- *A volume in parameter space that gives rise to the observed quantities*

Moreover, Higgs fine-tuning does not appear in the SM!

Take home messages

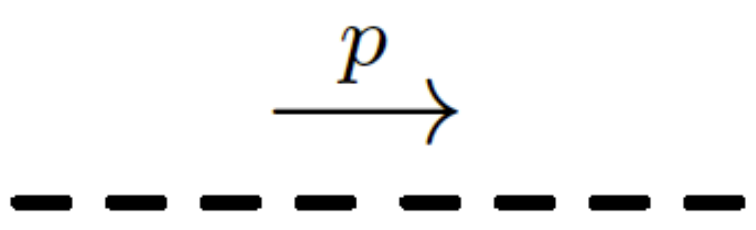
- Fine-tuning occurs when an observable (e.g. the Higgs mass) changes a lot as a consequence of a tiny change in the other observables of the theory
- Is not directly caused by a hierarchy of scales
- Can only occur in beyond-the-SM scenarios; the SM *has no fine-tuning problem*

Take home messages

- Fine-tuning occurs when an observable (e.g. the Higgs mass) changes a lot as a consequence of a tiny change in the other observables of the theory
- Is not directly caused by a hierarchy of scales
- Can only occur in beyond-the-SM scenarios; the SM *has no fine-tuning problem*

And now the fun begins…

Let’s put this into formulas!

Higgs propagator at tree level: $\dfrac{1}{p^2 - m_{\mathrm{h}}^2}$ $=$ 

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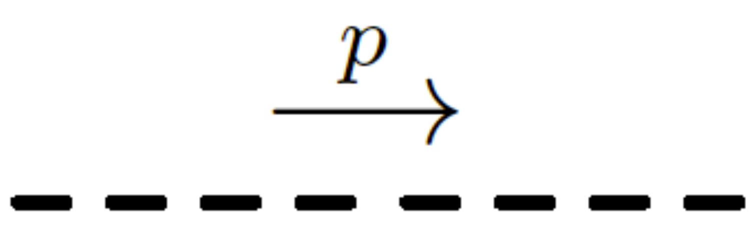
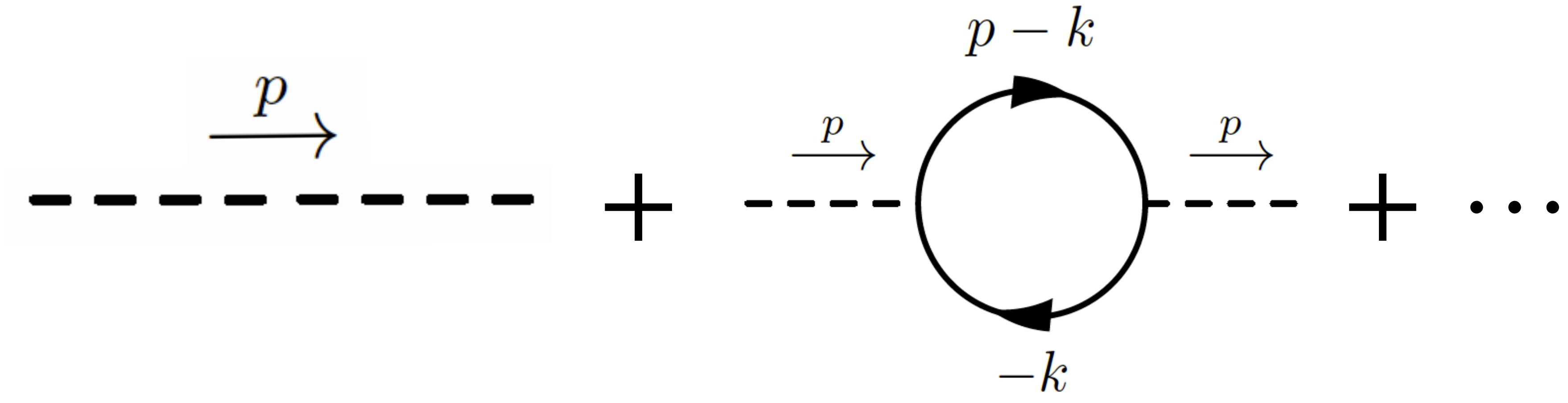
Higgs propagator at tree level: $$\frac{1}{p^2 - m_\mathrm{h}^2} =$$ 

Full Higgs propagator: $$\frac{1}{p^2 - m_\mathrm{h}^2 - i\Pi(p^2)} =$$ 

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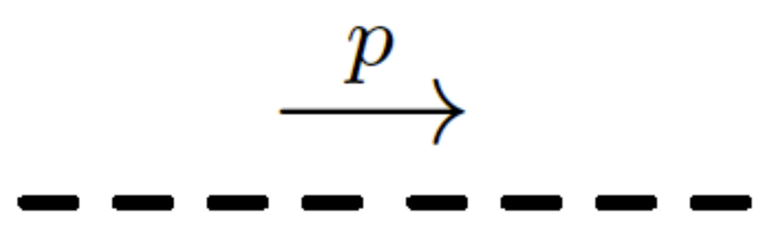

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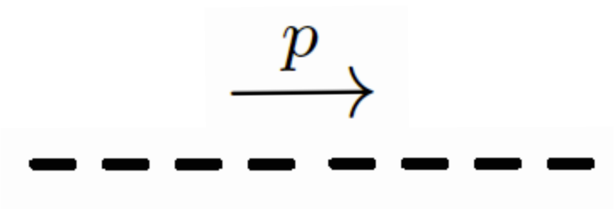
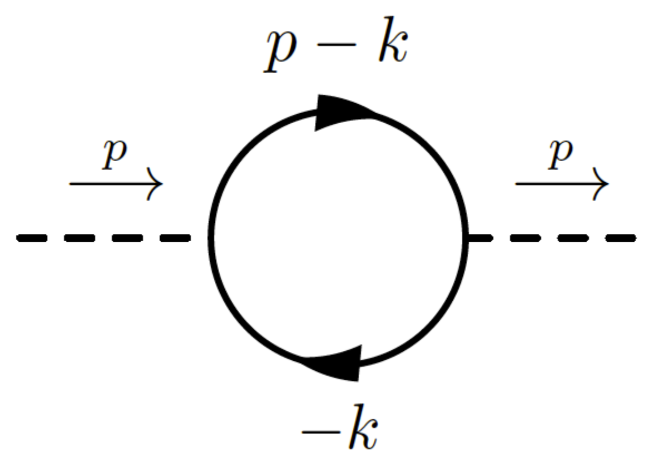


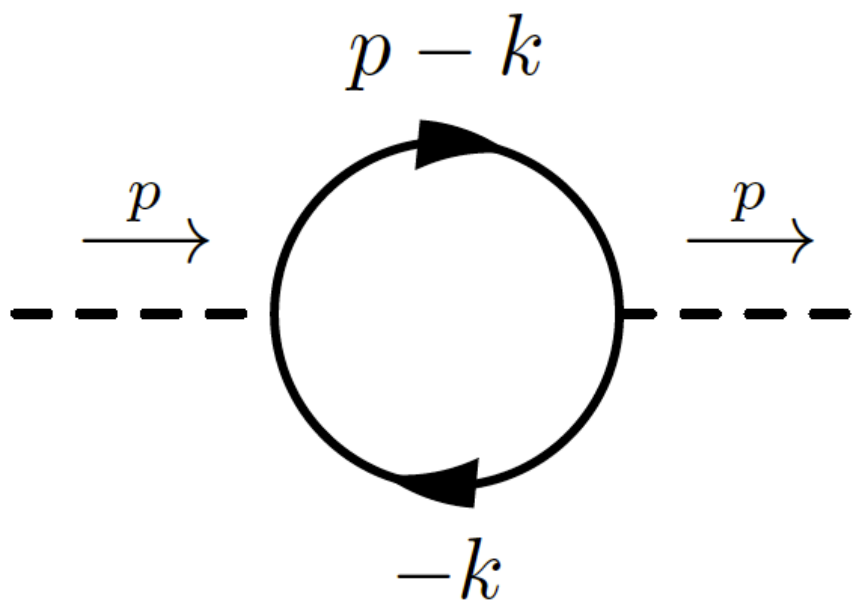
$+$



$+ \cdots$

a contribution to the one-loop self energy

Calculation of the one-loop self energy

$i\Pi(p^2) =$ 

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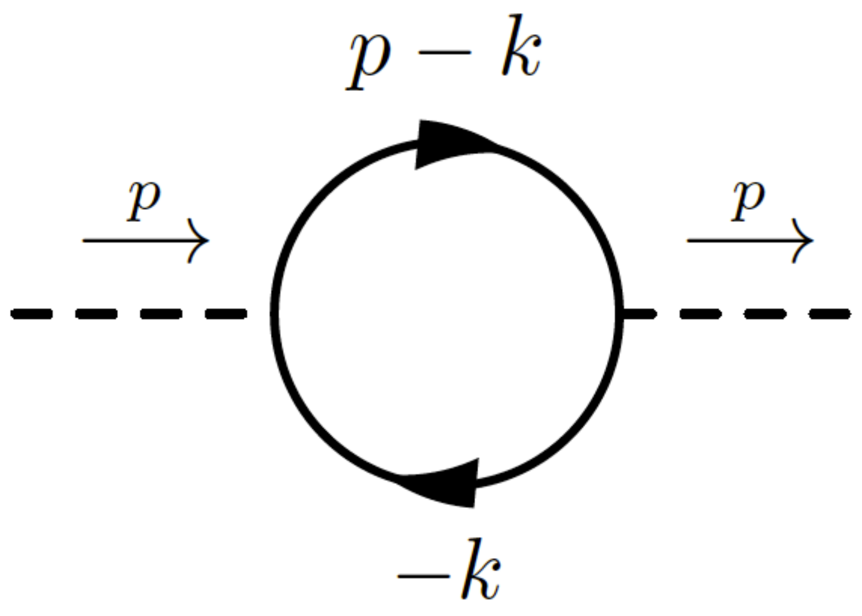
$i\Pi(p^2) =$ 

$=$

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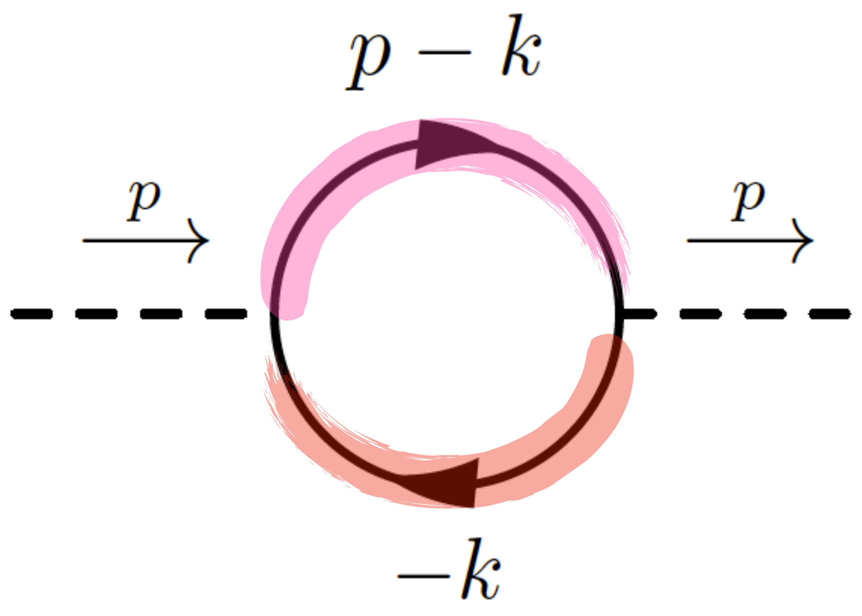
$i\Pi(p^2) =$ 

$$= \qquad \frac{i(\not{p} - \not{k} + m_f)}{(p-k)^2 - m_f^2}\,\frac{i(-\not{k} + m_f)}{k^2 - m_f^2}$$

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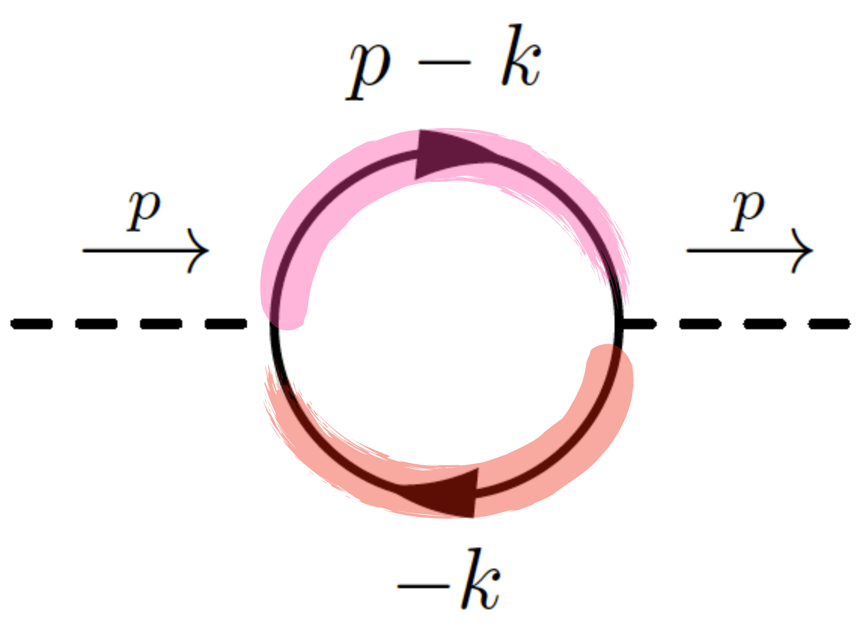
$i\Pi(p^2) =$ 

$$= \quad -\int \frac{\mathrm{d}^4\mathrm{k}}{(2\pi)^4} \, \mathrm{Tr}\Big[\frac{(\not{p} - \not{k} + m_f)}{(p-k)^2 - m_f^2} \, \frac{(-\not{k} + m_f)}{k^2 - m_f^2}\Big]$$

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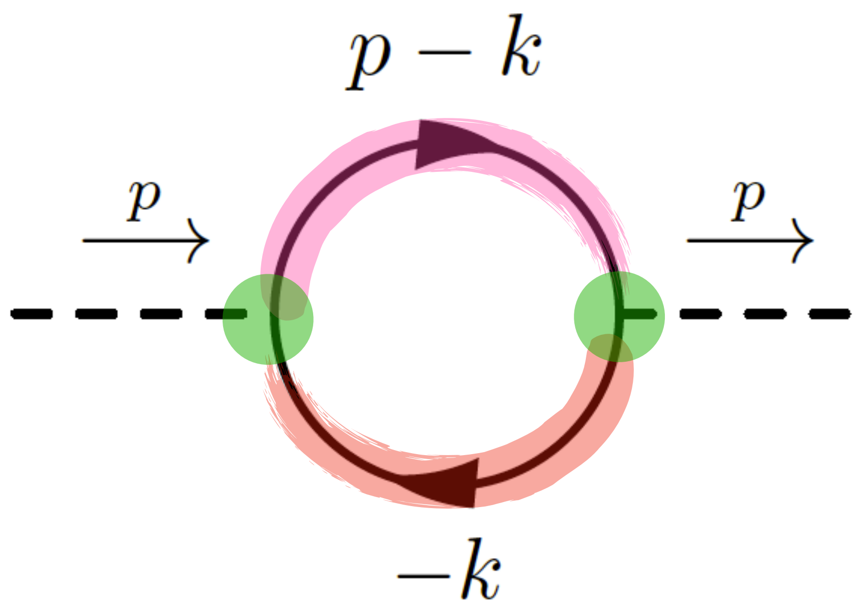
$i\Pi(p^2) =$ 

$$= \quad -\int \frac{\mathrm{d}^4\mathrm{k}}{(2\pi)^4}\, \mathrm{Tr}\left[\frac{(\cancel{p} - \cancel{k} + m_f)}{(p-k)^2 - m_f^2}\; \frac{(-\cancel{k} + m_f)}{k^2 - m_f^2}\right] \left(\frac{-iy_f}{\sqrt{2}}\right)^2$$

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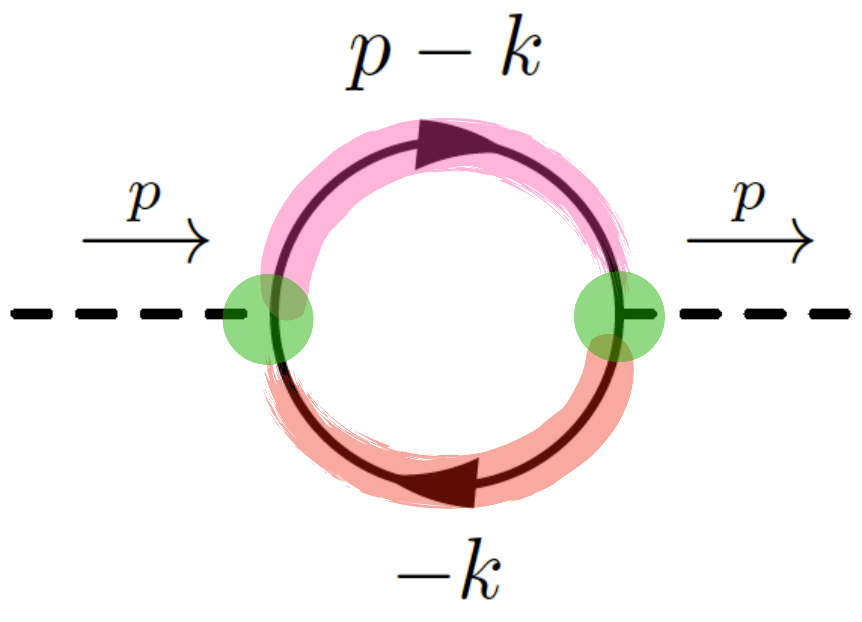
$i\Pi(p^2) =$ 

Proportional to k^6

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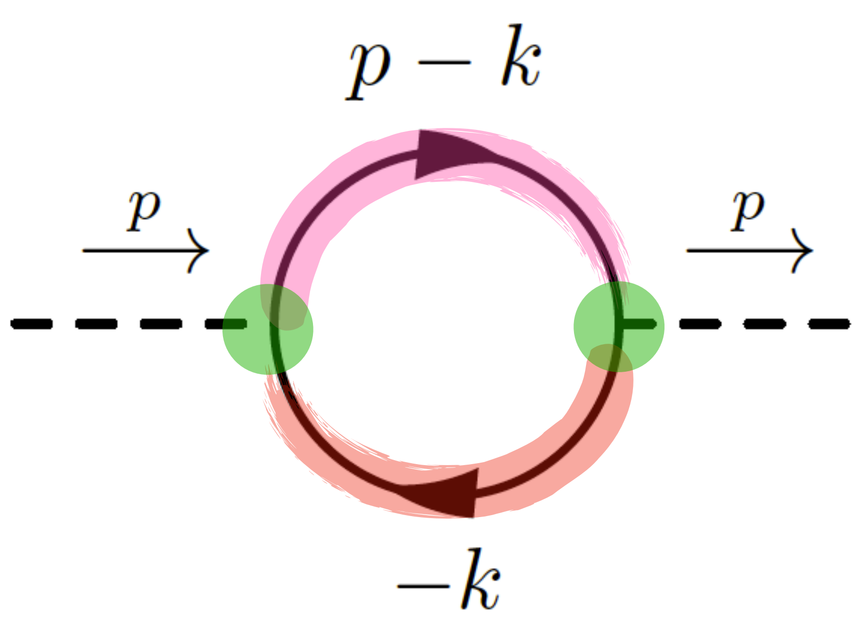
$i\Pi(p^2) =$ 

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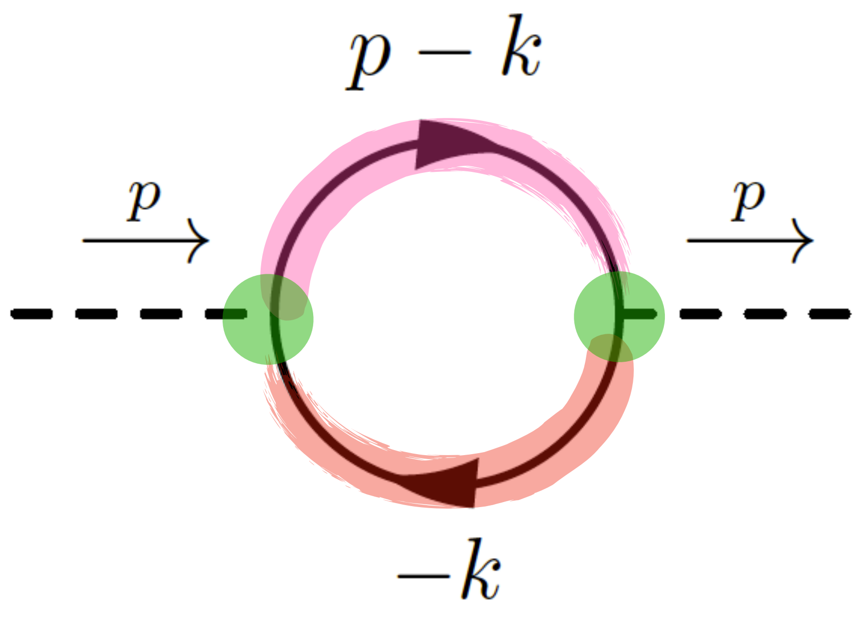
Proportional to k^6

Proportional to k^4

Calculation of the one-loop self energy

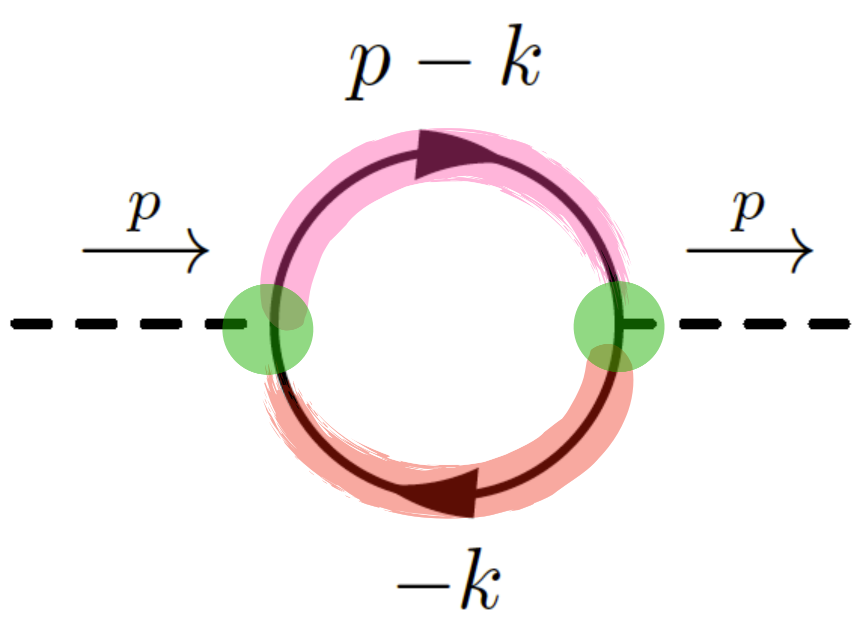
$i\Pi(p^2) =$ 

Proportional to k^6

$$= \quad -\int \frac{\mathrm{d}^4\mathrm{k}}{(2\pi)^4}\,\mathrm{Tr}\left[\frac{(\cancel{p}-\cancel{k}+m_f)}{(p-k)^2-m_f^2}\;\frac{(-\cancel{k}+m_f)}{k^2-m_f^2}\right]\left(\frac{-iy_f}{\sqrt{2}}\right)^2 \quad \propto \int \mathrm{d}(k^2)$$

Proportional to k^4

Calculation of the one-loop self energy

$i\Pi(p^2) =$ 

$$= \quad -\int \frac{\mathrm{d}^4\mathrm{k}}{(2\pi)^4}\, \mathrm{Tr}\left[\frac{(\not{p} - \not{k} + m_f)}{(p-k)^2 - m_f^2}\; \frac{(-\not{k} + m_f)}{k^2 - m_f^2}\right] \left(\frac{-iy_f}{\sqrt{2}}\right)^2 \quad \propto \int \mathrm{d}(k^2)$$

This diverges, so we need to regulate it!

Ways of regulating divergent integral

1. Use a 'UV cut-off' regulator Λ

$$\int \mathrm{d}(k^2) \quad \rightarrow \quad \int_0^{\Lambda^2} \mathrm{d}(k^2) = \Lambda^2$$

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It carries no physical meaning

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One has to absorb Λ in the bare (unmeasurable!) parameters of the theory

$$m_\mathrm{h}^2 \rightarrow m_\mathrm{h,phys}^2 - \Lambda^2 \qquad m_\mathrm{h}^2 + i\Pi \rightarrow m_\mathrm{h,phys}^2$$

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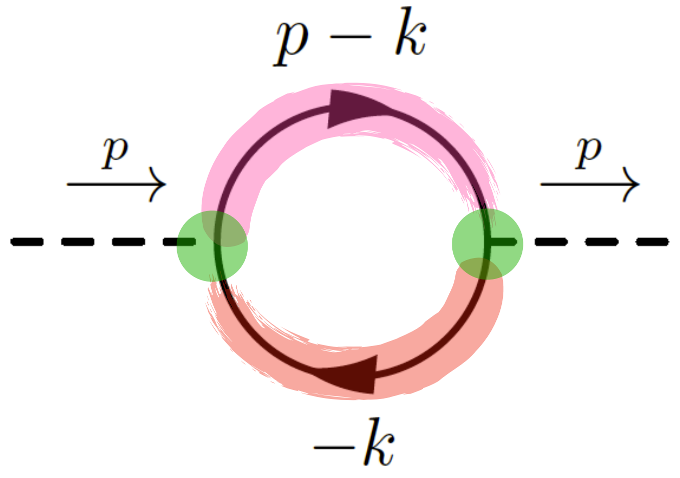
2. Use dimensional regularization

$$\int \frac{d^4 k}{(2\pi)^4} \quad \to \quad \int \frac{d^{4-\epsilon} k}{(2\pi)^{4-\epsilon}} \qquad\qquad y_f \to y_f\, \mu^{-\frac{\epsilon}{2}}$$

Using dimensional regularization

$i\Pi(p^2) =$ 

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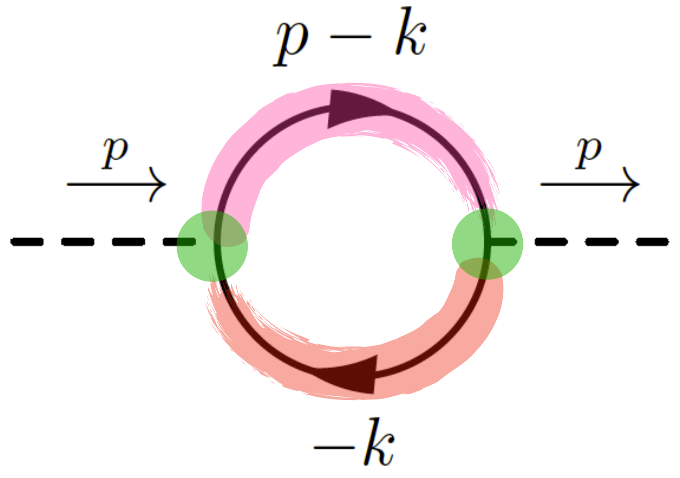
$i\Pi(p^2) =$ 

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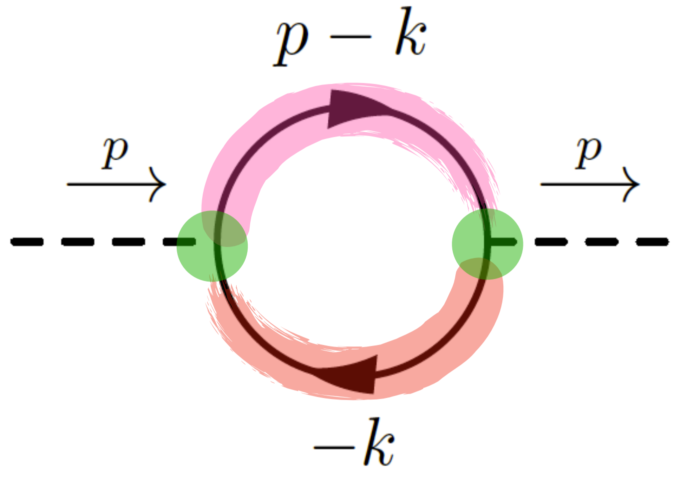
$i\Pi(p^2) =$ 

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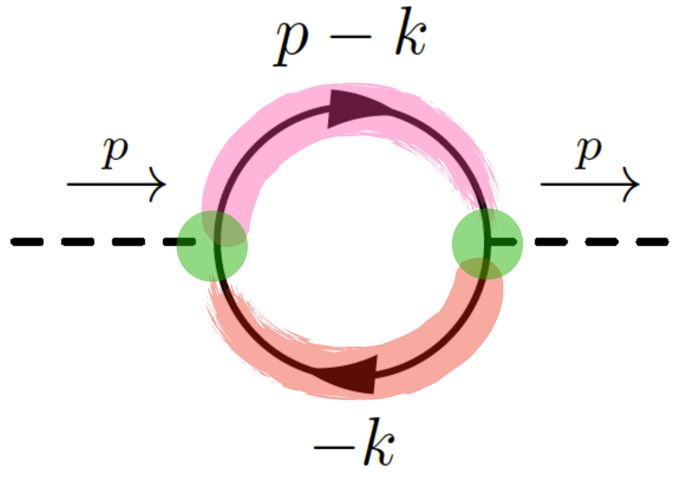

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The regulator can be absorbed in a redefinition of the bare parameters

$$\frac{1}{p^2-m_{\mathrm{h}}^2-i\Pi(p^2)} \rightarrow \frac{1}{p^2-m_{\mathrm{h,finite}}^2-i\Pi_{\mathrm{finite}}(p^2)}$$

$$= \frac{1}{p^2-m_{\mathrm{h,phys}}^2}$$

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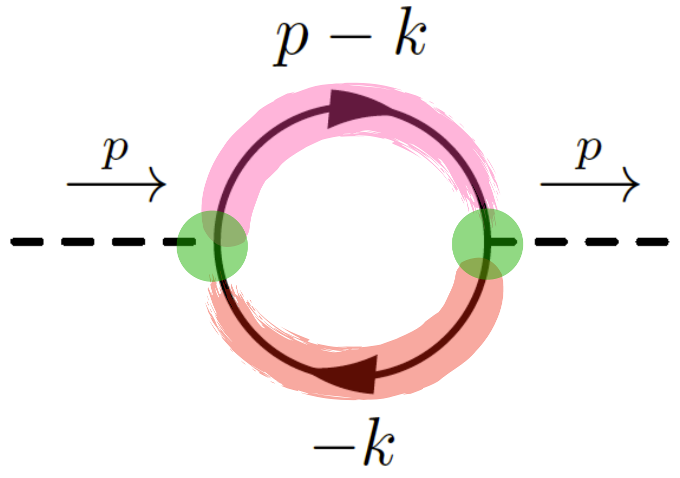

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But this is a real physical effect!

$$\frac{1}{p^2 - m^2_{\mathrm{h,finite}} - i\Pi_{\mathrm{finite}}(p^2)}$$

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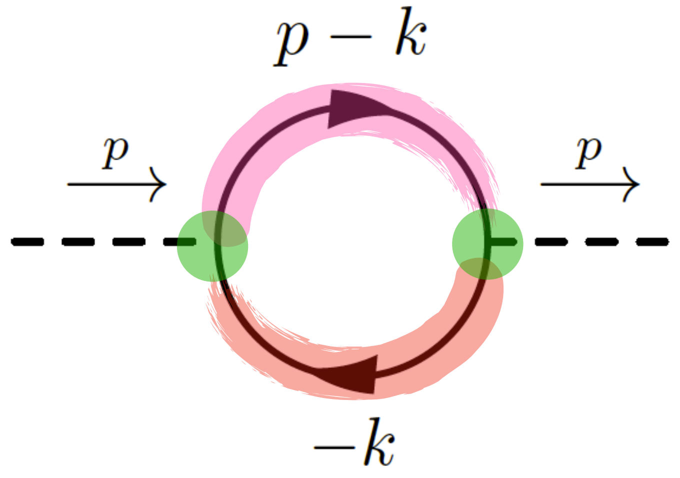
$i\Pi(p^2) =$ 

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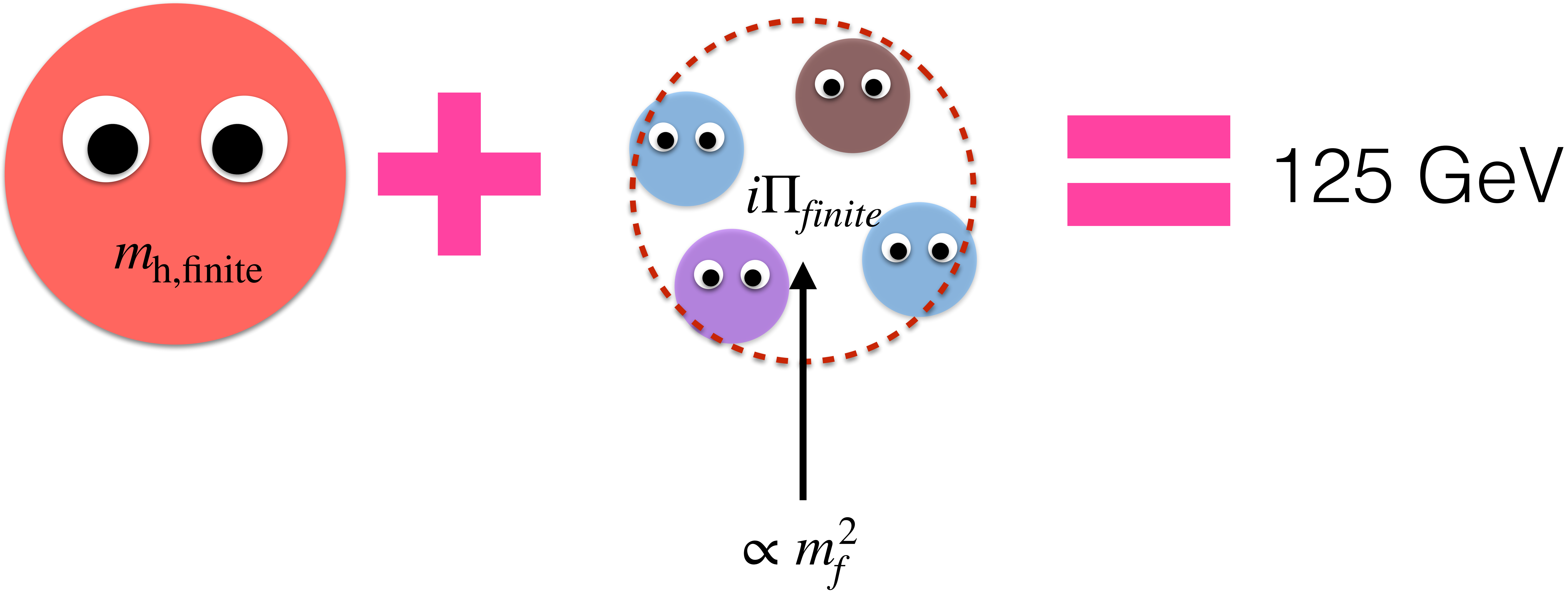
$$\frac{1}{p^2-m^2_{\mathrm{h,finite}}-i\Pi_{\mathrm{finite}}(p^2)}$$

The shift is proportional to the mass of the fermion

The Higgs FT problem



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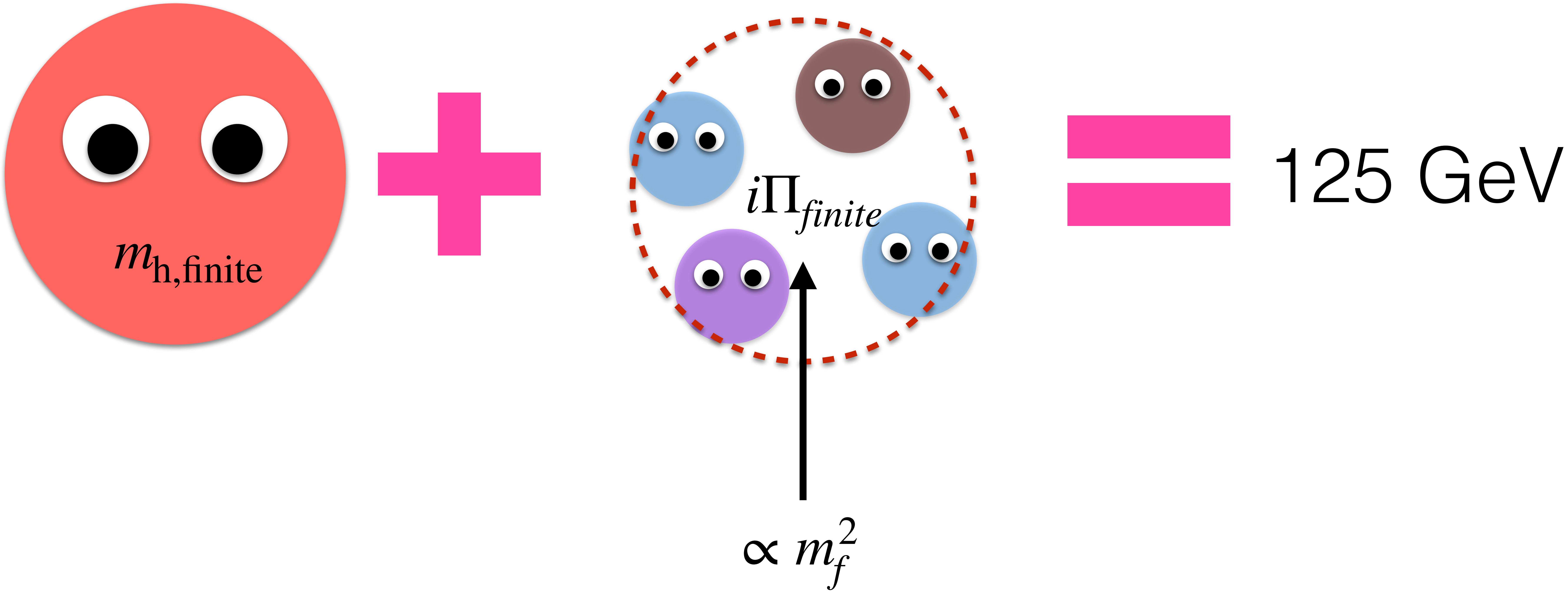
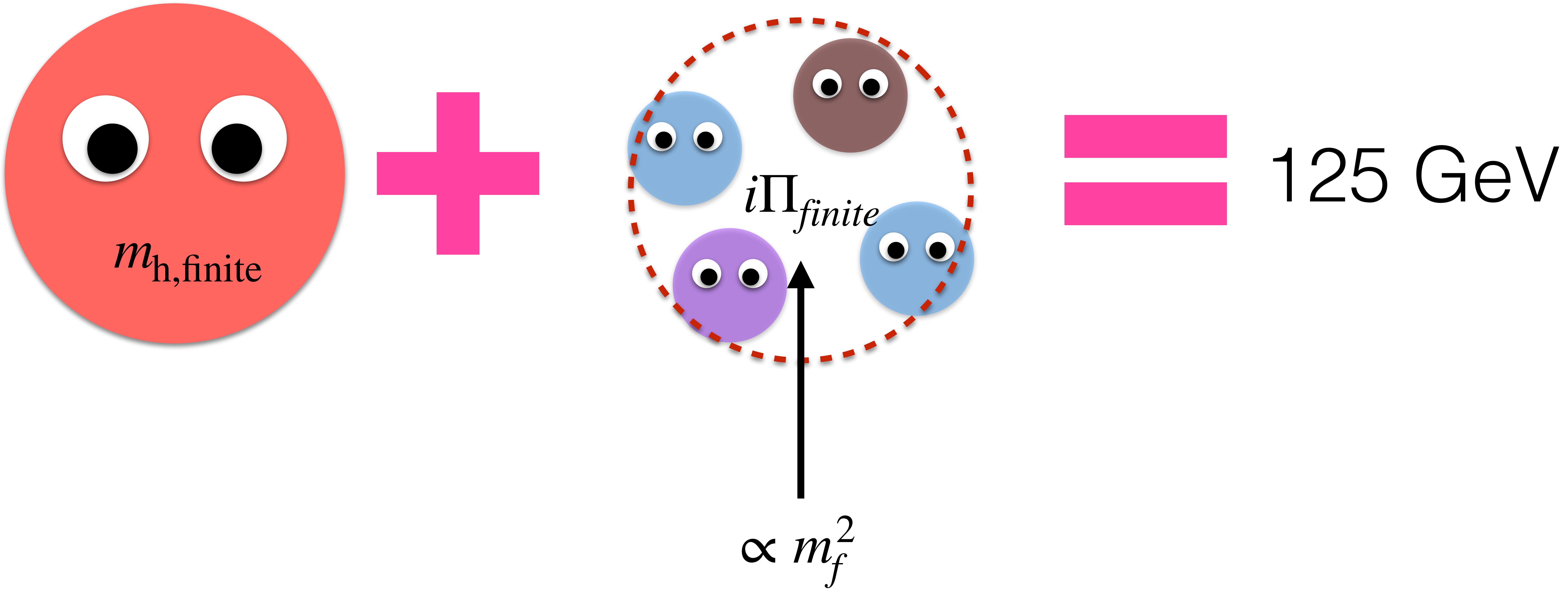


In the SM, $m_f \simeq 175\ \mathrm{GeV} \simeq m_{h,\mathrm{phys}}$

The SM has no FT problem

The Higgs FT problem



In BSM, who knows what value m_f might become…

… and what happens if you shift the value of this observable by a small amount

What about the other particles?

Higgs boson	$i\Pi_{\mathrm{Higgs}} \propto m_f^2$
Gauge bosons	$i\Pi_V \propto m_V^2$
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The key issue is that the Higgs is renormalized *additively,*
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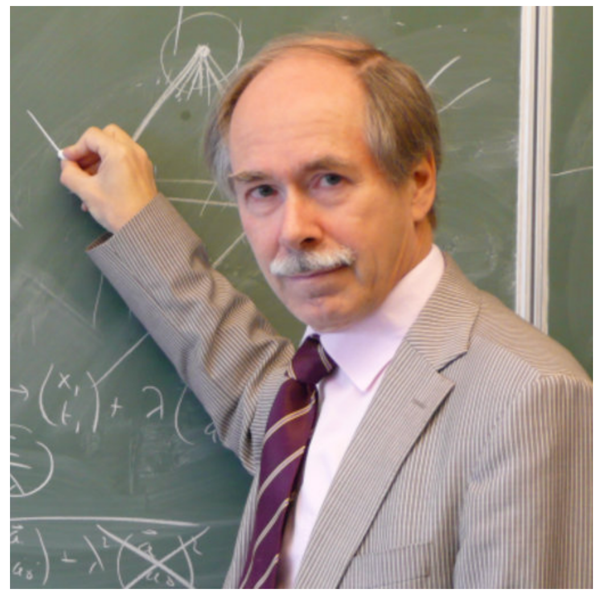
This, in turn, is caused by the absence of a protecting symmetry for the Higgs boson



Take home messages

- Fine-tuning occurs when an observable (e.g. the Higgs mass) changes a lot as a consequence of a tiny change in the other observables of the theory
- Is not directly caused by a hierarchy of scales
- Can only occur in beyond-the-SM scenarios; the SM *has no fine-tuning problem*

But why is there so much discussion about it?

The LHC did not show conclusive evidence of NP at the TeV scale

Is FT a good guiding principle to search for NP?

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Is FT a good guiding principle to search for NP?

It is not a theoretical requirement: a theory is internally consistent with FT

But it is also not merely an aesthetic requirement

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Why is there an apparent breakdown of this principle in the Higgs sector?

But of course, this does not mean that nature is required to be free of FT!

Find BSM models w/o fine-tuning

- BSM that does not couple to the SM
- Composite Higgs particle
- A new symmetry that protects the Higgs boson
- ‘Miracle’ gravity scenarios at the Planck scale

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- But why the EFT breakdown?
- Multiverse/Antropic solution

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Experimentalists are needed to settle the issue, and every outcome is possible

This is the scientific method at work!

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Understanding fine-tuning

- How to quantify FT?
- What levels of FT are allowed?
- How should ‘FT’ be interpreted?
- What is the role of renormalization?

Conclusions

- Fine-tuning occurs when an observable (e.g. the Higgs mass) changes a lot as a consequence of a tiny change in the other observables of the theory
- Fine-tuning is not directly caused by a hierarchy of scales
- The SM has no Higgs fine-tuning problem (!!!)
- Fine-tuning is not merely an aesthetic problem, and whatever outcome of the experiment will be, it needs an explanation