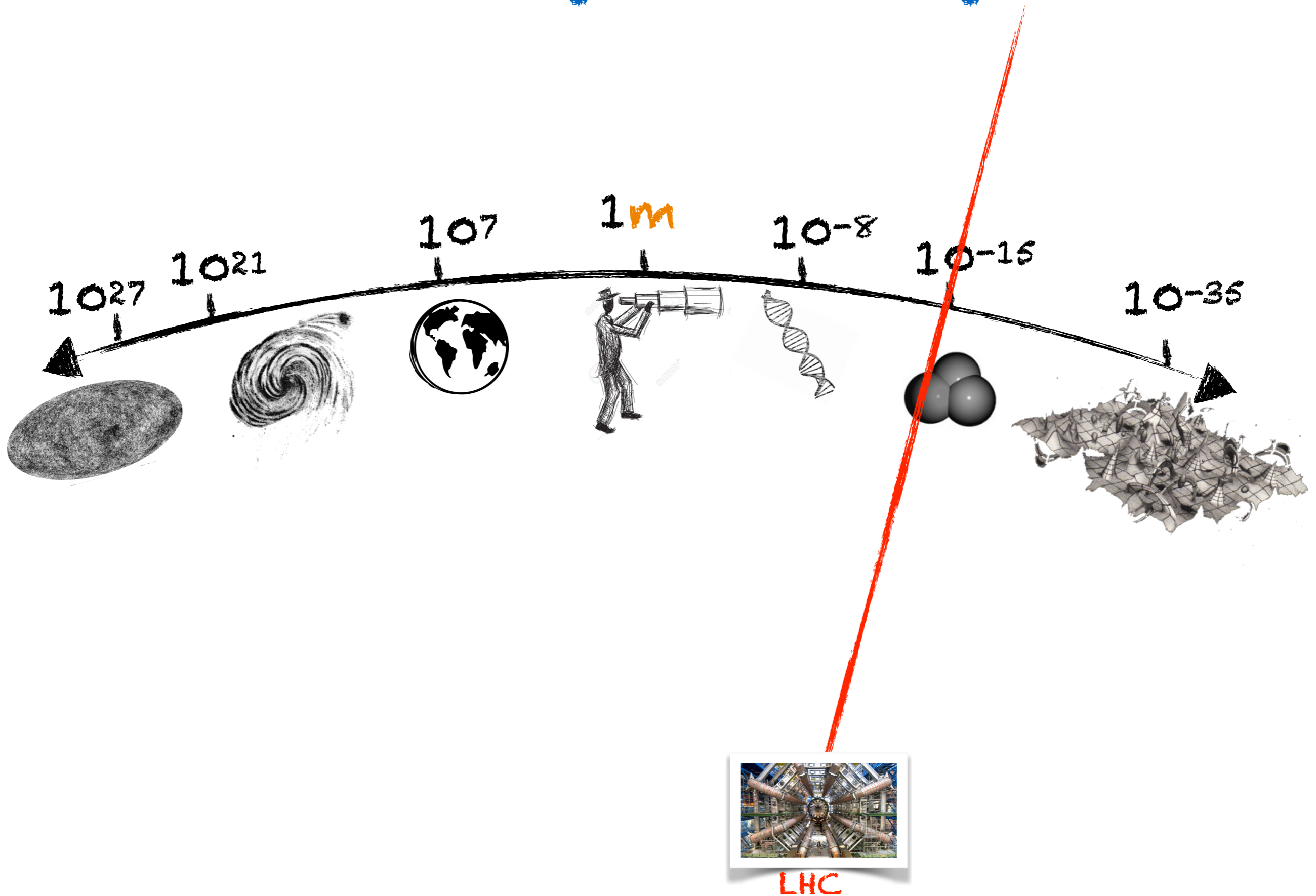


FCC and the size of the Higgs boson

Francesco Riva  
(Geneva University)



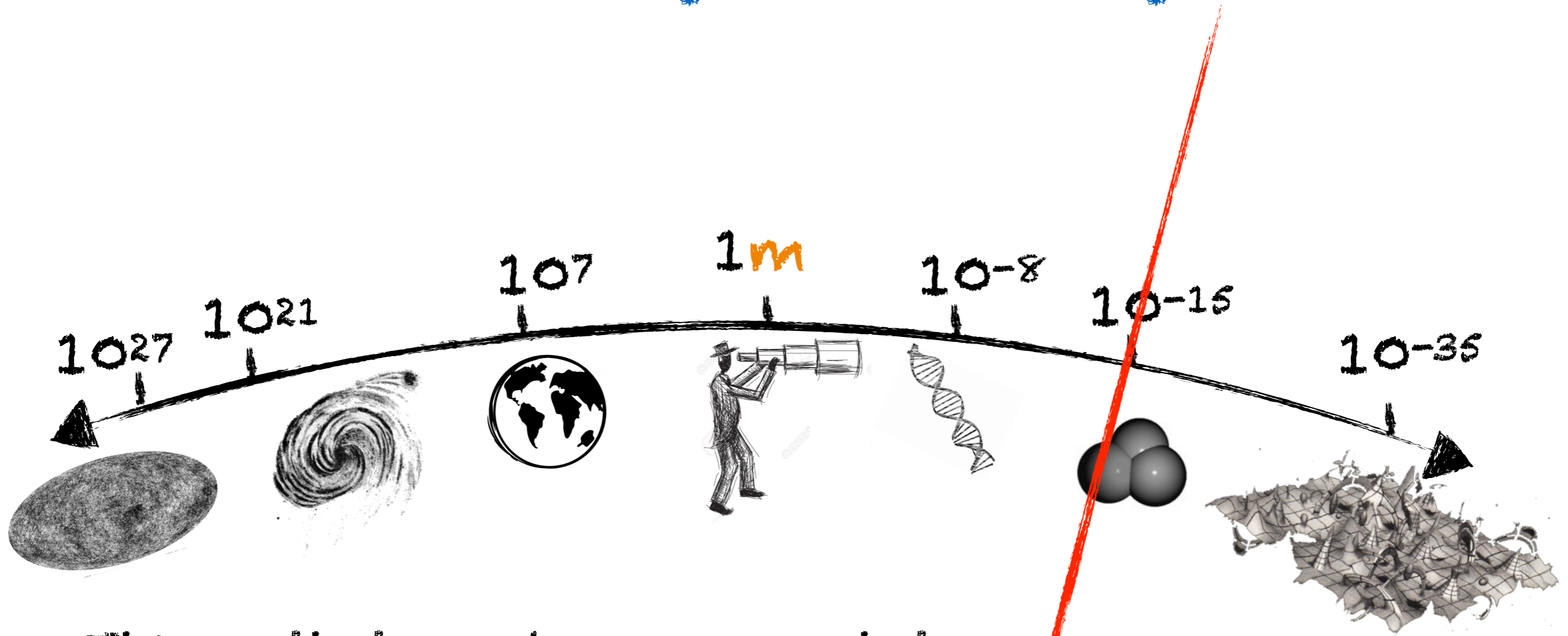
# High-Energy Particle Physics



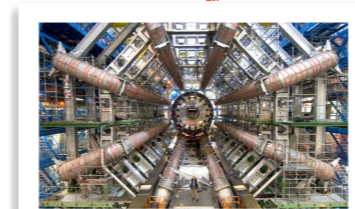
LHC



# High-Energy Particle Physics



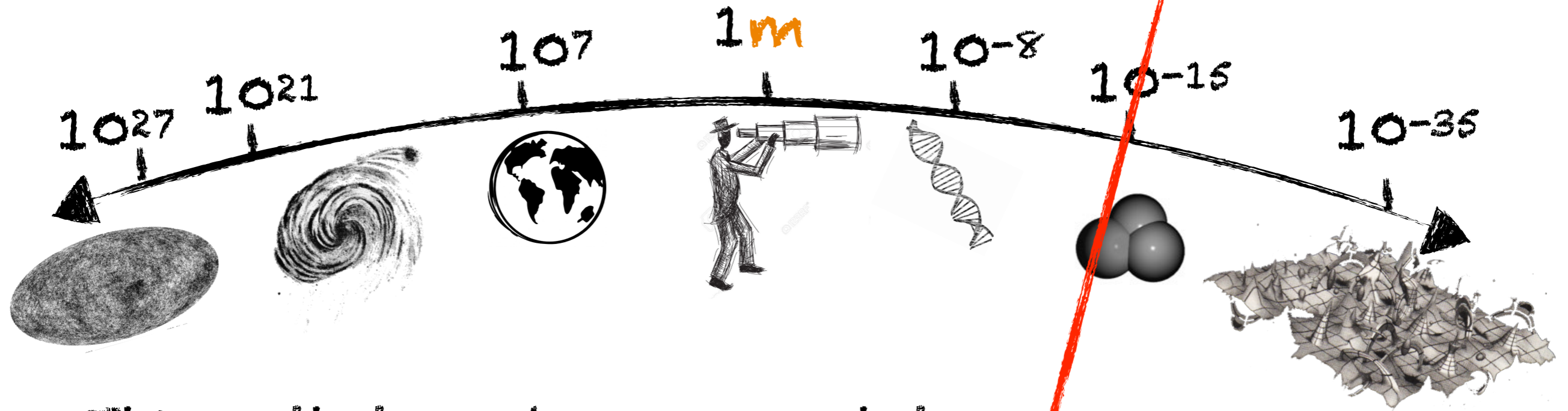
Things that are large enough to be accessed in experiments...



LHC

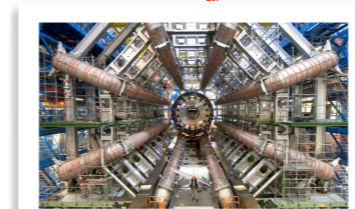


# High-Energy Particle Physics



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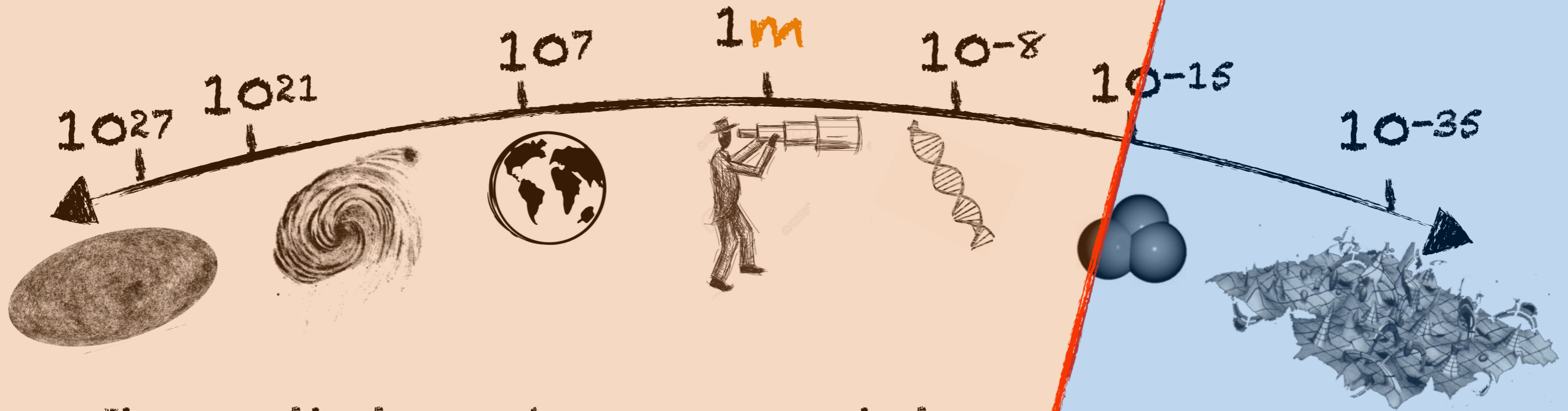
...things too small to be seen...



LHC

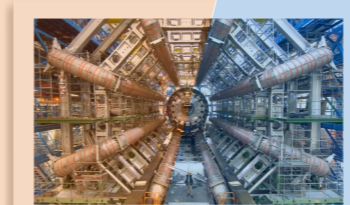


# High-Energy Particle Physics



Things that are large enough to be accessed in experiments...

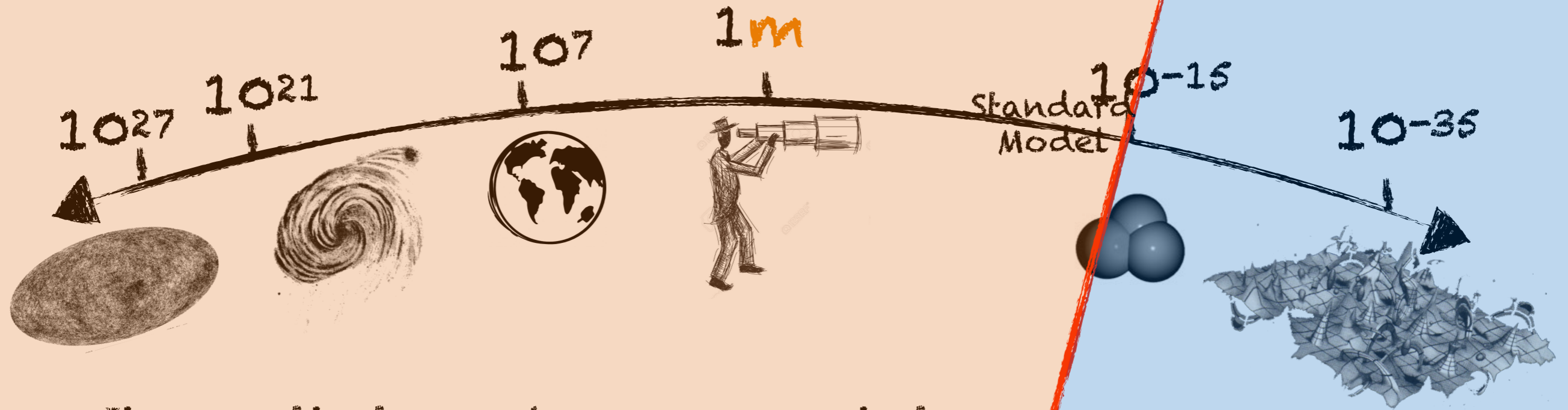
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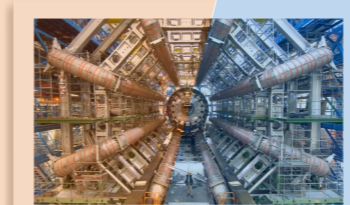


# High-Energy Particle Physics



Things that are large enough to be accessed in experiments...

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LHC

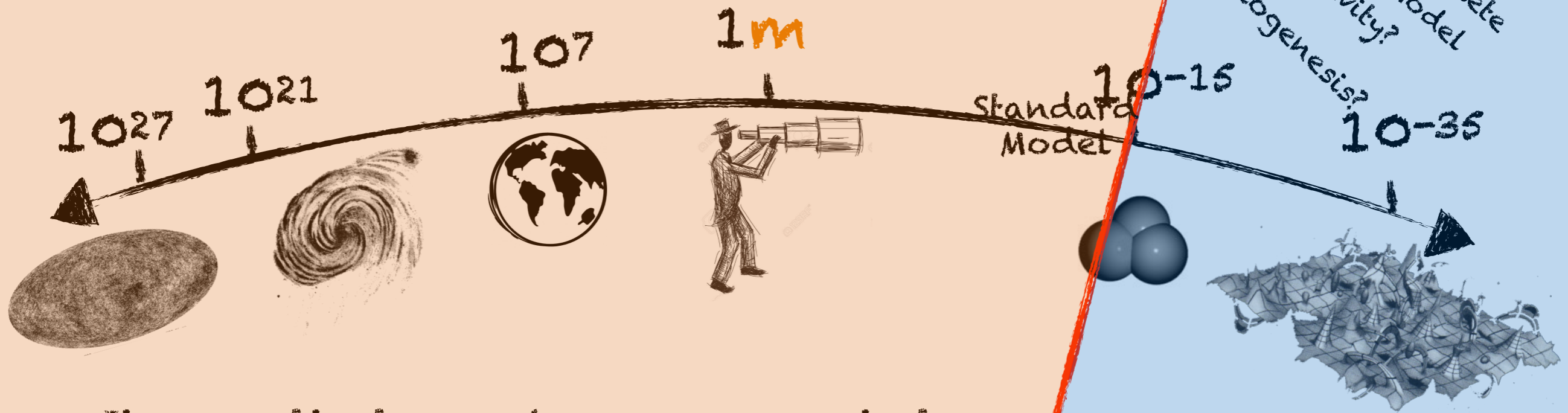


# High-Energy Particle Physics

Is the Higgs boson  
composite or elementary?

EWSB?  
Dark Matter?

What can UV complete  
the Standard Model  
with gravity?  
Baryogenesis?



Things that are large enough to  
be accessed in experiments...

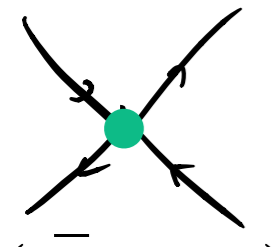
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LHC

# No Lose Theorems

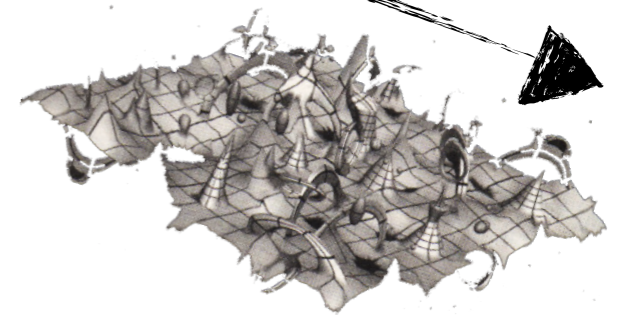
HEP: a history of guaranteed discoveries



A Feynman diagram showing a fermion loop. Two external lines enter from the left and two exit to the right, meeting at a central vertex marked with a green dot. The lines are labeled with  $\psi$  and  $\bar{\psi}$ .

$$\frac{1}{v^2} (\bar{\psi} \gamma_\mu \psi)^2$$

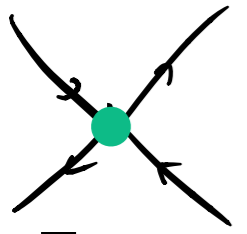
$$\psi\psi \rightarrow \psi\psi$$





# No Lose Theorems

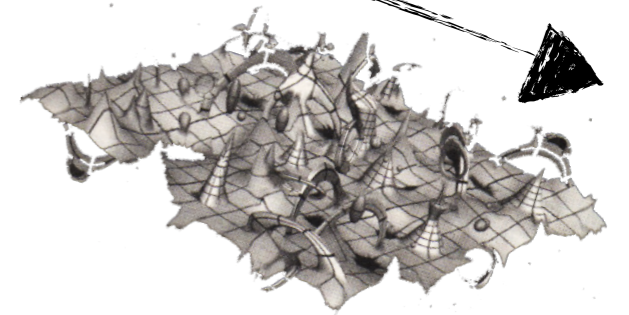
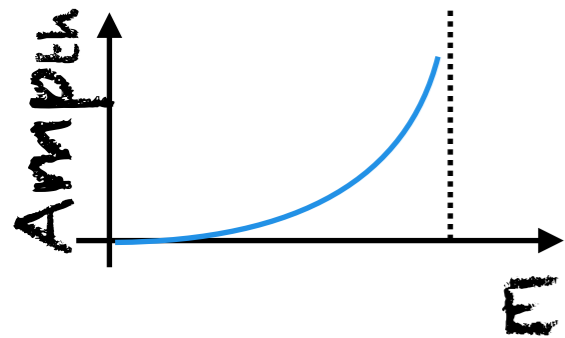
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A Feynman diagram showing a fermion loop. Two external fermion lines enter from the left and two exit to the right, meeting at a central vertex. The vertex is marked with a green dot. The diagram is associated with the mathematical expression  $\frac{1}{v^2}(\bar{\psi}\gamma_\mu\psi)^2$ .

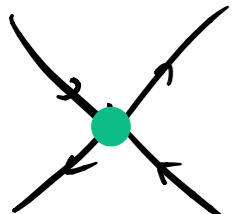
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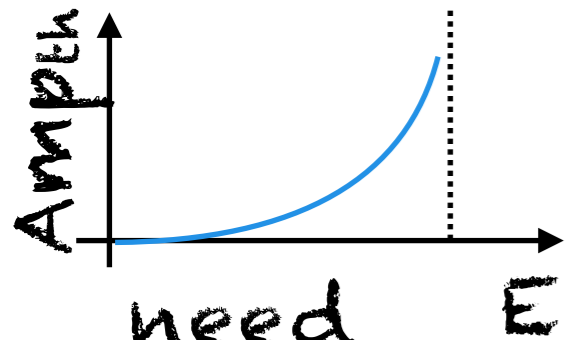
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HEP: a history of guaranteed discoveries

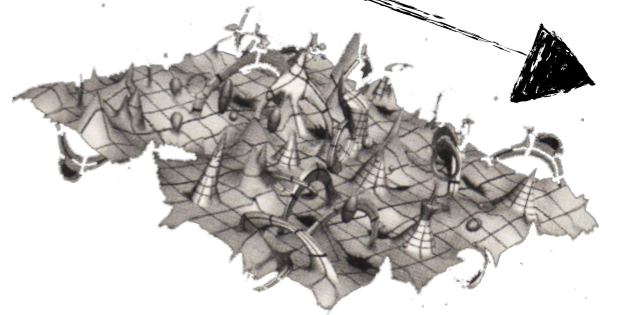


$\frac{1}{v^2}(\bar{\psi}\gamma_{\mu}\psi)^2$

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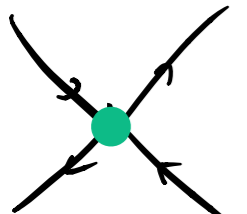
need  
W-boson  
 $m_W \lesssim 3\text{TeV}$





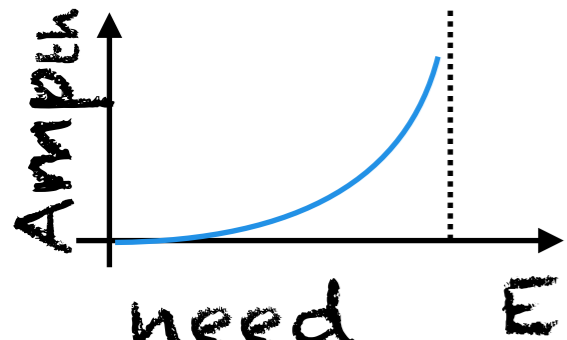
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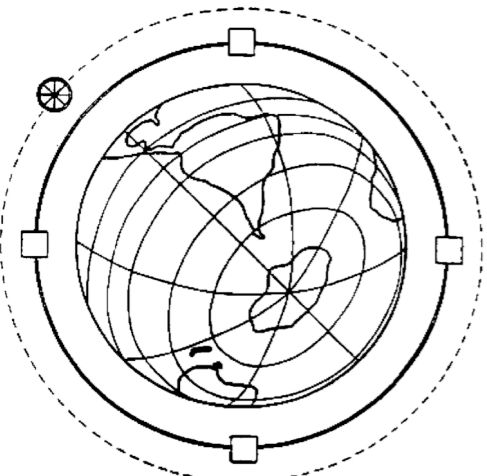
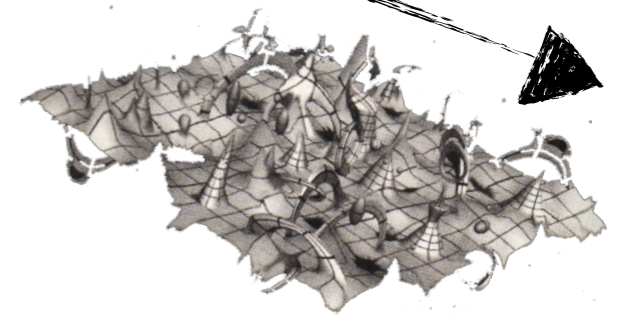


$\frac{1}{v^2}(\bar{\psi}\gamma_{\mu}\psi)^2$

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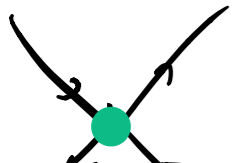


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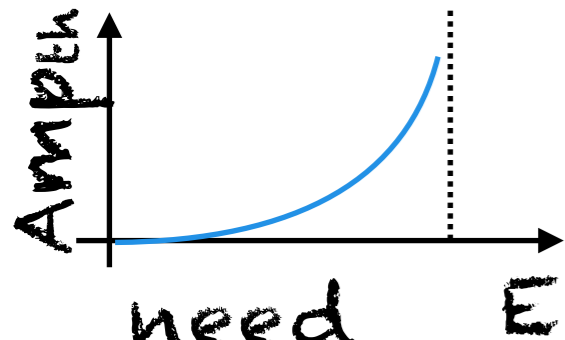
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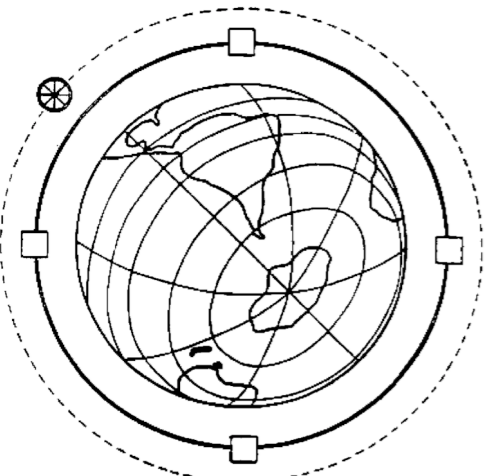
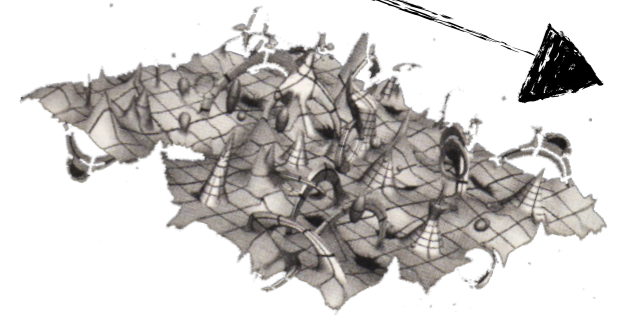

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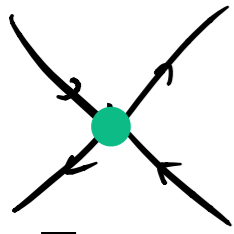
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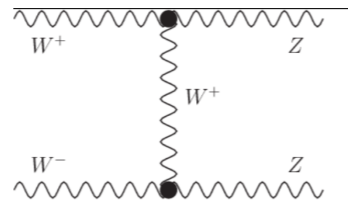




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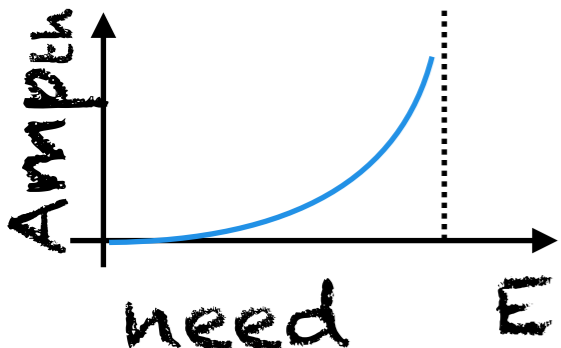
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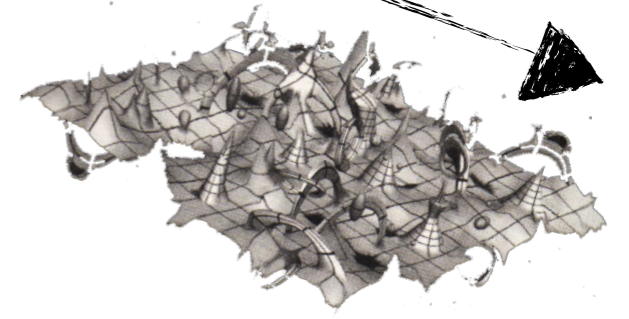
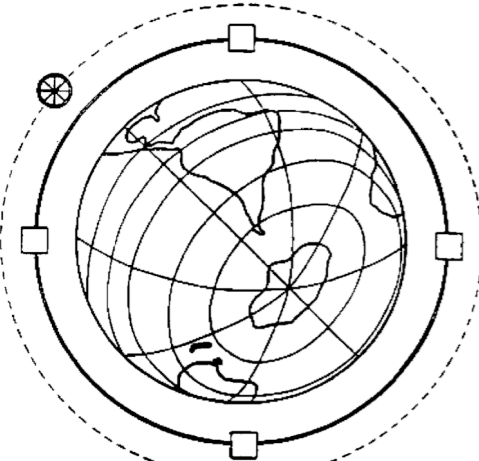


$$m^2 A_\mu A^\mu$$

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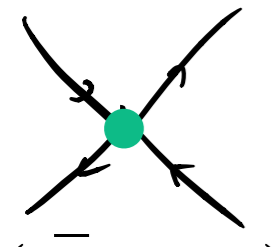


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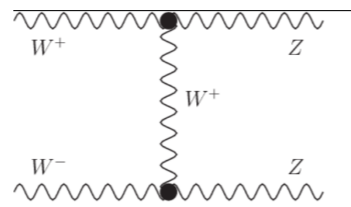


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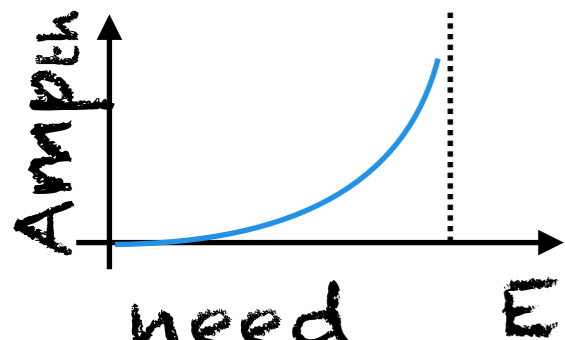
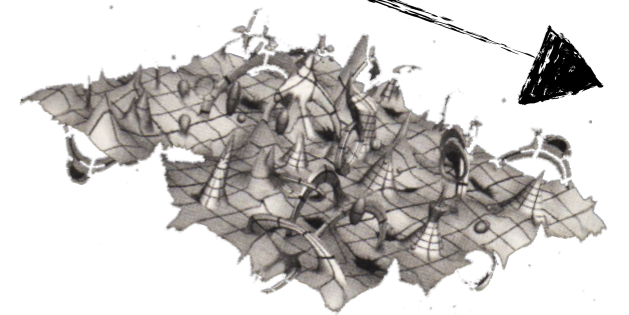
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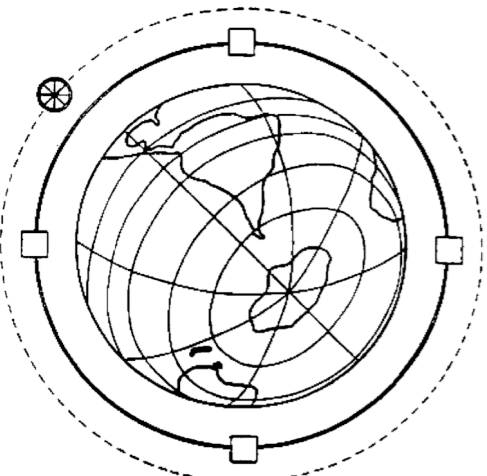
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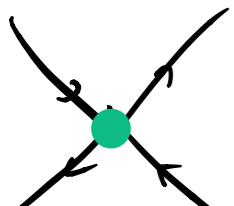
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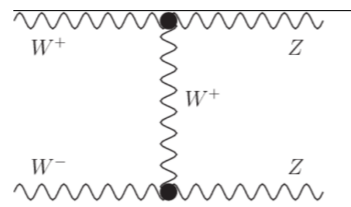
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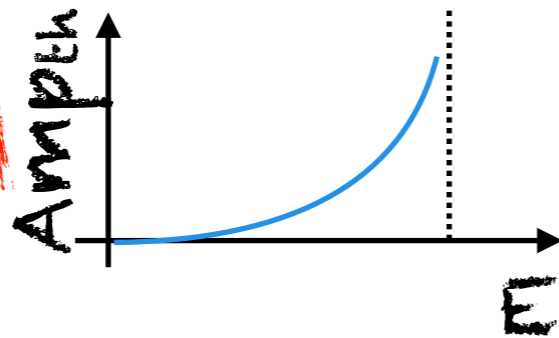
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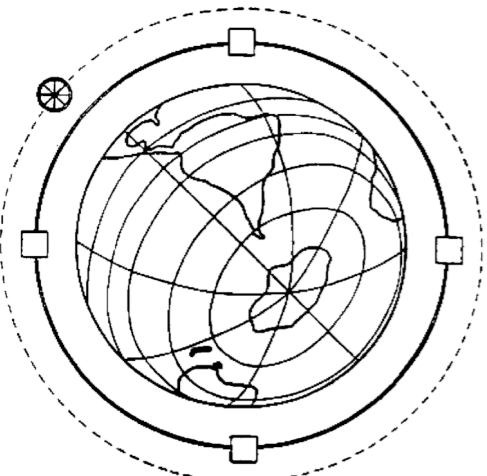
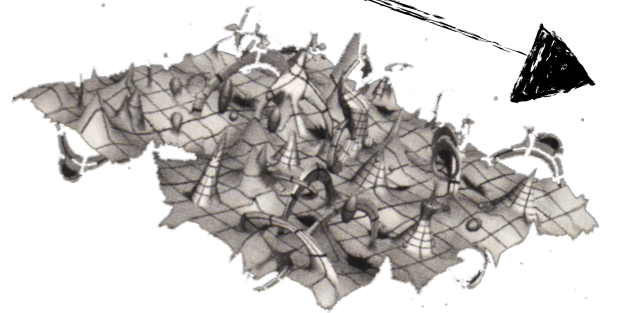


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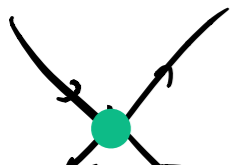


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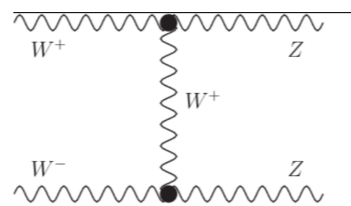


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HEP: a history of guaranteed discoveries



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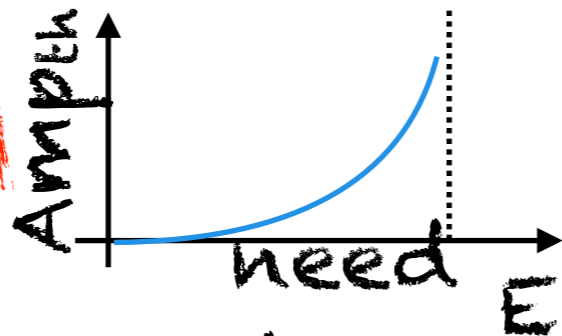


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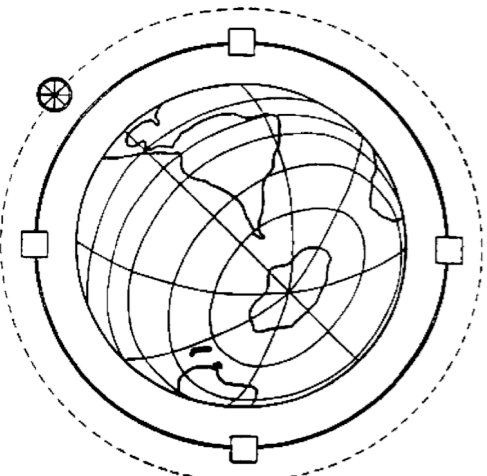
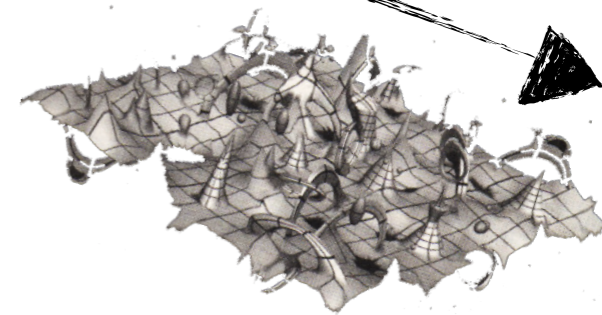
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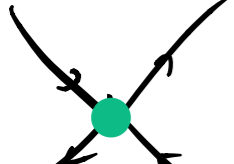
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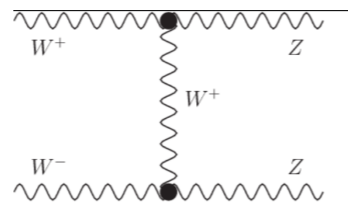
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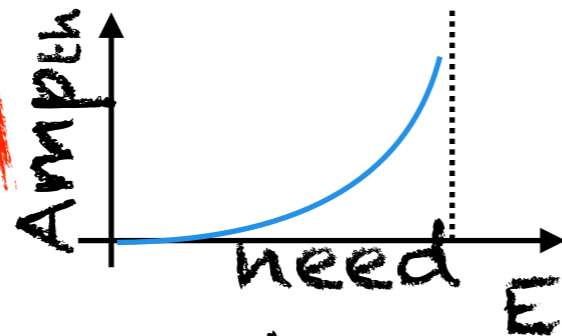
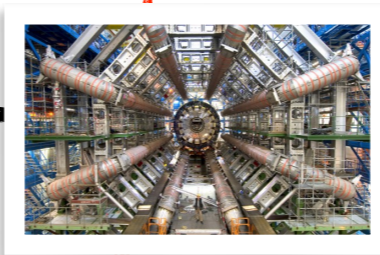
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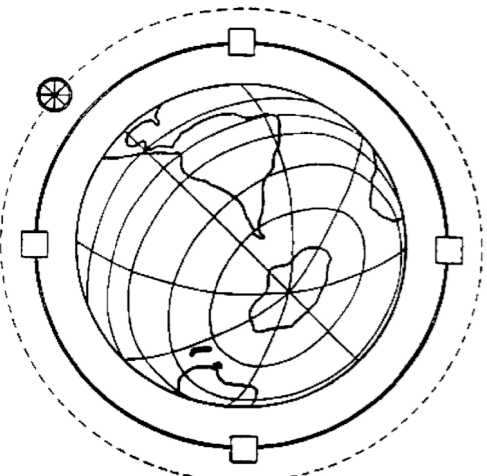
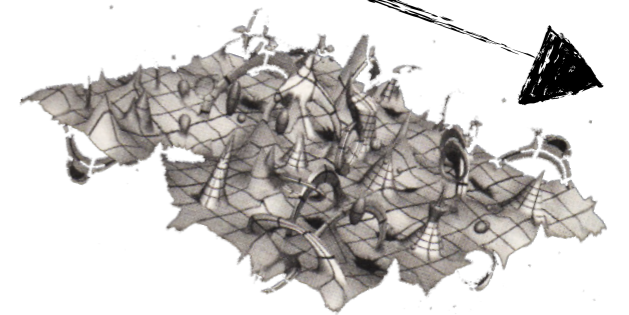
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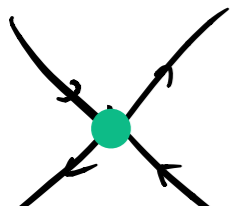
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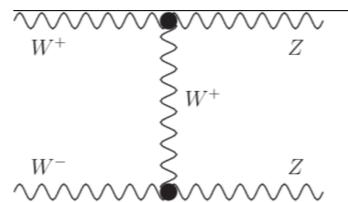
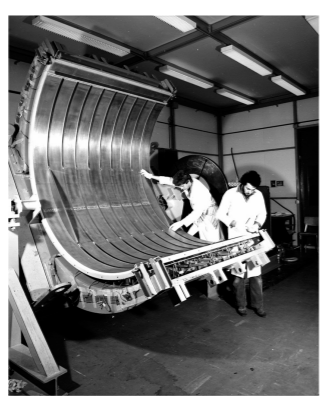
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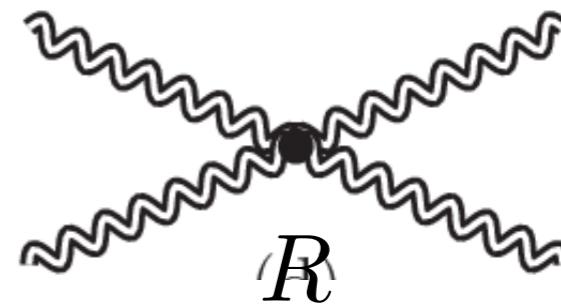
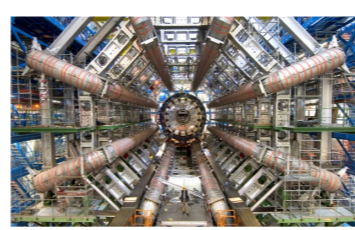
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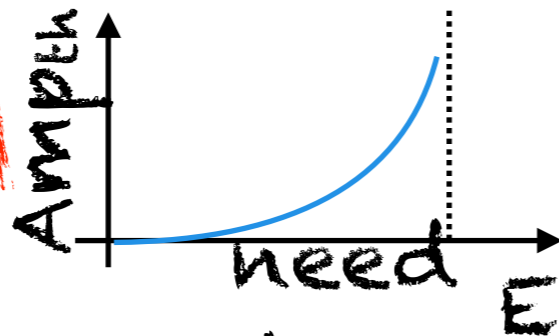
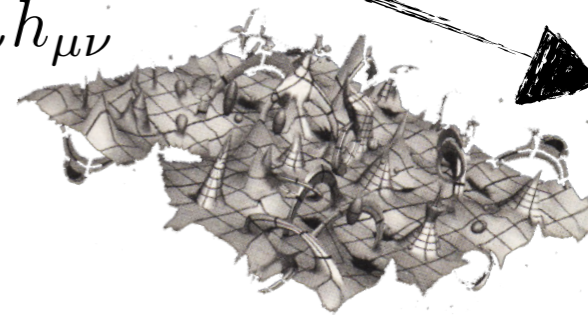
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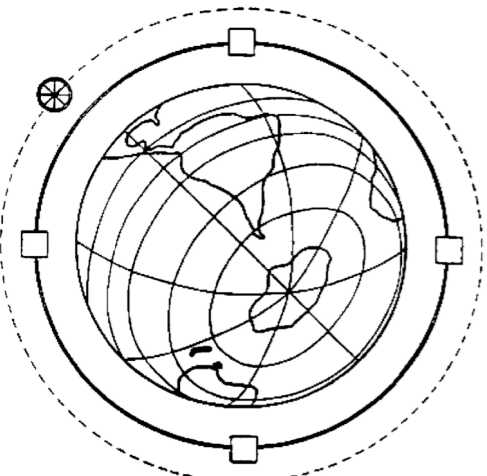
$$\frac{R}{M_{Pl}^2}$$

$$h_{\mu\nu} h_{\mu\nu} \rightarrow h_{\mu\nu} h_{\mu\nu}$$



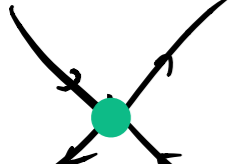
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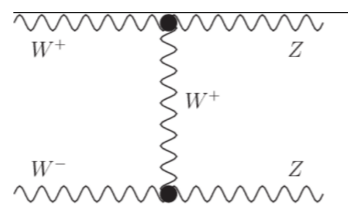


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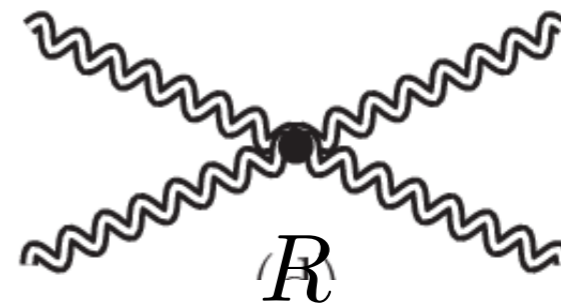
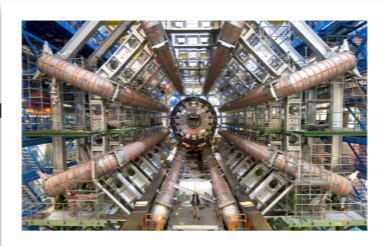
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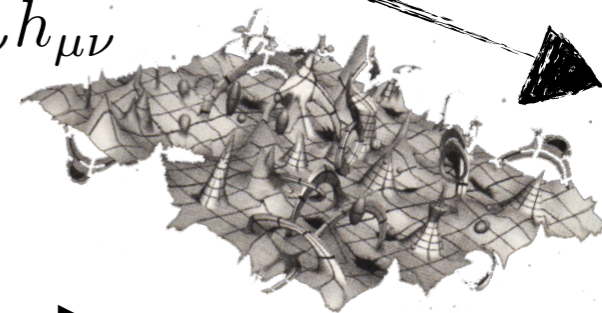
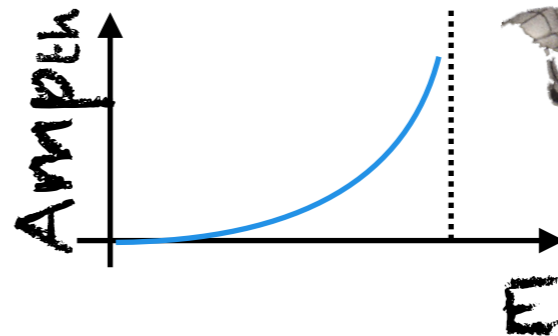
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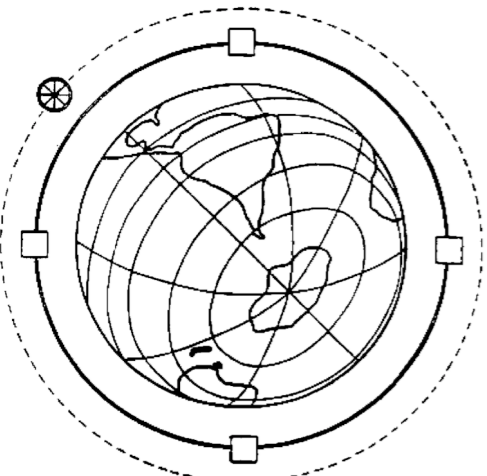
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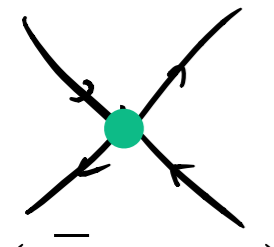
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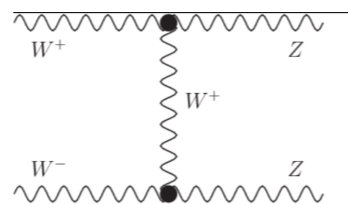


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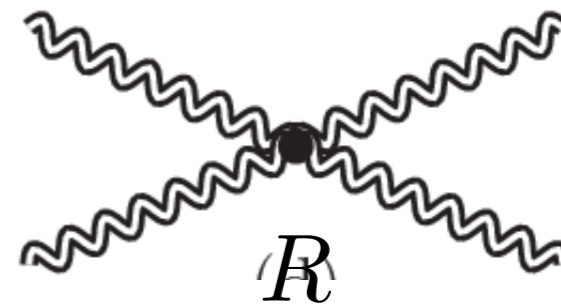
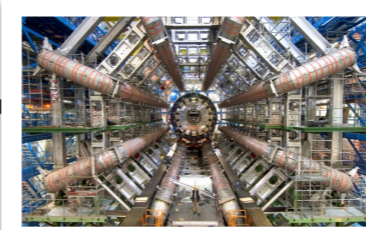
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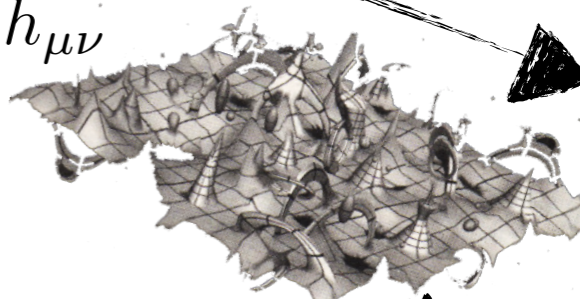
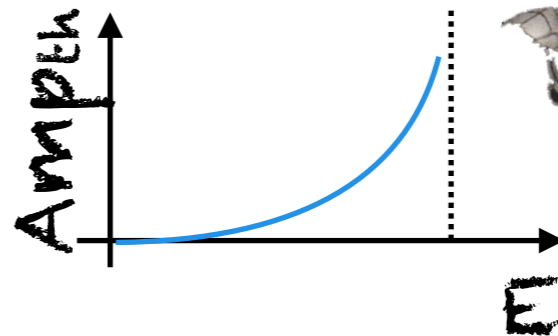
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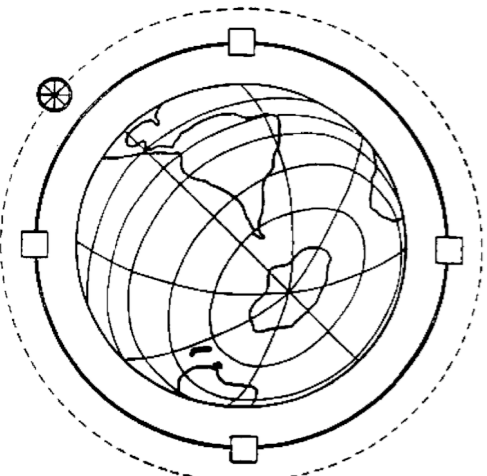
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H-boson  
 $m_h \lesssim 3TeV$

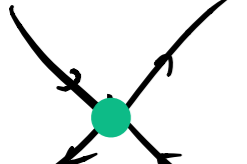
need  
something  
 $m_{QG} \lesssim 10^{19} GeV$





# No Lose Theorems

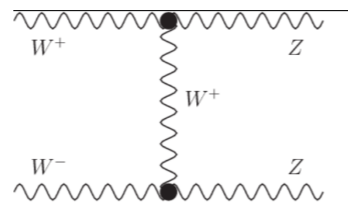
HEP: a history of guaranteed discoveries



$$\frac{1}{v^2} (\bar{\psi} \gamma_\mu \psi)^2$$

$$\psi\psi \rightarrow \psi\psi$$

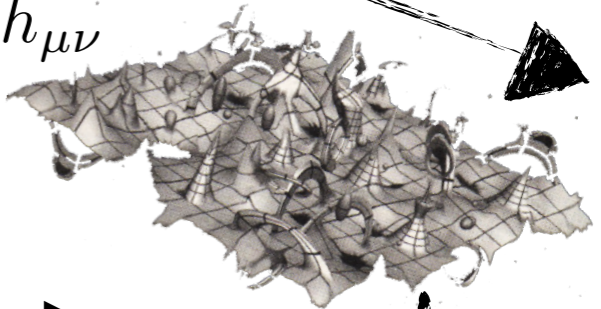
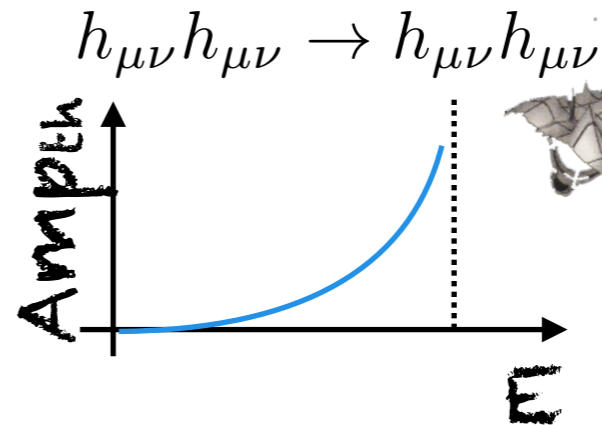
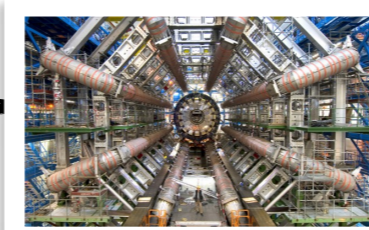
need  
W-boson  
 $m_W \lesssim 3TeV$



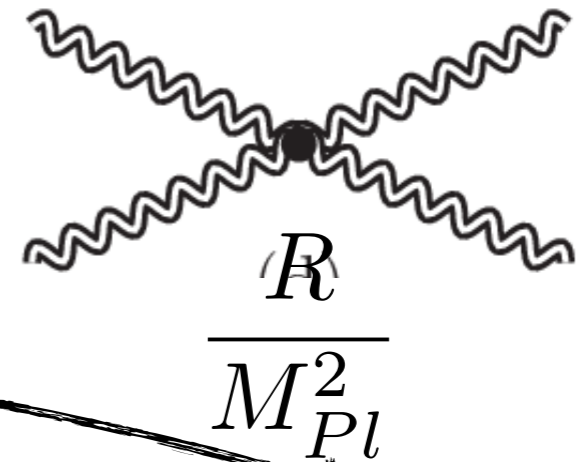
$$m^2 A_\mu A^\mu$$

$$WW \rightarrow WW$$

need  
H-boson  
 $m_h \lesssim 3TeV$



need  
something  
 $m_{QG} \lesssim 10^{19} GeV$



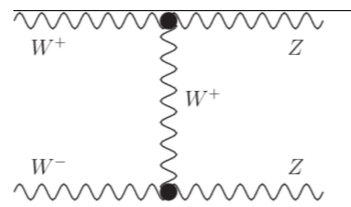
# No Lose Theorems

HEP: a history of guaranteed discoveries

$$\frac{1}{v^2} (\bar{\psi} \gamma_\mu \psi)^2$$

$$\psi\psi \rightarrow \psi\psi$$

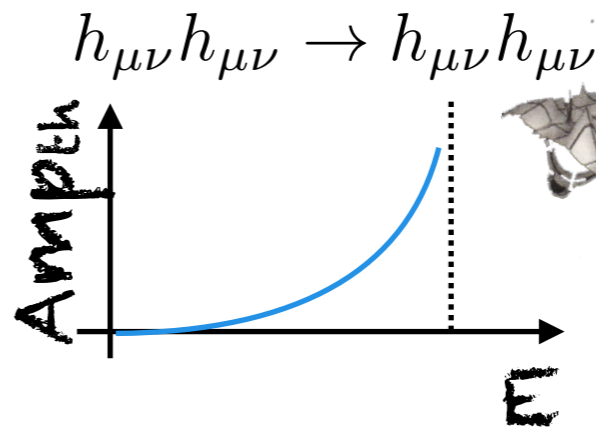
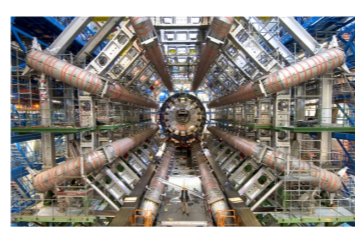
need  
W-boson  
 $m_W \lesssim 3\text{TeV}$



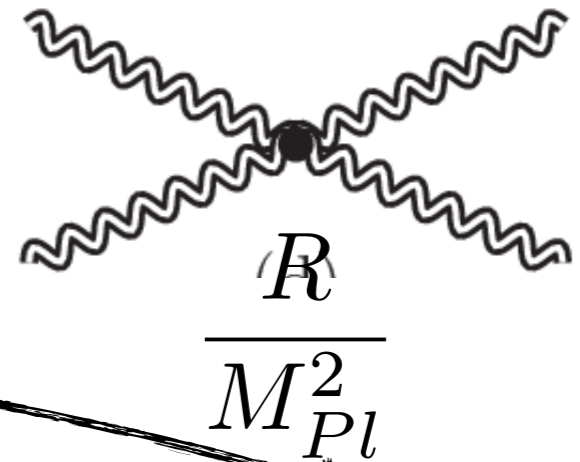
$$m^2 A_\mu A^\mu$$

$$WW \rightarrow WW$$

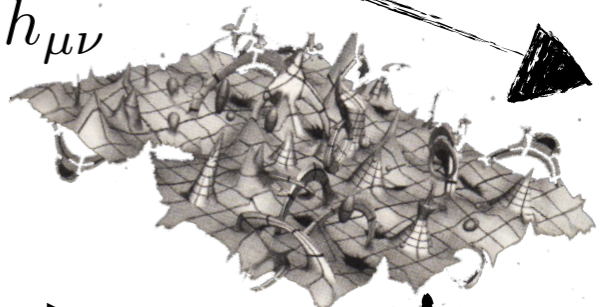
need  
H-boson  
 $m_h \lesssim 3\text{TeV}$



need  
something  
 $m_{QG} \lesssim 10^{19}\text{GeV}$



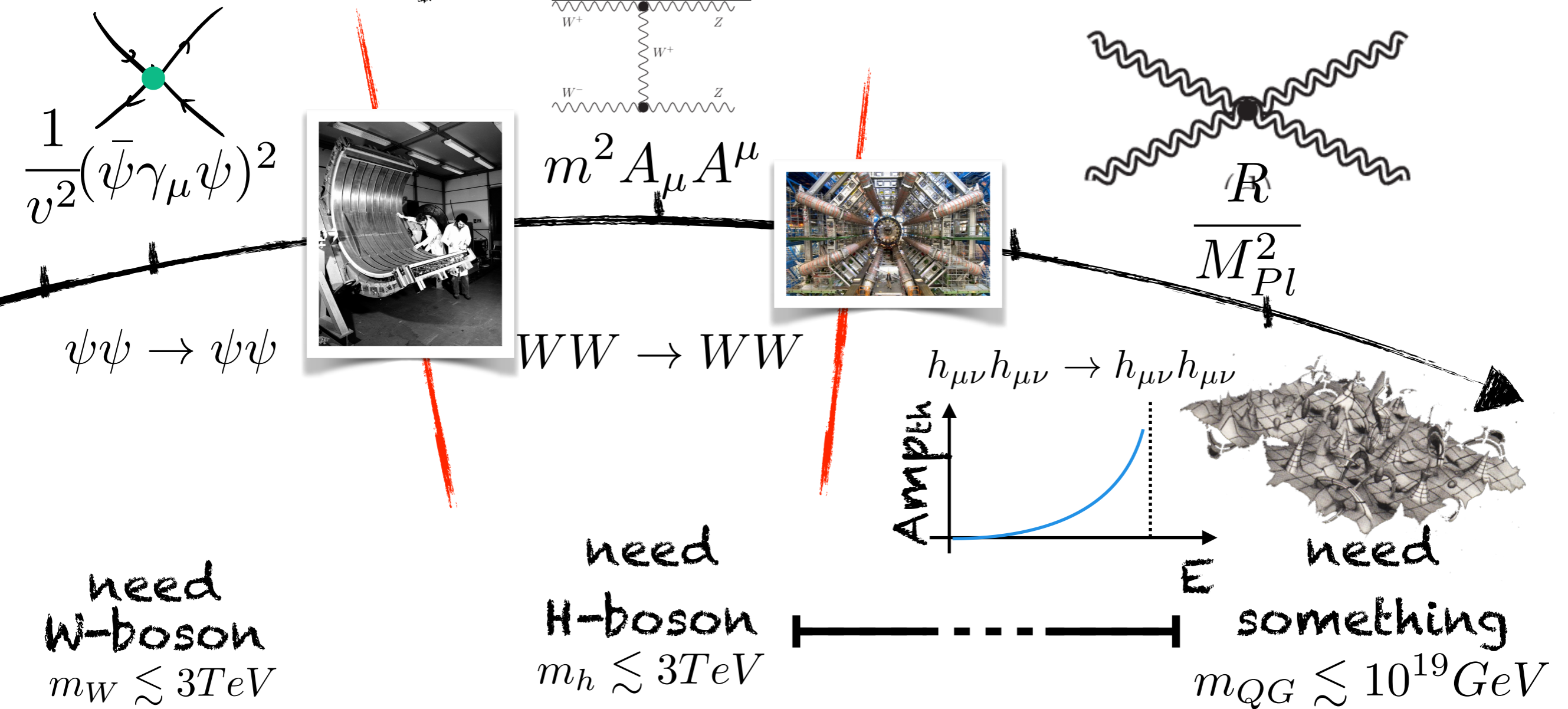
$$\frac{R}{M_{Pl}^2}$$



➔ Exceptional story, but science is not about no lose theorems

# No Lose Theorems

HEP: a history of guaranteed discoveries



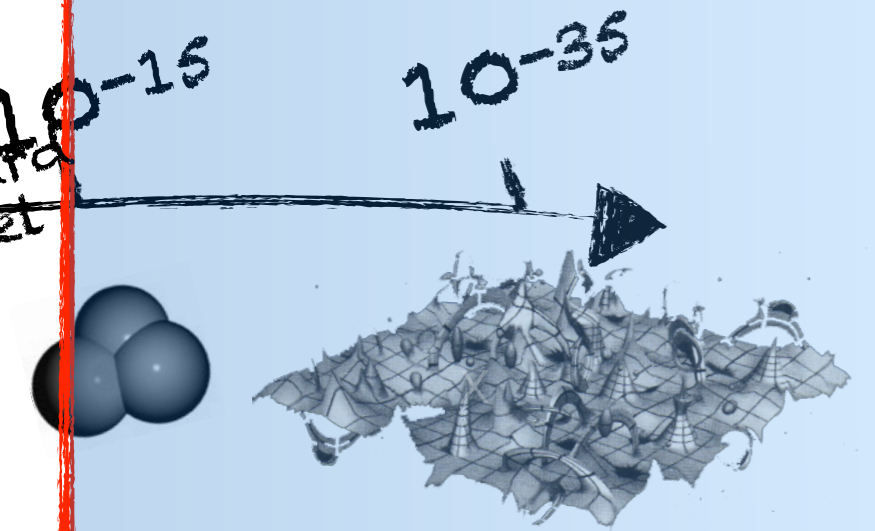
- Exceptional story, but science is not about no lose theorems
- What will we **learn** from this exploration?



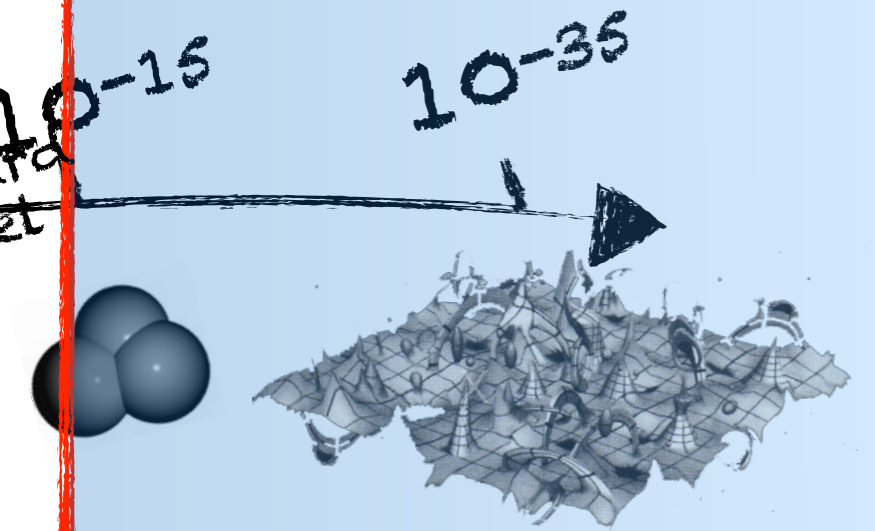
# High-Energy Particle Physics Mindset

?

- ▶ Think of the unexplored as **REALLY** unknown



# High-Energy Particle Physics Mindset

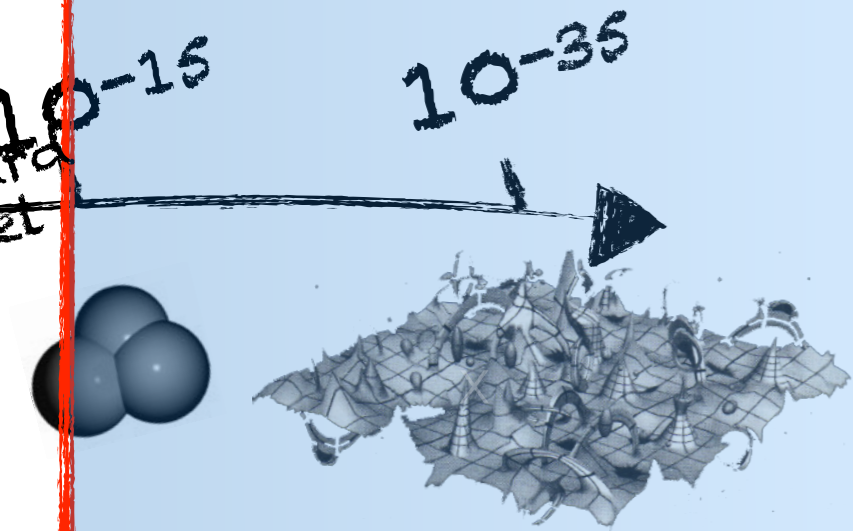


- ▶ Think of the unexplored as **REALLY unknown**
- ▶ **No** notion of "confirming the SM": there is no SM+Gravity theory!



FCs

# High-Energy Particle Physics Mindset



- ▶ Think of the unexplored as **REALLY unknown**
- ▶ No notion of "confirming the SM": there is no SM+Gravity theory!
- ▶ The SM really is an **EFT** with many possible features: every new measurement teaches us **something new** about these

microscopic laws of nature

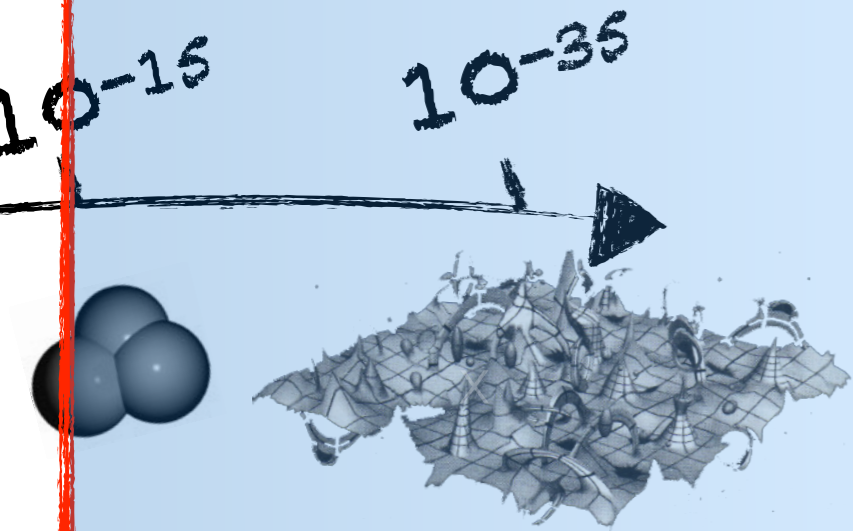
$$\mathcal{L} = \sum_i c_i \frac{O_i^{(n)}}{\Lambda_i^{n-4}}$$





# High-Energy Particle Physics

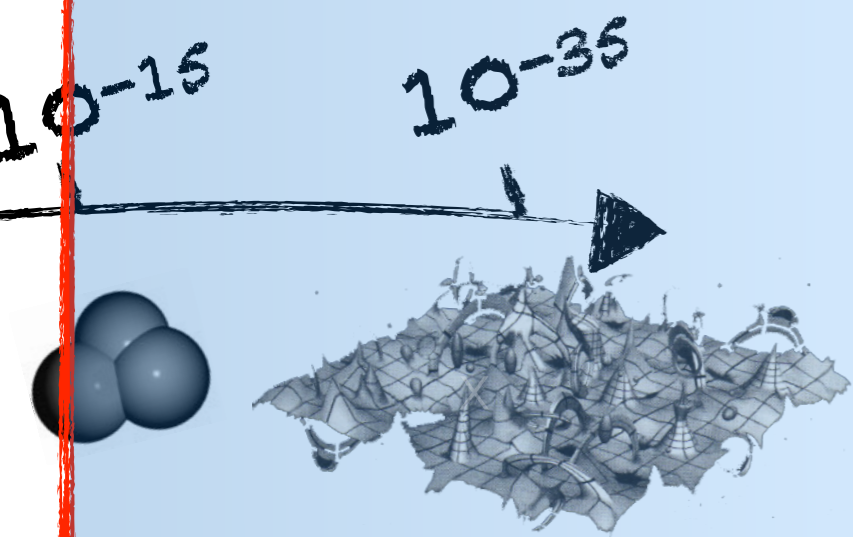
$$\frac{1}{\Lambda_{\text{P}}^2} [(d_p^\alpha)^T C u_r^\beta] [(q_s^{\gamma j})^T C l_t^k]$$



FCs

# High-Energy Particle Physics

$$\frac{1}{\Lambda_{\text{P}}^2} [(d_p^\alpha)^T C u_r^\beta] [(q_s^{\gamma j})^T C l_t^k] \quad \text{Proton Lifetime } t_p > 10^{34} \text{ y}$$



# High-Energy Particle Physics

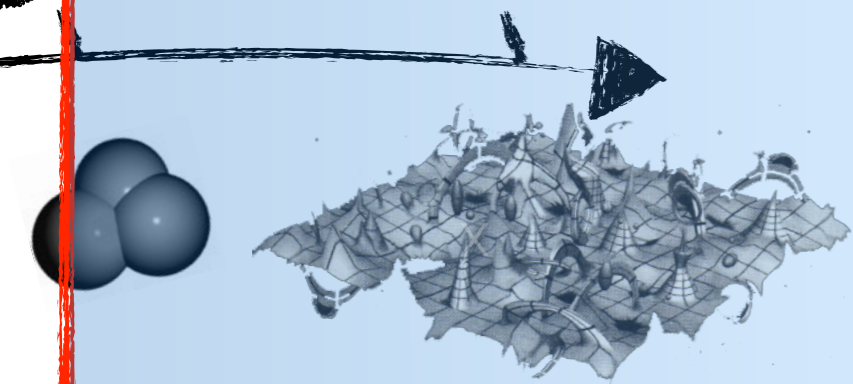
$$\Lambda_{\mathcal{B}} > 10^{16} \text{ GeV}$$

$$\frac{1}{\Lambda_{\mathcal{B}}^2} [(d_p^\alpha)^T C u_r^\beta] [(q_s^{\gamma j})^T C l_t^k]$$

Proton Lifetime  $t_p > 10^{34} y$

$10^{-15}$

$10^{-35}$



FCs



# High-Energy Particle Physics

$$\Lambda_B > 10^{16} \text{ GeV}$$

$$\frac{1}{\Lambda_B^2} [(d_p^\alpha)^T C u_r^\beta] [(q_s^{\gamma j})^T C l_t^k]$$

Proton Lifetime  $t_p > 10^{34} y$

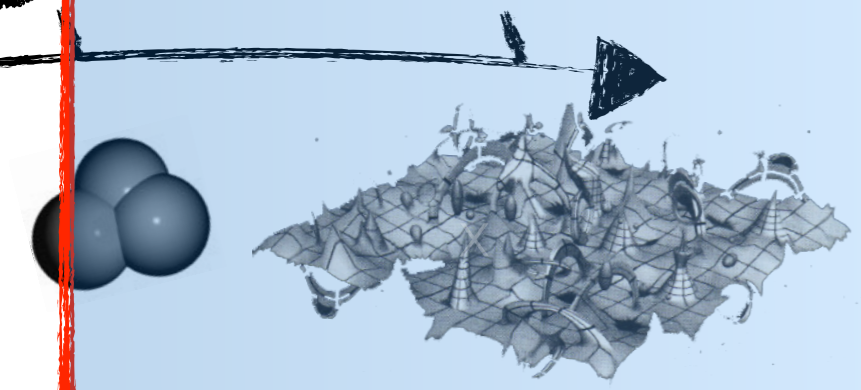
$$\Lambda_U > 10^{14} \text{ GeV}$$

$$\frac{1}{\Lambda_U} (\tilde{\varphi}^\dagger l_p)^T C (\tilde{\varphi}^\dagger l_r)$$

Neutrino mass  $m_\nu \sim 0.1 \text{ eV}$

$10^{-15}$

$10^{-35}$



FCs

# High-Energy Particle Physics

$$\Lambda_B > 10^{16} \text{ GeV}$$

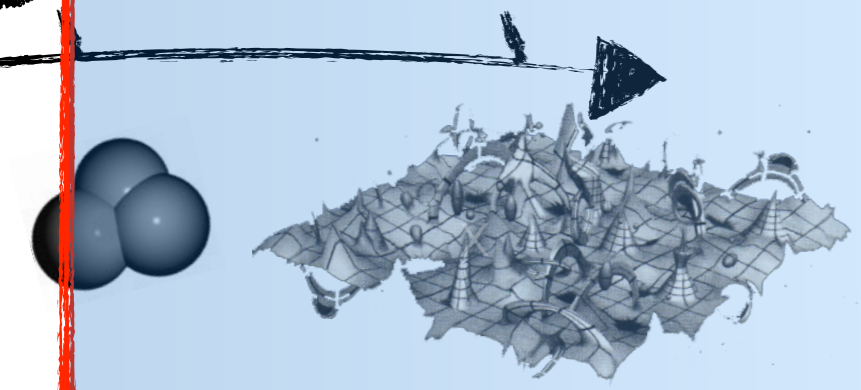
$$\frac{1}{\Lambda_B^2} [(d_p^\alpha)^T C u_r^\beta] [(q_s^{\gamma j})^T C l_t^k] \quad \text{Proton Lifetime } t_p > 10^{34} y$$

$$\Lambda_U > 10^{14} \text{ GeV}$$

$$\frac{1}{\Lambda_U} (\tilde{\varphi}^\dagger l_p)^T C (\tilde{\varphi}^\dagger l_r) \quad \text{Neutrino mass } m_\nu \sim 0.1 \text{ eV}$$

$10^{-15}$

$10^{-35}$



→ Laws of nature governed by (emerging) symmetries



FCs

# High-Energy Particle Physics

$$\Lambda_{\mathcal{B}} > 10^{16} \text{ GeV}$$

$$\frac{1}{\Lambda_{\mathcal{B}}^2} [(d_p^\alpha)^T C u_r^\beta] [(q_s^{\gamma j})^T C l_t^k] \quad \text{Proton Lifetime } t_p > 10^{34} y$$

$$\Lambda_{\mathcal{L}} > 10^{14} \text{ GeV}$$

$$\frac{1}{\Lambda_{\mathcal{L}}} (\tilde{\varphi}^\dagger l_p)^T C (\tilde{\varphi}^\dagger l_r) \quad \text{Neutrino mass } m_\nu \sim 0.1 \text{ eV}$$

$10^{-15}$

$10^{-35}$



→ Laws of nature governed by (emerging) symmetries

$$\frac{1}{\Lambda^2} (\bar{l}_p \gamma_\mu l_r) (\bar{u}_s \gamma^\mu u_t)$$



FCs



# High-Energy Particle Physics

$\Lambda_B > 10^{16} \text{ GeV}$

$$\frac{1}{\Lambda_B^2} [(d_p^\alpha)^T C u_r^\beta] [(q_s^{\gamma j})^T C l_t^k]$$

Proton Lifetime  $t_p > 10^{34} y$

$\Lambda_{\mathcal{L}} > 10^{14} \text{ GeV}$

$$\frac{1}{\Lambda_{\mathcal{L}}} (\tilde{\varphi}^\dagger l_p)^T C (\tilde{\varphi}^\dagger l_r)$$

Neutrino mass  $m_\nu \sim 0.1 \text{ eV}$

10<sup>-15</sup> 10<sup>-35</sup>

→ Laws of nature governed by (emerging) symmetries

$$\frac{1}{\Lambda^2} (\bar{l}_p \gamma_\mu l_r) (\bar{u}_s \gamma^\mu u_t)$$

ATLAS Heavy Particle Searches\* - 95% CL Upper Exclusion Limits

Model	$\ell, \gamma$	Jets†	$E_{\text{miss}}^\dagger$	$f_{\text{cut}}(\text{fb}^{-1})$	Limit	Reference
Extra dim.	ADD $G_{\mu\nu} + g^2/\epsilon$	0 $\mu, \tau, \gamma$	1-4‡	Yes	130	1702.0479
	ADD nonrenorm. $\gamma\gamma$	0 $\mu, \tau, \gamma$	1-4‡	Yes	36.7	1707.0447
	ADD BH	-	2‡	-	139	1910.0447
	ADD BH multijet	-	2‡	-	139	1912.0447
	RSL $G_{\mu\nu} + \gamma\gamma$	2 $\gamma$	2‡	-	139	2102.13405
	Bulk RS $G_{\mu\nu} + WW/ZZ$	1 $\mu, \tau$	2‡ b, 2‡ b	Yes	36.1	1908.0320
	2UED/RSF	1 $\mu, \tau$	2‡ b, 2‡ b	Yes	36.1	1904.19823
	Scalar $Z \rightarrow \gamma\gamma$	0 $\mu, \tau, \gamma$	1-4‡	Yes	36.1	1902.0479
	Leptoquark $Z \rightarrow b\bar{b}$	0 $\mu, \tau, \gamma$	1-4‡	Yes	36.1	1805.0429
	Leptoquark $Z \rightarrow t\bar{t}$	0 $\mu, \tau, \gamma$	1-4‡	Yes	139	2005.0116
	SSM $W \rightarrow \nu\bar{\nu}$	1 $\mu, \tau$	-	Yes	139	1905.0560
	SSM $W \rightarrow \nu\bar{\nu}$	1 $\mu, \tau$	-	Yes	139	1905.0560
	SSM $W \rightarrow \nu\bar{\nu}$	1 $\mu, \tau$	-	Yes	139	1905.0560
	HVT $W \rightarrow WZ$ model B	0 $\mu, \tau, \gamma$	2‡ (1, 2)	Yes	139	2004.1403
	HVT $W \rightarrow WZ$ model C	0 $\mu, \tau, \gamma$	2‡ (1, 2)	Yes	139	2007.0392
	HVT $Z \rightarrow WW$ model B	1 $\mu, \tau$	2‡ (1, 2)	Yes	20	2004.1403
	HVT $Z \rightarrow WW$ model C	1 $\mu, \tau$	2‡ (1, 2)	Yes	20	2004.1403
CI	CI $\nu\nu$	2 $\mu, \tau$	2‡	-	37.0	1709.0479
	CI $\nu\nu$	2 $\mu, \tau$	2‡	-	139	2006.1246
	CI $\nu\nu$	2 $\mu, \tau$	2‡	-	139	2105.1347
	CI $\nu\nu$	2 $\mu, \tau$	2‡	-	139	2105.1347
	CI $\nu\nu$	2 $\mu, \tau$	2‡	-	139	1811.0330
DM	Axial-vector med. (Dirac DM)	-	2‡	-	139	1709.0479
	Pseudo-scalar med. (Dirac DM)	0 $\mu, \tau, \gamma$	1-4‡	Yes	139	2102.0479
	Pseudo-scalar med. (Dirac DM)	0 $\mu, \tau, \gamma$	1-4‡	Yes	139	2102.0479
	Pseudo-scalar med. (Dirac DM)	0 $\mu, \tau, \gamma$	1-4‡	Yes	139	2102.0479
LO	Scalar LO 1 <sup>st</sup> gen	2 $\mu, \tau$	2‡	Yes	139	2004.0572
	Scalar LO 2 <sup>nd</sup> gen	2 $\mu, \tau$	2‡	Yes	139	2004.0572
	Scalar LO 3 <sup>rd</sup> gen	2 $\mu, \tau$	2‡	Yes	139	2004.0572
	Scalar LO 4 <sup>th</sup> gen	2 $\mu, \tau$	2‡	Yes	139	2004.0572
	Scalar LO 5 <sup>th</sup> gen	2 $\mu, \tau$	2‡	Yes	139	2004.0572
	Scalar LO 6 <sup>th</sup> gen	2 $\mu, \tau$	2‡	Yes	139	2004.0572
	Scalar LO 7 <sup>th</sup> gen	2 $\mu, \tau$	2‡	Yes	139	2004.0572
	Scalar LO 8 <sup>th</sup> gen	2 $\mu, \tau$	2‡	Yes	139	2004.0572
	Scalar LO 9 <sup>th</sup> gen	2 $\mu, \tau$	2‡	Yes	139	2004.0572
	Scalar LO 10 <sup>th</sup> gen	2 $\mu, \tau$	2‡	Yes	139	2004.0572
	Scalar LO 11 <sup>th</sup> gen	2 $\mu, \tau$	2‡	Yes	139	2004.0572
	Scalar LO 12 <sup>th</sup> gen	2 $\mu, \tau$	2‡	Yes	139	2004.0572
	Scalar LO 13 <sup>th</sup> gen	2 $\mu, \tau$	2‡	Yes	139	2004.0572
	Scalar LO 14 <sup>th</sup> gen	2 $\mu, \tau$	2‡	Yes	139	2004.0572
	Scalar LO 15 <sup>th</sup> gen	2 $\mu, \tau$	2‡	Yes	139	2004.0572
	Scalar LO 16 <sup>th</sup> gen	2 $\mu, \tau$	2‡	Yes	139	2004.0572
	Scalar LO 17 <sup>th</sup> gen	2 $\mu, \tau$	2‡	Yes	139	2004.0572
	Scalar LO 18 <sup>th</sup> gen	2 $\mu, \tau$	2‡	Yes	139	2004.0572
	Scalar LO 19 <sup>th</sup> gen	2 $\mu, \tau$	2‡	Yes	139	2004.0572
	Scalar LO 20 <sup>th</sup> gen	2 $\mu, \tau$	2‡	Yes	139	2004.0572
	Scalar LO 21 <sup>st</sup> gen	2 $\mu, \tau$	2‡	Yes	139	2004.0572
	Scalar LO 22 <sup>nd</sup> gen	2 $\mu, \tau$	2‡	Yes	139	2004.0572
	Scalar LO 23 <sup>rd</sup> gen	2 $\mu, \tau$	2‡	Yes	139	2004.0572
	Scalar LO 24 <sup>th</sup> gen	2 $\mu, \tau$	2‡	Yes	139	2004.0572
	Scalar LO 25 <sup>th</sup> gen	2 $\mu, \tau$	2‡	Yes	139	2004.0572
	Scalar LO 26 <sup>th</sup> gen	2 $\mu, \tau$	2‡	Yes	139	2004.0572
	Scalar LO 27 <sup>th</sup> gen	2 $\mu, \tau$	2‡	Yes	139	2004.0572
	Scalar LO 28 <sup>th</sup> gen	2 $\mu, \tau$	2‡	Yes	139	2004.0572
	Scalar LO 29 <sup>th</sup> gen	2 $\mu, \tau$	2‡	Yes	139	2004.0572
	Scalar LO 30 <sup>th</sup> gen	2 $\mu, \tau$	2‡	Yes	139	2004.0572
	Scalar LO 31 <sup>st</sup> gen	2 $\mu, \tau$	2‡	Yes	139	2004.0572
	Scalar LO 32 <sup>nd</sup> gen	2 $\mu, \tau$	2‡	Yes	139	2004.0572
	Scalar LO 33 <sup>rd</sup> gen	2 $\mu, \tau$	2‡	Yes	139	2004.0572
	Scalar LO 34 <sup>th</sup> gen	2 $\mu, \tau$	2‡	Yes	139	2004.0572
	Scalar LO 35 <sup>th</sup> gen	2 $\mu, \tau$	2‡	Yes	139	2004.0572
	Scalar LO 36 <sup>th</sup> gen	2 $\mu, \tau$	2‡	Yes	139	2004.0572
	Scalar LO 37 <sup>th</sup> gen	2 $\mu, \tau$	2‡	Yes	139	2004.0572
	Scalar LO 38 <sup>th</sup> gen	2 $\mu, \tau$	2‡	Yes	139	2004.0572
	Scalar LO 39 <sup>th</sup> gen	2 $\mu, \tau$	2‡	Yes	139	2004.0572
	Scalar LO 40 <sup>th</sup> gen	2 $\mu, \tau$	2‡	Yes	139	2004.0572
	Scalar LO 41 <sup>st</sup> gen	2 $\mu, \tau$	2‡	Yes	139	2004.0572
	Scalar LO 42 <sup>nd</sup> gen	2 $\mu, \tau$	2‡	Yes	139	2004.0572
	Scalar LO 43 <sup>rd</sup> gen	2 $\mu, \tau$	2‡	Yes	139	2004.0572
	Scalar LO 44 <sup>th</sup> gen	2 $\mu, \tau$	2‡	Yes	139	2004.0572
	Scalar LO 45 <sup>th</sup> gen	2 $\mu, \tau$	2‡	Yes	139	2004.0572
	Scalar LO 46 <sup>th</sup> gen	2 $\mu, \tau$	2‡	Yes	139	2004.0572
	Scalar LO 47 <sup>th</sup> gen	2 $\mu, \tau$	2‡	Yes	139	2004.0572
	Scalar LO 48 <sup>th</sup> gen	2 $\mu, \tau$	2‡	Yes	139	2004.0572
	Scalar LO 49 <sup>th</sup> gen	2 $\mu, \tau$	2‡	Yes	139	2004.0572
	Scalar LO 50 <sup>th</sup> gen	2 $\mu, \tau$	2‡	Yes	139	2004.0572
	Scalar LO 51 <sup>st</sup> gen	2 $\mu, \tau$	2‡	Yes	139	2004.0572
	Scalar LO 52 <sup>nd</sup> gen	2 $\mu, \tau$	2‡	Yes	139	2004.0572
	Scalar LO 53 <sup>rd</sup> gen	2 $\mu, \tau$	2‡	Yes	139	2004.0572
	Scalar LO 54 <sup>th</sup> gen	2 $\mu, \tau$	2‡	Yes	139	2004.0572
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	Scalar LO 58 <sup>th</sup> gen	2 $\mu, \tau$	2‡	Yes	139	2004.0572
	Scalar LO 59 <sup>th</sup> gen	2 $\mu, \tau$	2‡	Yes	139	2004.0572
	Scalar LO 60 <sup>th</sup> gen	2 $\mu, \tau$	2‡	Yes	139	2004.0572
	Scalar LO 61 <sup>st</sup> gen	2 $\mu, \tau$	2‡	Yes	139	2004.0572
	Scalar LO 62 <sup>nd</sup> gen	2 $\mu, \tau$	2‡	Yes	139	2004.0572
	Scalar LO 63 <sup>rd</sup> gen	2 $\mu, \tau$	2‡	Yes	139	2004.0572
	Scalar LO 64 <sup>th</sup> gen	2 $\mu, \tau$	2‡	Yes	139	2004.0572
	Scalar LO 65 <sup>th</sup> gen	2 $\mu, \tau$	2‡	Yes	139	2004.0572
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	Scalar LO 67 <sup>th</sup> gen	2 $\mu, \tau$	2‡	Yes	139	2004.0572
	Scalar LO 68 <sup>th</sup> gen	2 $\mu, \tau$	2‡	Yes	139	2004.0572
	Scalar LO 69 <sup>th</sup> gen	2 $\mu, \tau$	2‡	Yes	139	2004.0572
	Scalar LO 70 <sup>th</sup> gen	2 $\mu, \tau$	2‡	Yes	139	2004.0572
	Scalar LO 71 <sup>st</sup> gen	2 $\mu, \tau$	2‡	Yes	139	2004.0572
	Scalar LO 72 <sup>nd</sup> gen	2 $\mu, \tau$	2‡	Yes	139	2004.0572
	Scalar LO 73 <sup>rd</sup> gen	2 $\mu, \tau$	2‡	Yes	139	2004.0572
	Scalar LO 74 <sup>th</sup> gen	2 $\mu, \tau$	2‡	Yes	139	2004.0572
	Scalar LO 75 <sup>th</sup> gen	2 $\mu, \tau$	2‡	Yes	139	2004.0572
	Scalar LO 76 <sup>th</sup> gen	2 $\mu, \tau$	2‡	Yes	139	2004.0572
	Scalar LO 77 <sup>th</sup> gen	2 $\mu, \tau$	2‡	Yes	139	2004.0572
	Scalar LO 78 <sup>th</sup> gen	2 $\mu, \tau$	2‡	Yes	139	2004.0572
	Scalar LO 79 <sup>th</sup> gen	2 $\mu, \tau$	2‡	Yes	139	2004.0572
	Scalar LO 80 <sup>th</sup> gen	2 $\mu, \tau$	2‡	Yes	139	2004.0572
	Scalar LO 81 <sup>st</sup> gen	2 $\mu, \tau$	2‡	Yes	139	2004.0572
	Scalar LO 82 <sup>nd</sup> gen	2 $\mu, \tau$	2‡	Yes	139	2004.0572
	Scalar LO 83 <sup>rd</sup> gen	2 $\mu, \tau$	2‡	Yes	139	2004.0572
	Scalar LO 84 <sup>th</sup> gen	2 $\mu, \tau$	2‡	Yes	139	2004.0572
	Scalar LO 85 <sup>th</sup> gen	2 $\mu, \tau$	2‡	Yes	139	2004.0572
	Scalar LO 86 <sup>th</sup> gen	2 $\mu, \tau$	2‡	Yes	139	2004.0572
	Scalar LO 87 <sup>th</sup> gen	2 $\mu, \tau$	2‡	Yes	139	2004.0572
	Scalar LO 88 <sup>th</sup> gen	2 $\mu, \tau$	2‡	Yes	139	2004.0572
	Scalar LO 89 <sup>th</sup> gen	2 $\mu, \tau$	2‡	Yes	139	2004.0572
	Scalar LO 90 <sup>th</sup> gen	2 $\mu, \tau$	2‡	Yes	139	2004.0572
	Scalar LO 91 <sup>st</sup> gen	2 $\mu, \tau$	2‡	Yes	139	2004.0572
	Scalar LO 92 <sup>nd</sup> gen	2 $\mu, \tau$	2‡	Yes	139	2004.0572
	Scalar LO 93 <sup>rd</sup> gen	2 $\mu, \tau$	2‡	Yes	139	2004.0572
	Scalar LO 94 <sup>th</sup> gen	2 $\mu, \tau$	2‡	Yes	139	2004.0572
	Scalar LO 95 <sup>th</sup> gen	2 $\mu, \tau$	2‡	Yes	139	2004.0572
	Scalar LO 96 <sup>th</sup> gen	2 $\mu, \tau$	2‡	Yes	139	2004.0572
	Scalar LO 97 <sup>th</sup> gen	2 $\mu, \tau$	2‡	Yes	139	2004.0572
	Scalar LO 98 <sup>th</sup> gen	2 $\mu, \tau$	2‡	Yes	139	2004.0572
	Scalar LO 99 <sup>th</sup> gen	2 $\mu, \tau$	2‡	Yes	139	2004.0572
	Scalar LO 100 <sup>th</sup> gen	2 $\mu, \tau$	2‡	Yes	139	2004.0572
	Scalar LO 101 <sup>st</sup> gen	2 $\mu, \tau$	2‡	Yes	139	2004.0572
	Scalar LO 102 <sup>nd</sup> gen	2 $\mu, \tau$	2‡	Yes	139	2004.0572
	Scalar LO 103 <sup>rd</sup> gen	2 $\mu, \tau$	2‡	Yes	139	2004.0572
	Scalar LO 104 <sup>th</sup> gen	2 $\mu, \tau$	2‡	Yes	139	2004.0572
	Scalar LO 105 <sup>th</sup> gen	2 $\mu, \tau$	2‡	Yes	139	2004.0572
	Scalar LO 106 <sup>th</sup> gen	2 $\mu, \tau$	2‡	Yes	139	2004.0572
	Scalar LO 107 <sup>th</sup> gen	2 $\mu, \tau$	2‡	Yes	139	



# High-Energy Particle Physics

$\Lambda_B > 10^{16} \text{ GeV}$

$$\frac{1}{\Lambda_B^2} [(d_p^\alpha)^T C u_r^\beta] [(q_s^{\gamma j})^T C l_t^k]$$

Proton Lifetime  $t_p > 10^{34} y$

$\Lambda_{\mathbb{Z}} > 10^{14} \text{ GeV}$

$$\frac{1}{\Lambda_{\mathbb{Z}}} (\tilde{\varphi}^\dagger l_p)^T C (\tilde{\varphi}^\dagger l_r)$$

Neutrino mass  $m_\nu \sim 0.1 \text{ eV}$

10<sup>-15</sup>

10<sup>-35</sup>

➔ Laws of nature governed by (emerging) symmetries

$$\frac{1}{\Lambda^2} (\bar{l}_p \gamma_\mu l_r) (\bar{u}_s \gamma^\mu u_t)$$

ATLAS Heavy Particle Searches\* - 95% CL Upper Exclusion Limits

Model	$\ell, \gamma$	Jets†	$E_{T,miss}^{\min}$	$f_{cut}(b^{-1})$	Limit	Reference
Extra dim.	ADD $G_{\mu\nu} + g/\epsilon$	0 $\mu, \tau, \gamma$	1-4	Yes	1.2 TeV	1102.0879
	ADD nonrenorm. $\gamma\gamma$	0 $\mu, \tau, \gamma$	1-4	Yes	6.6 TeV	1707.0447
	ADD BH	0 $\mu, \tau, \gamma$	1-4	Yes	8.8 TeV	1910.0847
	ADD BH multijet	0 $\mu, \tau, \gamma$	1-4	Yes	3.6 TeV	1512.0289
	RSL $G_{\mu\nu} + \gamma\gamma$	0 $\mu, \tau, \gamma$	1-4	Yes	3.6 TeV	2102.1345
	Bulk RS $G_{\mu\nu} + WW/ZZ$	0 $\mu, \tau, \gamma$	1-4	Yes	2.3 TeV	1808.0280
	Bulk RS $G_{\mu\nu} + tt$	0 $\mu, \tau, \gamma$	1-4	Yes	3.6 TeV	1804.1802
	2UED/3UED	0 $\mu, \tau, \gamma$	1-4	Yes	1.4 TeV	2002.0870
Gravitational	SM $Z \rightarrow \gamma\gamma$	0 $\mu, \tau, \gamma$	1-4	Yes	2.4 TeV	1705.0127
	Leptoquark $Z \rightarrow bb$	0 $\mu, \tau, \gamma$	1-4	Yes	2.1 TeV	1805.0629
	Leptoquark $Z \rightarrow tt$	0 $\mu, \tau, \gamma$	1-4	Yes	4.1 TeV	2005.0110
	SSM $W \rightarrow \nu\bar{\nu}$	0 $\mu, \tau, \gamma$	1-4	Yes	5.0 TeV	1905.0560
	SSM $W \rightarrow \nu\bar{\nu}$	0 $\mu, \tau, \gamma$	1-4	Yes	4.8 TeV	2005.0110
	SSM $W \rightarrow \nu\bar{\nu}$	0 $\mu, \tau, \gamma$	1-4	Yes	4.8 TeV	ATLAS-CONF-20-013
	HVT $W \rightarrow WZ$ model B	0 $\mu, \tau, \gamma$	1-4	Yes	340 GeV	2004.1403
	HVT $W \rightarrow WZ$ model C	0 $\mu, \tau, \gamma$	1-4	Yes	340 GeV	2007.0390
	HVT $Z \rightarrow WW$ model B	0 $\mu, \tau, \gamma$	1-4	Yes	3.9 TeV	2004.1403
CI	CI $gggg$	0 $\mu, \tau, \gamma$	1-4	Yes	21.8 TeV	1709.0427
	CI $gggg$	0 $\mu, \tau, \gamma$	1-4	Yes	2.0 TeV	2006.1296
	CI $gggg$	0 $\mu, \tau, \gamma$	1-4	Yes	1.8 TeV	2105.1347
	CI $gggg$	0 $\mu, \tau, \gamma$	1-4	Yes	2.0 TeV	2105.1344
	CI $gggg$	0 $\mu, \tau, \gamma$	1-4	Yes	2.0 TeV	1811.0305

- $\Lambda$  21.8 TeV  $\eta_{\bar{L}\bar{L}}$
- $\Lambda$  35.8 TeV  $\eta_{LL}$
- $\Lambda$  1.8 TeV
- $\Lambda$  2.0 TeV
- $\Lambda$  2.57 TeV

$g_* = 1$   
 $g_* = 1$   
 $|C_{4t}| = 4\pi$

➔ Quark/Lepton size smaller than 10<sup>-20</sup> m





# High-Energy Particle Physics

$\Lambda_B > 10^{16} \text{ GeV}$

$\frac{1}{\Lambda_B^2} [(d_p^\alpha)^T C u_r^\beta] [(q_s^{\gamma j})^T C l_t^k]$  Proton Lifetime  $t_p > 10^{34} y$

$\Lambda_{\mathbb{Z}} > 10^{14} \text{ GeV}$

$\frac{1}{\Lambda_{\mathbb{Z}}} (\tilde{\varphi}^\dagger l_p)^T C (\tilde{\varphi}^\dagger l_r)$  Neutrino mass  $m_\nu \sim 0.1 \text{ eV}$

10<sup>-15</sup> 10<sup>-35</sup>

→ Laws of nature governed by (emerging) symmetries



$\frac{1}{\Lambda^2} (\bar{l}_p \gamma_\mu l_r) (\bar{u}_s \gamma^\mu u_t)$

ATLAS Heavy Particle Searches\* - 95% CL Upper Exclusion Limits

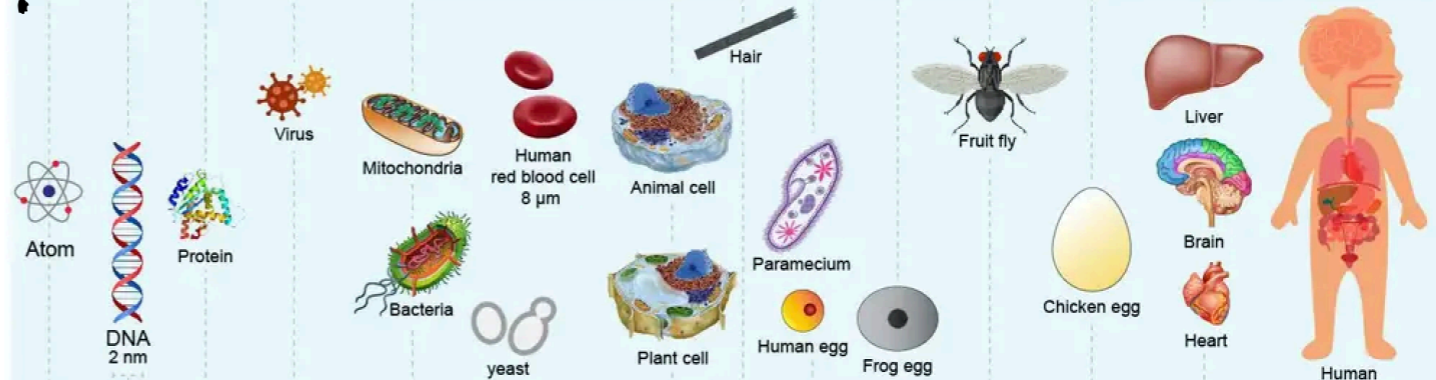
Status: March 2023

Model	$\ell, \gamma$	Jets†	$E_{T,miss}^{\min}$	$f_{cut}(fb^{-1})$	Limit	Reference
Extra dim.	ADD $G_{\mu\nu} + g^2$	0 $\mu, \tau, \gamma$	1-4†	Yes	1.2 TeV	n=2
	ADD nonrenorm. $\gamma\gamma$	0 $\mu, \tau, \gamma$	1-4†	Yes	6.6 TeV	n=3 HL NLO
	ADD BH	0 $\mu, \tau, \gamma$	1-4†	Yes	8.8 TeV	n=6, $M_{\text{pl}} = 3 \text{ TeV}$ not BH
	ADD BH multijet	0 $\mu, \tau, \gamma$	1-4†	Yes	3.8 TeV	n=6, $M_{\text{pl}} = 3 \text{ TeV}$ not BH
	RSL $G_{\mu\nu} + \gamma\gamma$	0 $\mu, \tau, \gamma$	1-4†	Yes	3.8 TeV	n=6, $M_{\text{pl}} = 3 \text{ TeV}$ not BH
	Bulk RS $G_{\mu\nu} + WW/ZZ$	0 $\mu, \tau, \gamma$	1-4†	Yes	2.3 TeV	$k/M_{\text{pl}} = 0.1$
	Bulk RS $G_{\mu\nu} + tt$	0 $\mu, \tau, \gamma$	1-4†	Yes	3.1 TeV	$k/M_{\text{pl}} = 0.1$
	2UED/3UED	0 $\mu, \tau, \gamma$	1-4†	Yes	1.4 TeV	$\tan(\beta), M_{\text{pl}}(\mu, \tau, \gamma) \geq 1$
Graviton	SM $Z \rightarrow \gamma\gamma$	0 $\mu, \tau, \gamma$	1-4†	Yes	2.4 TeV	$\Gamma_{\text{tot}} = 12\%$
	Leptoquark $Z \rightarrow bb$	0 $\mu, \tau, \gamma$	1-4†	Yes	2.1 TeV	$\Gamma_{\text{tot}} = 12\%$
	SSM $W \rightarrow \nu\bar{\nu}$	0 $\mu, \tau, \gamma$	1-4†	Yes	4.1 TeV	$\Gamma_{\text{tot}} = 12\%$
	SSM $W \rightarrow \nu\bar{\nu}$	0 $\mu, \tau, \gamma$	1-4†	Yes	5.0 TeV	$\Gamma_{\text{tot}} = 12\%$
	SSM $W \rightarrow \nu\bar{\nu}$	0 $\mu, \tau, \gamma$	1-4†	Yes	4.8 TeV	$\Gamma_{\text{tot}} = 12\%$
	HVT $W \rightarrow WZ$ model B	0 $\mu, \tau, \gamma$	1-4†	Yes	3.0 TeV	$\kappa = 3$
	HVT $W \rightarrow WZ$ model C	0 $\mu, \tau, \gamma$	1-4†	Yes	3.0 TeV	$\kappa = 1, \mu = 0$
	HVT $Z \rightarrow WW$ model B	0 $\mu, \tau, \gamma$	1-4†	Yes	3.0 TeV	$\kappa = 1$
	HVT $Z \rightarrow WW$ model C	0 $\mu, \tau, \gamma$	1-4†	Yes	3.0 TeV	$\kappa = 1$
CI	CI $gg$	0 $\mu, \tau, \gamma$	1-4†	Yes	21.8 TeV	$\mu = 1$
	CI $gg$	0 $\mu, \tau, \gamma$	1-4†	Yes	1.8 TeV	$\mu = 1$
	CI $gg$	0 $\mu, \tau, \gamma$	1-4†	Yes	2.0 TeV	$\mu = 1$
	CI $gg$	0 $\mu, \tau, \gamma$	1-4†	Yes	2.57 TeV	$\mu = 1$

$\Lambda$  21.8 TeV  $\eta_{\mathbb{L}\mathbb{L}}$   
 $\Lambda$  35.8 TeV  $\eta_{\mathbb{L}\mathbb{L}}$   
 $\Lambda$  1.8 TeV  
 $\Lambda$  2.0 TeV  
 $\Lambda$  2.57 TeV

$g_* = 1$   
 $g_* = 1$   
 $|C_{4t}| = 4\pi$

→ Quark/Lepton size smaller than 10<sup>-20</sup> m





If you have to choose on **ONE** question for future colliders, what will it be?

(for me...)

What is the size of the Higgs boson?

# The size of spin-0 particles in HEP

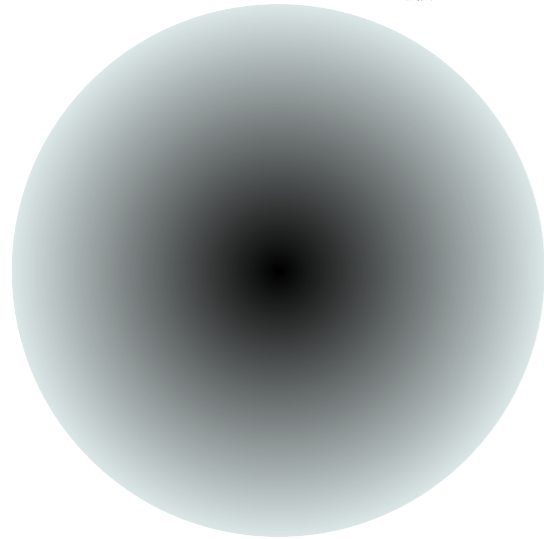
$$L_{\text{compton}} \sim \frac{1}{m}$$





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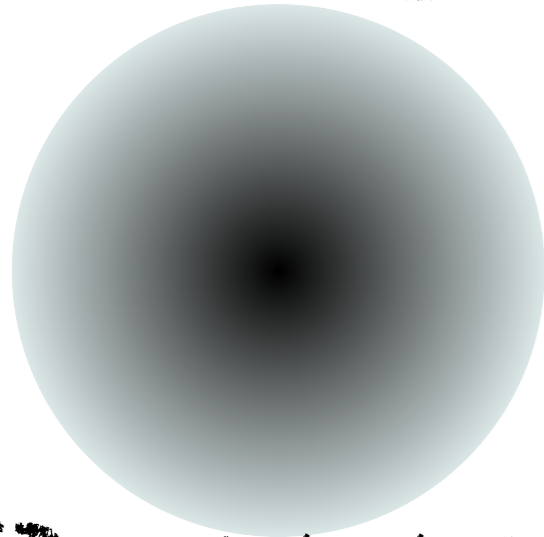


**QCD resonances**

$$L \sim \frac{1}{m} \sim \frac{1}{\text{GeV}}$$

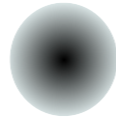
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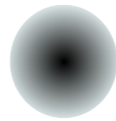
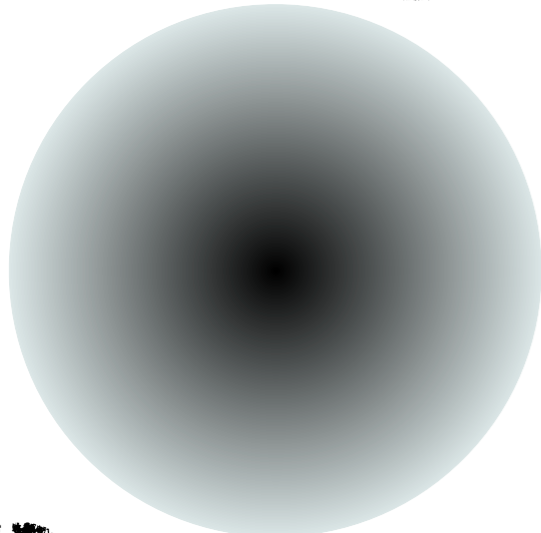


Pions

$$L \sim \frac{1}{10m} \sim \frac{0.1}{\text{GeV}}$$

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$$L \sim \frac{1}{m} \sim \frac{1}{\text{GeV}}$$

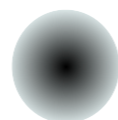
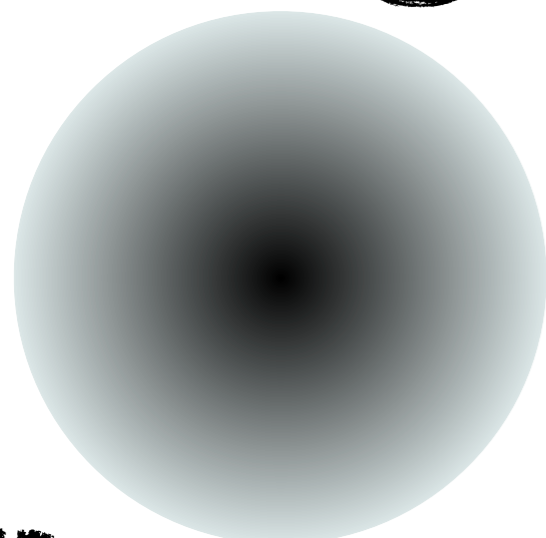
$$L \sim \frac{1}{10m} \sim \frac{0.1}{\text{GeV}}$$

Pseudo Goldstone Bosons



# The size of spin-0 particles in HEP

$$L_{\text{compton}} \sim \frac{1}{m}$$



QCD resonances

Pions

Higgs in the "SM+Grav"

$$L \sim \frac{1}{m} \sim \frac{1}{\text{GeV}}$$

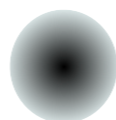
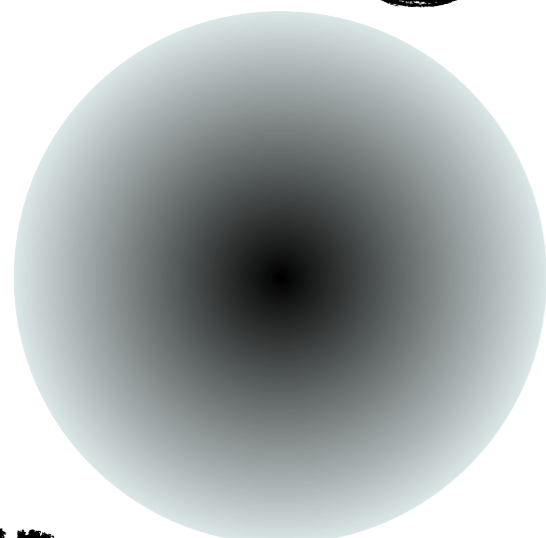
$$L \sim \frac{1}{10m} \sim \frac{0.1}{\text{GeV}}$$

$$L \lesssim \frac{1}{10^{17}m} \sim \frac{10^{-19}}{\text{GeV}}$$

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Pions

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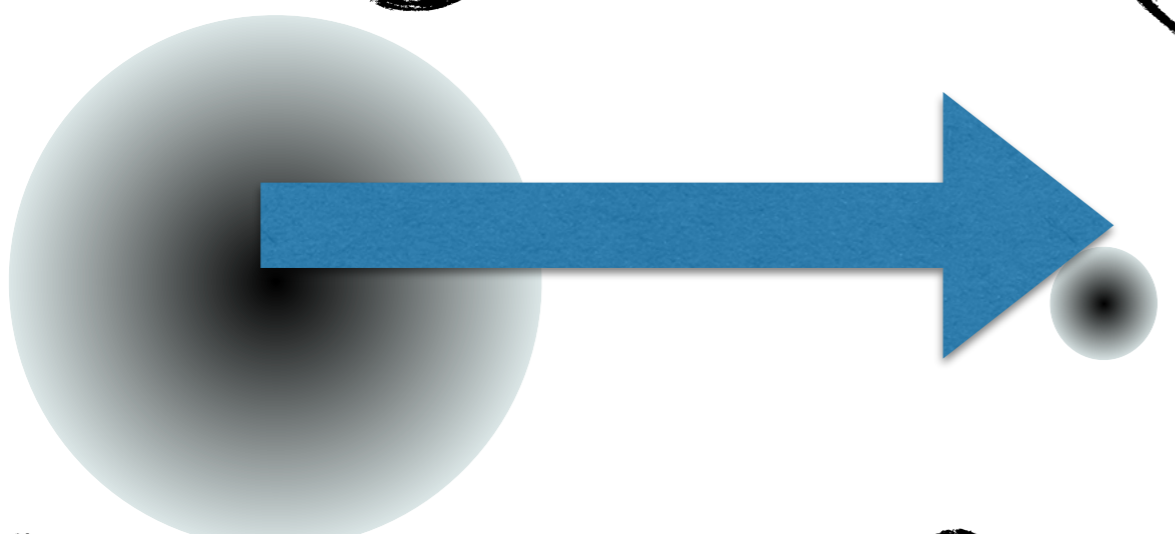
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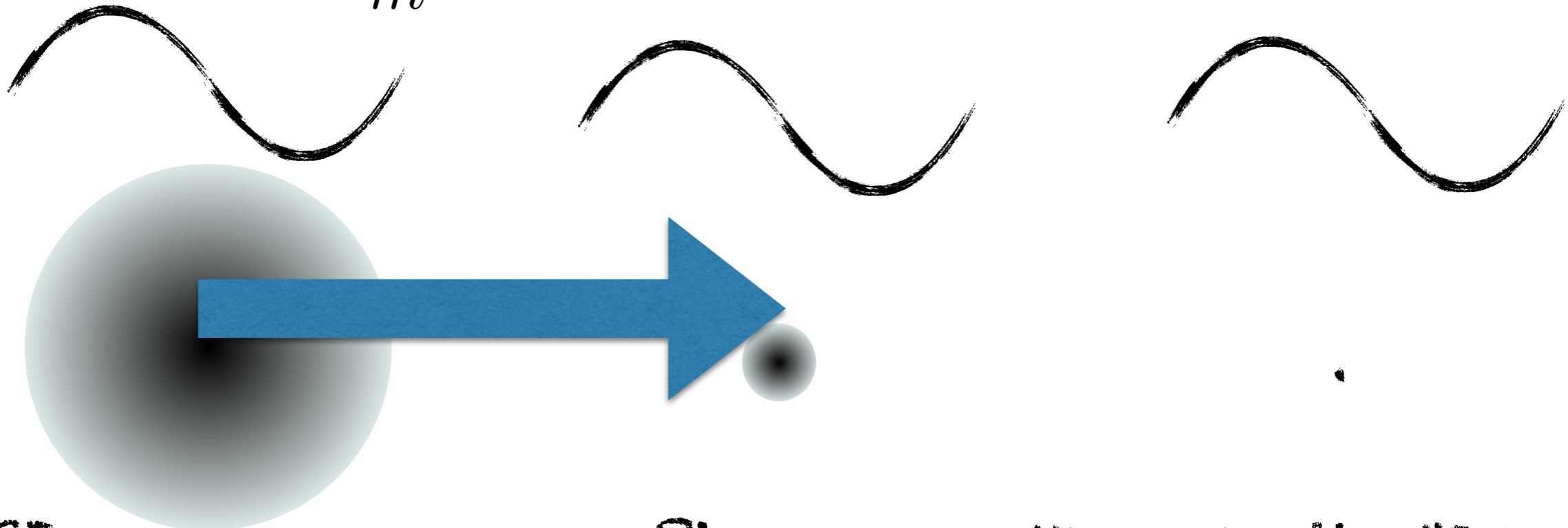
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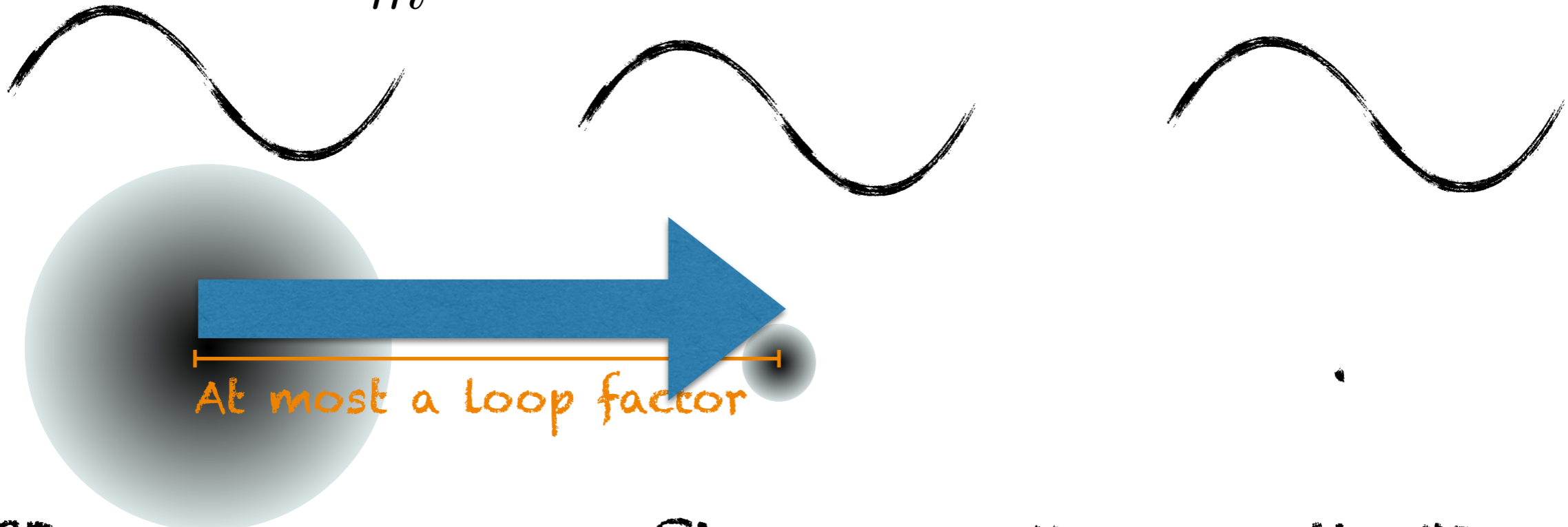
Intuitively\*: as localized to smaller distances, quantum fluctuation have large energy/mass

\* this intuition works in theories where the Higgs mass is calculable, but fails in e.g. SUSY where quantum fluctuation can cancel each-other out in their contribution to the mass



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Pseudo Goldstone Bosons

Higgs in the "SM+Grav"

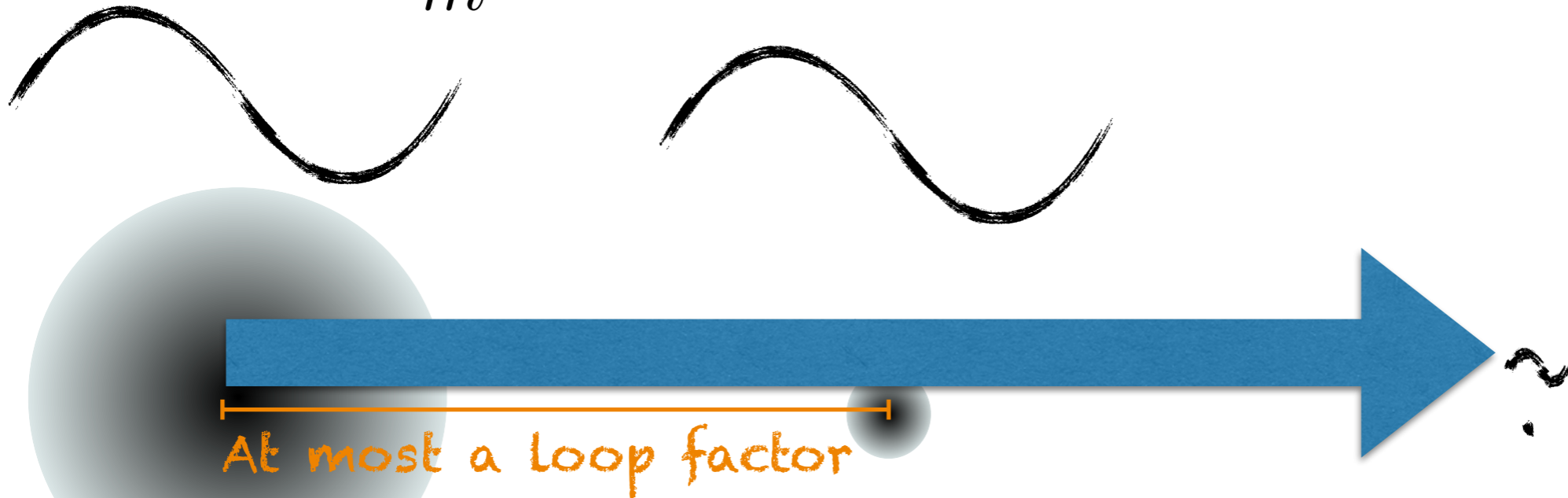
$$L \lesssim \frac{1}{10^{17}m} \sim \frac{10^{-19}}{\text{GeV}}$$

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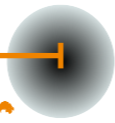
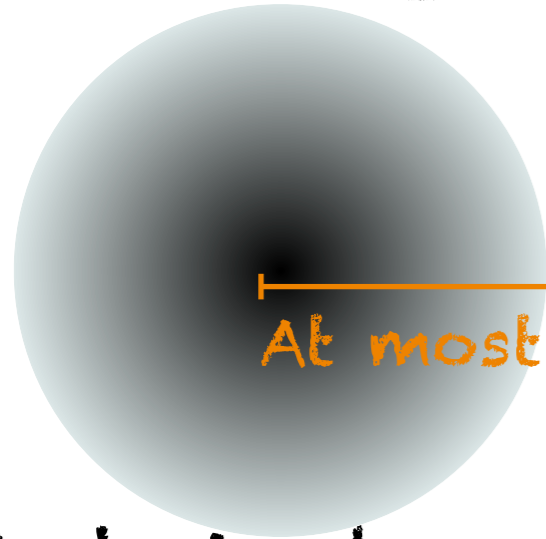
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# The size of the Higgs

$$L_{\text{compton}} \sim \frac{1}{m}$$



~?



At most a loop factor

Technicolor

$$L \sim \frac{1}{m} \sim \frac{1}{125 \text{ GeV}}$$

Composite  
PGB Higgs

$$L \sim \frac{1}{10m} \sim \frac{1}{\text{TeV}}$$

Pseudo Goldstone Bosons

Higgs in the "SM+Grav"

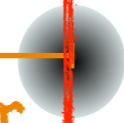
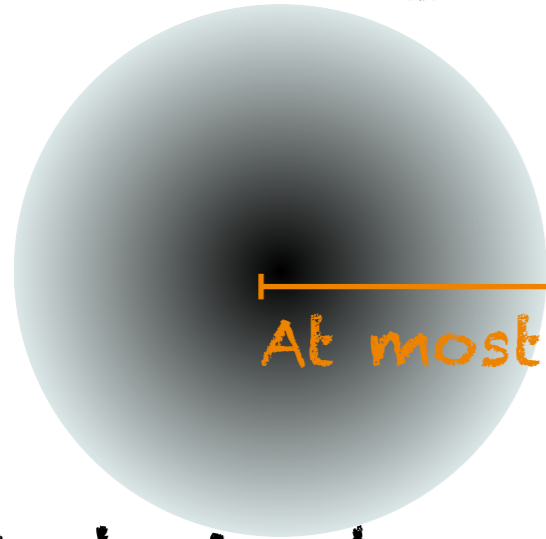
$$L \lesssim \frac{1}{10^{17} m} \sim \frac{10^{-19}}{\text{GeV}}$$

# The size of the Higgs

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~?



At most a loop factor

Technicolor

Composite  
PGB Higgs

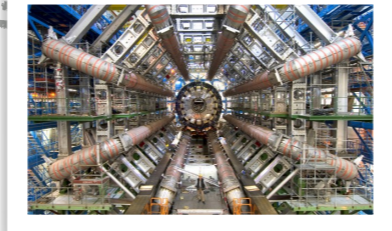
Higgs in the "SM+Grav"

$$L \sim \frac{1}{m} \sim \frac{1}{125\text{GeV}}$$

$$L \sim \frac{1}{10m} \sim \frac{1}{\text{TeV}}$$

$$L \lesssim \frac{1}{10^{17}m} \sim \frac{10^{-19}}{\text{GeV}}$$

Pseudo Goldstone Bosons

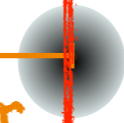
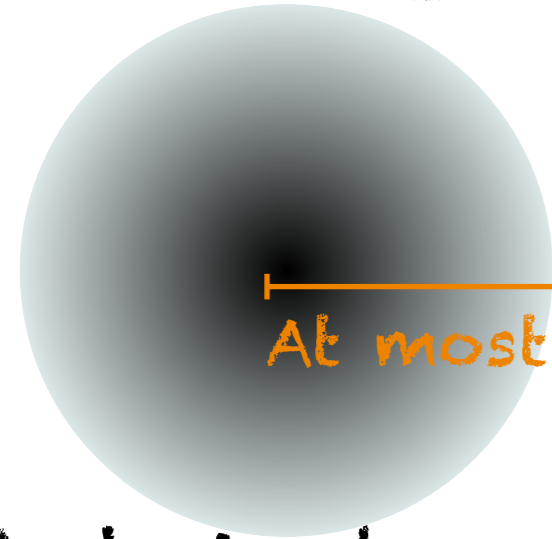


LHC



# The size of the Higgs

$$L_{\text{compton}} \sim \frac{1}{m}$$



At most a loop factor

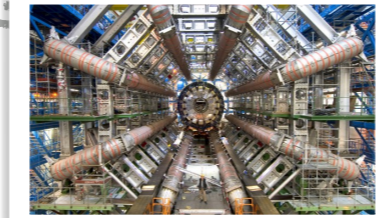
Technicolor

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Composite  
PGB Higgs

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Pseudo Goldstone Boson

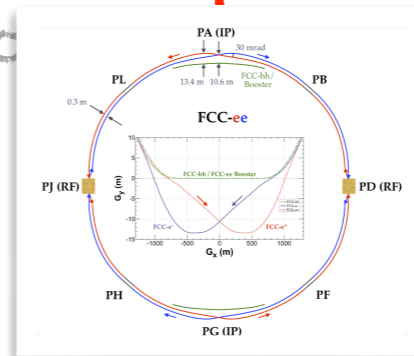


LHC

Higgs in the "SM+Grav"

$$L \lesssim \frac{1}{10^{17} m} \sim \frac{10^{-19}}{\text{GeV}}$$

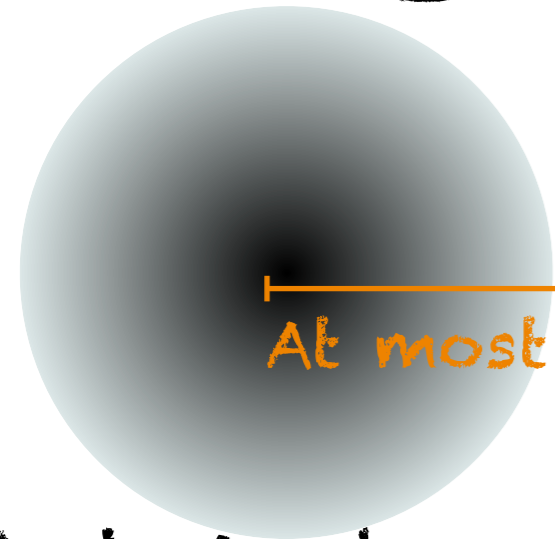
??



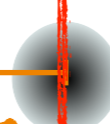
FCS

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At most a loop factor



~?

Technicolor

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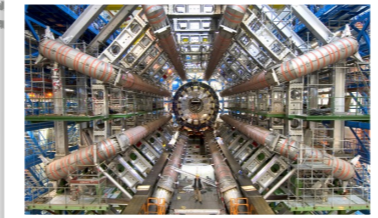
Composite PGB Higgs

$$L \sim \frac{1}{10m} \sim \frac{1}{\text{TeV}}$$

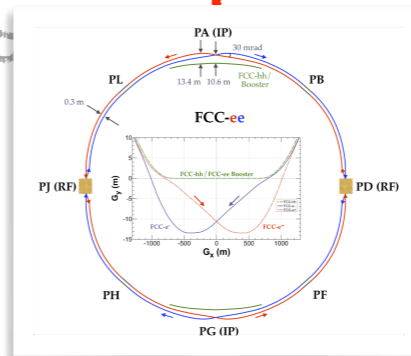
Pseudo Goldstone Boson

Higgs in the "SM+Grav"

$$L \lesssim \frac{1}{10^{17} m} \sim \frac{10^{-19}}{\text{GeV}}$$



LHC



FCCs

Future colliders will tell us how much the Higgs resembles one of the spin-0 particles that we already know, by measuring its size

# Is this a good question for e+e- machines?

To create composites with size, we need UV theories that are strongly coupled,

$$g_* \gtrsim 1$$

These have particles with substructure, like pions or protons, but are also little understood and unexplored.

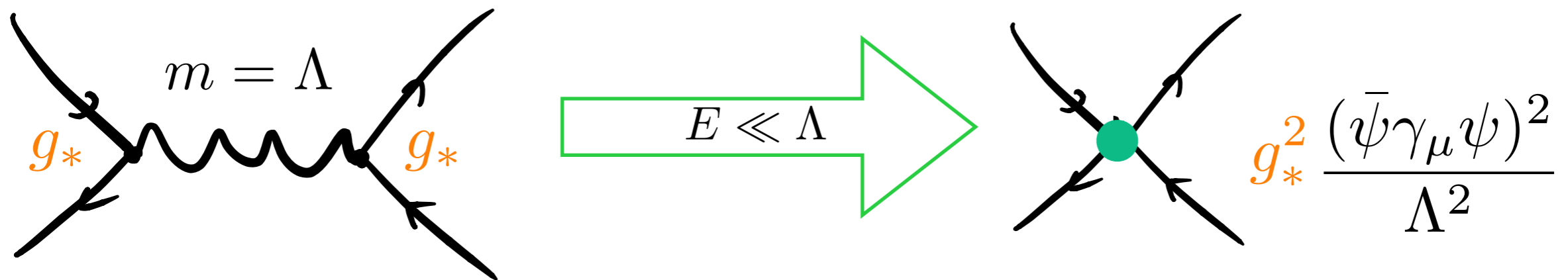
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Lepton colliders designed for precision physics, EFTs...





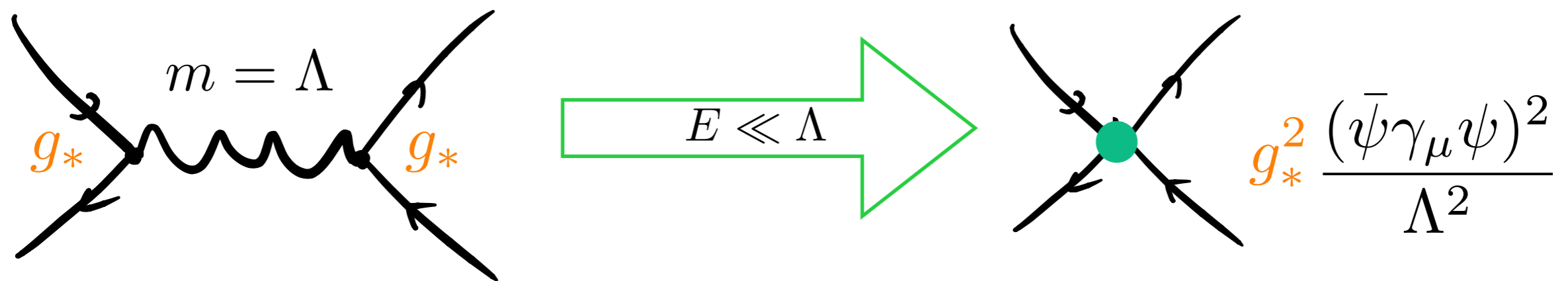
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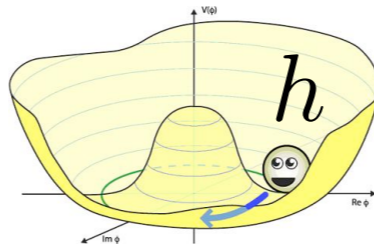
Lepton colliders designed for precision physics, EFTs...



- ▶ Strongly coupled theories are the ones that have the largest effects in EFTs and are more visible at FCCee!

# A Higgs smaller than its size?

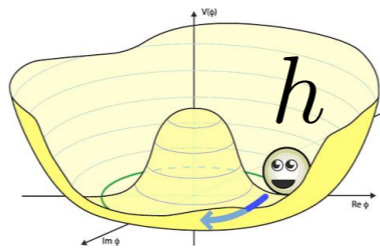
To be composite and lighter than its size, it must be a (Pseudo) Goldstone Boson:



$y$

# A Higgs smaller than its size?

To be composite and lighter than its size, it must be a (Pseudo) Goldstone Boson:



SM

$h$

$\bar{\psi}\psi h$

BSM

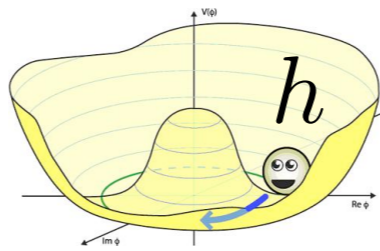
$$\sin \frac{h}{f} = \frac{h}{f} - \frac{h^3}{3!f^3} + \dots$$

$$\bar{\psi}\psi h + c \bar{\psi}\psi h^3$$

$y$

# A Higgs smaller than its size?

To be composite and lighter than its size, it must be a (Pseudo) Goldstone Boson:



SM

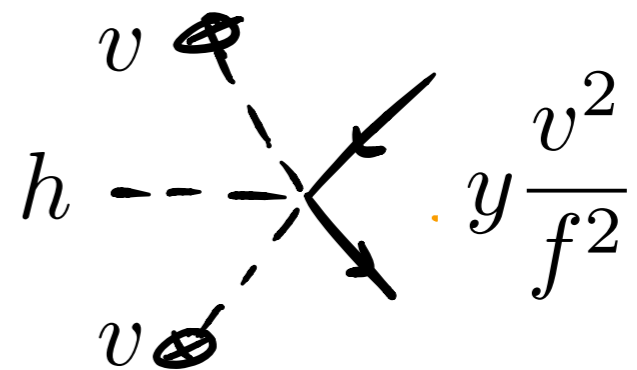
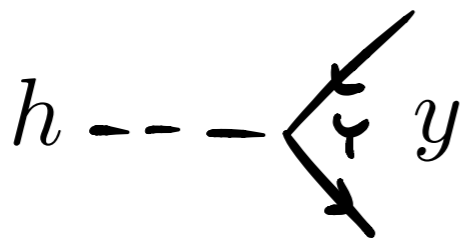
$h$

$\bar{\psi}\psi h$

BSM

$$\sin \frac{h}{f} = \frac{h}{f} - \frac{h^3}{3!f^3} + \dots$$

$$\bar{\psi}\psi h + c \bar{\psi}\psi h^3$$



tree-level Higgs Couplings are modified

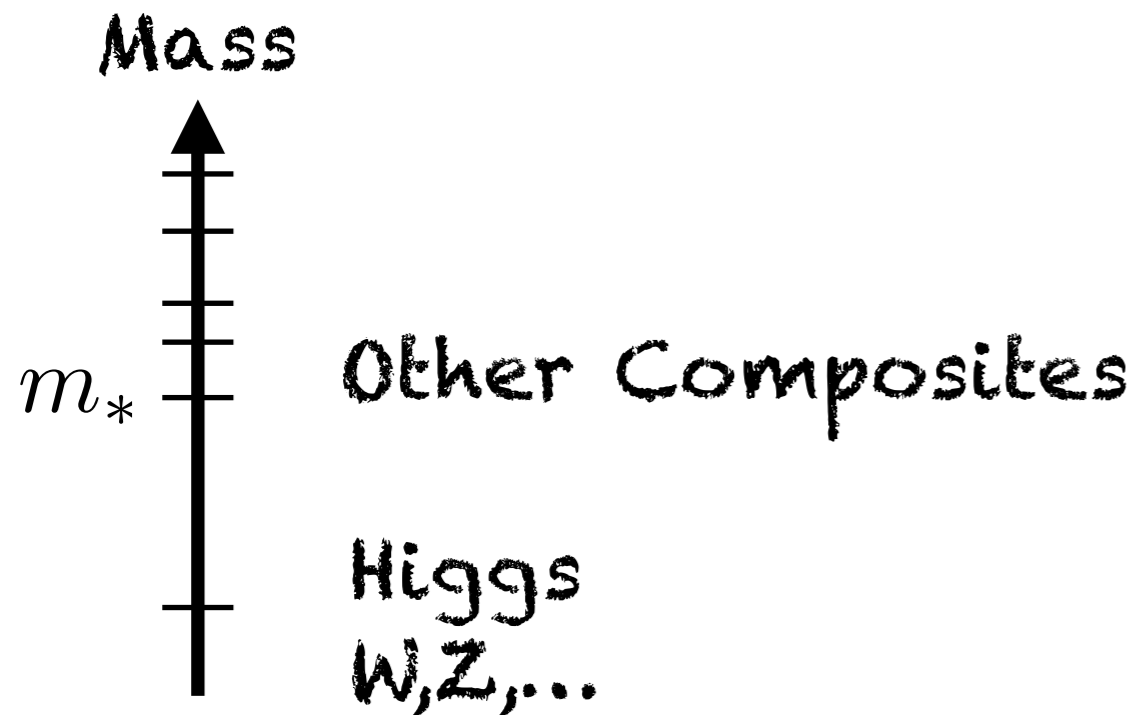


# Strongly Interacting Light Higgs

Giudice, Grojean, Pomarol, Rattazzi '08

The same constituents that make up the Higgs can make up other composites with

$$m_* \sim \frac{1}{L_H}$$

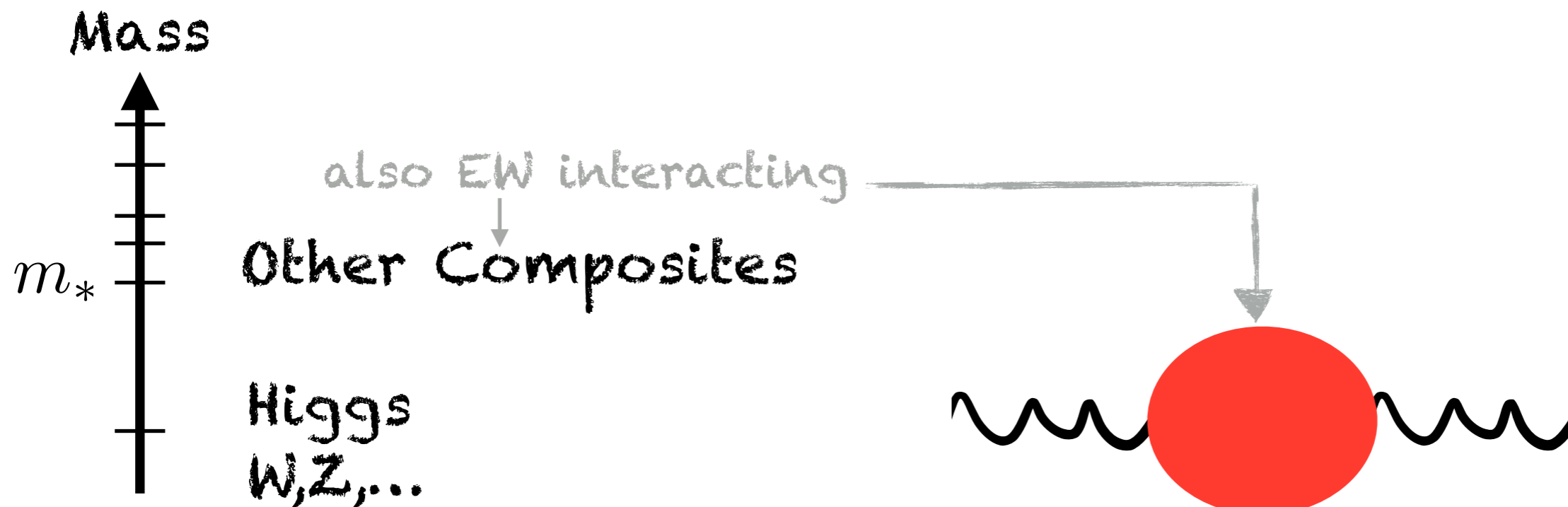


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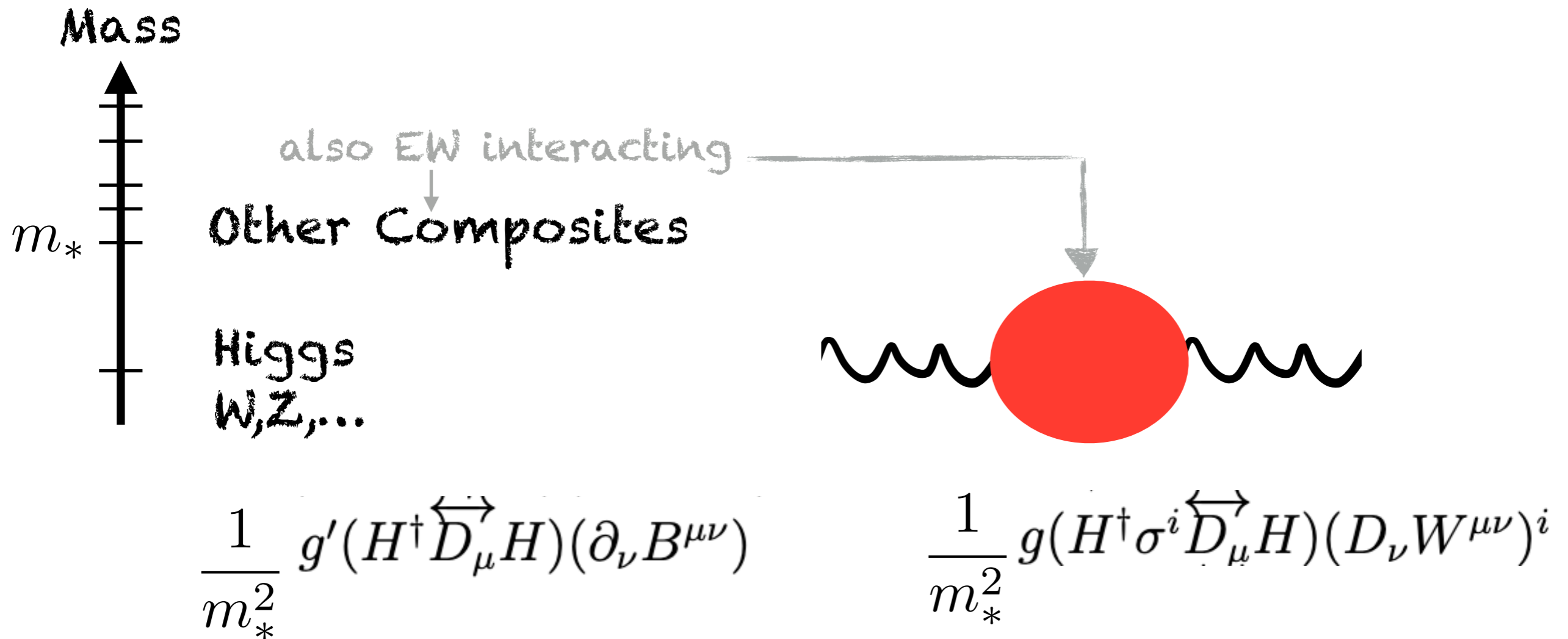


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modify Z-boson propagation (S-Parameter)

# A Higgs smaller than its size?

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Higgs size reflected into EFT effects:

$$\mathcal{O}_r = \frac{|H|^2 \partial_\mu H^\dagger \partial^\mu H}{f^2}$$

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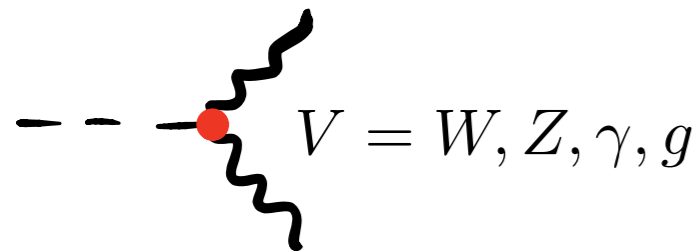
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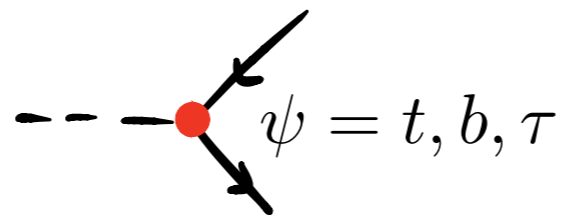
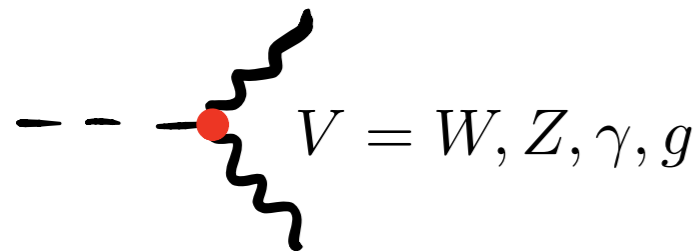
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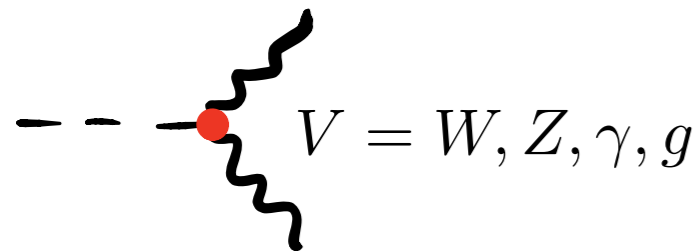


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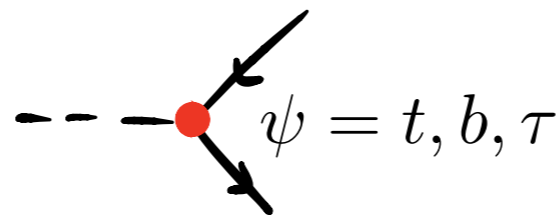
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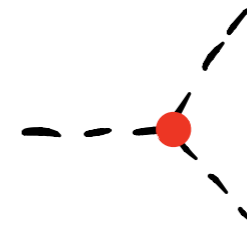
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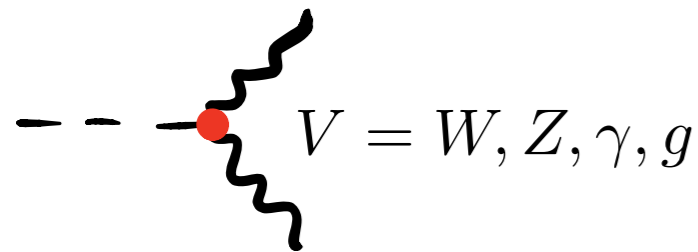


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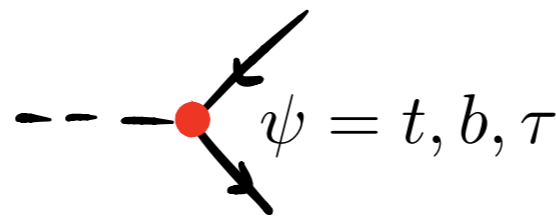
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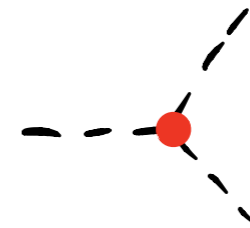
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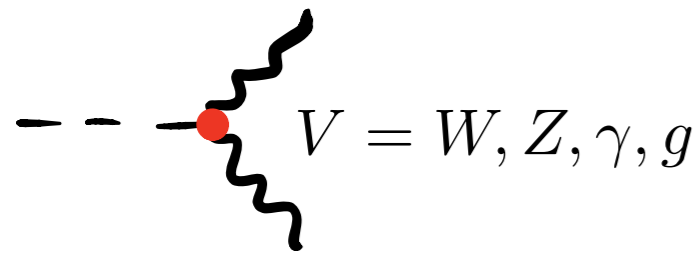
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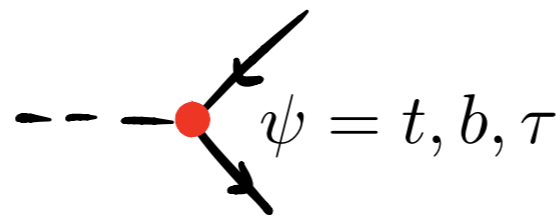
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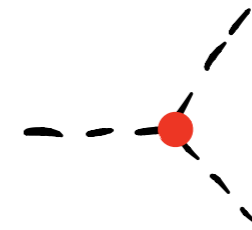
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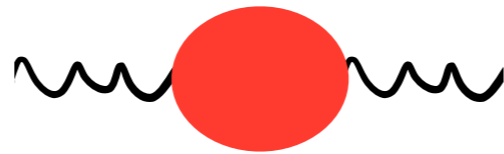
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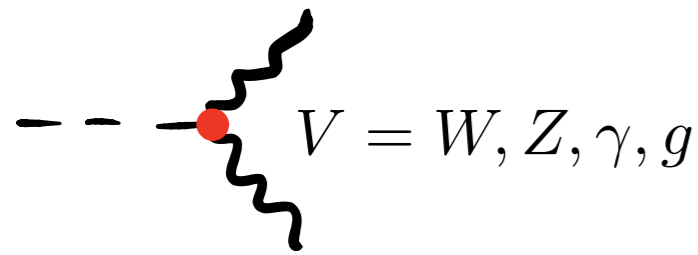


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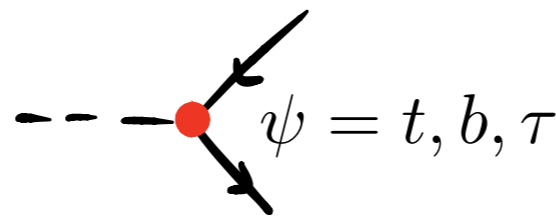
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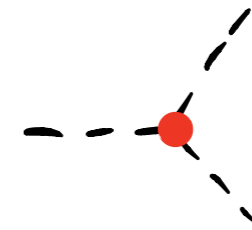
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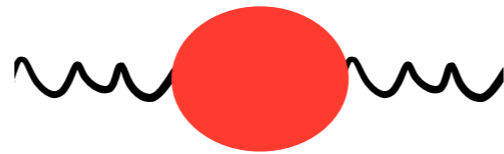
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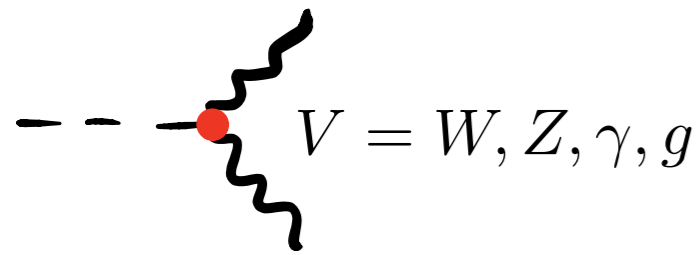
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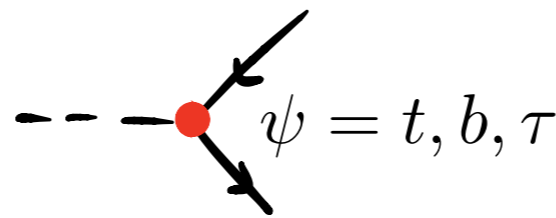
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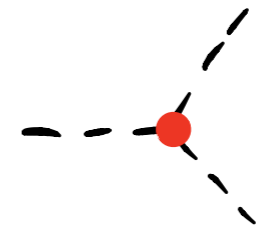
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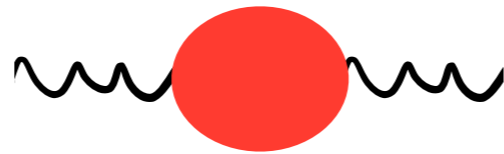
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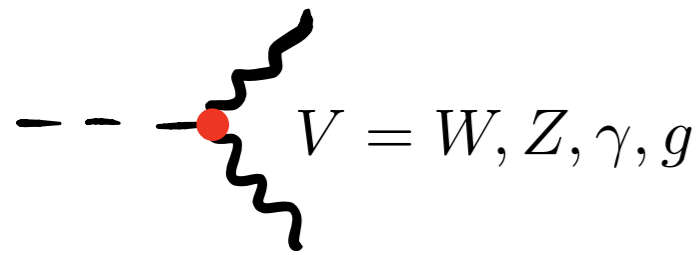
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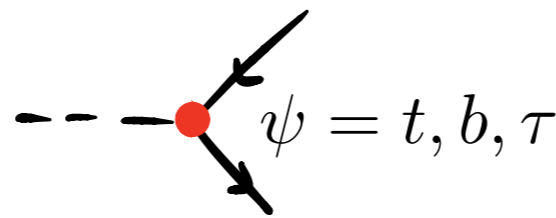
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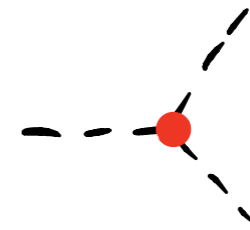
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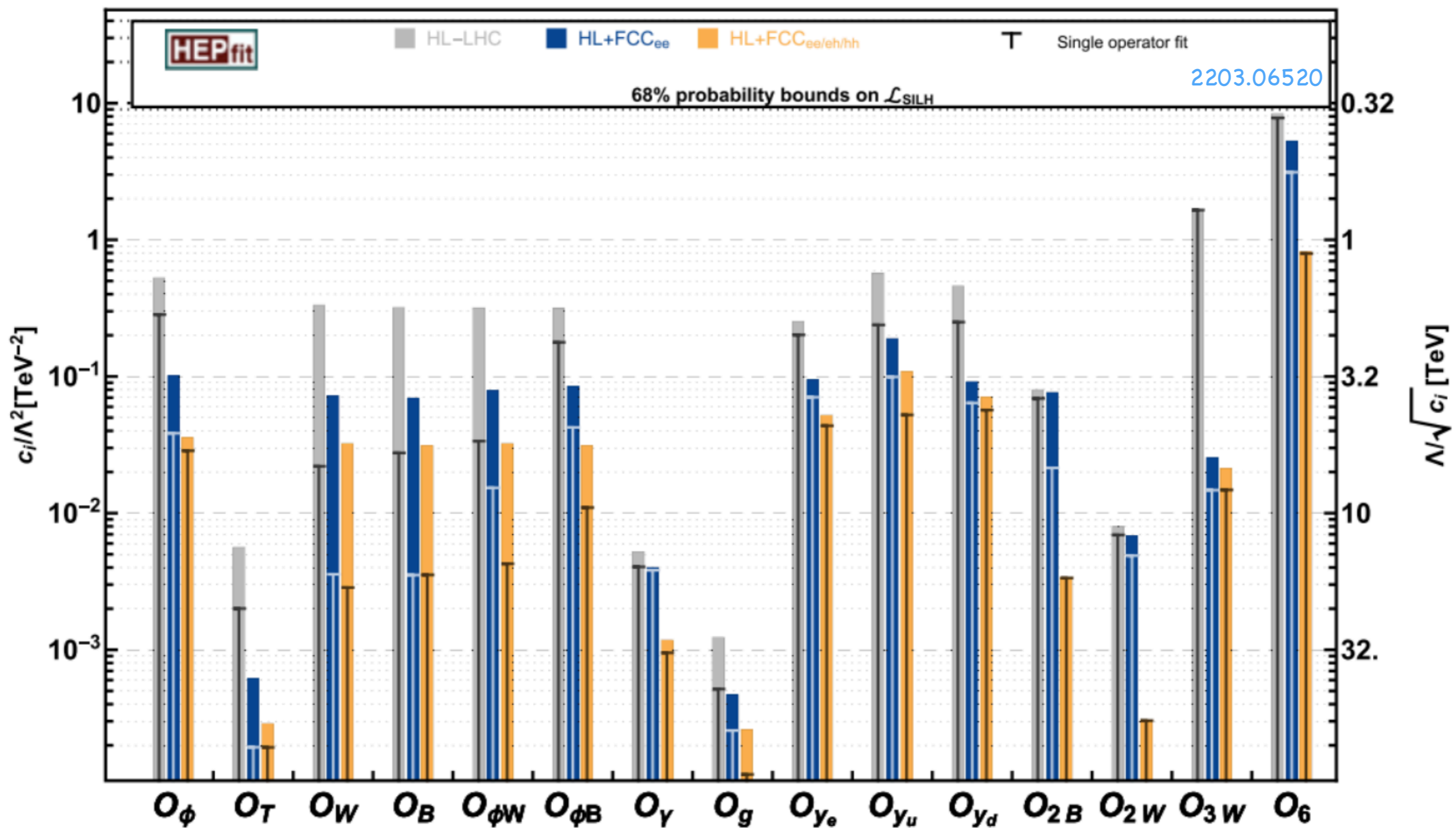


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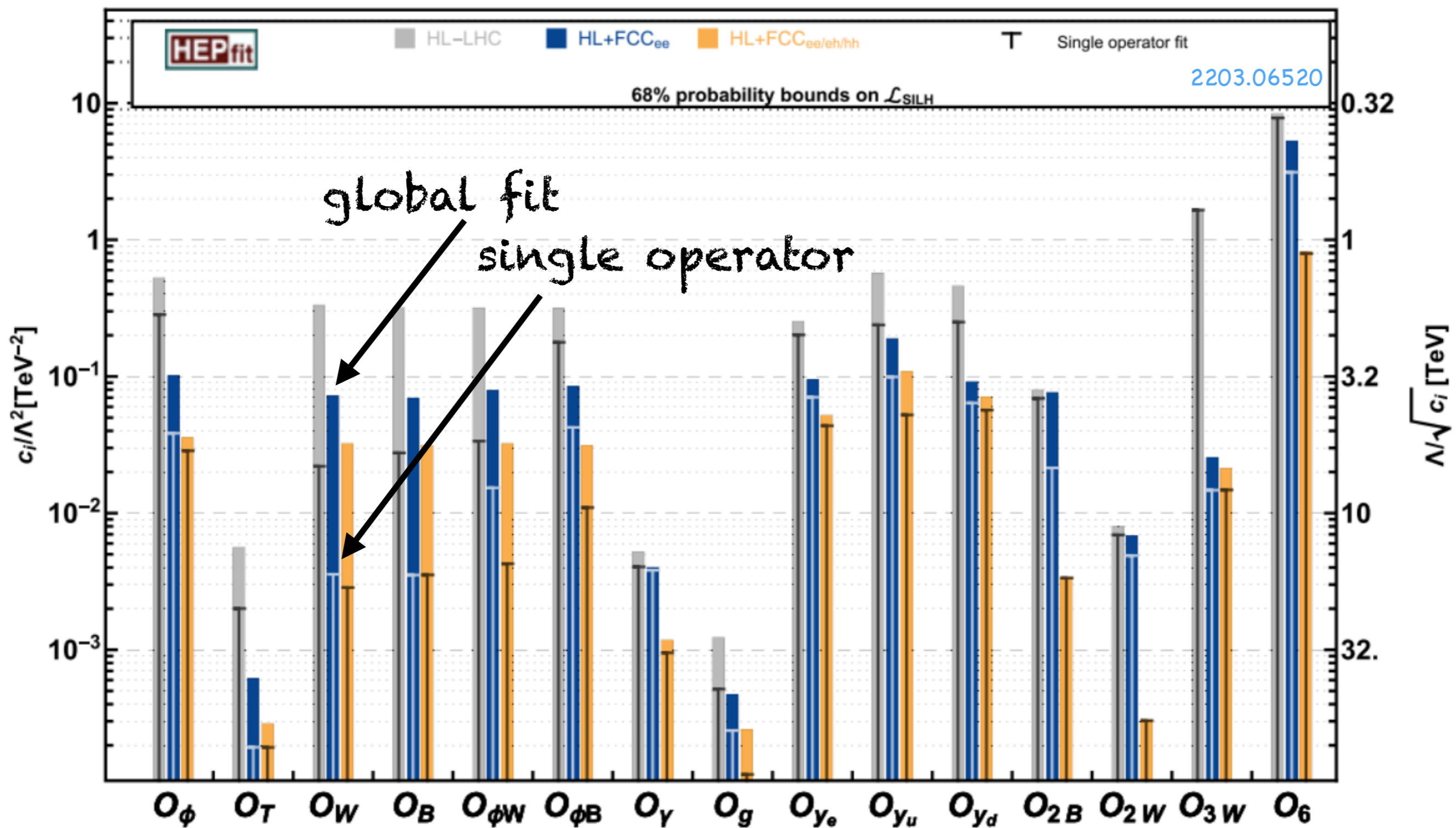
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Pions would have  $v=f \rightarrow v/f$  measures how SM-like the Higgs size is

# Physics Questions vs Global Fits

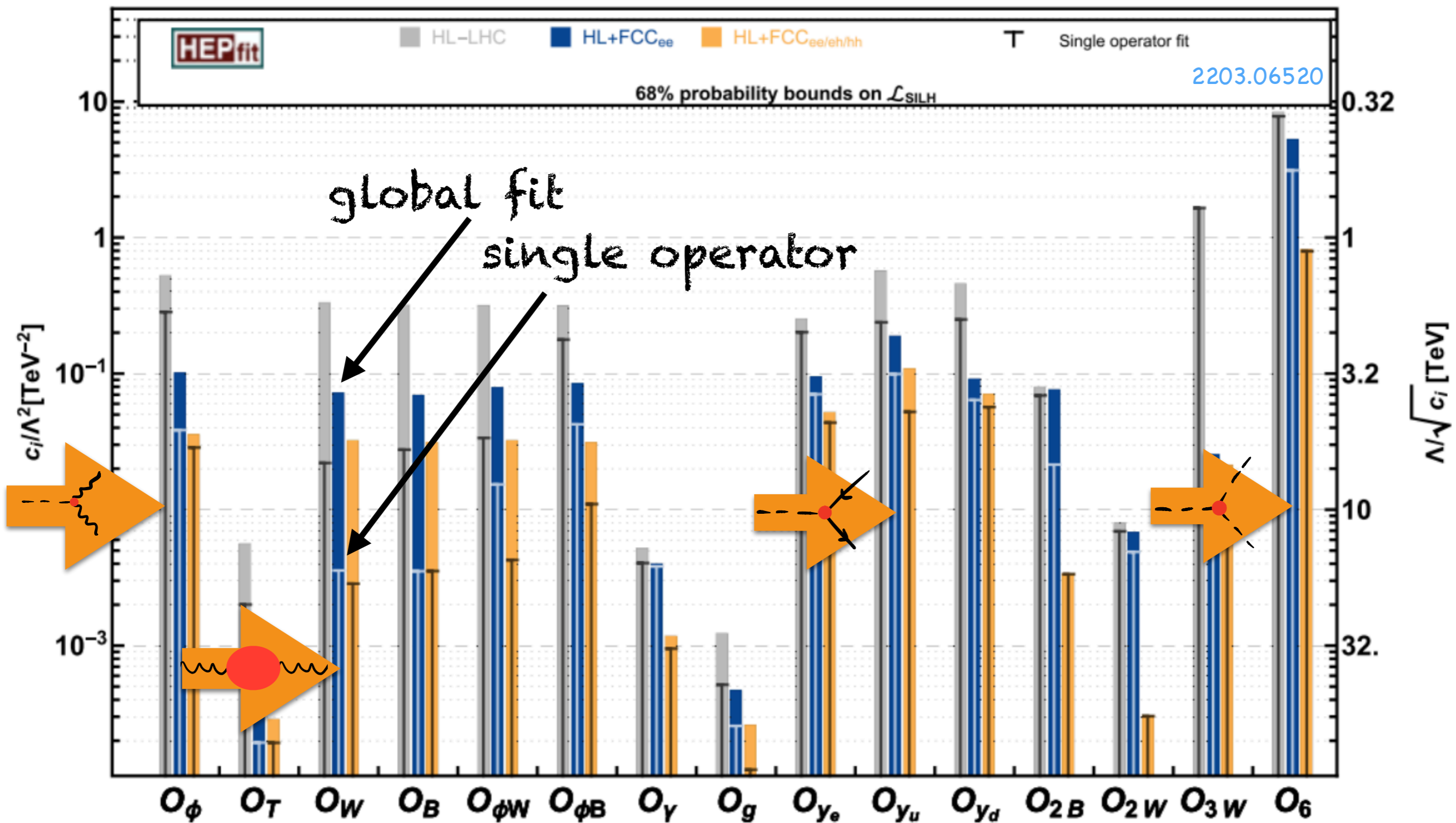


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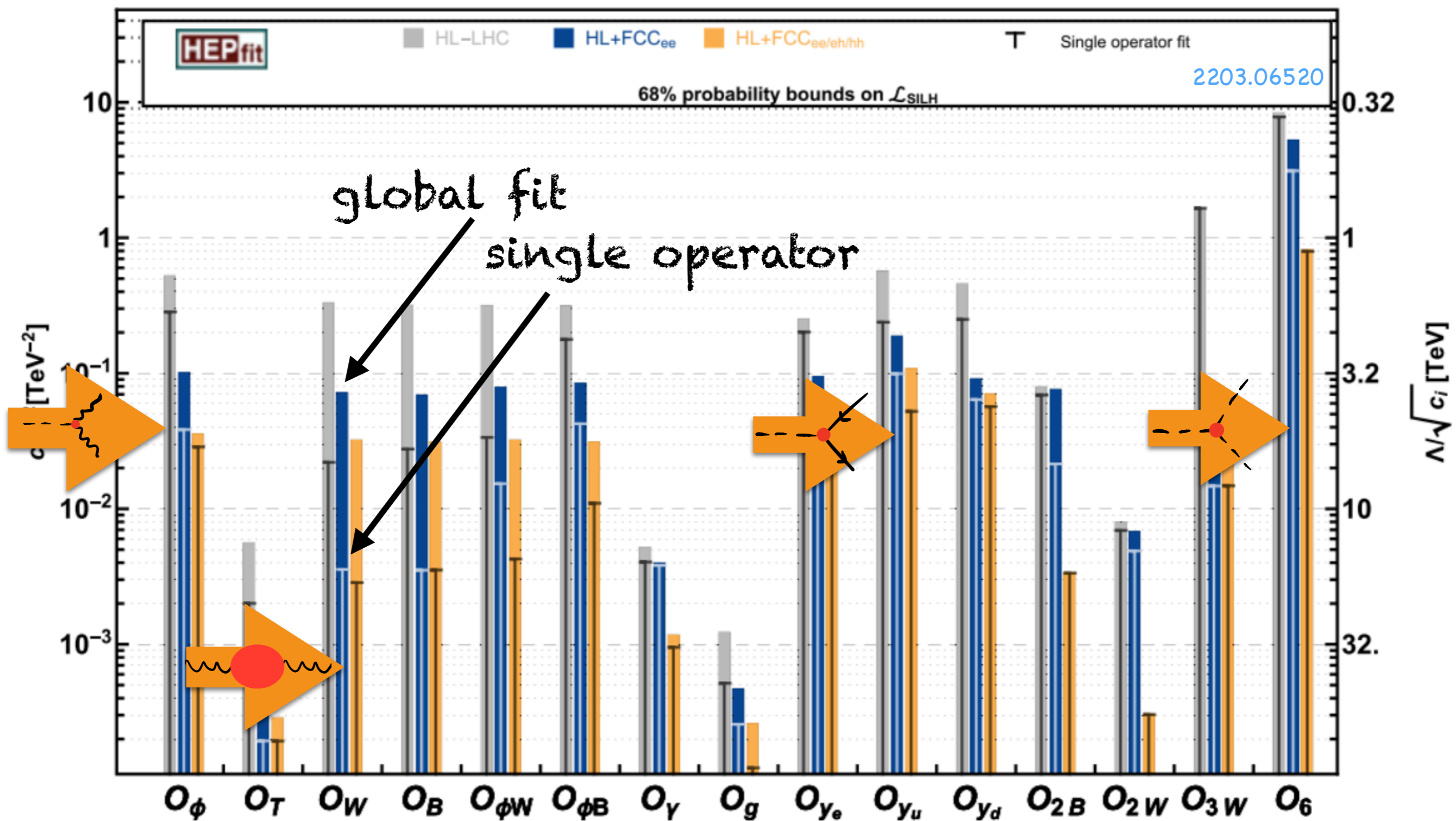




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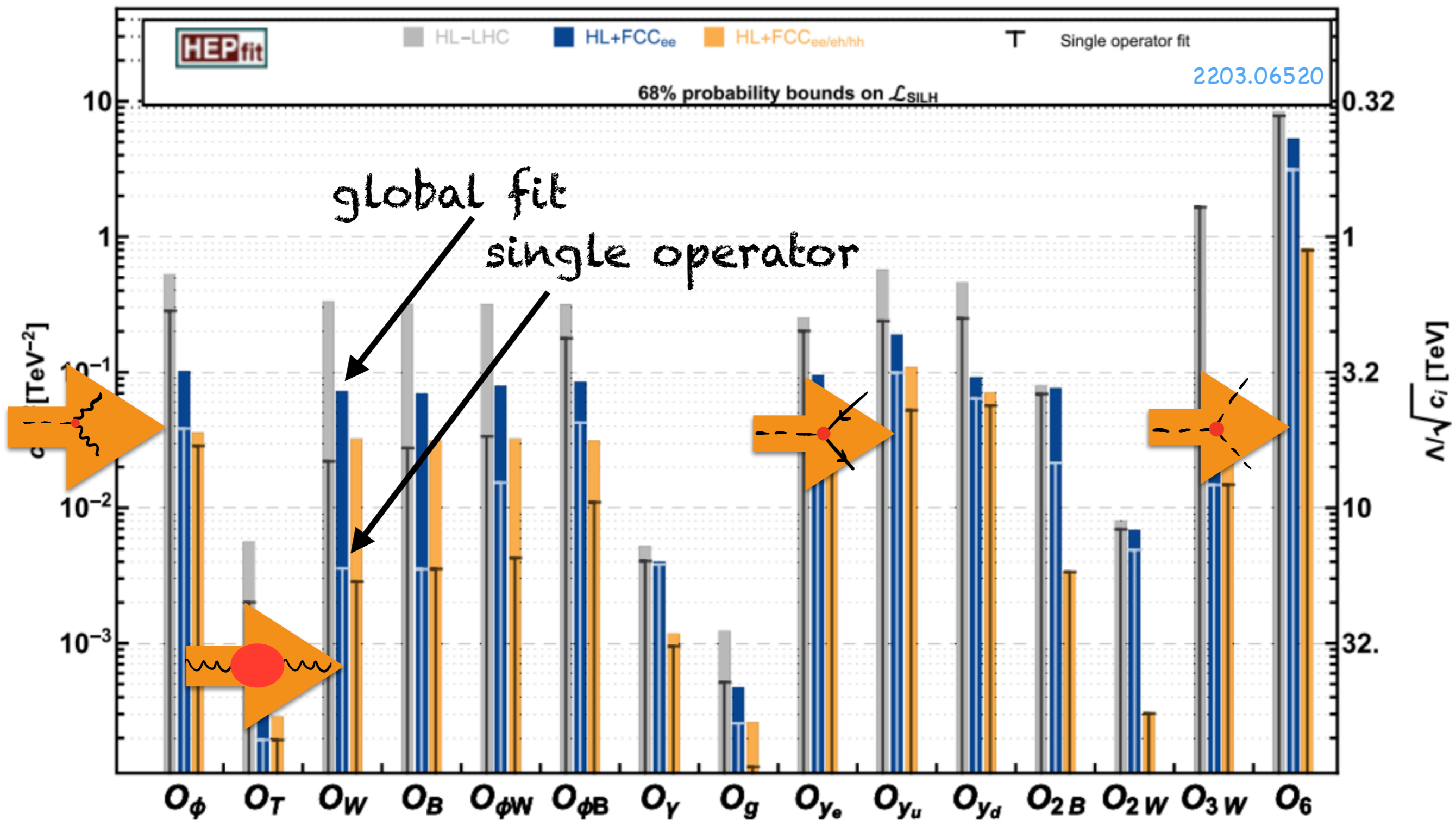


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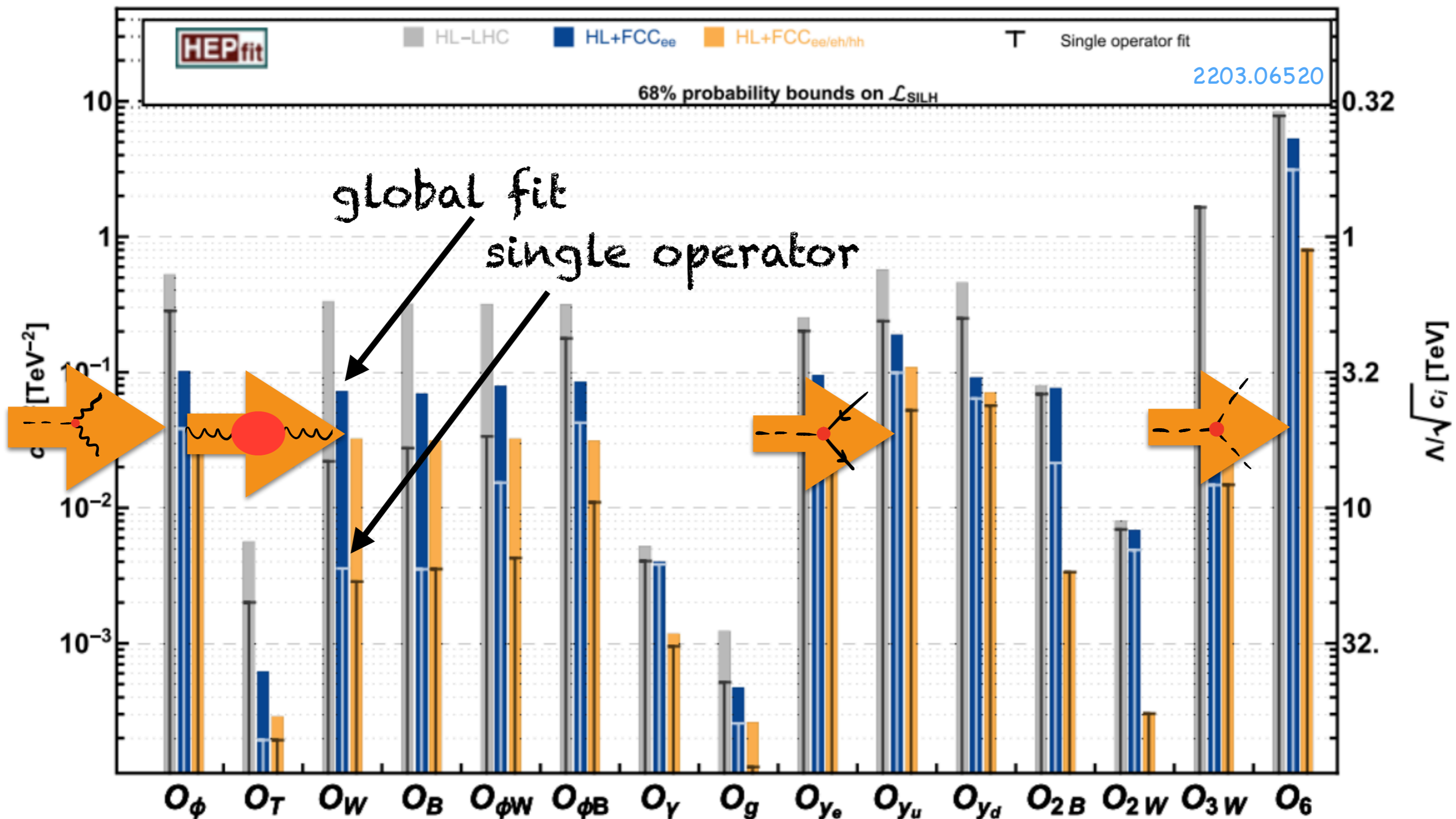
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Higgs couplings:  $\frac{v^2}{f^2} \lesssim 10^{-3}$   
(hZZ)



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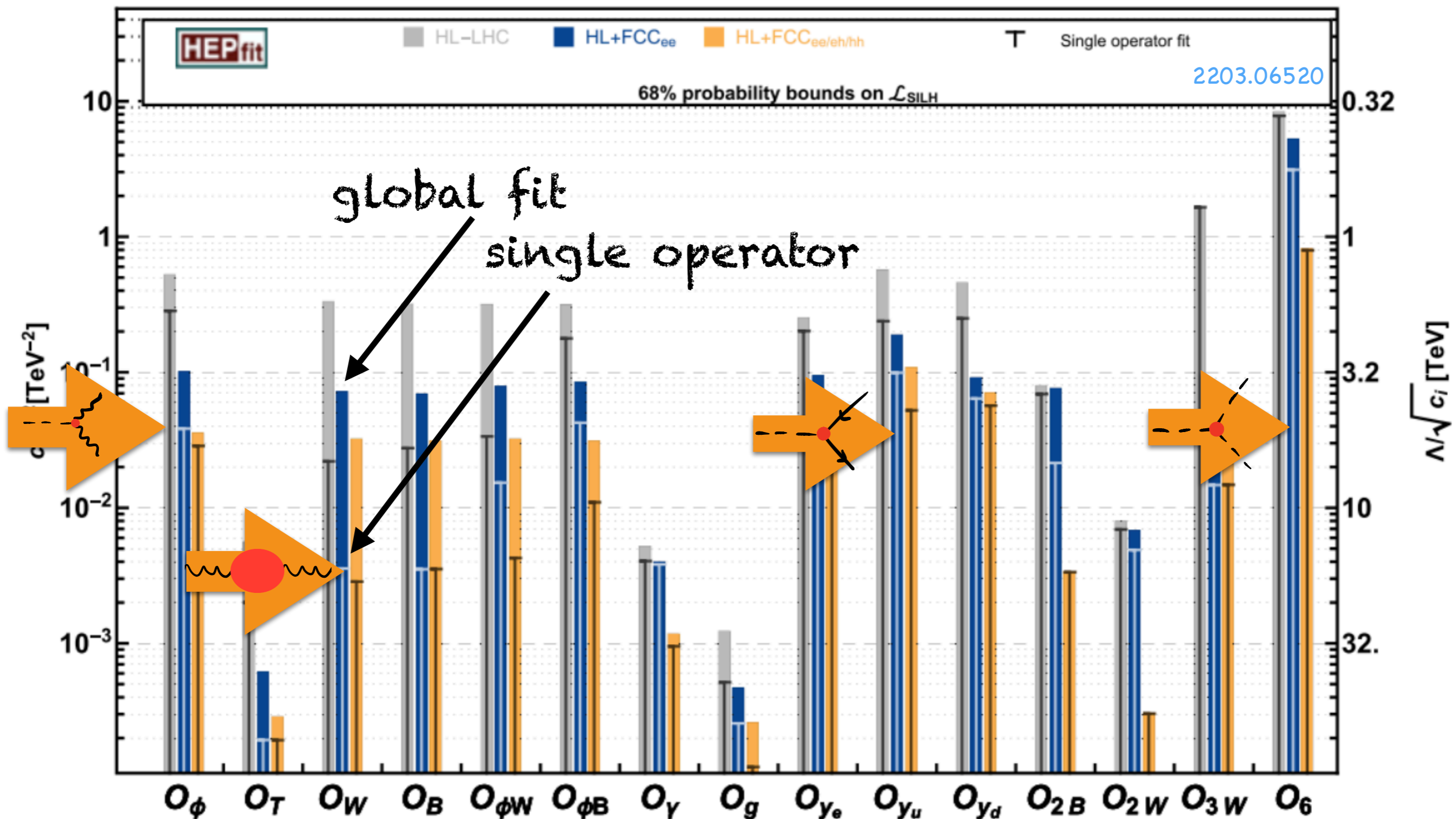
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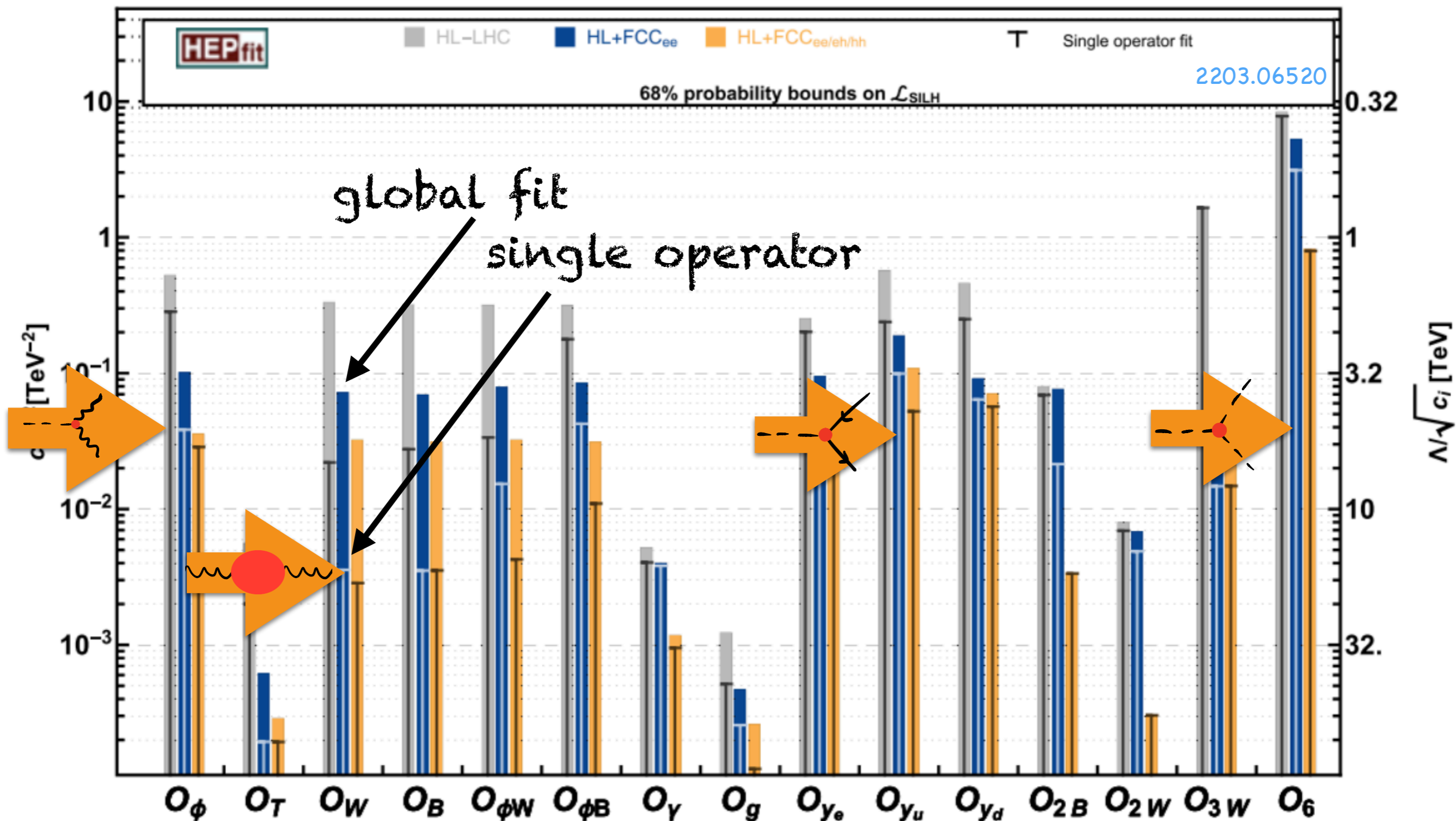




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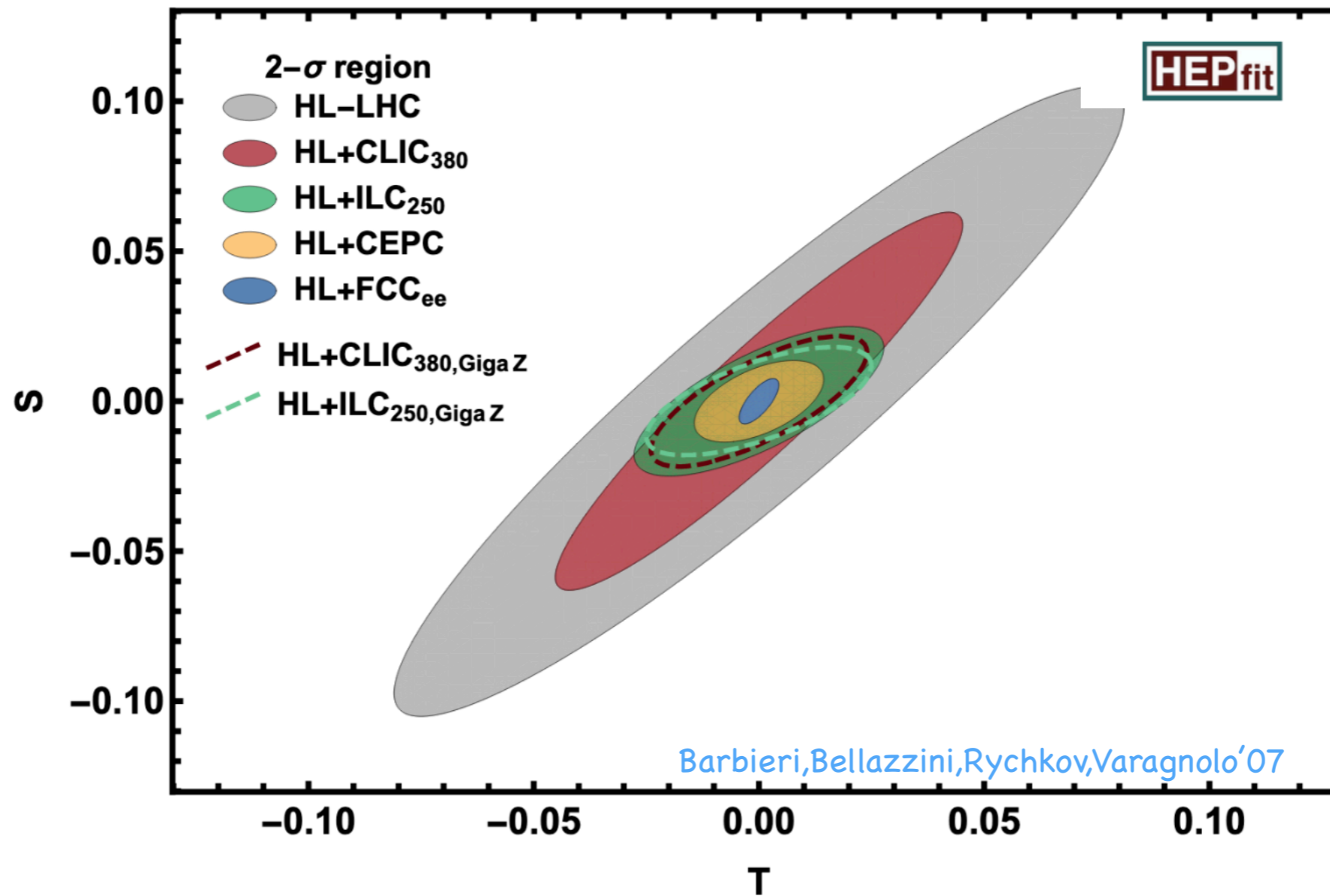
EW physics:  $\frac{v^2}{f^2} \lesssim 10^{-3} \left(\frac{g_*}{5}\right)^2$



# The Z-Boson run and the Higgs

S (and T) parameters:

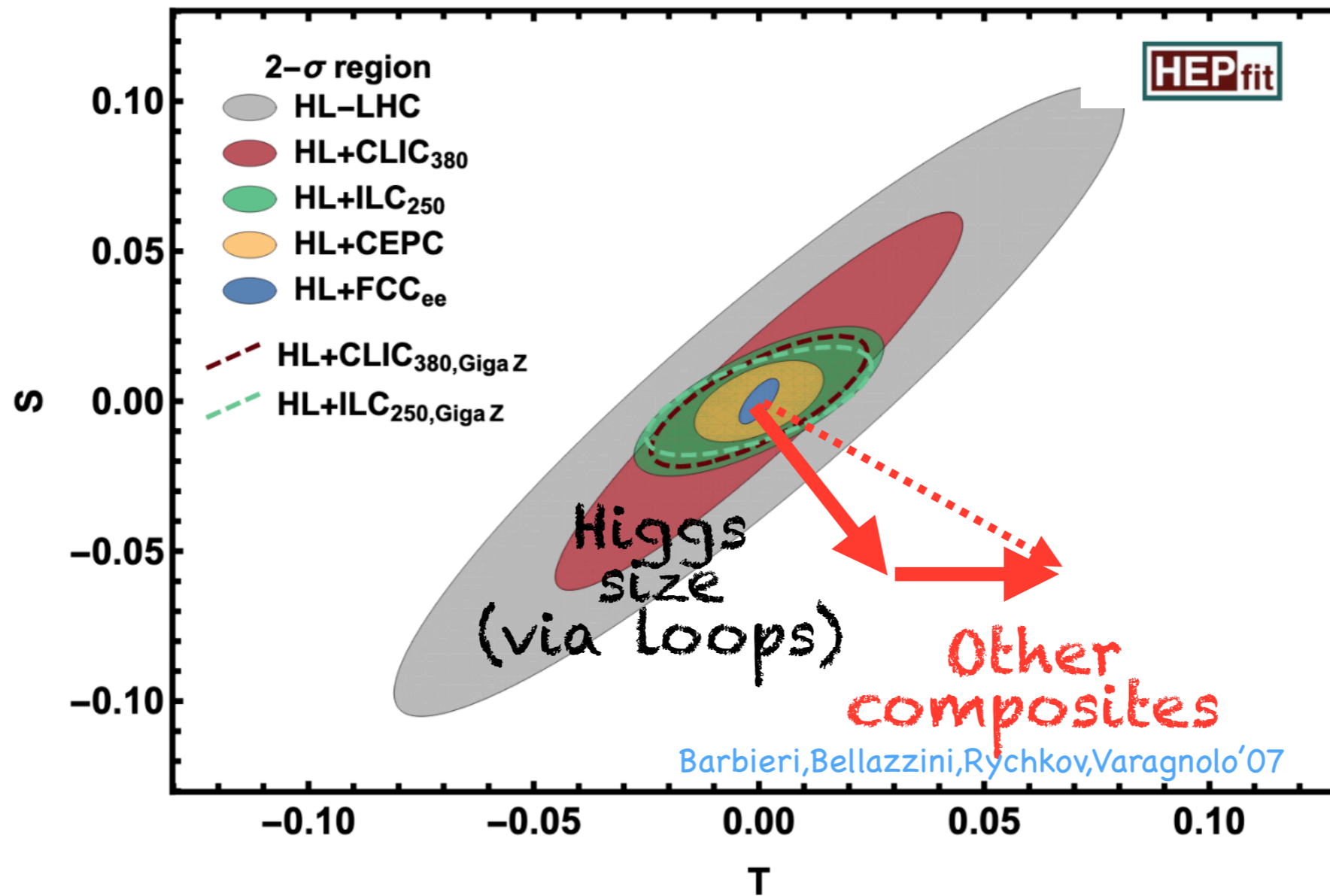
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- ▶ if it couples to the Higgs it must enter in S,T



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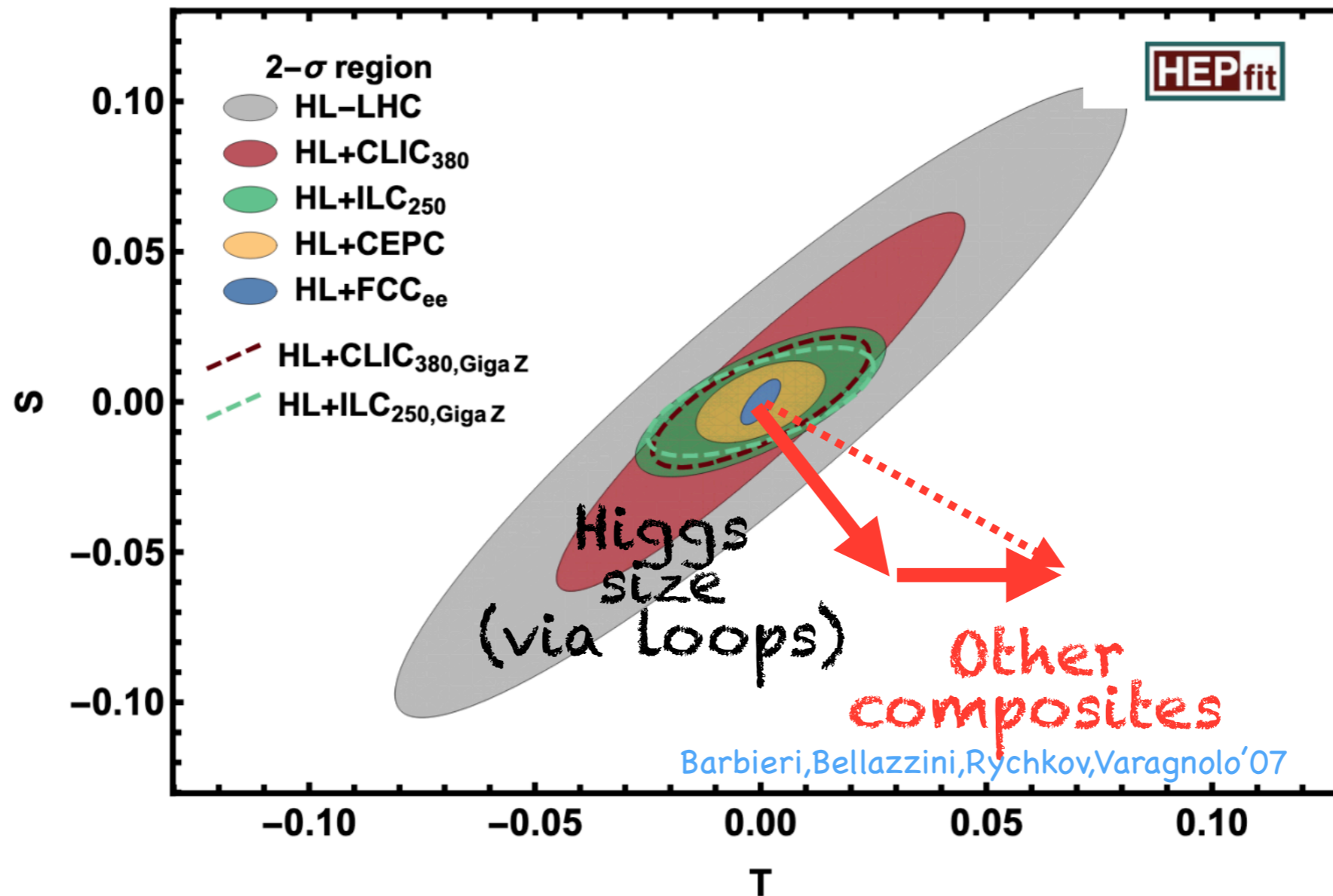
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- ▶ A Z-pole run is crucial!

# summary

Future colliders **can** discover many exciting new physics  
(new particles, Dark Matter, matter asymmetry... )



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For sure: we will **learn** about particles size  
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Z-Pole run will teach us much about the Higgs, as well

# Outreach - TUTTI QUANTUM



phdcomics.com

BEFORE  
GRAD SCHOOL

GRAD STUDENT

ASSISTANT  
PROFESSOR

TENURED  
PROFESSOR

EMERITUS  
PROFESSOR

2020

2030

2040

2050

2060

2070

2080

2090

2100

LHC & HL-LHC

FCC-ee

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2020

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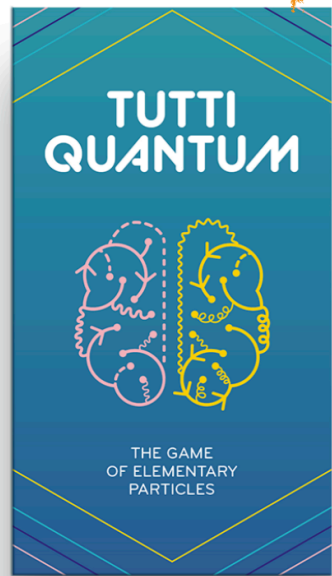
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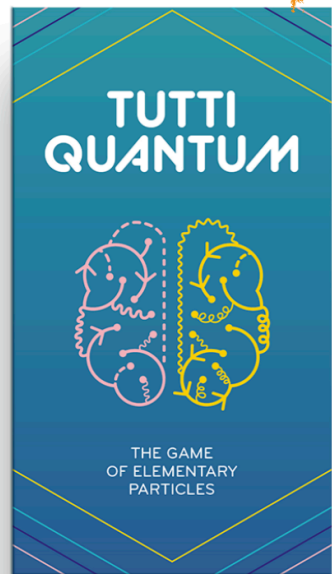
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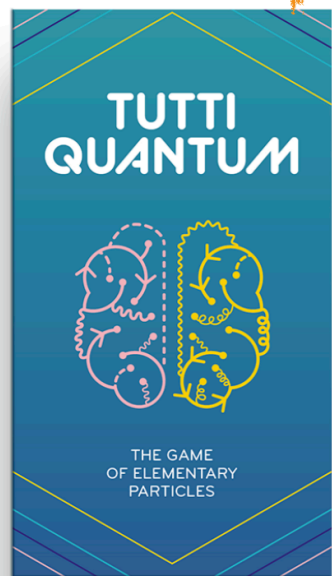
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Particles are simple (simpler than e.g. cells)

- ▶ Learn laws of nature as rules of a card game (even before you realize you are learning physics)



# The Hierarchy Problem

EFT decouples:  $\frac{O_i^{(n)}}{\Lambda_i^{n-4}}$  Details of UV not important

- ▶ Small observables  $\Leftrightarrow$  Larger scales

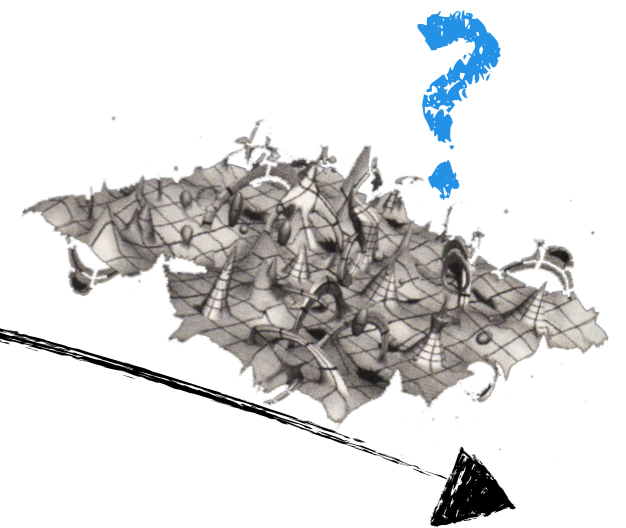
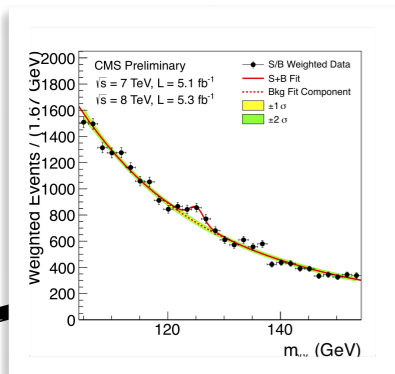
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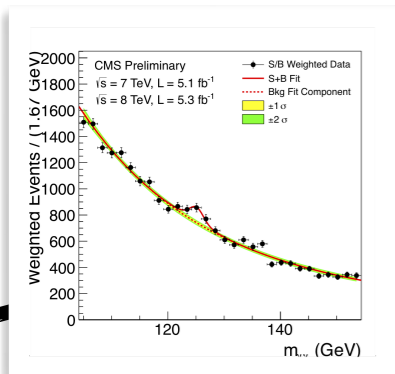
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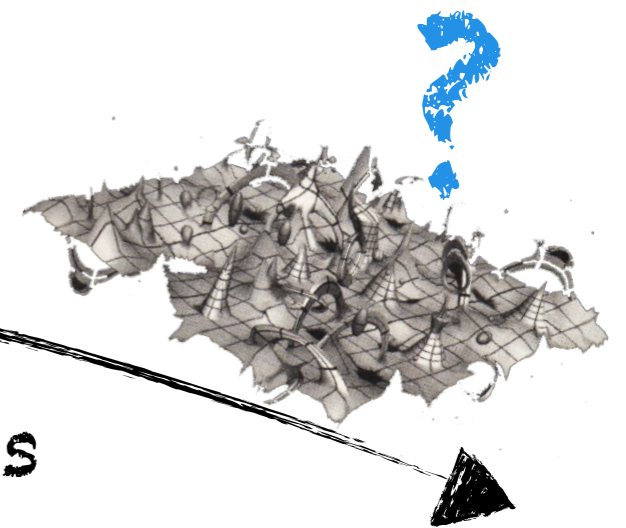
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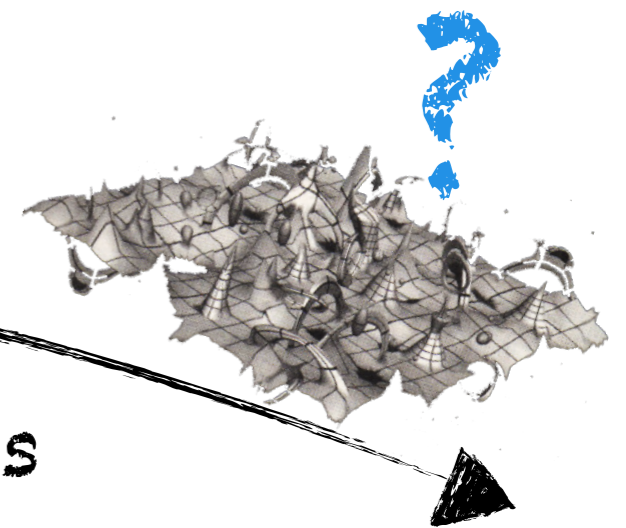
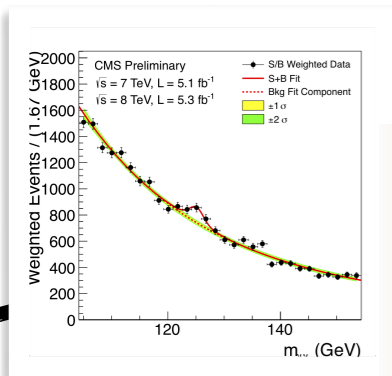
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Theories with finite size Higgs **screen** us from our QG ignorance, and are **computable** and **testable at FCC**