

Lessons from future colliders



SECOND • ECFA • WORKSHOP
on e^+e^- Higgs / Electroweak / Top Factories

11-13 October 2023
Paestum / Salerno / Italy

Topics:

- Physics potential of future Higgs and electroweak/top factories
- Required precision (experimental and theoretical)
- EFT (global) interpretation of Higgs factory measurements
- Reconstruction and simulation
- Software
- Detector R&D

Francesco Riva
(Geneva University)

Disclaimer

There is little I can add to the great work that has been presented these days...

Disclaimer

There is little I can add to the great work that has been presented these days...

... I will say less, less precisely, and with less generality

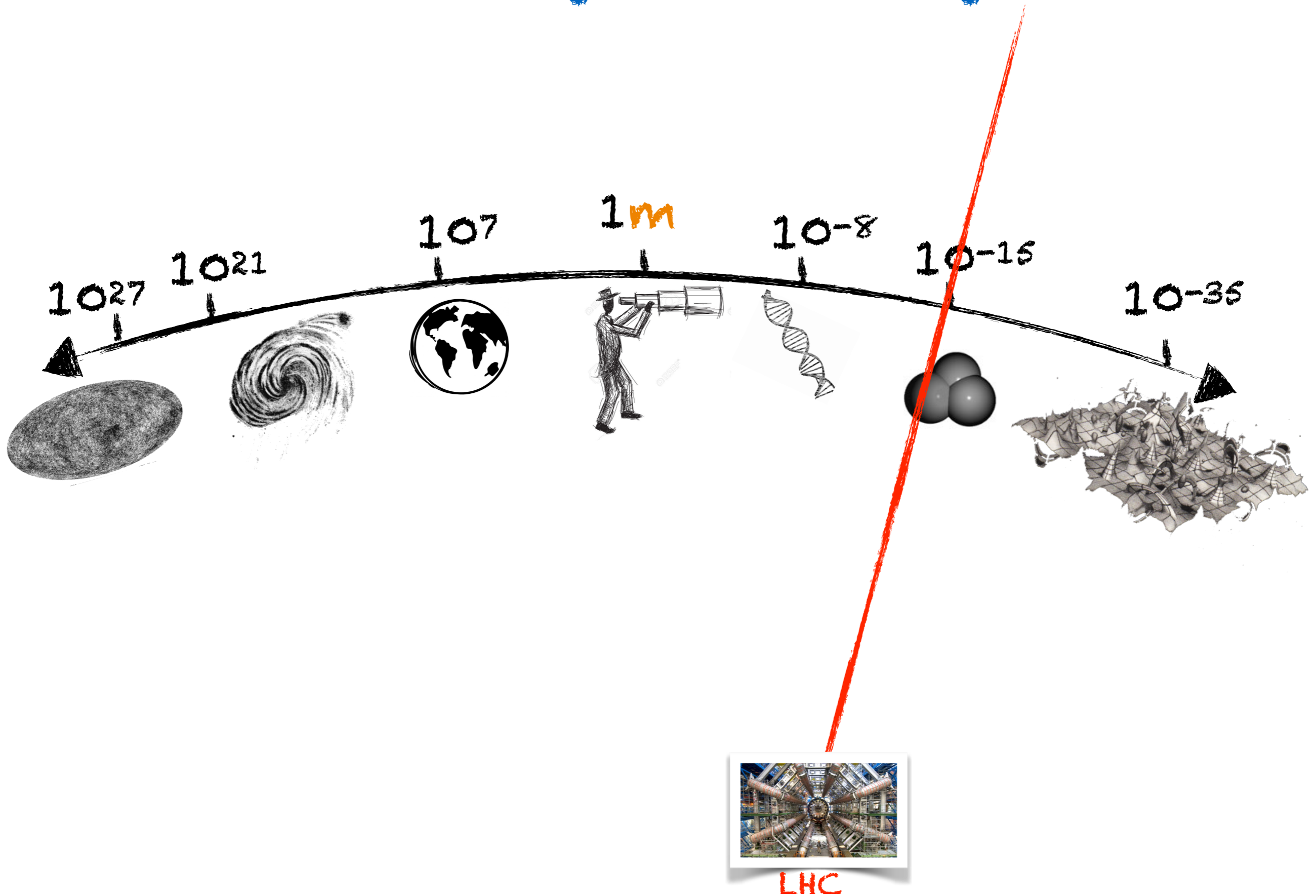
Disclaimer

There is little I can add to the great work that has been presented these days...

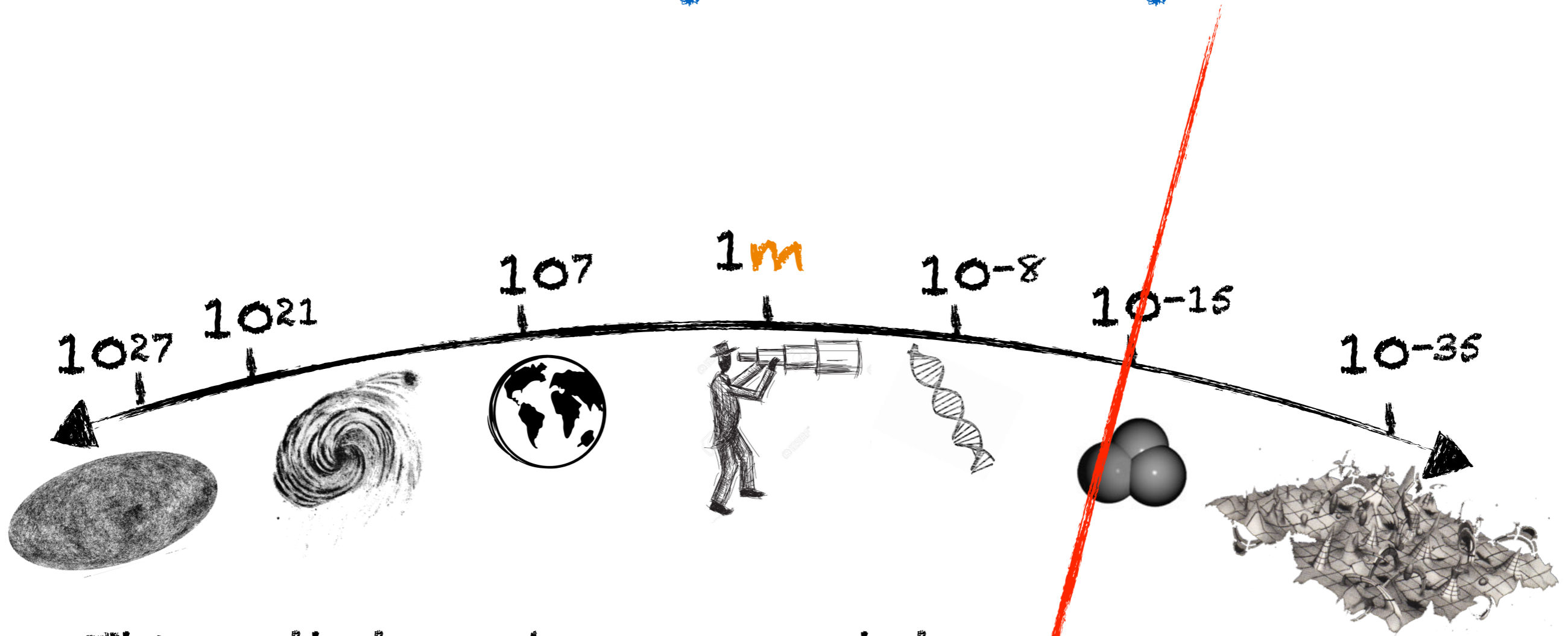
... I will say less, less precisely, and with less generality

- ▶ I'm ~~not~~ a model builder → talk ~~not~~ about fancy ideas or ideologies

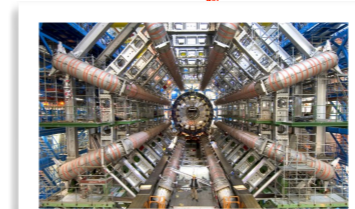
High-Energy Particle Physics



High-Energy Particle Physics

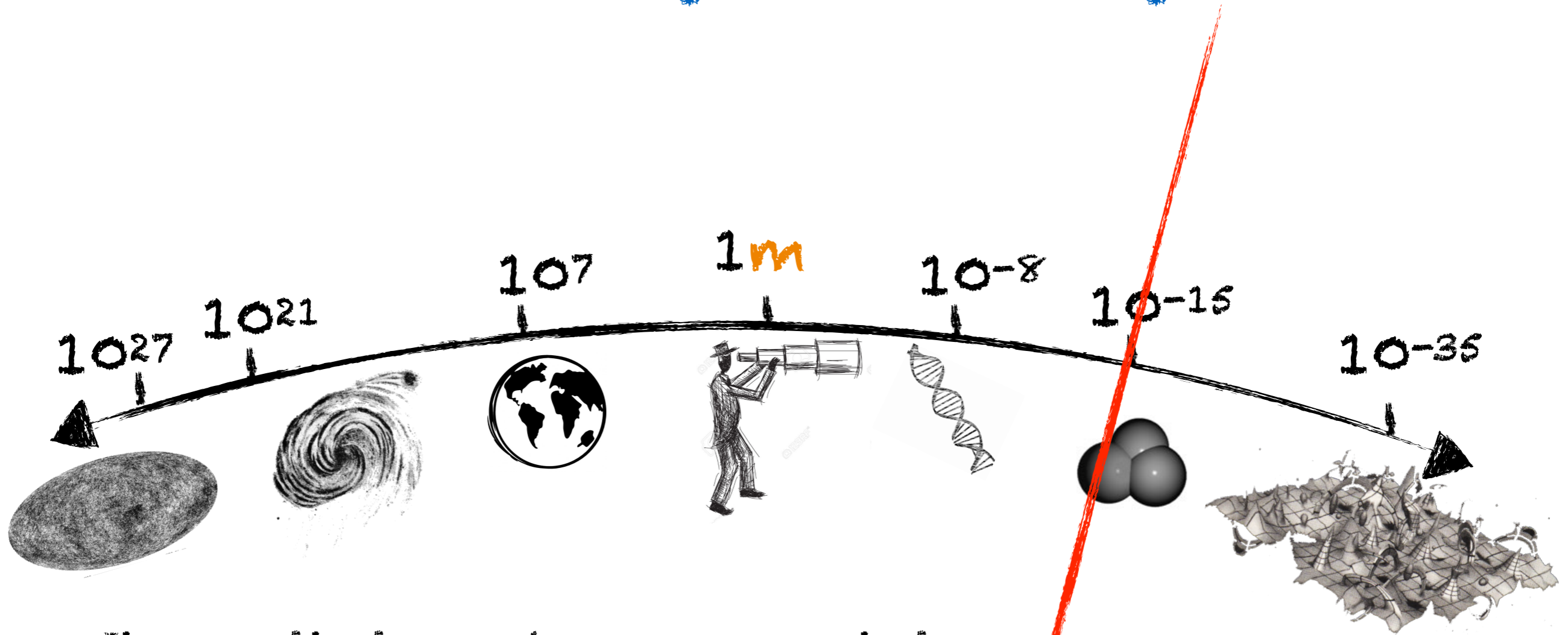


Things that are large enough to be accessed in experiments...



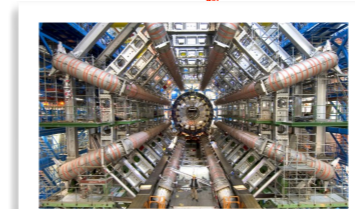
LHC

High-Energy Particle Physics

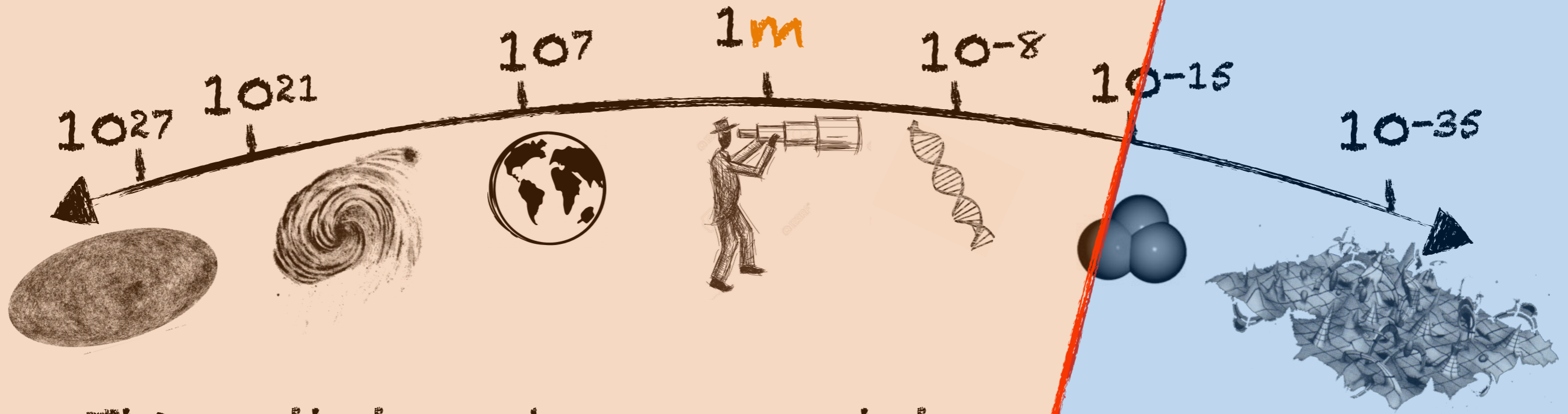


Things that are large enough to be accessed in experiments...

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

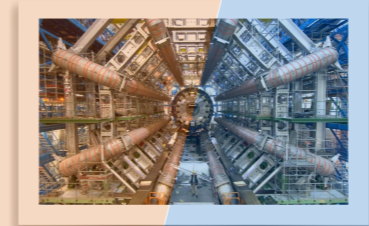


LHC

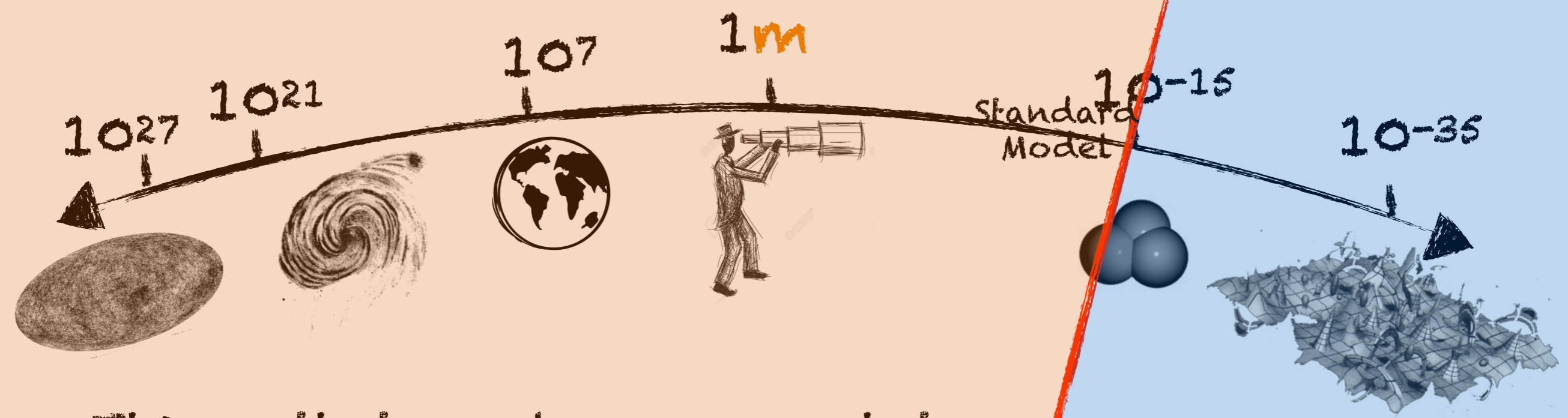


Things that are large enough to be accessed in experiments...

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



LHC



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

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

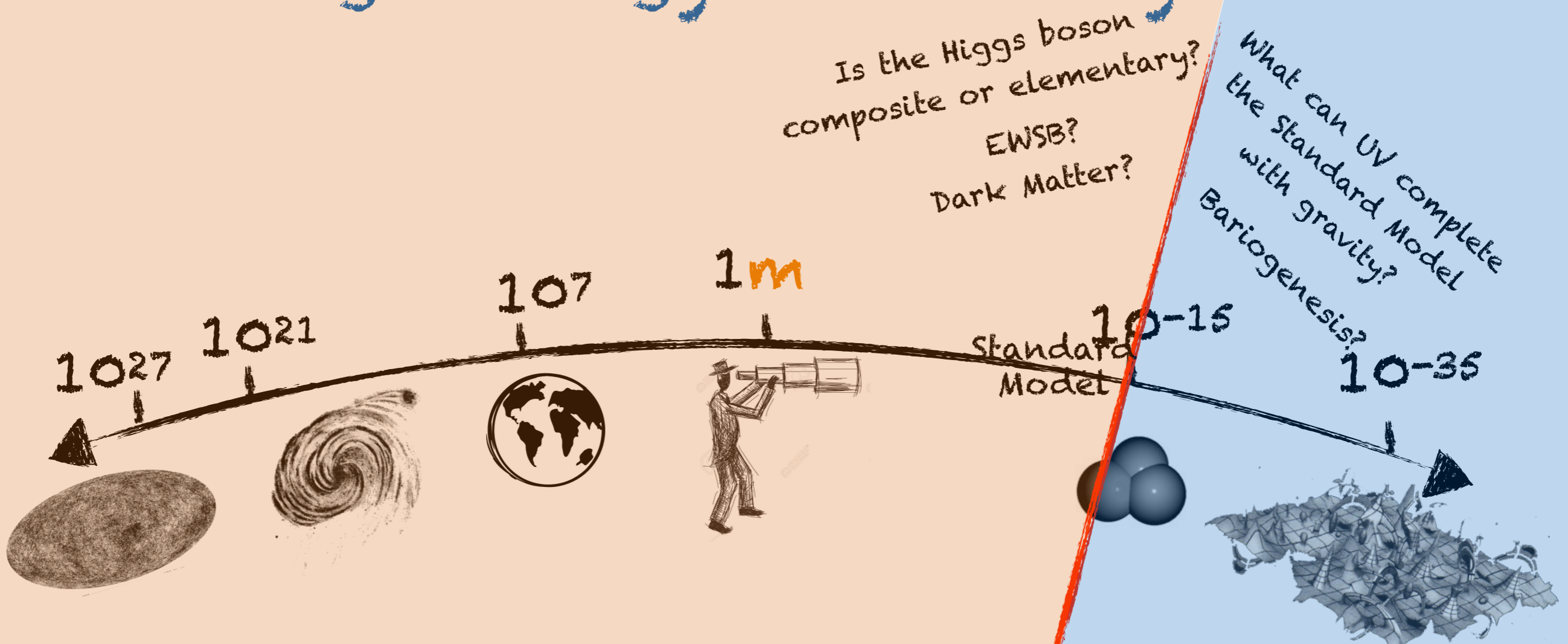


LHC

IR

High-Energy Particle Physics

UV



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...

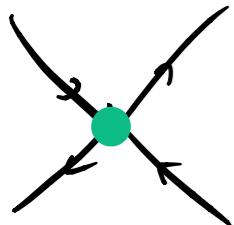
...things too small to be seen...



LHC

No Lose Theorems

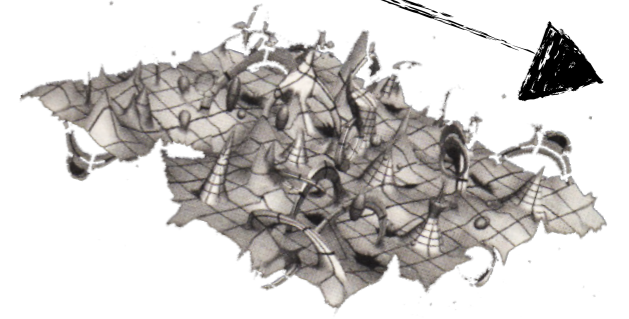
HEP: a history of guaranteed discoveries



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 marked with a green dot. The lines are labeled with ψ and $\bar{\psi}$.

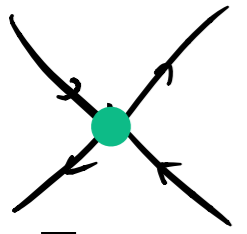
$$\frac{1}{v^2} (\bar{\psi} \gamma_\mu \psi)^2$$

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



No Lose Theorems

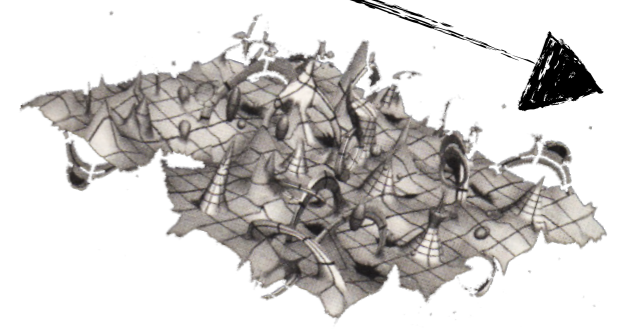
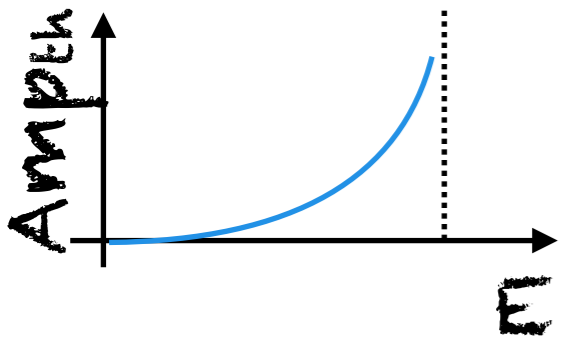
HEP: a history of guaranteed discoveries



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 have arrows indicating the direction of fermion flow.

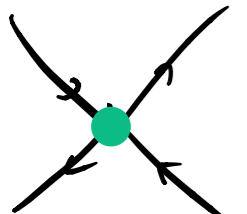
$$\frac{1}{v^2} (\bar{\psi} \gamma_\mu \psi)^2$$

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



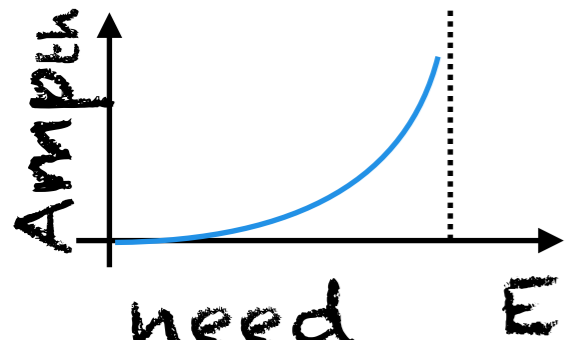
No Lose Theorems

HEP: a history of guaranteed discoveries

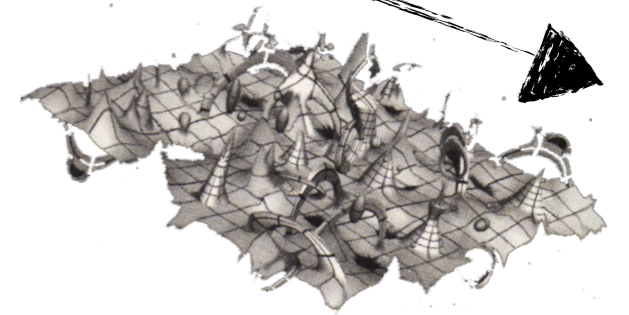


$\frac{1}{v^2}(\bar{\psi}\gamma_{\mu}\psi)^2$

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

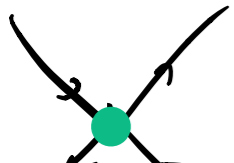


need
W-boson
 $m_W \lesssim 3\text{TeV}$



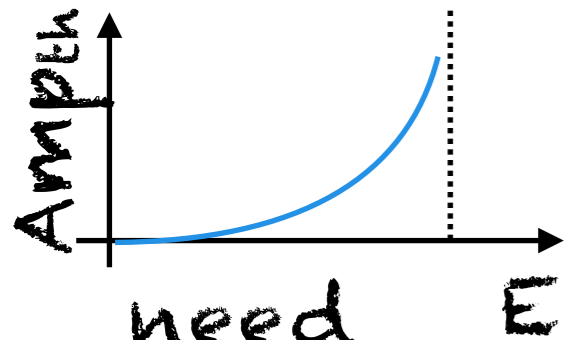
No Lose Theorems

HEP: a history of guaranteed discoveries

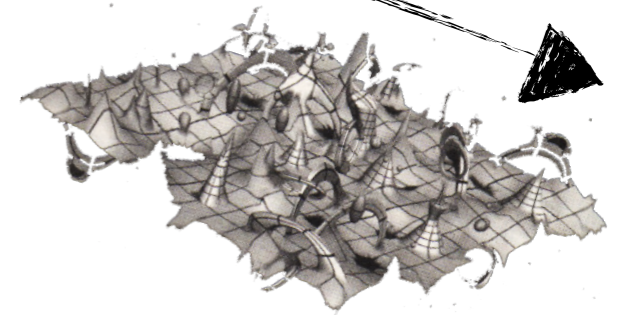

$$\frac{1}{v^2}(\bar{\psi}\gamma_\mu\psi)^2$$



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

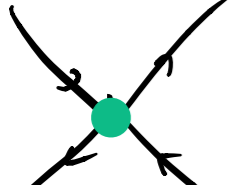


need
W-boson
 $m_W \lesssim 3\text{TeV}$

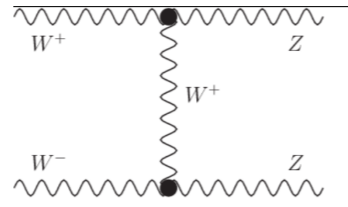


No Lose Theorems

HEP: a history of guaranteed discoveries

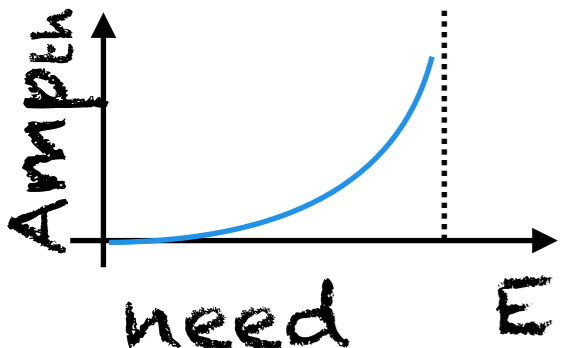


$\frac{1}{v^2}(\bar{\psi}\gamma_\mu\psi)^2$

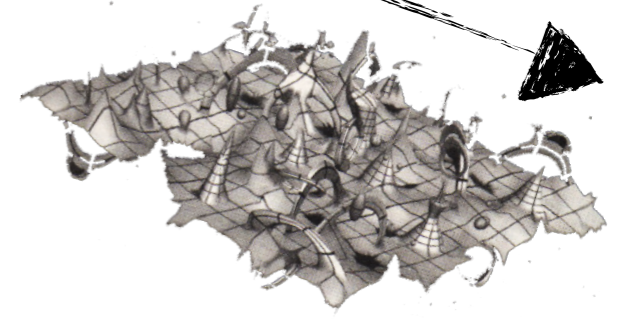


$m^2 A_\mu A^\mu$

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

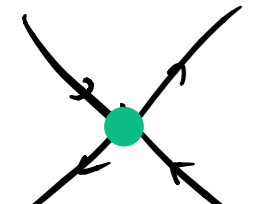


need
W-boson
 $m_W \lesssim 3TeV$

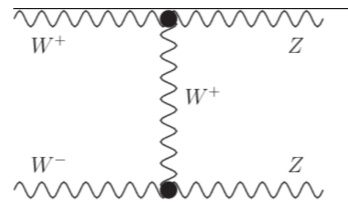


No Lose Theorems

HEP: a history of guaranteed discoveries

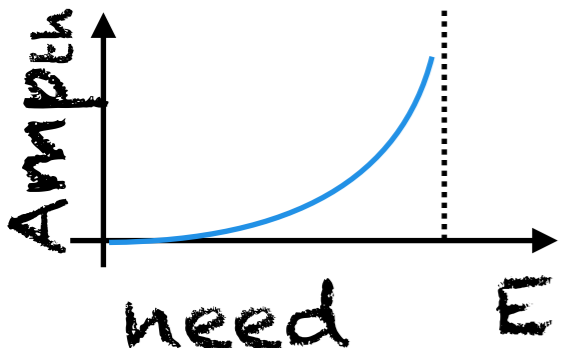


$\frac{1}{v^2}(\bar{\psi}\gamma_\mu\psi)^2$

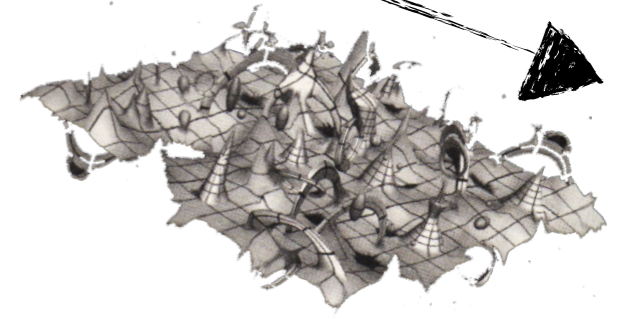


$$m^2 A_\mu A^\mu$$

$$WW \rightarrow WW$$

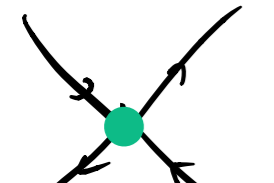


need
W-boson
 $m_W \lesssim 3\text{TeV}$



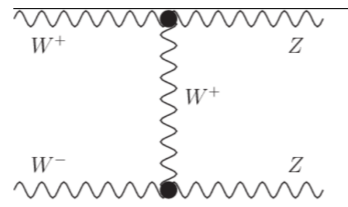
No Lose Theorems

HEP: a history of guaranteed discoveries



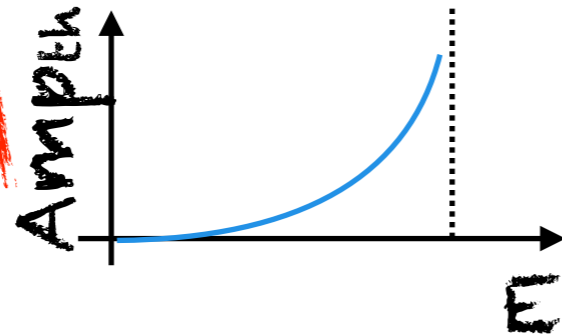
$\frac{1}{v^2} (\bar{\psi} \gamma_\mu \psi)^2$

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

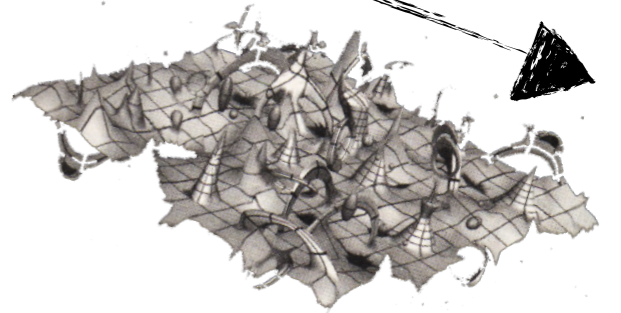


$m^2 A_\mu A^\mu$

$WW \rightarrow WW$

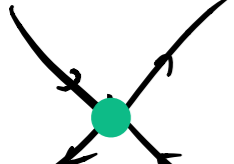


need
W-boson
 $m_W \lesssim 3\text{TeV}$



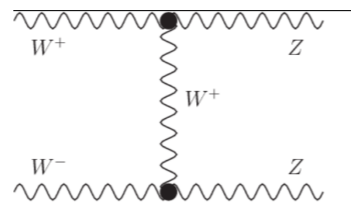
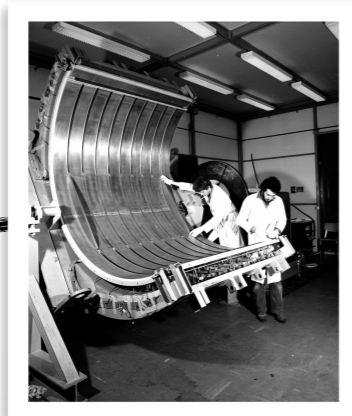
No Lose Theorems

HEP: a history of guaranteed discoveries



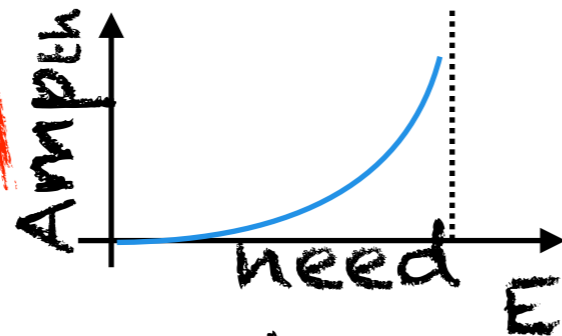
$$\frac{1}{v^2} (\bar{\psi} \gamma_\mu \psi)^2$$

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



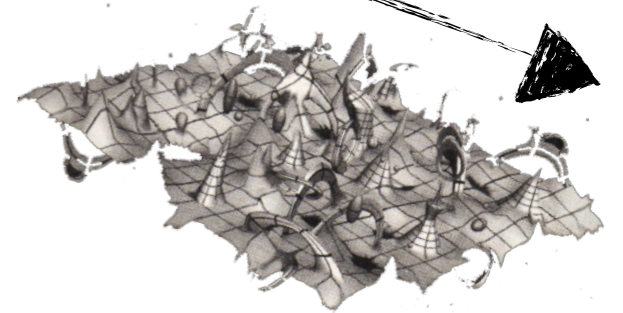
$$m^2 A_\mu A^\mu$$

$$WW \rightarrow WW$$



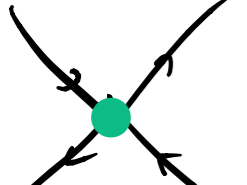
need
W-boson
 $m_W \lesssim 3TeV$

need
H-boson
 $m_h \lesssim 3TeV$



No Lose Theorems

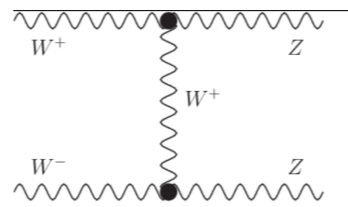
HEP: a history of guaranteed discoveries



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

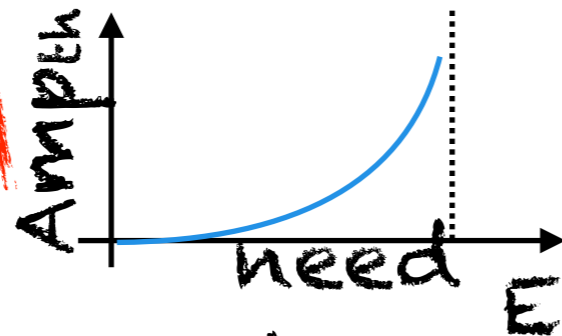
$$\psi\psi \rightarrow \psi\psi$$

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

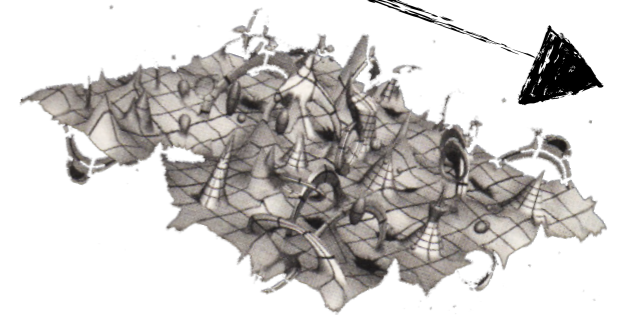
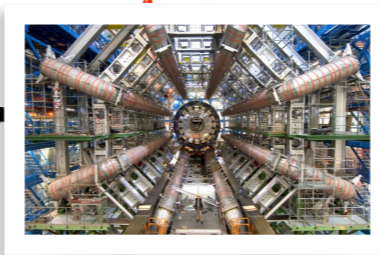


$$m^2 A_\mu A^\mu$$

$$WW \rightarrow WW$$

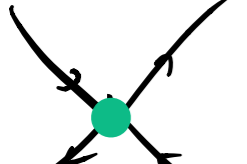


need
H-boson
 $m_h \lesssim 3\text{TeV}$



No Lose Theorems

HEP: a history of guaranteed discoveries

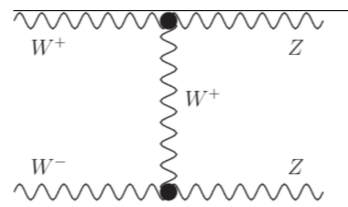


$$\frac{1}{v^2} (\bar{\psi} \gamma_\mu \psi)^2$$

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

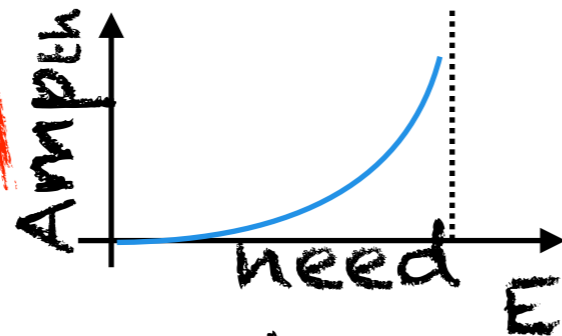


need
W-boson
 $m_W \lesssim 3\text{TeV}$

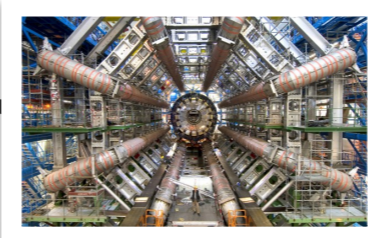


$$m^2 A_\mu A^\mu$$

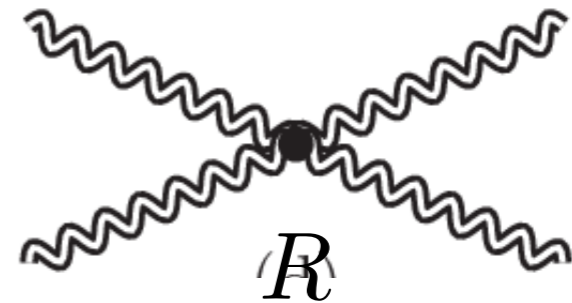
$$WW \rightarrow WW$$



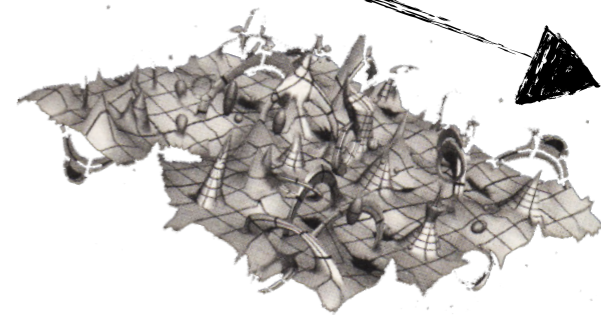
need
H-boson
 $m_h \lesssim 3\text{TeV}$



$$hh \rightarrow hh$$

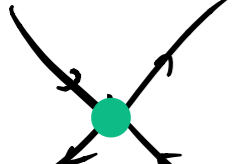


$$\frac{R}{M_{Pl}^2}$$



No Lose Theorems

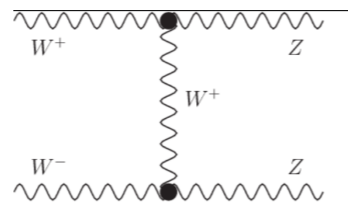
HEP: a history of guaranteed discoveries



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

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

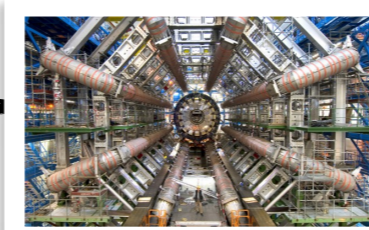
need
W-boson
 $m_W \lesssim 3\text{TeV}$



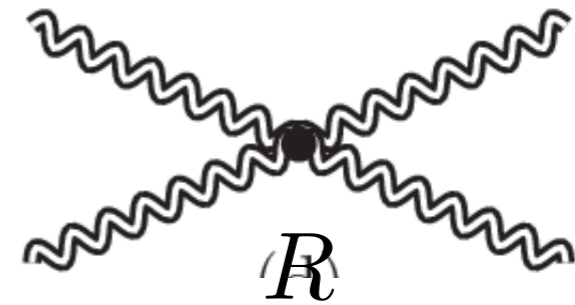
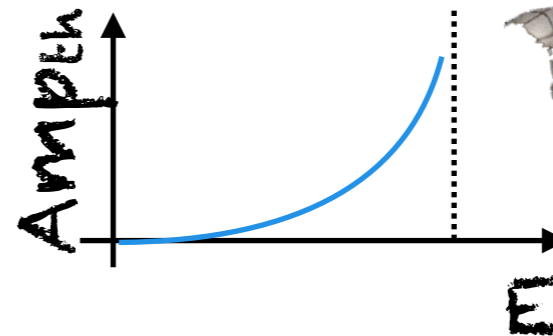
$$m^2 A_\mu A^\mu$$

$$WW \rightarrow WW$$

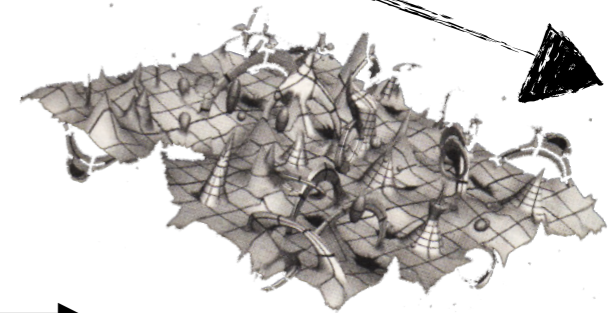
need
H-boson
 $m_h \lesssim 3\text{TeV}$



$$hh \rightarrow hh$$

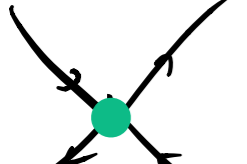


$$\frac{\mathcal{R}}{M_{Pl}^2}$$



No Lose Theorems

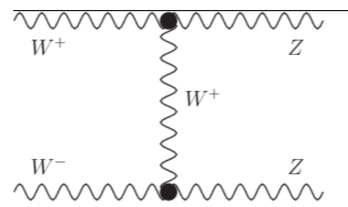
HEP: a history of guaranteed discoveries



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

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

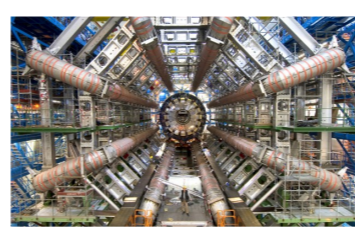
need
W-boson
 $m_W \lesssim 3\text{TeV}$



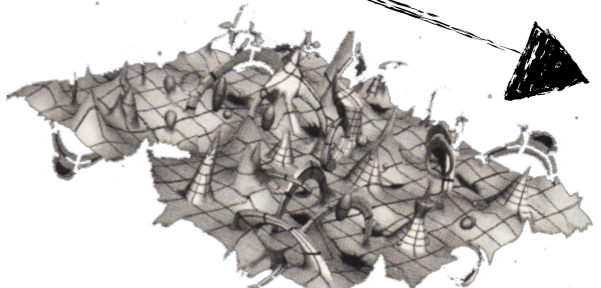
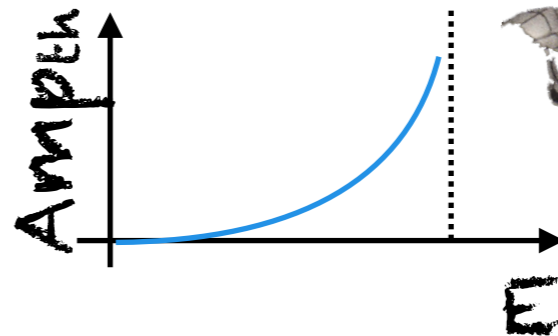
$$m^2 A_\mu A^\mu$$

$$WW \rightarrow WW$$

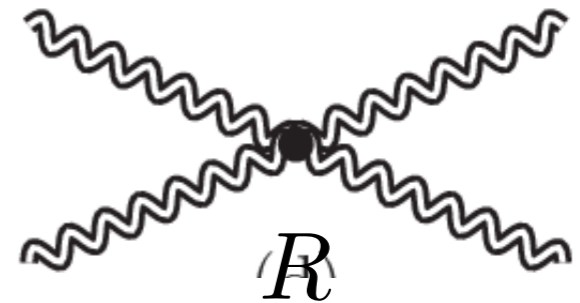
need
H-boson
 $m_h \lesssim 3\text{TeV}$



$$hh \rightarrow hh$$



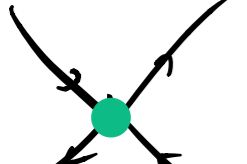
need
something
 $m_{QG} \lesssim 10^{19}\text{GeV}$



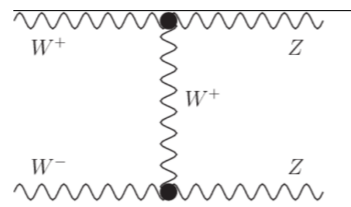
$$\frac{R}{M_{Pl}^2}$$

No Lose Theorems

HEP: a history of guaranteed discoveries

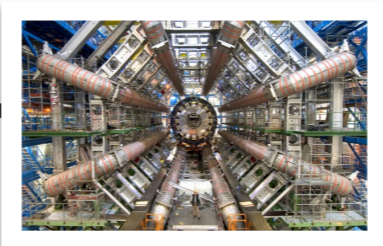
$$\frac{1}{v^2} (\bar{\psi} \gamma_\mu \psi)^2$$


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

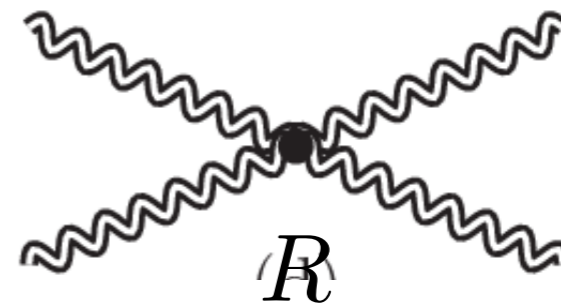


$$m^2 A_\mu A^\mu$$

$$WW \rightarrow WW$$



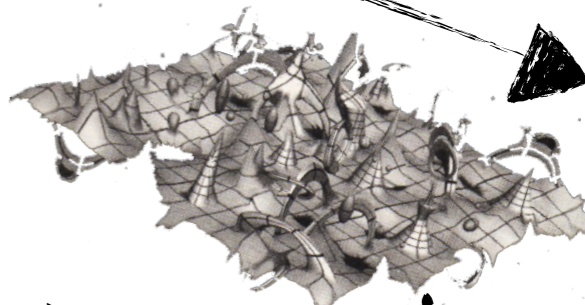
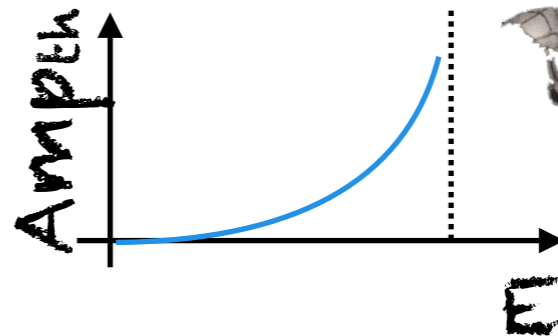
$$hh \rightarrow hh$$



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

need
W-boson
 $m_W \lesssim 3TeV$

need
H-boson
 $m_h \lesssim 3TeV$

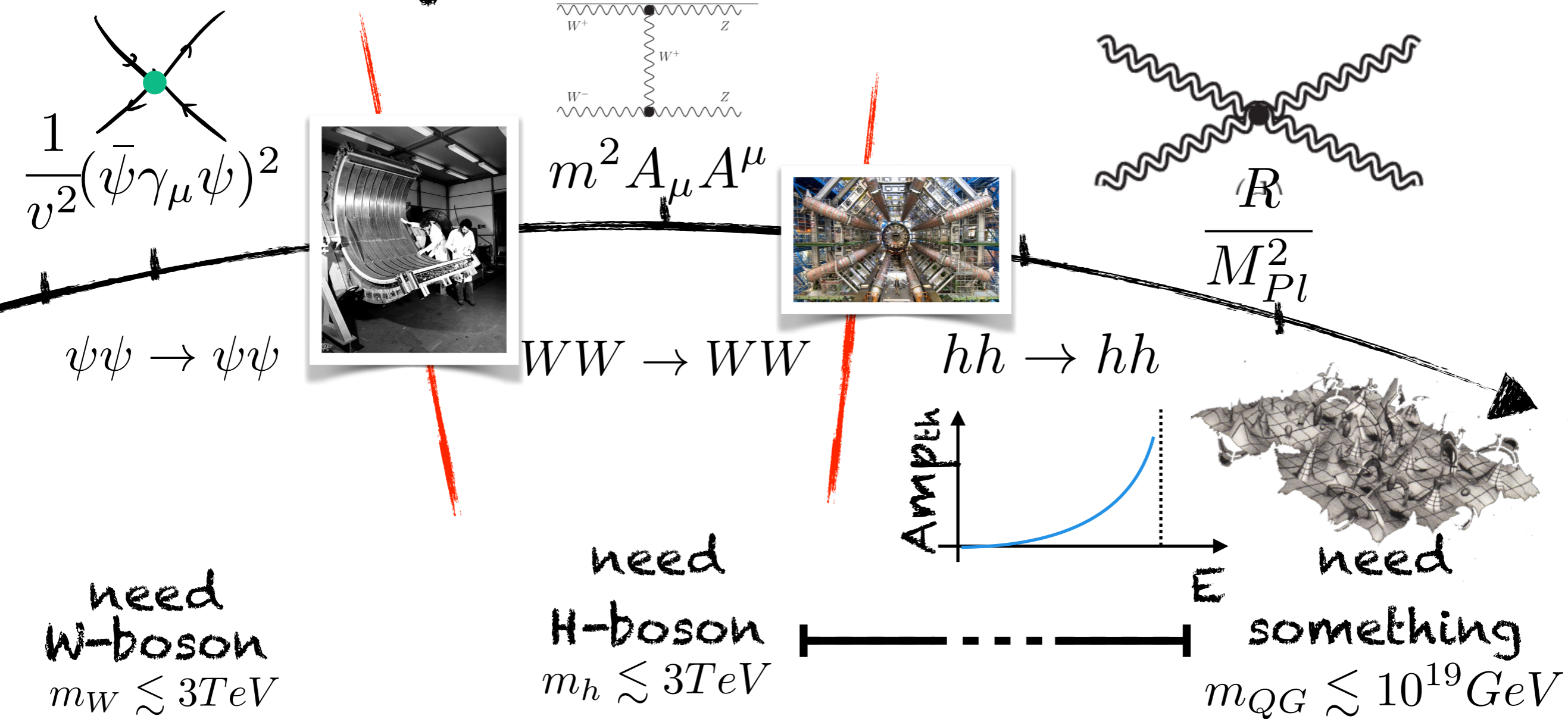


need
something
 $m_{QG} \lesssim 10^{19} GeV$

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

No Lose Theorems

HEP: a history of guaranteed discoveries

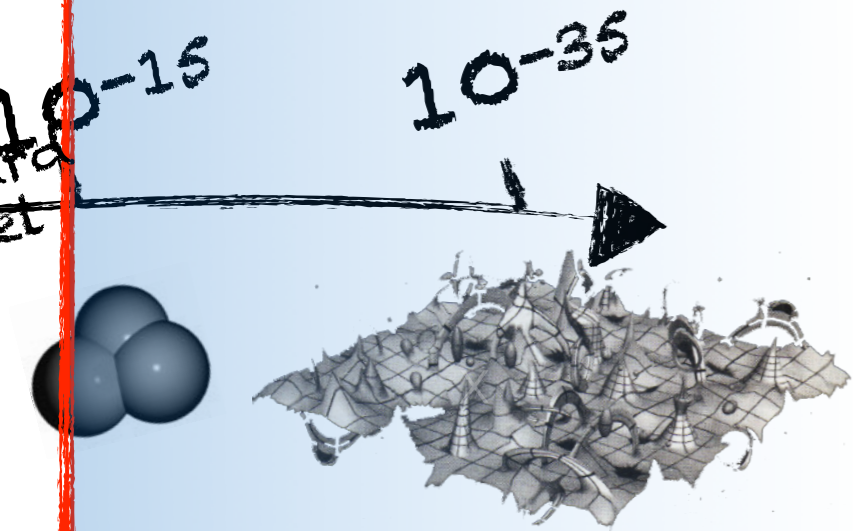


- Exceptional story, but science is not about no lose theorems
- What will we **learn** from this exploration?
- If you have to focus on **one** question, what will it be?

High-Energy Particle Physics Mindset



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

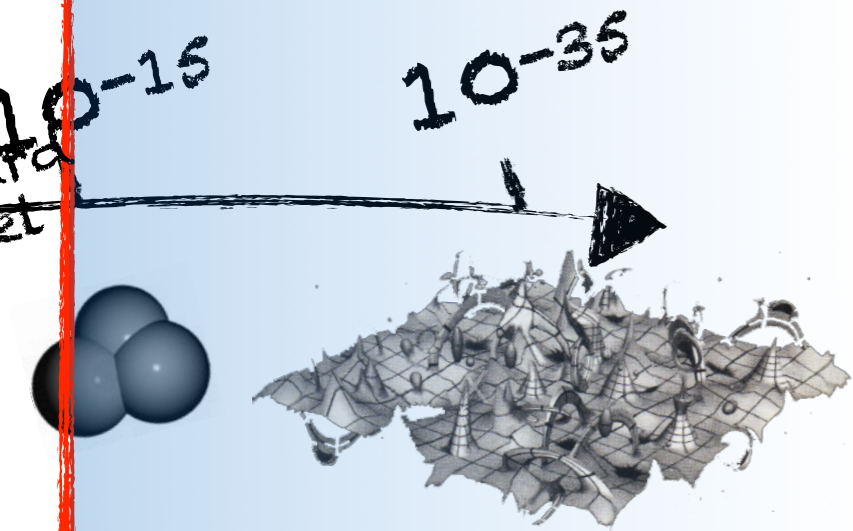


FCS

High-Energy Particle Physics Mindset



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

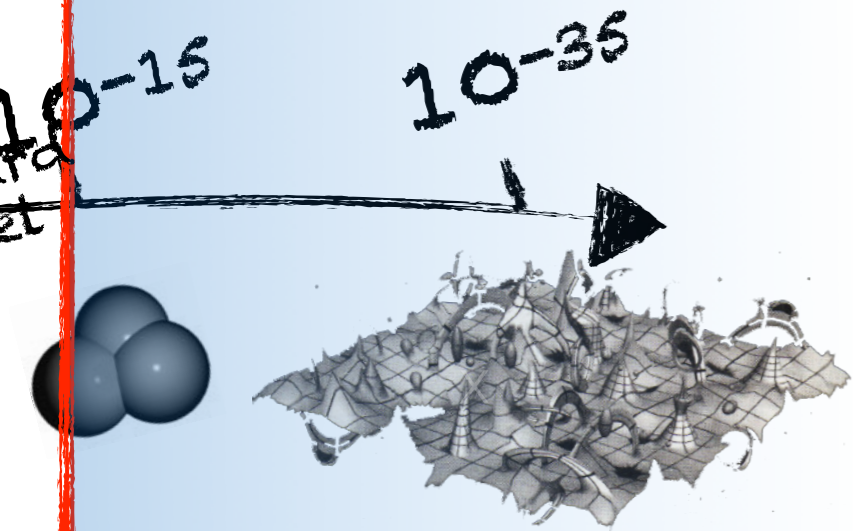


FCs

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



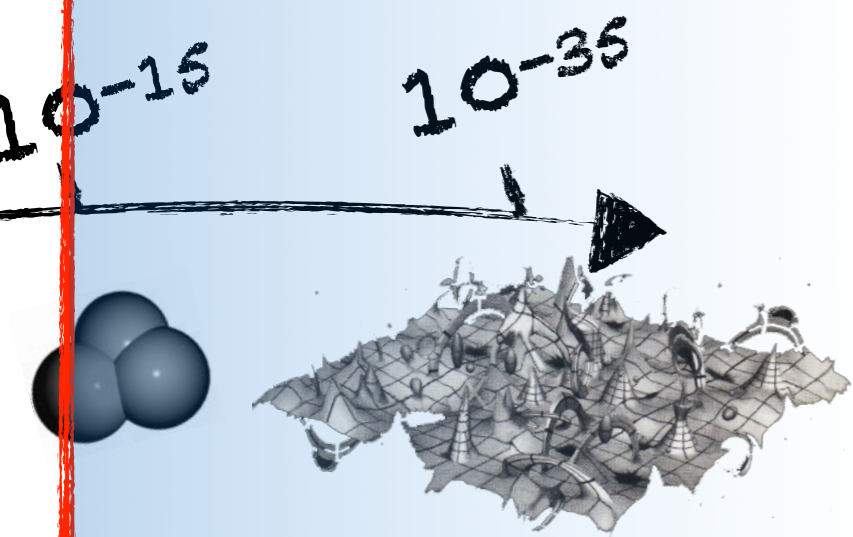
microscopic laws of nature

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



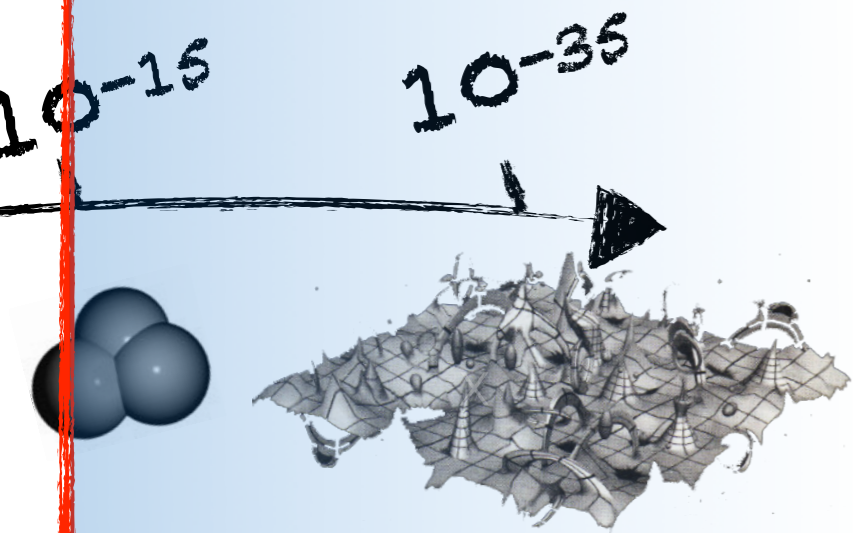
High-Energy Particle Physics

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



High-Energy Particle Physics

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



FCS

High-Energy Particle Physics

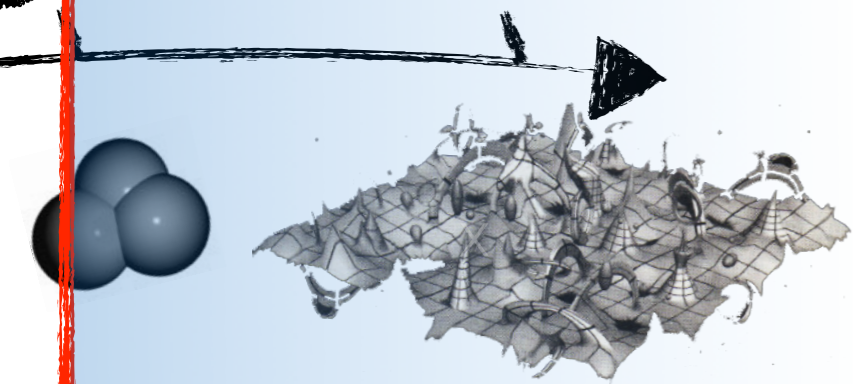
$$\Lambda_{\mathcal{B}} > 10^{16} \text{ GeV}$$

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

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

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

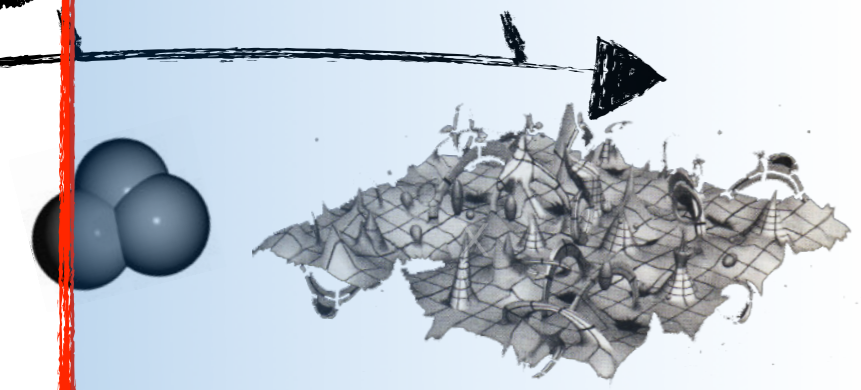
$$\frac{1}{\Lambda_B^2} [(d_p^\alpha)^T C u_r^\beta] [(q_s^{\gamma j})^T C l_t^k] \quad \text{Proton Lifetime } t_p > 10^{34} y$$

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

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

10^{-15}

10^{-35}



→ Laws of nature governed by (emerging) symmetries



FCs

High-Energy Particle Physics

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

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

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

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

10^{-15}

10^{-35}

→ Laws of nature governed by (emerging) symmetries

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



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

10⁻¹⁵

10⁻³⁵

→ Laws of nature governed by (emerging) symmetries



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

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

Status: March 2023

ATLAS Preliminary $\sqrt{s} = 13 \text{ TeV}$

$[L dt = (3.6 - 139) \text{ fb}^{-1}]$

Model	ℓ, γ	Jets†	E_{miss}^T	$f_{cut}(fb^{-1})$	Limit	Reference
Extra dim.	ADD $G_{uv} + g/\epsilon$	0 μ, τ, γ	1-4‡	Yes	130	1702.0479
	ADD nonrenorm. $\gamma\gamma$	0 μ, τ, γ	1-4‡	Yes	32.7	1707.0447
	ADD BH	0 μ, τ, γ	1-4‡	Yes	130	1910.0447
	ADD BH multijet	0 μ, τ, γ	1-4‡	Yes	130	1912.0447
	RSL $G_{uv} \rightarrow \gamma\gamma$	2 μ, τ	0-3‡	Yes	130	2102.1345
	Bulk RS $G_{uv} \rightarrow WW/ZZ$	1 μ, τ	0-3‡	Yes	36.1	1908.0380
	Bulk RS $G_{uv} \rightarrow t\bar{t}$	1 μ, τ	0-3‡	Yes	36.1	1904.1982
	ADD/RS	0 μ, τ, γ	1-4‡	Yes	36.1	2004.0476
Scalar bosons	Scalar $Z \rightarrow \gamma\gamma$	0 μ, τ, γ	1-4‡	Yes	36.1	1905.0476
	Leptoquark $Z \rightarrow b\bar{b}$	0 μ, τ, γ	1-4‡	Yes	36.1	1905.0476
	Leptoquark $Z \rightarrow t\bar{t}$	0 μ, τ, γ	1-4‡	Yes	130	2005.0116
	SSM $W \rightarrow \nu\bar{\nu}$	1 μ, τ	0-3‡	Yes	130	1905.0560
	SSM $W \rightarrow \nu\bar{\nu}$	1 μ, τ	0-3‡	Yes	130	1905.0560
	SSM $W \rightarrow \nu\bar{\nu}$	1 μ, τ	0-3‡	Yes	130	1905.0560
	HVT $W \rightarrow WZ$ model B	0 μ, τ, γ	1-4‡	Yes	130	2004.1403
	HVT $W \rightarrow WZ$ model C	0 μ, τ, γ	1-4‡	Yes	130	2007.0392
	HVT $Z \rightarrow WW$ model B	0 μ, τ, γ	1-4‡	Yes	130	2004.1403
	HVT $Z \rightarrow WW$ model C	0 μ, τ, γ	1-4‡	Yes	130	2004.1403
CI	CI $qq\bar{q}$	2 μ, τ	0-3‡	Yes	130	1709.0479
	CI $qq\bar{q}$	2 μ, τ	0-3‡	Yes	130	2006.1246
	CI $qq\bar{q}$	2 μ, τ	0-3‡	Yes	130	2105.1347
	CI $qq\bar{q}$	2 μ, τ	0-3‡	Yes	130	2105.1347
	CI $qq\bar{q}$	2 μ, τ	0-3‡	Yes	130	1811.0305
DM	Axial-vector med. (Dirac DM)	0 μ, τ, γ	1-4‡	Yes	130	1709.0479
	Pseudo-scalar med. (Dirac DM)	0 μ, τ, γ	1-4‡	Yes	130	2105.1347
	Vector med. Z' -SDM (Dirac DM)	0 μ, τ, γ	1-4‡	Yes	130	2108.1339
	Pseudo-scalar med. Z' -SDM $\nu\bar{\nu}$ multi-channel	0 μ, τ, γ	1-4‡	Yes	130	2108.1339
LO	Scalar LO 1 st gen	2 μ, τ	0-3‡	Yes	130	2004.0572
	Scalar LO 2 nd gen	2 μ, τ	0-3‡	Yes	130	2004.0572
	Scalar LO 3 rd gen	2 μ, τ	0-3‡	Yes	130	2003.0124
	Scalar LO 3 rd gen	2 μ, τ	0-3‡	Yes	130	2004.0400
	Scalar LO 3 rd gen	2 μ, τ	0-3‡	Yes	130	2101.1180
	Vector LO 1 st gen	2 μ, τ	0-3‡	Yes	130	2101.1180
	Vector LO 2 nd gen	2 μ, τ	0-3‡	Yes	130	2101.1180
	Vector LO 3 rd gen	2 μ, τ	0-3‡	Yes	130	2101.1180
Vector-like fermions	VLF T $\bar{T} \rightarrow Z\gamma + X$	2 μ, τ	0-3‡	Yes	130	2003.0124
	VLF $BB \rightarrow W\gamma/Z\gamma + X$	2 μ, τ	0-3‡	Yes	130	1808.0243
	VLF $TC \rightarrow F\gamma/Z\gamma + X$	2 μ, τ	0-3‡	Yes	130	2003.0124
	VLF $T \rightarrow W\gamma/Z\gamma$	1 μ, τ	0-3‡	Yes	130	2003.0124
	VLF $B \rightarrow W\gamma/Z\gamma$	1 μ, τ	0-3‡	Yes	130	2003.0124
	VLF $B \rightarrow W\gamma/Z\gamma$	1 μ, τ	0-3‡	Yes	130	2003.0124
	VLF $T \rightarrow Z\gamma/\nu\bar{\nu}$	1 μ, τ	0-3‡	Yes	130	2003.0124
Exotic fermions	Excited quark $q^* \rightarrow q\gamma$	1 μ, τ	0-3‡	Yes	130	1910.0447
	Excited quark $q^* \rightarrow q\gamma$	1 μ, τ	0-3‡	Yes	130	1709.0440
	Excited quark $q^* \rightarrow q\gamma$	1 μ, τ	0-3‡	Yes	130	1910.0447
	Excited lepton $l^* \rightarrow l\gamma$	1 μ, τ	0-3‡	Yes	130	1910.0447
Other	Type III Seesaw	2,3 μ, τ	0-3‡	Yes	130	2002.0039
	LPM Higgs $h \rightarrow W^+W^-$	2,3 μ, τ	0-3‡	Yes	130	1809.1105
	Higgs triplet $h^{\pm\pm} \rightarrow W^{\pm}W^{\pm}$	2,3 μ, τ	0-3‡	Yes	130	2101.1180
	Higgs triplet $h^{\pm\pm} \rightarrow Z\gamma$	2,3 μ, τ	0-3‡	Yes	130	2011.0505
	Multi-charged particles	0 μ, τ, γ	1-4‡	Yes	130	2011.0505
	Magnetic monopoles	0 μ, τ, γ	1-4‡	Yes	130	1905.1039



FCS

High-Energy Particle Physics

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

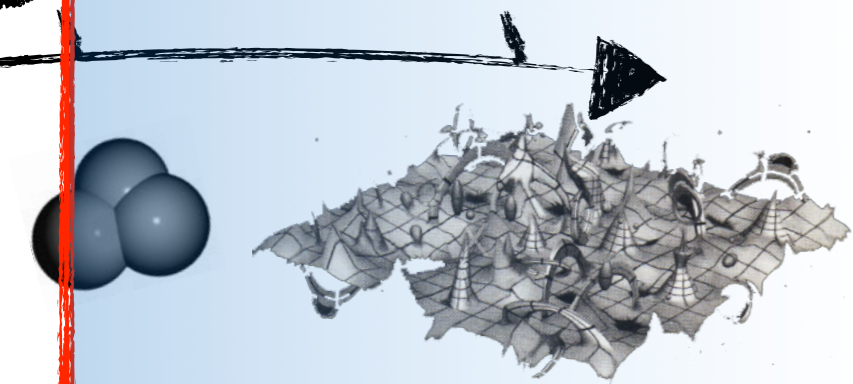
$\frac{1}{\Lambda_B^2} [(d_p^\alpha)^T C u_r^\beta] [(q_s^{\gamma j})^T C l_t^k]$ Proton Lifetime $t_p > 10^{34} y$

$\Lambda_{\cancel{U}} > 10^{14} \text{ GeV}$

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

10⁻¹⁵ 10⁻³⁵

→ 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	ℓ, γ	Jets†	$E_{T,miss}^{\min}$	$f_{\cancel{C}}(\text{fb}^{-1})$	Limit	Reference
Extra dimen.	ADD $G_{UV} + g/\epsilon$	0 μ, τ, γ	1-4†	139	M_{pl}	1102.0879
	ADD nonrenorm. $\gamma\gamma$	-	-	36.7	M_{pl}	1707.0447
	ADD BH multijet	-	2†	139	M_{pl}	1910.0847
	ADD BH multijet	-	2†	3.6	M_{pl}	1912.0285
	RSL $G_{UV} + \gamma\gamma$	2 γ	-	139	$G_{UV} \text{ mass}$	2102.13405
	Bulk RS $G_{UV} + WW/ZZ$	multi-channel	-	36.1	$G_{UV} \text{ mass}$	1808.0320
	Bulk RS $G_{UV} + tt$	1 μ, τ	1†, 2†	36.1	$G_{UV} \text{ mass}$	1804.1802
	2UED/3UED	1 μ, τ	1†, 2†	36.1	$G_{UV} \text{ mass}$	2006.0676
Gravitational	SSM $Z \rightarrow \gamma\gamma$	0†	-	36.1	$Z \text{ mass}$	1705.0127
	Leptoquark $Z \rightarrow bb$	2 b	-	36.1	$Z \text{ mass}$	1805.0629
	Leptoquark $Z \rightarrow tt$	0 μ, τ	1†, 2†, 2†	139	$Z \text{ mass}$	2005.0116
	SSM $W \rightarrow \nu\bar{\nu}$	1 ν	-	139	$W \text{ mass}$	1905.0560
	SSM $W \rightarrow \nu\bar{\nu}$	1 ν	-	139	$W \text{ mass}$	1905.0560
	SSM $W \rightarrow \nu\bar{\nu}$	1 ν	-	139	$W \text{ mass}$	1905.0560
	HVT $W \rightarrow \nu\bar{\nu}$ model B	0 μ, τ	2†, 1†	139	$W \text{ mass}$	2004.1403
	HVT $W \rightarrow WZ$ model C	3 μ, τ	2†, 1†	139	$W \text{ mass}$	2007.0300
	HVT $Z \rightarrow WW$ model B	1 μ, τ	2†, 1†	139	$Z \text{ mass}$	2004.1403
CI	CI $qqqq$	2 μ, τ	2†	37.0	A	1705.0127
	CI $qqqq$	2 μ, τ	2†	139	A	2006.1246
	CI $qqqq$	2 μ, τ	1†	139	A	2105.1347
	CI $qqqq$	2 μ, τ	1†	139	A	2105.1347
	CI $tttt$	1†, 2†	1†, 2†	36.1	A	1811.0305

- Λ 21.8 TeV $\eta_{\cancel{LL}}$
- Λ 35.8 TeV $\eta_{\cancel{LL}}$
- Λ 1.8 TeV
- Λ 2.0 TeV
- Λ 2.57 TeV

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



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 $t_p > 10^{34} y$

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

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

10⁻¹⁵ 10⁻³⁵

➔ Laws of nature governed by (emerging) symmetries



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

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

Status: March 2023

Model	ℓ, γ	Jets†	$E_{T,miss}^{\text{min}}$	$f_{\text{cut}}(\text{fb}^{-1})$	Limit	Reference
Extra dim.	ADD $G_{\mu\nu} + g/\epsilon$	0 μ, τ, γ	1-4†	139	1.2 TeV	1102.0879
	ADD nonrenormizable	0 μ, τ, γ	1-4†	36.7	6.6 TeV	1707.0447
	ADD BH	0 μ, τ, γ	1-4†	139	8.8 TeV	1910.0847
	ADD BH multijet	0 μ, τ, γ	1-4†	36.7	8.8 TeV	1910.0847
	RSL $G_{\mu\nu} + \gamma\gamma$	0 μ, τ, γ	1-4†	139	2.3 TeV	2102.13405
	Bulk RS $G_{\mu\nu} + WW/ZZ$	0 μ, τ, γ	1-4†	36.1	3.9 TeV	1908.02820
	Bulk RS $G_{\mu\nu} + t\bar{t}$	0 μ, τ, γ	1-4†	36.1	3.9 TeV	1908.02820
	2UED/3UED	0 μ, τ, γ	1-4†	36.1	1.4 TeV	1908.02820
Group theory	SSM $Z \rightarrow t\bar{t}$	0 μ, τ, γ	1-4†	36.1	2.4 TeV	1908.02820
	Leptoquark $Z \rightarrow b\bar{b}$	0 μ, τ, γ	1-4†	36.1	2.1 TeV	1908.02820
	SSM $W \rightarrow \nu\bar{\nu}$	0 μ, τ, γ	1-4†	139	4.1 TeV	1908.02820
	SSM $W \rightarrow \nu\bar{\nu}$	0 μ, τ, γ	1-4†	139	5.0 TeV	1908.02820
	SSM $W \rightarrow \nu\bar{\nu}$	0 μ, τ, γ	1-4†	139	4.8 TeV	1908.02820
	HVT $W \rightarrow WZ$ model B	0 μ, τ, γ	1-4†	139	3.9 TeV	1908.02820
	HVT $W \rightarrow WZ$ model C	0 μ, τ, γ	1-4†	139	3.9 TeV	1908.02820
	HVT $Z \rightarrow WW$ model B	0 μ, τ, γ	1-4†	139	3.9 TeV	1908.02820
	HVT $Z \rightarrow WW$ model C	0 μ, τ, γ	1-4†	139	3.9 TeV	1908.02820
CI	CI $g_{\mu\nu}$	0 μ, τ, γ	1-4†	37.0	21.8 TeV	1709.0427
	CI $g_{\mu\nu}$	0 μ, τ, γ	1-4†	139	1.8 TeV	2008.1296
	CI $g_{\mu\nu}$	0 μ, τ, γ	1-4†	139	2.0 TeV	2108.13847
	CI $g_{\mu\nu}$	0 μ, τ, γ	1-4†	139	2.0 TeV	2108.13847
	CI $g_{\mu\nu}$	0 μ, τ, γ	1-4†	36.1	2.0 TeV	1811.03305

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

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

➔ Quark/Lepton size smaller than 10⁻²⁰ m



FCS

High-Energy Particle Physics

$\Lambda_B > 10^{16}$ 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 $t_p > 10^{34} y$

$\Lambda_{ll} > 10^{14}$ GeV

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

10⁻¹⁵ 10⁻³⁵

➔ Laws of nature governed by (emerging) symmetries



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

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

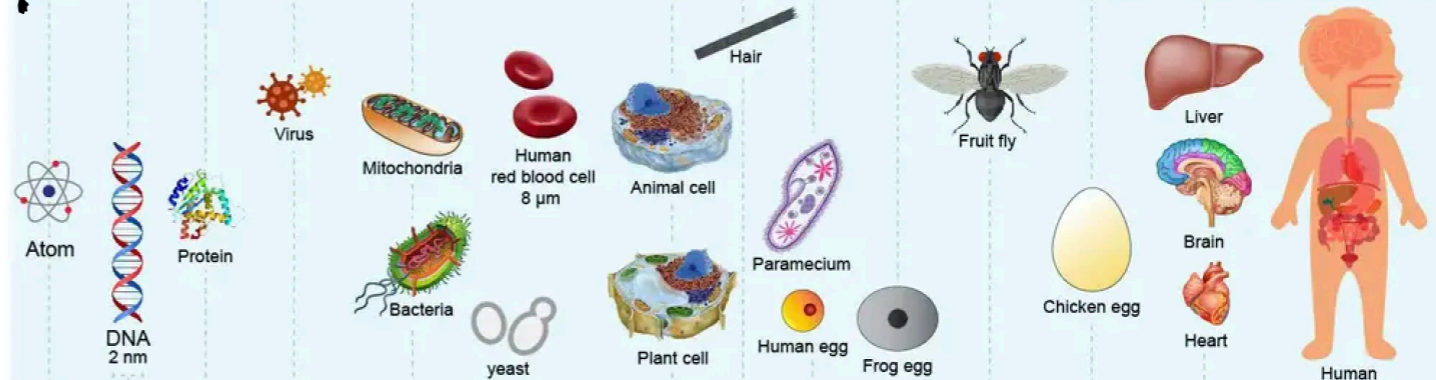
Status: March 2023

Model	ℓ, γ	Jets†	E_{miss}^\ddagger	$f_{cut}(fb^{-1})$	Limit	Reference
Extra dim.	ADD $G_{\mu\nu} + g/\epsilon$	0 μ, τ, γ	1-4‡	Yes	1.0 TeV	1102.0879
	ADD nonrenorm. $\gamma\gamma$	0 μ, τ, γ	1-4‡	Yes	0.6 TeV	1707.0447
	ADD BH	0 μ, τ, γ	1-4‡	Yes	0.8 TeV	1910.0847
	ADD BH multijet	0 μ, τ, γ	1-4‡	Yes	0.8 TeV	1910.0847
	RSL $G_{\mu\nu} + \gamma\gamma$	0 μ, τ, γ	1-4‡	Yes	0.8 TeV	1910.0847
	Bulk RS $G_{\mu\nu} + WW/ZZ$	0 μ, τ, γ	1-4‡	Yes	0.8 TeV	1910.0847
	Bulk RS $G_{\mu\nu} + tt$	0 μ, τ, γ	1-4‡	Yes	0.8 TeV	1910.0847
	2UED/3UED	0 μ, τ, γ	1-4‡	Yes	0.8 TeV	1910.0847
Group theory	SSM $Z' \rightarrow \mu\mu$	0 μ, τ, γ	1-4‡	Yes	2.0 TeV	1910.0847
	Leptoquark $Z' \rightarrow bb$	0 μ, τ, γ	1-4‡	Yes	2.1 TeV	1910.0847
	SSM $W' \rightarrow \nu\tau$	0 μ, τ, γ	1-4‡	Yes	4.1 TeV	1910.0847
	SSM $W' \rightarrow \nu\tau$	0 μ, τ, γ	1-4‡	Yes	5.0 TeV	1910.0847
	SSM $W' \rightarrow \nu\tau$	0 μ, τ, γ	1-4‡	Yes	4.8 TeV	1910.0847
	HVT $W' \rightarrow WZ$ model B	0 μ, τ, γ	1-4‡	Yes	3.0 TeV	1910.0847
	HVT $W' \rightarrow WZ$ model C	0 μ, τ, γ	1-4‡	Yes	3.0 TeV	1910.0847
	HVT $Z' \rightarrow WW$ model B	0 μ, τ, γ	1-4‡	Yes	3.0 TeV	1910.0847
	HVT $Z' \rightarrow WW$ model C	0 μ, τ, γ	1-4‡	Yes	3.0 TeV	1910.0847
CI	CI $\mu\mu$	0 μ, τ, γ	1-4‡	Yes	21.8 TeV	1709.0427
	CI $\tau\tau$	0 μ, τ, γ	1-4‡	Yes	1.8 TeV	2108.1847
	CI $e\mu$	0 μ, τ, γ	1-4‡	Yes	2.0 TeV	2108.1847
	CI $e\tau$	0 μ, τ, γ	1-4‡	Yes	2.0 TeV	1811.0305

Λ	21.8 TeV	η_{ll}
Λ	35.8 TeV	η_{ll}
Λ	1.8 TeV	
Λ	2.0 TeV	
Λ	2.57 TeV	

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

➔ Quark/Lepton size smaller than 10⁻²⁰ m



High-Energy Particle Physics

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

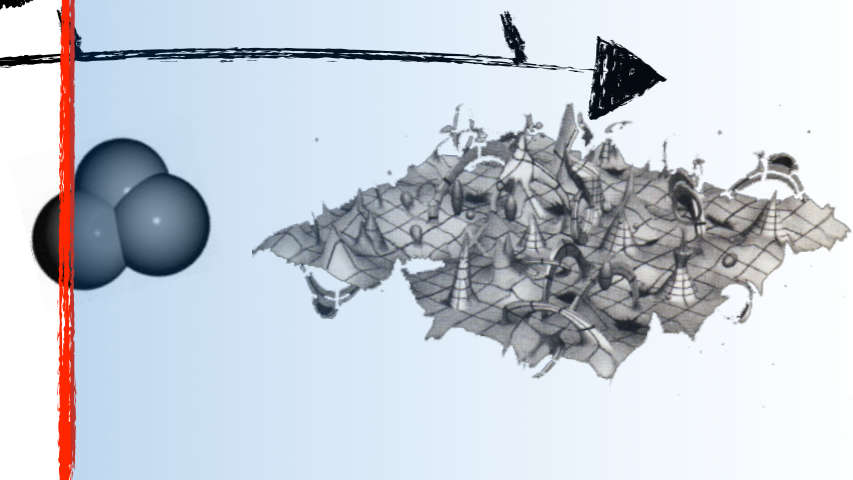
$\frac{1}{\Lambda_B^2} [(d_p^\alpha)^T C u_r^\beta] [(q_s^{\gamma j})^T C l_t^k]$ Proton Lifetime $t_p > 10^{34} y$

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

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

10⁻¹⁵ 10⁻³⁵

→ Laws of nature governed by (emerging) symmetries



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

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

Status: March 2023

Model	ℓ, γ	Jets†	$E_{T,miss}^\ddagger$	$f_{cut}(fb^{-1})$	Limit	Reference
Extra dim.	ADD $G_{UV} + g/\epsilon$	0 μ, τ, γ	1-4‡	Yes	1.0 TeV	1102.0879
	ADD nonrenorm. $\gamma\gamma$	2‡	-	Yes	6.6 TeV	1707.0447
	ADD BH multigr.	2‡	-	Yes	8.8 TeV	1910.0847
	ADD BH multigr.	2‡	-	Yes	8.8 TeV	1910.0847
	RSL $G_{UV} \rightarrow \gamma\gamma$	2‡	-	Yes	2.3 TeV	2102.13405
	Bulk RS $G_{UV} \rightarrow WW/ZZ$	multi-channel	-	Yes	2.3 TeV	1908.02820
	Bulk RS $G_{UV} \rightarrow t\bar{t}$	1 μ, τ	21 b, 21 j	Yes	36.1 TeV	1904.19825
	ZUSZ/WW	1 μ, τ	25 b, 25 j	Yes	36.1 TeV	2006.08770
Graviton bosons	SM $Z \rightarrow \gamma\gamma$	2‡	-	Yes	2.42 TeV	1705.01271
	Leptoquark $Z \rightarrow b\bar{b}$	2 b	-	Yes	2.1 TeV	1805.06029
	Leptoquark $Z \rightarrow t\bar{t}$	0 μ, τ	21 b, 22 j	Yes	2.1 TeV	2005.01120
	SSM $W \rightarrow \nu\bar{\nu}$	1 ν	-	Yes	139 TeV	1905.05690
	SSM $W \rightarrow \nu\bar{\nu}$	1 ν	-	Yes	139 TeV	1905.05690
	SSM $W \rightarrow \nu\bar{\nu}$	1 ν	-	Yes	139 TeV	1905.05690
	HVT $W \rightarrow WZ$ model B	0 μ, τ	21 j, 1 j	Yes	139 TeV	2004.14028
	HVT $W \rightarrow WZ$ model C	3 μ, τ	21(VBF)	Yes	139 TeV	2007.03900
	HVT $Z \rightarrow WW$ model B	1 μ, τ	21 j, 1 j	Yes	39 TeV	2004.14028
CI	CI none	2 μ, τ	21	-	37.0 TeV	1705.01271
	CI free	2 μ, τ	1 b	-	139 TeV	2105.13847
	CI rebr	2 μ, τ	1 b	-	139 TeV	2105.13847
	CI ttrr	21 μ, τ	21 b, 21 j	Yes	36.1 TeV	1811.02050

Λ

Λ

Λ

Λ

Λ

1.8 TeV

2.0 TeV

2.57 TeV

21.8 TeV η_{LL}

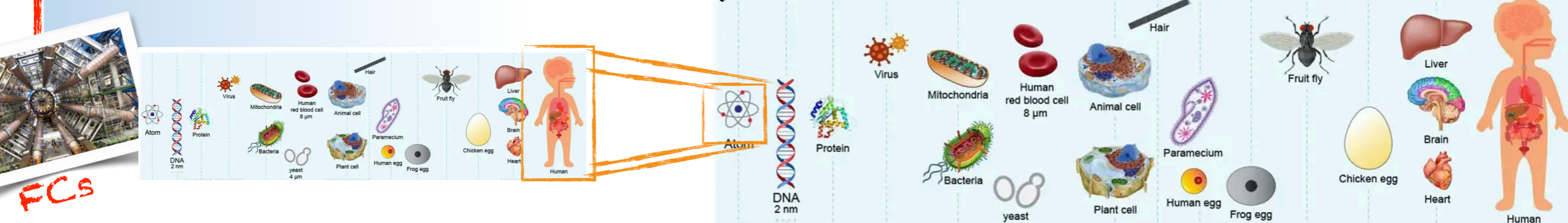
35.8 TeV η_{LL}

$g_* = 1$

$g_* = 1$

$|C_{4t}| = 4\pi$

→ Quark/Lepton size smaller than 10⁻²⁰ m



FCS

One question for future colliders:

What is the size of the Higgs boson?

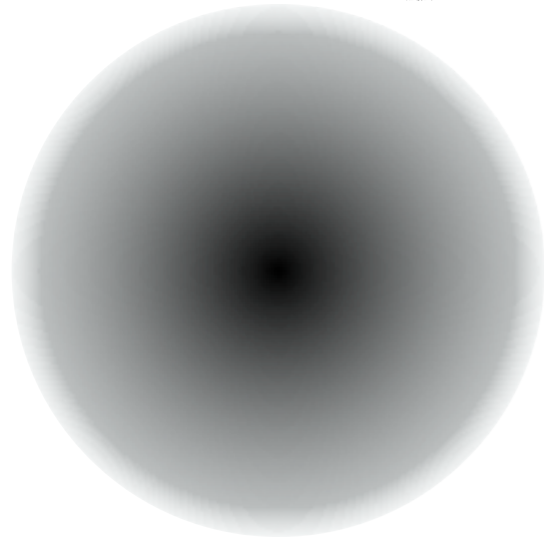
The size of spin-0 particles in HEP

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



The size of spin-0 particles in HEP

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



The size of spin-0 particles in HEP

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

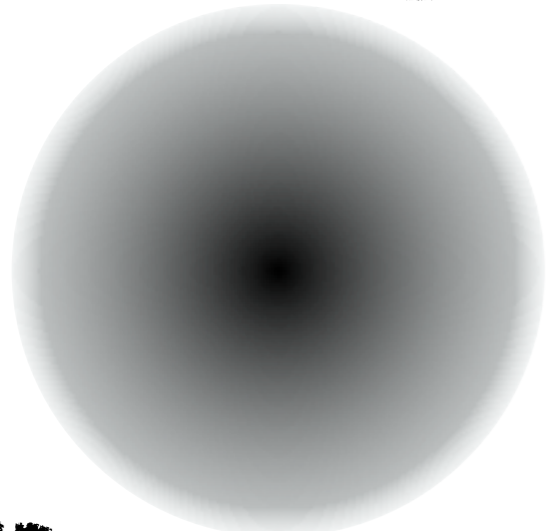


QCD resonances

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

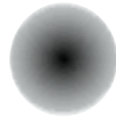
The size of spin-0 particles in HEP

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



QCD resonances

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

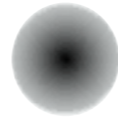
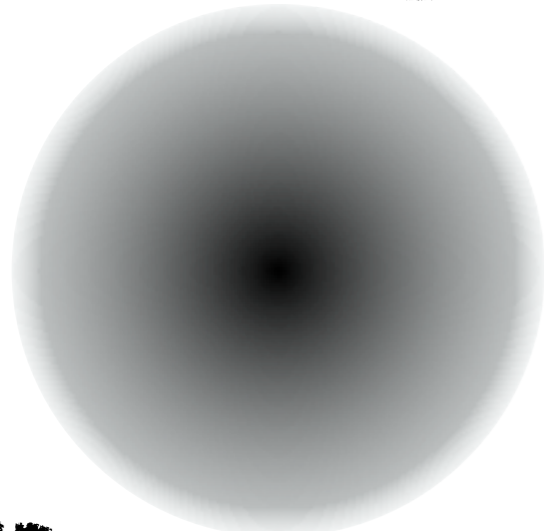


Pions

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

The size of spin-0 particles in HEP

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



QCD resonances

Pions

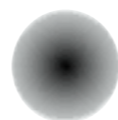
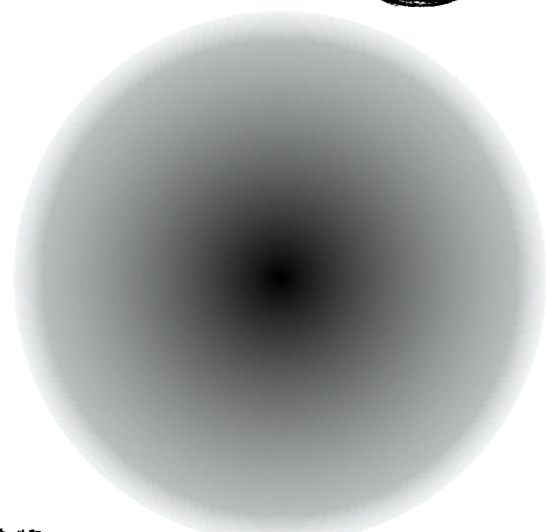
$$L \sim \frac{1}{m} \sim \frac{1}{\text{GeV}}$$

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

Pseudo Goldstone Bosons

The size of spin-0 particles in HEP

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



QCD resonances

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

Pions

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

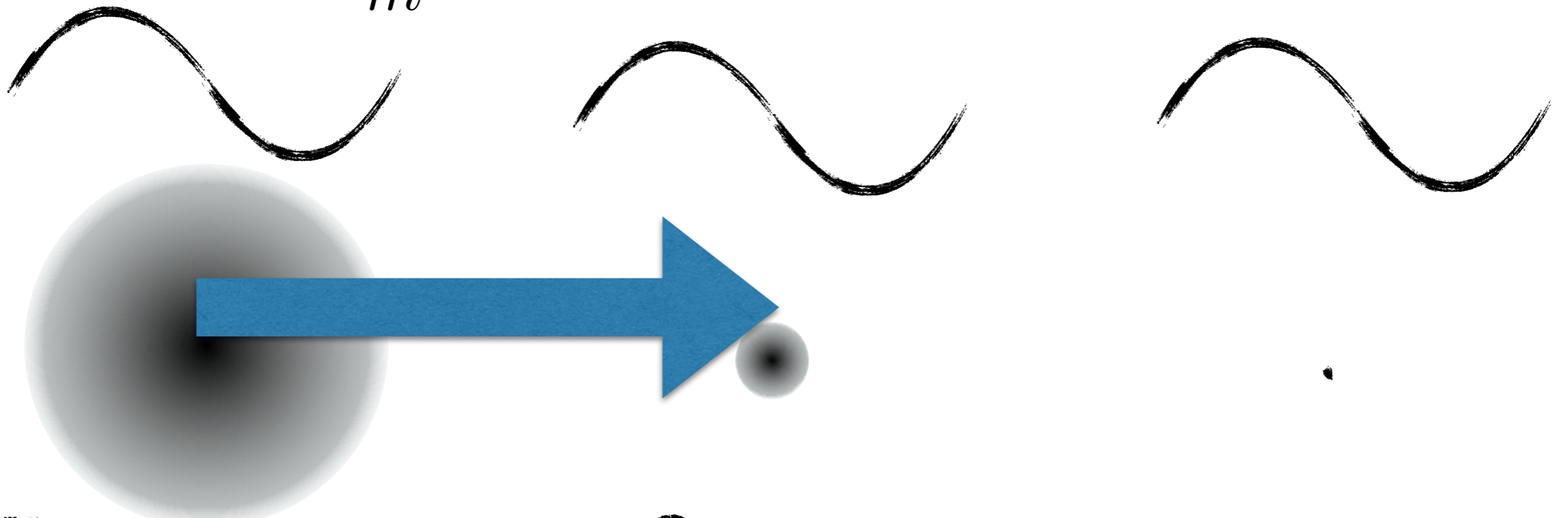
Higgs in the "SM+Grav"

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

Pseudo Goldstone Bosons

The size of spin-0 particles in HEP

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



QCD resonances

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

Pions

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

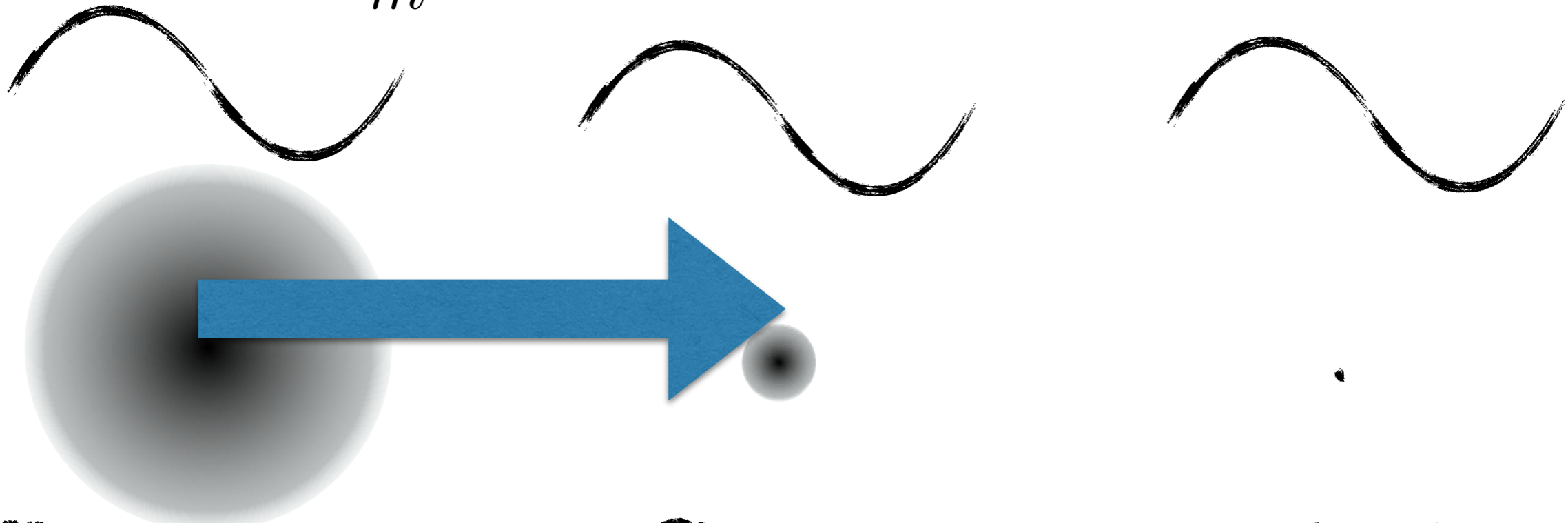
Higgs in the "SM+Grav"

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

Pseudo Goldstone Bosons

The size of spin-0 particles in HEP

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



QCD resonances

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

Pions

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

Higgs in the "SM+Grav"

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

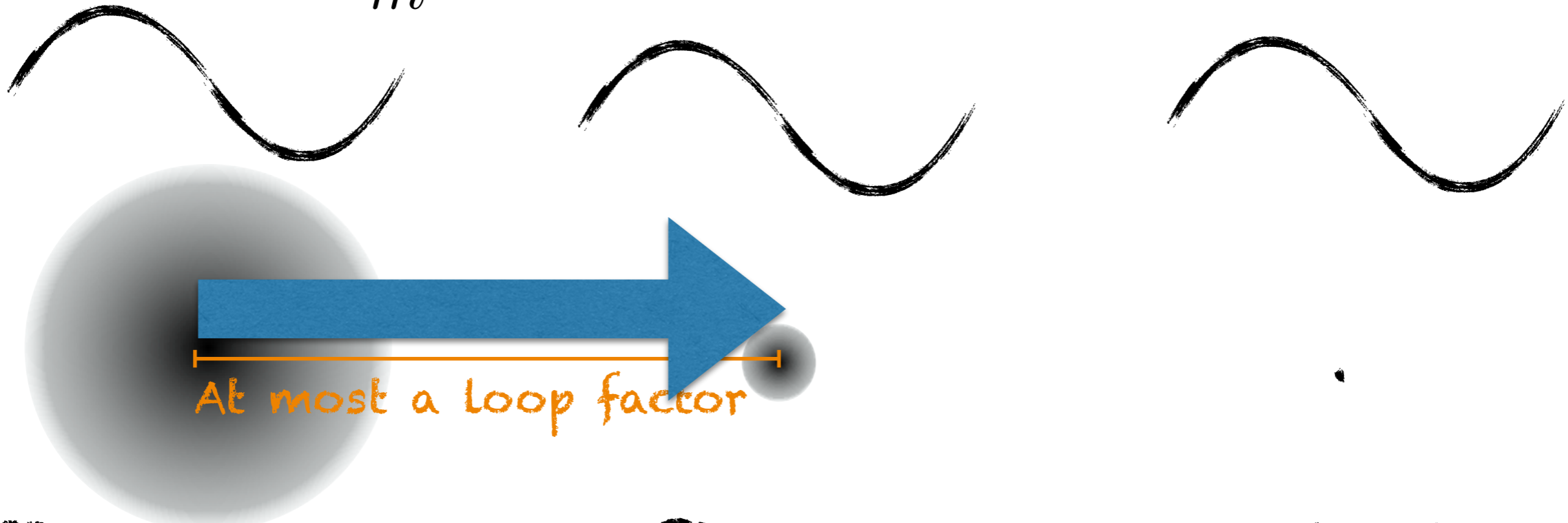
Pseudo Goldstone Bosons

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 SUSY where quantum fluctuation can cancel each-other out in their contribution to the mass

The size of spin-0 particles in HEP

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



QCD resonances

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

Pions

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

Pseudo Goldstone Bosons

Higgs in the "SM+Grav"

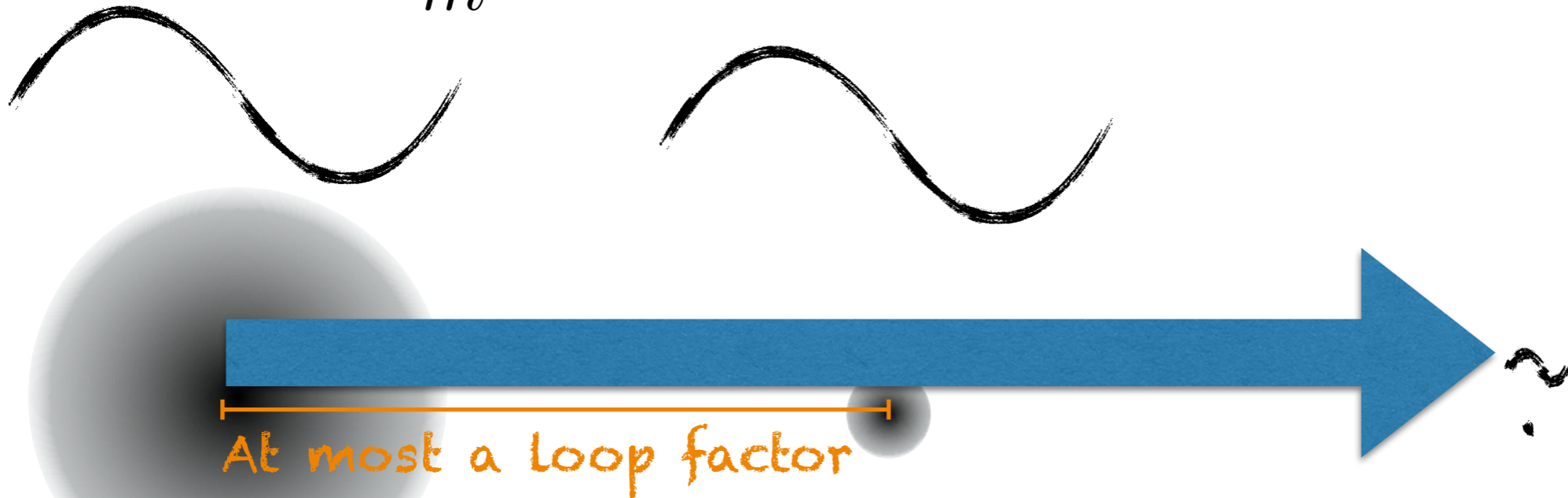
$$L \lesssim \frac{1}{10^{17}m} \sim \frac{10^{-19}}{\text{GeV}}$$

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

* this intuition works in theories where the Higgs mass is calculable, but fails in SUSY where quantum fluctuations can cancel each other out in their contribution to the mass

The size of spin-0 particles in HEP

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



QCD resonances

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

Pions

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

Higgs in the "SM+Grav"

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

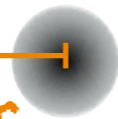
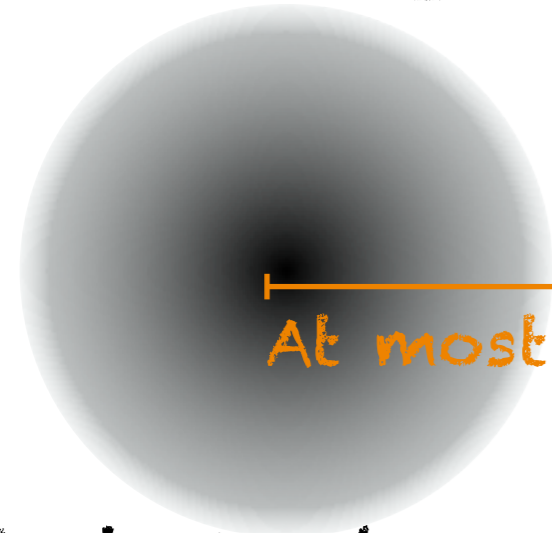
Pseudo Goldstone Bosons

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

* this intuition works in theories where the Higgs mass is calculable, but fails in SUSY where quantum fluctuations can cancel each other out in their contribution to the mass

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

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



~?

At most a loop factor

Technicolor

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

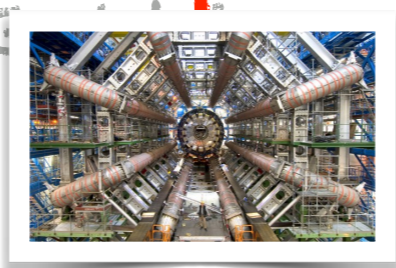
Composite
PGB Higgs

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

Pseudo Goldstone Bosons

Higgs in the "SM+Grav"

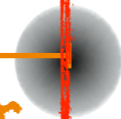
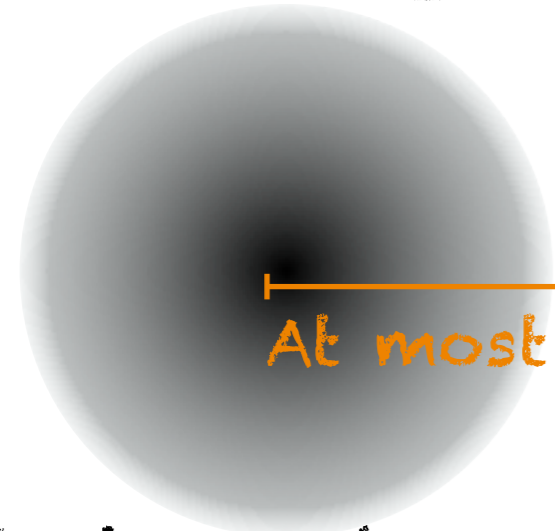
$$L \lesssim \frac{1}{10^{17} m} \sim \frac{10^{-19}}{\text{GeV}}$$



LHC

The size of the Higgs

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



At most a loop factor

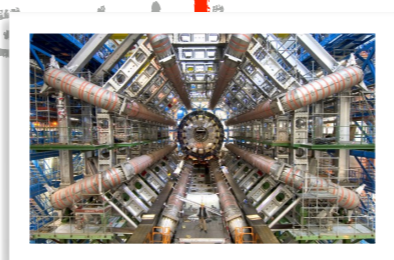
Technicolor

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

Composite
PGB Higgs

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

Pseudo Goldstone Boson

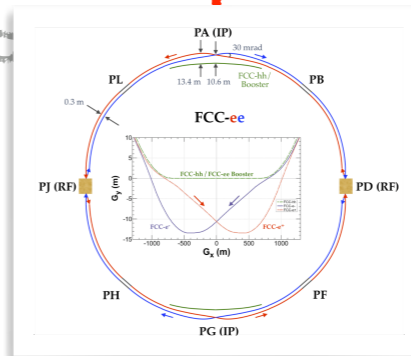


LHC

Higgs in the "SM+Grav"

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

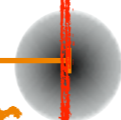
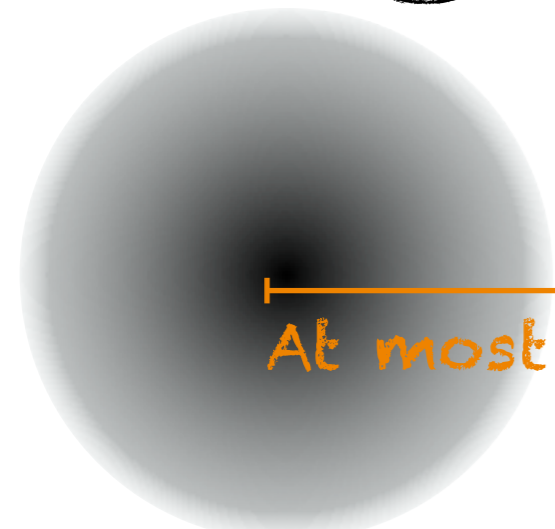
??



FCS

The size of the Higgs

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



At most a loop factor

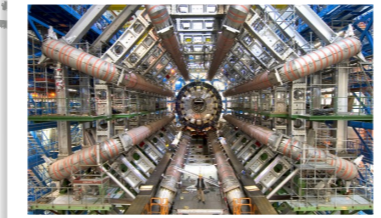
Technicolor

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

Composite PGB Higgs

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

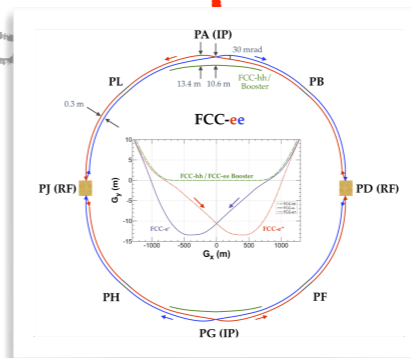
Pseudo Goldstone Boson



LHC

Higgs in the "SM+Grav"

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



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

The Hierarchy Problem

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

- ▶ Small observables \Leftrightarrow Larger scales

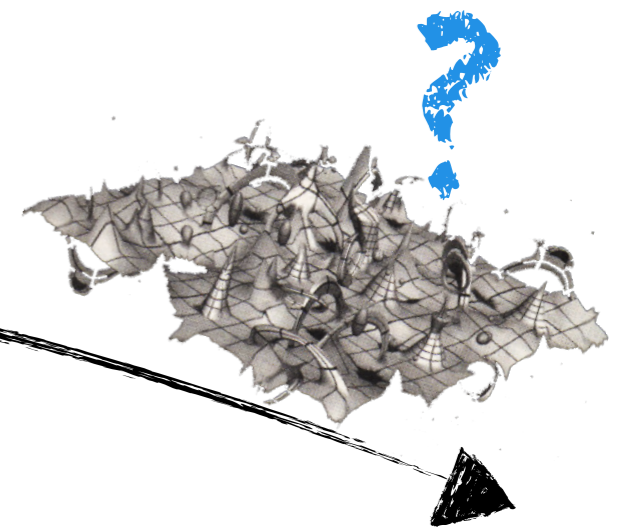
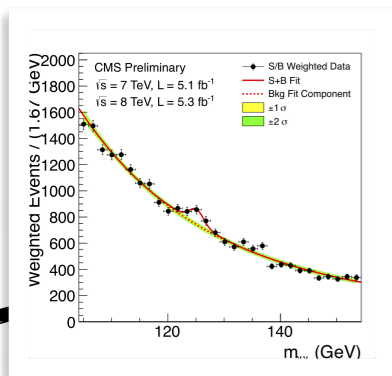
The Hierarchy Problem

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

→ Small observables \Leftrightarrow Larger scales

Higgs-mass: $\Lambda_H^2 |H|^2$

→ Small observable \Leftrightarrow Small scale



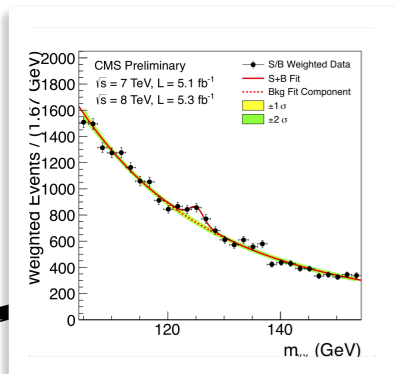
The Hierarchy Problem

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

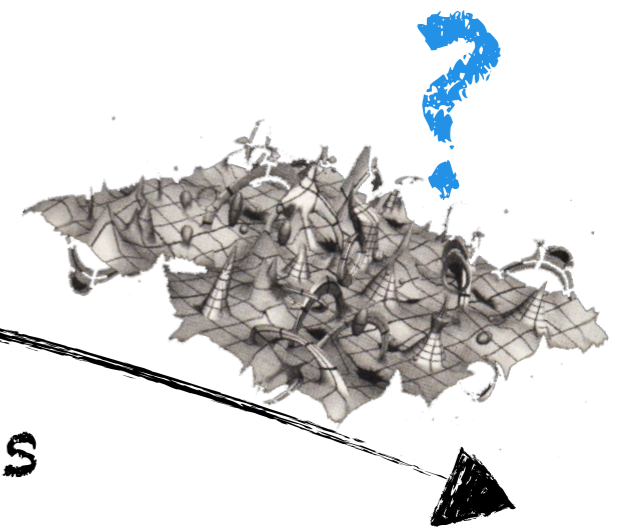
→ Small observables \Leftrightarrow Larger scales

Higgs-mass: $\Lambda_H^2 |H|^2$

→ Small observable \Leftrightarrow Small scale



Maybe Quantum Gravity solves all of this
(no model/no understanding/not testable)



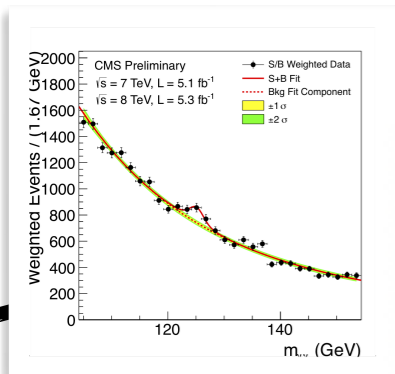
The Hierarchy Problem

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

→ Small observables \Leftrightarrow Larger scales

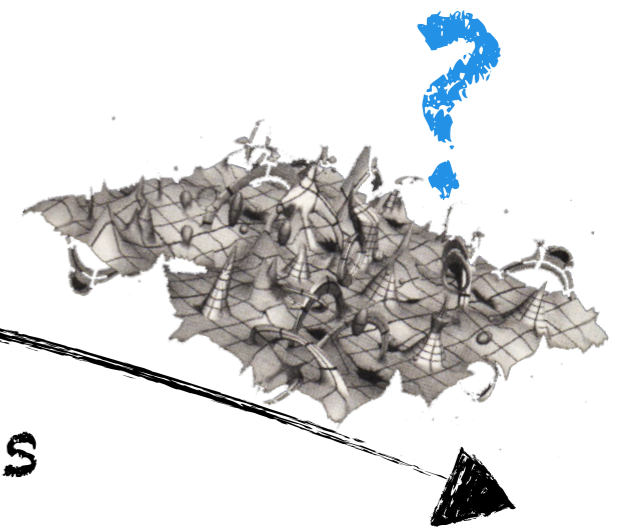
Higgs-mass: $\Lambda_H^2 |H|^2$

→ Small observable \Leftrightarrow Small scale



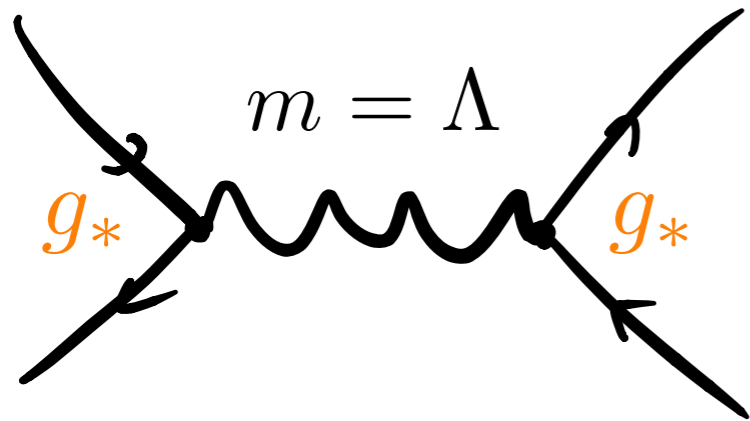
Maybe Quantum Gravity solves all of this
(no model/no understanding/not testable)

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



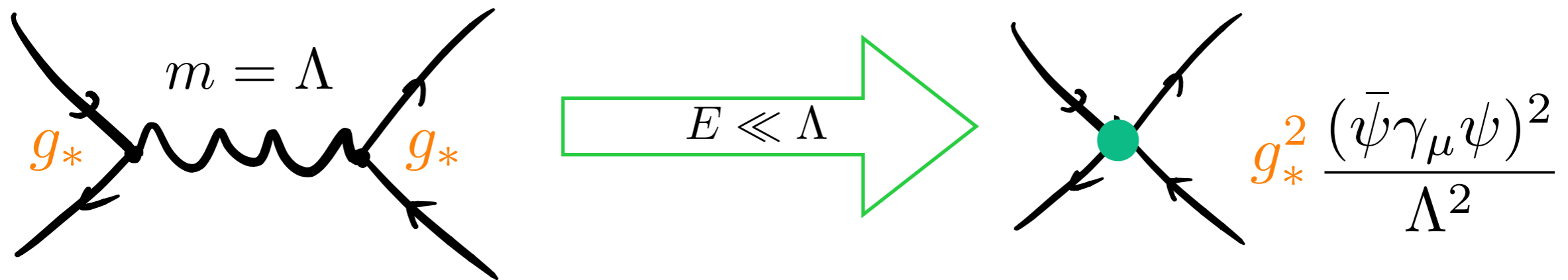
Is this a good question for e^+e^- machines?

Lepton colliders designer for precision physics, EFTs...



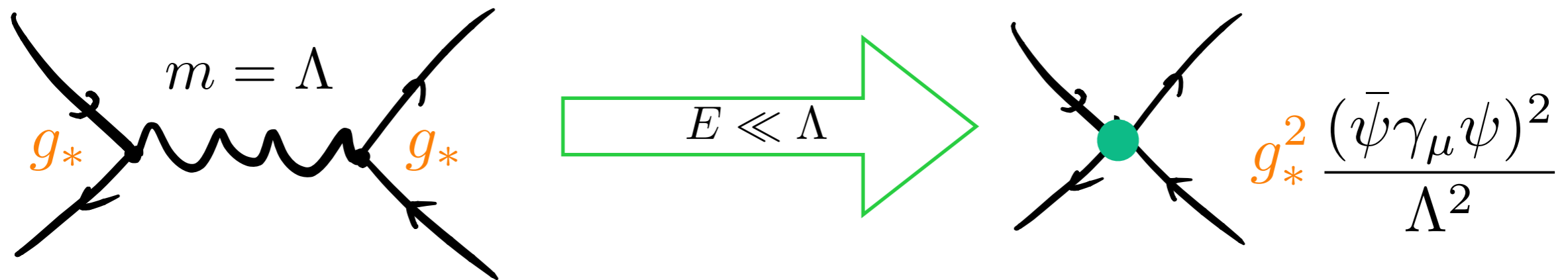
Is this a good question for e^+e^- machines?

Lepton colliders designer for precision physics, EFTs...



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

Lepton colliders designer for precision physics, EFTs...



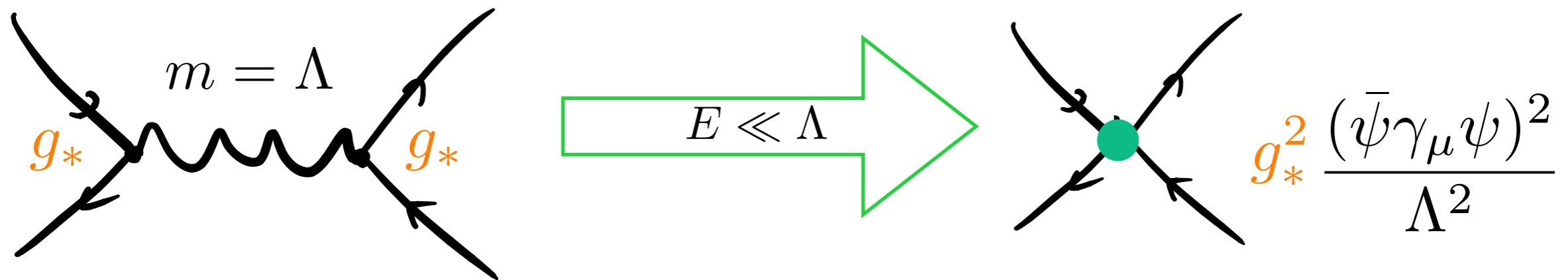
UV theories that are strongly coupled,

$$g_* \gtrsim 1$$

create composites and have particles with substructure,
like pions or protons.

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

Lepton colliders designer for precision physics, EFTs...



UV theories that are strongly coupled,

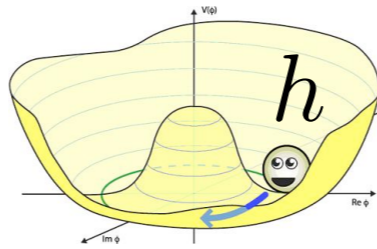
$$g_* \gtrsim 1$$

create composites and have particles with substructure, like pions or protons.

But are also the ones that have the largest effects at lower energies

A Higgs smaller than its size?

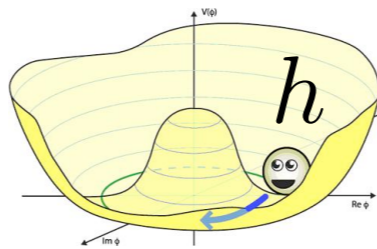
To be composite and lighter than its size, it must be a (Pseudo) Goldstone Boson:



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

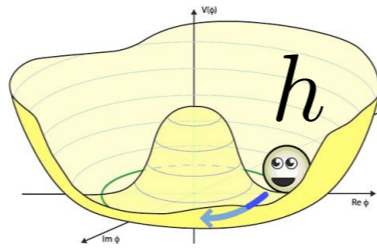
$$\sin \frac{h}{f} = \frac{h}{f} - \frac{h^3}{3!f^3} + \dots$$

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

y

A Higgs smaller than its size?

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



SM

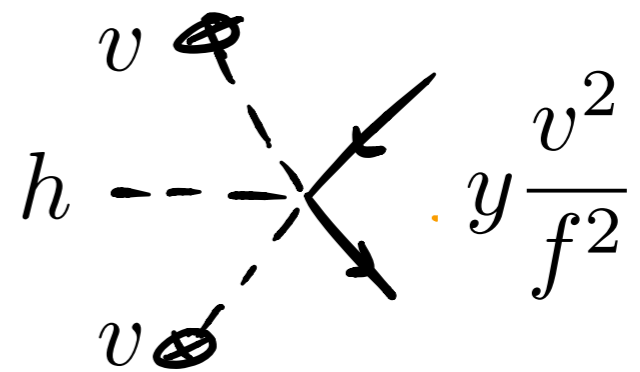
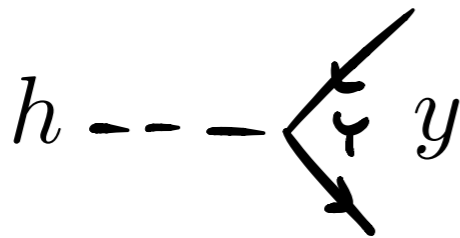
h

$\bar{\psi}\psi h$

BSM

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

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

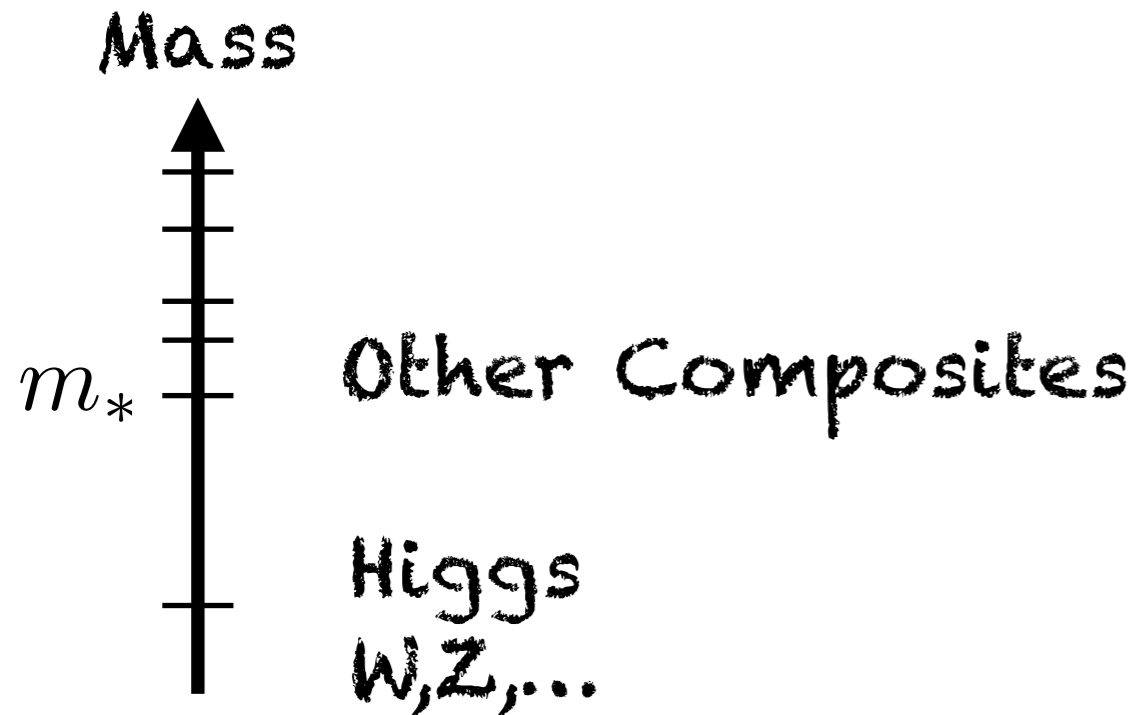


tree-level Higgs Couplings are modified

Strongly Interacting Light Higgs

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

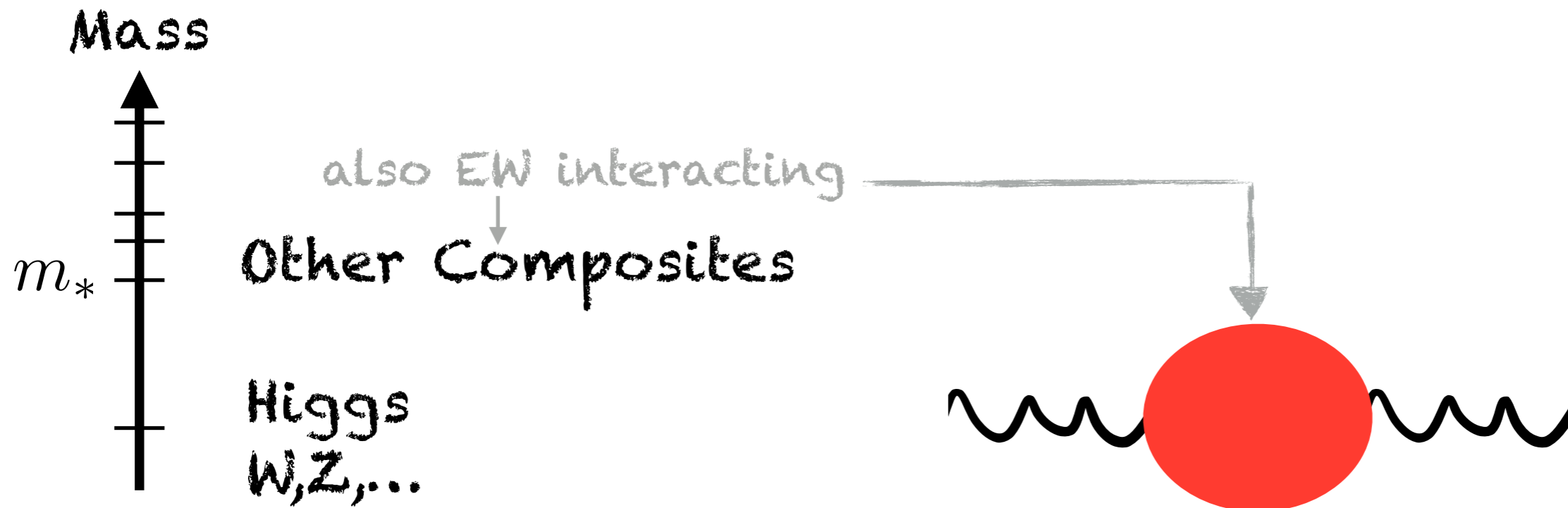
$$m_* \sim \frac{1}{L_H}$$



Strongly Interacting Light Higgs

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

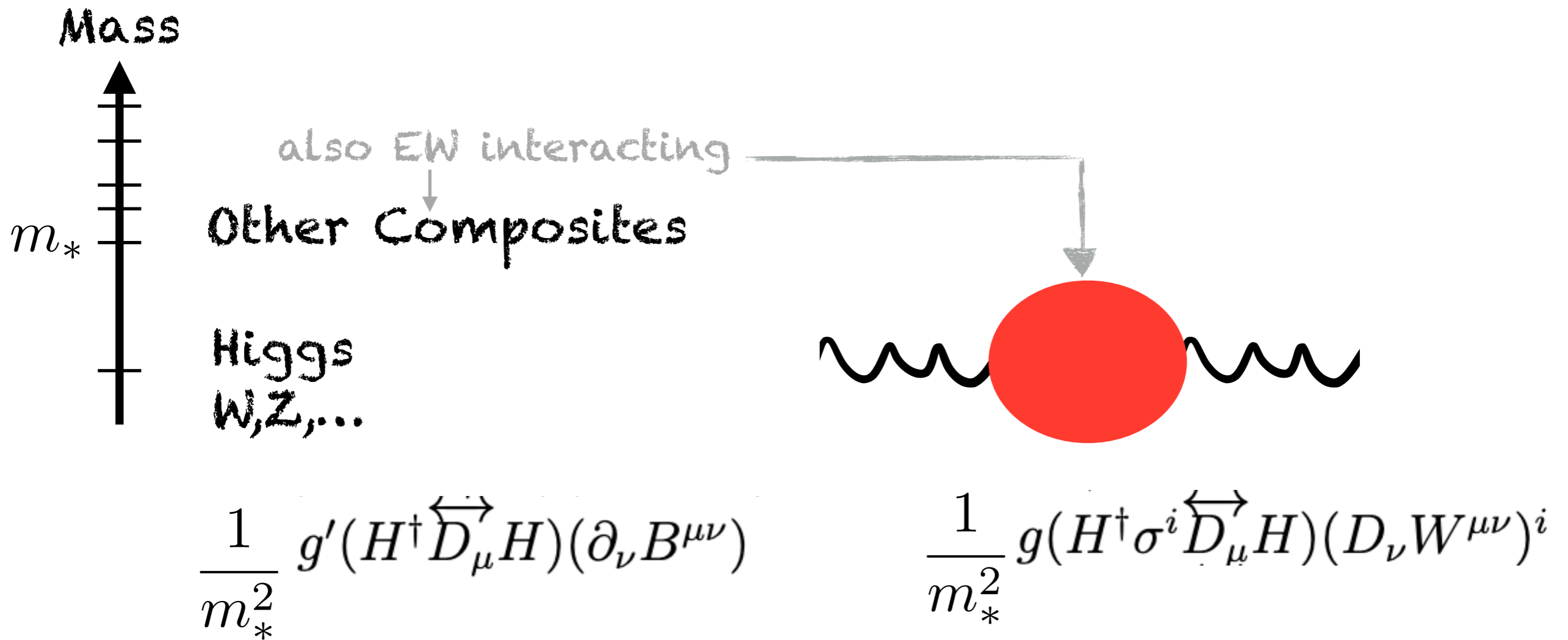
$$m_* \sim \frac{1}{L_H}$$



Strongly Interacting Light Higgs

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

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



modify Z-boson propagation (S-Parameter)

A Higgs smaller than its size?

Giudice, Grojean, Pomarol, Rattazzi '08

Higgs size reflected into EFT effects:

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

$$\mathcal{O}_{y_\psi} = Y_\psi \frac{|H|^2 \psi_L H \psi_R}{f^2}$$

$$\mathcal{O}_6 = \frac{|H|^6}{f^2}$$

A Higgs smaller than its size?

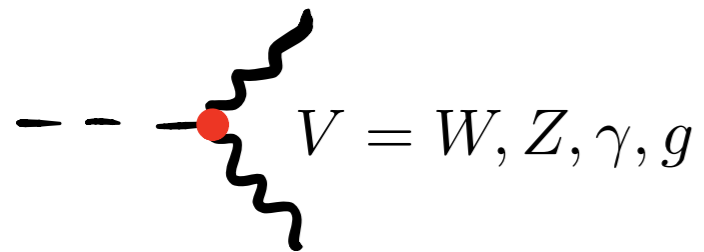
Giudice, Grojean, Pomarol, Rattazzi '08

Higgs size reflected into EFT effects:

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

$$\mathcal{O}_{y_\psi} = Y_\psi \frac{|H|^2}{f^2} \psi_L H \psi_R$$

$$\mathcal{O}_6 = \frac{|H|^6}{f^2}$$



A Higgs smaller than its size?

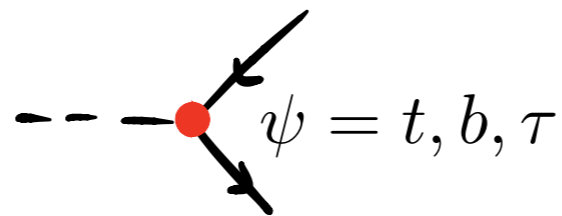
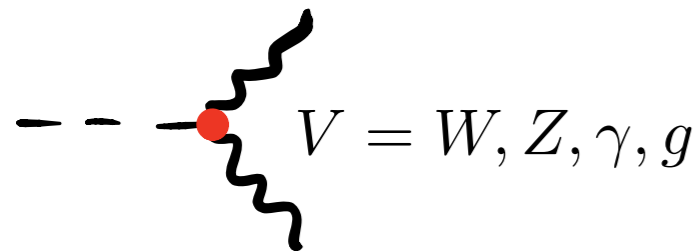
Giudice, Grojean, Pomarol, Rattazzi '08

Higgs size reflected into EFT effects:

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

$$\mathcal{O}_{y_\psi} = \frac{Y_\psi |H|^2 \psi_L H \psi_R}{f^2}$$

$$\mathcal{O}_6 = \frac{|H|^6}{f^2}$$

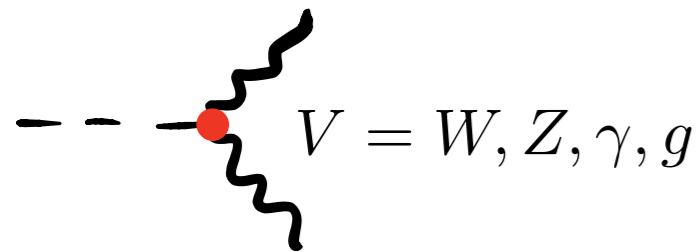


A Higgs smaller than its size?

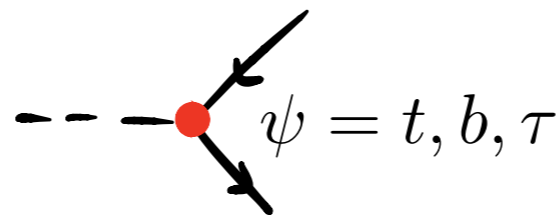
Giudice, Grojean, Pomarol, Rattazzi '08

Higgs size reflected into EFT effects:

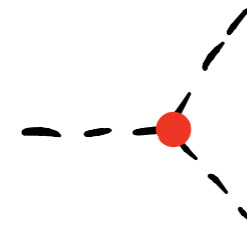
$$\mathcal{O}_r = \frac{|H|^2 \partial_\mu H^\dagger \partial^\mu H}{f^2}$$



$$\mathcal{O}_{y_\psi} = \frac{Y_\psi |H|^2 \psi_L H \psi_R}{f^2}$$



$$\mathcal{O}_6 = \frac{|H|^6}{f^2}$$

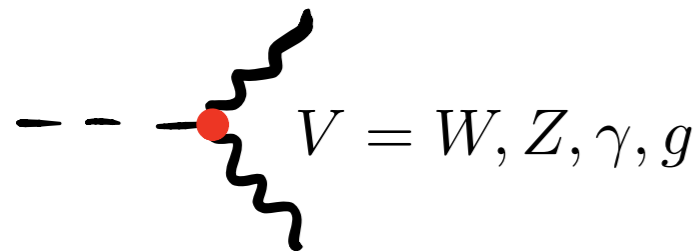


A Higgs smaller than its size?

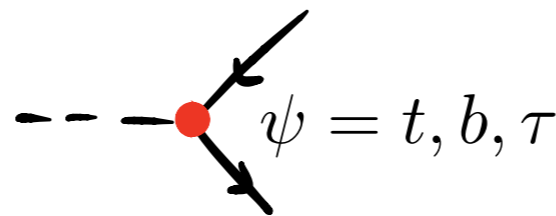
Giudice, Grojean, Pomarol, Rattazzi '08

Higgs size reflected into EFT effects:

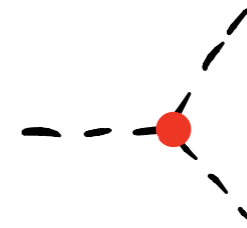
$$\mathcal{O}_r = \frac{|H|^2 \partial_\mu H^\dagger \partial^\mu H}{f^2}$$



$$\mathcal{O}_{y_\psi} = \frac{Y_\psi |H|^2 \psi_L H \psi_R}{f^2}$$



$$\mathcal{O}_6 = \frac{|H|^6}{f^2}$$



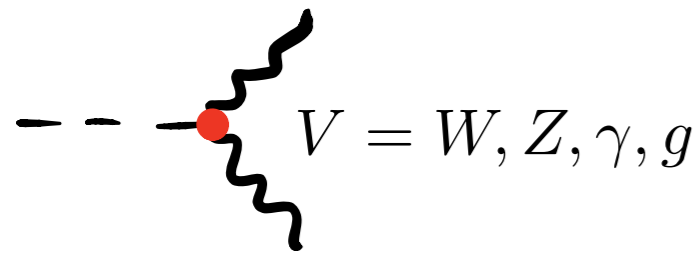
$$\frac{\delta}{SM} \sim \frac{v^2}{f^2}$$

A Higgs smaller than its size?

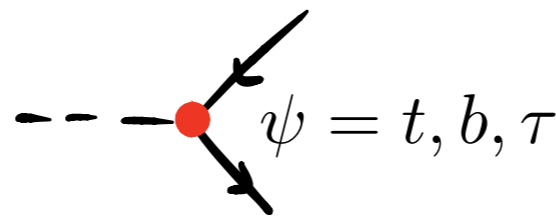
Giudice, Grojean, Pomarol, Rattazzi '08

Higgs size reflected into EFT effects:

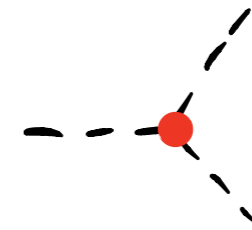
$$\mathcal{O}_r = \frac{|H|^2 \partial_\mu H^\dagger \partial^\mu H}{f^2}$$



$$\mathcal{O}_{y_\psi} = \frac{Y_\psi |H|^2 \psi_L H \psi_R}{f^2}$$



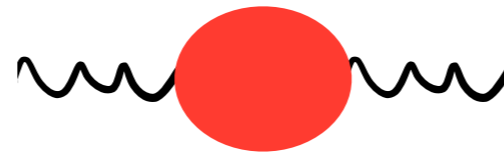
$$\mathcal{O}_6 = \frac{|H|^6}{f^2}$$



$$\frac{\delta}{SM} \sim \frac{v^2}{f^2}$$

$$\frac{1}{m_*^2} g' (H^\dagger \overleftrightarrow{D}_\mu H) (\partial_\nu B^{\mu\nu})$$

$$\frac{1}{m_*^2} g (H^\dagger \sigma^i \overleftrightarrow{D}_\mu H) (D_\nu W^{\mu\nu})^i$$



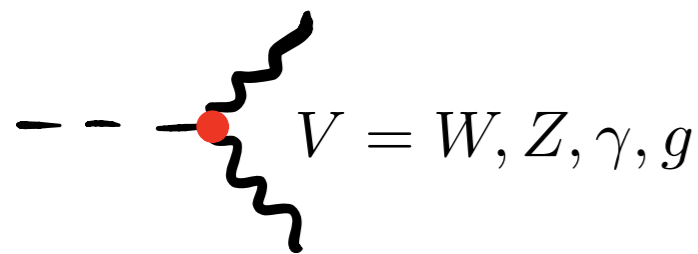
$$\frac{\delta}{SM} \sim \frac{m_Z^2}{m_*^2}$$

A Higgs smaller than its size?

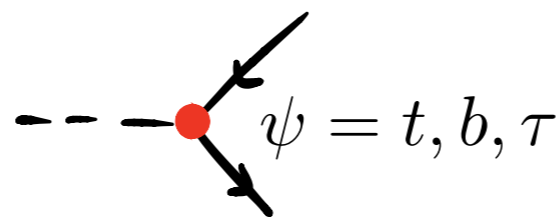
Giudice, Grojean, Pomarol, Rattazzi '08

Higgs size reflected into EFT effects:

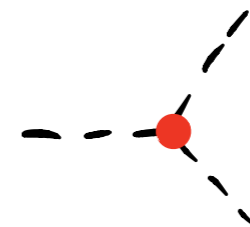
$$\mathcal{O}_r = \frac{|H|^2 \partial_\mu H^\dagger \partial^\mu H}{f^2}$$



$$\mathcal{O}_{y_\psi} = \frac{Y_\psi |H|^2 \psi_L H \psi_R}{f^2}$$



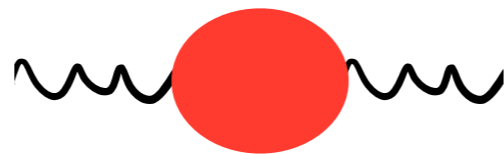
$$\mathcal{O}_6 = \frac{|H|^6}{f^2}$$



$$\frac{\delta}{SM} \sim \frac{v^2}{f^2}$$

$$\frac{1}{m_*^2} g' (H^\dagger \overleftrightarrow{D}_\mu H) (\partial_\nu B^{\mu\nu})$$

$$\frac{1}{m_*^2} g (H^\dagger \sigma^i \overleftrightarrow{D}_\mu H) (D_\nu W^{\mu\nu})^i$$



$$\frac{\delta}{SM} \sim \frac{m_Z^2}{m_*^2}$$

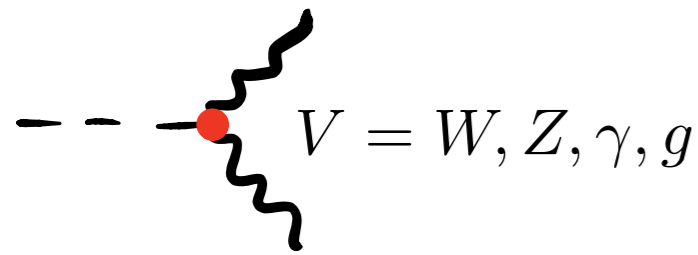
Similarly to $m_W = gv$ we have $m_* = g_* f$

A Higgs smaller than its size?

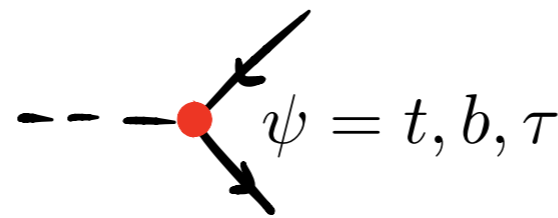
Giudice, Grojean, Pomarol, Rattazzi '08

Higgs size reflected into EFT effects:

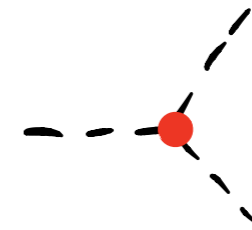
$$\mathcal{O}_r = \frac{|H|^2 \partial_\mu H^\dagger \partial^\mu H}{f^2}$$



$$\mathcal{O}_{y_\psi} = \frac{Y_\psi |H|^2 \psi_L H \psi_R}{f^2}$$



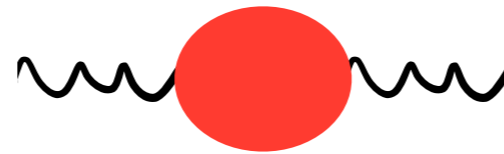
$$\mathcal{O}_6 = \frac{|H|^6}{f^2}$$



$$\frac{\delta}{SM} \sim \frac{v^2}{f^2}$$

$$\frac{1}{m_*^2} g' (H^\dagger \overleftrightarrow{D}_\mu H) (\partial_\nu B^{\mu\nu})$$

$$\frac{1}{m_*^2} g (H^\dagger \sigma^i \overleftrightarrow{D}_\mu H) (D_\nu W^{\mu\nu})^i$$



$$\frac{\delta}{SM} \sim \frac{m_Z^2}{m_*^2} \sim \frac{g^2}{g_*^2} \frac{v^2}{f^2}$$

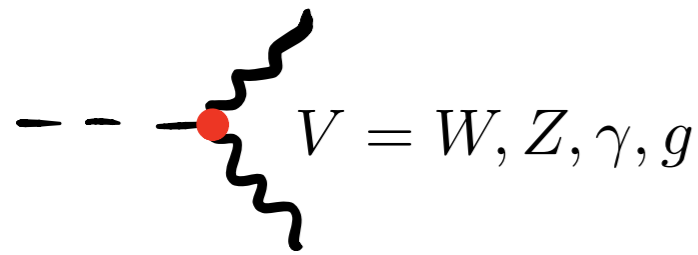
Similarly to $m_W = gv$ we have $m_* = g_* f$ $\xrightarrow{0.01 < \uparrow < 1}$

A Higgs smaller than its size?

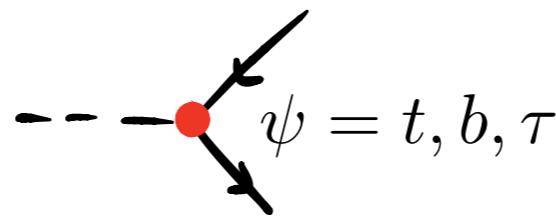
Giudice, Grojean, Pomarol, Rattazzi '08

Higgs size reflected into EFT effects:

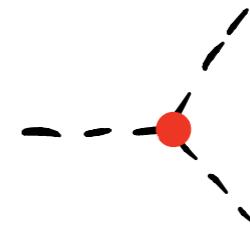
$$\mathcal{O}_r = \frac{|H|^2 \partial_\mu H^\dagger \partial^\mu H}{f^2}$$



$$\mathcal{O}_{y_\psi} = \frac{Y_\psi |H|^2 \psi_L H \psi_R}{f^2}$$



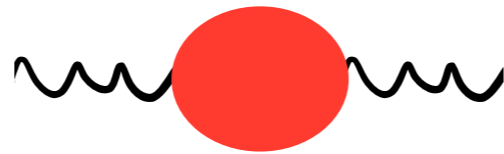
$$\mathcal{O}_6 = \frac{|H|^6}{f^2}$$



$$\frac{\delta}{SM} \sim \frac{v^2}{f^2}$$

$$\frac{1}{m_*^2} g' (H^\dagger \overleftrightarrow{D}_\mu H) (\partial_\nu B^{\mu\nu})$$

$$\frac{1}{m_*^2} g (H^\dagger \sigma^i \overleftrightarrow{D}_\mu H) (D_\nu W^{\mu\nu})^i$$

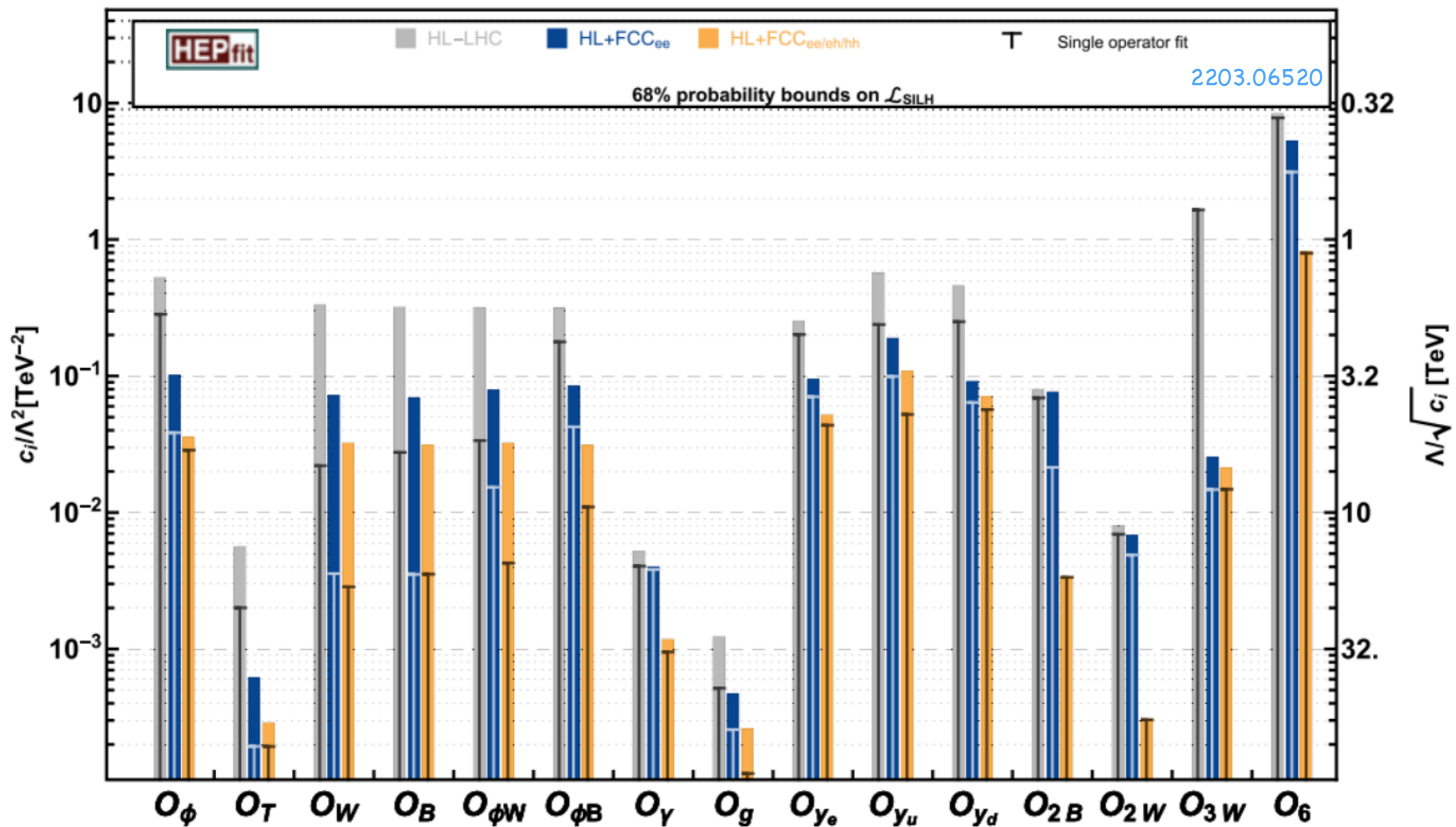


$$\frac{\delta}{SM} \sim \frac{m_Z^2}{m_*^2} \sim \frac{g^2}{g_*^2} \frac{v^2}{f^2}$$

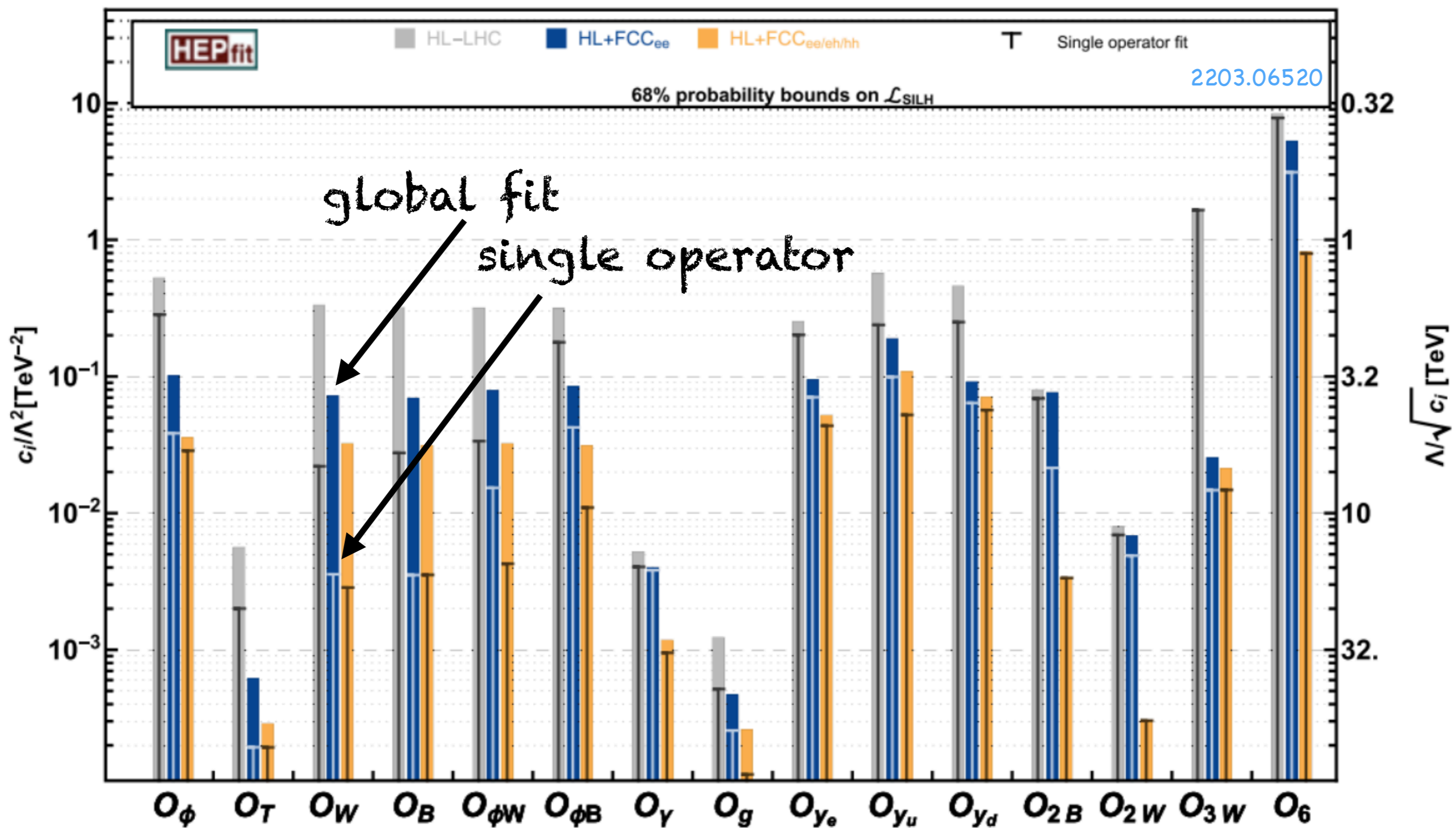
Similarly to $m_W = gv$ we have $m_* = g_* f$ $\xrightarrow{0.01 < \uparrow < 1}$

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

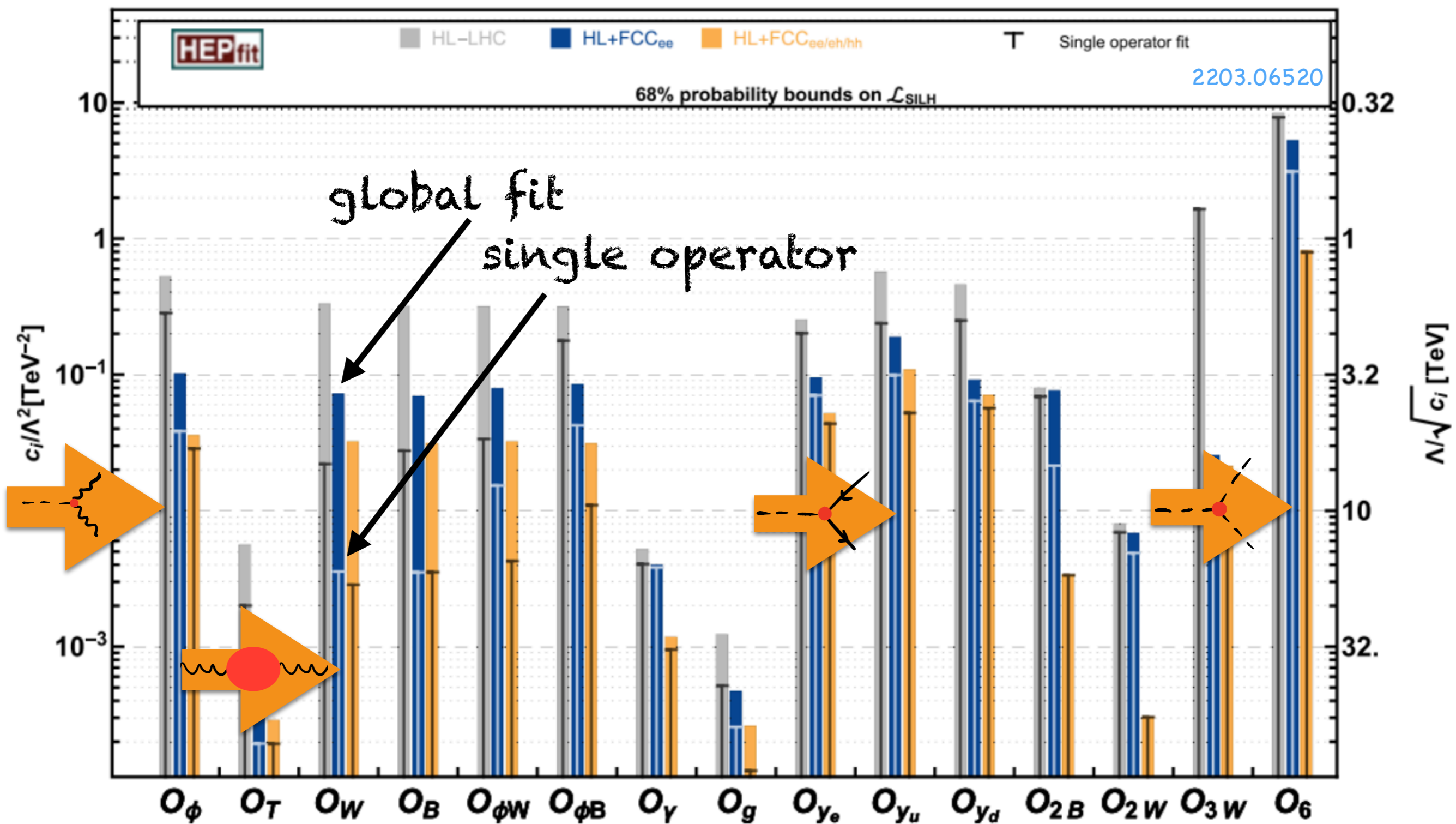
Physics Questions vs Global Fits



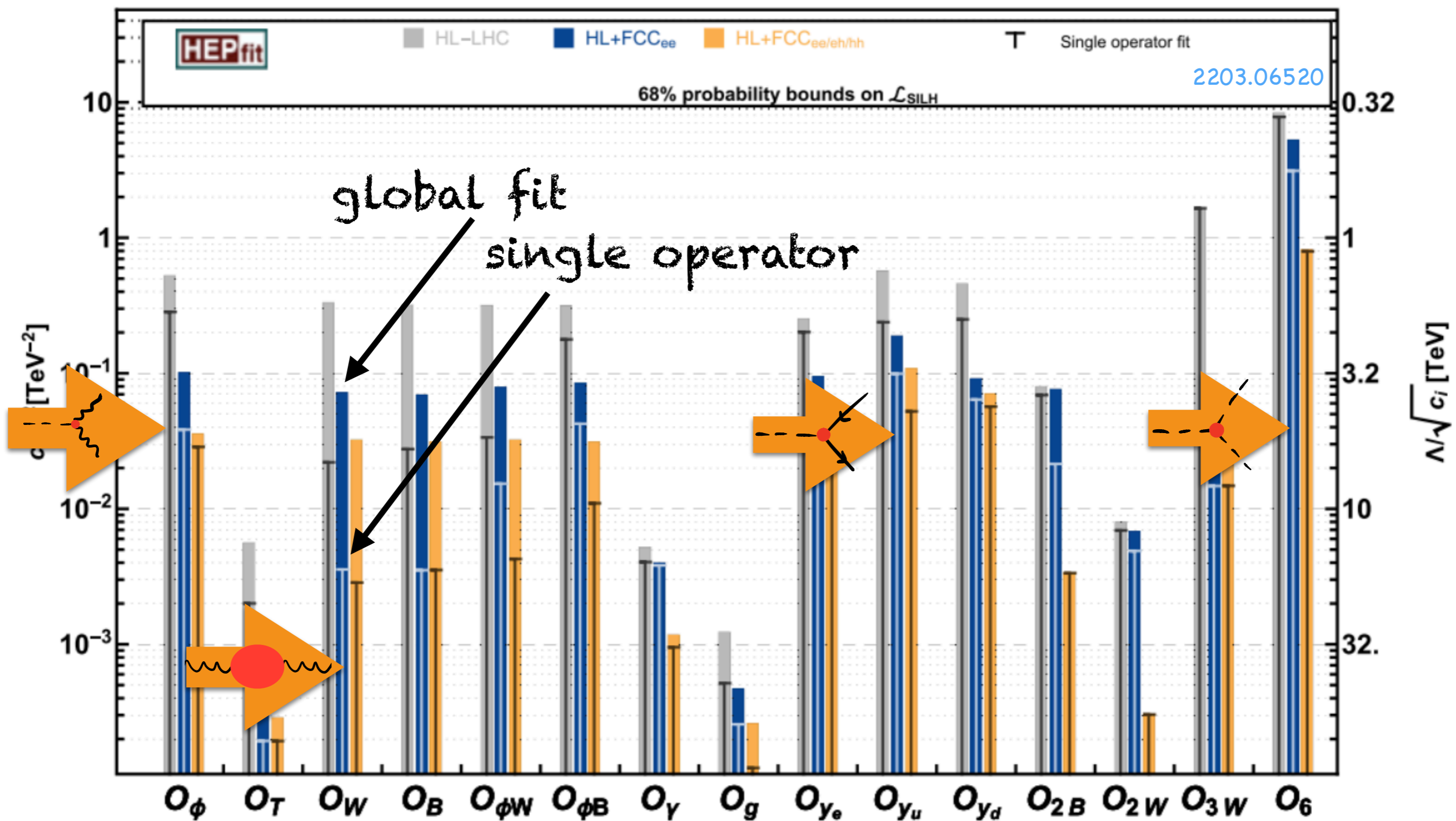
Physics Questions vs Global Fits



Physics Questions vs Global Fits

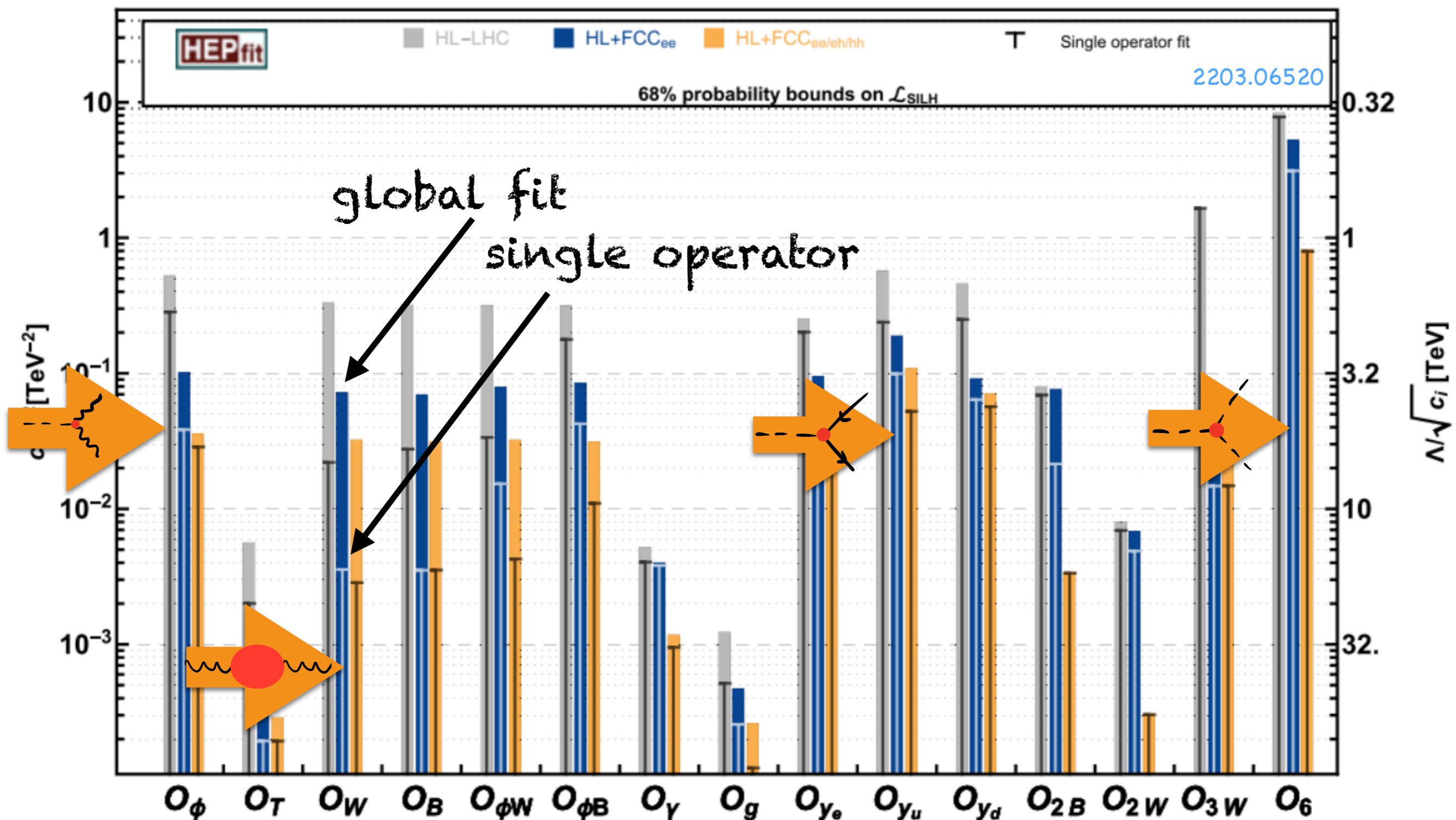


Physics Questions vs Global Fits



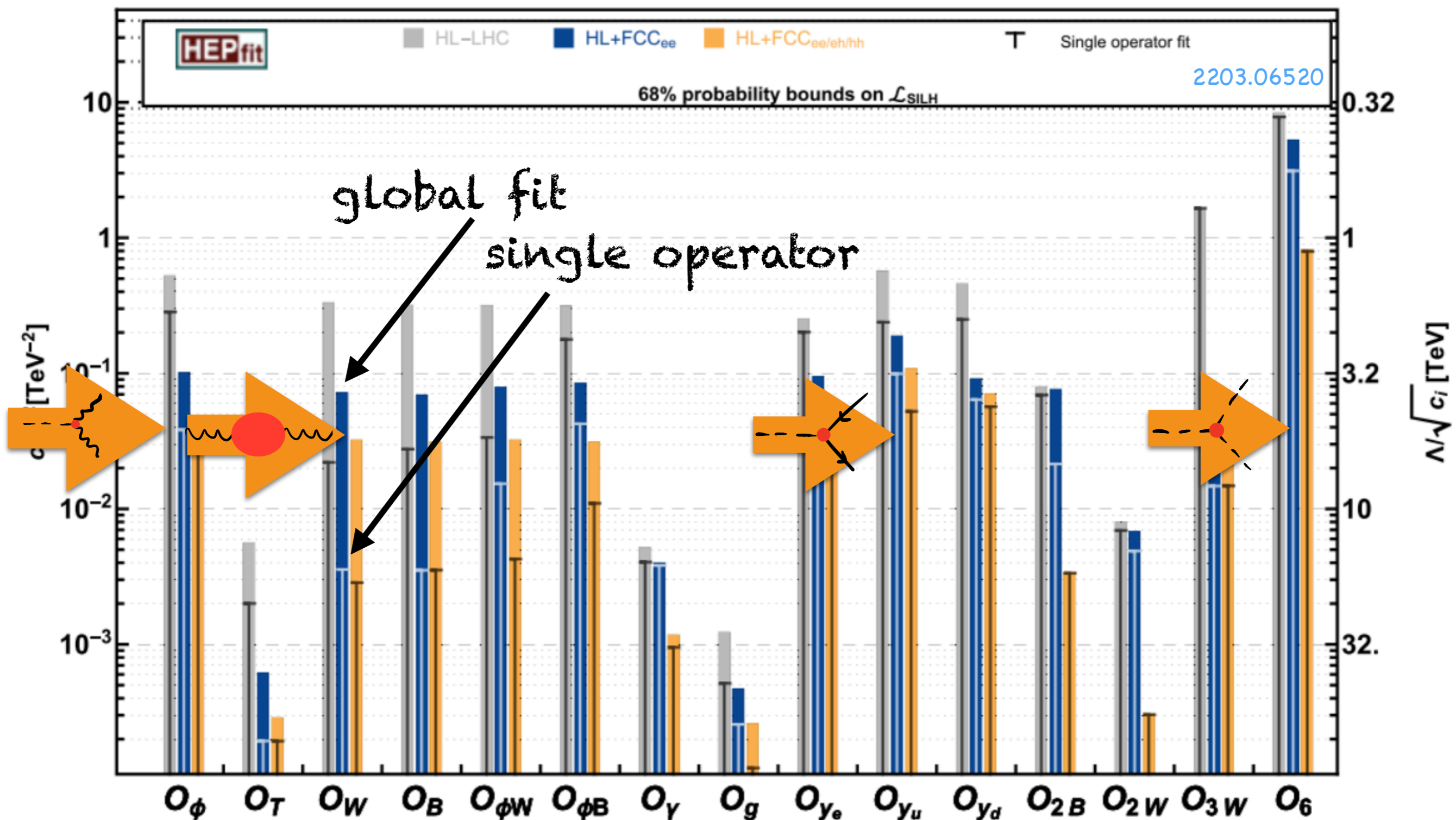
Physics Questions vs Global Fits

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



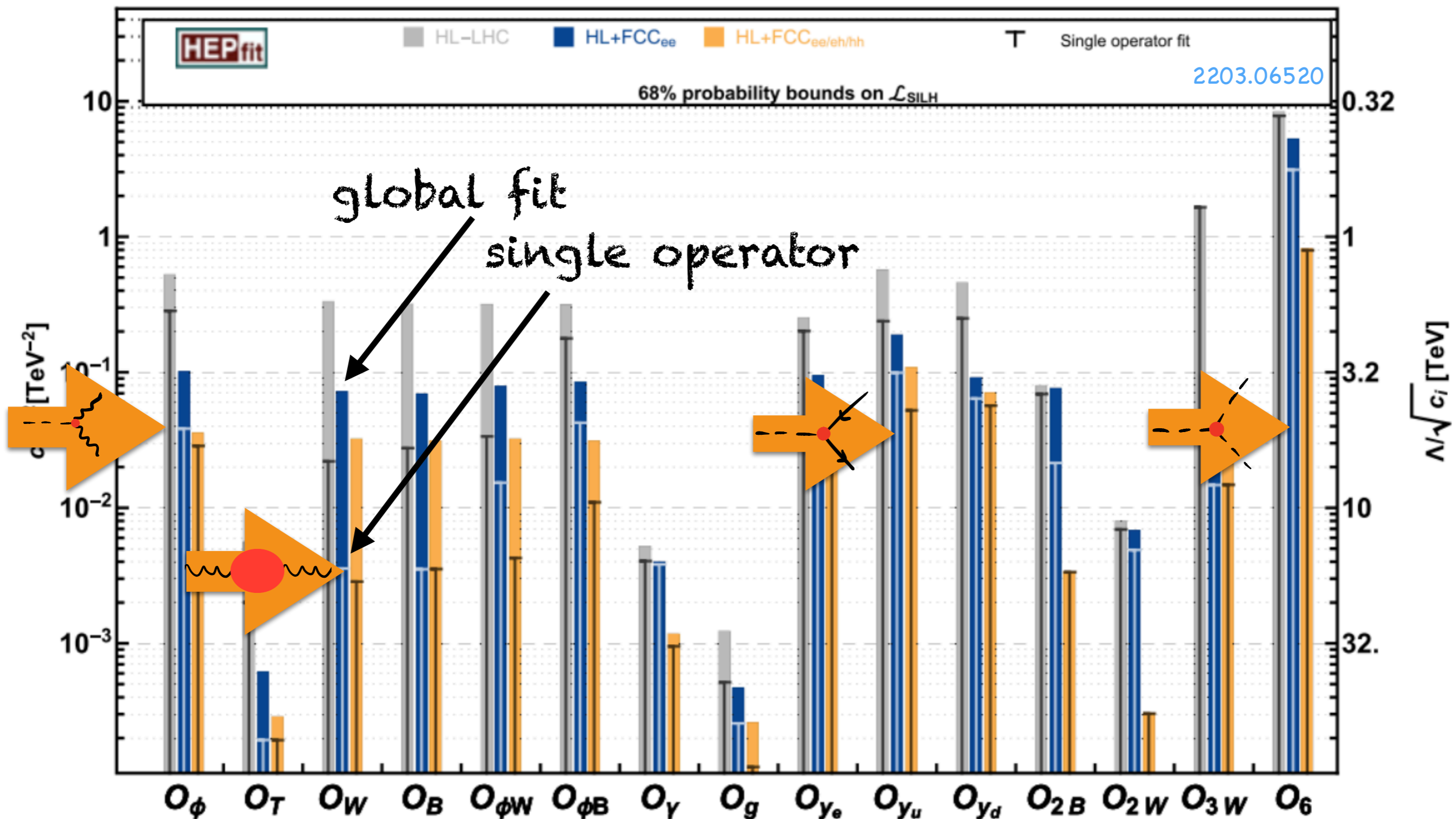
Physics Questions vs Global Fits

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



Physics Questions vs Global Fits

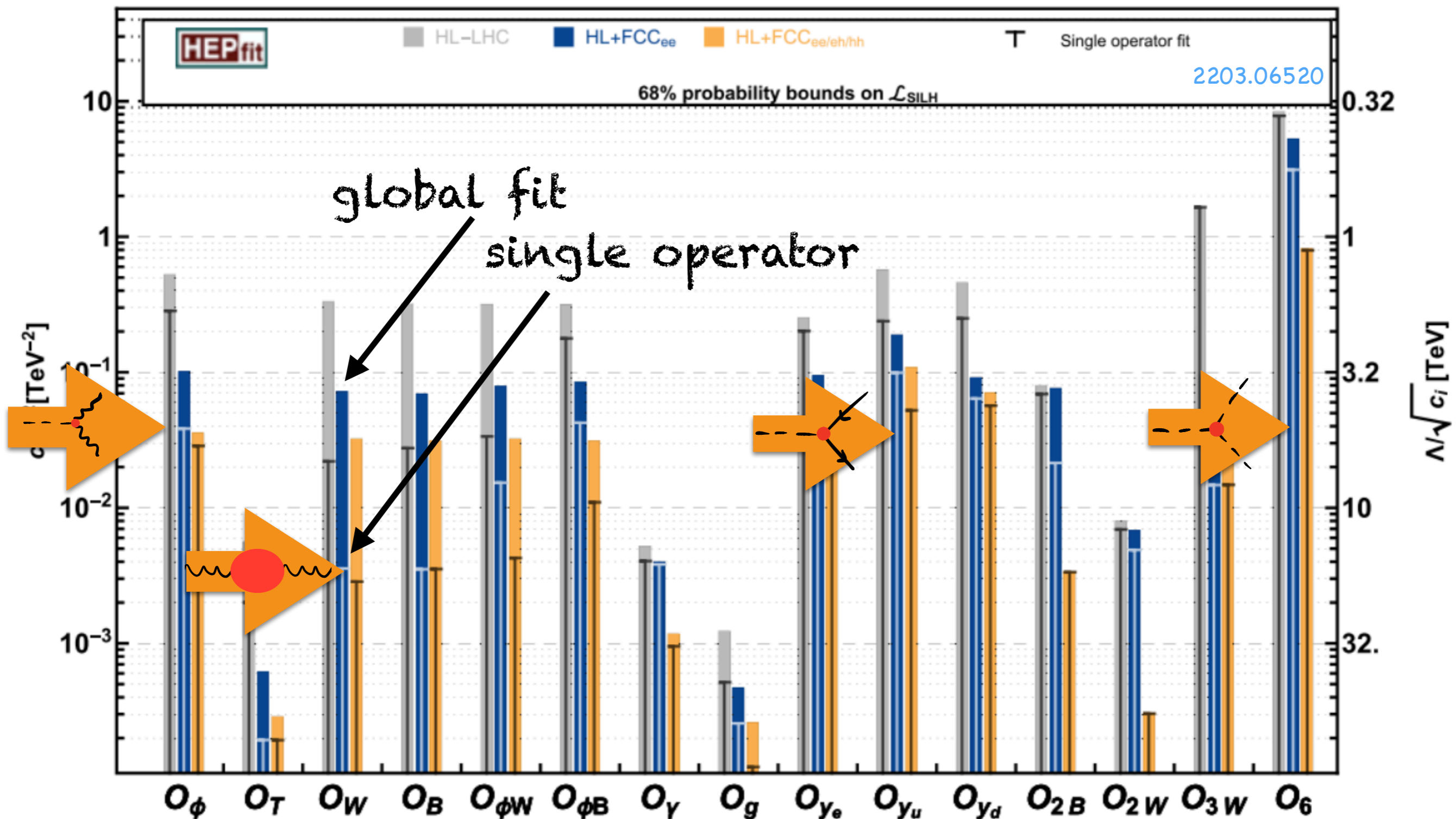
Higgs couplings:
(hZZ)

$$\frac{v^2}{f^2} \lesssim 10^{-3}$$


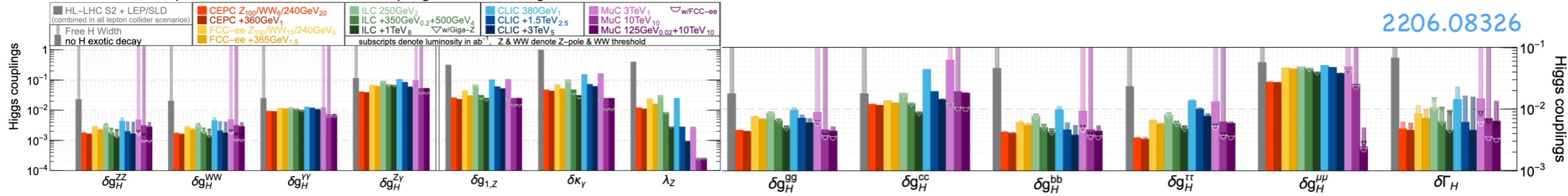
Physics Questions vs Global Fits

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

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

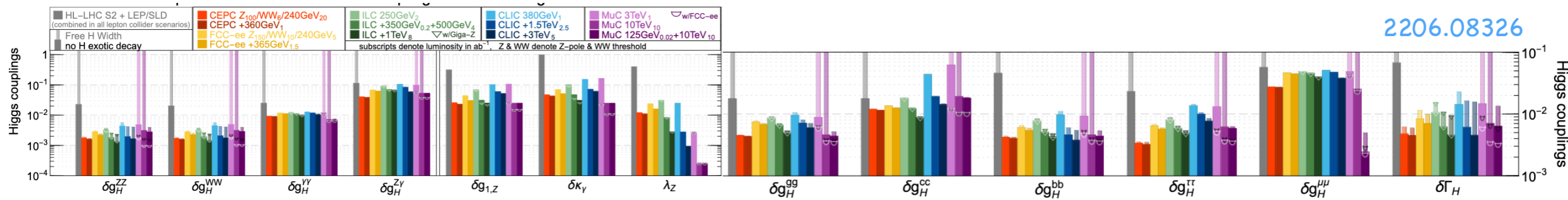


Physics Questions vs Global Fits



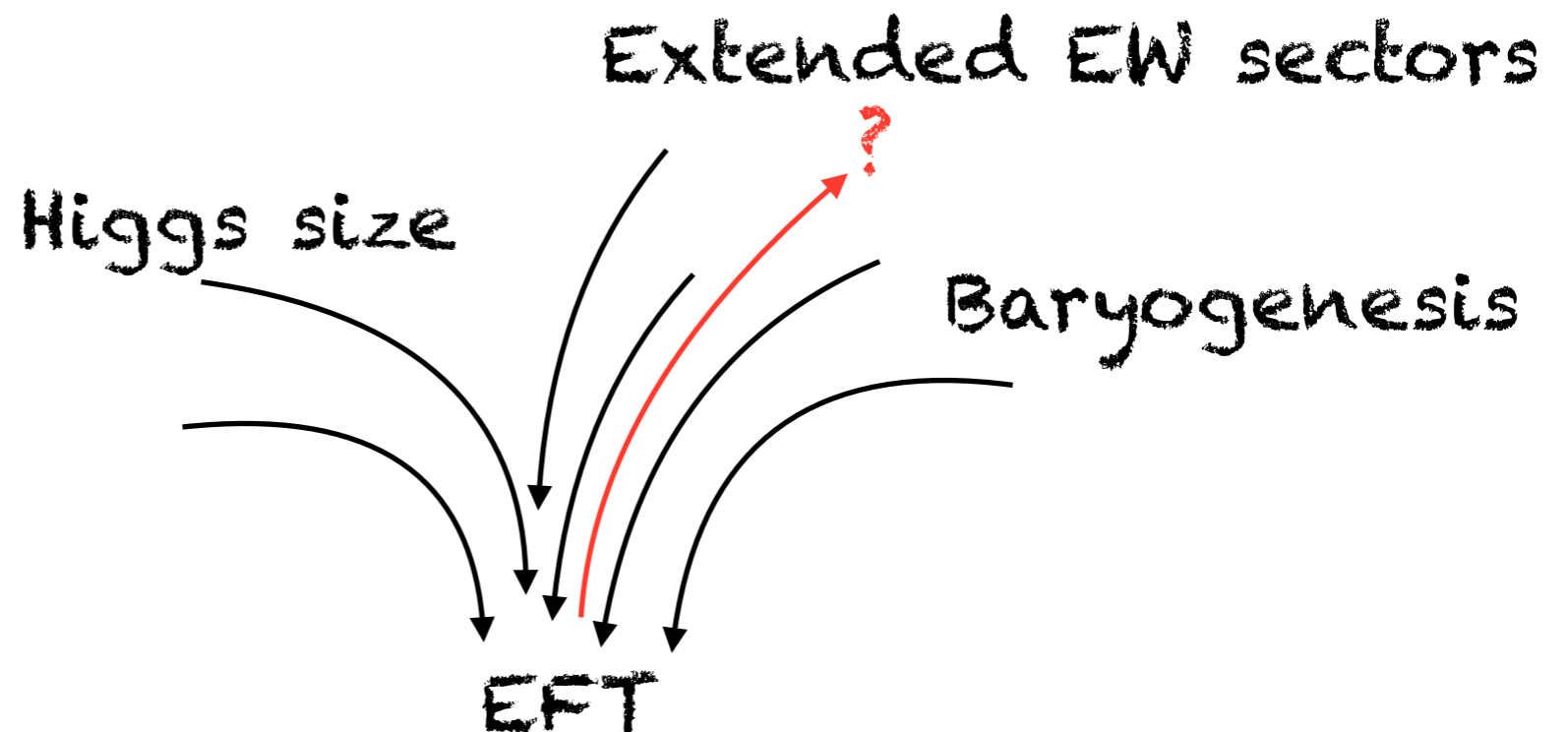
Global fits are important for generic quantitative statements about different machines...

Physics Questions vs Global Fits



Global fits are important for generic quantitative statements about different machines...

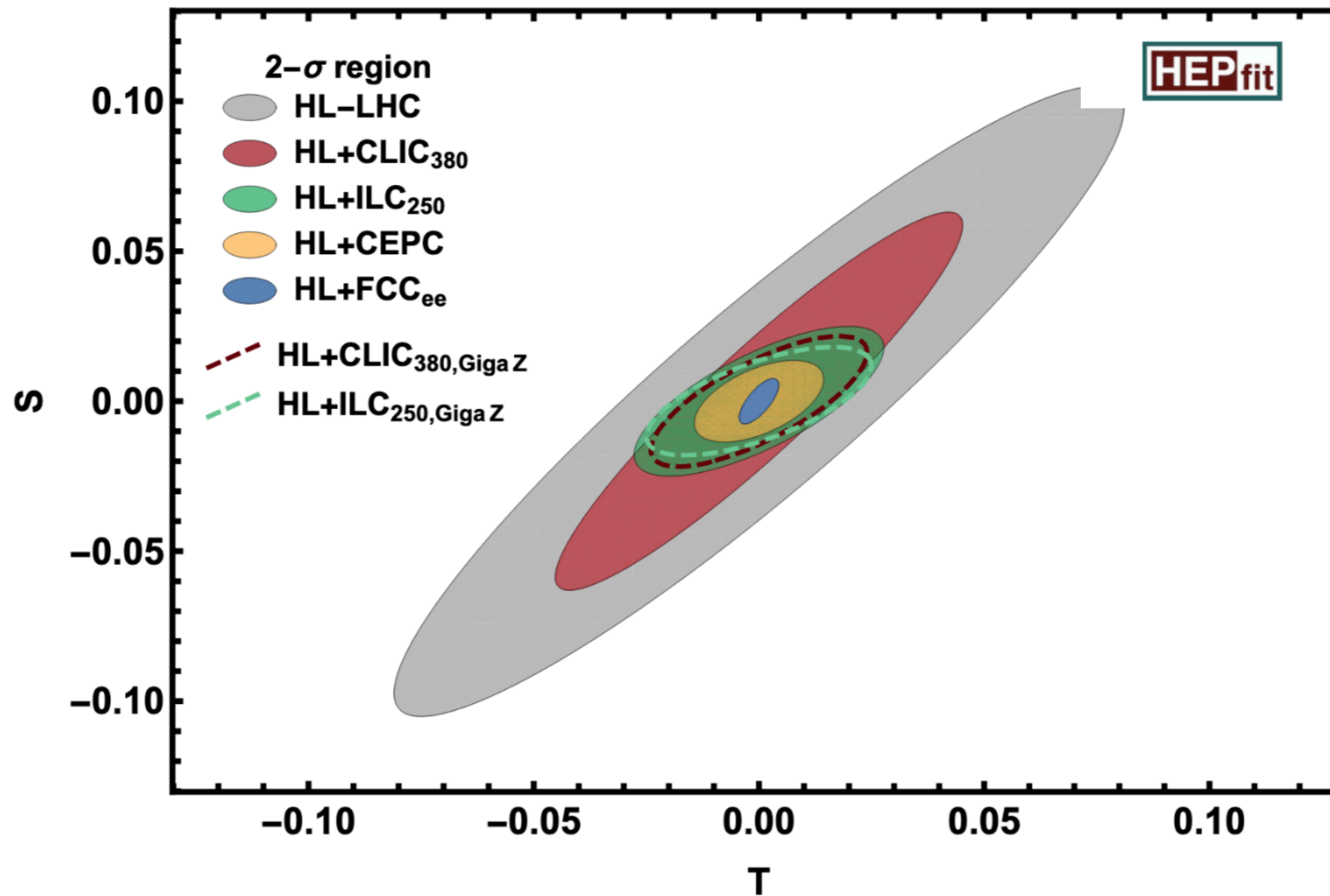
... but have the danger of hiding important hypotheses under too much information



The Z-Boson run and the Higgs

S (and T) parameters:

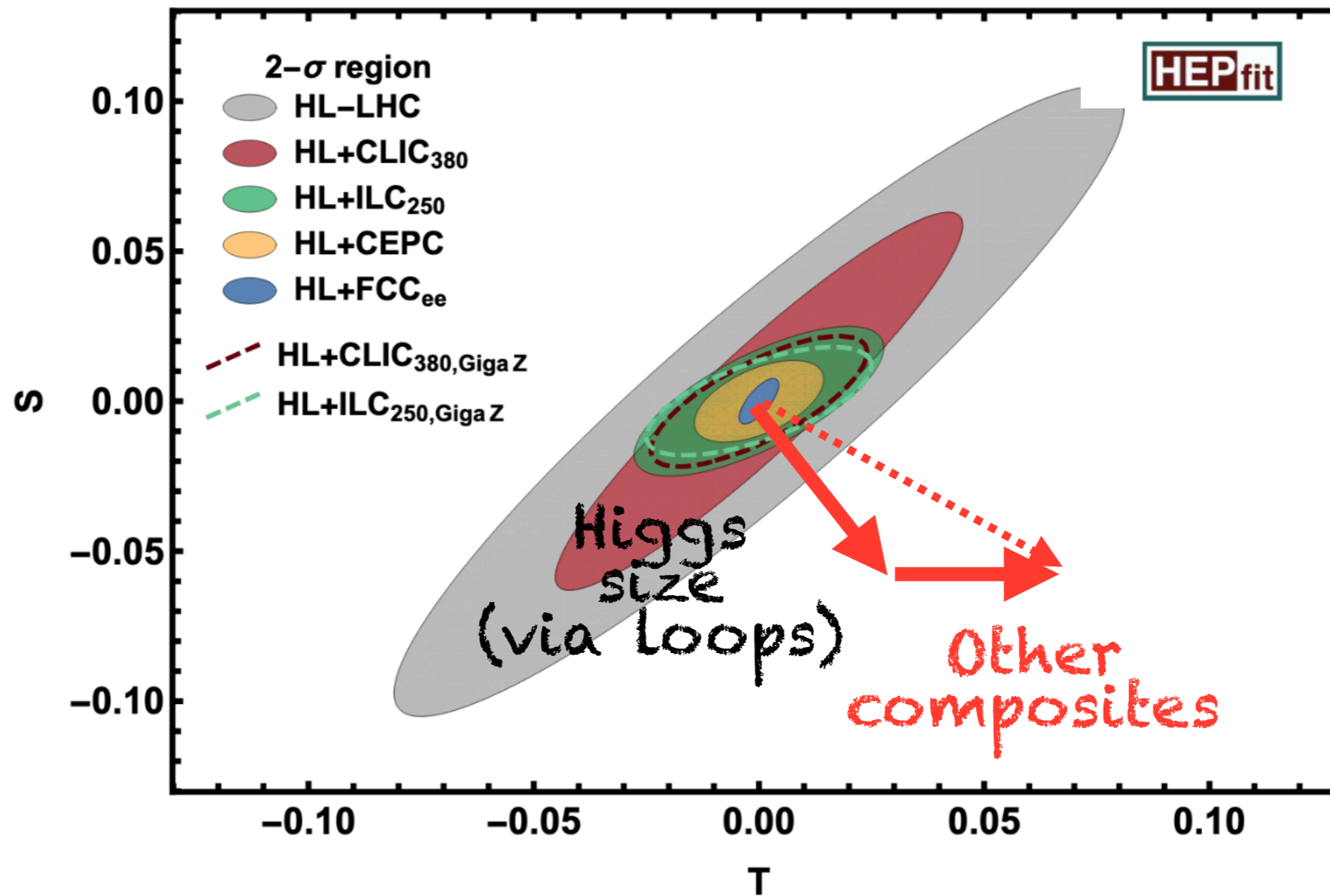
- ▶ best universal tests for EW related physics
- ▶ if it couples to the Higgs it will likely enter in S,T



The Z-Boson run and the Higgs

S (and T) parameters:

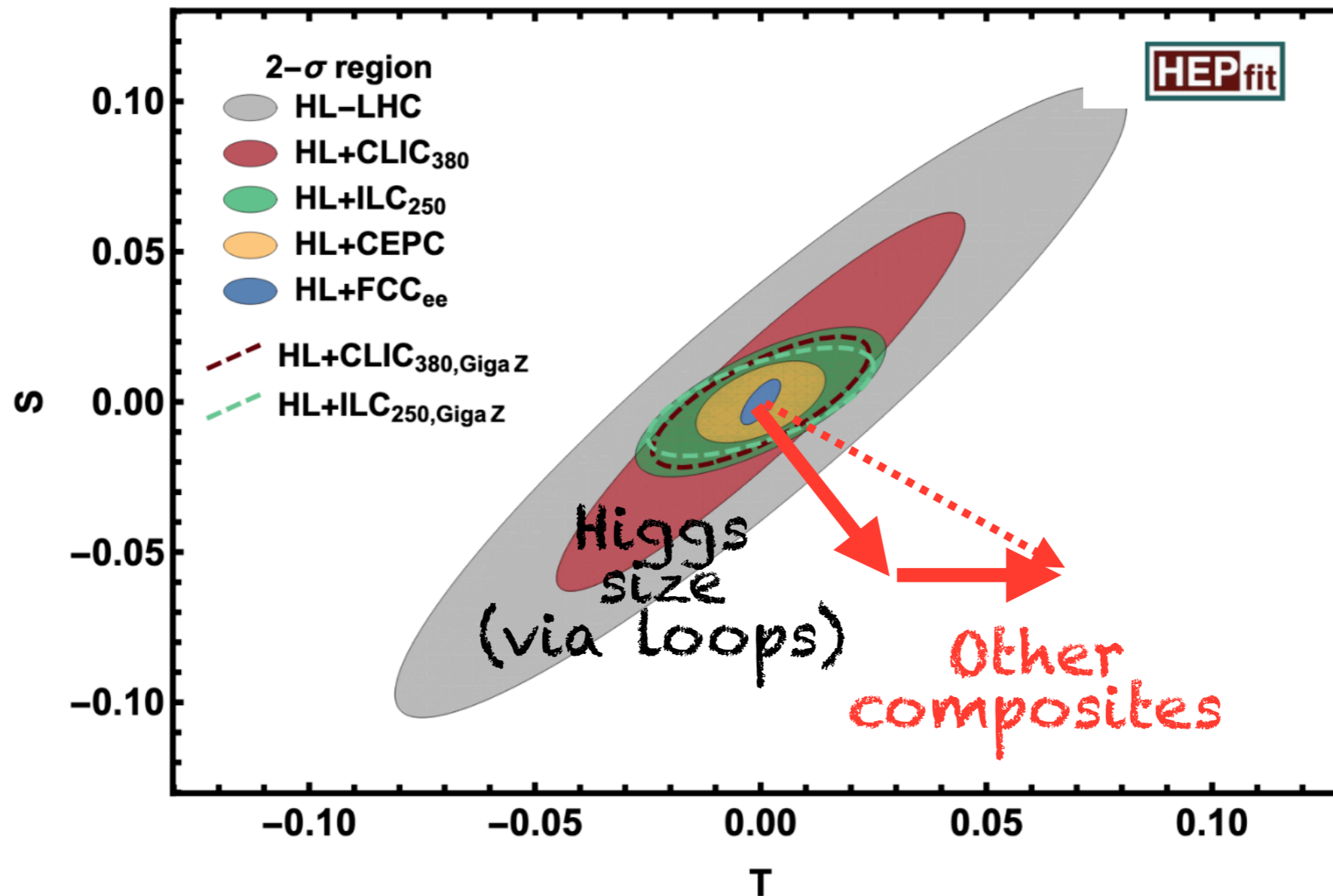
- ▶ best universal tests for EW related physics
- ▶ if it couples to the Higgs it will likely enter in S,T



The Z-Boson run and the Higgs

S (and T) parameters:

- ▶ best universal tests for EW related physics
- ▶ if it couples to the Higgs it will likely enter in S,T



- ▶ A Z-pole run is crucial!

summary

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

summary

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

For sure: we will **learn** about particles size
- especially Higgs -

summary

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

For sure: we will **learn** about particles size
- especially Higgs -

Specific models that implement specific **hypothesis** (e.g. finite Higgs radius) require subsets of measurements

summary

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

For sure: we will **learn** about particles size
- especially Higgs -

Specific models that implement specific **hypothesis** (e.g. finite Higgs radius) require subsets of measurements

Z-Pole run will teach us much about the Higgs, as well

Social Experiment

Pollev.com/francescoriva506



How much are you excited by the physics of FCs?

I'm willing to invest 25 years of my life fully on one of these projects (or would like my children to)

I'm willing to invest 25 years of my life partially (e.g. in parallel with other experiments)

I want a job in HEP, no matter the specific context

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

FCC-hh

Outreach - TUTTI QUANTUM



phdcomics.com

2020

2030

2040

2050

2060

2070

2080

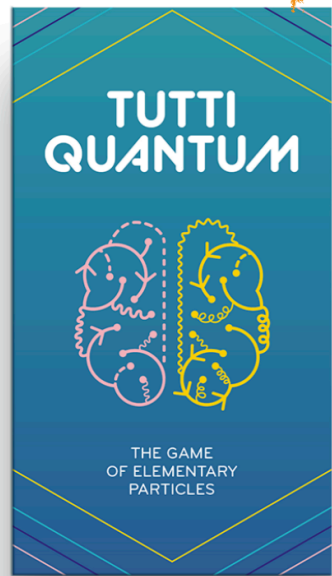
2090

2100

LHC & HL-LHC

FCC-ee

FCC-hh



8-99 2-4 15' 48

Outreach - TUTTI QUANTUM



phdcomics.com

2020

2030

2040

2050

2060

2070

2080

2090

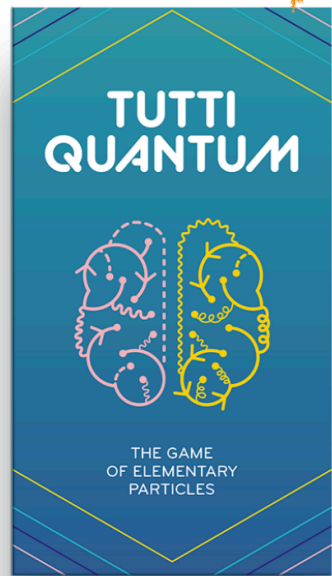
2100

LHC & HL-LHC

FCC-ee

FCC-hh

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



Outreach - TUTTI QUANTUM



phdcomics.com

2020

2030

2040

2050

2060

2070

2080

2090

2100

LHC & HL-LHC

FCC-ee

FCC-hh

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)

