FCC and the Physics Landscape

G.F. Giudice

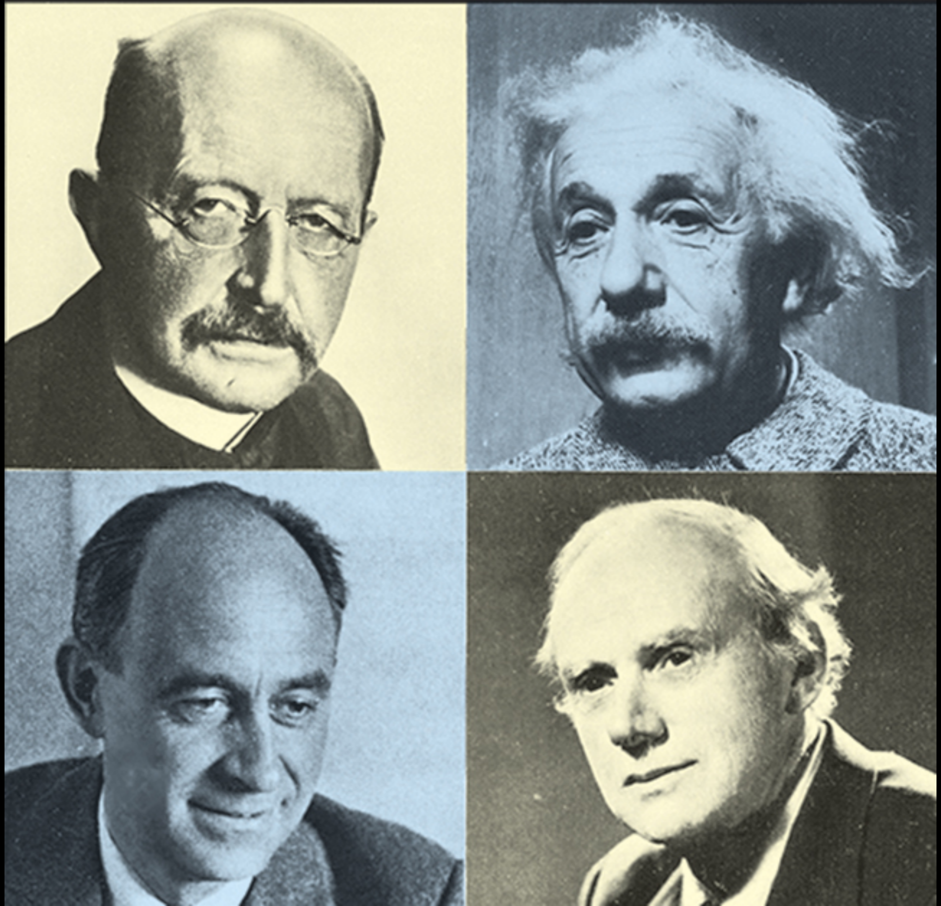
SOTTO L'ALTO PATRONATO DEL PRESIDENTE DELLA REPUBBLICA

UNDER THE HIGH PATRONAGE OF THE PRESIDENT OF THE ITALIAN REPUBLIC

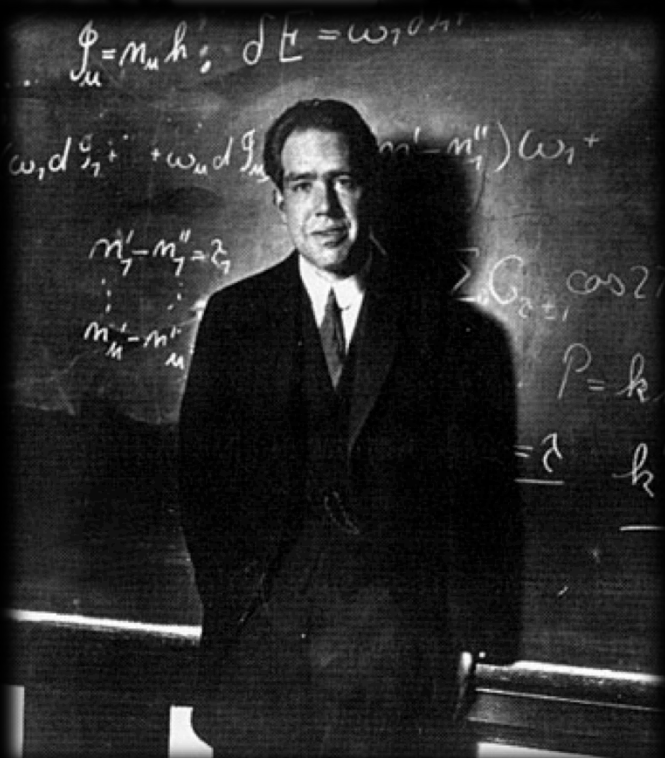
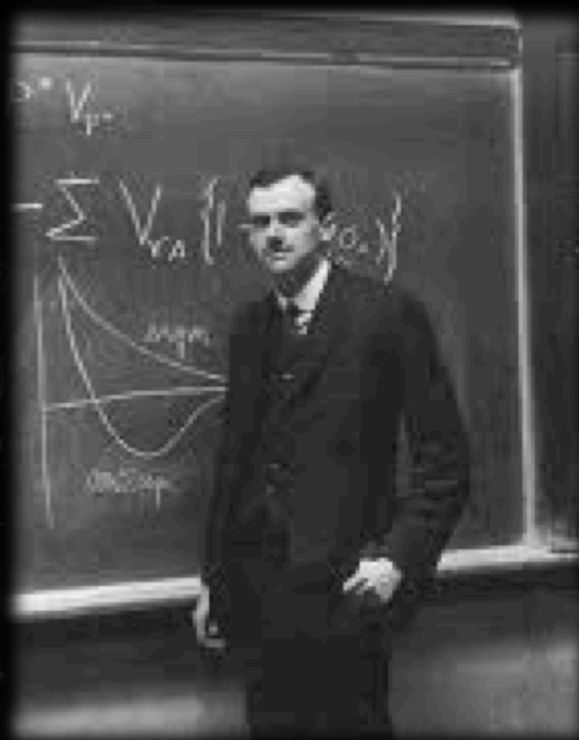
George Gamow

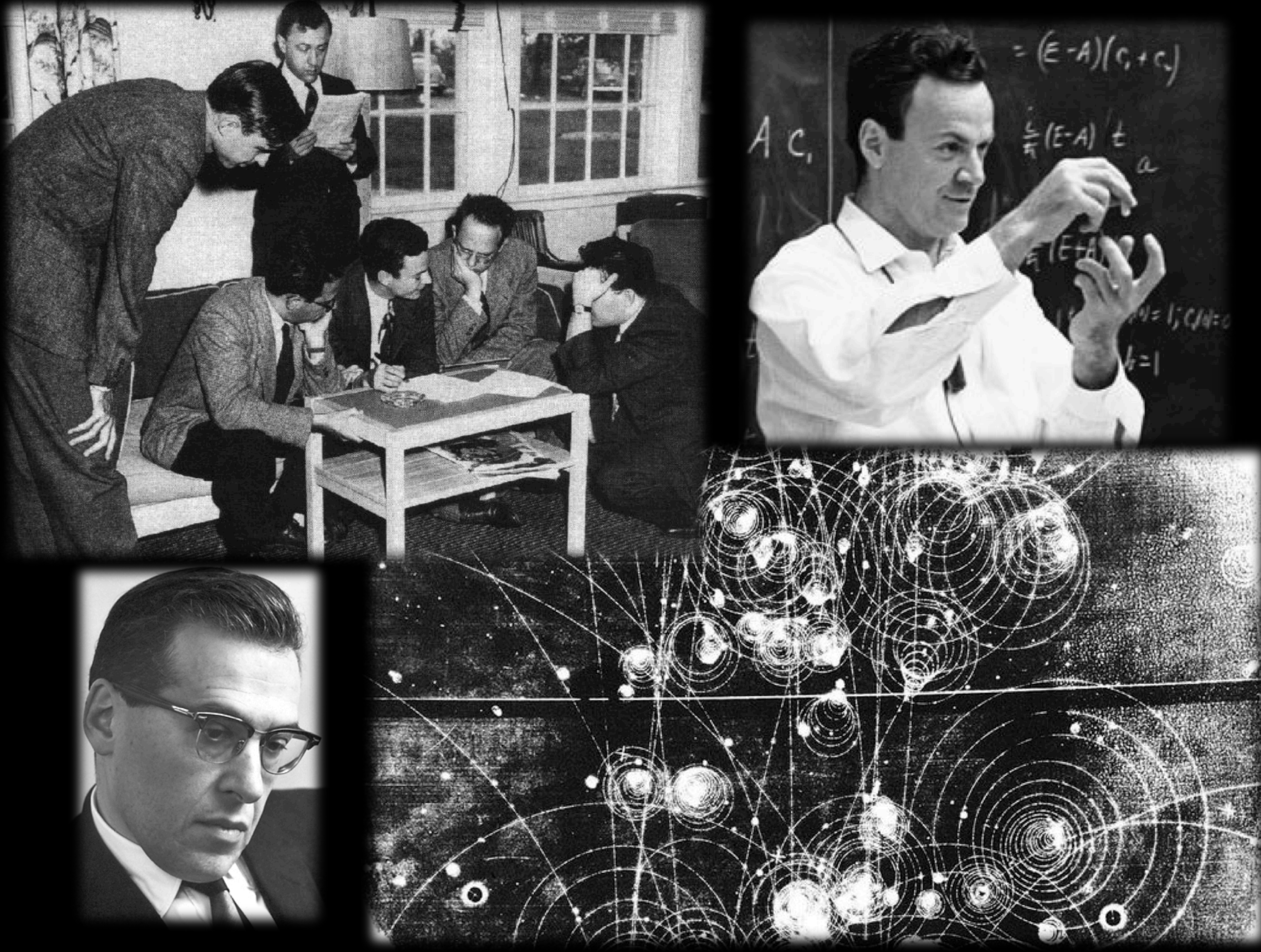
THIRTY YEARS THAT SHOOK PHYSICS

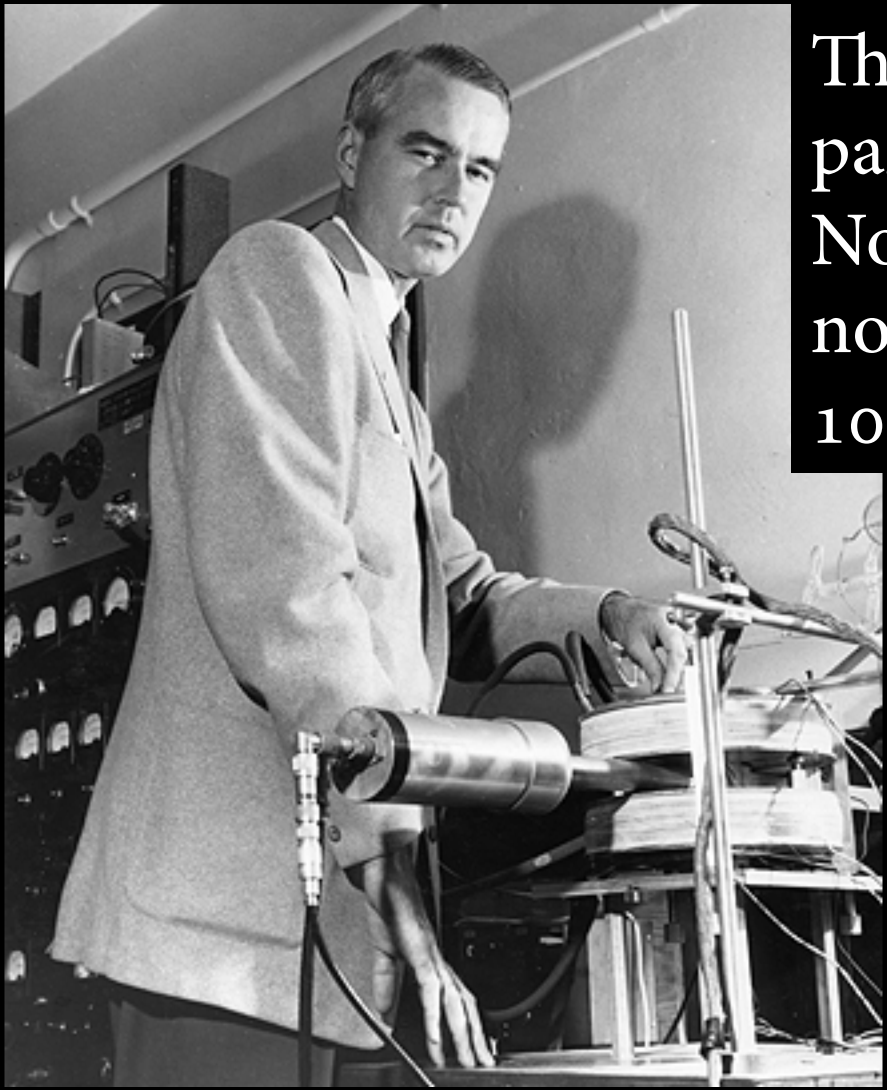
The Story of Quantum Theory





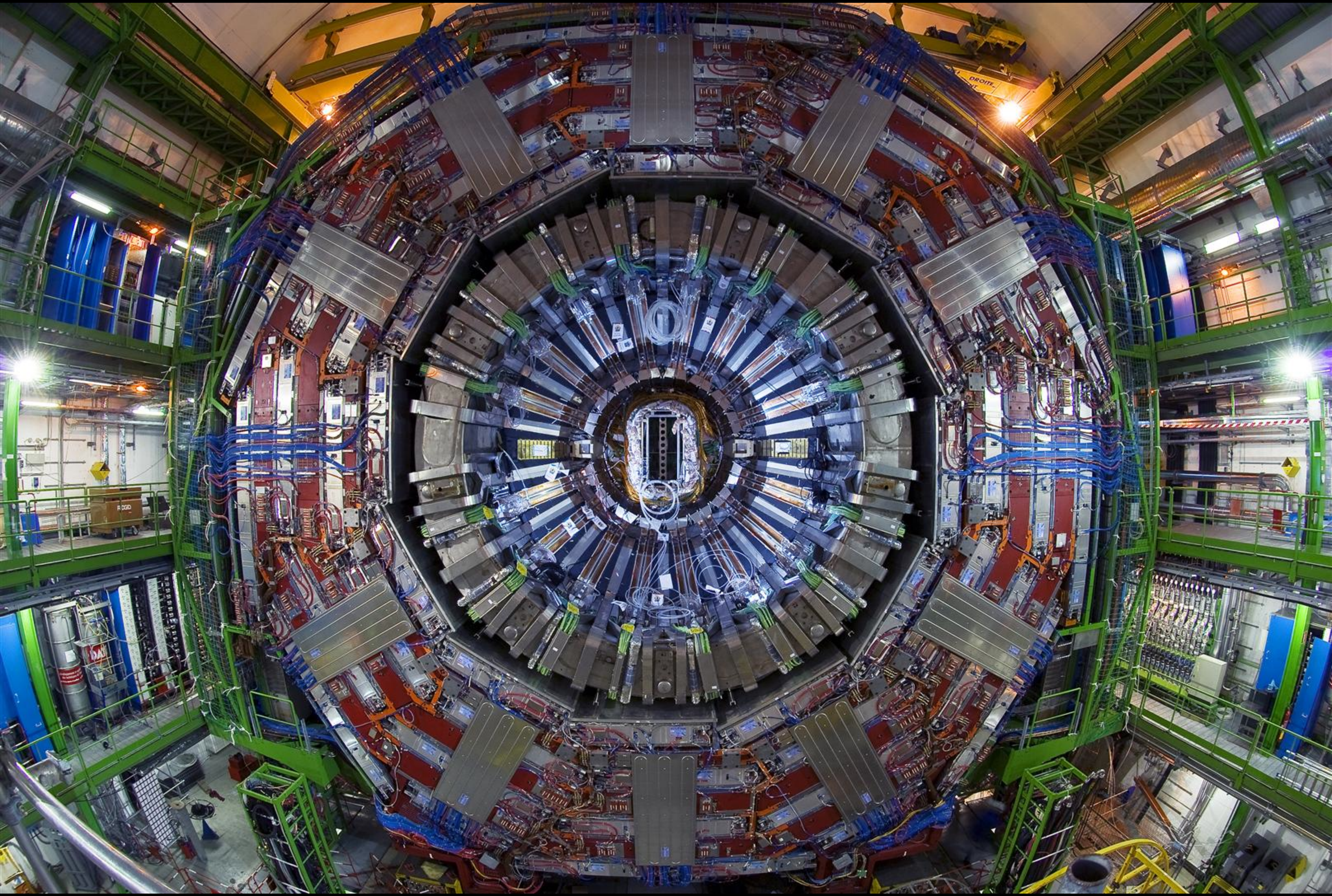



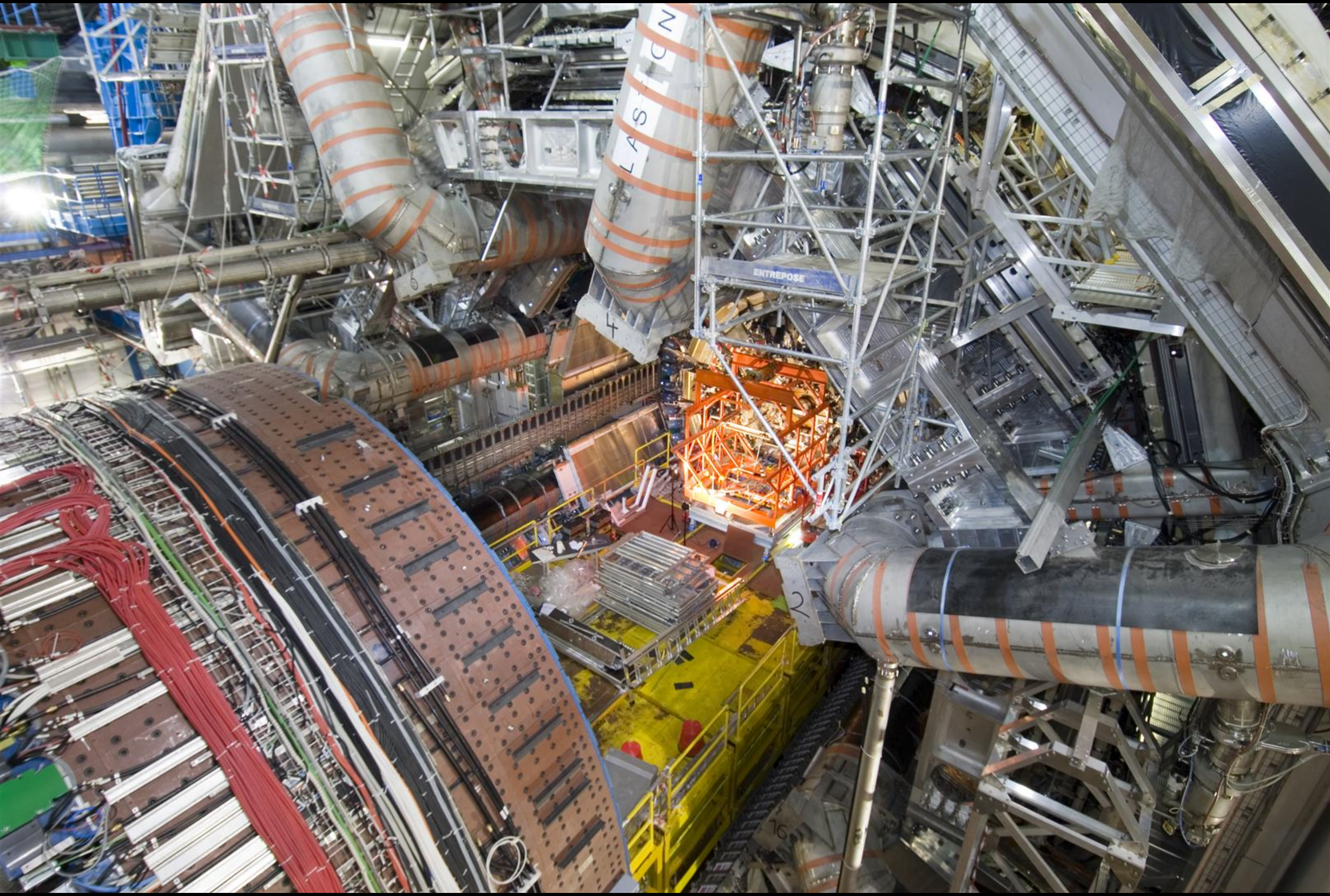





The finder of a new elementary particle used to be rewarded by a Nobel Prize, but such a discovery now ought to be punished by a 10,000 dollar fine.

Willis Lamb

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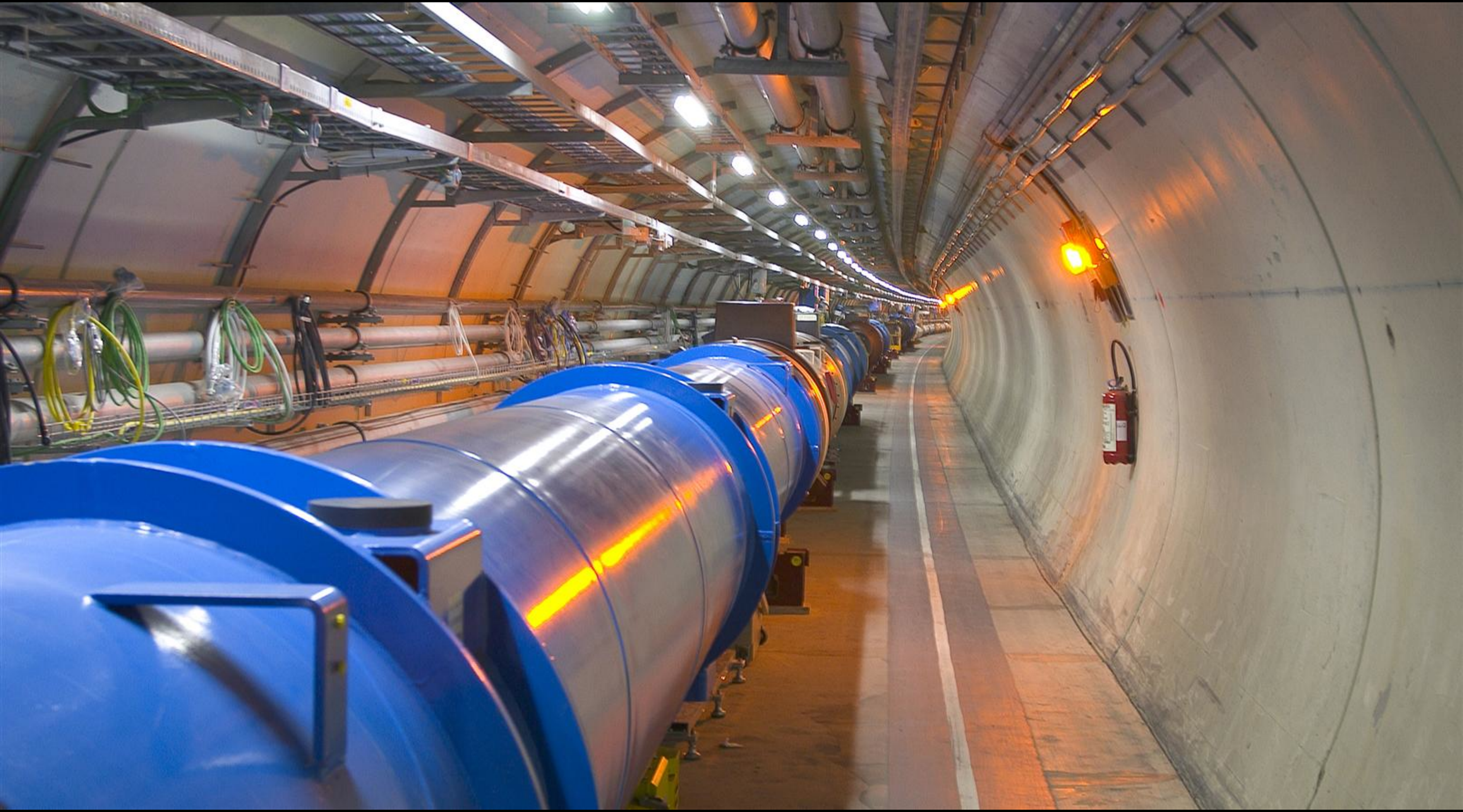


LHC Run 1 taught us that we live in a metastable state

I don't refer to the EW vacuum,
but to the HEP community

Confusion is the best moment in science

Many of our past expectations have been shattered

Naturalness as guiding principle

Technicolor → no fundamental Higgs

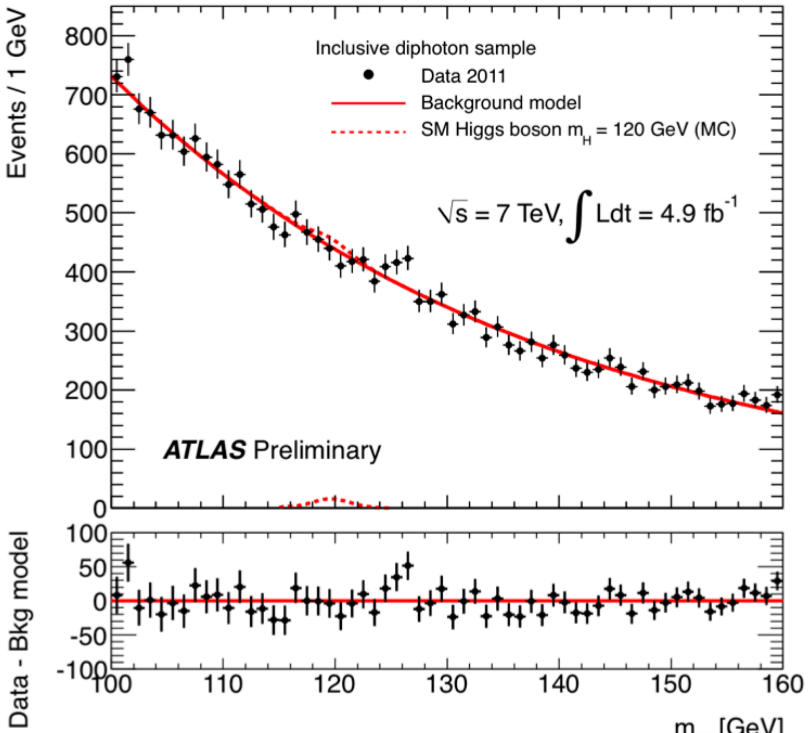
Supersymmetry → $m_h \lesssim 120$ GeV, $\tilde{m}_t \lesssim 300$ GeV, $\tilde{m}_g \lesssim 1$ TeV

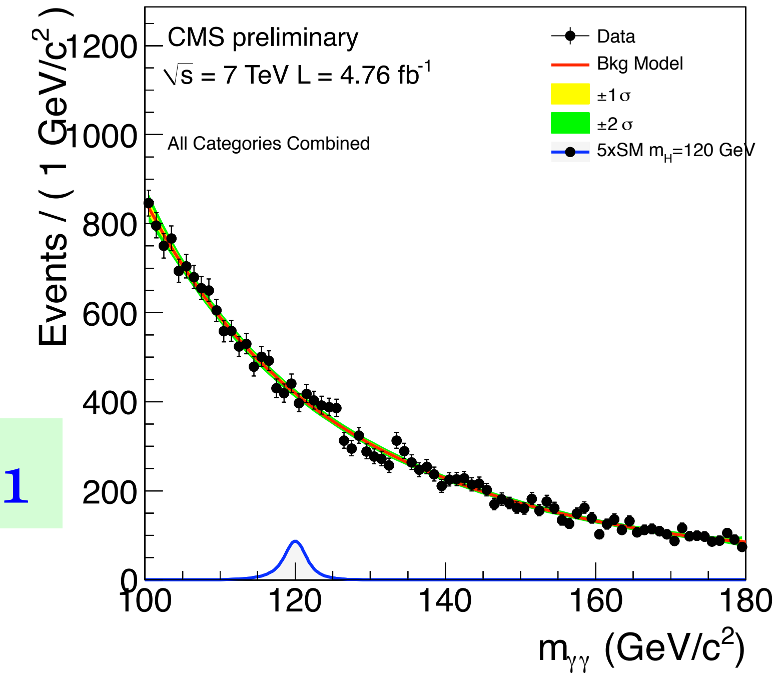
Extra dimensions → hell breaks loose at TeV

Composite Higgs → $\Delta \mathrm{BR}_h \sim O(1)$

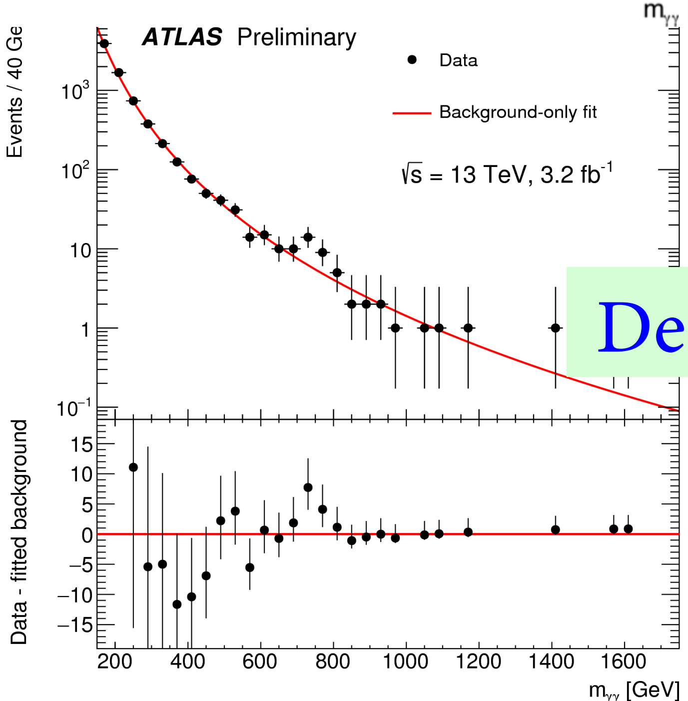
Change of paradigm?

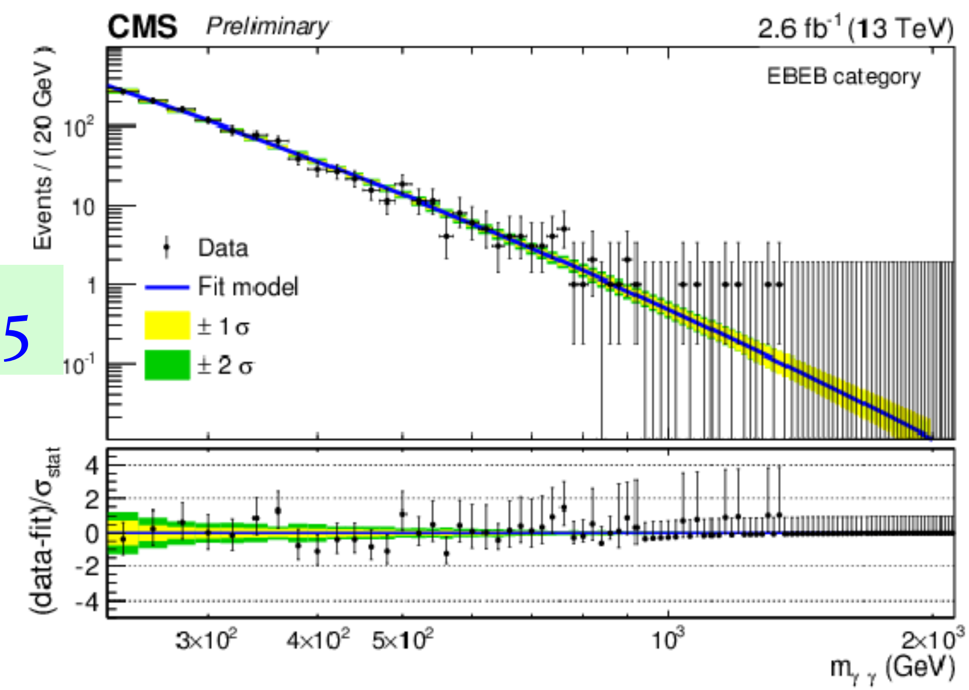
The epiphany of a new era...





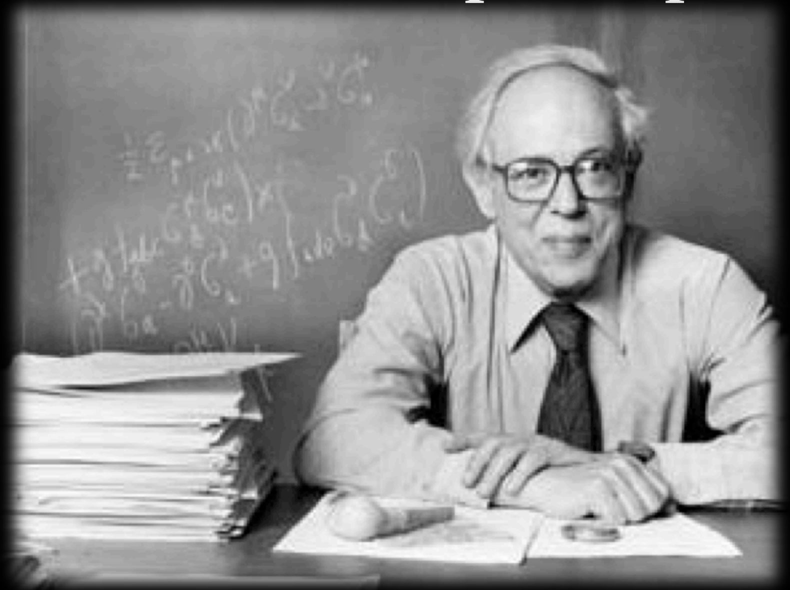
Dec 2011





Dec 2015

Today we live in the midst of upheaval and crisis. We do not know where we are going, nor even where we ought to be going. Awareness is spreading that our future cannot be a straight extension of the past or the present. [...] Progress leads to confusion leads to progress and on and on without respite. Every one of the many major advances [...] created sooner or later, more often sooner, new problems. These confusions, never twice the same, are not to be deplored. Rather, those who participate experience them as a privilege.

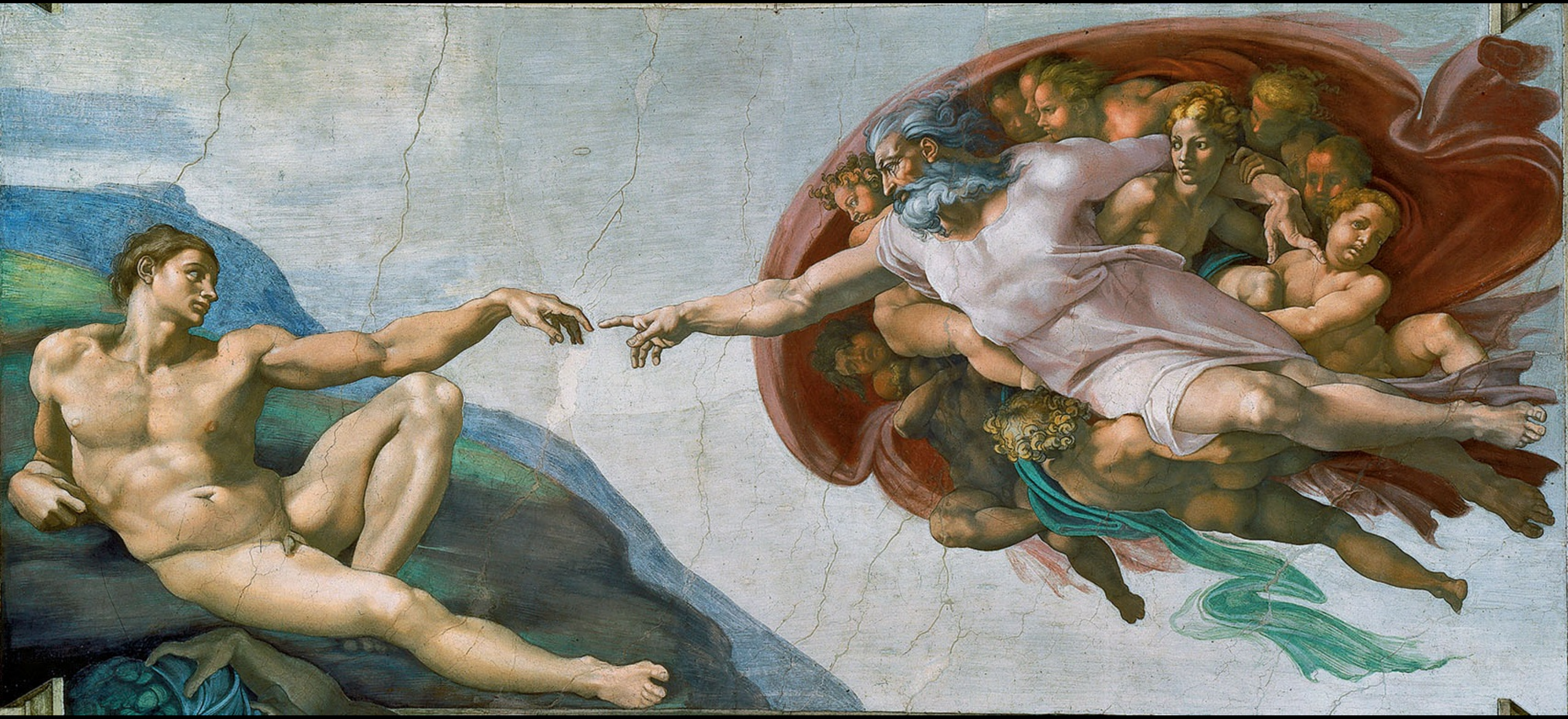


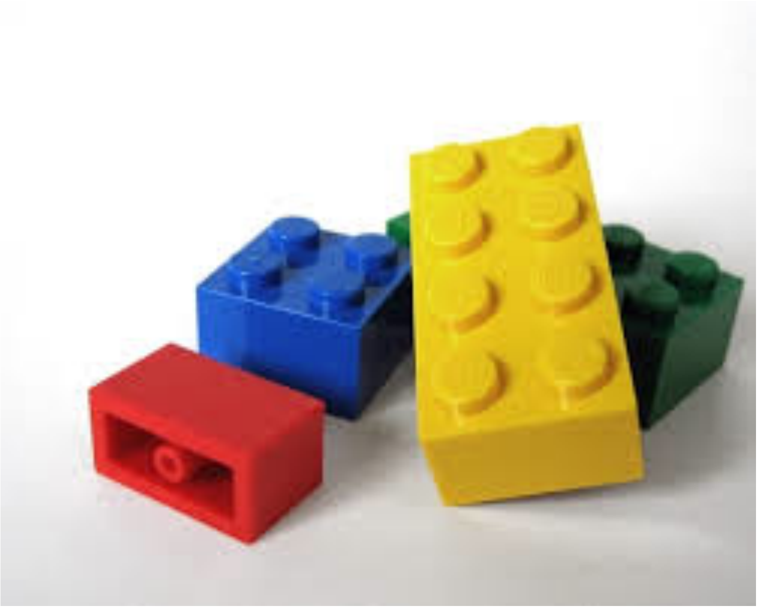
Abraham Pais

The privilege of being in a state of confusion

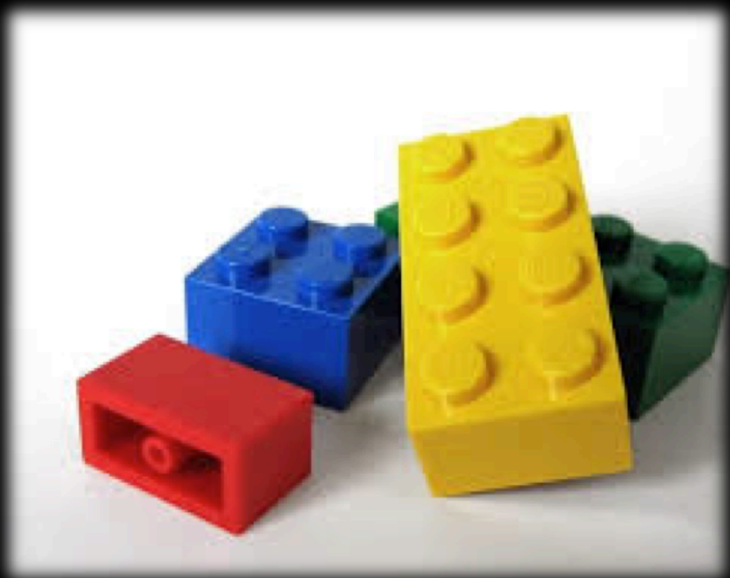
Where are we in particle physics?

Gauge quantum field theory





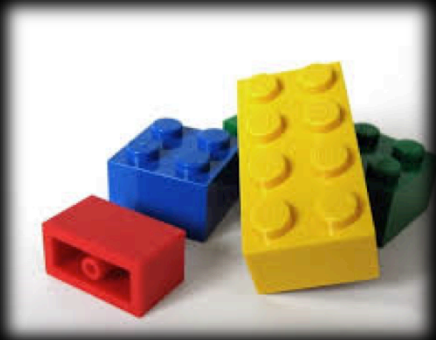
simplicity or complexity



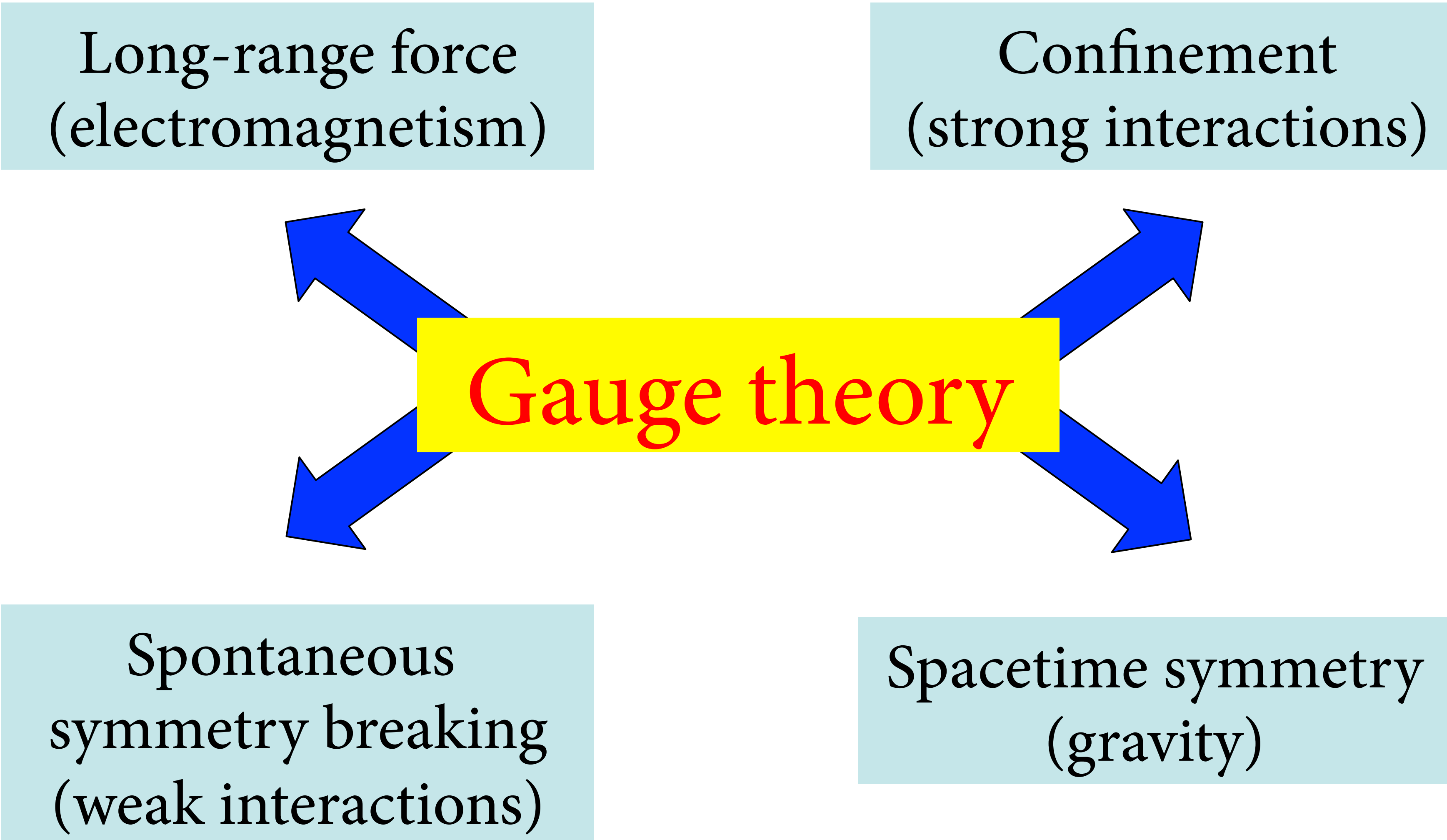
?

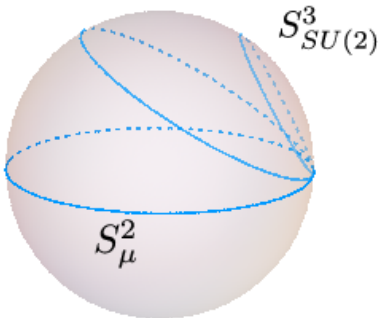
Gauge quantum field theory

logical simplicity

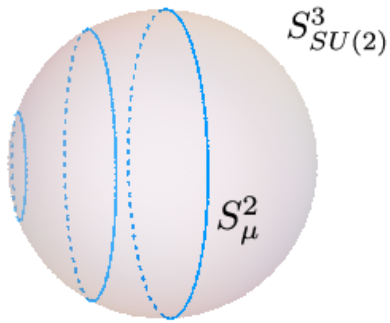


emergent complexity

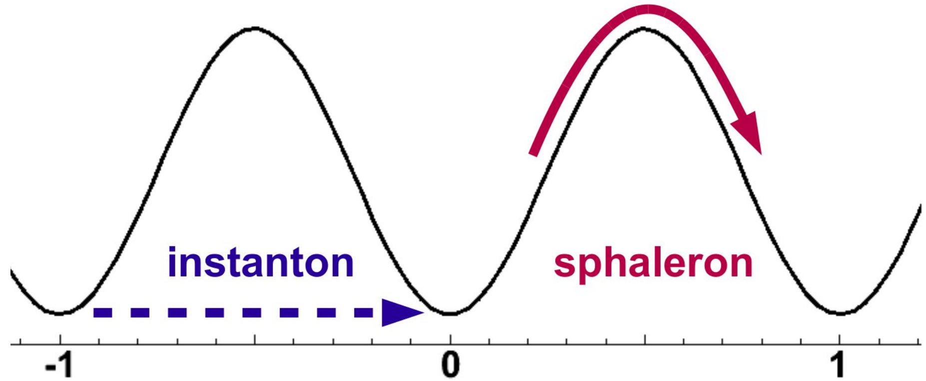

Long-range force
(electromagnetism)
Confinement
(strong interactions)
Gauge theory
Spontaneous
symmetry breaking
(weak interactions)
Spacetime symmetry
(gravity)

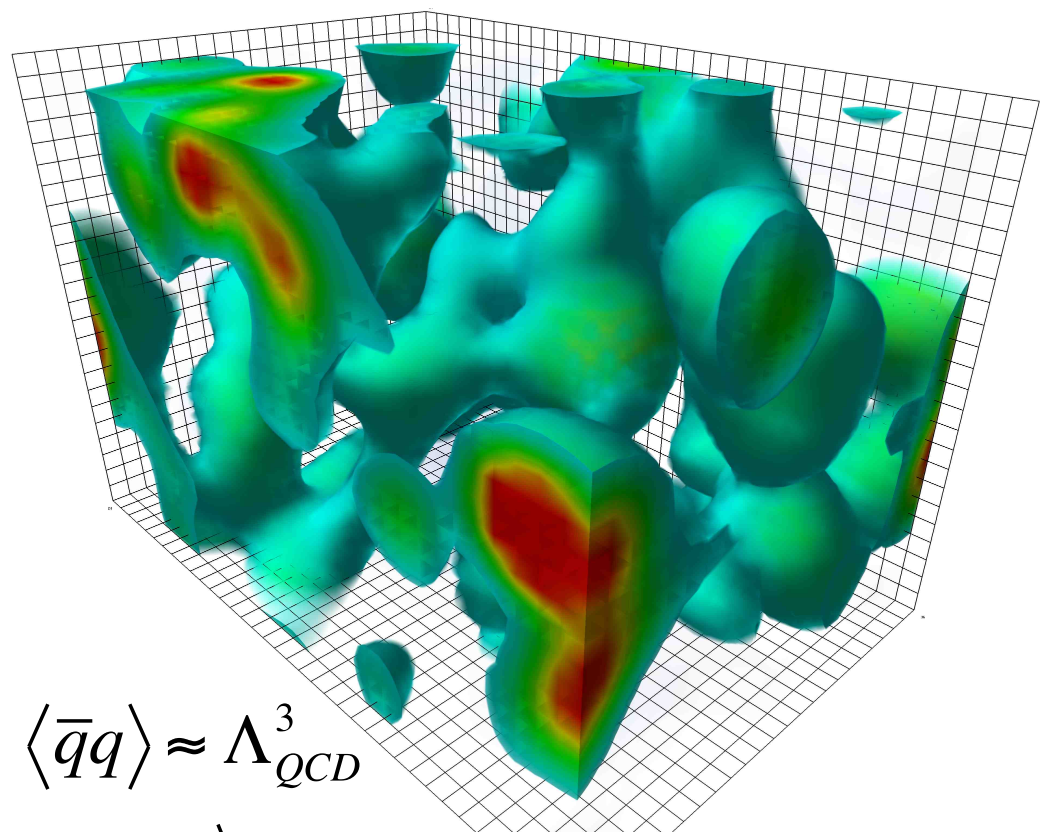


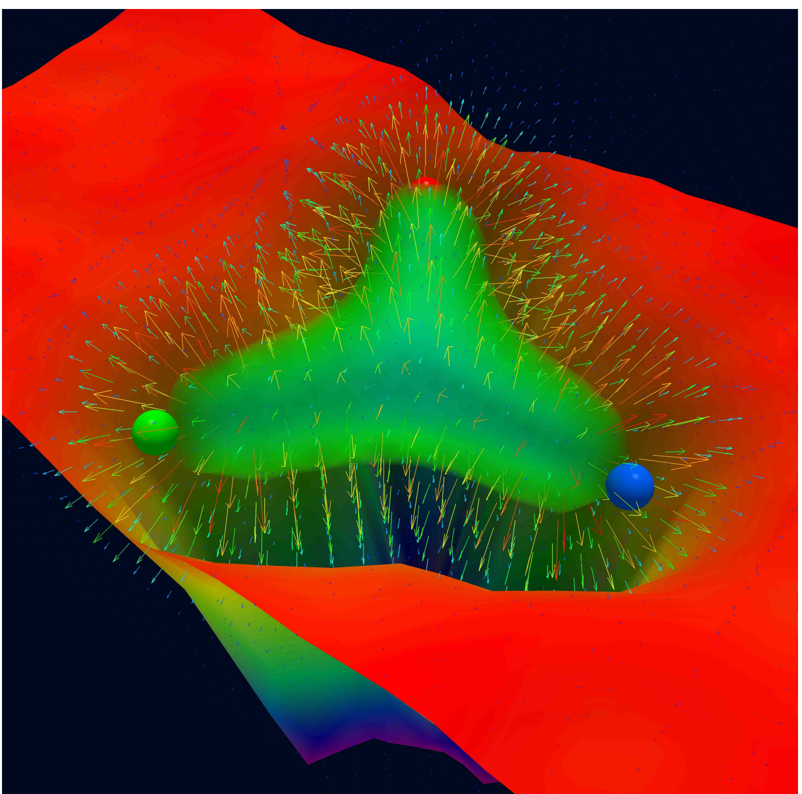
(a)



(b)

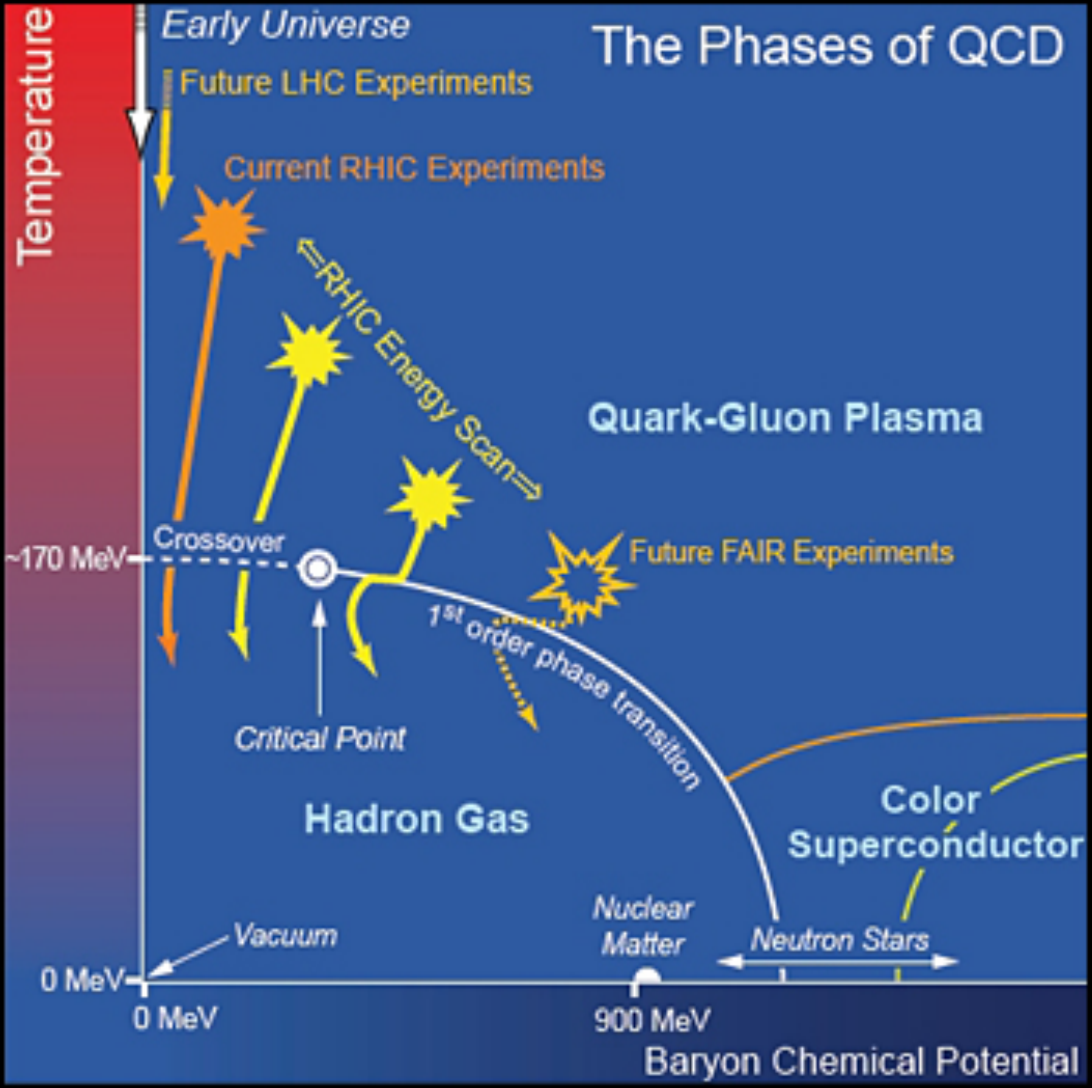






$$\langle \bar{q} q \rangle \approx \Lambda^3_{QCD}$$

$$\langle G^a_{\mu\nu} G^{a\mu\nu} \rangle \approx \Lambda^4_{QCD}$$



The Phases of QCD
Temperature
Early Universe
Future LHC Experiments
Current RHIC Experiments
⇐RHIC Energy Scan⇒
Quark-Gluon Plasma
Future FAIR Experiments
~170 MeV
Crossover
1st order phase transition
Critical Point
Hadron Gas
Color Superconductor
Nuclear Matter
Neutron Stars
Vacuum
0 MeV
0 MeV
900 MeV
Baryon Chemical Potential

Gauge sector $L = i\bar{\psi}\gamma^{\mu}D_{\mu}\psi - \frac{1}{2}F_{\mu\nu}F^{\mu\nu}$

Higgs sector

$$L = \left(h_{ij}\bar{\psi}_i\psi_j H + \text{h.c.}\right) - \lambda\left|H\right|^4 + \mu^2\left|H\right|^2 - \Lambda_{CC}^4$$

Non-gauge fundamental forces!

Flavor puzzle

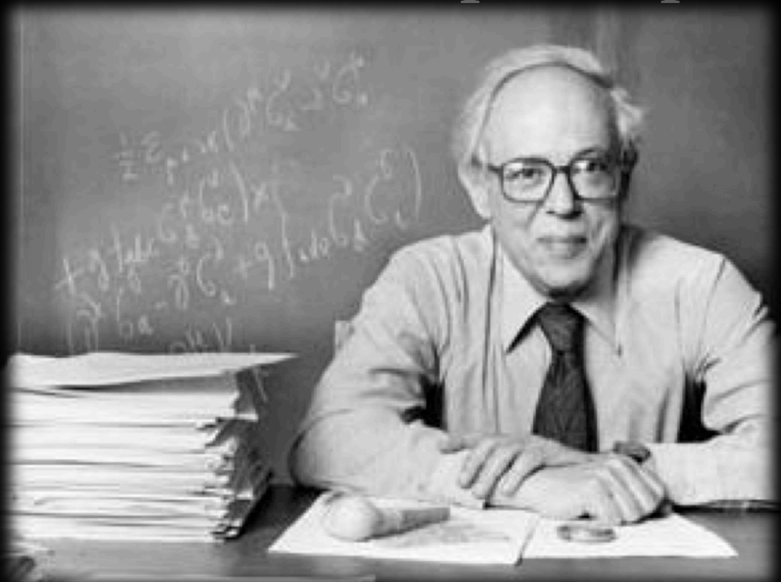
Stability of the potential

Naturalness problem

Cosmological constant problem


gravity
electro
magn.
Higgs
weak
force
strong
force

Today we live in the midst of upheaval and crisis. We do not know where we are going, nor even where we ought to be going. Awareness is spreading that our future cannot be a straight extension of the past or the present. [...] Progress leads to confusion leads to progress and on and on without respite. **Every one of the many major advances [...] created sooner or later, more often sooner, new problems.** These confusions, never twice the same, are not to be deplored. Rather, those who participate experience them as a privilege.



Abraham Pais

		κ_γ	κ_W	κ_Z	κ_g	κ_b	κ_t	κ_τ	$\kappa_{Z\gamma}$	κ_μ
$300fb^{-1}$	ATLAS	[9,9]	[9,9]	[8,8]	[11,14]	[22,23]	[20,22]	[13,14]	[24,24]	[21,21]
$300fb^{-1}$	CMS	[5,7]	[4,6]	[4,6]	[6,8]	[10,13]	[14,15]	[6,8]	[41,41]	[23,23]
$3000fb^{-1}$	ATLAS	[4,5]	[4,5]	[4,4]	[5,9]	[10,12]	[8,11]	[9,10]	[14,14]	[7,8]
$3000fb^{-1}$	CMS	[2,5]	[2,5]	[2,4]	[3,5]	[4,7]	[7,10]	[2,5]	[10,12]	[8,8]

(A. Nisati, talk at IAS, 20 Jan 2015)

–ATLAS: [no theory uncert., full theory uncert.]

–CMS: [Scenario 2, Scenario1]

(P. Janot, talk at FCC-ee, 24 Sep 2015)

Error on	μμ Collider	ILC	FCC-ee
m_H (MeV)	0.06	30	8
Γ_H (MeV)	0.17	0.16	0.04
g_{Hbb}	2.3%	1.5%	0.4%
g_{HWW}	2.2%	0.8%	0.2%
$g_{H\tau\tau}$	5%	1.9%	0.5%
$g_{H\gamma\gamma}$	10%	7.8%	1.5%
$g_{H\mu\mu}$	2.1%	20%	6.2%
g_{HZZ}	–	0.6%	0.15%
g_{Hcc}	–	2.7%	0.7%
g_{Hgg}	–	2.3%	0.8%
BR_{invis}	–	<0.5%	<0.1%

LHC: 5-20 %

HL-LHC: 2-10%

FCC-ee: 0.2-1%

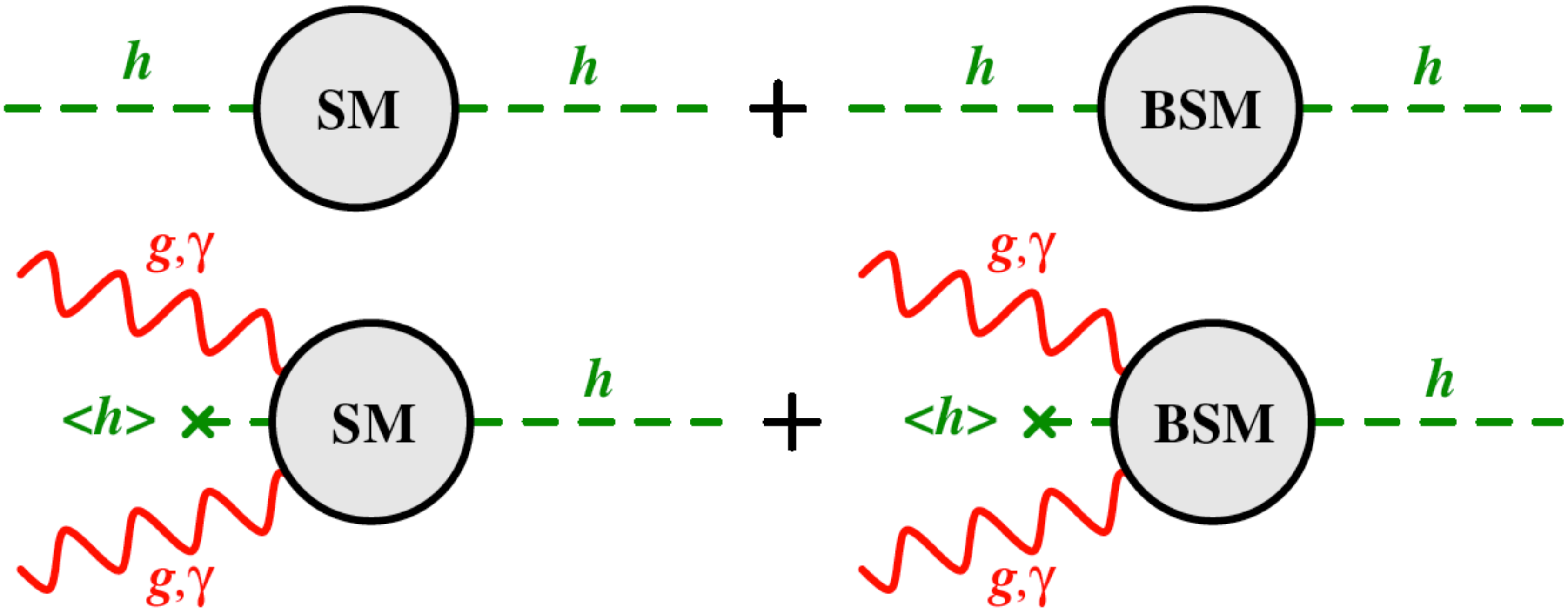
↵See talk by Patrizia Azzi

What do you learn from accuracy?

In composite Higgs:

$$\Delta = \frac{v^2}{f^2} \quad \Rightarrow \quad \text{compositeness scale } \; 4\pi f > \sqrt{\frac{0.1\%}{\Delta}} \; 100 \text{ TeV}$$

In general, testing Higgs couplings is testing naturalness:



The more natural the Higgs is,
the more its properties deviate from the SM

LCC-ee 4 phases of precision physics

$Z \rightarrow$ 90 GeV (10^{13} Z)
$WW \rightarrow$ 160 GeV (6×10^{7} WW)
$HZ \rightarrow$ 240 GeV (2×10^{6} H)
$tt \rightarrow$ 350 GeV (2×10^{5} tt)

↵See talks by Jorge De Blas Mateo, Sven Heinemeyer, Staszek Jadach, Barbara Mele, Oliver Fischer, Stefania De Curtis, Graziano Venanzoni

$\sqrt{s}$ (GeV):	90 (Z)	125 (eeH)	160 (WW)	240 (HZ)	350 ($t\bar{t}$)	350 (VV → H)
$\mathcal{L}$/IP ($cm^{-2}\,s^{-1}$)	$2.2\cdot10^{36}$	$1.1\cdot10^{36}$	$3.8\cdot10^{35}$	$8.7\cdot10^{34}$	$2.1\cdot10^{34}$	$2.1\cdot10^{34}$
$\mathcal{L}_{int}$ (ab^{-1}/yr/IP)	22	11	3.8	0.87	0.21	0.21
Events/year (4 IPs)	$3.7\cdot10^{12}$	$1.3\cdot10^{4}$	$6.1\cdot10^{7}$	$7.0\cdot10^{5}$	$4.2\cdot10^{5}$	$2.5\cdot10^{4}$
Years needed (4 IPs)	2.5	1.5	1	3	0.5	3

D'Enterria 1601.06640

Observable	Measurement	Current precision	FCC-ee stat.	Possible syst.	Challenge
m_Z (MeV)	Z lineshape	91187.5 ± 2.1	0.005	< 0.1	QED corrs.
Γ_Z (MeV)	Z lineshape	2495.2 ± 2.3	0.008	< 0.1	QED corrs.
R_ℓ	Z peak	20.767 ± 0.025	0.0001	< 0.001	QED corrs.
R_b	Z peak	0.21629 ± 0.00066	0.000003	< 0.00006	$g \to b\bar{b}$
$A_{FB}^{\mu\mu}$	Z peak	0.0171 ± 0.0010	0.000004	< 0.00001	E_{beam} meas.
N_ν	Z peak	2.984 ± 0.008	0.00004	0.004	Lumi meas.
N_ν	$e^+e^- \to \gamma Z(\text{inv.})$	2.92 ± 0.05	0.0008	< 0.001	–
$\alpha_s(m_Z)$	$R_\ell, \sigma_{had}, \Gamma_Z$	0.1196 ± 0.0030	0.00001	0.00015	New physics
$1/\alpha_{QED}(m_Z)$	$A_{FB}^{\mu\mu}$ around Z peak	128.952 ± 0.014	0.004	0.002	EW corr.
m_W (MeV)	WW threshold scan	80385 ± 15	0.3	< 1	QED corr.
$\alpha_s(m_W)$	B_{had}^W	$B_{had}^W = 67.41 \pm 0.27$	0.00018	0.00015	CKM matrix
m_t (MeV)	threshold scan	173200 ± 900	10	10	QCD
$F_{1V,2V,1A}^{\gamma t, Zt}$	$d\sigma^{t\bar{t}}/dx\, d\cos(\theta)$	4%–20% (LHC-14 TeV)	(0.1–2.2)%	(0.01–100)%	–

D'Enterria 1601.06640

$\delta m_Z \approx 100$ keV ($\delta m_{Z\text{today}} / \delta m_Z \approx 20$)

$\delta m_W \approx 500$ keV ($\delta m_{W\text{today}} / \delta m_W \approx 30$, $\delta m_{W\text{LHC}} / \delta m_W \approx 16$)

$\delta N_\nu \approx 10\text{-}4\times10^{-4}$ ($\delta N_{\nu\text{today}} / \delta N_\nu \approx 8\text{-}20$)

$\delta\alpha_s(m_Z)_{\text{today}} / \delta\alpha_s(m_Z) \approx 10\text{-}100$ (see Workshop on high-precision α_s measurements from LHC to FCC-ee, 12-13 Oct 2015)

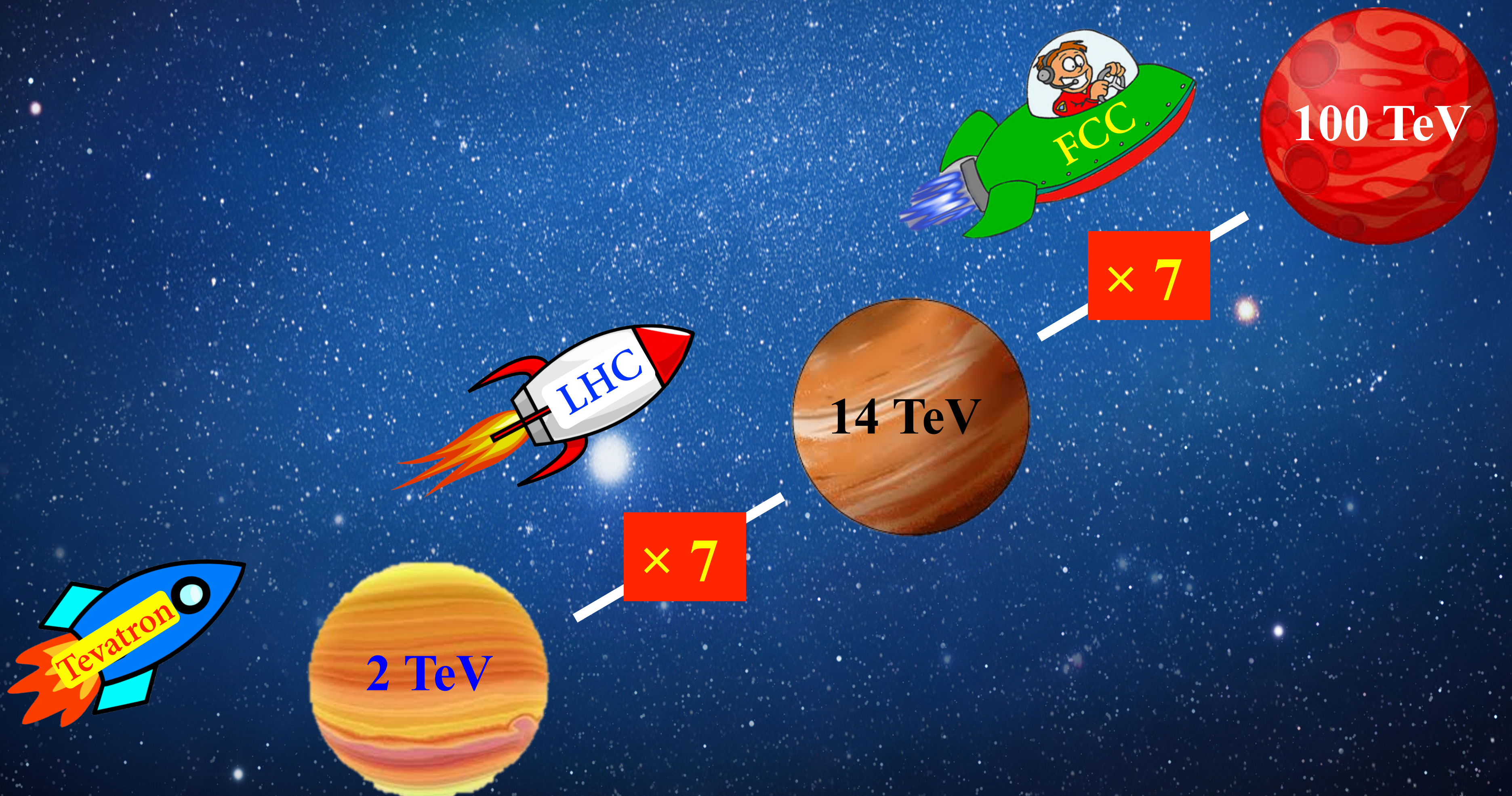
$\delta\alpha_{QED}(m_Z)_{\text{today}} / \delta\alpha_{QED}(m_Z) \approx 3\text{-}4$

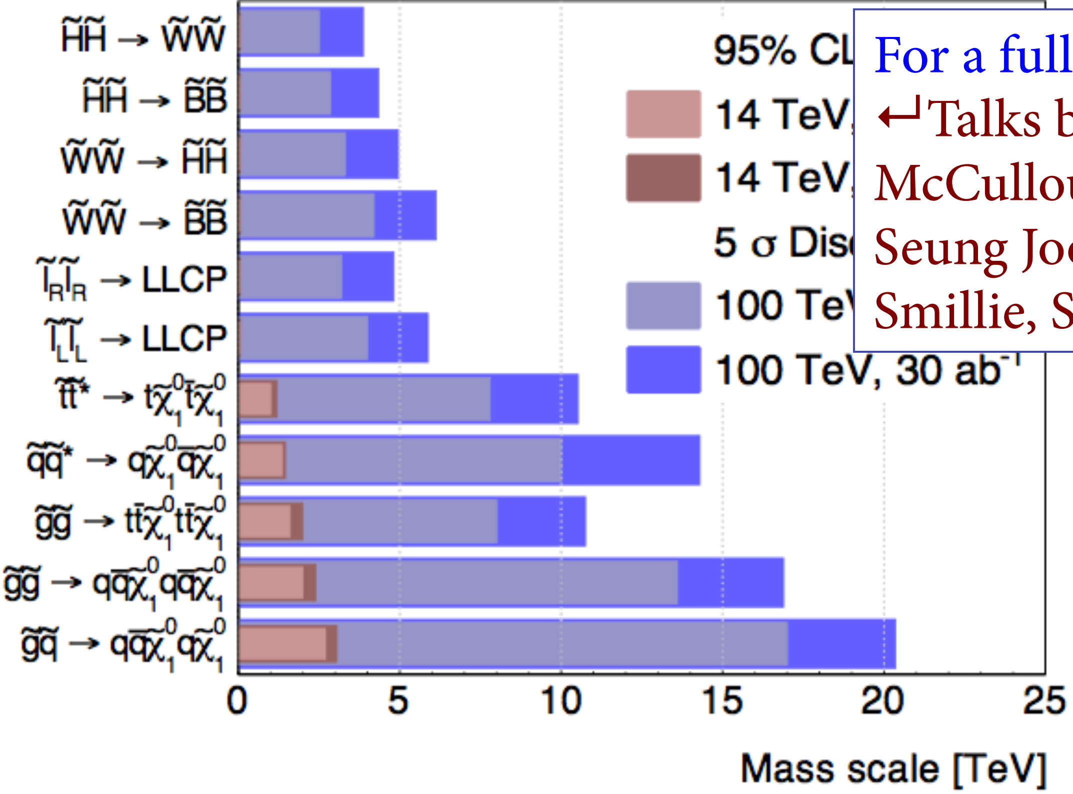
S and T improve by a factor 10, while ILC promises 2-3

FCC-he testifies to the versatility and richness of the FCC facility

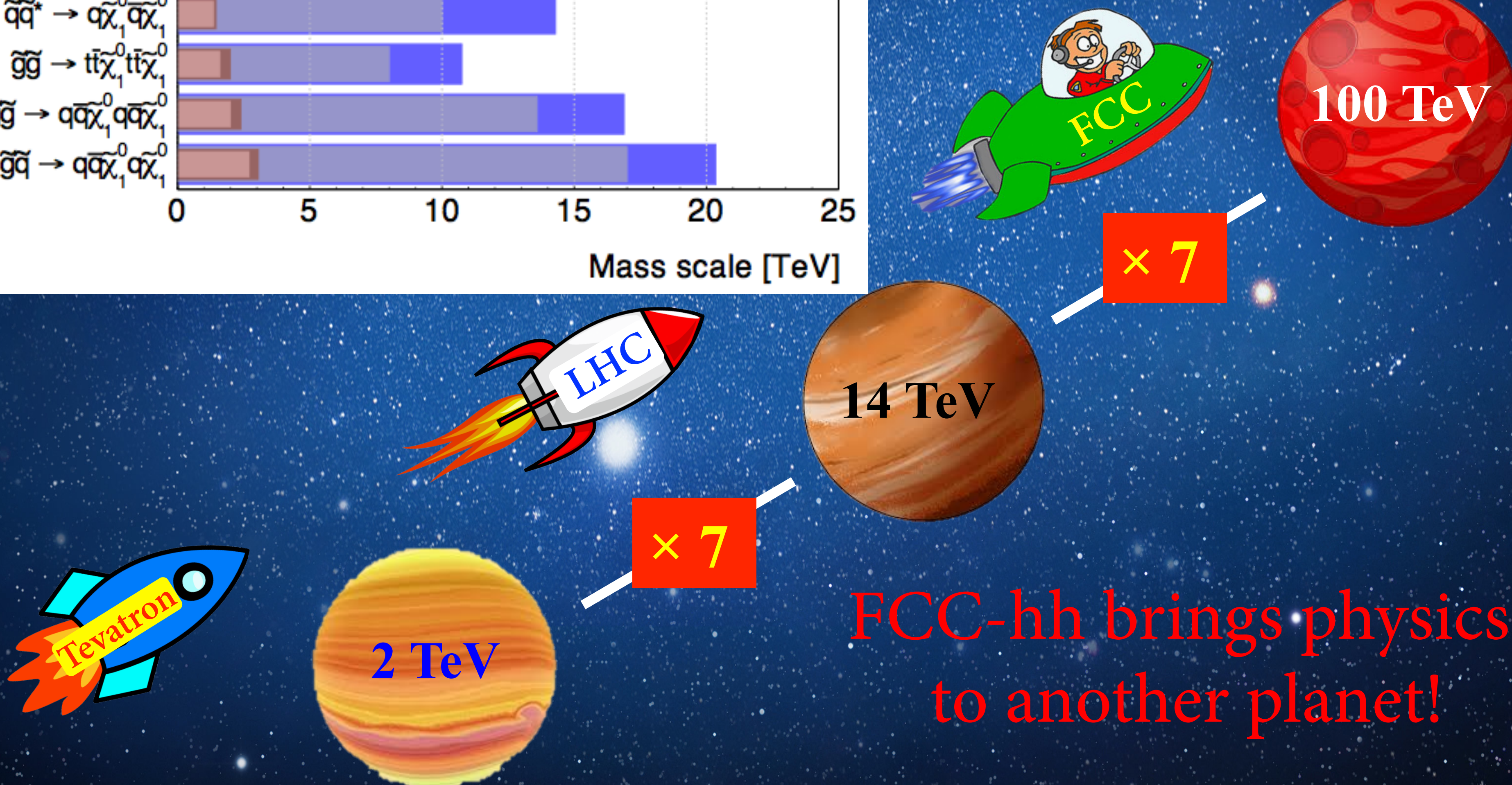
For the full story, see
↵Talk by Uta Klein
↵Talk by Voica Radescu
↵Talk by Cheng Zhang

FCC-hh brings physics to another planet!





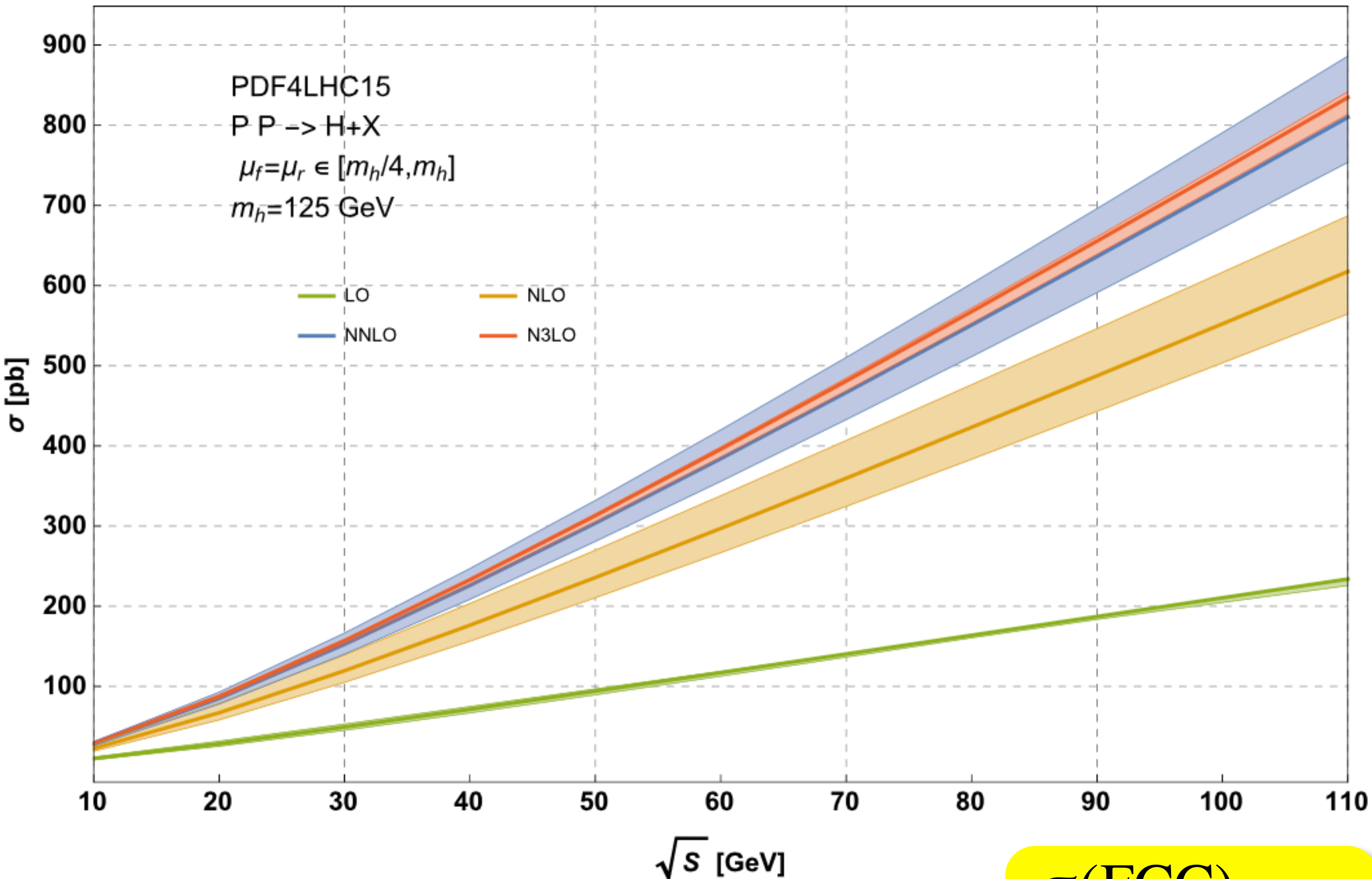
For a full account, see
↵Talks by Philip Allport, Matthew McCullough (BSM), Roberto Contino (Higgs), Seung Joon Lee, Jurgen Reuter, Jennifer Smillie, Stefan Antusch, Tomasz Jelinski



FCC-hh brings physics to another planet!

FCC-hh can also be a precision tool

Fantastic progress:
detector performance & theoretical calculations



N^{3}LO calculation of $gg \to h$!!!

$$\frac{\sigma(\mathrm{FCC})}{\sigma(\mathrm{LHC})} = 16$$

	N_{100}	N_{100}/N_8	N_{100}/N_{14}
$gg \to H$	16×10^9	4×10^4	110
VBF	1.6×10^9	5×10^4	120
WH	3.2×10^8	2×10^4	65
ZH	2.2×10^8	3×10^4	85
$t\bar{t}H$	7.6×10^8	3×10^5	420

Number of produced Higgs bosons taking

L_8=20 fb^{-1} (LHC Run1)

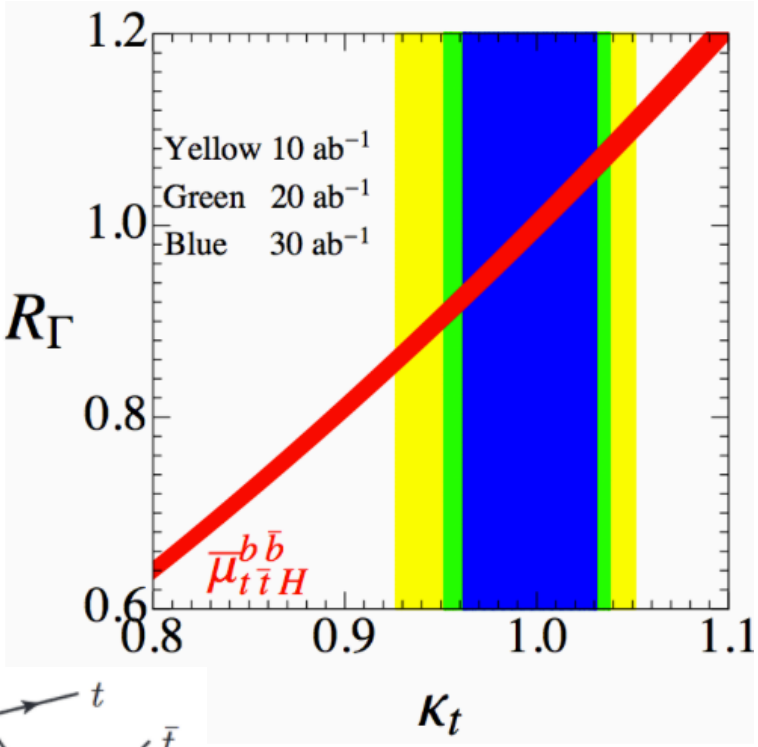
L_{14}=3000 fb^{-1} (HL-LHC)

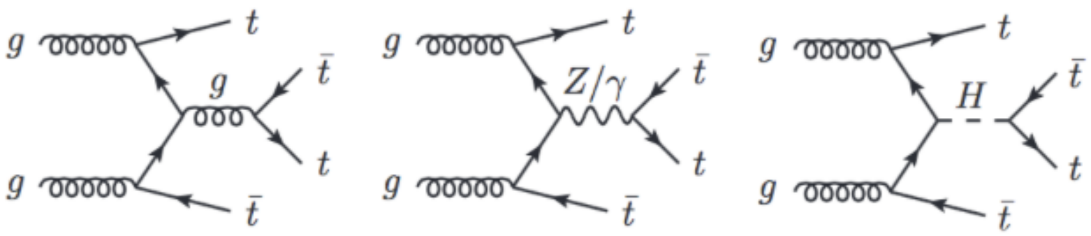
L_{100}=20 ab^{-1} (FCC)

Higgs-top coupling

$$\kappa_t \text{ from } \frac{t\bar{t}\,h}{t\bar{t}\,Z} \Rightarrow 1\% \text{ precision}$$

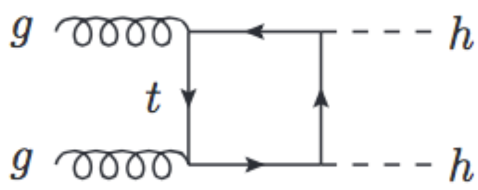
$$\Gamma_h \text{ and } \kappa_t \text{ from } \frac{t\bar{t}\,h}{t\bar{t}\,t\bar{t}} \Rightarrow$$

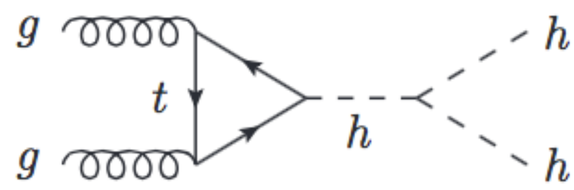




Triple Higgs coupling

(direct test of EW phase transition)





process	precision on σ_{SM}	68% CL interval on Higgs self-couplings
$HH \to b\bar{b}\gamma\gamma$	2%	$\lambda_3 \in [0.97, 1.03]$
$HH \to b\bar{b}b\bar{b}$	5%	$\lambda_3 \in [0.9, 1.5]$
$HH \to b\bar{b}4\ell$	$O(25\%)$	$\lambda_3 \in [0.6, 1.4]$
$HH \to b\bar{b}\ell^+\ell^-$	$O(15\%)$	$\lambda_3 \in [0.8, 1.2]$
$HH \to b\bar{b}\ell^+\ell^-\gamma$	–	–
$HHH \to b\bar{b}b\bar{b}\gamma\gamma$	$O(100\%)$	$\lambda_4 \in [-4, +16]$

From $hh \to bb\gamma\gamma$: 5% precision within reach with 20-30 ab^{-1}

Gauge sector

$$L = i\bar{\psi}\gamma^{\mu}D_{\mu}\psi - \frac{1}{2}F_{\mu\nu}F^{\mu\nu}$$

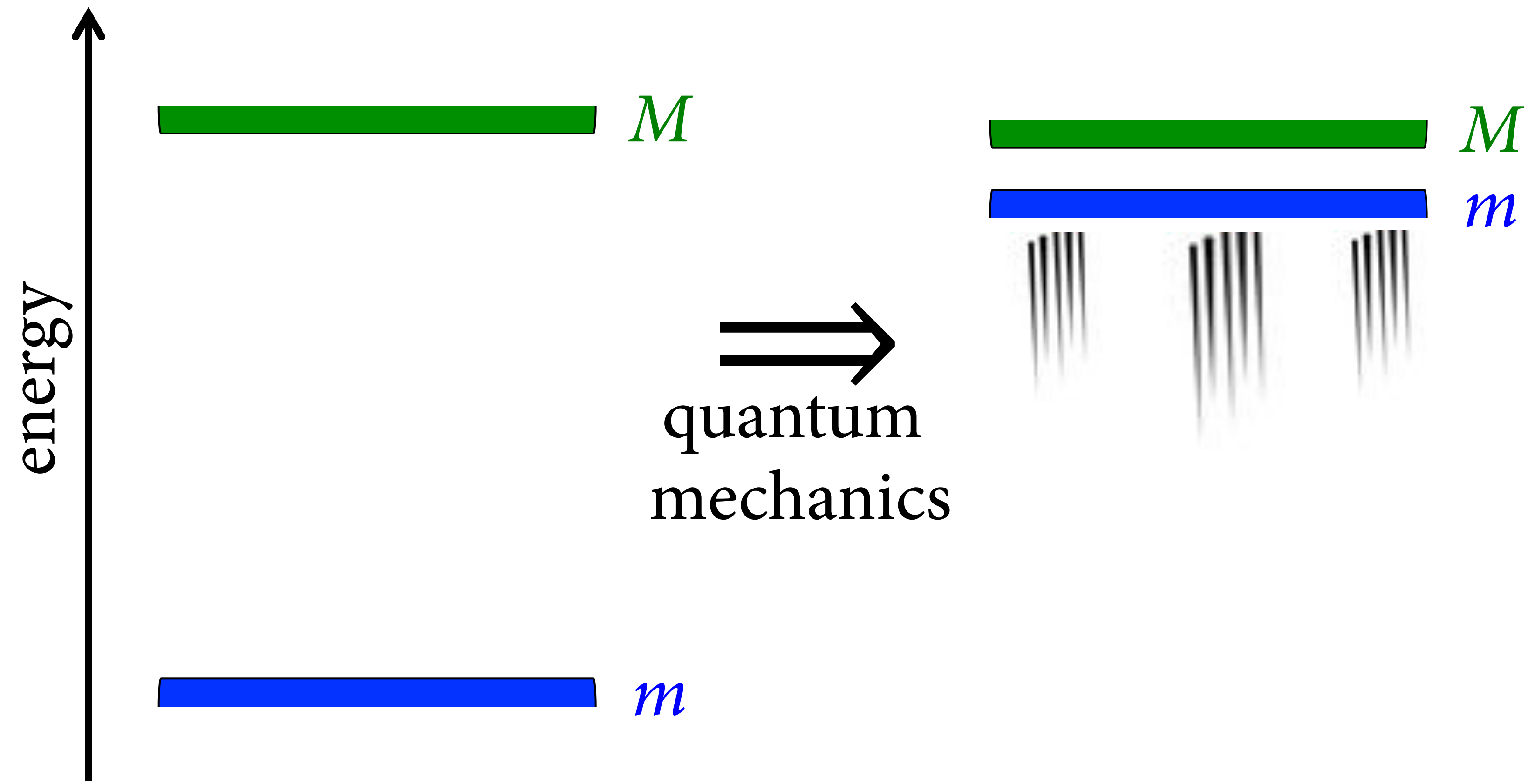
Higgs sector

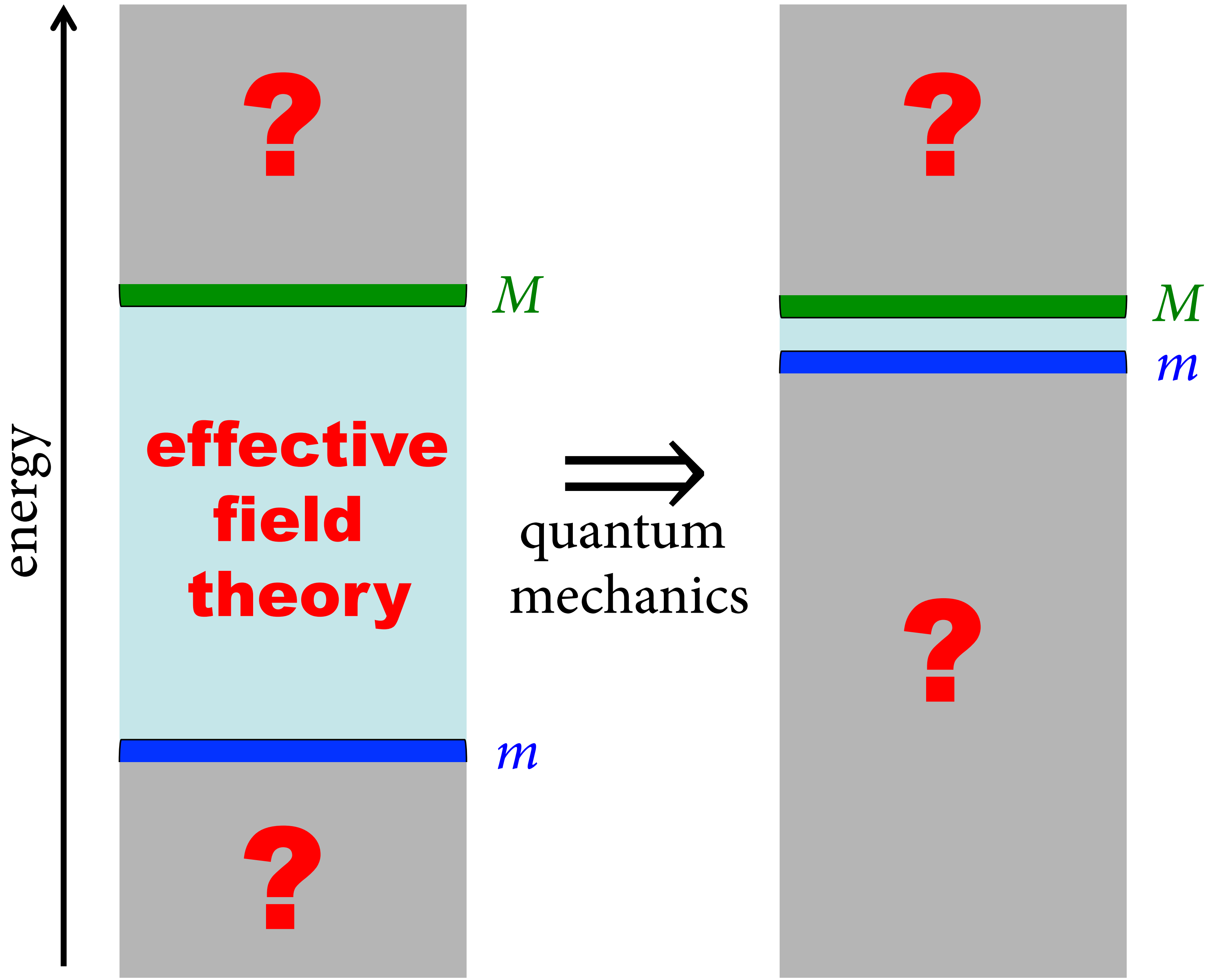
$$L = \left(h_{ij}\bar{\psi}_i\psi_j H + \text{h.c.}\right) - \lambda|H|^4 + \mu^2|H|^2 - \Lambda_{CC}^4$$

Non-gauge fundamental forces!

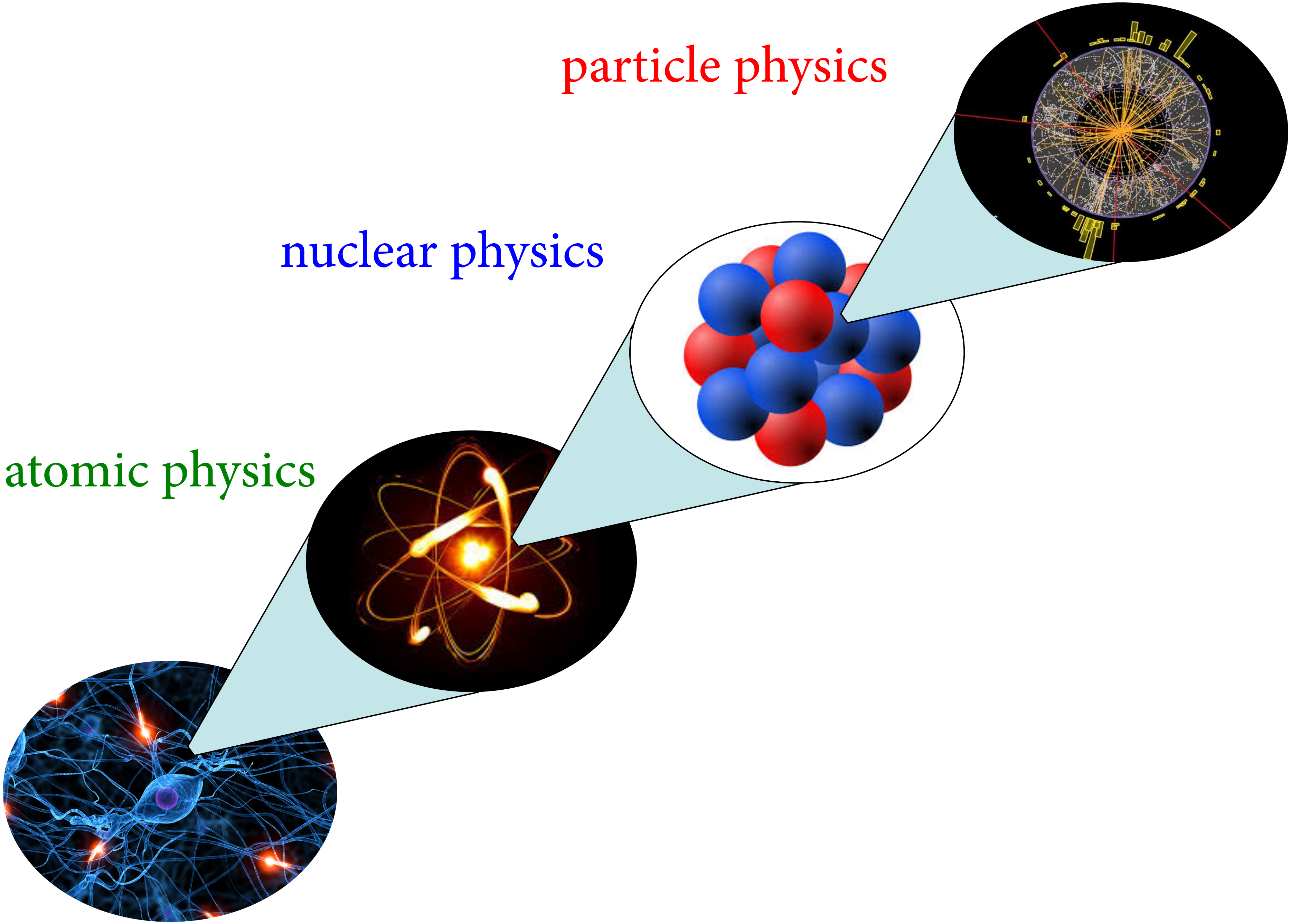
Naturalness problem

Naturalness is not about quadratic divergences, it is about separation of scales

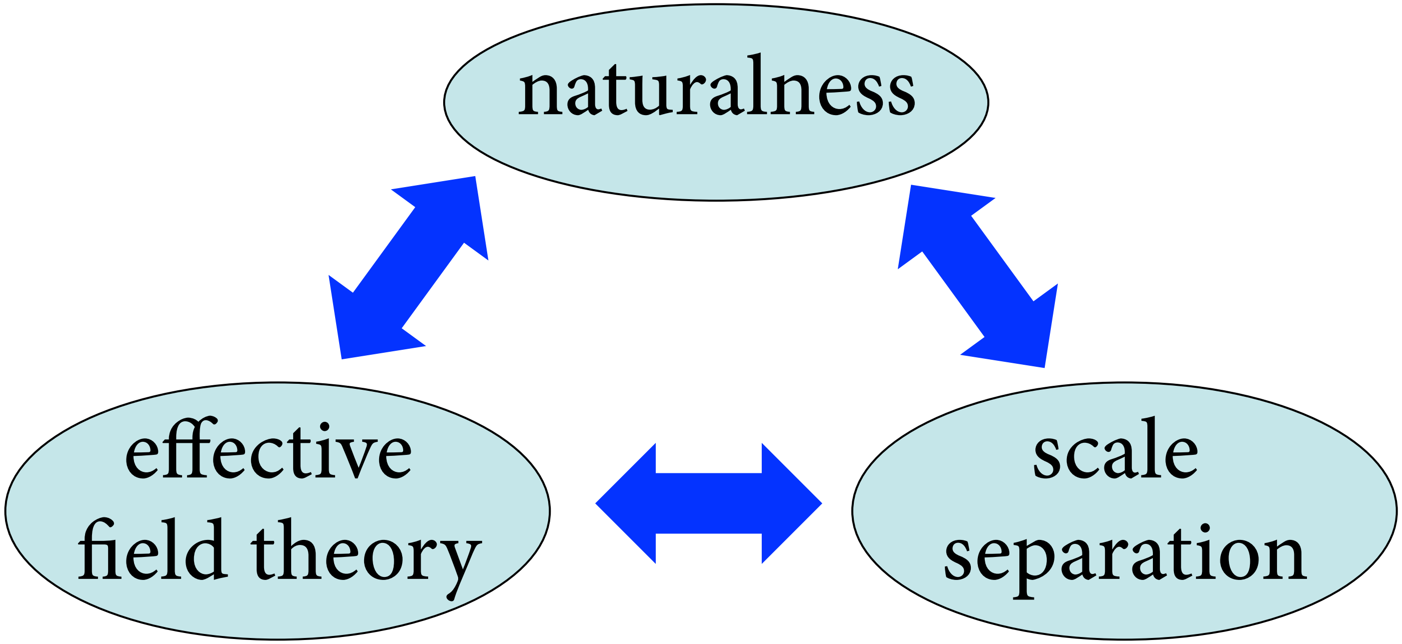




energy
?
M
effective field theory
m
?
quantum mechanics
?
M
m
?



particle physics
nuclear physics
atomic physics



Not a logical necessity, but a tool to make progress

Tests of naturalness

Process	Naturalness cutoff	"New-physics" mass
Electron self-energy	3 MeV	$m_{e+} = 0.5$ MeV
π^+-π^0 mass difference	900 MeV	$m_\rho = 770$ MeV
K^0-K^0 mass difference	2 GeV	$m_c = 1.2$ GeV
Higgs mass	500 GeV	?
Cosmological constant	10^{-3} eV	?

LHC will settle the issue of Higgs naturalness

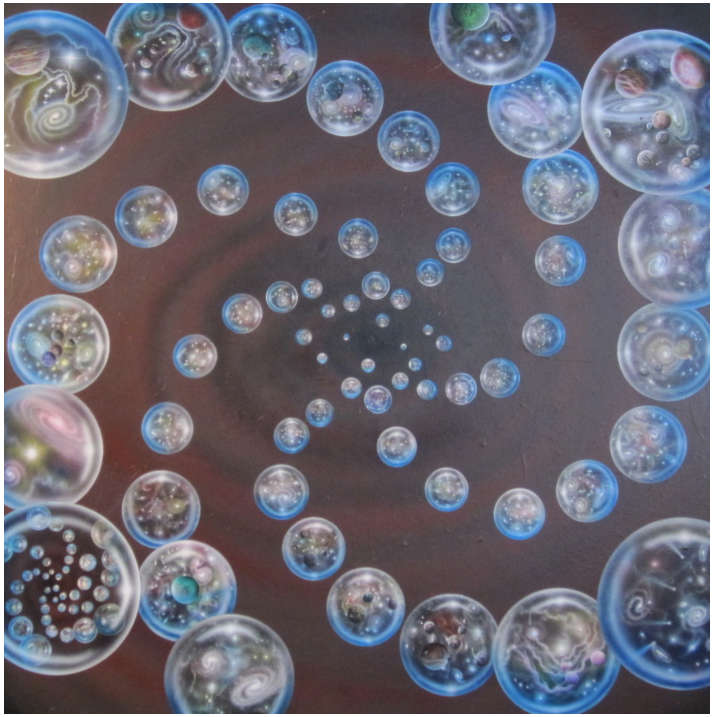
If discoveries are made at the LHC, they will redesign the priorities of HEP.
It is difficult to imagine any discovery at the LHC that does not need a follow up at higher energy.

If no discoveries are made at the LHC, our ideas about Higgs naturalness were wrong.
A profound change of paradigm will be required.

Multiverse

weak scale from selection process

(akin to Darwin's natural selection)

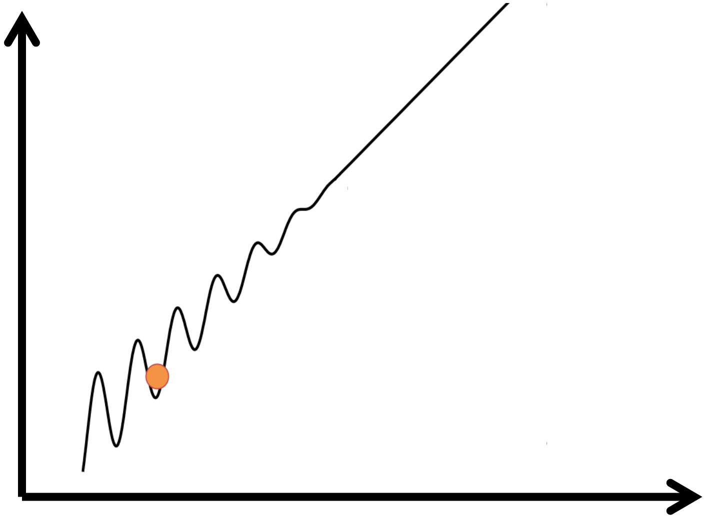


While environmental solutions of Higgs naturalness are possible, it is difficult to believe that they can take care of the full picture

Cosmological relaxation

weak scale from selection process

(akin to self-organised criticality)



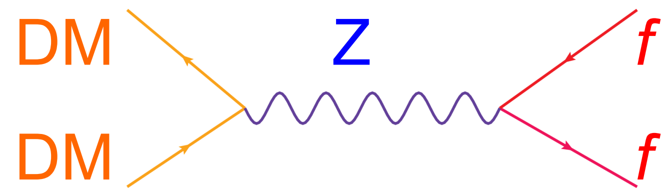
Can we expect new physics within reach of a 100 TeV collider, if we lose the link provided by Higgs naturalness?

Dark Matter

Thermal relic: $$\frac{\Omega_\chi h^2}{0.12} \approx \frac{\text{pb}}{\langle \sigma_\chi v \rangle}$$

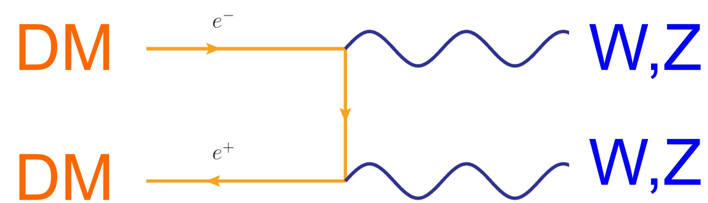
“Old” WIMP miracle:

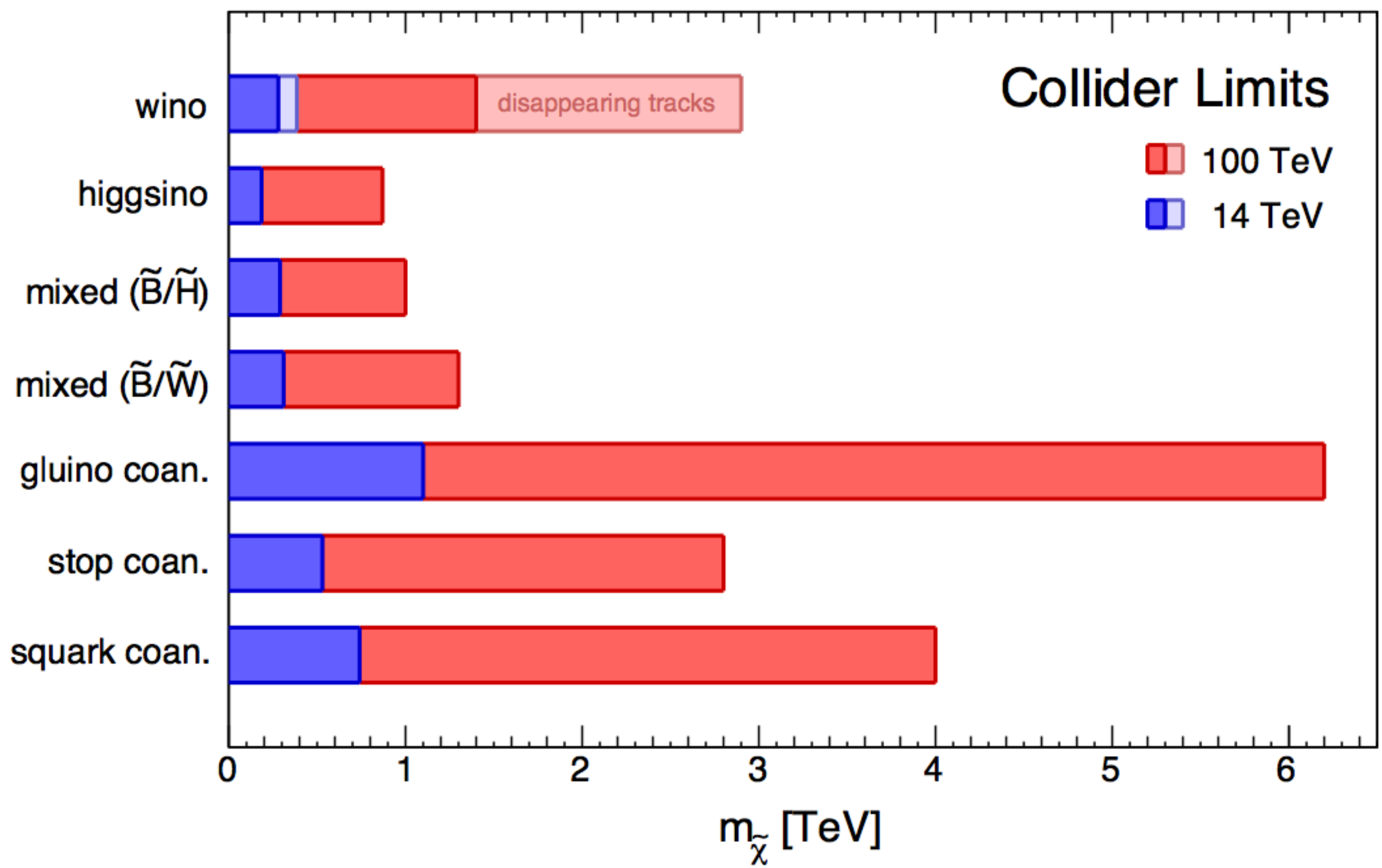
$$\langle \sigma_\chi v \rangle \approx \frac{G_F^2 m_\chi^2}{\pi} \approx \left(\frac{m_\chi}{10 \text{ GeV}} \right)^2 \text{ pb}$$



“New” WIMP miracle:

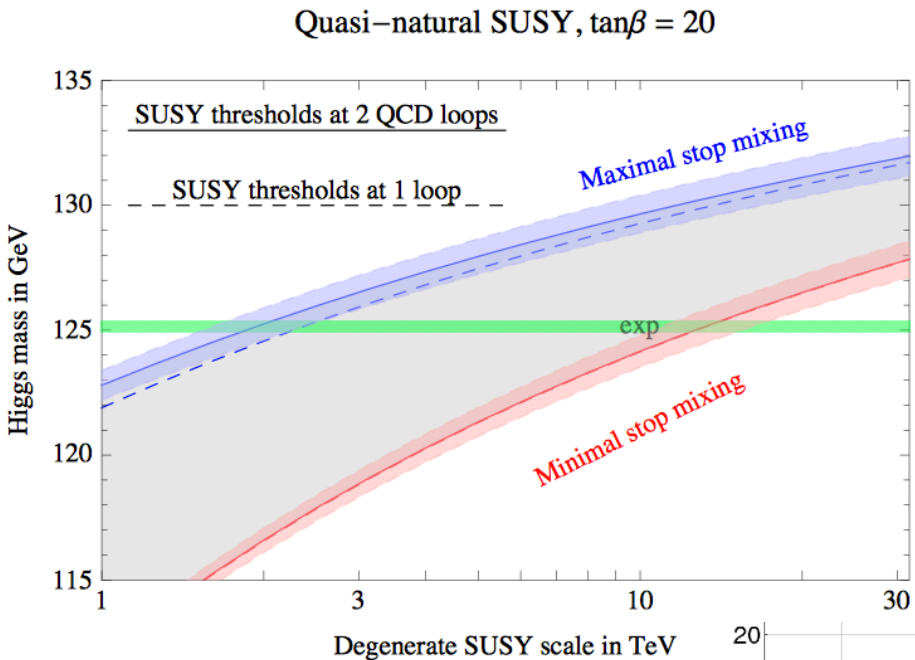
$$\langle \sigma_\chi v \rangle \approx \frac{g^4}{16\pi m_\chi^2} \approx \left(\frac{\text{TeV}}{m_\chi} \right)^2 \text{ pb}$$





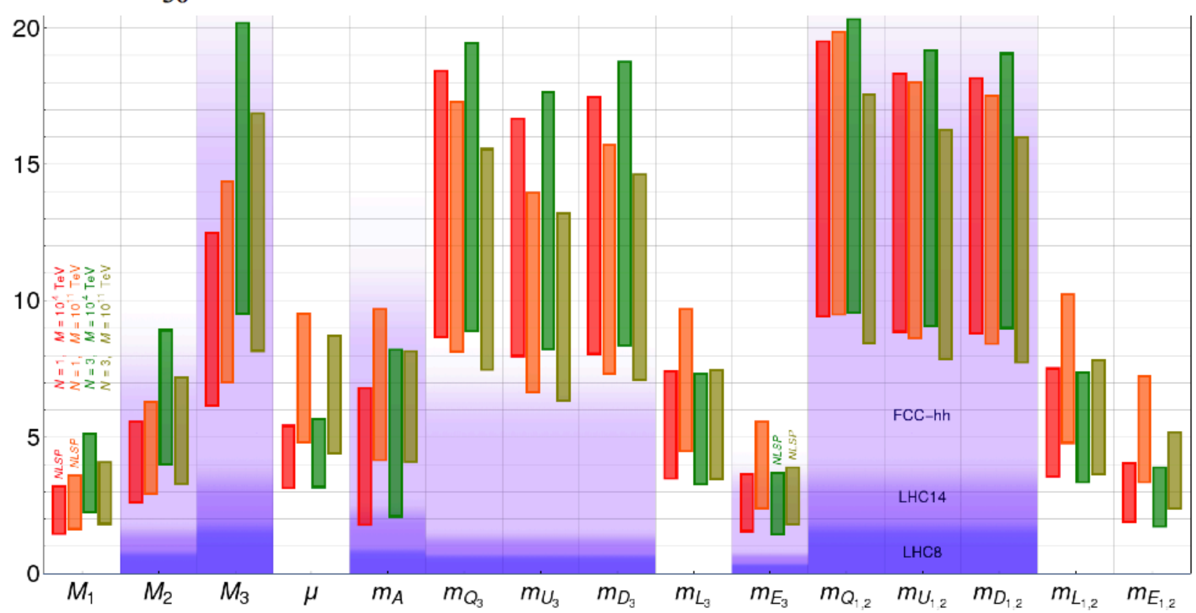
wino
higgsino
mixed (B̃/H̃)
mixed (B̃/W̃)
gluino coan.
stop coan.
squark coan.
disappearing tracks
Collider Limits
100 TeV
14 TeV
0
1
2
3
4
5
6
m$_{\tilde{\chi}}$ [TeV]

Can we expect new physics within reach of a 100 TeV collider, if we lose the link provided by Higgs naturalness?



Higgs mass?

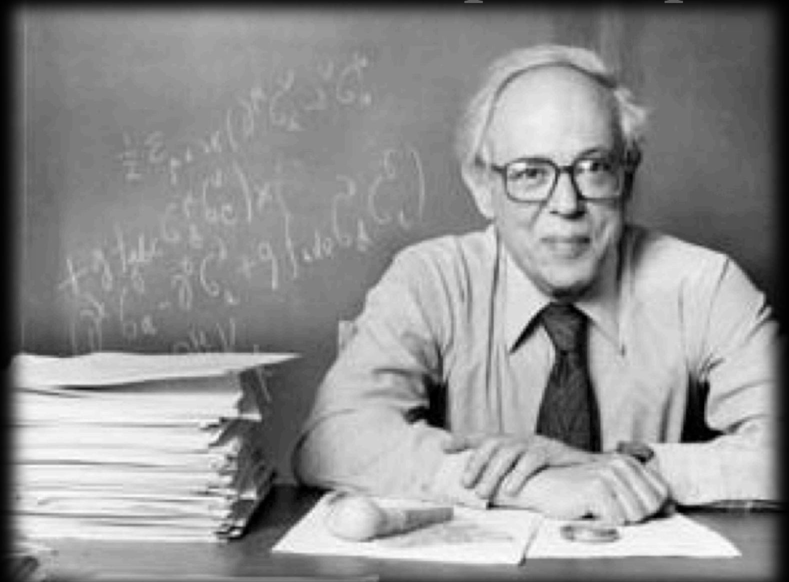
Vega-Villadoro



The LHC has naturalness as a target and is going to deliver the final word.

If the LHC verdict is negative, the FCC program cannot be regarded as a mere extension of the LHC searches.

Today we live in the midst of upheaval and crisis. We do not know where we are going, nor even where we ought to be going. Awareness is spreading that our future cannot be a straight extension of the past or the present. [...] Progress leads to confusion leads to progress and on and on without respite. Every one of the many major advances [...] created sooner or later, more often sooner, new problems. These confusions, never twice the same, are not to be deplored. Rather, those who participate experience them as a privilege.



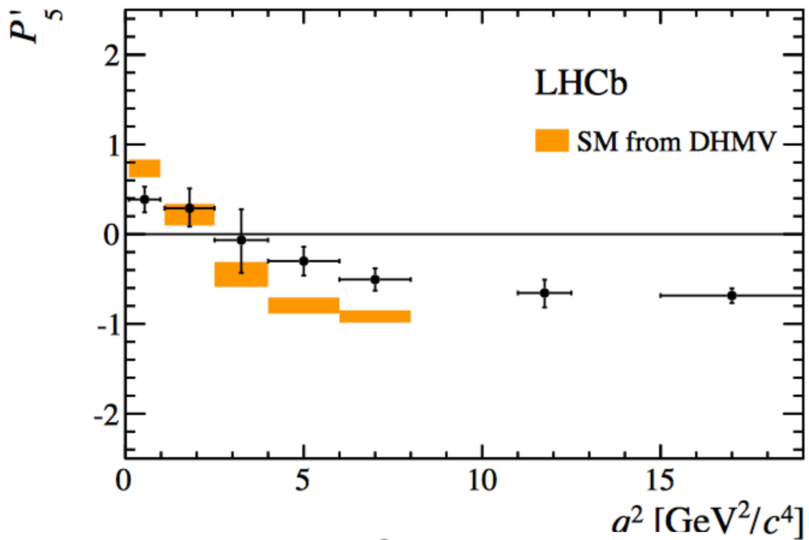
Abraham Pais

If the LHC is the machine of the naturalness era, the FCC could become the machine of the post-naturalness era.

Other frontiers

Flavour frontier

Global analysis in $B \to K^* \mu^+ \mu^-$



$2.8\,\sigma$ in $[4,6]$ GeV^2

$3.0\,\sigma$ in $[6,8]$ GeV^2

Deviations in $Q_{9V} = \frac{\alpha_e}{4\pi} (\bar{s}_L \gamma_\mu b_L)(\bar{\ell}\gamma^\mu \ell)$ raise concerns with long-distance effects

Similar tension at 3σ in $B_s \to \phi\, \mu^+ \mu^-$

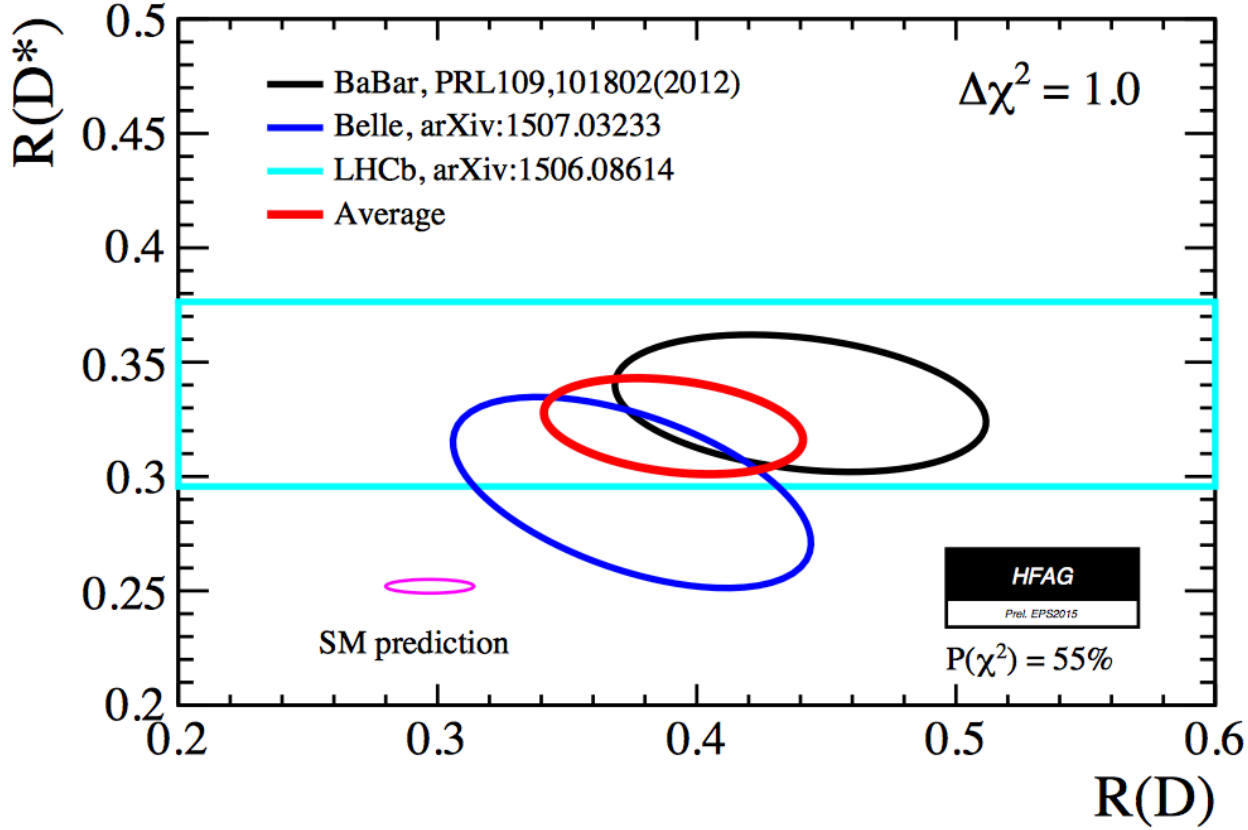
Lepton universality in $B \to K\, l^+ l^-$

$$R(K) = \mathrm{Br}(B \to K \mu^+ \mu -)/\mathrm{Br}(B \to K e^+ e^-) \stackrel{\text{exp.}}{=} 0.75^{+0.09}_{-0.07} \pm 0.04$$

2.6 sigma deviation from clean SM prediction $R(K) = 1$

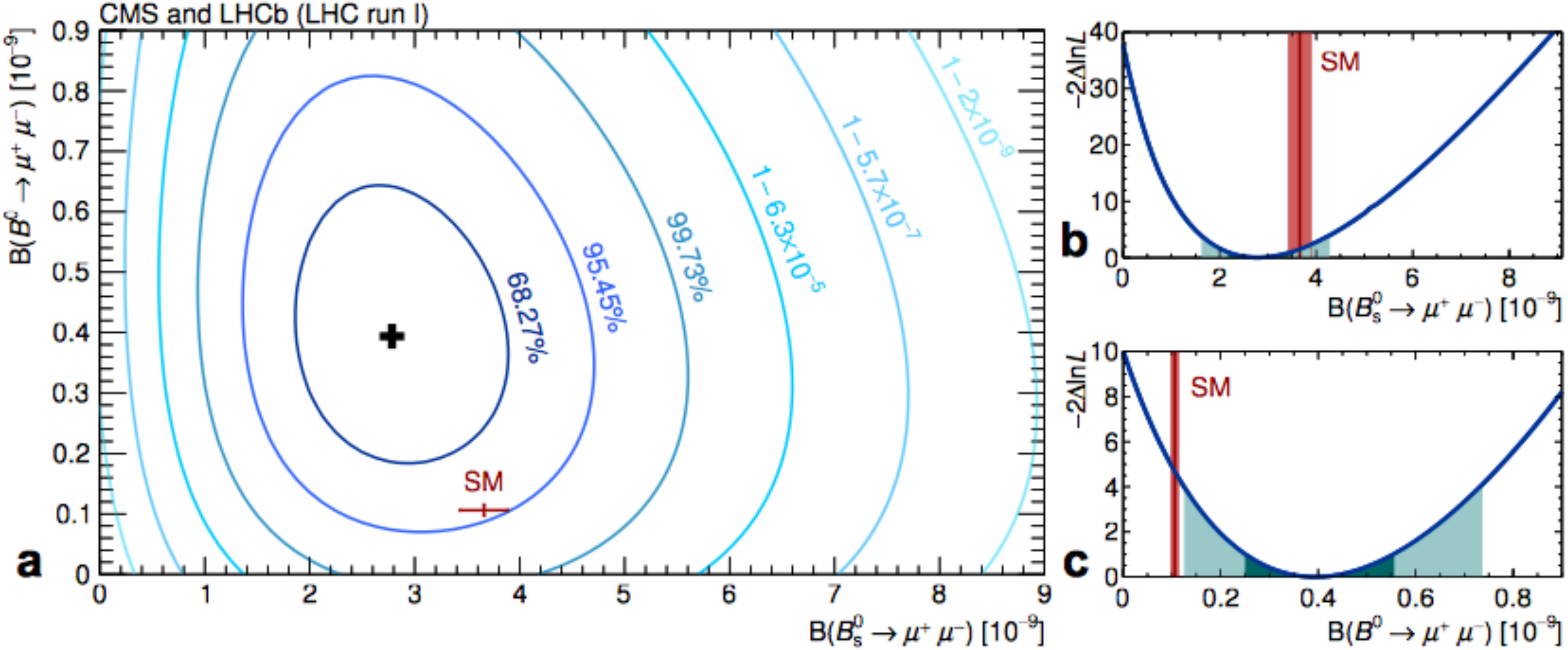
Lepton universality in $B \to D^{(*)}\tau\nu$

$$\mathcal{R}(D^{(*)}) = \frac{\mathcal{B}(\overline{B} \to D^{(*)}\tau\nu)}{\mathcal{B}(\overline{B} \to D^{(*)}\ell\nu)}$$



3.9σ combined deviation

$B^0_{(s)} \to \mu^+\mu^-$



Compatibility with SM: $B^0 \to \mu^+ \mu^-$ 2.2σ

$B^0_s \to \mu^+ \mu^-$ 1.2σ

Neutrino frontier

- Indication for a new heavy mass scale
- Part of the flavor embarrassment
- Surprises with light sterile neutrinos?
- Connections with the cosmo (CMB, DM, baryogenesis)

Low-energy frontier

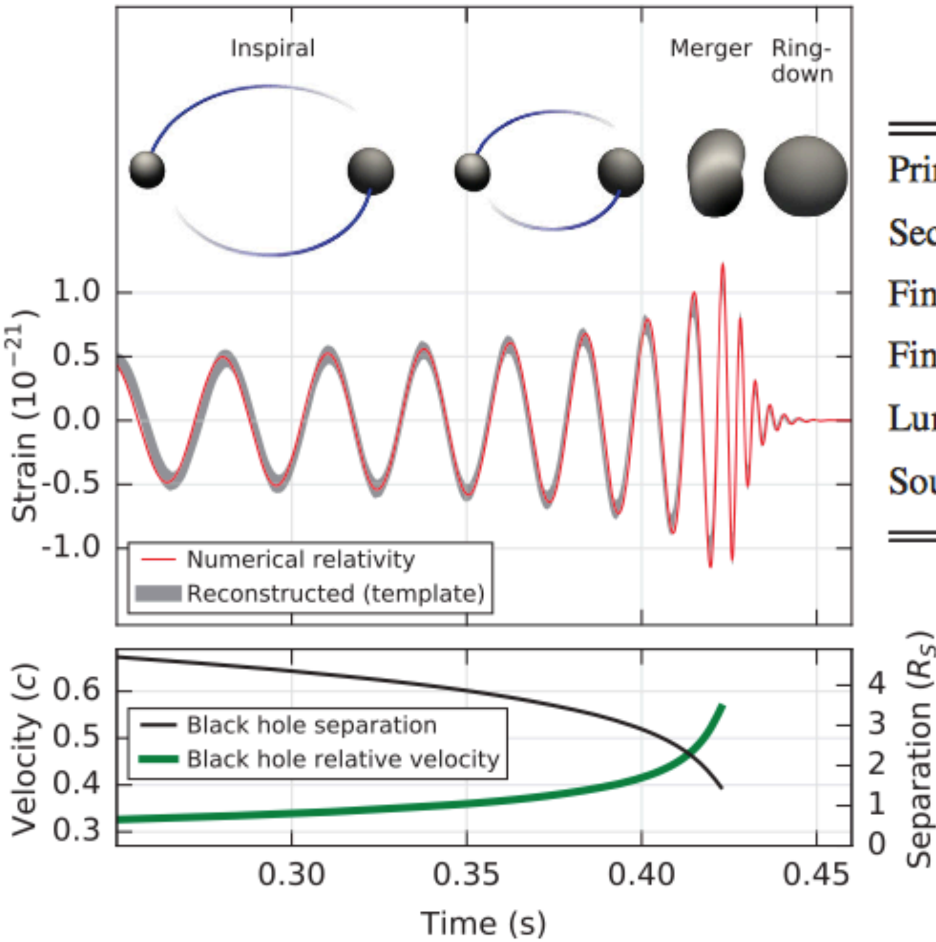
Many emerging ideas with light, very weakly coupled particles
(often post-WIMP motivations):
asymmetric dark matter, dark forces, hidden photons, mirror sectors, macroscopic modifications of gravity, light sterile neutrinos, axions, and axion-like particles, millicharged particles, moduli, dilatons, chameleon fields, ...

New experimental techniques
(often borrowed from other fields):
lasers, microwave cavities, torsion balances, cantilever experiments, resonant mass detectors, beam dump, frequency metrology in atomic clocks, atom interferometry, ...

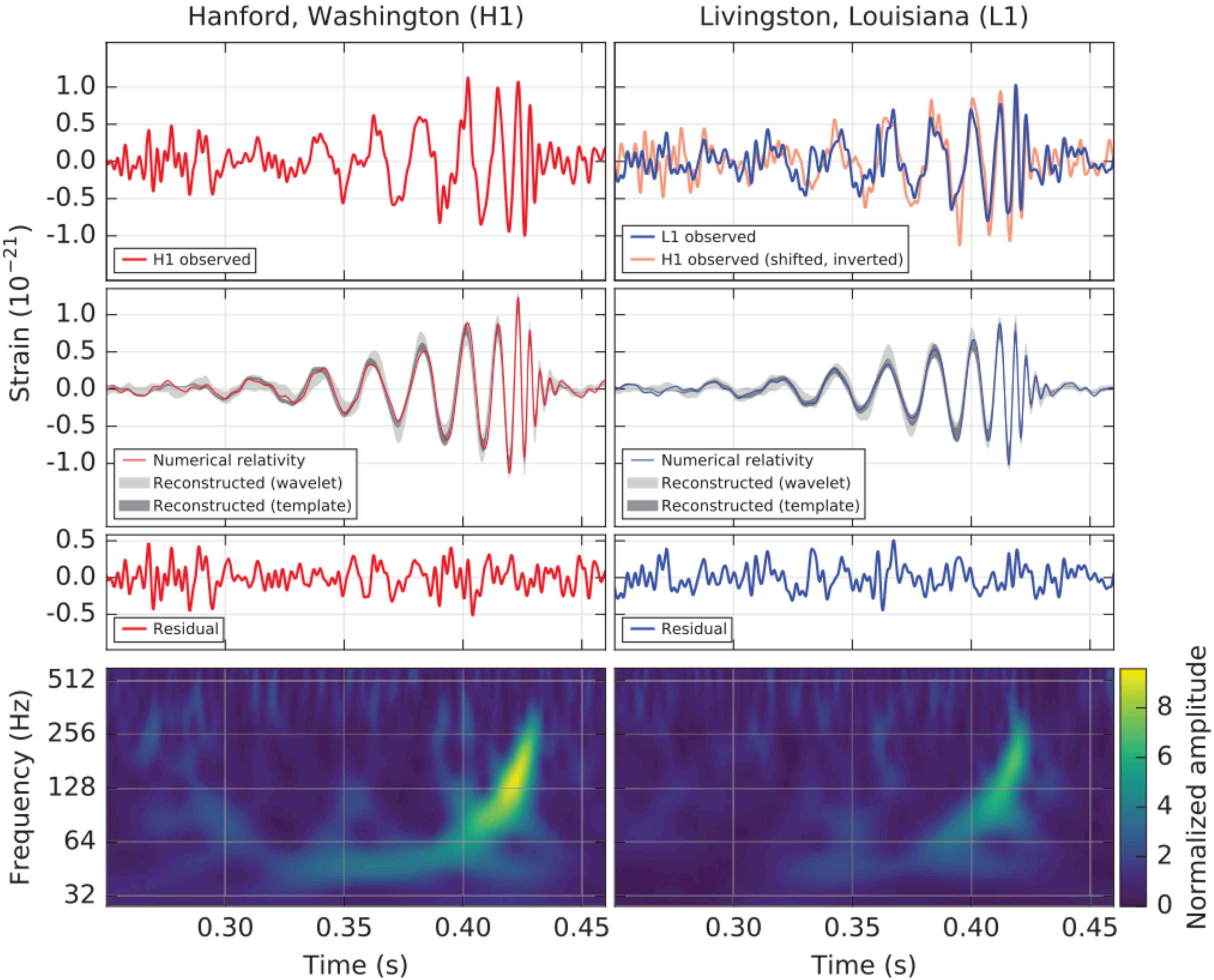
Large-scale frontier

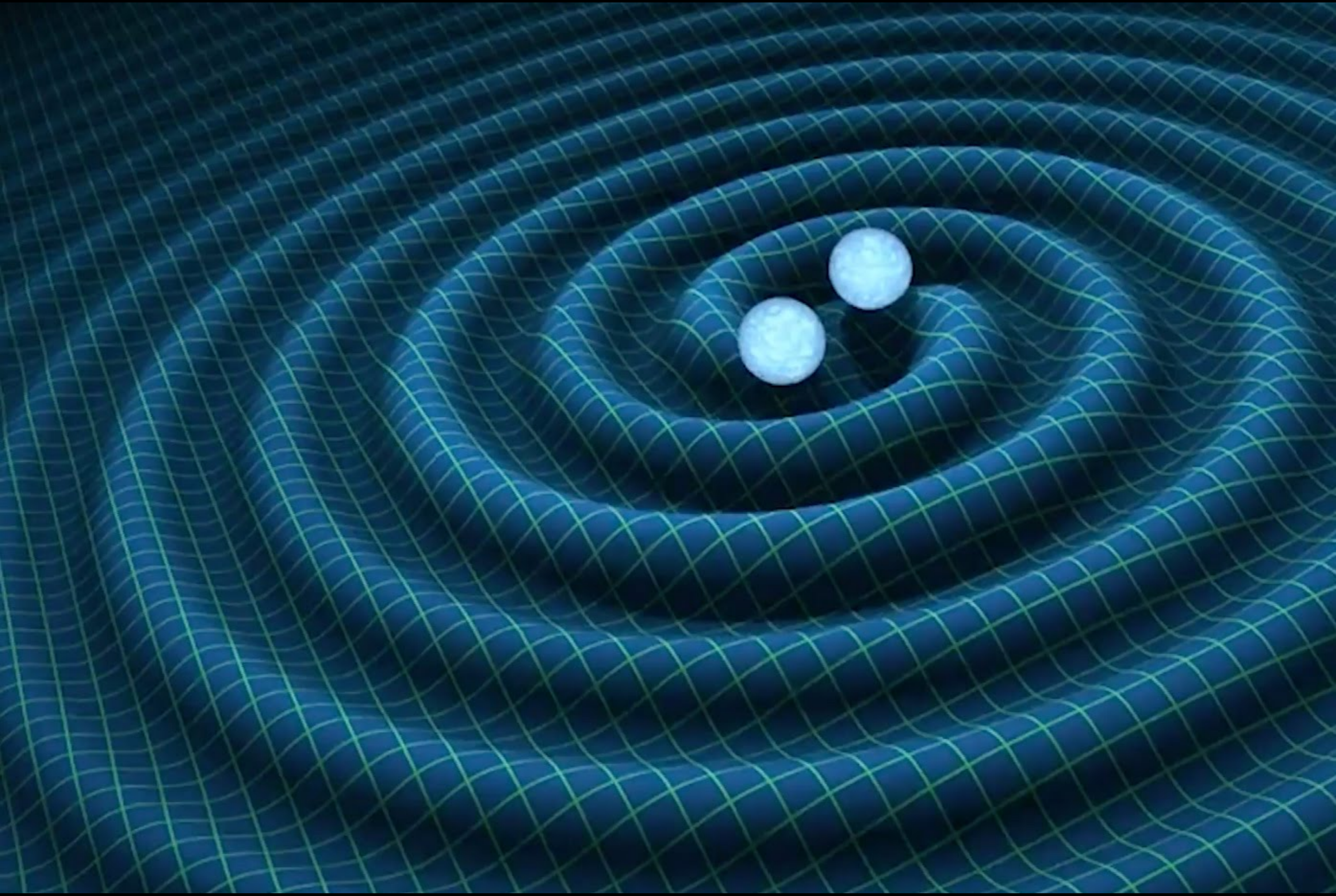
The universe as an experimental facility


CERN/Science Source/Photo Researchers, Inc.

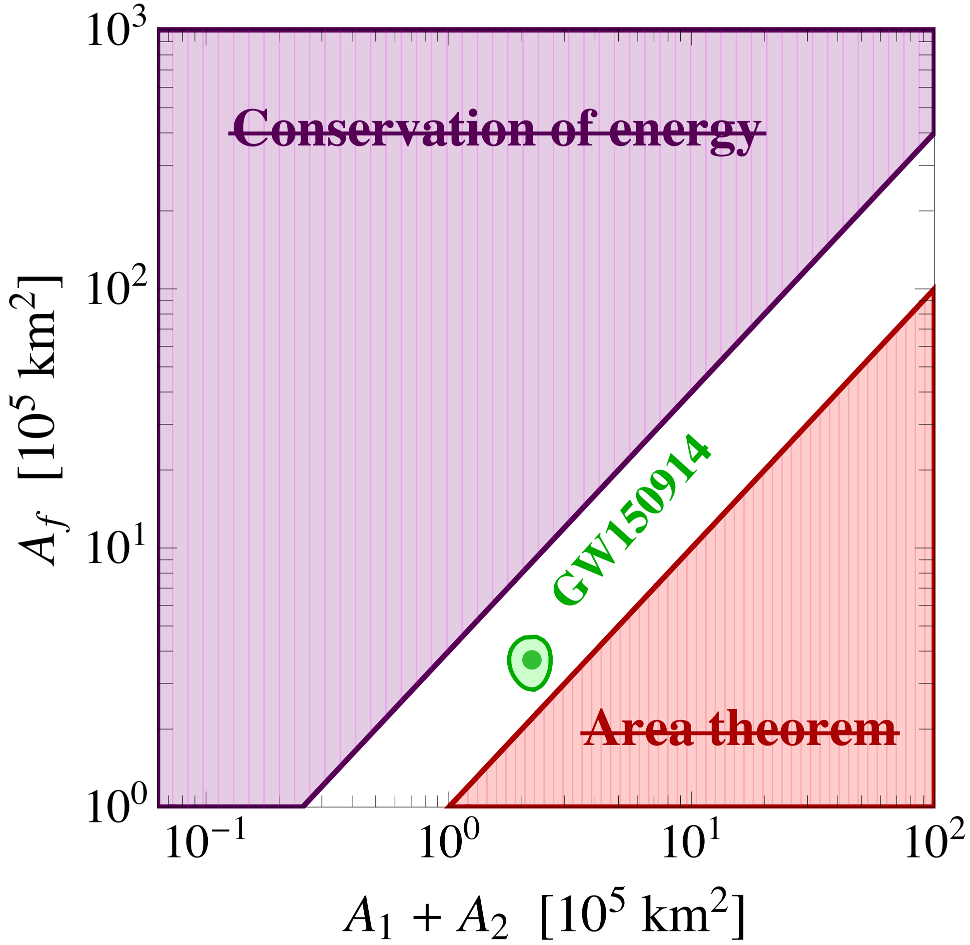


Primary black hole mass	$36^{+5}_{-4} M_\odot$
Secondary black hole mass	$29^{+4}_{-4} M_\odot$
Final black hole mass	$62^{+4}_{-4} M_\odot$
Final black hole spin	$0.67^{+0.05}_{-0.07}$
Luminosity distance	410^{+160}_{-180} Mpc
Source redshift z	$0.09^{+0.03}_{-0.04}$


Hanford, Washington (H1)
Livingston, Louisiana (L1)
Strain (10^{-21})
H1 observed
L1 observed
H1 observed (shifted, inverted)
Numerical relativity
Reconstructed (wavelet)
Reconstructed (template)
Residual
Frequency (Hz)
Normalized amplitude
Time (s)
1.0
0.5
0.0
-0.5
-1.0
512
256
128
64
32
0.30
0.35
0.40
0.45
0
2
4
6
8



Testing Hawking's Area Theorem

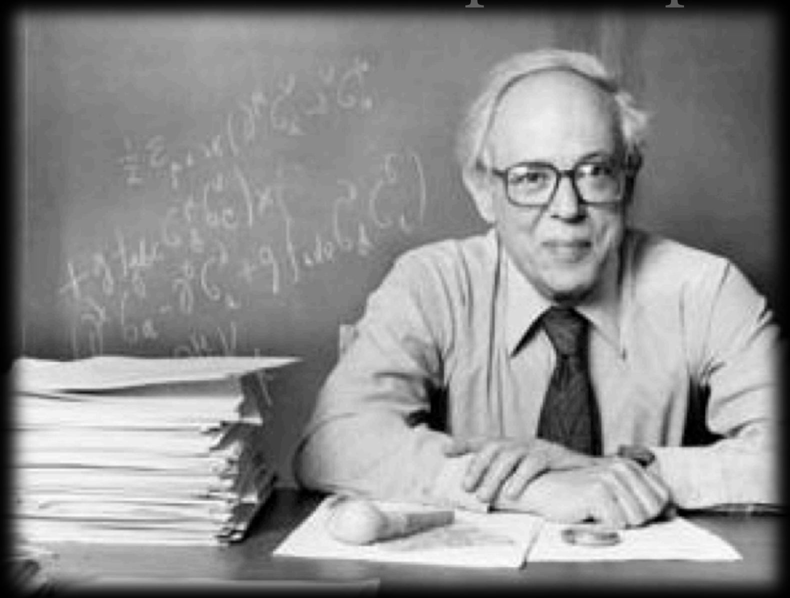


G.G.-McCullough-Urbano

CONCLUSIONS

The very soul of particle physics is exploration. Our history is a history of pushing frontiers, crossing boundaries between the known and unknown, exploring virgin territories.

Today we live in the midst of upheaval and crisis. We do not know where we are going, nor even where we ought to be going. Awareness is spreading that our future cannot be a straight extension of the past or the present. [...] Progress leads to confusion leads to progress and on and on without respite. Every one of the many major advances [...] created sooner or later, more often sooner, new problems. These confusions, never twice the same, are not to be deplored. Rather, those who participate experience them as a privilege.



Abraham Pais

Our scientific priorities are likely to shift in the next few years, but the high-energy frontier seems, more than ever, the most promising direction for us to gain new knowledge in fundamental physics.