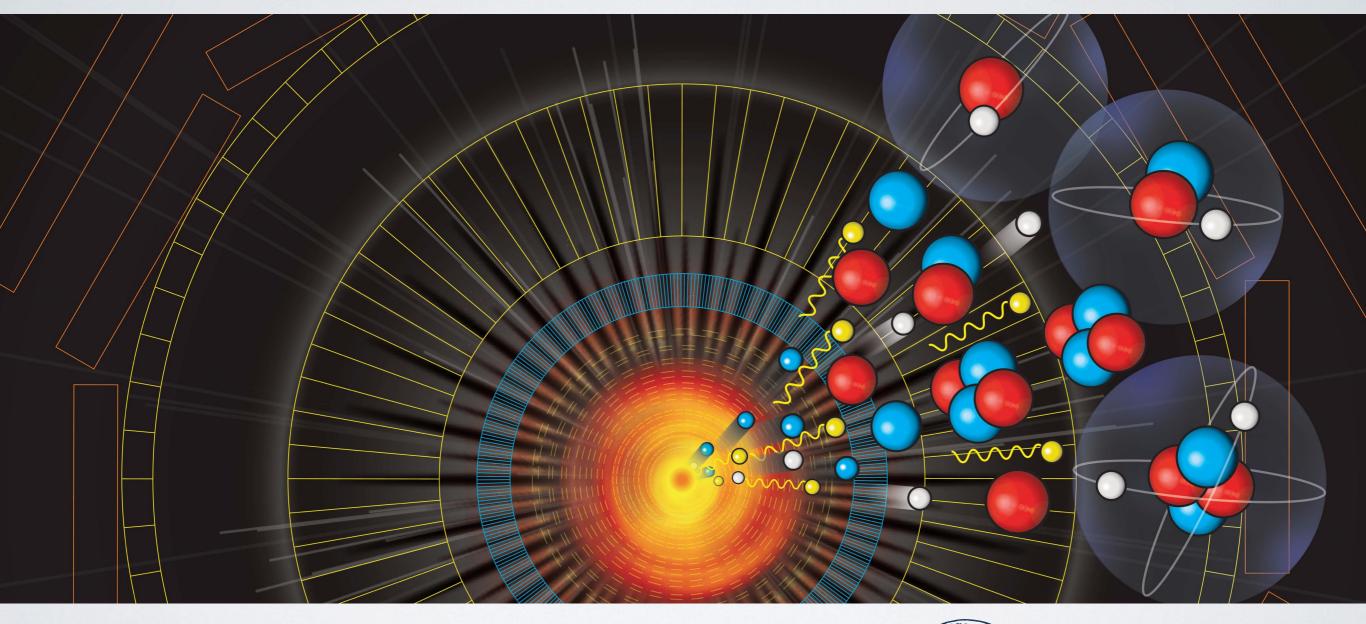
Theory

Francesco Sannino

rECFA visit May, 2022

















Difficult exercise

What is a theorist?

Amorphous category:

Crosses boundaries between formal topics and phenomenology

Contributes to different disciplines/subjects via similar tools



Giorgio Parisi

The Nobel Prize in Physics 2021

Prize motivation: "for the discovery of the interplay of disorder and fluctuations in physical systems from atomic to planetary scales."

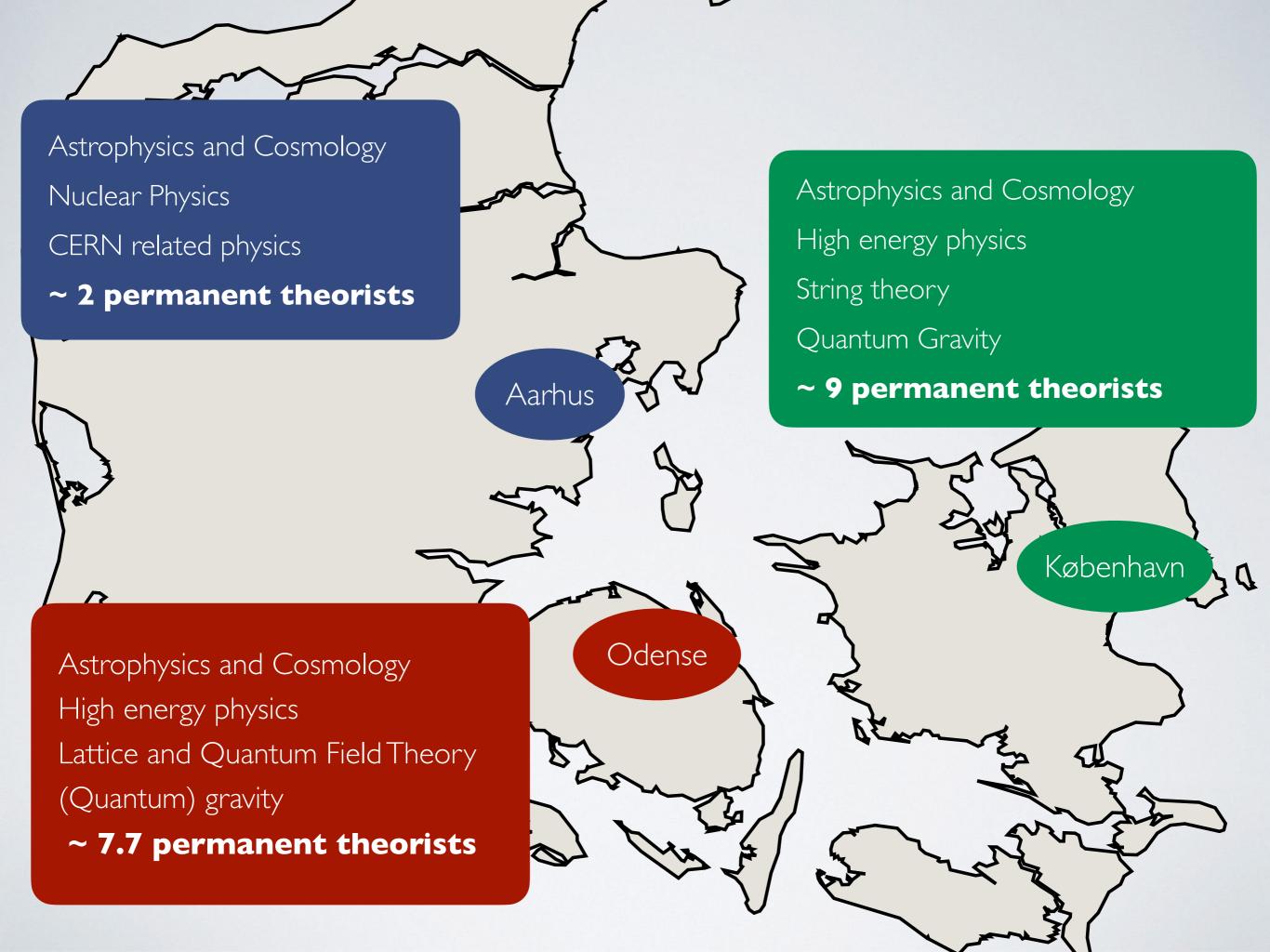
Prize share: 1/2

I apologise if I will not cover or forget fields or activities



Geography

... everyone has a role to play



Astrophysics, Cosmology and CERN-related

- ~ 2 Postdocs in the past few years
- ~ I.4 PhD/year

junior/senior ~ 0.7

Astrophysics, Gravity and Cosmology

- ~ 2 Assistant Professors
- ~ 3 Postdocs
- ~ 3 PhD

High energy physics [Particle, Lattice and QFT]

~ 2 postdocs (lattice)

junior/senior ~ 1.3

NB: None in particle physics

Astro, Cosmology, High energy physics [Particle, Gravity and Strings]

- ~ 5 Assistant Professors
- ~ 8 Postdocs
- ~ I non-tenured Associate Professor
- ~ I tenure-trak Assistant Professor
- ~ IO PhD

Aarhus

Odense

junior/senior = 3.6



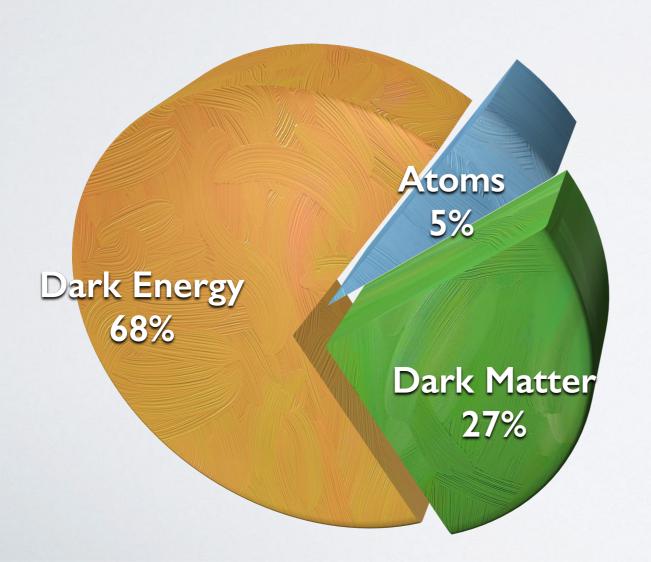
Caveat: Abrupt changes can happen in DK

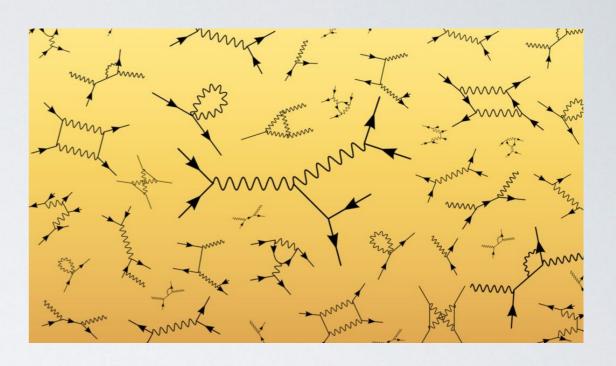
Source: Institute/section leaders: Harmark, Uggerhøj, Frandsen

Activities I

Particle physics

- Standard model physics and beyond,
- Collider physics and phenomenology
- Higgs and flavour physics.
- Effective field theories





Astroparticle and cosmology

- Dark matter and energy
- Neutrino physics
- Multi-messenger astronomy
- Gravity waves analysis and genesis
- Cosmo parameters from CMB
- Inflation

Activities 2

CERN-TH-2021-191 JLAB-THY-21-3528

Lattice QFT & nuclear physics

- Numerical solutions to QFTs
- Strong dynamics
- QCD in extreme conditions
- Quark gluon plasma
- Heavy ion collisions
- Form factors for flavour physics
- Hadronic spectrum and physics
- HVP for g-2 of muon
- Composite BSM and DM

FLAG Review 2021

Flavour Lattice Averaging Group (FLAG)

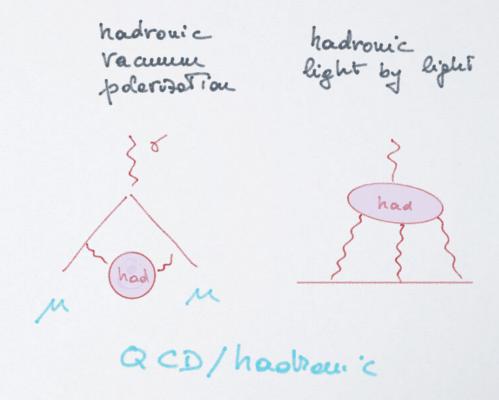
Y. Aoki¹, T. Blum^{2,3}, G. Colangelo⁴, S. Collins⁵, M. Della Morte⁶, P. Dimopoulos^{7,8}, S. Dürr^{9,10}, X. Feng^{11,12,13,14}, H. Fukaya¹⁵, M. Golterman¹⁶, Steven Gottlieb¹⁷, R. Gupta¹⁸, S. Hashimoto^{19,20}, U. M. Heller²¹, G. Herdoiza²², P. Hernandez²³, R. Horsley²⁴, A. Jüttner^{25,26,27}, T. Kaneko^{19,20}, E. Lunghi¹⁷, S. Meinel²⁸,
C. Monahan^{29,30}, A. Nicholson³¹, T. Onogi¹⁵, C. Pena²², P. Petreczky³², A. Portelli²⁴, A. Ramos²³, S. R. Sharpe³³, J. N. Simone³⁴, S. Simula³⁵, S. Sint³⁶, R. Sommer^{37,38}, N. Tantalo³⁹, R. Van de Water³⁴, U. Wenger^{4,27}, and H. Wittig⁴⁰

¹RIKEN Center for Computational Science, Kobe 650-0047, Japan

²Physics Department, University of Connecticut, Storrs, CT 06269-3046, USA

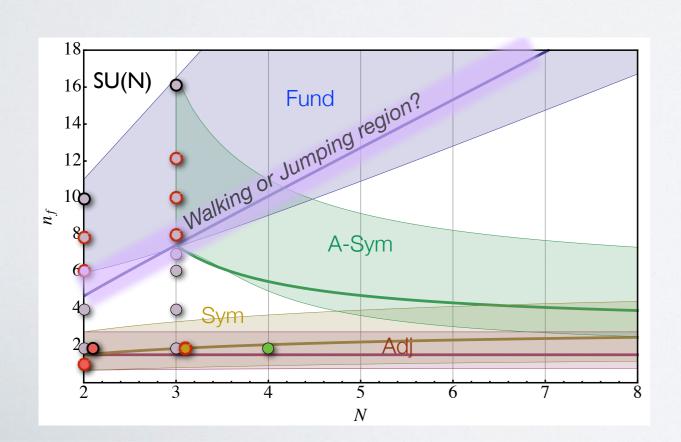
³RIKEN BNL Research Center, Brookhaven National Laboratory, Upton, NY 11973, USA

⁴Albert Einstein Center for Fundamental Physics, Institut für Theoretische Physik, Universität Bern,

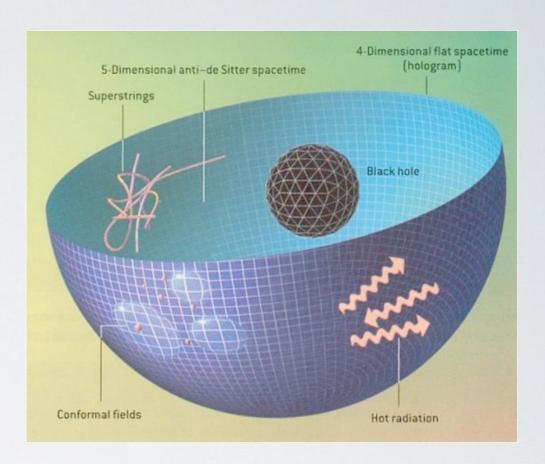


Strings, formal aspects and gravity

- String theory, AdS/CFT
- Integrable models
- Scattering amplitudes
- Perturbative gravity/tools for gravity waves
- Non-relativistic geometry
- Out-of-equilibrium physics
- Quantum gravity and black holes



Activities 3



Solving quantum field theory

- Map fundamental theories
- Quantum field theories phases
- Conformal dynamics
- Semiclassical approaches

Activities 4 From strings and particle physics to pandemics

Rationalising infectious diseases

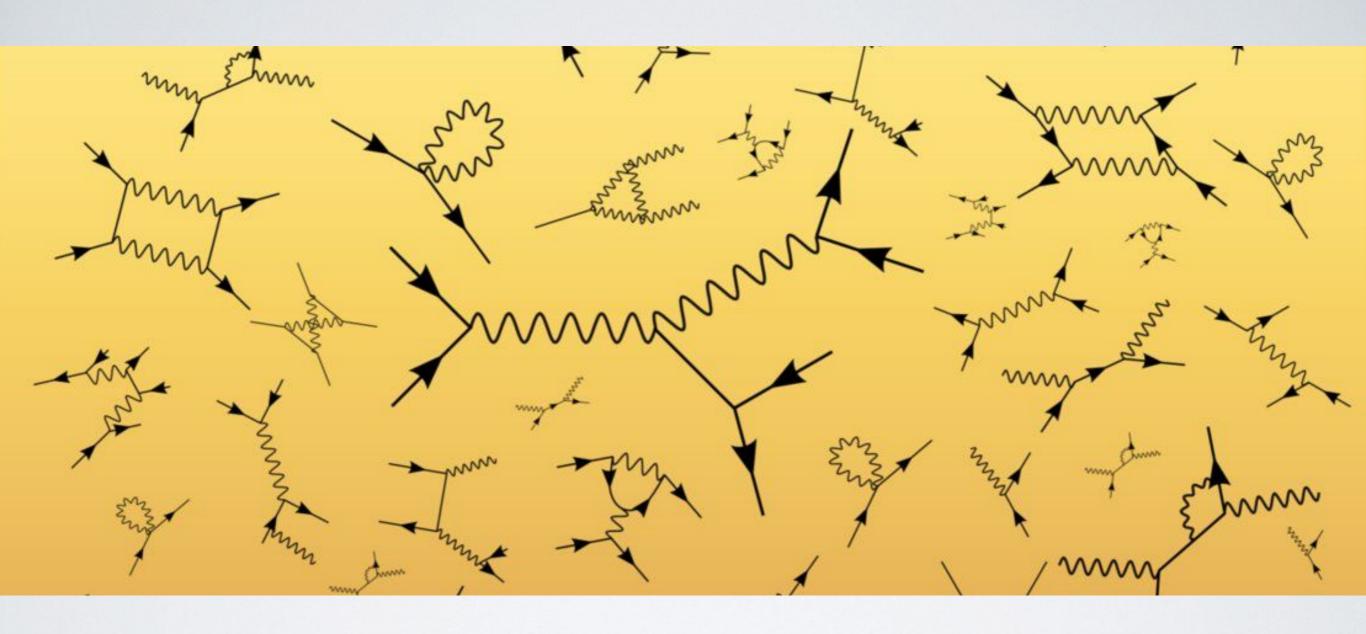
- eRG application to epidemiology
- Complex fixed points/multiwave pandemics [2021 editor pick for mathematics and statics]
- Theory of virus variants/genomics
- eRG + AI (ATLAS colleagues) early warning tool]
- Math of health passes
- Many exciting/useful things to do…

The pleasure of working with amazing people





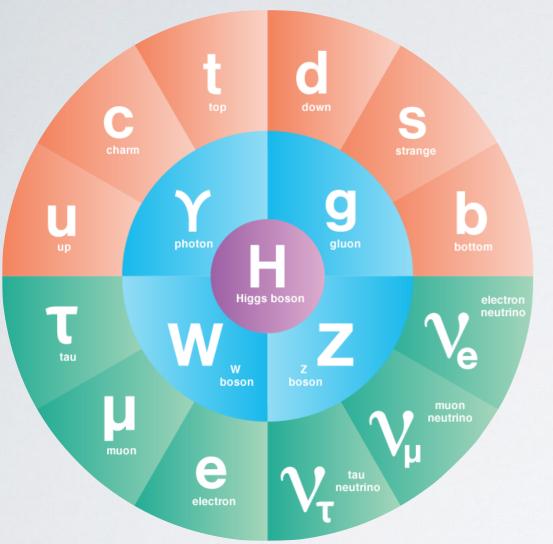


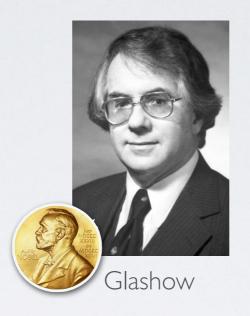


Particles physics

Standard model and beyond

Standard model, 1979, 2004, 2013





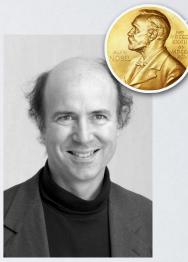




Salam Weinberg



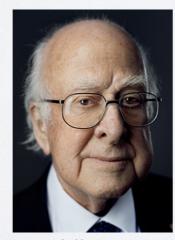




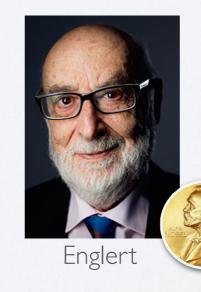
Gross

Politzer

Wilczek



Higgs

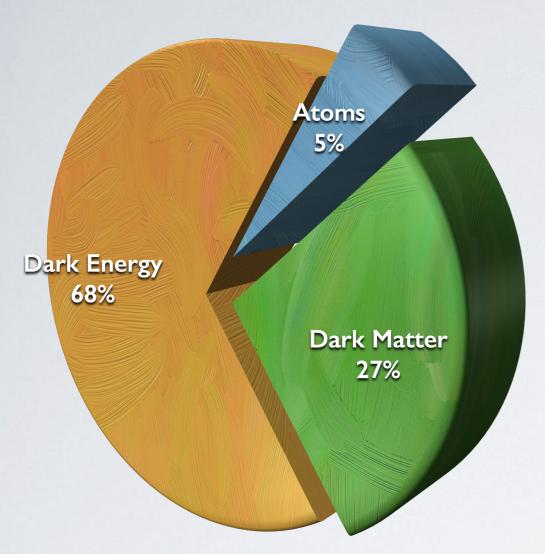


Standard model ~ 2022

$$L = \boxed{-\frac{1}{2}F^2 + i\overline{Q}\gamma_\mu D^\mu Q} + \boxed{y(\overline{Q}_L H Q_R + \text{h.c.})} \quad \text{Yukawa}$$
 Gauge
$$\boxed{\text{Tr}\left[\text{DH}^\dagger \text{DH}\right] - \left[\lambda_u \text{Tr}\left[(\text{H}^\dagger \text{H})^2\right] - \lambda_v \text{Tr}\left[(\text{H}^\dagger \text{H})\right]^2\right]}$$

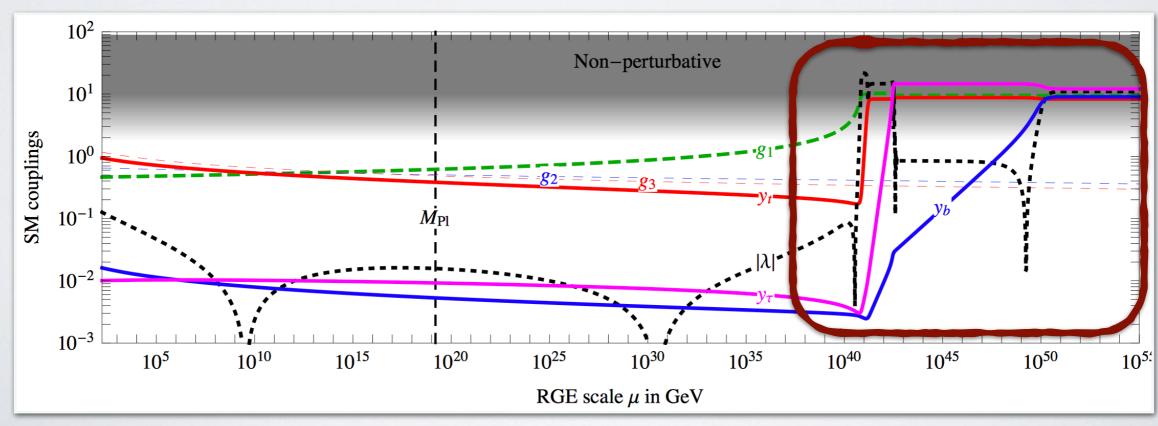
Scalar selfinteractions

- Gauge structure established
- Yukawa structure to be determined
- · Higgs (nature) self-coupling to be determined



SM is incomplete

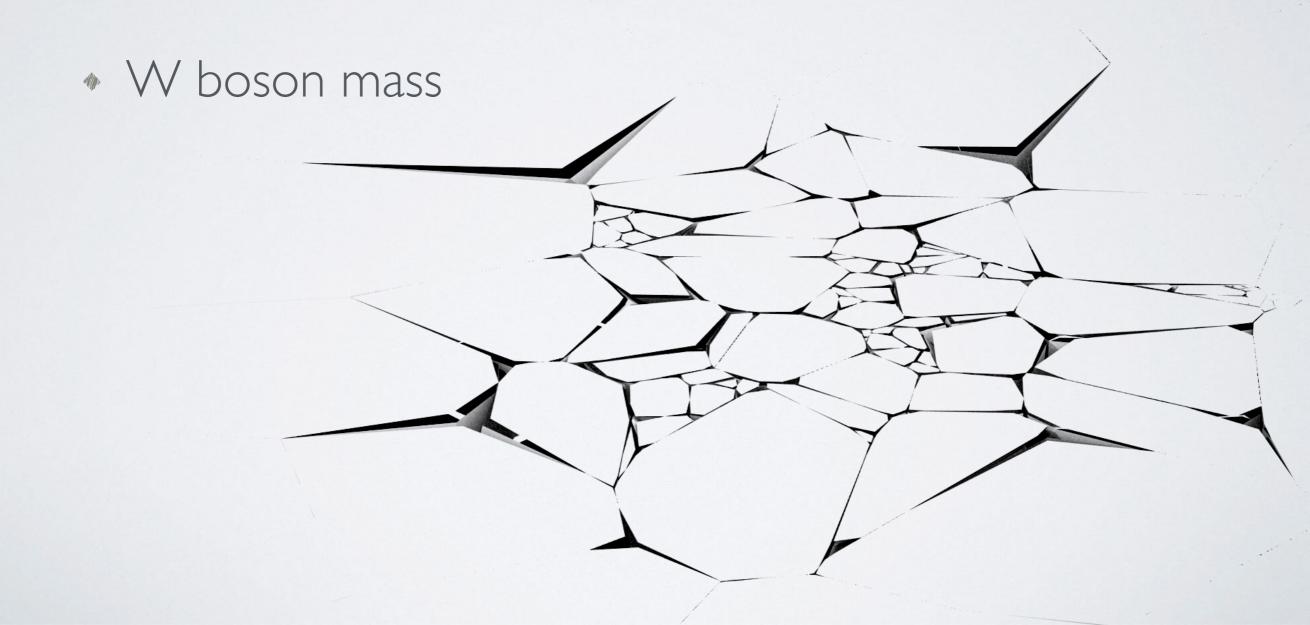
- Dark matter & energy
- Matter over antimatter
- Neutrino (nature) masses
- Inflation
- Quantum Gravity



Cracks

Lepton flavour (non) universality

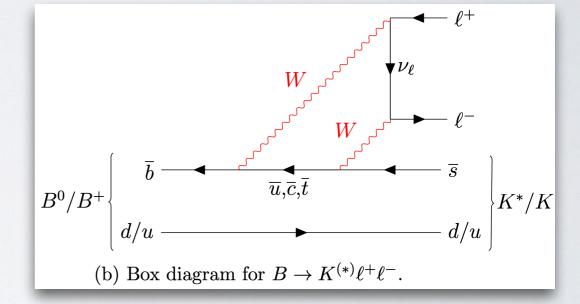
⋄ g-2 of the muon



Lepton flavor (non) universality

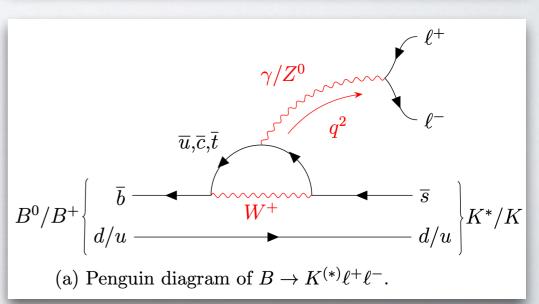
$$R_K = \frac{\text{BR}\left(B^+ \to K^+ \mu^+ \mu^-\right)}{\text{BR}\left(B^+ \to K^+ e^+ e^-\right)} = 0.846^{+0.042}_{-0.039} (\text{stat})^{+0.013}_{-0.012} (\text{syst}) \quad [1.1,6] \text{ GeV}^2$$

$$R_{K^*} = \begin{cases} 0.660_{-0.070}^{+0.110} \pm 0.024 & (2m_{\mu})^2 < q^2 < 1.1 \text{ GeV}^2 \\ 0.685_{-0.069}^{+0.113} \pm 0.047 & 1.1 \text{ GeV}^2 < q^2 < 6 \text{ GeV}^2 \end{cases}$$

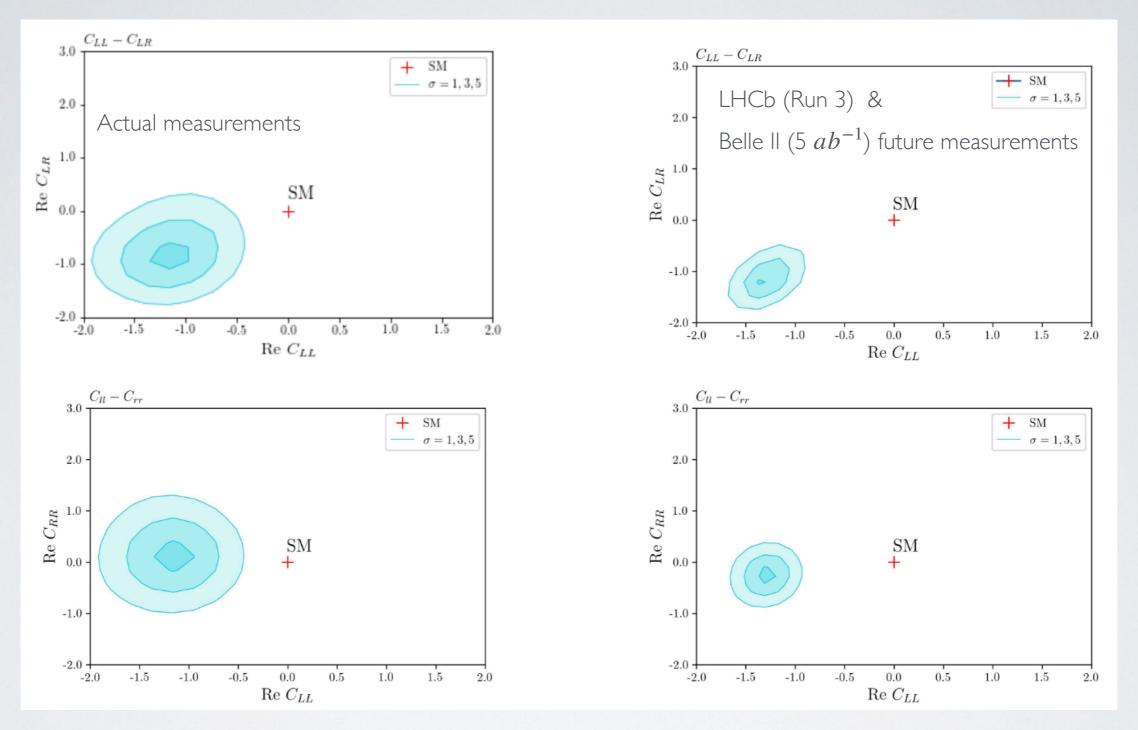


$$R_K \simeq 1 + 2 \frac{\text{Re}C_{b_{L+R}(\mu-e)_L}^{\text{BSM}}}{C_{b_L\mu_L}^{\text{SM}}}$$

R. Aaij et al. [LHCb], Nature Phys. 18 (2022)



Global fit to HI and HS observables



 4.7σ (6.1 σ) SM deviation, single Wilson coefficient HI (HI + HS)

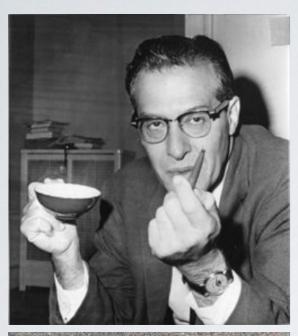
 7.2σ four Wilson coefficients HI + HS

 4.9σ if Rk(*) set to unity

D'Alise, De Nardo, Di Luca, Fabiano, Frattulillo, Gaudino, lacobacci, Merola, Sannino, Santorelli, Vignaroli, 2204.03686

collaboration with Belle II colleagues

Muon g-2



<u>α</u> 2π JULIAN SCHWINGER 2·12·1918 — 7·16·1994 1948

$$a_{\ell} = \frac{g_{\ell} - 2}{2} = \frac{\alpha}{2\pi} + \mathcal{O}(\alpha^2)$$



hadrouic Vacuum poleridos ion

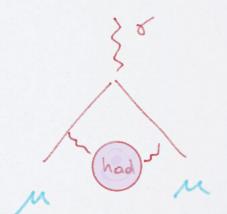
hadronic light by light

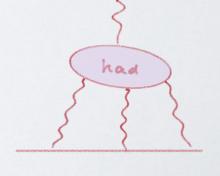


QED

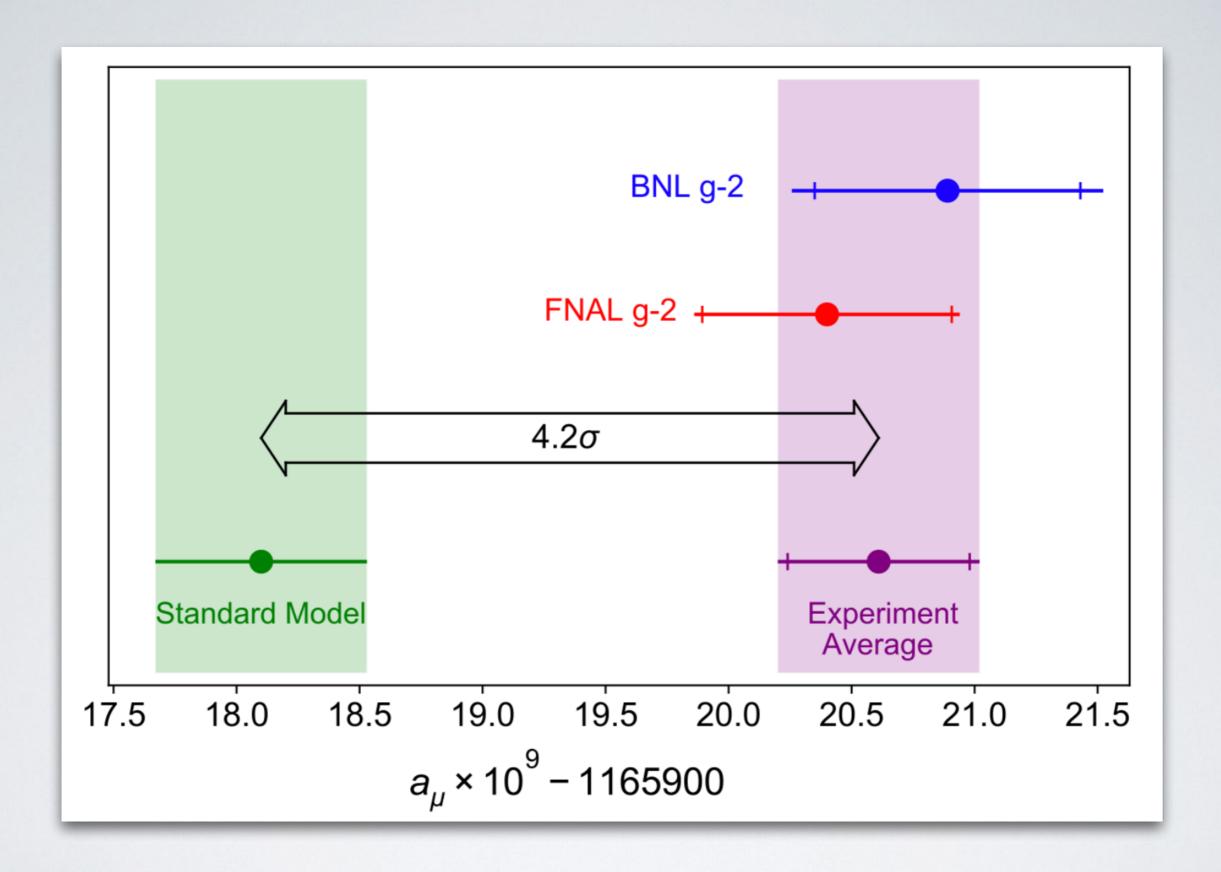


Week



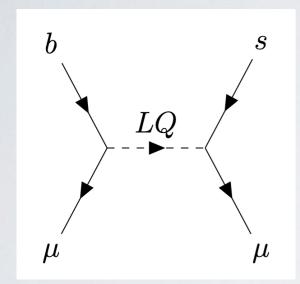


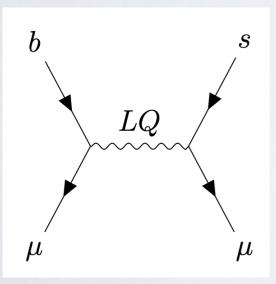
QCD/haobreuic



$$\Delta a_{\mu} = a_{\mu}(\text{Exp}) - a_{\mu}(\text{SM}) = (251 \pm 59) \times 10^{-11}$$

μ μ

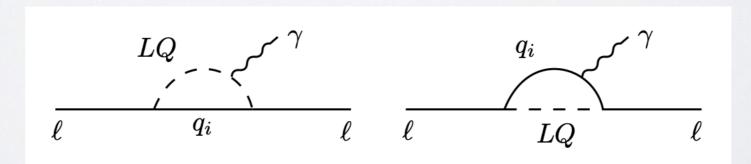




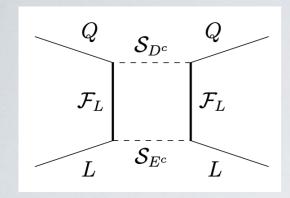
New physics

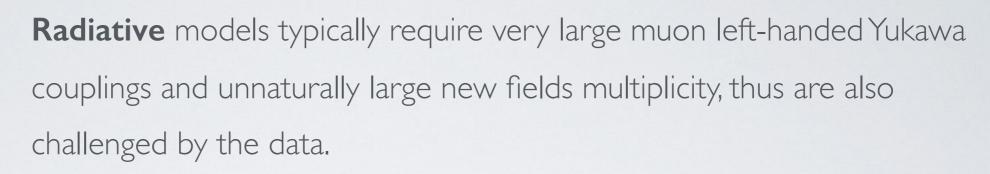
Z' can't easily explain LFU anomalies because of the Bs mass mixing and LHC bounds, and too light to explain g-2 unless appears radiatively.

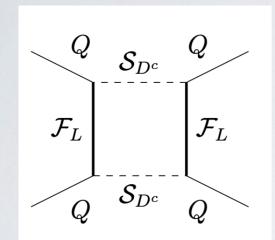
Scalar leptoquarks, either a singlet or a doublet of weak interactions, can explain the anomalies. In the first case one has to forbid di-quark couplings and in the latter the contribution to flavour anomalies is radiatively generated.



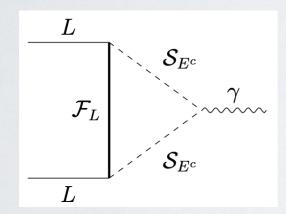
New physics







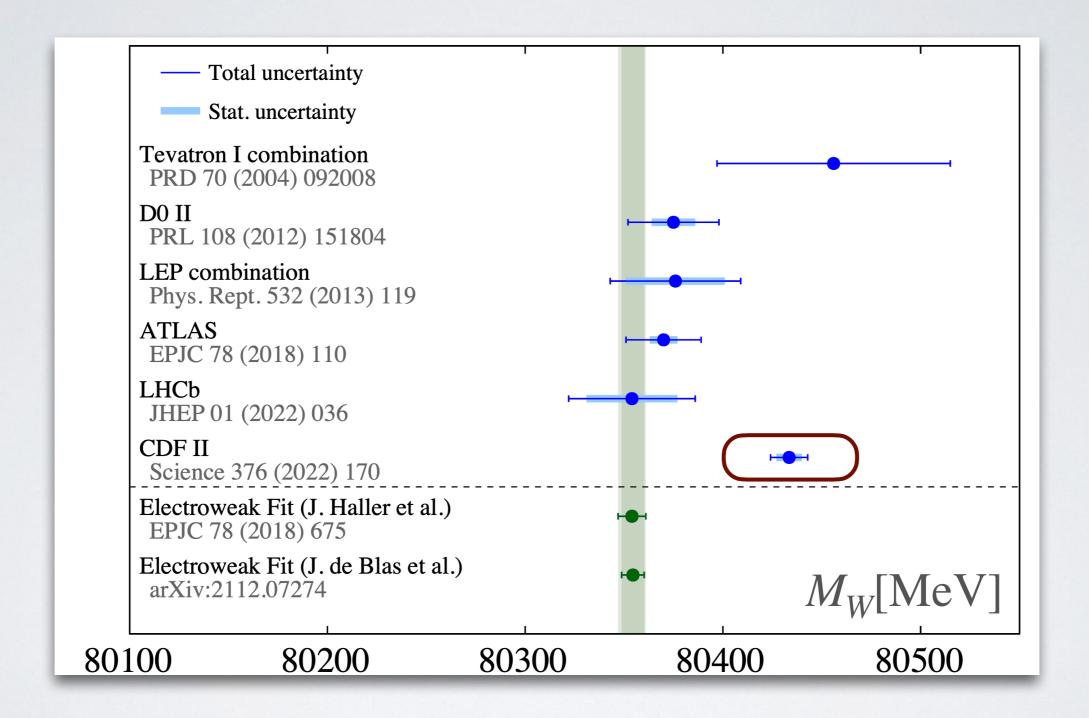
Technicolor/composite-like models, with a scale of new physics around $2 \, \text{TeV}$, can explain LFU violations as well as the g -2 of the muon.



Composite Goldstone Higgs scenarios are challenged by the low energy composite scale required by the g-2 anomaly, and therefore are disfavoured.

It is possible to accommodate dark matter and anomalies by either freeze-in or freeze-out type of constructions. The first mechanism can be realized in leptoquark type of models.

W - mass



 7σ deviation from the SM

What can we say?

Result due to increase statistics/better understanding of PDFs and CDF detector (PDFs alone reduce uncertainty from 10 to 3.9 MeV)

Tension with ATLAS and SM!

PDF correlations, higher order QCD and QED effects.

CDF used old ResBos (NNLL+NLO) with ResBos2 (NNNLL+NNLO)

Data driven techniques capture HO corrections.

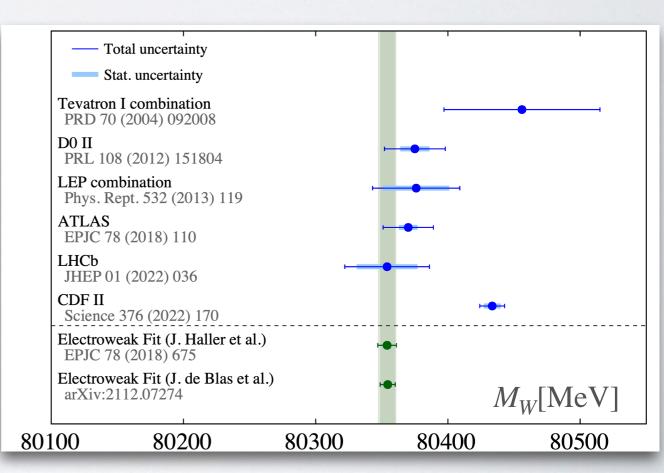
IOMeV shift.

Isaacson, Fu and Yuan, 2005.02788

Naive weighted average

$$M_W$$
 = 80,410 ± 7 MeV

 5σ discrepancy with SM



Non-standard Higgs

 $\Delta M_W \approx 300 \text{ MeV} \times (1.43 T - 0.86 S)$

Altarelli, Barbieri, Caravaglios PLB 349, 145 (1995)

Non-standard Higgs coupling to WW/ZZ

$$\kappa_V^2 = \frac{\sigma_{\text{VBF}}}{\sigma_{\text{VBF}}^{\text{SM}}} \equiv \frac{\Gamma_{h \to WW/ZZ}}{\Gamma_{h \to WW/ZZ}^{\text{SM}}}$$

$$T = -\frac{3}{16\pi c_W^2} (1 - \kappa_V^2) \ln \frac{\Lambda^2}{m_h^2},$$

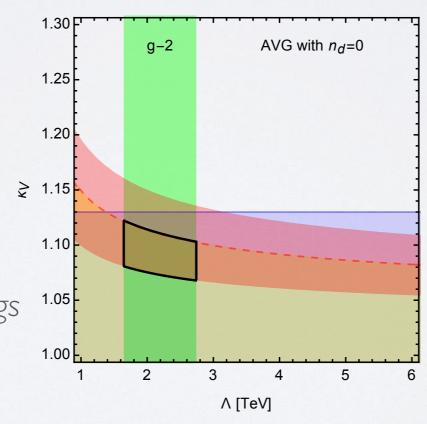
$$T = -\frac{3}{16\pi c_W^2} (1 - \kappa_V^2) \ln \frac{\Lambda^2}{m_h^2}, \qquad S = \frac{1}{12\pi} (1 - \kappa_V^2) \ln \frac{\Lambda^2}{m_h^2} + \Delta S_{\text{UV}} \qquad S = -\frac{4}{9} c_W^2 T + \Delta S_{\text{UV}}$$

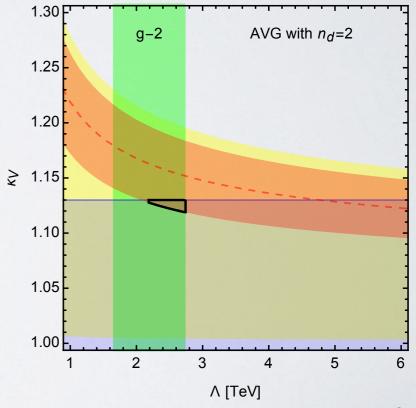
$$S = -\frac{4}{9}c_W^2T + \Delta S_{\rm UV}$$

$$\Delta S_{\rm UV} = \frac{n_d}{6\pi}$$

Enhancement of 5% or more

Dilaton, Techni & glueball Higgs work Too Small coupling for Goldstone Higgs





Yellow band = bound on direct s_w^2 Blue region allowed by ATLAS

Cacciapaglia, Sannino 2204.045 | 4

Sannino, Phys. Rev. D. 93 (2016), 1508.07413

Exciting times!

"Our imagination is stretched to the utmost, not, as in fiction, to imagine things which are not really there, but just to comprehend those things which 'are' there."

Richard Feynman