

Beyond the Standard Model

BND School 2025

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09 September 2025



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About Me

CALTECH

Univ. Edinburgh

Niels Bohr Inst.

UvA/Nikhef

CERN

São Paulo Univ.

CMS: 2008-2013

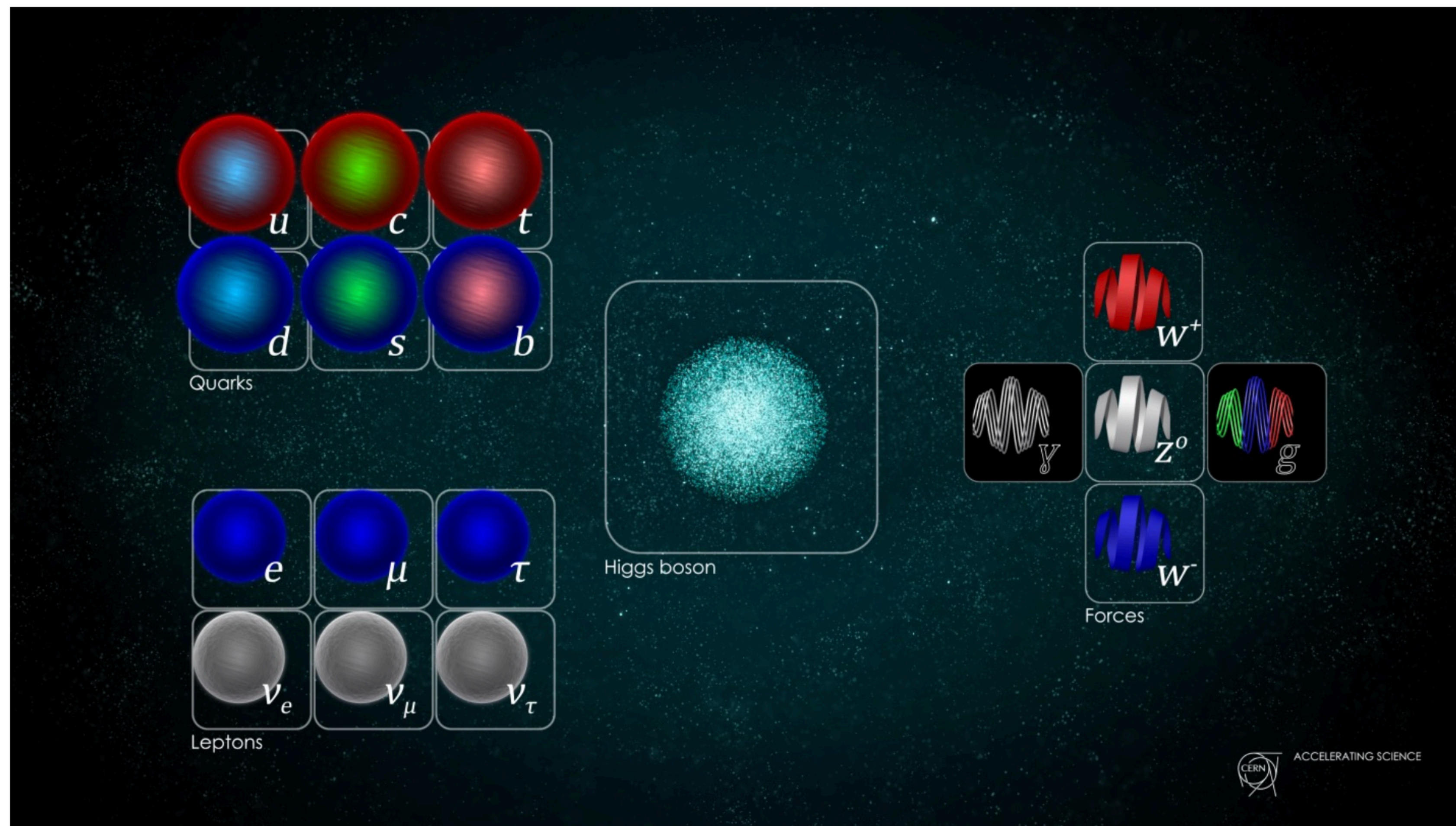
ATLAS: 2013-



The Standard Model of Particle Physics

Matter particles

Interactions



Matter Particles

- Fundamental matter: point-like spin- $1/2$ fermions

	LEPTONS			QUARKS		
		q	m/GeV		q	m/GeV
First Generation	e^-	-1	0.0005	d	$-1/3$	0.3
	ν_1	0	≈ 0	u	$+2/3$	0.3
Second Generation	μ^-	-1	0.106	s	$-1/3$	0.5
	ν_2	0	≈ 0	c	$+2/3$	1.5
Third Generation	τ^-	-1	1.77	b	$-1/3$	4.5
	ν_3	0	≈ 0	t	$+2/3$	173

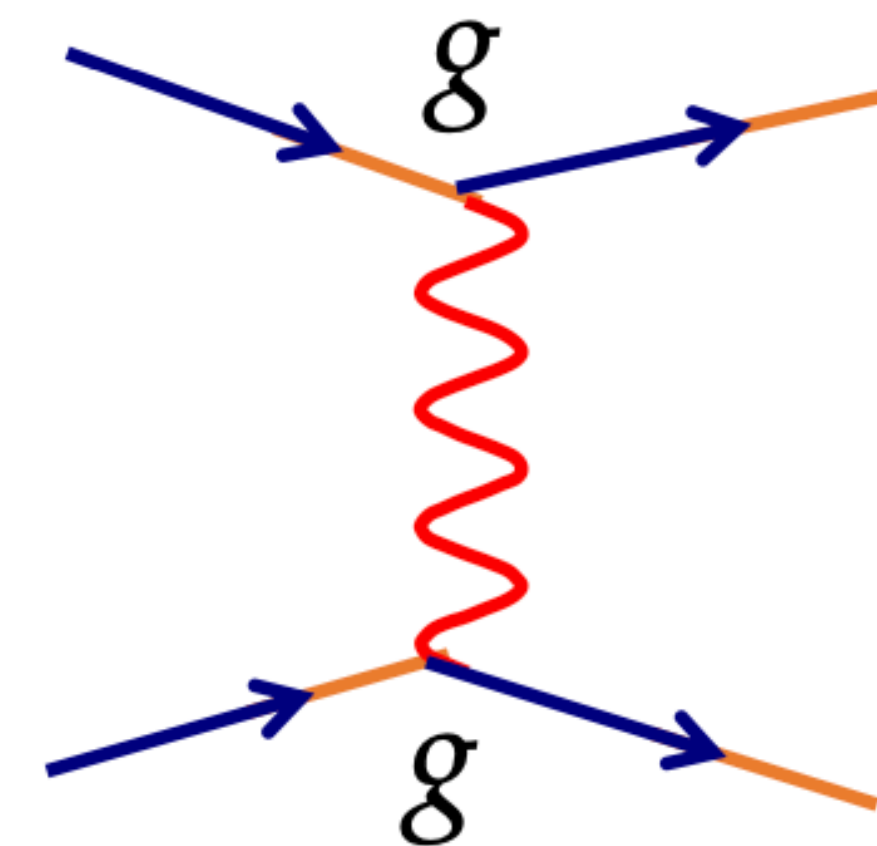
The masses quoted for the quarks are the “constituent masses”, i.e. the effective masses for quarks confined in a bound state

- Three generations
- Very light neutrinos

Interactions

- Forces: exchange of spin-1 *gauge bosons*

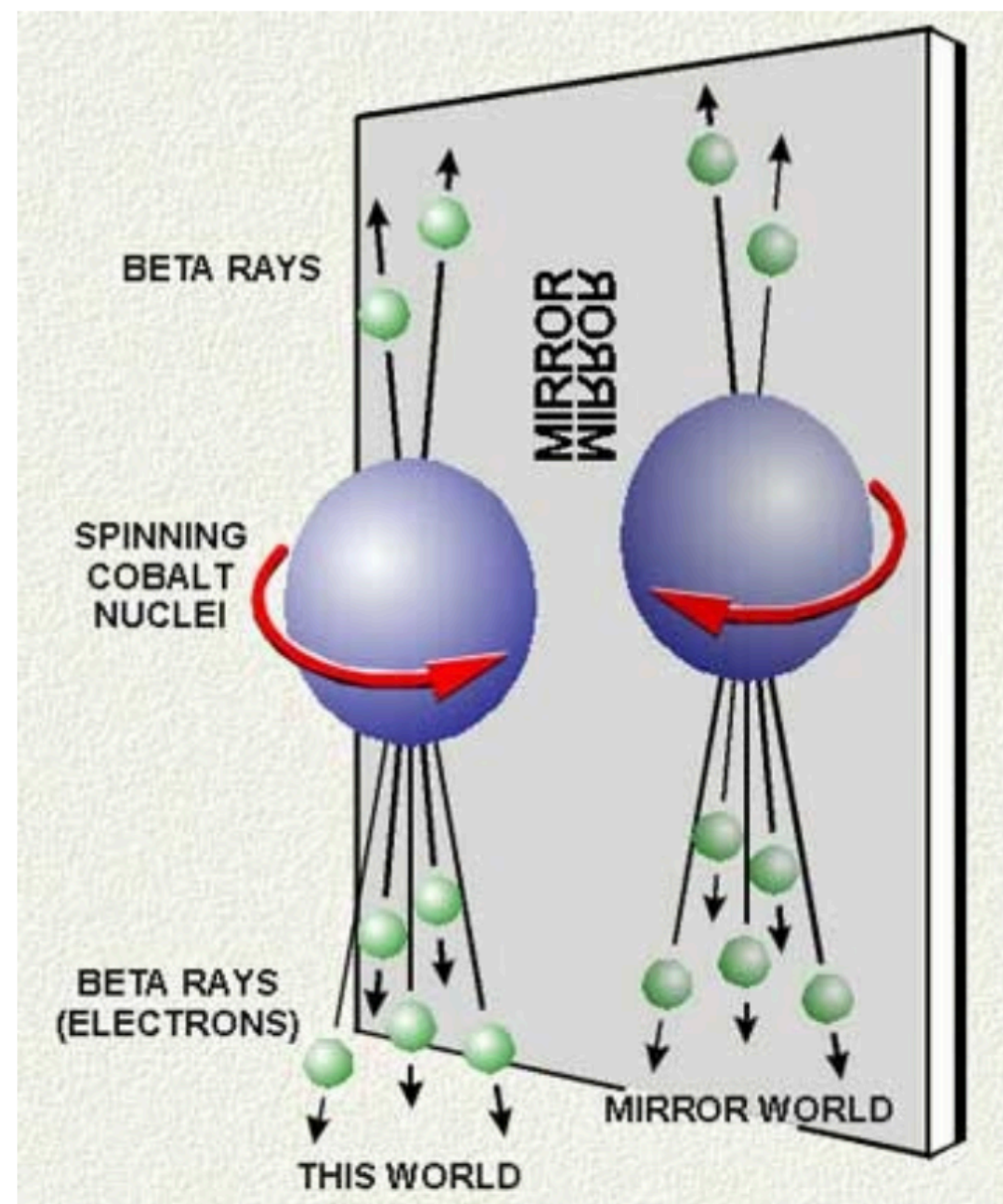
Force	Boson(s)	J^P	m/GeV
EM (QED)	Photon γ	1^-	0
Weak	$W^\pm / Z$	1^-	80 / 91
Strong (QCD)	8 Gluons g	1^-	0
Gravity (?)	Graviton?	2^+	0



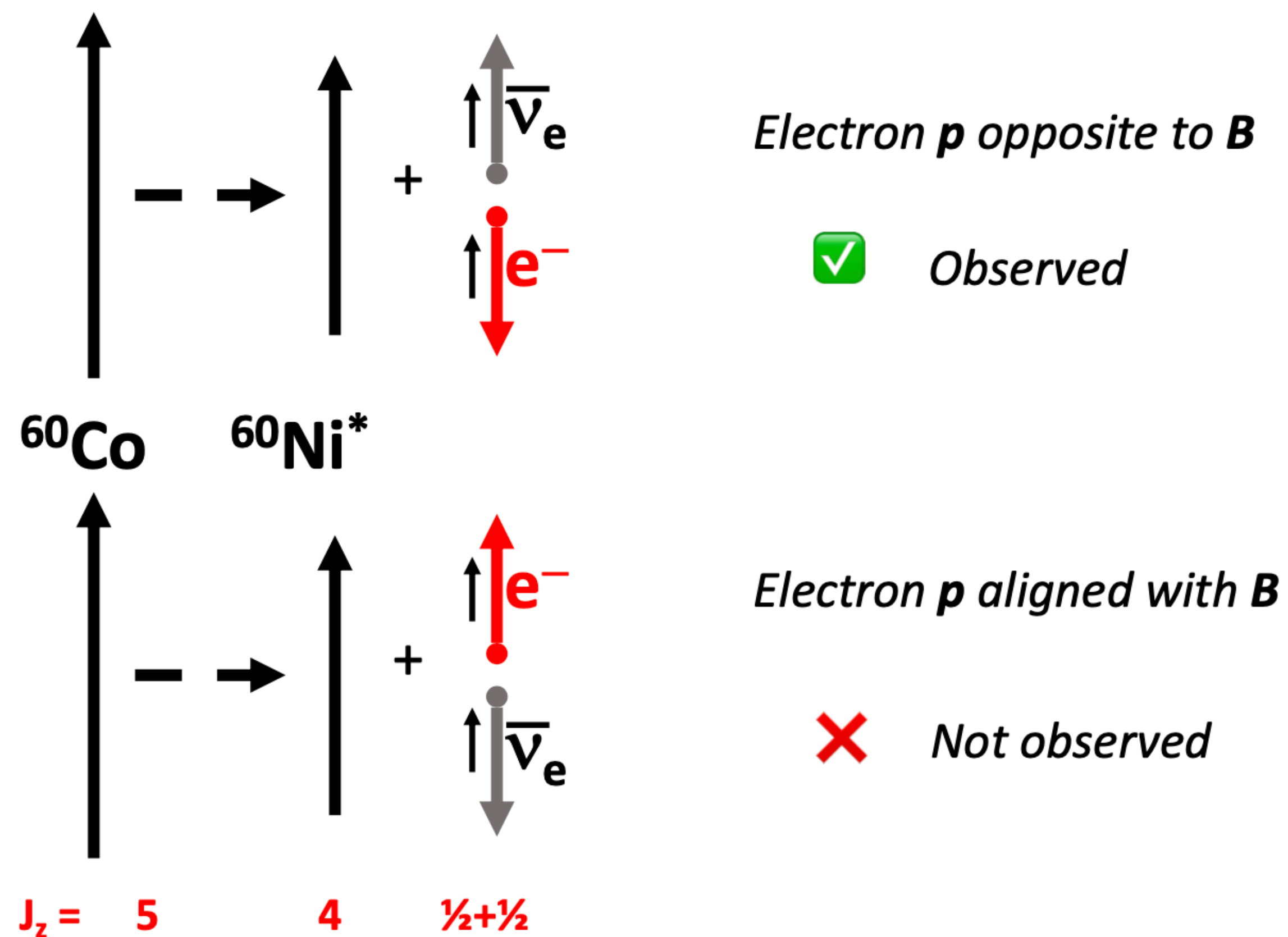
- ➔ Matter fermions charges $g \Rightarrow$ interactions (*local gauge invariances*)
- ➔ No gravity!

Weak interaction violates parity!

Nuclear β -decay:
 $^{60}\text{Co} \rightarrow ^{60}\text{Ni}^* + e^- \bar{\nu}_e$



C.S. Wu, 1956

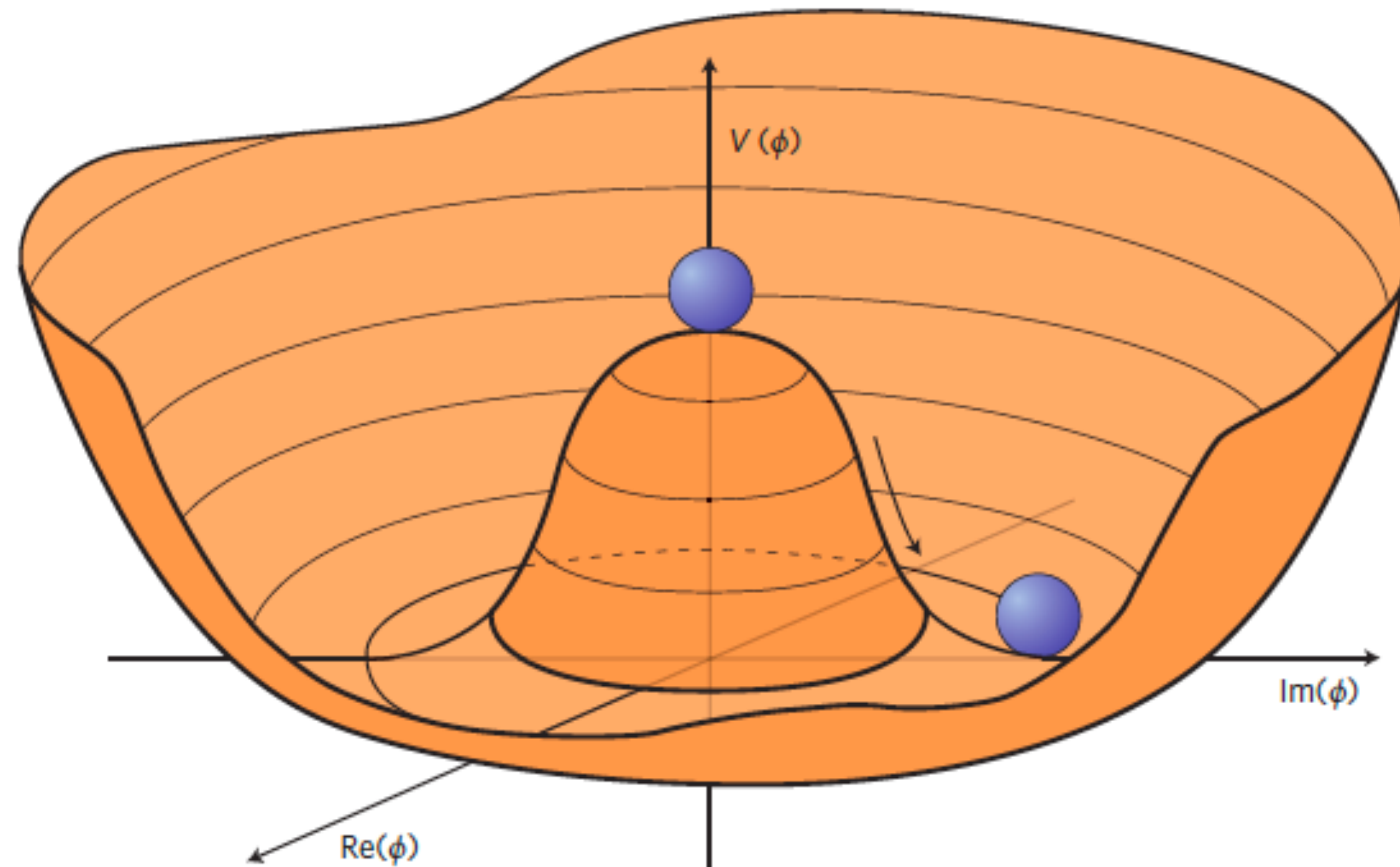


$$SU(3)_C \times SU(2)_I \times U(1)_Y$$

- Standard Model Lagrangian invariant under $SU(3)_C \times SU(2)_I \times U(1)_Y$
 - ➔ C = colour charge (strong interaction)
 - ➔ I = weak isospin (electroweak interaction)
 - ➔ Y = hypercharge (electroweak interaction)

Combine to form the electromagnetic and weak interactions
- We need the **Brout-Englert-Higgs mechanism** to make the weak gauge bosons massive!

The Brout-Englert-Higgs Mechanism



- Introduction of a potential to the Lagrangian
- ➔ Induce spontaneous **electroweak symmetry breaking**
 - Gives mass to $W^\pm/Z$ weak bosons
 - Leaves γ massless 😊
 - Resulting particle - Higgs boson

Standard Model - What works well

- Very precisely measured in different energy scales
- Any new theory must respect all of these measurements too!



Number of Generations

Measured: $\Gamma_Z = 2.4952 \pm 0.0023 \text{ GeV}$

$$\Gamma_Z = \Gamma_{ee} + \Gamma_{\mu\mu} + \Gamma_{\tau\tau} + \Gamma_{\text{hadrons}} + \Gamma_{\nu_1\nu_1} + \Gamma_{\nu_2\nu_2} + \Gamma_{\nu_3\nu_3} + ?$$

Peak cross section: $\sigma_{f\bar{f}}^0 = \frac{12\pi}{m_Z^2} \frac{\Gamma_{ee}\Gamma_{f\bar{f}}}{\Gamma_Z^2}$

$$\Gamma_Z = 3\Gamma_{\ell\ell} + \Gamma_{\text{hadrons}} + N_\nu \Gamma_{\nu\nu}$$

measured from
Z lineshape

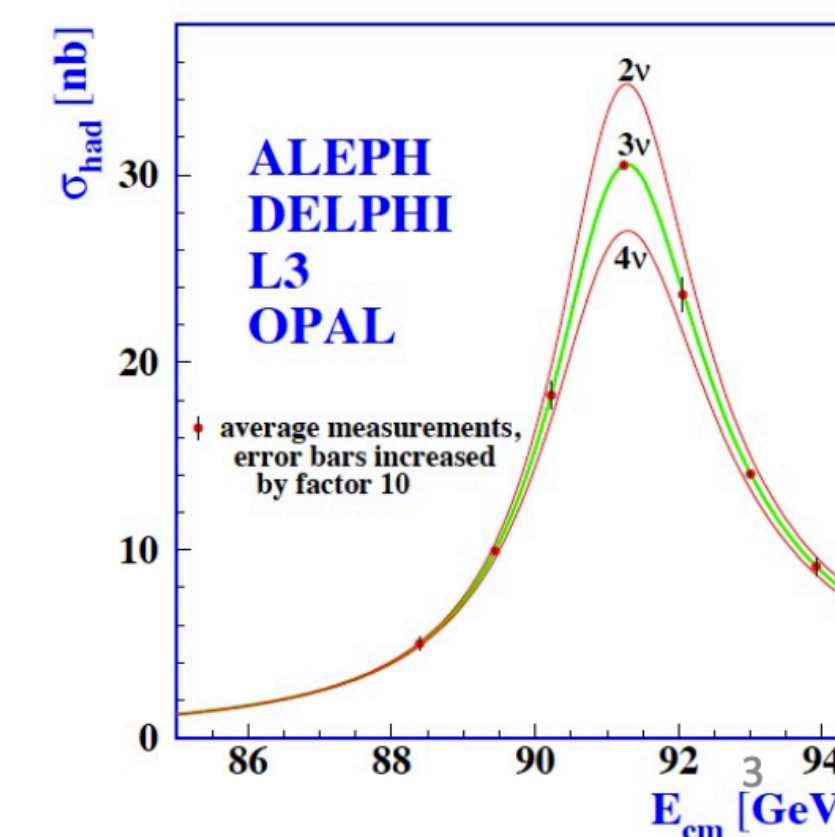
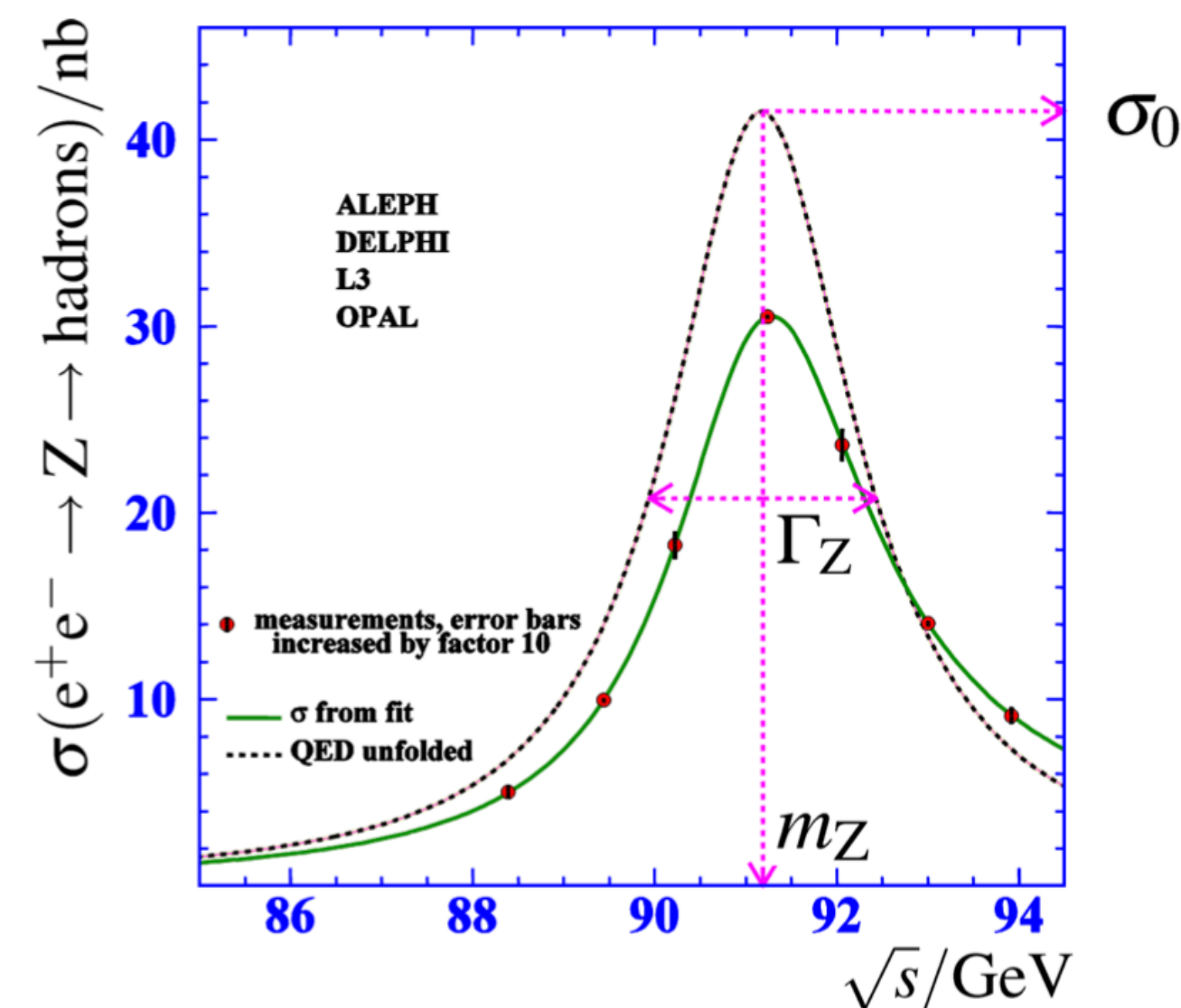
measured from
peak cross sections

calculated



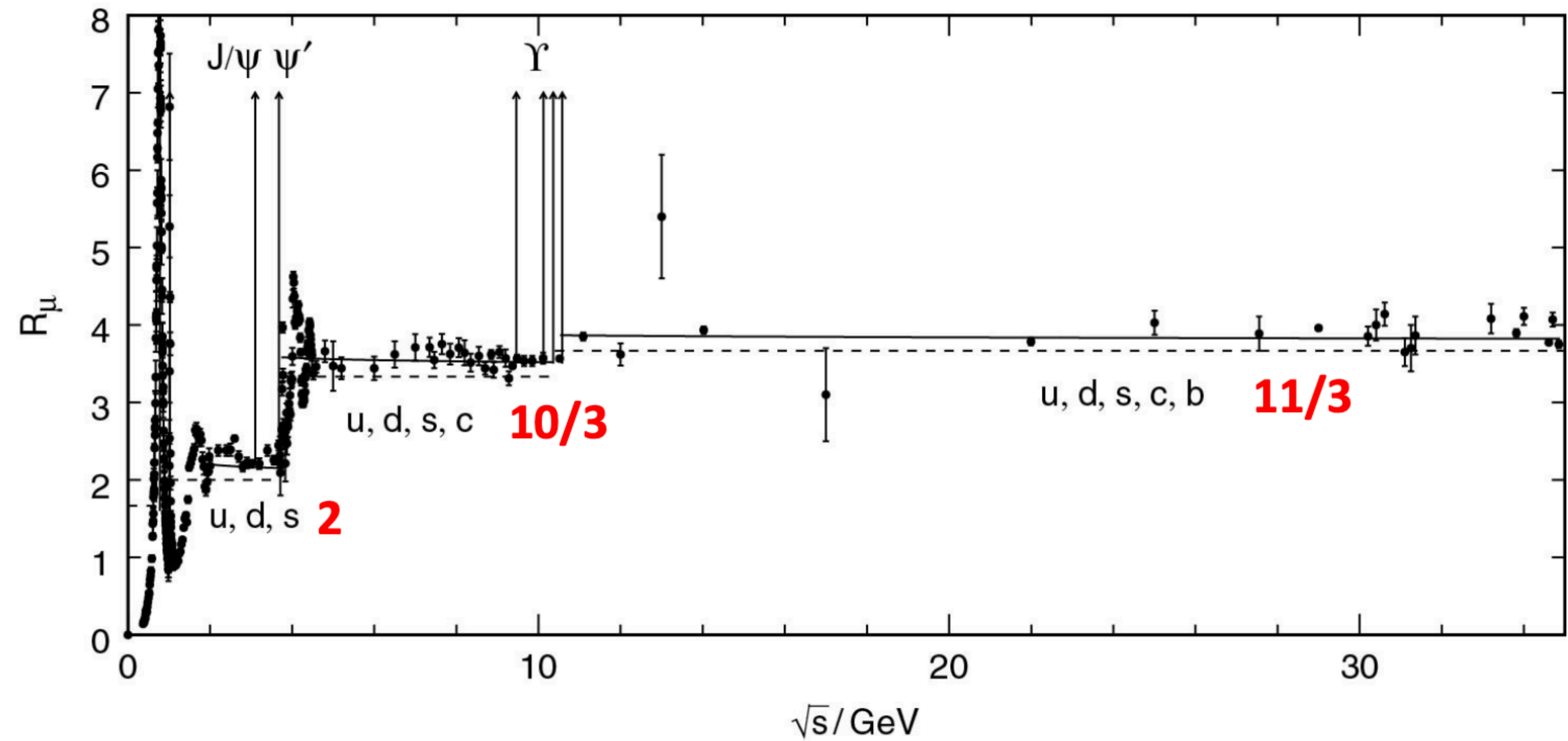
$$N_\nu = 2.9963 \pm 0.0074$$

(Plus: limits on other invisible Z decays)



Quark Colours

$$R_\mu = \frac{\sigma(e^+e^- \rightarrow \text{hadrons})}{\sigma(e^+e^- \rightarrow \mu^+\mu^-)} = \underset{\substack{\text{nr of colors} \\ \downarrow}}{3} \sum_{\text{flavours}} Q_q^2$$



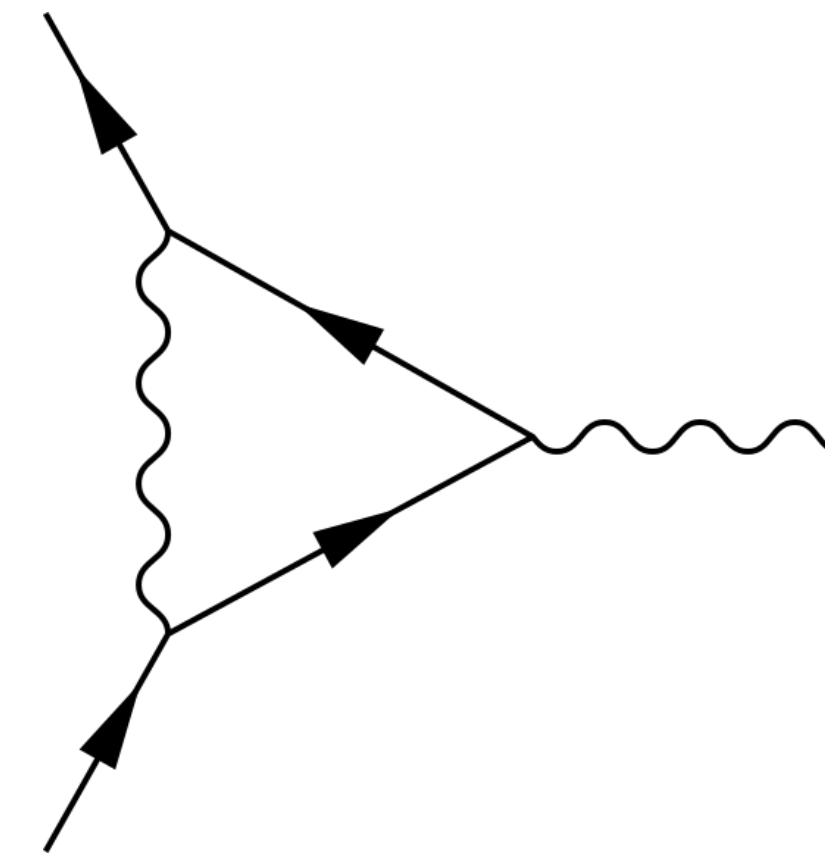
Further evidence: $\Gamma(\pi^0 \rightarrow \gamma\gamma) \sim N_C^2$

Branching fractions of Z and W into hadrons scale with number of colors

Running of α_s

Electron Anomalous Magnetic Dipole Moment

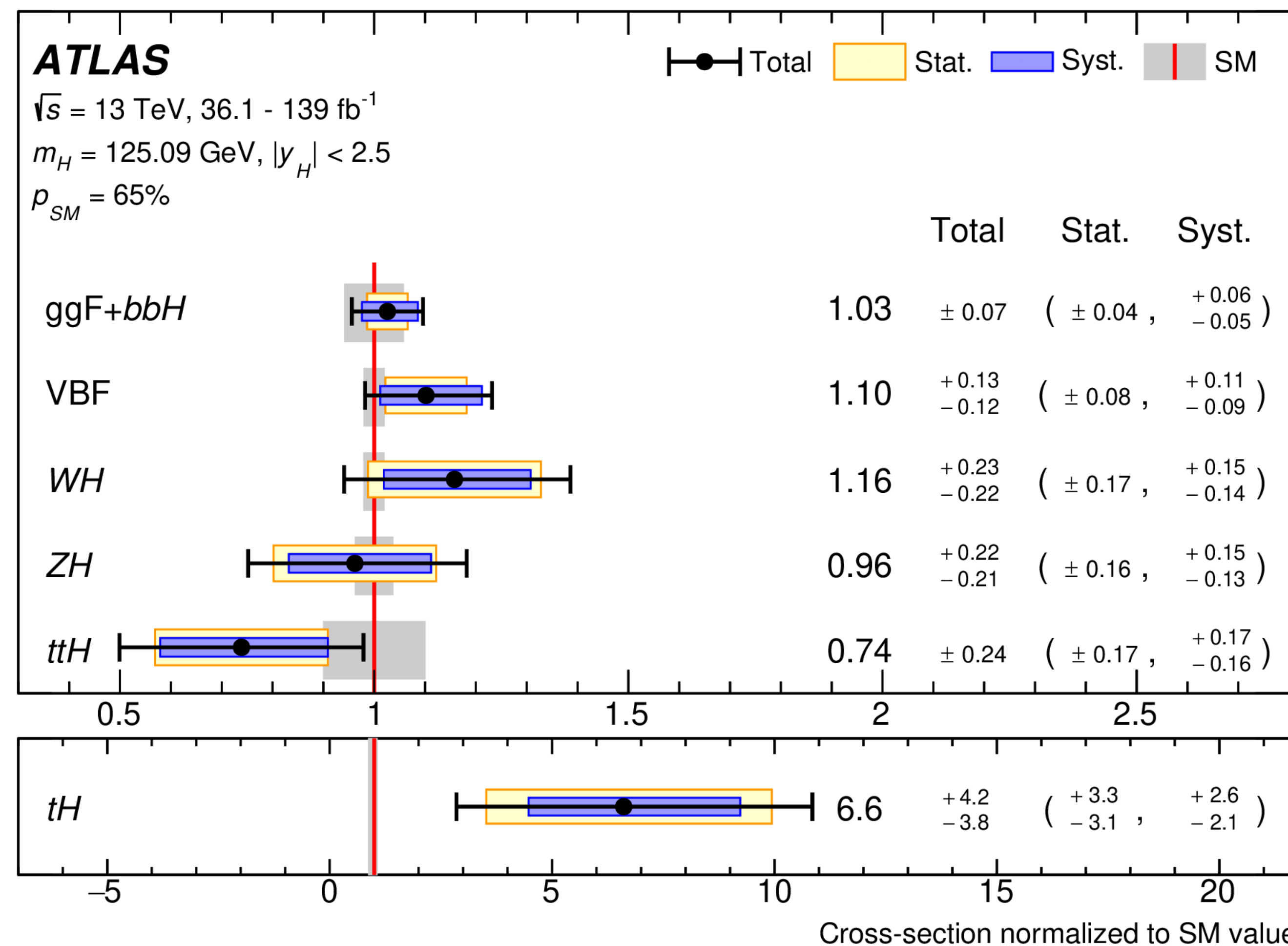
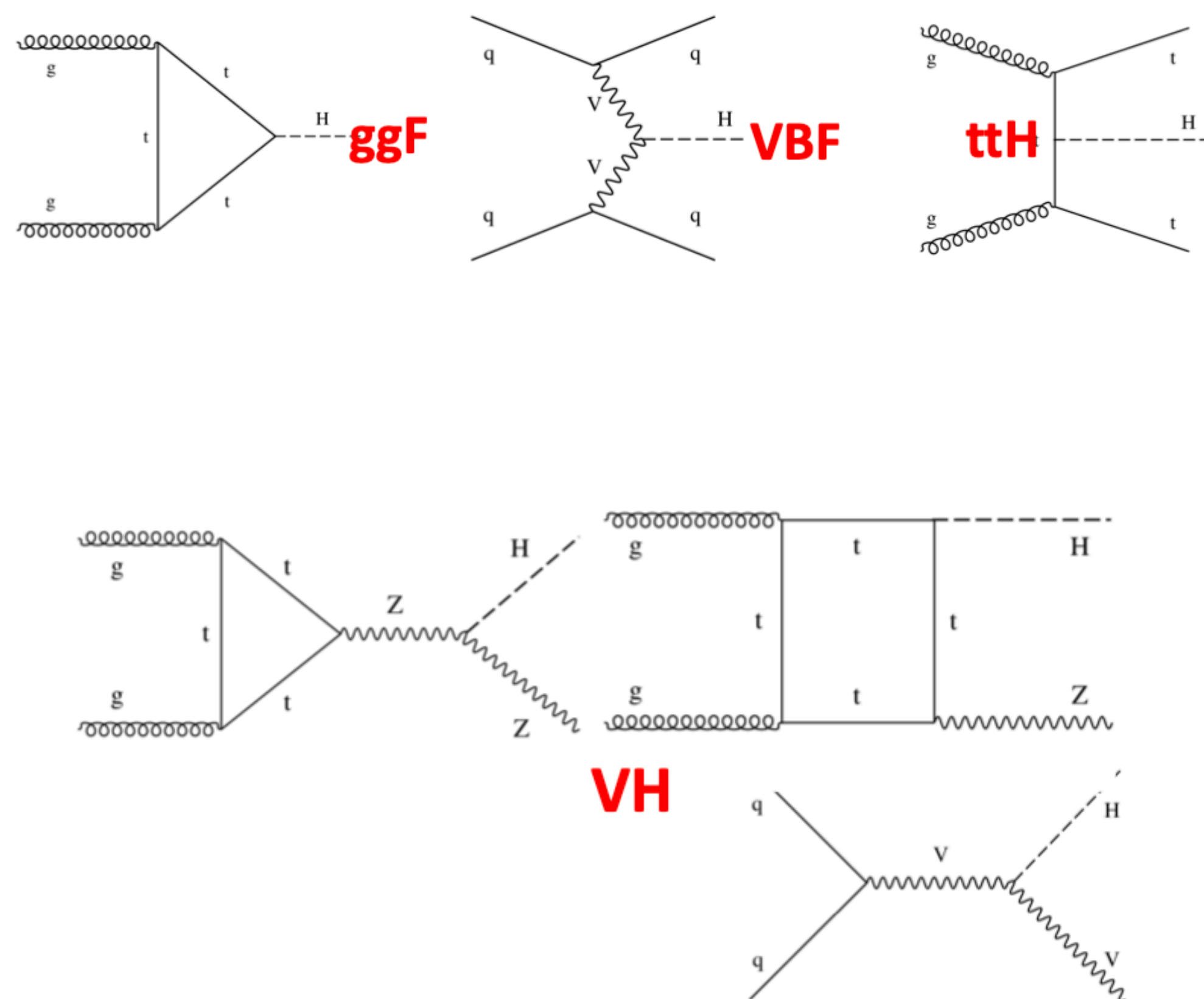
- a_e : contribution of effects of quantum mechanics (loops) to the magnetic moment g of the electron
- ➔ the most accurately verified prediction in the history of physics



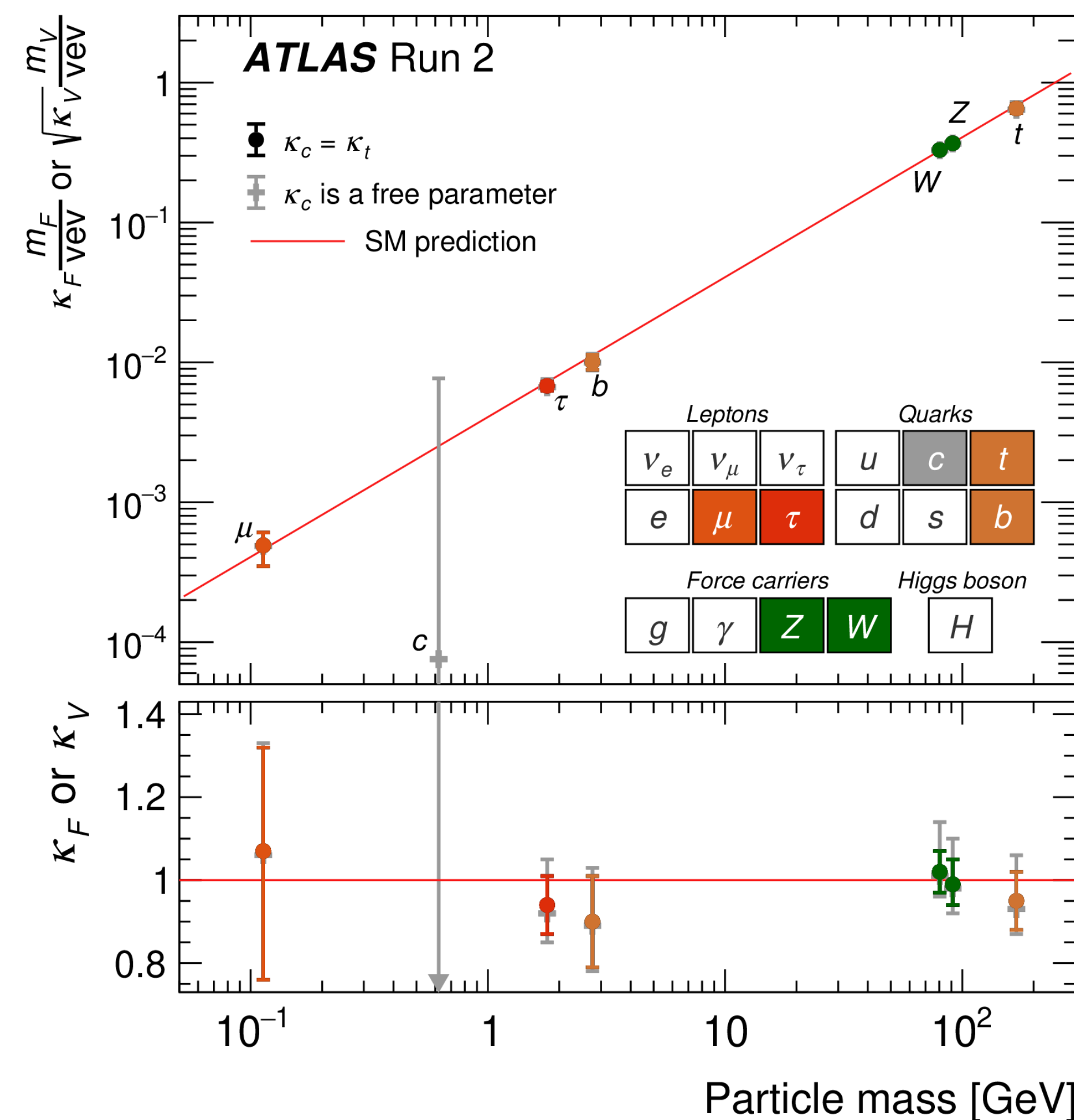
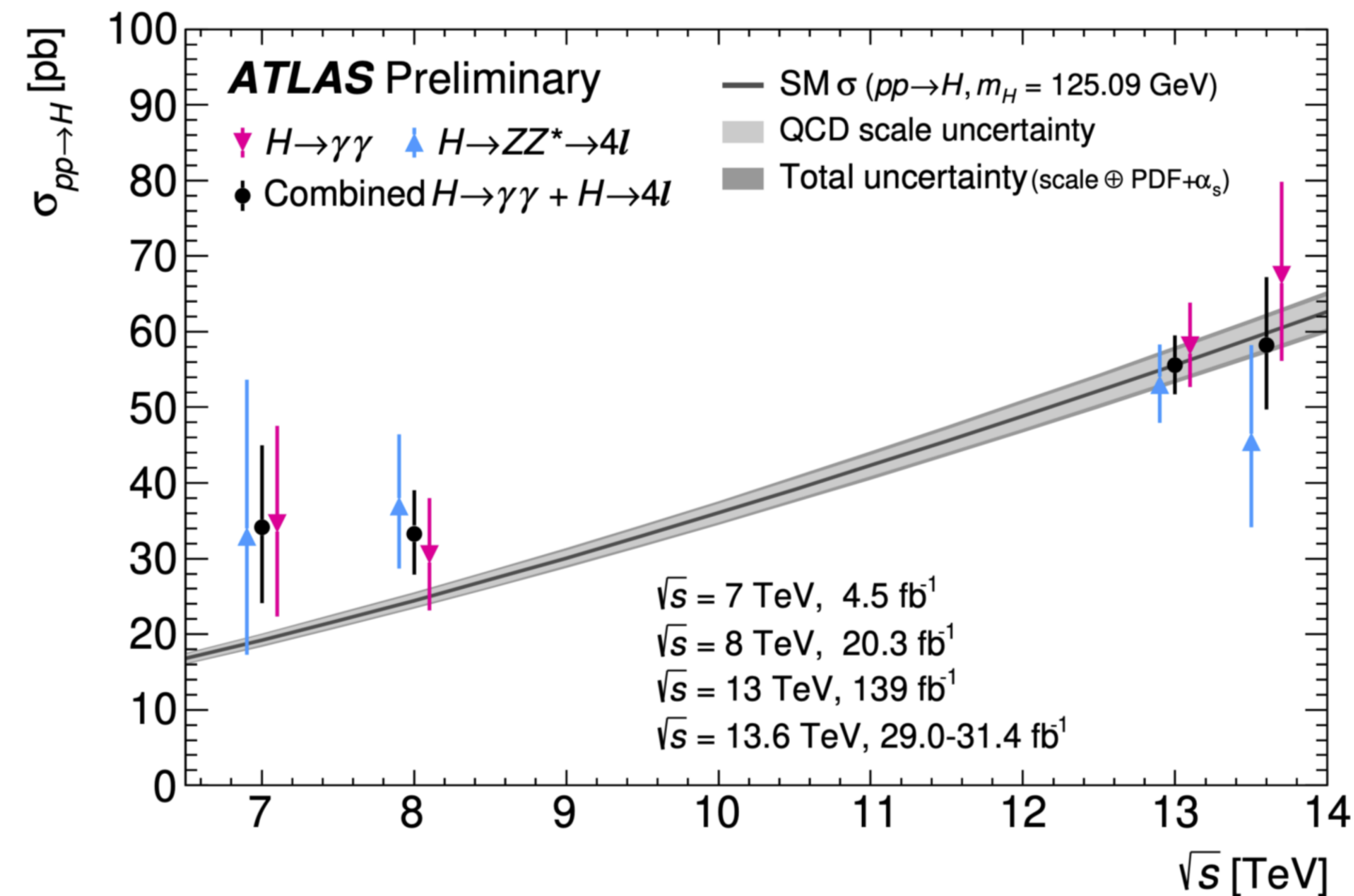
Predicted (QED)	$a_e = 0.001\,159\,652\,181\,643(764)$
Measured	$a_e = 0.001\,159\,652\,180\,73(28)$

Required measuring g to an accuracy of around 1 part in 1 trillion (10^{12})

Higgs Production at the LHC

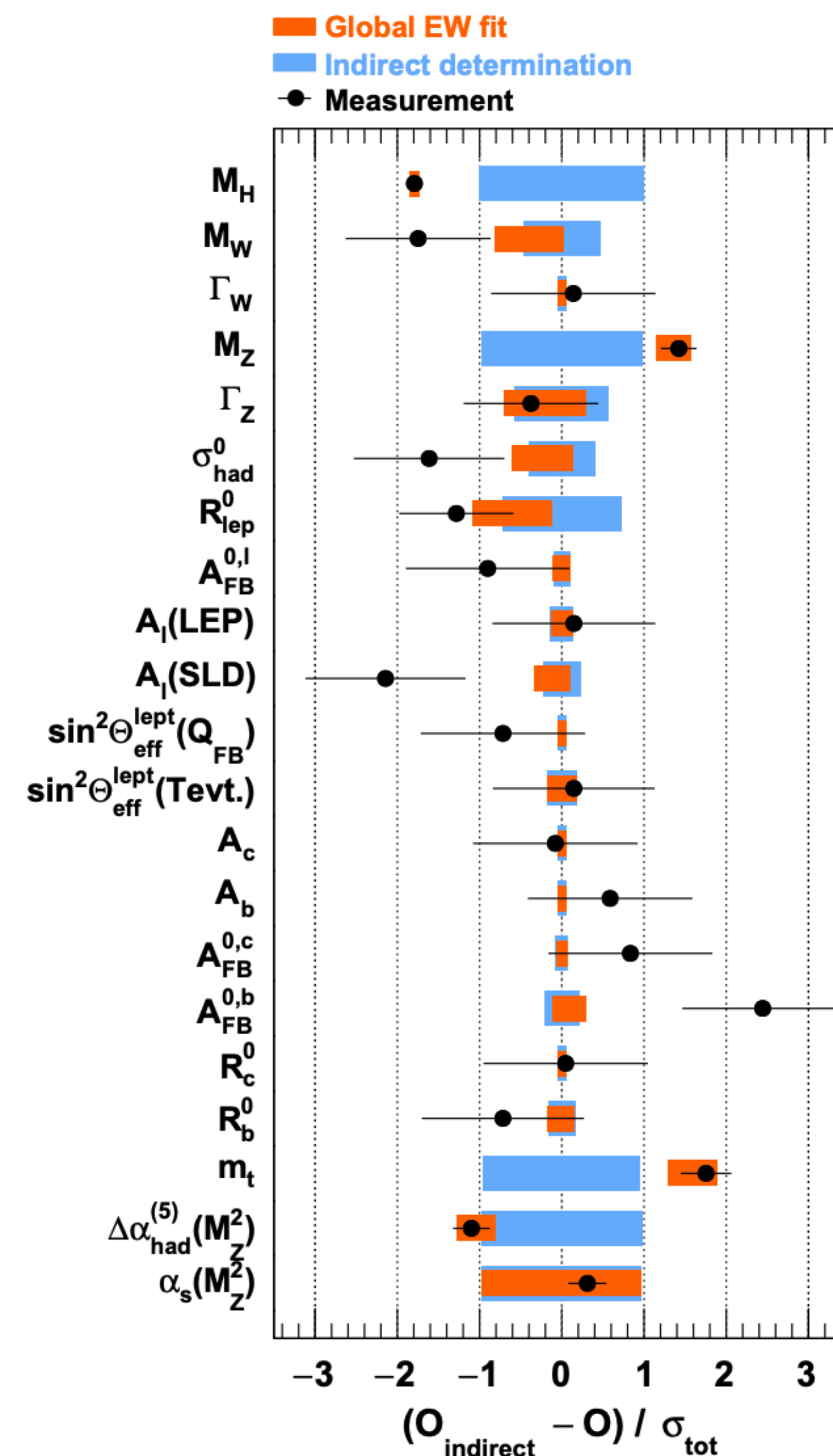
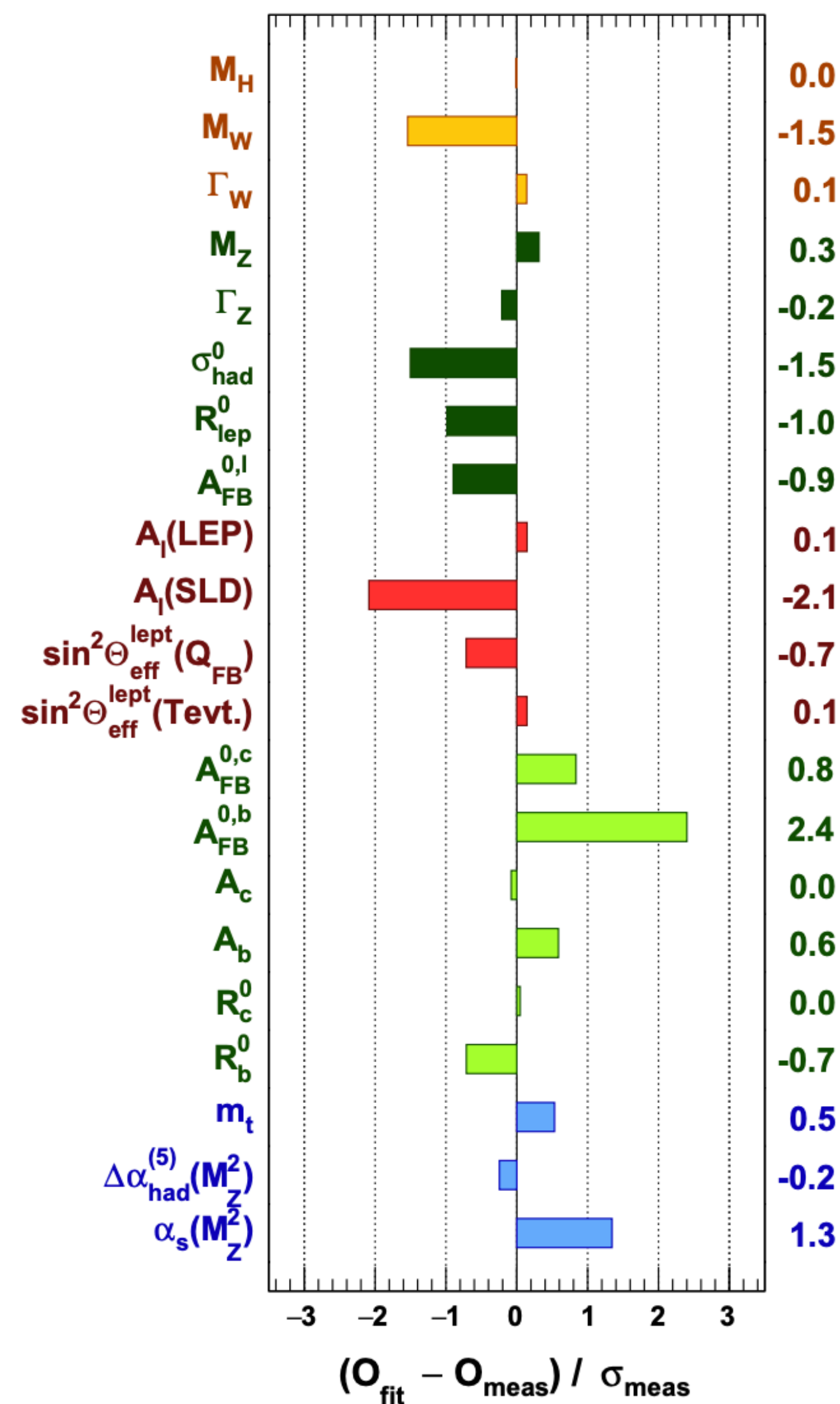


Higgs Cross Sections and Couplings



The Electroweak Fit

- Global fit:
 - Checks consistency of SM free parameters as measured in various experiments
 - $\chi^2/\text{dof} = 18.6/15$
 - p-value 0.23
 - Largest deviation: A_{FB}^b at 2.4 sigma

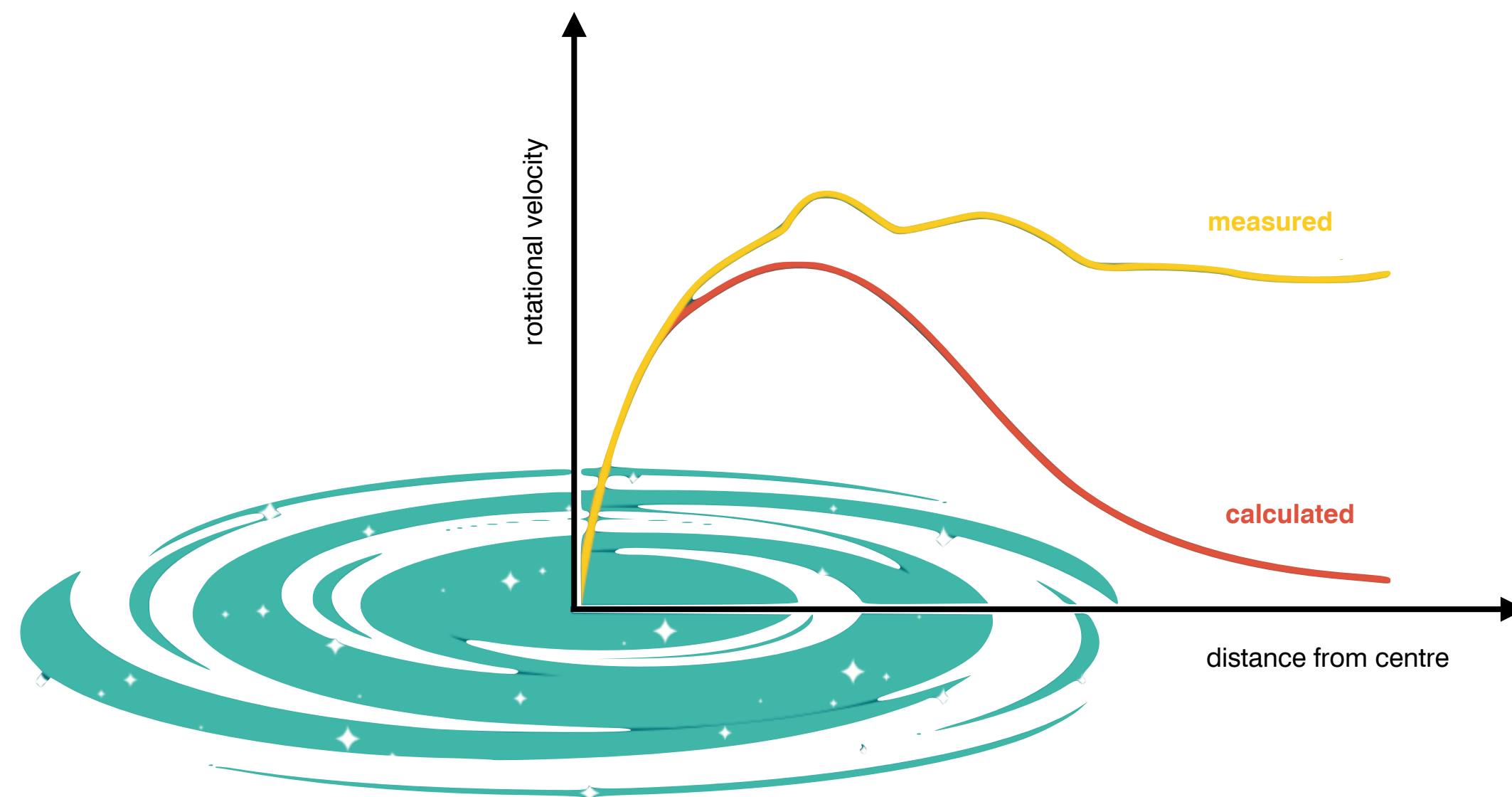


Standard Model - What does not work so well

- A few observations cannot be explained by the the Standard Model
- New theories try to address those!

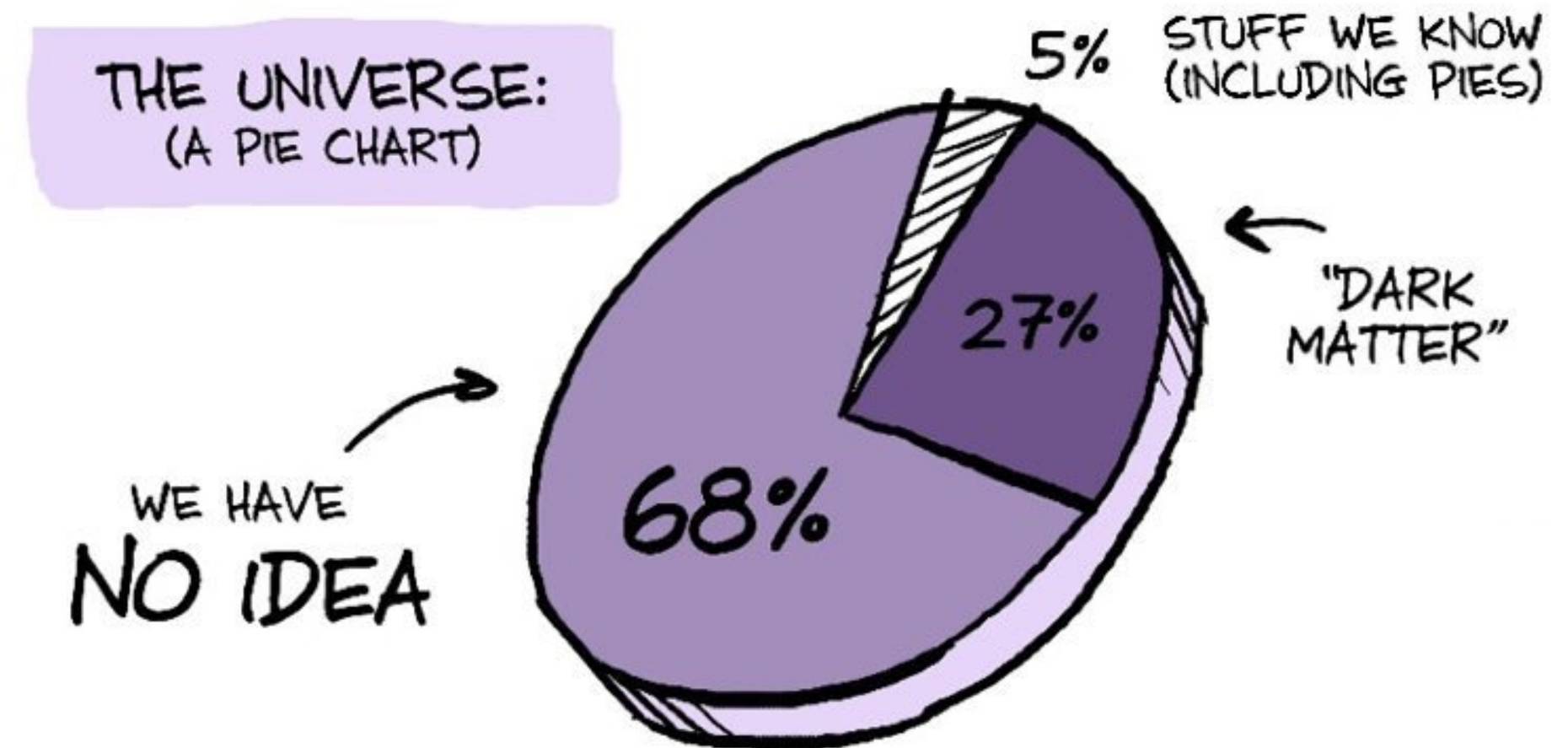


Dark Matter / Dark Energy



Credit: Higgs Boson & Beyond

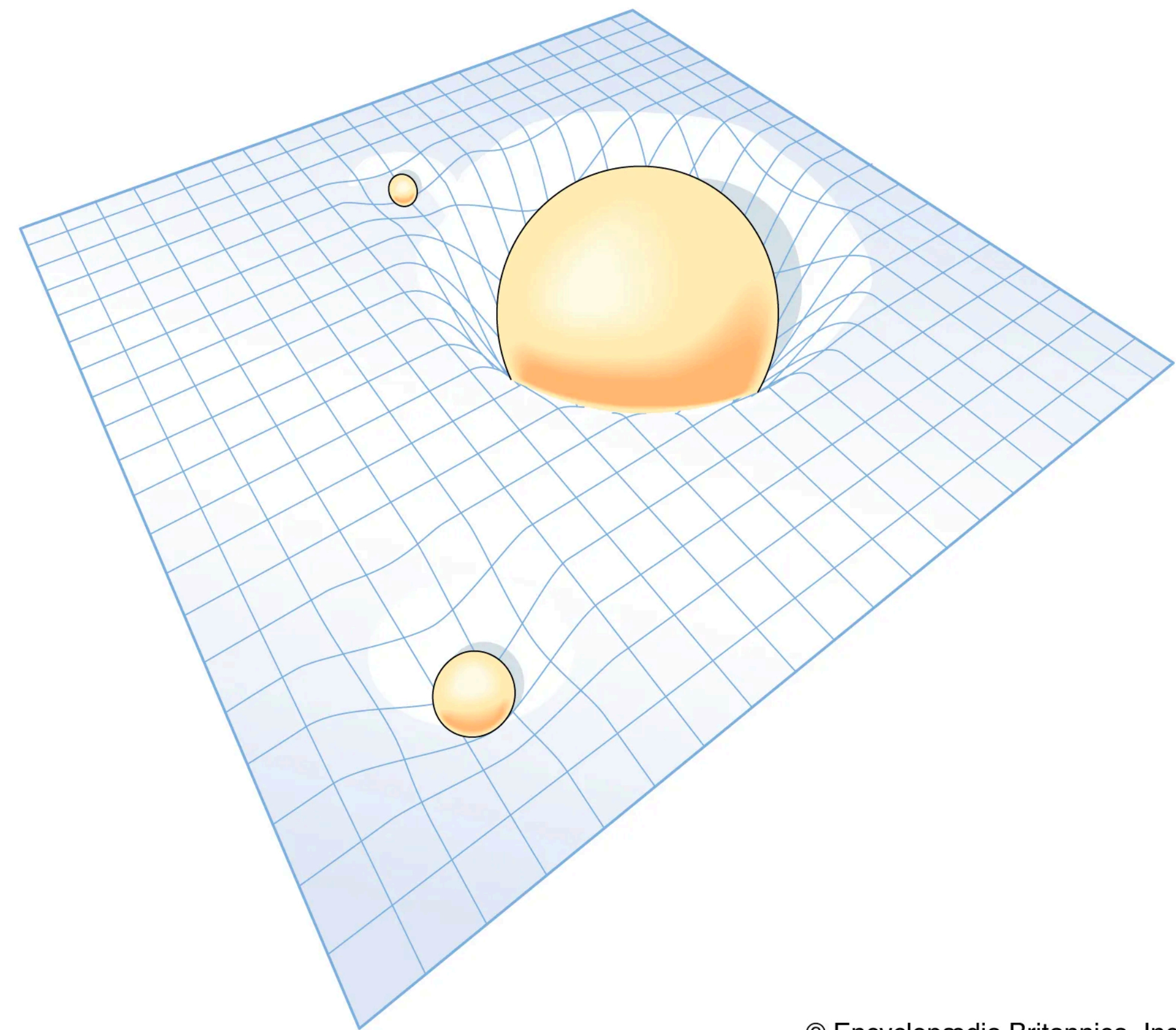
Precision Ignorance: Accurate measurements of our cluelessness



Credit: Cham & Whiteson

Gravity!

- No consistent quantum theory for gravity
- Only force not described by the Standard Model

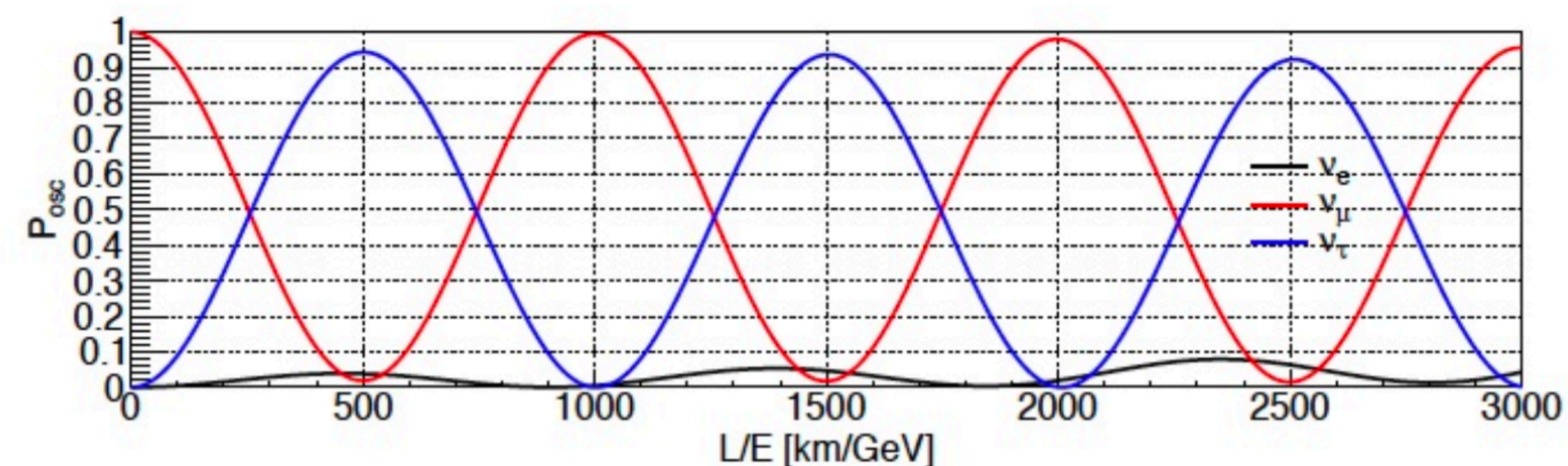


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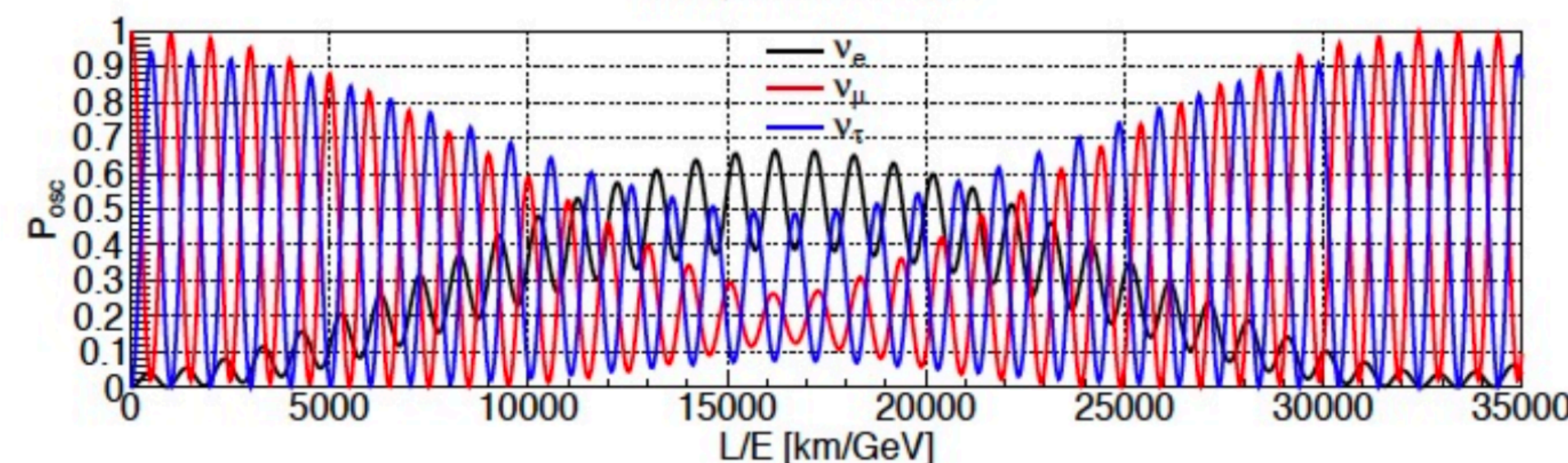
Neutrinos have mass

- Neutrinos' flavour observed to change with propagation
 - ➔ This can only happen when the neutrino is massive!
 - ➔ Mass eigenstate $\neq$ weak eigenstate

Oscillations in vacuum, starting with muon neutrino



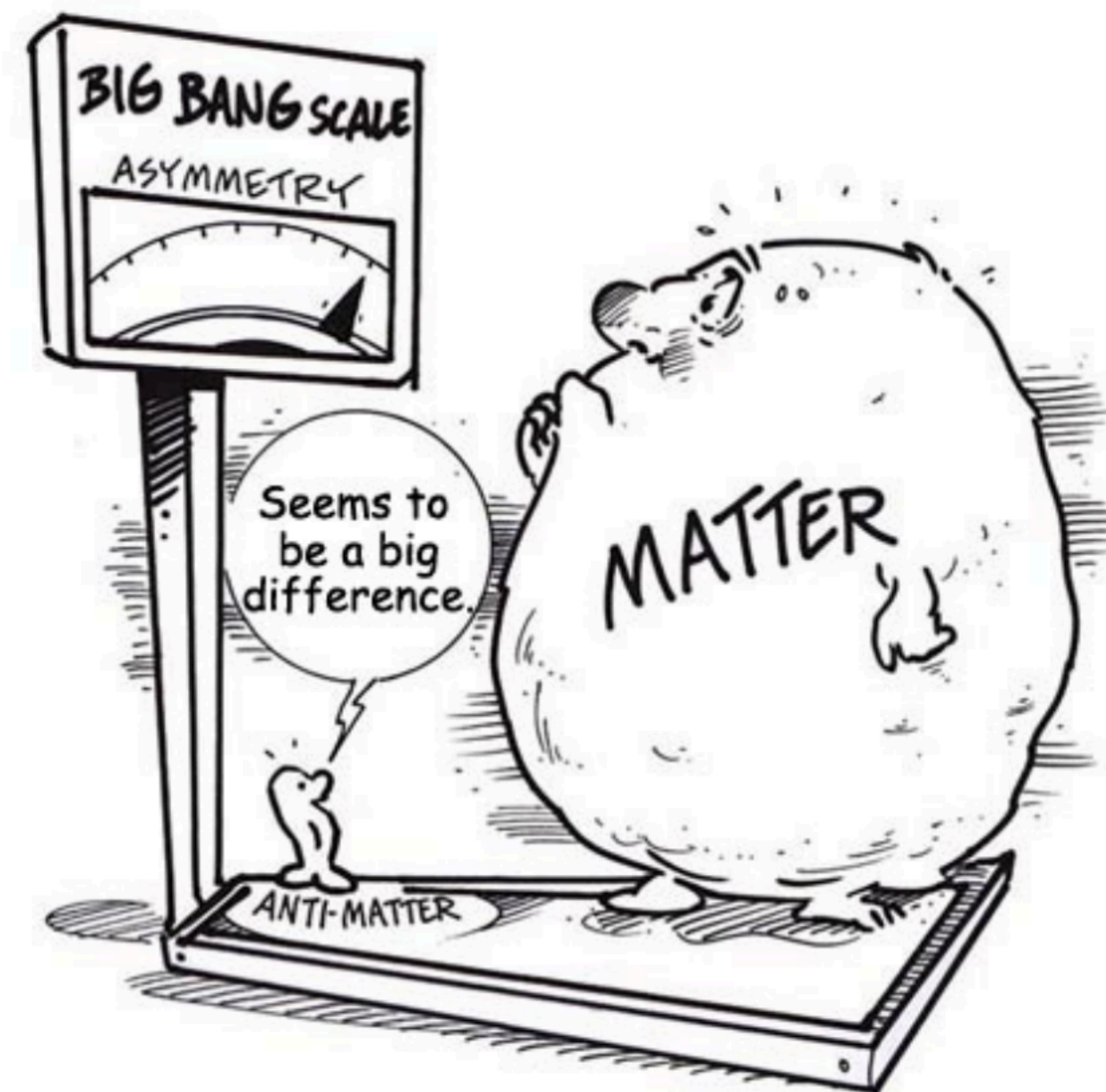
(c) ν_μ , short range



(d) ν_μ , long range

Matter-Antimatter Asymmetry

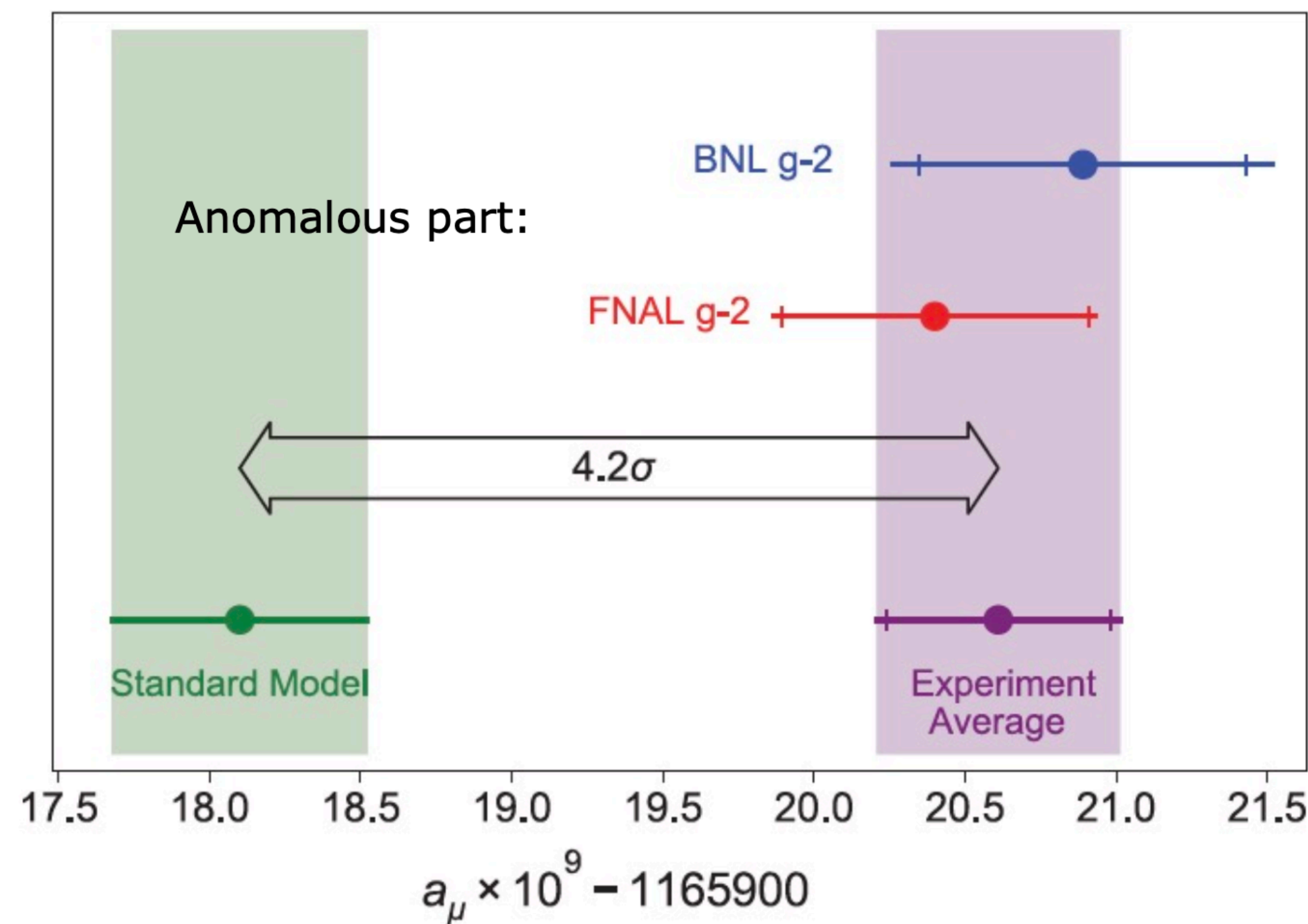
- Universe is mostly made of matter (and we don't know why!)



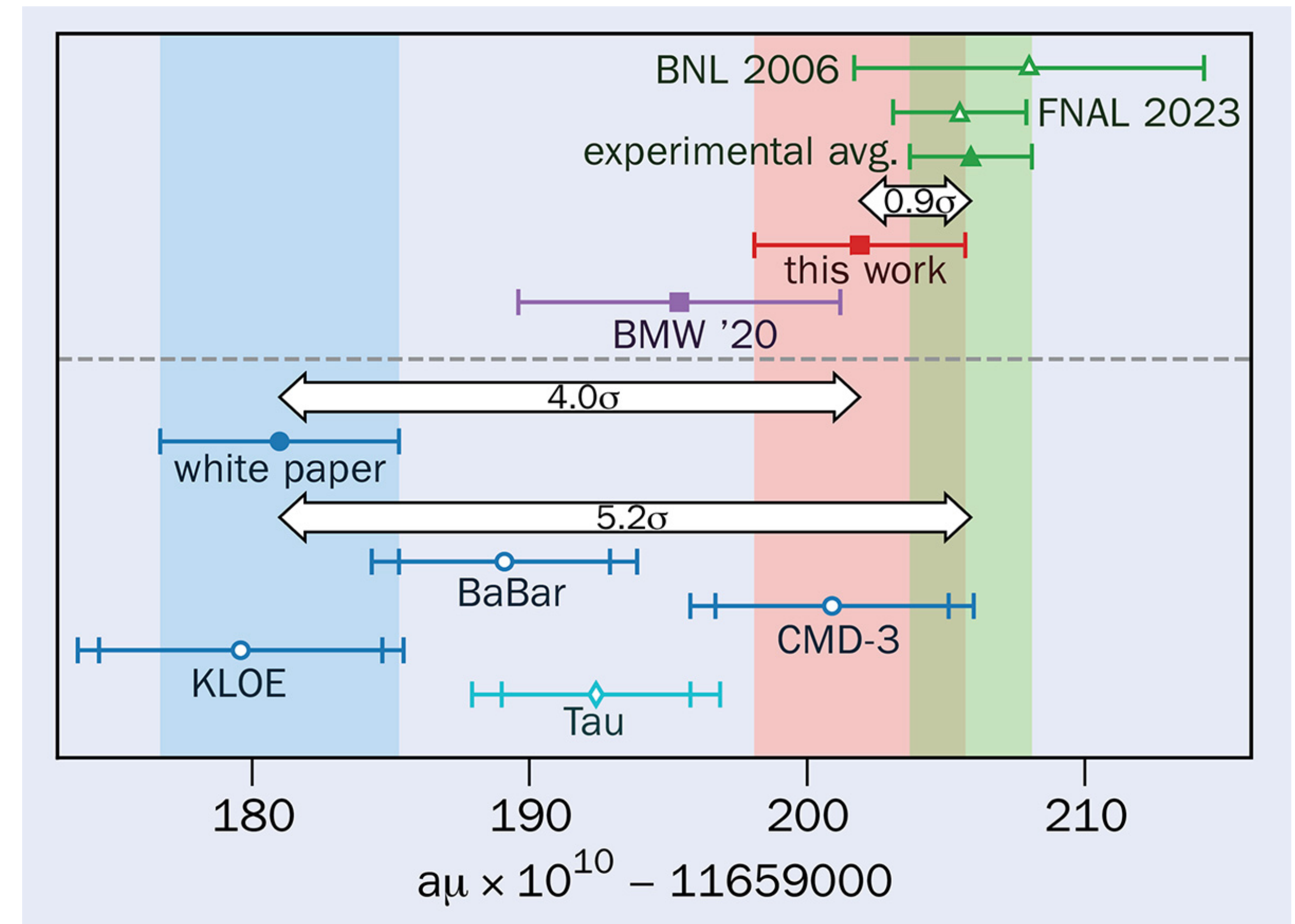
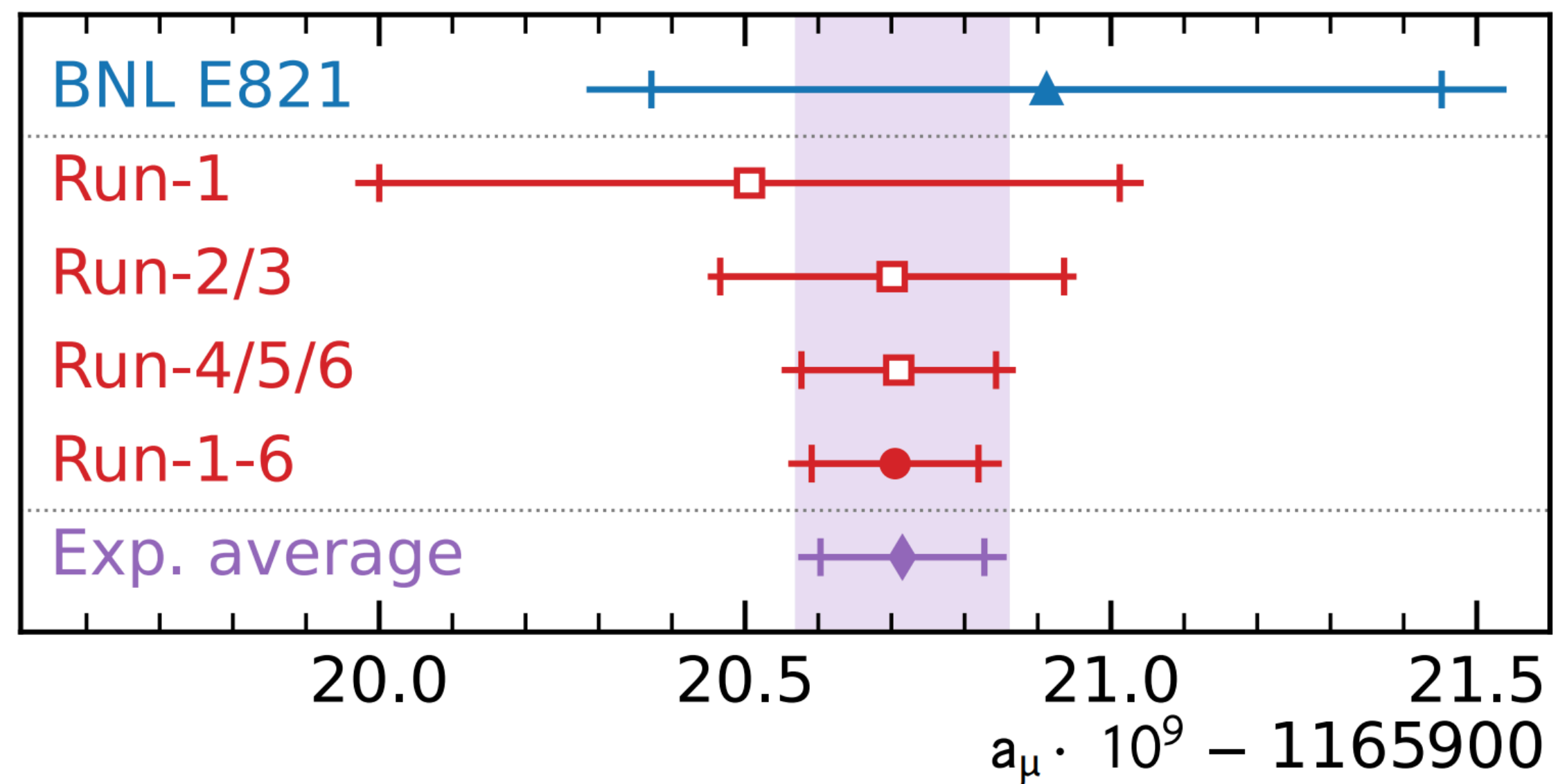
Muon Magnetic Moment?

Muon magnetic moment: $\vec{\mu} = g_{\mu} \frac{e}{2m_{\mu}} \vec{s}$

Anomalous part: $a_{\mu} = \frac{g_{\mu} - 2}{2}$

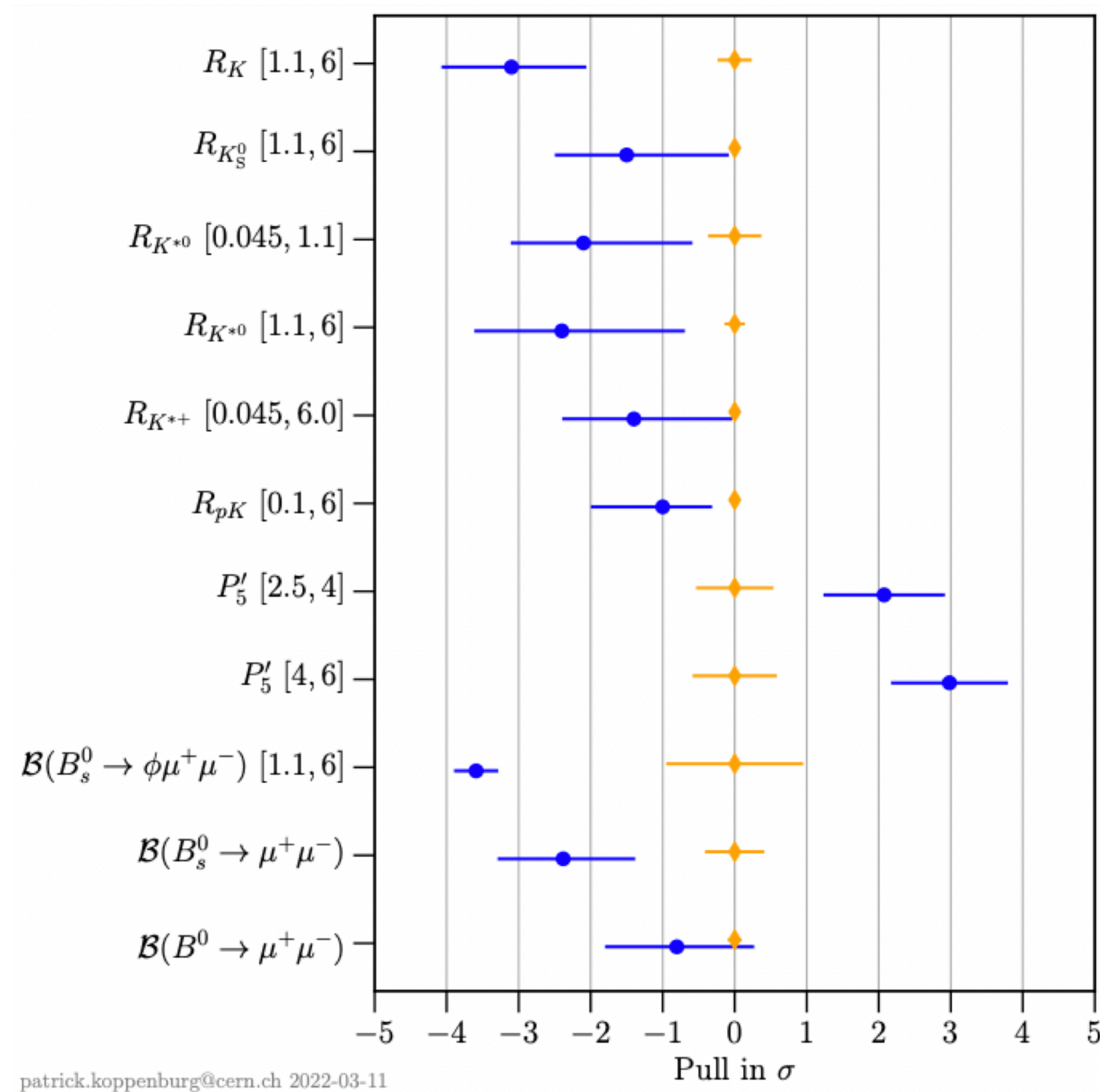


Muon Magnetic Moment?



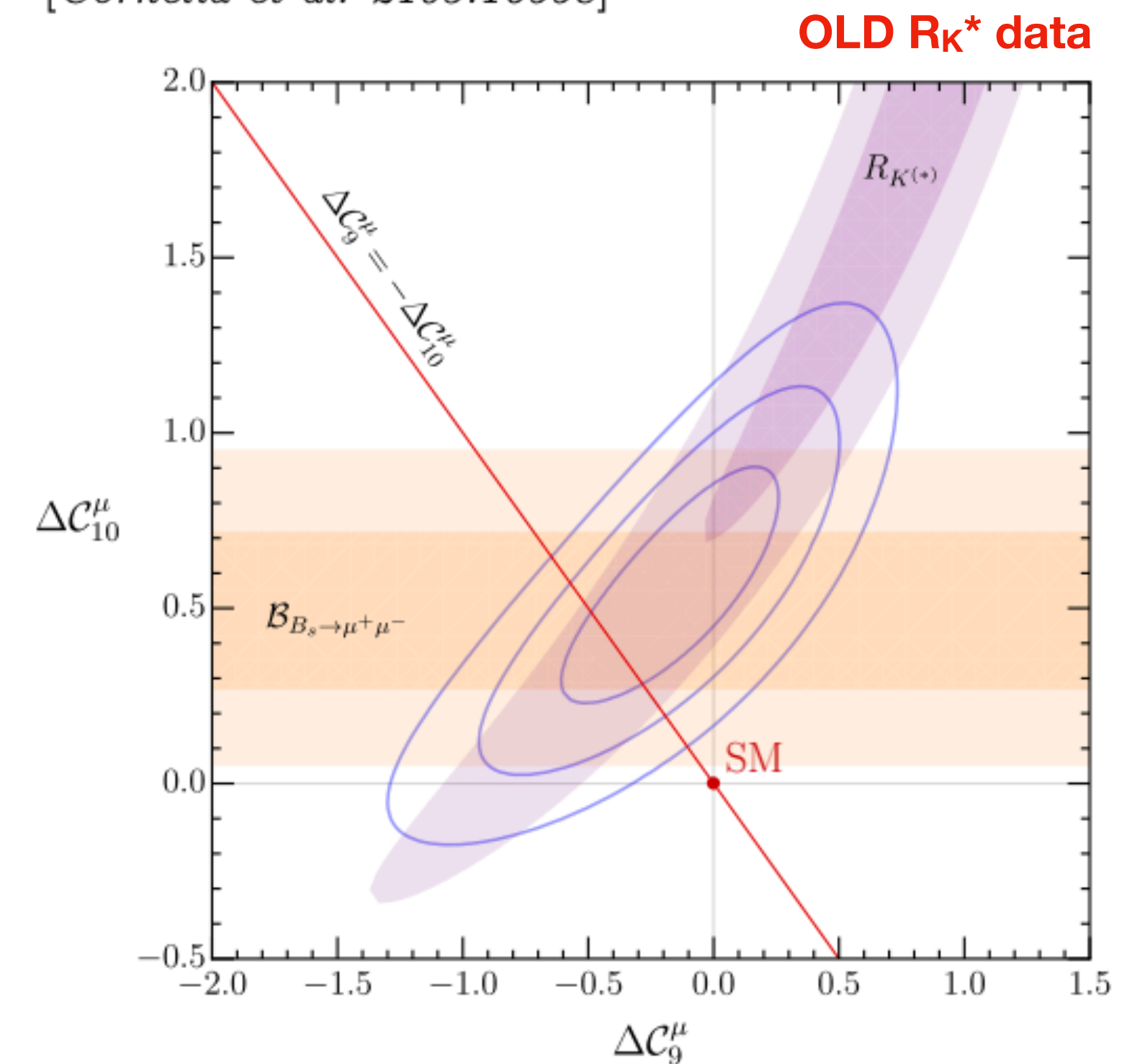
<https://arxiv.org/abs/2407.10913>

Anomalies in the flavour sector?

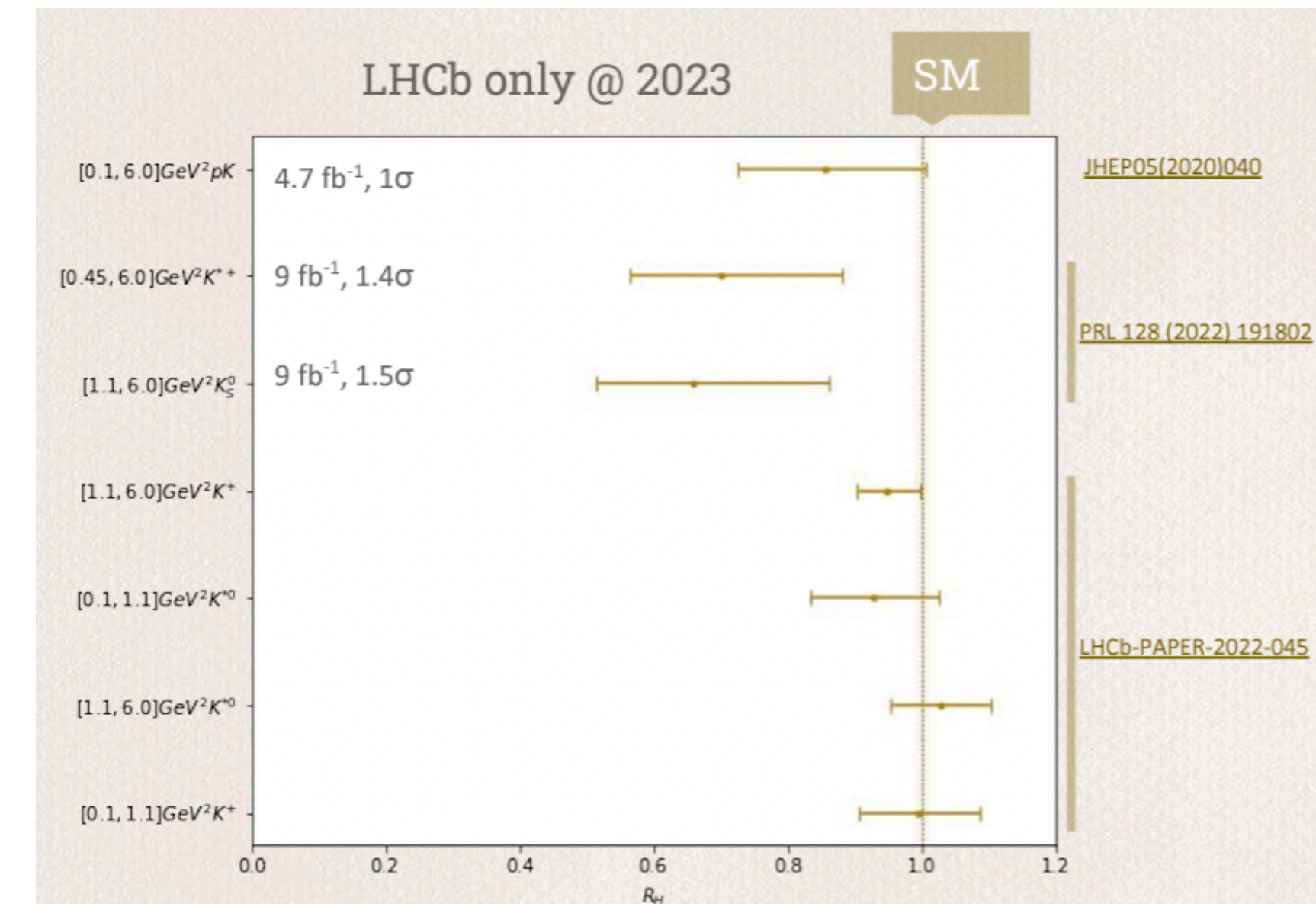
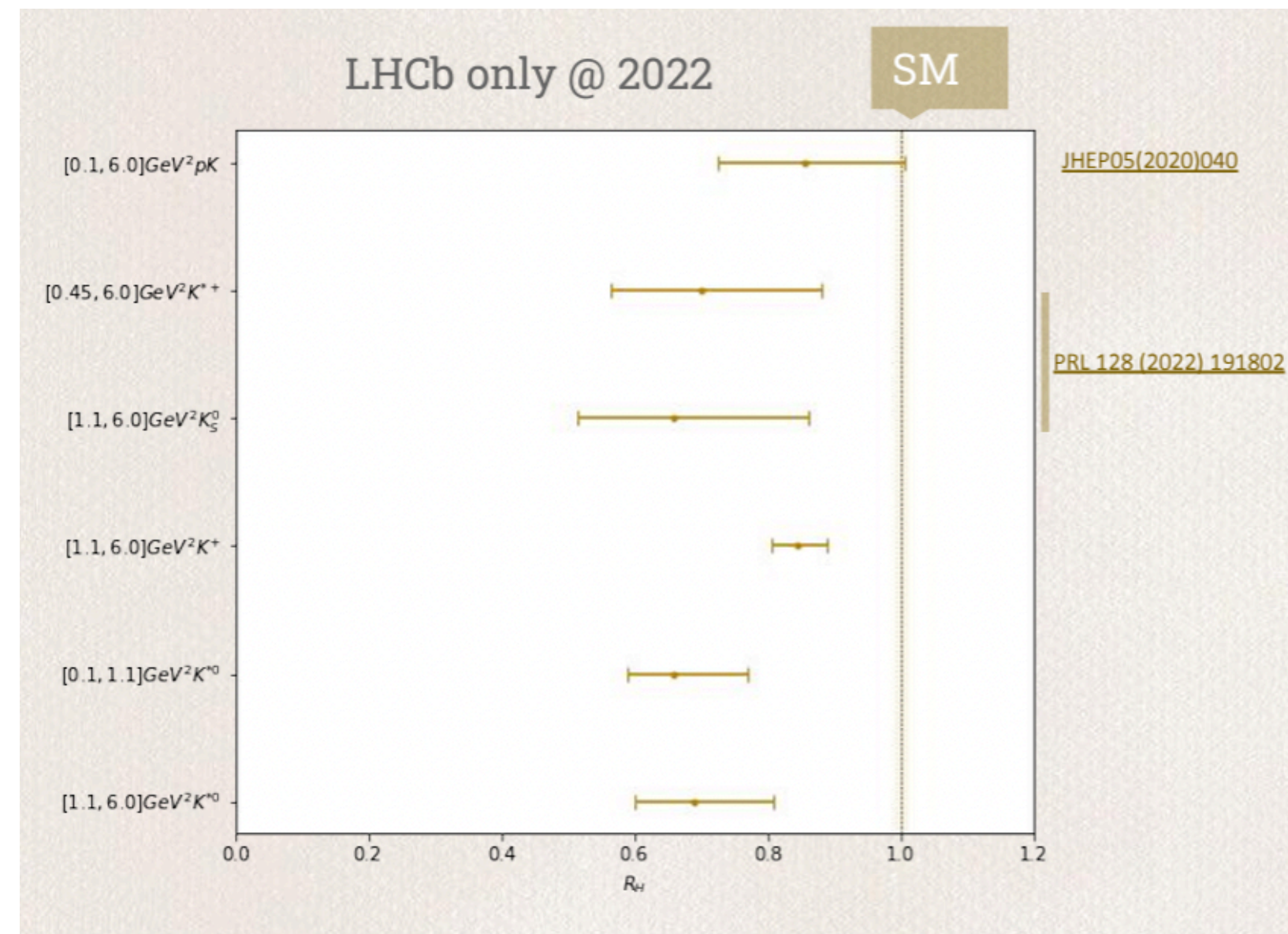


Pattern of 2-4 σ deviations in lepton flavour universality tests

[Cornella et al. 2103.16558]

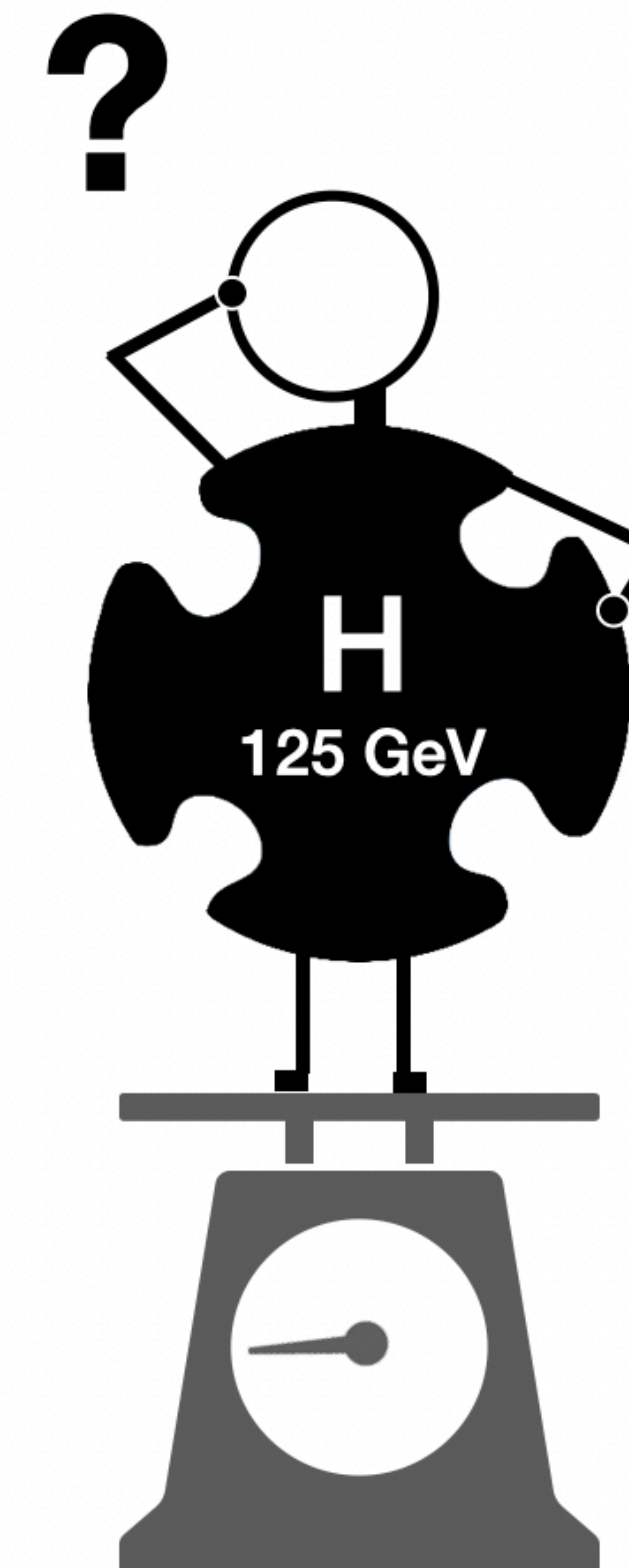
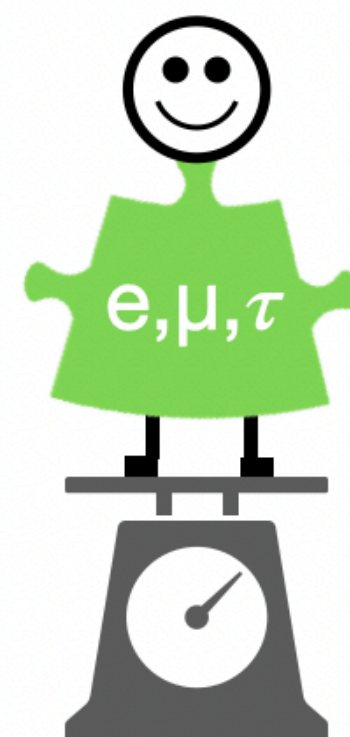


Bad news...



Hierarchy Problem

Higgs mechanism



Due to *new particles* or
new interactions?

Summary

- Standard Model: particles and interactions
 - ➔ Quantum Field Theory with nice features
 - ➔ Very precise experimental measurements confirming it
 - ➔ Observations and theoretical arguments that there is something missing
 - We will, in the next modules, talk about some of the theories trying to explain some of its shortcomings