Flavor Physics Team

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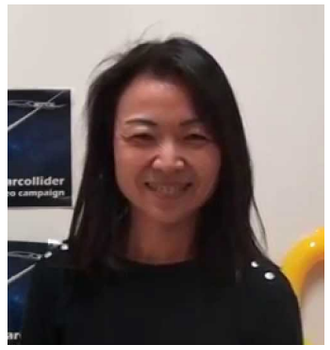

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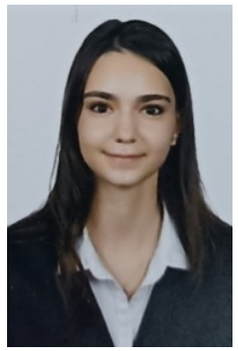

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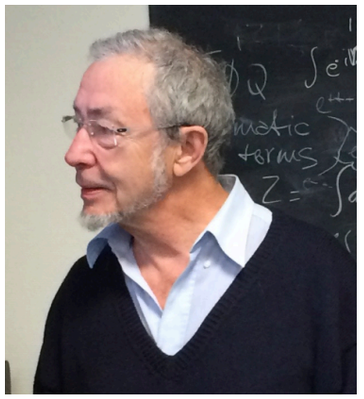

Jean-Pierre Leroy
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QCD: Véronique Bernard, Bachir Moussallam; BSM: Asmaa Abada, Adam Falkowski

Flavor Physics

- The **Standard Model** is an **effective theory** at low-energies of a more fundamental *(unknown)* theory:

  ⇒ Hierarchy and flavor problems unanswered — *among many other problems.*

  ⇒ Quest for **physics beyond the SM**!

- *Fermions* appear as three almost *identical replicas*:

  ⇒ **Flavor physics** is the study of **flavor-changing phenomena** and **CP violation**.

Twofold role of flavor physics:

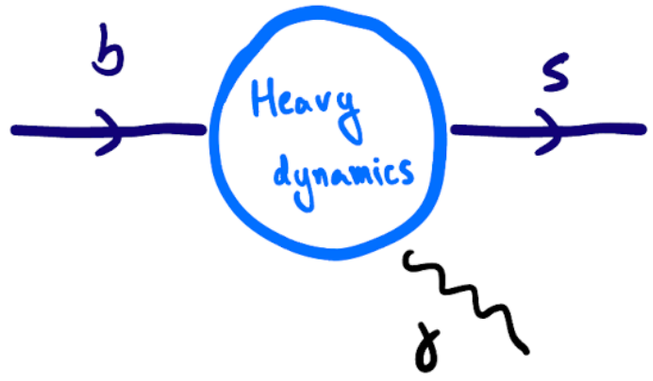
I. To identify new symmetries:

$$\begin{pmatrix} u_L \\ d_L \end{pmatrix} \quad \begin{pmatrix} c_L \\ s_L \end{pmatrix} \quad \begin{pmatrix} t_L \\ b_L \end{pmatrix}$$

Gauge symmetry

Flavor symmetry?

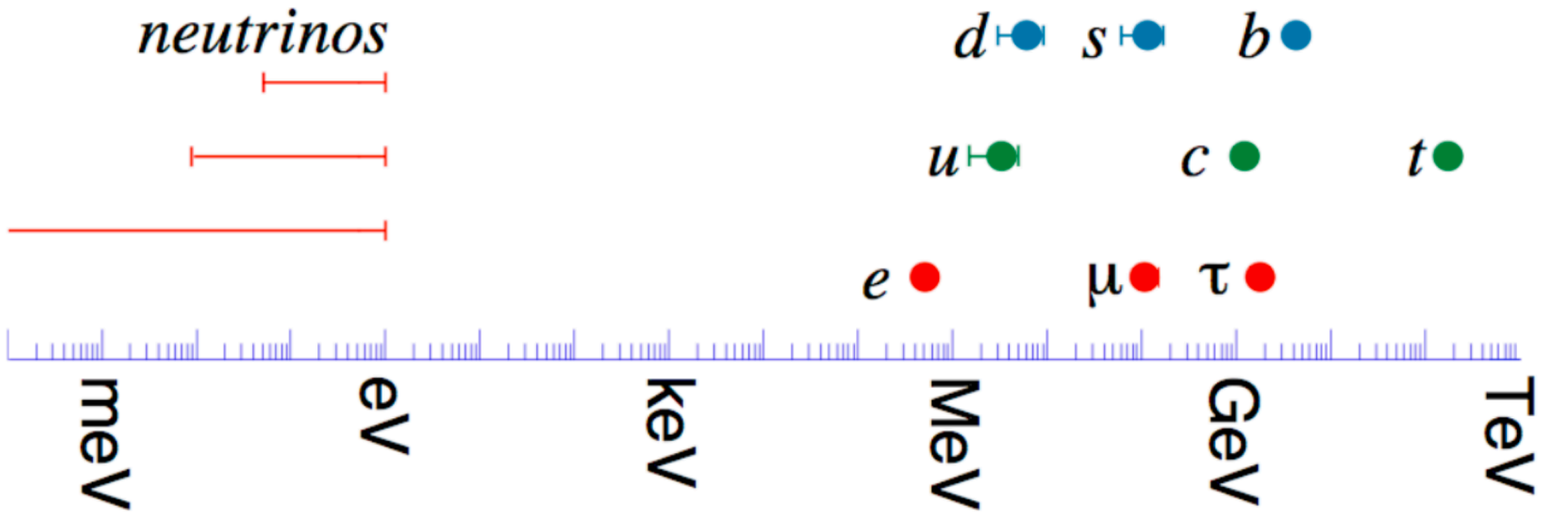
II. Search of New Physics:



***Through precision!**

I. Origin of flavor? "Who ordered that?"

- **Striking hierarchy** of fermion masses *[does not look accidental...]*



- Why **three families**? Why do **quarks** and **leptons** mix in **different ways**?

$$V_{\rm CKM} = \begin{pmatrix} \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \end{pmatrix} \qquad V_{\rm PMNS} = \begin{pmatrix} \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \end{pmatrix}$$

How to **explain** the **observed patterns** in terms of **less** and **more fundamental parameters**?

Steve Weinberg interview @ The Guardian (2013)

"After experiments started to show the electroweak theory was right... **it was obvious to anyone that the theory has a lot of arbitrary features.** It contains the electron and another particle called the muon, which is to all appearances identical to the electron but its mass is 210 times larger. **We have no idea why this ratio of masses is what it is. We have no idea why there even is a muon."**

"One summer I sat down and said: 'This is the summer when I'm not going to do anything but solve that problem.' This was 40 years ago and I haven't solved it. No one has. I thought it would be a simple matter of extending the kind of symmetry principles I used in the electroweak theory to have some kind of symmetry that involved electrons turning into muons and I could never make it work. **That's been a frustration now for 40 years."**

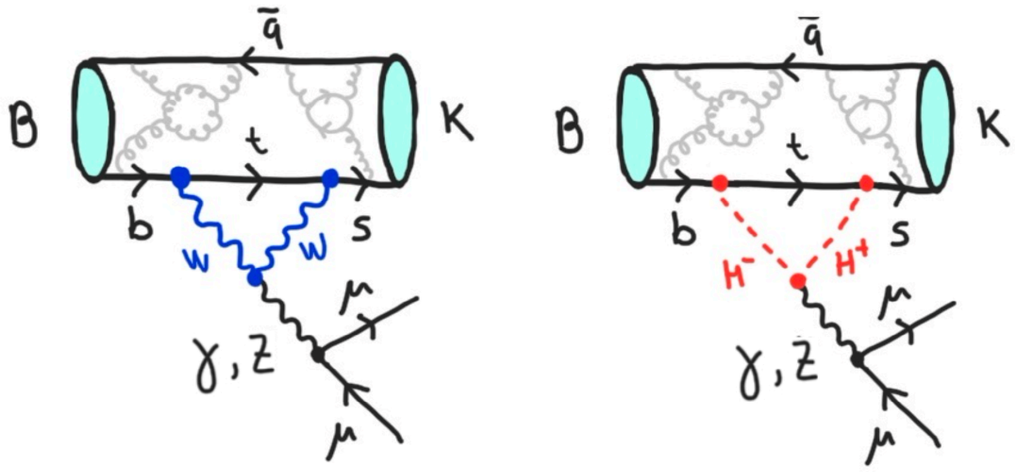
For Weinberg we are at a dangerous point in the history of physics. Both cosmology and particle physics have "standard models" that contain mysteries, **like his electron/ muon problem or the existence of dark matter and dark energy**, the unexpected extra mass of galaxies and the accelerating expansion of the cosmos, accounting for 95% of the mass and energy of the universe.

Weinberg does not see how we can solve these problems without new data – which means pushing the boundaries.

II. Indirect searches of New Physics

Search deviations w.r.t. SM predictions:

e.g.,



$$\mathcal{O}_{\rm exp} = \mathcal{O}_{\rm SM}\,(1 + \delta_{\rm NP})$$

Both **exp.** and **theory** must be **precise**!

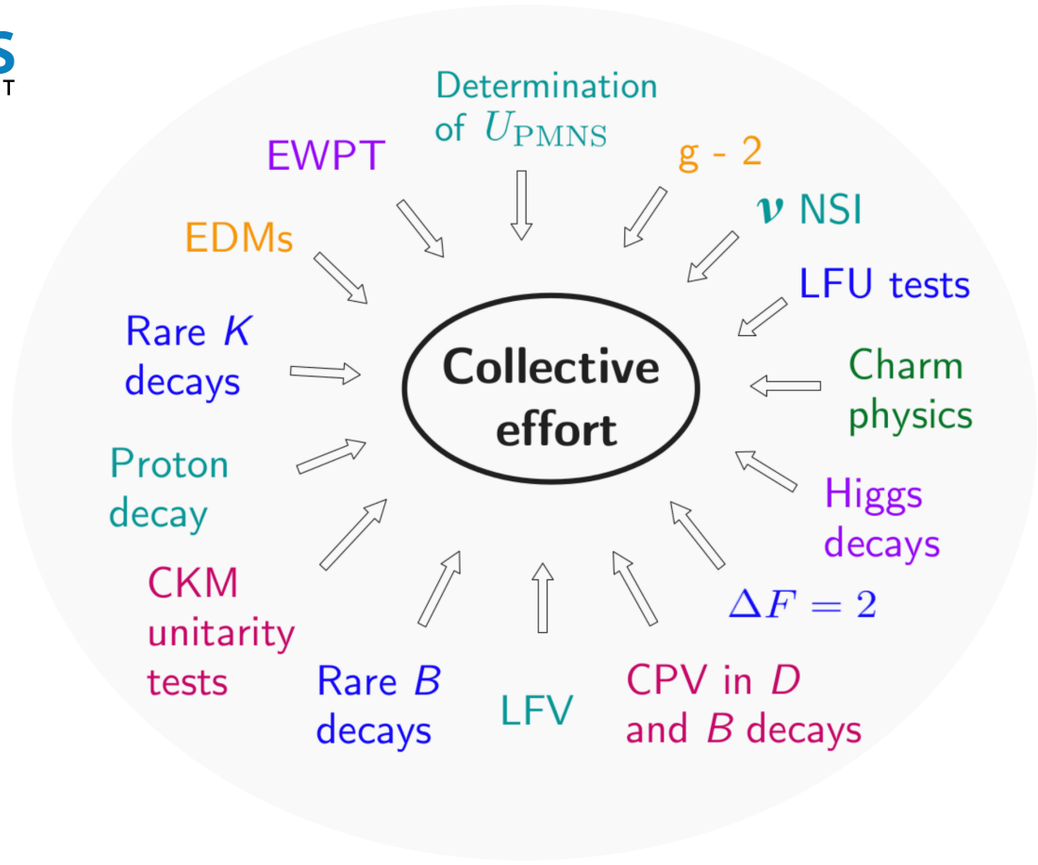
Look for observables:

- (Highly) sensitive to contributions from New Physics
- Mildly sensitive to hadronic uncertainties
- Accessible in current and/or (near) future experiments.

⇒ **Challenging task!**

QCD ⇔ Flavor ⇔ BSM

The precision frontier



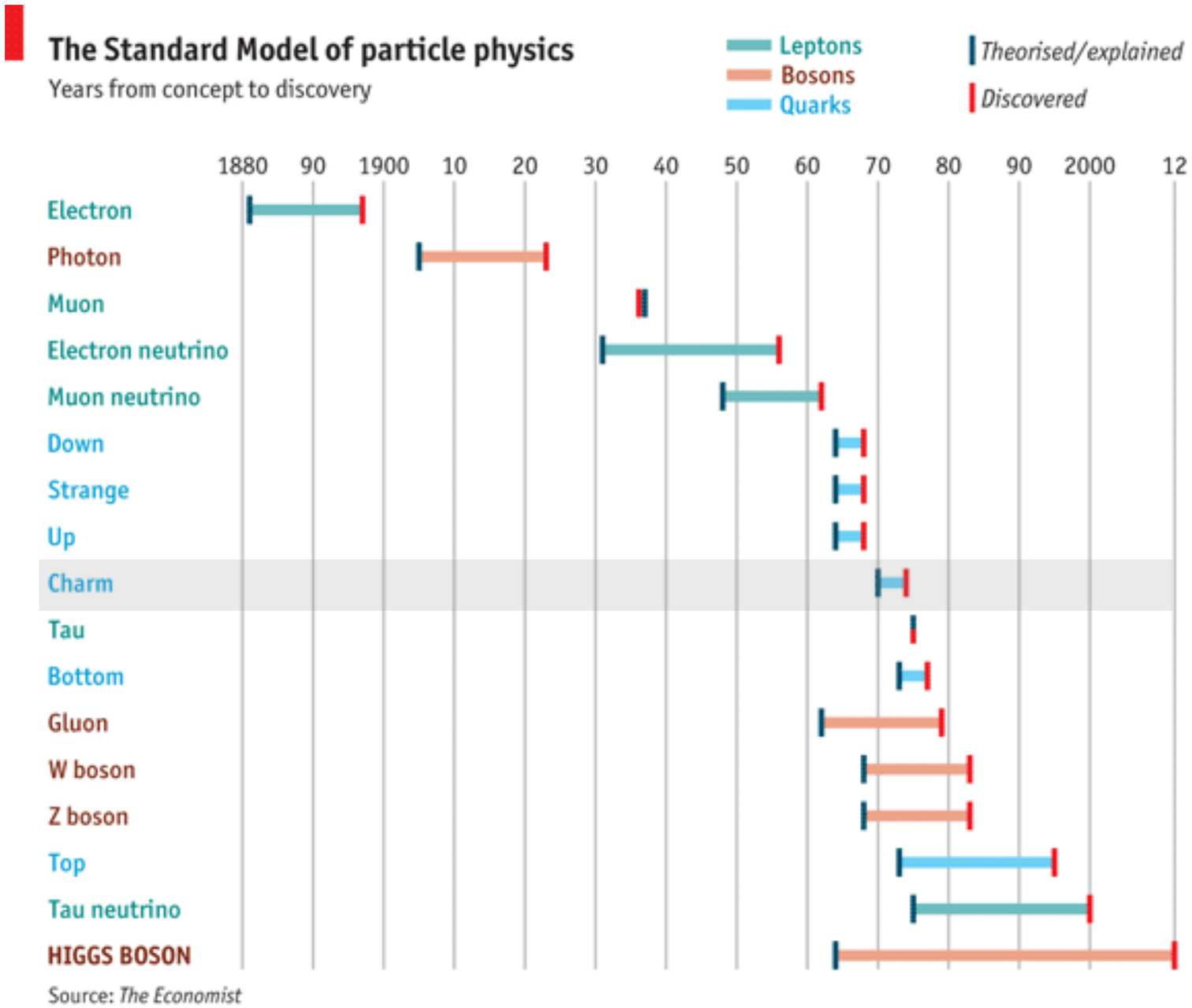
Flavor physics is a collective effort — *complementary to Higgs/EW and direct searches!*

Rich experimental landscape: *large experiments (with extensive physics program) and small experiments (with specific targets).*

Taming hadronic uncertainties is **essential** in order to **probe New Physics** effects!

Historically...

Indirect searches guided later discoveries:



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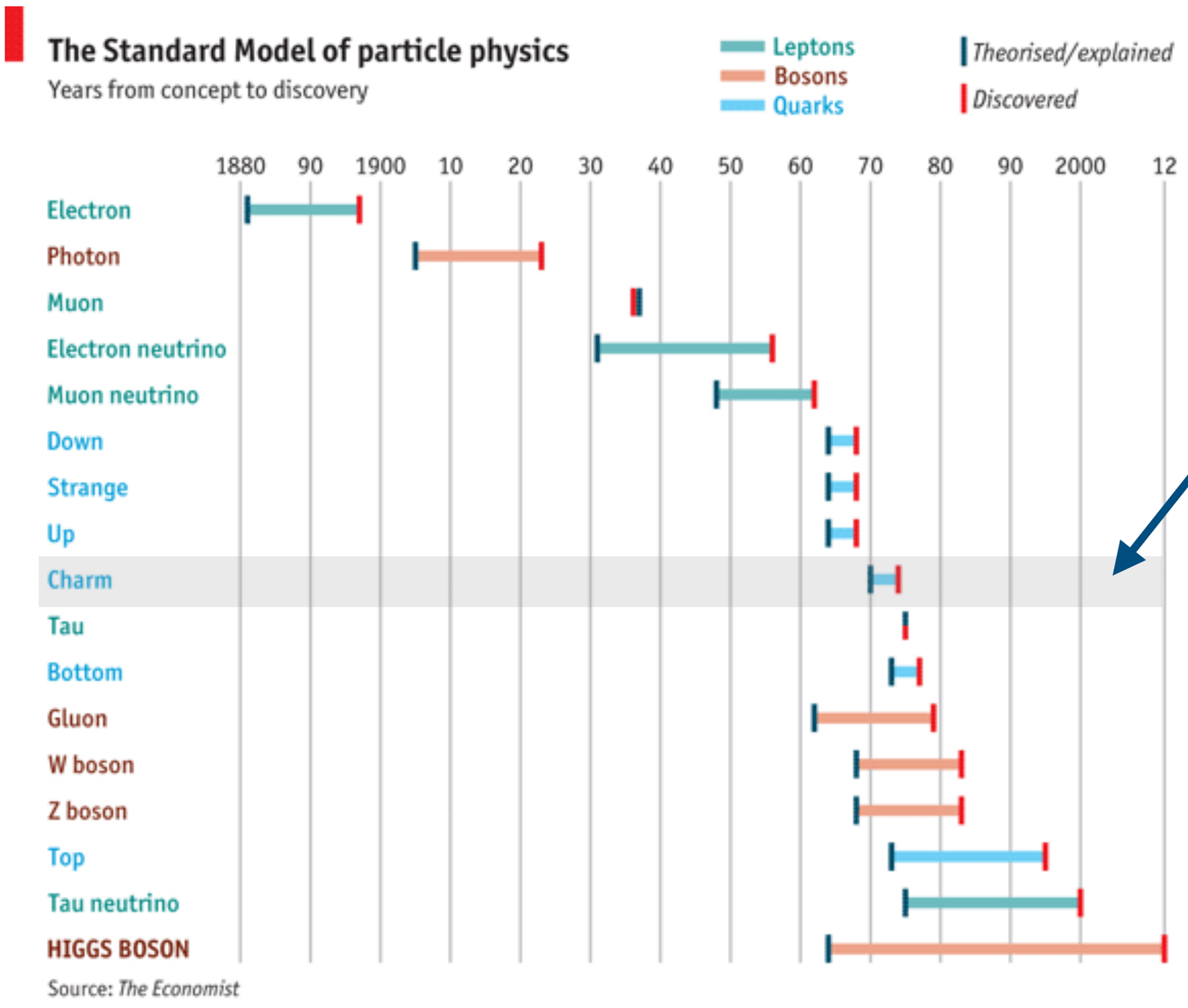

GIM mechanism ['70] and the **existence of charm**:

$$\Gamma(K_L \to \mu\mu) \ll \Gamma(K \to \mu\nu)$$

Indirect determination of the **charm mass** by **Gaillard and Lee** from $K^0 - \overline{K^0}$ **mixing ['73]**

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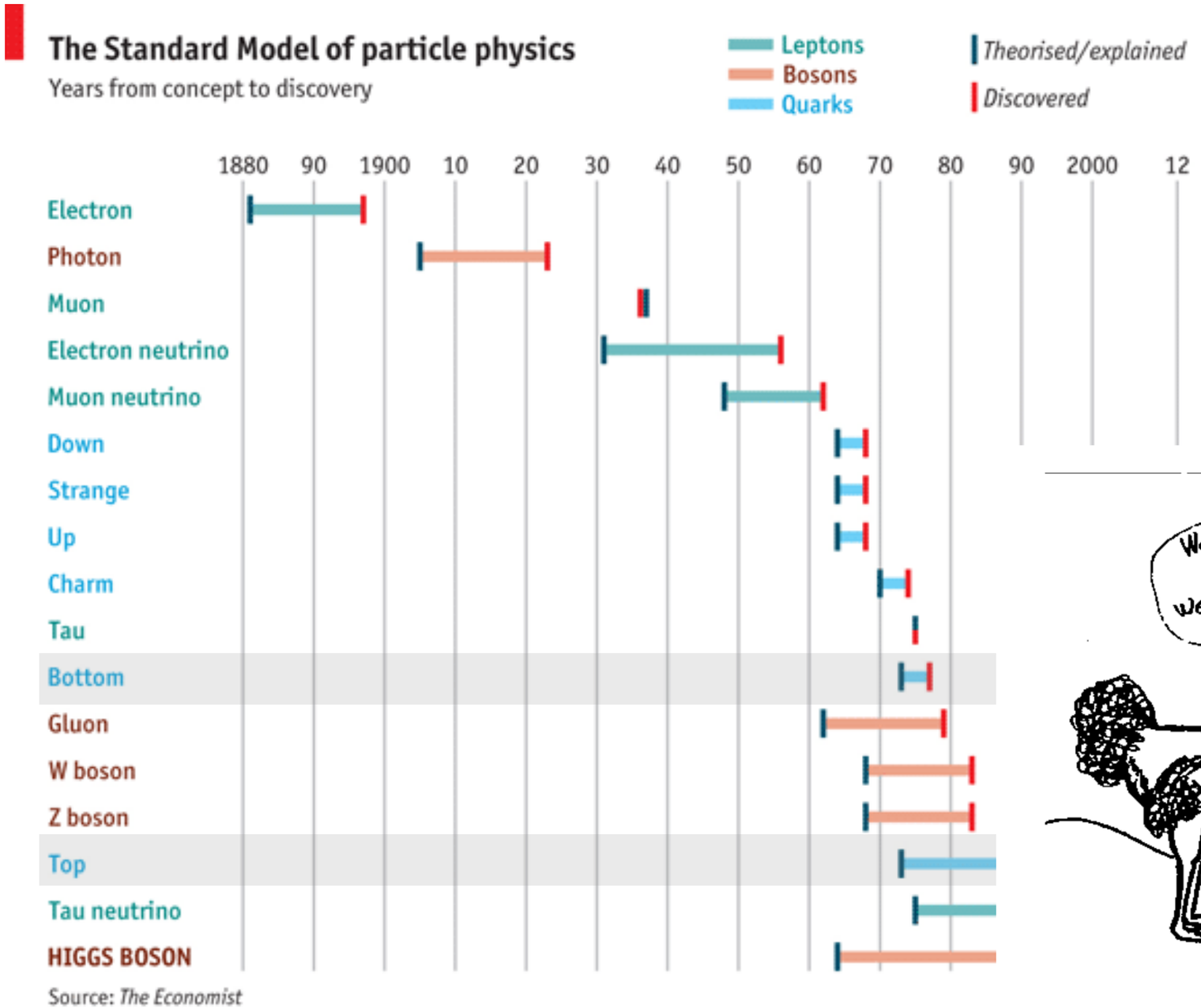

Discovery of CP violation and the CKM mechanism:

⇒ 3rd-gen of quarks!

Cartoon shown by N. Cabibbo in 1966...

Historically...

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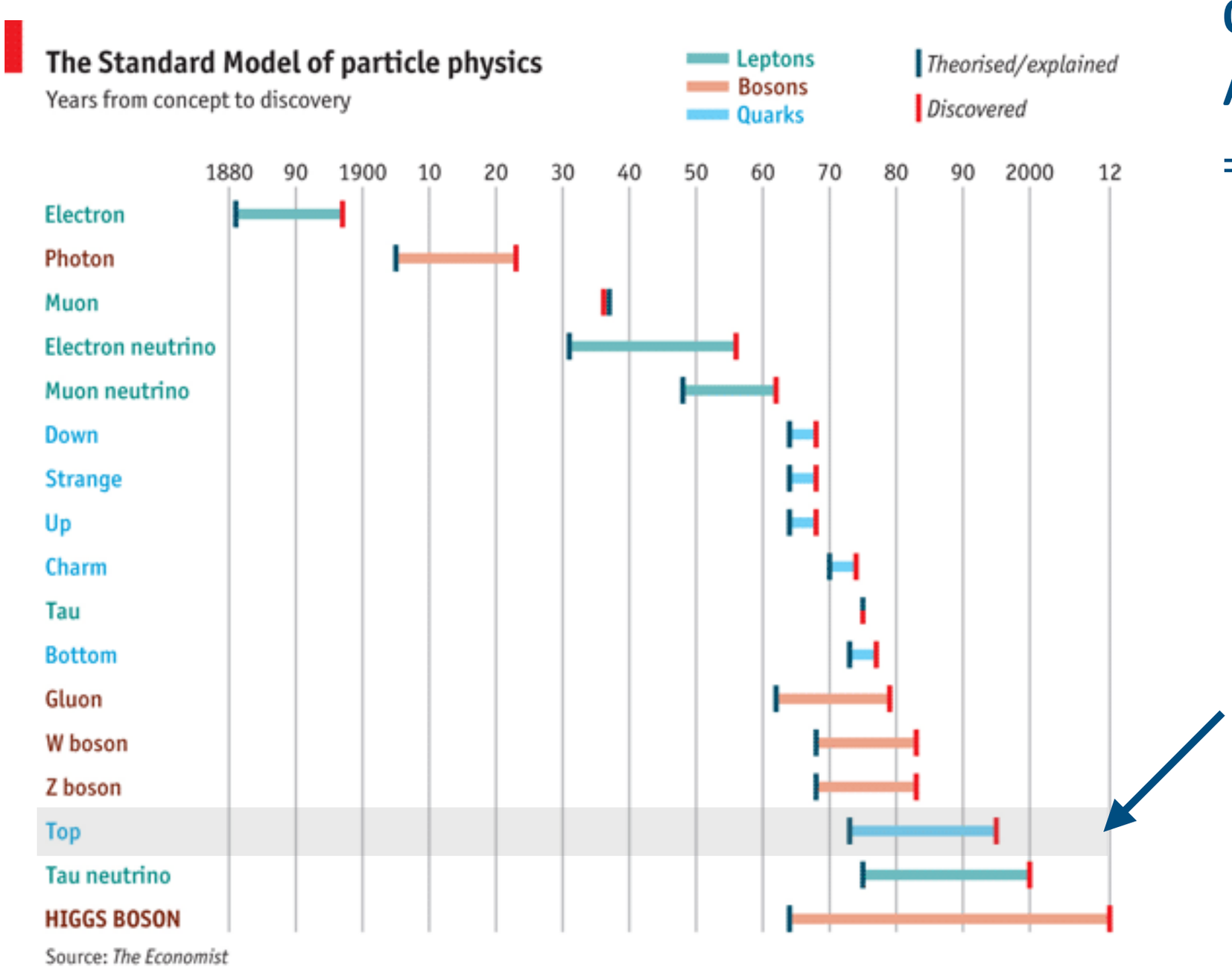


Observation of $B^0 - \overline{B^0}$ by Argus [1987]:

$\Rightarrow$ the top-quark is heavy!

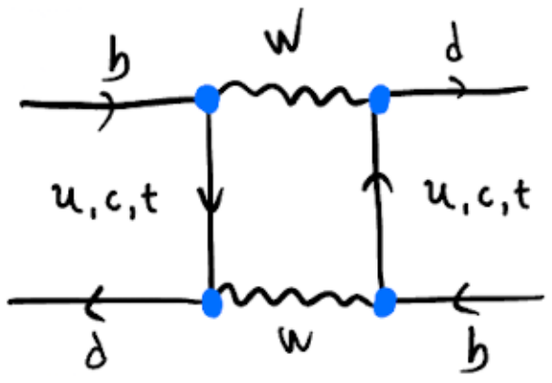
PLB 192 (1987)

OBSERVATION OF B^0–$\bar{B}^0$ MIXING

ARGUS Collaboration

In summary, the combined evidence of the investigation of B^0 meson pairs, lepton pairs and B^0 meson–lepton events on the $\Upsilon(4S)$ leads to the conclusion that B^0–$\bar{B}^0$ mixing has been observed and is substantial.

Parameters	Comments
$r > 0.09$ (90%CL)	this experiment
$x > 0.44$	this experiment
$B^{1/2} f_B \approx f_\pi < 160$ MeV	B meson ($\approx$ pion) decay constant
$m_b < 5$ GeV/c^2	b-quark mass
$\tau < 1.4 \times 10^{-12}$s	B meson lifetime
$\lvert V_{td} \rvert < 0.018$	Kobayashi–Maskawa matrix element
$\eta_{QCD} < 0.86$	QCD correction factor [a]
$m_t > 50$ GeV/c^2	t quark mass



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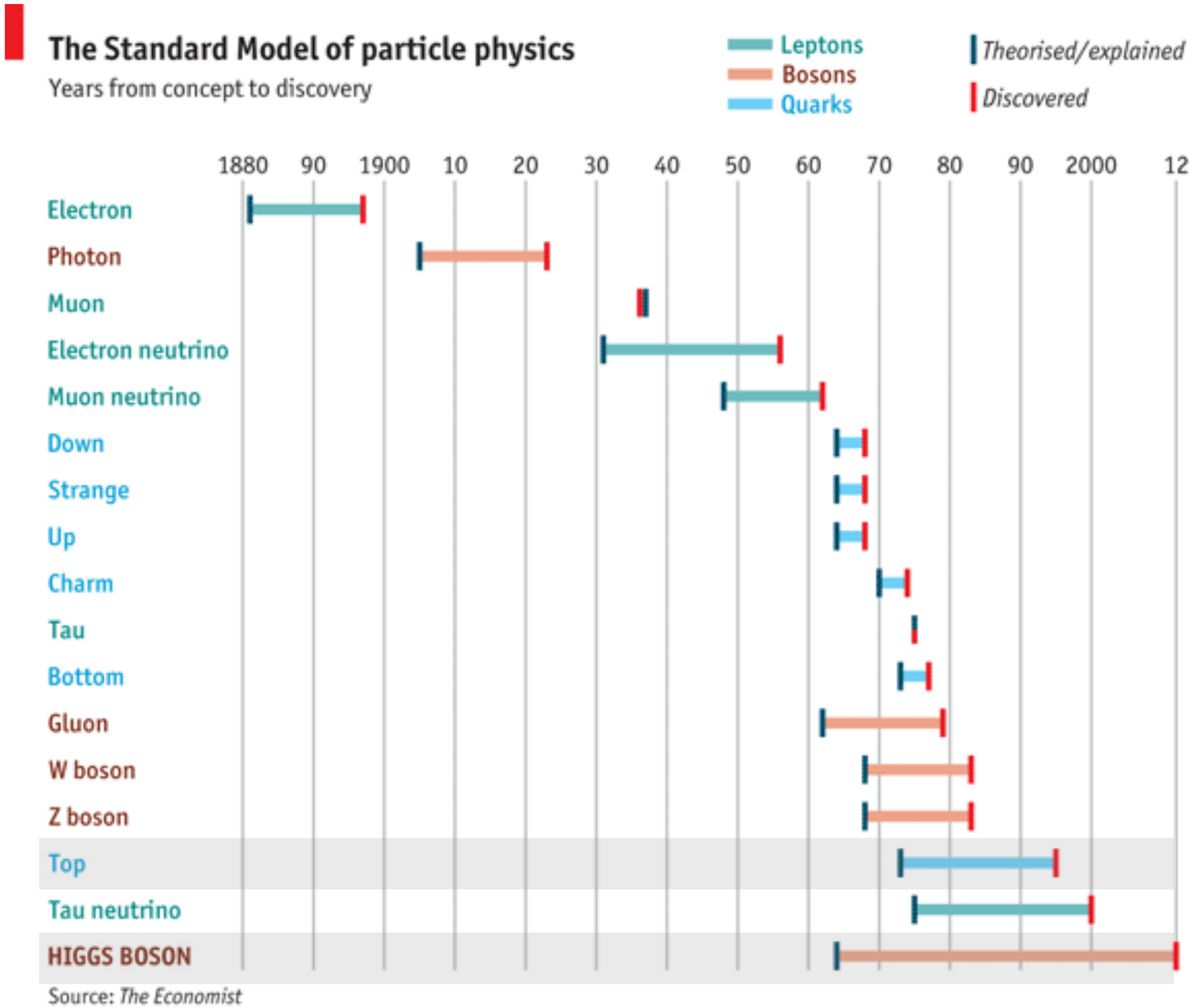
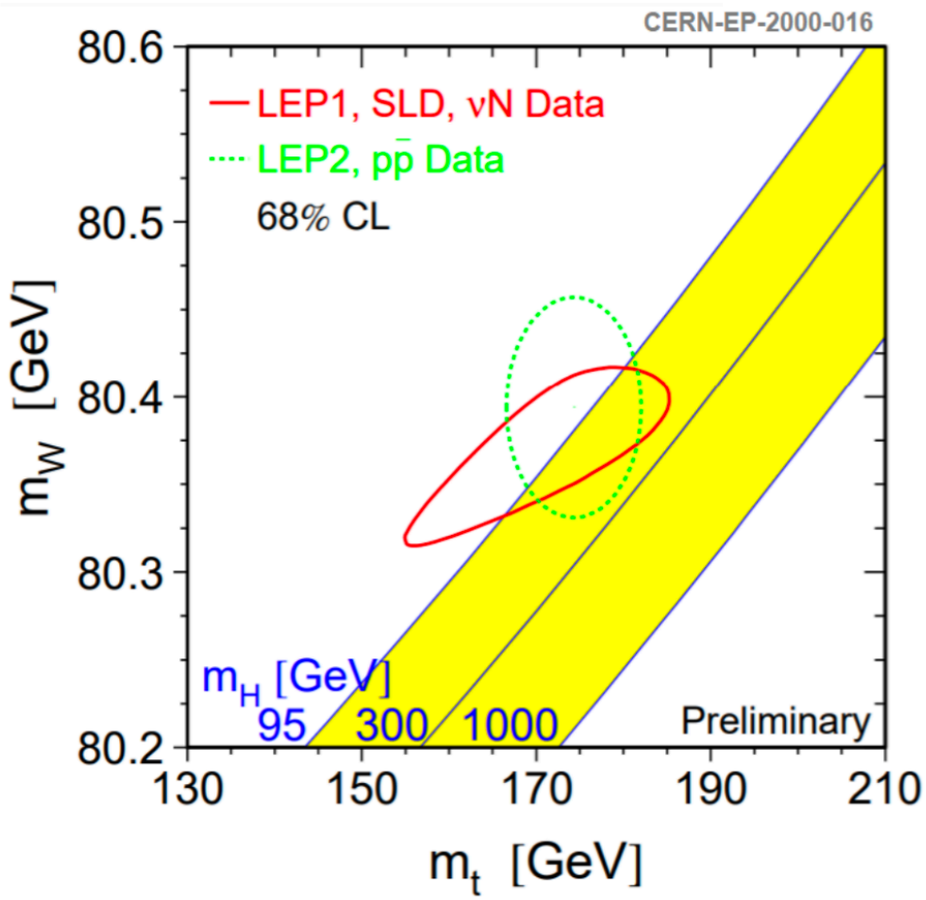


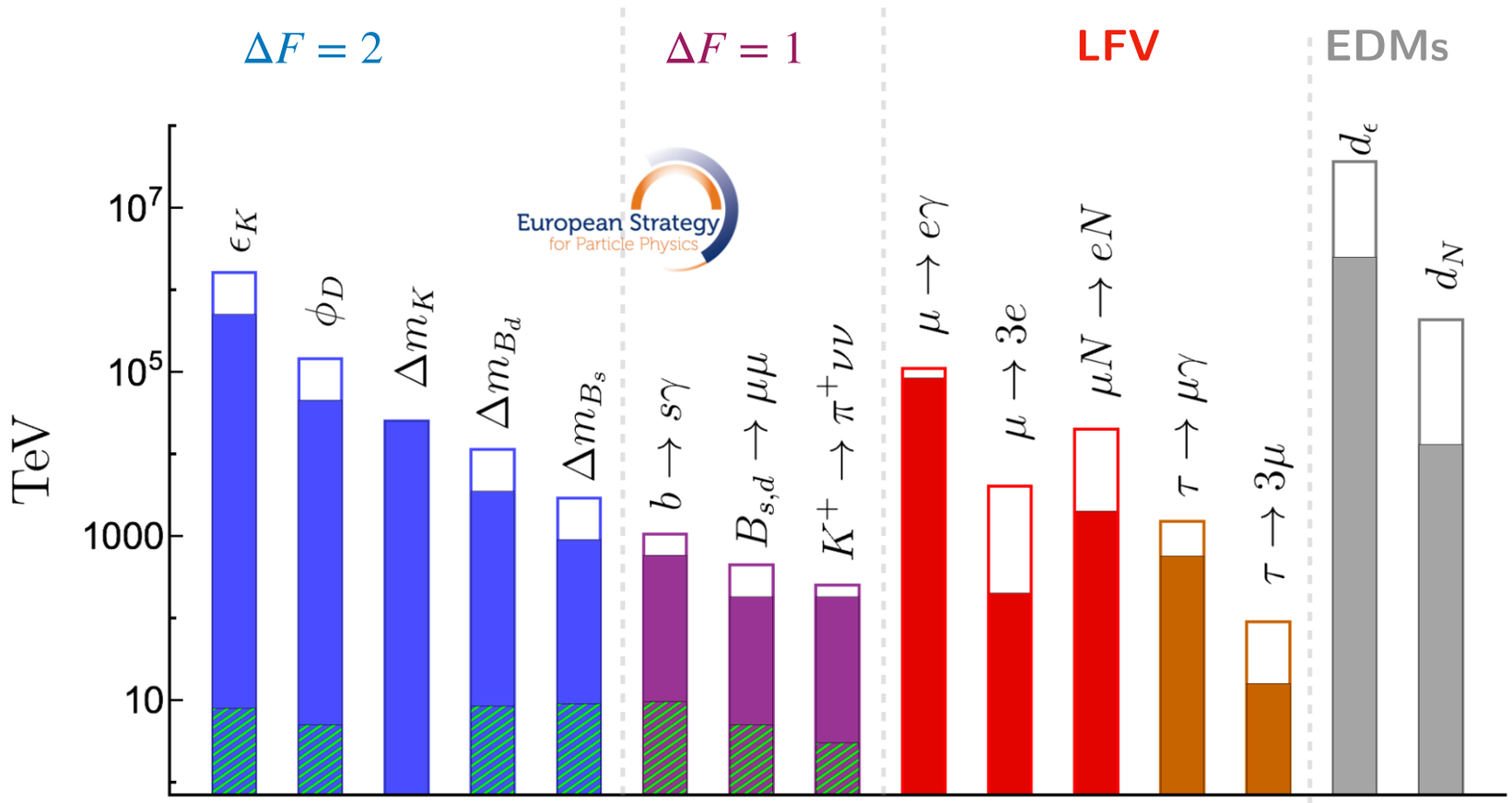
Electroweak precision measurements at LEP:



The precision frontier

Rare and forbidden processes

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{\mathcal{C}^{(5)}}{\Lambda_L}\mathcal{O}^{(5)} + \sum_i \frac{\mathcal{C}_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)} + \dots$$



$$\frac{\mathcal{C}^{(6)}}{\Lambda^2} = \frac{1}{\Lambda^2}$$

Indirect searches are also a powerful guide beyond the SM!

Main research activities

INTENSITY frontier GDR-InF

I. Understanding of flavor physics measurements (phenomenology)

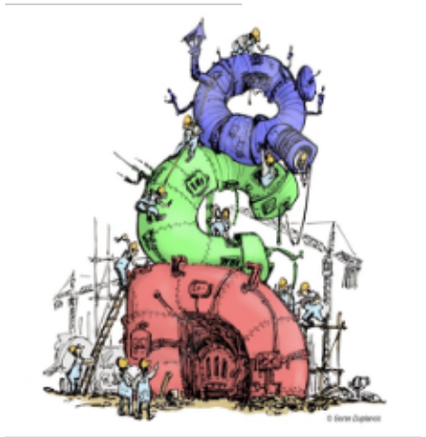
II. Interplay of quark and lepton flavors (phenomenology)

III. Careful assessment of hadronic uncertainties (lattice QCD)

IV. Flavor constraints on physics beyond the SM (EFTs at low- and high-p_T)

V. Theory of flavor (model building)

QCD ⇔ Flavor ⇔ BSM



@Goran Duplancic

@GDR-Inf

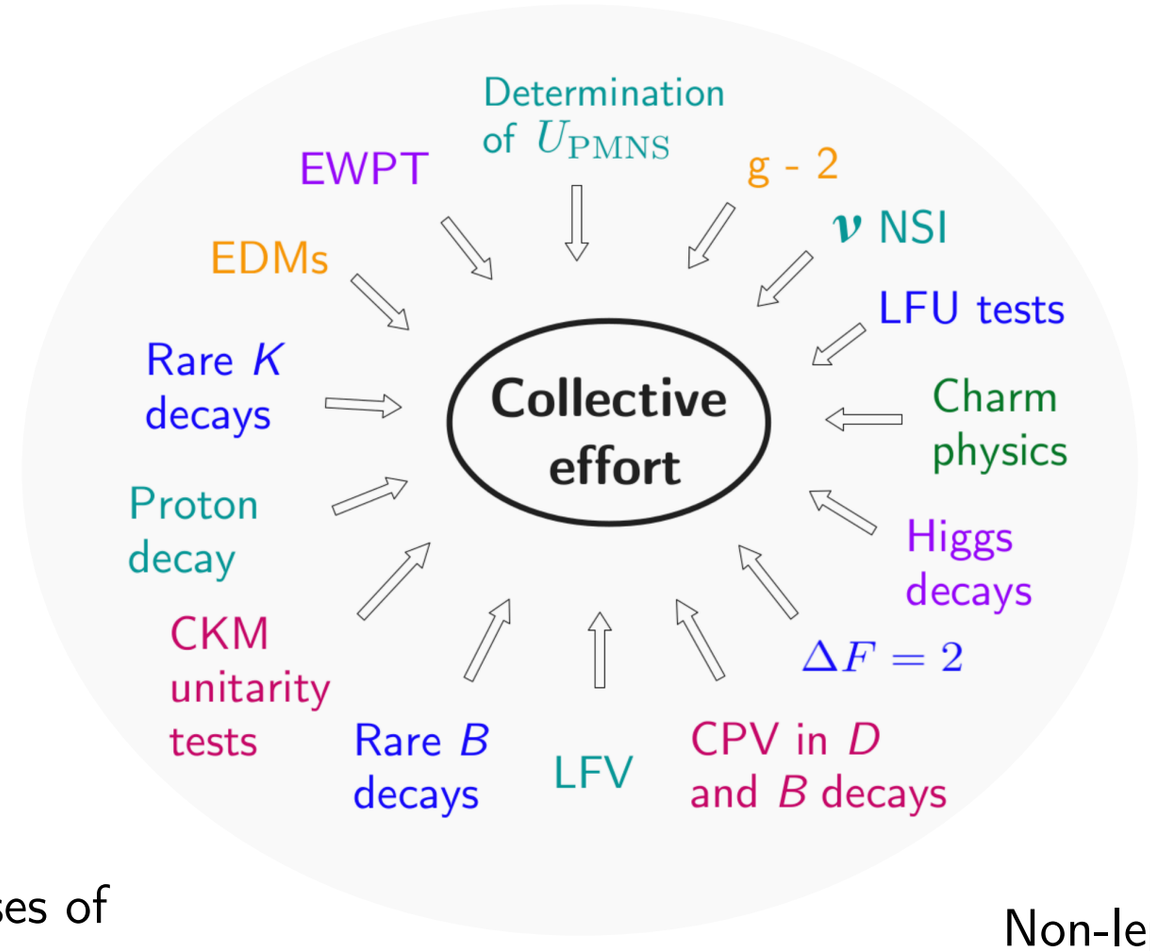
@Symmetry Magazine

Flavor physics at IJCLab

$K \to \pi \ell \ell$ form-factors and LD effects
[Bernard, Moussallam]

Flavor constraints from high-p_T data
[Falkowski, Sumensari]

Charmonium on the lattice
[Becirevic, Blossier]



CPV via EDM and β-decays
[Abada, Falkowski]

$\langle D_{(s)} | \bar{c} \Gamma b | B_{(s)} \rangle$ on the lattice at $w = 1$
[Becirevic, Blossier]

LFV and LNV in various ways
[Abada, Sumensari]

Dispersive parameterization of form-factors
[Bernard, Reboud]

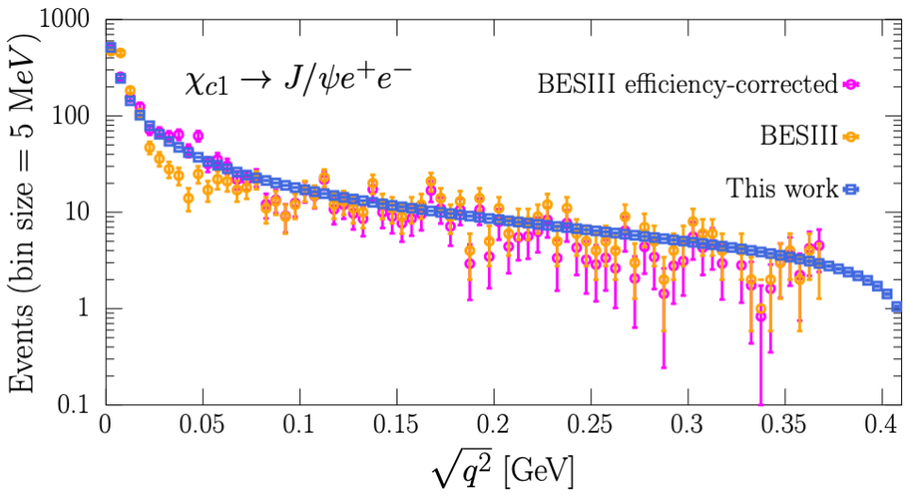
BSM through angular analyses of exclusive $b \to c\tau\nu$ and $b \to s\ell\ell$ processes
[Becirevic, Kou, Reboud, Sumensari]

Model building and SMEFT constraints
[Becirevic, Falkowski, Sumensari]

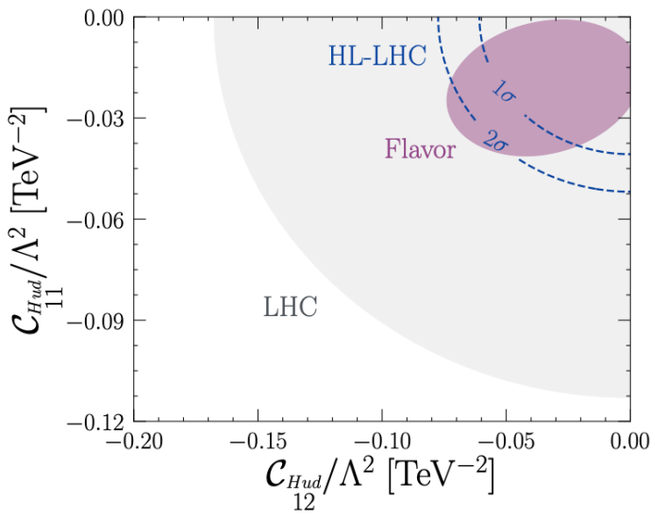
Non-leptonic D- and B-decays
[Kou, Moussallam, Reboud, Leroy, Le Yaouanc]

■ ■ ■

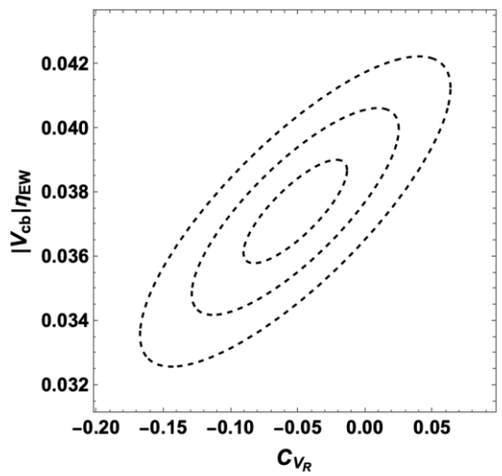
Our recent activity (snapshot)...



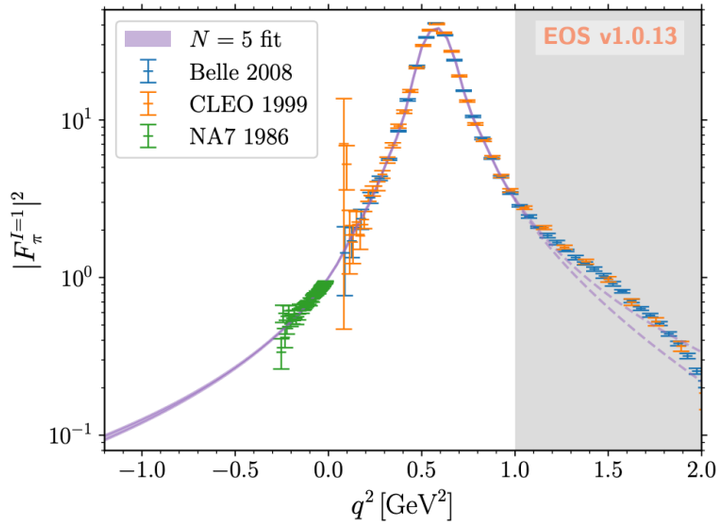
[**Becirevic**, Di Palma, Frezzotti, Gagliardi, Lubicz. '26]



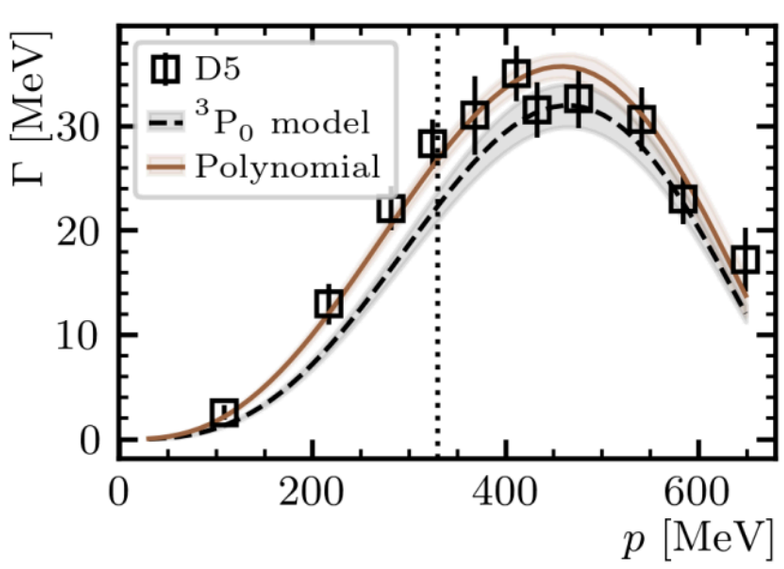
[Eboli, Leal, Martines, **Sumensari**. '25]



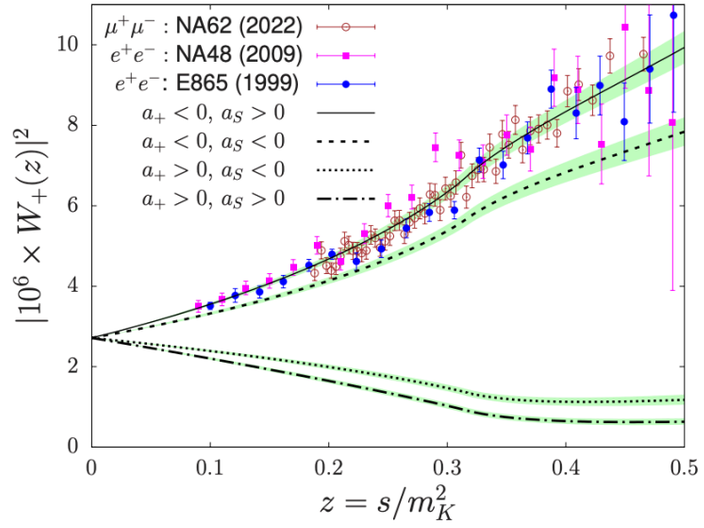
[Kapoor, Huang, **Kou**. '24]



[Kirk, Kubis, **Reboud**, van Dyk. '25]



[San Jose, **Blossier**, Heitger, Neuendorf. '24]



[**Bernard**, **Descotes-Genon**, Knecht, **Moussallam**. '25]

https://eos.github.io/

[**Reboud** + collaborators]

https://highpt.github.io/

[**Sumensari** + collaborators]

+ much more!