The flavor of the fundamental interactions

J. Martin Camalich



Physics Colloquium at the UNAM

March 21st 2019

Outline



- Where we are in particle physics?
- 2 What is flavor physics?
 - Flavor in the Standard Model of Particle Physics
 - Flavor beyond the Standard Model
- 3 The flavor anomalies

Where do we stand in Particle Physics?

We have a fundamental theory that explains almost all experimental data!

Standard Model (SM) of Particle Physics



- ② ... and the Large Hadron Collider (LHC) to *directly* explore the shortest scales ever probed ($\lambda \sim 10^{-3}$ fm) ...
- $E \simeq h/\lambda$: High-energy physics



• $E = m c^2$: New & heavy (TeV) particles!



Discovery of the Higgs! (2012)

Produced at the LHC!



$\blacktriangleright\,$ Mass of the Higgs $\simeq 125 \times proton$ mass







Major milestone of the LHC and completion of the SM!

J. Martin Camalich (IAC)

- Compelling empirical facts that the SM do not explain. For example:
 - What is the astrophysical & cosmological dark matter?





- Theoretical problems about the values and quantum stability of the parameters...
 - Why is the Higgs mass so much smaller than $M_{\text{Planck}} \simeq 10^{18}$ GeV?



 Quantum corrections *quadratically* sensitive to mass of new physics

$$(m_{H}^{\rm phys})^{2} = (m_{H}^{0})^{2} + \frac{\gamma_{\rm top}^{2} N_{c}}{8\pi^{2}} \left(\Lambda_{\rm NewPhysics}^{2} + \ldots\right)$$

Strong motivations to search for TeV-scale New Physics

Super-Symmetry (SUSY)

J. Martin Camalich (IAC)

ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

ATLAS Preliminary

Status: March 2019

 $\int \mathcal{L} dt = (3.2 - 139) \text{ fb}^{-1}$ $\sqrt{s} = 8, 13 \text{ TeV}$

	Model	ℓ, γ	Jets†	ET	∫£ dt[fb	-1 Limit	Reference
AC Admensions Education Structures of the second structure of the second struc	DD $G_{NX} + g/q$ DD non-resonant $\gamma\gamma$ DD OBH high Z_{PT} DD BH high Z_{PT} DD BH multipet S1 $G_{NX} \rightarrow \gamma\gamma$ MLR S5 $G_{NX} \rightarrow WW/ZZ$ m MLR S5 $G_{NX} \rightarrow WW/ZZ \rightarrow qequil MLR S5 G_{NX} \rightarrow ttUED / RPP$	0 e,µ 2 y 21 e,µ 2 g 0 e,µ 1 e,µ 1 e,µ	1 - 4j 2j $\ge 2j$ $\ge 3j$ -1 N 2J $\ge 1b, \ge 1J$ $\ge 2b, \ge 3$	Yes - - - - 2) Yes j Yes	36.1 36.7 37.0 3.2 3.6 36.7 36.1 139 36.1 36.1	No. 2 Junit	1711.05901 1707.04147 1703.09127 1606.0295 1512.02888 1707.04147 1803.02888 1707.04147 1803.02888 1707.04147 1803.02888 1803.05828 1803.05678
Gauge bosons	$\begin{array}{l} \mathrm{SM} \ Z' \to \ell\ell \\ \mathrm{SM} \ Z' \to rr \\ \mathrm{sptophobic} \ Z' \to bb \\ \mathrm{sptophobic} \ Z' \to tr \\ \mathrm{SM} \ W' \to \ell \nu \\ \mathrm{SM} \ W' \to \psi \\ \mathrm{VT} \ V' \to WV \to \mathrm{opag} \ \mathrm{model} \ \mathrm{B} \\ \mathrm{VT} \ V' \to WV \to \mathrm{opag} \ \mathrm{model} \ \mathrm{B} \\ \mathrm{RSM} \ W''_H \to tb \\ \end{array}$	2 e,μ 2 τ - 1 e,μ 1 e,μ 1 τ 0 e,μ nuti channe nuti channe	- 2b 21b, 21J - 2J	- - Yes Yes -	139 36.1 36.1 79.8 36.1 139 36.1 36.1 36.1	Evene 5.758 rem 2.0716 rem 2.0716 rem 3.070 rem 3.070 rem 3.070 rem 0.0716	1903.06248 1709.07242 1805.09299 1804.10823 ATLAS-CONF-2018-017 1801.06982 ATLAS-CONF-2019-003 1712.06518 1807.10473
C CI	l qaqa I ff qq I tttt	_ 2 e,μ ≥1 e,μ	2 j 	- Yes	37.0 36.1 36.1	A 21.5 TeV V ₁₁ A 40.0 TeV V ₁₂ A 2.57 TeV [Cel = 4 r	1703.09127 1707.02424 1811.02305
WQ So	xial-vector mediator (Dirac DM) olored scalar mediator (Dirac DM $V_{\ell \ell} \in EFT$ (Dirac DM) calar reson. $\phi \rightarrow t_{\ell}$ (Dirac DM)	0 e,µ 1) 0 e,µ 0 e,µ 0-1 e,µ	$\begin{array}{c} 1-4 \ j \\ 1-4 \ j \\ 1 \ J, \leq 1 \ j \\ 1 \ b, 0 \ 1 \ J \end{array}$	Yes Yes Yes Yes	36.1 36.1 3.2 36.1	Name 1.55 TeV cs-0.55 cs-0.1 cs, (1) = 1.00' Name 1.87 TeV cs-0.0 cs, (1) = 1.00' Ma 700 GeV rd, (1) = 1.00' Ma 700 GeV rd, (1) = 1.00' Ma 700 GeV rd, (1) = 1.00'	1711.03301 1711.03301 1608.02372 1812.00743
0 50 50 50	calar LQ 1 st gen calar LQ 2 nd gen calar LQ 3 rd gen calar LQ 3 rd gen	1.2 e 1.2 μ 2 τ 0-1 e,μ	≥ 2 j ≥ 2 j 2 b 2 b	Yes Yes - Yes	36.1 36.1 36.1 36.1	LD reson 1.4/TeV β = 1 50 reson 1.50/TeV β = 1 LC [*] ₁ reson 1.00 TeV β = 1 LC [*] ₁ reson 1.00 TeV β = 1 LC [*] ₁ reson 1.00 TeV β = 1 LC [*] ₁ reson 9.00 TeV 8/L(L) [*] ₁ = tr) = 1 LC [*] ₁ reson 9.00 SeV 8/L(L) [*] ₁ = tr) = 0	1902.00377 1902.00377 1902.08103 1902.08103
Heavy quarks	$\begin{array}{llllllllllllllllllllllllllllllllllll$	nuti-channe nuti-channe δ(SS)/≥3 e _µ 1 e,μ 0 e,μ, 2 γ 1 e,μ	N 1 ≥1 b, ≥1 ≥1 b, ≥1 ≥1 b, ≥1 ≥4 j	Yes J Yes J Yes Yes	36.1 36.1 36.1 79.8 20.3	Transi 1.37 SW/ 50/2 no.be/ Breasi 1.34 FW/ 50/2 no.be/ Tra, max 1.44 FW/ 87 (r_0, w/w) + 1 Yama 1.85 TW/ 87 (r_0, w/w) + 1 Breasi 1.25 TW/ 87 (r_0, w/w) + 1 Breasi 1.25 TW/ 87 (r_0, w/w) + 1 Breasi 1.25 TW/ 4 = 0.5	1808.02343 1808.02343 1807.11883 1812.07343 ATLAS-CONF-2018-024 1509.04281
Excited fermions a a a a	solited quark $q^* \rightarrow qg$ solited quark $q^* \rightarrow q\gamma$ solited quark $b^* \rightarrow bg$ solited lepton ℓ^* solited lepton τ^*	- 1 γ - 3 ε,μ 3 ε,μ, τ	2j 1j 1b,1j -	-	139 36.7 36.1 20.3 20.3	Straw 6.7 TeV c+/y × ted x*. h = m(x*) 10 moto 5.3 TeV c+/y × ted x*. h = m(x*) 10 moto 5.3 TeV c+/y × ted x*. h = m(x*) 10 moto 2.8 TeV c+/y × ted x*. h = m(x*) 11 moto 3.0 TeV A = 1.0 TeV 11 moto 1.6 TeV A - 1.6 TeV	ATLAS-CONF-2019-007 1709.10440 1805.09299 1411.2921 1411.2921
Typer of the second sec	pe III Seesaw RSM Majosana v jogs tripte $H^{\pm\pm} \rightarrow \ell \tau$ uti-charged particles lagnetic monopoles $\sqrt{s} = 8 \text{ TeV}$ \sqrt{s}	1 e,μ 2 μ 3.4 e,μ (St 3 e,μ, τ - - - - - - - - - - - - - - - - - - -	≥ 2 j 2 j 5) - - - - tull d	Yes 3 TeV lata	79.8 36.1 36.1 20.3 36.1 7.0	Minimum Minimum <t< td=""><td>ATLAS-CONF-2018-020 1809.11105 1710.00748 1411.2821 1812.0073 1509.08059</td></t<>	ATLAS-CONF-2018-020 1809.11105 1710.00748 1411.2821 1812.0073 1509.08059

"Only a selection of the available mass limits on new states or phenomena is shown

†Small-radius (large-radius) jets are denoted by the letter j (J).

No new particles found at the LHC

J. Martin Camalich (IAC)



Precision SM calculations agree with high-energy data...

J. Martin Camalich (IAC)



Precision SM calculations agree with low-energy data...

Summary

Overwhelming majority of particle-physics experiments agree with the SM predictions

• Except for a few remarkable exceptions ...



Flavor Anomalies

- "Coherent set of tensions" with SM in decays of "*B* mesons" in "charged leptons"
- Violation of symmetry of interactions for different leptons ("lepton universality")

• Example: $B \to K^* \mu^+ \mu^-$ vs. $B \to K^* e^+ e^-$



► The "*R_{K*}* anomaly"



• Other persisting "anomalies": like muon's (g - 2) or proton charge radius

What is Flavor?



Gell-Mann and Fritzsch (1971)

- "Just as ice-cream has both *colour* and *flavour* so do quarks."
- Only three quarks known at the time *up*, *down* and *strange*.
- Extended to leptons.

Modern SM



3 almost identical families of "Matter" (fermions)

- * "Neutral leptons": Neutrinos
- ★ "Charged leptons": e, μ and τ
- * "Up quarks": "up", "charm", "top"
- * "Down quarks": "down", "strange", "bottom"
- "Identical": Same "charges" of the gauge forces (e.g. electric charge)
- "Almost": Different masses!

Flavor Physics in the Standard Model

Yukawa sector of the Standard Model $-\mathcal{L}_{Y} = \bar{q}_{L}Y_{D}d_{R}H + \bar{q}_{L}Y_{U}u_{R}\tilde{H} + \bar{\ell}_{L}Y_{\theta}e_{R}H + h.c.$

- ► Fermion mass generation: H → vev + h⁰
- Yukawa matrices diagonalizable



$$M_{U} \equiv \begin{pmatrix} m_{u} & 0 & 0 \\ 0 & m_{c} & 0 \\ 0 & 0 & m_{t} \end{pmatrix} = \operatorname{vev} \times L_{u}^{\dagger} Y_{U} R_{u}$$
$$M_{D} \equiv \begin{pmatrix} m_{d} & 0 & 0 \\ 0 & m_{s} & 0 \\ 0 & 0 & m_{b} \end{pmatrix} = \operatorname{vev} \times L_{d}^{\dagger} Y_{D} R_{d}$$

• Cabibbo-Kobayashi-Maskawa: Flavor violation in W^{\pm} (charged-current) coup's

$$V_{\rm CKM} = L_u^{\dagger} L_d$$

Flavor Physics in the Standard Model

Yukawa sector of the Standard Model $-\mathcal{L}_{Y} = \bar{a}_{l} Y_{D} d_{B} H + \bar{a}_{l} Y_{l} u_{B} \tilde{H} + \bar{\ell}_{l} Y_{c} e_{B} H + h.c.$



• The CKM are very hierarchical (almost diagonal matrix)



The CKM unitary triangle

• Complex and Unitary matrix \implies Parametrized by **3 angles** and **1** *CP* **phase**



Experimental sources of the "UT"

Unitary Triangle

- Unitary relations: Triangles in complex plane
- Few parameters compared to thousands of processes they describe – PDG





The CKM unitary triangle

• Complex and Unitary matrix \implies Parametrized by **3 angles** and **1** *CP* **phase**



Unitary Triangle

- Unitary relations: Triangles in complex plane
- Few parameters compared to thousands of processes they describe – PDG

• Flavor Physics has become a very mature field



J. Martin Camalich (IAC)

The CKM unitary triangle

• Complex and Unitary matrix \implies Parametrized by **3 angles** and **1** *CP* **phase**



Unitary Triangle

- Unitary relations: Triangles in complex plane
- Few parameters compared to thousands of processes they describe – PDG

• Flavor Physics has become a very mature field



The SM Flavor Puzzle

• CKM and mass matrices: Parametrizations of flavor phenomena in the SM

Strong hierarchies in masses and mixings (PDG) $m_{up} = 0.0022(5) \text{ GeV}$ $m_{top} = 173.0(4) \text{ GeV}$



- Specific values of light quarks seem "tuned" (Anthropic arguments!)
- Origin of CP-violation
- Why does Nature need three generations at all?

Where is "flavor" coming from?

Testing the Standard Model with Flavor Physics

- Effective field theories
 - Add all operators consistent with symmetries and matter content
 - Infinite terms? NO if there is a mass gap $\Lambda_{NewPhysics} \gg vev$
- The classic example: Fermi theory for β decay!



 $\mathcal{L}_{\text{Fermi}} = \frac{G_F}{\sqrt{2}} (\bar{p}n)_{V-A} (\bar{e}\nu)_{V-A}$

► Size of coupling contain info about ∧

$$G_F = 1.1663787(6) \times 10^{-5} \text{GeV}^{-2} \simeq \frac{1}{m_W^2}$$

Standard Model EFT (
$$\Lambda \gg v_{\rm EW}$$
) Buchmuller & Wyler '88

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda} \mathcal{O}_W^{(5)} + \underbrace{\frac{1}{\Lambda^2} \sum_{i} \mathcal{O}_i^{(6)}}_{i}$$

J. Martin Camalich (IAC)

The Flavor Changing Neutral Currents (FCNC)

• Theorem: FCNC are "Loop-Suppressed" in the SM!

The Penguin Diagram



- Powerful probes of new physics!
- Prototypical example: Neutral-meson mixing





Generic bounds without a flavor symmetry

M. Neubert at EPS 2011

The experimental landscape in flavor physics

- Very exciting times in Flavor physics!
- Hadronic Machines: Huge Statistics vs. Large backgrounds LHCb and ATLAS and CMS (CERN)





Electron-Positron colliders: Small statistics vs Clean environment SuperKEK-B and Belle 2 (Japan)



The Flavor Anomalies



LFUV in charged currents: $b \rightarrow c \tau \nu$



Several tensions in two decay channels by three experiments

 $\Lambda_{\text{New-Physics}} \sim 3 \text{ TeV}$

EFT of new-physics in b ightarrow c au u

• Form factors: Decays difficult to predict because of strong interactions

Leptons do not feel the strong force Form factors should cancel in ratios!

The SM + 5 New-Physics operators

"V - A was the key", S. Weinberg

● New-Physics Scale is 3 TeV ⇒ New-Physics is accesible at the LHC!





Lepton-universality in Flavor-Changing-Neutral-Currents: $b \rightarrow s \ell^+ \ell^-$



- Other "anomalies" in \sim **100 observables** of the $b \rightarrow s \mu^+ \mu^-$ mode
 - Consistent tension with the SM at close to discovery (5σ)!

 $\Lambda_{New-Physics}\sim 30 \text{ TeV}$

Are we really on the verge of discovering new physics?

New stron-neutral particles: Vector triplet W', Z'



► New strong-interacting particles: Leptoquarks *S*, *U*^µ



- Extra bounds from low energy
- Z' exchange at tree level



LQ exchanges at loop level



The fate of the Flavor Anomalies

 If confirmed Flavor anomalies would lead to a new revolution in Fundamental Physics

The new analysis of R_{K} is expected to be announced **tomorrow**

- LHCb and Belle II, but may more experiments doing specific studies
- ... and heavy involvement of ATLAS and CMS looking for the new particles!
 - Also important in shaping the future experimental program in Particle Physics





13-16 May 2019 - Granada, Spain



• LHCb and ATLAS and CMS

2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	203+
		1	Run II	I				Run IV					Run V	
LS2						LS3					LS4			
LHCb 40 MHz UPGRADE		$L = 2 x \ 10^{33}$		LHCb Consolidation			$L = 2 x 10^{33} 50 fb^{-1}$		LHCb Ph II UPGRADE *		$L = 2 x 10^{34}$ $300 fb^{-1}$			
ATLAS Phase I Upgr		$L = 2 \times 10^{34}$		ATLAS Phase II UPGRADE			$HL-LHC$ $L = 5 \times 10^{34}$		ATLAS HL-LHC L = 5 x 10		. HC x 10 ³⁴			
CMS Phase I Upgr		300 fb ⁻¹		CMS Phase II UPGRADE						CMS		3000) fb-1	
Belle I	I	5 ab-1	L = 8 x	1035	50	ab-1								

• LHCb now: $\sim 10 \text{ fb}^{-1}$ with many analysis only with $\sim 3 \text{ fb}^{-1}$!

• Belle2



Concluding Remarks

Flavor physics was instrumental in discovering and shaping the SM

- Nuclear β-decays: Discovery weak interactions and neutrino
- Rare Kaon-decays: Discovery of the charm quark

Flavor physics in the 21st century: A powerful field for discoveries!

- Addresses very fundamental theoretical questions
- Strong experimental program extending for the next two decades
- Strong interplay with other areas: Cosmology, Neutrinos, Collider Physics,...
 - Discovery of CP violation in charmed system announced TODAY by LHCb!

