Title: Flavorful New Physics

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Abstract: The known basic building blocks of matter, the quarks and leptons, come in three generations or flavors.
The masses and interactions of the different flavors show a very hierarchical structure and the origin of these hierarchies remains an unsolved mystery of particle physics. The same hierarchies lead to a very high sensitivity of flavor changing processes to new undiscovered particles even outside the reach of direct searches at particle colliders.
In this colloquium I will present recent developments in constructing a theory of flavor and highlight the complementarity of flavor, Higgs, and collider physics in searching for new phenomena at the TeV scale and beyond.

Flavorful New Physics

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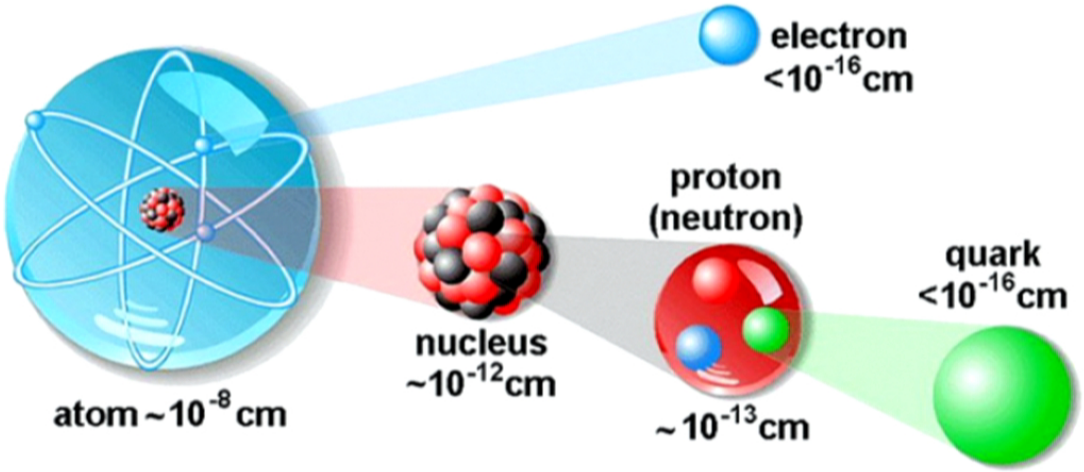
PERIMETER INSTITUTE

Colloquium

May 7, 2015

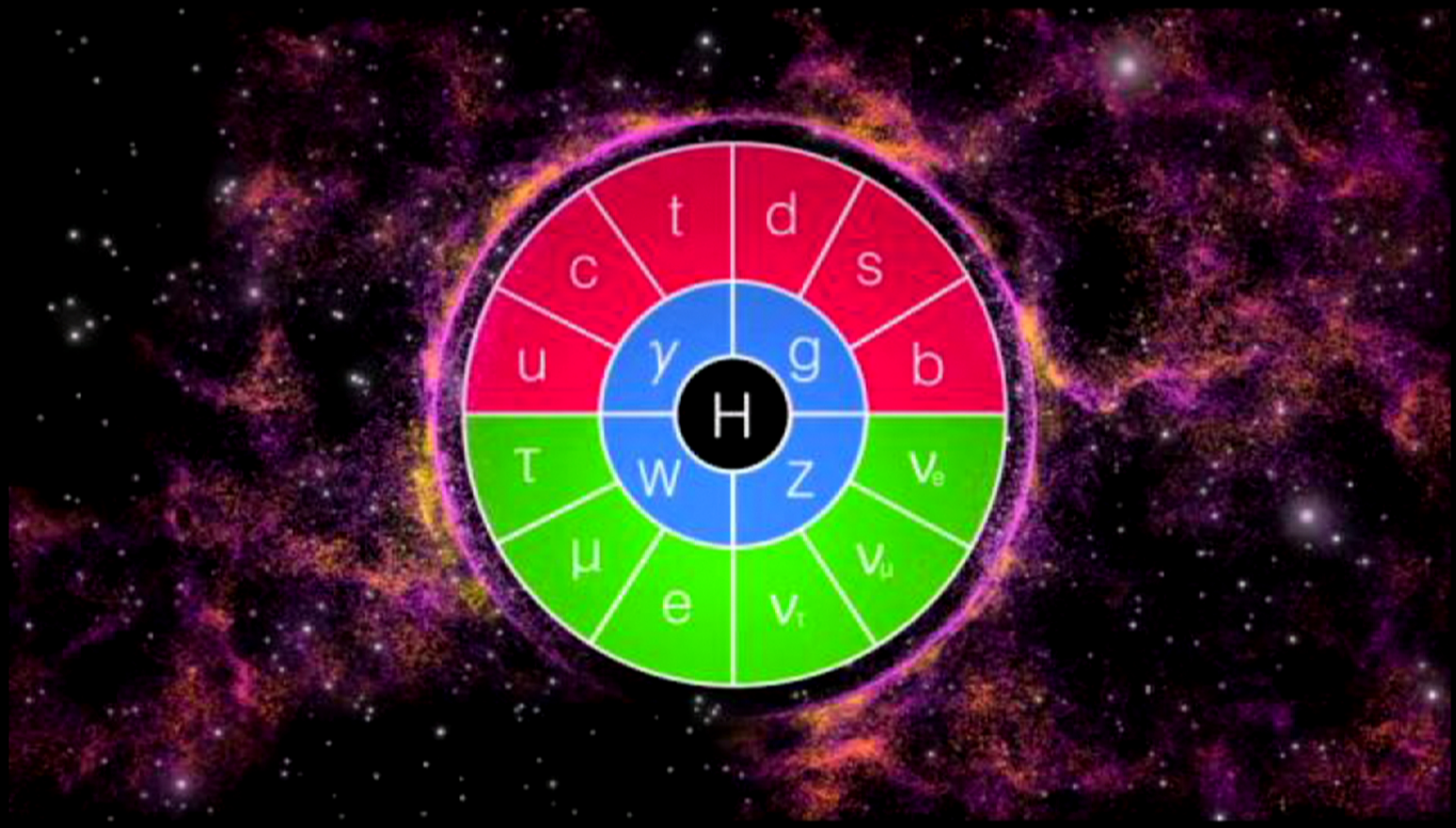
The Search for the Fundamental



What is the world made of?

What holds it together?

The Standard Model Particle Content



particlefever.com

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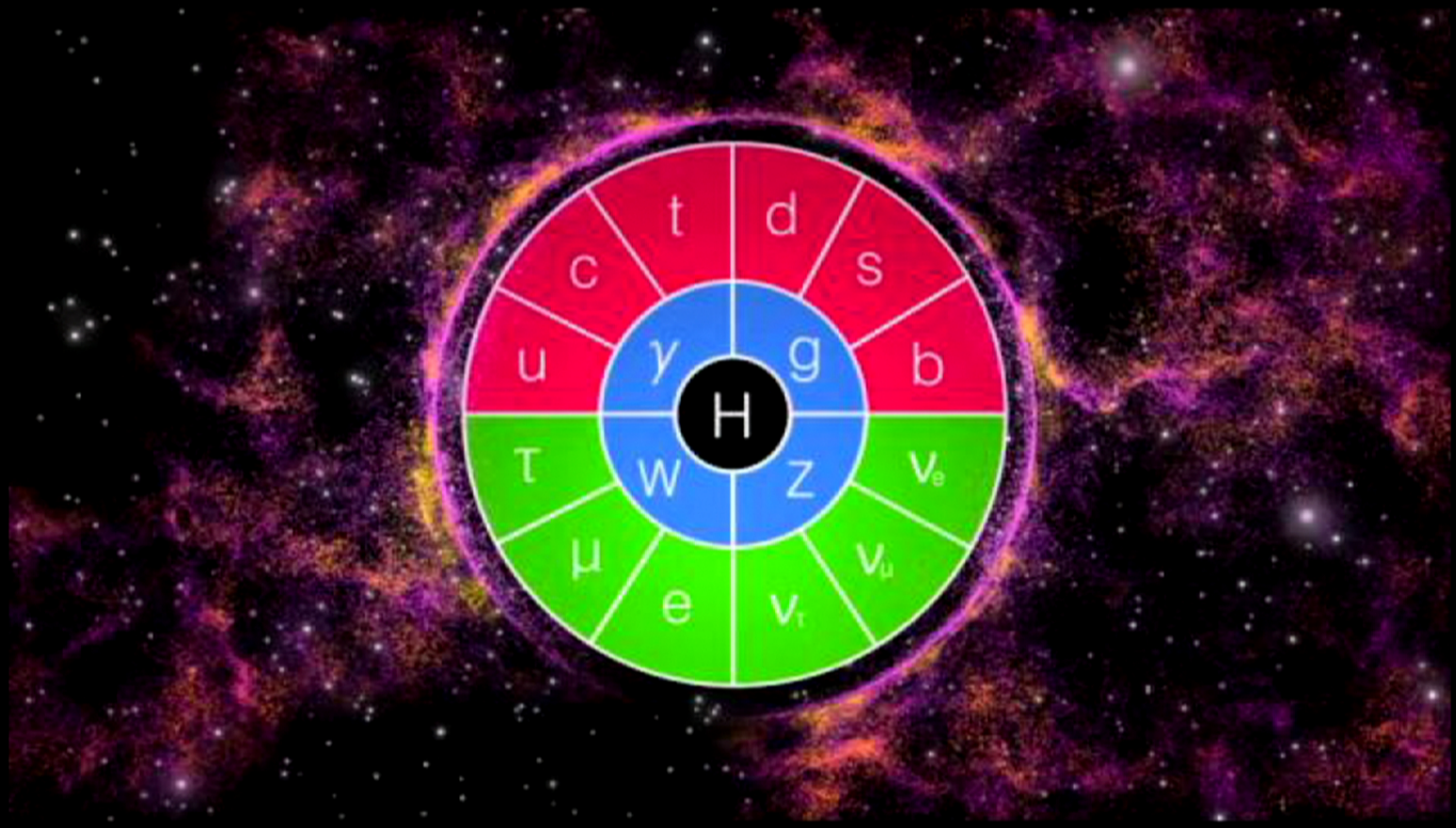

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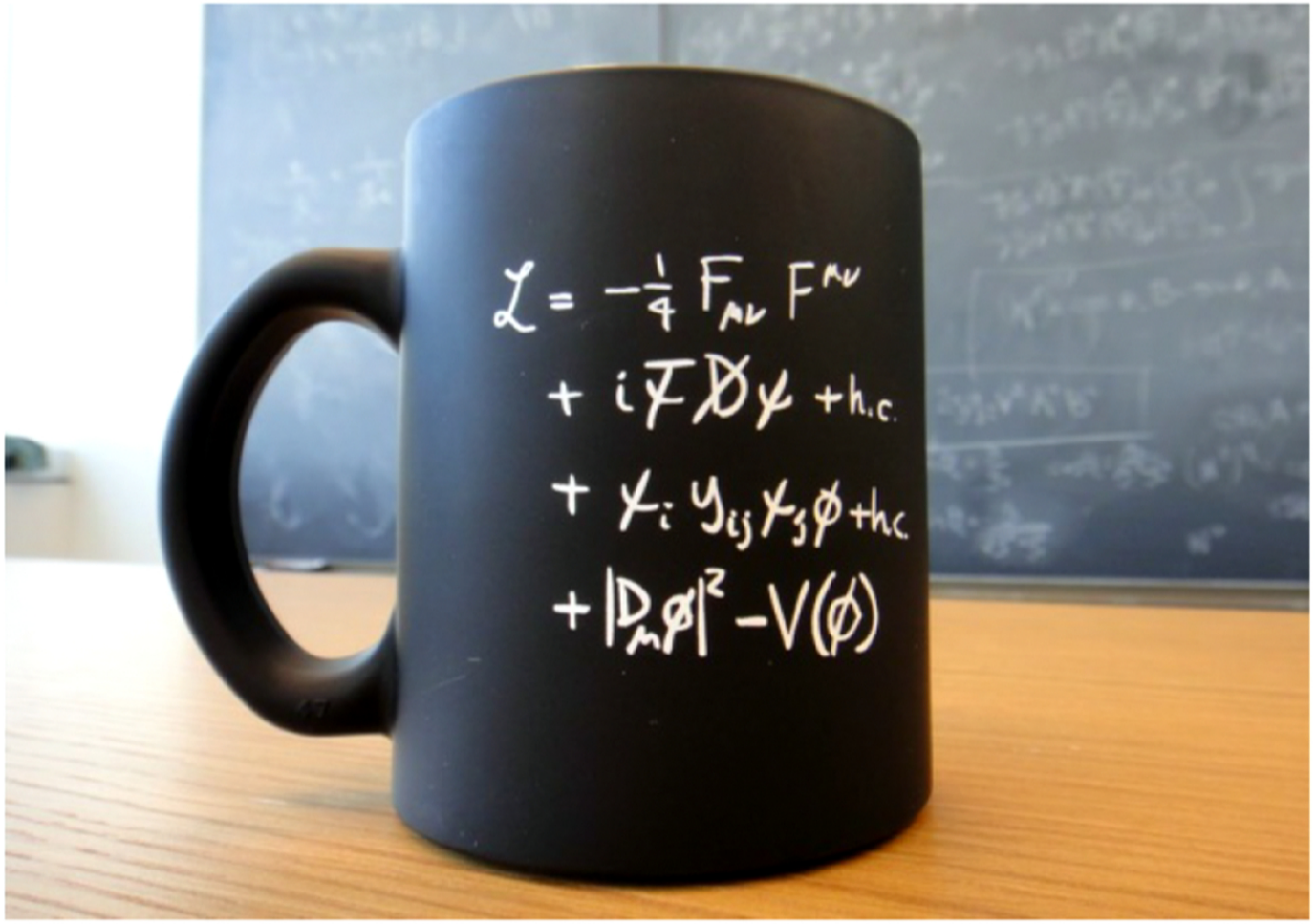
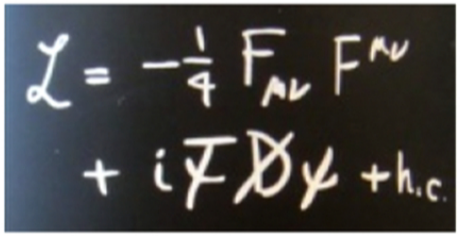
The Standard Model on a Cup of Coffee



Flavor and the Proliferation of Parameters

gauge sector



describes the gauge interactions of the quarks and leptons

parametrized by
3 gauge couplings
g_1, g_2, g_3

symmetric under a large flavor symmetry
$G_{SM} = SU(3)^5$

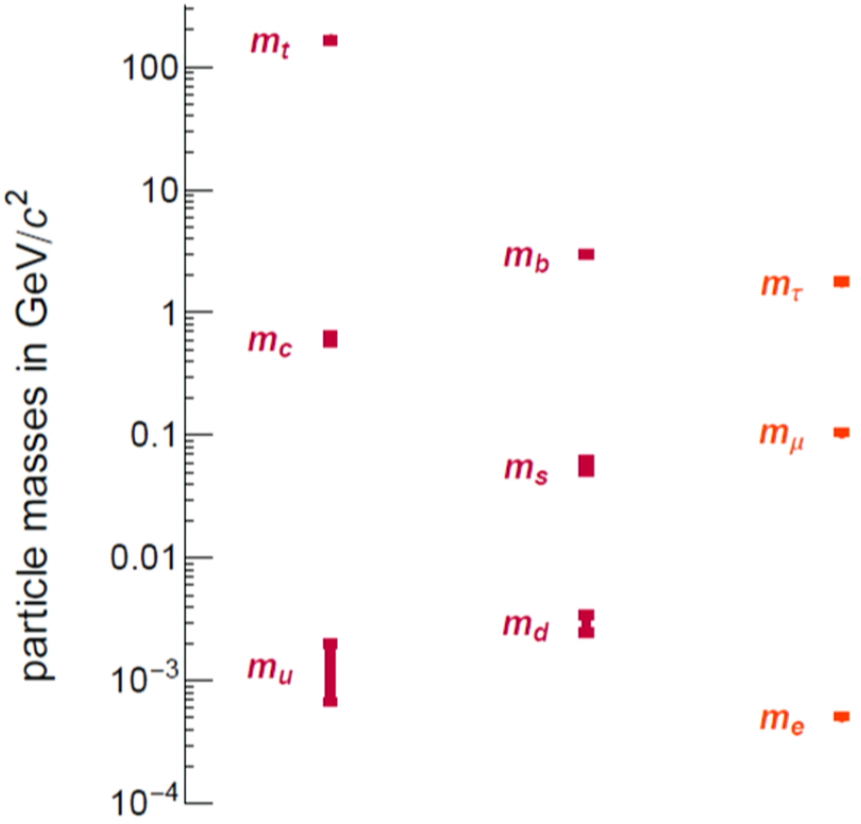
Flavor and the Proliferation of Parameters

gauge sector	Higgs sector	flavor sector
$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i \bar{\psi} \not{D} \psi + \text{h.c.}$	$+ \lvert D_\mu \phi \rvert^2 - V(\phi)$	$+ \bar{\psi}_i y_{ij} \psi_j \phi + \text{h.c.}$
describes the gauge interactions of the quarks and leptons	breaks electro-weak symmetry and gives mass to the $W^\pm$ and Z bosons	leads to masses and mixings of the quarks and leptons
parametrized by 3 gauge couplings g_1, g_2, g_3	2 free parameters Higgs mass Higgs vev	22 free parameters to describe the masses and mixings of the quarks and leptons

symmetric under a large flavor symmetry $G_{SM} = SU(3)^5$

only source of flavor symmetry breaking

Quark and Lepton Masses



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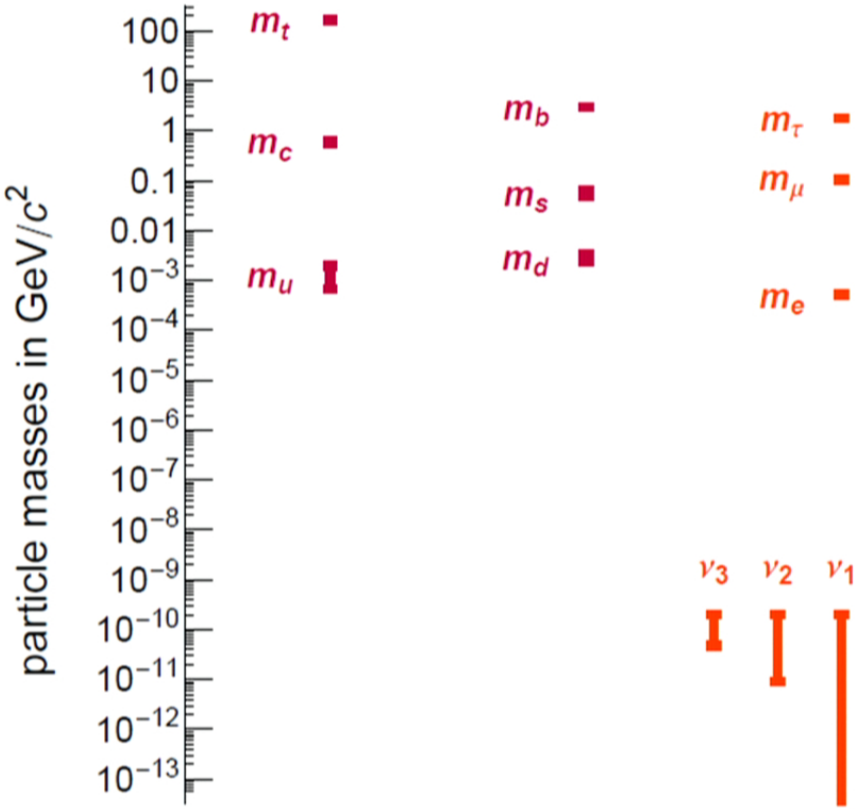
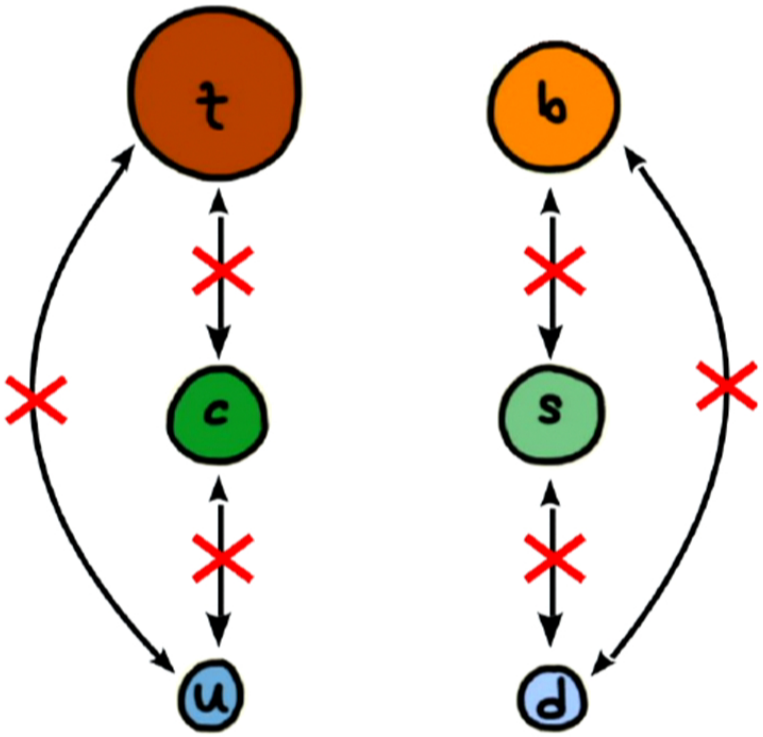


Distinct Decay Pattern of the Quarks in the SM



in the Standard Model there are
no direct transitions
within up-type or down-type quarks

→ GIM mechanism
(Glashow, Iliopoulos, Maiani)

no flavor changing neutral currents
(FCNCs) at tree level

Testing the CKM Picture of Flavor Violation

CKM matrix is the only source of quark flavor violation in the Standard Model

depends on only 4 parameters

$$\lambda, A, \bar{\rho}, \bar{\eta}$$

measuring many flavor transitions allows to over-constrain the 4 CKM parameters and to test the CKM picture of quark flavor violation

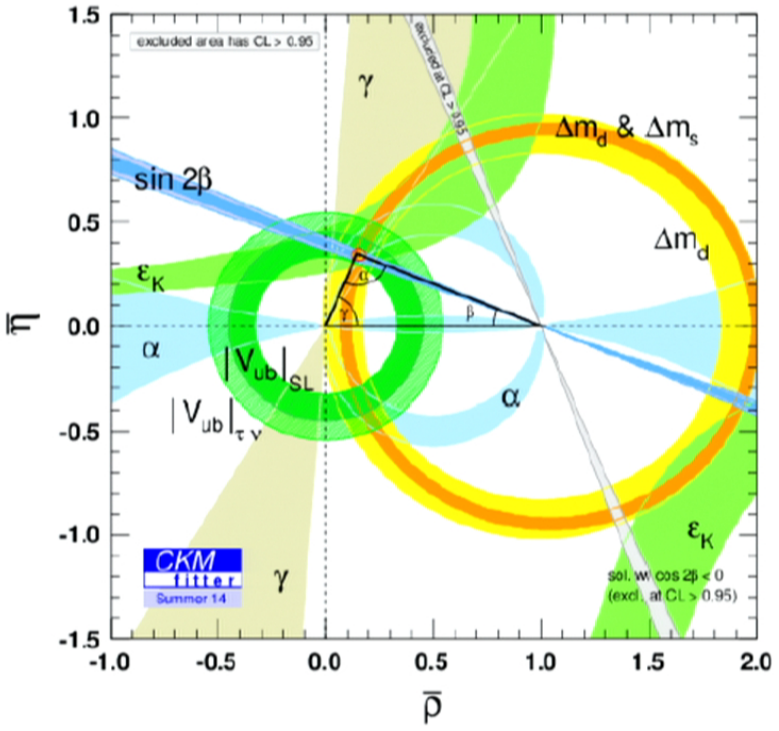
A Consistent Description of All Data

Within the experimental and theoretical uncertainties, the CKM matrix gives a consistent description of the observed flavor changing phenomena

Nobel Prize 2008 for

Makoto Kobayashi

Toshihide Maskawa



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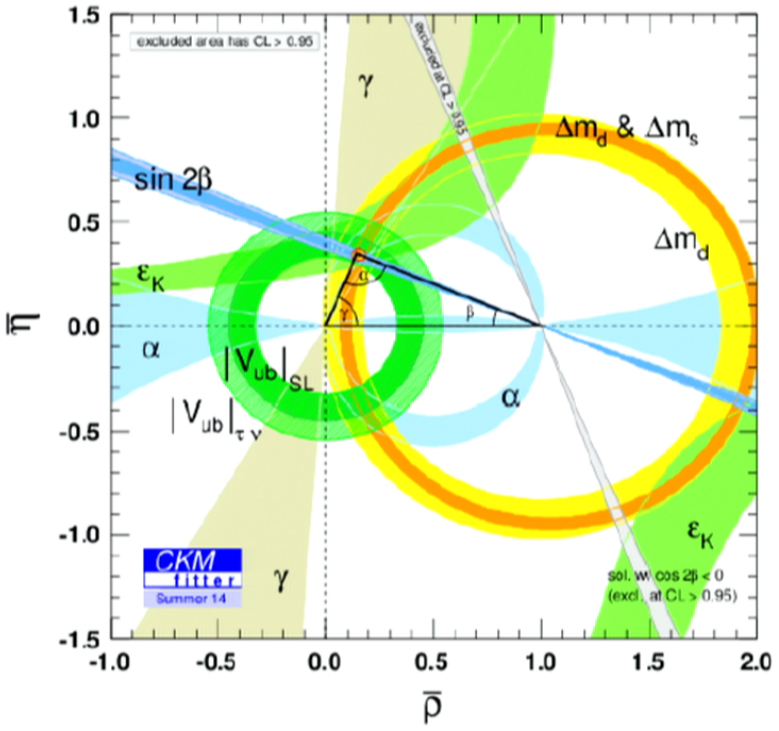
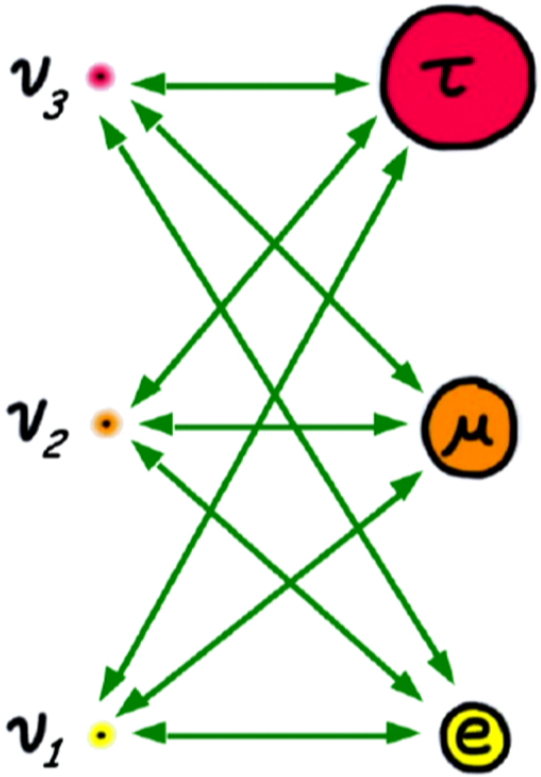


Flavor Mixing in the Lepton Sector



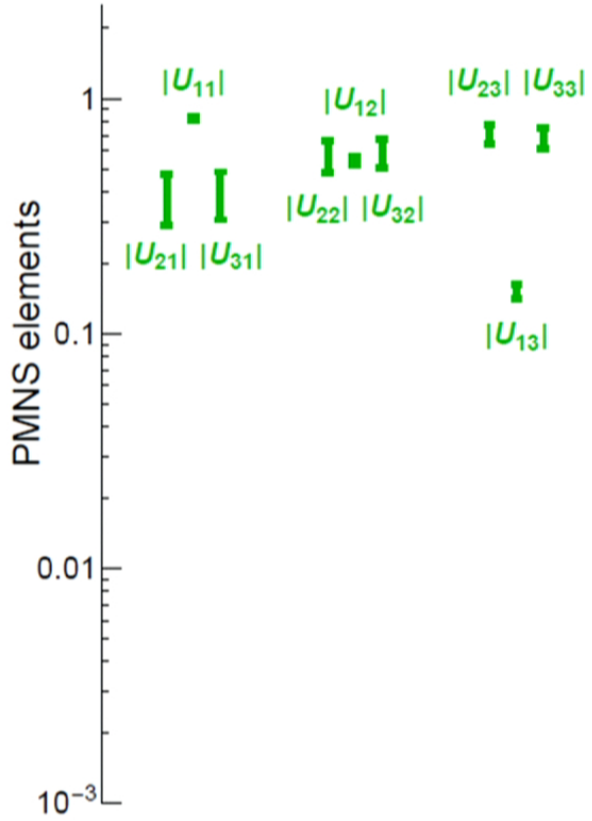
since the observation of neutrino oscillations, we know that there is also mixing in the lepton sector

as in the quark sector, no FCNCs

lepton flavor mixing is parametrized by the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix

$$U_{\text{PMNS}} = \begin{pmatrix} U_{11} & U_{12} & U_{13} \\ U_{21} & U_{22} & U_{23} \\ U_{31} & U_{32} & U_{33} \end{pmatrix}$$

Status of Lepton Mixing



unlike the CKM elements, the PMNS elements do not show a hierarchical pattern

is the PMNS matrix tri-bimaximal?

$$|U| \simeq \begin{pmatrix} \sqrt{\frac{2}{3}} & \sqrt{\frac{1}{3}} & 0 \\ \sqrt{\frac{1}{6}} & \sqrt{\frac{1}{3}} & \sqrt{\frac{1}{2}} \\ \sqrt{\frac{1}{6}} & \sqrt{\frac{1}{3}} & \sqrt{\frac{1}{2}} \end{pmatrix}$$

or is it anarchic?

$$|U| \simeq \begin{pmatrix} O(0.6) & O(0.6) & O(0.6) \\ O(0.6) & O(0.6) & O(0.6) \\ O(0.6) & O(0.6) & O(0.6) \end{pmatrix}$$

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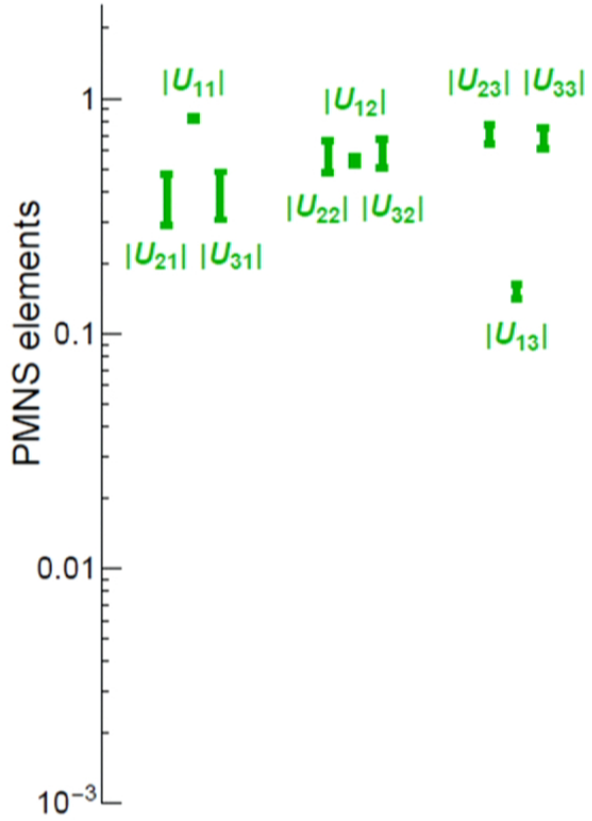

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The Standard Model Flavor Puzzle

we are lacking a
theory of flavor

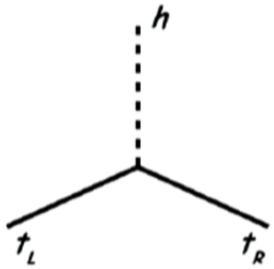
The Standard Model gives a reasonable description of all flavor transitions measured up to now, but it does not explain its mysteries

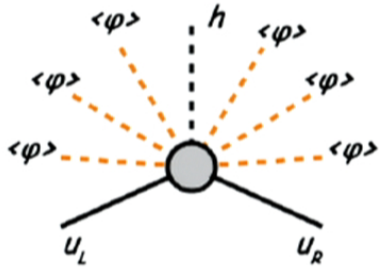
- Why are there three generations of quarks and leptons?
- What is the origin of the hierarchies in the fermion spectrum?
- What is the origin of the hierarchies in the quark mixing?
- Is lepton mixing anarchic?

Hierarchy from Symmetry

(Froggatt, Nielsen '79; ...)

fermion masses are forbidden by flavor symmetries
and arise only after spontaneous breaking of the symmetry





Simple U(1) model:

$Q(t_L)=Q(t_R)=0$
$Q(u_L)=-Q(u_R)=3$
$Q(h)=0$
$Q(\varphi)=-1$

$$h\bar{t}_R t_L \qquad \frac{\varphi^6}{M^6} h\bar{u}_R u_L$$

mass and mixing hierarchies given by
powers of the "spurion" $\langle\varphi\rangle/M$

$$\frac{m_u}{m_t} \sim \left(\frac{\langle\varphi\rangle}{M}\right)^n$$

can lead to characteristic new physics
effects in flavor observables

(WA, Guadagnoli, Raby, Straub '08;
WA, Buras, Gori, Paradisi, Straub '09;
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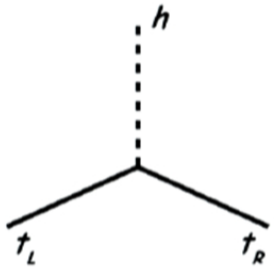

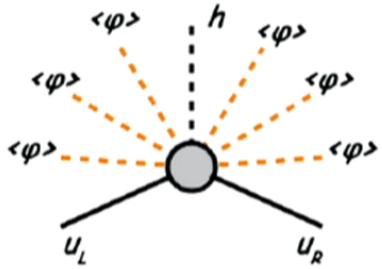

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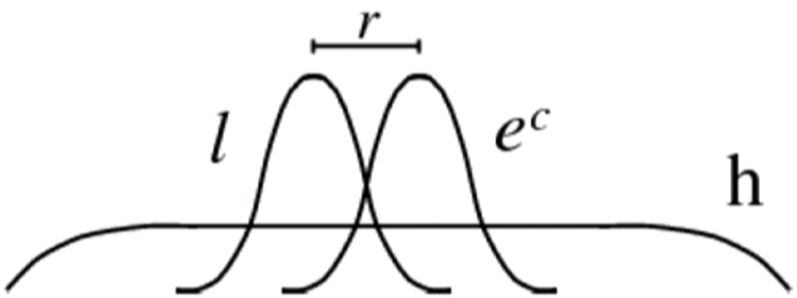
Hierarchy without Symmetry: Geometry

(Arkani-Hamed, Schmaltz '99; ...)

fermions are localized at different positions in an extra dimension



hierarchies from exponentially small wave-function overlap
between left-handed and right-handed fermions

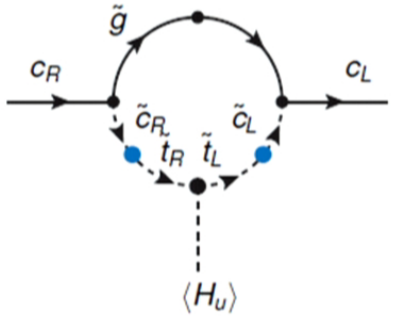
$$\frac{m_u}{m_t} \sim e^{-\Delta}$$

Fermion Hierarchy from Sfermion Anarchy

(WA, Frugiuele, Harnik '14)

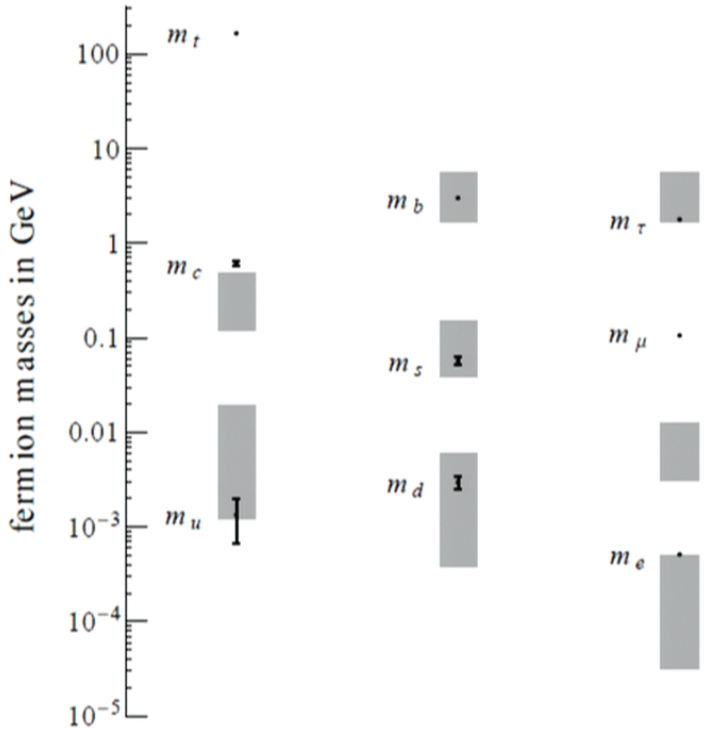
A simple setup for
loop induced fermion masses:

- MSSM particle content
- rank 1 Yukawa couplings
- flavor anarchic sfermion masses
("superpartners" of SM fermions)



Works remarkably well!

(muon mass can be fixed by
adding new gauge interactions)



The Hierarchy Problem

Canada
9,984,670 km^2

United States
9,826,675 km^2

$= 157{,}995\ \text{km}^2$

The Hierarchy Problem

$-$

$= \quad 1\ \text{Å}^2$

Canada
$9{,}984{,}670\ \text{km}^2$ $-$ United States
$9{,}826{,}675\ \text{km}^2$ $= 157{,}995\ \text{km}^2$

tuning of the Higgs mass would correspond to
the surface area of Canada and the United States
differing by approximately the size of an atom!

In order to protect the Higgs mass
from huge quantum corrections and to avoid finetuning,
we expect New Physics at or below the TeV scale
not far above the mass of the Higgs

Direct Searches for New Physics

unique effort towards high energies

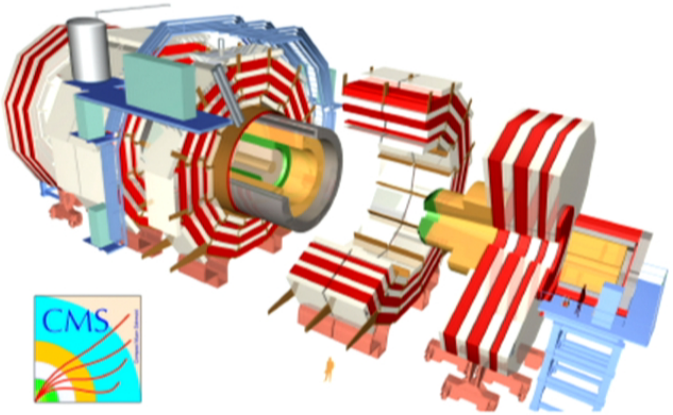
a very successful approach:

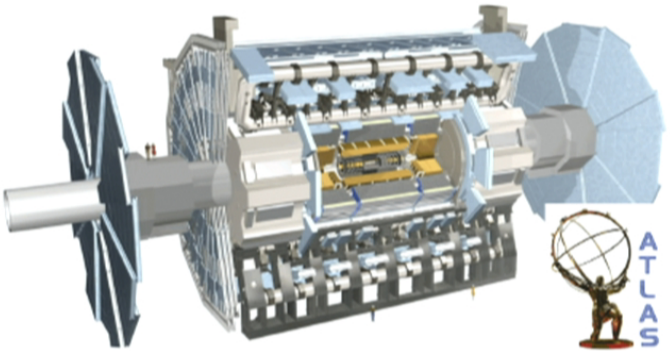
- Super Proton Synchrotron at CERN
(center of mass energy 0.54 TeV)
discovery of the W and Z bosons 1983

- Tevatron at Fermilab
(center of mass energy 1.96 TeV)
discovery of the top quark 1995

- Large Hadron Collider at CERN
(center of mass energy 8 TeV)
discovery of the Higgs boson 2012

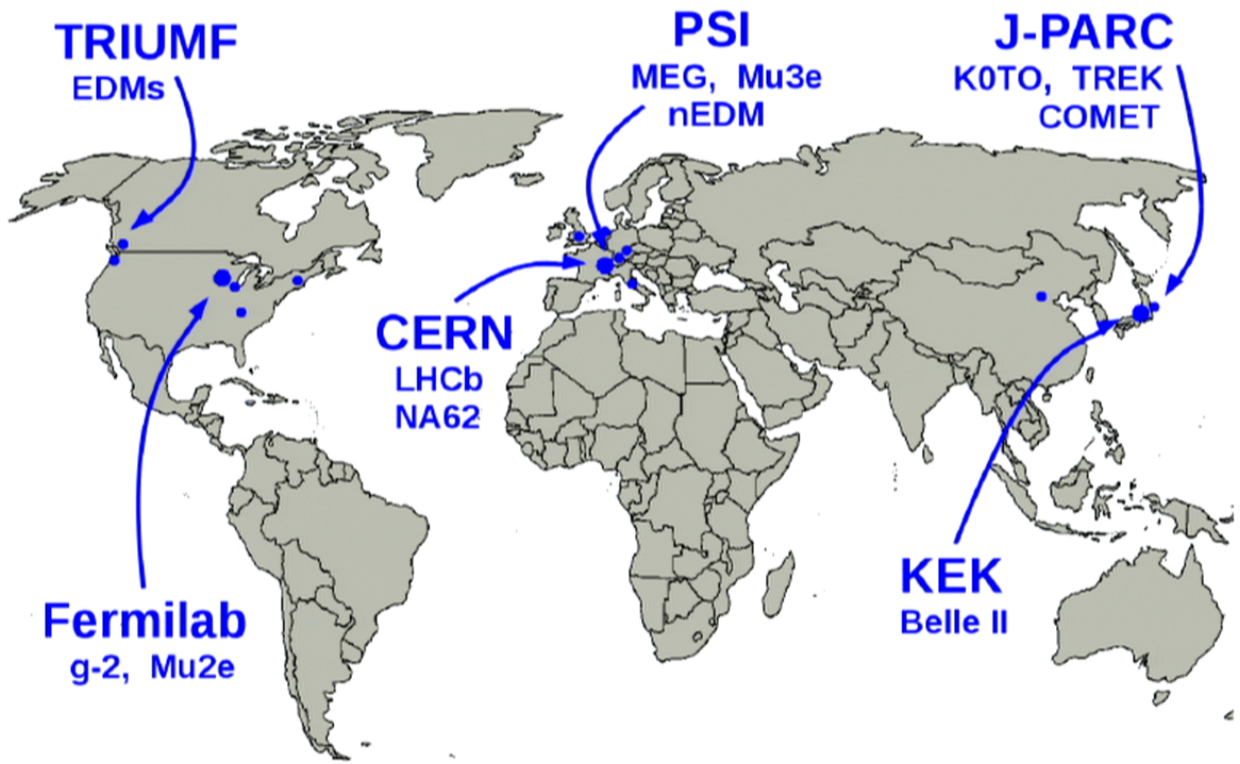
- Run II of the Large Hadron Collider
(center of mass energy 13 TeV)
discovery of ??? in 2016?





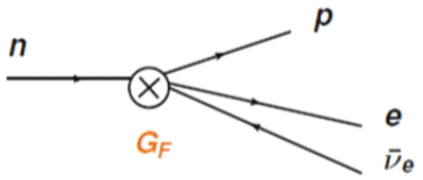

Indirect searches for New Physics
Look for virtual effects of new particles
in low energy experiments

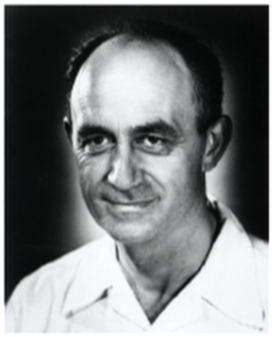
A Broad and Diverse Experimental Program



searching for flavor violating processes involving B and D mesons,
rare Kaon decays, lepton flavor violating decays, lepton flavor universality tests,
electric dipole moments, the g-2 of the muon, ...

Historic Example: Beta Decay





effective low energy description
of nuclear beta decay by a
4 fermion contact interaction

the interaction strength is given by
the Fermi constant

$$G_F \simeq 1.17 \times 10^{-5}\ \text{GeV}^{-2}$$

this defines an energy scale

$$\Lambda = (G_F\sqrt{2})^{-1/2} \simeq 246\ \text{GeV}$$

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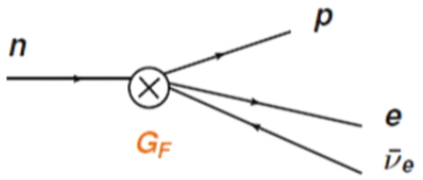

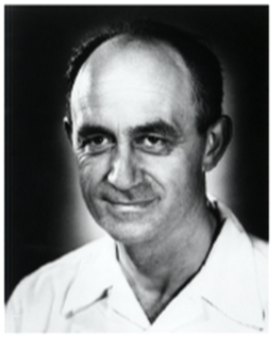

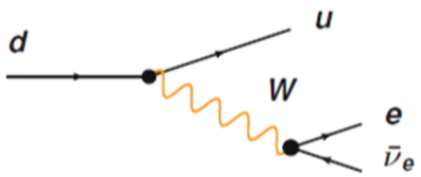

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in the Standard Model
we understand beta decay
as consequence of
the exchange of virtual
weak gauge bosons

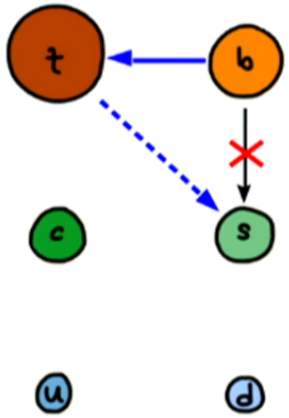
$$\frac{G_F}{\sqrt{2}} = \frac{g_2^2}{8m_W^2}$$

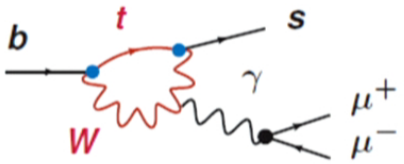
$$m_W \simeq 80\ \text{GeV}$$

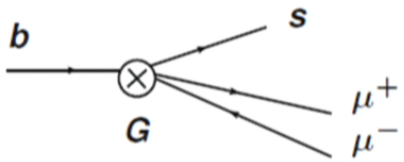
Flavor Changing Neutral Currents in the SM

In the SM, flavor changing neutral currents (FCNCs) are absent at the tree level

FCNCs can arise at the loop level
they are suppressed by loop factors
and small CKM elements







$$G \sim \frac{1}{16\pi^2} \frac{g^4}{m_W^2} \frac{m_t^2}{m_W^2} V_{tb} V_{ts}^*$$

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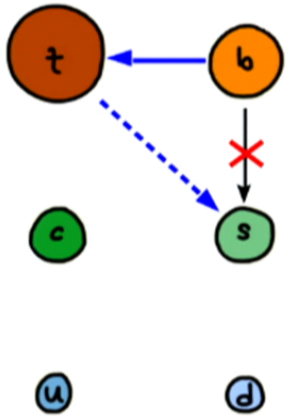

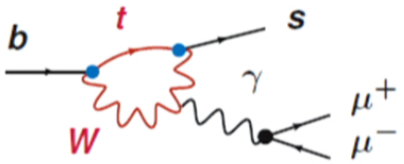

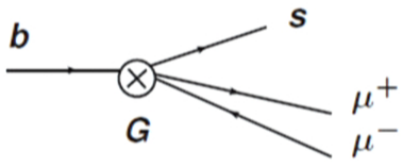

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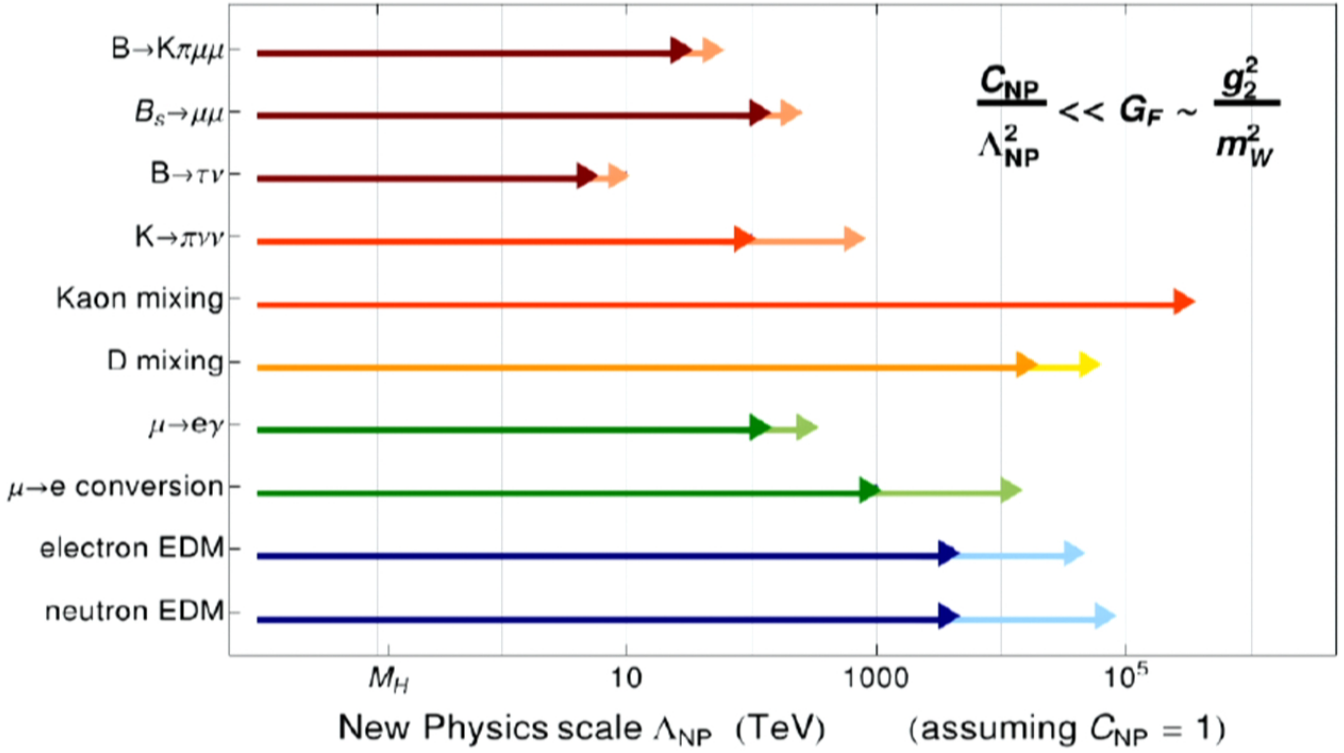
The New Physics Flavor Puzzle

Low energy flavor observables are sensitive to
New Physics far beyond the TeV scale

High Sensitivity to Flavorful New Physics



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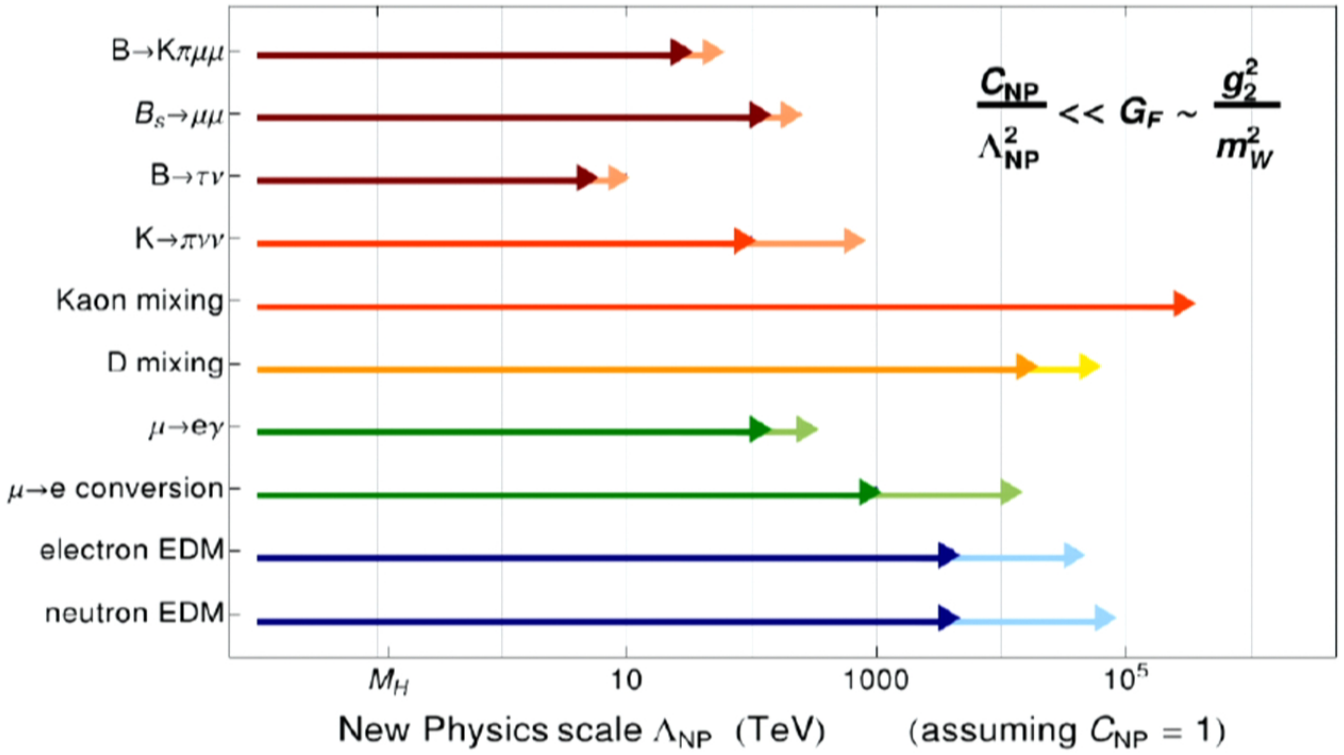

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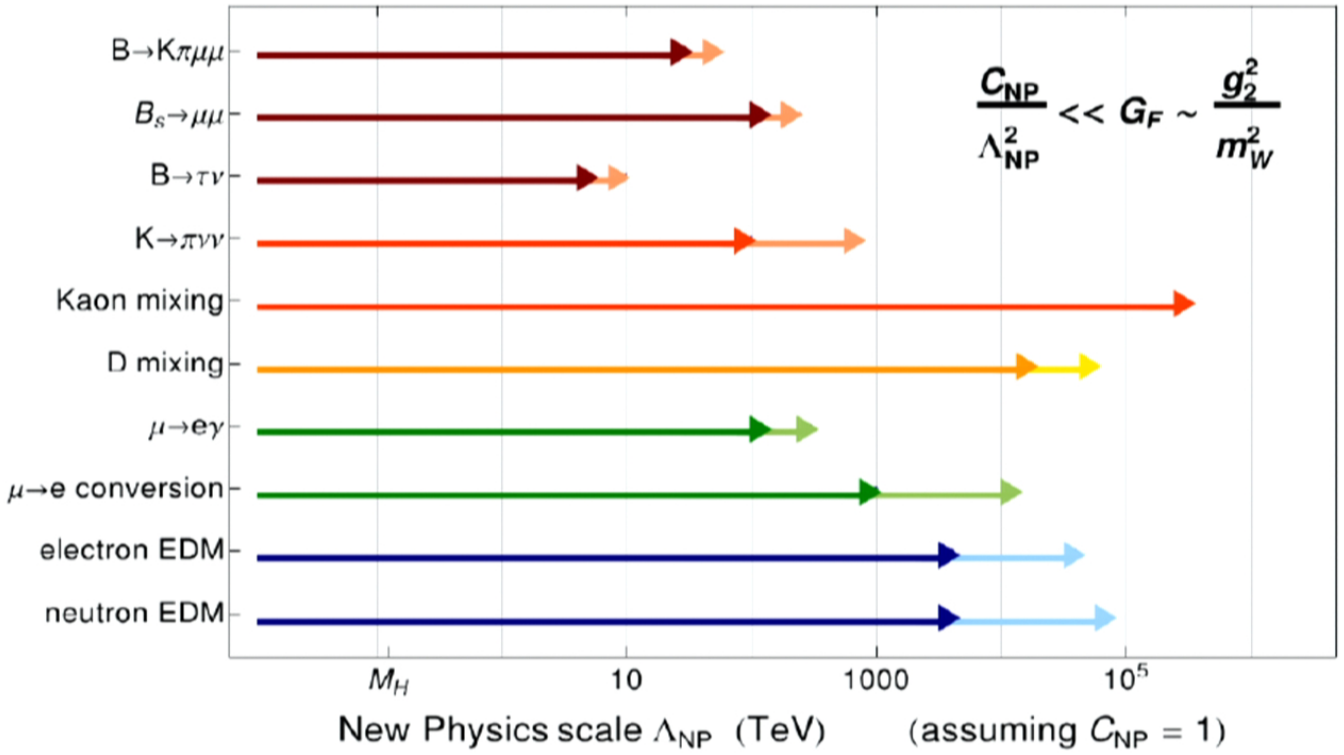
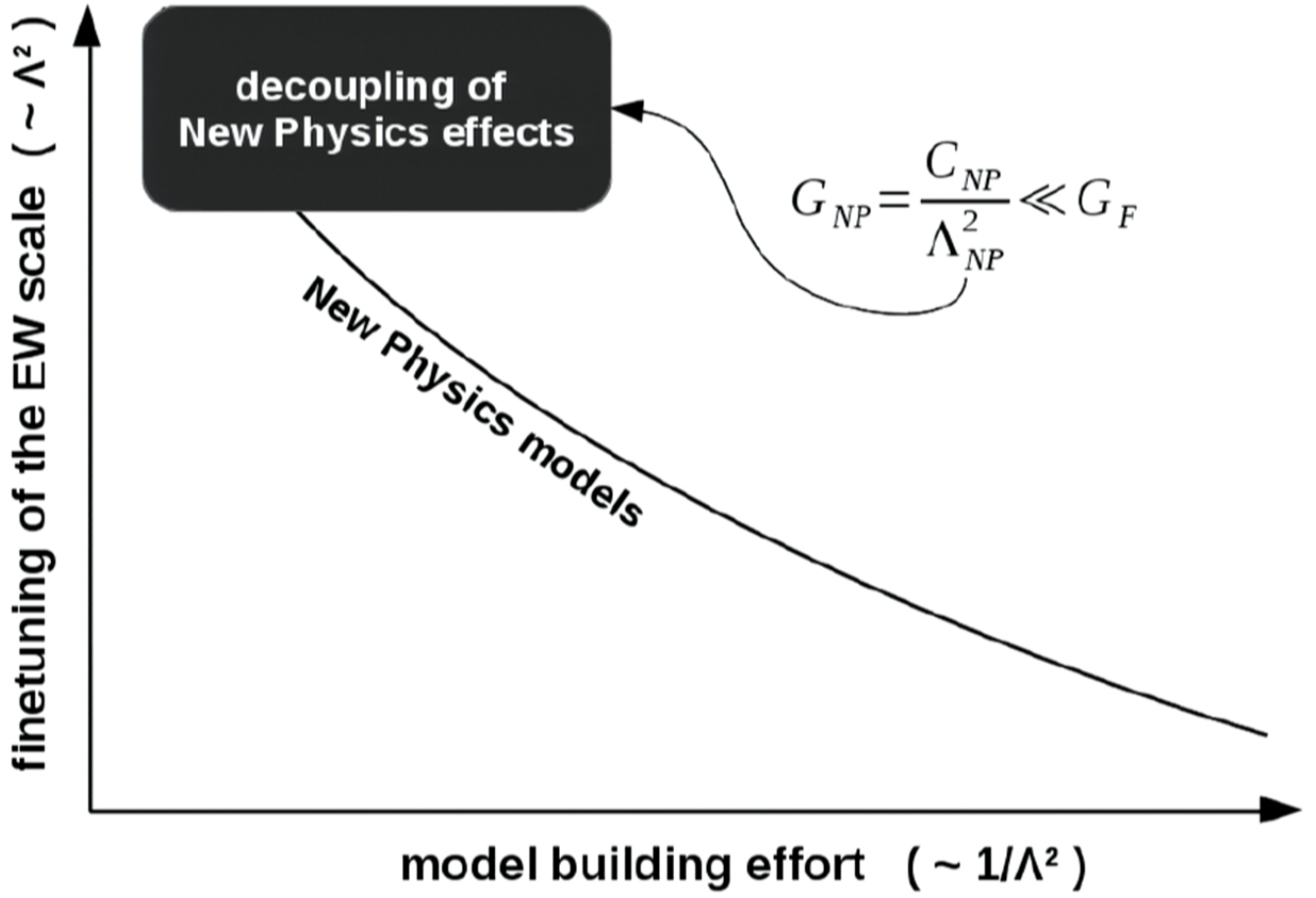
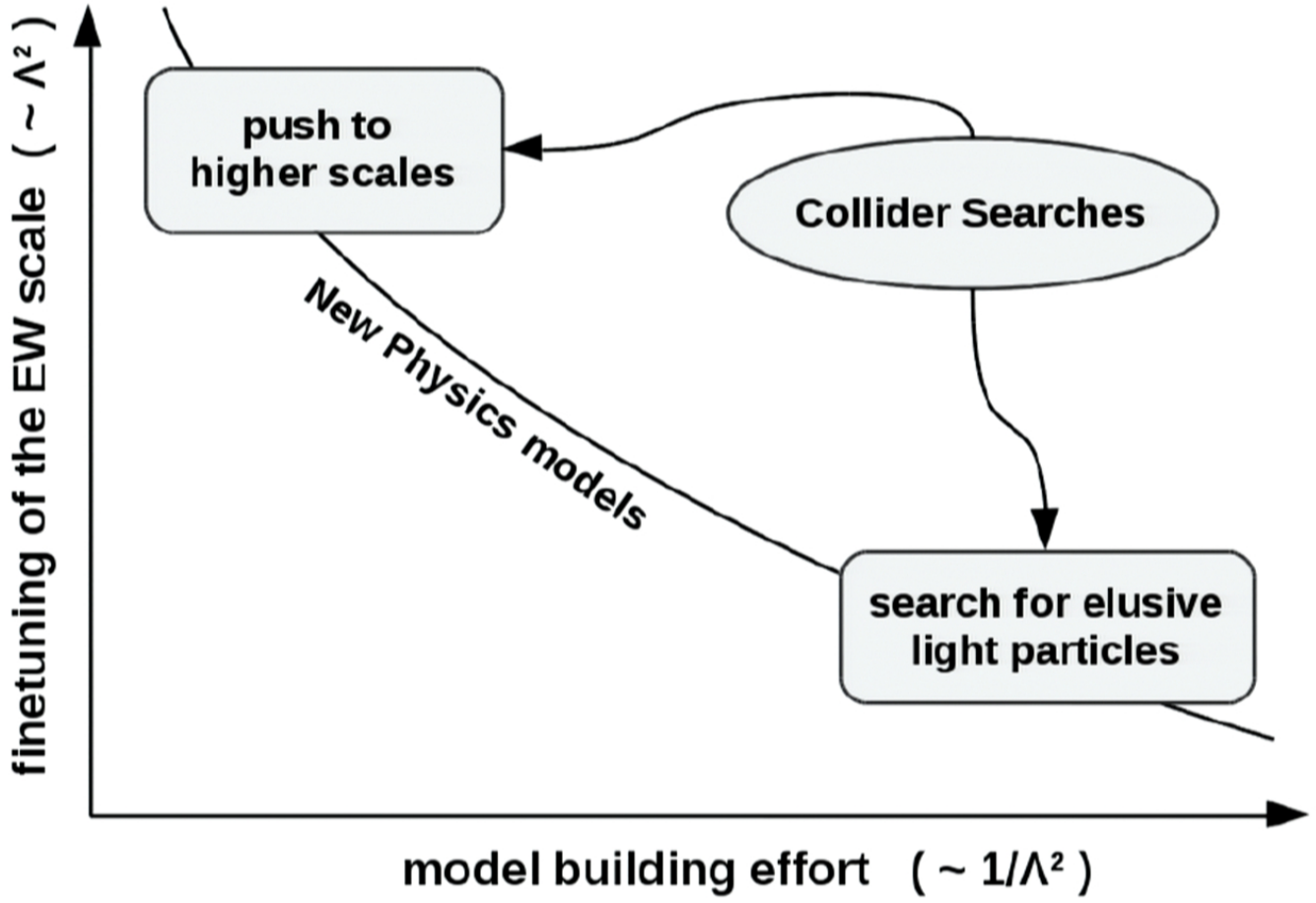


Reactions to the New Physics Flavor Puzzle



The Role of Collider Physics



The Flavor of the Higgs

$$\mathcal{L}_{\text{Yukawa}} = Y_{ij}\, \bar{\Psi}_i \Psi_j\, H$$

In the Standard Model the Yukawa couplings are the only sources of flavor and CP violation

$\rightarrow$ the couplings of the Higgs to fermion mass eigenstates are flavor diagonal and CP conserving

$$\frac{1}{v} \begin{pmatrix} m_{u,d,e} & 0 & 0 \\ 0 & m_{c,s,\mu} & 0 \\ 0 & 0 & m_{t,b,\tau} \end{pmatrix}$$

The Flavor of the Higgs

$$\mathcal{L}_{\text{Yukawa}} = Y_{ij}\,\bar{\Psi}_i \Psi_j\, H + \frac{\tilde{Y}_{ij}}{\Lambda^2}\,\bar{\Psi}_i \Psi_j\, H^3$$

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1) New Physics can modify the flavor diagonal Higgs couplings
2) New Physics can lead to flavor and CP violating Higgs couplings

Flavor Conserving Higgs Couplings

flavor diagonal couplings directly measured at the LHC with current accuracy for 3rd gen. $\sim 30\% - 50\%$

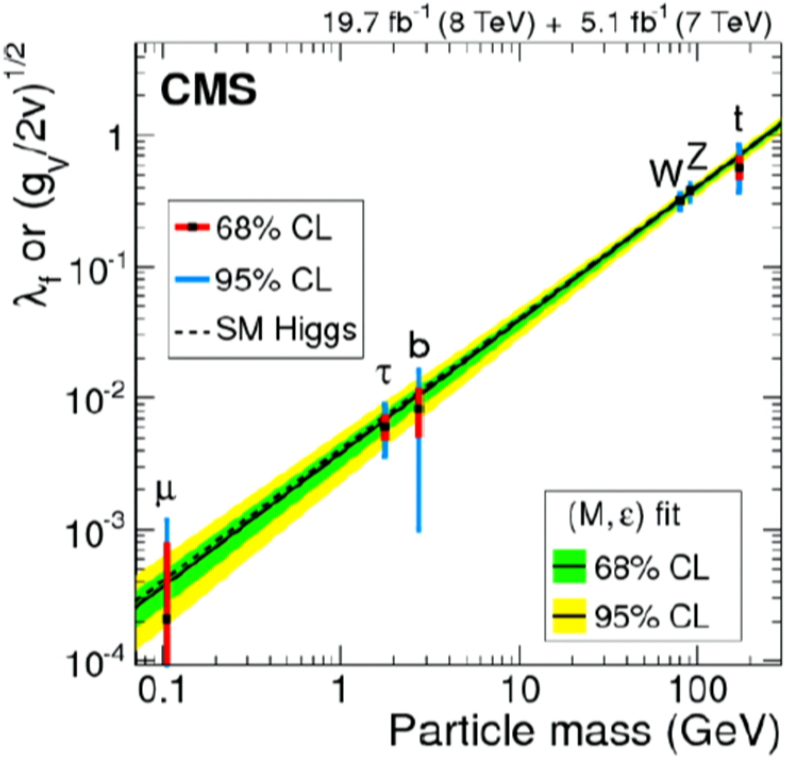
can be improved to:
$\sim 5\% - 10\%$ at a HL-LHC
few % at a ILC

1st and 2nd generation couplings?

charm
Bodwin et al. '13; Delaunay et al. '13; Perez et al. '15

up, down, strange
Kagan et al. '14

electrons
WA, Brod, Schmaltz '15



The $B \to K^*(\to K\pi)\mu^+\mu^-$ Decay

loop suppressed, CKM suppressed

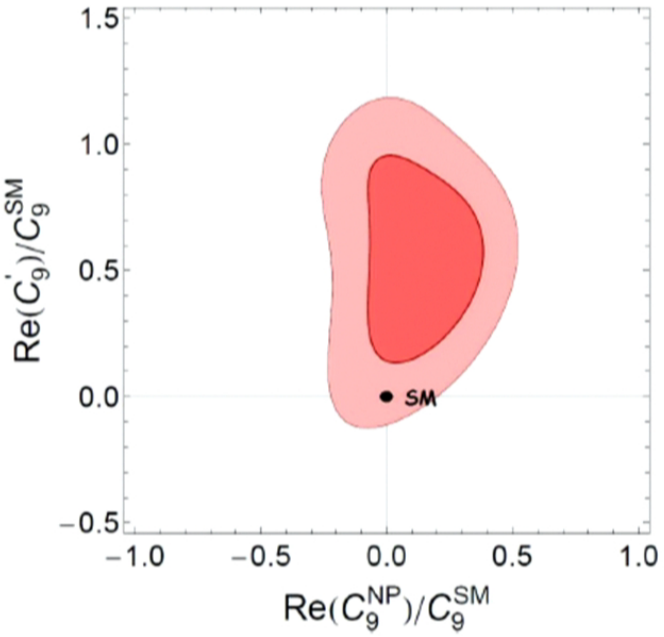
a rare decay:
only 1 out of $\sim$ 2.5 million
B mesons decays in that way

we proposed observables
that are theoretically clean and
highly sensitive to new physics
(WA, Ball, Bharucha, Buras, Straub, Wick '08)

the LHCb experiment at the
Large Hadron Collider
has already collected
thousands $B \to K^*\mu^+\mu^-$ events
and is starting to systematically
measure the proposed observables

favored new physics
parameter space

2011



(WA, Straub '13, '14)

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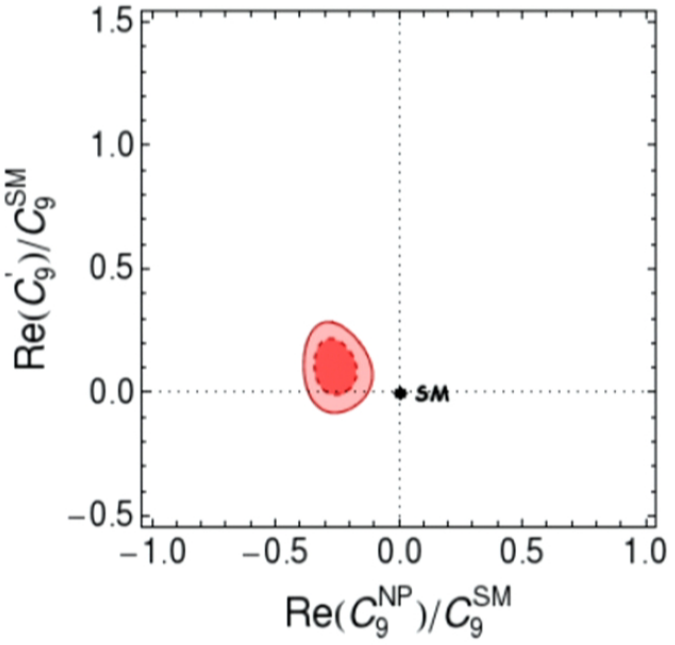
2015



(WA, Straub '13, '14)

Summary

Flavor is the most puzzling aspect of the Standard Model

The peculiar flavor structure of the Standard Model makes flavor observabels highly sensitive to New Physics effects

What is the origin of the hierarchies in the masses and mixings of the Standard Model quarks and leptons?

If there is New Physics at or below the TeV scale, why have we not seen it yet in flavor observables?

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If there is New Physics at or below the TeV scale, why have we not seen it yet in flavor observables?

Flavor and Collider Physics complement each other in our search for New Phenomena at the TeV scale and beyond

1) New Physics found at colliders:
need to measure flavor observables to understand its flavor/CP properties

2) New Physics found in low energy flavor experiments:
defines a scale to be directly explored with future colliders