The Flavor Puzzle

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PERIMETER INSTITUTE

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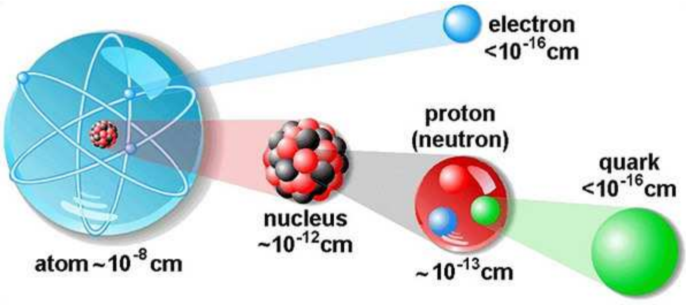
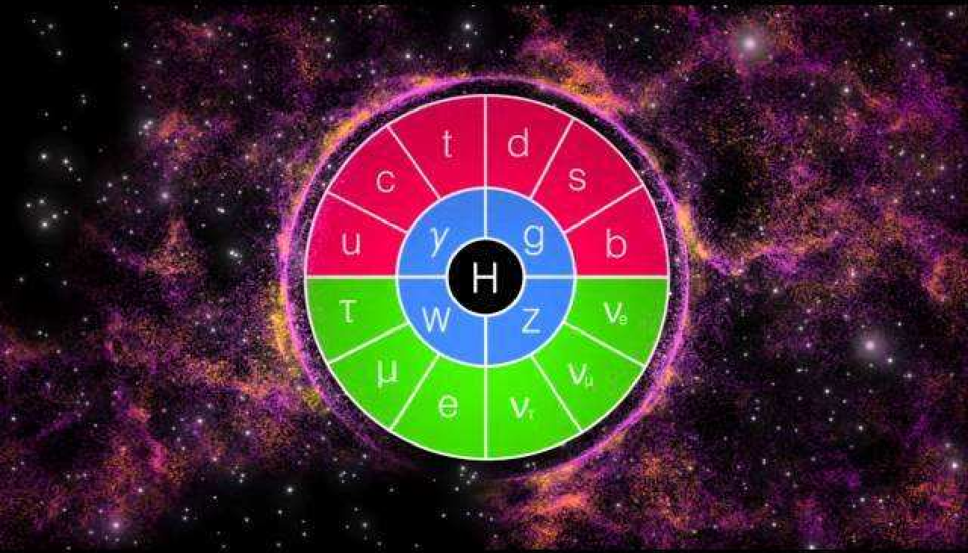
The Search for the Fundamental



What is the world made of?

What holds it together?

The Standard Model of Particle Physics

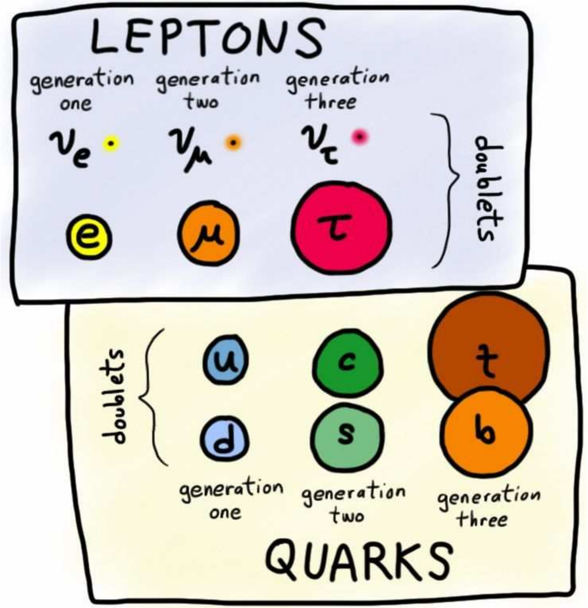


particlefever.com

The Basic Building Blocks of Matter

$Q = 0$

$Q = -1$

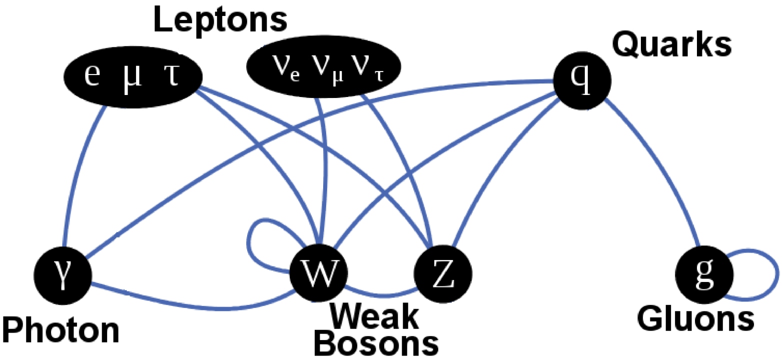


$Q = \frac{2}{3}$

$Q = -\frac{1}{3}$

Interactions of Quarks and Leptons

what makes a quark a quark, what makes a lepton a lepton?
the gauge interactions!

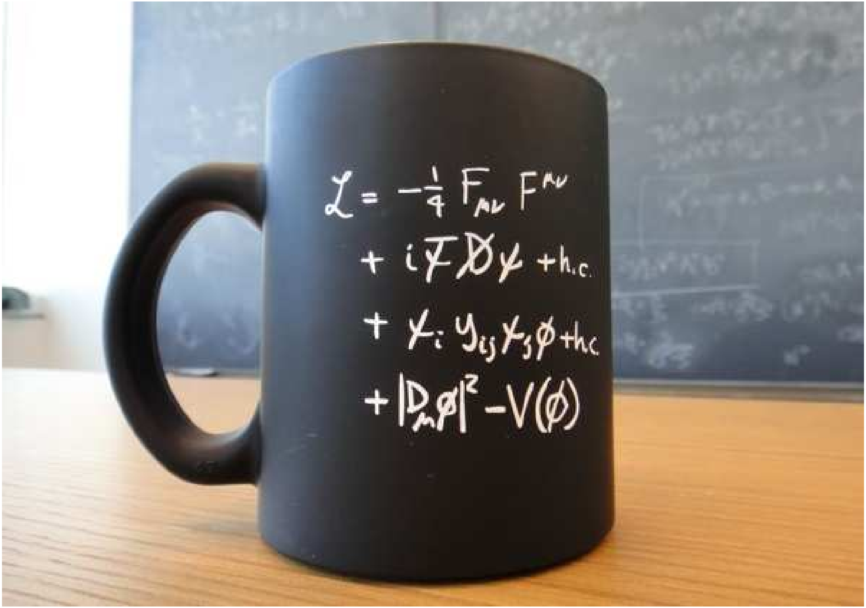


but: the gauge interactions are identical for the 3 generations/flavors

What distinguishes the three generations/flavors of quarks and leptons?

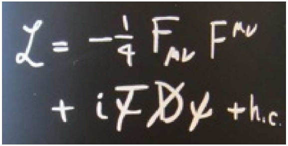
Enter Higgs

The Standard Model of Particle Physics



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

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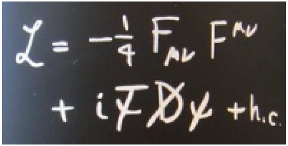

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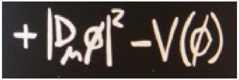
Higgs sector



breaks electro-weak symmetry and gives mass to the $W^\pm$ and Z bosons

2 free parameters
Higgs mass
Higgs vev

Flavor and the Proliferation of Parameters

gauge sector

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i \bar{\psi} \not{D} \psi + h.c.$$

describes the gauge interactions of the quarks and leptons

parametrized by
3 gauge couplings
g_1, g_2, g_3

Higgs sector

$$+ |D_\mu \phi|^2 - V(\phi)$$

breaks electro-weak symmetry and gives mass to the $W^\pm$ and Z bosons

2 free parameters
Higgs mass
Higgs vev

flavor sector

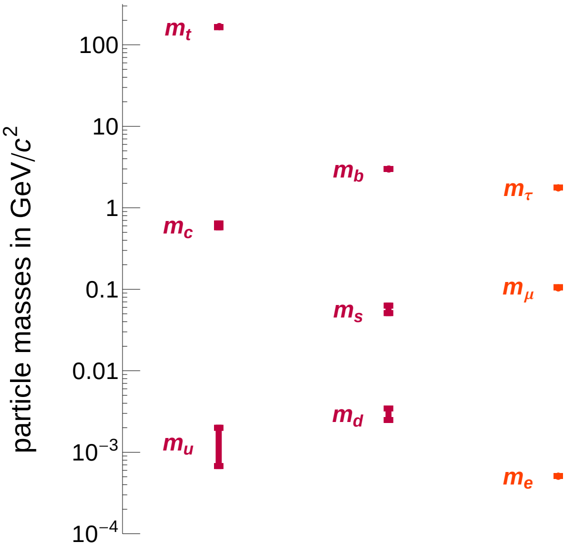
$$+ \bar{\psi}_i y_{ij} \psi_j \phi + h.c.$$

leads to masses and mixings of the quarks and leptons

22 free parameters
to describe the masses and mixings of the quarks and leptons

the flavor sector is the most puzzling part of the Standard Model

Quark and Lepton Masses



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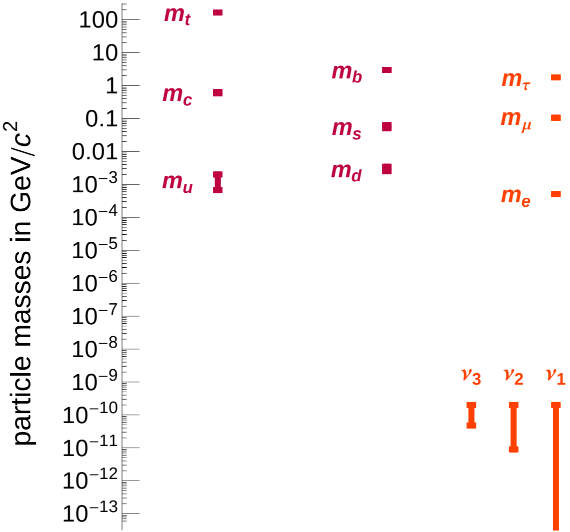
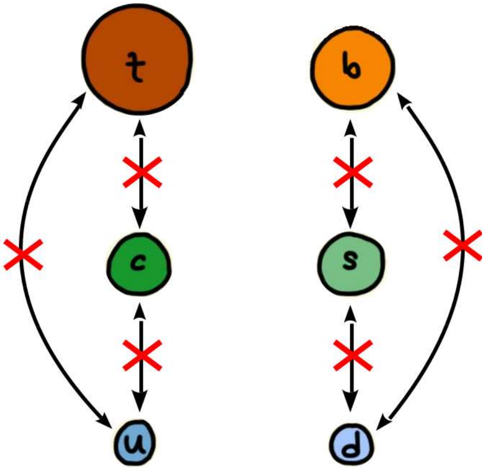


Distinct Decay Pattern of the Quarks in the SM



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

$\rightarrow$ GIM mechanism
(Glashow, Iliopoulos, Maiani)

no flavor changing neutral currents
(FCNCs) at tree level

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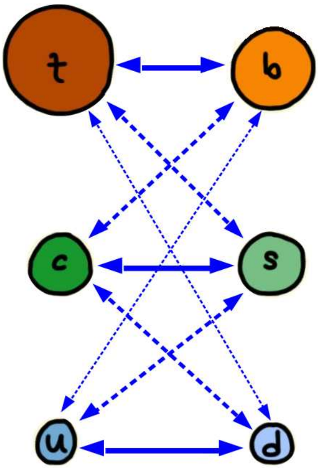

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transitions among the generations
are mediated by the $W^\pm$ bosons
and their relative strength is
parametrized by the
Cabibbo-Kobayashi-Maskawa
(CKM) matrix

$$V_{\text{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

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

λ, 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

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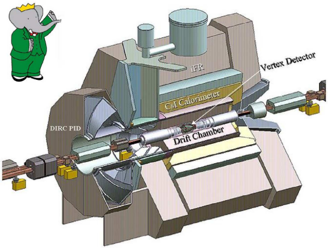
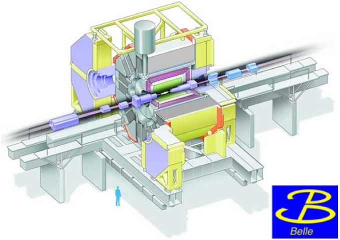
such tests were carried out at the *B* factories BaBar and Belle

BaBar @ SLAC 1999 - 2008





Belle @ KEK 1999 - 2010

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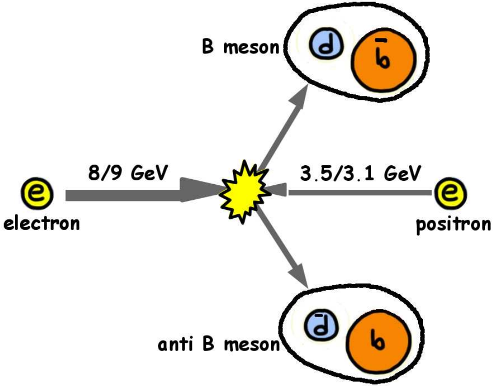
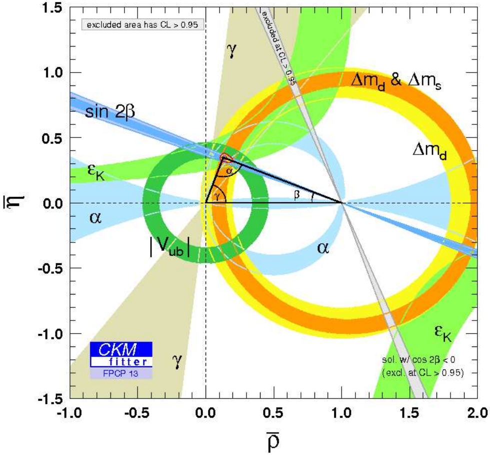


the B factories produced more than 1 billion $B\bar{B}$ pairs and studied their properties and decays

A Consistent Description of All Data

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



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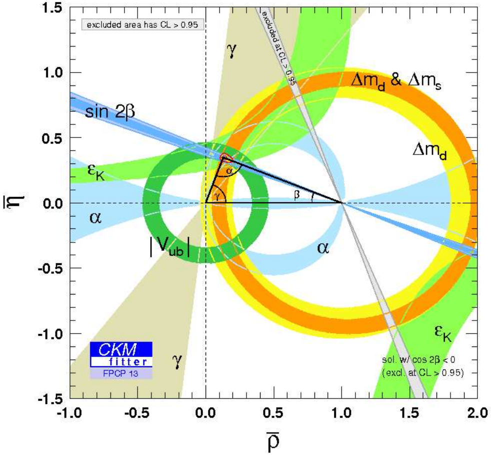
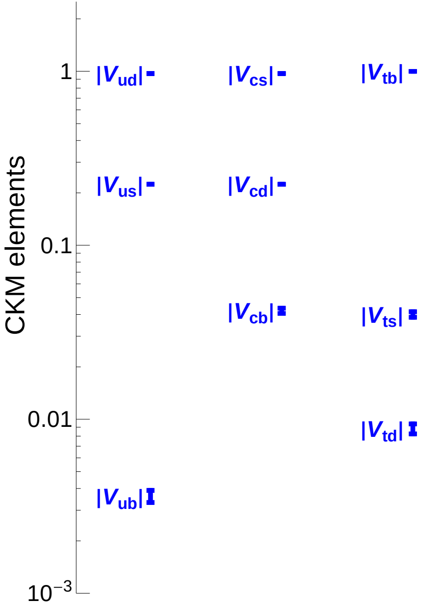
Nobel Prize 2008 for

Makoto Kobayashi

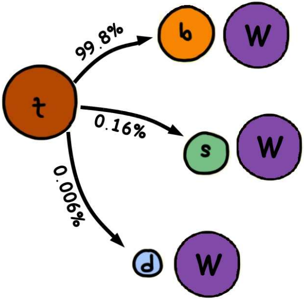
Toshihide Maskawa



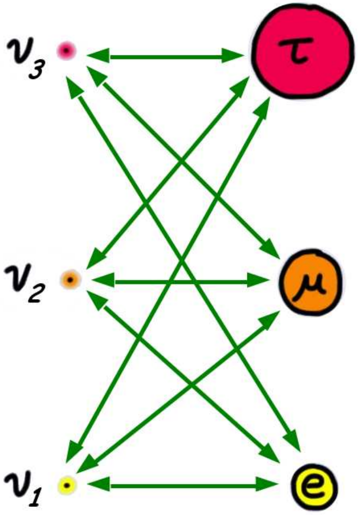


the measured CKM elements show a very hierarchical pattern

$$|V| \simeq \begin{pmatrix} 1 & \lambda & \lambda^3 \\ \lambda & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix}, \quad \lambda \simeq 0.2$$



Flavor Mixing in the Lepton Sector

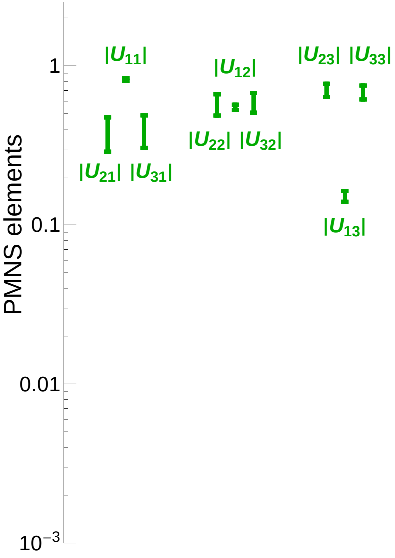


since the observation of neutrino oscillations, we know that there is also mixing in the lepton sector

as in the quark sector, no FCNCs

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

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



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?

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

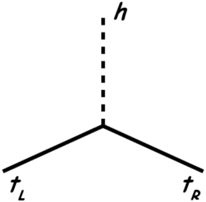
The Standard Model Flavor Puzzle

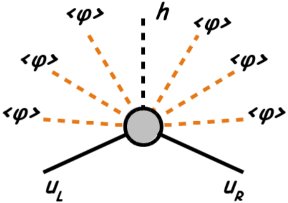
The Standard Model gives an accurate description of all flavor transitions measured up to now, but it does not explain its mysteries

- 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?
- (Why) is lepton mixing anarchic?

(Froggatt, Nielsen ’79)

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





Simple U(1) model:

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

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

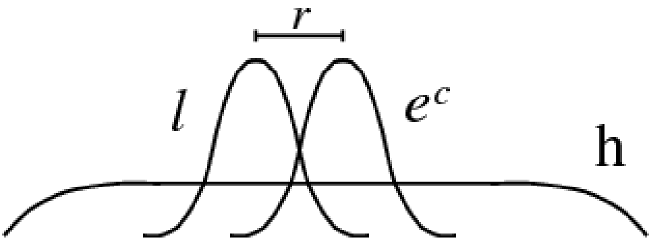
mass and mixing hierarchies given by powers of the “spurion” $\langle\varphi\rangle/M$

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

Hierarchies without Symmetries: Geometry

(Arkani-Hamed, Schmaltz ’99)

fermions are localized on different positions in an extra dimension

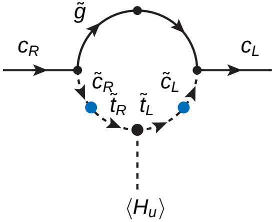


hierarchies from exponentially small wave-function overlap
between left-handed and right-handed fermions

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

(Weinberg '72)

light fermion masses arise only from quantum effects



light fermions do not couple to the higgs directly

couplings are loop-induced by flavor violating new particles

mass and mixing hierarchies from "loop factors"

$$\frac{m_u}{m_t} \sim \left(\frac{1}{16\pi^2} \right)^n$$

(works remarkably well in high scale SUSY: WA, Frugiuele, Harnik in preparation)

In addition to the flavor puzzle,
the Standard Model
leaves many questions
unanswered

- Dark Matter
- Dark Energy
- Matter-Antimatter Asymmetry
- Grand Unification
- Hierarchy Problem
- ...

The Hierarchy Problem

What gives mass to the Higgs itself?

$$m^2 = m^2_{(0)} + \Delta m^2 \sim (125\text{GeV})^2$$

The Higgs mass parameter
is not forbidden by any
symmetry of the Standard Model

1) can be added by hand

2) not protected from
quantum corrections

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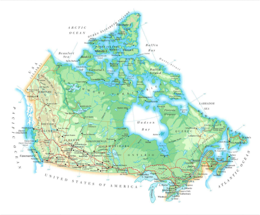
quantum corrections to
the Higgs mass are
sensitive to the largest scales

$$\Delta m^2 \sim \frac{1}{16\pi^2} M^2_{\text{Planck}} \simeq 10^{36}\text{GeV}^2$$

fine tuned cancellation between the
quantum corrections and the "bare mass" is required



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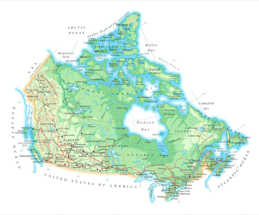
Canada $9{,}984{,}670\ \text{km}^2$ $-$ United States $9{,}826{,}675\ \text{km}^2$ $=$ $157{,}995\ \text{km}^2$

The Hierarchy Problem

 $-$  $= \quad 1\,\text{Å}^2$

Canada		United States	
9,984,670 km^2	$-$	9,826,675 km^2	$=$ 157,995 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!

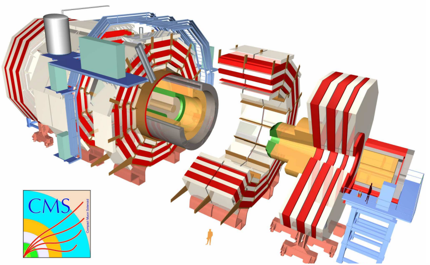
In order to protect the Higgs mass
from huge quantum corrections and to avoid finetuning,
we expect New Physics at or below the TeV scale
not far above the mass of the Higgs

Direct searches for New Physics

Directly produce new particles
in high energy collisions

Direct Searches for New Physics

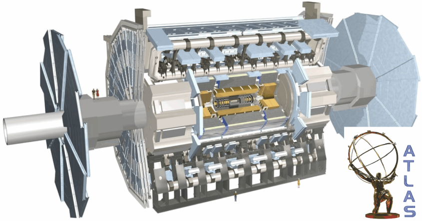
unique effort towards high energies



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 2015?

Indirect searches for New Physics

Look for virtual effects of new particles
in low energy experiments

Discoveries from Flavor Physics

- the tiny branching ratio of the decay $K_L \to \mu^+\mu^-$
  led to the prediction of the charm quark to suppress FCNCs
  (Glashow, Iliopoulos, Maiani 1970)

- the measurement of the frequency of kaon anti-kaon oscillations allowed a successful prediction of the charm quark mass
  (Gaillard, Lee 1974)

(direct discovery of the charm quark in 1974 at SLAC and BNL)

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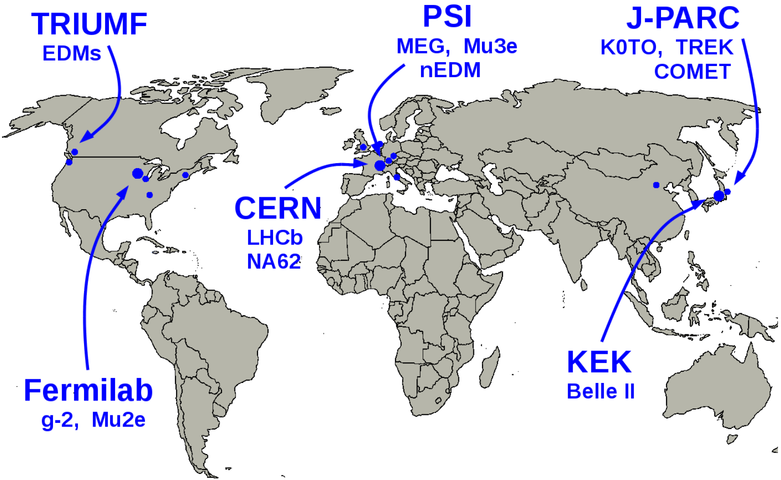
  (direct discovery of the charm quark in 1974 at SLAC and BNL)

- the observation of CP violation in kaon anti-kaon oscillations
  led to the prediction of the 3rd generation of quarks
  (Kobayashi, Maskawa 1973)

- the measurement of the frequency of B - $\bar{B}$ oscillations
  allowed to predict the large top quark mass
  (various authors in the late 80's)

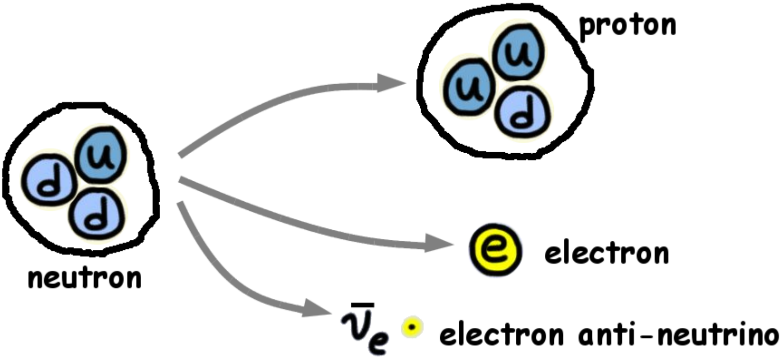
  (direct discovery of the bottom quark in 1977 at Fermilab)
  (direct discovery of the top quark in 1995 at Fermilab)

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



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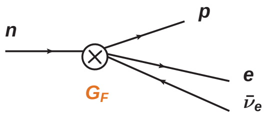
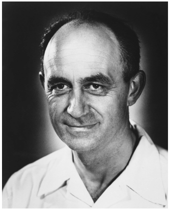




effective low energy description
of nuclear beta decay by a
4 fermion contact interaction

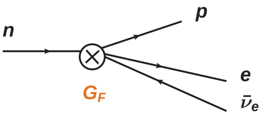
the interaction strength is given by
the Fermi constant

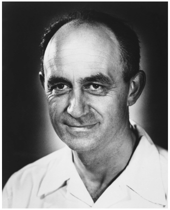
$$G_F \simeq 1.17 \times 10^{-5}\ \text{GeV}^{-2}$$

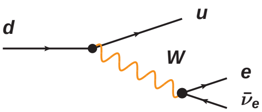
this defines an energy scale

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

Historic Example: Beta Decay







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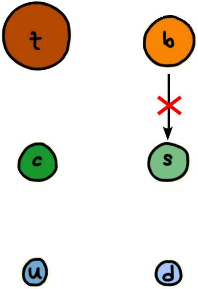
in the Standard Model
we understand beta decay
as consequence of
the exchange of virtual
weak gauge bosons

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

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

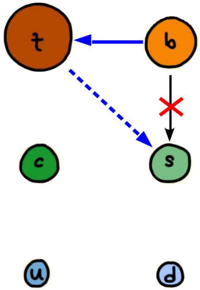
Flavor Changing Neutral Currents in the SM

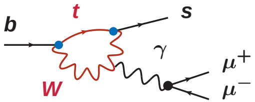
In the SM, flavor changing neutral currents (FCNCs) are absent at the tree level

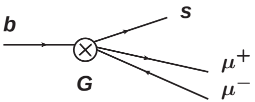


In the SM, flavor changing neutral currents (FCNCs) are absent at the tree level

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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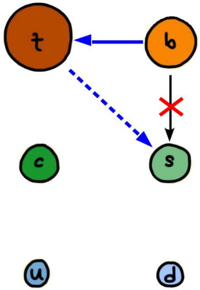

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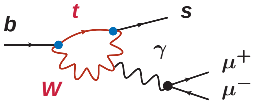
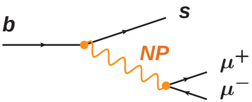
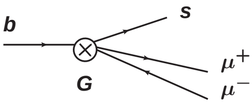
and small CKM elements



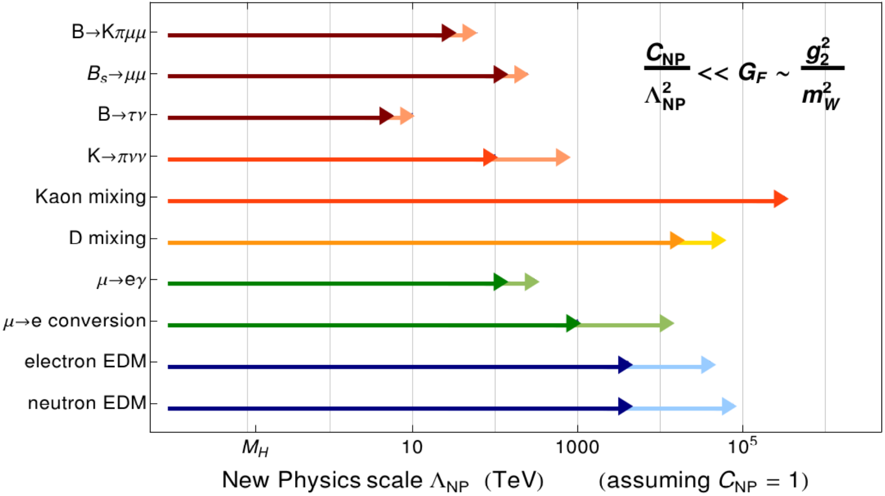




$$G \sim \frac{1}{16\pi^2} \frac{g^4}{m_W^2} \frac{m_t^2}{m_W^2} V_{tb} V_{ts}^* + \frac{C_{\rm NP}}{\Lambda_{\rm NP}^2}$$

$\rightarrow$ measuring low energy flavor observables gives information on new physics flavor couplings and the new physics mass scale

High Sensitivity to New Physics



The New Physics Flavor Puzzle

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

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solutions of the hierarchy problem require
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The New Physics Flavor Puzzle

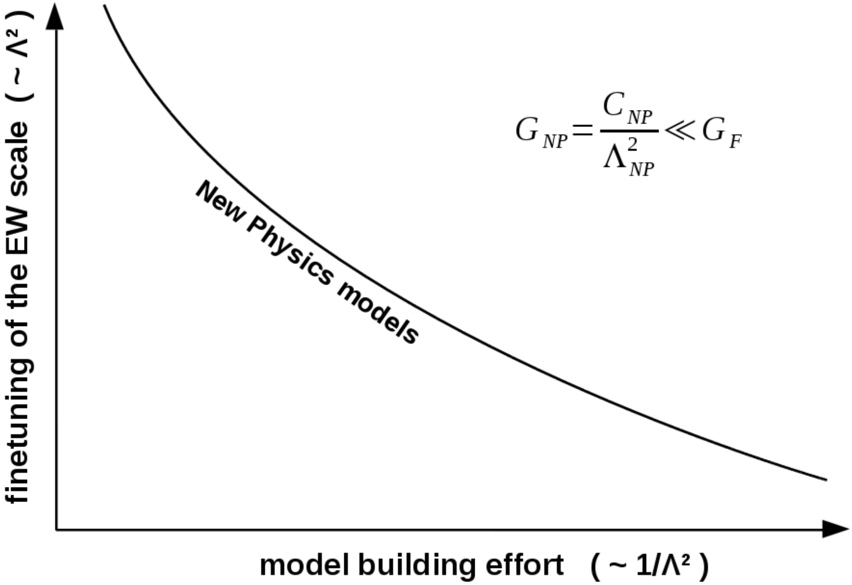
Low energy flavor observables are sensitive to
New Physics far beyond the TeV scale

currently no convincing evidence for deviations from Standard Model predictions in flavor experiments

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

solutions of the hierarchy problem require
New Physics at or below the TeV scale

Reactions to the New Physics Flavor Puzzle



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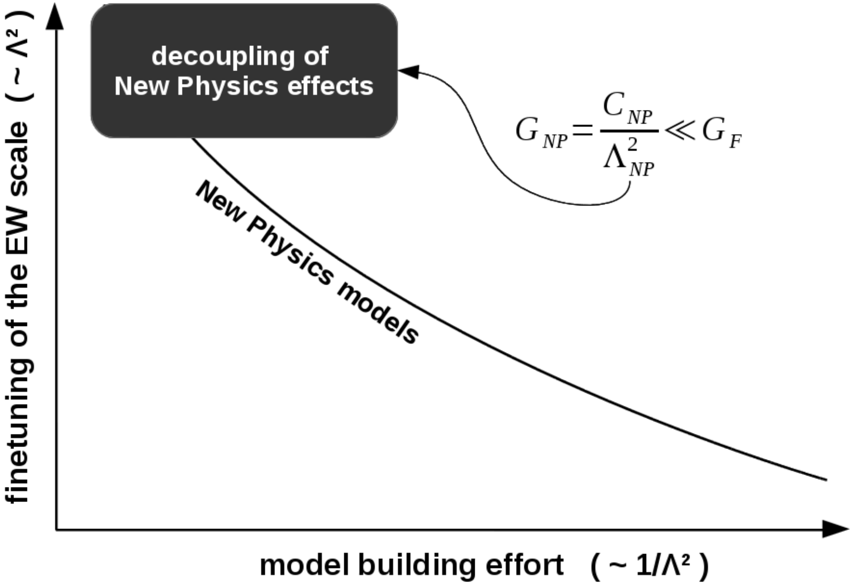

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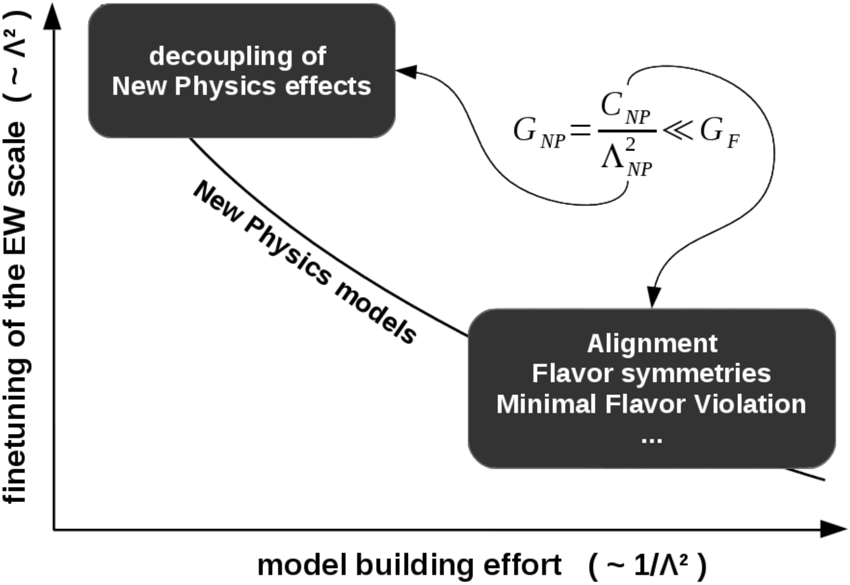
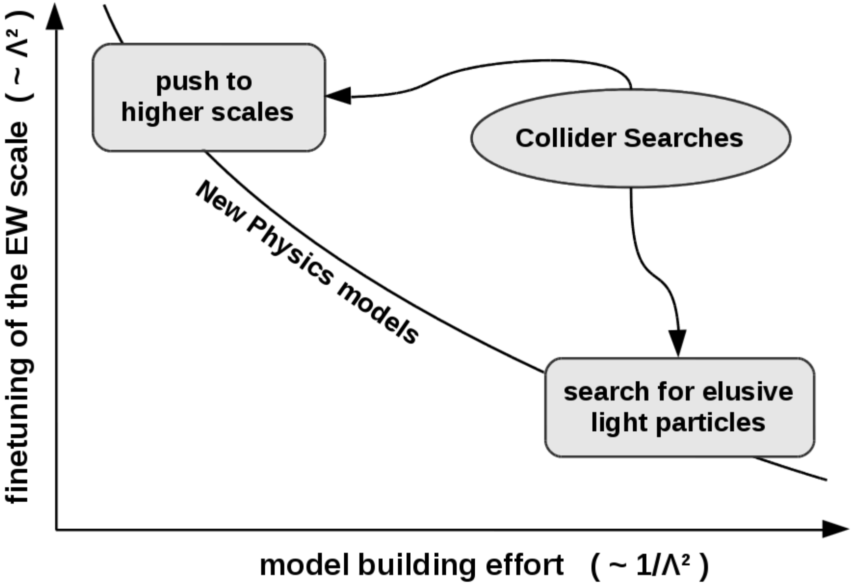
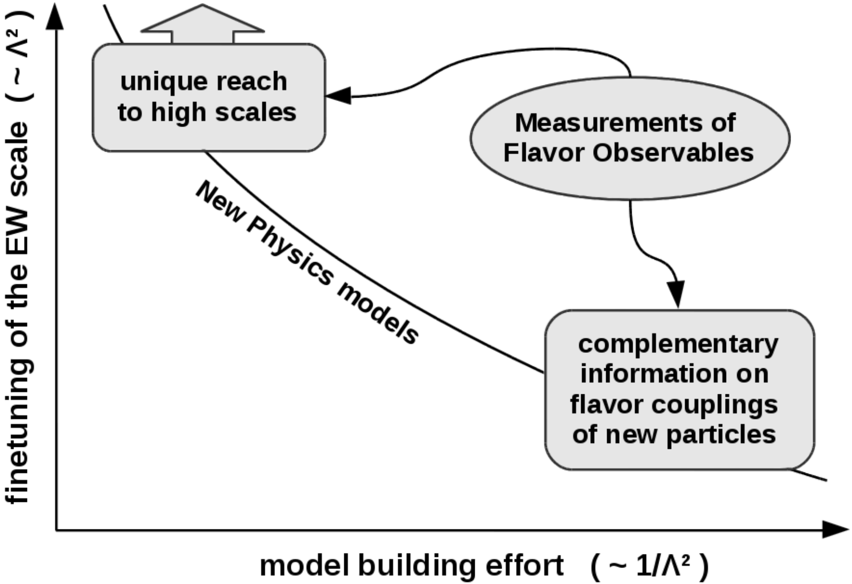


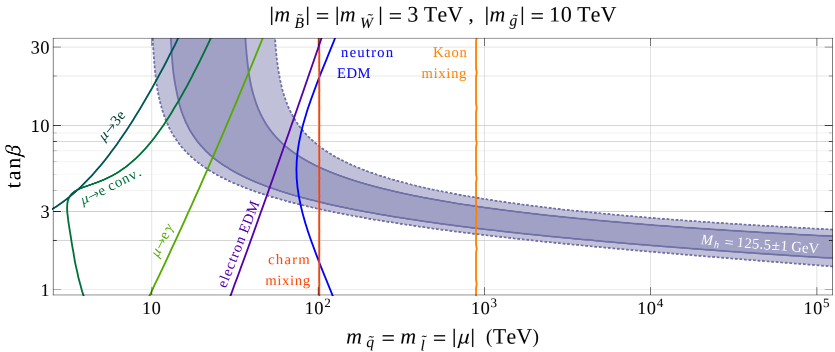
The Role of Collider Physics



The Role of Flavor Physics

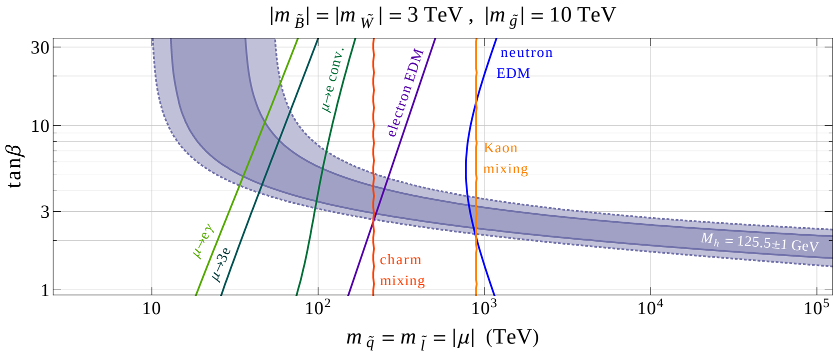


WA, Harnik, Zupan ’13



a large host of low energy observables can probe squarks and sleptons (spin 0 partners of the quarks and leptons in supersymmetric models) with masses far above the direct reach of current and future colliders

WA, Harnik, Zupan '13



a large host of low energy observables can probe squarks and sleptons (spin 0 partners of the quarks and leptons in supersymmetric models) with masses far above the direct reach of current and future colliders

experimental sensitivities are expected to improve significantly in the next decade

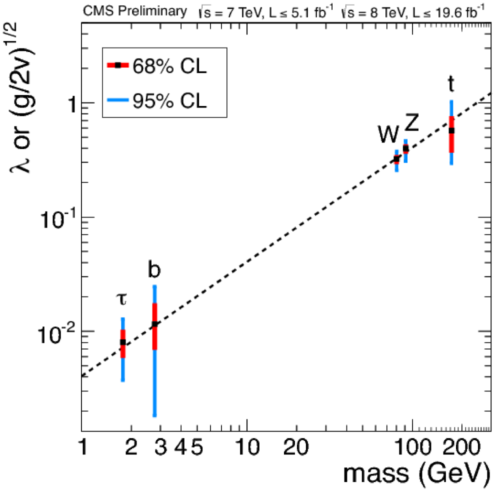
in the Standard Model
the couplings of fermions
to the Higgs are determined
by the fermion masses

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

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

can be improved to:

$\sim$ 10% at a HL-LHC
few % at a ILC

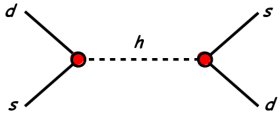


The Higgs and Flavor Violation

flavor violating couplings
of the Higgs are absent
in the Standard Model
but can be present
in new physics models

$$y_{u,d,\ell} = \begin{pmatrix} \star & \star & \star \\ \star & \star & \star \\ \star & \star & \star \end{pmatrix}$$

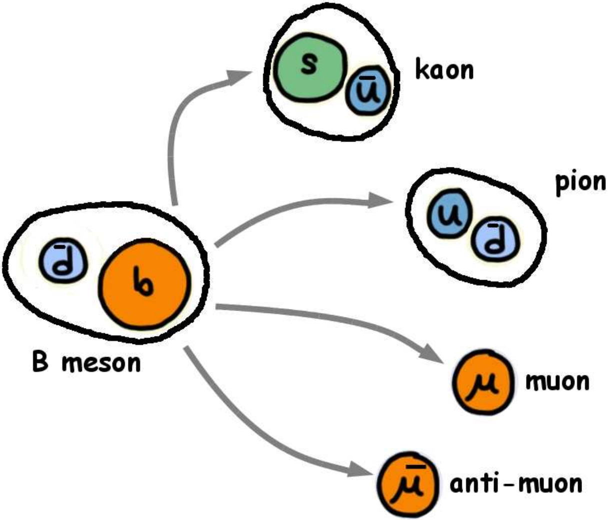
usually best probed by
low energy flavor observables



Technique	Coupling	Constraint
D^0 oscillations [48]	$\lvert Y_{uc}\rvert^2$, $\lvert Y_{cu}\rvert^2$	$< 5.0 \times 10^{-9}$
	$\lvert Y_{uc}Y_{cu}\rvert$	$< 7.5 \times 10^{-10}$
B_d^0 oscillations [48]	$\lvert Y_{db}\rvert^2$, $\lvert Y_{bd}\rvert^2$	$< 2.3 \times 10^{-8}$
	$\lvert Y_{db}Y_{bd}\rvert$	$< 3.3 \times 10^{-9}$
B_s^0 oscillations [48]	$\lvert Y_{sb}\rvert^2$, $\lvert Y_{bs}\rvert^2$	$< 1.8 \times 10^{-6}$
	$\lvert Y_{sb}Y_{bs}\rvert$	$< 2.5 \times 10^{-7}$
K^0 oscillations [48]	$\mathrm{Re}(Y_{ds}^2)$, $\mathrm{Re}(Y_{sd}^2)$	$[-5.9\ldots5.6] \times 10^{-10}$
	$\mathrm{Im}(Y_{ds}^2)$, $\mathrm{Im}(Y_{sd}^2)$	$[-2.9\ldots1.6] \times 10^{-12}$
	$\mathrm{Re}(Y_{ds}^* Y_{sd})$	$[-5.6\ldots5.6] \times 10^{-11}$
	$\mathrm{Im}(Y_{ds}^* Y_{sd})$	$[-1.4\ldots2.8] \times 10^{-13}$
single-top production [49]	$\sqrt{\lvert Y_{tc}^2\rvert + \lvert Y_{ct}\rvert^2}$	< 3.7
	$\sqrt{\lvert Y_{tu}^2\rvert + \lvert Y_{ut}\rvert^2}$	< 1.6
$t \to hj$ [50]	$\sqrt{\lvert Y_{tc}^2\rvert + \lvert Y_{ct}\rvert^2}$	< 0.34
	$\sqrt{\lvert Y_{tu}^2\rvert + \lvert Y_{ut}\rvert^2}$	< 0.34
D^0 oscillations [48]	$\lvert Y_{ut}Y_{ct}\rvert$, $\lvert Y_{tu}Y_{tc}\rvert$	$< 7.6 \times 10^{-3}$
	$\lvert Y_{tu}Y_{ct}\rvert$, $\lvert Y_{ut}Y_{tc}\rvert$	$< 2.2 \times 10^{-3}$
	$\lvert Y_{ut}Y_{tu}Y_{ct}Y_{tc}\rvert^{1/2}$	$< 0.9 \times 10^{-3}$
neutron EDM [37]	$\mathrm{Im}(Y_{ut}Y_{tu})$	$< 4.4 \times 10^{-8}$

Blankenburg, Ellis, Isidori'12; Harnik, Kopp, Zupan '12; ...

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



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

crucial to construct observables
that are theoretically clean and
highly sensitive to new physics

Egede et al ’08,’10; Bobeth et al ’08,’10,’11;
WA, Ball, Bharucha, Buras, Straub, Wick ’08;
Matias, Mescia, Ramon, Virto ’12;
Descotes-Genon et al ’13; ...

the LHCb experiment at the
Large Hadron Collider
has already collected
thousands $B \to K^*\mu^+\mu^-$ events
and is starting to systematically
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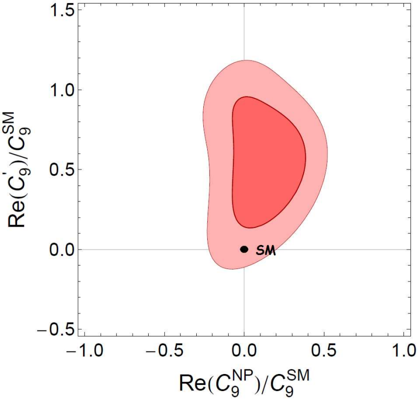
favored new physics
parameter space

2011



WA, Straub '13

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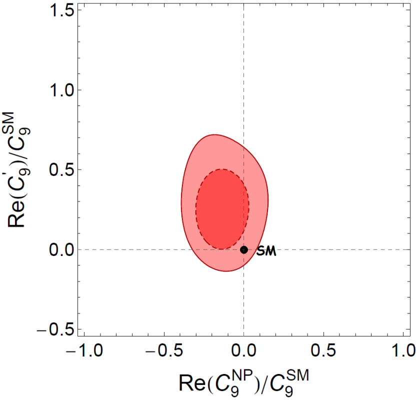
2012



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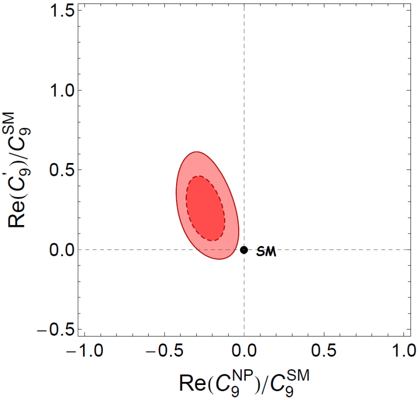
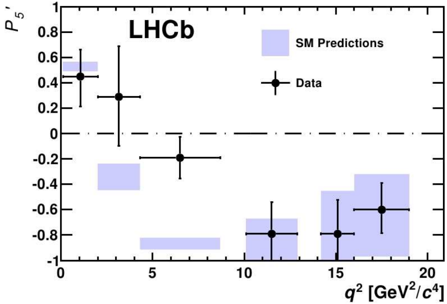
2013



WA, Straub '13

The $B \to K^*\mu^+\mu^-$ "Anomaly"

$B \to K^*\mu^+\mu^-$ angular analysis
from LHCb (with 1fb^{-1}) 1308.1707



3.7σ discrepancy
in the $4.3 < q^2 < 8.68$ GeV^2 bin
with respect to a SM prediction
(Descotes-Genon, Hurth, Matias, Virto '13)

- statistical fluctuation?
  (update with full 7+8 TeV data hopefully soon)
- underestimated SM uncertainties?
  (see Jäger, Martin Camalich '12)
- New Physics?
  can anomaly be explained model independently?
  can anomaly be explained in concrete NP models?

(WA, Straub '13)

generic tree	$\frac{1}{\Lambda_{\rm NP}^2}(\bar{s}\gamma_\nu P_L b)(\bar{\mu}\gamma^\nu \mu)$	$\Lambda_{\rm NP} \simeq 35$ TeV
MFV tree	$\frac{1}{\Lambda_{\rm NP}^2} V_{tb}V_{ts}^* (\bar{s}\gamma_\nu P_L b)(\bar{\mu}\gamma^\nu \mu)$	$\Lambda_{\rm NP} \simeq 7$ TeV
generic loop	$\frac{1}{\Lambda_{\rm NP}^2}\frac{1}{16\pi^2}(\bar{s}\gamma_\nu P_L b)(\bar{\mu}\gamma^\nu \mu)$	$\Lambda_{\rm NP} \simeq 3$ TeV
MFV loop	$\frac{1}{\Lambda_{\rm NP}^2}\frac{1}{16\pi^2} V_{tb}V_{ts}^* (\bar{s}\gamma_\nu P_L b)(\bar{\mu}\gamma^\nu \mu)$	$\Lambda_{\rm NP} \simeq 0.6$ TeV

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
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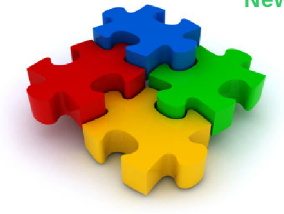
quarks and leptons?



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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?

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