Flavor now and then

fefo

Universidad de Colima - DCIHEP

XIII Mexican Workshopn on Particles and Fields
León, 22 de octubre de 2011

Flavor in the SM and *hints* of BSM

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B_d-meson system

- Tensions in UT fit
- V_{ub} crisis
- sin2β tree vs. penguin
- $B \to \pi K$ puzzle

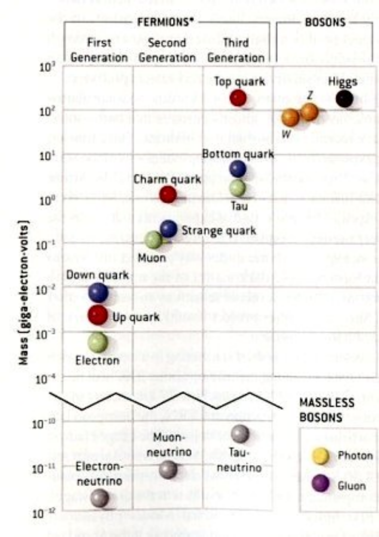
B_s-meson system

- CPV in B_s-meson mixing
- Anomalous like-sign dimuon production
- Rare decay $B_s \to \mu^+\mu^-$

At present, some of the most tantalizing hints (not more) of BSM physics -- besides $(g-2)_\mu$ and the top-quark forward-backward asymmetry at the Tevatron -- come from the flavor sector!

We live in exciting times, since many of these hints will very soon be cross-checked and perhaps corroborated at LHC!

Flavor issues related to BSM



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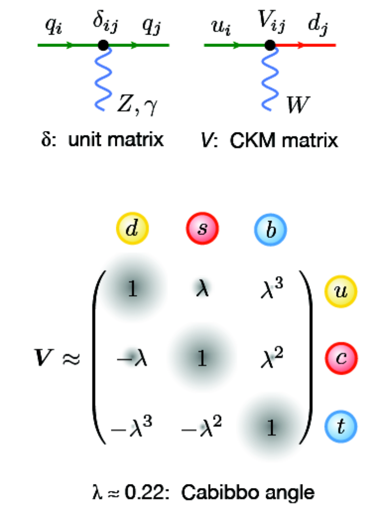

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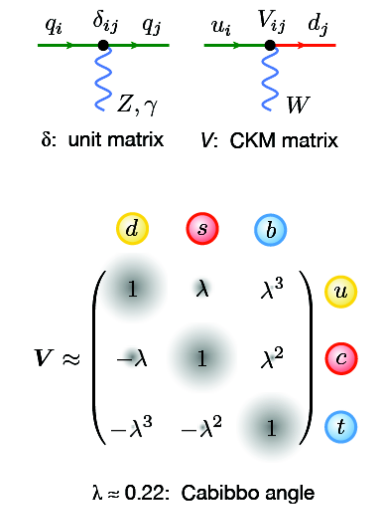

tribimaximal mixing

	ν_1	ν_2	ν_3
e	$2/3$	$1/3$	0
μ	$1/6$	$1/3$	$1/2$
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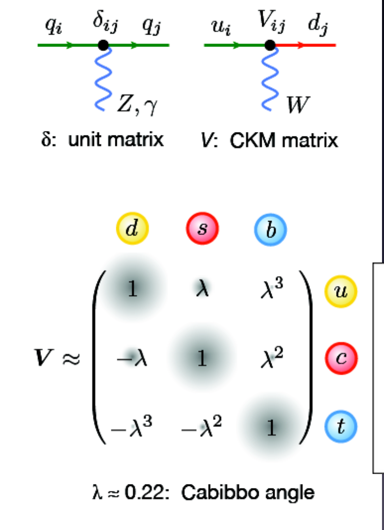

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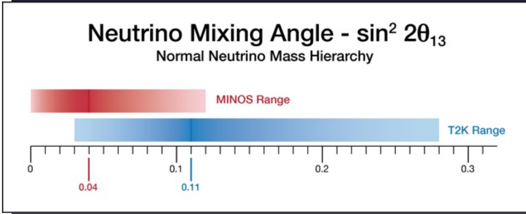

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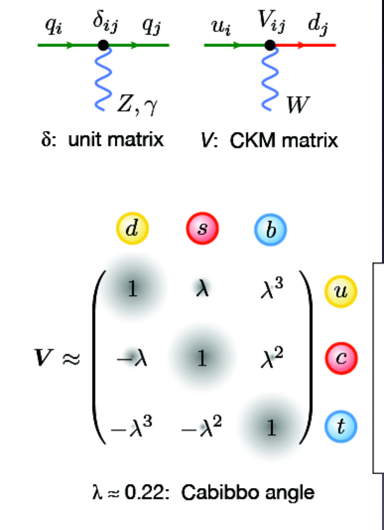

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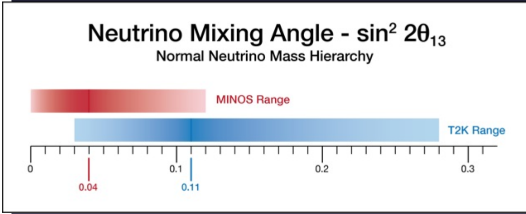

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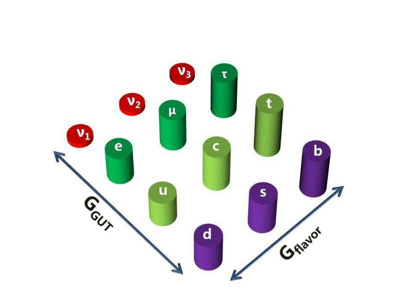

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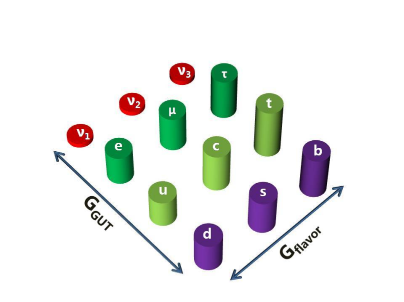

Old and over-studied?

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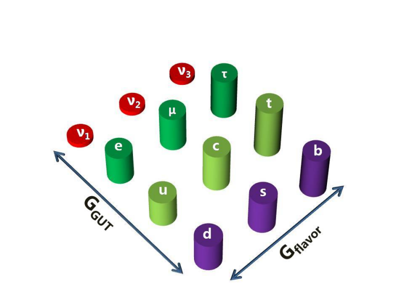
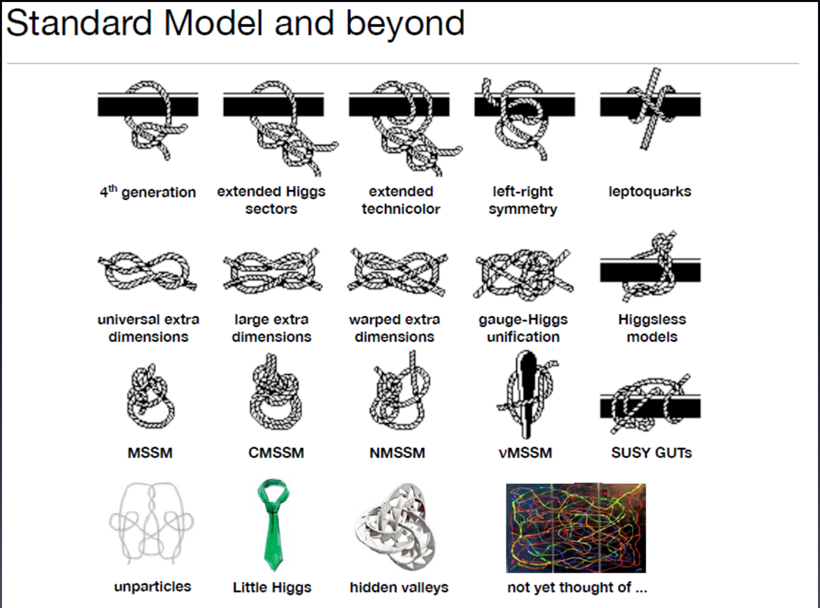


Old and over-studied?

Are there other ideas?

You bet!


Standard Model and beyond
4th generation
extended Higgs sectors
extended technicolor
left-right symmetry
leptoquarks
universal extra dimensions
large extra dimensions
warped extra dimensions
gauge-Higgs unification
Higgsless models
MSSM
CMSSM
NMSSM
νMSSM
SUSY GUTs
unparticles
Little Higgs
hidden valleys
not yet thought of ...

Basic idea

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$$\bar{\Psi}_1 \Phi \xi_1 \Psi_1 + \bar{\Psi}_1 \Phi \xi_2 \Psi_2 + \cdots + \bar{\Psi}_3 \Phi \Psi_3$$

Flavor symmetries

- When the symmetry is present

$$\mathbf{Y_u} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

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- A remnant symmetry remains and *protects* first generation fields

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- Goal: find a symmetry and breaking pattern that works!!!

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  Tipically require a large number of additional fields to those of the SM
  Main price: lack of predictivity.

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.... and they even travel faster than c!

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Smallest possible scalar sector

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Quaternion group Q_4

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representations: $\mathbf{1}^{++}$, $\mathbf{1}^{+-}$, $\mathbf{1}^{-+}$, $\mathbf{1}^{--}$, $\mathbf{2}$

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SM matter:

$$\begin{aligned}
\overline{Q} &\sim \mathbf{1}^{++} \oplus \mathbf{1}^{+-} \oplus \mathbf{1}^{-+} \equiv \{\overline{Q}_1 \oplus \overline{Q}_2 \oplus \overline{Q}_3\} \\
d_R &\sim \mathbf{2} \oplus \mathbf{1}^{+-} \equiv \{(d_{R1} \quad d_{R2}) \oplus d_{R3}\} \\
u_R &\sim \mathbf{2} \oplus \mathbf{1}^{+-} \equiv \{(u_{R2} \quad u_{R1}) \oplus u_{R3}\} \\
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Additional fields:

$$\begin{aligned} H &\sim \mathbf{2} \oplus \mathbf{1}^{++} \oplus \mathbf{1}^{--} \equiv \{H_D \equiv (H_1 \;\; H_2) \oplus H_3 \oplus H_4\} \\ \eta &\sim \mathbf{2} \equiv \{\eta_D \equiv (\eta_1 \;\; \eta_2)\} \end{aligned}$$

Mass matrices for charged fermions:

$$M_{u,d} = \begin{pmatrix} 0 & A_{u,d} & 0 \\ -A_{u,d} & 0 & B_{u,d} \\ 0 & D_{u,d} & C_{u,d} \end{pmatrix} .$$

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$\Longrightarrow$

$$|V_{CKM}^{th}| = \begin{pmatrix} 0.974386 & 0.224853 & 0.00363 \\ 0.224723 & 0.973587 & 0.0403354 \\ 0.00844 & 0.0396092 & 0.99918 \end{pmatrix}$$

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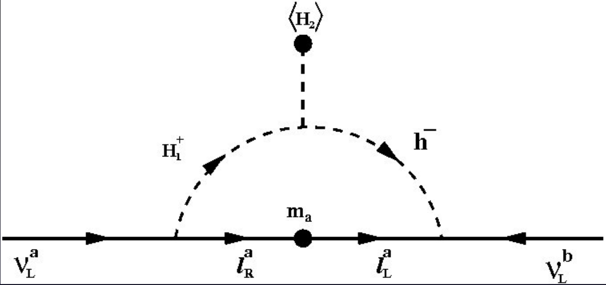
$$V_{CKM}^{exp} = \begin{pmatrix} 0.97428 \pm 0.00015 & 0.2253 \pm 0.0007 & 0.00347^{+0.00016}_{-0.00012} \\ 0.2252 \pm 0.0007 & 0.97345^{+0.00015}_{-0.00016} & 0.0410^{+0.0011}_{-0.0007} \\ 0.00862^{+0.00026}_{-0.00020} & 0.0403^{+0.0010}_{-0.0007} & 0.999152^{+0.000030}_{-0.000045} \end{pmatrix}$$

$$\delta_{CKM} = 1.20146^{+0.04758}_{-0.06963}$$

Majorana neutrino masses obtained radiatively



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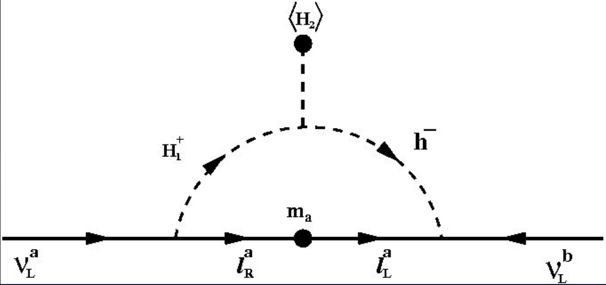

$$
\begin{aligned}
m_{ab} &= \kappa^{ab}(m_b^2 - m_a^2)\frac{\lambda_{12} v_2}{v_1}\frac{1}{(4\pi)^2}\frac{1}{m_{H_1}^2 - m_h^2}\log\frac{m_{H_1}^2}{m_h^2} \\
&= \kappa^{ab}(m_b^2 - m_a^2)\frac{\lambda_{12} v_2}{v_1} F(m_h^2, m_H^2)
\end{aligned}
$$

with

$$
F(x,y) = \frac{1}{16\pi^2}\frac{1}{x-y}\log\frac{x}{y}
$$

$$M_\nu = \begin{pmatrix} a & b & c \\ b & 0 & 0 \\ c & 0 & d \end{pmatrix}$$

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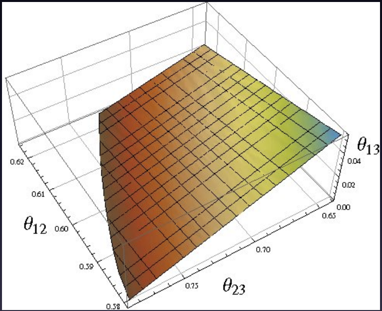

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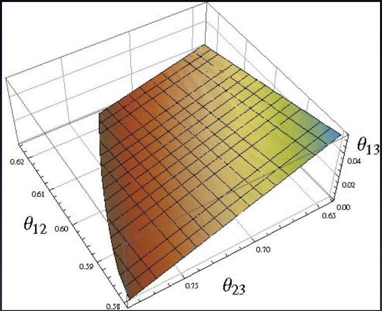

$$\begin{aligned} \Delta m^2_{21} &= 7.59^{+0.19}_{-0.21} \times 10^{-5}\ \mathrm{eV}^2 \\ \Delta m^2_{32} &= 2.43 \pm 0.13 \times 10^{-3}\ \mathrm{eV}^2 \end{aligned}$$

It is possible to reproduce all fermion masses and mixing angles!!

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Pheno

- **predictions for $\theta_{13} \rightarrow$**

Pheno

- **predictions for $\theta_{13} \to \theta_{13} > 0$**

Pheno

- predictions for $\theta_{13} \to \theta_{13} > 0$
- predictions for neutrino mass hierarchy $\to$

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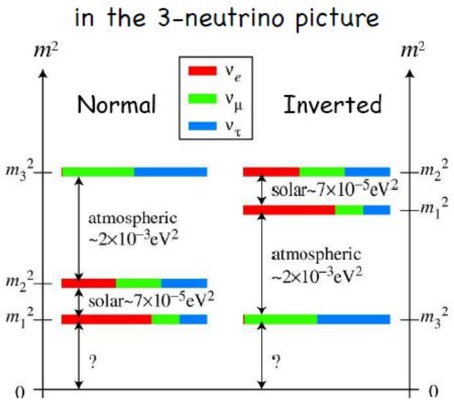
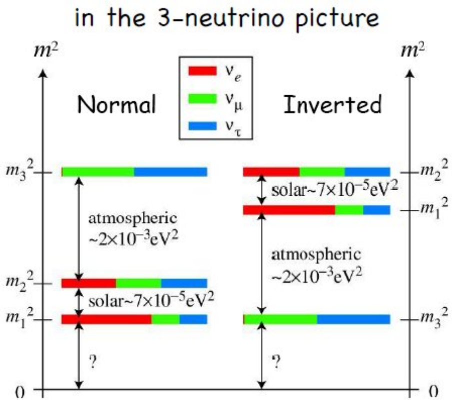


Pheno

- predictions for $\theta_{13} \to \theta_{13} > 0$
- predictions for neutrino mass hierarchy $\to$ INVERTED



In progress:

- Search fro interesting signals at LHC (scalar sector)

Pheno

- predictions for $\theta_{13} \to \theta_{13} > 0$
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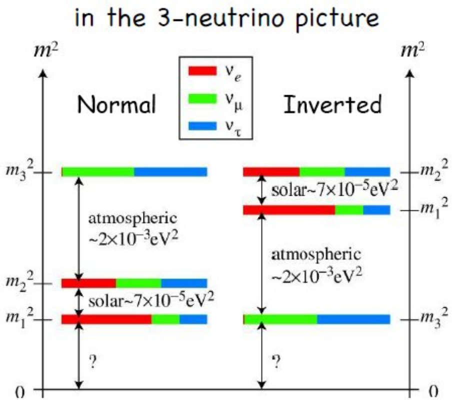
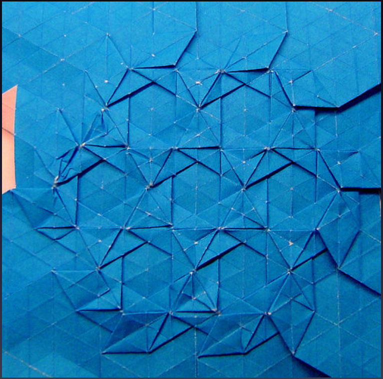


In progress:

- Search fro interesting signals at LHC (scalar sector)
- Dark matter (??)

other possible explorations

Discrete symmetries $\Longleftrightarrow$ orbifolds?



other possible explorations

Discrete symmetries as remnants from GUTs

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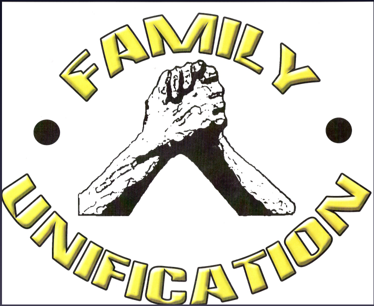
Discrete symmetries as remnants from GUTs

Famili unification (?)



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Discrete symmetries as remnants from GUTs

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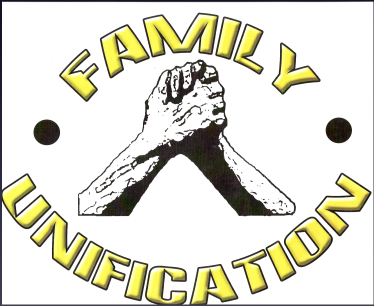

Mass spectrum?

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... but they really don't say much about mass patterns

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maybe combined with something else?

Extra dimensions

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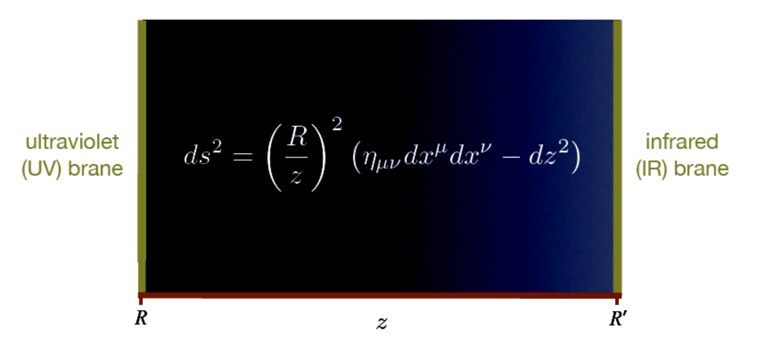
Flavor in Randall Sundrum [Randall, Sundrum]



Extra dimensions

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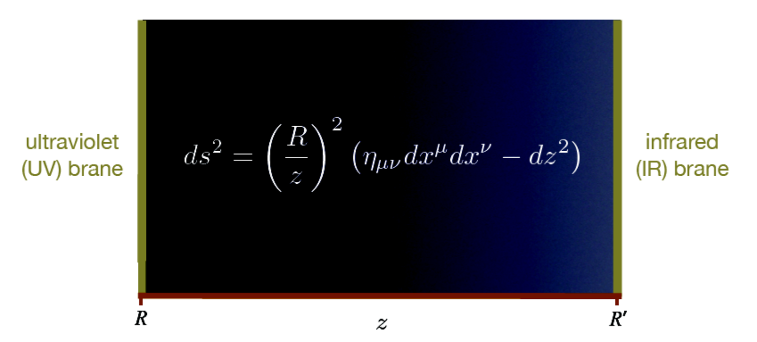


Solution to the gauge hierarchy problem

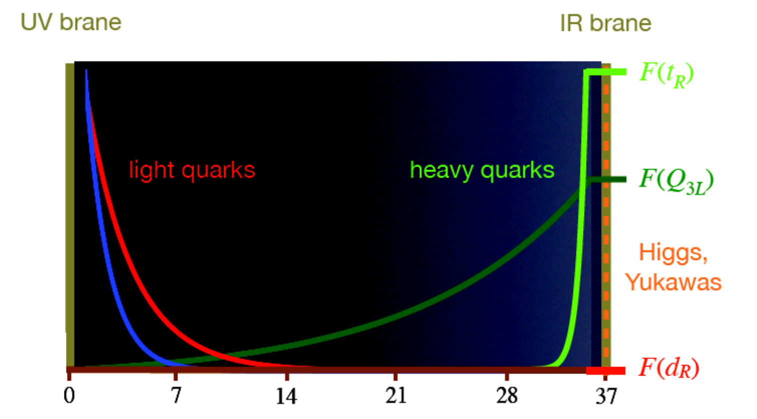
Ads/CFT calculable strong EW braking: Holographic technicolor, composite Higgs

Possible to achieve unification ...

Extra dimensions

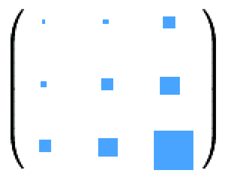
Localization - O(1) parameters (5D-masses)

Overlaps exponentially small for light fields and O(1) for top quark [Grossman, Neubert, Ghergetta, Pomarol]



SM mass matrices become:

$$m_q = \frac{v}{\sqrt{2}} diag[F(Q_i)]\mathbf{Y_q} diag[F(q_i)] =$$



Y_q Structureless O(1) entries

$F(Q_i) \ll F(Q_j)$, $F(q_i) \ll F(q_j)$, for $i < j$ [Casagrande et. al. , Blanke et. al]

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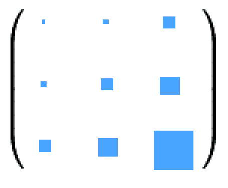

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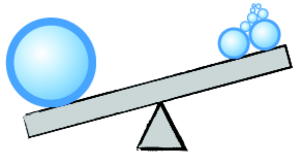
- Matrices of this form give rise to hierarchical mass eigenvalues and mixing matrices (in analogy to seesaw mech.)
- Hierarchies adjusted by O(1) variations in bulk mass parameters
- CKM phase predicted to be O(1)



Lepton sector?

Localization - also works for neutrino mass smallness

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mixing can be obtained as before $\rightarrow$ **discrete symmetry**

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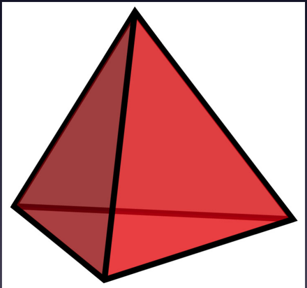
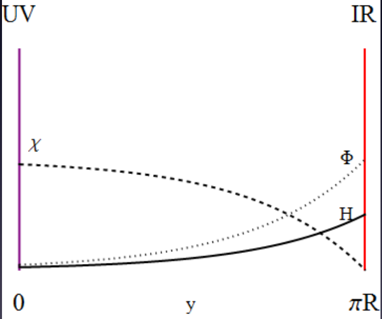
An interesting scenario incorporating these ideas uses A_4 symmetry [Kadosh, Pallante]





Recap....

Symmetries might help us explain the observed patterns.

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Simple conclusions:

- **We do not know *much* about mass**

Recap....

Symmetries might help us explain the observed patterns.
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Extra dimensions can help as well. Still lots to be explored: GHU, compactification and discrete symmetries, ...

... yet other approaches? (see talk by Ramos)

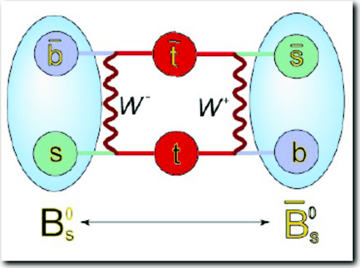
Simple conclusions:

- **We do not know *much* about mass**
- **Neutrinos are really weird!**

Thanks.....

......

Hints for New Physics in B-meson mixing



Basic formulae

Schrödinger equation: $$i\frac{d}{dt}\begin{pmatrix}|B_q(t)\rangle\\|\bar{B}_q(t)\rangle\end{pmatrix}=\left(M^q-\frac{i}{2}\Gamma^q\right)\begin{pmatrix}|B_q(t)\rangle\\|\bar{B}_q(t)\rangle\end{pmatrix}$$

Three observables:

$$\phi_q = \arg(-M_{12}^q/\Gamma_{12}^q)$$ CPV phase

$$\Delta M_q = M_H^q - M_L^q = 2\,|M_{12}^q|$$ oscillation frequency (short-distance)

$$\Delta\Gamma_q = \Gamma_L^q - \Gamma_H^q = 2\,|\Gamma_{12}^q|\cos\phi_q$$ width difference (common final states)

Flavor-specific (e.g. semileptonic) asymmetries, assuming no CPV in the decay amplitudes:

$$a_{\rm fs}^q = a_{\rm SL}^q = \operatorname{Im}\frac{\Gamma_{12}^q}{M_{12}^q} = \frac{|\Gamma_{12}^q|}{|M_{12}^q|}\sin\phi_q = \frac{\Delta\Gamma_q}{\Delta M_q}\tan\phi_q$$

Parametrization of New Physics effects (assuming NP only in M_{12}^q):

$$\frac{M_{12}^q}{M_{12}^{\mathrm{SM},q}} = \Delta_q = |\Delta_q|\,e^{i\phi_q^\Delta} = 1 + h_q\,e^{i2\sigma_q}$$

CP-violating observables

Mixing-induced, time-dependent CP asymmetries in decays to CP eigenstates:

$$S_{\psi K} = \sin(2\beta + \phi_d^{\Delta}) \qquad S_{\psi\phi} = \sin(2\beta_s - \phi_s^{\Delta})$$

Semileptonic asymmetry measured at B factories: $a^d_{\rm SL}$

Flavor-specific asymmetry in tree-level $B_s^0 \to \mu^+ D_s^- X$ decays (D0): $a^s_{\rm fs} = a^s_{\rm SL}$

Like-sign dimuon charge asymmetry (D0):

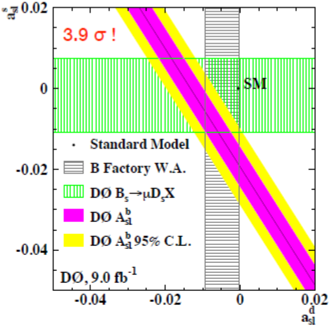
$$A^b_{\rm sl} = \frac{N_b^{++} - N_b^{--}}{N_b^{++} + N_b^{--}} = C_d\, a^d_{\rm SL} + (1 - C_d)\, a^s_{\rm SL}\,; \quad C_d = 0.594 \pm 0.022$$

determined from data

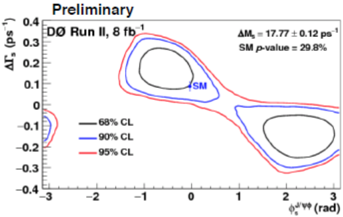
Tevatron data

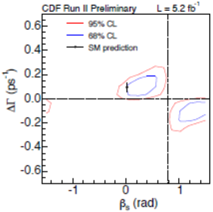
Like-sign dimuon charge asymmetry (DØ):

- not an easy measurement
- if taken at face value, a rather compelling hint of New Physics!



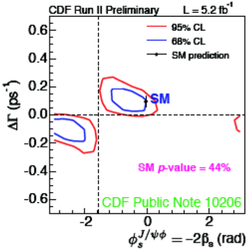
Mixing-induced CP asymmetry (Bs):

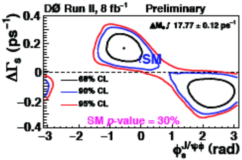




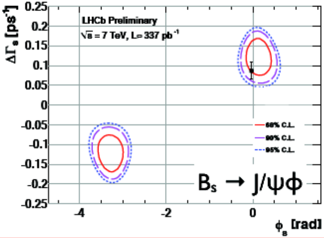
The drama of Lepton-Photon 2011

Tevatron results for Φ_s





LHCb result for Φ_s at LP11



$\phi_s = 0.13 \pm 0.18\ (stat) \pm 0.07\ (syst)$

$\Delta\Gamma s = 0.123 \pm 0.029\ (stat) \pm 0.008\ (syst)\ ps^{-1}$

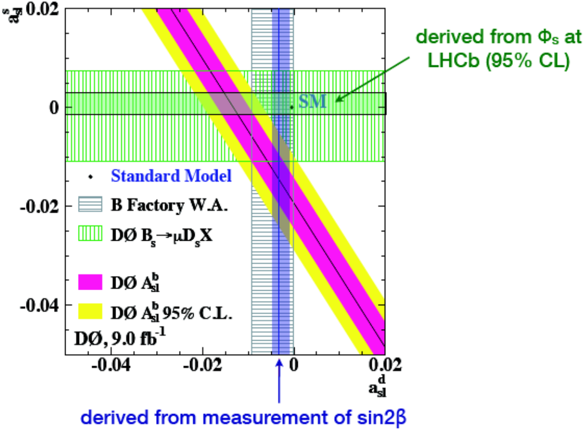
When combined with $B_s \rightarrow J/\psi\ f_0$:

$\phi_s = 0.03 \pm 0.16 \pm 0.07$ rad

SM: $\Phi_s = -0.004$

The drama of Lepton-Photon 2011

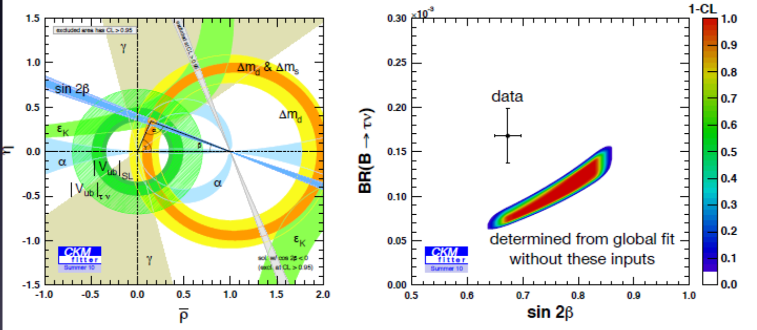
Implication for the interpretation of the DØ dimuon asymmetry:



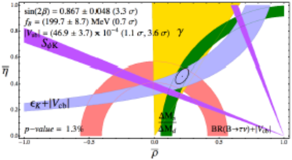
Theoretical analyses without CPV in B_s mixing

Much of this is driven by the **anomalous like-sign dimuon asymmetry** seen at DØ, but there is also **tension** in the standard **unitarity-triangle fit** if the results on CP violating in B_s mixing and the dimuon asymmetry are left out:

Lenz, Nierste + CKMfitter (2010)



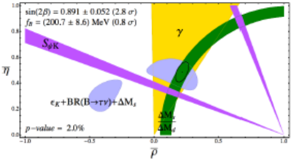
Theoretical analyses without CPV in B_s mixing



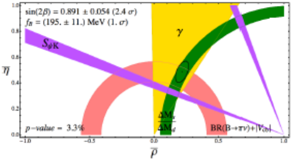
Unitarity-triangle fit with different inputs:

- input: V_{cb}, ε_K, γ, $\Delta M_{d,s}$, $B \to \tau\nu$
- output: $\sin 2\beta$, f_B, $|V_{ub}|$

➡ obtain excellent fit, hinting at New Physics in B_d mixing



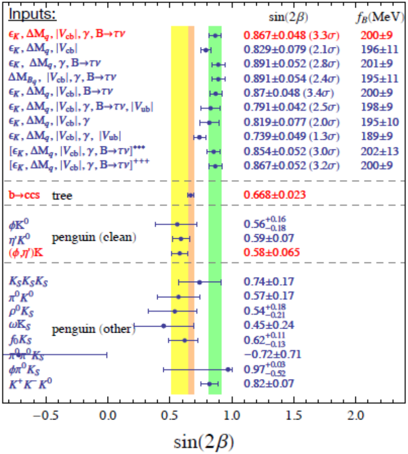
- input: same as above, but without use of semileptonic decays (V_{cb})



- input: same as above, but without use of K-$\overline{K}$ mixing

Lunghi, Soni (2010)

Theoretical analyses without CPV in B_s mixing



*** lattice errors increased by 50%

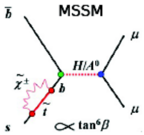
+++ adding hadronic uncertainty $\delta\Delta S_{\psi K}$=0.021

- ➡ consistent determination of sin2β **much larger** than direct measurement !
- ➡ direct measurement from mixing-induced CP violation in tree-level decays
- ➡ direct measurement from mixing-induced CP violation in penguin modes (interpreted as a hint for New Physics in penguin-induced FCNC processes)

Lunghi, Soni (2010)

Rare decays $B_{d,s} \to \mu^+\mu^-$

- interesting rare decays, which can be much enhanced in models with a warped extra dimension or SUSY models with large tanβ



Excess in B_s mode reported by CDF:

$\mathcal{B}(B_s \to \mu^+\mu^-) = (1.8^{+1.1}_{-0.9}) \cdot 10^{-8}$	SM: $(3.2 \pm 0.2) \cdot 10^{-9}$
$\mathcal{B}(B_d \to \mu^+\mu^-) < 6.0 \cdot 10^{-9}$	SM: $(1.0 \pm 0.1) \cdot 10^{-10}$

Unfortunately no excess seen at LHCb and CMS:

$$\mathcal{B}(B_s \to \mu^+\mu^-) < 1.1 \cdot 10^{-8} \quad \text{(at 95\% CL)}$$

These bounds to not rule out the CDF result, but without refined LHC measurements the situation is inconclusive!