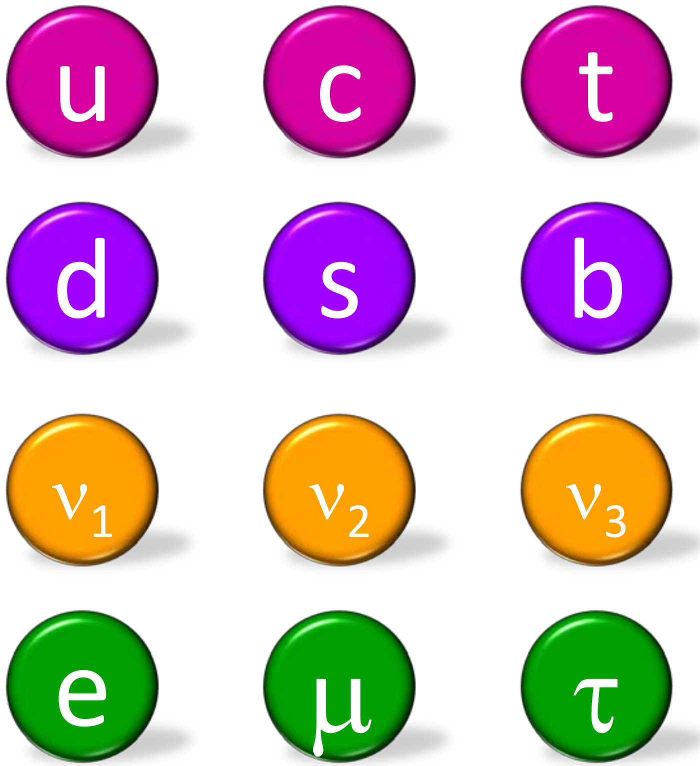
フレーバー物理はどこまで展開したか

Flavor Physics in Perspective

日笠健一（東北大）

フレーバー:

クォーク･レプトンの種類



A06理論

A06: フレーバー混合における標準理論を超える物理の理論的研究

- 超対称理論
  - モデルの構築
  - 実験とのインターフェイス
- 余剰次元理論 etc
- 初期宇宙

- 原著論文72篇

PHYSICAL REVIEW D **85**, 035015 (2012)

Flavor structure of the three-site Higgsless model

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(Received 3 October 2011; published 14 February 2012)

We study the flavor structure of the three-site Higgsless model and evaluate the constraints on the model arising from flavor physics. We find that current data constrain the model to exhibit only minimal flavor violation at tree level. Moreover, at the one-loop level, by studying the leading chiral-logarithmic corrections to chirality-preserving $\Delta F = 1$ and $\Delta F = 2$ processes from new physics in the model, we show that the combination of minimal flavor violation and ideal delocalization ensures that these flavor-changing effects are sufficiently small that the model remains phenomenologically viable.

DOI: 10.1103/PhysRevD.85.035015 PACS numbers: 12.60.Cn, 12.15.Lk

A06 人員

2006	2007	2008	2009	2010	2011
日笠	日笠	日笠	日笠	日笠	日笠
山口	山口	山口	山口	山口	(山口)
棚橋	棚橋(名大)	棚橋(名大)	棚橋(名大)	棚橋(名大)	棚橋(名大)
諸井	諸井	諸井	諸井	諸井(東大)	諸井(東大)
山田	山田	山田	山田	山田	山田
	戸部	戸部(名大)	戸部(名大)	戸部(名大)	戸部(名大)
		奥村	奥村(九大)	奥村(九大)	奥村(九大)
			北野	北野	北野
			郡	野村	野村
					(高橋)


17番目の素粒子
ヒッグス粒子とは
素粒子
1
2
3
4
5
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13
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16
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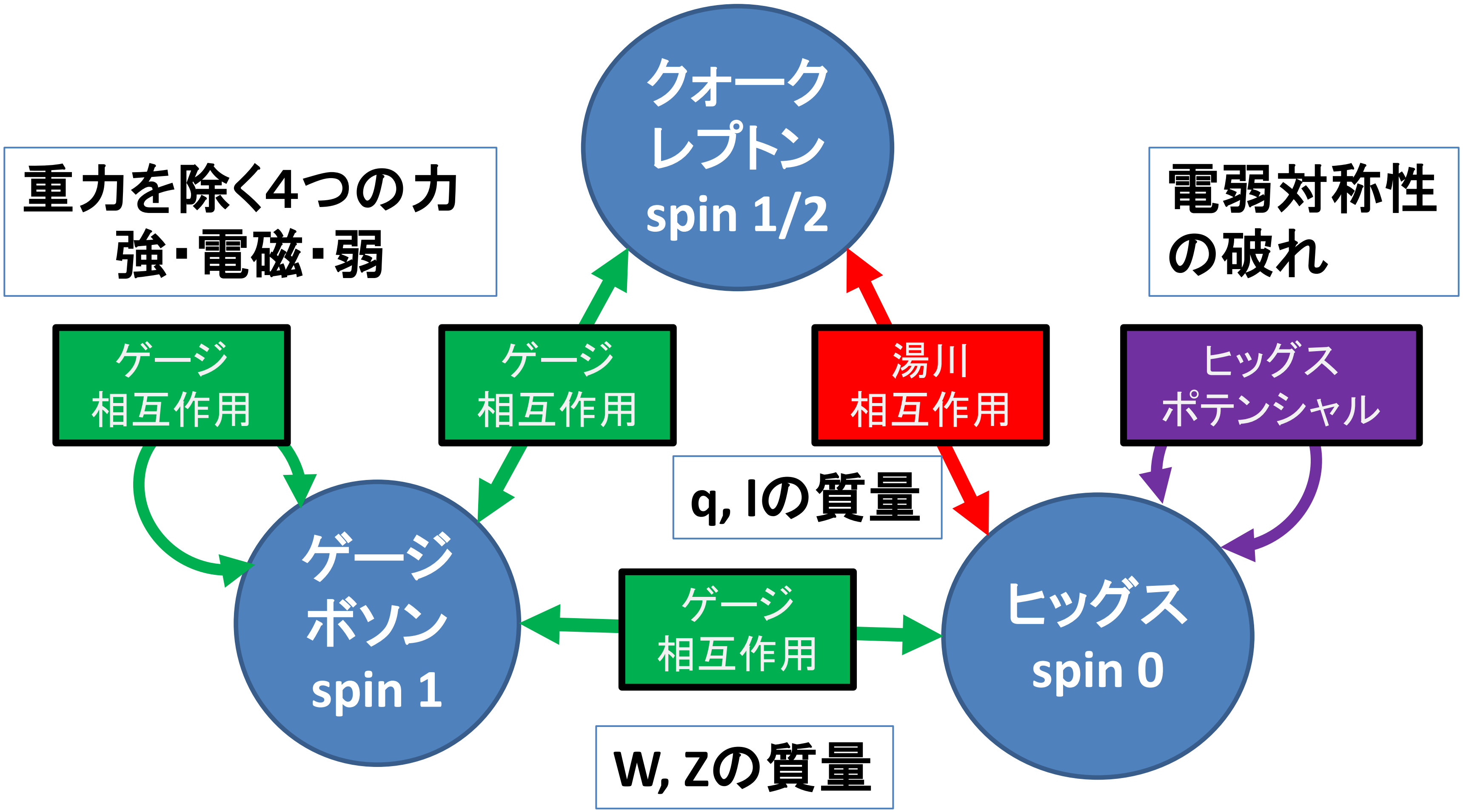
ヒッグス粒子
NHK

SM

Standard Model



ゲージ相互作用

- 数十–数百種類の相互作用がたった3つの結合定数（g_s, g, g'）で記述される。

普遍性

湯川相互作用

- ゲージ相互作用と異なり，対称性による強いしばりが存在しない

  →個々のクォーク･レプトンはヒッグスとは思い思いの強さで結合

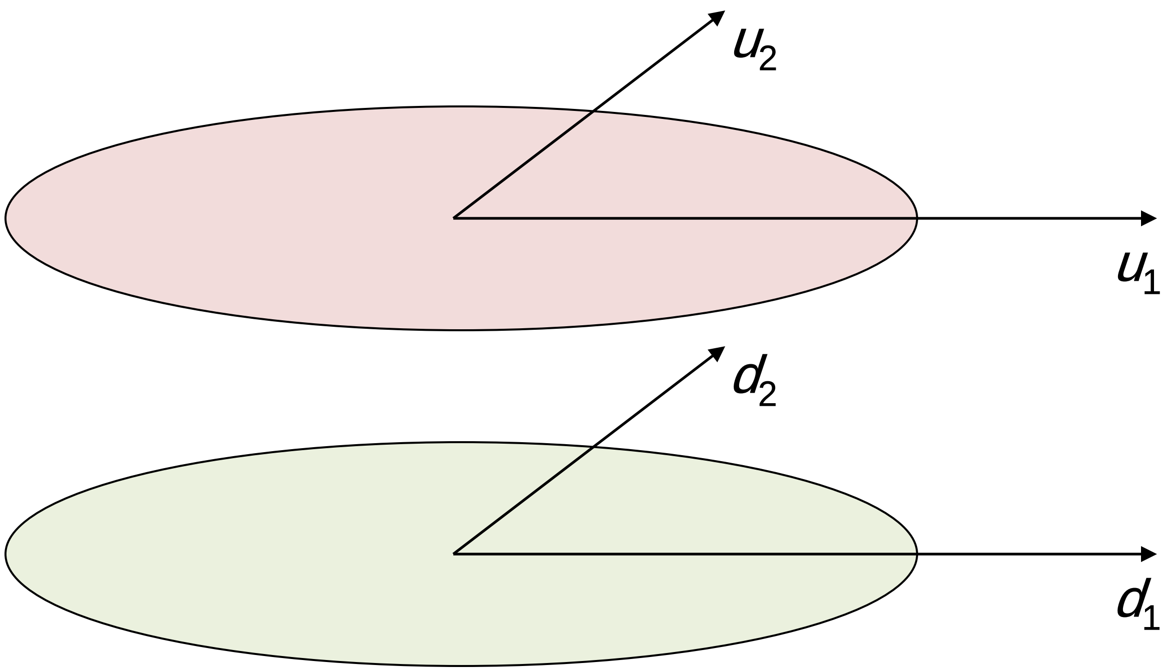
個性

湯川相互作用

- 素粒子の世代の違いはすべて湯川相互作用を起源とする。
- アップとダウンの質量はそれぞれ別の湯川相互作用から→世代の混合

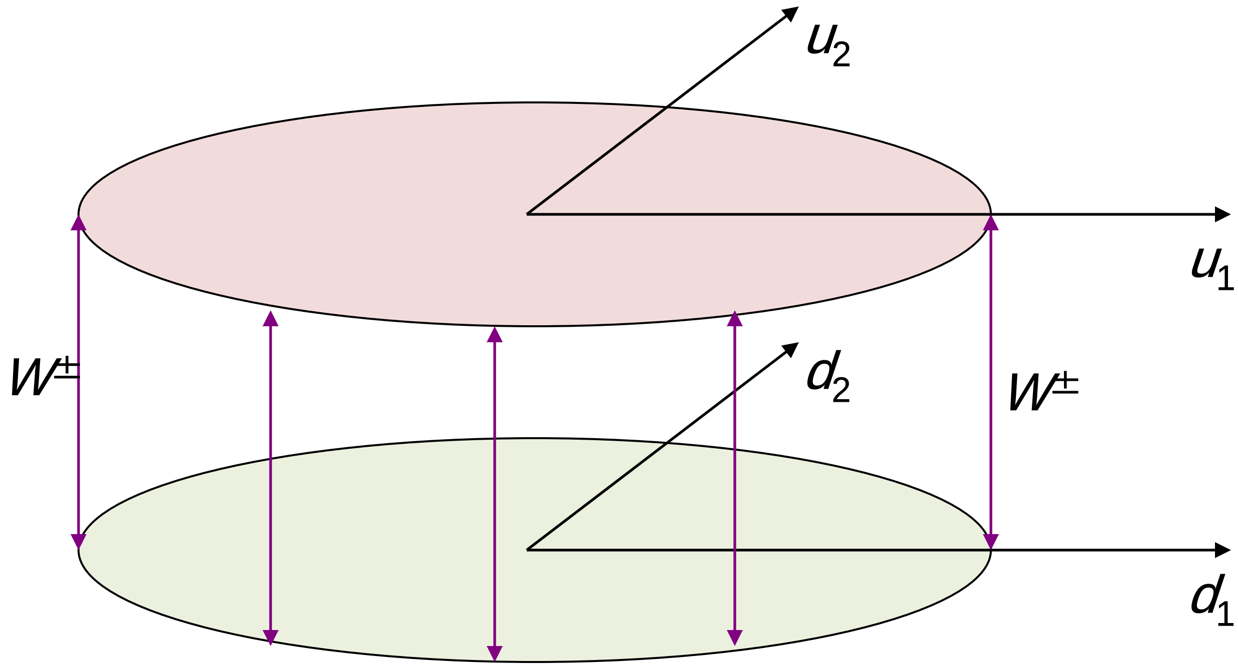
Generation mixing in SM

If no Yukawa coupling, generation labels has no meaning



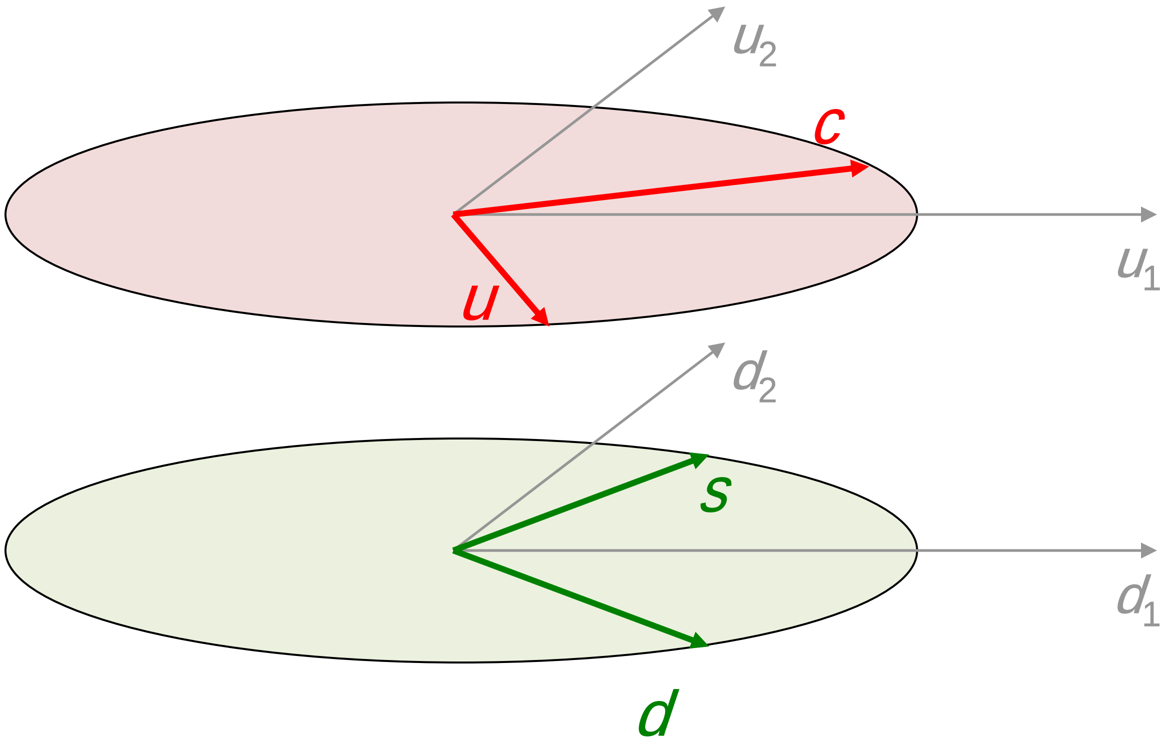
Generation mixing in SM

Charged current interactions connects ups and downs



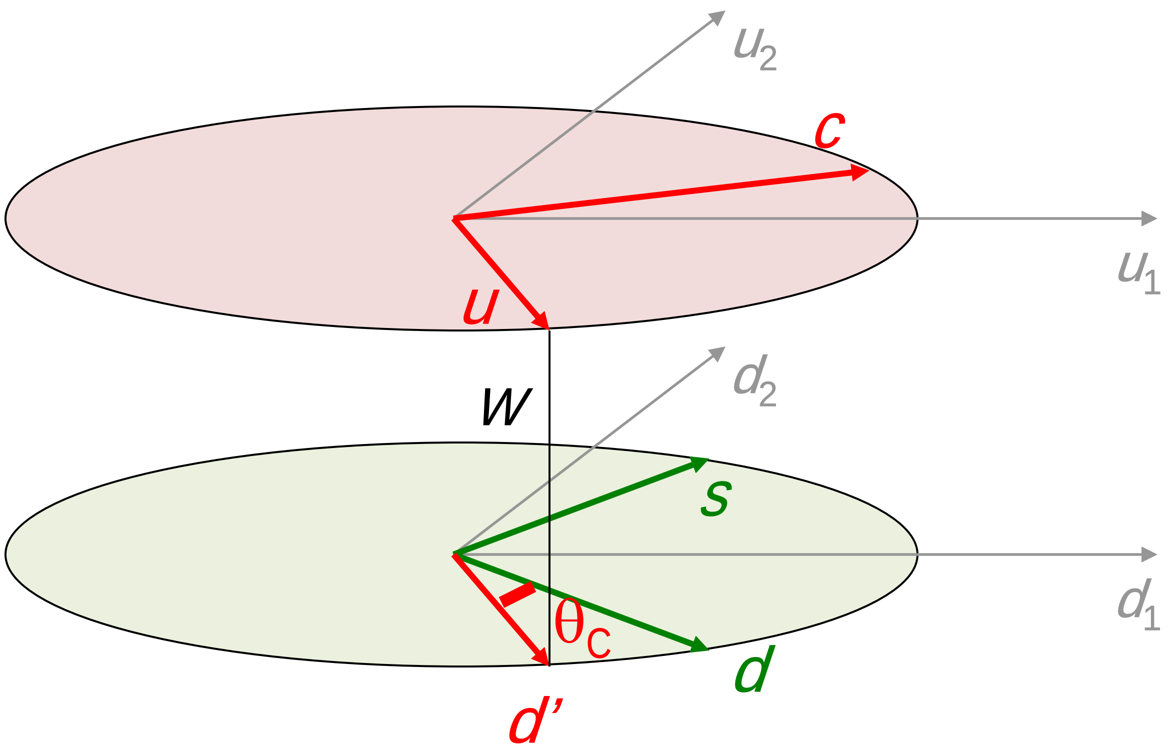
Generation mixing in SM

Yukawa couplings breaks the generation symmetry



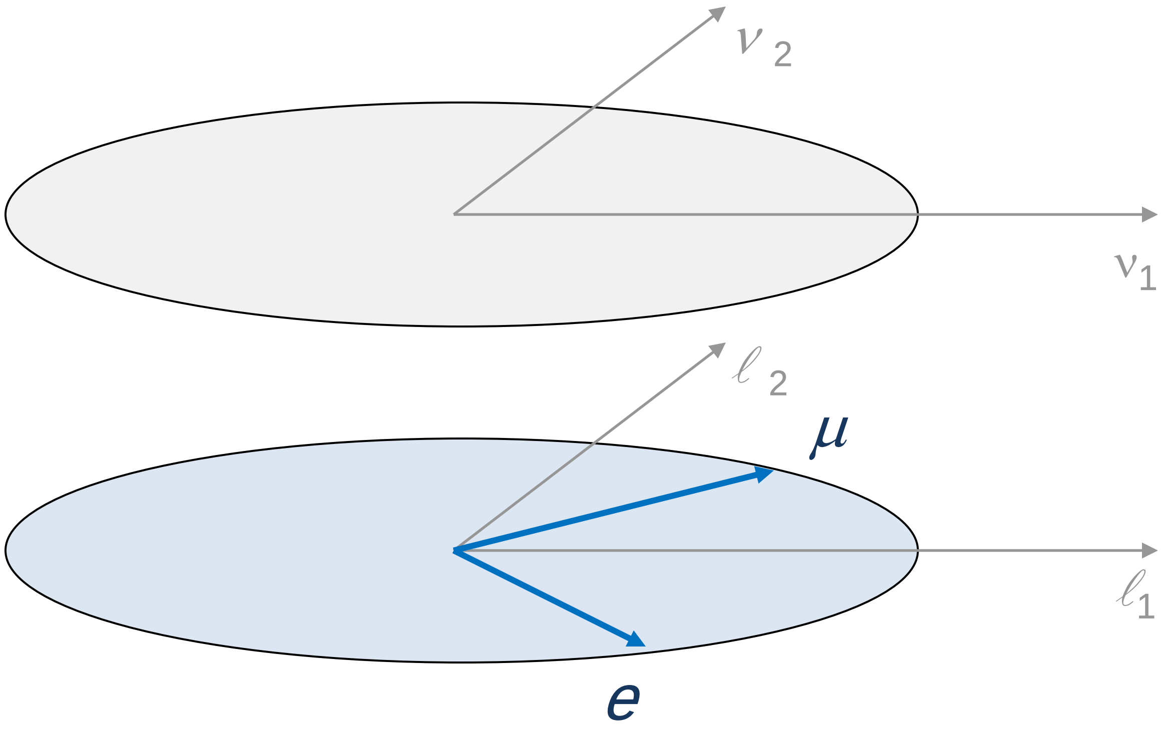
Generation mixing in SM

Mismatch of ups and downs leads to the Cabibbo mixing



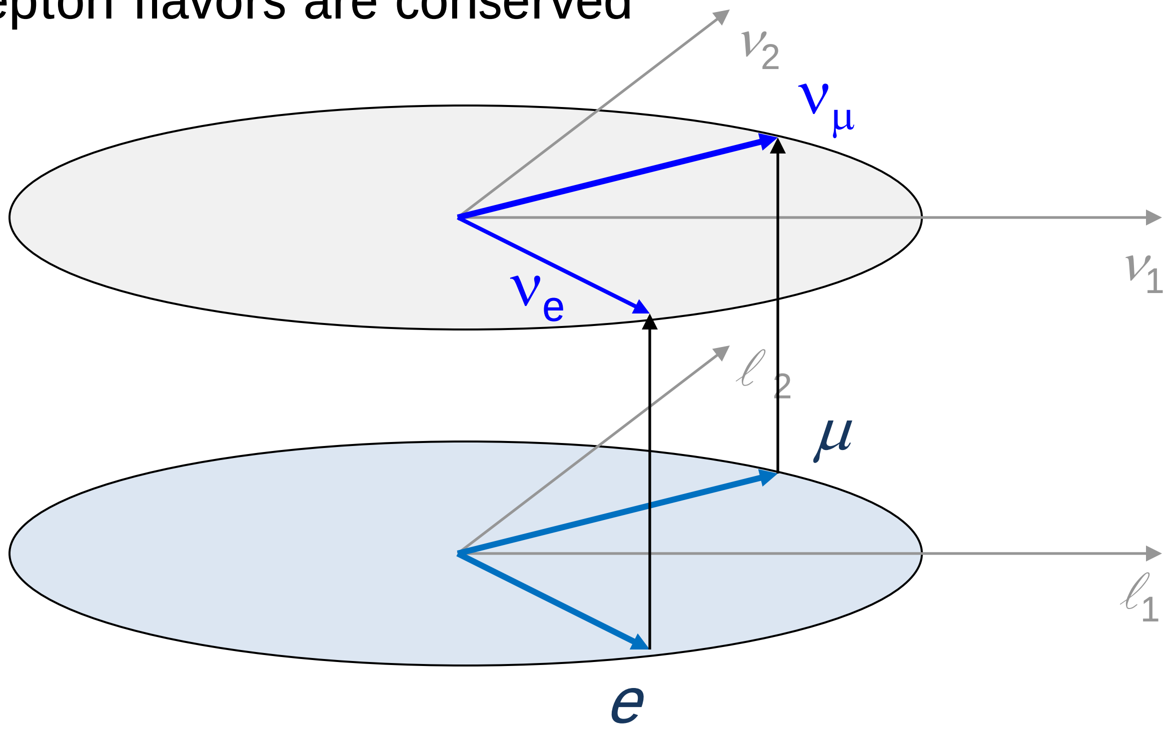
Leptons in SM

If the neutrinos were massless…



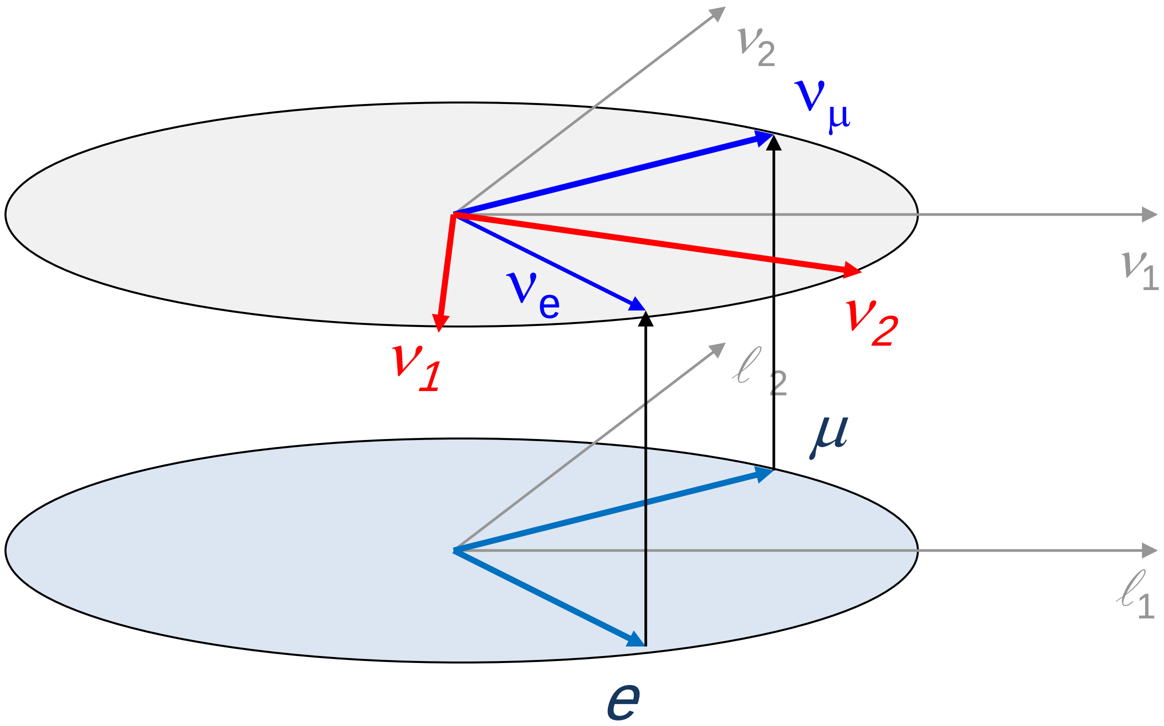
Leptons in SM

Neutrino eigenstates can be defined only by charged current and the lepton flavors are conserved



With neutrino mass

Neutrino mass eigenstates are superpositions of the "flavor" eigenstates, parallel situation with quarks
Experimentally, mass eigenstates cannot be detected directly

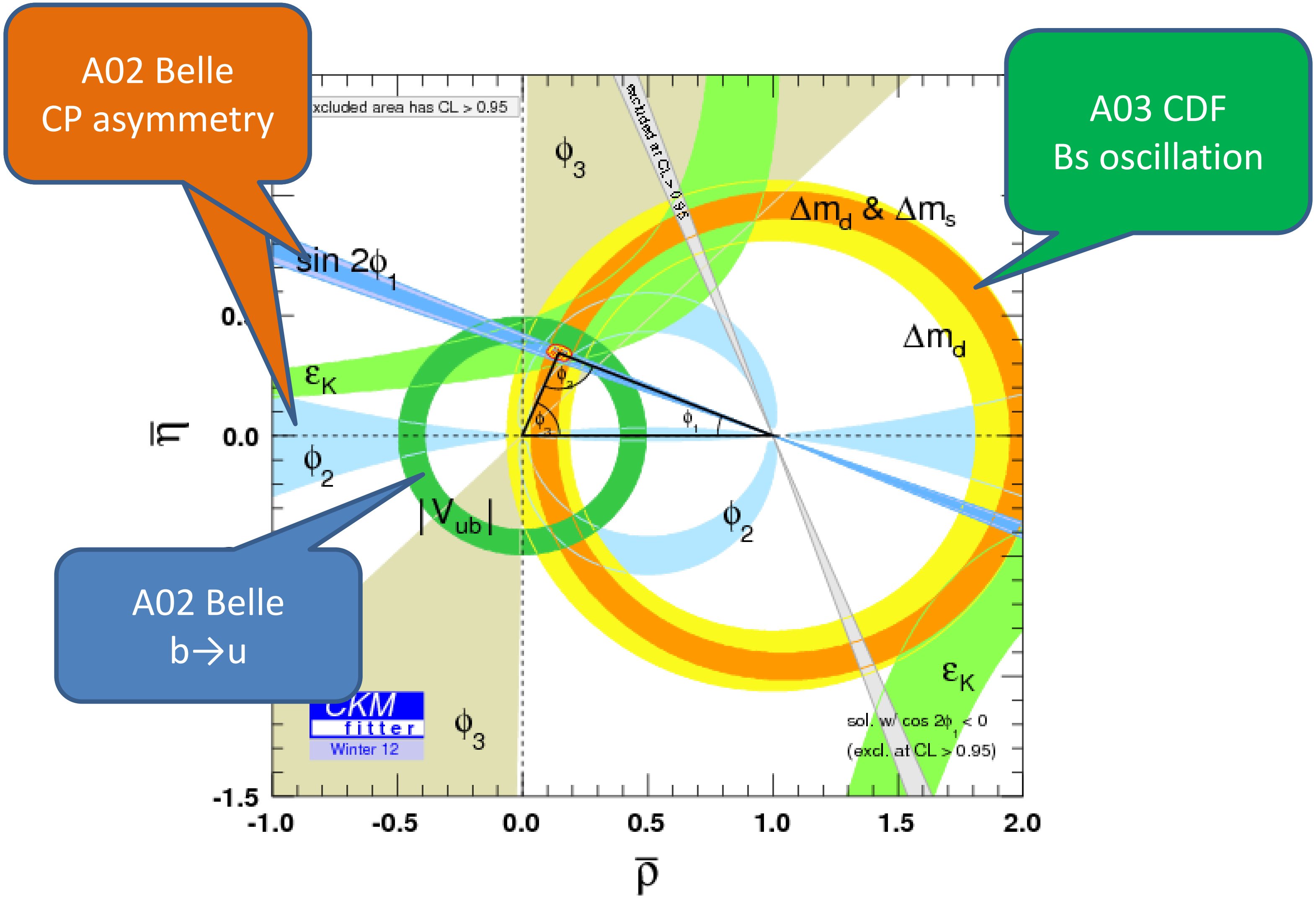


Flavor mixing in SM: Quarks

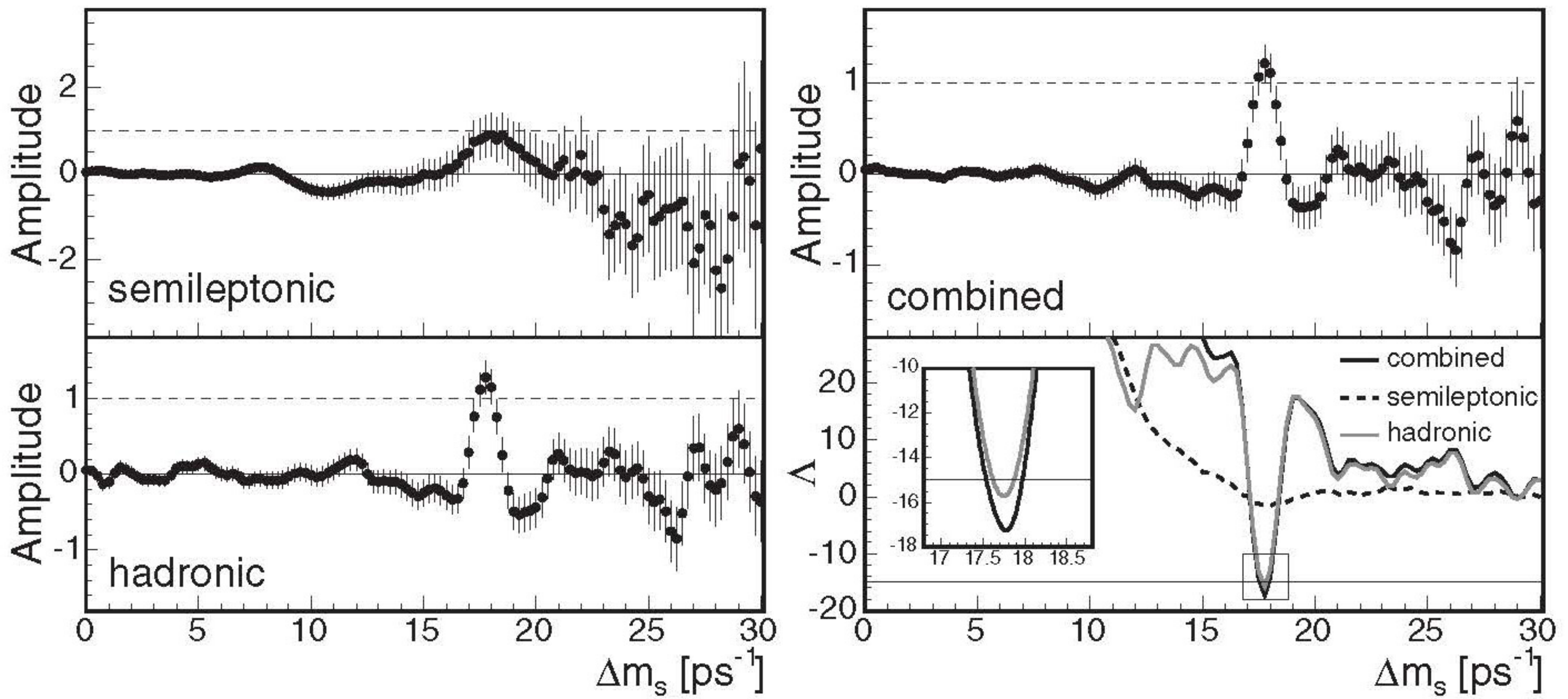
- Wの相互作用のみがフレーバーを変える
- フレーバー混合はCKM行列によりすべて決定
- ４つのパラメータ（混合角３，CP位相１）によりあらゆる現象が記述される
- Wolfenstein parameters: $\lambda=\sin\theta_C$, A, ρ, η (η: CP viol.)

$$V \cong \begin{pmatrix} 1 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & A\lambda^2 & 1 \end{pmatrix}$$

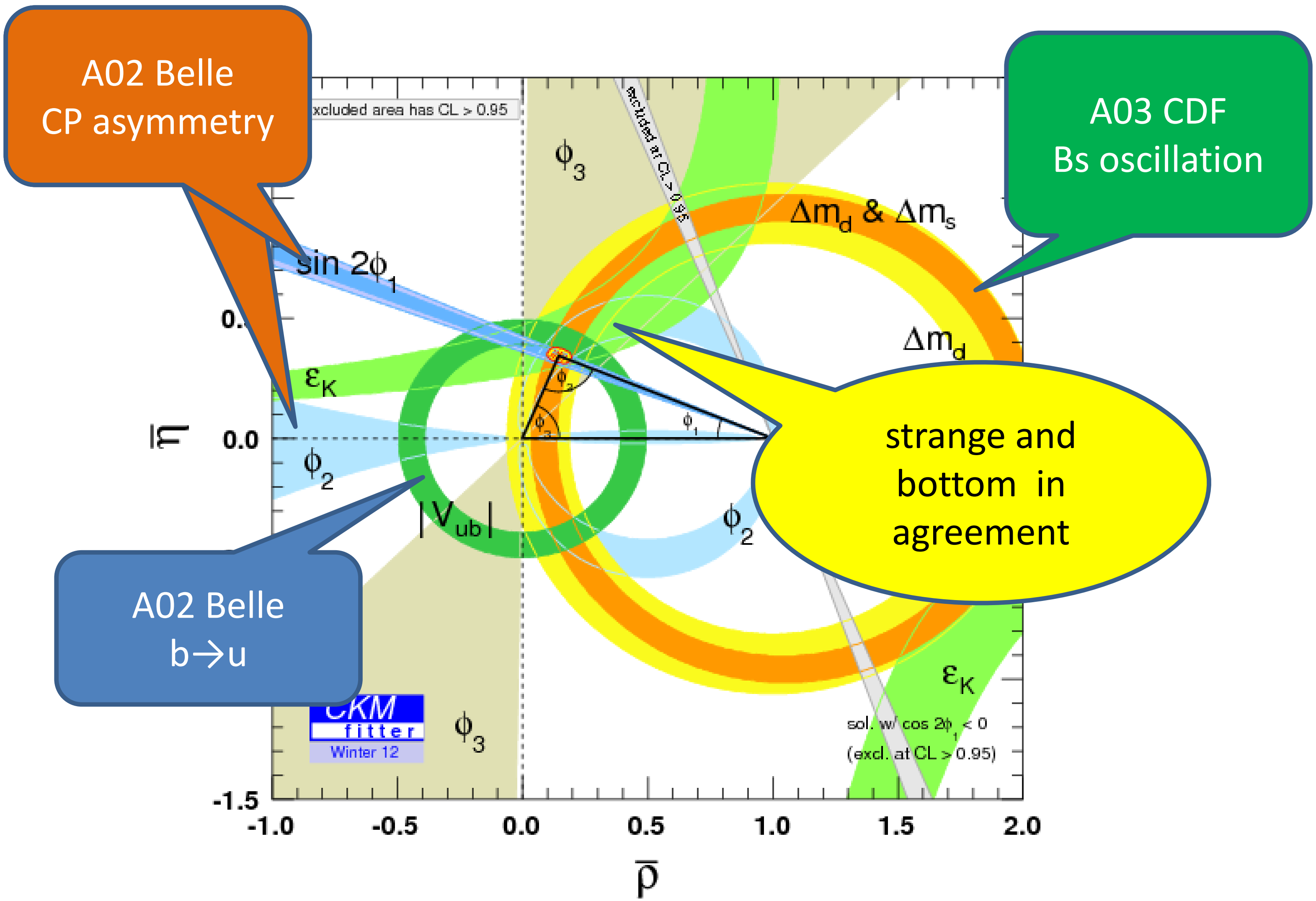
Success of CKM scheme



Bs Oscillation 【A03】



Success of CKM scheme



Success of CKM scheme

- Both
  - very small Kaon CP violation: $\varepsilon \sim 10^{-3}$
  - large Beon CP violation: $\sin 2\phi_1 \sim 0.7$

can be derived from the single CP violating parameter η

Unresolved question

- Quarks have "generation" structure: ups and downs are almost aligned
- As SM parameters, up and down Yukawa couplings have no relation with each other
- Why are up and down Yukawas can be diagonalized simultaneously up to mismatch of $O(\sin\theta_C)$?
- Indicate deeper structure to govern the Yukawa couplings

FCNC

- Kaon
  - $\Gamma_K \sim 1/10^{-10}$ sec (CC) $|\text{Amplitude}|^2 \sim G_F^2\, m_K^4$
  - $\Delta m_K \sim 1/10^{-10}$ sec (NC) $\text{Amplitude} \sim G_F^2\, m_K^4$

FCNC in SM

- フレーバー（クォーク･レプトンの種類）を変える相互作用はWだけ
- 中性カレント（Zの相互作用）はフレーバーを保存　　　s ⟺̸ d + Z
- Wの高次の効果でフレーバーを変える中性カレント（FCNC）が生ずる ➔ 小さい
- 実はGIM suppression のため非常に小さい

$K^+ \to \mu^+ \nu$　分岐比: 64%

$K_L^0 \to \mu^+ \mu^-$　分岐比: 10^{-8}

FCNC Processes

- SMでは非常に抑制 → New Physics の効果見えやすい
  - Neutral boson mixing: $K^0 - \overline{K}^0$, $B^0 - \overline{B}^0$
  - $K_L \to \mu^+\mu^-$,
  - $b \to s\gamma$, $d\gamma$
  - $K \to \pi\nu\nu$, $b \to sl^+l^-$

A01: KEK E391 $B(K_L \to \pi^0\nu\nu) < 2.6\ 10^{-8}$

PHYSICS BEYOND SM

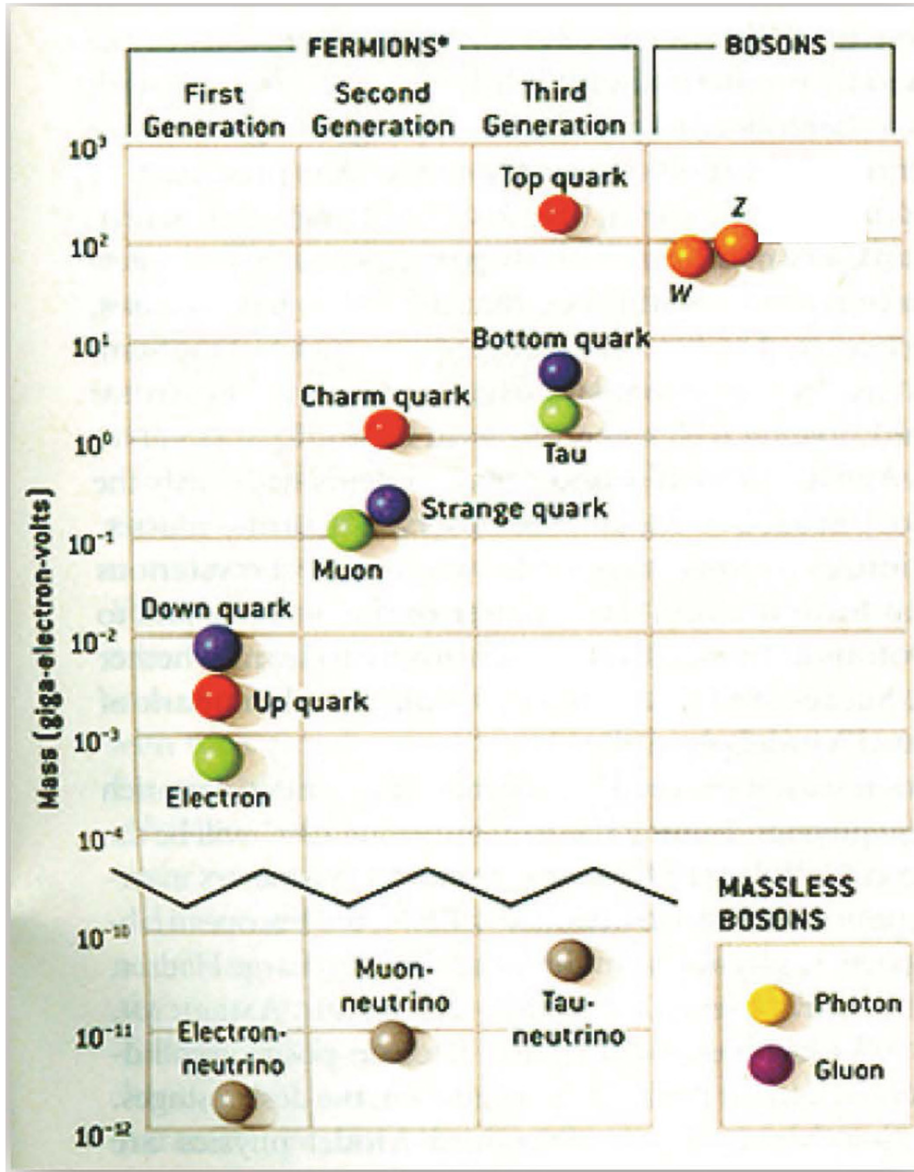
BSMを要請する実験的事実

- ニュートリノの質量

- 物質反物質非対称
- 暗黒物質
- 暗黒エネルギー
- 宇宙背景放射のゆらぎ (Inflation?)
- 重力

ニュートリノの質量

- 標準模型の枠組に自然に入る
- 右巻きニュートリノ場（ゲージ相互作用しない！のでその存在は検証困難）を加えればクォークと同様に質量・混合
- 矛盾はないが，どうしてニュートリノだけ軽いのか??


FERMIONS*
BOSONS
First Generation
Second Generation
Third Generation
Mass (giga-electron-volts)
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-10}
10^{-11}
10^{-12}
Top quark
Z
W
Bottom quark
Charm quark
Tau
Strange quark
Muon
Down quark
Up quark
Electron
MASSLESS BOSONS
Muon-neutrino
Tau-neutrino
Electron-neutrino
Photon
Gluon

ニュートリノの質量

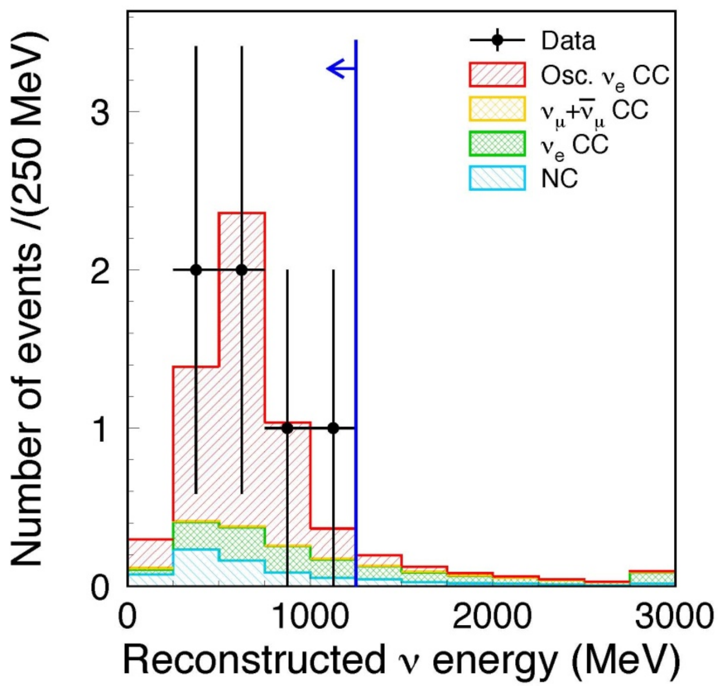
- 右巻きニュートリノ場はゲージ量子数を持たないのでマヨラナ質量を持てる（粒子＝反粒子，レプトン数非保存）
- 左巻きとの湯川結合とのinterplayにより左巻きもマヨラナとなる
- 右巻きが重ければ左巻きは逆に軽くなる（see-saw 機構）

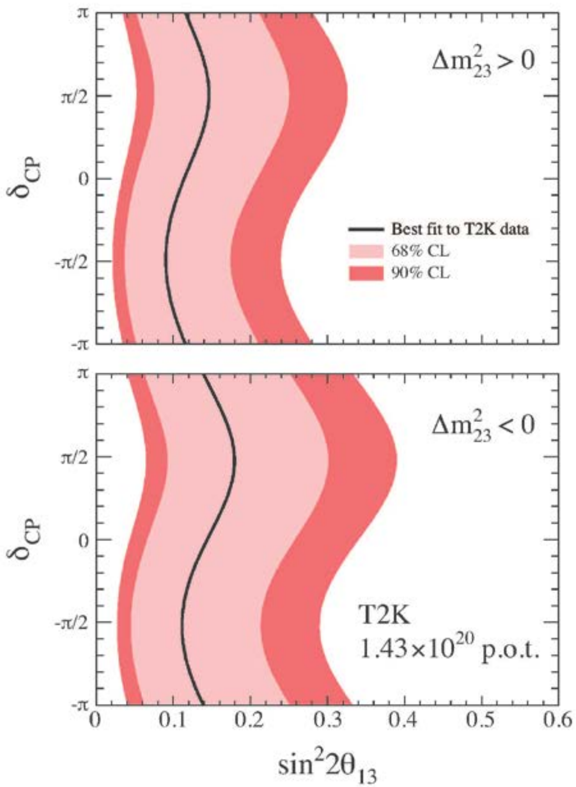
ニュートリノの混合

- ディラック or マヨラナ（右巻き重い）のとき
  - 世代の混合はクォークと同様に3×3行列（（Pontecorvo・）牧・中川・坂田行列）で記述
  - マヨラナ質量の場合CP非保存位相が2つ増（レプトン数非保存過程のみで観測可）
- マヨラナ（右巻き軽い）場合は6×6

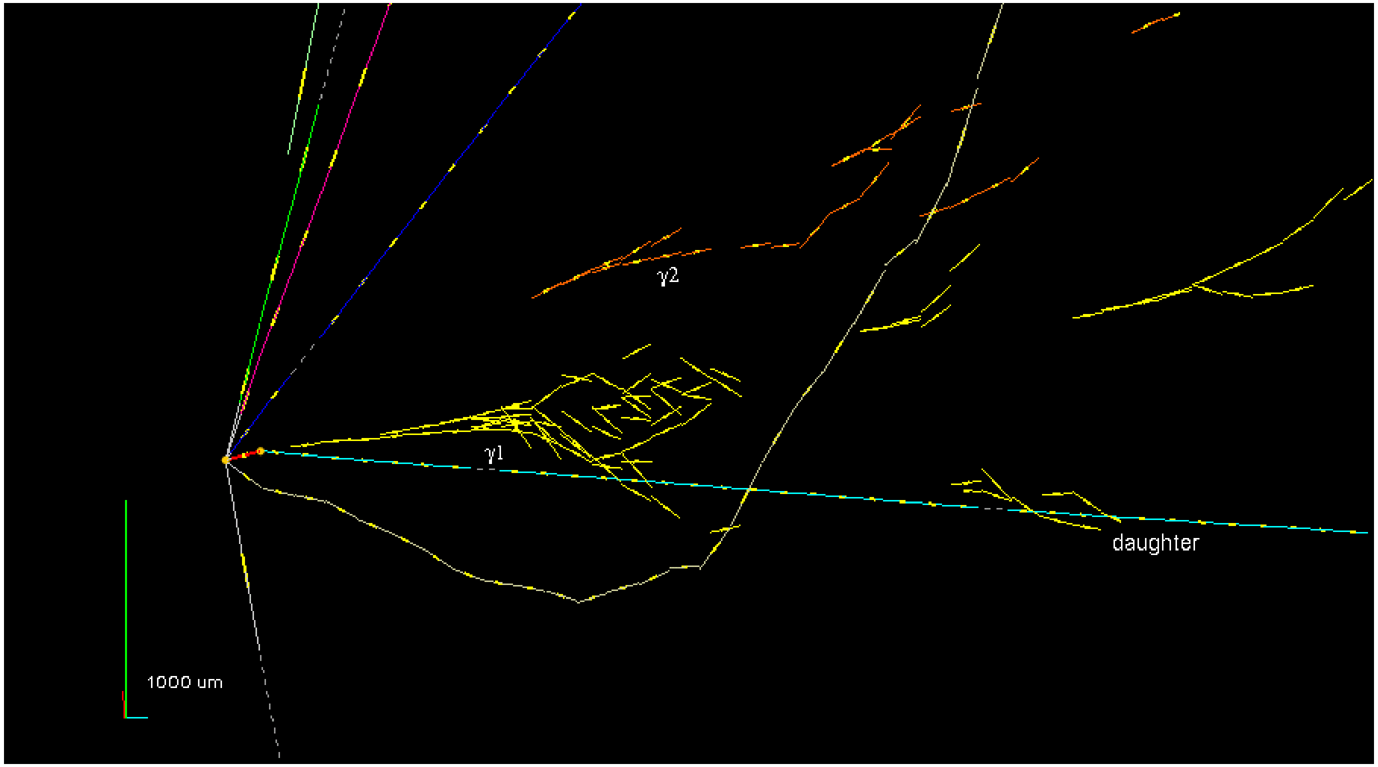
最後の角度 $\theta_{13} \neq 0$【A04】

大気ν質量差スケールでの$\nu_\mu \rightarrow \nu_e$ 振動





Observation of ν_τ appearance from ν_μ beam 【A05】



BSMを要請する実験的事実

- ニュートリノの質量

- 宇宙のバリオン数非対称
- 暗黒物質
- 暗黒エネルギー
- 宇宙背景放射 (Inflation?)
- 重力

PHYSICS (REALLY) BEYOND SM

重力

- 重力を含む最終理論の有力候補：超弦理論
  - スピン2のゼロ質量粒子を含み，重力と同じくエネルギー運動量テンソルと結合
  - スピン1のゼロ質量粒子（ゲージ場）も含む
  - 理論の整合性から超対称性を持つ
    ➔超対称理論
  - 理論の整合性から時空の次元は10次元
    ➔余剰次元

BSMの有力候補：超対称性

- スピンの異なる粒子の間の対称性
- 時空に関係した対称性として，ローレンツ群を拡張する唯一の可能性
- 標準模型の階層性問題の解としては，フェルミスケールあたりに超対称性があればよい

超対称標準模型

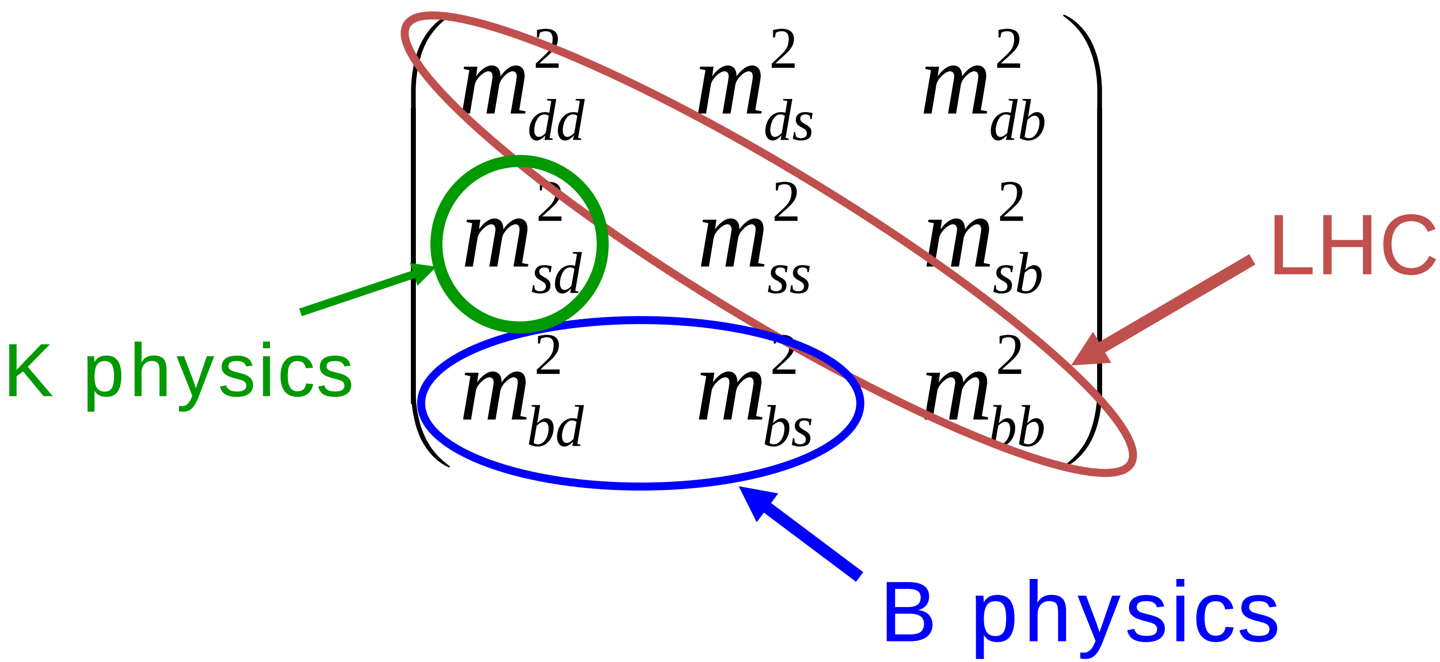
- 素粒子はすべて超対称パートナーを持つ
- ･･･

- 暗黒物質の候補を含む
- 新しい（CKM以外の）フレーバー構造

Squark masses

- 一般に湯川結合とは異なるフレーバー構造
- 新しいフレーバー混合，FCNCの原因

$$\begin{pmatrix} m_{dd}^2 & m_{ds}^2 & m_{db}^2 \\ m_{sd}^2 & m_{ss}^2 & m_{sb}^2 \\ m_{bd}^2 & m_{bs}^2 & m_{bb}^2 \end{pmatrix}$$



Flavor problem in SUSY

- You can easily have large FCNC in general SUSY models

JHEP

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Flavor and CP conserving moduli mediated SUSY breaking in flux compactification

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ABSTRACT: In certain class of flux compactification, moduli mediated supersymmetry (SUSY) breaking preserves flavor and CP at leading order in the perturbative expansion controlled by the vacuum expectation value of the messenger modulus. Nevertheless there still might be dangerous flavor or CP violation induced by higher order Kähler potential.

SUSY contribution to FCNC

PHYSICAL REVIEW D **77,** 014025 (2008)

$b \to s\nu\bar{\nu}$ decay in the MSSM: Implication of $b \to s\gamma$ at large $\tan\beta$

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(Received 19 September 2007; published 24 January 2008)

The decay $b \to s\nu\bar{\nu}$ is discussed in the minimal supersymmetric standard model with general flavor mixing for squarks, at large $\tan\beta$. In this case, in addition to the chargino loop contributions which were analyzed in previous studies, $\tan\beta$-enhanced contributions from the gluino and charged Higgs boson loops might become sizable compared with the standard model contribution, at least in principle. However, it is demonstrated that the experimental bounds on the new physics contributions to the radiative decay $b \to s\gamma$ should strongly constrain these contributions to $b \to s\nu\bar{\nu}$, especially on the gluino contribution. V also briefly comment on a possible constraint from the $B_s \to \mu^+\mu^-$ decay.

DOI: 10.1103/PhysRevD.77.014025 PACS numbers: 13.20.He, 12.60

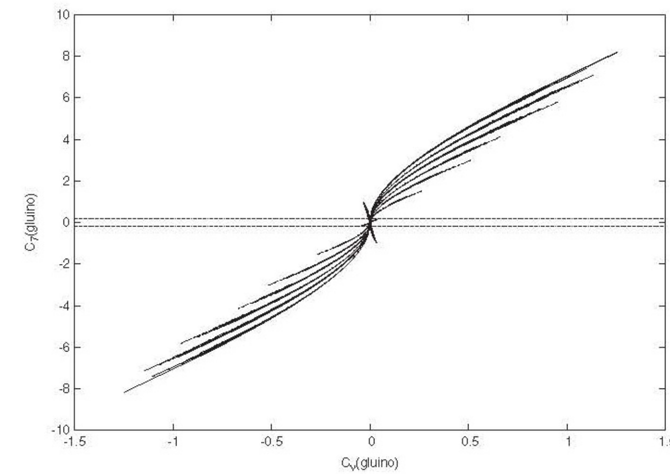
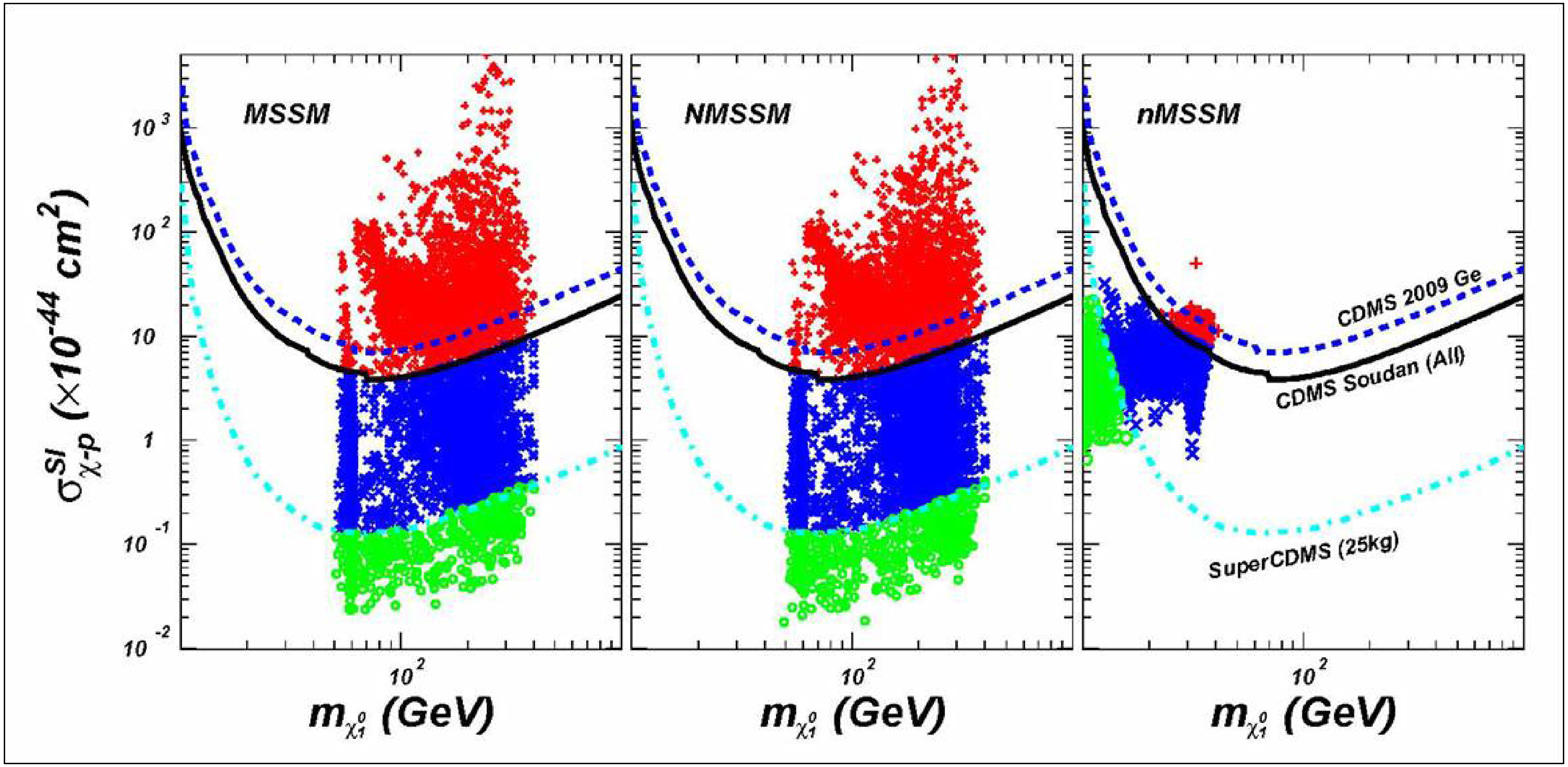


FIG. 1. Correlation between $C_{\nu,c\tilde{g}}$ and $C_{7,\tilde{g}}$. Parameters are $\tan\beta = 50$, $\mu = [-550, 550]$ GeV, $(\delta^d_{LL,RR})_{23} = [-0.3, 0.3]$. Other parameters are given in the text. Horizontal lines indicate the region $|C_{7,\tilde{g}}| < 0.2$.

超対称模型での暗黒物質断面積



J. Cao et al., JHEP 1007, 044

余剰次元模型

PHYSICAL REVIEW D **78**, 055018 (2008)

Testing the littlest Higgs model with T parity at the CERN Large Hadron Collider

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(Received 2 July 2008; published 25 September 2008)

In the framework of the littlest Higgs model with T parity (LHT), we study the production processes of T-even (T_+) and T-odd (T) partners of the top quark at the Large Hadron Collider (LHC). We show that the signal events can be distinguished from the standard model backgrounds, and that information about mass and mixing parameters of the top partners can be measured with relatively good accuracies. With the measurements of these parameters, we show that a nontrivial test of the LHT can be performed. We also discuss a possibility to reconstruct the thermal relic density of the lightest T-odd particle A_H using the LHC results and show that the scenario where A_H becomes dark matter may be checked.

DOI: 10.1103/PhysRevD.78.055018 PACS numbers: 12.60.−i

More exotic possibilities

PHYSICAL REVIEW D **85,** 014025 (2012)

Testing new physics models by top charge asymmetry and polarization at the LHC

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(Received 11 October 2011; published 25 January 2012)

As a top quark factory, the LHC can test new physics models used to explain the top quark forward-backward asymmetry A_{FB}^{t} measured at the Tevatron. In this work we perform a comparative study for two such models: the W' model and the color triplet diquark (ϕ) model. Requiring these models to explain A_{FB}^{t} and also satisfy the top pair production rate measured at the Tevatron, we examine their contributions to the LHC observables such as the polarizations and charge asymmetries in top quark productions and the charge asymmetry in W' (or ϕ) pair production. We find that these observables can be enhanced to their observable levels and current LHC measurement on the top charge asymmetry has already tightly constrained the W' model. We also find that each observable shows different characteristics in different models, which can be utilized to discriminate the models.

DOI: 10.1103/PhysRevD.85.014025 PACS numbers: 14.65.Ha, 12.60.Cn, 14.70.Pw

LEPTON FLAVOR VIOLATION

Lepton flavor violation (LFV)

- Neutrino mixing breaks lepton flavor conservation, but
- Hard to observe in charged lepton decays: rate GIM-suppressed by $(\Delta m_\nu^2/m_W^2)^2 \sim 10^{-56}$
- New physics (e.g. supersymmetry) can lead to observable decay rates for τ, μ decays

PHYSICAL REVIEW D **80,** 013002 (2009)

Model discriminating power of $\mu \to e$ conversion in nuclei

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(Received 15 April 2009; published 6 July 2009)

We assess the model discriminating power of a combined phenomenological analysis of $\mu \to e\gamma$ and $\mu \to e$ conversion on different target nuclei, including the current hadronic uncertainties. We find that the theoretical uncertainties can be largely reduced by using input from lattice QCD, and do not constitute a limiting factor in discriminating models where one or, at most, two underlying operators (dipole, scalar, vector) provide the dominant source of lepton flavor violation. Our results show that a realistic discrimination among underlying mechanisms requires a measurement of the ratio of conversion rates at the 5% level (two light nuclei) or at the 20% level (one light and one heavy nucleus). We also illustrate these main conclusions in the context of a supersymmetric model.

DOI: 10.1103/PhysRevD.80.013002

PACS numbers: 13.35.Bv, 11.30.Hv

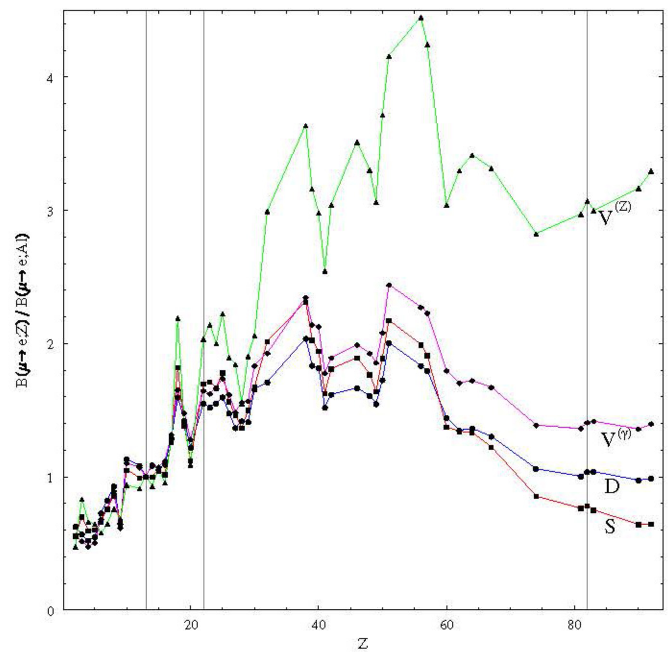

FIG. 3 (color online). Target dependence of the $\mu \to e$ conversion rate in different single-operator dominance models. We plot the conversion rates normalized to the rate in aluminum ($Z = 13$) versus the atomic number Z for the four theoretical models described in the text: D (blue), S (red), $V^{(\gamma)}$ (magenta), $V^{(Z)}$ (green). The vertical lines correspond to $Z = 13$(Al), $Z = 22$(Ti), and $Z = 83$(Pb).

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Physics Letters B

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B_s mixing phase and lepton flavor violation in supersymmetric SU(5)

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ABSTRACT

We inspect consequences of the latest
supersymmetric SU(5) theory. The $\mathcal{O}(1)$
implies $\tau \to (e+\mu)\gamma$ and $\mu \to e\gamma$. Dep
as $\tan\beta$, the rates turn out to be detecta
type squarks is nonzero. We find that it
violation given: gaugino to scalar square
sizes, and low $\tan\beta$.

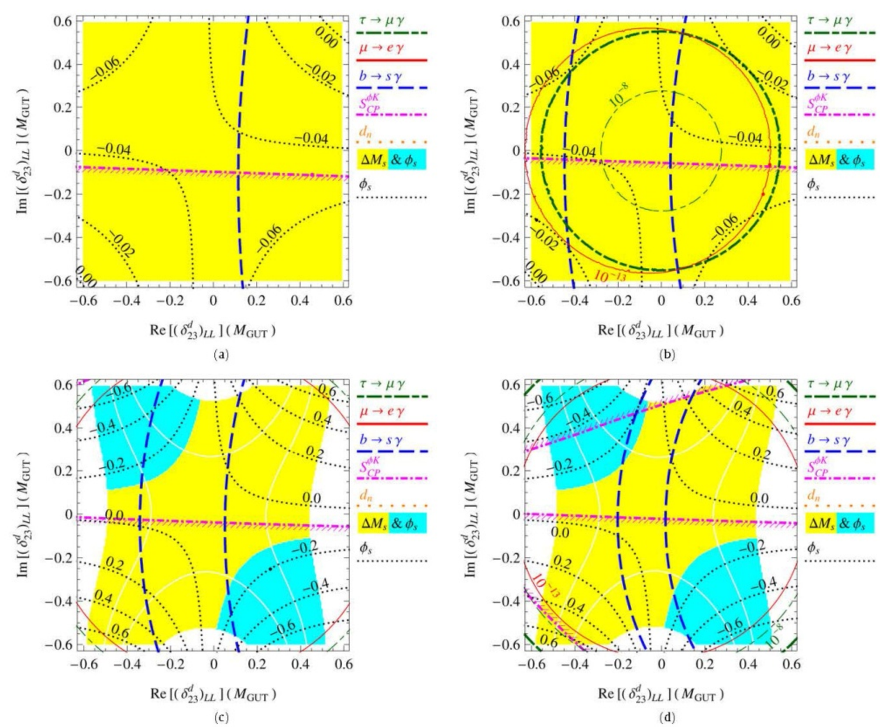
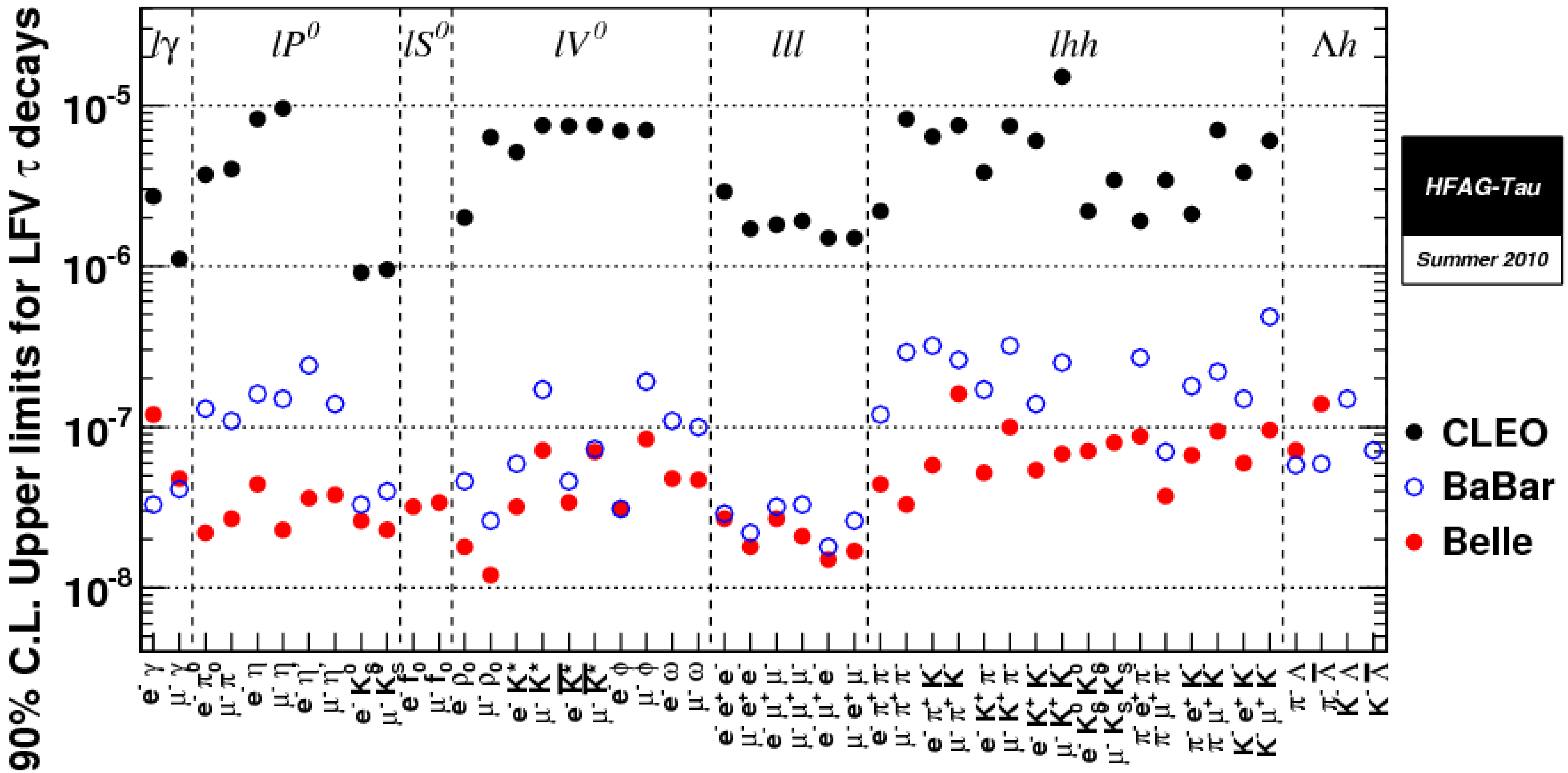
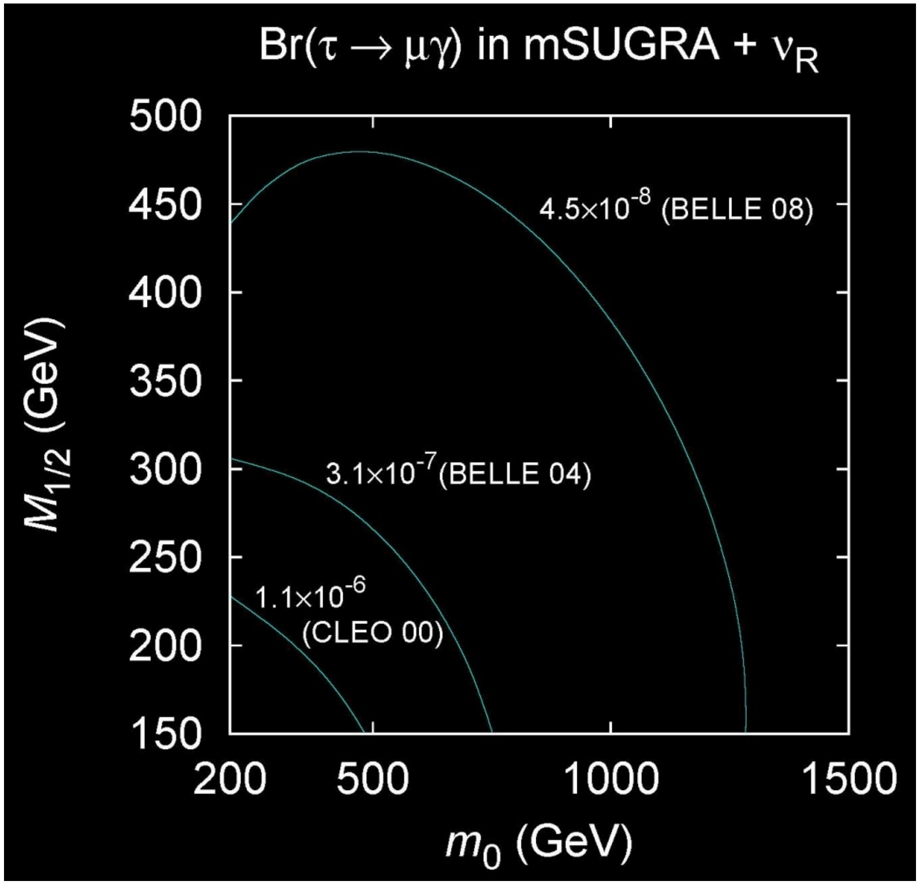


Fig. 1. Constraints on the complex plane of $(\delta_{23}^d)_{LL}$, with $(\delta_{12}^d)_{LL}$ and $(\delta_{13}^d)_{LL}$ generated from RG running between the reduced Planck scale and the GUT scale. For $\tau \to \mu\gamma$, the thick circle is the current upper bound, and the thin circle is an upper bound from the prospective branching ratio limit, 10^{-8}. For $\mu \to e\gamma$, the thin circle shows the projected bound on the branching ratio, 10^{-13}. A light gray (yellow) region is allowed by ΔM_s, given 30% uncertainty in the $\Delta B = 2$ matrix element, and a gray (cyan) region is further consistent with ϕ_s. The white curves mark a possible improved constraint from ΔM_s with 8% hadronic uncertainty. Of the two sides of the $S_{CP}^{\phi K}$ curve, the excluded one is indicated by thin short lines. (a) $m_0 = 220$ GeV, $M_{1/2} = 180$ GeV, $\tan\beta = 5$; (b) $m_0 = 220$ GeV, $M_{1/2} = 180$ GeV, $\tan\beta = 10$; (c) $m_0 = 600$ GeV, $M_{1/2} = 180$ GeV, $\tan\beta = 5$; (d) $m_0 = 600$ GeV, $M_{1/2} = 180$ GeV, $\tan\beta = 10$. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this Letter.)

Limits on τ LFV【A02】



超対称模型でのLFV



野村大輔

- ある超対称模型
- ニュートリノ振動のパラメータ (T2K, ..) からくりこみ群によりレプトン数非保存過程を予言
- Belle の上限からモデルに対する制限

OUTREACH

Public lectures

一般向け講演会

KEK公開講座「J-PARCで探るニュートリノの世界」	
日程	2011年12月3日(土)
場所	高エネルギー加速器研究機構（KEK） 小林ホール
講演タイトル	「謎の素粒子ニュートリノ日本縦断300km ーT2K実験ー」 小林 隆 (KEK素粒子原子核研究所 教授)

東北大学祭2010 研究公開講演	
日程	2010年10月31日(日)
場所	仙台市 東北大学川内キャンパス
講演タイトル	「極微の宇宙のシンメトリー」 日笠 健一 (東北大学大学院理学研究科教授)

科学講演	
日程	2009年11月07日(土)
場所	静岡県立沼津東高等学校
講演タイトル	「ビッグバン宇宙の極初期を高エネルギー粒子加速器で探るー質量起源のヒッグス粒子を探してー」 金 信弘 (筑波大学数理物質科学研究科 教授)

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