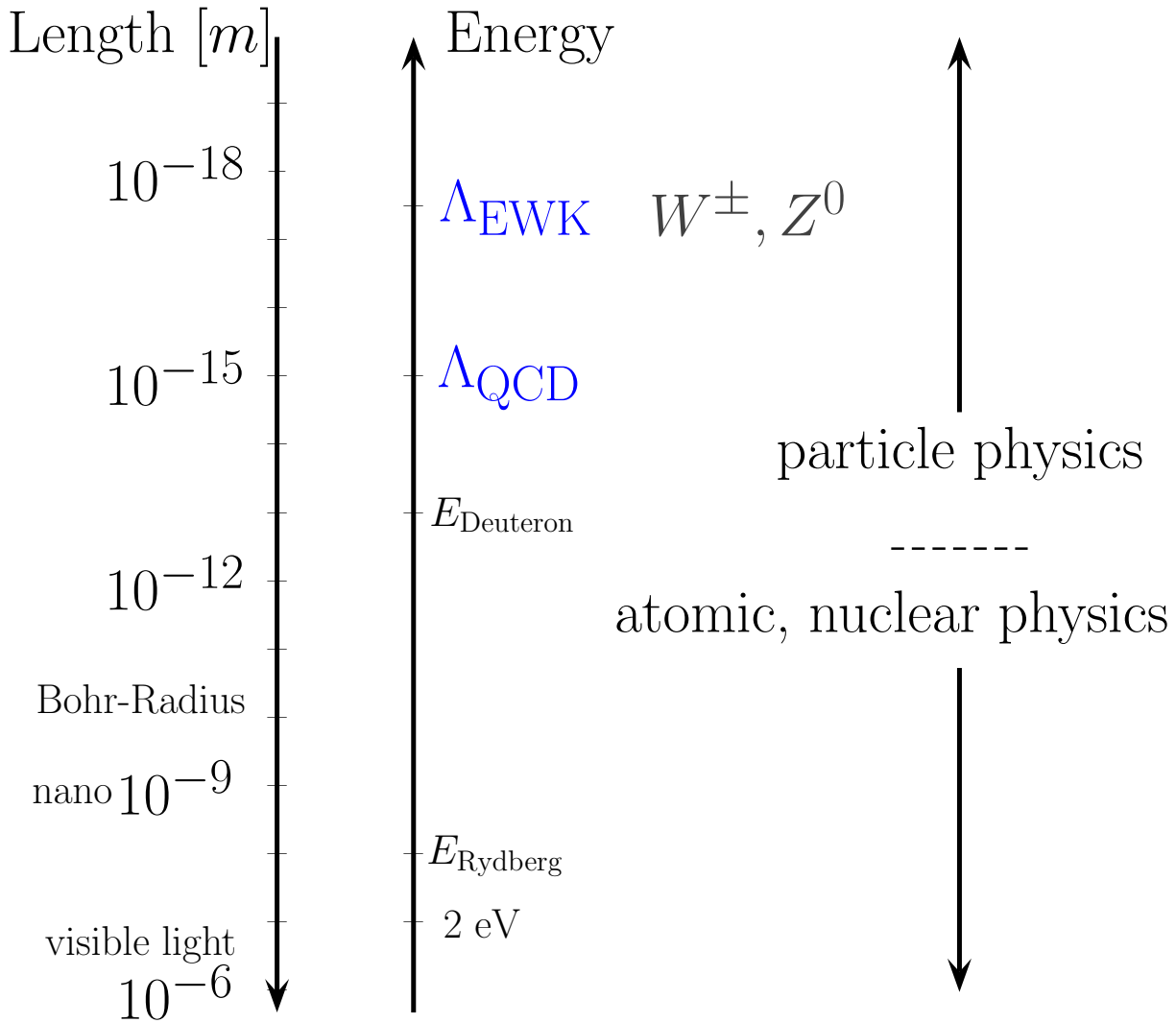
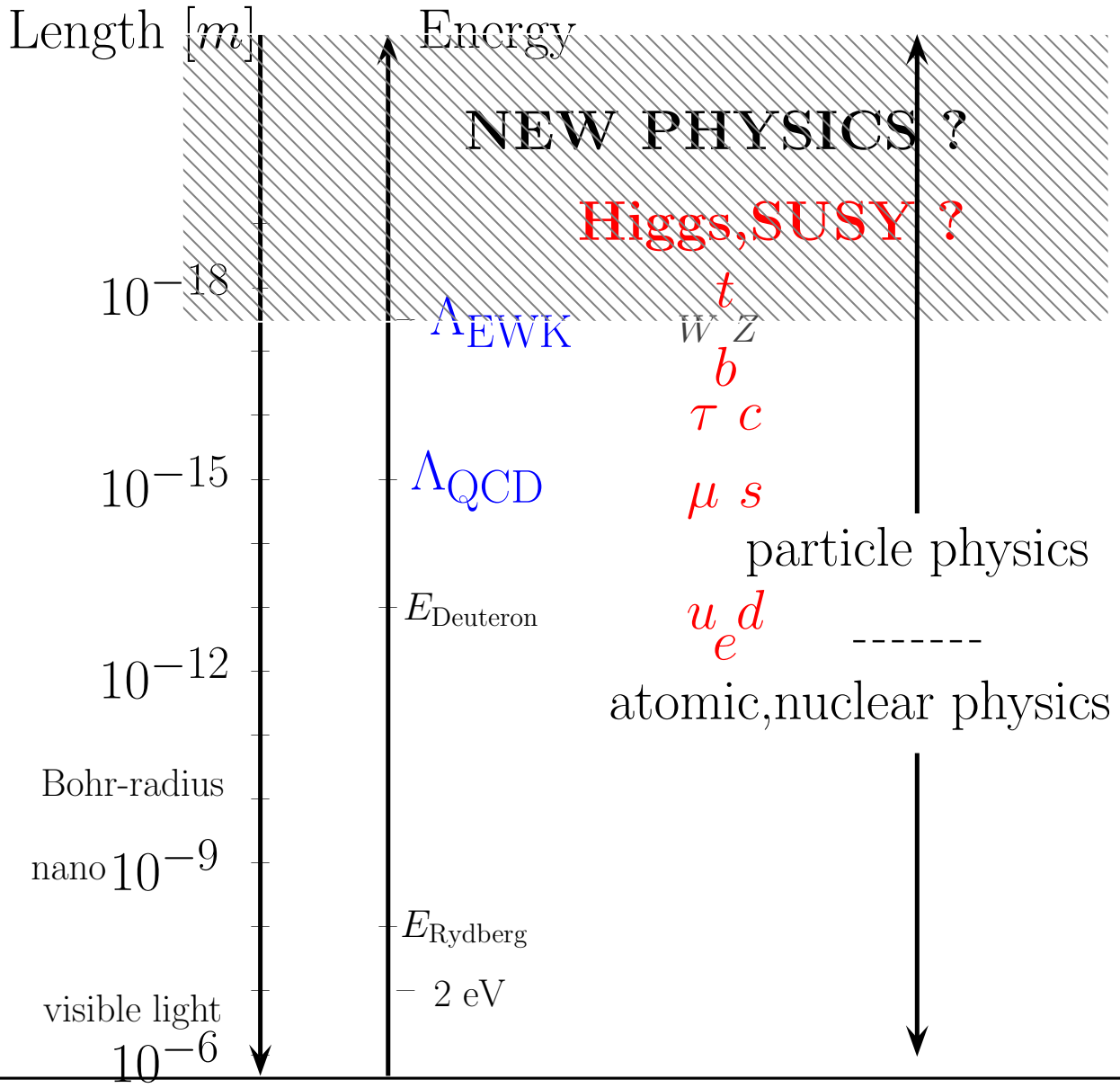
FLAVOR
at the TERASCALE

Gudrun Hiller, Dortmund

Particle Physics Scales



Terascale Physics



Known fundamental matter comes in generations $\psi \to \psi_i$, $i = 1, 2, 3$.

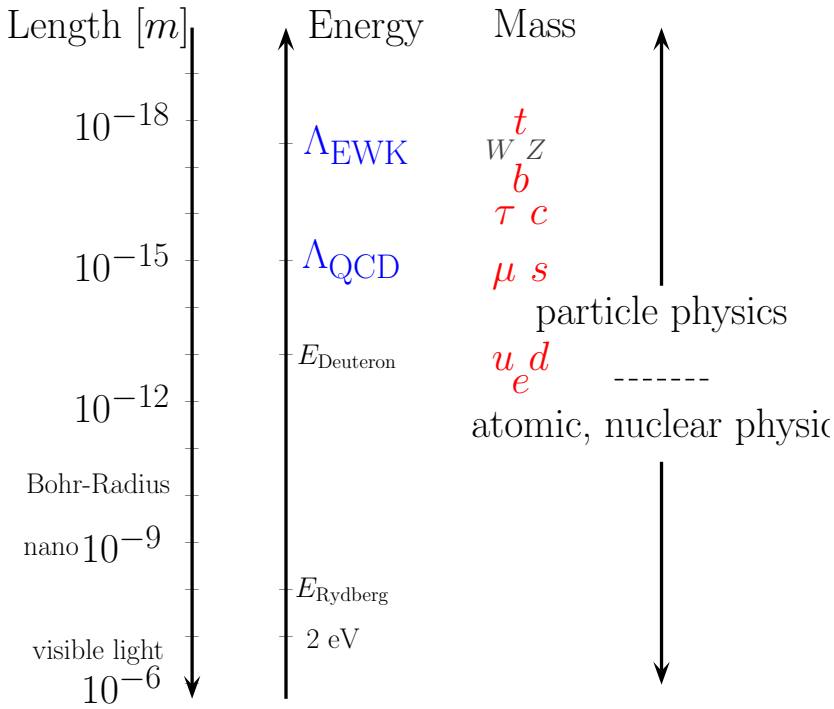
quarks: $\begin{pmatrix} u \\ d \end{pmatrix}, \begin{pmatrix} c \\ s \end{pmatrix}, \begin{pmatrix} t \\ b \end{pmatrix}$

leptons: $\begin{pmatrix} \nu_e \\ e \end{pmatrix}, \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}, \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}$

$$SU(3)_C \times SU(2)_L \times U(1)_Y \to SU(3)_C \times U(1)_{em}$$

The gauge interactions are generation independent.

Quark Spectrum



$m_u\,(2\ \text{GeV})$	$m_d\,(2\ \text{GeV})$	$m_s\,(2\ \text{GeV})$
$2.8 \pm 0.6\ \text{MeV}$	$5.0 \pm 1.0\ \text{MeV}$	$95 \pm 15\ \text{MeV}$
$m_c\,(m_c)$	$m_b\,(m_b)$	$m_t\,(m_t)$
$1.28 \pm 0.05\ \text{GeV}$	$4.22 \pm 0.05\ \text{GeV}$	$163 \pm 3\ \text{GeV}$

hierarchical! Spectrum spans five orders of magnitude.

Quarks mix and change flavor in weak interaction:

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \sim \begin{pmatrix} 1 & \lambda & \lambda^3 \\ \lambda & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix} \; ; \quad \lambda \simeq 0.2$$

$$\vartheta_{13} \sim \lambda^3 \ll \vartheta_{23} \sim \lambda^2 \ll \vartheta_{12} \sim \lambda \ll 1$$

hierachical!

Large mixing angles for leptons (PMNS-Matrix):

$$\vartheta_{23} \sim 45^\circ, \vartheta_{12} \sim 35^\circ, \vartheta_{13} \lesssim O(10^\circ)$$

CP is violated!.. together with Quark Flavor

Quark mixing matrix has a physical CP violating phase δ_{CKM}.

(with 3 generations)

Kobayashi and Maskawa, Prog.Theor.Phys 49 (1973) 652

Nobelprize in Physics 2008

The Nobel Prize in Physics 2008

"for the discovery of the mechanism of spontaneous broken symmetry in subatomic physics"

"for the discovery of the origin of the broken symmetry which predicts the existence of at least three families of quarks in nature"

Photo: Universtity of Chicago

Yoichiro Nambu

◑ 1/2 of the prize

Photo: KEK

Makoto Kobayashi

◔ 1/4 of the prize

Photo: Kyoto University

Toshihide Maskawa

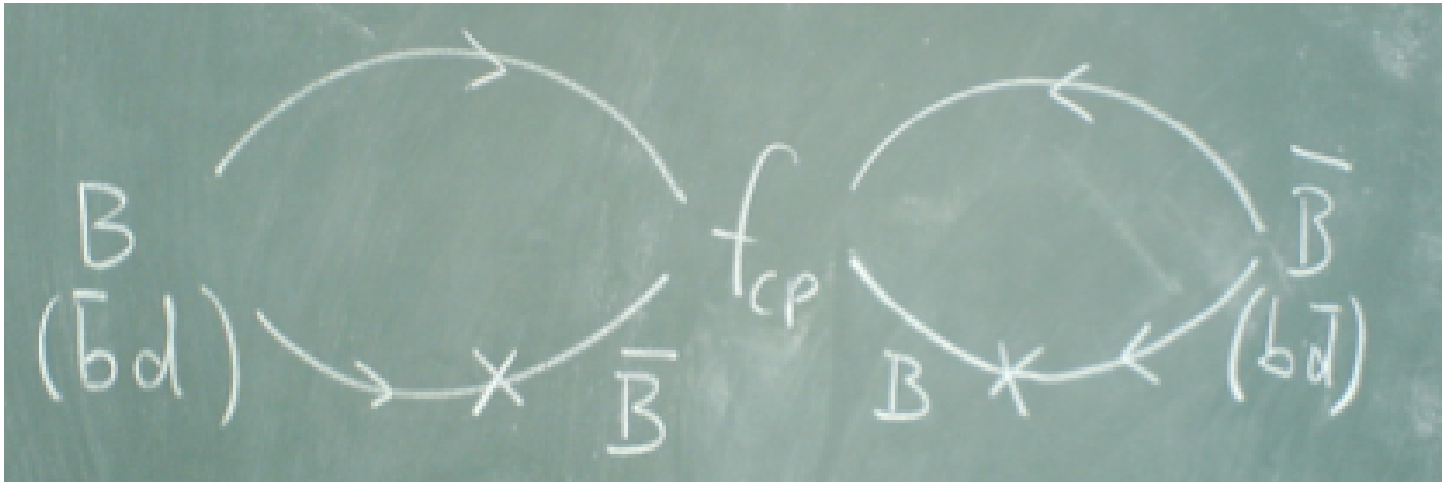
◔ 1/4 of the prize

Kobayashi and Maskawa, Prog.Theor.Phys 49 (1973) 652

CP is violated!.. together with Quark Flavor

Quark mixing matrix has a physical CP violating phase δ_{CKM}.

Verified in $B\bar{B}$ mixing $\sin 2\beta = 0.672 \pm 0.023$ HFAG Aug 2010



δ_{CKM} is large, $O(1)$!

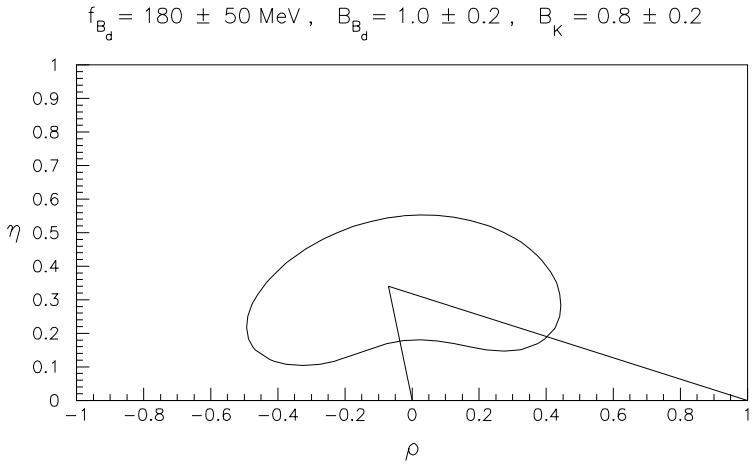
CPX also observed in B-decay $A_{CP}(B \to K^{\pm}\pi^{\mp}) = -0.098 \pm 0.013$

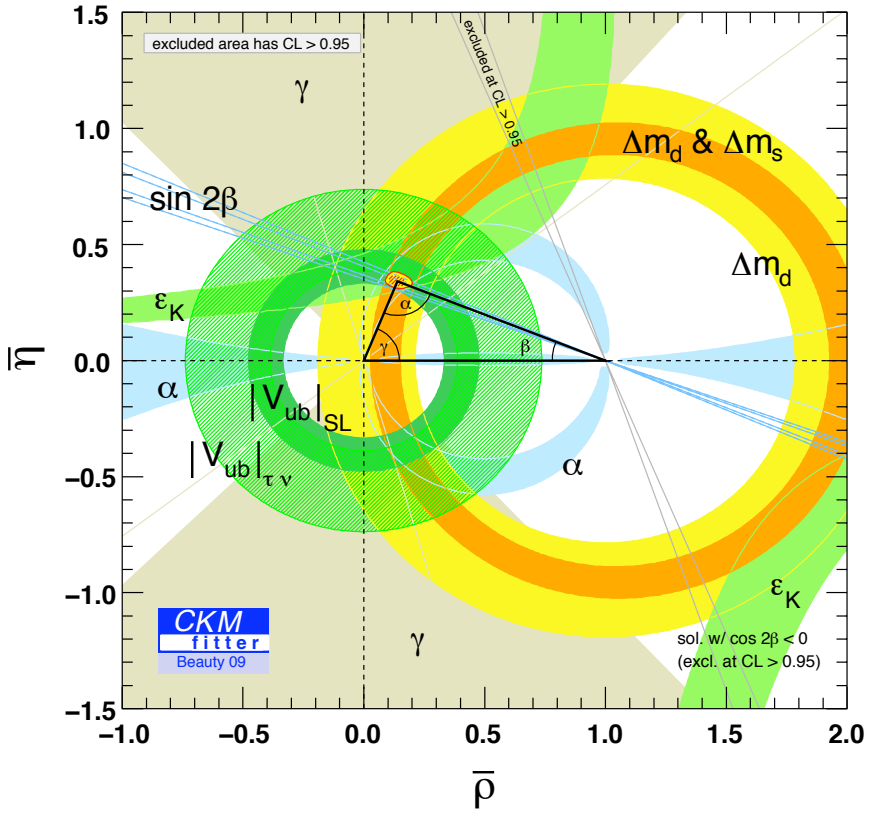
HFAG Aug 2010 LHCb'10 (S.Stone Talk CERN): -0.134 ± 0.041 (stat. err only, no corr)

$$\Gamma(B \to K^+\pi^-) \neq \Gamma(\bar{B} \to K^-\pi^+)$$

SM Flavor and CP Violation/CKM 1995 vs today

The CKM-picture of flavor and CP violation is currently consistent with all – and quite different – laboratory observations, although some tensions exist.





$$V_{CKM} V_{CKM}^{\dagger} = 1$$

Modulo ”hints” all hadronic flavor changing data are currently ok with the SM within uncertainties.

Flavor changing neutral currents (FCNCs):

$s \to d$: $K^0 - \bar{K}^0$, $K \to \pi\nu\bar{\nu}$

$c \to u$: $D^0 - \bar{D}^0$ (first data on FCNC in up-sector)

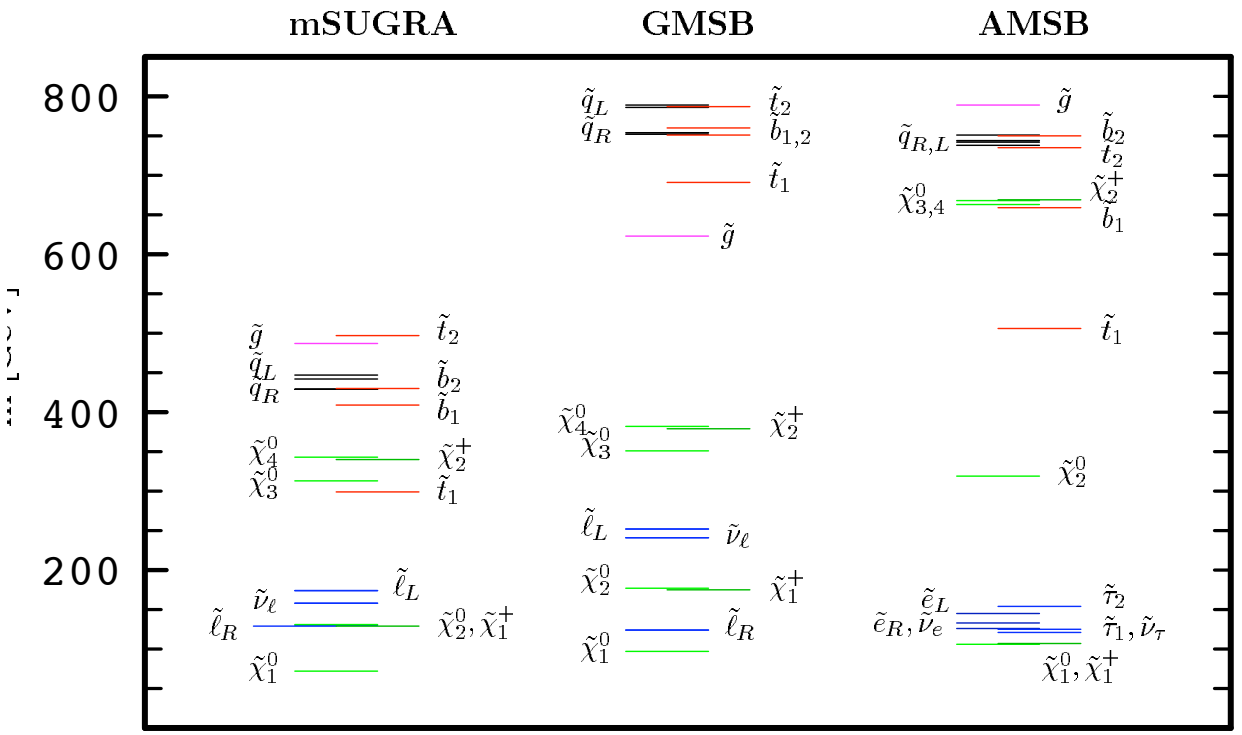
$b \to d$: $B^0 - \bar{B}^0$, $B \to \rho\gamma$, $b \to d\gamma$ ($B \to \pi ll$ close)

$b \to s$: $B_s - \bar{B}_s$, $b \to s\gamma$, $B \to K_s\pi^0\gamma$, $b \to sll$, $B \to K^{(*)}ll$ (precision, angular observables starting), $B_s \to \mu\mu$ (bound improving)

$t \to c, u$ and $l \to l'$: not observed

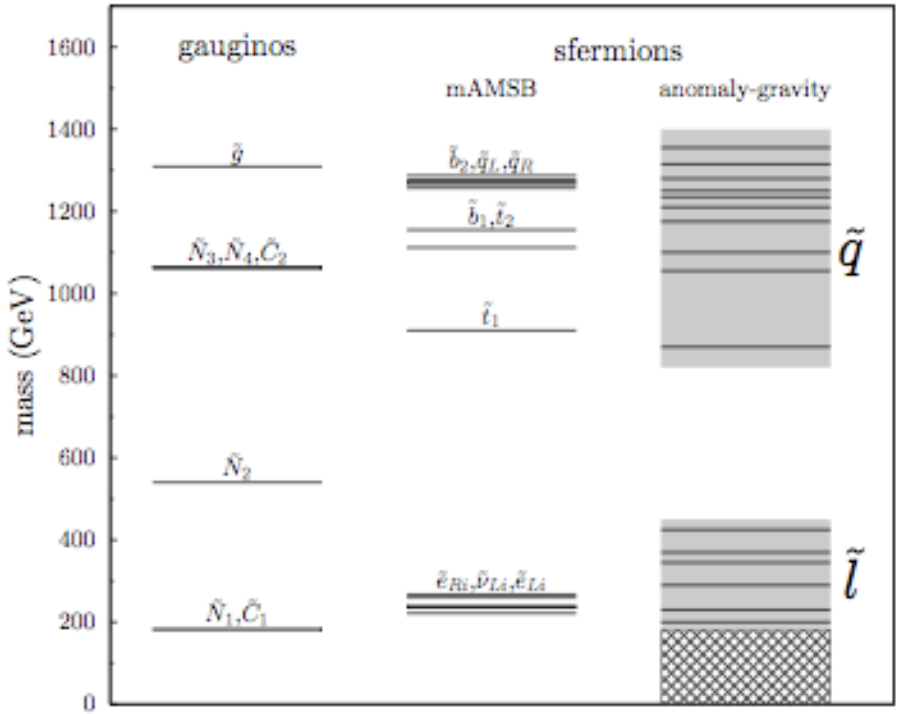
New TeV-sector; whats the flavor of the SM partners?

Flavored spectrum of $\tilde{q}$ and $\tilde{\ell}$ degenerate?



TESLA TDR Part III '01

or with large splitting?

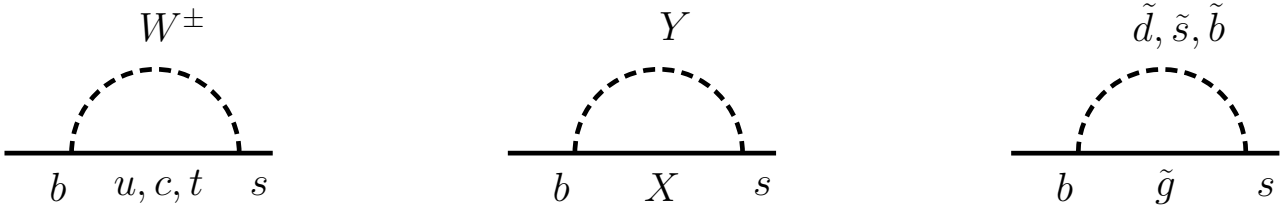


C.Gross and GH, 1101.5352 [hep-ph]

and how about flavor mixing and CP violation?

Terascale Flavor facing todays FCNC Data

$$\mathcal{A}_{FCNC} \sim \underbrace{V_{ij}V_{kj}^*}_{mixing} \times \underbrace{\Delta m_{ik}^2}_{splitting(GIM)} \times \underbrace{(1/\Lambda_{NP})^n}_{decoupling}$$



With no suppression from flavor (mixing nor splitting) at 95 % C.L:

	$K^0\bar{K}^0$	$D^0\bar{D}^0$	$B_d^0\bar{B}_d^0$	$B_s^0\bar{B}_s^0$
$\Lambda_{\rm NP}$ [TeV]	$2 \cdot 10^5$	$5 \cdot 10^3$	$2 \cdot 10^3$	$3 \cdot 10^2$

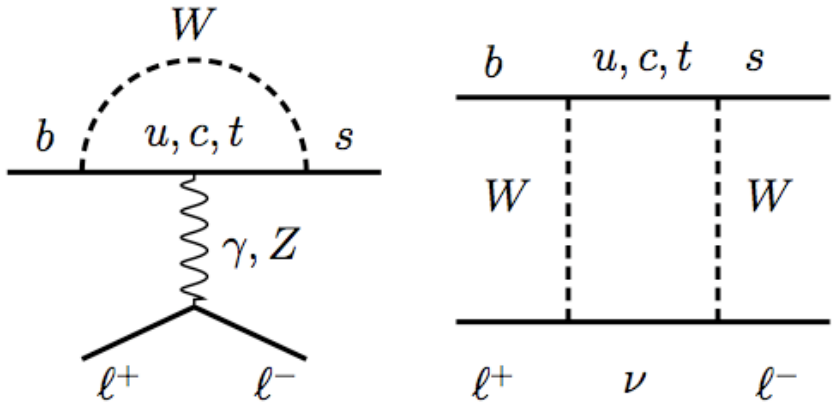
Bona et al, 0707.0636 [hep-ph]

Connection to TeV-scale is lost, or TeV-scale flavor non-generic!

FCNC loops probe product of mixing and splitting

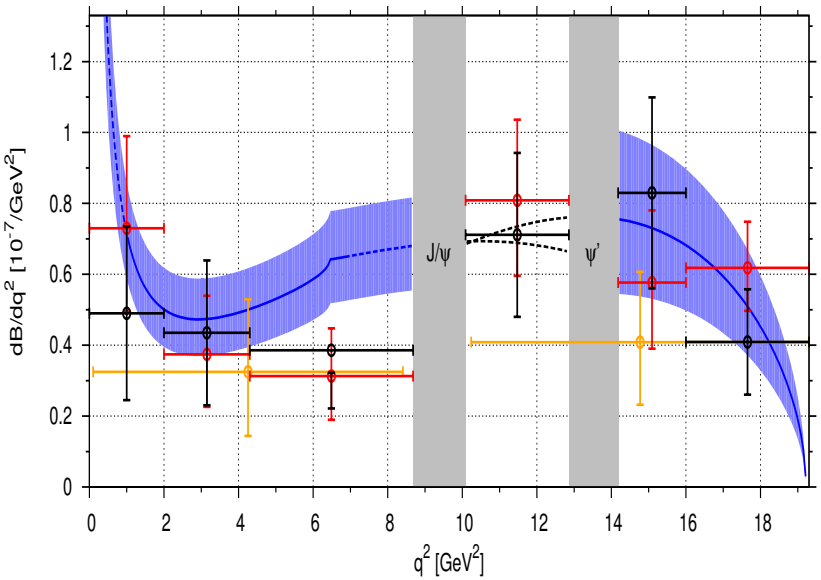
$$\mathcal{A}_{FCNC} \sim \underbrace{V_{ij}V_{kj}^*}_{mixing} \cdot \underbrace{\Delta m_{ik}^2}_{splitting(GIM)} \cdot \underbrace{(1/\Lambda_{NP})^n}_{decoupling}$$

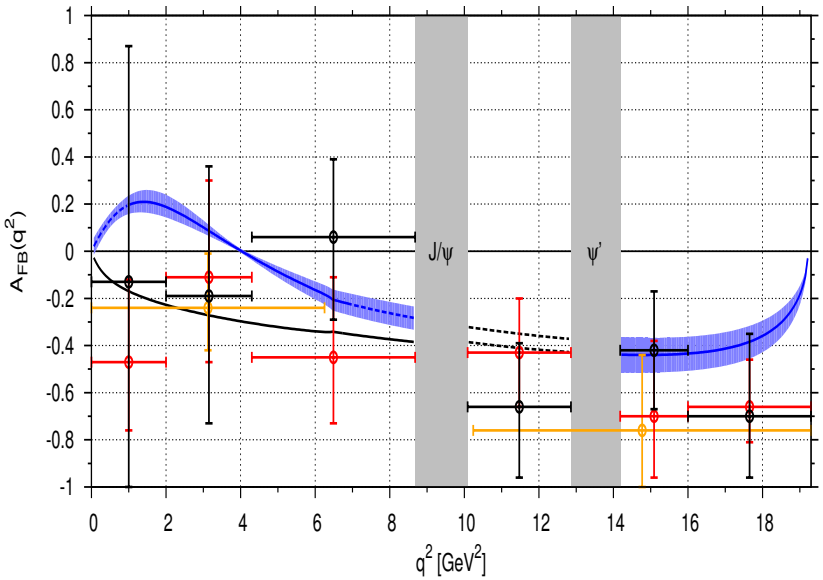
Example: Precision studies in rare semileptonic $B \to K^{(*)}l^+l^-$ decays, $Br \sim 10^{-6}$.

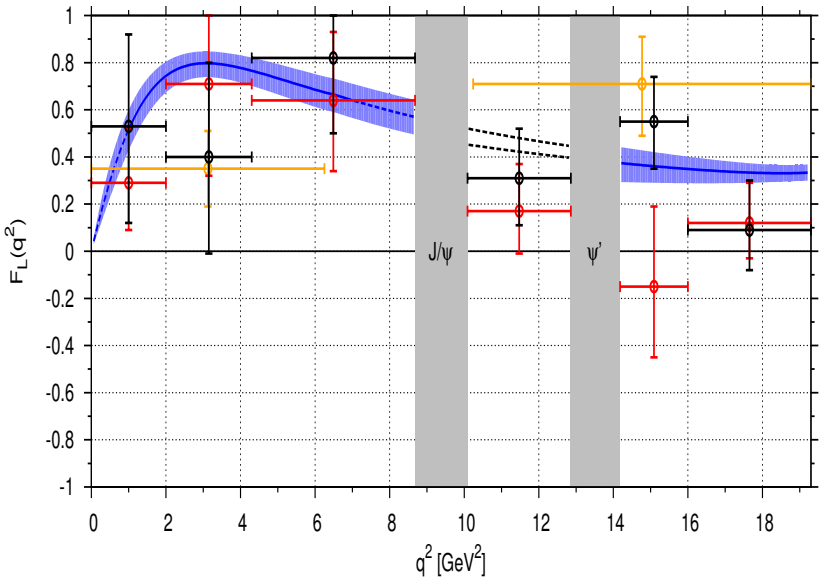


(Analysis workshop on this at DESY HH June 15-17, 2011)

SM testing with $B \to K^* l^+ l^-$ Spectra Bobeth, GH,vanDyk '10

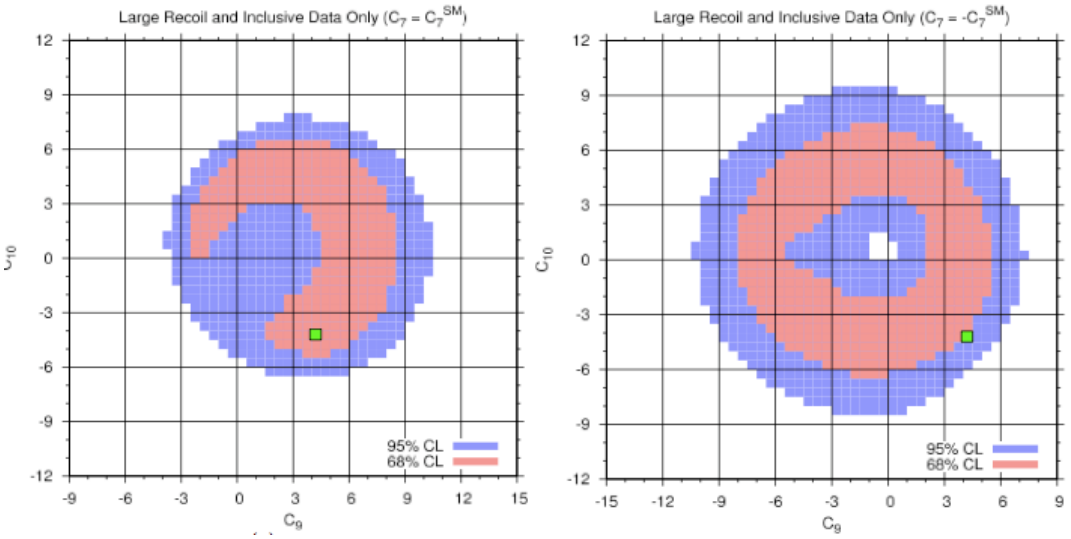




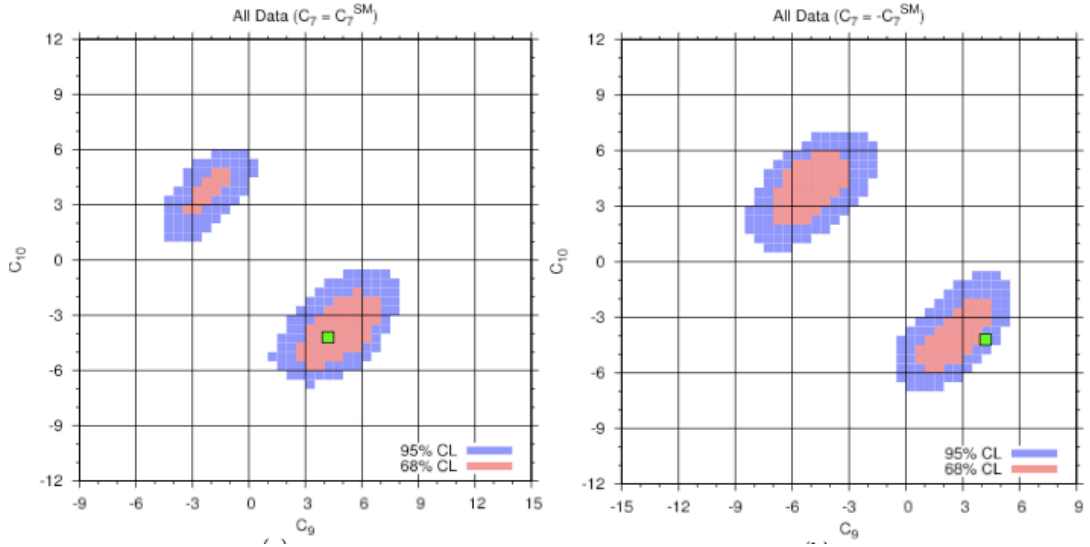


black: CDF'10 4.4fb^{-1}, gold: BaBar'08, red: Belle'09; blue: SM; $q^2 = m_{ll}^2$

C_i-Coupling Scans $B \to K^* l^+ l^-$ 2010



global fits to (real) C_9, C_{10} for $C_7 = \pm C_7^{SM}$



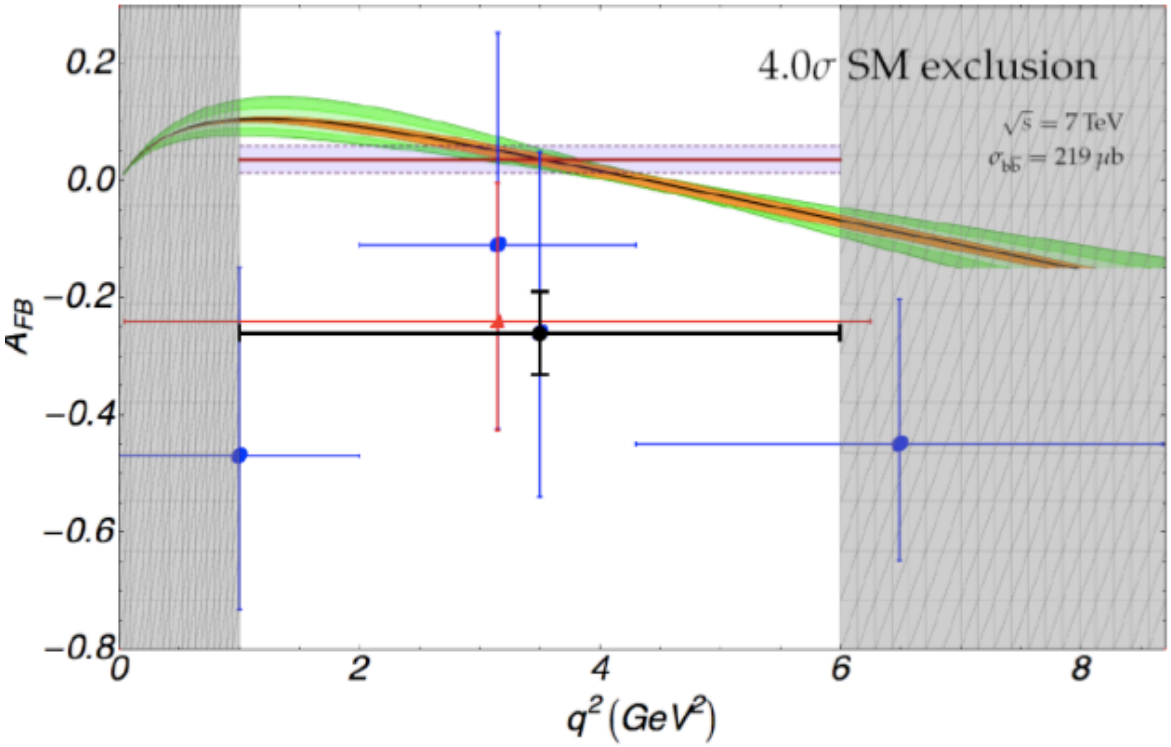
green box: SM value for (C_9, C_{10})

EOS project: http://project.het.physik.tu-dortmund.de/eos/ Bobeth, GH,vanDyk '10 1006.5013 [hep-ph]

Forward Backward Asymmetry -LHCb Prospects

$B_d \to K^* \mu\mu$

- Prospects at LHCb: if we consider **most sensitive bin** ($1<q^2<6$ GeV^2), and if we assume **Belle central value**: with 1 fb^{-1} (2011) LHCb will get statistical precision enough to exclude SM A_{FB} average value by **4σ**.



Data (fb^{-1})	SM exclusion
0.1	1.5σ
0.3	2.4σ
0.5	3.1σ
1.0	4.0σ

SM bin average
SM prediction
BaBar
Belle
LHCb MC (1 fb-1)

flavor splitting Δm_{ij} versus flavor mixing K_{ij}; a) today b) hypothetical

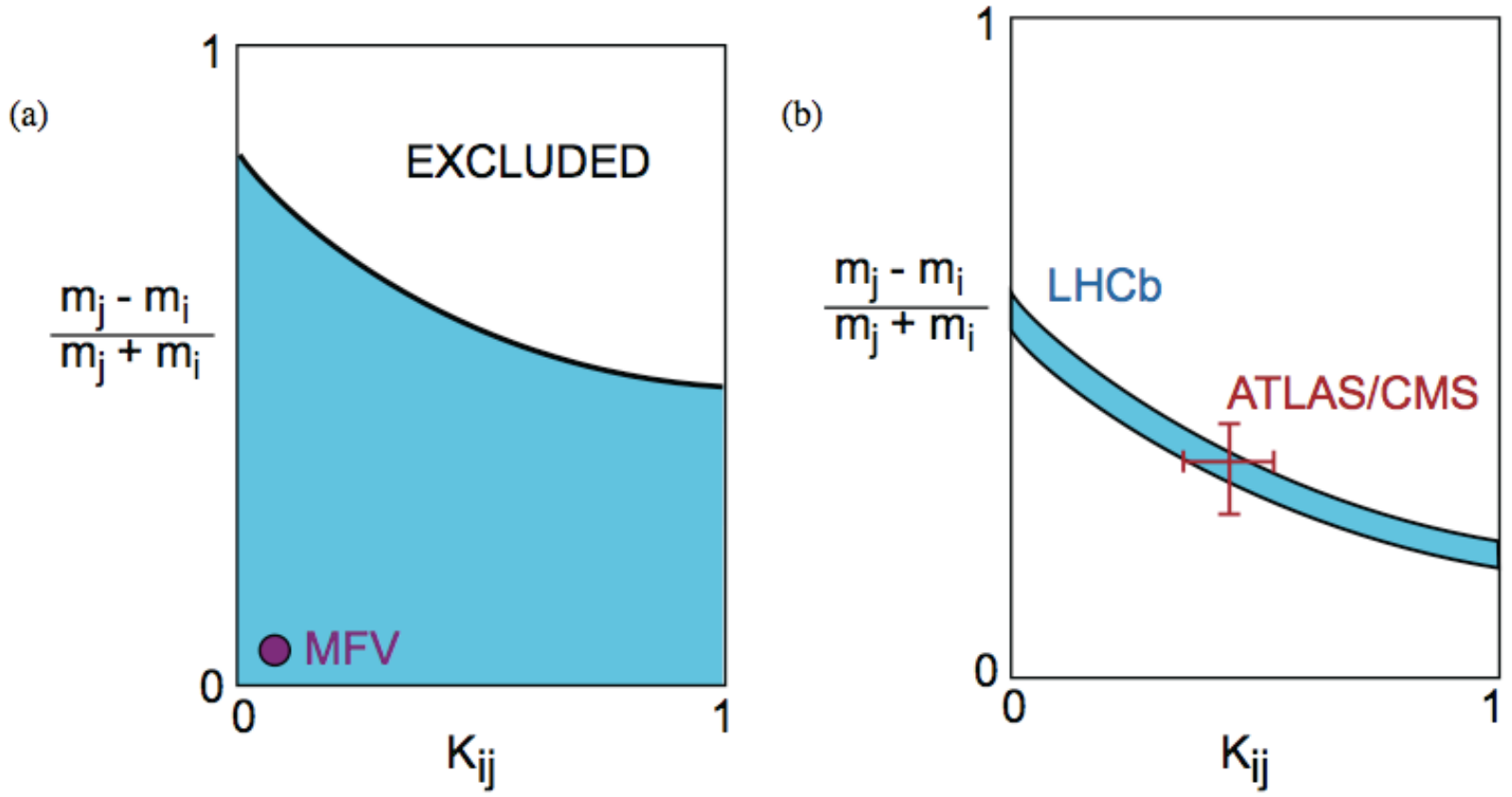
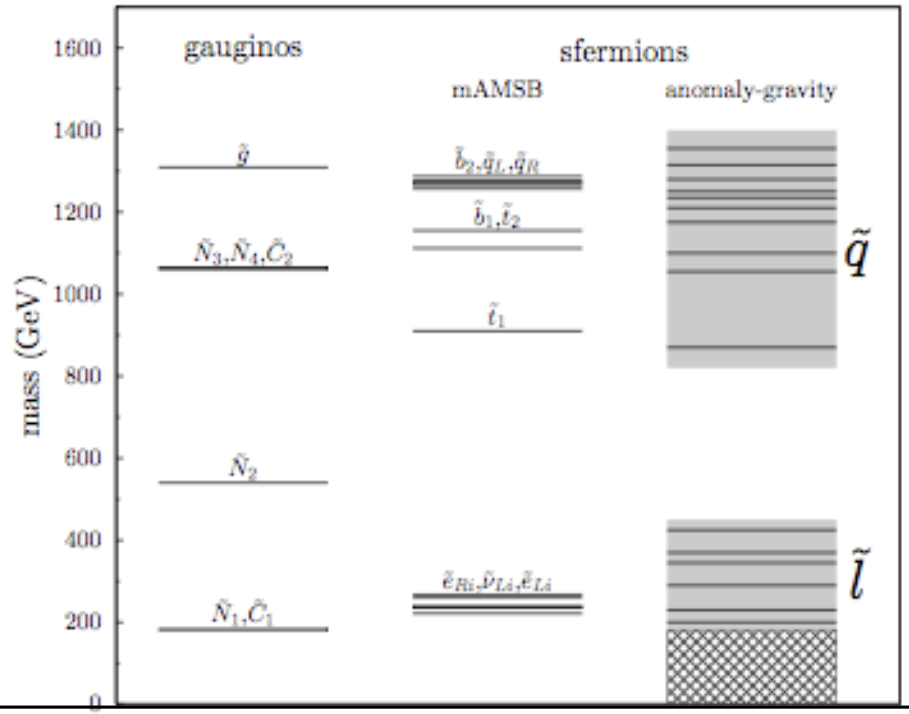


fig from Y.Nir 1010.2666 [hep-ph]

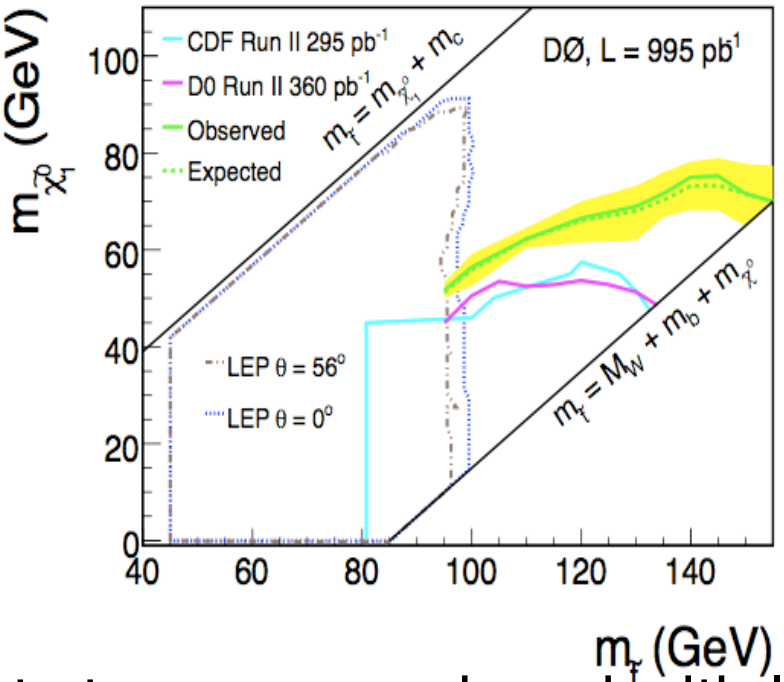
Measuring the mass splitting Δm_{ij}:

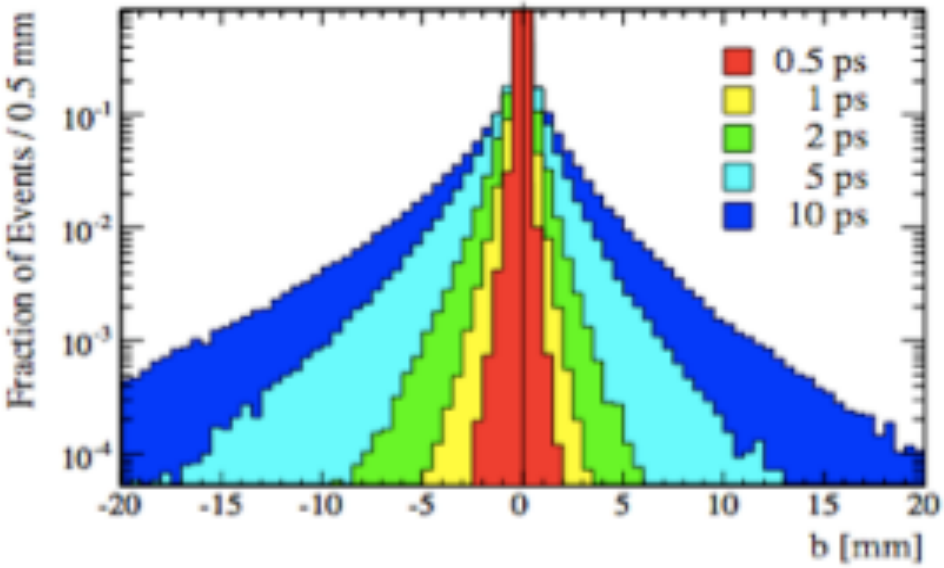
in cascades $\chi_2^0 \to \chi_1^0 l^+ l^-$ and comparing e^+e^- with $\mu^+\mu^-$ edges Allanach et al 0801.3666 [hep-ph] mSUGRA/CMSSM: splitting percent-permille; Hybrid anomaly-gravity: $O(1)$ slepton splitting, uses alignement to escape FCNC bounds C.Gross and GH, 1101.5352 [hep-ph]



Measuring the flavor mixing K_{ij}: from decay length measurements with long lived stop decaying predominantly FCNC $\tilde{t} \to c\chi_1^0$

left: 0803.2263 [hep-ex], right: GH, JS.Kim, H.Sedello 0910.2124 [hep-ph]





Light stops are produced with low BGD in association with like-sign tops $pp \to \tilde{t}^*\tilde{t}^*tt, \tilde{t}\tilde{t}\overline{tt}$ Kraml, Raklev '05

Up to 10 events with 1 fb^{-1} (no detector effects, 14TeV).

$$
\begin{aligned}
Y_u &\sim \begin{pmatrix} 10^{-5} & -0.002 & 0.008 + i\,0.003 \\ 10^{-6} & 0.007 & -0.04 \\ 10^{-8} + i\,10^{-7} & 0.0003 & 0.94 \end{pmatrix} \\
Y_d &\sim \mathrm{diag}\left(10^{-5}, 5 \cdot 10^{-4}, 0.025\right) \quad (\cdot \frac{\langle H_u \rangle}{\langle H_d \rangle}) \\
Y_e &\sim \mathrm{diag}\left(10^{-6}, 6 \cdot 10^{-4}, 0.01\right) \quad (\cdot \frac{\langle H_u \rangle}{\langle H_d \rangle})
\end{aligned}
$$

Very peculiar pattern.

$Y_u Y_u^\dagger$, $Y_u^\dagger Y_u$, $Y_d Y_d^\dagger$,.... (SM flavor)

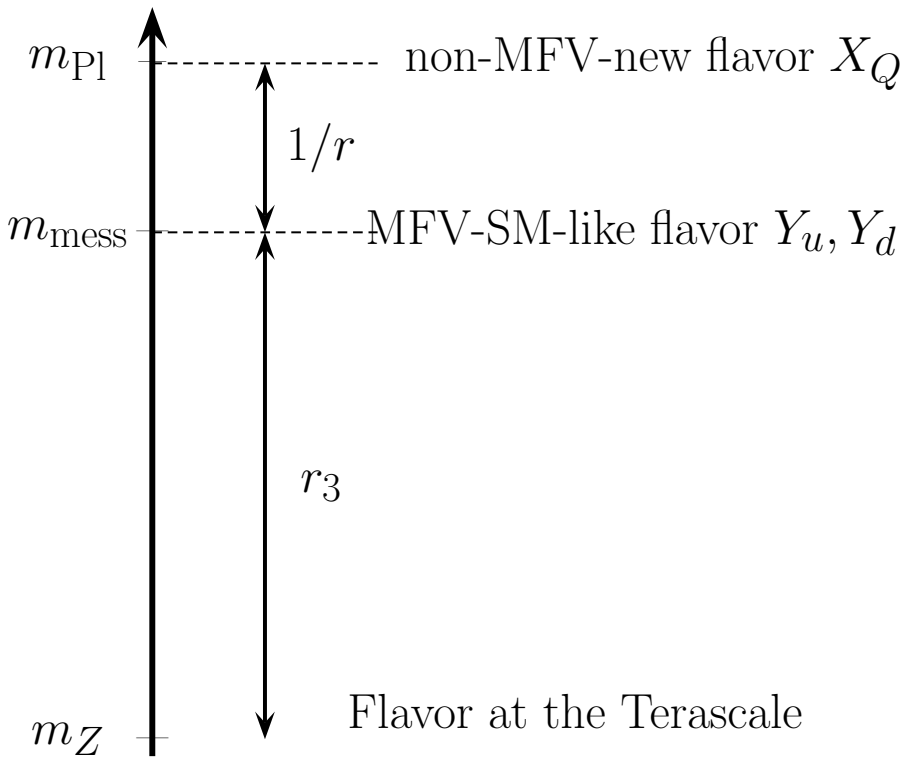
squark mass terms $\mathcal{L} = \tilde{Q}^\dagger_{L\,i} (M^2_{\tilde{Q}_L})_{ij} \tilde{Q}_{L\,j} + \ldots$ (sflavor)

Could have common origin, e.g. Froggatt-Nielsen symmetries:

$$(Y_u)_{ij} \sim \epsilon^{Z_{uj} - Z_{qi}} \ , \qquad (M^2_{\tilde{Q}_L})_{ij} \sim \epsilon^{Z_{qj} - Z_{qi}}$$

or not, as in anarchy scenarios $(M^2_{\tilde{Q}_L})_{ij} \sim O(1)$.

Hybrid Gauge-Gravity Mediation



$$M^2_{\tilde{Q}_L}(m_Z) \sim \tilde{m}^2_{Q_L} \cdot (\underbrace{r_3 \mathbf{1} + c_u Y_u Y_u^\dagger + c_d Y_d Y_d^\dagger}_{SM-like flavor} + \underbrace{r X_{Q_L}}_{BSM flavor})$$

flavor observables probe off-diagonals: $\sim r/r_3 X_{Q_L}$.

observable signatures+ experimental program GH,Hochberg,Nir 0812.0511, 1001.1513

Summary

* The Standard Model is a good description of microscopic processes up to energies of $\mathcal{O}(100)$ GeV.
* The forthcoming seaches at LHC and precision experiments will explore the Terascale. What are the flavor quantum numbers of new particles/SM partners ?
* Exisiting FCNC-data imply already strong constraints on the flavor structure of physics beyond the SM. These bounds will be tightened significantly.
* The observation of New Physics flavor couplings could point towards the origin of generational mixing and hierarchies, i.e., flavor.

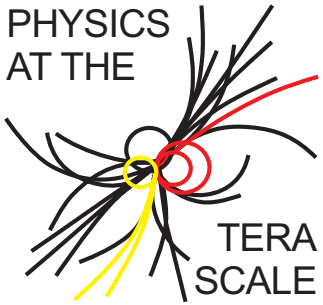
Thanks for Support to

Christoph Bobeth, Christian Gross, Yonit Hochberg, Yossi Nir, Danny van Dyk, Jong Soo Kim, Henning Sedello

bmb+f - Förderschwerpunkt

Elementarteilchenphysik

Großgeräte der physikalischen Grundlagenforschung



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