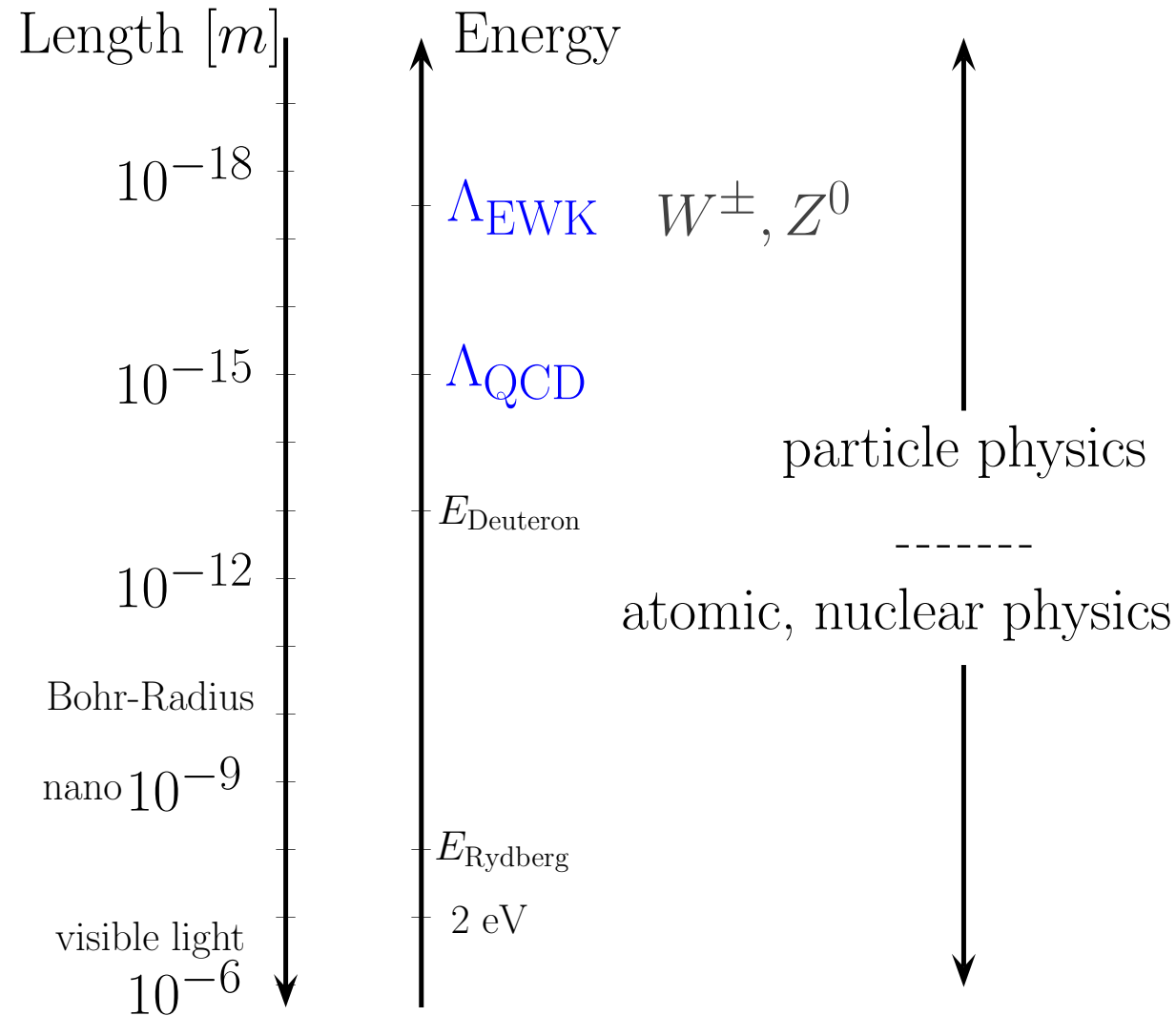
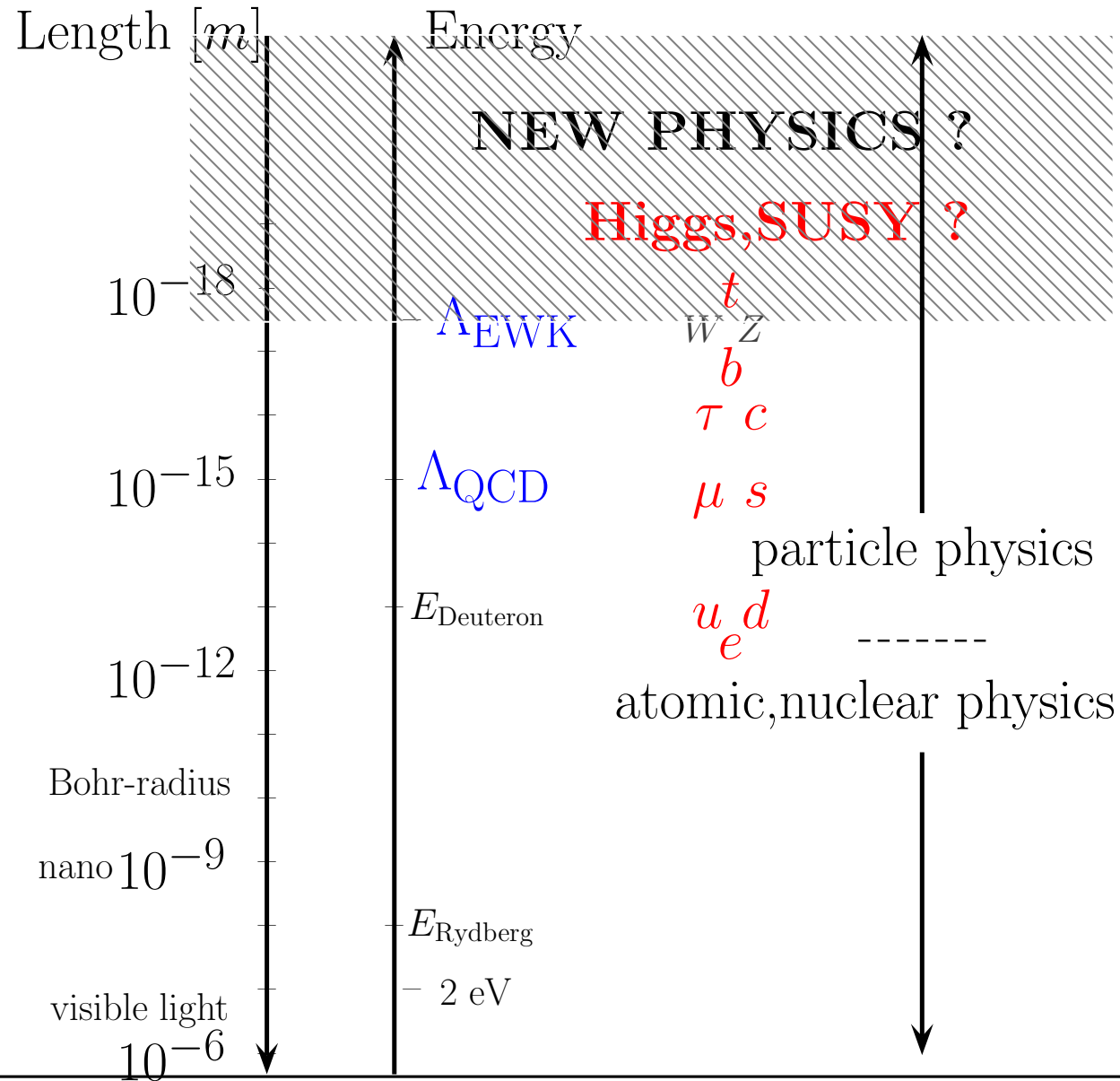


FLAVOR **at the TERASCALE**

Gudrun Hiller, Dortmund

Particle Physics Scales





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

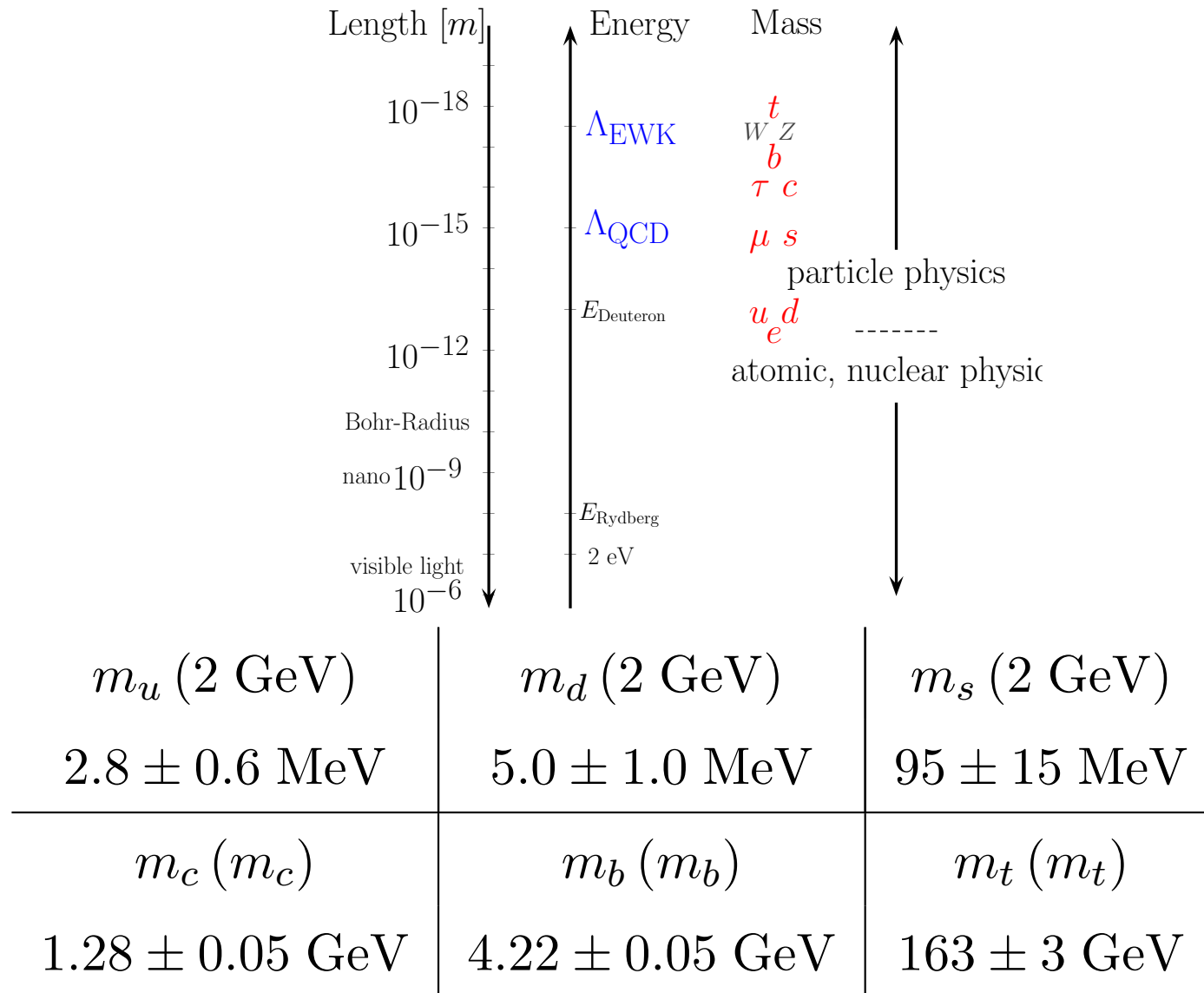
quarks: $\begin{pmatrix} u \\ d \end{pmatrix}, \begin{pmatrix} c \\ s \end{pmatrix}, \begin{pmatrix} t \\ b \end{pmatrix}$

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

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

The gauge interactions are generation independent.

Quark Spectrum



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: University 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

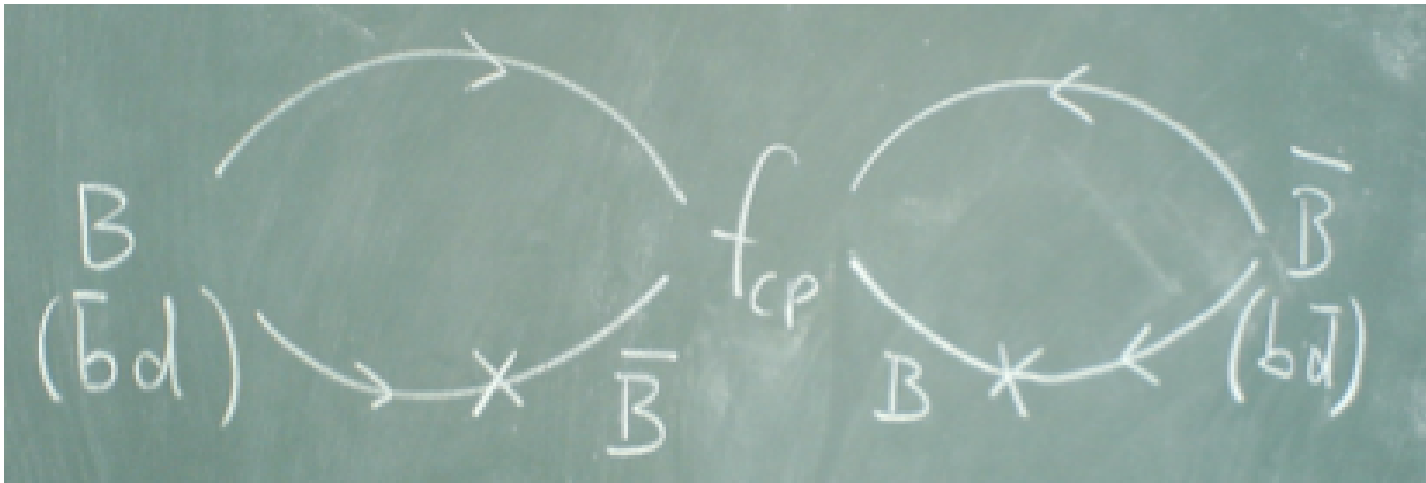
Kobayashi and Maskawa, Prog.Theor.Phys 49 (1973) 652

CP is violated!.. together with Quark Flavor

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

Verified in $B\bar{B}$ mixing

$$\sin 2\beta = 0.672 \pm 0.023 \quad \text{HFAG Aug 2010}$$



δ_{CKM} is large, $O(1)$!

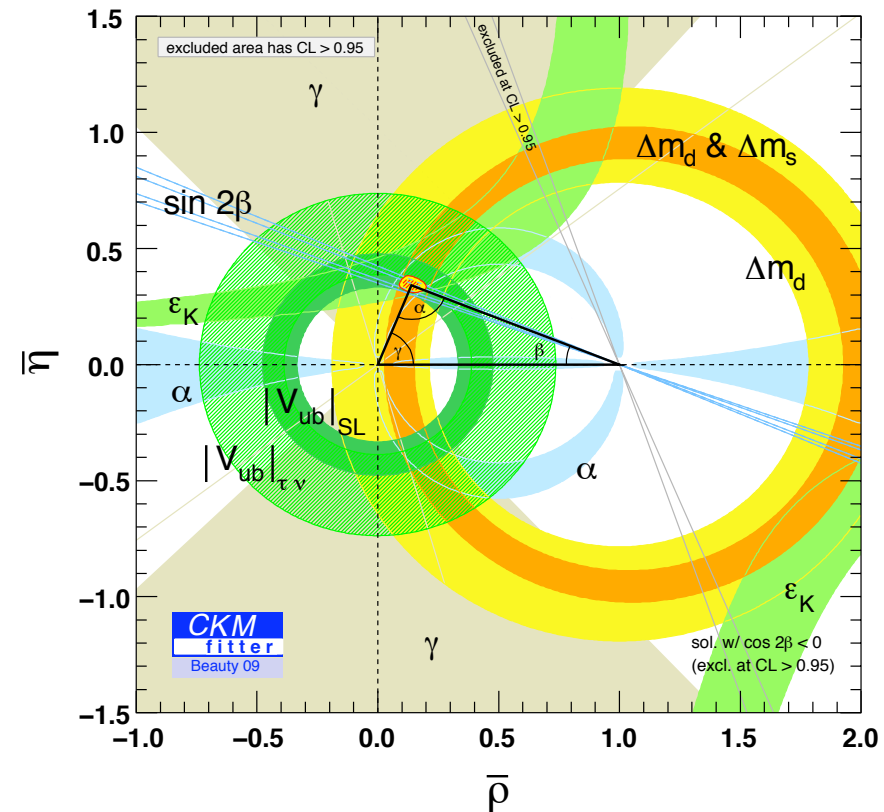
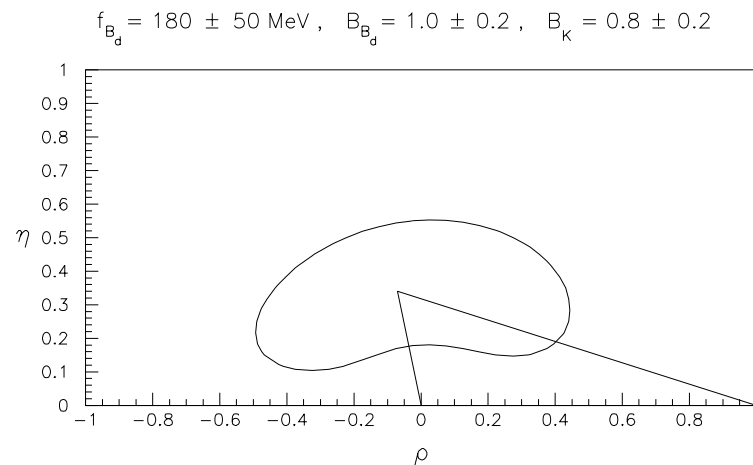
CP violation also observed in B -decay

$$A_{CP}(B \rightarrow K^{\pm}\pi^{\mp}) = -0.098 \pm 0.013$$

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

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):

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

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

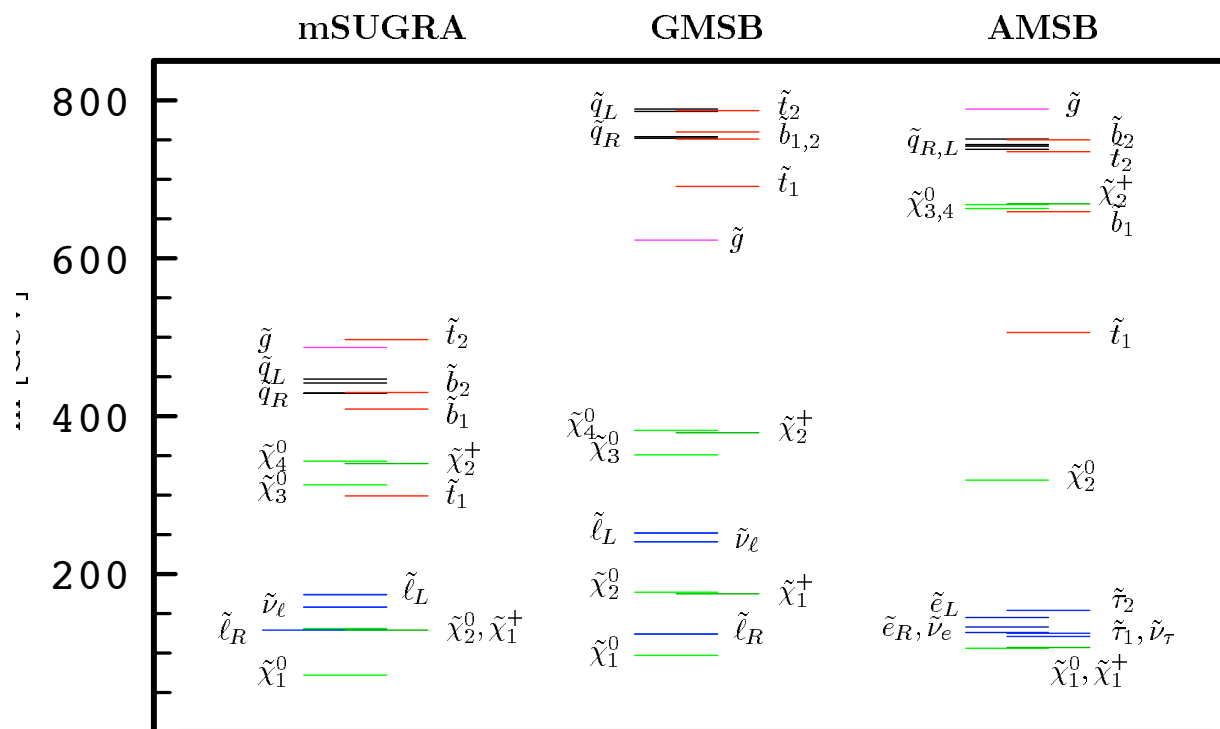
$$b \rightarrow d: B^0 - \bar{B}^0, B \rightarrow \rho \gamma, b \rightarrow d \gamma \text{ (} B \rightarrow \pi l l \text{ close)}$$

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

$$t \rightarrow c, u \text{ and } l \rightarrow l': \text{ not observed}$$

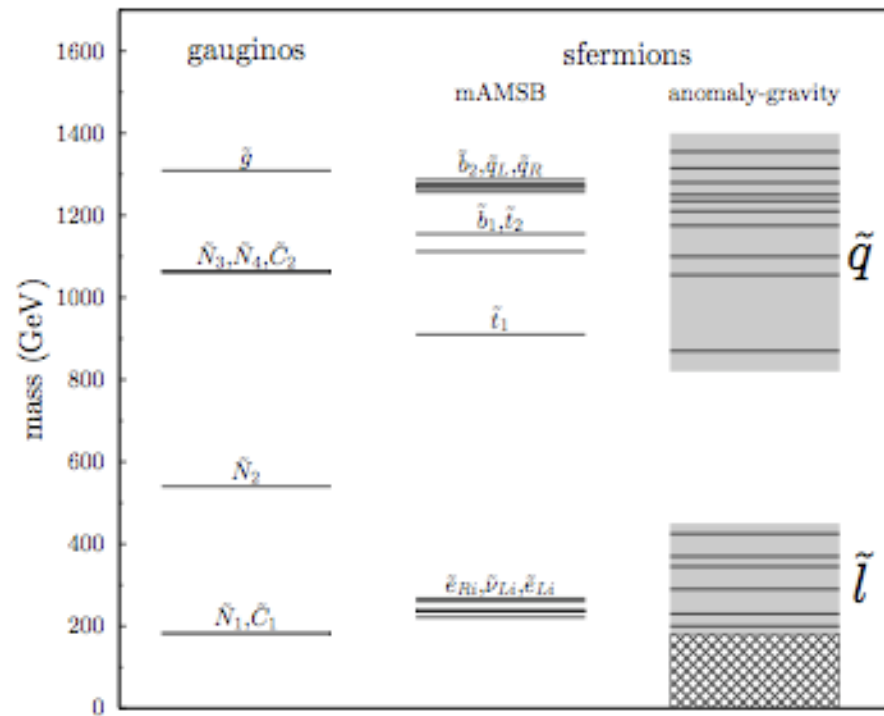
New TeV-sector; whats the flavor of the SM partners?

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



TESLA TDR Part III '01

or with large splitting?

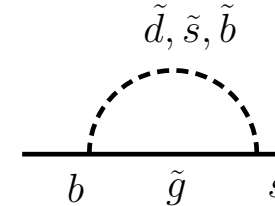
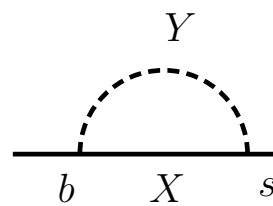
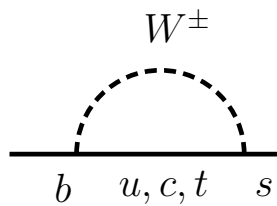


C.Gross and GH, 1101.5352 [hep-ph]

and how about flavor mixing and CP violation?

Terascale Flavor facing today's FCNC Data

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



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

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

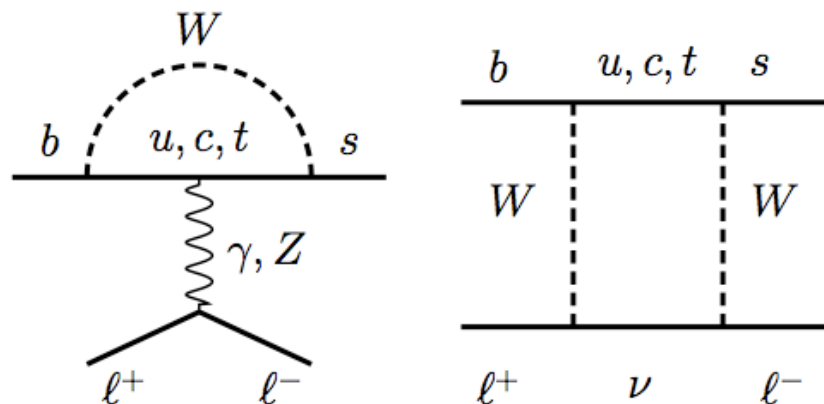
Bona et al, 0707.0636 [hep-ph]

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

FCNC loops probe product of mixing and splitting

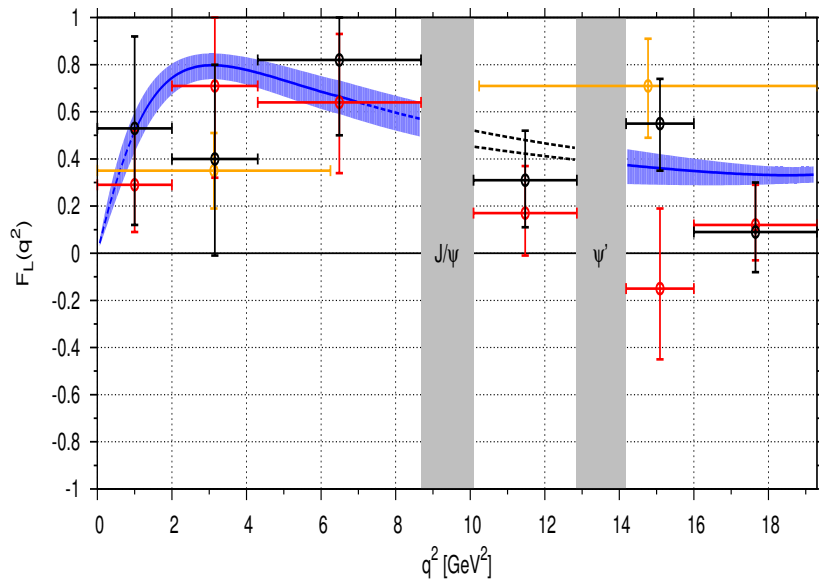
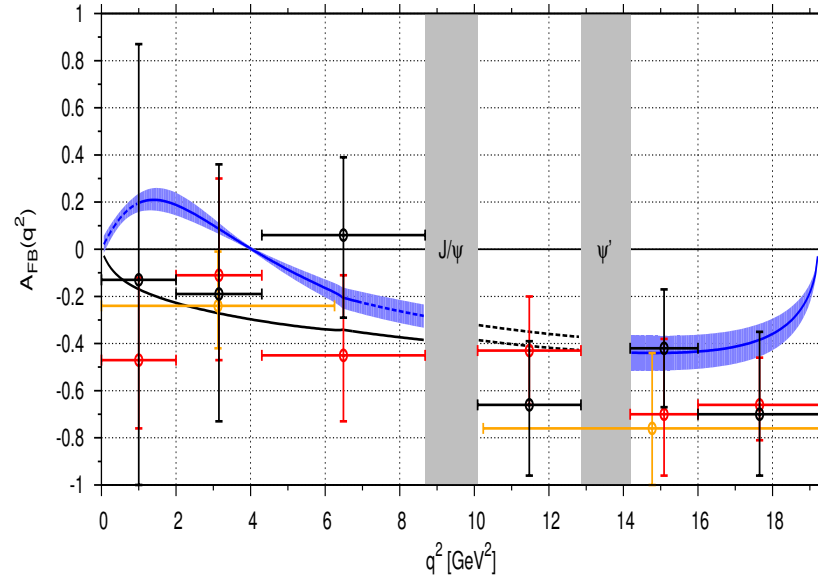
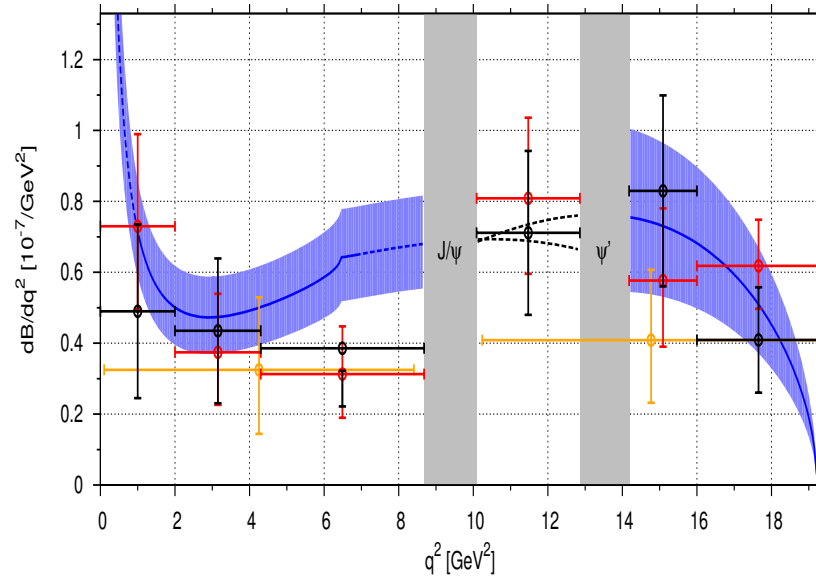
$$\mathcal{A}_{FCNC} \sim \underbrace{V_{ij}V_{kj}^*}_{\text{mixing}} \cdot \underbrace{\Delta m_{ik}^2}_{\text{splitting}(GIM)} \cdot \underbrace{(1/\Lambda_{NP})^n}_{\text{decoupling}}$$

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



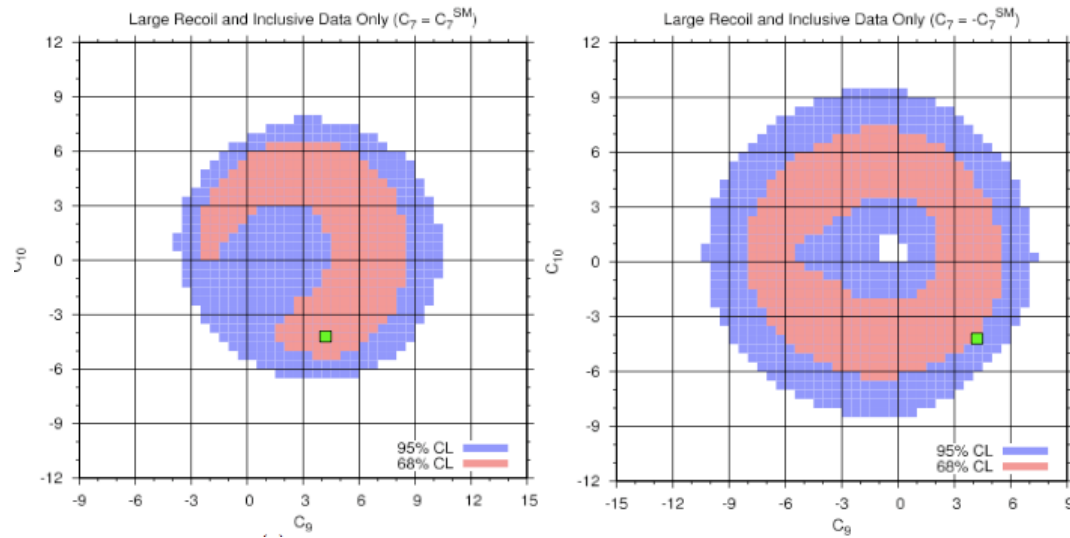
(Analysis workshop on this at DESY HH June 15-17, 2011)

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

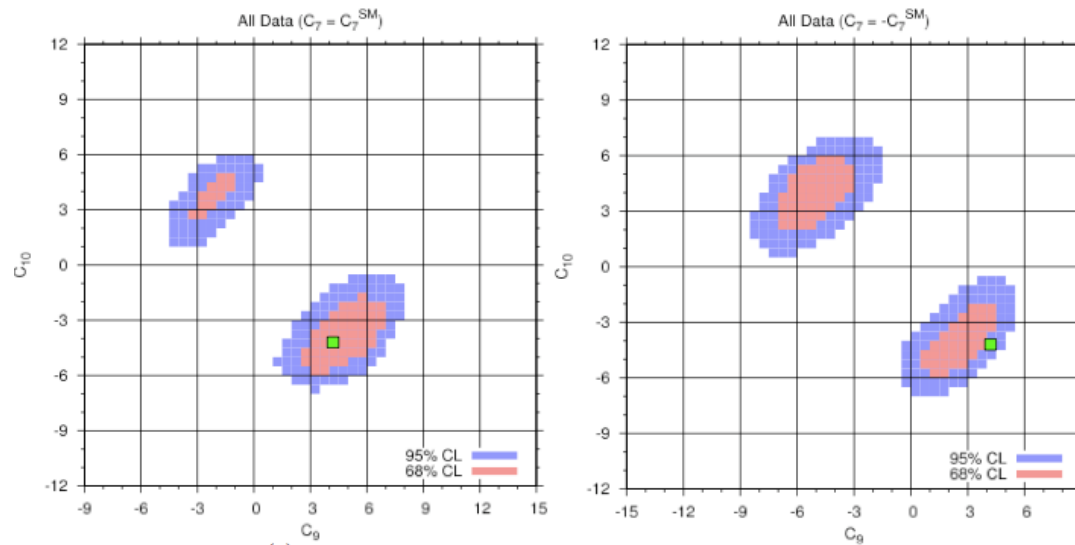


black: CDF'10 4.4fb^{-1} , gold: BaBar'08, red: Belle'09; blue: SM; $q^2 = m_{ll}^2$

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



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



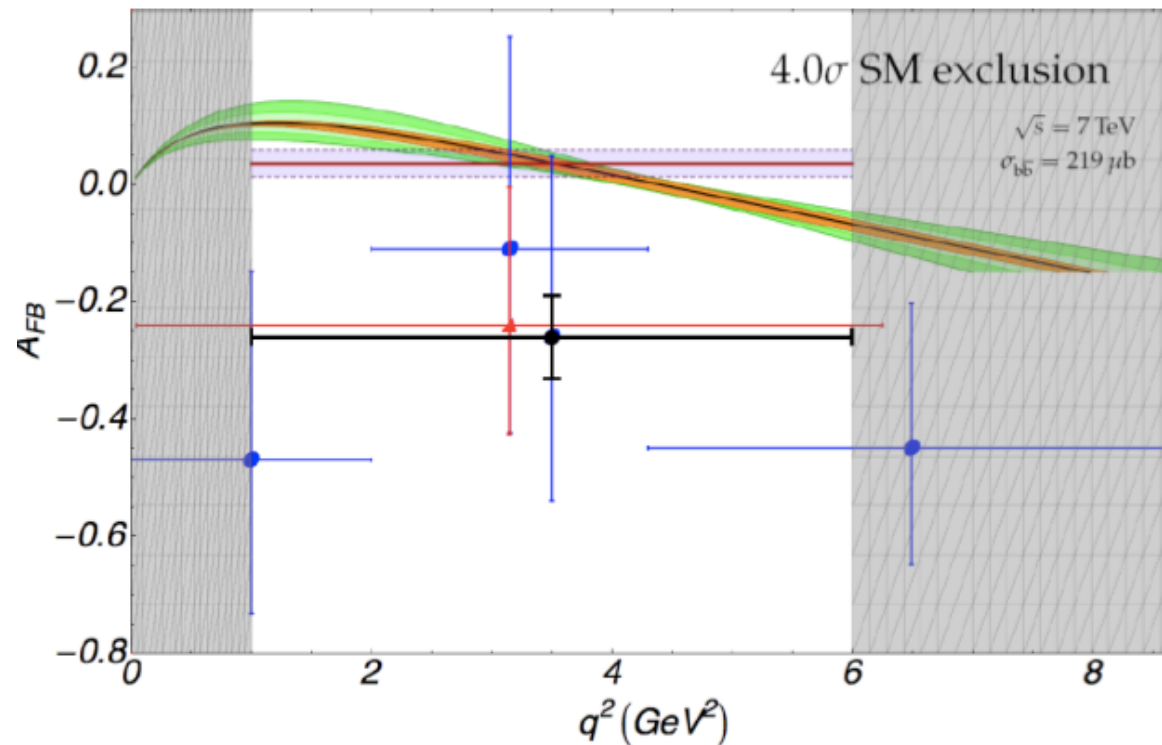
green box: SM value for (C_9, C_{10})

Forward Backward Asymmetry -LHCb Prospects



$$B_d \rightarrow K^* \mu \mu$$

- Prospects at LHCb: if we consider **most sensitive bin** ($1 < q^2 < 6 \text{ GeV}^2$), 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)

Collider-Precision Complementarity

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

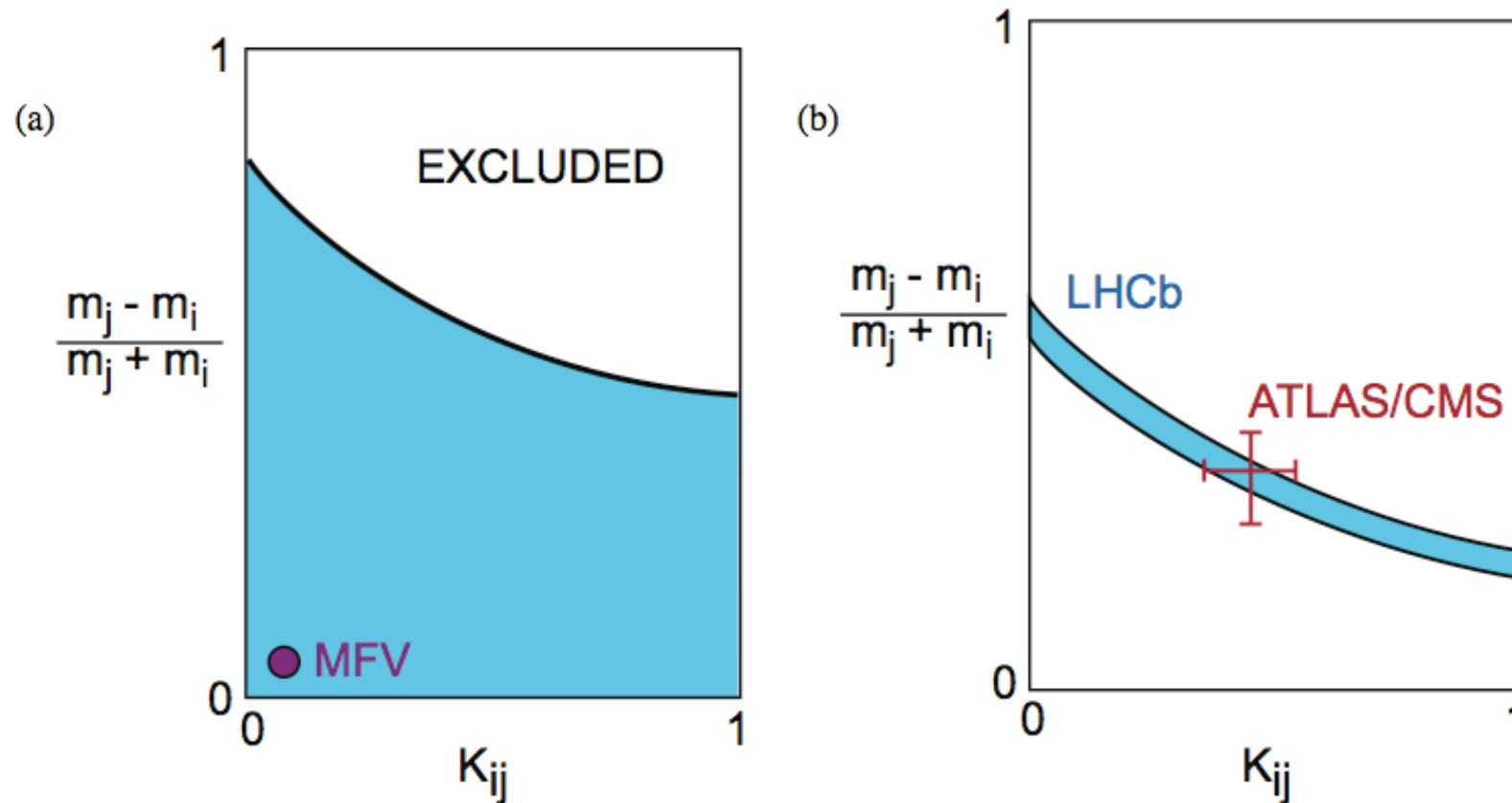
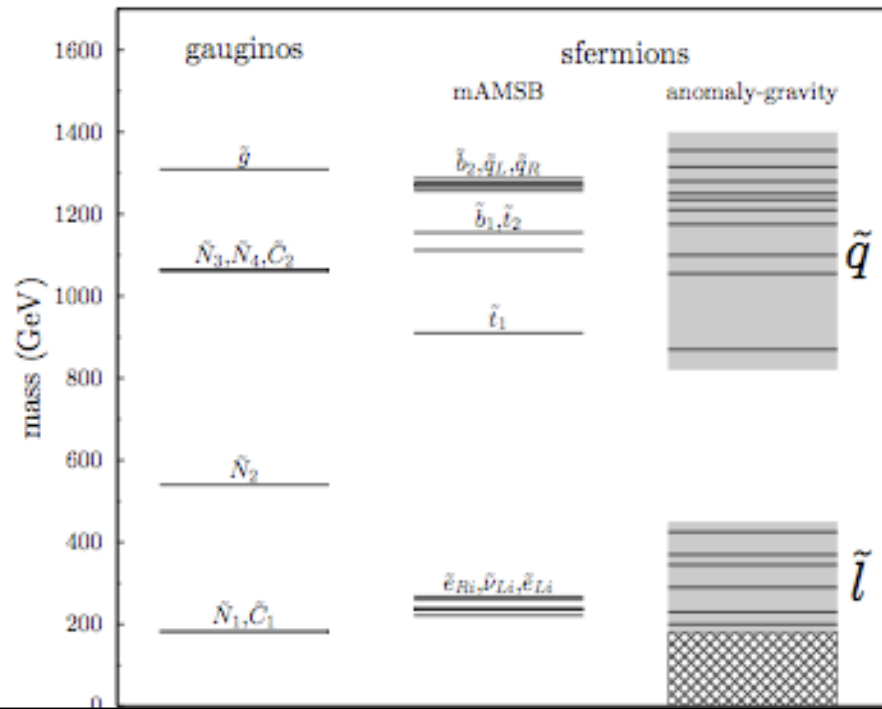


fig from Y.Nir 1010.2666 [hep-ph]

Collider-Flavor Physics (Examples)

Measuring the mass splitting Δm_{ij} :

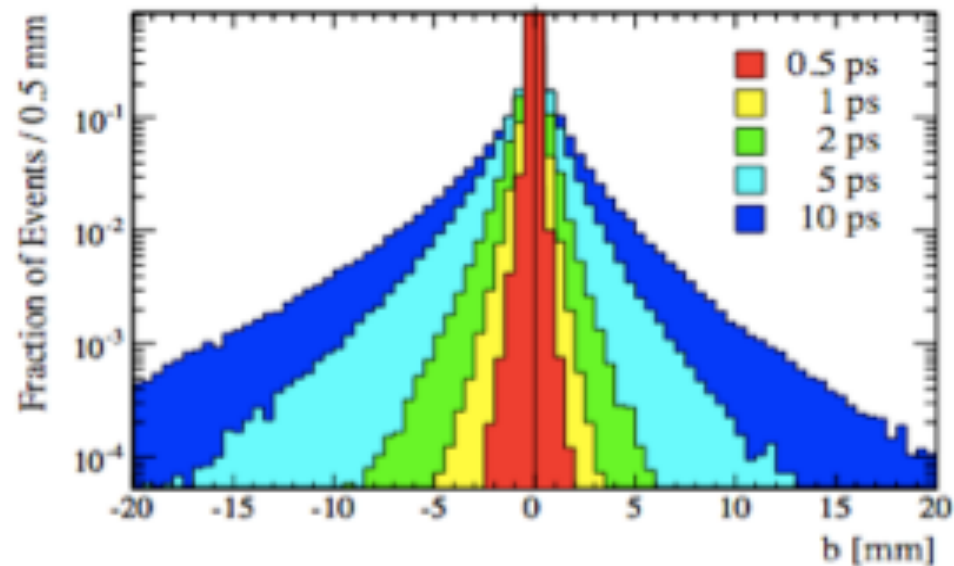
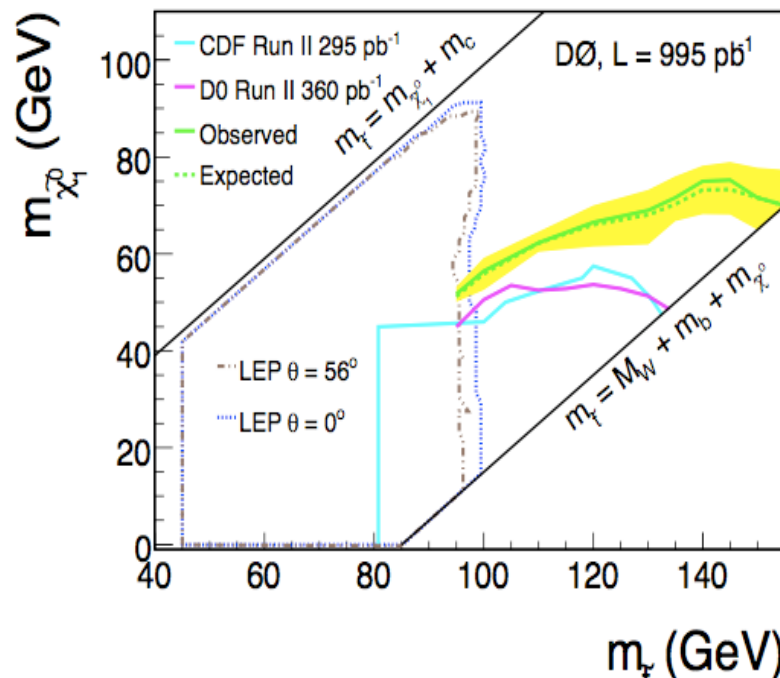
in cascades $\chi_2^0 \rightarrow \chi_1^0 l^+ l^-$ and comparing $e^+ e^-$ with $\mu^+ \mu^-$ edges [Allanach et al 0801.3666 \[hep-ph\]](#) mSUGRA/CMSSM: splitting percent-permille; Hybrid anomaly-gravity: $O(1)$ slepton splitting, uses alignment to escape FCNC bounds [C.Gross and GH, 1101.5352 \[hep-ph\]](#)



Collider-Flavor Physics (Examples)

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

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 $pp \rightarrow \tilde{t}^* \tilde{t}^* tt, \tilde{t} \tilde{t} \tilde{t} \tilde{t}$ Kraml, Raklev '05

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

$$Y_u \sim \begin{pmatrix} 10^{-5} & -0.002 & 0.008 + i 0.003 \\ 10^{-6} & 0.007 & -0.04 \\ 10^{-8} + i 10^{-7} & 0.0003 & 0.94 \end{pmatrix}$$

$$Y_d \sim \text{diag} (10^{-5}, 5 \cdot 10^{-4}, 0.025) \left(\cdot \frac{\langle H_u \rangle}{\langle H_d \rangle} \right)$$

$$Y_e \sim \text{diag} (10^{-6}, 6 \cdot 10^{-4}, 0.01) \left(\cdot \frac{\langle H_u \rangle}{\langle H_d \rangle} \right)$$

Very peculiar pattern.

$$Y_u Y_u^\dagger, Y_u^\dagger Y_u, Y_d Y_d^\dagger, \dots \text{ (SM flavor)}$$

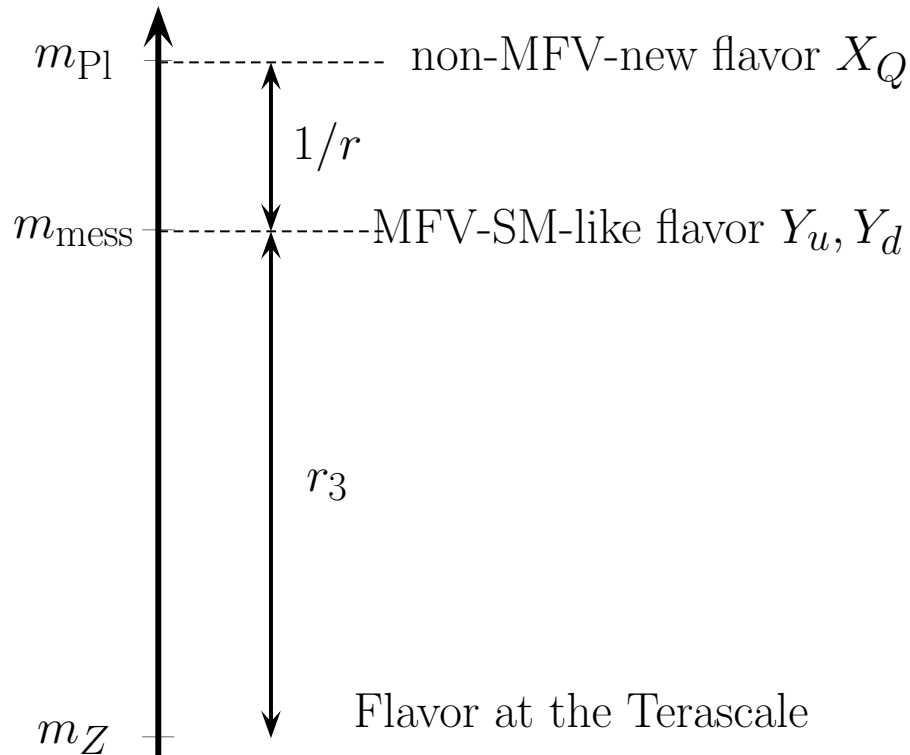
$$\text{squark mass terms } \mathcal{L} = \tilde{Q}_{Li}^\dagger (M_{\tilde{Q}_L}^2)_{ij} \tilde{Q}_{Lj} + \dots \text{ (sflavor)}$$

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

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

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

Hybrid Gauge-Gravity Mediation



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

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

observable signatures + experimental program [GH,Hochberg,Nir 0812.0511, 1001.1513](#)

- * 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.

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



bmb+f - Förderschwerpunkt

Elementarteilchenphysik

Großgeräte der physikalischen
Grundlagenforschung

