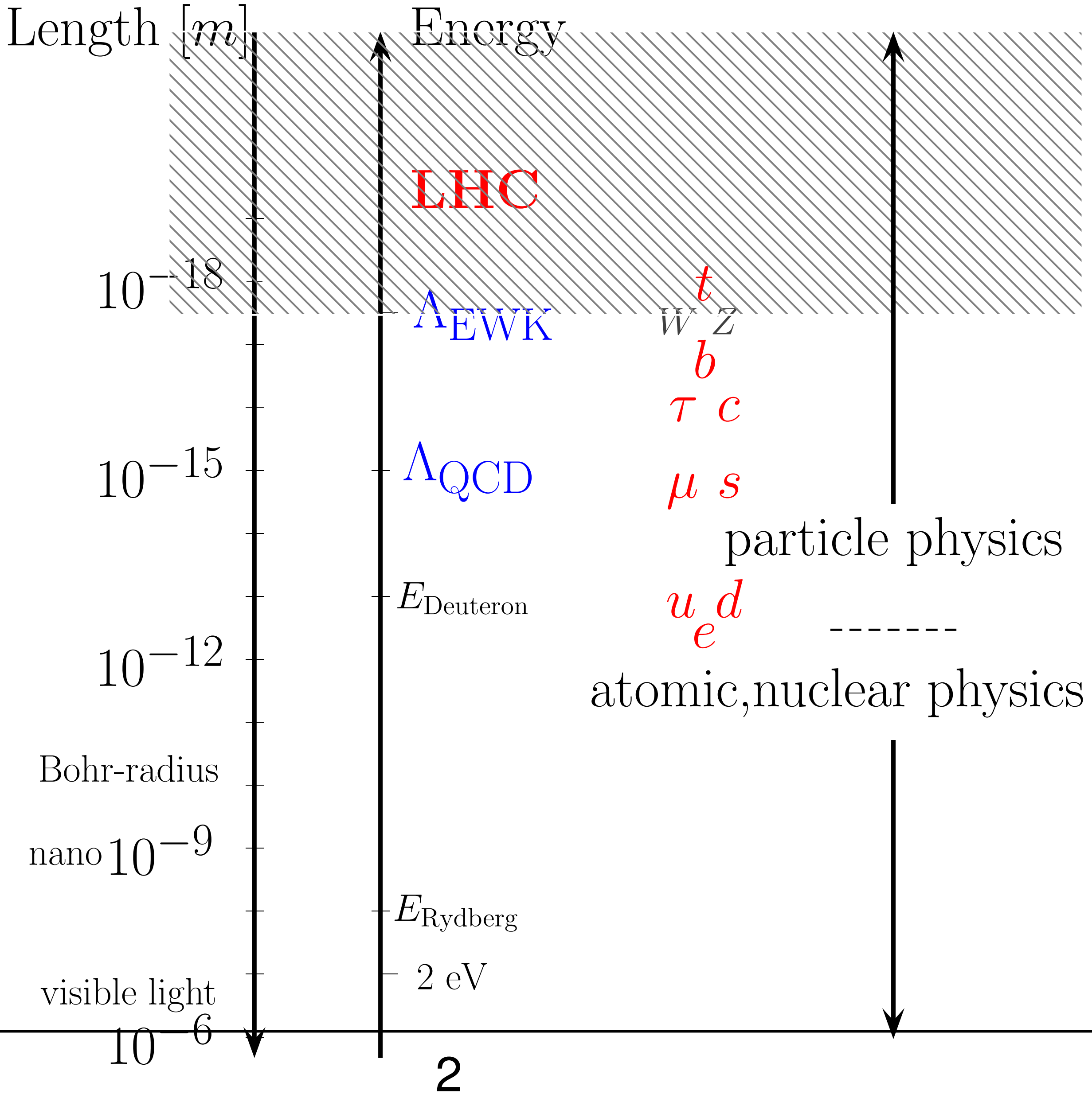
Flavor Theory and $B \to K^{(*)} \mu^+ \mu^-$ Implications

May 14, 2012

Gudrun Hiller, Dortmund

Particle Physics Scales & the LHC



The Flavor of Matter

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

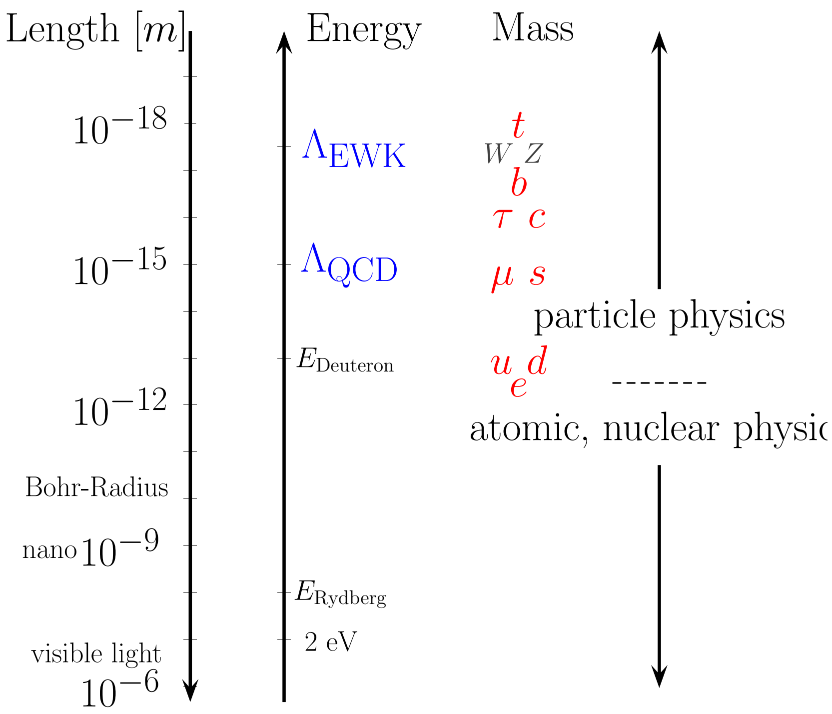
quarks: $\begin{pmatrix} u \\ d \end{pmatrix}, \begin{pmatrix} c \\ s \end{pmatrix}, \begin{pmatrix} t \\ b \end{pmatrix}$

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



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

hierarchical! Spectrum spans five orders of magnitude.

Flavor Mixing

Quarks mix and change flavor in weak interaction:

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

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

hierarchical!

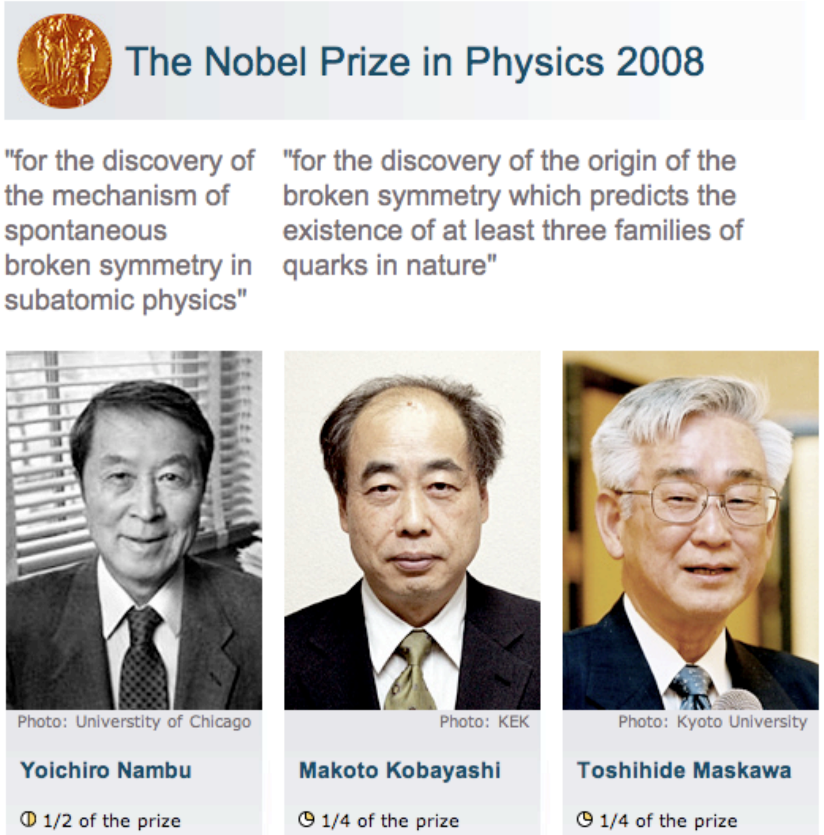
Large mixing angles for leptons (PMNS-Matrix):

$\vartheta_{23} \sim 45^\circ$, $\vartheta_{12} \sim 35^\circ$, $\vartheta_{13} \sim O(10^\circ)$ all O(1) – anarchy?

CP is violated!.. together with Quark Flavor

Quark mixing matrix has 1 physical CP violating phase δ_{CKM}.

(with 3 generations)



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

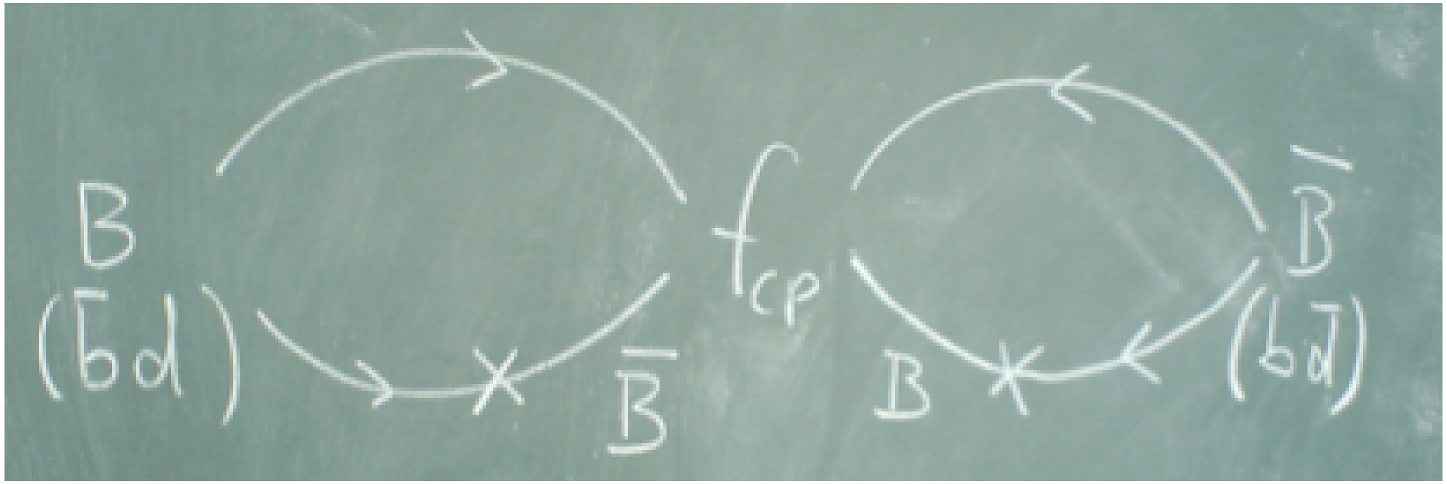
◔ 1/4 of the prize

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

CP is violated!.. together with Quark Flavor

Quark mixing matrix has 1 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, $O(1)$!

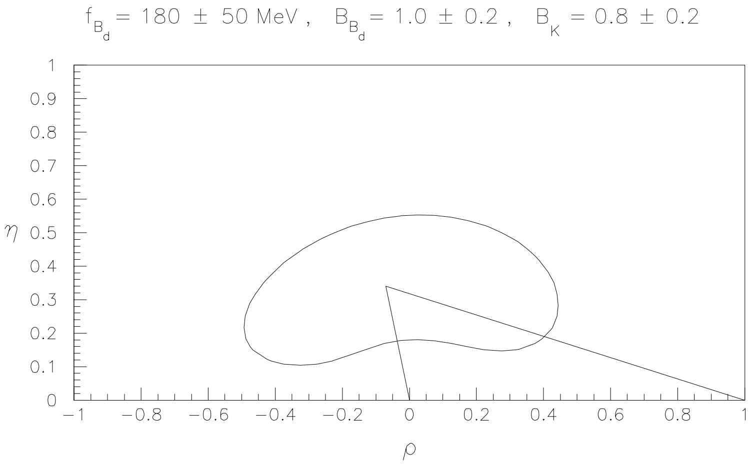
CPX also observed in B-decay $A_{CP}(B \to K^{\pm}\pi^{\mp}) = -0.098 \pm 0.013$

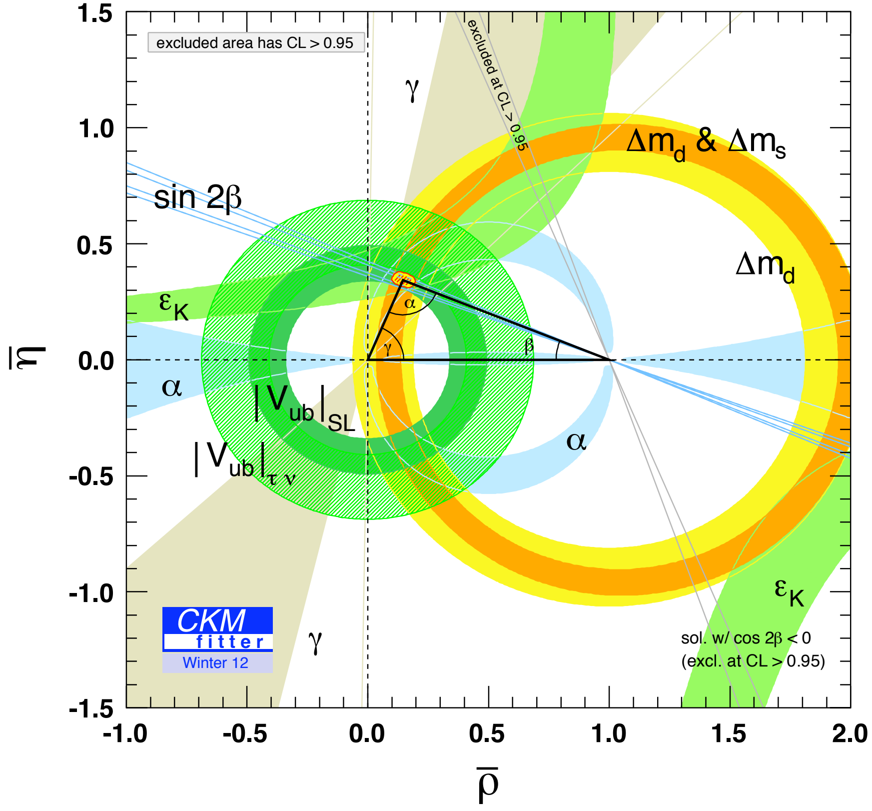
HFAG Aug 2010

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

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.





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

Rare Processes observed Today

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

Flavor changing neutral currents (FCNCs):

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

$c \longrightarrow u$: $D^0 - \bar{D}^0$ (first data on FCNC in up-sector)
dir. CPX CDF,LHCb’11,12

$b \longrightarrow d$: $B^0 - \bar{B}^0$, $B \longrightarrow \rho\gamma$, $b \longrightarrow d\gamma$, $B \longrightarrow \pi\mu\mu$ LHCb’12

$b \longrightarrow s$: $B_s - \bar{B}_s$, $b \longrightarrow s\gamma$, $B \longrightarrow K_s\pi^0\gamma$, $b \longrightarrow sll$, $B \longrightarrow K^{(*)}ll$ (precision, angular observables avaliable Belle’09,CDF’11,BaBar,LHCb’12),
$B_s \longrightarrow \mu\mu$ (bound at SM-level $< 4.5 \times 10^{-9}$ 95 %CL LHCb’12)

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

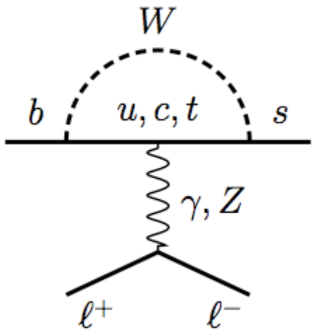
Plan

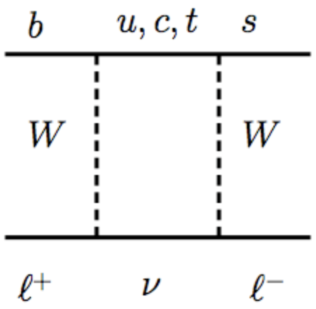
Precision tests of the SM with $O(1000)$ plus events in $B \rightarrow K^{(*)}\mu^+\mu^-$

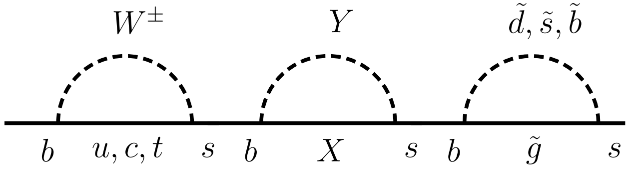
- – a lattice benchmark test opportunity
- – BSM/SUSY implications

Exclusive semileptonic FCNC $b \to s\mu^+\mu^-$ decays

$Br_{\rm SM} \sim 10^{-6} - 10^{-7}$







observed (at SM level):

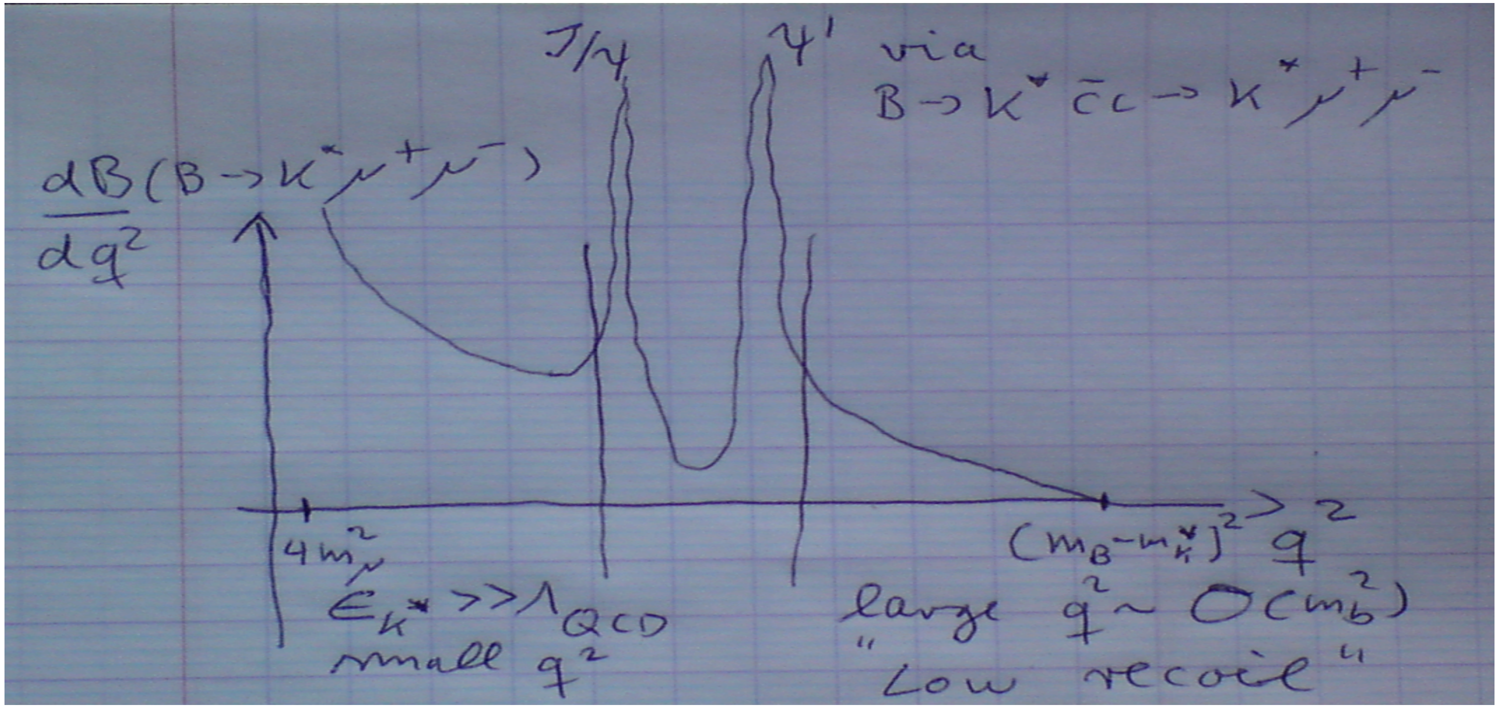
$B \to K^{(*)}\mu^+\mu^-$ BaBar, Belle, CDF 6.8 fb^{-1} and LHCb 1 fb^{-1} LHCb-CONF-2012-008

$B_s \to \Phi\mu^+\mu^-$ CDF 2011 1101.1028 [hep-ex] LHCb 2012 LHCb-CONF-2012-008

$\Lambda_b \to \Lambda\mu^+\mu^-$ CDF 2011 1107.3753 [hep-ex]

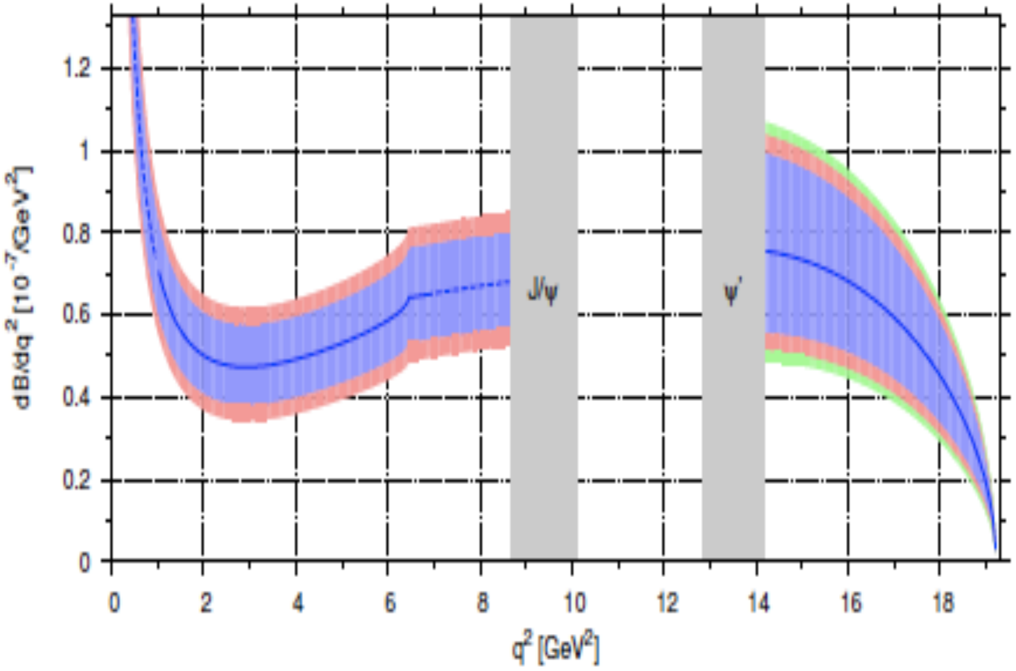
distributions measured. precision physics started.

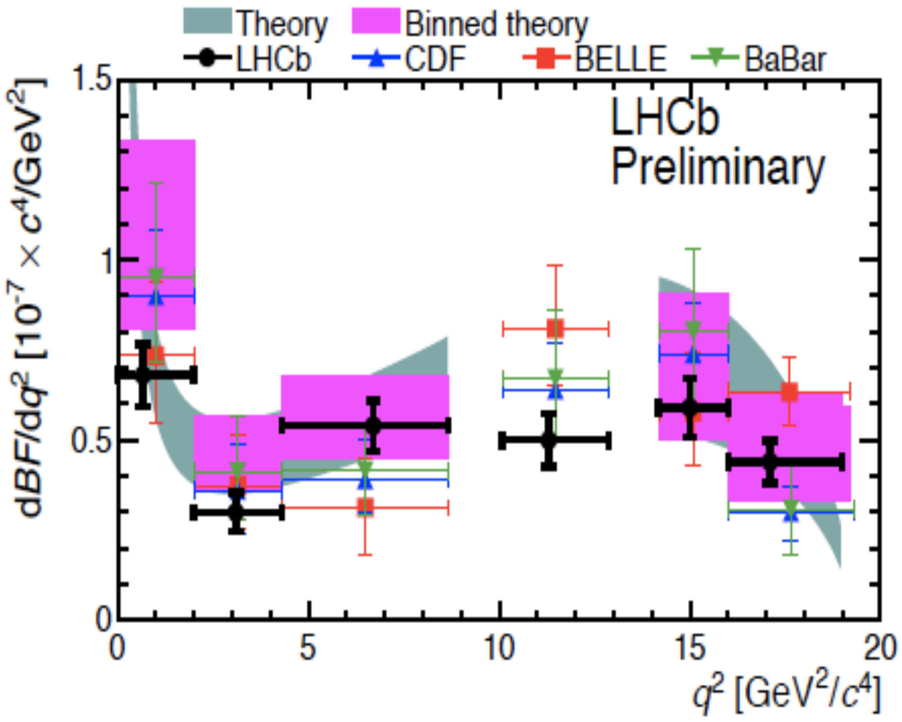
Dilepton Mass Spectra in $B \to K^* \mu^+ \mu^-$



Different TH at low q^2 QCDF; BBNS, Beneke, Feldmann, Seidel'01,04 and high q^2/low recoil OPE in $1/m_b$ Grinstein,Pirjol '04, Beylich, Buchalla,Feldmann'11; Low recoil $B \to K^{(*)} \mu^+ \mu^-$ predictions/pheno Bobeth,GH,vanDyk, Wacker '10,11 Binned data needed. New developments at low recoil in theory pheno+lattice greatly support exploitation of todays and tomorrows data. E.g., Preliminary unquenched lattice $B \to K^{(*)}$ form factors by Liu et al 1101.2726 [hep-ph].

Dilepton Mass Spectra in $B \to K^* \mu^+ \mu^-$





left-hand Fig. from 1006.5013 [hep-ph] Blue band: form factor uncertainties, red: $1/m_b$ right-hand Fig. from LHCb-CONF-2012-008

Biggest source of TH uncertainty: the $B \to K^*$ form factors.

Hadronic uncertainties $B \to K^*$ Form factors

$$\langle K^*(k,\epsilon)|\,\bar{s}\gamma_\mu b\,|B(p)\rangle = \frac{2\,V(q^2)}{m_B + m_{K^*}}\varepsilon_{\mu\rho\sigma\tau}\epsilon^{*\rho}p^\sigma k^\tau,$$

$$\langle K^*(k,\epsilon)|\,\bar{s}\gamma_\mu\gamma_5 b\,|B(p)\rangle =$$

$$i\epsilon^{*\rho}\left[2A_0(q^2)\,m_{K^*}\frac{q_\mu q_\rho}{q^2} + A_1(q^2)\,(m_B + m_{K^*})(g_{\mu\rho} - \frac{q_\mu q_\rho}{q^2})\right.$$

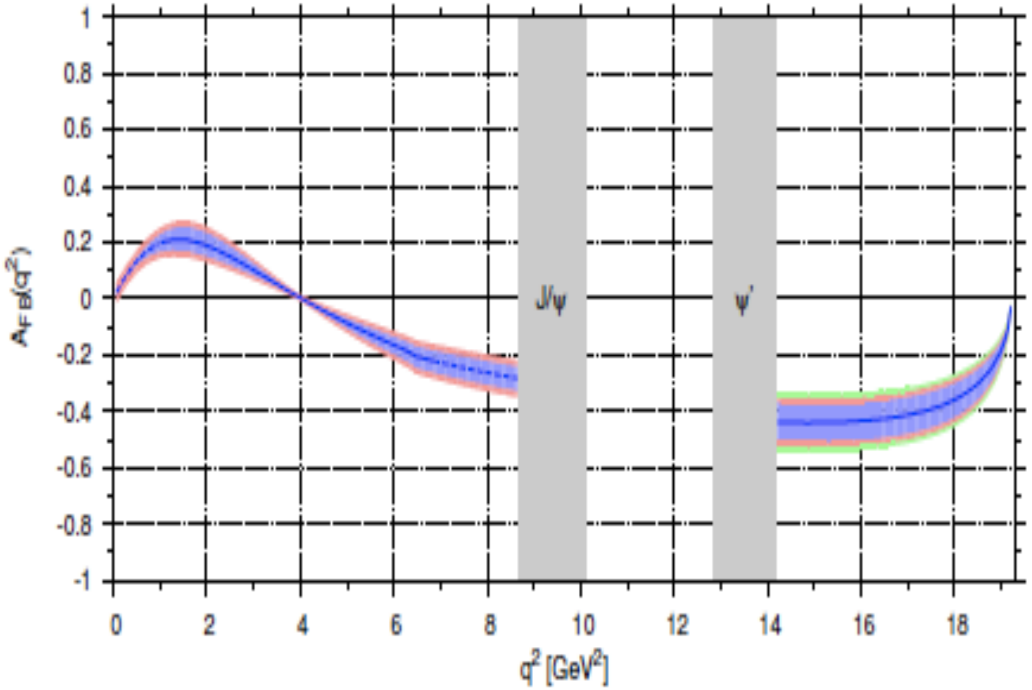
$$\left. -\ A_2(q^2)\,q_\rho\left(\frac{(p+k)_\mu}{m_B + m_{K^*}} - \frac{m_B - m_{K^*}}{q^2}(p-k)_\mu\right)\right]$$

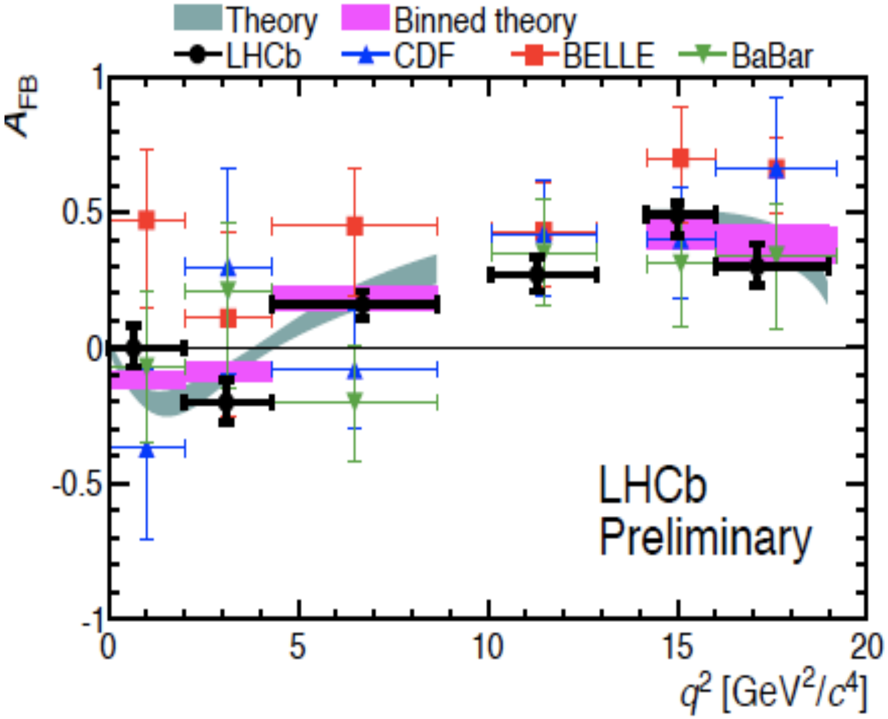
plus tensor currents $\langle K^*(k,\epsilon)|\,\bar{s}\sigma_{\mu\nu}b\,|B(p)\rangle$ with $T_{1,2,3}$.

Low recoil: improved isgur-wise relations, accessible to lattice QCD

$T_1(q^2) = \kappa\,V\,(q^2), T_2(q^2) = \kappa\,A_1(q^2), \kappa = 1 - 2\,\frac{\alpha_s}{3\pi}\ln\left(\frac{\mu}{m_b}\right) \simeq 1$

Forward-backward asymmetry A_{FB} in $B \to K^* \mu^+ \mu^-$





left-hand Fig. from 1006.5013 [hep-ph] Blue band: form factor uncertainties, red: $1/m_b$ right-hand Fig. from LHCb-CONF-2012-008

Sign of A_{FB} at large dilepton mass is SM-like. 0805.2525 [hep-ph]

Sign/zero of A_{FB} at low dilepton mass SM-like (LHCb'12)

$q_0^2|_{\mathrm{LHCb}} = 4.9^{+1.1}_{-1.3}$ GeV^2 in SM: $q_0^2|_{\mathrm{SM}} = 4.0 \pm 0.3$ GeV^2

Opportunity: Angular Analysis $B \to V(\to PP)\mu^+\mu^-$

$$d\Gamma^4 \sim J dq^2 d\cos\Theta_l d\cos\Theta_{K^*} d\Phi$$ hep-ph/9907386

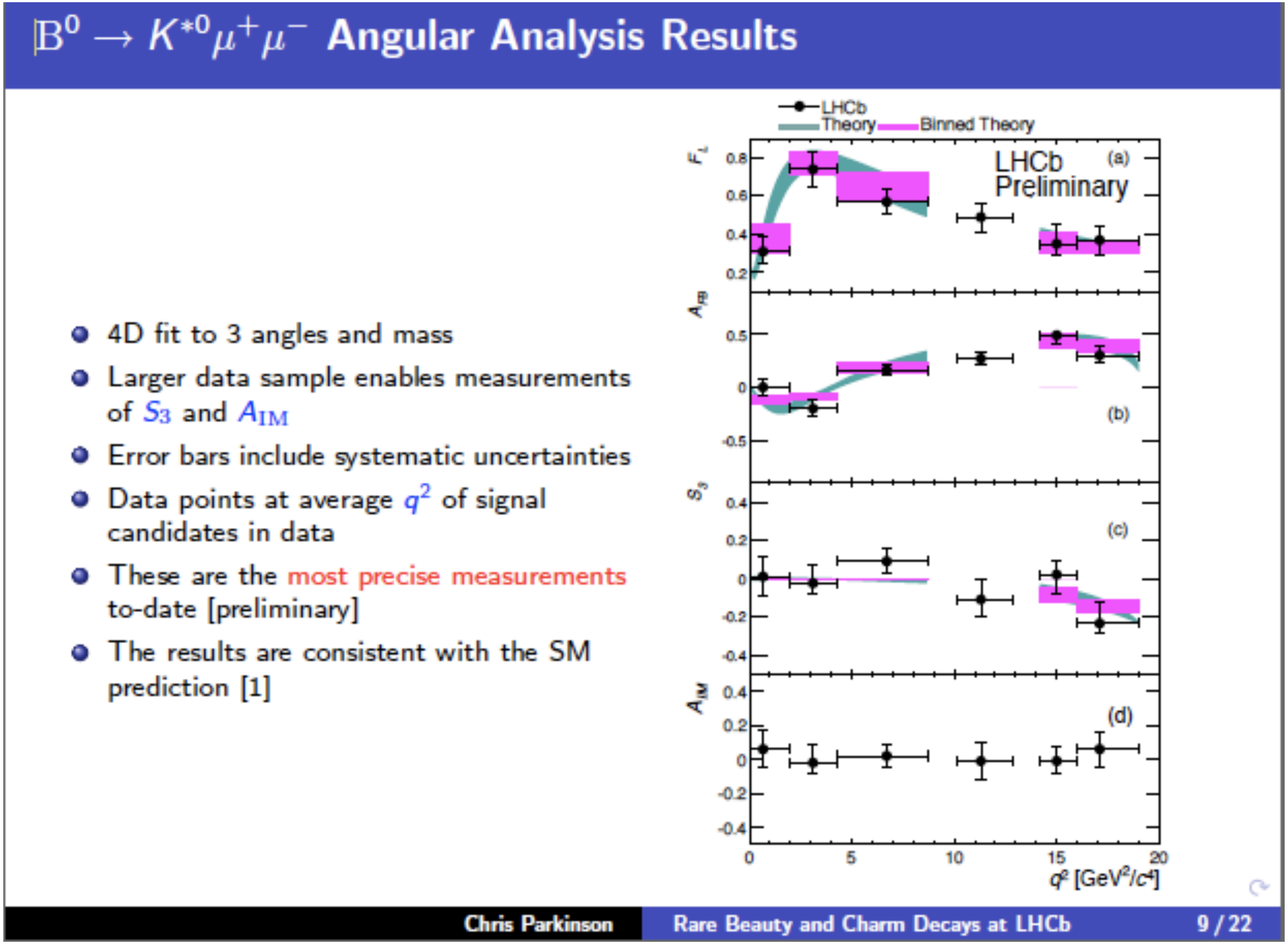
$$\begin{aligned}
J(q^2, \theta_l, \theta_{K^*}, \phi) = {} & J_1^s \sin^2\theta_{K^*} + J_1^c \cos^2\theta_{K^*} + (J_2^s \sin^2\theta_{K^*} + J_2^c \cos^2\theta_{K^*}) \cos 2\theta_l \\
& + J_3 \sin^2\theta_{K^*} \sin^2\theta_l \cos 2\phi + J_4 \sin 2\theta_{K^*} \sin 2\theta_l \cos\phi + J_5 \sin 2\theta_{K^*} \sin\theta_l \cos\phi \\
& + J_6 \sin^2\theta_{K^*} \cos\theta_l + J_7 \sin 2\theta_{K^*} \sin\theta_l \sin\phi \\
& + J_8 \sin 2\theta_{K^*} \sin 2\theta_l \sin\phi + J_9 \sin^2\theta_{K^*} \sin^2\theta_l \sin 2\phi, \qquad (2.3)
\end{aligned}$$

Θ_l: angle between l^- and $\bar{B}$ in dilepton CMS (warning: different conventions in literature)

Θ_{K^*}: angle between K and $\bar{B}$ in K^*-CMS

Φ: angle between normals of the $K\pi$ and l^+l^- plane

More angular distributions avaliable 2012



$B^0 \to K^{*0}\mu^+\mu^-$ Angular Analysis Results

- 4D fit to 3 angles and mass
- Larger data sample enables measurements of S_3 and A_{IM}
- Error bars include systematic uncertainties
- Data points at average q^2 of signal candidates in data
- These are the most precise measurements to-date [preliminary]
- The results are consistent with the SM prediction [1]

Extracting $B \to K^*$ form factors from data

At low hadronic recoil: OPE in $1/m_b$ Grinstein, Pirjol '04, Beylich et al '10

$$A_i^{L,R} \propto C^{L,R} f_i + \mathcal{O}(\alpha_s \Lambda/m_b, C_7/C_9 1/m_b), \qquad i = \perp, ||, 0$$ Bobeth et al '10

$C^{L,R}$: universal short-dist.-physics; $C^{L,R} = (C_9^{\text{eff}} \mp C_{10}) + \kappa \frac{2\hat{m}_b}{\hat{s}} C_7^{\text{eff}}$

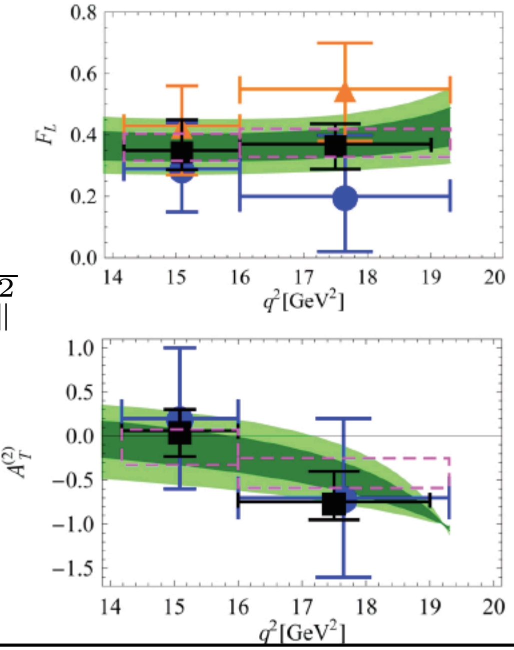
f_i: generalized form factors: $f_\perp \propto V, f_{||} \propto A_1, f_0 \sim A_1, \lambda A_2$

$C^{L,R}$ drops

out in ratios:

$$F_L = \frac{|A_0^L|^2 + |A_0^R|^2}{\sum_{X=L,R}(|A_0^X|^2 + |A_\perp^X|^2 + |A_{||}^X|^2)} = \frac{f_0^2}{f_0^2 + f_\perp^2 + f_{||}^2}$$

$$A_T^{(2)} = \frac{|A_\perp^L|^2 + |A_\perp^R|^2 - |A_{||}^L|^2 - |A_{||}^R|^2}{|A_\perp^L|^2 + |A_\perp^R|^2 + |A_{||}^L|^2 + |A_{||}^R|^2} = \frac{f_\perp^2 - f_{||}^2}{f_\perp^2 + f_{||}^2}$$

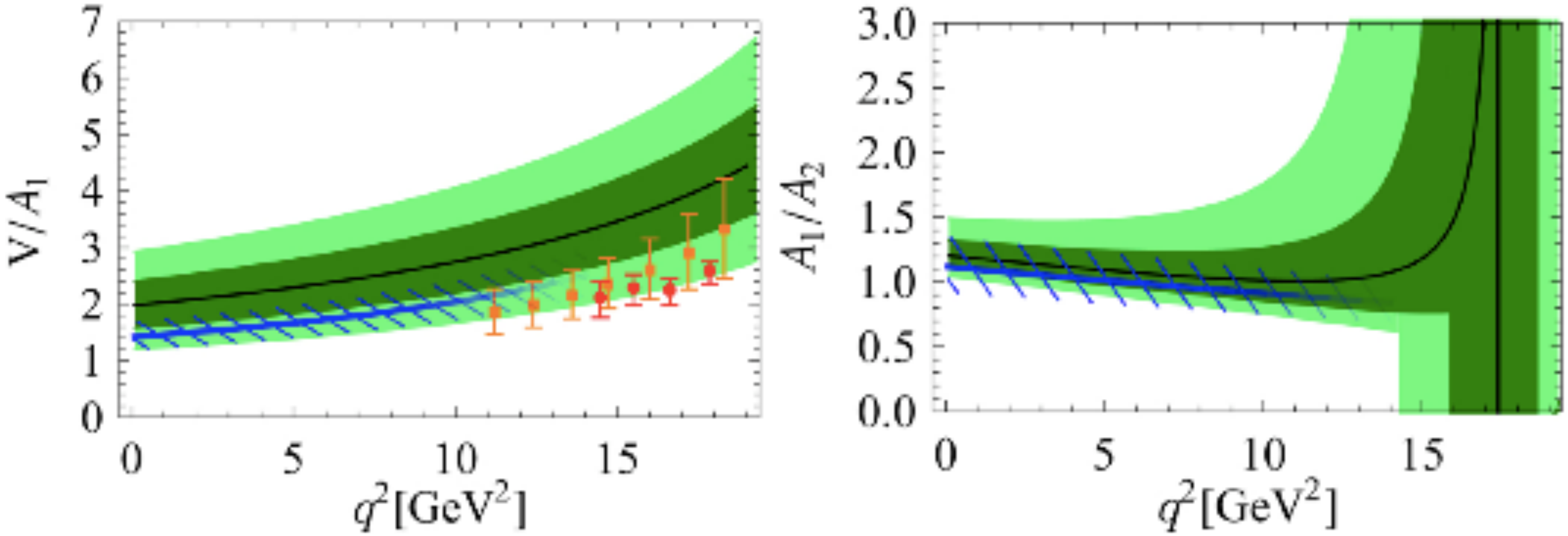


Extracting $B \to K^*$ form factors from data

Series expansion $z(t) \equiv z(t,t_0) = \frac{\sqrt{t_+ - t} - \sqrt{t_+ - t_0}}{\sqrt{t_+ - t} + \sqrt{t_+ - t_0}}$,

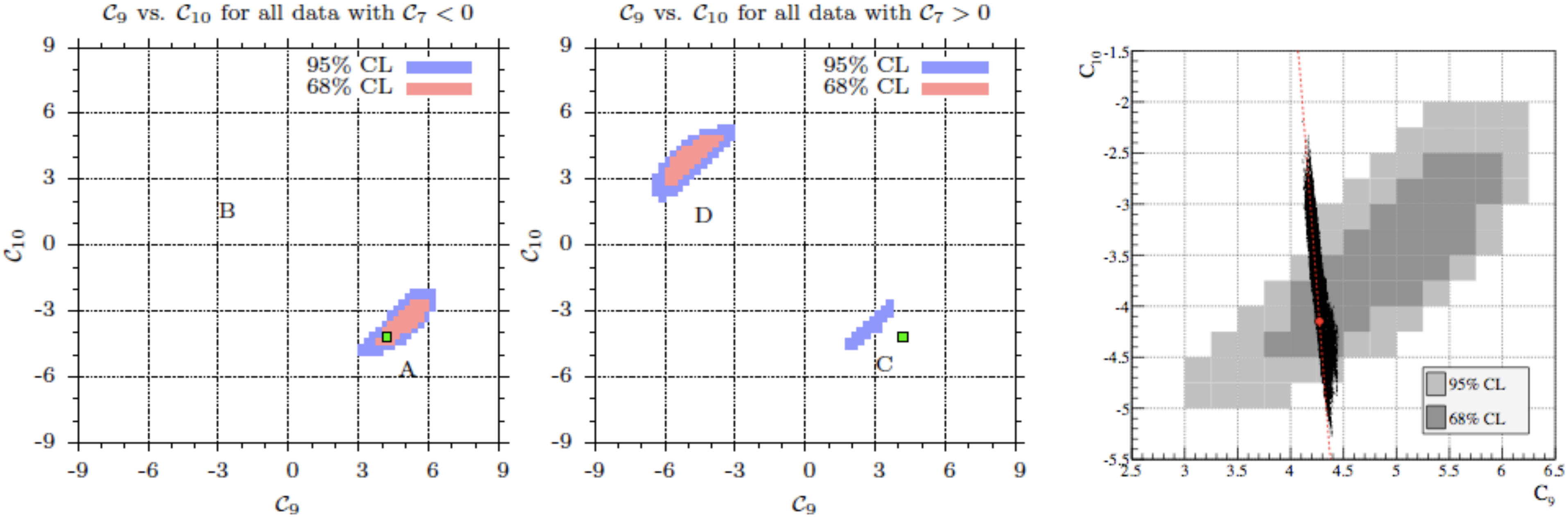
$$\hat{f}_i(t) = \frac{(\sqrt{-z(t,0)})^m (\sqrt{z(t,t_-)})^l}{B(t)\,\varphi_f(t)} \sum_k \alpha_{i,k}\, z^k(t)\,,$$

The best-fit results: $\alpha_\parallel/\alpha_\perp = 0.43^{+0.11}_{-0.08}$, $\alpha_0/\alpha_\perp = 0.15^{+0.03}_{-0.02}$



Yellow, red points; lattice QCD; blue bands: QCD sum rules Ball, Zwicky ’05: green bands: $1,2\sigma$ fit 1204.4444 [hep-ph]

Precision tests from global fits $\mathcal{L} \sim \sum C_i O_i$



left: global analysis 1111.2558 [hep-ph], also Altmannshofer et al ’11 ; solution C is ruled out by AFB-zero. right: red dot: SM; grey areas: allowed by $b \to s$ data; black points: SUSY model with squark flavor mixing 1205.1500 [hep-ph]

flavor suppression with NP at $\Lambda_{NP} = 1$ TeV: $|\tilde{c}_{10}| < 5 \cdot 10^{-4} (4 \cdot 10^{-3})$

limit on scale iff no suppression $\tilde{c}_{10} = 1$: $\Lambda_{NP} >$ 44 TeV (16 TeV)

Bayesian Fit to 2012 data

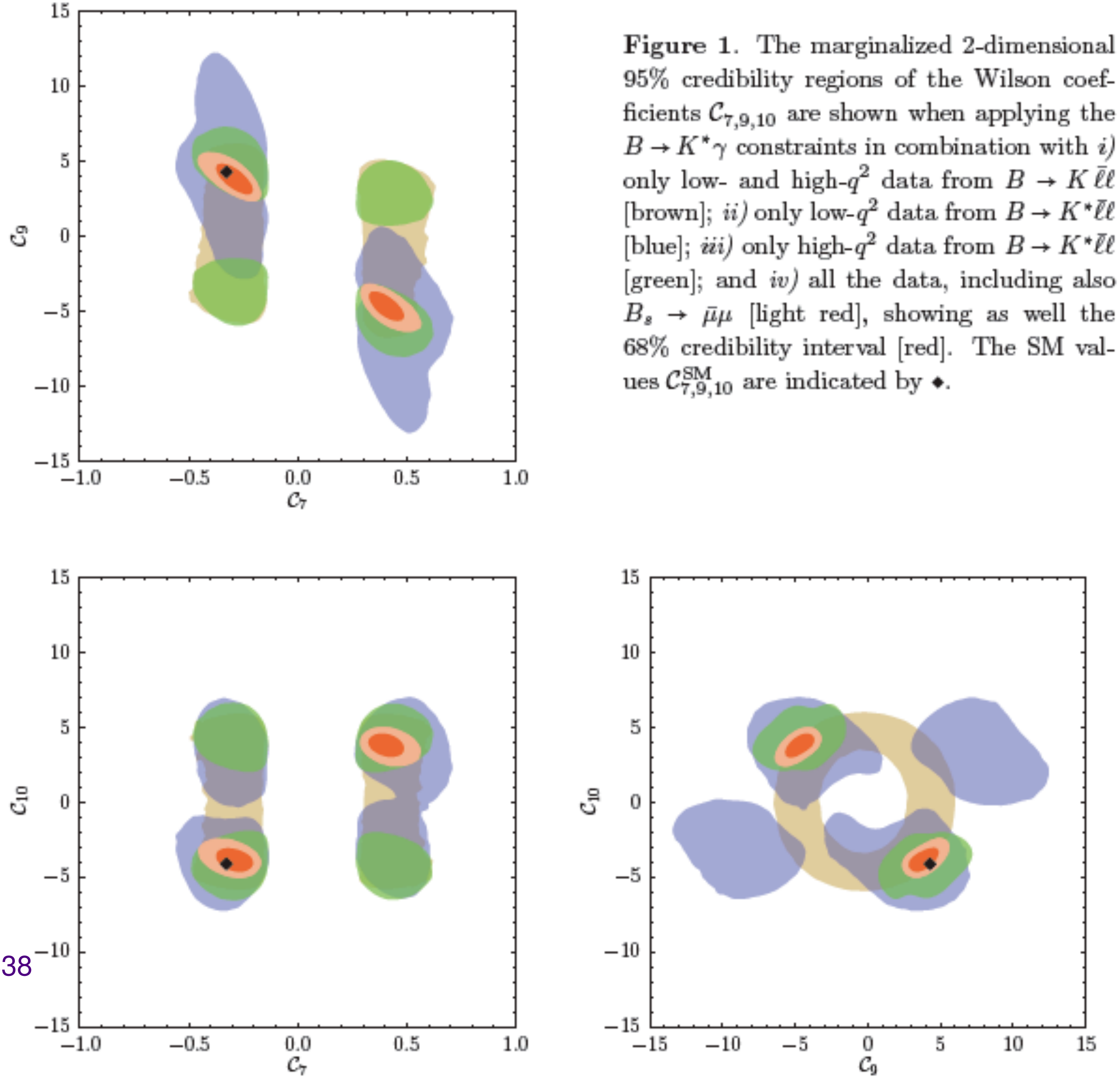


Figure 1. The marginalized 2-dimensional 95% credibility regions of the Wilson coefficients $\mathcal{C}_{7,9,10}$ are shown when applying the $B \to K^* \gamma$ constraints in combination with *i)* only low- and high-q^2 data from $B \to K \bar{\ell}\ell$ [brown]; *ii)* only low-q^2 data from $B \to K^* \bar{\ell}\ell$ [blue]; *iii)* only high-q^2 data from $B \to K^* \bar{\ell}\ell$ [green]; and *iv)* all the data, including also $B_s \to \bar{\mu}\mu$ [light red], showing as well the 68% credibility interval [red]. The SM values $\mathcal{C}_{7,9,10}^{\mathrm{SM}}$ are indicated by ◆.

Beaujean et al 1205.1838

Figure 5: SUSY spread of the $A_{FB}(B \to K^*\mu^+\mu^-)$ at low q^2 in function of the lightest stop mass, for tan β=50 (upper panel) and tan β=30 (lower panel), in the left for $A_0 = 0$ and in the right for $A_0 = -1000$ GeV.

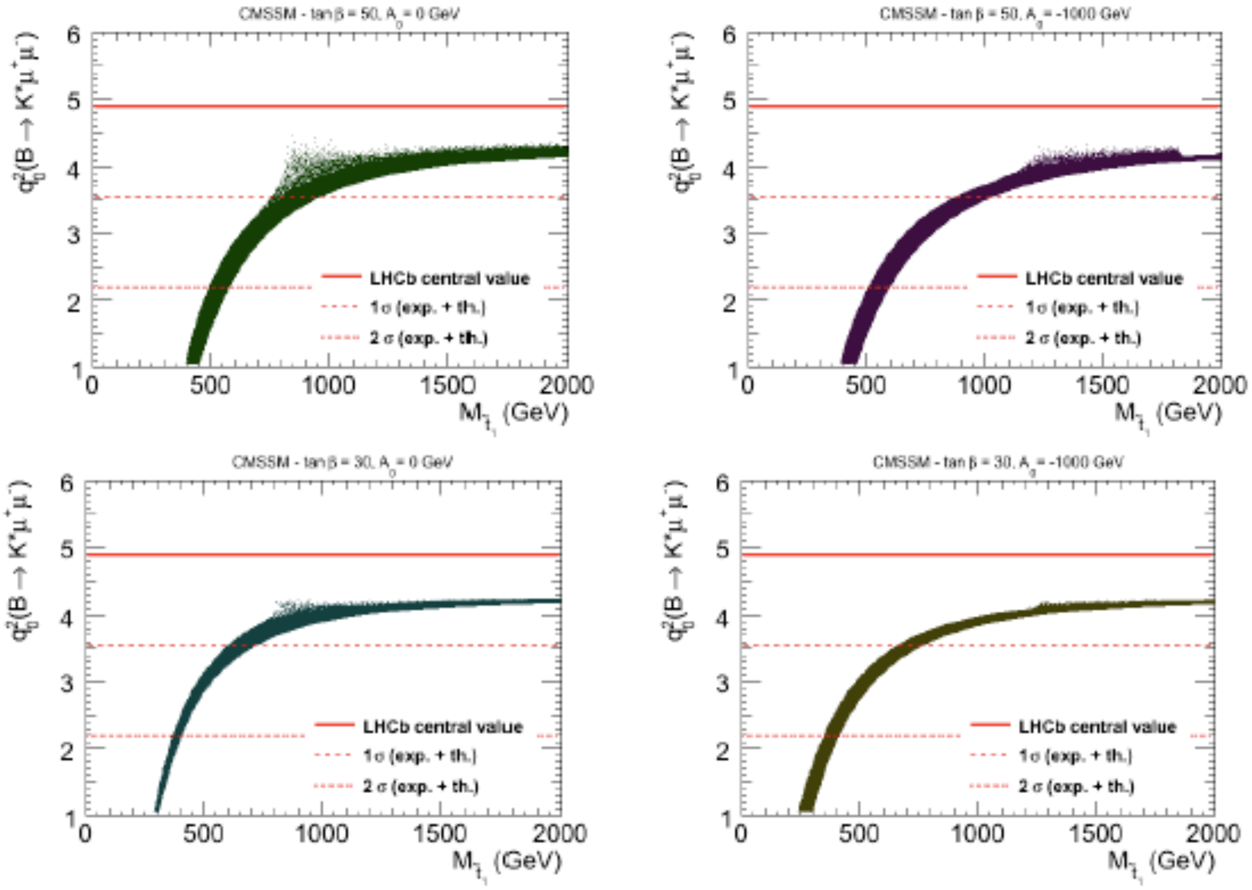


Figure 6: SUSY spread of the $A_{FB}(B \to K^*\mu^+\mu^-)$ zero–crossing, similar to Fig. 5.

Mahmoudi et al, 1205.1845 $q_0^2|_{\rm LHCb} = 4.9^{+1.1}_{-1.3}$ GeV^2

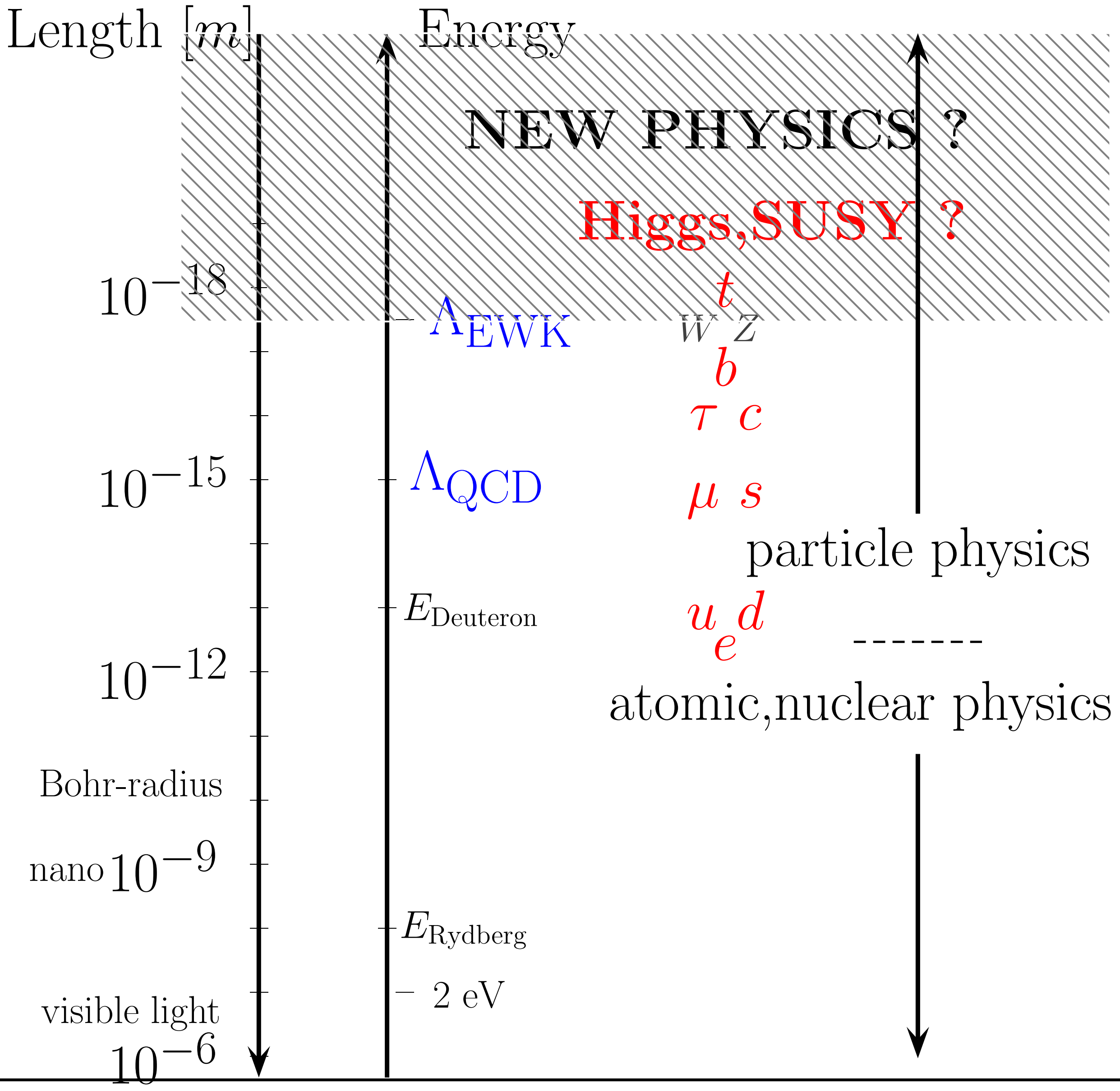
More Opportunities w. $B \to V(\to PP)\mu^+\mu^-$

CP-asymmetries from angular distribution $A_i \propto J_i - \bar{J}_i$: SM: all doubly Cabbibo-suppressed and null tests of the SM.

A_3, A_9 vanish in SM by helicity conservation: sens. to RH currents
$A_3, A_9, (A_6)$ can be extracted from single-diff distribution in $\Phi(\Theta_l)$
$A_{7,8,9}$ T-odd: not suppressed by small strong phases; O(1) with BSM
$A_{5,6,8,9}$ CP-odd: can be extracted without tagging from $\Gamma + \bar{\Gamma}$; advantageous for $B_s, \bar{B}_s \to (\Phi \to K^+K^-)\mu^+\mu^-$.

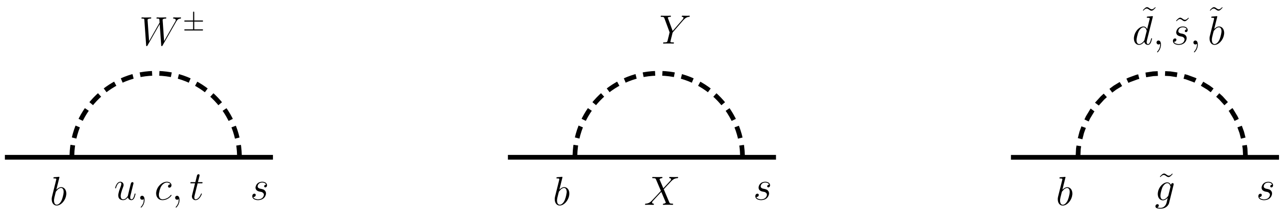
Low recoil region allows to design (high-q^2) observables which are
– independent of form factors ($H_T^{(2,3)}$, $a^i_{\rm CP}$)
– independent of short-distance coefficients and test the form factors
– independent of either ones and test the theoretical low recoil framework $H_T^{(1)} = 1, H_T^{(2)}/H_T^{(3)} = 1$ Bobeth et al 1006.5013, and 1105.0376

Terascale Physics



Terascale Flavor facing todays FCNC Data

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



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

	$K^0\bar{K}^0$	$D^0\bar{D}^0$	$B^0_d\bar{B}^0_d$	$B^0_s\bar{B}^0_s$
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!

Quark Flavor Masses and Mixings in SM

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

6 masses, 3 angles and 1 phase:

$$
\begin{aligned}
Y_u &\sim \begin{pmatrix} 10^{-5} & -0.002 & 0.008 + i\,0.003 \\ 10^{-6} & 0.007 & -0.04 \\ 10^{-8} + i\,10^{-7} & 0.0003 & 0.94 \end{pmatrix} \\
Y_d &\sim \operatorname{diag}\left(10^{-5}, 5 \cdot 10^{-4}, 0.025\right)
\end{aligned}
$$

Very peculiar pattern.

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.

Summary

- It’s fun to have data!

Thanks for Flavor-Collaboration and Support to

Arnd Behring, Christoph Bobeth, Christian Gross, Christian Hambrock, Yonit Hochberg, Yossi Nir, Danny van Dyk, Jong Soo Kim, Stefan Schacht, Henning Sedello, Christian Wacker

bmb+f - Förderschwerpunkt
Elementarteilchenphysik
Großgeräte der physikalischen
Grundlagenforschung

PHYSICS
AT THE
TERA
SCALE
Helmholtz Alliance

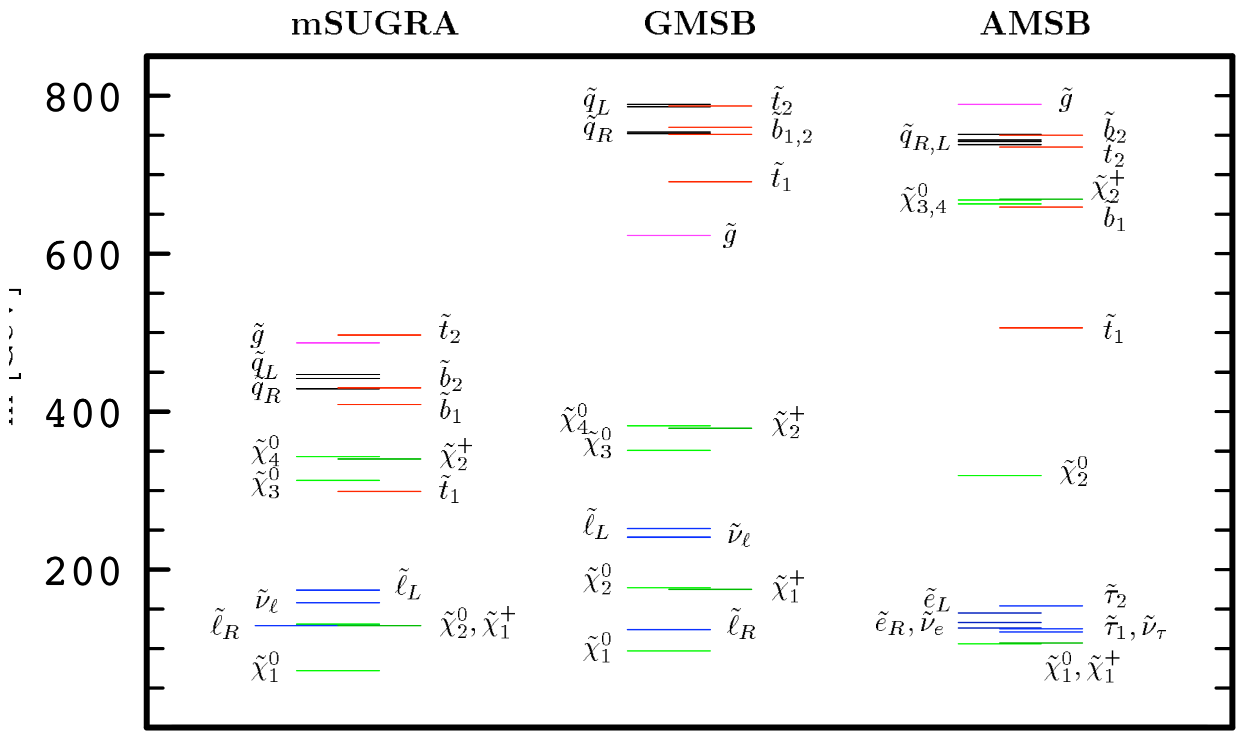
GIF

Abstract

Abtract: Flavor physics studies have identified the standard model as the dominant source of quark flavor and CP violation (modulo ”anomalies”). This has strong implications for the physics at the TeV scale. We briefly review the status of flavor physics and discuss how one could discover a breakdown of the standard model in flavor physics and understand flavor in and beyond the standard model. Emphasis is given on rare exclusive FCNC-decays into di-muons, which are well-suited for precision studies at the Large Hadron Collider (LHC) experiments.

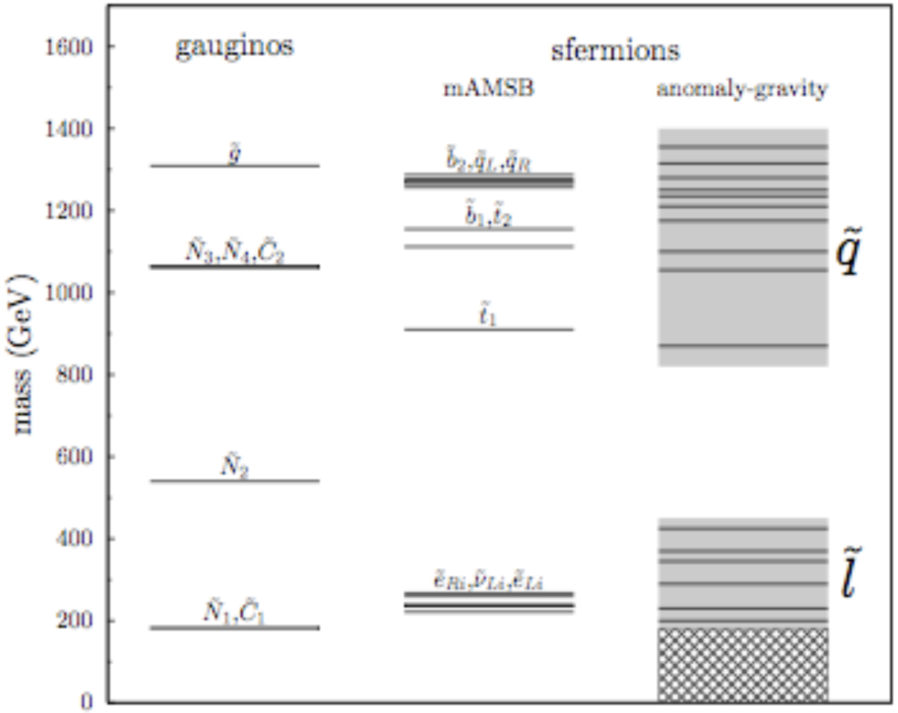
New TeV-sector; what's the flavor of the SM partners?

Is the flavored spectrum of $\tilde{q}$ and $\tilde{\ell}$ degenerate?



TESLA TDR Part III '01

or with large mass splitting?



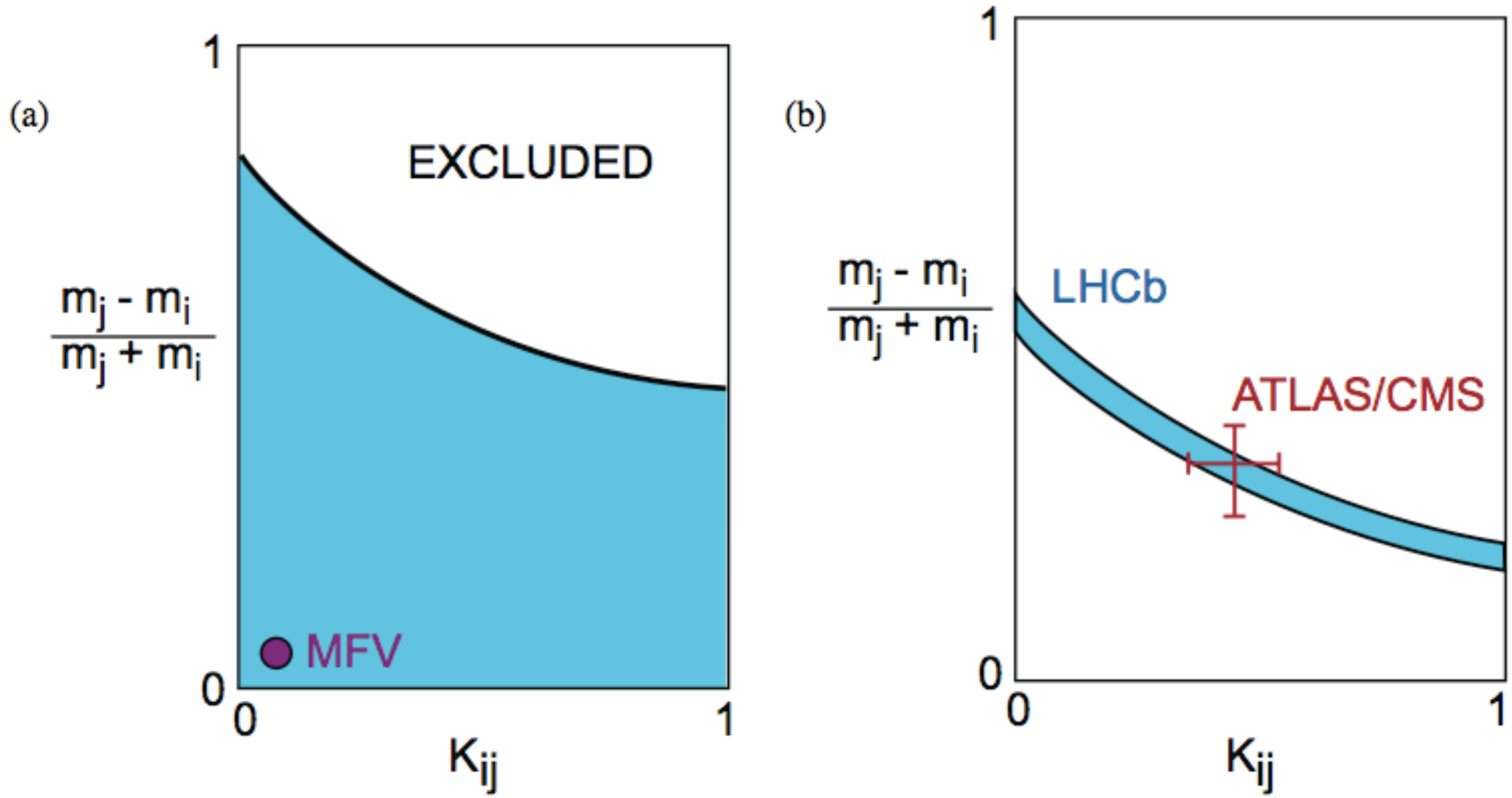
C.Gross and GH, 1101.5352 [hep-ph]

and how about flavor mixing and CP violation?

Testing Flavor at the Terascale

FCNC loops probe product of flavor mixing K_{ij} and splitting Δm_{ij}

$$\mathcal{A}_{FCNC} \sim K_{ij} K^*_{kj} \;\cdot\; \Delta m^2_{ik}$$

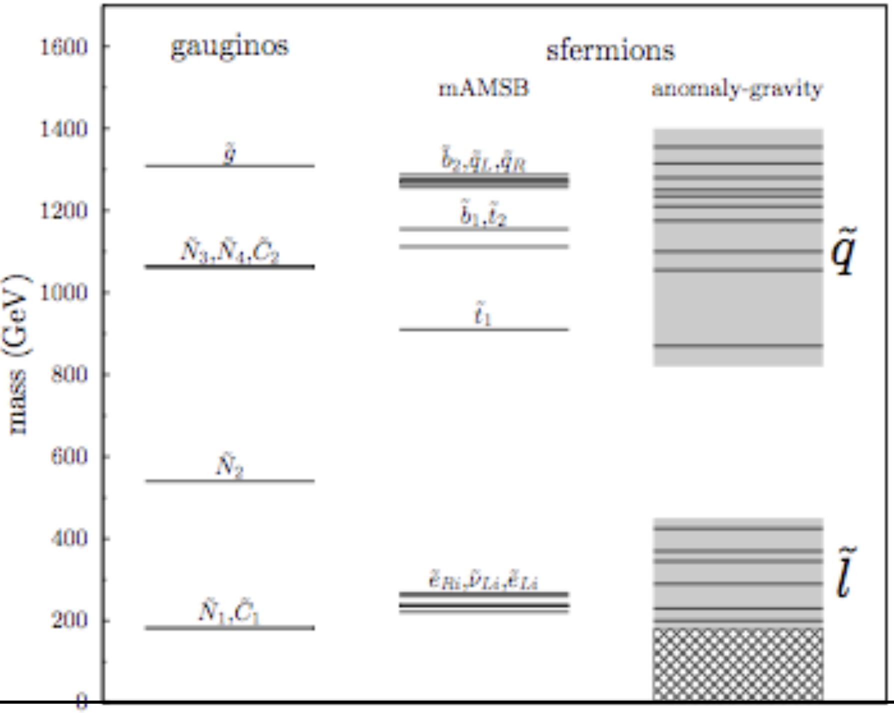


figs from Y.Nir 1010.2666 [hep-ph] schematic a) today b) hypothetical

Collider-Flavor Physics (Examples)

Measuring the mass splitting Δm_{ij}:

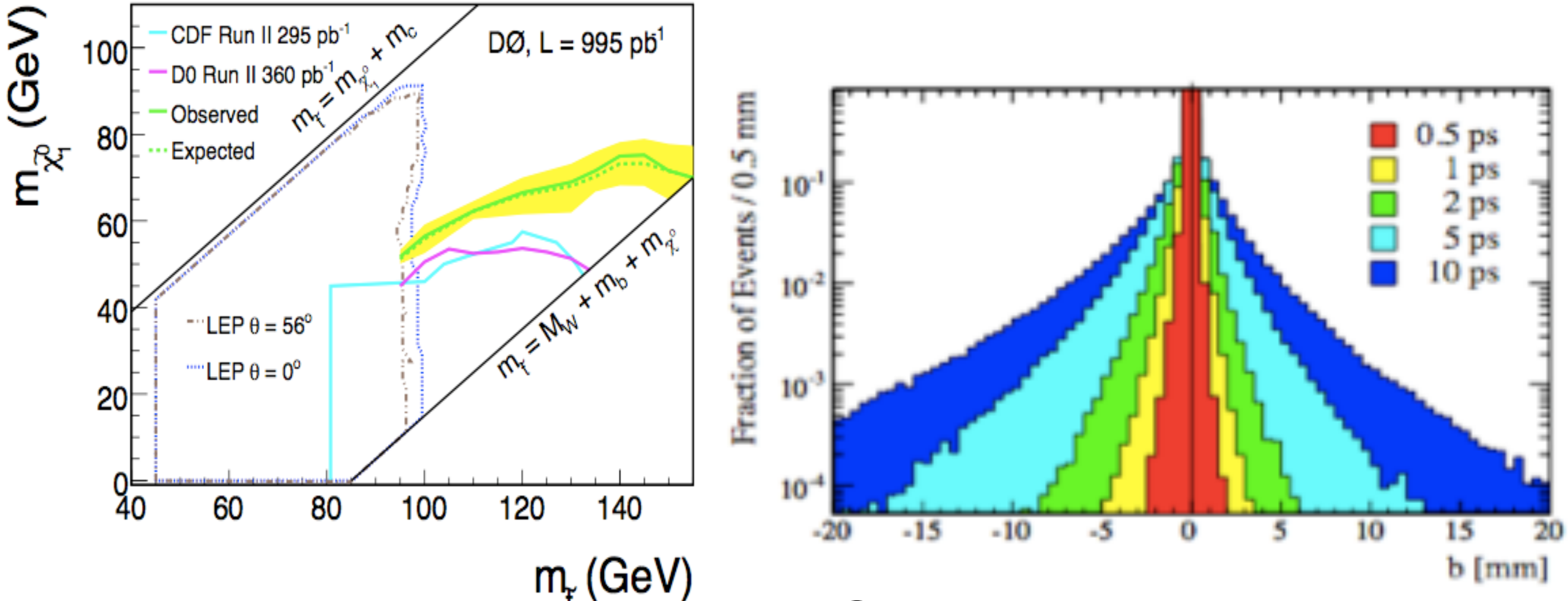
in cascades $\chi_2^0 \to \chi_1^0 l^+ l^-$ and comparing e^+e^- with $\mu^+\mu^-$ edges Allanach et al 0801.3666 [hep-ph] mSUGRA/CMSSM: splitting percent-permille; Hybrid anomaly-gravity: $O(1)$ slepton splitting, uses alignment $|K_{ij}| \ll 1$ to escape FCNC bounds 1101.5352 [hep-ph]



Collider-Flavor Physics (Examples)

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

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).

Flavor Masses and Mixings in SM

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

Very peculiar pattern.

Mismatch SM vs BSM Flavor

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

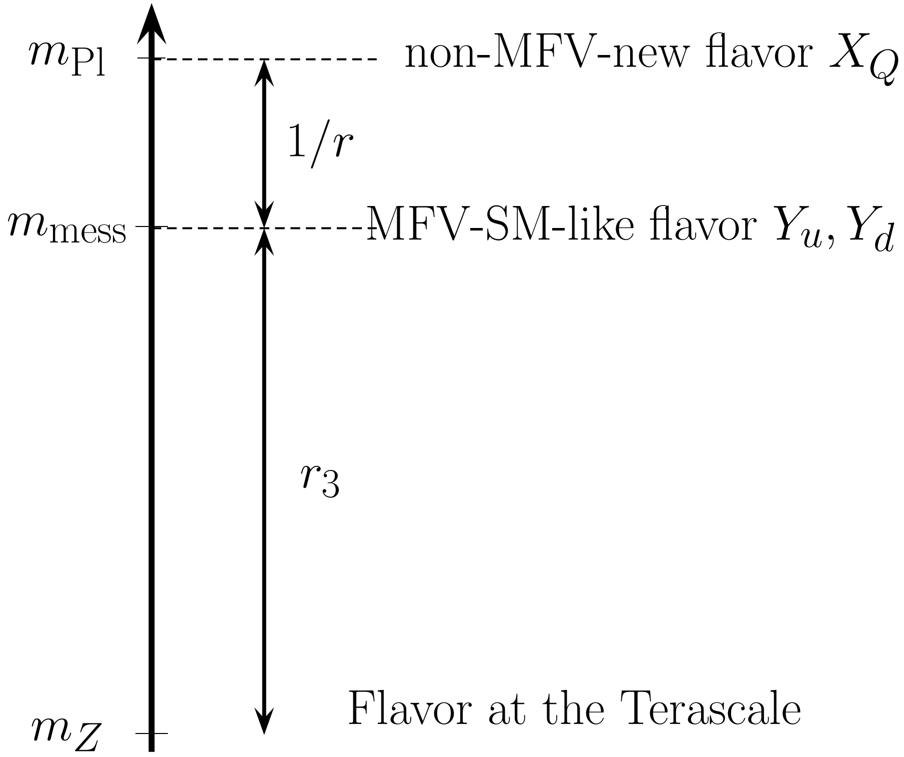
squark mass terms $\mathcal{L} = \tilde{Q}^\dagger_{L\,i} (M^2_{\tilde{Q}_L})_{ij} \tilde{Q}_{L\,j} + \ldots$ (sflavor)

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