B Physics Theory Overview

Standard Model @ LHC
Copenhagen
April 13, 2012

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Excellence Cluster `Universe´

Flavour Physics

Flavour Physics:
Effects of highly virtual particles at lower energies

Measure the standard model $W^{\pm}$ couplings in B and K decays

Test the standard model in process
i) where CP is violated
ii) which are suppressed through (accidental) symmetries, and
iii) which can be calculated with high precision

Symmetries: CP and Flavour

Flavour Symmetry

The standard model gauge sector $\mathcal{L}_g = \sum_f \bar{\psi}_f \not{D} \psi_f + \sum_i \frac{1}{4} g_i \vec{F}^i_{\mu\nu} \vec{F}^{i\,\mu\nu}$

conserves CP $f \in \{u, d, e, Q, L\}$

large global flavour symmetry $G_{\text{flavour}} = \prod_f SU(3)_f \times \prod_x U(1)_x$

[Chivukula, Georgi `87]

Yukawa couplings breaks symmetry

$$-\mathcal{L}_Y^q = \bar{u}_R Y_u \tilde{\varphi}^\dagger Q_L + \bar{d}_R Y_u \varphi^\dagger Q_L$$

Mass $\neq$ flavour eigenstates

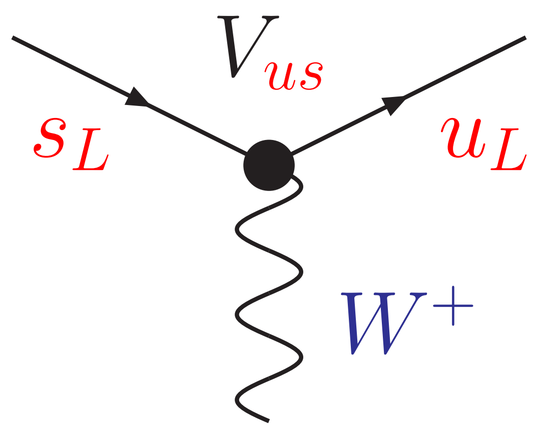
diagonal Y_d: $Y_u = \frac{1}{v} \begin{pmatrix} m_u & & \\ & m_c & \\ & & m_t \end{pmatrix} \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$

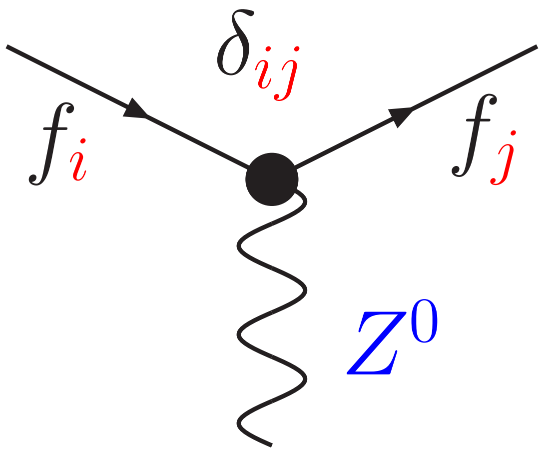
CKM matrix: CP and flavour violation in the SM

B tree and loop decays: determine CKM matrix

Flavour Changing Interactions

Mass ≠ flavour eigenstates





Loop-suppression tests TeV-scale

SM: Only charged currents change the flavour ($\propto V_{us}$)

SM: Neutral currents do not change the flavour (i=j) at tree-level

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

CKM matrix: CP and flavour violation in the SM

B tree and loop decays: determine CKM matrix

Unitarity Triangle

3 CKM angles $|V_{ub}|$, $|V_{cb}|$ & $|V_{us}|$ from semileptonic B & K decays

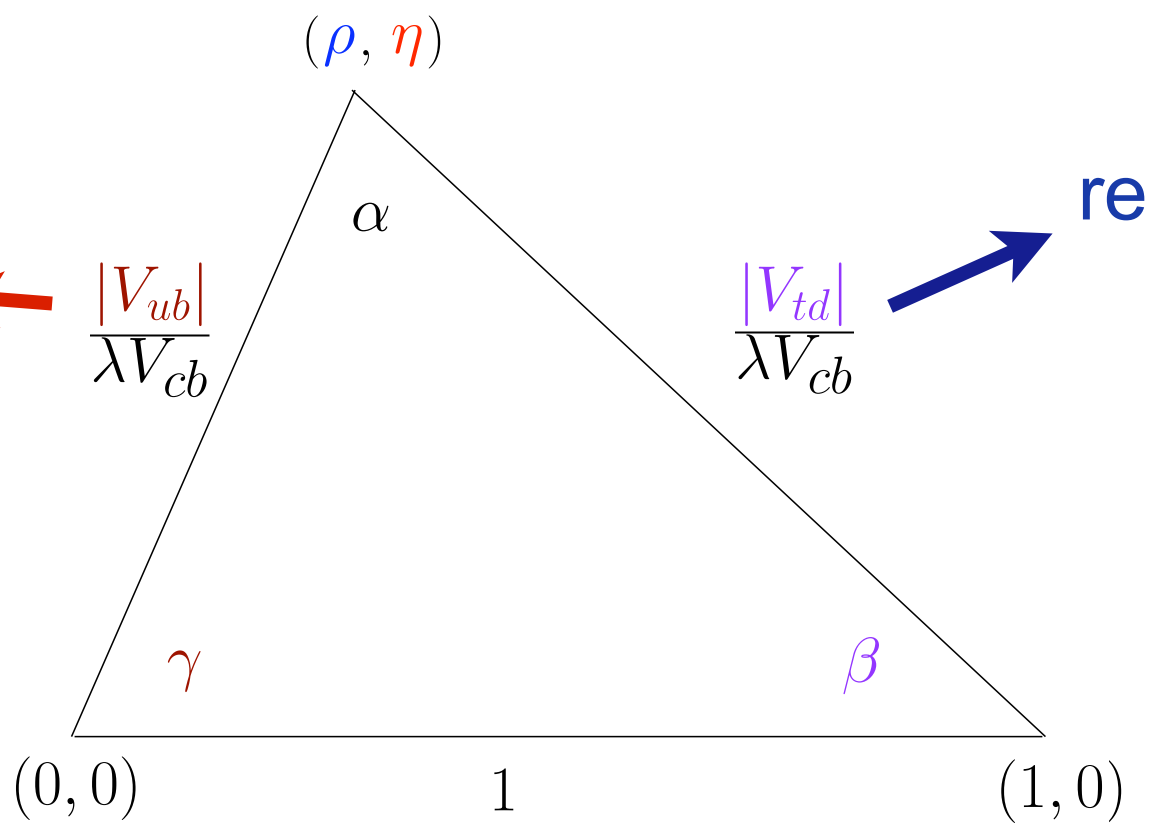
CP violation in the standard model ∝ area of unitarity triangle

Unitarity of $V \Rightarrow$

$$\begin{aligned} V_{ub}^* V_{ud} &+ V_{cb}^* V_{cd} + V_{tb}^* V_{td} = 0 \\ A\lambda^3(\rho + i\eta) &- A\lambda^3 + A\lambda^3(1-\rho-i\eta) = 0 \end{aligned}$$

Graphically,

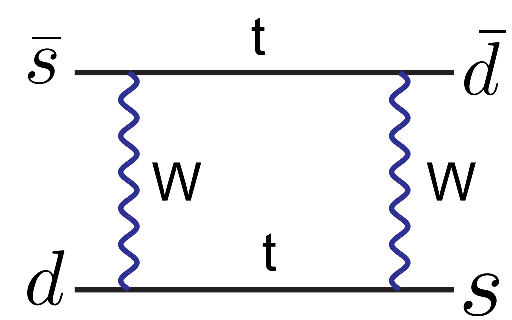
b → u l v
b → u q q
(tree-level
Weak int.)

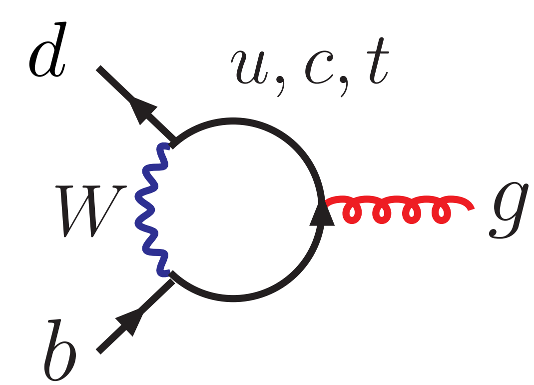


requires top loop

$V_{ub} = |V_{ub}|e^{-i\gamma}$

$V_{td} = |V_{td}|e^{-i\beta}$



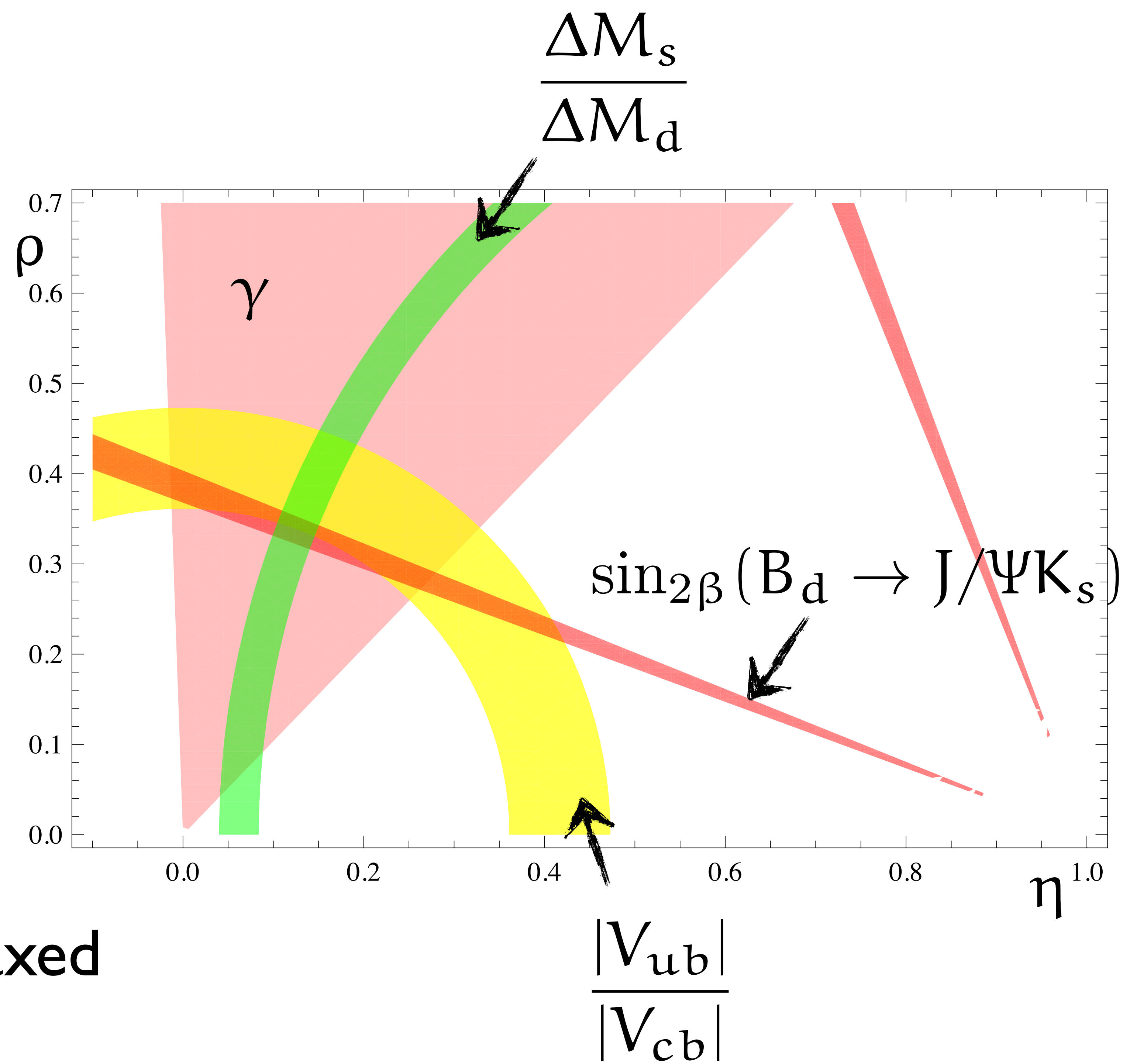


Minimal Flavour Violation

unitarity triangle implicitly depends on new physics

Minimal Flavour Violation
Universal Unitarity Triangle
[Buras, Gambino, MG, Jäger, Silvestrini `00]

Independent of details of new physics



Restrictive scenario can be relaxed
[d'Ambrosio et al `02; ...]

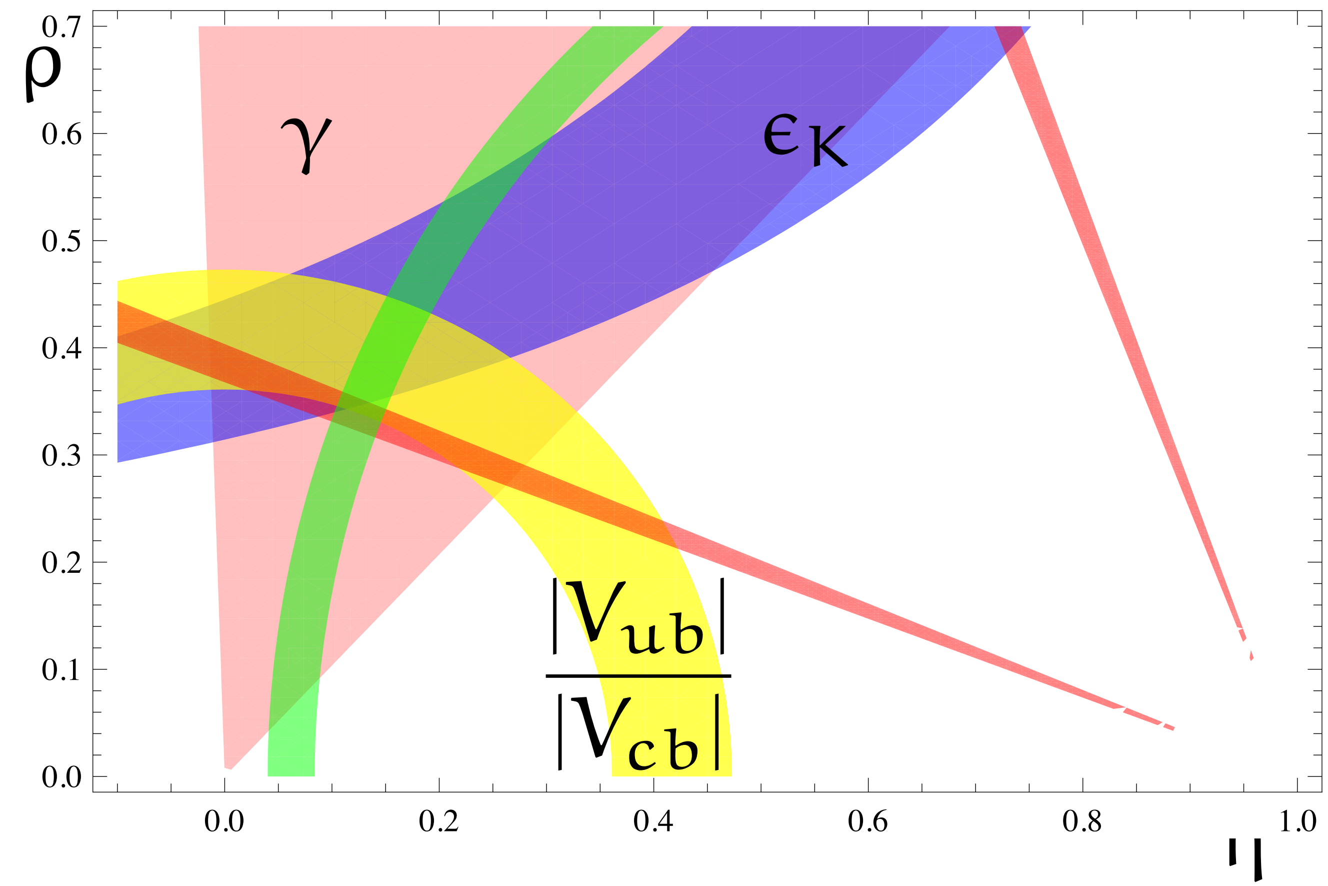
Yet, models of dynamical flavour breaking do not follow these scenarios

CKM input for tests of SM

CKM parameters: input for new physics sensitive observables

Tree level determination of UT

Precise new physics independent determination of γ important (talk: γ from B → DK)



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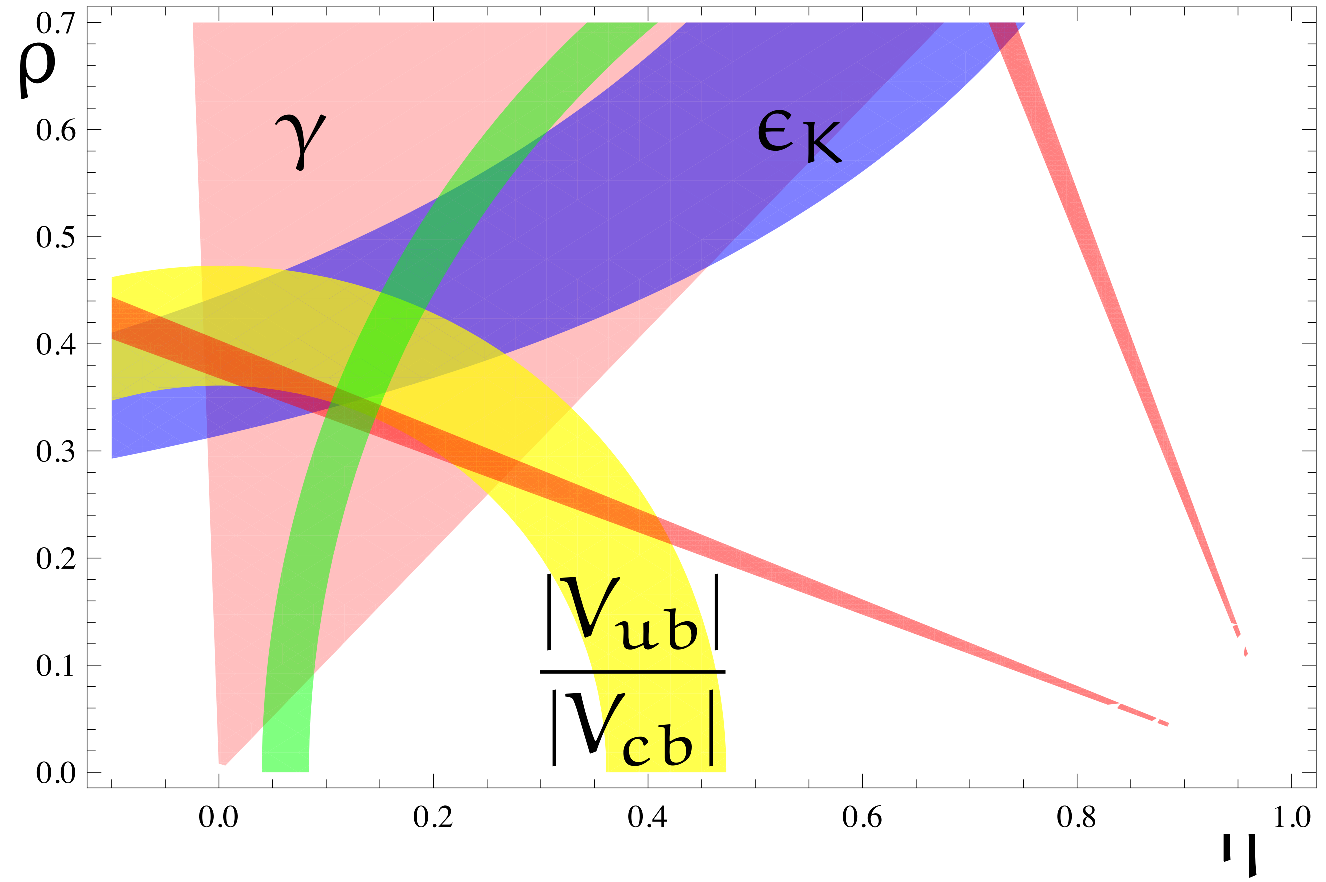
Important for CP violation in Kaons: ε_K at NNLO [Brod, MG `11]



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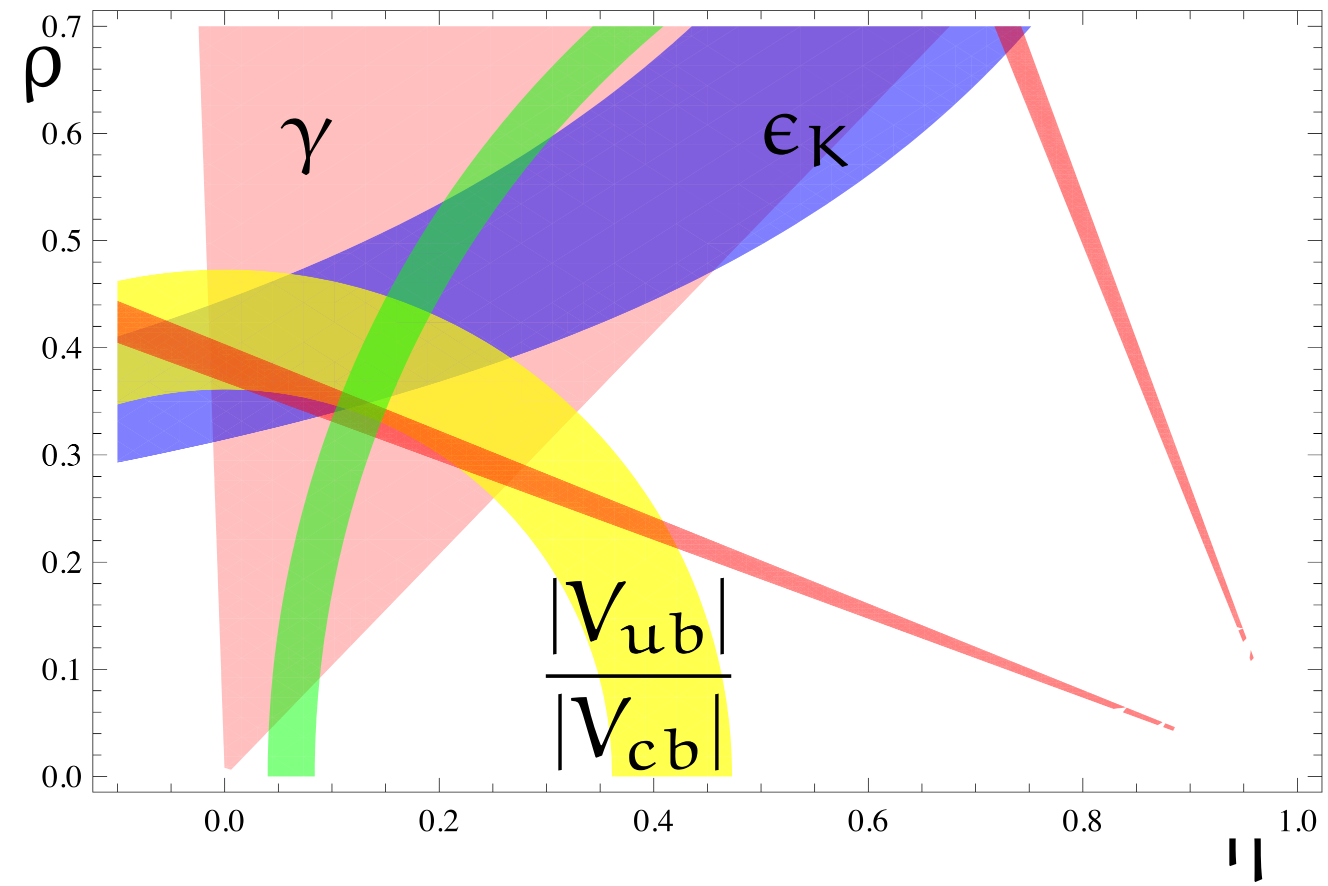
CP violation in B_d mixing

b → s transitions almost independent of ρ and η: Domain of LHCb

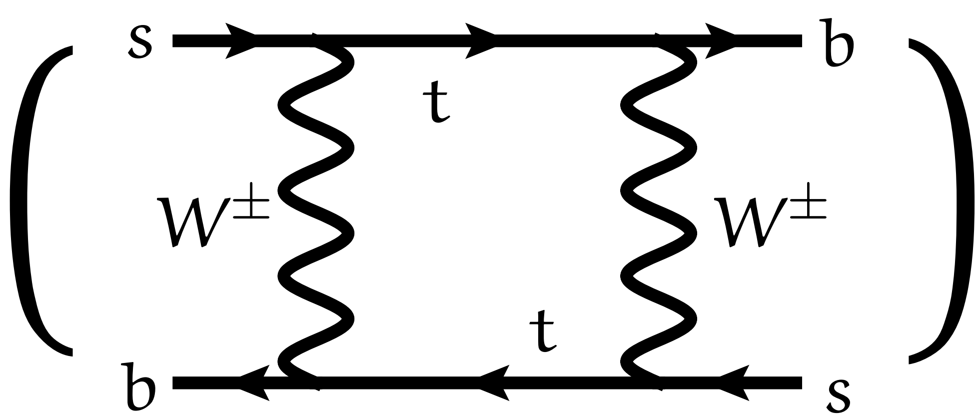


B_s Mixing

$$i\frac{d}{dt}\begin{pmatrix}|B^0(t)\rangle\\|\overline{B}^0(t)\rangle\end{pmatrix} = \left[\begin{pmatrix}M_{11} & M_{12}\\M_{12}^* & M_{11}\end{pmatrix} - \frac{i}{2}\begin{pmatrix}\Gamma_{11} & \Gamma_{12}\\\Gamma_{12}^* & \Gamma_{11}\end{pmatrix}\right]\begin{pmatrix}|B^0(t)\rangle\\|\overline{B}^0(t)\rangle\end{pmatrix}$$

CP ± eigenstates of time evolution: $|B_{L/H}\rangle = p|B^0\rangle \mp q|\overline{B}^0\rangle$

dispersive part: $M_{12} \propto$

Re 

``off-shell´´ top-quark; one-loop sensitive to new physics

small complex phase in SM:

$$\phi_s = \arg\left(-\frac{M_{12}}{\Gamma_{12}}\right) = -2\beta_s$$

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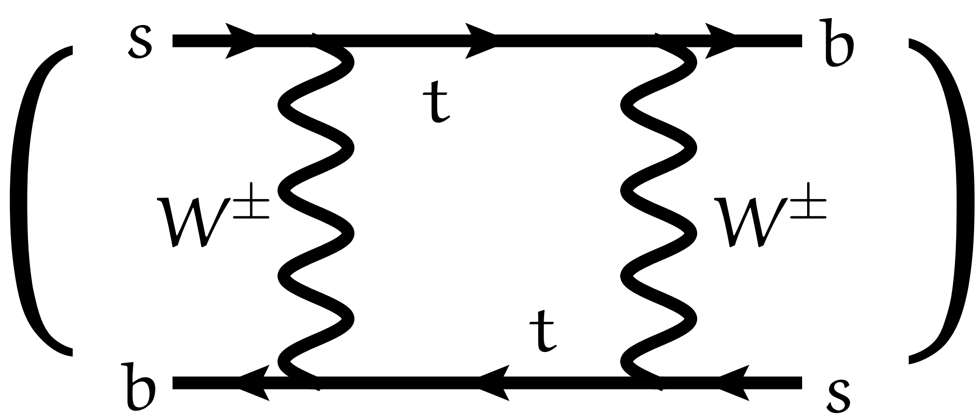
Re 

``off-shell´´ top-quark; one-loop sensitive to new physics

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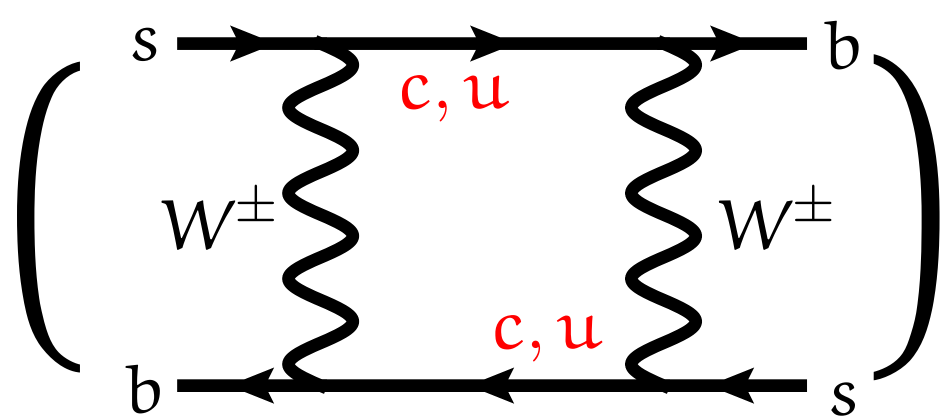
absorptive part: $\Gamma_{12} \propto$

Im 

tree decay into light up-quarks

new physics has to compete with tree-level ΔF=1 operators

strong constraints from experiment

Observables in B_s Mixing

Mass difference $M_H - M_L = 2\,|M_{12}| + \ldots$

Decay rate difference $\Gamma_L - \Gamma_H = 2\,|\Gamma_{12}| + \ldots$

Mixing induced CP violation e.g.
$A^{mix}_{CP}(B_s \to J/\Psi\ \Phi) = \sin(\Phi_s) = \sin(-\,2\,\beta_s)$

Flavour Specific CP asymmetries

$B_s(t=0) \not\to \bar{f}$ and $\bar{B}_s(t=0) \not\to f$

$$a^s_{sl} = \frac{\Gamma(\bar{B}_s(t) \to f) - \Gamma(B_s(t) \to \bar{f})}{\Gamma(\bar{B}_s(t) \to f) + \Gamma(B_s(t) \to \bar{f})} = \frac{\Delta\Gamma}{\Delta M} \tan\phi_s$$

SM Predictions vs Data

Observable	Theory [Lenz, Nierste 1006.6308]	Experiment
ΔM_s[ps^-1]	17.3 ± 2.6	17.73 ± 0.05 [CDF&LHCb]
$\Delta\Gamma_s$ [ps^-1]	0.087 ± 0.021	0.116 ± 0.019 [LHCb]
Φ_s(J/Ψ Φ) [°]	-2.1±0.1	-0.1 ± 5.0 [LHCb]

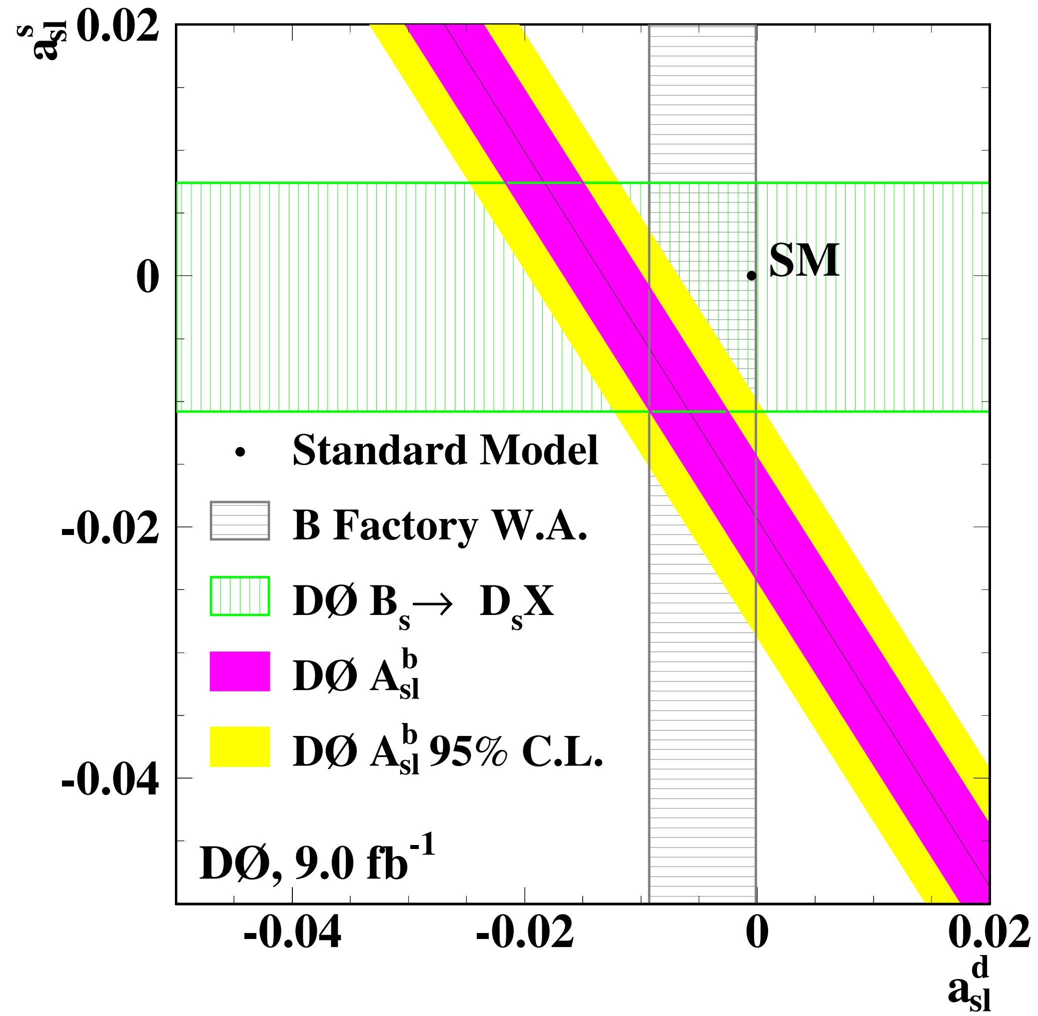
(talk: Φ_s – LHCb)

Like-sign dimuon asymmetry

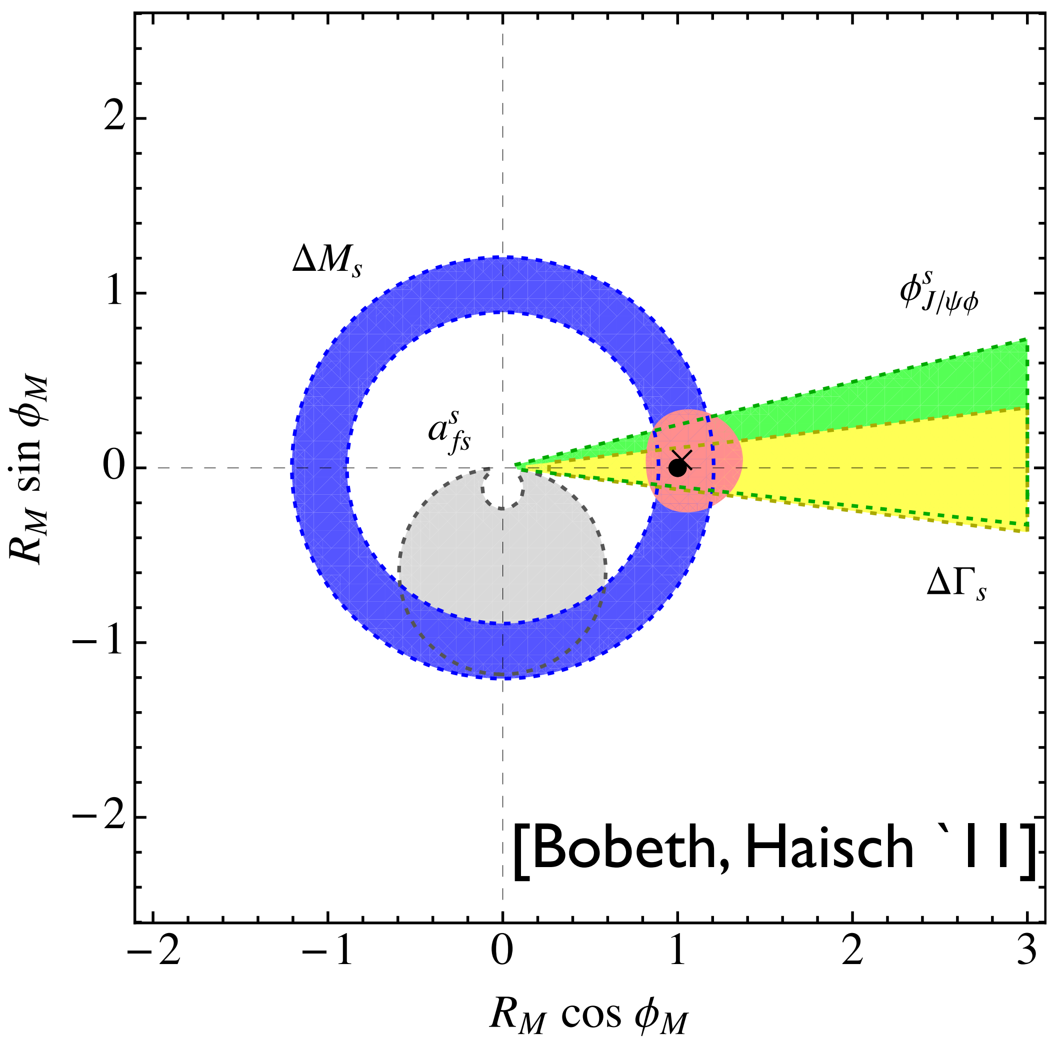
Like-sign dimuon charge asymmetry disagrees with SM

$$A^b_{SL} = \frac{N_b^{++} - N_b^{--}}{N_b^{++} + N_b^{--}}$$

$$= C_d a^d_{fs} + C_s a^s_{fs}$$



If there is only NP in M_{12}:
Φ_s and A_{SL} would be correlated:



How large can NP modify Γ_{12}?

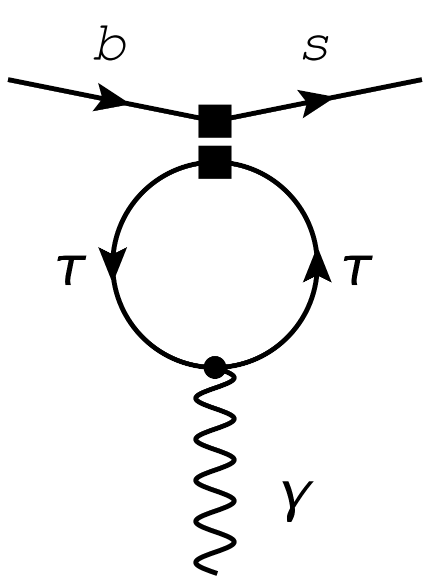
New Physics in Γ_{12} ?

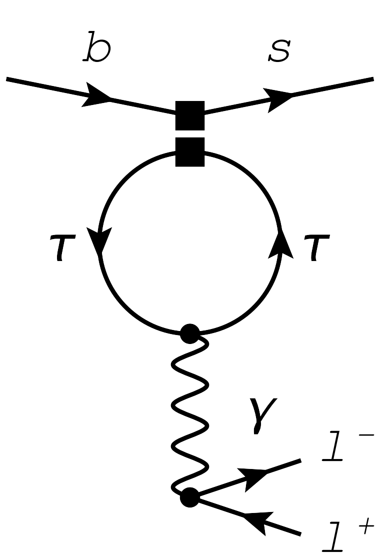
New Physics contributing to Γ_{12} is tightly constrained
(They must couple light SM particles to the B_s)

One possible exception: $(\bar{b}\, s)(\bar{\tau}\, \tau)$ operators
[Dighe, Kundu, Nandi `07 ...]

Recent analysis for scalar, vector and tensor operators:

Constraints from rare decays do not allow for large effects
[Bobeth, Haisch `11]





plus $b \to s\, \tau\, \tau$

Rare decays

Many interesting rare decays – two highlights at LHCb:

theory accuracy

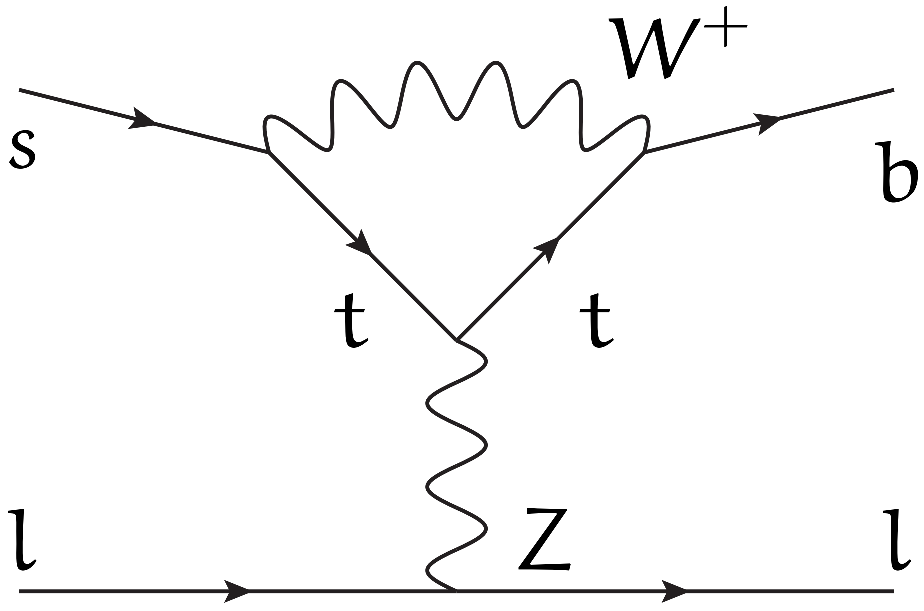
←

$$B_s \to \mu^+\mu^- \qquad B \to K^{(*)}\ell^+\ell^-$$

→

# of observables

$B_s \to \mu^+\mu^-$



B_s is pseudoscalar – no photon penguin

$$Q_A = (\bar{b}_L \gamma_\mu q_L)(\bar{l}\gamma_\mu\gamma_5 l)$$

Dominant operator (SM) Wilson

helicity suppression $\left(\propto \frac{m_l^2}{M_B^2}\right)$

Effective Hamiltonian in the SM (NP + chirality flipped):

$$\mathcal{L}_{\text{eff}} = -\frac{G_F}{\sqrt{2}}\frac{\alpha\, V_{tb}^* V_{ts}}{\pi \sin^2\theta_W}(C_S Q_S + C_P Q_P + C_A Q_A) + \text{h.c.}$$

$$Q_S = m_b(\bar{b}_R q_L)(\bar{l}l) \quad Q_P = m_b(\bar{b}_R q_L)(\bar{l}\gamma_5 l)$$

$$\mathcal{B}(B_s(t=0) \to \mu^+\mu^-) = 3.2(2) \times 10^{-9}$$

[De Bruyn, Fleischer et. al. `12]

measurement is time integrated

$$\mathcal{B}(B_s \to \mu^+\mu^-) = 3.5(2) \times 10^{-9}$$

MSSM: MFV and Large $\tan\beta$

Lagrangian of 2HDM of type 2

$$H_u \leftrightarrow u_R$$

$$-\mathcal{L} = Y^d_{ij} H_d \bar{d}^i_R q^j + Y^u_{ij} H_u \bar{u}^i_R q^j + \text{h.c.}$$

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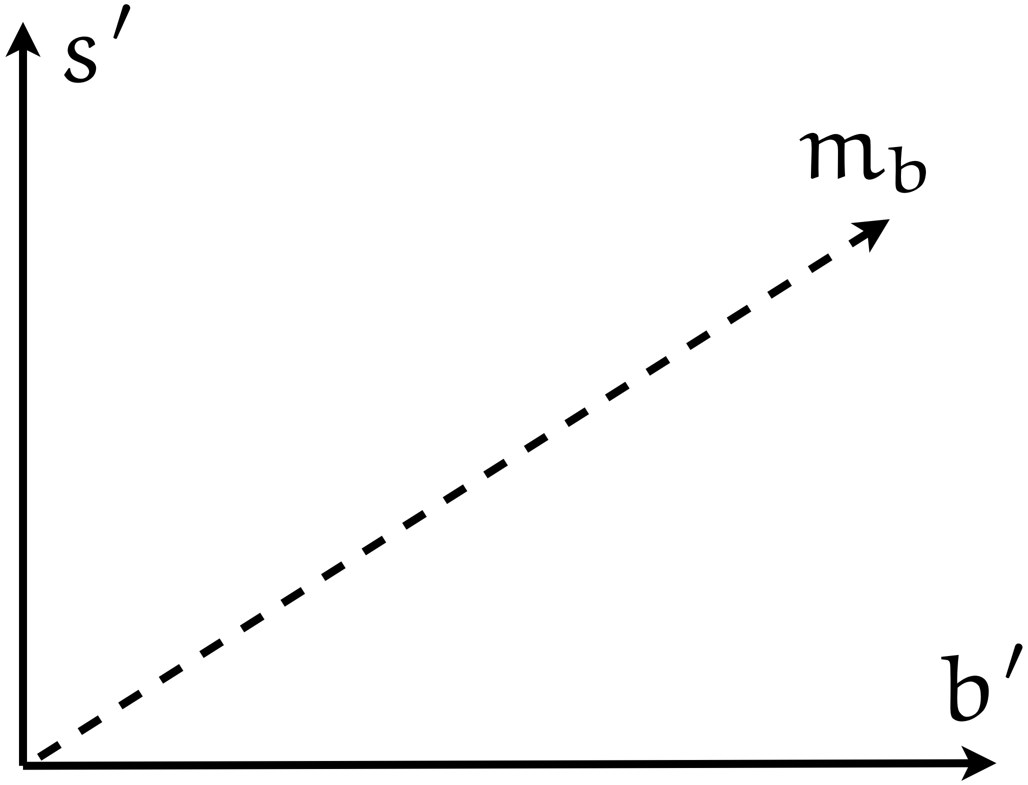

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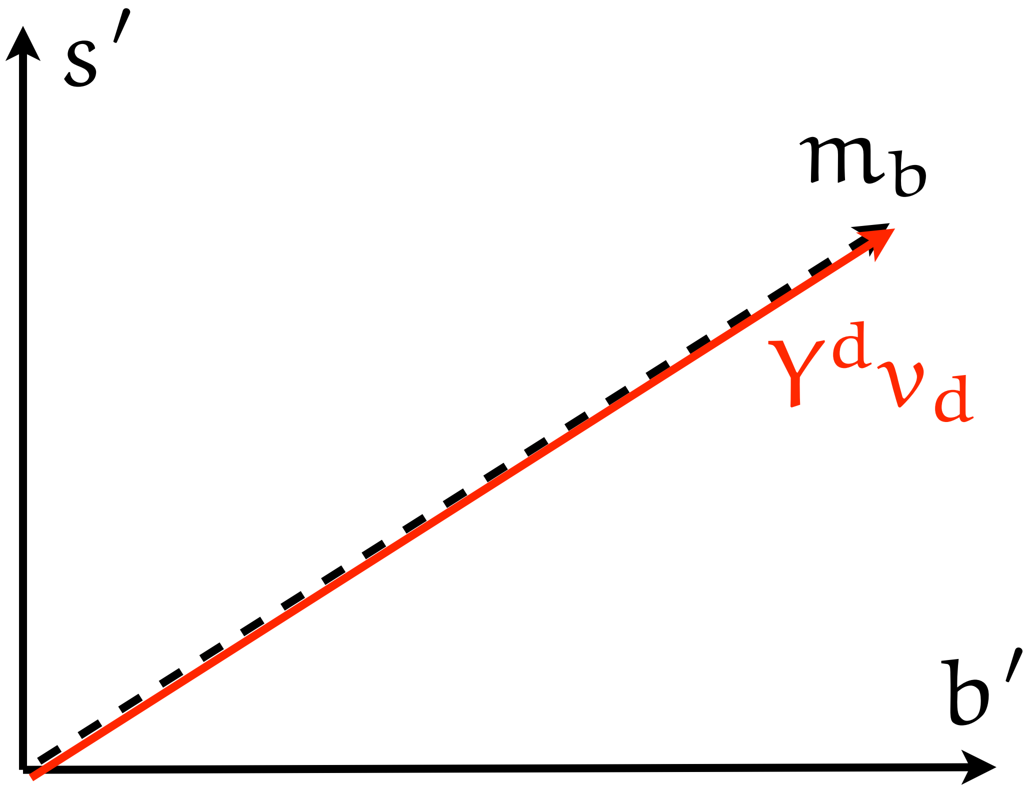

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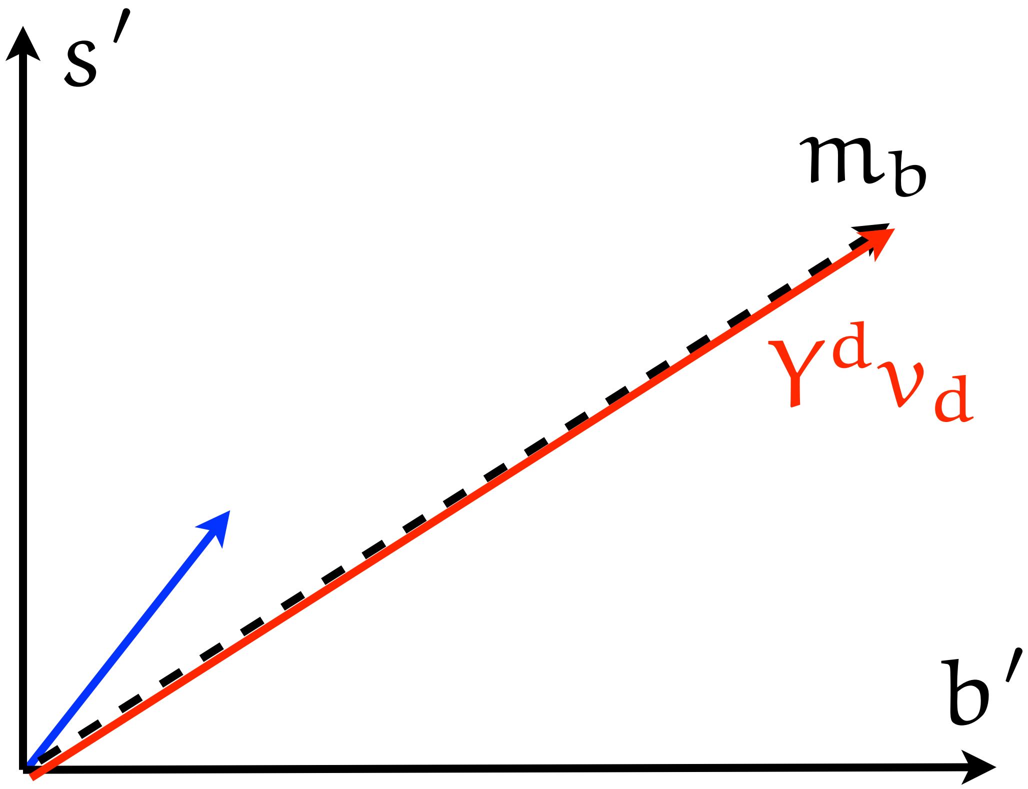

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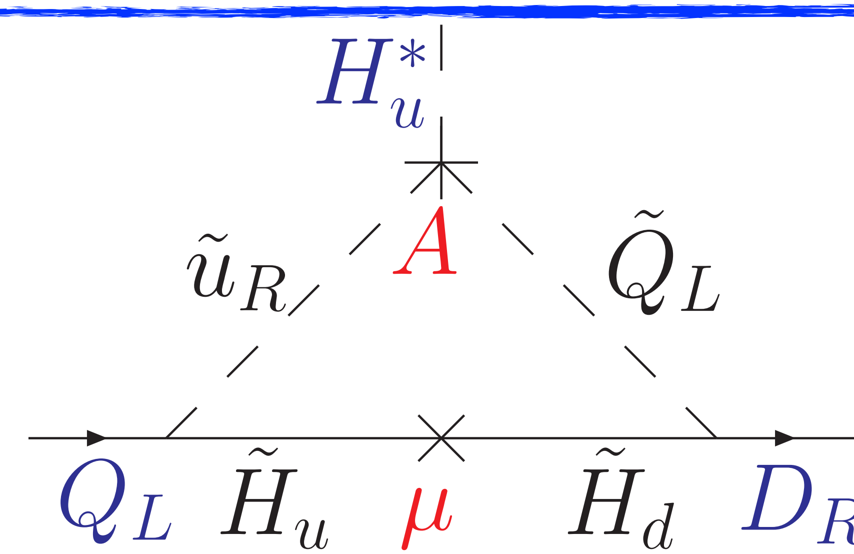

One loop: 2HDM of type 3

$$\Delta\mathcal{L}^Y_{\text{eff}} = \epsilon_Y \bar{d}_R Y^d Y^{u\dagger} Y^u H_u^* \cdot Q_L$$

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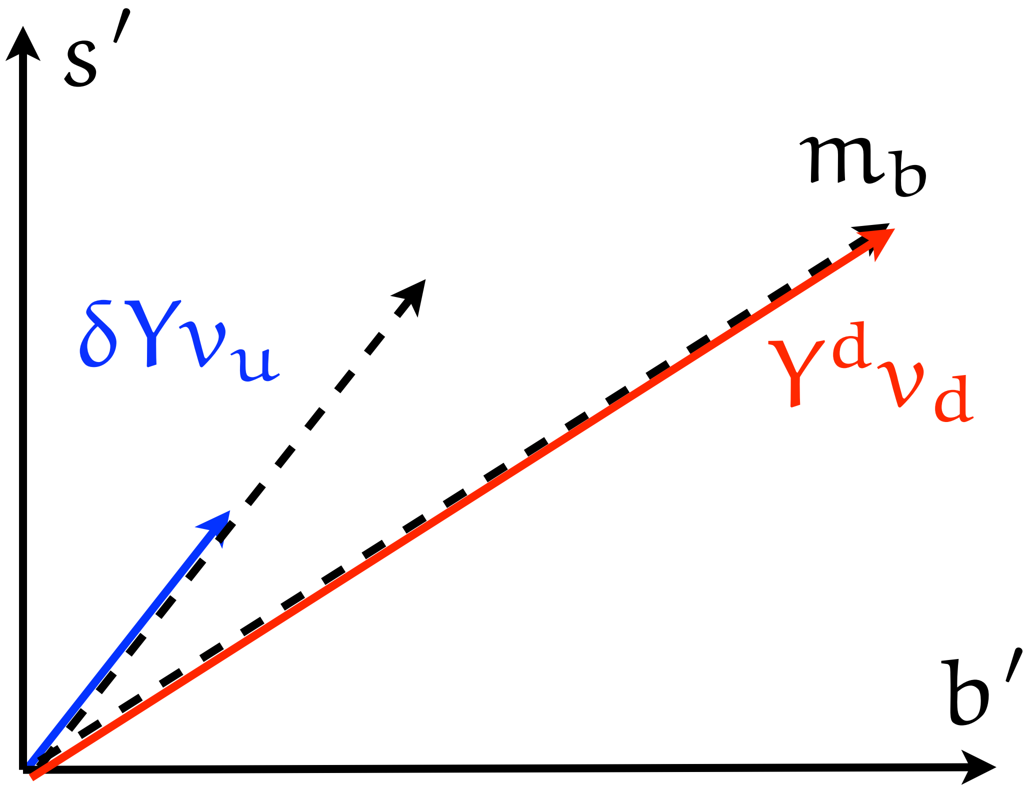

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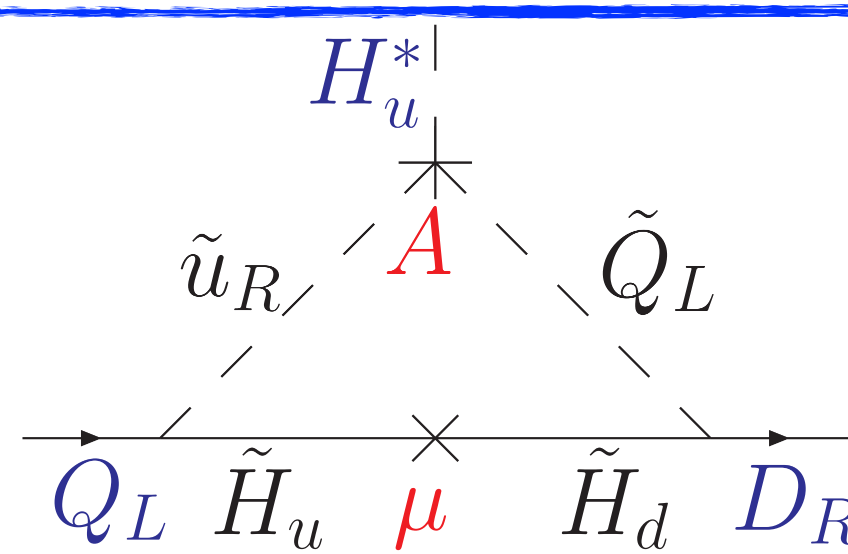

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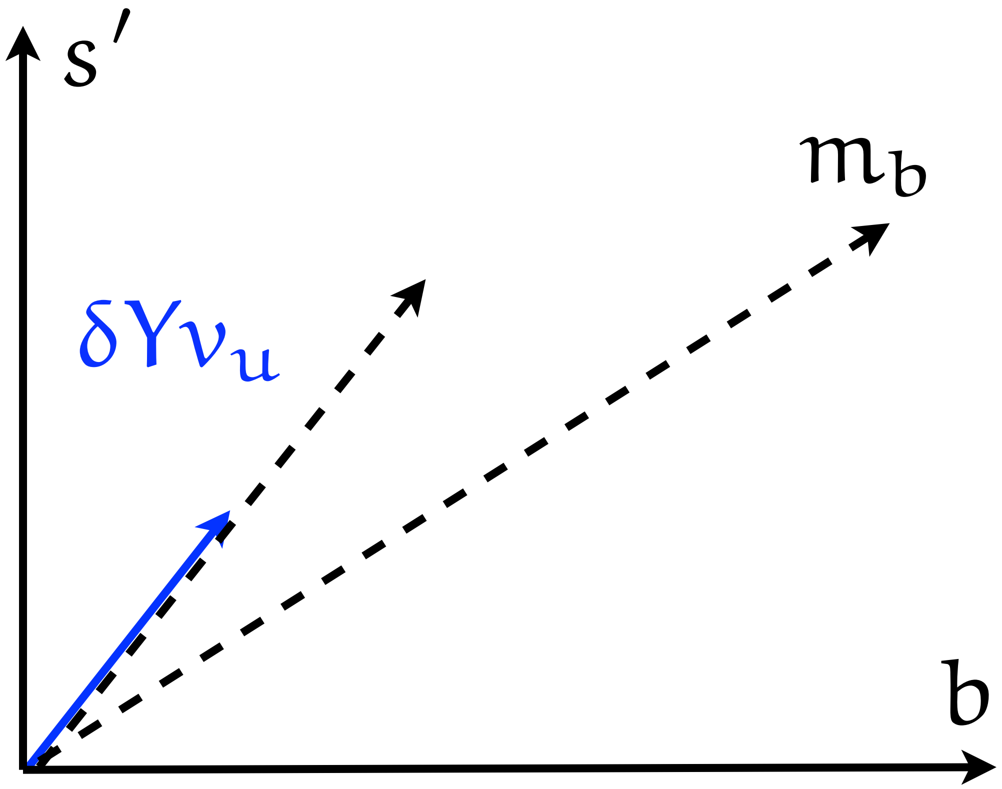

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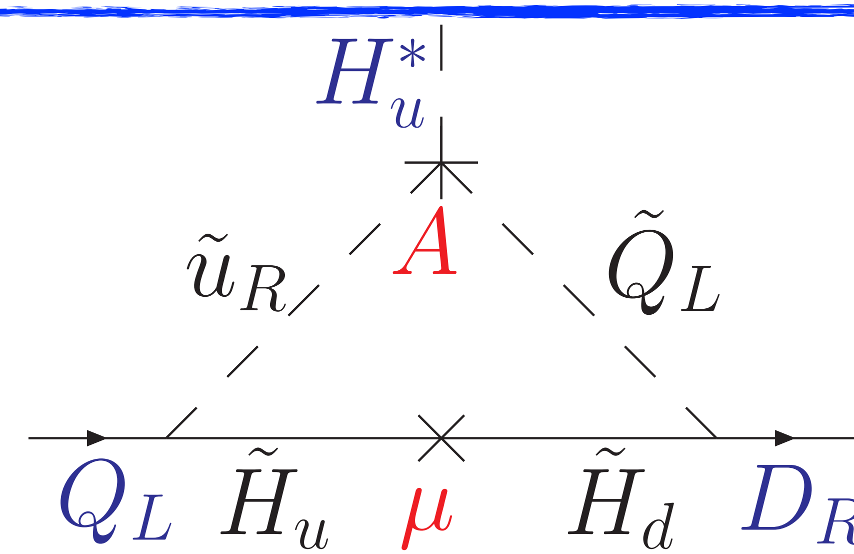

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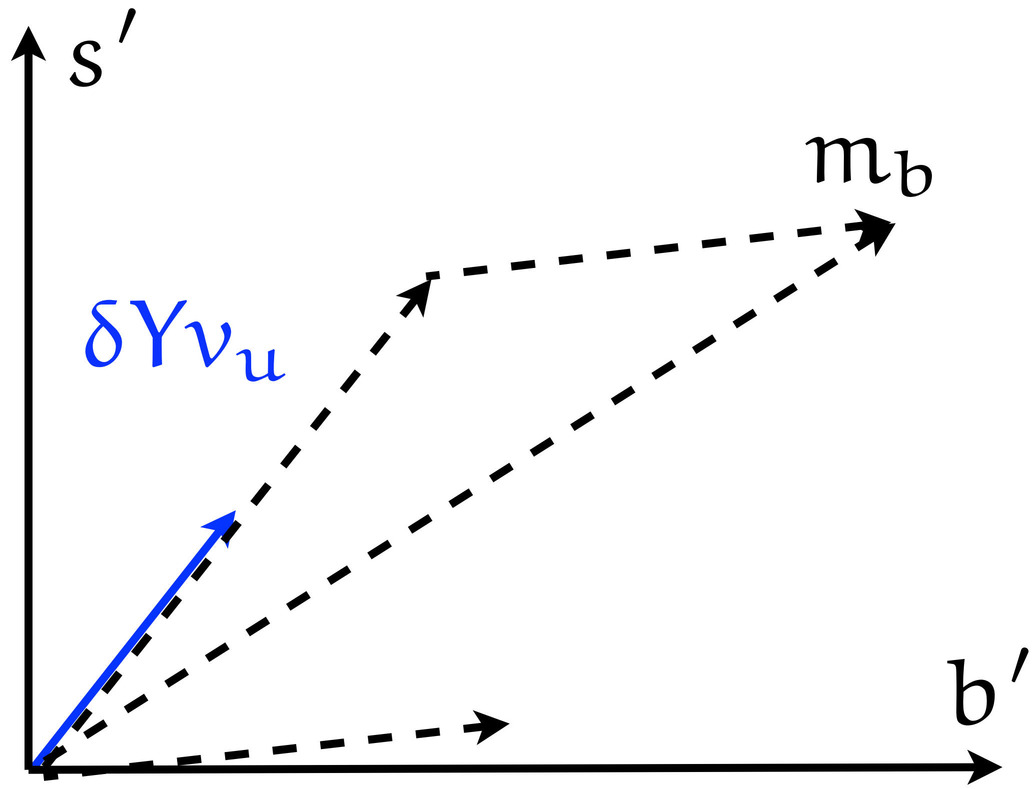

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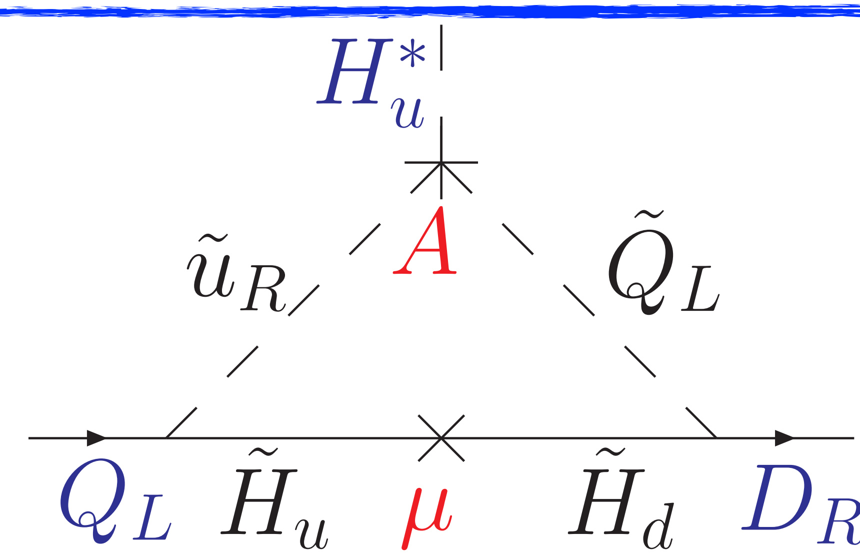

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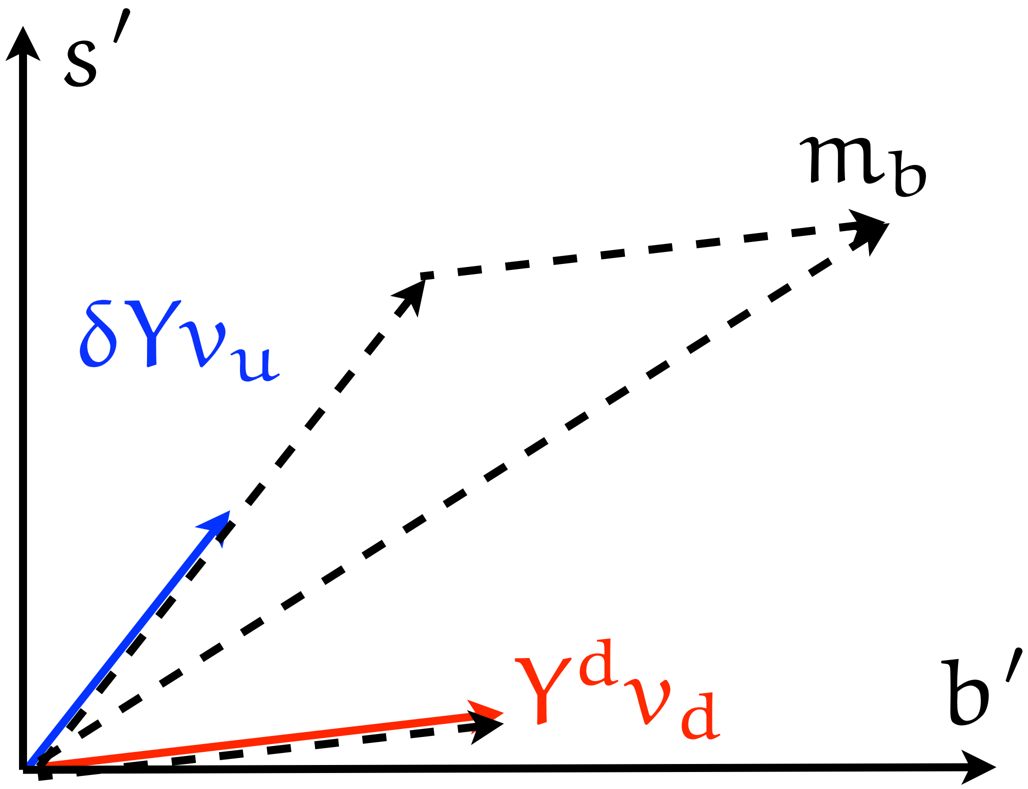

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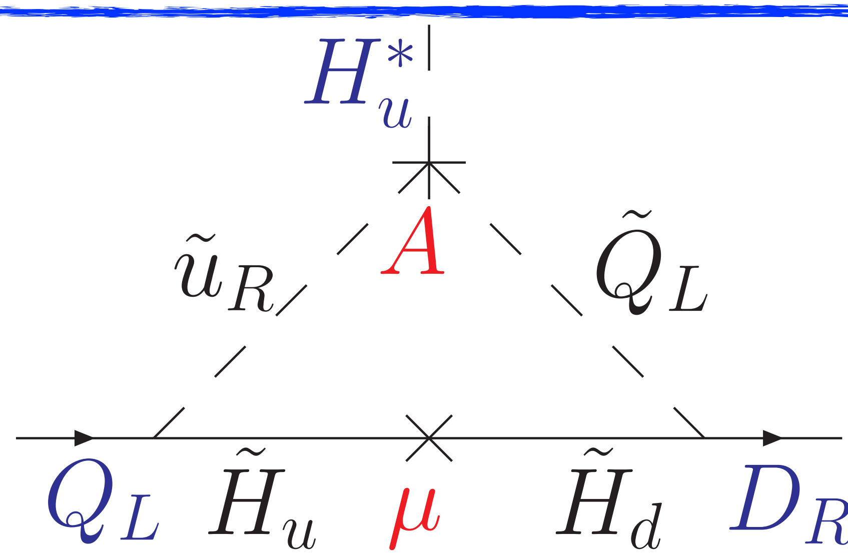

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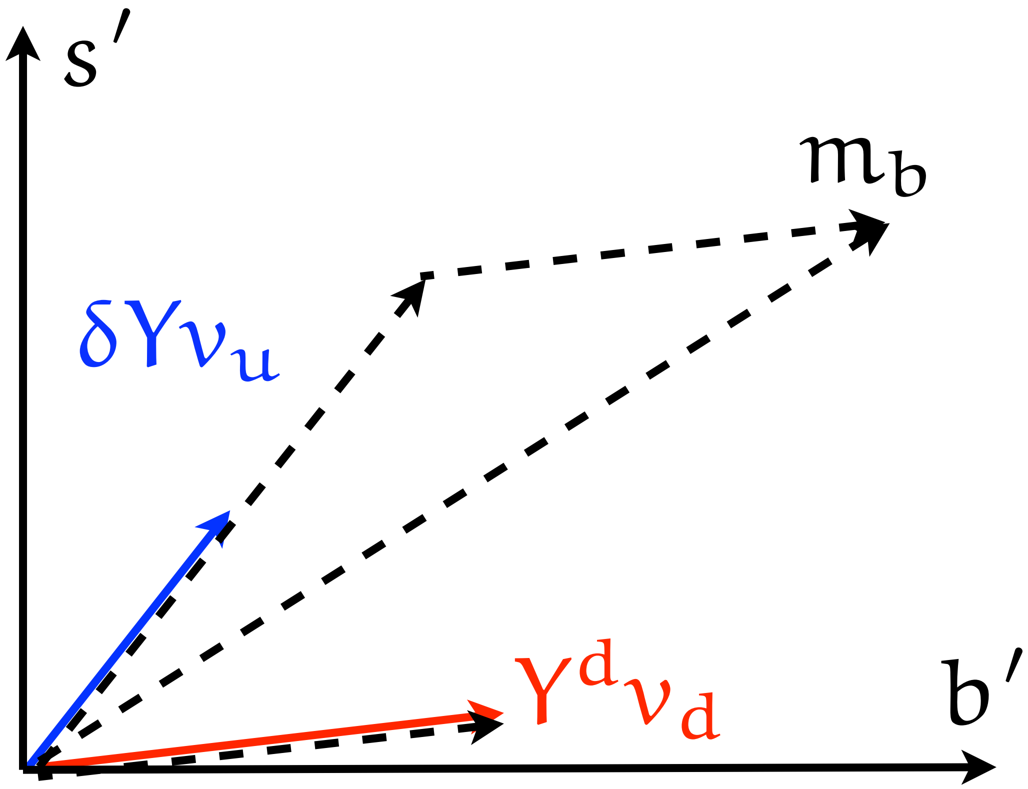

Redefinition

m_b & V_{CKM}

Masses and Yukawas not aligned

Lagrangian of 2HDM of type 2

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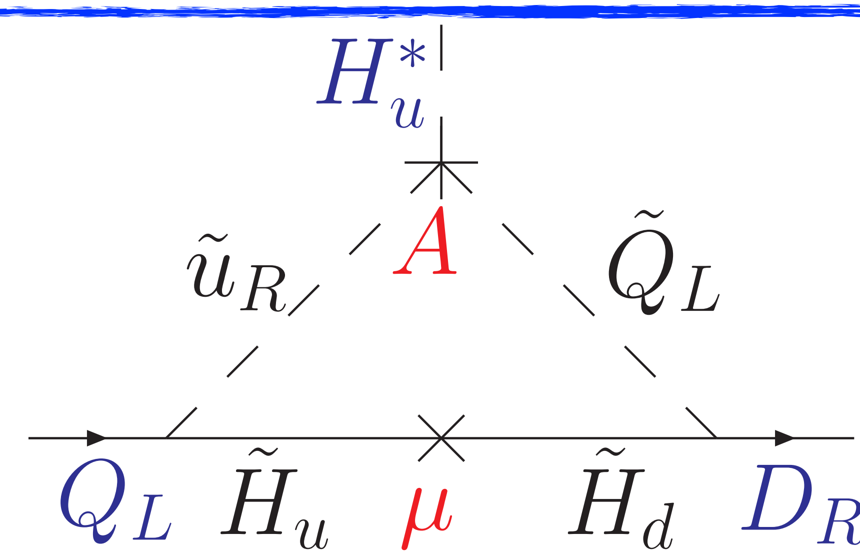

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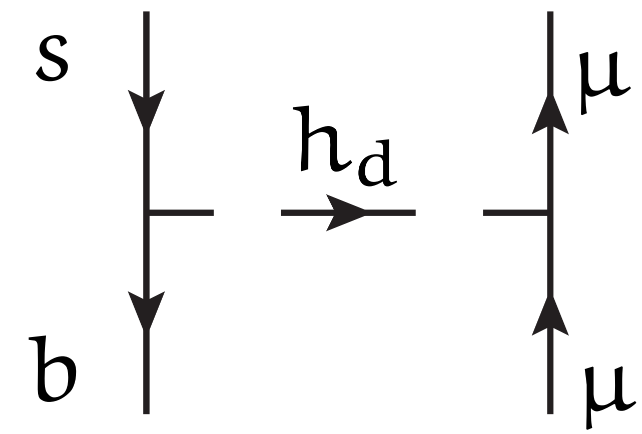
Flavour Violation at large tan β

Large tan β: O(1) flavour violation
[Babu, Kolda '02]
and O(1) couplings to quarks and leptons



$$\mathcal{B}(B_s \to \mu^+\mu^-) \sim 5 \cdot 10^{-7} \left(\frac{\tan\beta}{50}\right)^6 \left(\frac{300\text{GeV}}{M_A}\right)^4$$

can be small for large M_A, medium tan β, or different A terms to fulfil the experimental upper bound from LHCb: (ATLAS &CMS)

$$\mathcal{B}(B_s \to \mu^+\mu^-) < 4.5 \times 10^{-9}$$

$B_s \to \mu\,\mu$ (so far) not relevant for

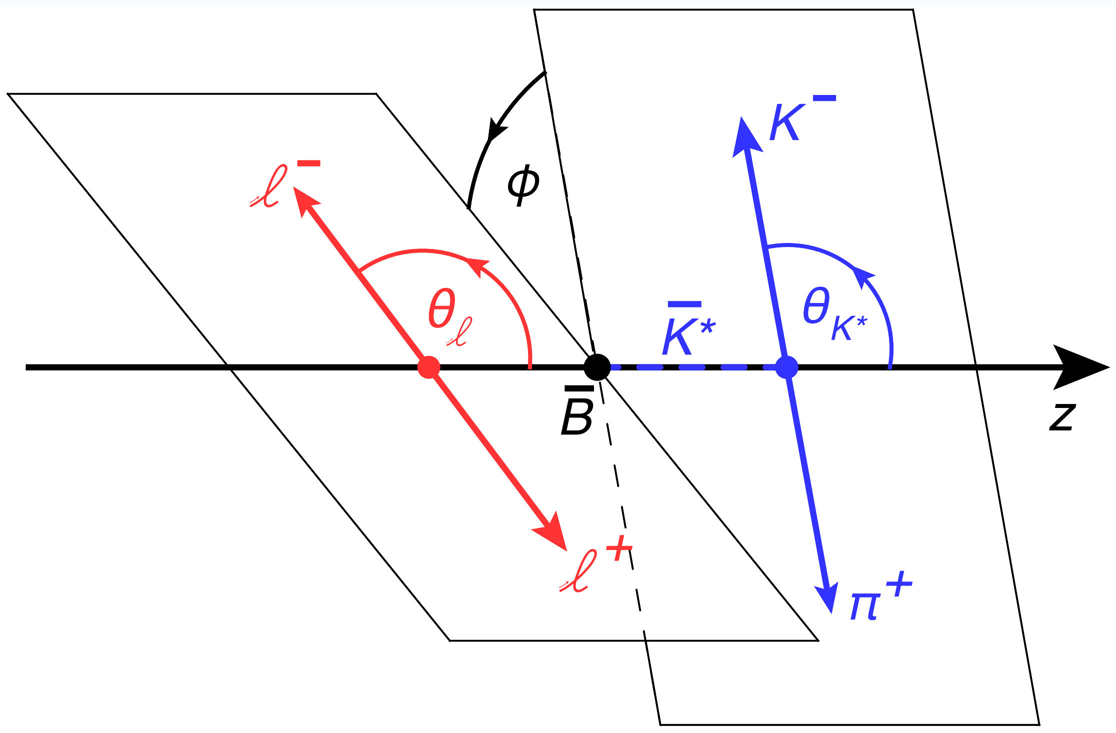
$$Q_9 = (\bar{b}_L \gamma_\mu s_L)(\bar{l}\gamma_\mu\gamma_5 l) \qquad Q_{10} = (\bar{b}_L \gamma_\mu s_L)(\bar{l}\gamma_\mu\gamma_5 l)$$

$$Q_9' = (\bar{b}_R \gamma_\mu s_R)(\bar{l}\gamma_\mu\gamma_5 l) \qquad Q_{10}' = (\bar{b}_R \gamma_\mu s_R)(\bar{l}\gamma_\mu\gamma_5 l)$$

$B \to K^{(*)}[\to K\pi] + \ell^+\ell^-$

Many angular observables for

$$B \to K^{(*)}[\to K\pi] + \ell^+\ell^-$$

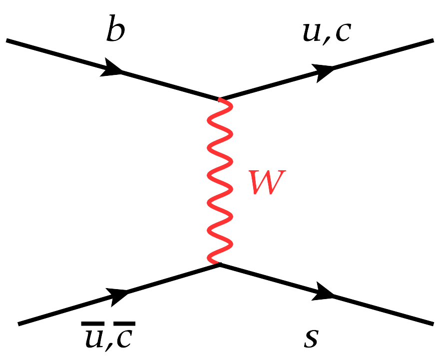


$$\frac{32\pi}{9}\frac{d^4\Gamma}{dq^2\, d\cos\theta_\ell\, d\cos\theta_K\, d\phi} = J_{1s}\sin^2\theta_K + J_{1c}\cos^2\theta_K + (J_{2s}\sin^2\theta_K + J_{2c}\cos^2\theta_K)\cos 2\theta_\ell$$
$$+J_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi + J_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi + J_5\sin 2\theta_K\sin\theta_\ell\cos\phi$$
$$+(J_{6s}\sin^2\theta_K + J_{6c}\cos^2\theta_K)\cos\theta_\ell + J_7\sin 2\theta_K\sin\theta_\ell\sin\phi$$
$$+J_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + J_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi$$

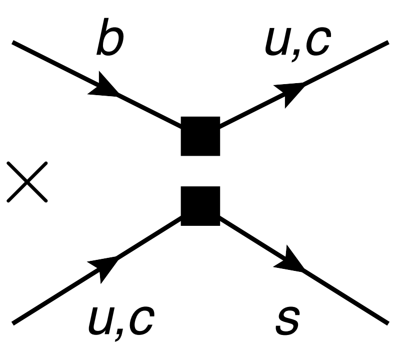
From these one can construct observables as e.g. forward backward asymmetry

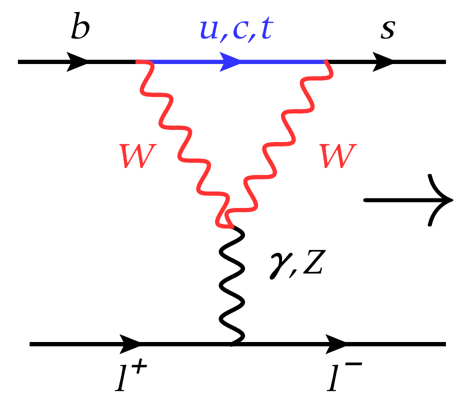
$\mathcal{L}_{\rm eff}$ for $b \to s\, l^+ l^-\ (q\,\bar{q})$

SM Wilson coefficients: Matching at $\mu \approx M_W$

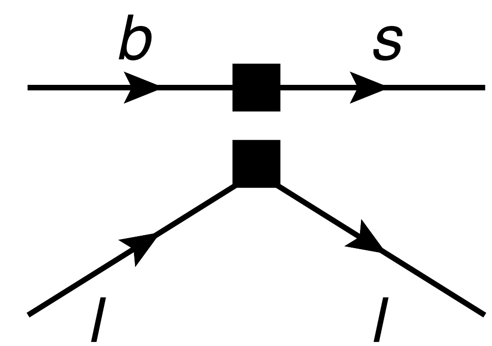


$\to C_2 \times$

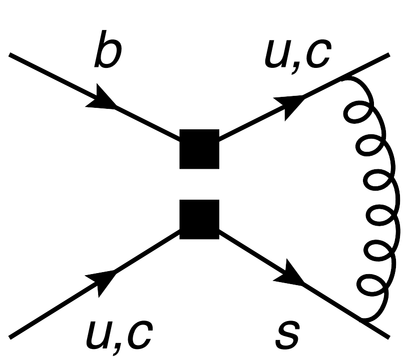


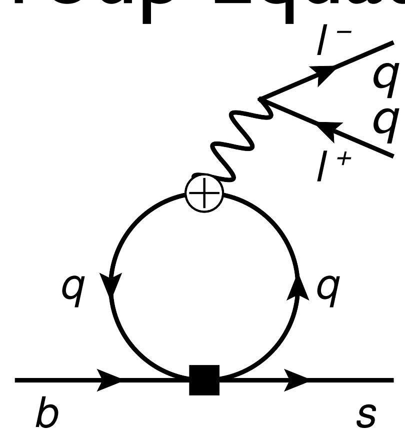


$\to C_{9,10} \times$

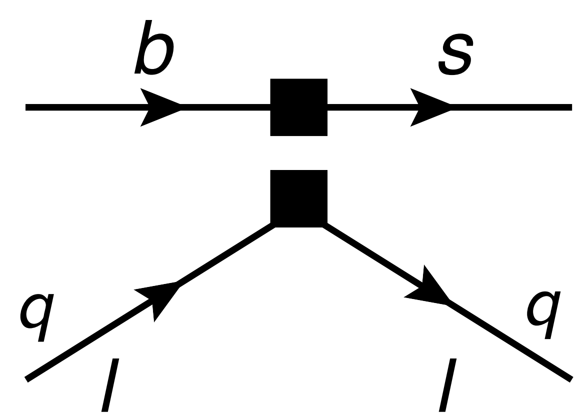


Renormalisation Group Equation → $\mu \approx M_W$





$\to C_{1\ldots10} \times$



$\to \mathcal{L}_{\rm eff}$ @ NNLL in QCD and NLL EW

[Bobeth, Gambino, MG `04, Haisch; MG, Haisch `05]

Exclusive $B \to K^{(*)} \ell^+ \ell^-$ decays

Systematic theoretical description based on heavy-quark expansion (Λ/mb) for $q^2 << m^2(J/\psi)$ (SCET)
[Benke, Feldmann, Seidel `01]

OPE for $q^2 >> m^2(J/\psi)$
[Grinstein et.al. ; Beylich et. al. `11]

Uncertainties: Form factors & power correction

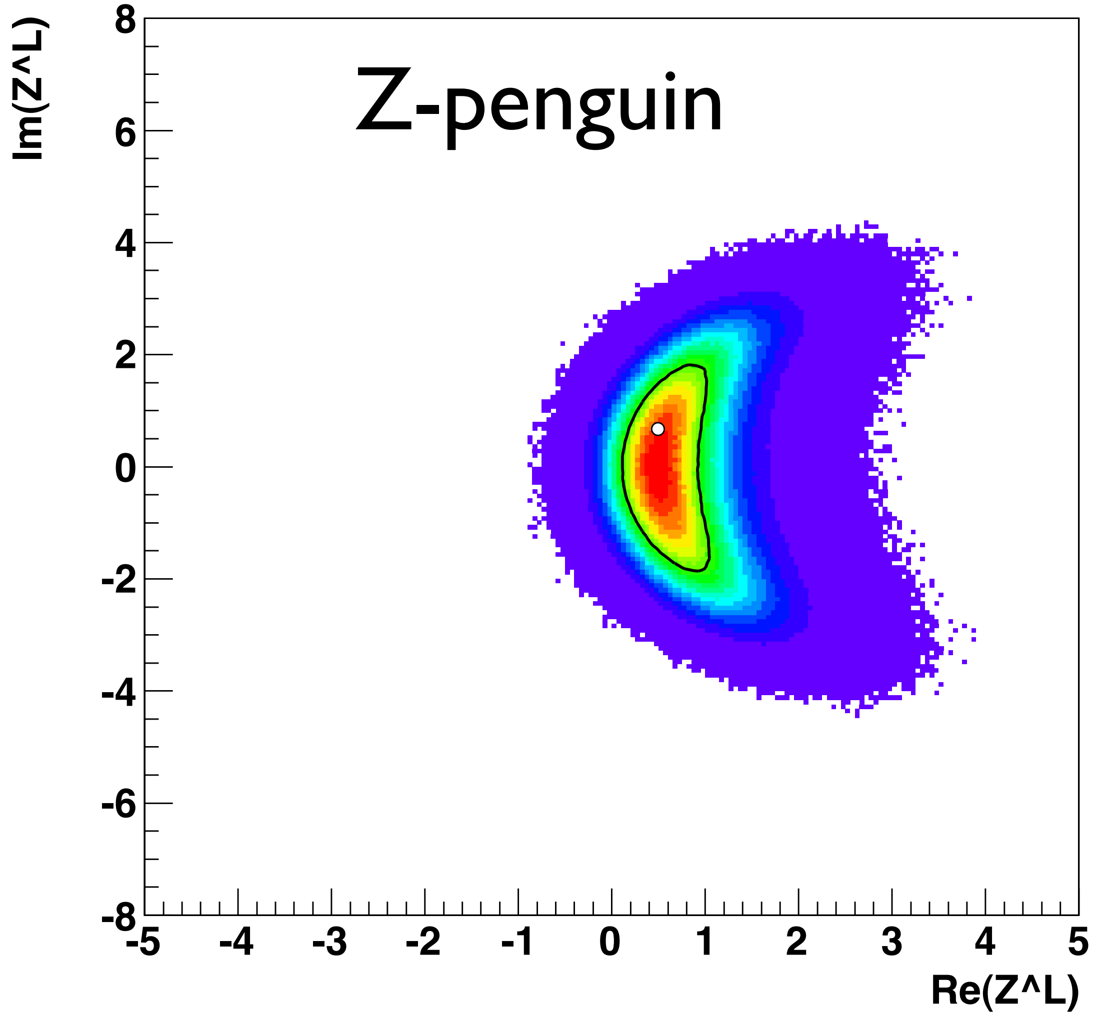
Form factor insensitive / sensitive quantities
[Krüger, Matias; ... Bobeth et. al.]

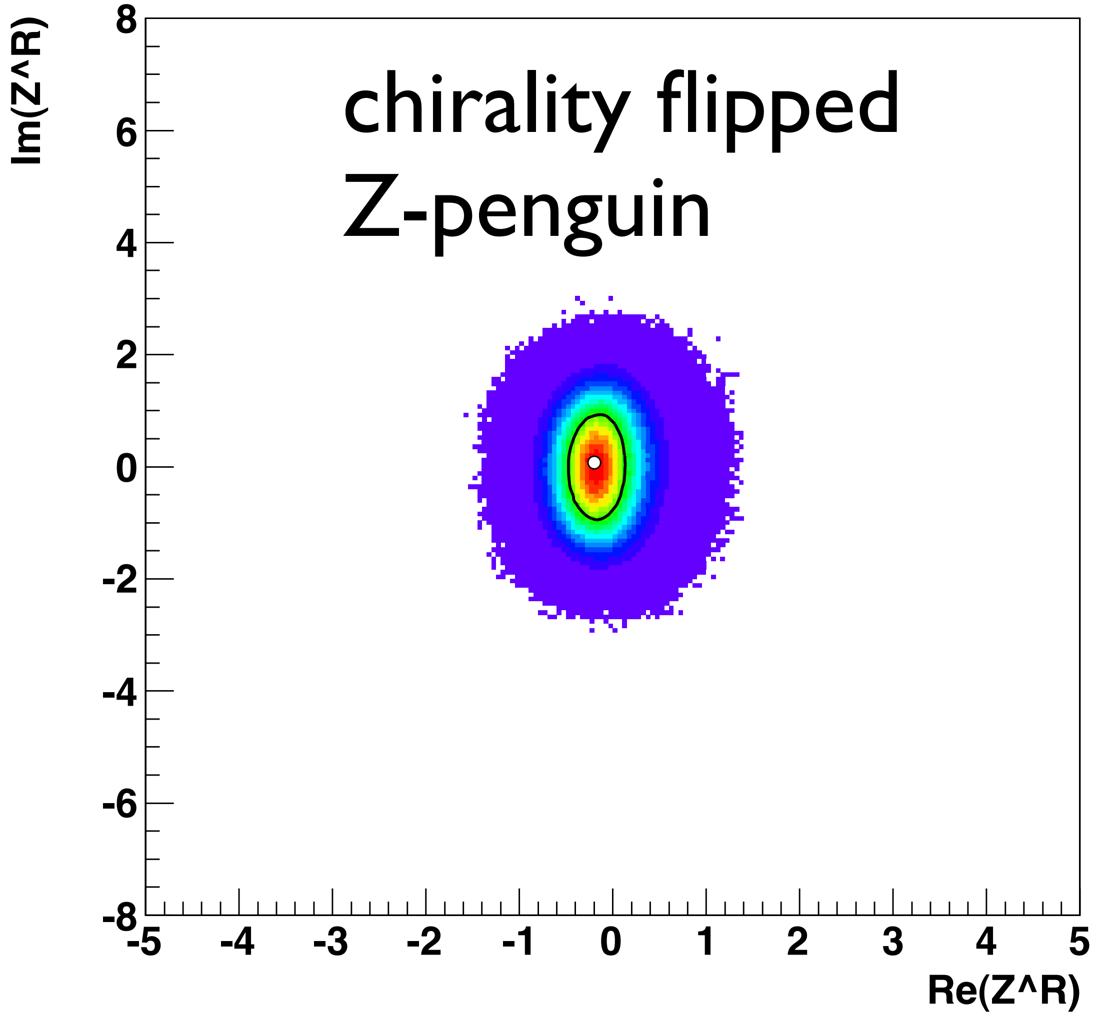
Constraints on New Physics

A new physics contribution to the Z-penguin correlates C_9 and C_{10} as well as hadronic and leptonic decays.

Sensitivity to the chirality of the couplings

[Bobeth, MG, Vickers] $b \to s\, l^+ l^-$



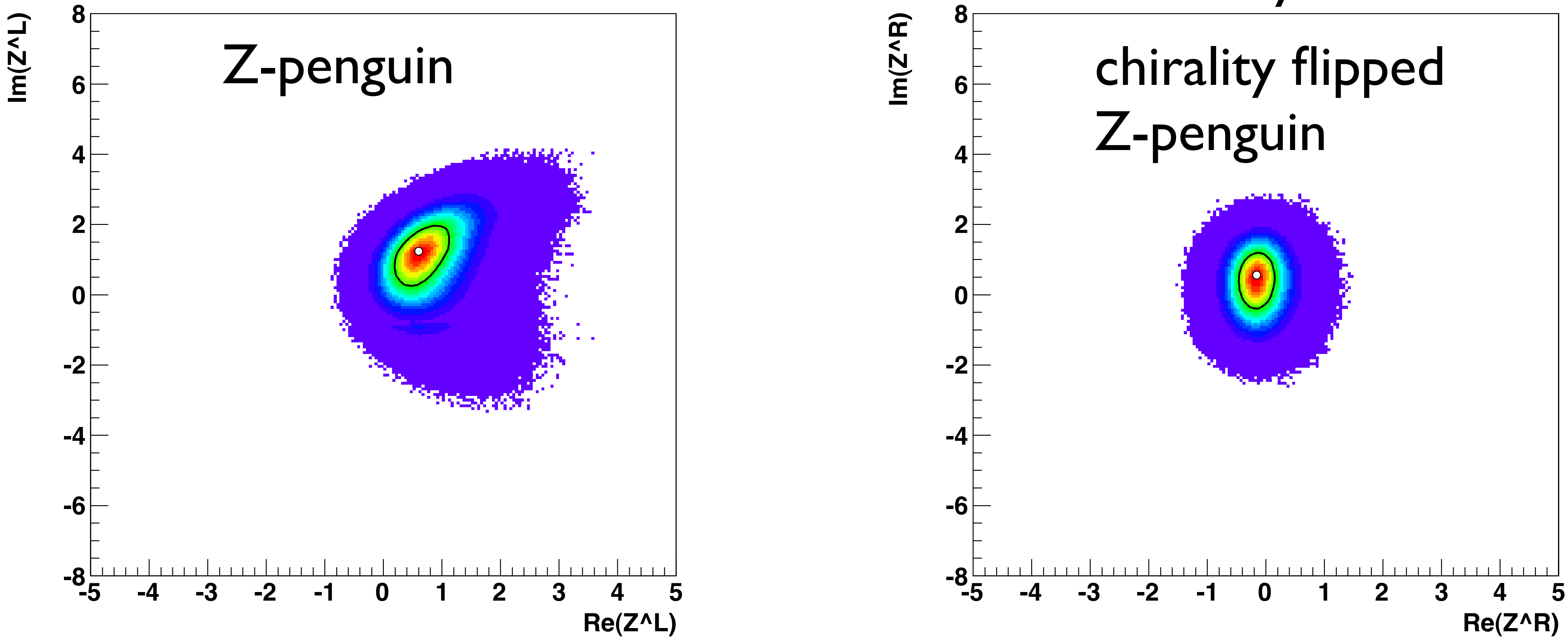


Constraints on New Physics

A new physics contribution to the Z-penguin correlates C_9 and C_{10} as well as hadronic and leptonic decays.

Sensitivity to the chirality of the couplings

[Bobeth, MG, Vickers] $b \rightarrow s\, l^+ l^-$ & hadronic decays



Conclusions

Overall: standard model agrees well with current LHCb data

Still: there is plenty of room to improve
i) the tests of the standard model
ii) search for new physics (also at NA62, Belle II)

Many more interesting things ($B \to X_s \gamma$, $B \to \tau \nu$, $B_s \to hh$, ...)