What can we learn from B physics?

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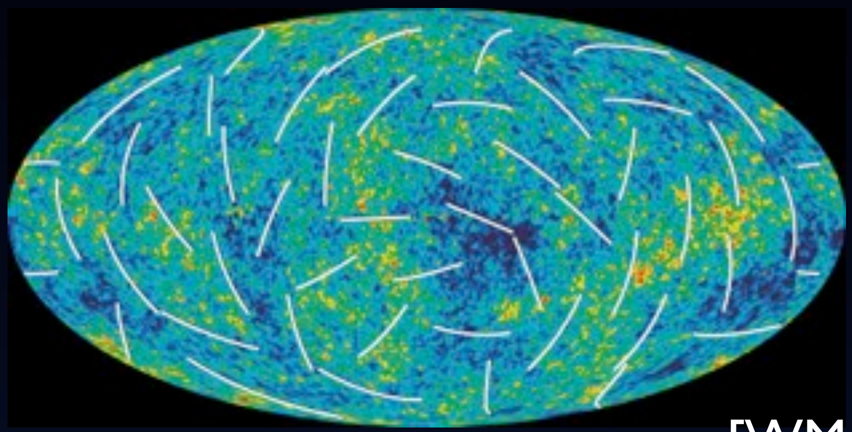
Content

- Flavour & CP: what & why
- Observables (selection), some theory issues
- A SUSY GUT model
- Conclusions

Baryogenesis

- There are many photons ... some baryons...



[WMAP]

[SDSS]

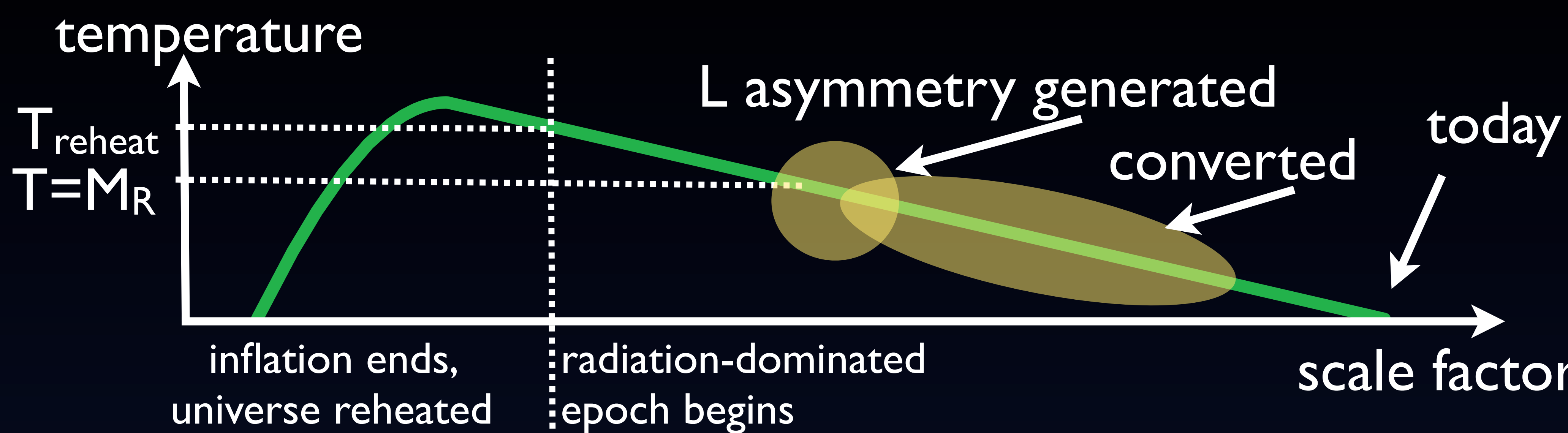
... and essentially no antibaryons in the universe

$$\boxed{\eta_B = \frac{n_B}{n_\gamma} = (6.3 \pm 0.3) \times 10^{-10}}$$

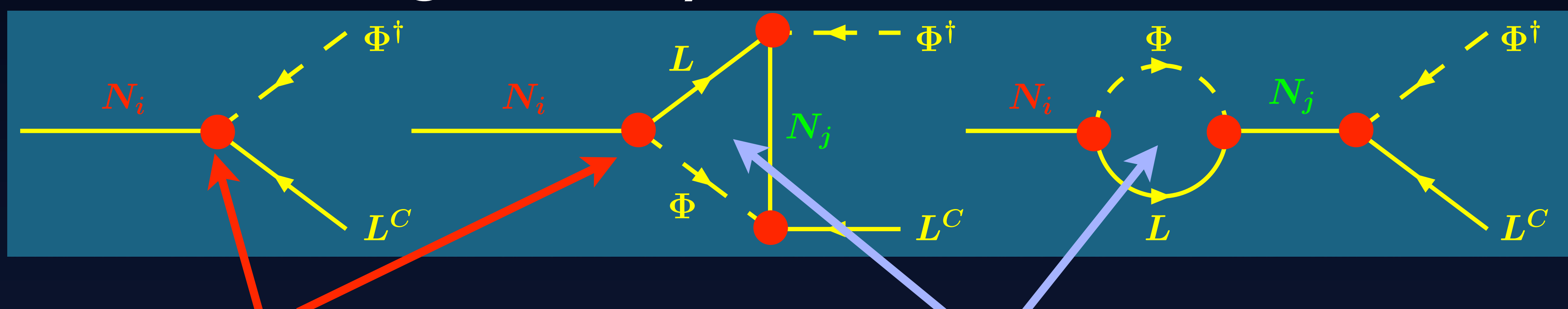
- Can arise dynamically from B=0 if sufficient...
(1) departure from equilibrium and
(2) C and CP violation and
(3) B violation

Sakharov 1967

Thermal leptogenesis



- CP-violating ν_R decay:

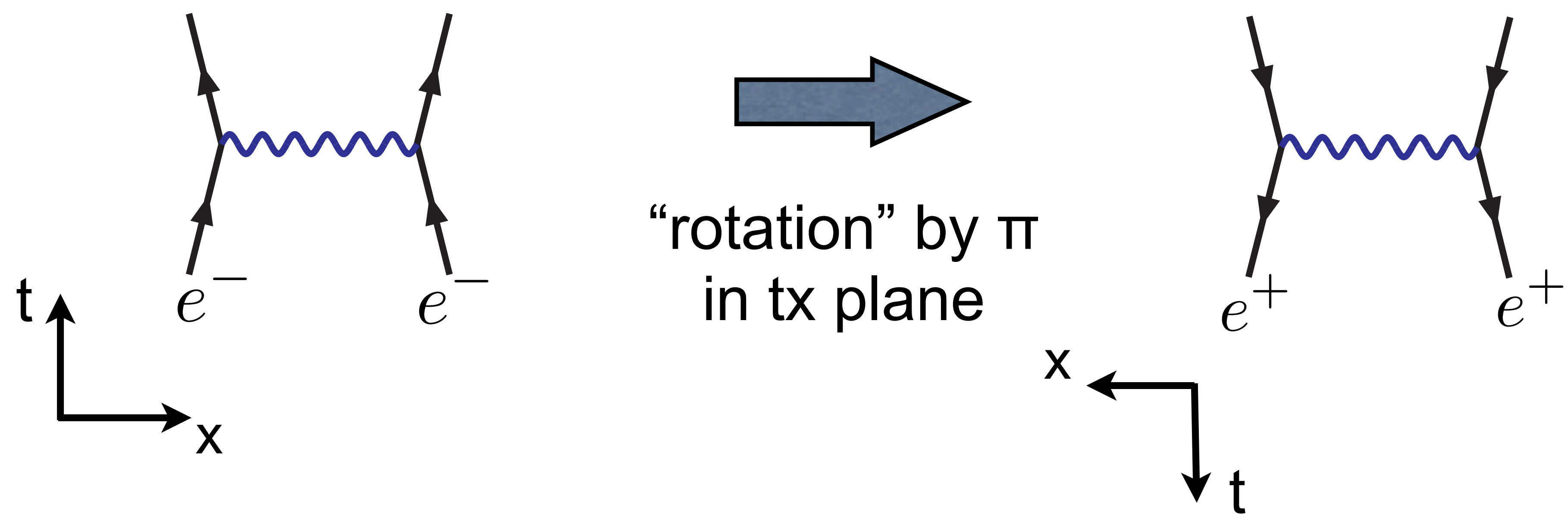


weak CPV phase in Y_ν CP-conserving phase from loop

- Resulting net lepton numbers $\langle L_l \rangle$ partially converted to $\langle B \rangle$ by equilibrium sphalerons

C, P and T

- In local quantum field theory CPT is a symmetry



i.e. simultaneously t ➔-t (time reversal T)
x ➔-x (parity P - up to a rotation)
particles ➔ antiparticles (charge conjugation C)

in particular CPT implies the existence of antiparticles with identical masses and lifetimes, and opposite conserved charges

(constructive proof at Lagrangian level, or more general proof in axiomatic field theory)

C and P violation

- C, P, T individually need not be symmetries
  - chiral fermions violate C & P maximally [no C,P partners]
  - gauge-fermion theories (renormalisable, only spins 1 and 1/2) preserve CP save for vacuum θ angle(s)
  - example: SM gauge sector (neglect θ_{QCD} for now)

$$\mathcal{L}_{\text{gauge}} = \sum_f \bar{\psi}_f \gamma^\mu D_\mu \psi_f - \sum_{i,a} \frac{1}{4} g_i F^{ia}_{\mu\nu} F^{ia\mu\nu}$$

$$f = Q_{Lj}, u_{Rj}, d_{Rj}, L_{Lj}, e_{Rj} \quad j = 1,2,3$$ chiral fermions

  - conserves CP; large global *flavour* symmetry

$$G_{\text{flavor}} = SU(3)^5 \times U(1)_B \times U(1)_A \times U(1)_L \times U(1)_E$$

$$Q_L \to e^{i(b/3+a)} V_{Q_L} Q_L,\ u_R \to e^{i(b/3-a)} V_{u_R} u_R,\ d_R \to e^{i(b/3-a)} V_{d_R} d_R$$

$$L_L \to e^{i(l+a)} V_L L_L,\ e_R \to e^{i(l+e-a)} V_R e_R$$

Chivukula, Georgi 1987

CP violation

- Vacuum θ angle(s) violate CP

$$\mathcal{L} \supset -\theta \frac{g^2}{32\,\pi^2} F^a_{\mu\nu}\tilde{F}^{\mu\nu\,a} \propto \vec{E}^a \cdot \vec{B}^a$$

P and CP odd

hadronic electric dipole moments (EDMs)

- CP violation generic if scalars are present
SM Yukawa interactions:

9 masses

3 mixing angles

$$\mathcal{L}_Y = -\bar{u}_R Y_U \phi^{c\dagger} Q_L - \bar{d}_R Y_D \phi^\dagger D_L - \bar{e}_R Y_E \phi^\dagger E_L$$

1 CP-violating phase

$$Y_U = 1/v\,\mathrm{diag}(m_u, m_c, m_t)\,V_{\mathrm{CKM}}$$

$$Y_D = 1/v\,\mathrm{diag}(m_d, m_s, m_b)$$

$$Y_E = 1/v\,\mathrm{diag}(m_e, m_\mu, m_\tau)$$

CP violation of this type requires 3 generations Kobayashi, Maskawa 1972

- flavour symmetry broken to $U(1)_B \times U(1)_e \times U(1)_\mu \times U(1)_\tau$

close connection CP - flavour - EW symmetry breaking (Higgs) sector

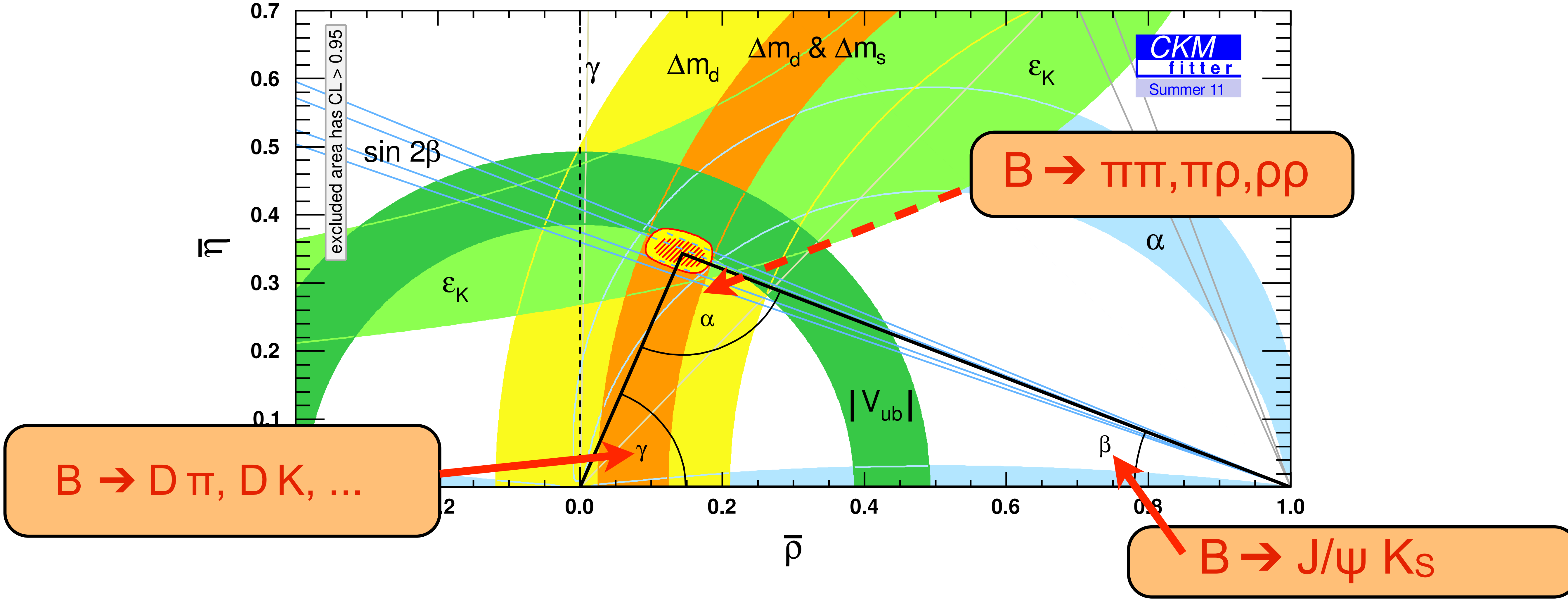
Observables

- CP-violating, flavour-conserving
  neutron, electron, atomic EDM's
  advantage: ultraclean tests of SM and we "know" that BSM CP violation exists
  disadvantage: CP violation could be at scales >> TeV and possibly out of reach

- CP-violating, flavour-violating
  CPV in K,D, B, B_s mixing and mixing-decay interference
  direct CPV (CPV in decay)
  triple-product asymmetries
  advantage: various clean tests of SM
  disadvantage: TeV scale need not be CPV (see above)

- CP-conserving, flavour-violating
  Rare K, (D,) B, B_s decays: BR's, kinematic distributions
  lepton flavour violation
  advantage: TeV physics is guaranteed to affect these
  disadvantage: fewer/less clean tests of SM

Unitarity Triangle 2011

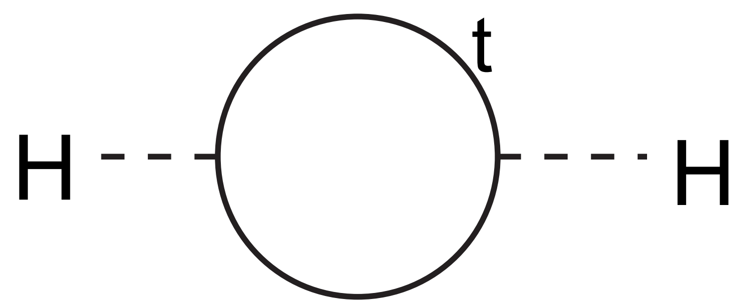


The CKM picture of flavour & CP violation is consistent with observations.

Within the Standard Model, all parameters (except higgs mass) including CKM have been determined, with good precision

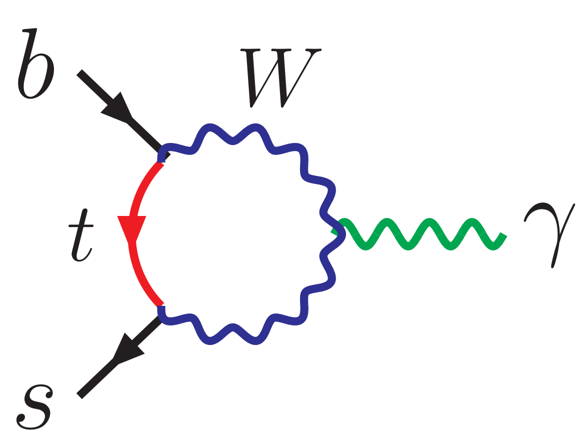
Flavour of the TeV scale

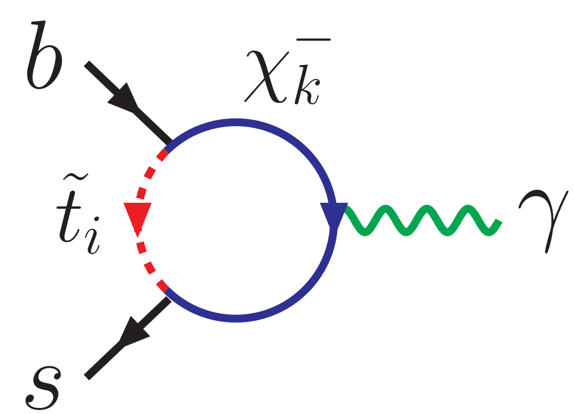
- Solutions to the hierarchy problem must bring in particles to cut off the top contribution to the weak scale (Higgs mass parameter).



$$\propto y_t^2 \Lambda_{\mathrm{UV}}^2$$

- The new particles' couplings tend to break flavour (they do in all the major proposals for TeV physics)

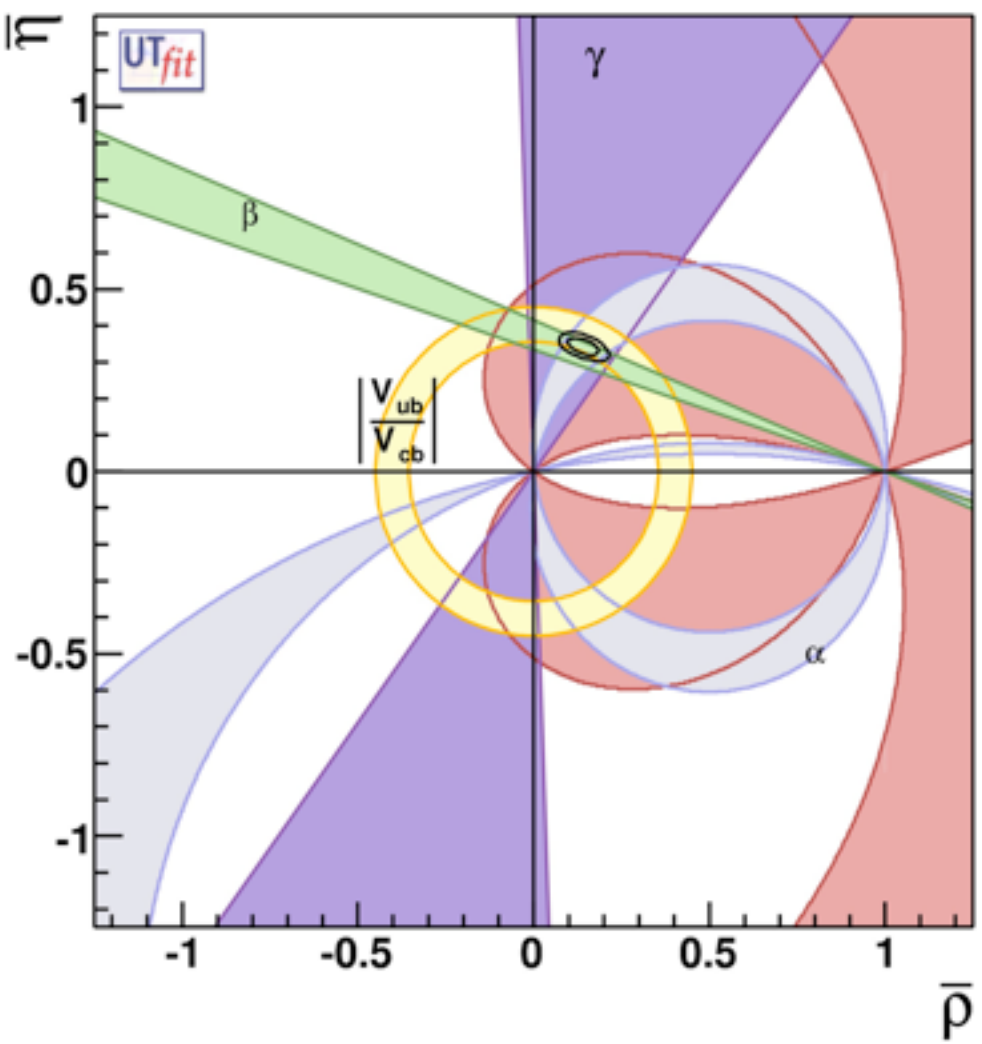




- At least they will have CKM-like flavour violations (minimal flavour violation), so will always affect rare decays

Minimal flavour violation

- in this case, CKM parameters can still be extracted unambiguously beyond the Standard Model



Universal unitarity triangle (UUT)

Buras, Gambino, Gorbahn, SJ, Silvestrini 2000

independent of details of new physics (particle content, masses, couplings)

UTfit collaboration (Bona et al)

- however, this is a very restrictive scenario; typically does not apply to dynamical BSM models

- can be generalized (relaxed)

d'Ambrosio et al 2002
Kagan et al 2009
...

SUSY flavour

Supersymmetry associates a scalar with every SM fermion

Squark mass matrices are 6x6 with independent flavour structure:

3x3 flavour-violating - and *supersymmetry-breaking*

$$\mathcal{M}^2_{\tilde{d}} = \begin{pmatrix} \hat{m}^2_{\tilde{Q}} + m_d^2 + D_{dLL} & v_1 \hat{T}_D - \mu^* m_d \tan\beta \\ v_1 \hat{T}_D^\dagger - \mu m_d \tan\beta & \hat{m}^2_{\tilde{d}} + m_d^2 + D_{dRR} \end{pmatrix} \equiv \begin{pmatrix} (\mathcal{M}^2_{\tilde{d}})^{LL} & (\mathcal{M}^2_{\tilde{d}})^{LR} \\ (\mathcal{M}^2_{\tilde{d}})^{RL} & (\mathcal{M}^2_{\tilde{d}})^{RR} \end{pmatrix}$$

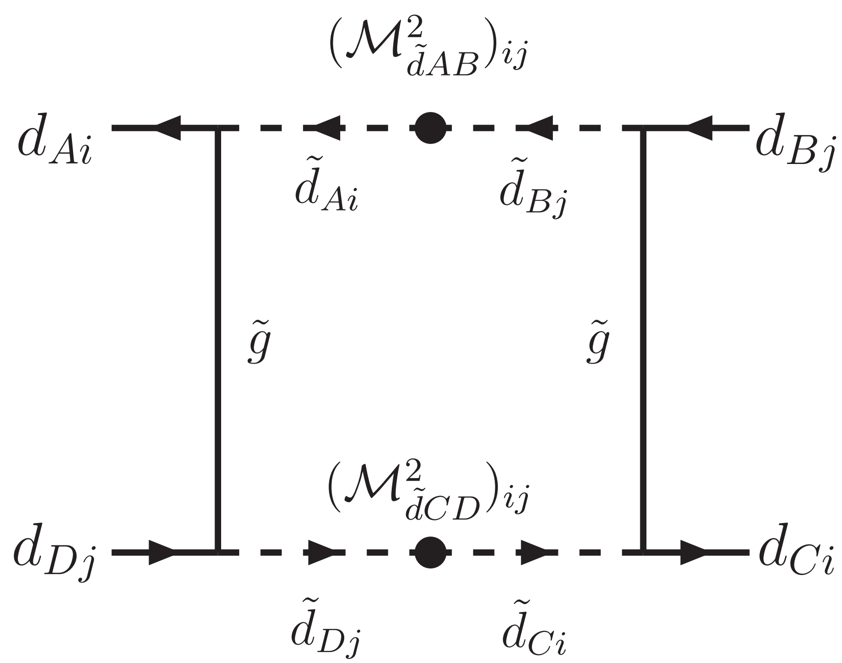
similar for up squarks, charged sleptons. 3x3 LL for sneutrinos

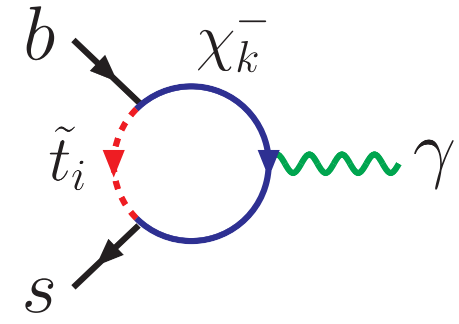
$$(\delta^{u,d,e,\nu}_{ij})_{AB} \equiv \frac{\left(\mathcal{M}^2_{\tilde{u},\tilde{d},\tilde{e},\tilde{\nu}}\right)^{AB}_{ij}}{m^2_{\tilde{f}}}$$

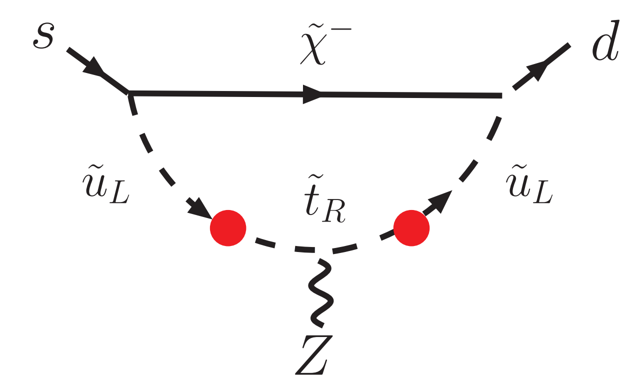
33 flavour-violating parameters

45 CPV (some flavour-conserving)

SUSY flavour - observables



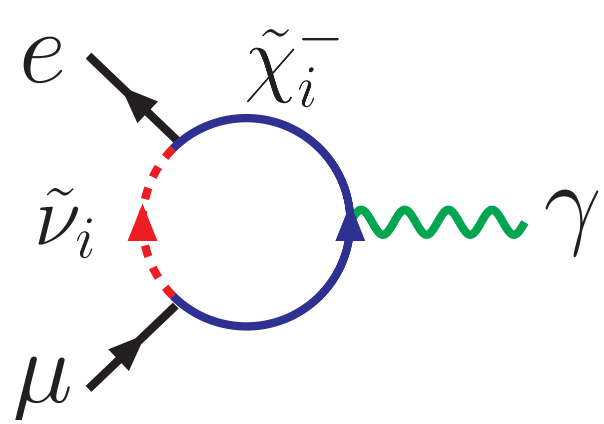




K-$\overline{K}$, B_d-$\overline{B}_d$, B_s-$\overline{B}_s$ mixing

$\Delta F=1$ decays

$B \rightarrow X_s\,\gamma$
$B \rightarrow X_s\,\mu^+\mu^-$
$B \rightarrow K^*\gamma$, $B \rightarrow K^*\mu^+\mu^-$, $B \rightarrow K\pi$
$B_{s,d} \rightarrow \mu^+\mu^-$
$K \rightarrow \pi\nu\nu$
$B \rightarrow K\nu\nu$
...



lepton flavour violation

$\mu \rightarrow e\gamma$, $\tau \rightarrow e\gamma$ $\tau \rightarrow \mu\gamma$
$\tau \rightarrow \mu\mu\mu$, ...
$\mu \rightarrow e$ conversion
...

SUSY flavour puzzle

$$\left(\delta_{ij}^{u,d,e,\nu}\right)_{AB} \equiv \frac{\left(\mathcal{M}^2_{\tilde{u},\tilde{d},\tilde{e},\tilde{\nu}}\right)^{AB}_{ij}}{m^2_{\tilde{f}}}$$

where are their effects?

Quantity	upper bound
$\sqrt{\lvert\mathrm{Re}(\delta^d_{ds})^2_{LL}\rvert}$	4.0×10^{-2}
$\sqrt{\lvert\mathrm{Re}(\delta^d_{ds})^2_{RR}\rvert}$	4.0×10^{-2}
$\sqrt{\lvert\mathrm{Re}(\delta^d_{ds})^2_{LR}\rvert}$	4.4×10^{-3}
$\sqrt{\lvert\mathrm{Re}(\delta^d_{ds})_{LL}(\delta^d_{ds})_{RR}\rvert}$	2.8×10^{-3}
$\sqrt{\lvert\mathrm{Im}(\delta^d_{ds})^2_{LL}\rvert}$	3.2×10^{-3}
$\sqrt{\lvert\mathrm{Im}(\delta^d_{ds})^2_{RR}\rvert}$	3.2×10^{-3}
$\sqrt{\lvert\mathrm{Im}(\delta^d_{ds})^2_{LR}\rvert}$	3.5×10^{-4}
$\sqrt{\lvert\mathrm{Im}(\delta^d_{ds})_{LL}(\delta^d_{ds})_{RR}\rvert}$	2.2×10^{-4}

Quantity	upper bound
$\sqrt{\lvert\mathrm{Re}(\delta^d_{db})^2_{LL}\rvert}$	9.8×10^{-2}
$\sqrt{\lvert\mathrm{Re}(\delta^d_{db})^2_{RR}\rvert}$	9.8×10^{-2}
$\sqrt{\lvert\mathrm{Re}(\delta^d_{db})^2_{LR}\rvert}$	3.3×10^{-2}
$\sqrt{\lvert\mathrm{Re}(\delta^d_{db})_{LL}(\delta^d_{db})_{RR}\rvert}$	1.8×10^{-2}
$\sqrt{\lvert\mathrm{Re}(\delta^d_{sb})^2_{LL}\rvert}$	4.8×10^{-1}
$\sqrt{\lvert\mathrm{Re}(\delta^d_{sb})^2_{RR}\rvert}$	4.8×10^{-1}
$\sqrt{\lvert\mathrm{Re}(\delta^d_{sb})^2_{LR}\rvert}$	1.62×10^{-2}
$\sqrt{\lvert\mathrm{Re}(\delta^d_{sb})_{LL}(\delta^d_{sb})_{RR}\rvert}$	8.9×10^{-2}

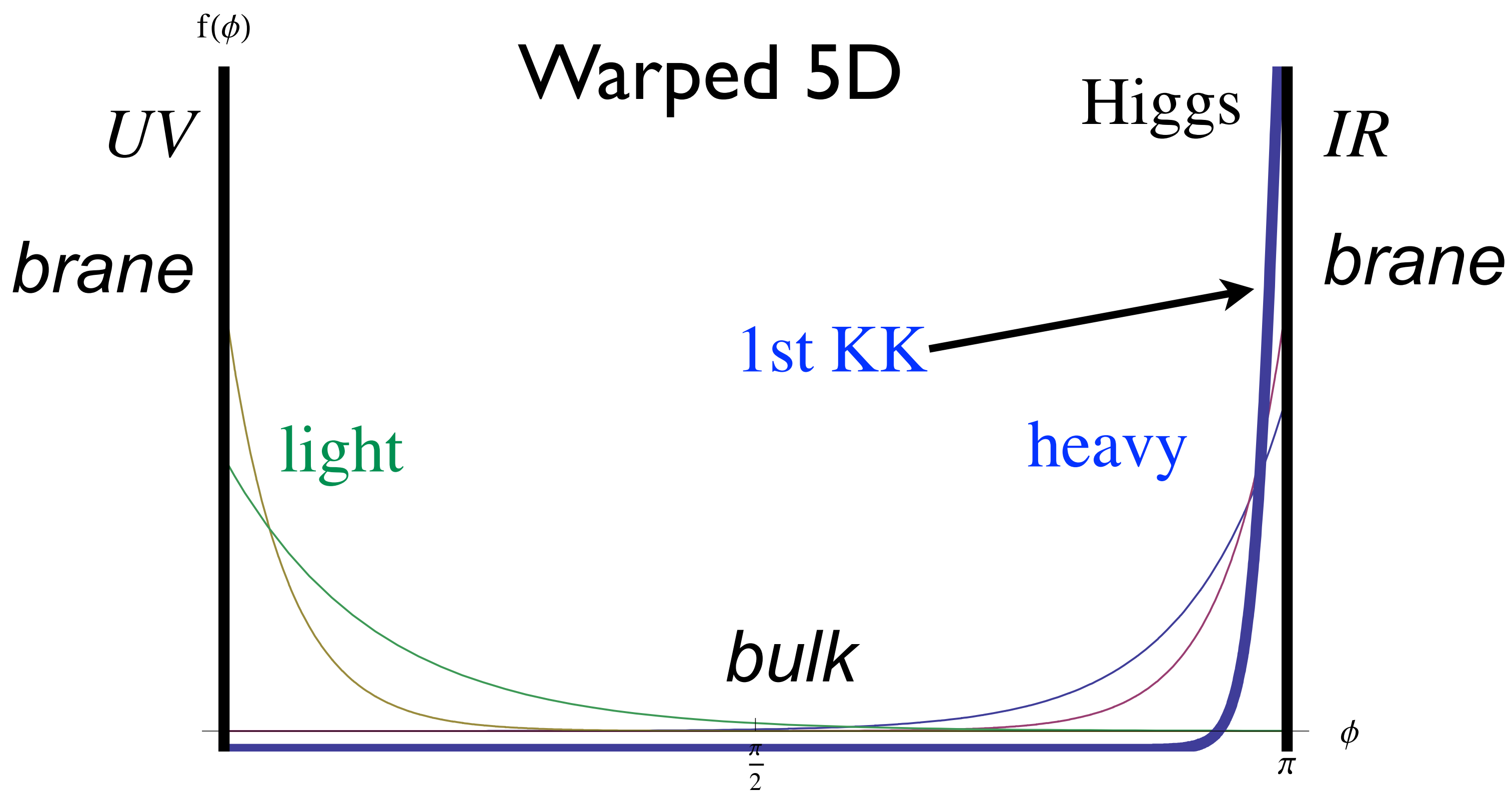
Quantity	upper bound
$\sqrt{\lvert\mathrm{Re}(\delta^{\tilde{u}}_{uc})^2_{LL}\rvert}$	3.9×10^{-2}
$\sqrt{\lvert\mathrm{Re}(\delta^{\tilde{u}}_{ud})^2_{RR}\rvert}$	3.9×10^{-2}
$\sqrt{\lvert\mathrm{Re}(\delta^{\tilde{u}}_{uc})^2_{LR}\rvert}$	1.20×10^{-2}
$\sqrt{\lvert\mathrm{Re}(\delta^{\tilde{u}}_{uc})_{LL}(\delta^{u}_{uc})_{RR}\rvert}$	6.6×10^{-3}

[Gabbiani et al 96; Misiak et al 97]
these numbers from [SJ, 0808.2044]

- elusiveness of deviations from SM in flavour physics seems to make MSSM look unnatural

- pragmatic point of view: flavour physics highly sensitive to MSSM parameters - and SUSY breaking mechanism in particular

Flavour - warped extra D



[G Perez, talk at CKM 2010]

SM fermions = zero modes (~ ground state WF of a particle in a box) of fields present in the bulk.

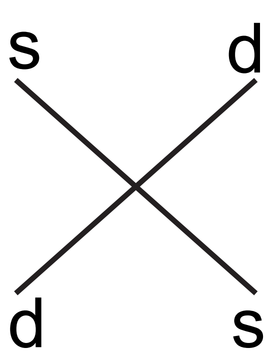
also infinitely many massive KK modes (~higher states of particle in box)

couplings (Yukawa and other) given by wave function overlaps

Higgs localized on IR brane

light (heavy) fermions localized near UV (IR) brane

hierarchical SM fermion masses



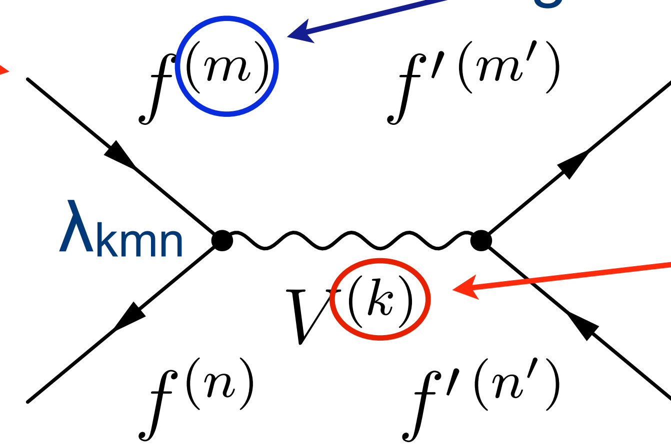
also, dangerous four-fermion operators on the IR brane, but fermions localized on the UV brane do not “feel” these much

Flavour - warped ED (2)

- dominant contribution to FCNC generically from tree-level KK boson exchange (rather than brane contact terms)

zero modes
=SM particles

generation



KK mode number

KK mode coupling
$$\lambda_{kmn} = \int d\phi \, w(\phi) f^{(m)}(\phi) f^{(n)}(\phi) f_V^{(k)}(\phi)$$

SM Yukawa coupling
$$Y_{mn} \propto f^{(m)}(\pi) f^{(n)}(\pi)$$

not aligned

non-minimal flavour violations !

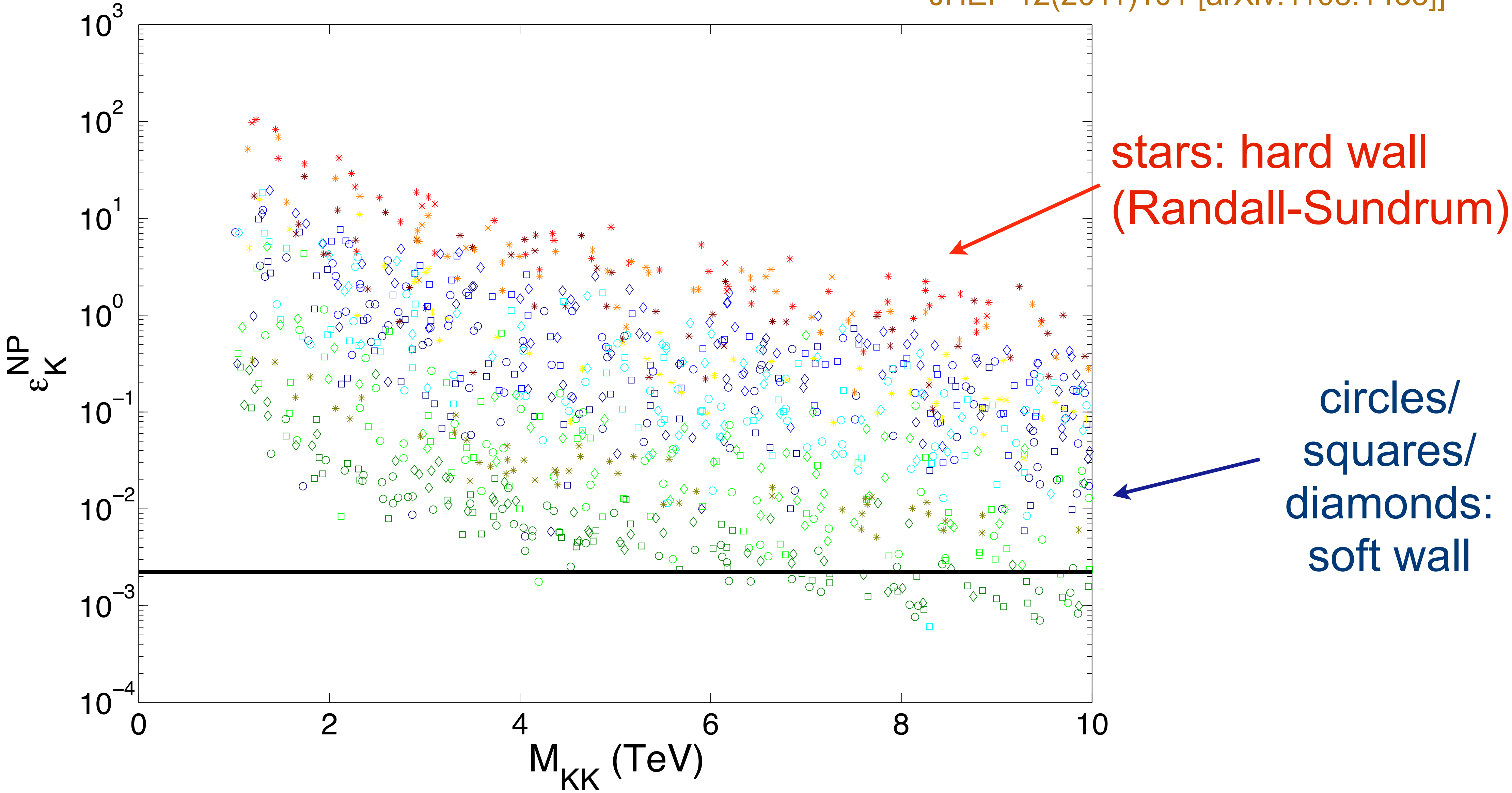
- where are their effects?

- strongest tension generally in Kaon sector, then EW precision tests

Soft-wall ED model

- hard brane replaced by extended, “soft” wall
  Higgs in bulk, localised toward wall
  eases EW precision constraints

[Archer, Huber, SJ
JHEP 12(2011)101 [arXiv:1108.1433]]



flavour still gives strongest constraints on these models

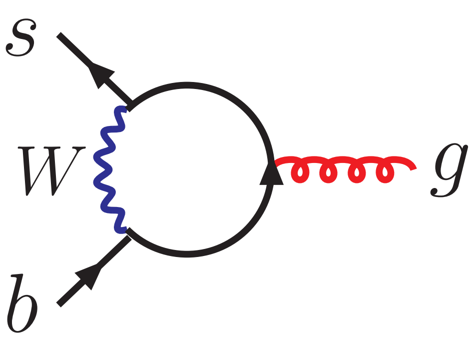
B physics of these models? [Granger, Huber, SJ, w.i.p.]

Other scenarios

- fourth SM generation
  CKM matrix becomes 4x4, giving new sources of flavour and CP violation

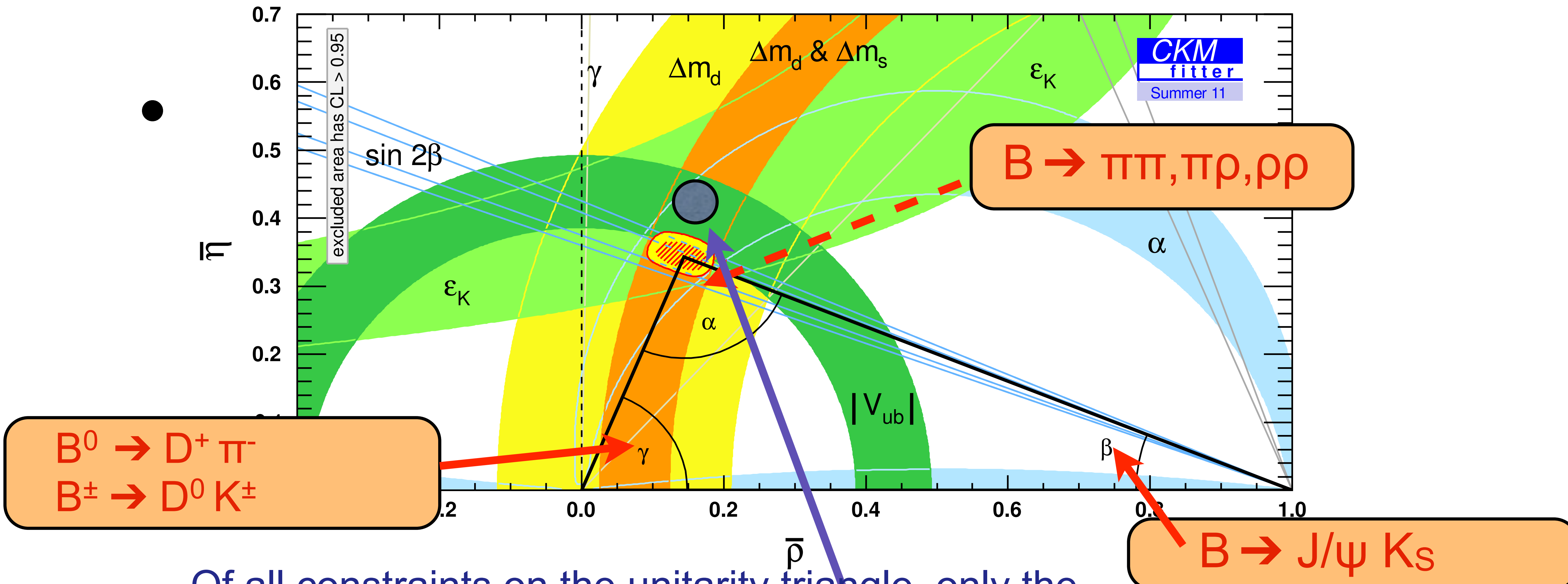
- little(st) higgs model with T parity
  (higgs light because a pseudo-goldstone boson)
  finite, calculable 1-loop contributions due to new heavy particles with new flavour violating couplings

- ...



non-minimal flavour violation !

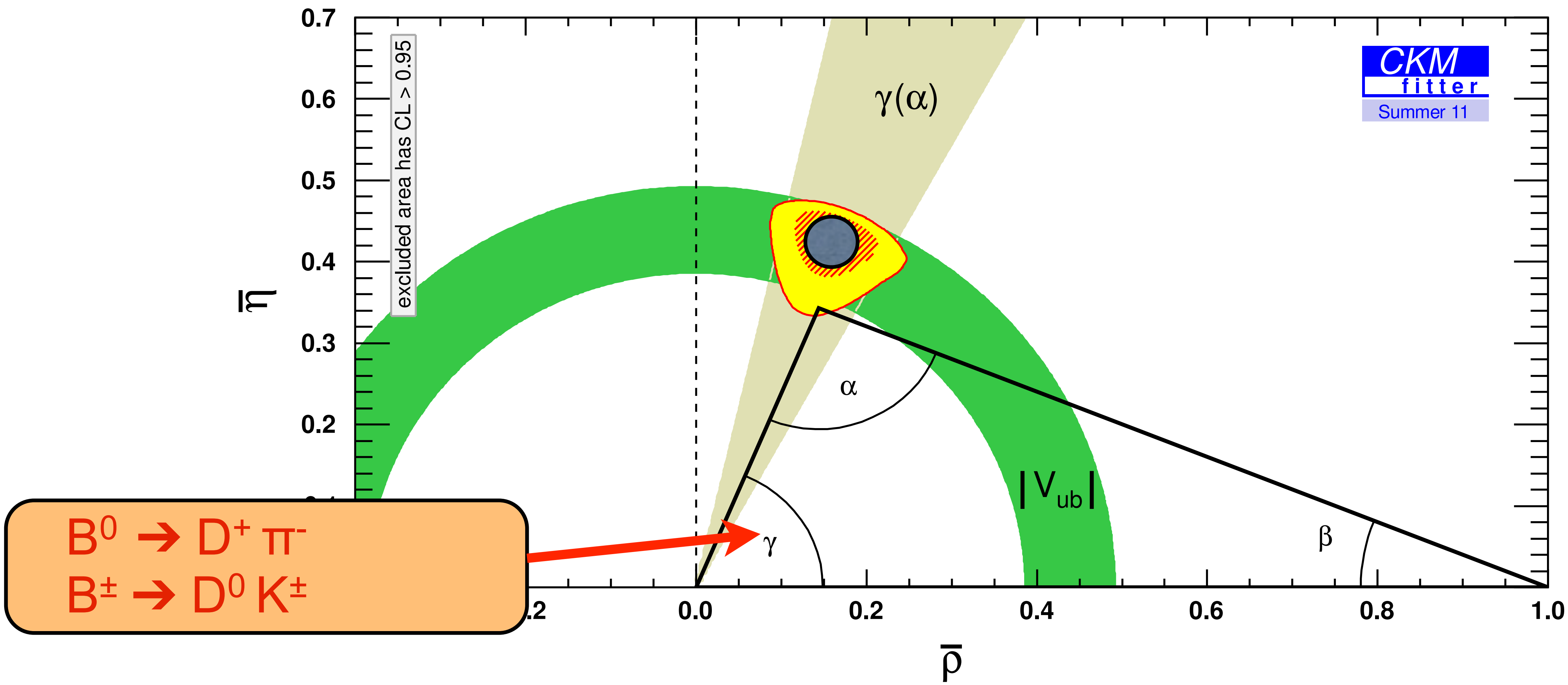
Unitarity Triangle revisited



Of all constraints on the unitarity triangle, only the γ and $|V_{ub}|$ determinations are robust against new physics as they do not involve loops.

It is possible that the TRUE $(\bar{\rho}, \bar{\eta})$ lies here (for example)

“Tree” determinations

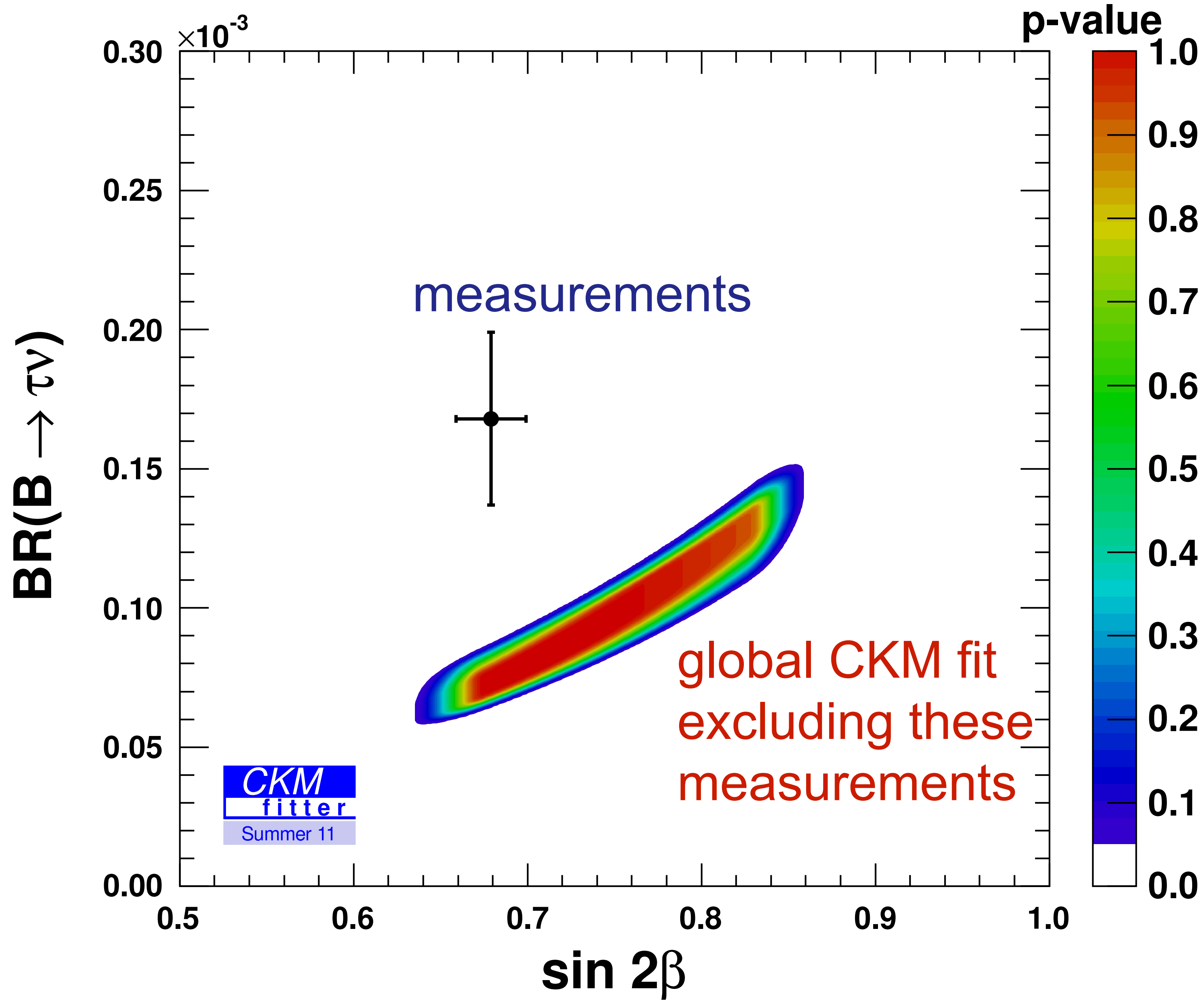


Only “robust” measurements of γ and $|V_{ub}|$. *Note: the γ(α) constraint shown depends on assumptions (absence of BSM ΔI=3/2 contributions in B->ππ); a truly robust γ determination should not include B->ππ. Such determinations will be greatly improved by LHCb.*

Certainly there is room for O(10%) NP in b->d transitions

Moreover, b->s transitions are almost unrelated to (ρ,η). They are the domain of LHCb

Another view



2.8 σ

BR ∝ $|V_{ub}|^2$ in SM

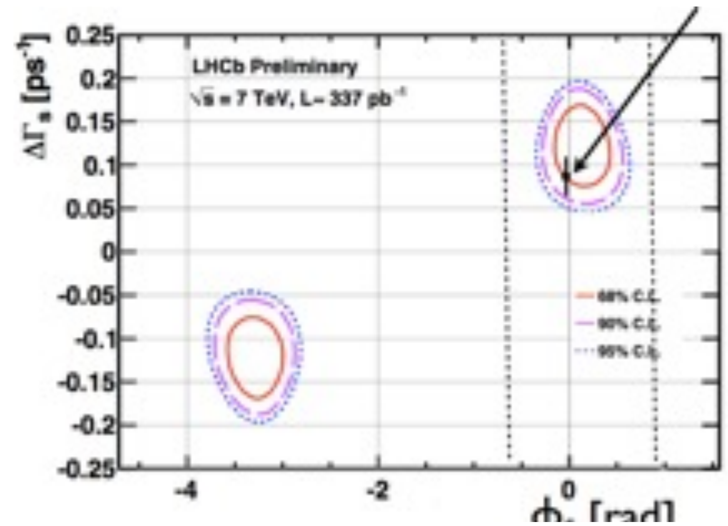
two-Higgs doublet model (II): $BR(B \to \tau\nu) = BR(B \to \tau\nu)_{\rm SM} \times \left|1 - \frac{M_B^2 \tan^2\beta}{M_{H^+}^2}\right|^2$

could be NP in B_d mixing; leading uncertainty is bag parameter

BOTTOM-UP

LHCb observables

- mixing

  theory well understood
  data consistent with SM
  errors still large
  but O(1) mixing phase ruled out

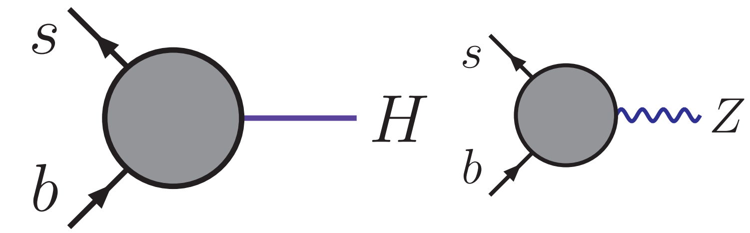
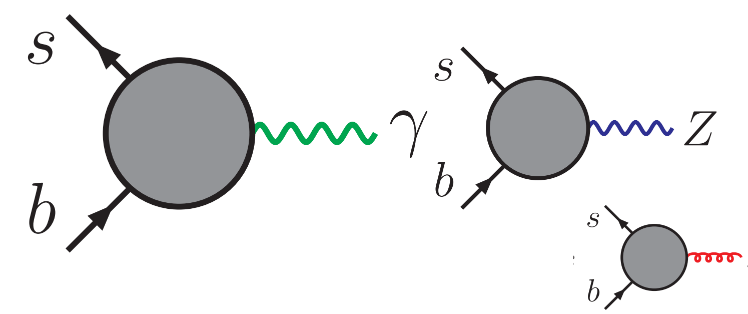
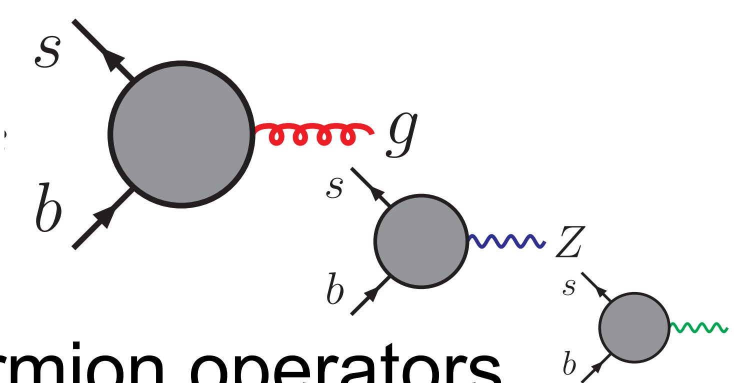
- hadronic CPV
  amplitudes
  time-dependent CP violation
  triple products
  ΔA_{CP} in D decays

- semileptonic B decays

  constraints on Wilson coefficients

- (This is a narrow subset of what I find interesting.)

Exclusive decays at LHCb

final state	strong dynamics	#obs	NP enters through
Leptonic $B \to l^+ l^-$	decay constant $\langle 0 \vert j^\mu \vert B \rangle \propto f_B$	O(1)	
semileptonic, radiative $B \to K^* l^+ l^-, K^*\gamma$	form factors $\langle \pi \vert j^\mu \vert B \rangle \propto f^{B\pi}(q^2)$	O(10)	
charmless hadronic $B \to \pi\pi, \pi K, \phi\phi, \ldots$	matrix element $\langle \pi\pi \vert Q_i \vert B \rangle$	O(100)	

Non-radiative modes also NP-sensitive via 4-fermion operators
Decay constants and form factors accessible by QCD sum rules and, increasingly, by lattice QCD.

QCD a big challenge particularly for nonleptonic modes

Hadronic decay amplitudes

- Any SM amplitude can be written

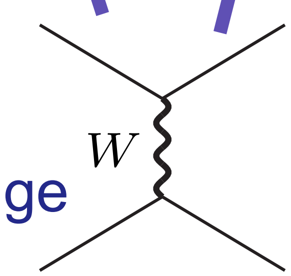
$$\mathcal{A}(\bar{B} \to M_1 M_2) = e^{-i\gamma} T_{M_1 M_2} + P_{M_1 M_2}$$

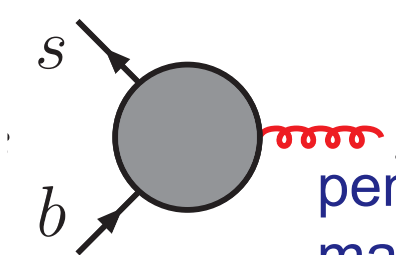
$$T_{M_1 M_2} = V_{uD} |V_{ub}| \left[C_1 \langle Q_1^u \rangle + C_2 \langle Q_2^u \rangle + \sum_{i=3}^{12} C_i \langle Q_i \rangle \right]$$ "tree"

$$P_{M_1 M_2} = V_{cD} |V_{cb}| \left[C_1 \langle Q_1^c \rangle + C_2 \langle Q_2^c \rangle + \sum_{i=3}^{12} C_i \langle Q_i \rangle \right]$$ "penguin"

CKM factor
(D=d or s)

tree W exchange



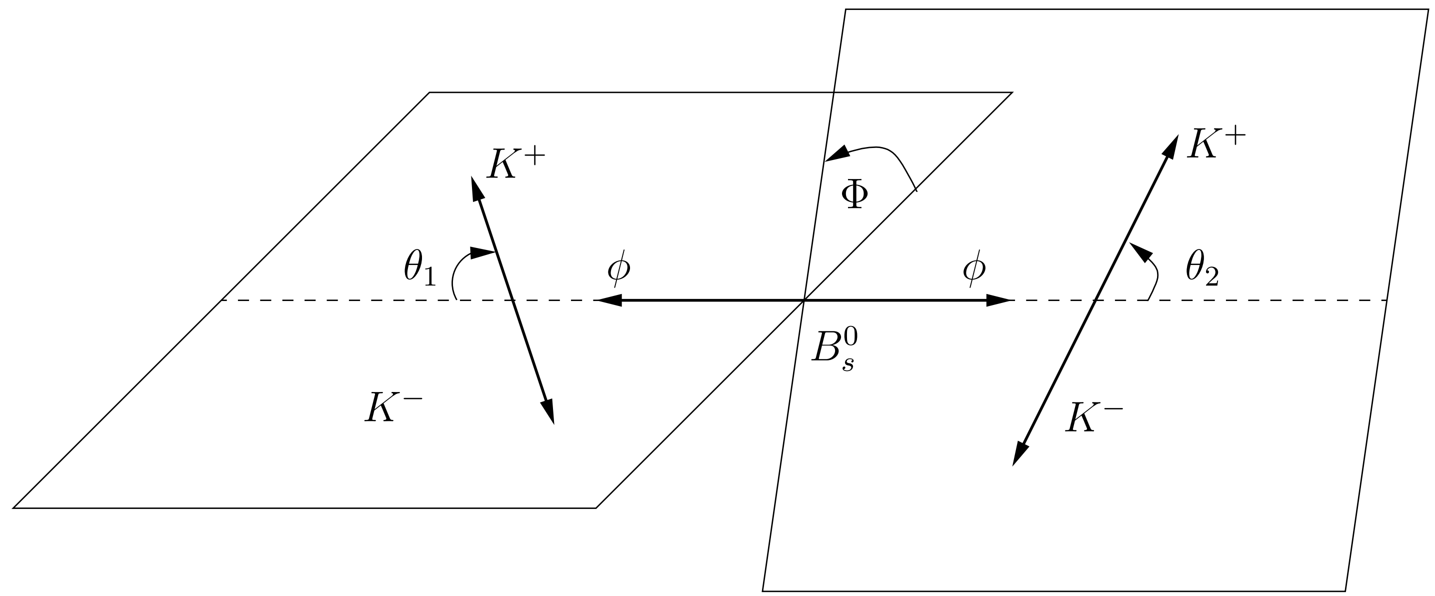


penguins (QCD, magnetic, EW)

Q_i: operators in weak hamiltonian
C_i: QCD corrections from short distances (< hc/m_b) & new physics
$\langle Q_i \rangle = \langle M_1 M_2 | Q_i | B \rangle$: QCD at distances > hc/m_b, strong phases

required for direct (decay rate) CP asymmetry

B→V V



$$\frac{d\Gamma}{d\cos\theta_1 d\cos\theta_2 d\phi} = N\Big(|A_0|^2\cos^2\theta_1\cos^2\theta_2 + \frac{|A_\parallel|^2}{2}\sin^2\theta_1\sin^2\theta_2\cos^2\phi + \frac{|A_\perp|^2}{2}\sin^2\theta_1\sin^2\theta_2\sin^2\phi + \frac{\mathrm{Re}(A_0 A_\parallel^*)}{2\sqrt{2}}\sin 2\theta_1\sin 2\theta_2\cos\phi - \boxed{\frac{\mathrm{Im}(A_\perp A_0^*)}{2\sqrt{2}}}\sin 2\theta_1\sin 2\theta_2\sin\phi - \boxed{\frac{\mathrm{Im}(A_\perp A_\parallel^*)}{2}}\sin^2\theta_1\sin^2\theta_2\sin 2\phi\Big)$$

(for $B_s \rightarrow \phi\phi$ coefficients are time-dependent due to oscillations)

- presence of polarization trebles number of amplitudes
- angular analysis allows extraction of all 6 amplitudes
- already relative *weak* phases imply CP-violating “triple products”, ie no strong phase knowledge required

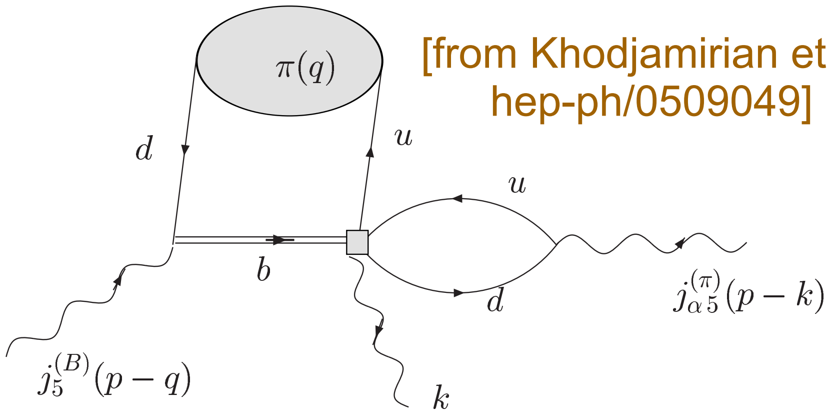
Theory approaches I

- $1/N_c$: hierarchies

[Buras et al 86, Bauer et al 87]

	T/a_1	C/a_2	P	E/b_1	A/b_1
1/N	1	1/N	1/N	1/N	1 [?]
Λ/m_B	1	1	1	Λ/m_B	Λ/m_B

- "naive factorization" for N_c -> infinity
- *strong phases:* T, P: O($1/N^2$), colour-suppressed tree O(1)
- main drawback: can't compute



[from Khodjamirian et al, hep-ph/0509049]

- QCD light-cone sum rules
evaluate correlation function off shell;
OPE & lightcone expansion
- express hadronic matrix elements
in terms of simpler objects (form factors etc.) and
a perturbatively evaluated dispersion integral.
- works also for form factors themselves (and other objects)
- main drawback: uncertainty due to "continuum threshold"
is difficult to quantify

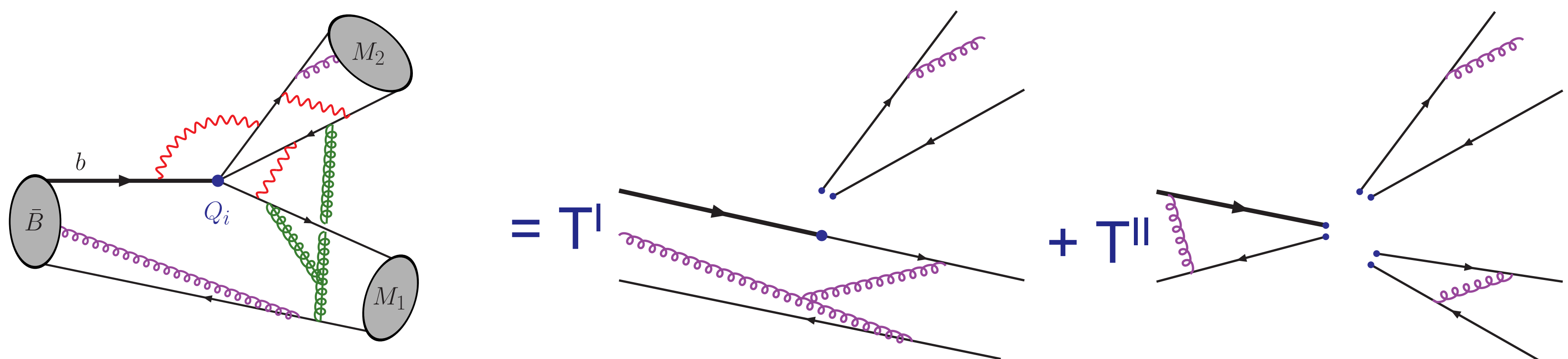
Theory approaches II

[Beneke, Buchalla, Neubert, Sachrajda (BBNS); Bauer et al]

- heavy-quark expansion in Λ_{QCD}/m_B

[QCDF / SCET; pQCD approach]

[Keum, Li, Sanda, ...]



$+ O(\Lambda_{QCD}/m_b)$

T^{I}, T^{II} computable in perturbation theory in strong coupling

- "naive factorization" for m_B -> infinity
- strong phases [imaginary parts] are $O(\alpha_s)$ or $O(\Lambda_{QCD}/m_b)$
- annihilation power suppressed altogether
- hierarchies of penguin amplitudes between final states containing pseudoscalars and vectors
- main drawback: $O(\Lambda_{QCD}/m_B)$ power corrections don't factorize, in general, and hard to estimate

- flavour SU(3) - relate b➔s and b➔d; eliminate amplitudes from data. Good if redundant observables (γ in SM), less powerful for NP search; SU(3) breaking not controlled

[Zeppenfeld 81; Gronau et al 94; Fleischer, ...]

$$\langle M_1 M_2 | Q_i | \bar{B} \rangle =$$

perturbative, includes strong phases

non-perturbative QCD

$$f_+^{BM_1}(0) f_{M_2} \int du\, T_i^{\mathrm{I}}(u) \phi_{M_2}(u) + f_B f_{M_1} f_{M_2} \int du\, dv\, d\omega\, T_i^{\mathrm{II}}(u,v,\omega)\, \phi_{B_+}(\omega) \phi_{M_1}(v) \phi_{M_2}(u) \quad + O(\Lambda_{QCD}/m_b)$$

soft overlap (form factor)

hard spectator scattering

$$T_i^{\mathrm{I}} \sim 1 \;+\; t_i\, \alpha_s \;+\; \mathcal{O}(\alpha_s^2)$$

"naive factorization"

BBNS 99-01

Bell 07, 09 (trees), Beneke et al 09 (trees)

$$T_i^{\mathrm{II}} \sim H_i \star J$$

$$\sim \left(1 + h_i\, \alpha_s + \mathcal{O}(\alpha_s^2)\right) \left(j^{(0)} \alpha_s + j^{(1)} \alpha_s^2 + \mathcal{O}(\alpha_s^3)\right)$$

BBNS 99-01

BBNS 99-01

Hill, Becher, Lee, Neubert 2004; Beneke, Yang 2005; Kirilin 2005

Beneke, SJ 2005 (trees), 2006 (penguins); Kivel 2006; Pilipp 2007 (trees);
Jain, Rothstein, Stewart 2007 (penguins)

Power corrections

- some power-suppressed contributions factorize (later slide); most do not
- varying relevance [size of Wilson/CKM factor multiplying them]
- BBNS proposed & used a (crude) "cut-off-plus-fudge-factor" model to estimate power corrections, including O(1) undetermined soft strong phases on them.

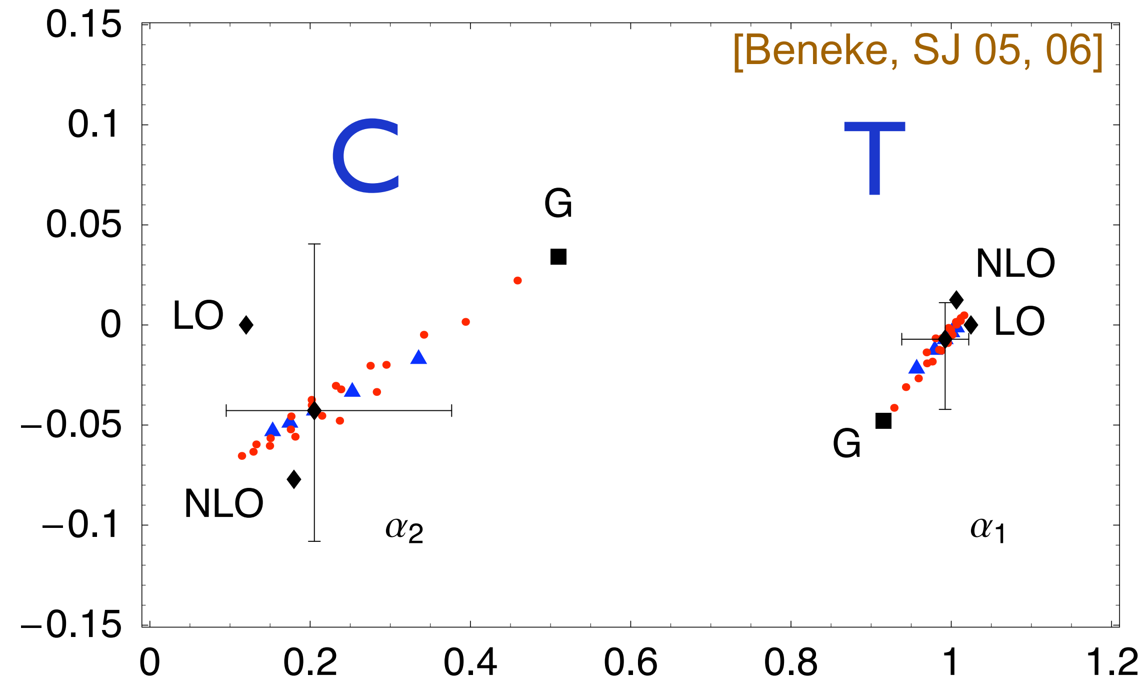
$$\underbrace{\int_0^1 \frac{dy}{y} \to X_A^{M_1}}_{\text{divergent expression}} \qquad\qquad X_A = \left(1 + \underbrace{\varrho_A\, e^{i\varphi_A}}_{\text{soft phase}}\right) \ln \underbrace{\frac{m_B}{\Lambda_h}}_{\text{IR cutoff}}$$

- Some authors have attempted to fit power corrections to data [at expense of predictivity] Feldmann & Hurth; Ciuchini et al
- In the 'pQCD' approach power corrections are (mostly) deemed calculable, but the "perturbative" expressions do not appear [to me] to be dominated by perturbative scales

phenomenological summary

- Corrections to naive factorization small for T and P_{EW}, stable perturbation series ; small uncertainties

- Corrections O(1) for C (and $P_{EW}{}^{c}$), stable perturbation series large uncertainties (hadronic inputs; large incalculable power correction for final states with pseudoscalars)

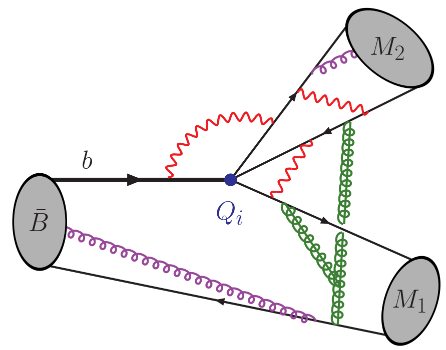


parameter set "G" (fit hadronic parameters to B➔ππ BR's):
C/T ~ 0.69 + 0.17 i
large magnitude, small phase

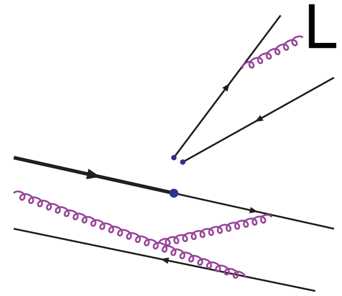
- (physical) penguin amplitudes moderately affected by power-suppressed incalculable penguin annihilation (&charm penguin) terms. Spoils precise predictions for direct CP asymmetries

- certain SU(3)-type relations satisfied in good approximation

Penguin anatomy: $1/m_b$

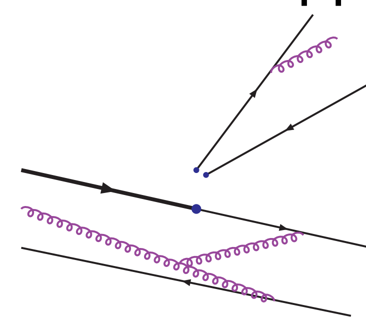


like quark chiralities



L L

opposite quark chiralities



L R

("scalar penguin")

$$\alpha_4^c = a_4 + r_\chi^{M_2} a_6$$

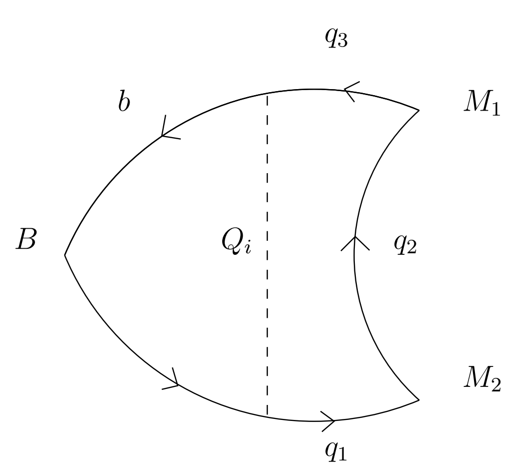
$O(1/m_b)$ but factorizes !

However: $$r_\chi^\pi(\mu) = \frac{2m_\pi^2}{m_b(\mu)\,(m_u + m_d)(\mu)} \sim \frac{\Lambda_{\mathrm{QCD}}}{m_b}$$

but ~ 1 numerically

"chiral enhancement"

no chiral enhancement present for vector M_2 -> much smaller penguin amplitudes



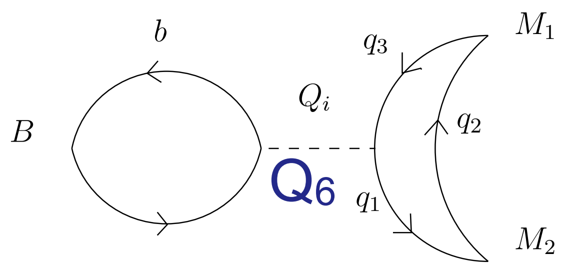
β_3

penguin annihilation [in QCDF terminology]:
$O(1/m_b)$, does *not* factorize
modeled by naively factorized expression with IR cutoff by BBNS

large and complex in pQCD approach [Keum, Li, Sanda 2000]
small in light-cone sum rules [Khodjamirian et al 2005]

Annihilation β_3

- The colour-leading piece to the annihilation contribution β_3 to the QCD penguin amplitude has a naively factorizing structure



(where Q_6 has been "Fierzed" to colour singlet x singlet form)

This is proportional to the "scalar form factor". A QCD sum rule calculation gives a small and approximately real result.

[Khodjamirian Mannel, Melcher, Melic, hep-ph/0509049]

- In contrast, the pQCD approach finds a large and complex value albeit with large uncertainties. [Keum, Li, Sanda 2000]

- This is also the case for the BBNS annihilation model.

Penguins (QCDF) vs data

$$P_{M_1 M_2}/(C_{\pi\pi} + T_{\pi\pi}) \sim \hat{\alpha}_4^c(M_1 M_2)/(\alpha_1(\pi\pi) + \alpha_2(\pi\pi))$$

can be fit to BR, A_{CP} (π^+K^-) and BR($\pi^+\pi^-$) using one SU(3) relation

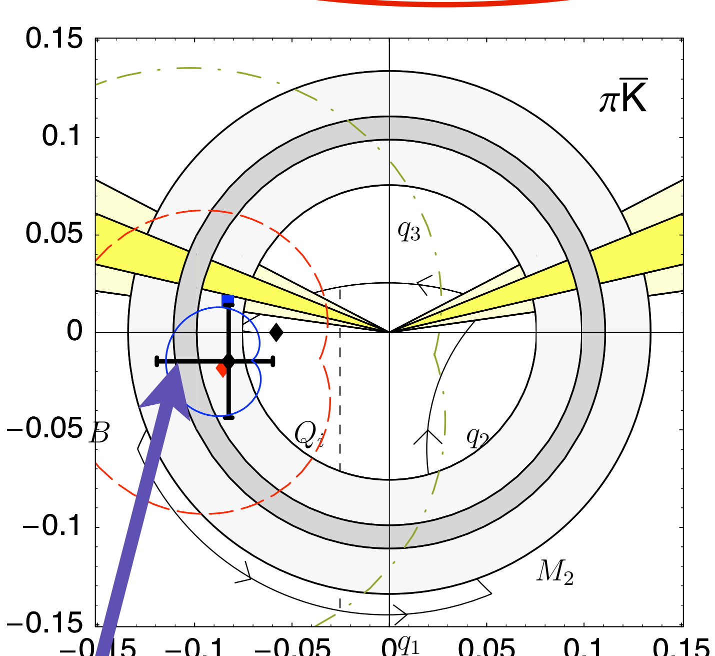
$$P_{M_1 M_2} \sim \hat{\alpha}_4^c(M_1 M_2) = a_4(M_1 M_2) \pm r_\chi^{M_2} a_6(M_1 M_2) + \beta_3^p(M_1 M_2)$$

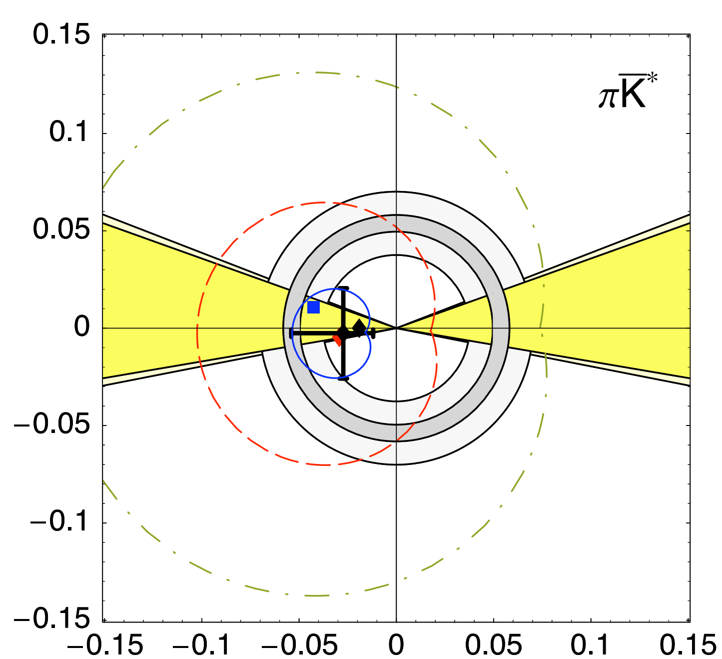
factorizable power correction

annihilation (modeled a la BBNS)

chirally enhanced for M_2 pseudoscalar

small for M_2 vector





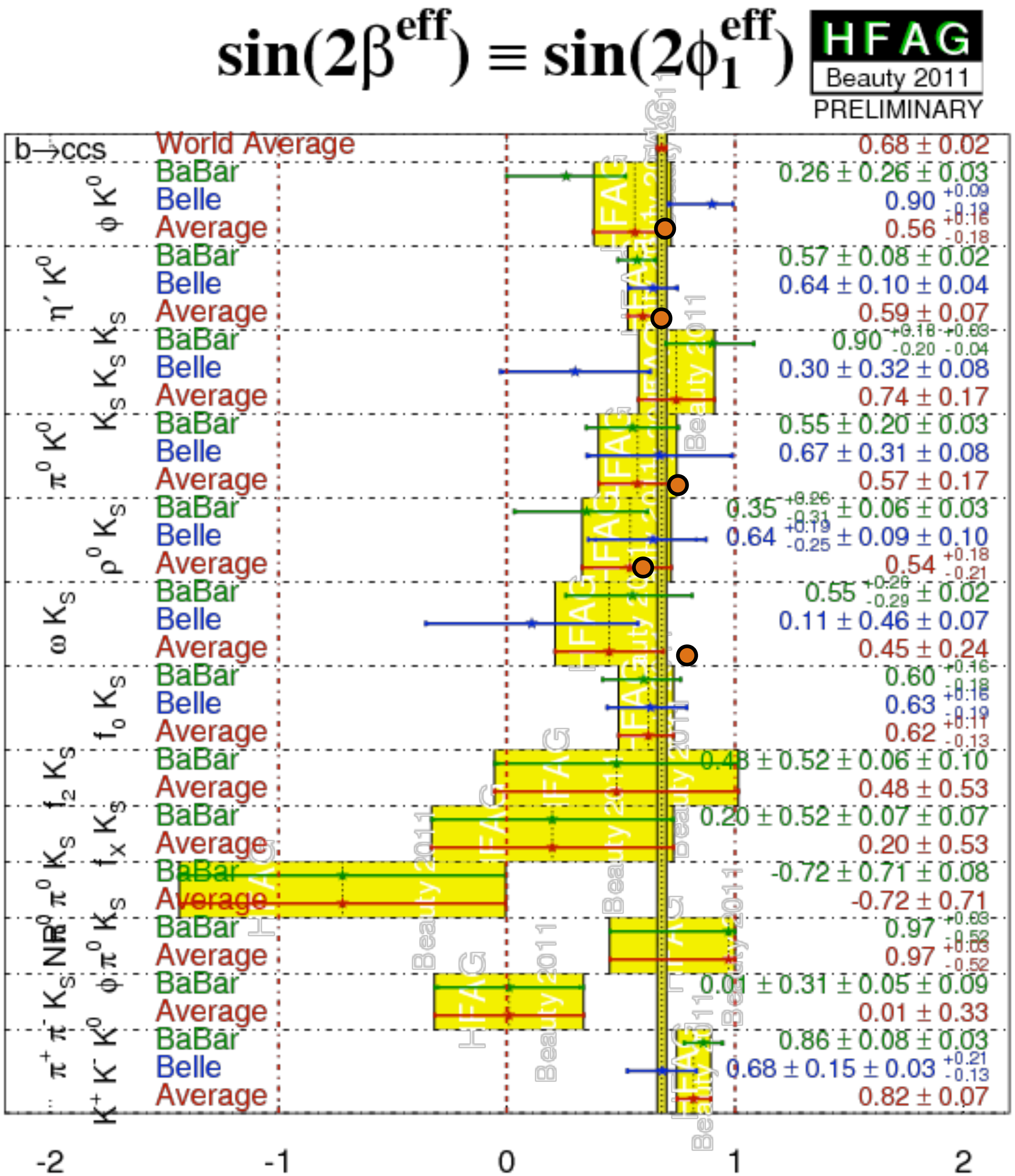
BBNS model of annihilation

[Beneke, Neubert 2003; Beneke, SJ 2007]

pattern (hierachies & numbers) agree quite well with $1/m_b$ expectations (also for ρK, ρK*)

wrong imaginary part for πK unless annihilation is fairly large (well known problem)

Comparison to data: S_{CP}



● Beneke 2005 (NLO QCDF)

small corrections (and small errors) to “naive” expectation

similar conclusion in BPRS approach [Williamson, Zupan 2006]

pQCD see Li, Mishima 2006

Theory: S_{CP}

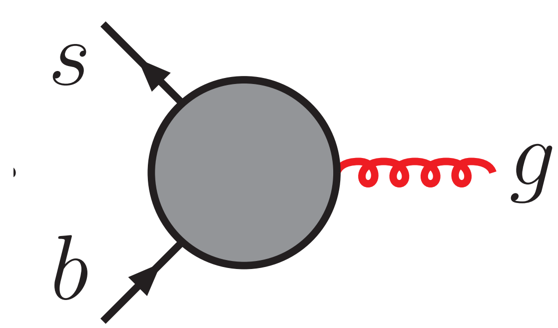
$$\begin{tikzcd}
B \arrow[rr, "A_f = \langle f|B\rangle", "\text{decay}"'] \arrow[dr, "\text{mixing}"', "e^{-2i\beta}"'] & & f \\
& \bar{B} \arrow[ur, "\bar{A}_f = \langle f|\bar{B}\rangle"'] &
\end{tikzcd}$$

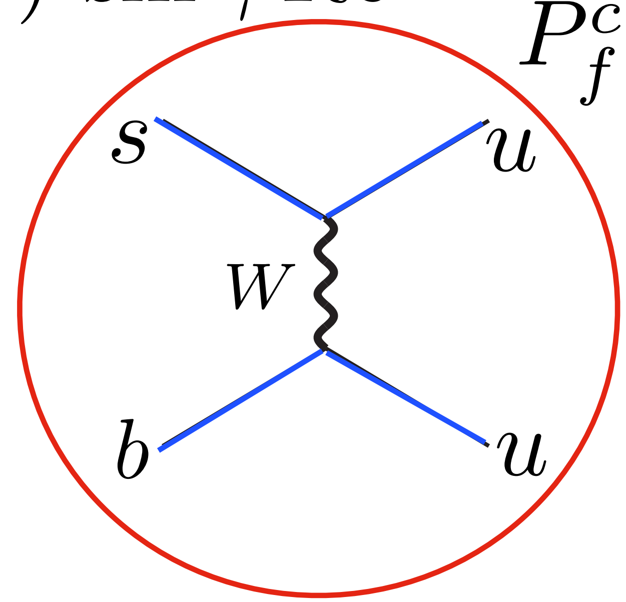
f CP eigenstate

$$\boxed{\frac{BR(B^0(t)\to f) - BR(\bar{B}^0(t)\to f)}{BR(B^0(t)\to f) + BR(\bar{B}^0(t)\to f)} = -S_f \sin(\Delta m_B t) + C_f \cos(\Delta m_B t)}$$

time-dependent CP asymmetry

$$\overbrace{-\eta_{\rm CP}(f)\cdot S_f}^{\sin(2\beta^{\rm eff})} \approx \sin(2\beta) + 2\cos(2\beta)\sin\gamma\,\mathrm{Re}\frac{T_f + P_f^u}{P_f^c} + S_f^{\rm N.P.}$$



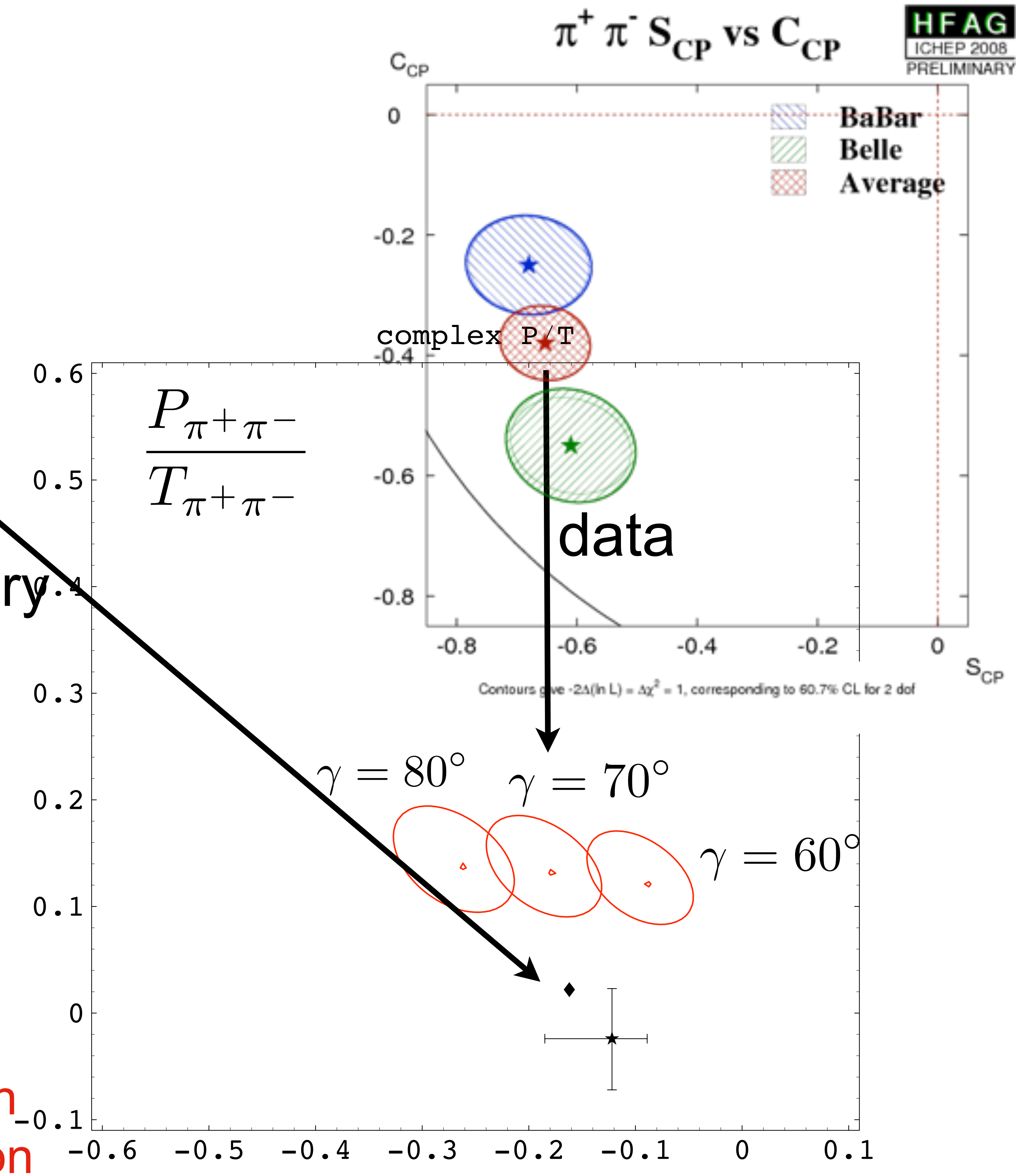


?

need only real part of small amplitude (weak strong-phase dependence)

$B \to \pi\pi, \pi\rho, \rho\rho$: P/T, C/T

Ratio	Value/Range	Value G
$\frac{P_{\pi\pi}}{T_{\pi\pi}}$	$-0.122^{+0.033}_{-0.063} + (-0.024^{+0.047}_{-0.048})i$	$-0.162 + 0.022i$
$\frac{P_{\rho\rho}}{T_{\rho\rho}}$	$-0.036^{+0.006}_{-0.009} + (-0.009^{+0.007}_{-0.007})i$	$-0.037 - 0.009i$
$\frac{P_{\pi\rho}}{T_{\pi\rho}}$	$-0.037^{+0.015}_{-0.028} + (-0.005^{+0.024}_{-0.024})i$	$-0.070 + 0.006i$
$\frac{P_{\rho\pi}}{T_{\rho\pi}}$	$0.042^{+0.039}_{-0.023} + (0.004^{+0.030}_{-0.030})i$	$0.051 - 0.024i$
$\frac{C_{\pi\pi}}{T_{\pi\pi}}$	$0.363^{+0.277}_{-0.156} + (0.029^{+0.166}_{-0.103})i$	$0.691 + 0.165i$
$\frac{C_{\rho\rho}}{T_{\rho\rho}}$	$0.198^{+0.233}_{-0.150} + (-0.009^{+0.145}_{-0.097})i$	$0.344 + 0.042i$
$\frac{C_{\pi\rho}}{T_{\pi\rho}}$	$0.250^{+0.229}_{-0.143} + (-0.012^{+0.127}_{-0.090})i$	$0.467 + 0.071i$
$\frac{C_{\rho\pi}}{T_{\rho\pi}}$	$0.134^{+0.199}_{-0.156} + (-0.024^{+0.152}_{-0.117})i$	$0.283 + 0.138i$
$\frac{T_{\rho\pi}}{T_{\pi\rho}}$	$0.869^{+0.275}_{-0.207} + (0.014^{+0.058}_{-0.057})i$	$0.945 - 0.004i$



[$|V_{ub}/V_{cb} = 0.09|$ in P/T extraction]

S parameter gives good γ determination
small corrections to naive factorisation
C parameter - direct CPV
zero in naive factorisation

Comparison to data: annihilation

- Annihilation power suppressed, small branching fractions predicted (but with large uncertainties)

- LHCb has published data on B_s->pi pi and B^0->K K

QCDF [Beneke, Neubert 2003 "S4"]

$$\mathcal{BR}(B_s^0 \to \pi^+\pi^-) = (0.98^{+0.23}_{-0.19} \pm 0.11) \times 10^{-6}$$ 0.155×10^{-6}

$$\mathcal{BR}(B^0 \to K^+K^-) = (0.13^{+0.06}_{-0.05} \pm 0.07) \times 10^{-6}$$ 0.07×10^{-6}

[LHCb-CONF-2011-042]

consistent with CDF

The B_s BF is in excess of estimates, whereas the B^0 decay fits nicely. Both decays are SU(3)-related.

However, BF is quadratic in annihilation (other processes are affected at linear order), need (only) about factor 2-3 enhancement of an annihilation contribution

- more an issue for SU(3) than for factorisation (which implies SU(3) relations) per se. Could this be NP ?

Polarisation & NP

- Triple-product asymmetries in B->ϕK*

[Valencia 1989, ...]

$$\mathcal{A}_T^{(1)\mathrm{chg-avg}} \equiv \frac{[\Gamma(S>0)+\bar{\Gamma}(\bar{S}>0)]-[\Gamma(S<0)+\bar{\Gamma}(\bar{S}<0)]}{[\Gamma(S>0)+\bar{\Gamma}(\bar{S}>0)]+[\Gamma(S<0)+\bar{\Gamma}(\bar{S}<0)]}$$
$$= -\frac{2\sqrt{2}}{\pi}\frac{\mathrm{Im}(A_\perp A_0^* - \bar{A}_\perp \bar{A}_0^*)}{(|A_0|^2+|A_\perp|^2+|A_\|}|^2)+(|\bar{A}_0|^2+|\bar{A}_\perp|^2+|\bar{A}_\||^2)}$$

[Datta, Duraisamy, London; Gronau, Rosner 2011]

$$\mathcal{A}_T^{(2)\mathrm{chg-avg}} \equiv \frac{[\Gamma(\sin 2\phi>0)+\bar{\Gamma}(\sin 2\bar{\phi}>0)]-[\Gamma(\sin 2\phi<0)+\bar{\Gamma}(\sin 2\bar{\phi}<0)]}{[\Gamma(\sin 2\phi>0)+\bar{\Gamma}(\sin 2\bar{\phi}>0)]+[\Gamma(\sin 2\phi<0)+\bar{\Gamma}(\sin 2\bar{\phi}<0)]}$$
$$= -\frac{4}{\pi}\frac{\mathrm{Im}(A_\perp A_\|^* - \bar{A}_\perp \bar{A}_\|^*)}{(|A_0|^2+|A_\perp|^2+|A_\||^2)+(|\bar{A}_0|^2+|\bar{A}_\perp|^2+|\bar{A}_\||^2)}\ .$$

- HFAG data for the entire set of polarization amplitudes exists; Triple products at most 5-10% in either case

[Gronau, Rosner 2011]

- A SM calculation in QCD factorization (based on the heavy-quark expansion) is consistent with the HFAG data

[Beneke, Rohrer, Yang 2006]

- Also “fake” triple-product asymmetries which require strong phases - small in QCDF, small in obs.

Polarisation observables

- "Factorization predicts $f_L \approx 1$, in disagreement with data." Really?
- comprehensive phenomenological analysis of polarisation observables in (QCD) factorization exists

Observable		Theory: default	Theory: constrained X_A	Theory: $\hat{\alpha}_4^{c-}$ from data	Experiment	HFAG 2010	
$f_L/\%$	ϕK^{*-}	45^{+0+58}_{-0-36}	45^{+0+35}_{-0-31}	44^{+0+23}_{-0-23}	50 ± 7		
	$\phi \bar{K}^{*0}$	44^{+0+59}_{-0-36}	44^{+0+35}_{-0-31}	43^{+0+23}_{-0-23}	49 ± 3		
$\phi_\parallel/^\circ$	ϕK^{*-}	-41^{+0+84}_{-0-53}	-41^{+0+35}_{-0-30}	-40^{+0+21}_{-0-21}	-60 ± 16	-46 ± 10	CP-averaged phase difference (mostly strong phase difference)
	$\phi \bar{K}^{*0}$	-42^{+0+87}_{-0-54}	-42^{+0+35}_{-0-30}	-42^{+0+21}_{-0-21}	-44 ± 8	-42 ± 8	
	$\phi\phi$	-39^{+0+86}_{-0-57}		-37^{+0+21}_{-0-24}			
$\Delta\phi_\parallel/^\circ$	ϕK^{*-}	0^{+0+0}_{-0-1}	0^{+0+0}_{-0-0}	0^{+0+0}_{-0-0}	n/a	4 ± 12	CP-asymmetric phase difference (mostly weak phase difference)
	$\phi \bar{K}^{*0}$	0^{+0+0}_{-0-0}	0^{+0+0}_{-0-0}	0^{+0+0}_{-0-1}	6 ± 8	6 ± 7	
		0^{+0+0}_{-0-1}		0^{+0+1}_{-0-1}			

[Beneke, Rohrer, Yang 2006]

- transverse polarisation fractions can be large, naive factorisation is *not* reliable; $f_\perp$ & $f_{||}$ depend on incalculable power corrections so 1-f_L *not* a good probe of new physics.
- QCDF does give negligible relative weak phases in the SM (this is because it preserves dominance of penguin amplitudes)

Polarisation & NP

- Triple-product asymmetries in $B_s \to \phi\phi$

  - similar pair of TP asymmetries
  - time-dependence -> mixing-decay interference
  - one can define two combinations A_U , A_V sensitive to

$$\mathrm{Im}[A_\perp(t)A_i^*(t) + \bar{A}_\perp(t)\bar{A}_i^*(t)] \qquad i = 0\,,\, \parallel$$

[Gronau, Rosner 2011]

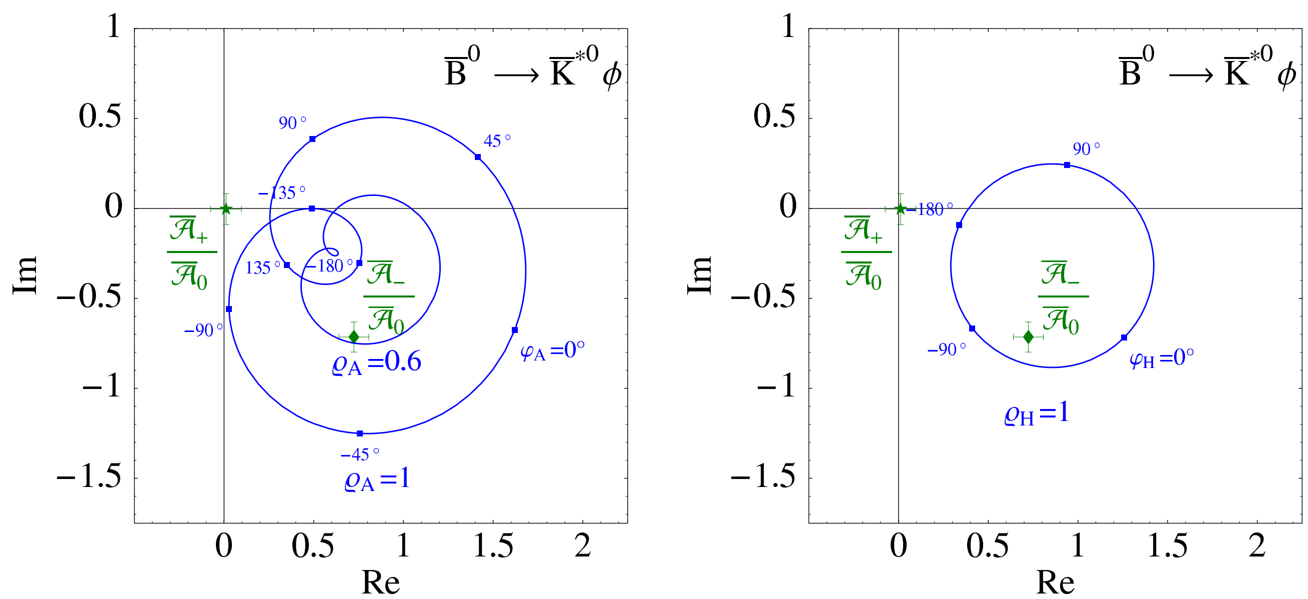
- CDF
$$A_U = -0.007 \pm 0.064(stat) \pm 0.018(syst)$$
$$A_V = -0.120 \pm 0.064(stat) \pm 0.016(syst).$$
[arXiv:1107.4999]

- LHCb
$$A_U = -0.064 \pm 0.057\ (stat.) \pm 0.014\ (syst.)$$
$$A_V = -0.070 \pm 0.057\ (stat.) \pm 0.014\ (syst.)$$
[LHCb-CONF-2011-052]

- No quantitative theoretical calculation exists at the moment but qualitatively it is clear that the SM predicts both TP asymmetries to be small (strong penguin dominance)

Polarisation & NP

- $1/m_b$ expansion predicts a hierarchy $\bar{A}_0 : \bar{A}_- : \bar{A}_+ = 1 : \frac{\Lambda_{\mathrm{QCD}}}{m_b} : \left(\frac{\Lambda_{\mathrm{QCD}}}{m_b}\right)^2$ in $\bar{\mathrm{B}}$ decay (+/- interchanged in B decays); [Korner, Goldstein 1979]
  however, the suppression of the negative-helicity amplitude is numerically spoiled by annihilation contributions [Kagan 2004]

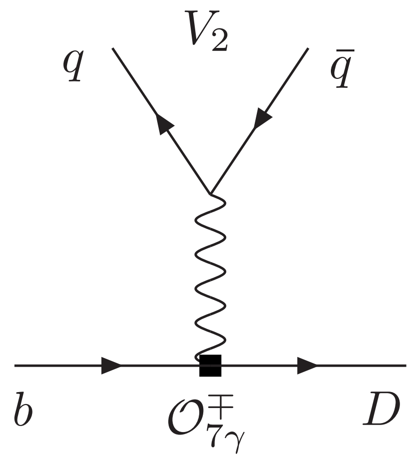


[Beneke, Rohrer,Yang 2006]

- A nonvanishing *positive*-helicity amplitude could be a sign of NP and could even be turned into quantitative information on “right-handed currents” [Kagan 2004]

- The (presumable) smallness of the *negative*-helicity amplitude suppresses one of the two triple-product asymmetries, making it a probe of right-handed currents

EWP effect in B->V V



low-virtuality photon, makes A_- formally leading (but α_{EM} suppressed), important contribution in the SM

[Beneke, Rohrer,Yang 2005]

- If NP involves a right-handed dipole operator Q_7' this can give a sizable A_+
- would be present in $B_s \to \phi\phi$
- full polarisation analysis would be interesting

CPV in D decays

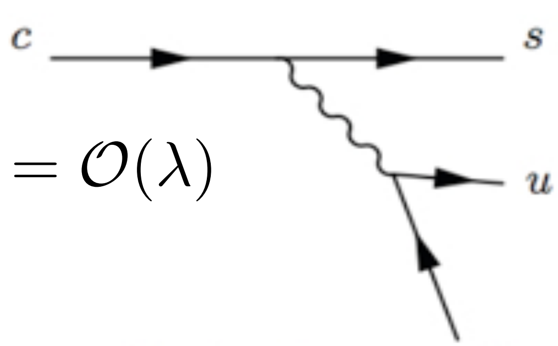
- LHCb has measured [essentially] the difference
  $\Delta A_{CP} = A_{CP}(D^0 \to K^+K^-) - A_{CP}(D^0 \to \pi^+\pi^-)$

$$\Delta A_{CP} = [-0.82 \pm 0.21(\text{stat.}) \pm 0.11(\text{sys.})]\,\%$$ [LHCb-CONF-2011-061]

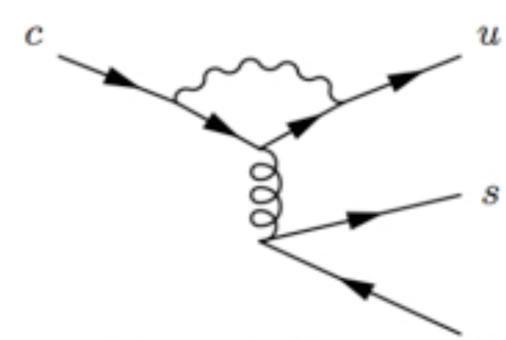
- SU(3) symmetry predicts equal and opposite relative sign between the two asymmetries, i.e. no cancellation expected

- but GIM cancellations suggest, in the SM, strong suppression of the penguin amplitude ($|P/T| \sim 10^{-3}$)

$\propto V_{us}V_{cs}^* = \mathcal{O}(\lambda)$



(a) *Tree diagram.*



(b) *Penguin diagram.*

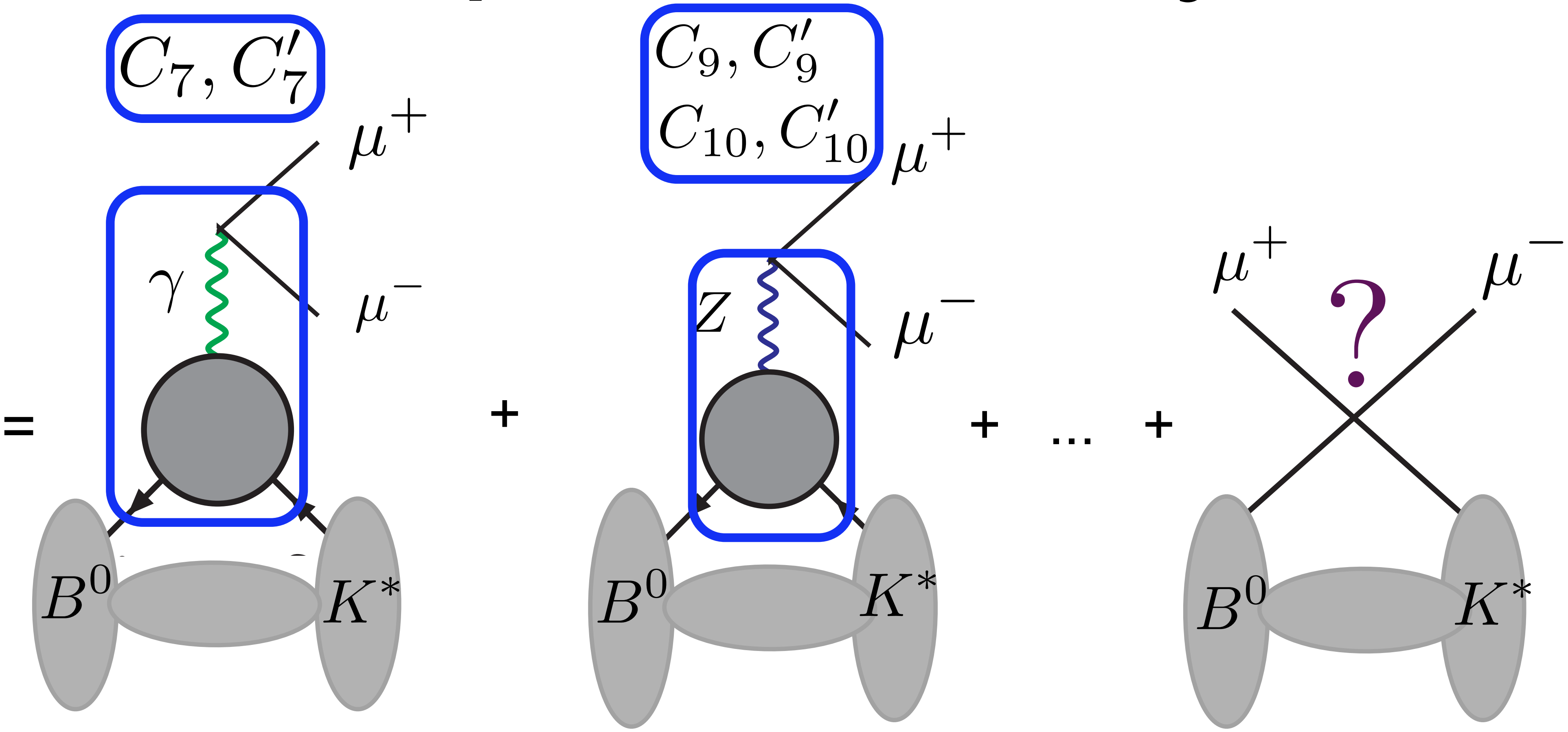
$\propto V_{ub}V_{cb}^* = \mathcal{O}(\lambda^5)$

- to explain in SM would need about an order of magnitude enhancement of the penguin amplitude. Current theoretical control much worse than for B decays; recent discussion in

[Brod, Kagan, Zupan 1111.5000]

Semileptonic decay

$A(B\to K^{*}l^{+}l^{-}) =$

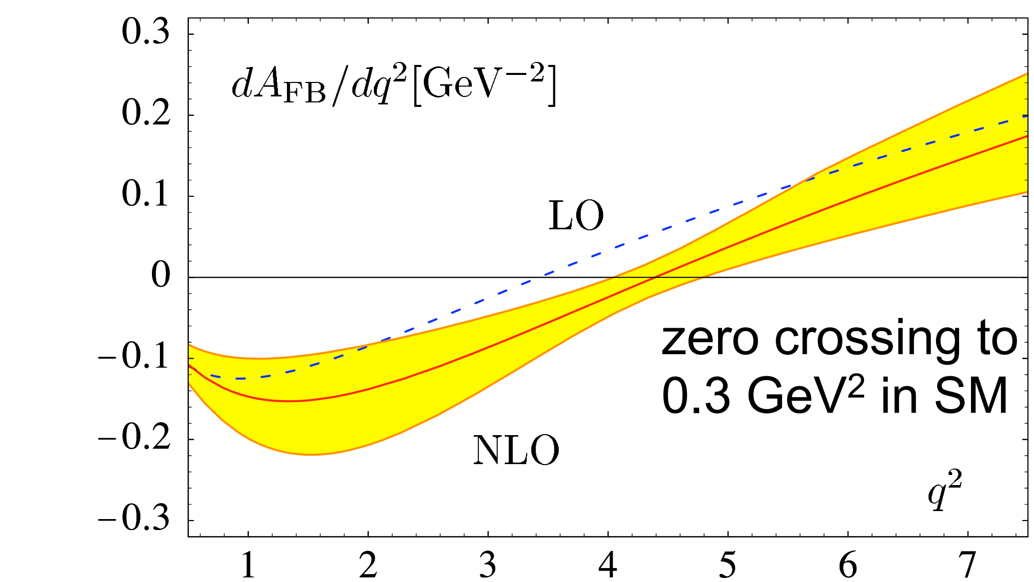


- kinematics described by dilepton invariant mass q^2 and three angles
- Systematic theoretical description based on heavy-quark expansion (Λ/m_b) for $q^2 \ll m^2(J/\psi)$ (SCET) Beneke, Feldmann, Seidel 01
  also for $q^2 \gg m^2(J/\psi)$ (OPE) Grinstein et al; Beylich et al 2011
  Theoretical uncertainties on form factors, power corrections

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

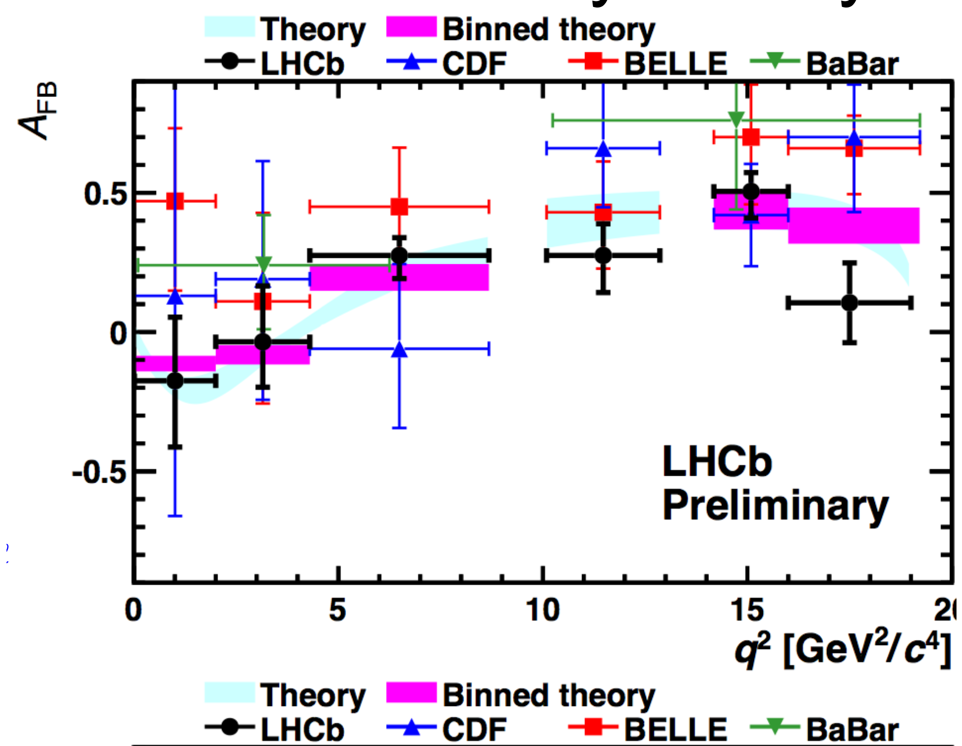
Ali et al ; Beneke et al; ...

- Most well-known observable: forward-backward asymmetry



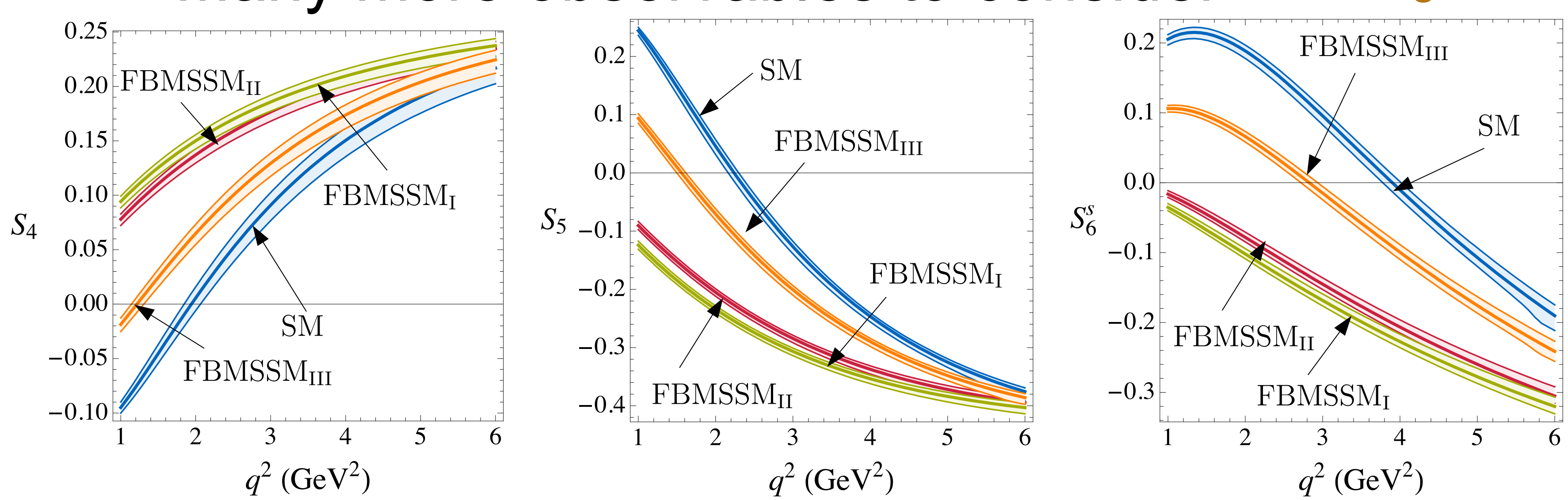
$$q_0^2[K^{*0}] = 4.36^{+0.33}_{-0.31}\,\mathrm{GeV}^2, \qquad q_0^2[K^{*+}] = 4.15^{+0.27}_{-0.27}\,\mathrm{GeV}^2$$

Beneke et al Eur Phys J C 41 (2005) 173



- Many more observables to consider

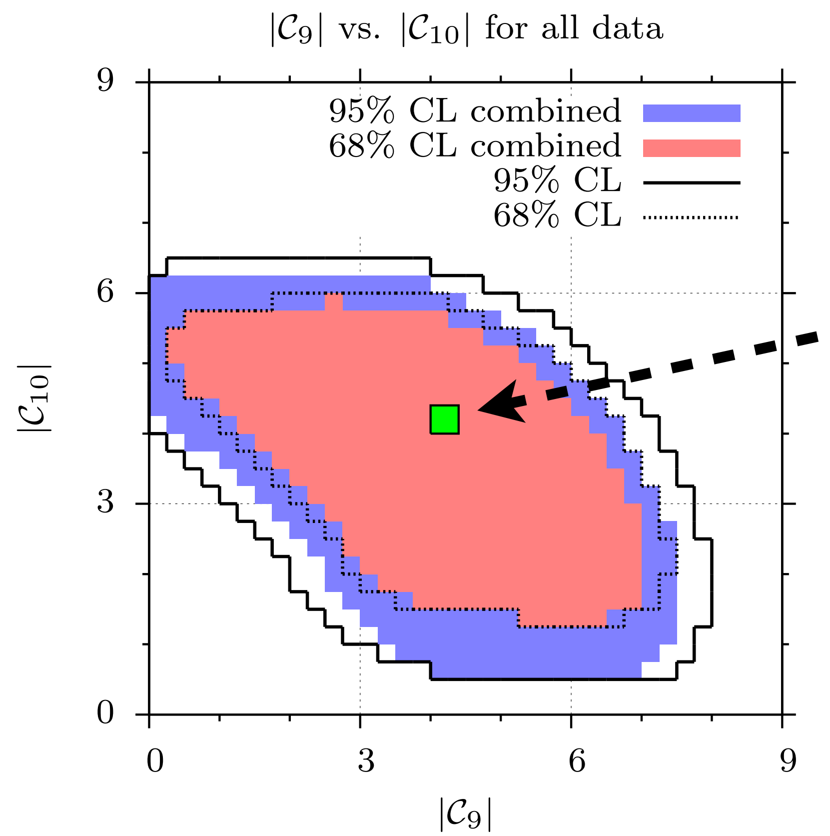
Krueger, Matias; ...



Altmannshofer et al 0811.1214v3

see also Bobeth et al 2008,10, 11; Egede et al 2009,2010; Alok et al 2010, Altmannshofer et al 2011 for recent analyses

Constraints on NP

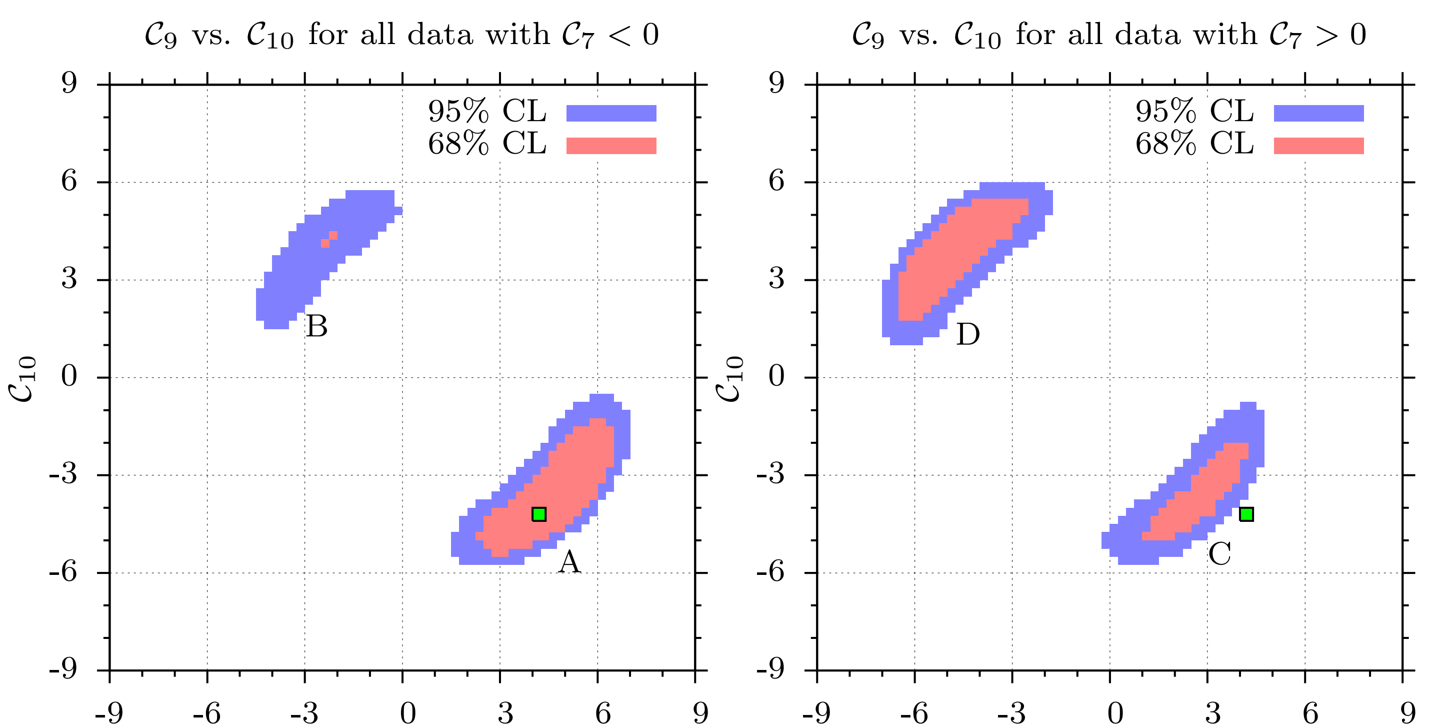


global fit to semileptonic decay data

Bobeth et al 1111.2558

Standard Model

allowing for new CP violation



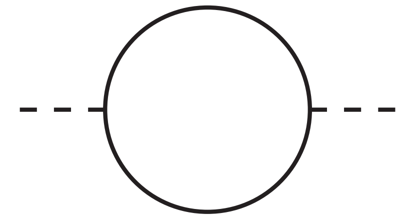
not allowing for new CP violation

see also Descotes-Genon et al 2011, Altmannshofer, Paradisi, Straub 2011

TOP-DOWN

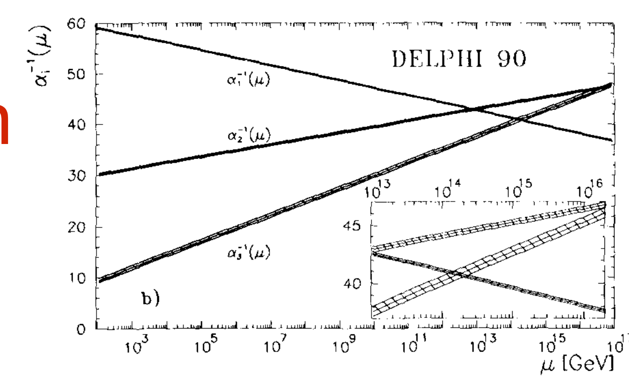
SUSY (again)

- SUSY virtues

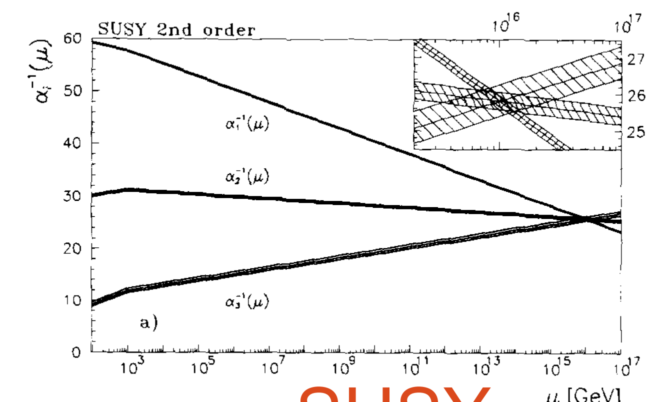
  solves naturalness problem  $\propto y_t^2 \Lambda_{\rm UV}^2$

  gauge coupling unification

  dark matter, strings, ...



SM



SUSY

[Amaldi et al 1991]

- many ‘soft’ parameters in absence of a theory of SUSY breaking violate flavour: flavour puzzle

$$\left(\delta_{ij}^{u,d,e,\nu}\right)_{AB} \equiv \frac{\left(\mathcal{M}^2_{\tilde{u},\tilde{d},\tilde{e},\tilde{\nu}}\right)_{ij}^{AB}}{m_{\tilde{f}}^2}$$

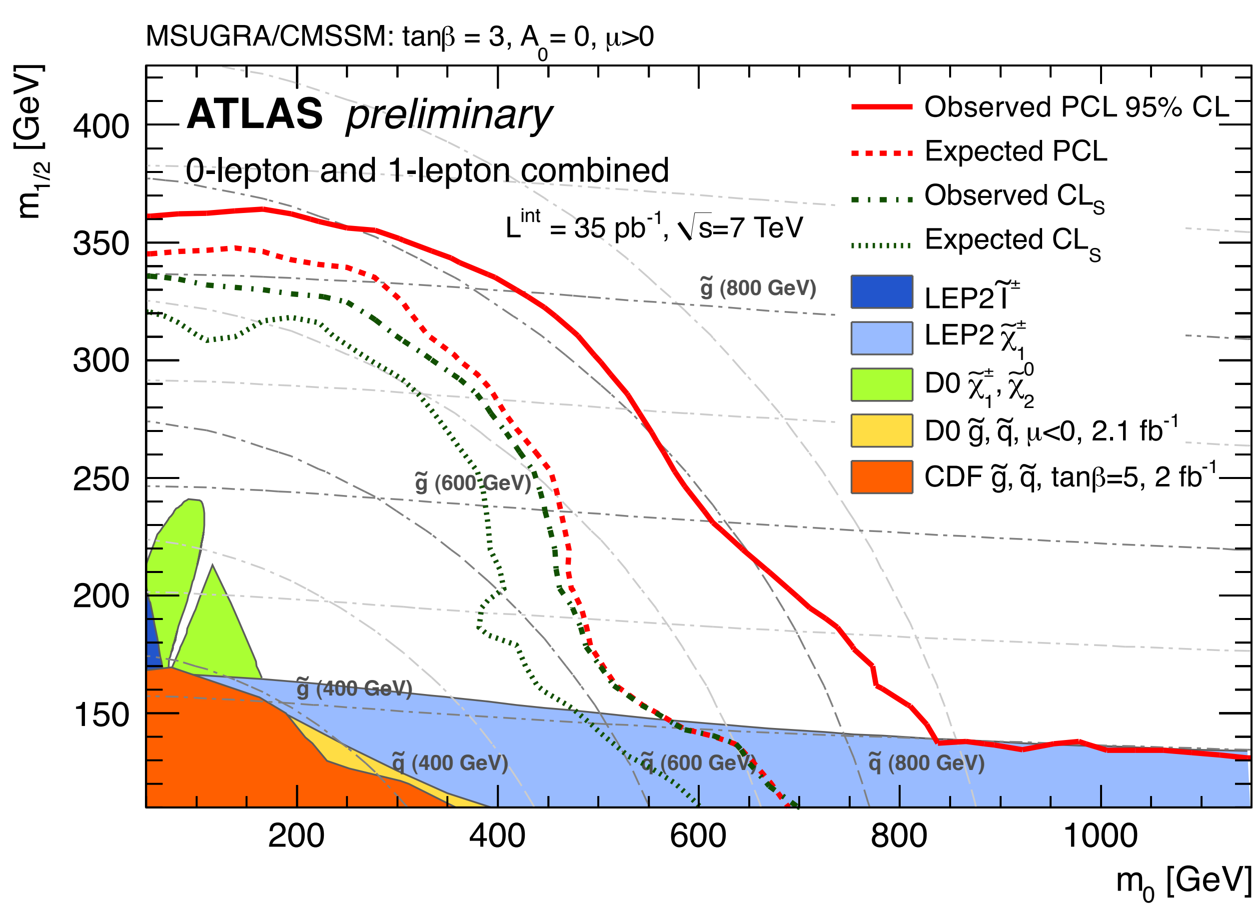
33 flavour-violating parameters

45 CPV (some flavour-conserving)

- flavour probes the SUSY breaking; GUT relations

CMSSM / mSUGRA

- standard approach: “CMSSM” (“mSUGRA”)
  - universal scalar mass, gaugino mass, A-terms (A_{ij}=a Y_{ij}) at the GUT scale, sign(μ)
  - 3 parameters & 1 sign, RG evolution down to TeV scale
- flavour puzzle absent [CMSSM still needs to be justified]
- Straightforward interpretation of experimental constraints



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Grand unification

$\begin{pmatrix} u_L \\ d_L \end{pmatrix}$	$\begin{matrix} u_R \\ d_R \end{matrix}$	$\begin{pmatrix} c_L \\ s_L \end{pmatrix}$	$\begin{matrix} c_R \\ s_R \end{matrix}$	$\begin{pmatrix} t_L \\ b_L \end{pmatrix}$	$\begin{matrix} t_R \\ b_R \end{matrix}$	$\begin{matrix} Q = +2/3 \\ Q = -1/3 \end{matrix}$
$\begin{pmatrix} \nu_{eL} \\ e_L \end{pmatrix}$	$\begin{matrix} - \\ e_R \end{matrix}$	$\begin{pmatrix} \nu_{\mu L} \\ \mu_L \end{pmatrix}$	$\begin{matrix} - \\ \mu_R \end{matrix}$	$\begin{pmatrix} \nu_{\tau L} \\ \tau_L \end{pmatrix}$	$\begin{matrix} - \\ \tau_R \end{matrix}$	$\begin{matrix} Q = 0 \\ Q = -1 \end{matrix}$

- SM in highly reducible representations of the gauge group
  SM gen = $(3,2)_{1/6} + (\bar{3},1)_{-2/3} + (\bar{3},1)_{1/3} + (1,2)_{-1/2} + (1,1)_{1}$

- however,
  SM gen = $[10 + \bar{5}]_{SU(5)}$
  SM gen + ν_R^c = $16_{SO(10)}$

- if either group is gauged, no gauge invariant distinction of baryons and leptons - baryon & lepton number violation

  what about flavour?

Flavour of SUSY GUTs

- small, hierarchical mixing in the quark sector

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

- large mixings in the lepton sector

$$U = \begin{pmatrix} c\, e^{i\alpha_1/2} & s\, e^{i\alpha_2/2} & s_{13}\, e^{-i\delta} \\ -s\, e^{i\alpha_1/2} & c\, e^{i\alpha_2/2}/\sqrt{2} & 1/\sqrt{2} \\ s\, e^{i\alpha_1/2} & -c\, e^{i\alpha_2/2}/\sqrt{2} & 1/\sqrt{2} \end{pmatrix}$$

$s = \mathcal{O}(1)$

SUSY radiative corrections can “transfer” leptonic mixing angles to the hadronic sector

Barbieri&Hall 1994, Barbieri,Hall,Strumia 1995

CMM Model

[Chang, Masiero, Murayama 03]

- SO(10) gauge theory with superpotential

$$W_Y = \frac{1}{2} 16_i \, \mathrm{Y}_1^{ij} \, 16_j \, 10_H \; + \; 16_i \, \mathrm{Y}_2^{ij} \, 16_j \, \frac{45_H \, 10'_H}{2\, M_{\mathrm{Pl}}} \; + \; 16_i \, \mathrm{Y}_N^{ij} \, 16_j \frac{\overline{16}_H \overline{16}_H}{2\, M_{\mathrm{Pl}}}$$

SO(10) spinor $\quad 16_i = (Q, u^c, d^c, L, e^c, \nu^c)_i \,, \qquad i = 1, 2, 3$

M_U, M_ν^{Dirac} $\qquad$ M_D, M_L $\qquad$ $M_{\nu R}$

- assumptions:
  - Y_1 and Y_N simultaneously diagonalisable
  - breaking via SU(5)

$$\mathrm{SO}(10) \xrightarrow{\langle 16_H \rangle, \langle \overline{16}_H \rangle, \langle 45_H \rangle} \mathrm{SU}(5) \xrightarrow{\langle 45_H \rangle} \mathrm{G}_{\mathrm{SM}} \equiv \mathrm{SU}(3)_C \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$$

$$\xrightarrow{\langle 10_H \rangle, \langle 10'_H \rangle} \mathrm{SU}(3)_C \times \mathrm{U}(1)_{\mathrm{em}}$$

  - MSSM Higgs doublets in different copies of 10 of SO(10)

$$\begin{aligned} \mathbf{10}_H &= (*, \mathbf{5}_H) = (*, (\mathbf{3}_H, H_u)) \\ \mathbf{10}'_H &= (\overline{\mathbf{5}}_H, *) = ((\overline{\mathbf{3}}_H, H_d), *) \end{aligned}$$

  Nonrenormalizable Y_2 term gives naturally small tan(β)

- keep universal (“CMSSM-like”) SUSY breaking, at M_{Planck}

Flavour structure

$$W_Y = \frac{1}{2} 16_i \, \mathsf{Y}_1^{ij} \, 16_j \, 10_H \;+\; 16_i \, \mathsf{Y}_2^{ij} \, 16_j \, \frac{45_H \, 10'_H}{2 \, M_{\mathrm{Pl}}} \;+\; 16_i \, \mathsf{Y}_N^{ij} \, 16_j \, \frac{\overline{16}_H \overline{16}_H}{2 \, M_{\mathrm{Pl}}}$$

$$\mathsf{Y}_1 = L_1 \, \mathsf{D}_1 \, L_1^\top \, ,$$
$$\mathsf{Y}_2 = L_2 \, \mathsf{D}_2 \, R_2^\dagger \, ,$$
$$\mathsf{Y}_N = R_N \, \mathsf{D}_N \, P_N \, R_N^\top$$

$$L_1^\dagger R_N = \mathbb{1}$$ (Y_1 and Y_N simultaneously diagonalisable)

$$V_q = L_1^\top L_2^*$$ CKM quark mixing matrix

$$U_D = P_N^* R_2^\dagger L_1^*$$ PMNS lepton mixing matrix

- Now fix a U-basis where Y_1 and Y_N are diagonal. Then

$$\mathsf{Y}_2 = V_q^* \, \mathsf{D}_2 \, U_D \longrightarrow M_D, M_L$$

contains all flavour violation
In the *SM*, U_D is unphysical in hadronic physics.

Flavour structure (2)

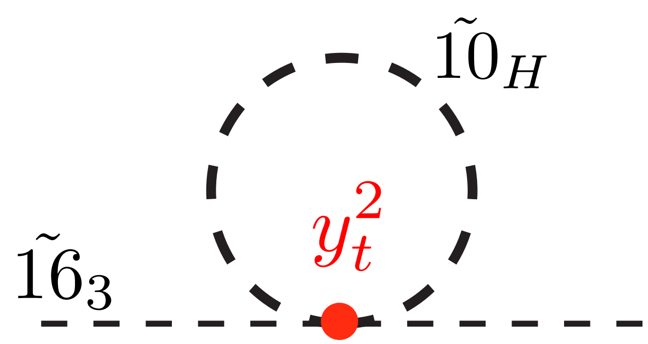
- work in the (U) basis

$$Y_2 = V_q^* \, D_2 \, U_D$$

$M_D = v_d \, Y_2$
  rotating to mass eigenstates eliminates U_D

$M_L = v_d \, Y_2^T$
  rotating to mass eigenstates eliminates V_q

M_U brought out of diagonal form, but only by CKM (V_q) angles
no physical effect of U_D in the SM, or unbroken SUSY theory



However, the large top Yukawa coupling in Y_1 fixes the U-basis as the *universal* mass eigenbasis for the sfermions

Observables

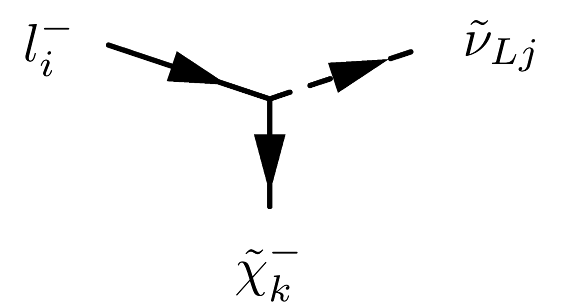
- There is now a mismatch of the sfermion and fermion mass bases for the right-handed down-type particles and the left-handed leptons

$$\mathsf{m}^2_D = U_D \mathsf{m}^2_{\tilde{d}} U_D^\dagger = \begin{pmatrix} m^2_{\tilde{d}} & 0 & 0 \\ 0 & m^2_{\tilde{d}} - \frac{1}{2}\Delta_{\tilde{d}} & -\frac{1}{2}\Delta_{\tilde{d}} \mathrm{e}^{i\xi} \\ 0 & -\frac{1}{2}\Delta_{\tilde{d}} \mathrm{e}^{-i\xi} & m^2_{\tilde{d}} - \frac{1}{2}\Delta_{\tilde{d}} \end{pmatrix}$$

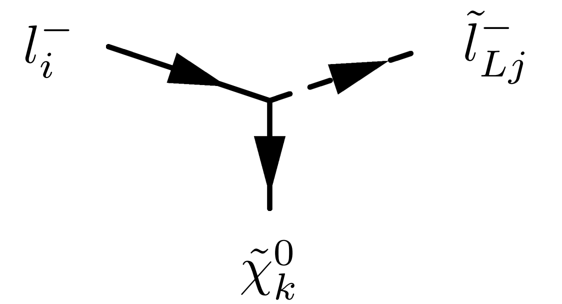
complex phase

- Diagonalizing the matrix introduces flavour violation into neutral current vertices

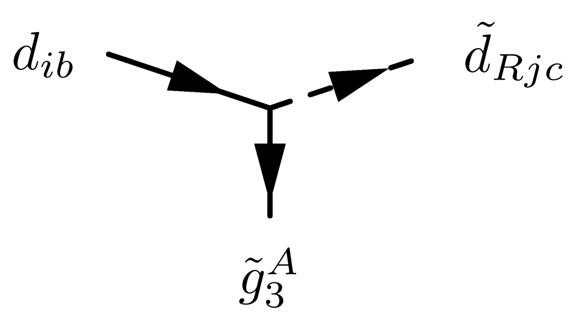
Soft flavour violation



$$-i\left(\frac{e}{\sin\theta_W} Z_+^{1i} P_L + y_{l_i^-} Z_-^{2i*} P_R\right) U_{ij}$$



$$i\left(\left[\frac{e}{\sqrt{2}\cos\theta_W} Z_N^{1k} + \frac{e}{\sqrt{2}\sin\theta_W} Z_N^{2k}\right] P_L + y_{l_i^-} Z_N^{3k*} P_R\right) U_{ij}$$



$$i\sqrt{2} g_3 T_{cb}^A P_R U_{ij}$$

may be complex

large effects in b ➔s transitions, CP violation
correlations of hadronic & leptonic observables

2 ➔1 and 3 ➔1 transitions less clearly correlated

but see Trine et al 2009, Girrbach et al 2010

Phenomenology: RG evolution

- 2-loop RGE for gauge couplings and y_t, analytic formulas for soft terms, matched at SUSY, SU(5) and SO(10) thresholds
- relate Planck-scale inputs to set of low-energy inputs:

at M_Z $\quad m^2_{\tilde{u}_1}(M_Z)\,, \qquad m^2_{\tilde{d}_1}(M_Z)\,, \qquad a^d_1(M_Z) \equiv \Big[a^d(M_Z)\Big]_{11}$

evolve to M_{GUT} $\downarrow$

$$m^2_{\tilde{\Psi}_1}(t_{\rm GUT}) = m^2_{\tilde{u}_1}(t_{\rm GUT})\,, \qquad m^2_{\tilde{\Phi}_1}(t_{\rm GUT}) = m^2_{\tilde{d}_1}(t_{\rm GUT})$$

evolve to M_{10} $\downarrow$

$$m^2_{\widetilde{16}_1}(t_{\rm SO(10)}) = \frac{1}{4}\Big[3m^2_{\tilde{\Psi}_1}(t_{\rm SO(10)}) + m^2_{\tilde{\Phi}_1}(t_{\rm SO(10)})\Big]$$

evolve to M_{Pl} $\downarrow$

$$m_0^2 = m^2_{\widetilde{16}_1}(t_{\rm Pl})$$

similarly for a_1^d

evolve all soft terms down to M_Z, calculate spectrum & observables

Example

$$M_{\tilde q} = 1500 \text{ GeV},\ m_{\tilde g_3} = 500 \text{ GeV},\ a_1^d(M_Z)/M_{\tilde q} = 1.5,\ \arg(\mu) = 0 \text{ and } \tan\beta = 6$$

upward evolution

$$a_0 = 1273 \text{ GeV}, \qquad m_0 = 1430 \text{ GeV}, \qquad m_{\tilde g} = 184 \text{ GeV}$$

SO(10) & SU(5) RGE

$$\hat{\hat{\mathsf{A}}}_u(M_{\rm GUT}) = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 46 \end{pmatrix} \text{GeV}, \quad \hat{\hat{\mathsf{A}}}_d(M_{\rm GUT}) = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0.3 & -3.5 \end{pmatrix} \text{GeV}$$

$$\hat{\hat{\mathsf{A}}}_\nu(M_{\rm GUT}) = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ -0.0013 & 0.0023 & 43.4 \end{pmatrix} \text{GeV},$$

non-universal at M_{GUT}!

$$m_{\tilde\Phi}(M_{\rm GUT}) = \mathrm{diag}\,(1426, 1426, 1074) \ \text{GeV},$$
$$m_{\tilde\Psi}(M_{\rm GUT}) = \mathrm{diag}\,(1444, 1444, 1077) \ \text{GeV},$$
$$m_{\tilde N}(M_{\rm GUT}) = \mathrm{diag}\,(1459, 1459, 1078) \ \text{GeV},$$
$$m_{H_u}(M_{\rm GUT}) = 1126 \text{ GeV}, \quad m_{H_d}(M_{\rm GUT}) = 1446 \text{ GeV},$$
$$m_{\tilde g}(M_{\rm GUT}) = 211 \text{ GeV}.$$

MSSM RGE

$$m_{\tilde g_1} = 83 \text{ GeV}, \quad m_{\tilde g_2} = 165 \text{ GeV},$$
$$m_{\tilde\chi_i^0} = (640,\ 632,\ 159,\ \underline{81}) \ \text{GeV}$$
$$m_{\tilde\chi_i^\pm} = (640,\ 159) \ \text{GeV}$$

LSP

$$M_{\tilde l_i} = (1427,\ 1427,\ \mathbf{1074},\ 1462,\ 1462,\ \mathbf{1095}) \ \text{GeV}$$
$$M_{\tilde u_i} = (1519,\ 1519,\ \mathbf{934},\ 1501,\ 1501,\ \mathbf{485}) \ \text{GeV}$$
$$M_{\tilde d_i} = (1519,\ 1519,\ \mathbf{908},\ 1498,\ 1498,\ \mathbf{1164}) \ \text{GeV}.$$

Mass splittings

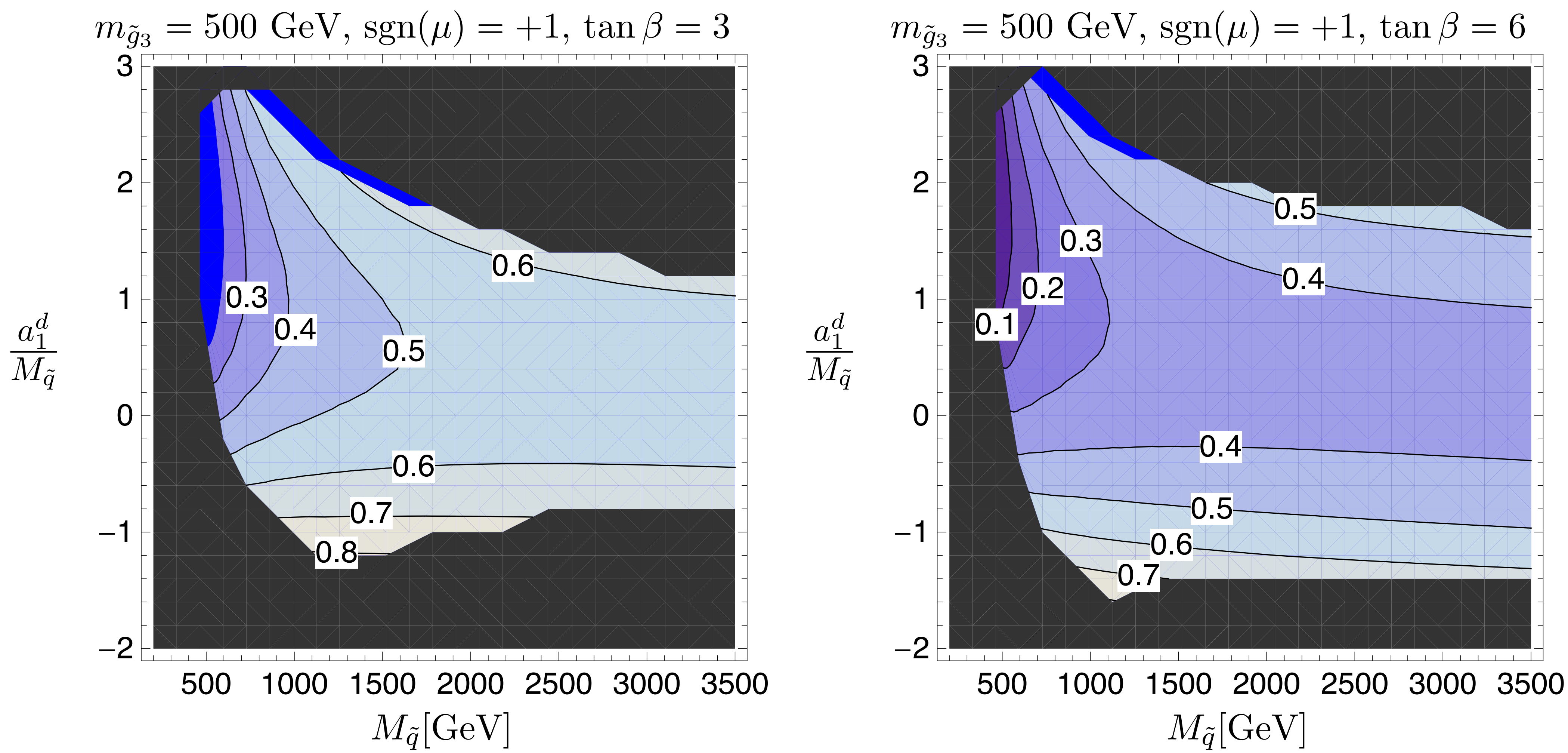


Figure 3: Relative mass splitting $\Delta_{\tilde{d}}^{\rm rel} = 1 - m_{\tilde{d}_3}^2/m_{\tilde{d}_2}^2$ among the bilinear soft terms for the right-handed squarks of the second and third generations with $\tan\beta = 3$ (left) and 6 (right) in the $M_{\tilde{q}}(M_Z) - a_1^d(M_Z)/M_{\tilde{q}}(M_Z)$ plane for $m_{\tilde{g}_3} = 500$ GeV and sgn$(\mu) = +1$.

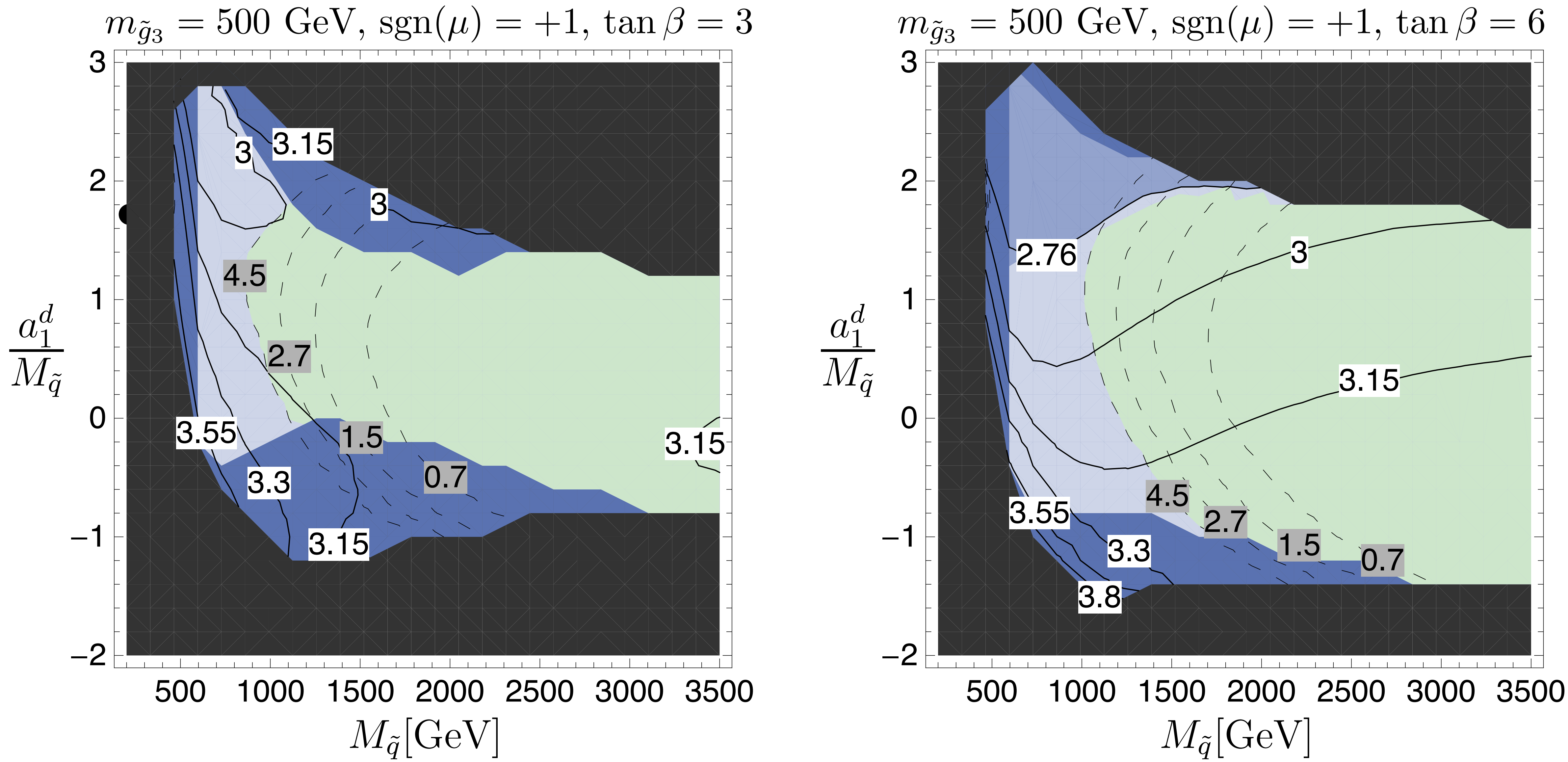
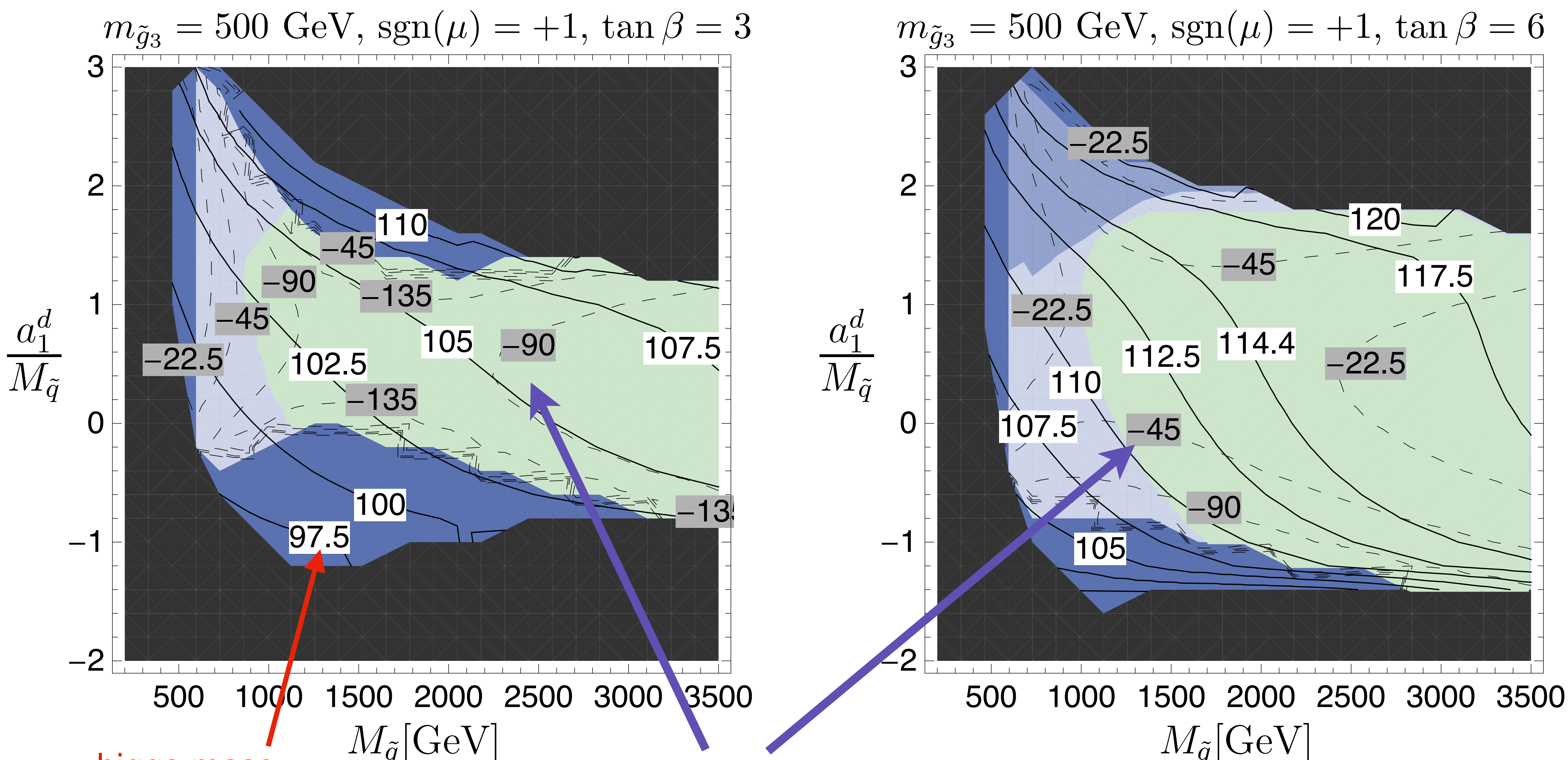


Figure 4: Correlation of FCNC processes as a function of $M_{\tilde{q}}(M_Z)$ and $a_1^d(M_Z)/M_{\tilde{q}}(M_Z)$ for $m_{\tilde{g}_3}(M_Z) = 500$ GeV and $\operatorname{sgn}\mu = +1$ with $\tan\beta = 3$ (left) and $\tan\beta = 6$ (right). $\mathcal{B}(b \to s\gamma)[10^{-4}]$ solid lines with white labels; $\mathcal{B}(\tau \to \mu\gamma)[10^{-8}]$ dashed lines with gray labels. Black region: $m_{\tilde{f}}^2 < 0$ or unstable $|0\rangle$; dark blue region: excluded due to $B_s - \overline{B}_s$; medium blue region: consistent with $B_s - \overline{B}_s$ but excluded due to $b \to s\gamma$; light blue region: consistent with $B_s - \overline{B}_s$ and $b \to s\gamma$ but inconsistent with $\tau \to \mu\gamma$; green region: compatible with all three FCNC constraints.

Higgs mass & CPV in B_s mixing



higgs mass

excludes whole green region at $\tan\beta = 3$

max possible B_s mixing phase (degrees)

higgs mass bound can be satisfied for $\tan\beta = 6$ (or greater)

A very brief history of flavour

1934 Fermi proposes Hamiltonian for beta decay

$$H_W = -G_F(\bar{p}\gamma^\mu n)(\bar{e}\gamma_\mu \nu)$$

1956-57 Lee&Yang propose parity violation to explain "θ-τ paradox".
Wu et al show parity is violated in β decay
Goldhaber et al show that the neutrinos produced in ^{152}Eu K-capture always have negative helicity

1957 Gell-Mann & Feynman, Marshak & Sudarshan

$$H_W = -G_F(\bar{\nu}_\mu \gamma^\mu P_L \mu)(\bar{e}\gamma_\mu P_L \nu_e) - G(\bar{p}\gamma^\mu P_L n)(\bar{e}\gamma_\mu P_L \nu_e) + \ldots$$

V-A current-current structure of weak interactions.
Conservation of vector current proposed
Experiments give G = 0.96 G_F (for the vector parts)

1960-63 To achieve a universal coupling, Gell-Mann&Levy and Cabibbo propose that a certain superposition of neutron and Λ particle enters the weak current. Flavour physics begins!

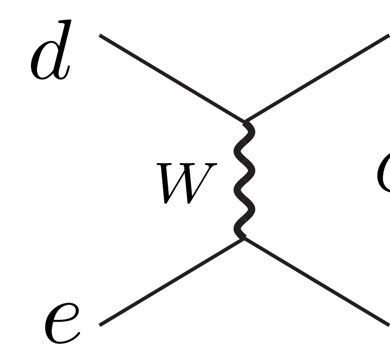
1964 Gell-Mann gives hadronic weak current in the quark model

$$H_W = -G_F J^\mu J^\dagger_\mu$$

$$J^\mu = \bar{u}\gamma^\mu P_L(\cos\theta_c d + \sin\theta_c s) + \bar{\nu}_e\gamma^\mu P_L e + \bar{\nu}_\mu\gamma^\mu P_L \mu$$

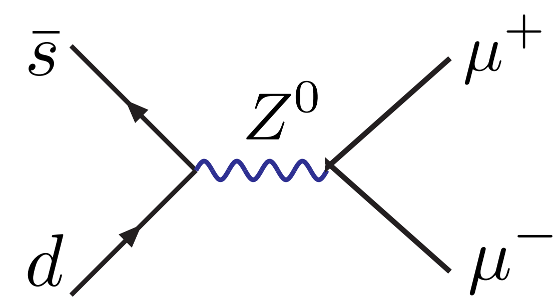
1964 CP violation discovered in Kaon decays (Cronin&Fitch)

1960-1968 J_μ part of triplet of weak gauge currents. Neutral current interactions predicted and, later, observed at CERN.



$$G_F = \frac{g^2}{4\sqrt{2}M_W^2}$$

However, the predicted flavour-changing neutral current (FCNC) processes such as $K_L \rightarrow \mu^+\mu^-$ are *not* observed!

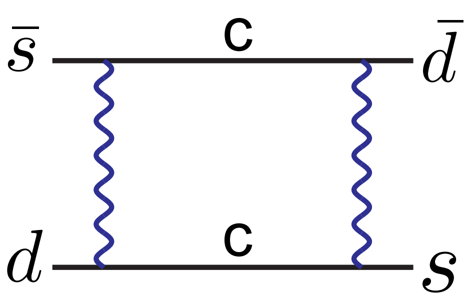


1970 To explain the absence of $K_L \rightarrow \mu^+\mu^-$, Glashow, Iliopoulos & Maiani (GIM) couple a "charmed quark" to the formerly "sterile" linear combination
$-\sin\theta_c d_L + \cos\theta_c s_L$
The doublet structure eliminates the Zsd coupling!

1971 Weak interactions are renormalizable ('t Hooft)

1972 Kobayashi & Maskawa show that CP violation requires extra particles, for example a third doublet. CKM matrix

1974 Gaillard & Lee estimate loop contributions to the K_L-K_S mass difference
Bound m_c < 5 GeV



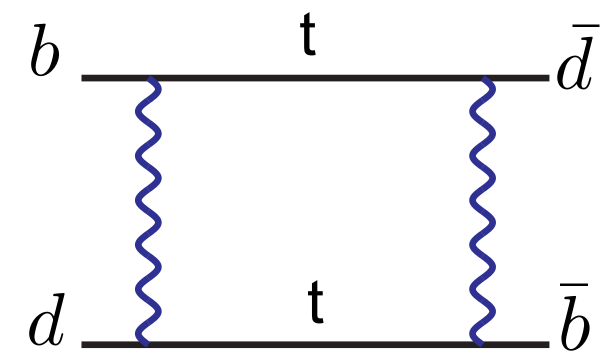
1974 Charm quark discovered

1977 τ lepton and bottom quark discovered

1983 W and Z bosons produced

1987 ARGUS measures B_d - B_d mass difference
First indication of a heavy top

The diagram depends quadratically on m_t



1995 top quark discovered at CDF & D0

u_L	u_R	c_L	c_R	t_L	t_R	$Q = +2/3$
d_L	d_R	s_L	s_R	b_L	b_R	$Q = -1/3$
ν_{eL}	$-$	$\nu_{\mu L}$	$-$	$\nu_{\tau L}$	$-$	$Q = 0$
e_L	e_R	μ_L	μ_R	τ_L	τ_R	$Q = -1$

2012- ? SUSY, new strong interactions, extra dimensions, ...

Summary: what can we learn?

- The case for flavour is strong (if there is anything at TeV or not too far above).
- For hadronic decays at LHCb, strong QCD dynamics is the main theory obstacle, but less so in some observables than in others
  - observables not depending on strong phases preferred [calculable phases O(as) ~ incalculable ones O(L/mb)]
  - feedback from experiment important (to fit/constrain some amplitudes, develop theory). Look at sine coefficients, TP's, and of course CP-conserving data - specifically "wrong polarisations" can probe RH currents
- Illustrated the power to probe fundamental scales within a SUSY GUT model

BACKUP

“msugra GUTs”

Assume that SUSY breaking is flavour blind and universal (like msugra) at or near the Planck scale

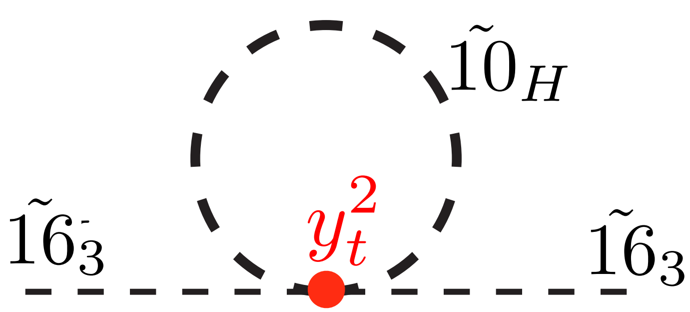
$$\begin{aligned}
\mathscr{L}_{\rm soft} = & -\widetilde{16}_i^* \, \mathsf{m}^{2\,ij}_{\widetilde{16}} \, \widetilde{16}_j - m^2_{10_H} \, 10^*_H 10_H - m^2_{10'_H} \, 10^*_{H'} 10_{H'} \\
& - m^2_{\overline{16}_H} \, \overline{16}^*_H \overline{16}_H - m^2_{16_H} 16^*_H 16_H - m^2_{45_H} \, 45^*_H 45_H \\
& - \left(\frac{1}{2} \widetilde{16}_i \, \mathsf{A}_1^{ij} \, \widetilde{16}_j \, 10_H + \widetilde{16}_i \, \mathsf{A}_2^{ij} \, \widetilde{16}_j \, \frac{45_H \, 10_{H'}}{2\, M_{\rm Pl}} + \widetilde{16}_i \, \mathsf{A}_N^{ij} \, \widetilde{16}_j \frac{\overline{16}_H \overline{16}_H}{2\, M_{\rm Pl}} + \text{h.c.} \right)
\end{aligned}$$

$$\mathsf{m}^2_{\widetilde{16}_i} = m_0^2 \; \mathbb{1} \, , \qquad m^2_{10_H} = m^2_{10'_H} = m^2_{16_H} = m^2_{\overline{16}_H} = m^2_{45_H} = m_0^2$$

$$\mathsf{A}_1 = a_0 \, \mathsf{Y}_1 \, , \qquad \mathsf{A}_2 = a_0 \, \mathsf{Y}_2 \, , \qquad \mathsf{A}_N = a_0 \, \mathsf{Y}_N \, ,$$

radiative corrections lead to a *nonuniversa*l sfermion mass matrix at the GUT scale, *diagonal in the U-basis*

[Hall, Kostelecky, Raby 86; Barbieri, Hall, Strumia 95]



$$m^2_{\tilde{16}_3} = m_0^2 - \Delta$$

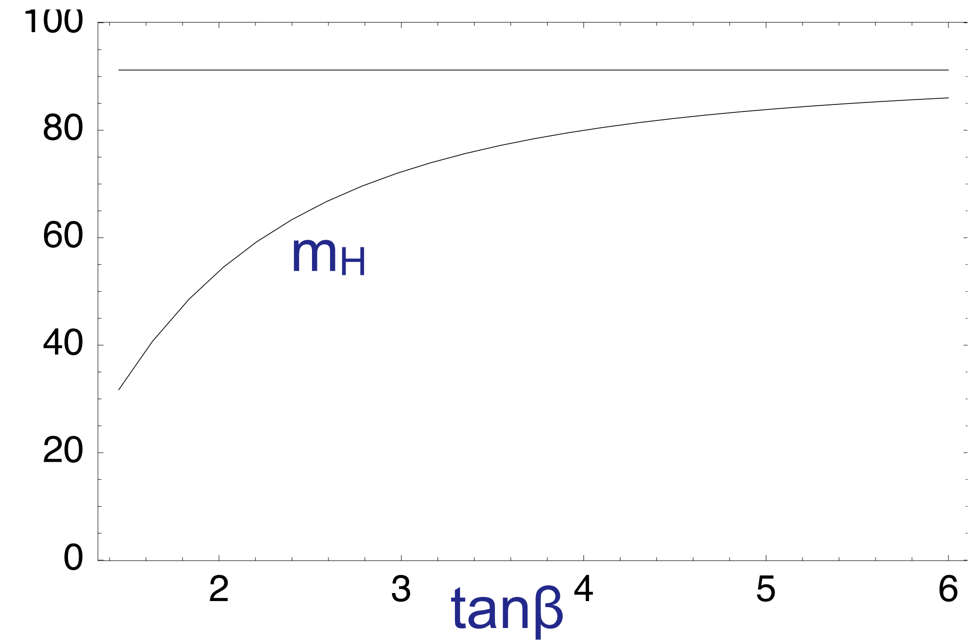
$$m^2_{\tilde{16}_1} \approx m^2_{\tilde{16}_2} = m_0^2 + \delta$$

Higgs mass constraint

- like in mSUGRA, the weak scale gives one relation between μ and the soft SUSY breaking parameters

- like always in the MSSM, the Higgs 'likes' to be light tree level

  (very) small values of tanβ disfavoured



- one & two loops

$$+\frac{3}{2}\frac{G_F\sqrt{2}\,\overline{m}_t^4}{\pi^2}\left\{-\ln\left(\frac{\overline{m}_t^2}{M_S^2}\right)+\frac{|X_t|^2}{M_S^2}\left(1-\frac{|X_t|^2}{12M_S^2}\right)\right\}$$

$$-3\frac{G_F\sqrt{2}\alpha_s\overline{m}_t^4}{\pi^3}\left\{\ln^2\left(\frac{\overline{m}_t^2}{M_S^2}\right)+\left[\frac{2}{3}-2\frac{|X_t|^2}{M_S^2}\left(1-\frac{|X_t|^2}{12M_S^2}\right)\right]\ln\left(\frac{\overline{m}_t^2}{M_S^2}\right)\right\}$$

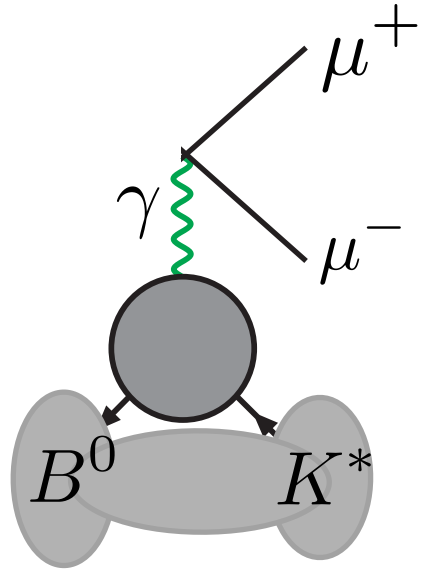
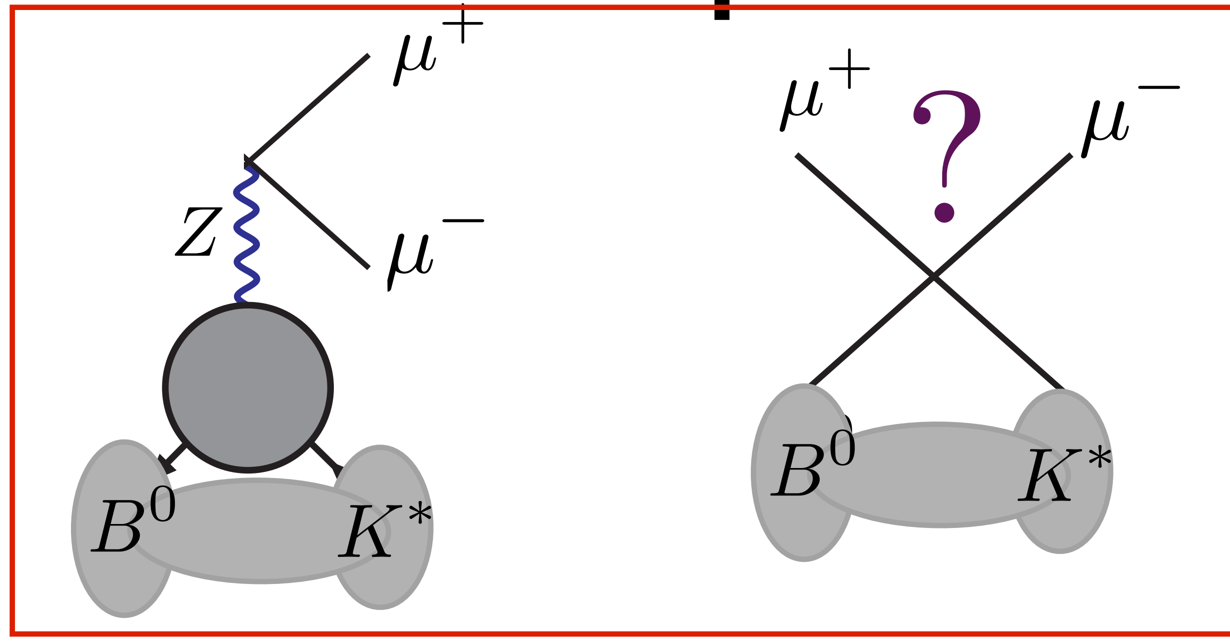
$$X_t=-\frac{A_t}{y_t}-\frac{\mu^*}{\tan\beta}$$

$$M_S^2=\sqrt{m_{\tilde{q}3}^2 m_{\tilde{u}3}^2}$$

- larger tanβ reduces y_t and size of flavour effects

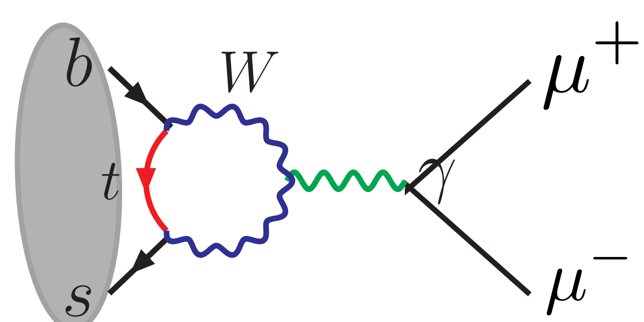
- could be relaxed by allowing the Higgs multiplets to have different Planck-scale masses from the sfermions (similarly to the 'non-universal Higgs model' (NUHM))

Theoretical description

- $A(B \rightarrow K^{*}l^{+}l^{-})$ =  + 

"naively" factorize into form factors and "effective" Wilson coefficients C_{9eff} , C_{10}

partly short distance

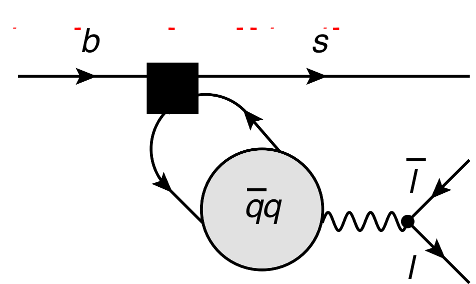


$T_{1,2,3}$ x C_7

Form factor (lattice, QCD sum rules)

Wilson coefficient (may receive NP corrections)

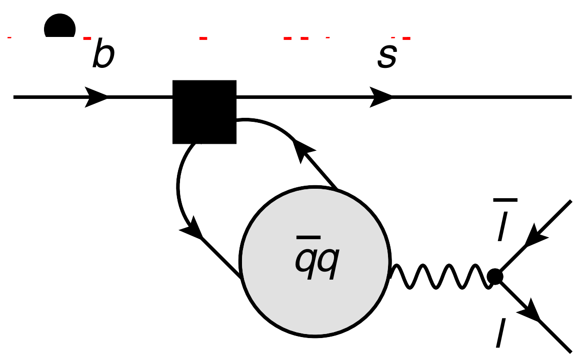
partly long distance



[Fig C Bobeth]

q = charm / u / d / s
not calculable in terms of form factors

Long-distance effects



no known way to treat charm resonance region to the necessary precision (would need << 1% to see short-distance contribution)
"solution": cut out 6 GeV^2 < q^2 < 14 GeV^2

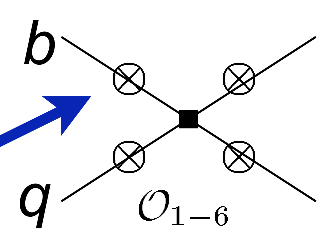
above (high-q^2) charm loops calculable in OPE

Grinstein et al; Beylich et al 2011

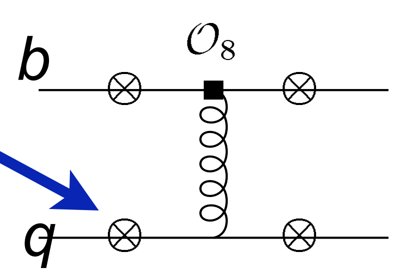
at *low* q^2 , long-distance charm effects also suppressed, but photon can now be emitted from *spectator* withouth power suppression

Beneke, Feldmann, Seidel 01

possible photon attachments



small Wilson coefficients



more significant for b ➔s transitions

$$\frac{\pi^2}{N_c}\,\frac{f_B f_{K^*,a}}{M_B}\,\Xi_a \sum_{\pm}\int\frac{d\omega}{\omega}\,\Phi_{B,\pm}(\omega)\int_0^1 du\,\Phi_{K^*,a}(u)\,T_{a,\pm}(u,\omega)$$

light-cone wave functions

calculable

long-distance "resonance" effects as in top figure (q=u,d,s) CKM and power suppressed