Discrete symmetries, flavour & BSM physics

Sebastian Jäger

University of Sussex

Amsterdam Particle Physics Symposium

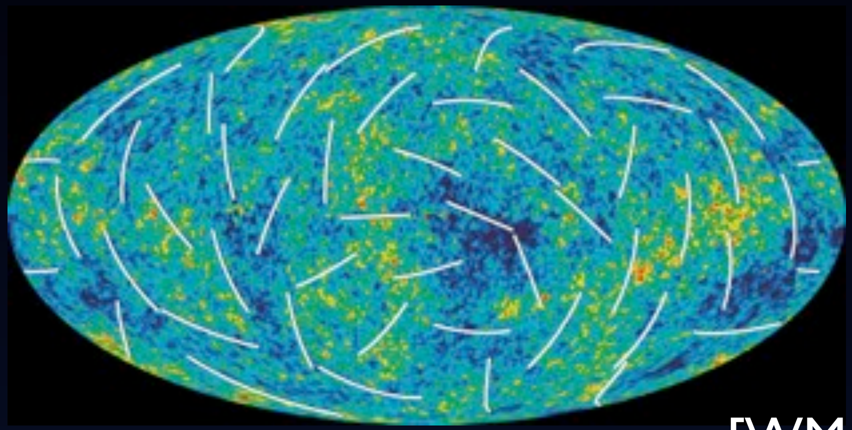
Amsterdam, 30/11/11-02/12/11

Content

- Discrete symmetries & flavour
- SM and beyond
- observables (selection)

Baryogenesis

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



[WMAP]

[SDSS]

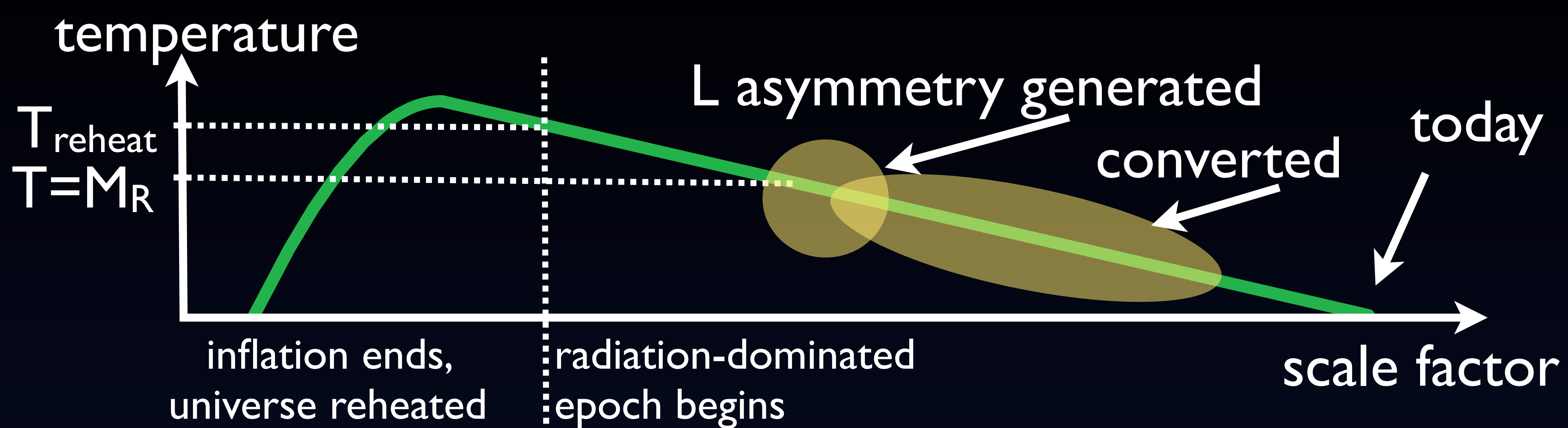
... and essentially no antibaryons in the universe

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

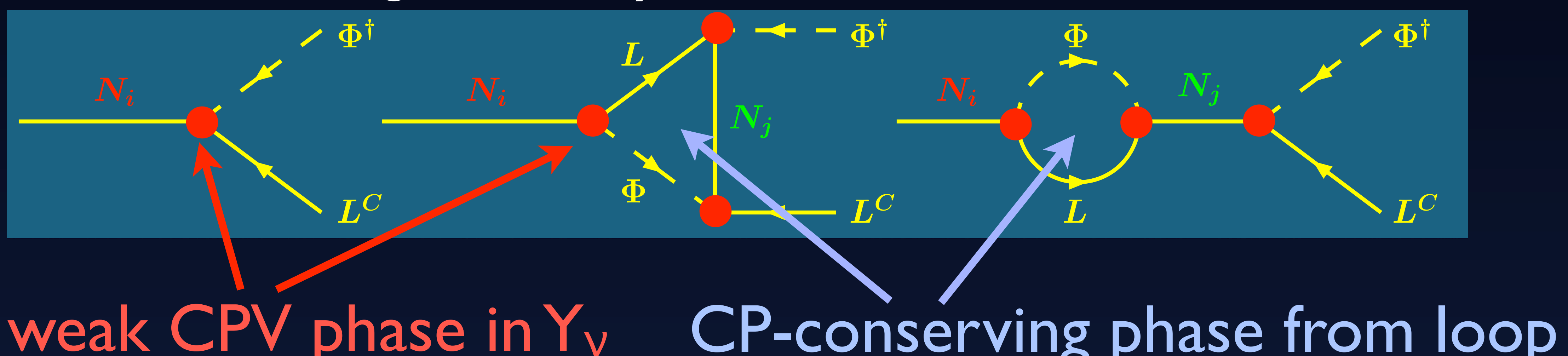
- Can arise dynamically from B=0 if sufficient...
  (1) departure from equilibrium and
  (2) C and CP violation and
  (3) B violation

Sakharov 1967

Thermal leptogenesis



- CP-violating ν_R decay:

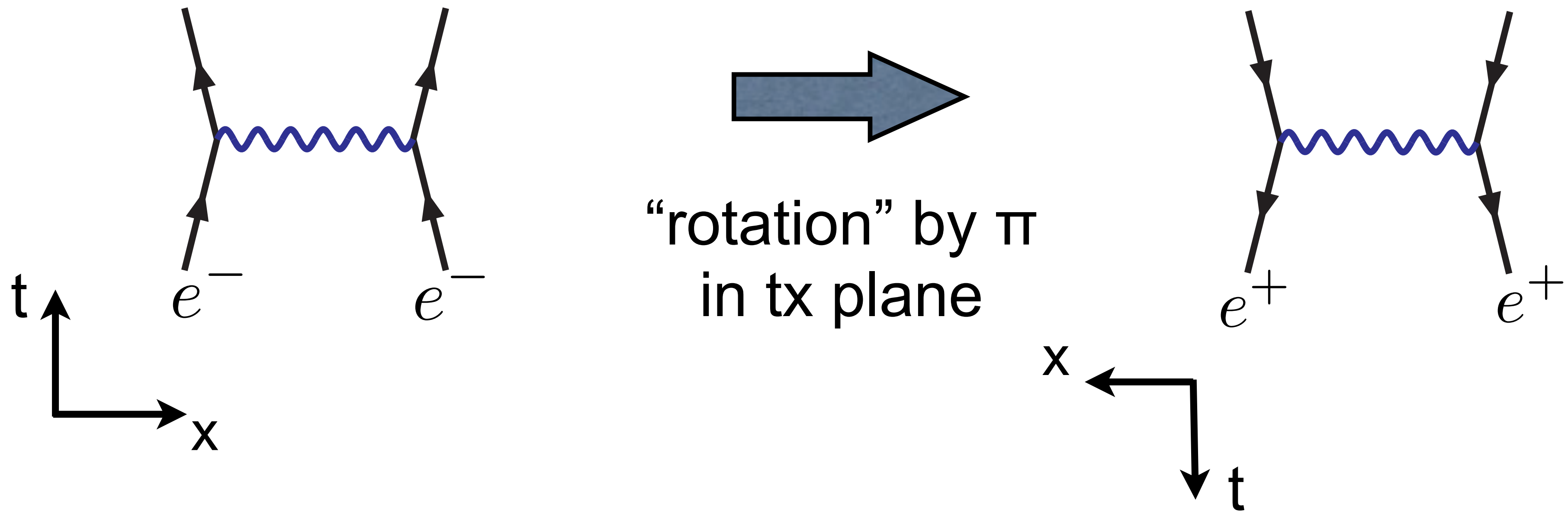


- Resulting net lepton numbers $\langle L_l \rangle$ partially converted to $\langle B \rangle$ by equilibrium sphalerons

see Bjoern Garbrecht's talk

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

(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:

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

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

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

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

9 masses

3 mixing angles

1 CP-violating phase

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

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

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

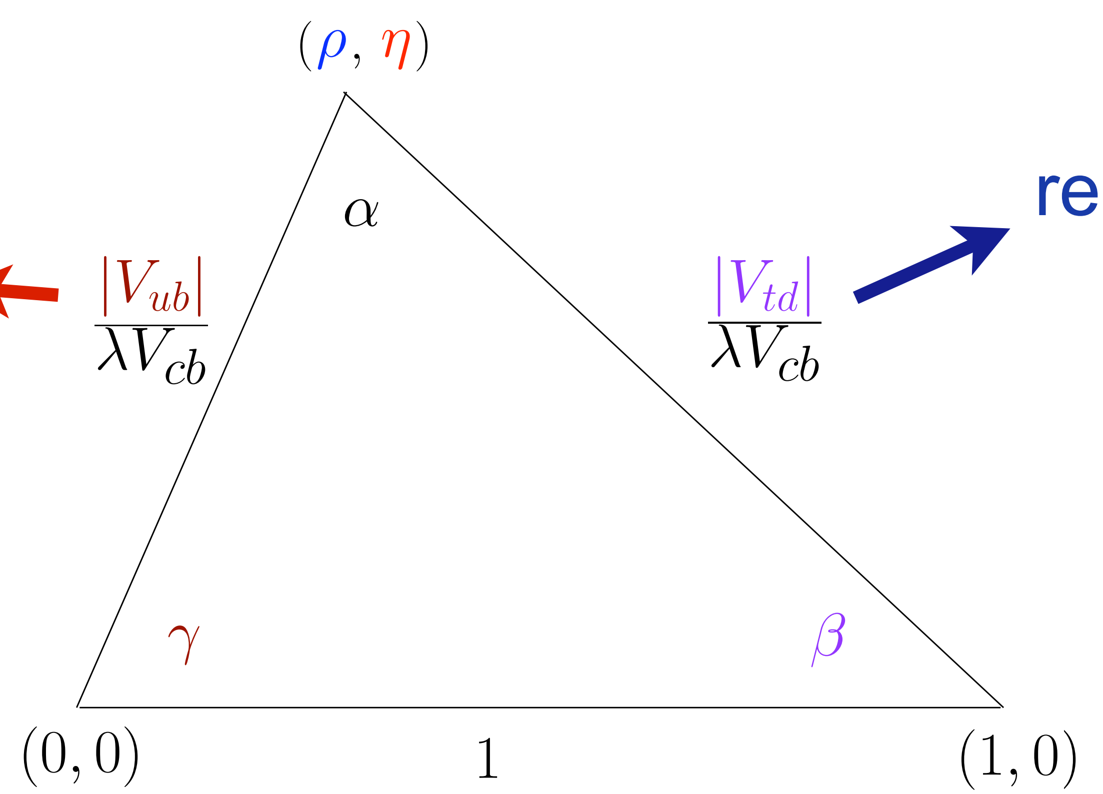
Unitarity triangle

Unitarity of $V \Rightarrow$

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

Graphically,

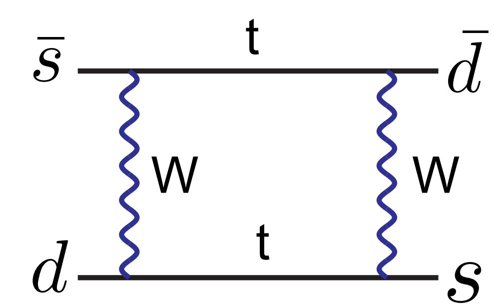
b → u l v
b → u q q
(tree-level
Weak int.)

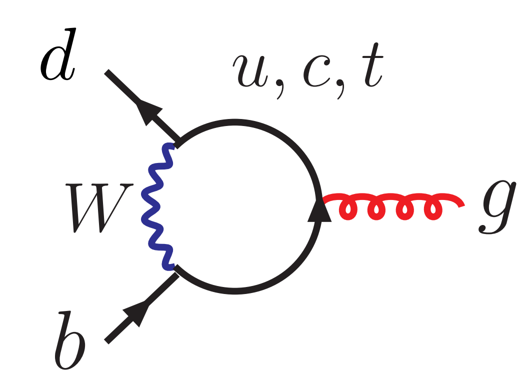


requires top loop

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

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



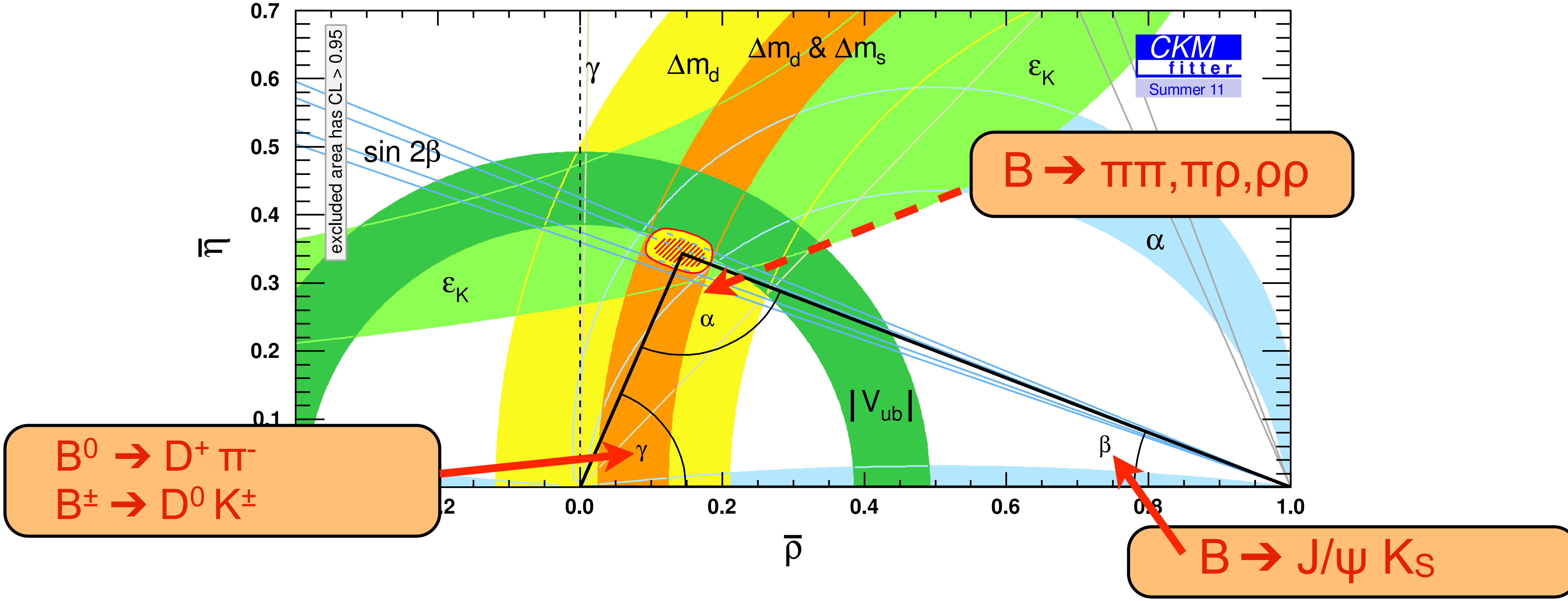


suppression of flavour-changing neutral currents (FCNC)
by loops and CKM hierarchy

This makes them sensitive to new physics!

Unitarity Triangle 2011

[UTfit obtain similar results]

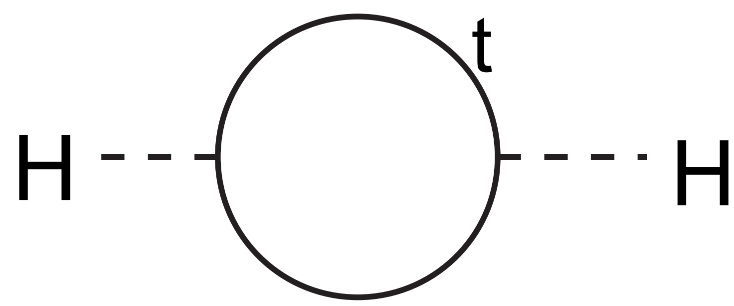


The CKM picture of flavour & CP violation is consistent with observations.

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

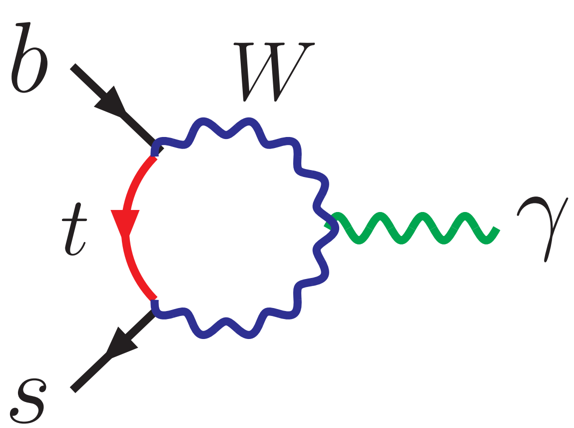
Flavour of the TeV scale

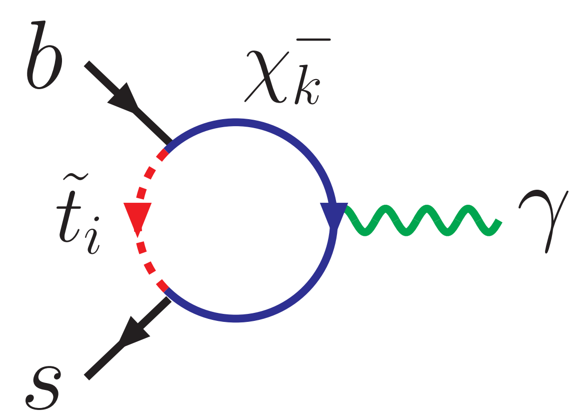
- Solutions to the hierarchy problem must bring in particles to cut off the top contribution to the weak scale (Higgs mass parameter).



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

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

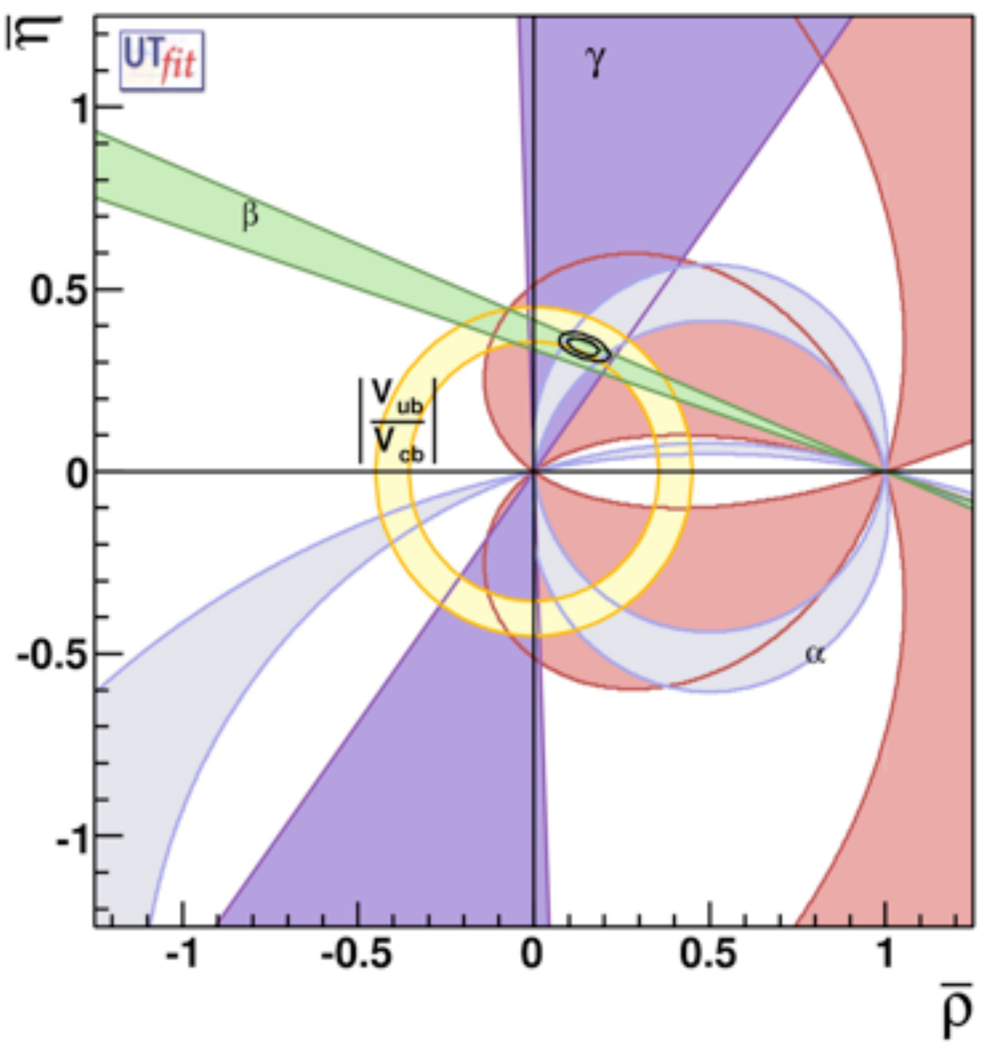




- At least they will have CKM-like flavour violations (minimal flavour violation), so will always affect rare decays

Minimal flavour violation

- in this case, CKM parameters can 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*

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

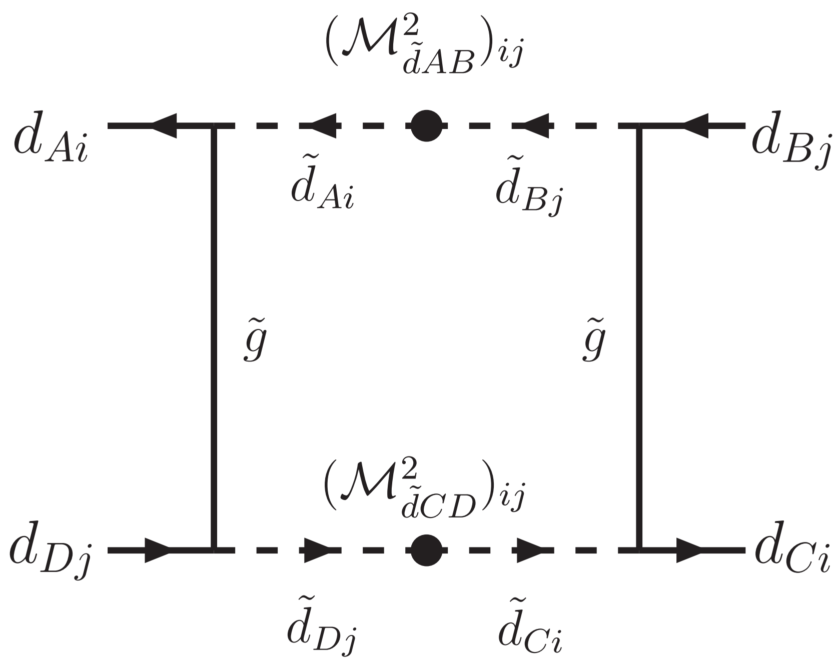
similar for up squarks, charged sleptons. 3x3 LL for sneutrinos

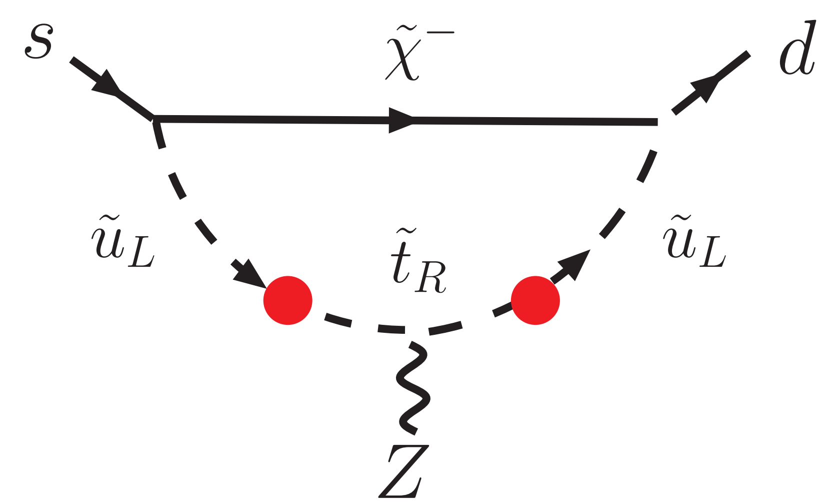
$$(\delta^{u,d,e,\nu}_{ij})_{AB} \equiv \frac{\left(\mathcal{M}^2_{\tilde{u},\tilde{d},\tilde{e},\tilde{\nu}}\right)^{AB}_{ij}}{m^2_{\tilde{f}}}$$

33 flavour-violating parameters

45 CPV (some flavour-conserving)

SUSY flavour (2)





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

ΔF=1 decays

- B ➔$K^*\mu^+\mu^-$
- B ➔$K^*\gamma$
- B ➔Kπ
- $B_{s,d}$ ➔$\mu^+\mu^-$
- K ➔πνν
- ...

SUSY flavour puzzle

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

where are their effects?

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

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

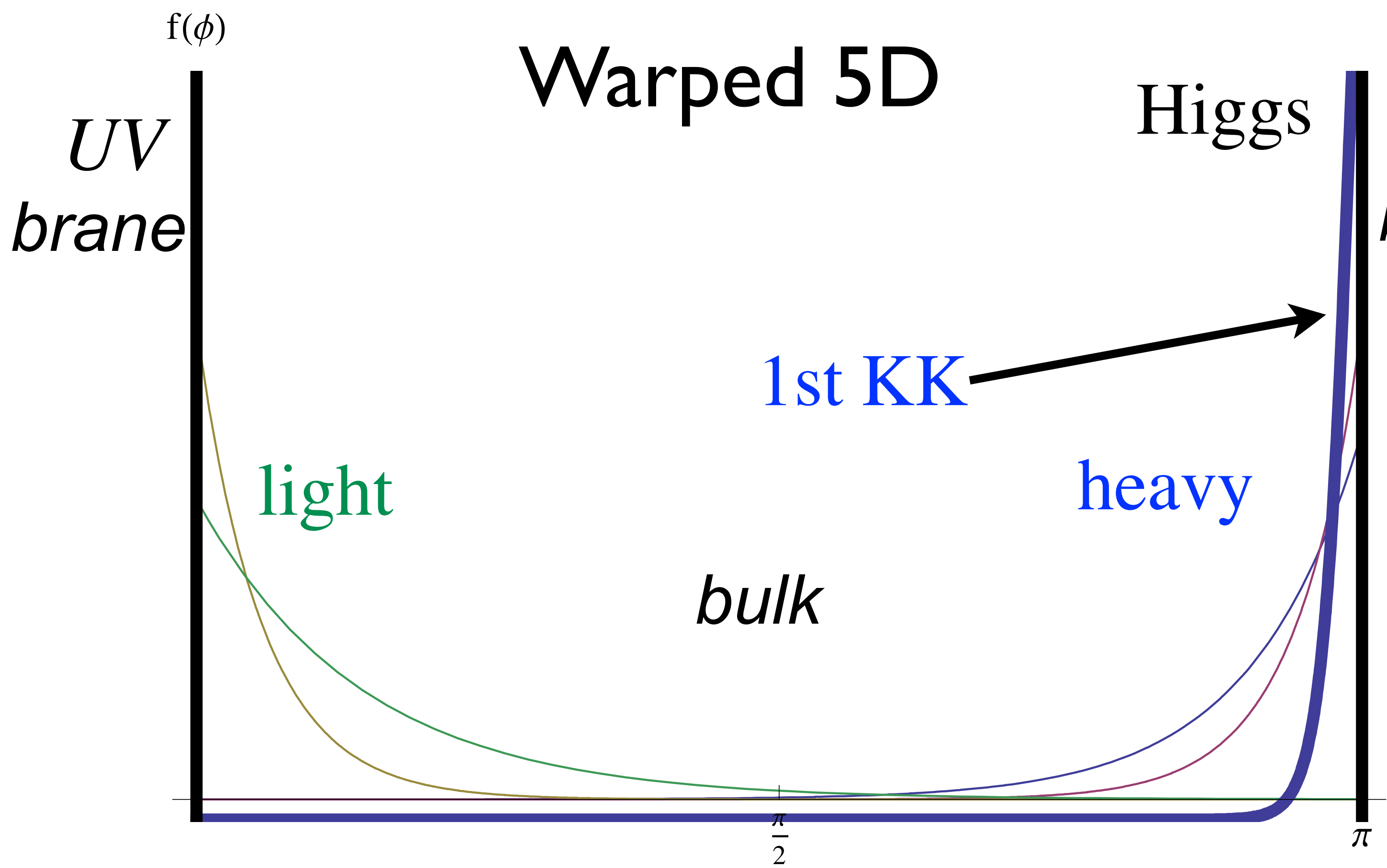
Quantity	upper bound
$\sqrt{\lvert \mathrm{Re}(\delta^{\tilde{u}}_{uc})^2_{LL} \rvert}$	3.9×10^{-2}
$\sqrt{\lvert \mathrm{Re}(\delta^{\tilde{u}}_{ud})^2_{RR} \rvert}$	3.9×10^{-2}
$\sqrt{\lvert \mathrm{Re}(\delta^{\tilde{u}}_{uc})^2_{LR} \rvert}$	1.20×10^{-2}
$\sqrt{\lvert \mathrm{Re}(\delta^{\tilde{u}}_{uc})_{LL}(\delta^{u}_{uc})_{RR}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



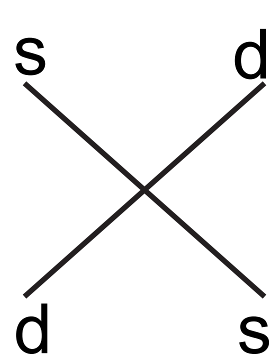
[G Perez, talk at CKM 2010]

SM fermions are zero modes (~ ground state waves of a particle in a box) of fields present in the bulk.
They also have infinitely many massive modes (KK modes, ~higher states of particle in box)

Higgs localized on IR brane

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

hierarchical SM fermion masses

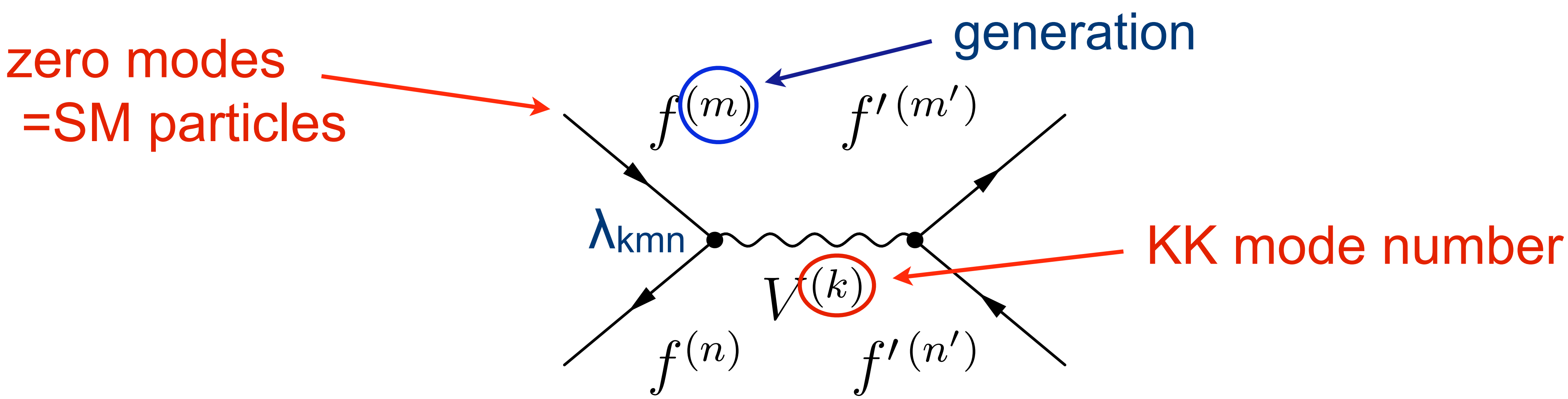


dangerous four-fermion operators with TeV suppression are “natural” on the IR brane

not so dangerous after taking into account localization of SM fermions (“RS-GIM”)

Flavour - warped ED (2)

- dominant contribution to FCNC usually *not* from brane contact terms but from tree-level KK boson exchange



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

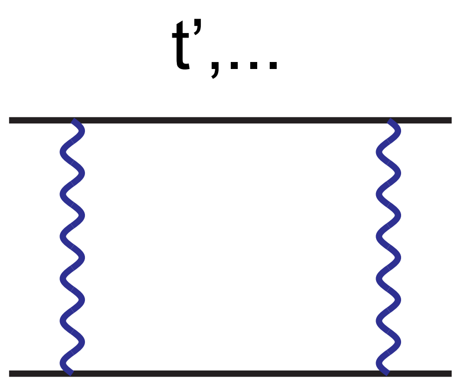
SM Yukawa coupling
$$Y_{mn} \propto f^{(m)}(\pi) f^{(n)}(\pi)$$

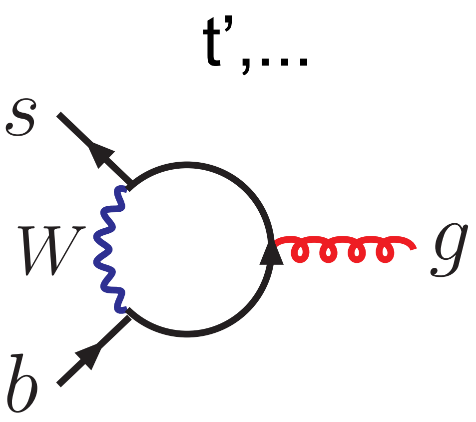
non-minimal flavour violations !

- where are their effects?

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
- ...

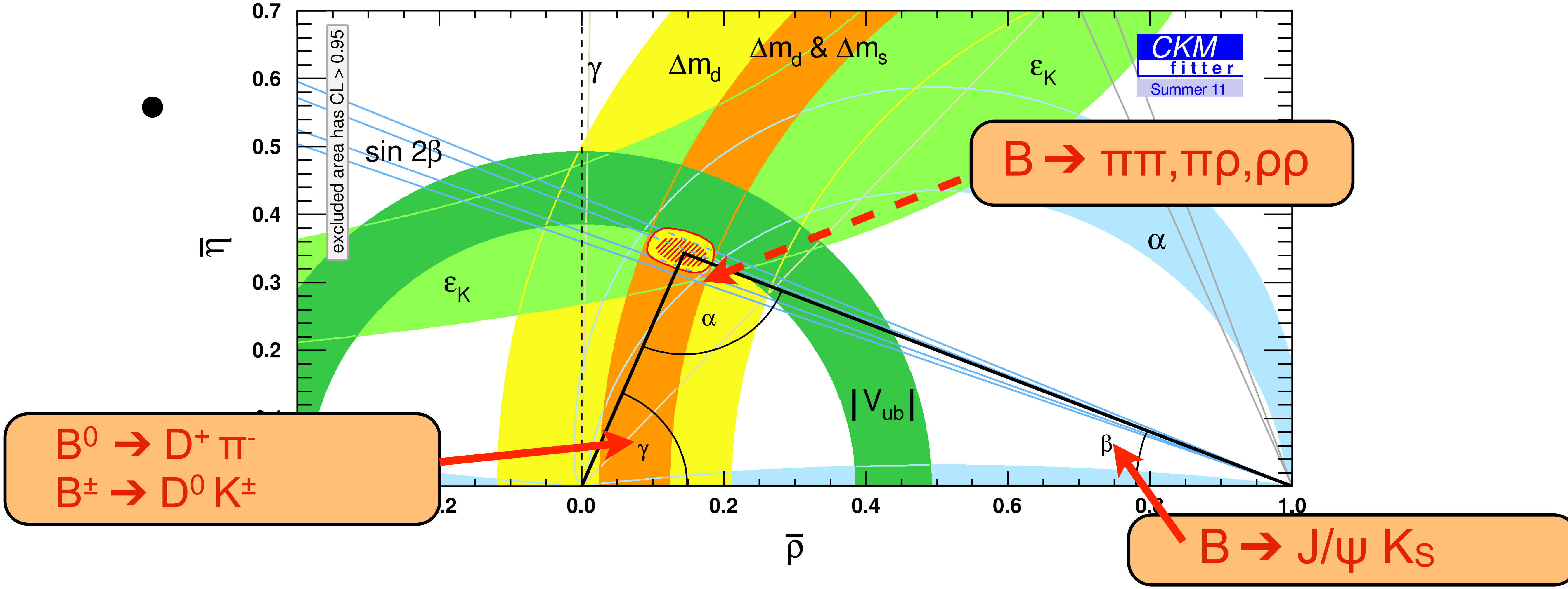




non-minimal flavour violation !

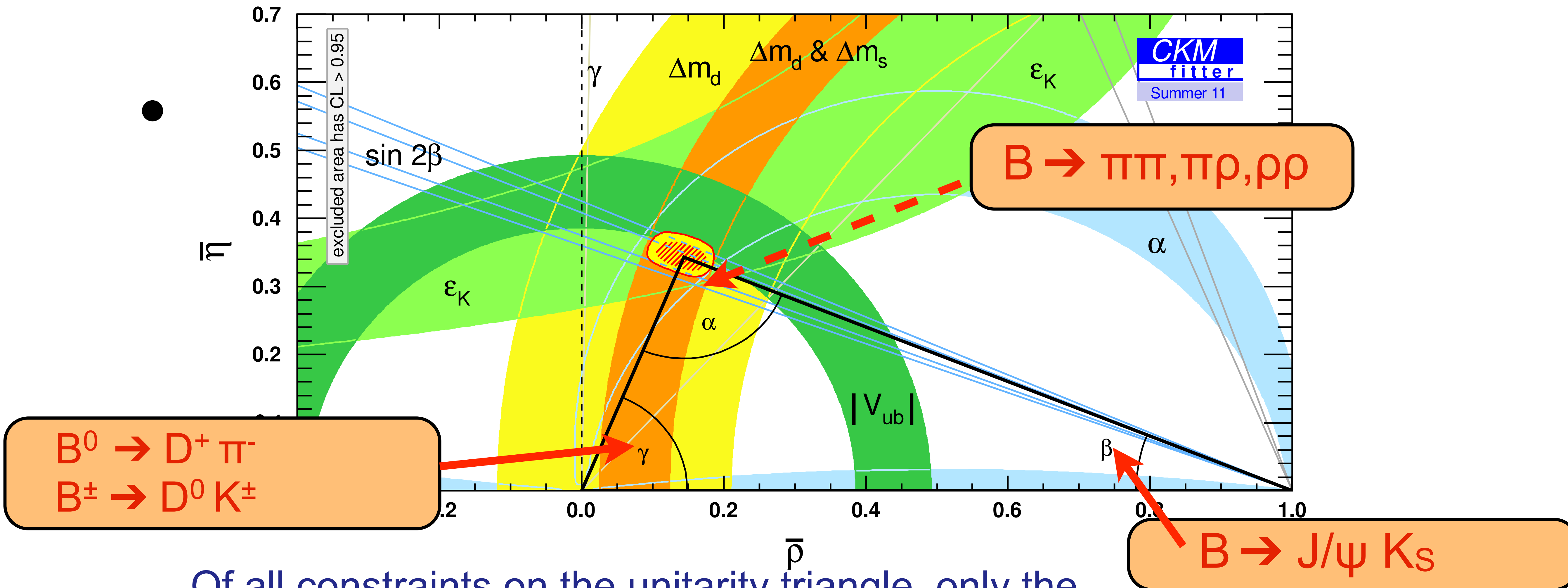
Unitarity Triangle revisited

-



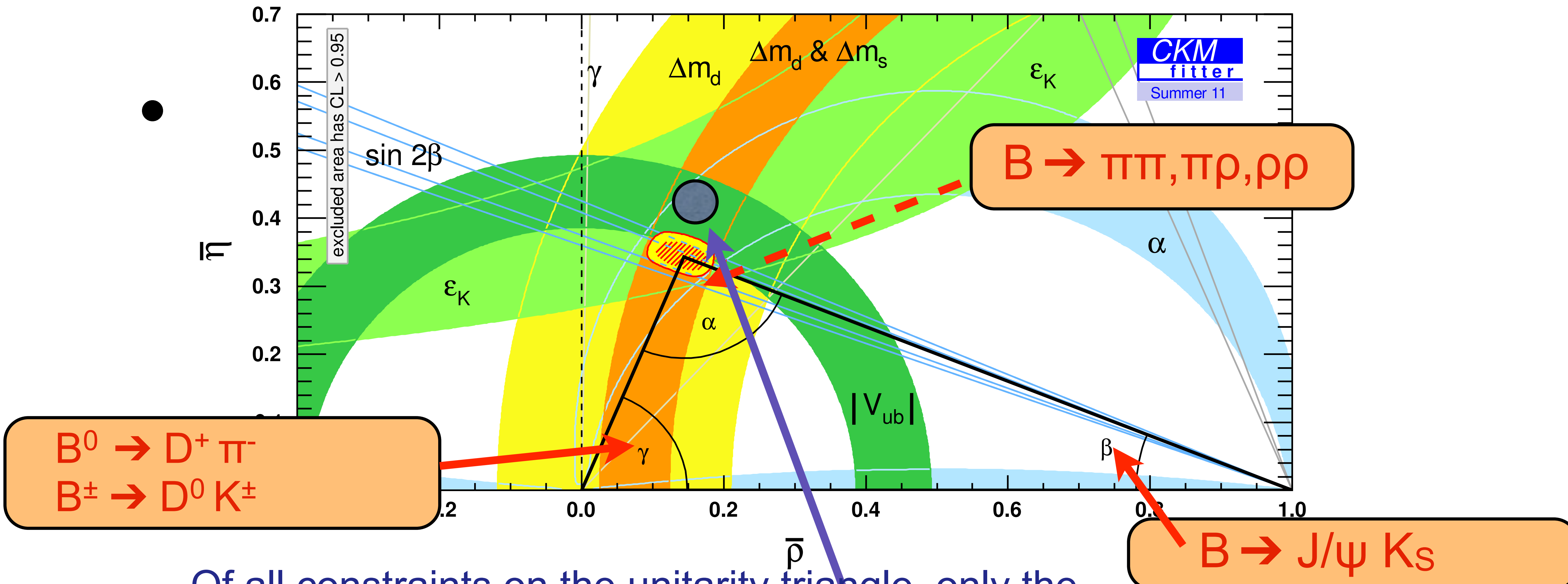
Unitarity Triangle revisited

•



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.

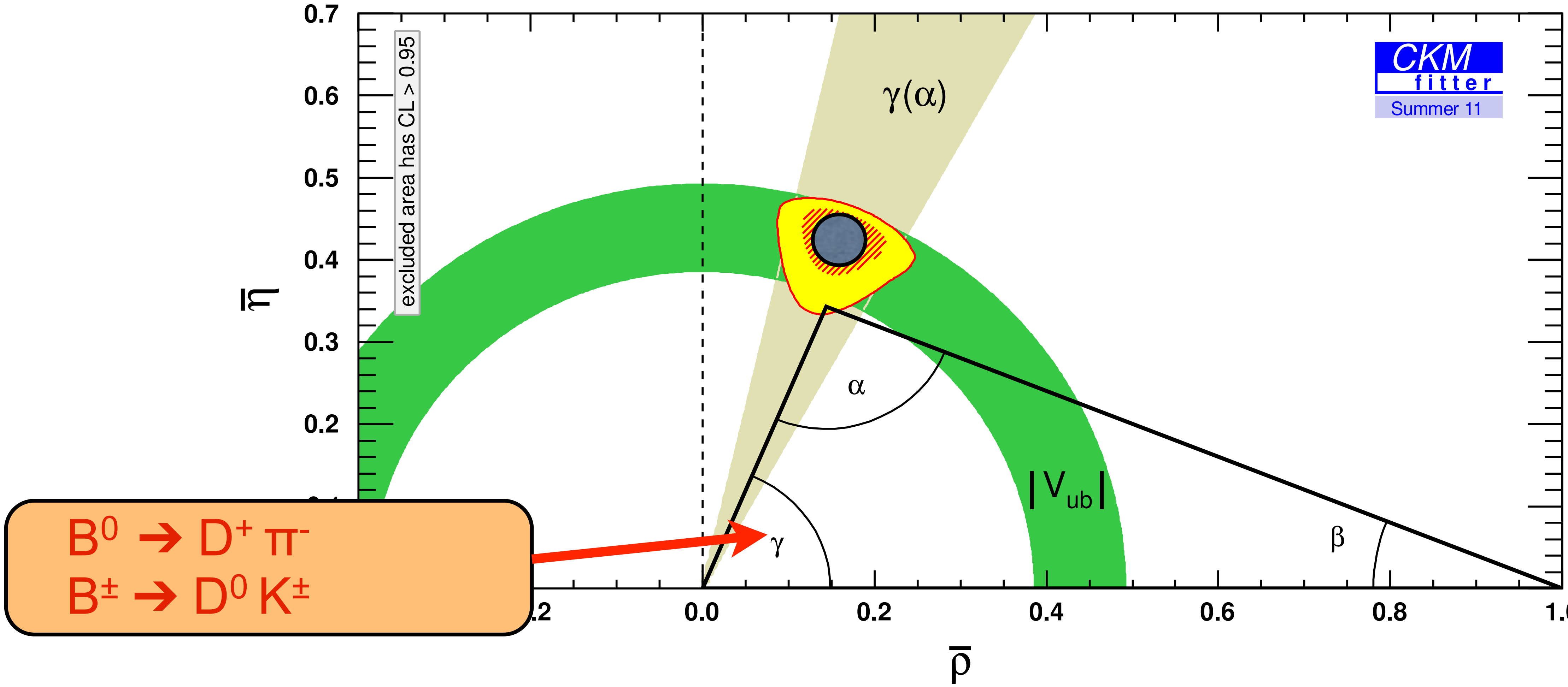
Unitarity Triangle revisited



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.

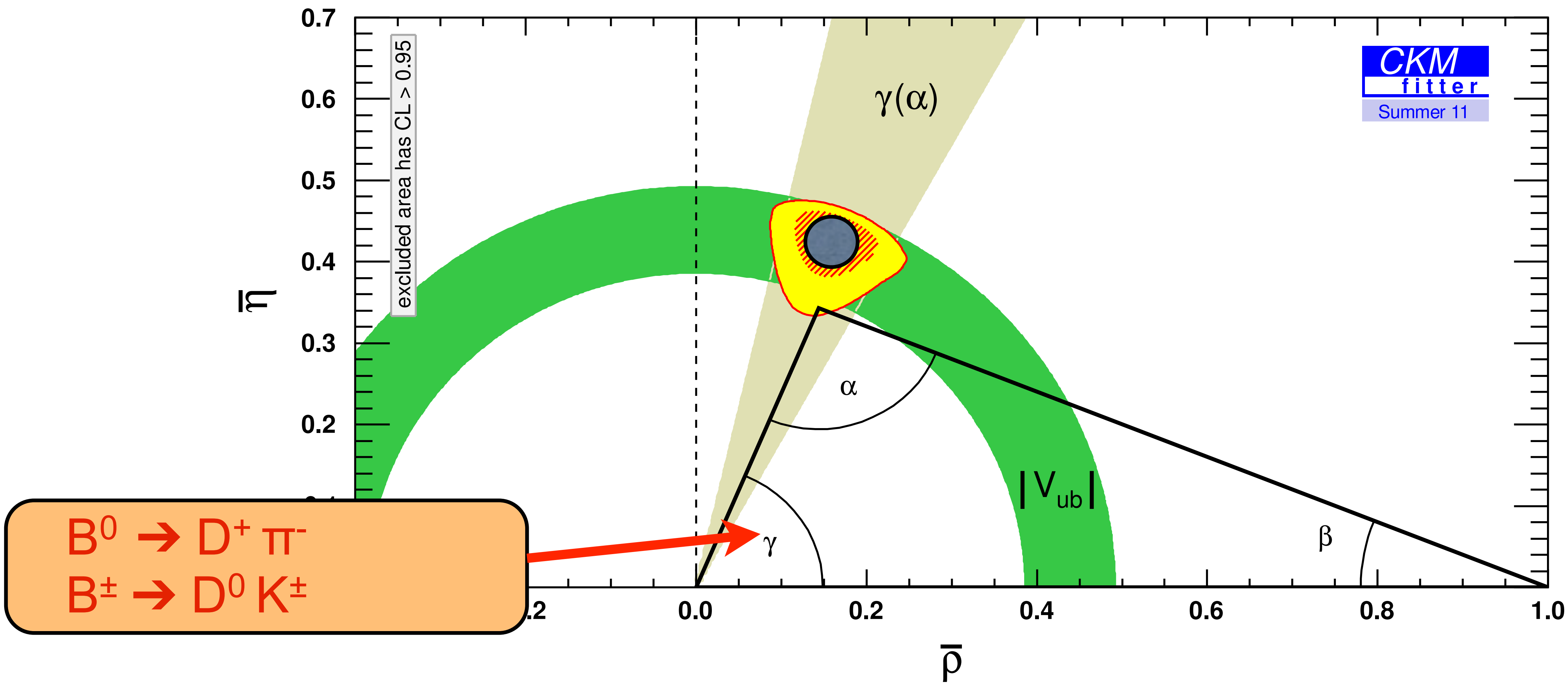
It is possible that the TRUE $(\bar{\rho}, \bar{\eta})$ lies here (for example)

“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 - N Serra’s talk.*

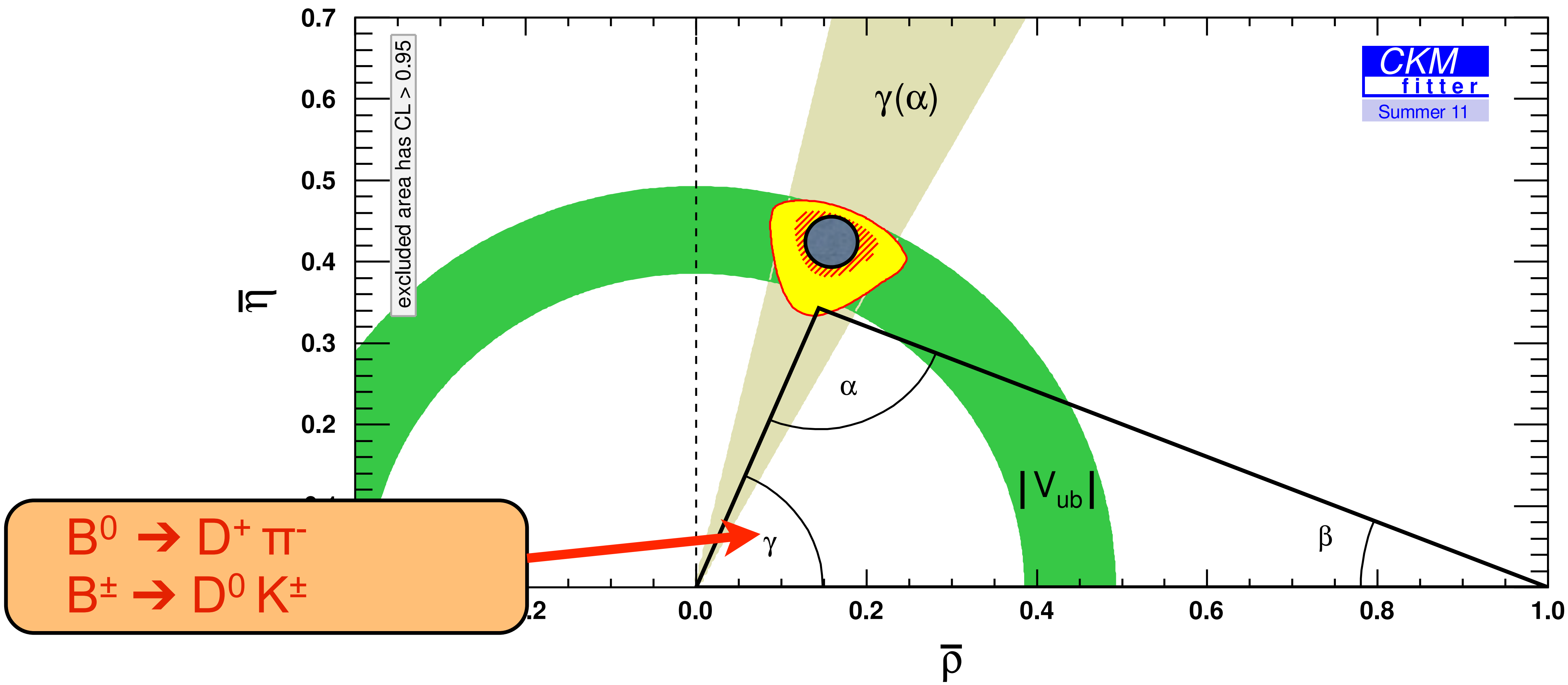
“Tree” determinations



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 - N Serra’s talk.*

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

“Tree” determinations

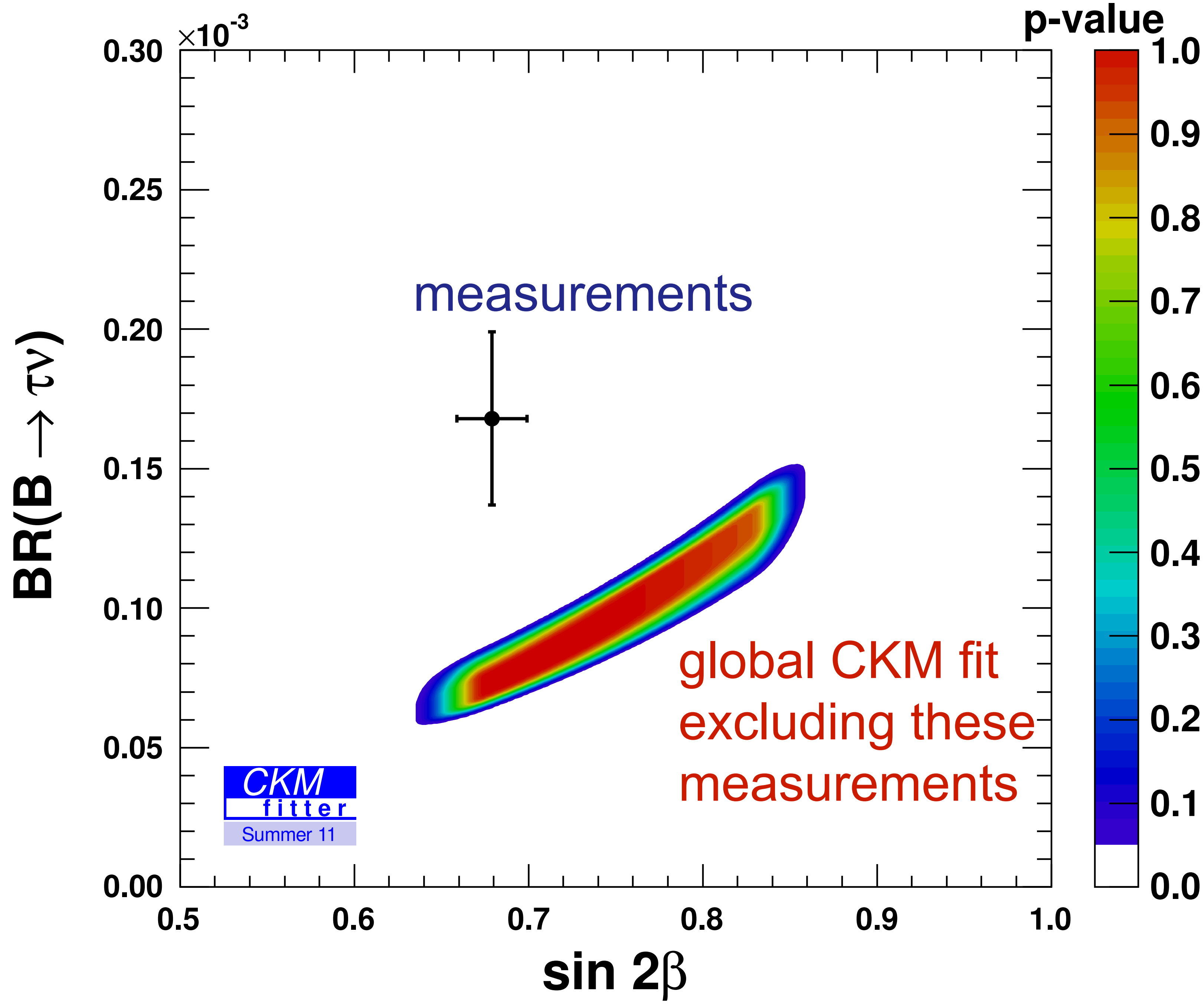


Only “robust” measurements of γ and $|V_{ub}|$. *Note: the γ(α) constraint shown depends on assumptions (absence of BSM ΔI=3/2 contributions in B->ππ); a truly robust γ determination should not include B->ππ. Such determinations will be greatly improved by LHCb - N Serra’s talk.*

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

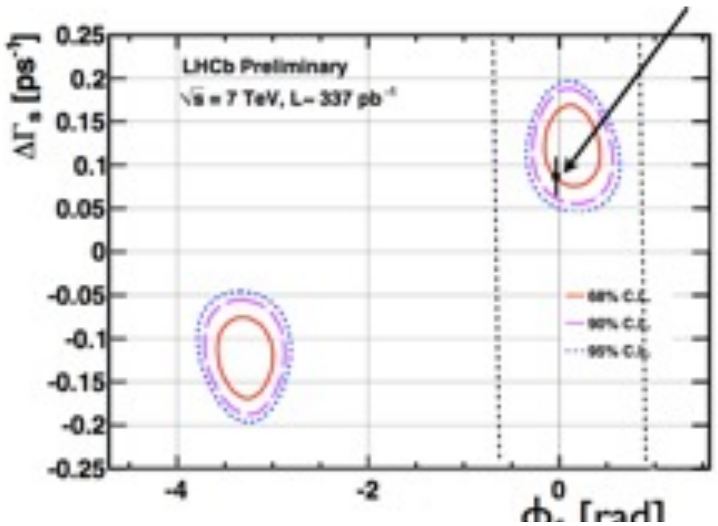
two-Higgs doublet model (II): $BR(B \to \tau\nu) = BR(B \to \tau\nu)_{\rm SM} \times \left|1 - \frac{M_B^2 \tan^2\beta}{M_{H^+}^2}\right|^2$

could be NP in mixing; leading uncertainty is bag parameter

LHCb observables

- mixing

  already detailed discussion yesterday
  consistent with SM (error still large)
  but O(1) mixing phase ruled out



- hadronic CPV

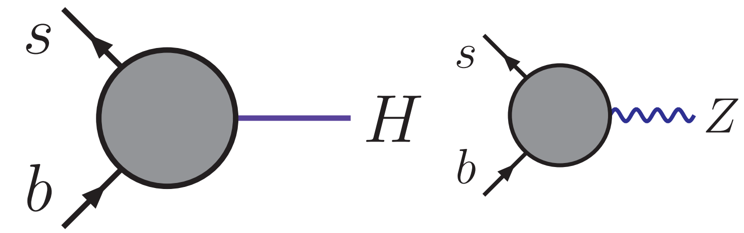
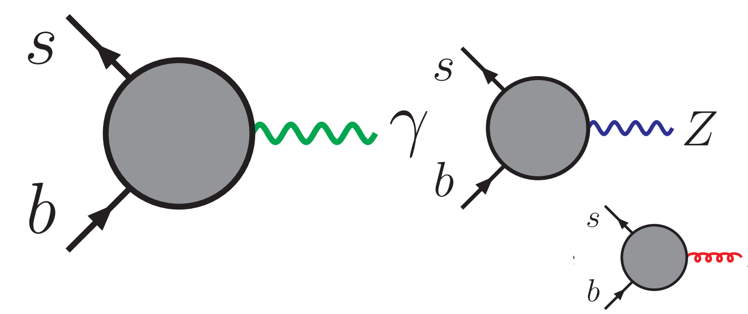
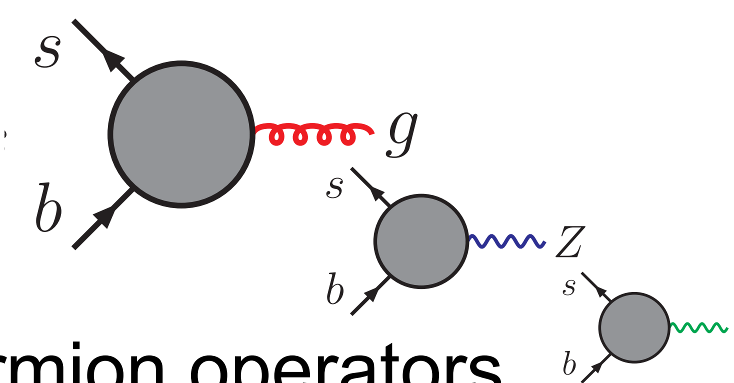
  triple products
  ΔA_{CP} in D decays

- 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 $B \to \pi\pi$, πK, $\phi\phi$, ...	matrix element $\langle \pi\pi \vert Q_i \vert B \rangle$	O(100)	

Non-radiative modes also NP-sensitive via 4-fermion operators

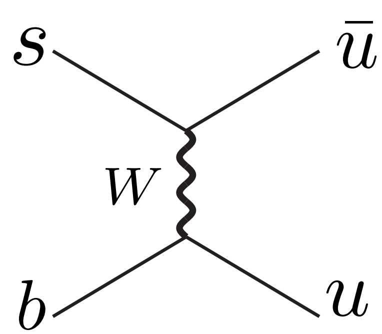
Decay constants and form factors accessible by QCD sum rules and, increasingly, by lattice QCD.

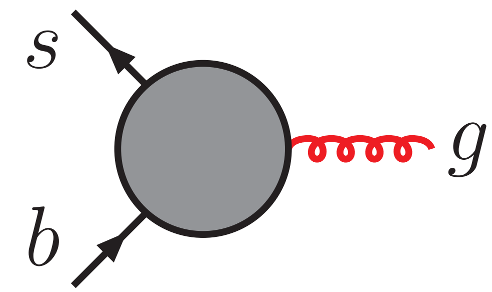
QCD a big challenge particularly for nonleptonic modes

hadronic b→s transitions

- trees carry small CKM factor ~ λ^4, hence sensitive to loops

  b➔s decays penguin-dominated in SM





- various "anomalies" or "puzzles" exist, of unclear significance
  - $A_{CP}(B^+ \to \pi^0 K^+) \neq A_{CP}(B^0 \to \pi^- K^+)$ at 5σ
  - dimuon charge asymmetry (mixing)

interpretation requires some knowledge of hadronic amplitudes

which observables are "clean"?

Physical amplitudes

- Any SM amplitude can be written

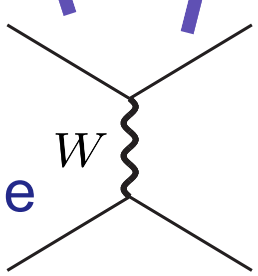
$$\mathcal{A}(\bar{B} \to M_1 M_2) = e^{-i\gamma} T_{M_1 M_2} + P_{M_1 M_2}$$

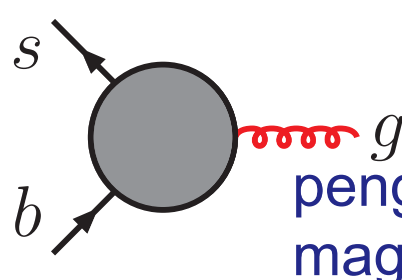
$$T_{M_1 M_2} = V_{uD} |V_{ub}| \Big[C_1 \langle Q_1^u \rangle + C_2 \langle Q_2^u \rangle + \sum_{i=3}^{12} C_i \langle Q_i \rangle \Big]$$ "tree"

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

CKM factor
(D=d or s)

tree W exchange





penguins (QCD, magnetic, EW)

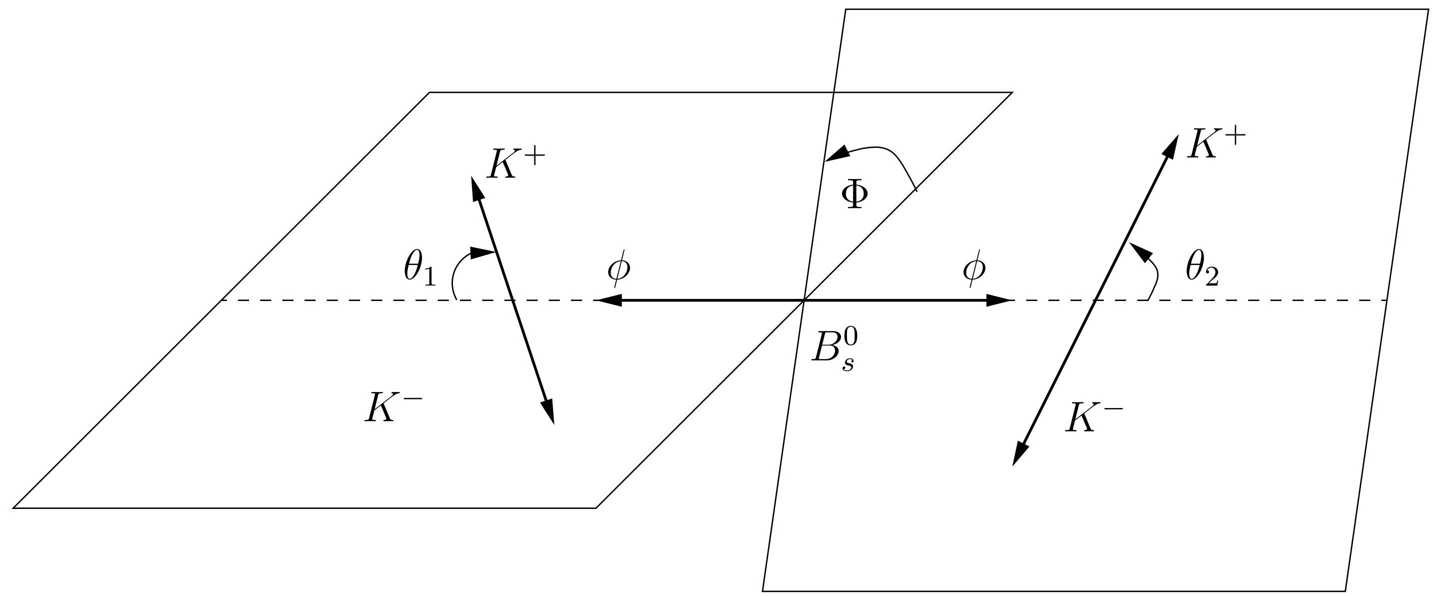
Q_i: operators in weak hamiltonian

C_i: QCD corrections from short distances (< hc/m_b) & new physics

$\langle Q_i \rangle = \langle M_1\ M_2 \mid Q_i \mid B \rangle$: QCD at distances > hc/$m_b$, strong phases

required for direct (decay rate) CP asymmetry

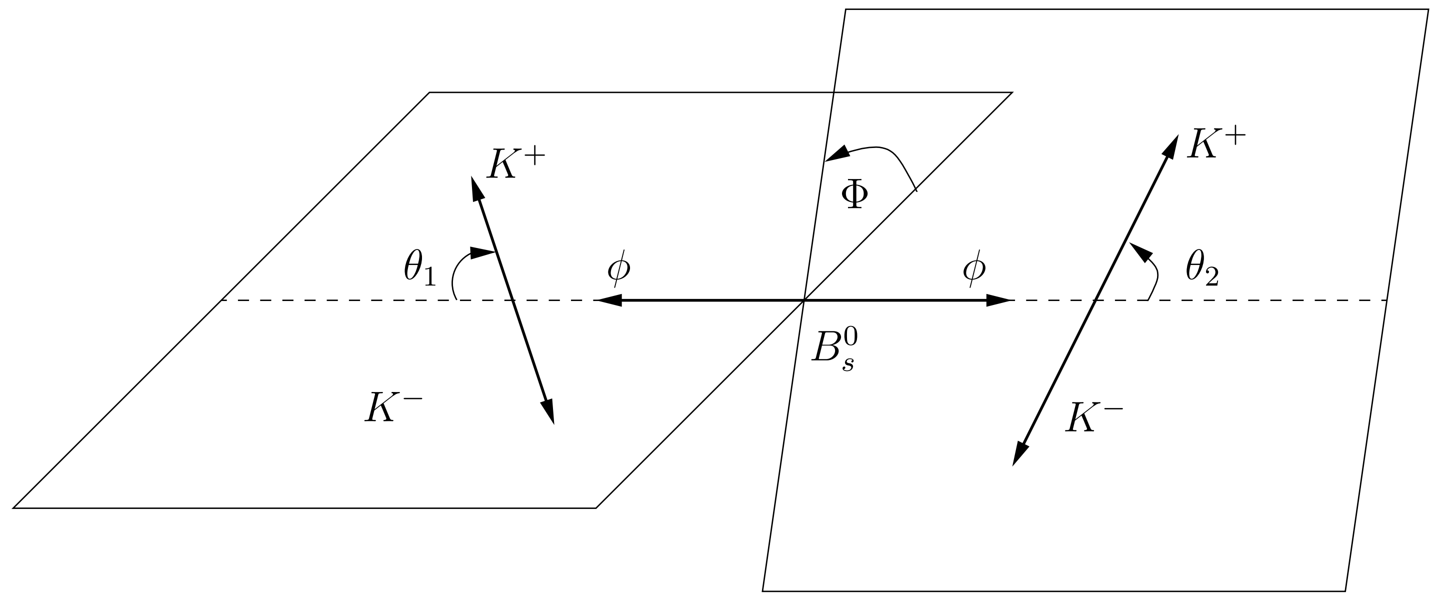
B→V V



$$\frac{d\Gamma}{d\cos\theta_1 d\cos\theta_2 d\phi} = N\bigg(|A_0|^2\cos^2\theta_1\cos^2\theta_2 + \frac{|A_\parallel|^2}{2}\sin^2\theta_1\sin^2\theta_2\cos^2\phi + \frac{|A_\perp|^2}{2}\sin^2\theta_1\sin^2\theta_2\sin^2\phi + \frac{\mathrm{Re}(A_0A_\parallel^*)}{2\sqrt{2}}\sin 2\theta_1\sin 2\theta_2\cos\phi - \frac{\mathrm{Im}(A_\perp A_0^*)}{2\sqrt{2}}\sin 2\theta_1\sin 2\theta_2\sin\phi - \frac{\mathrm{Im}(A_\perp A_\parallel^*)}{2}\sin^2\theta_1\sin^2\theta_2\sin 2\phi\bigg)$$

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

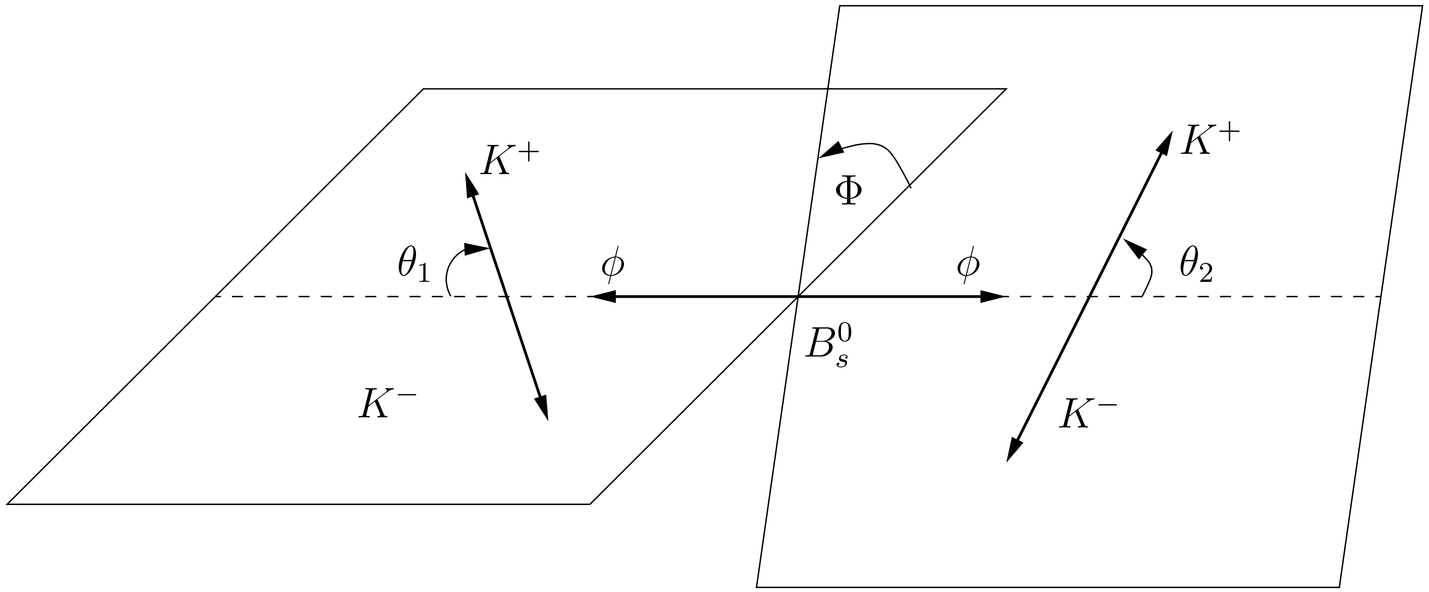
B→V V



$$\frac{d\Gamma}{d\cos\theta_1 d\cos\theta_2 d\phi} = N\Bigg(|A_0|^2\cos^2\theta_1\cos^2\theta_2 + \frac{|A_\parallel|^2}{2}\sin^2\theta_1\sin^2\theta_2\cos^2\phi$$
$$+ \frac{|A_\perp|^2}{2}\sin^2\theta_1\sin^2\theta_2\sin^2\phi + \frac{\mathrm{Re}(A_0A_\parallel^*)}{2\sqrt{2}}\sin 2\theta_1\sin 2\theta_2\cos\phi$$
$$- \frac{\mathrm{Im}(A_\perp A_0^*)}{2\sqrt{2}}\sin 2\theta_1\sin 2\theta_2\sin\phi - \frac{\mathrm{Im}(A_\perp A_\parallel^*)}{2}\sin^2\theta_1\sin^2\theta_2\sin 2\phi\Bigg)$$

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

B→V V

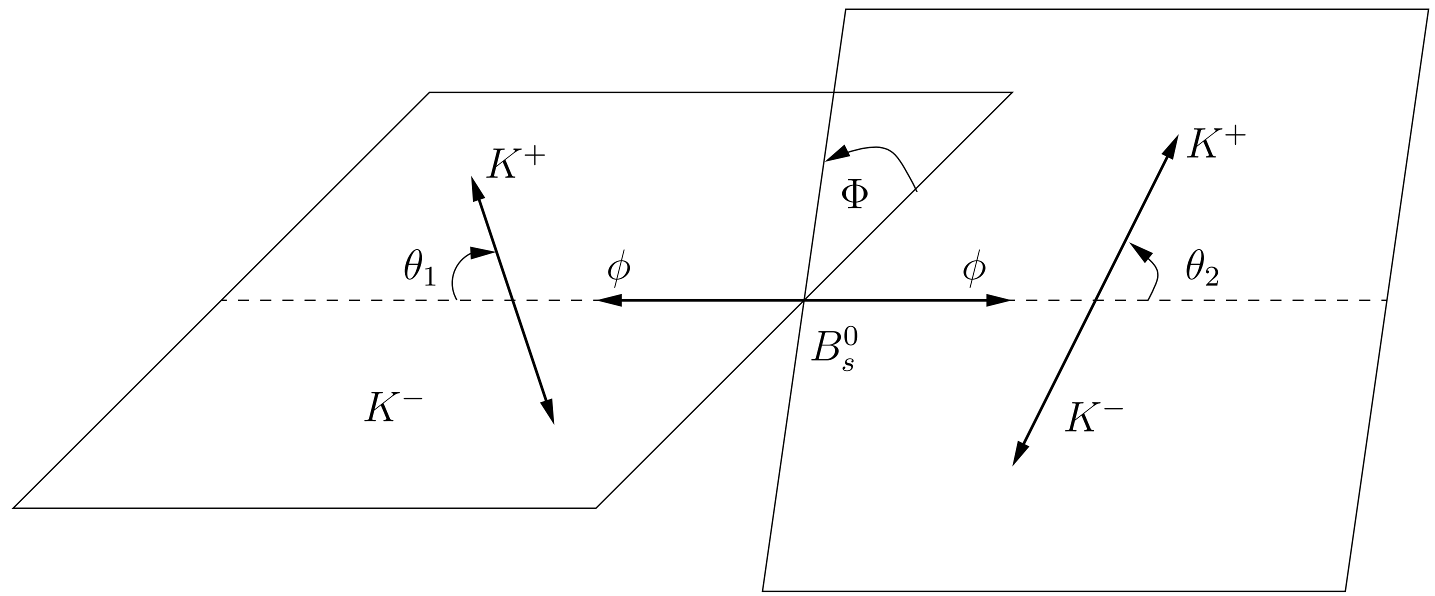


$$\begin{aligned}\frac{d\Gamma}{d\cos\theta_1 d\cos\theta_2 d\phi} &= N\Bigg(|A_0|^2\cos^2\theta_1\cos^2\theta_2 + \frac{|A_\parallel|^2}{2}\sin^2\theta_1\sin^2\theta_2\cos^2\phi \\ &+ \frac{|A_\perp|^2}{2}\sin^2\theta_1\sin^2\theta_2\sin^2\phi + \frac{\mathrm{Re}(A_0 A_\parallel^*)}{2\sqrt{2}}\sin 2\theta_1\sin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

(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

B→V V



$$\frac{d\Gamma}{d\cos\theta_1 d\cos\theta_2 d\phi} = N\Big(|A_0|^2\cos^2\theta_1\cos^2\theta_2 + \frac{|A_\parallel|^2}{2}\sin^2\theta_1\sin^2\theta_2\cos^2\phi + \frac{|A_\perp|^2}{2}\sin^2\theta_1\sin^2\theta_2\sin^2\phi + \frac{\mathrm{Re}(A_0A_\parallel^*)}{2\sqrt{2}}\sin 2\theta_1\sin 2\theta_2\cos\phi - \boxed{\frac{\mathrm{Im}(A_\perp A_0^*)}{2\sqrt{2}}}\sin 2\theta_1\sin 2\theta_2\sin\phi - \boxed{\frac{\mathrm{Im}(A_\perp A_\parallel^*)}{2}}\sin^2\theta_1\sin^2\theta_2\sin 2\phi\Big)$$

(for B_s➔φφ 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

Polarisation & NP

- Triple-product asymmetries in B->φK*

[Valencia 1989, ...]

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

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

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

- 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 & 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

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

[Gronau, Rosner 2011]

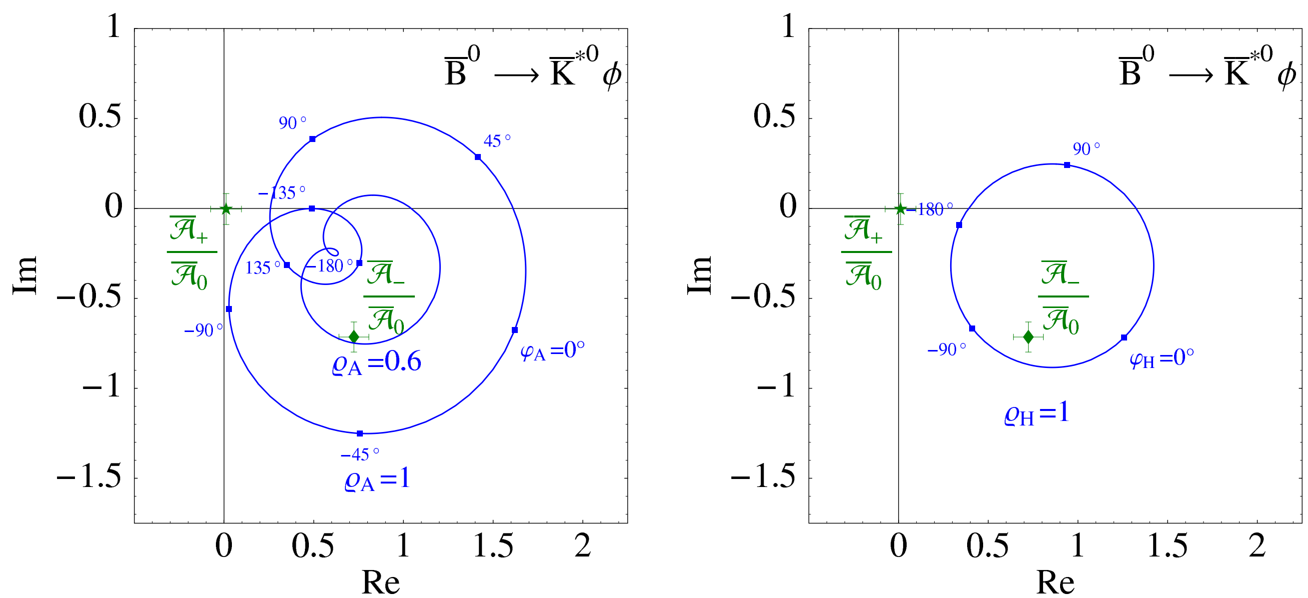
- CDF
$$A_U = -0.007 \pm 0.064(stat) \pm 0.018(syst)$$
$$A_V = -0.120 \pm 0.064(stat) \pm 0.016(syst).$$
[arXiv:1107.4999]

- 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 domination)

Polarisation & NP

- $1/m_b$ expansion predicts a hierarchy $\bar{\mathcal{A}}_0 : \bar{\mathcal{A}}_- : \bar{\mathcal{A}}_+ = 1 : \frac{\Lambda_{QCD}}{m_b} : \left(\frac{\Lambda_{QCD}}{m_b}\right)^2$ in $\overline{B}$ 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 smallness (presumably) of the *negative*-helicity amplitude suppresses one of the two triple-product asymmetries, making it a probe of right-handed currents

CPV in D decays

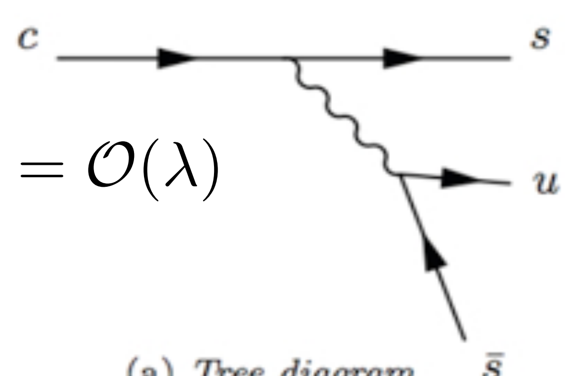
- LHCb has measured the difference
  $\Delta A_{CP} = A_{CP}(D^0 \rightarrow K^+K^-) - A_{CP}(D^0 \rightarrow \pi^+\pi^-)$ (see N Serra's talk)

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

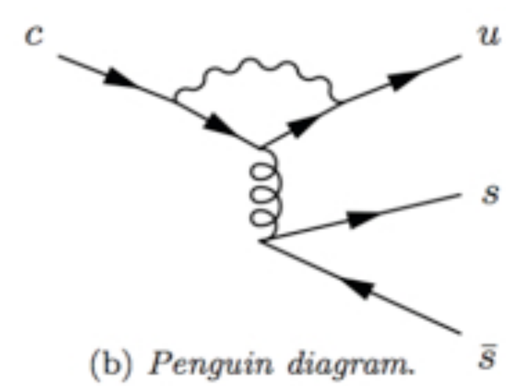
- SU(3) symmetry predicts equal and opposite sign, i.e. no cancellation expected

- 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.



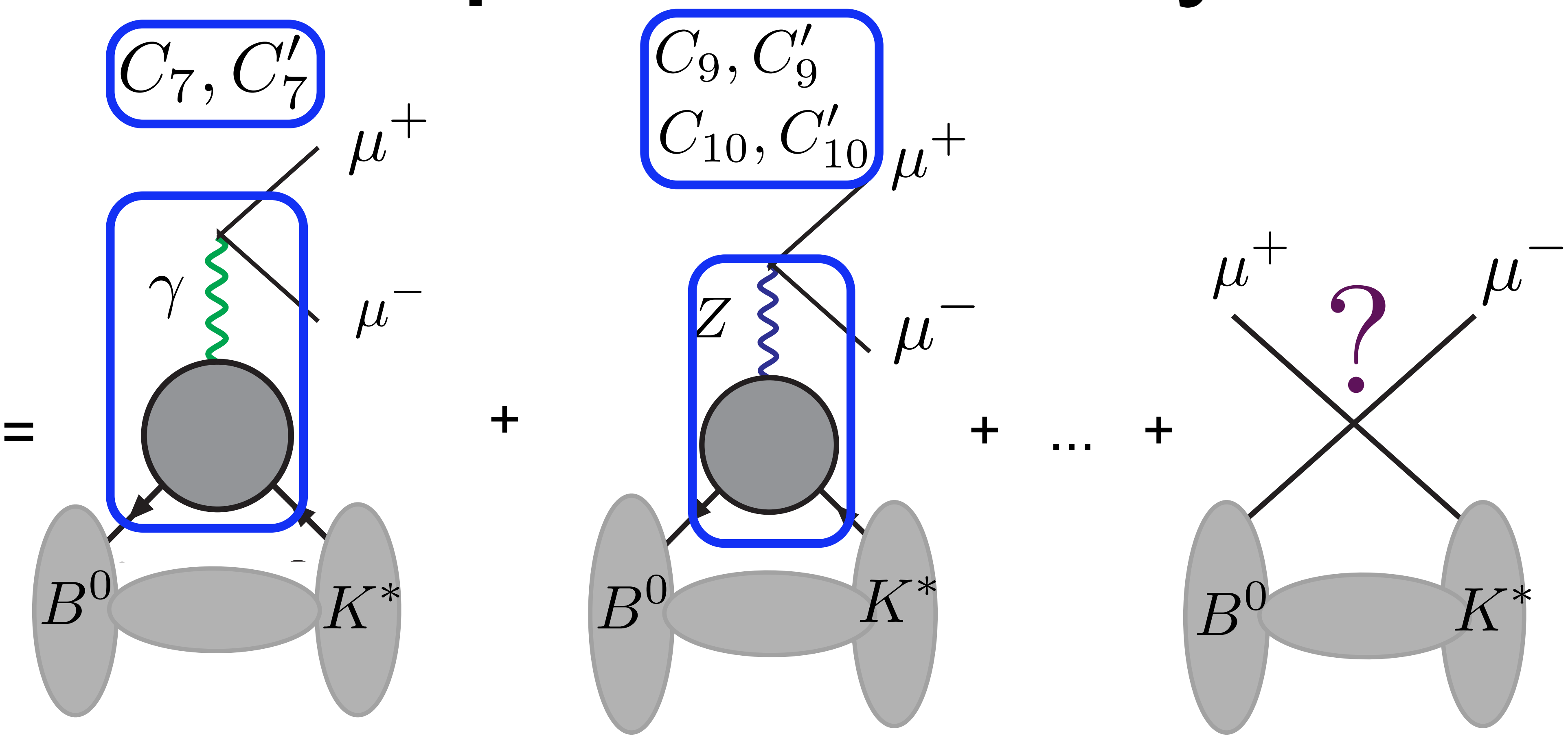
(b) Penguin diagram.

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

- 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.

Semileptonic decay

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



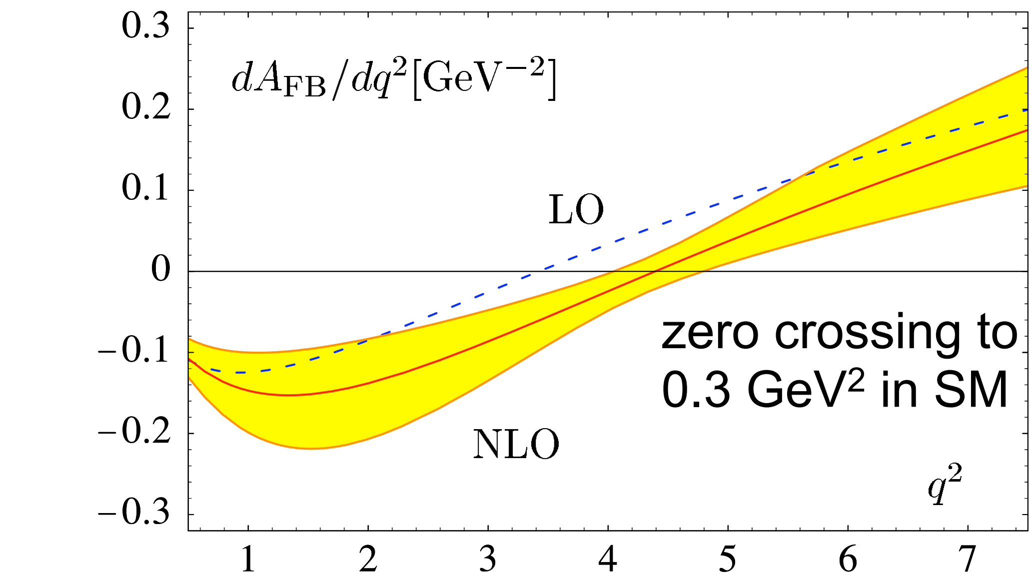
- kinematics described by dilepton invariant mass q^2 and three angles

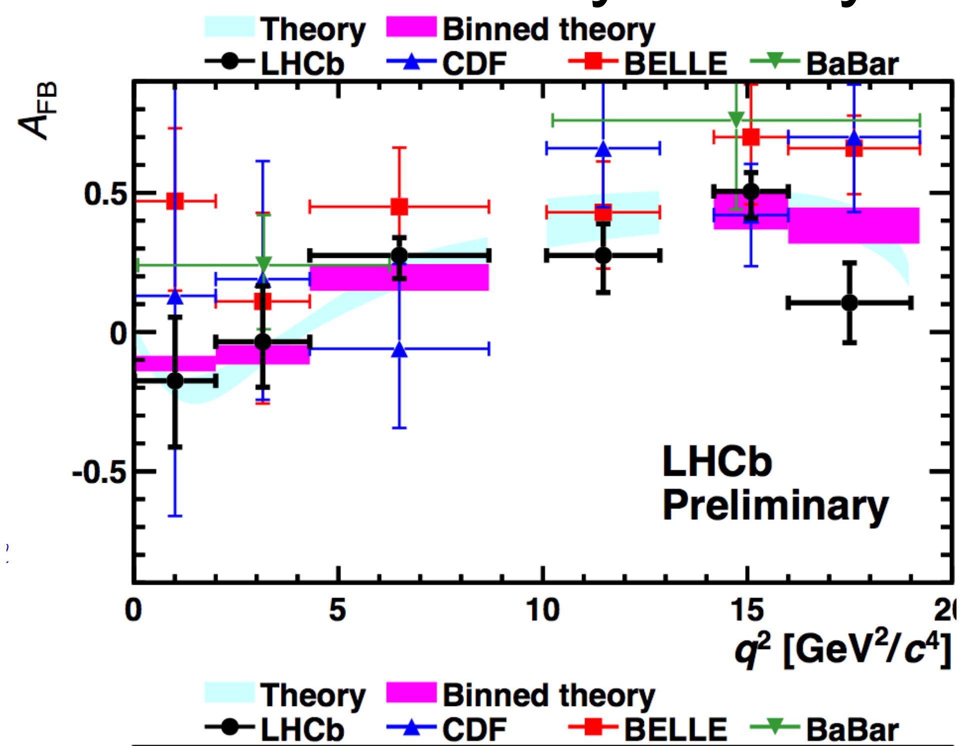
- Systematic theoretical description based on heavy-quark expansion (Λ/m_b) for $q^2 << m^2(J/\psi)$ (SCET) Beneke, Feldmann, Seidel 01
  also for $q^2 >> m^2(J/\psi)$ (OPE) Grinstein et al; Beylich et al 2011
  Theoretical uncertainties on form factors, power corrections

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

Ali et al ; Beneke et al; ...

- Most well-known observable: forward-backward asymmetry



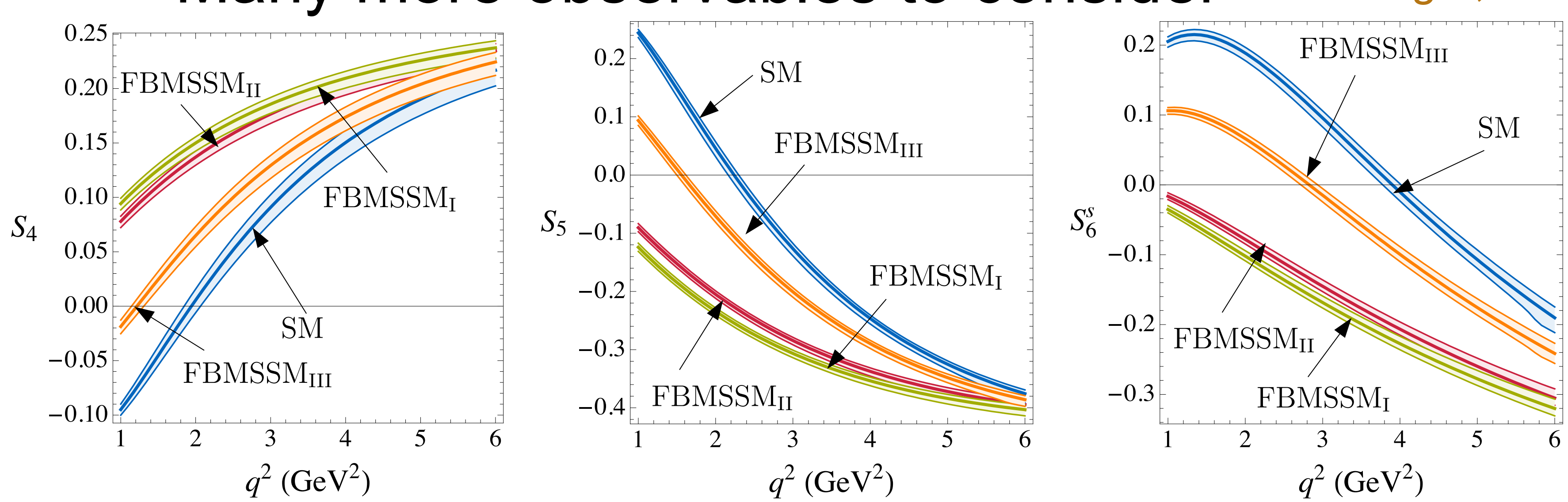


$$q_0^2[K^{*0}] = 4.36^{+0.33}_{-0.31}\,\mathrm{GeV}^2, \qquad q_0^2[K^{*+}] = 4.15^{+0.27}_{-0.27}\,\mathrm{GeV}^2$$

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

- Many more observables to consider

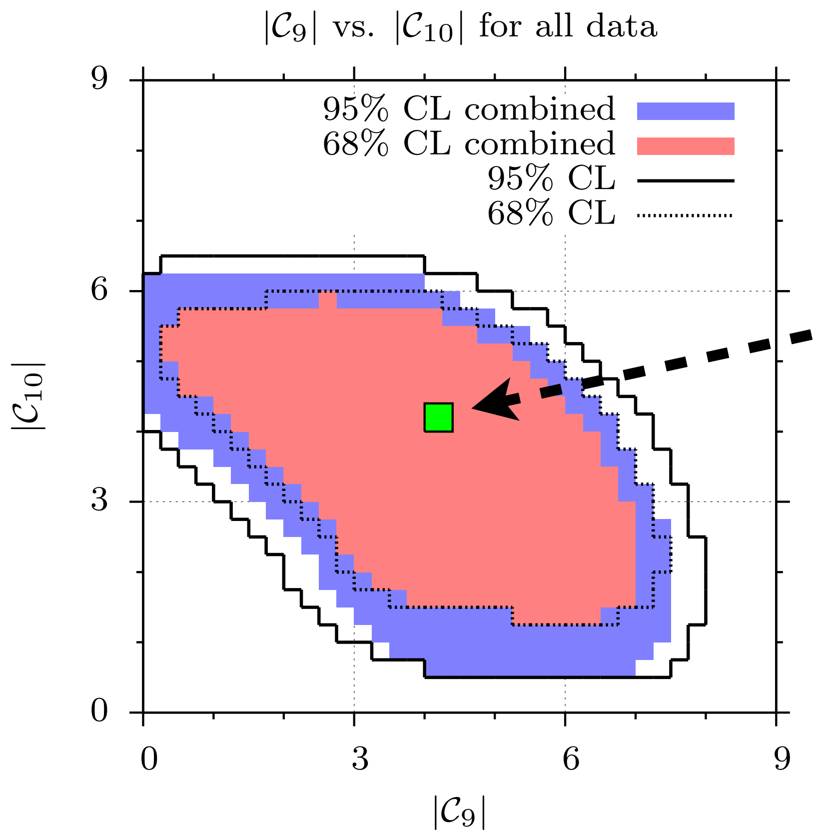
Krueger, Matias; ...



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

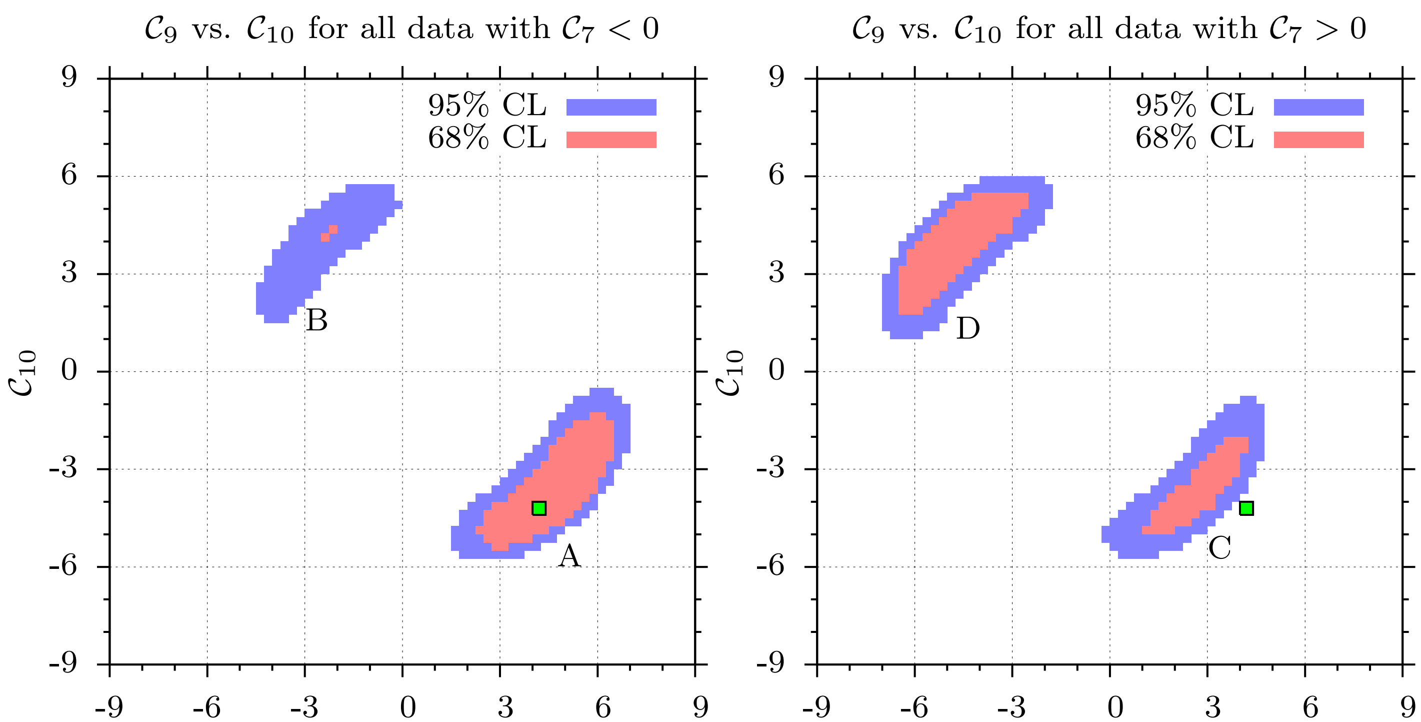


global fit to semileptonic decay data

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

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!

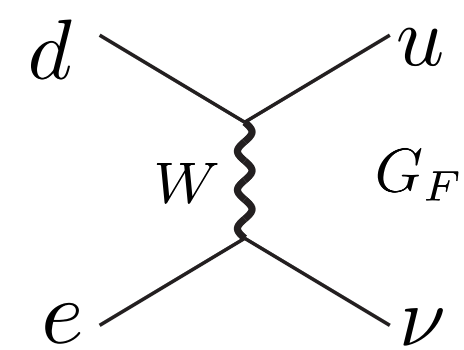
1964 Gell-Mann gives hadronic weak current in the quark model

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

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

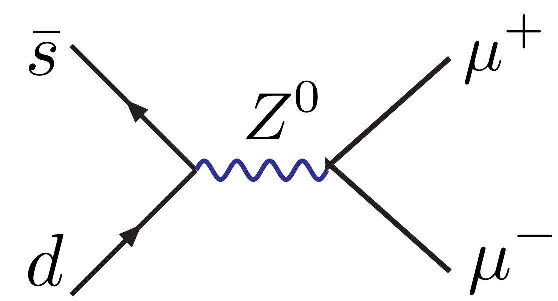
1964 CP violation discovered in Kaon decays (Cronin&Fitch)

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

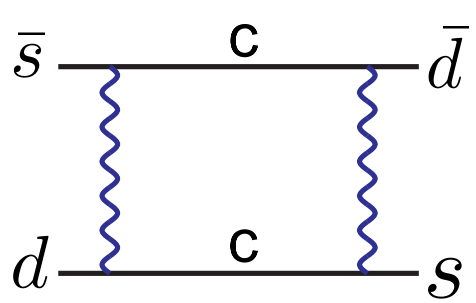
$-\sin\theta_c d_L + \cos\theta_c s_L$

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



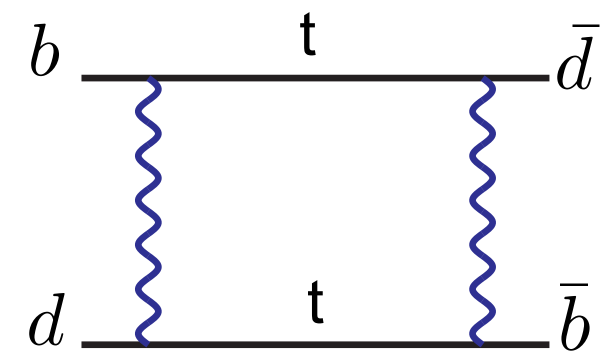
1974 Charm quark discovered

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, ...

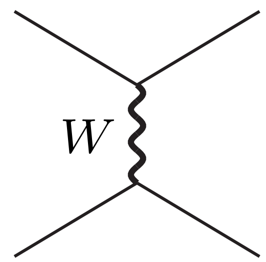
Summary/outlook

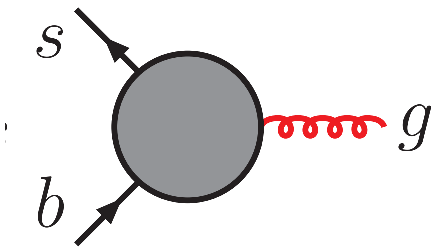
- Theories of the electroweak scale bring in new particles which contribute to flavour and CP-violating observables
- Consistency of CKM fit and the Φ_s measurements disfavor large BSM CP violation (but some tensions in b->d exist, and there is similar (or greater) room in b->s)
- interesting direct CP asymmetry observation in D decays. Much larger than previous SM estimates, but theoretically challenging
- many more observables, including CP-conserving ones (rare semileptonic/radiative/hadronic decays) that have not been analysed or still have large statistical uncertainties could show signs of new physics

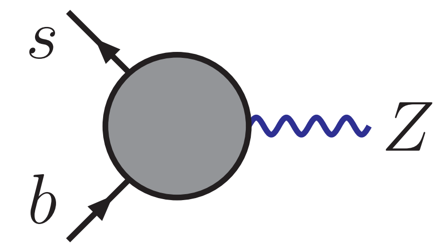
BACKUP

B→πK direct CP puzzle

$$A(B^0 \rightarrow \pi^- K^+) \;=\; T\,e^{i\gamma} \;+\; P \;+\; P^c_{EW}$$







$$-\,A(B^+ \rightarrow \pi^0 K^+) \;=\; (T+C)\,e^{i\gamma} \;+\; P \;+\; P_{EW} \;+\; P^c_{EW}$$

data: $A_{CP}(B^+ \rightarrow \pi^0 K^+) - A_{CP}(B^0 \rightarrow \pi^- K^+) = 0.14 \pm 0.03$ (expt)

[Belle collab: in Nature (2008)]

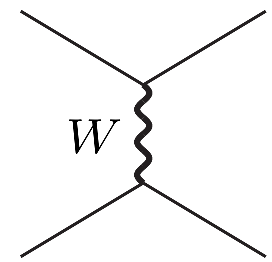
In general, only isospin relation [Gronau 2005; Gronau & Rosner 2006]

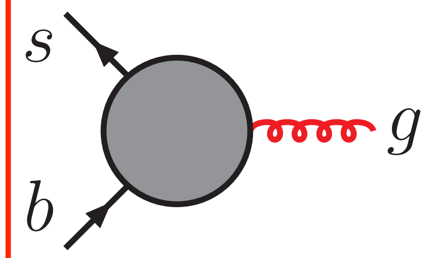
$$A_{CP}(B^+ \rightarrow \pi^0 K^+) + A_{CP}(B^0 \rightarrow \pi^0 K^0) \approx A_{CP}(B^0 \rightarrow \pi^- K^+) + A_{CP}(B^+ \rightarrow \pi^0 K^0)$$

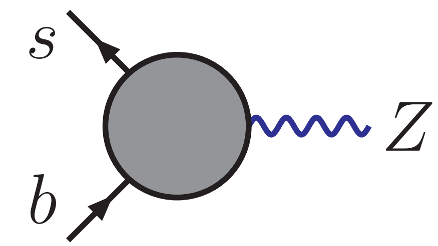
how small are the “small” amplitude ratios C/T and P_{EW}/T

$B \to \pi K$ direct CP puzzle

$$A(B^0 \to \pi^- K^+) = T e^{i\gamma} + P + P^c_{EW}$$







$$-A(B^+ \to \pi^0 K^+) = (T+C) e^{i\gamma} + P + P_{EW} + P^c_{EW}$$

(QCD) penguin amplitudes

data: $A_{CP}(B^+ \to \pi^0 K^+) - A_{CP}(B^0 \to \pi^- K^+) = 0.14 \pm 0.03$ (expt)

[Belle collab: in Nature (2008)]

In general, only isospin relation [Gronau 2005; Gronau & Rosner 2006]

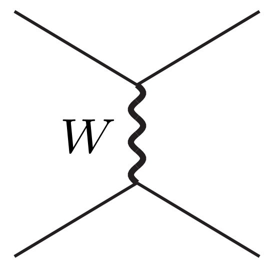
$$A_{CP}(B^+ \to \pi^0 K^+) + A_{CP}(B^0 \to \pi^0 K^0) \approx A_{CP}(B^0 \to \pi^- K^+) + A_{CP}(B^+ \to \pi^0 K^0)$$

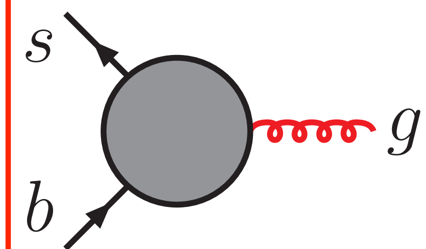
how small are the “small” amplitude ratios C/T and P_{EW}/T

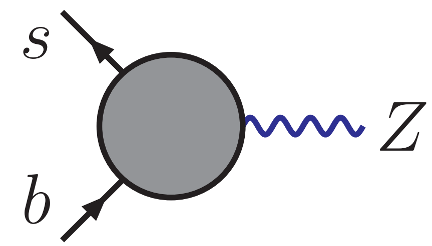
$B \to \pi K$ direct CP puzzle

$A(B^0 \to \pi^- K^+) = T e^{i\gamma} + P + P^c_{EW}$

tree amplitudes







$-A(B^+ \to \pi^0 K^+) = (T+C) e^{i\gamma} + P + P_{EW} + P^c_{EW}$

(QCD) penguin amplitudes

EW penguin amplitudes

data: $A_{CP}(B^+ \to \pi^0 K^+) - A_{CP}(B^0 \to \pi^- K^+) = 0.14 \pm 0.03$ (expt)

[Belle collab: in Nature (2008)]

In general, only isospin relation [Gronau 2005; Gronau & Rosner 2006]

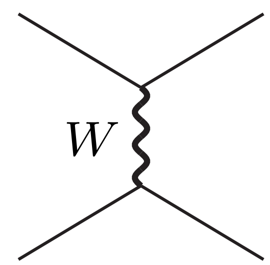
$A_{CP}(B^+ \to \pi^0 K^+) + A_{CP}(B^0 \to \pi^0 K^0) \approx A_{CP}(B^0 \to \pi^- K^+) + A_{CP}(B^+ \to \pi^0 K^0)$

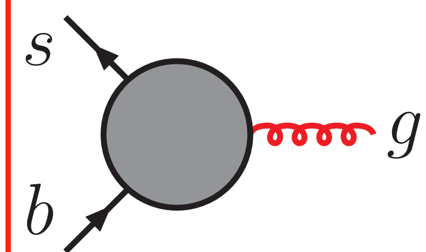
how small are the "small" amplitude ratios C/T and P_{EW}/T

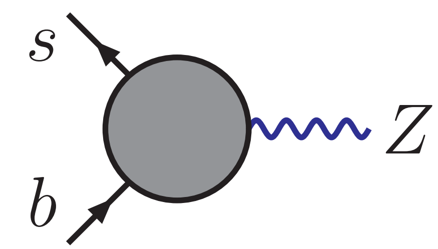
B→πK direct CP puzzle

$A(B^0 \to \pi^- K^+) \;=\; T\, e^{i\gamma} \;+\; P \;+\; P^c_{EW}$

tree amplitudes







$-A(B^+ \to \pi^0 K^+) \;=\; (T+C)\, e^{i\gamma} \;+\; P \;+\; P_{EW} \;+\; P^c_{EW}$

(QCD) penguin amplitudes

EW penguin amplitudes

data: $A_{CP}(B^+ \to \pi^0 K^+) - A_{CP}(B^0 \to \pi^- K^+) = 0.14 \pm 0.03$ (expt)

[Belle collab: in Nature (2008)]

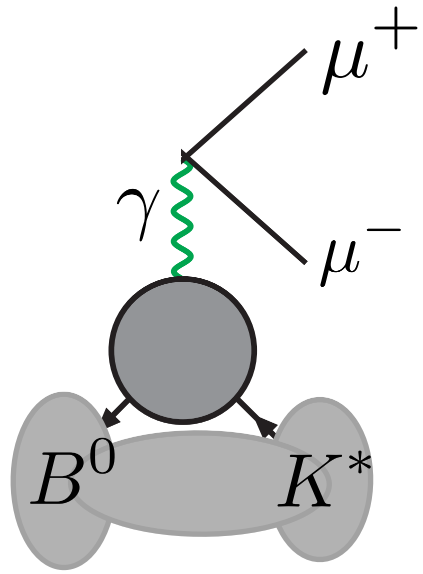
In general, only isospin relation [Gronau 2005; Gronau & Rosner 2006]

$A_{CP}(B^+ \to \pi^0 K^+) + A_{CP}(B^0 \to \pi^0 K^0) \approx A_{CP}(B^0 \to \pi^- K^+) + A_{CP}(B^+ \to \pi^0 K^0)$

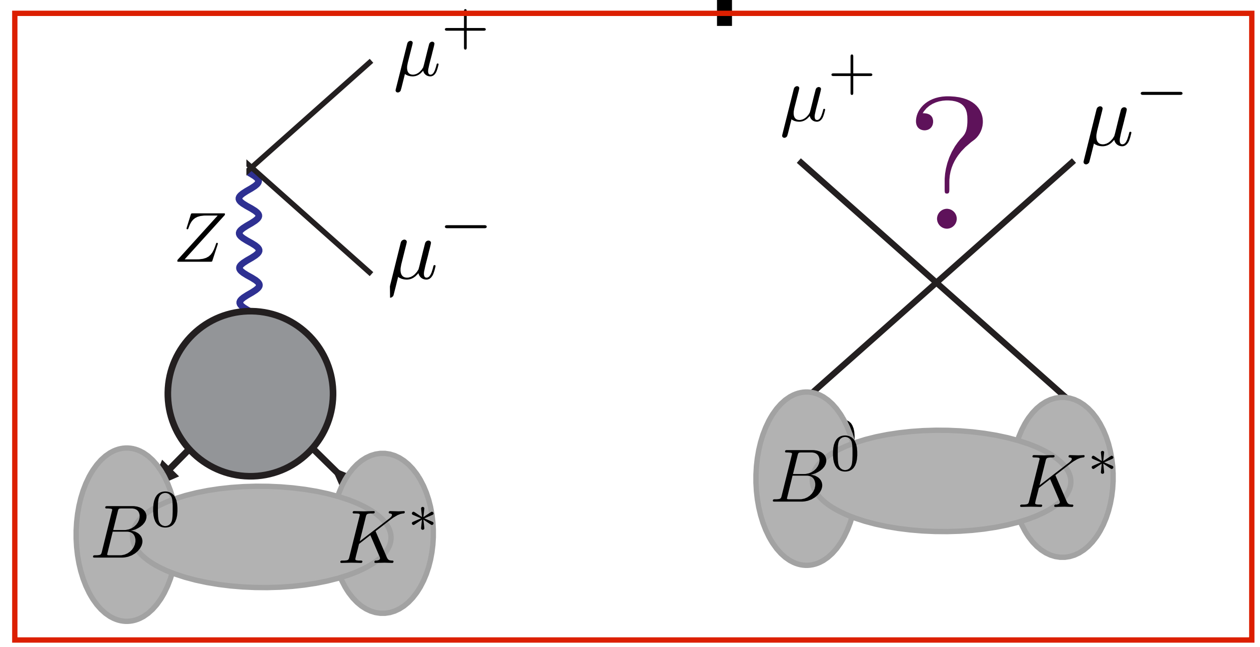
how small are the “small” amplitude ratios C/T and P_{EW}/T

Theoretical description

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

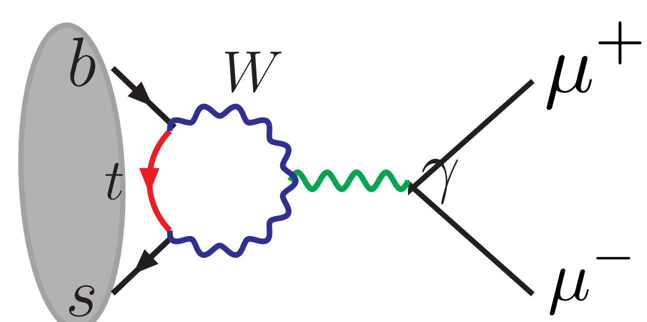


+



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

partly short distance

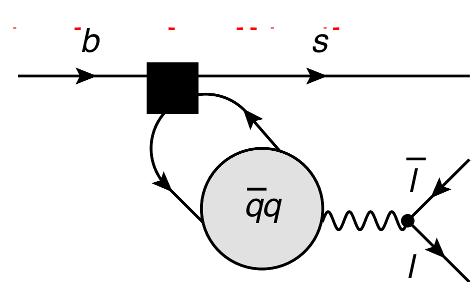


Form factor $T_{1,2,3}$ x C_7

(lattice, QCD sum rules)

Wilson coefficient (may receive NP corrections)

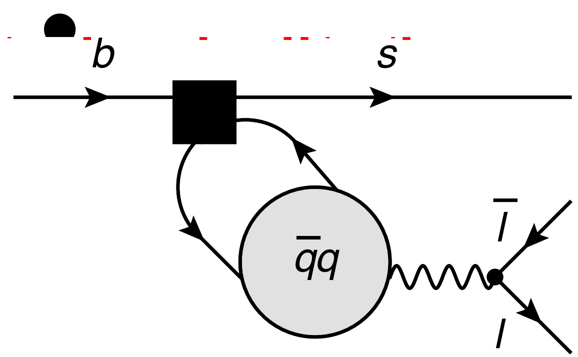
partly long distance



[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

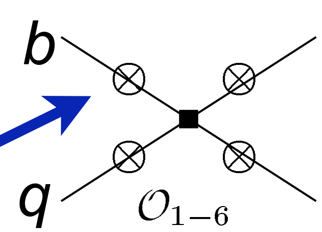
above (high-q^2) charm loops calculable in OPE

Grinstein et al; Beylich et al 2011

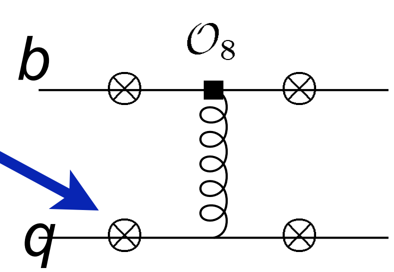
at *low* q^2 , long-distance charm effects also suppressed, but photon can now be emitted from *spectator* withouth power suppression

Beneke, Feldmann, Seidel 01

possible photon attachments



small Wilson coefficients



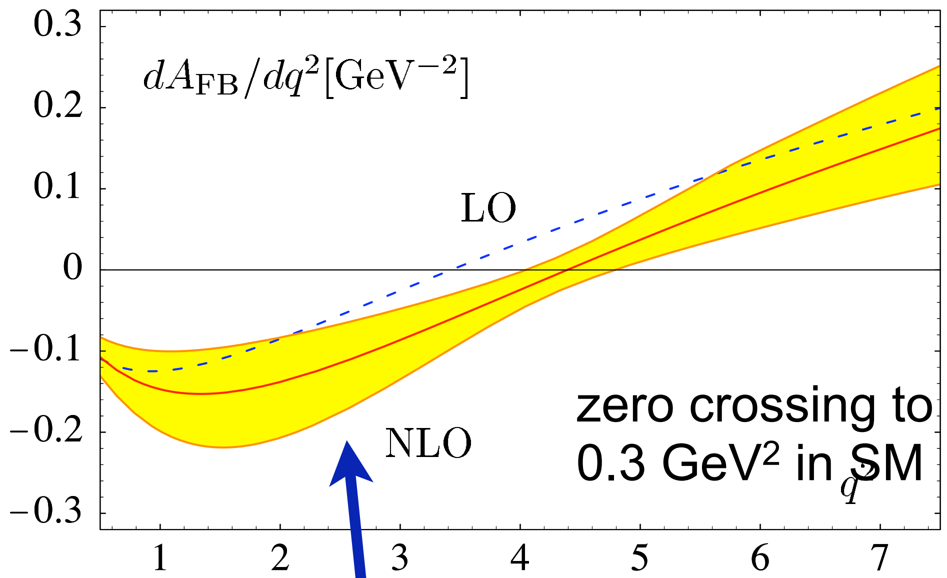
more significant for b ➔s transitions

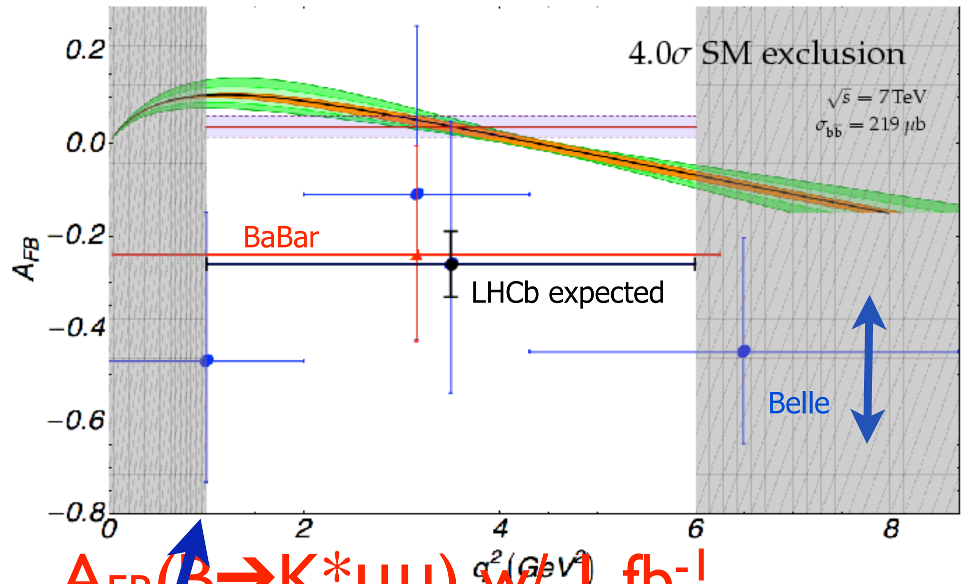
$$\frac{\pi^2}{N_c}\,\frac{f_B f_{K^*,a}}{M_B}\,\Xi_a \sum_{\pm}\int\frac{d\omega}{\omega}\,\Phi_{B,\pm}(\omega)\int_0^1 du\,\Phi_{K^*,a}(u)\,T_{a,\pm}(u,\omega)$$

light-cone wave functions

calculable

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





$A_{FB}(B \to K^*\mu\mu)$ w/ 1 fb^{-1}

F Muheim @ FPCP2010

- uncertainty due to mainly form factor precision (will improve); light cone distribution amplitudes (will to some degree improve)

cut at 1 GeV² is an ad-hoc procedure to remove/ reduce uncertainty from 'light resonances' however interesting physics in this region (C_7, C_7')