# QCD Effects in B Physics

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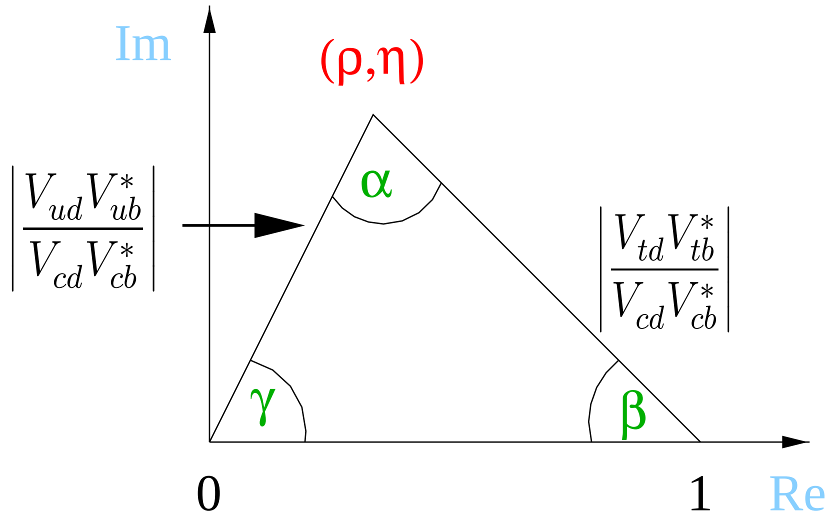
(a) test SM picture of flavour violation: the unitarity triangle

Unitarity of CKM matrix:

$$\boxed{\sum V_{dj} V_{jb}^* = 0}$$



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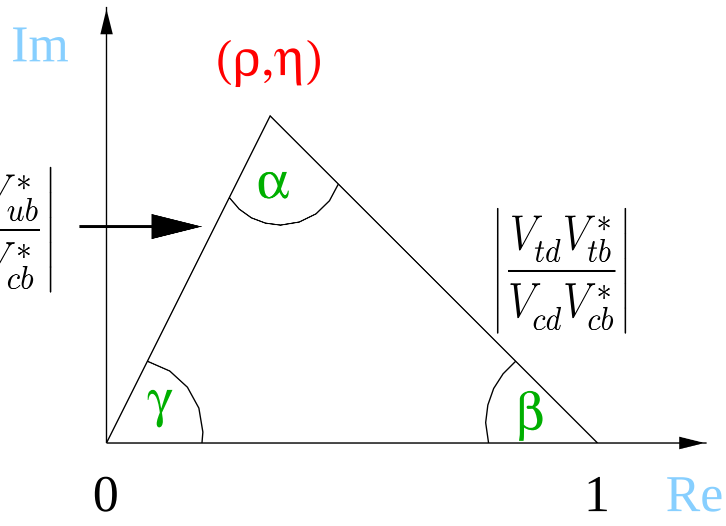
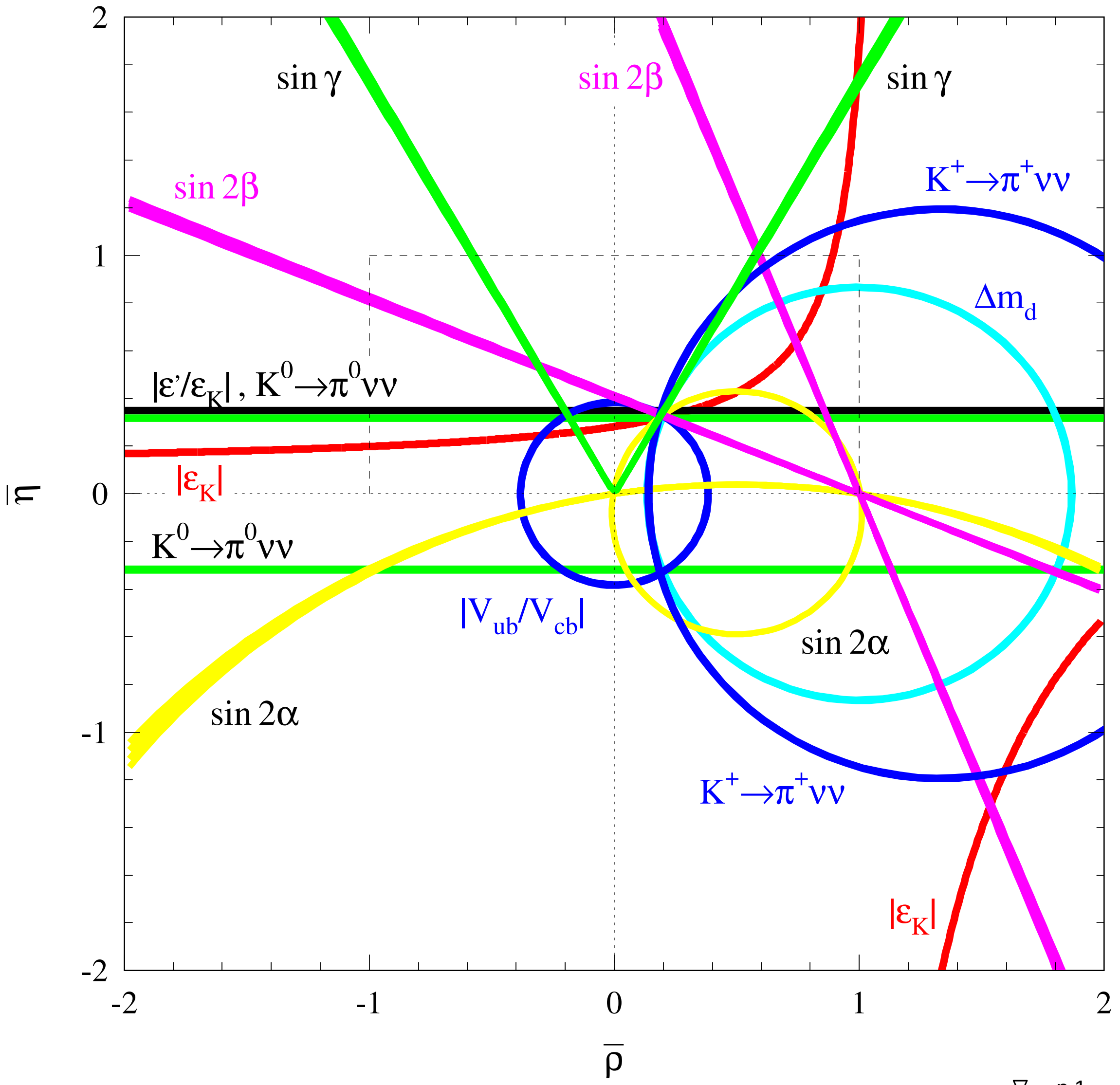



$$\left|\frac{V_{ud}V^*_{ub}}{V_{cd}V^*_{cb}}\right| \qquad \left|\frac{V_{td}V^*_{tb}}{V_{cd}V^*_{cb}}\right|$$



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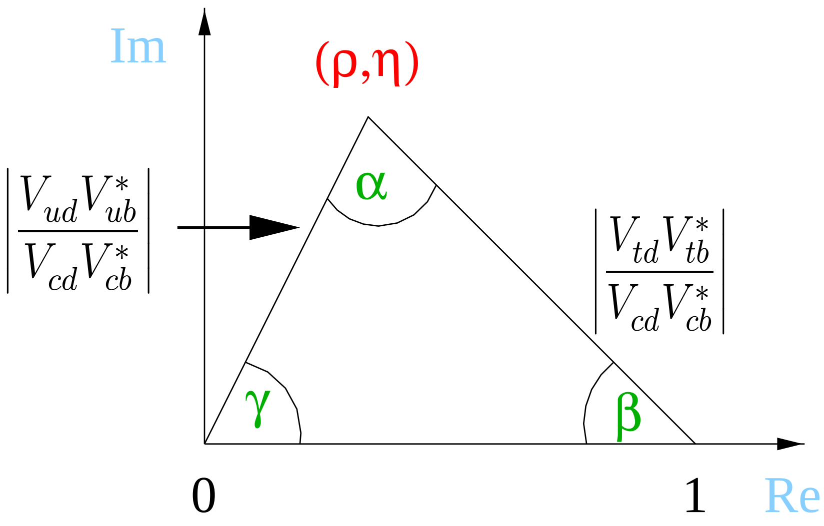


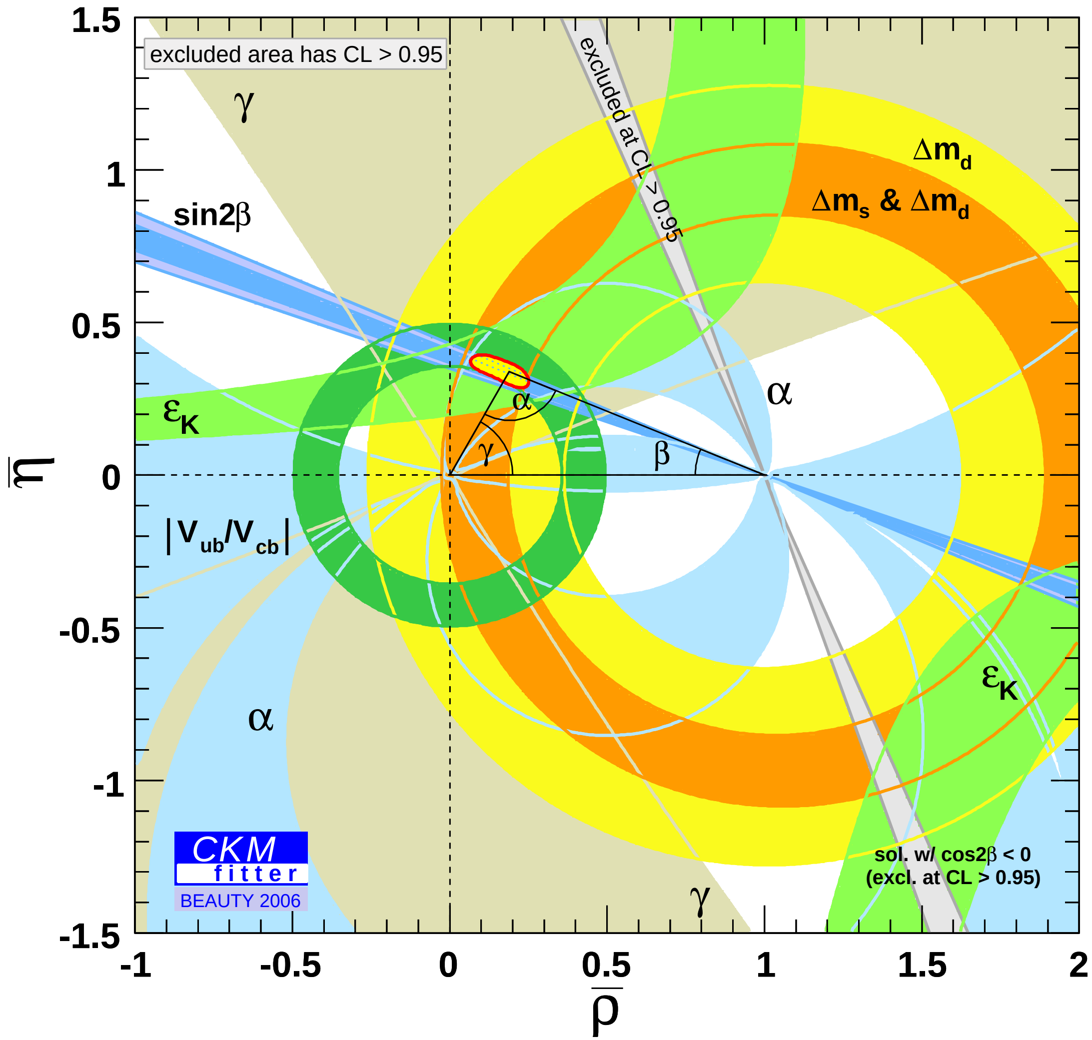

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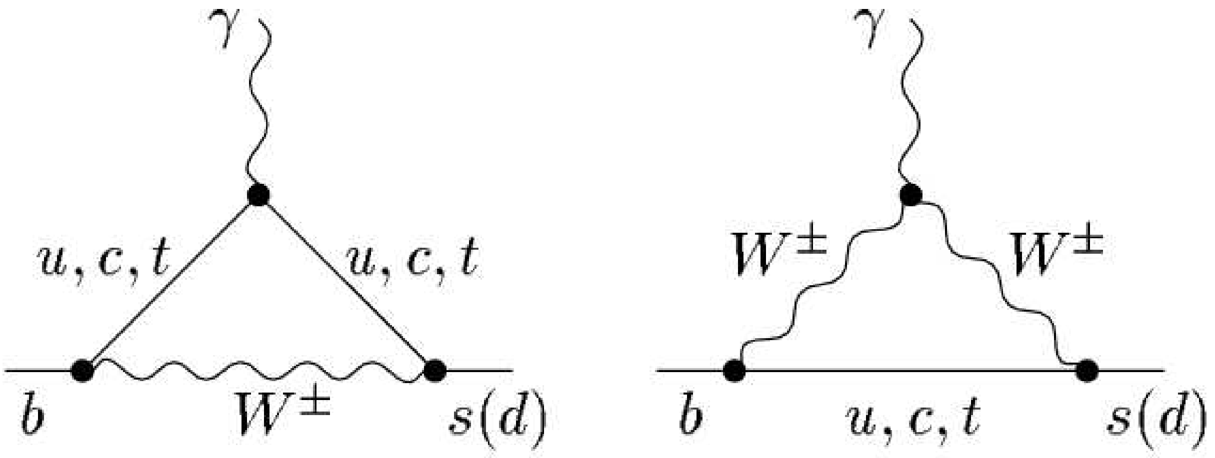

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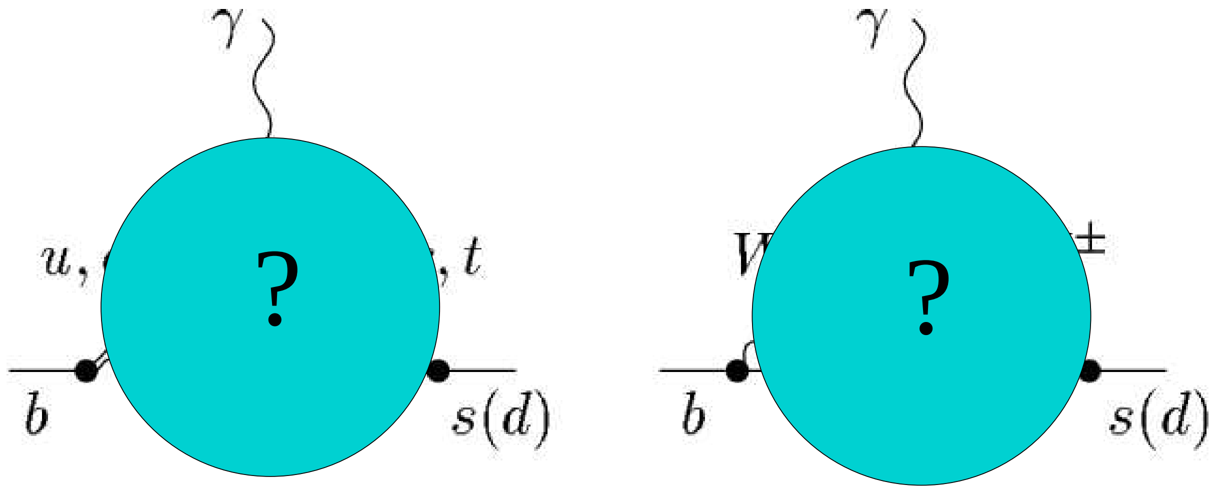

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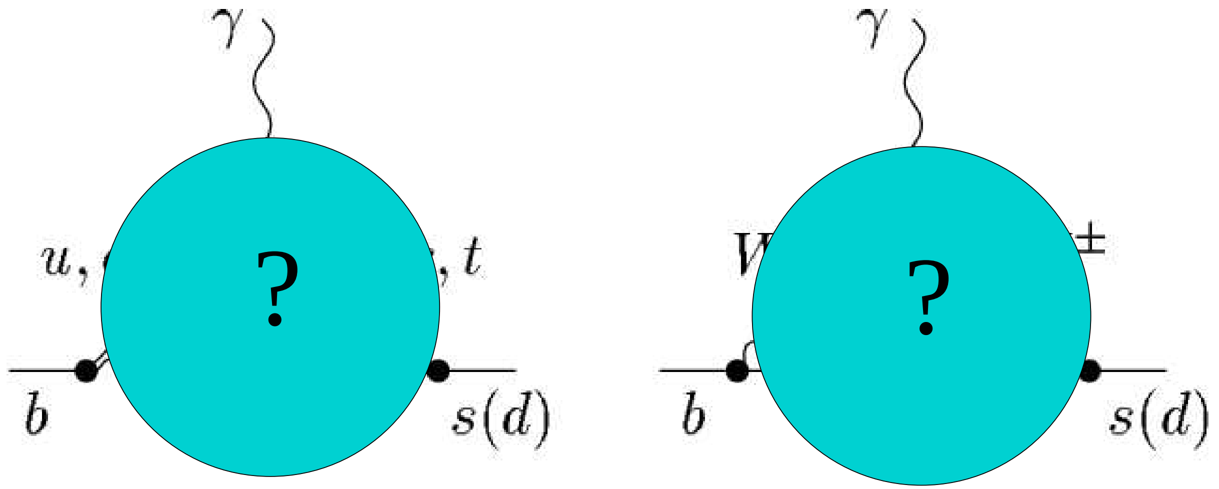


Basic problem: flavour physics masked by strong interactions .

How to control QCD effects?

# The B Physicist's Tool Box

- effective field theories
  - disentangle physics governed by different mass scales (SM: $m_W, m_t \gg m_b \gg \Lambda_{\rm QCD}$)
  - Fermi's 4-fermion theory ($1/m_W$), heavy quark effective theory ($1/m_b$), soft-collinear effective theory ($1/\sqrt{m_b}$, $1/m_b$)

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- nonperturbative methods (for all the dirty rest)
  - lattice, QCD sum rules. . .

# How to calculate decay amplitudes?

A simple 3 step procedure. . .

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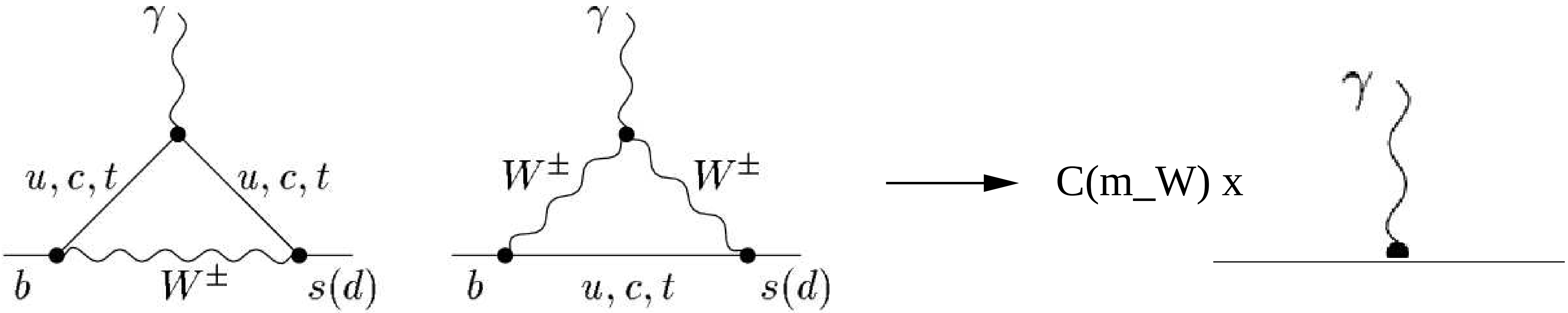
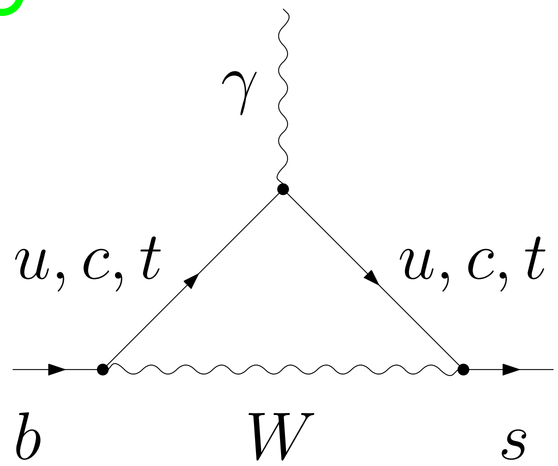
Step 1: obtain effective Lagrangian at scale $\sim m_W$ by integrating out effects from heavy particles: $W$, $t$ and any BSM particles:

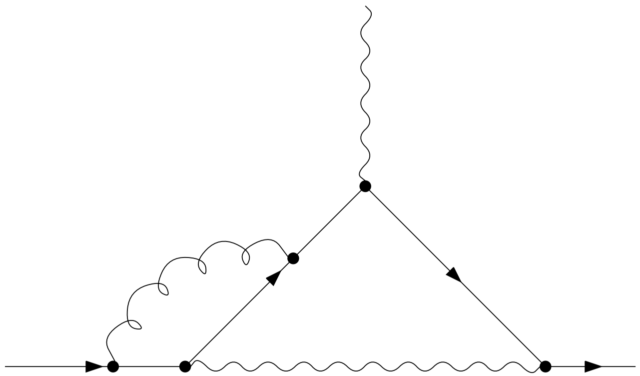



SM diagrams $\to$ short-distance coefficient $C(m_W) \times$ effective operator

# How to calculate decay amplitudes?

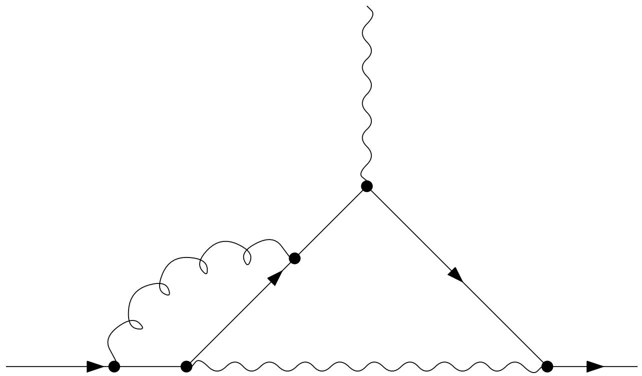
Step 2: include radiative corrections:

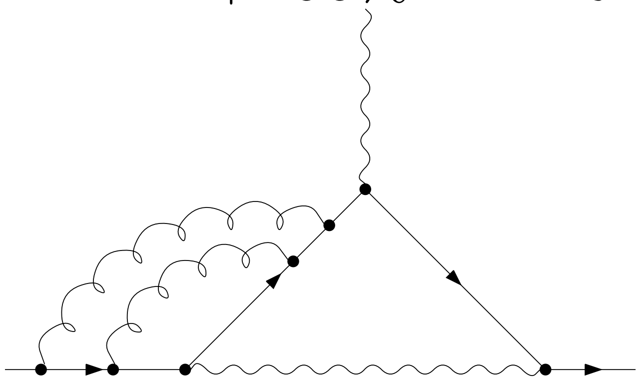


$\alpha_s \ln \frac{M_W^2}{m_b^2}$: $\sim +50\%$ in amplitude

$\sim +100\%$ in BR





non – logarithmic

logarithmic

$\sim +20\%$ in BR

# How to calculate decay amplitudes?

Step 2: include radiative corrections:

and resum large logs in $\alpha_s \ln(m_W/m_b)$:

$$\boxed{\mathcal{L}_{\rm eff} = \frac{G_F}{\sqrt{2}} \sum_i C_i(\mu) O_i(\mu) \left\{ 1 + \mathcal{O}\left(\frac{m_b^2}{m_W^2}\right)\right\}}$$

- $C_i$: Wilson-coefficients, containing short-distance effects
- $O_i$: dim-6 operators, e.g. $(\bar{d}u)_{V-A}(\bar{c}b)_{V-A}$, describing long-distance effects
- $\mathcal{L}_{\rm eff}$ for nonleptonic decays known to NNLO (Gorbahn/Haisch 04)
- $\mathcal{L}_{\rm eff}$ for radiative decays almost known to NNLO (Misiak et al. 06)
- BSM effects in some scenarios known to NLO, e.g. MSSM with Minimal Flavour Violation (Degrassi/Gambino/Slavich 06)

# How to calculate decay amplitudes?

Step 3: take hadronic matrix elements

This is where important developments took place in the last $\sim 7$ years...

- full calculation on the lattice or from QCD sum rules
  - form factors, i.e. matrix elements $\langle F|O_i|B\rangle$

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  - total width of inclusive decays and moments of $b\to ce\nu$ transitions
- expansion in $1/m_b$ and factorisation in terms of nonlocal (light-cone) matrix elements
  - inclusive $b\to$ light transitions with experimental cuts
  - exclusive (in particular nonleptonic and radiative) decays, e.g. $B\to\pi\pi$, $B\to K^*\gamma$

Let’s focus on a few examples. . .

# $B_s$ Mixing & New Physics

**Ball/Fleischer, hep-ph/0604249**

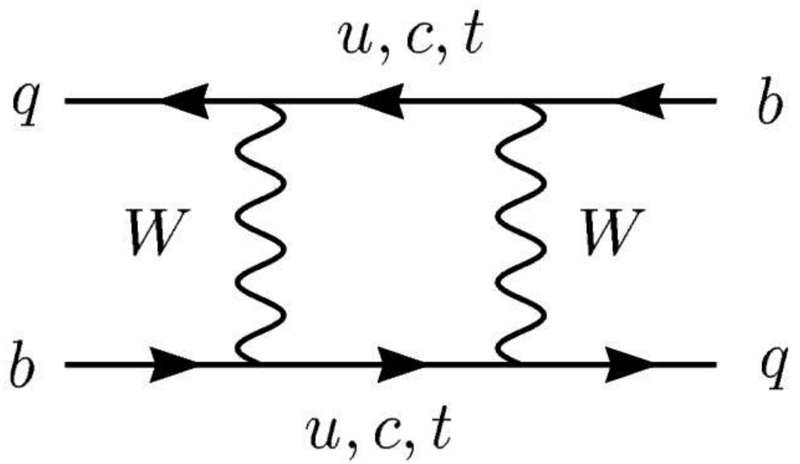
# Phenomenology of $B$ Mixing

- $\bar{B}^0 = (b\bar{q})$ and $B^0 = (q\bar{b})$ ($q = d, s$) with definite flavour content, but not mass eigenstates $\rightsquigarrow$ Mixing!
- mixing induces mass and width mixing matrices $M_{ab}$, $\Gamma_{ab}$
- observables: $\Delta M$, $\Delta\Gamma$, mixing-induced CP asymmetries $A_{\rm CP}(B_d \to J/\psi K_S)$, $A_{\rm CP}(B_s \to J/\psi\phi)$, semileptonic CP asymmetry $A_{\rm SL}^q$
- $\Delta M_d$ well known, $\Delta M_s$ first measured in 2006 (CDF)
- $\arg M_{12}^d = 2\beta$ (in the SM);
  $\arg M_{12}^s \approx 0$ (in the SM): no direct measurement yet, wait for LHC(b)
- $M_{12}$ loop induced, sensitive to new physics

**Any hint of new physics yet?**

# $\Delta M_q$ in the SM

$$M_{12}^{\rm SM} \quad =$$




$$= \quad \frac{G_{\rm F}^2 M_W^2}{12\pi^2} M_{B_q} \hat{\eta}^B \hat{B}_{B_q} f_{B_q}^2 (V_{tq}^* V_{tb})^2 S_0(x_t)$$

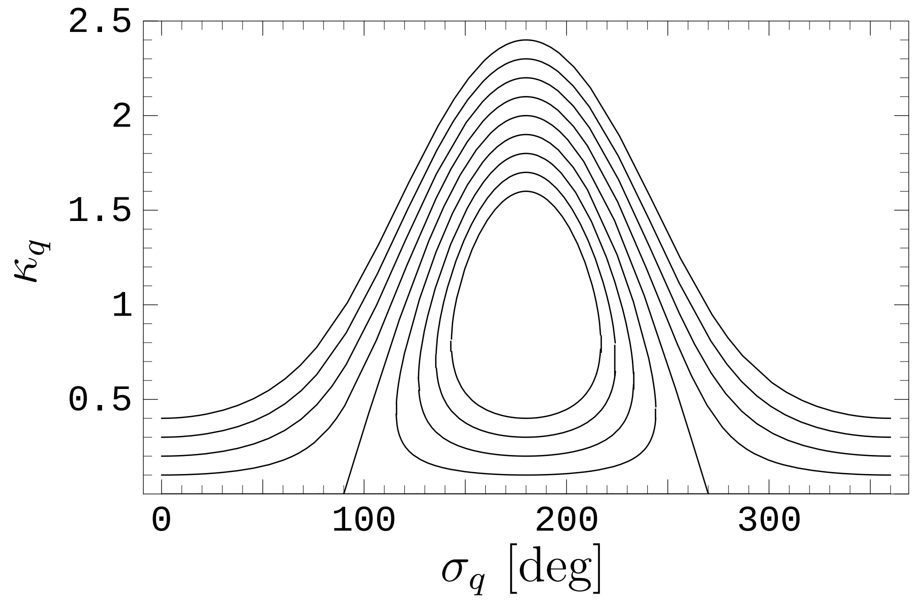
- $S_0(x_t = m_t^2/M_W^2) = 2.35 \pm 0.06$: Inami-Lim function
- $\hat{\eta}^B \; = 0.552$: NLO QCD correction (Buras/Jamin/Weiss '90)
- $\hat{B}_{B_q} f_{B_q}^2 \; \propto \langle B_q^0 | (\bar{q}b)_{V-A} (\bar{q}b)_{V-A} | \bar{B}_q^0 \rangle$: hadronic matrix element, from lattice
- $V_{tq}^* V_{tb}$: from tree-level processes

# Generic Parametrisation of New Physics

$\Delta M_s = 2|M_{12}^s|$ with

- $\boxed{M_{12}^s = M_{12}^{s,\mathrm{SM}}(1+\kappa_s e^{i\sigma_s})}$
- $\kappa_s > 0$: NP amplitude
- $\sigma_s$: new CP-violating phase

Lines of $\rho_s$ =const.:




Deviation from SM measured by

$$\boxed{\rho_s \equiv \left|\frac{\Delta M_s}{\Delta M_s^{\mathrm{SM}}}\right| = (1 + 2\kappa_s \cos\sigma_s + \kappa_s^2)^{1/2}}$$

Q: What is the SM prediction of $\Delta M_s$?

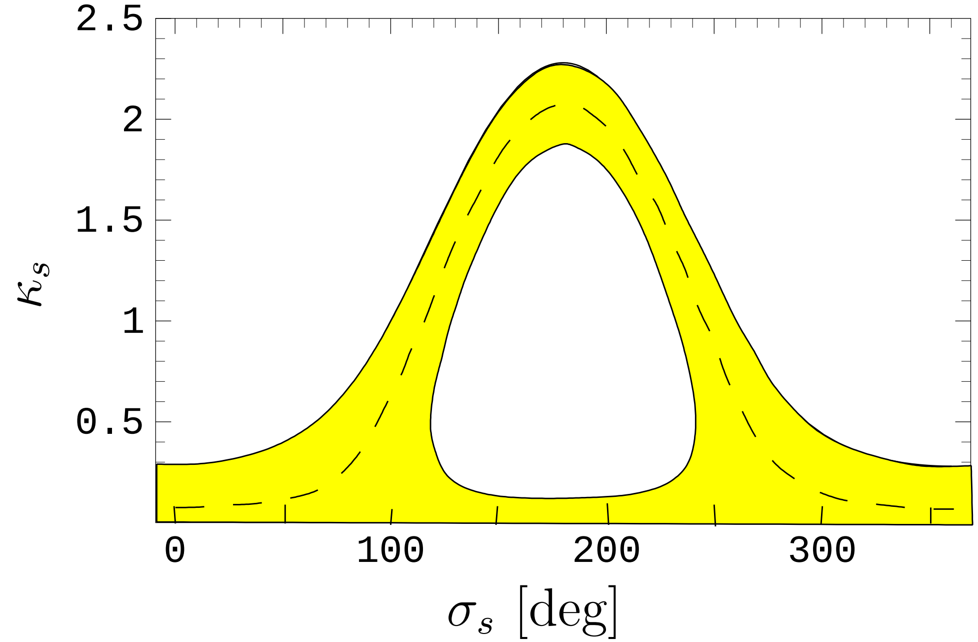
# Predictions of $\Delta M_s^{\rm SM}$

Need hadronic matrix elements from lattice.

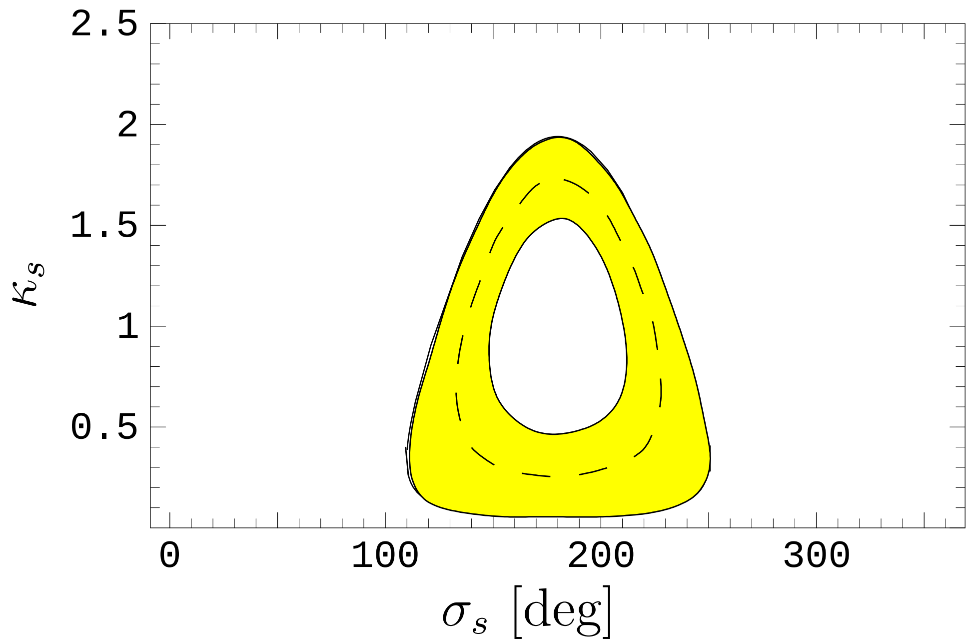
Two unquenched calculations available:

- JLQCD: $N_f = 2$ Wilson fermions
- HPQCD: $N_f = 2+1$ staggered light + NRQCD heavy fermions

constraints from JLQCD:




HPQCD:



# Predictions of $\Delta M_s^{\rm SM}$

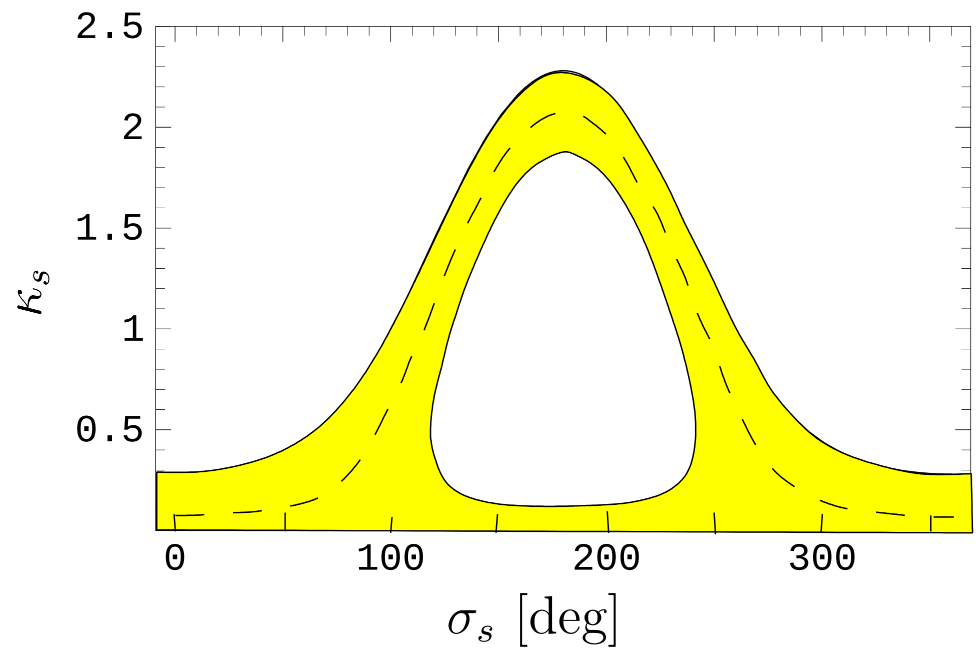
$$\Delta M_s^{\rm SM}\big|_{\rm JLQCD} = (16.1 \pm 2.8)\,{\rm ps}^{-1}$$

$$\rho_s\big|_{\rm JLQCD} = 1.08^{+0.03}_{-0.01}(\text{exp}) \pm 0.19(\text{th})$$

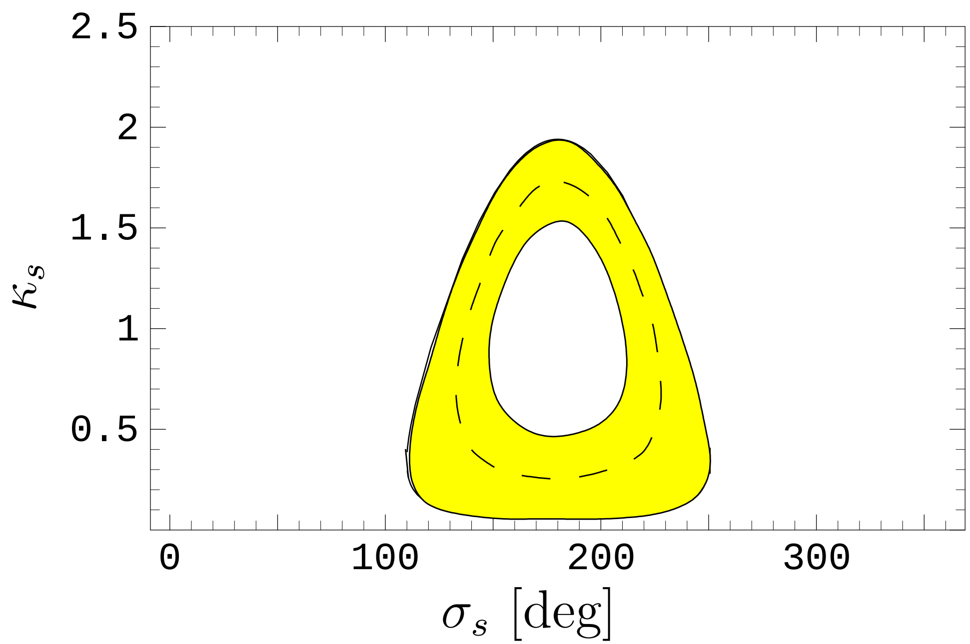
$$\Delta M_s^{\rm SM}\big|_{\rm HPQCD} = (21.2 \pm 3.2)\,{\rm ps}^{-1}$$

$$\rho_s\big|_{\rm HPQCD} = 0.82^{+0.02}_{-0.01}(\text{exp}) \pm 0.12(\text{th}) \qquad 1.5\sigma!$$

constraints from JLQCD:




HPQCD:



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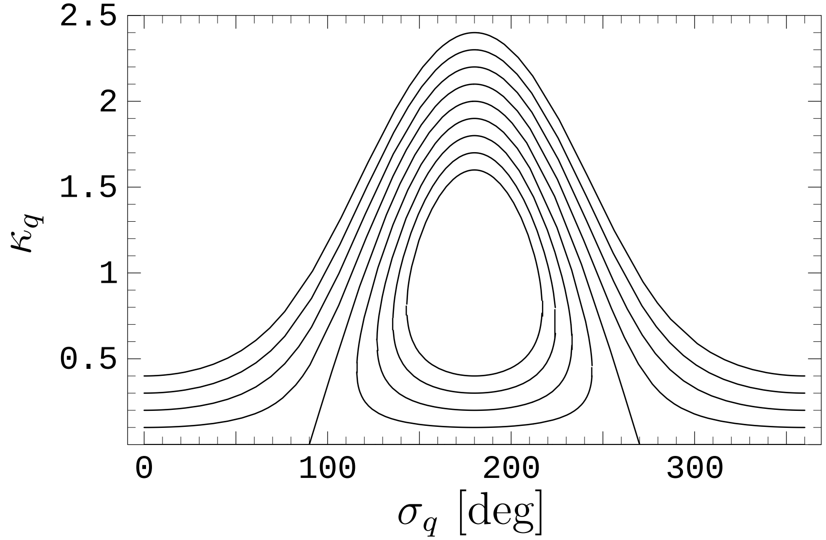
Conclusion from this exercise:

$\boxed{\Delta M_s^{\rm SM} \text{ is actually not very well known!}}$

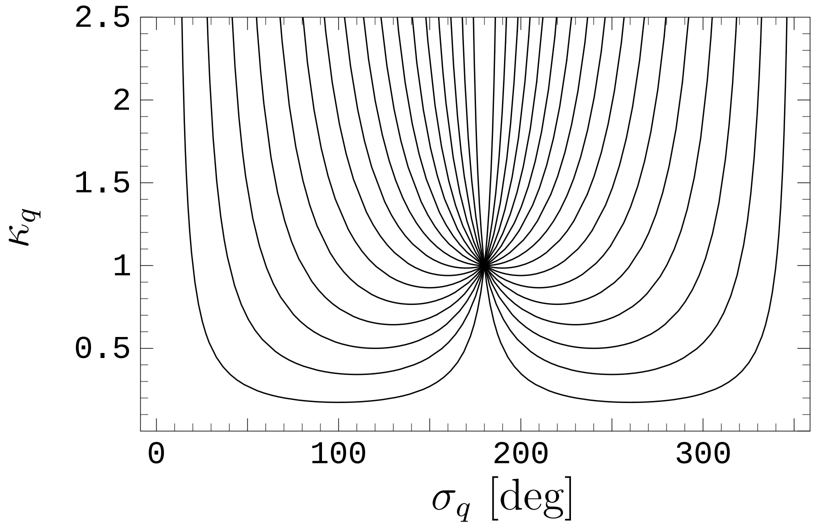
For better constraints, need mixing phase $\phi_s = \arg M_{12}^s$!

# Constraints from $\phi_q$

$\rho_q$ =const.:




$\phi_q^{\rm NP}$ =const.:




$$\boxed{\phi_q = \arg M_{12}^q = \phi_q^{\rm SM} + \phi_q^{\rm NP} \text{ with } \phi_s^{\rm SM} = -2\lambda^2 R_b \sin\gamma \approx -2^\circ}$$

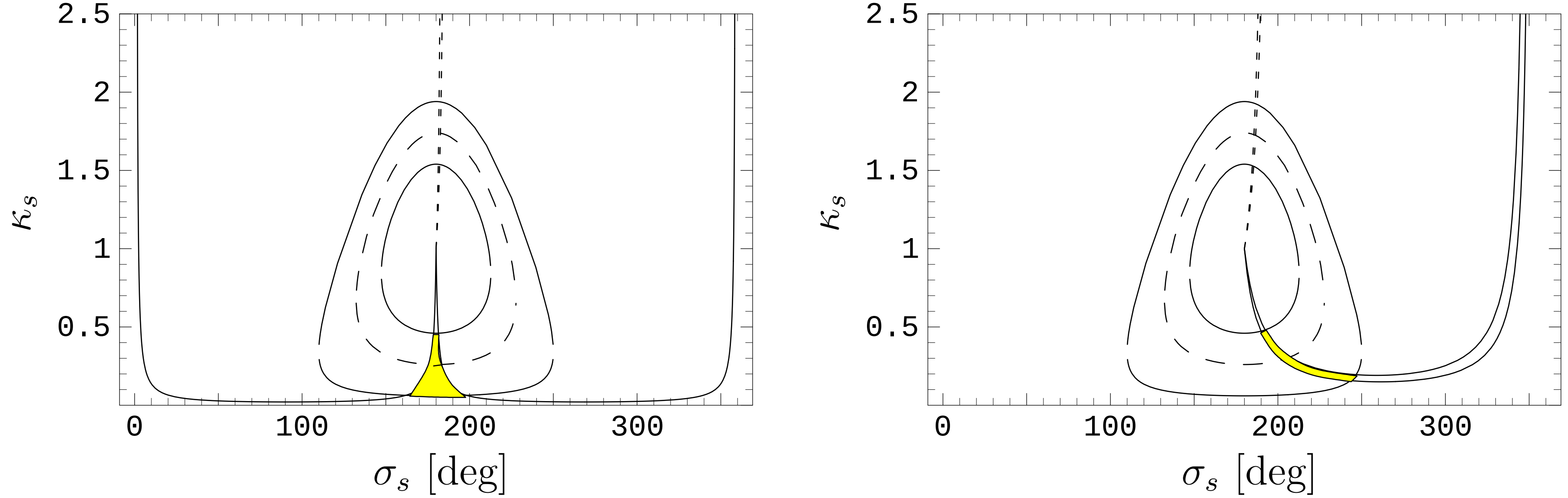
# Status of $\phi_s$

- brand-new constraints from $A^s_{\rm SL}$ and $\Delta\Gamma_s$: (Lenz/Nierste, hep-ph/0612167)

  $\boxed{\sin\phi_s = -0.77 \pm 0.04(\text{th}) \pm 0.34(\text{exp})}$ (SM: $\approx -0.06$)

  ⚠ result heavily theory dependent!

- for more precise results, have to wait for $A_{\rm CP}(B_s \to J/\psi\phi)$ at LHC



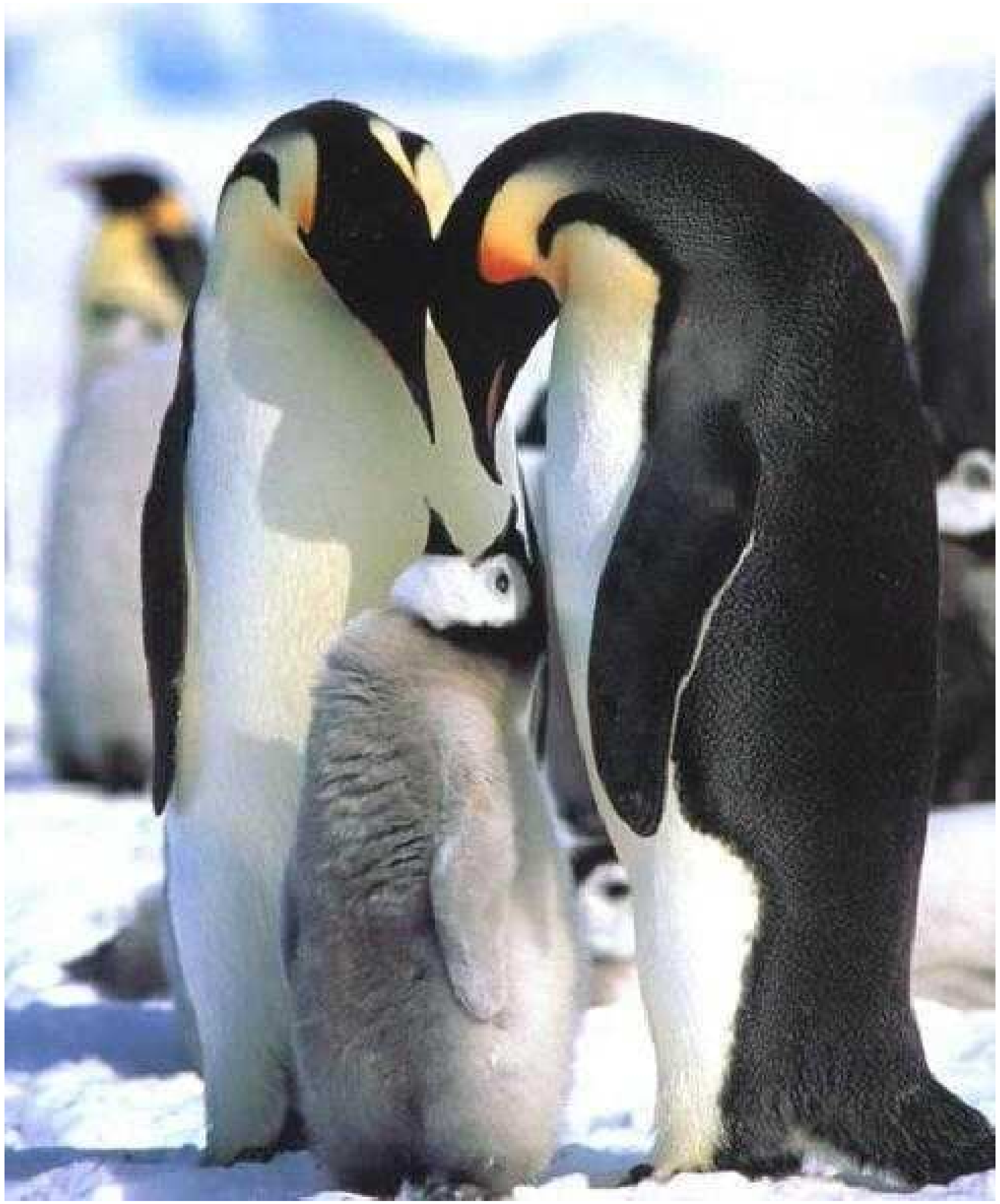

$\phi_s^{\rm SM}$ and HPQCD lattice results

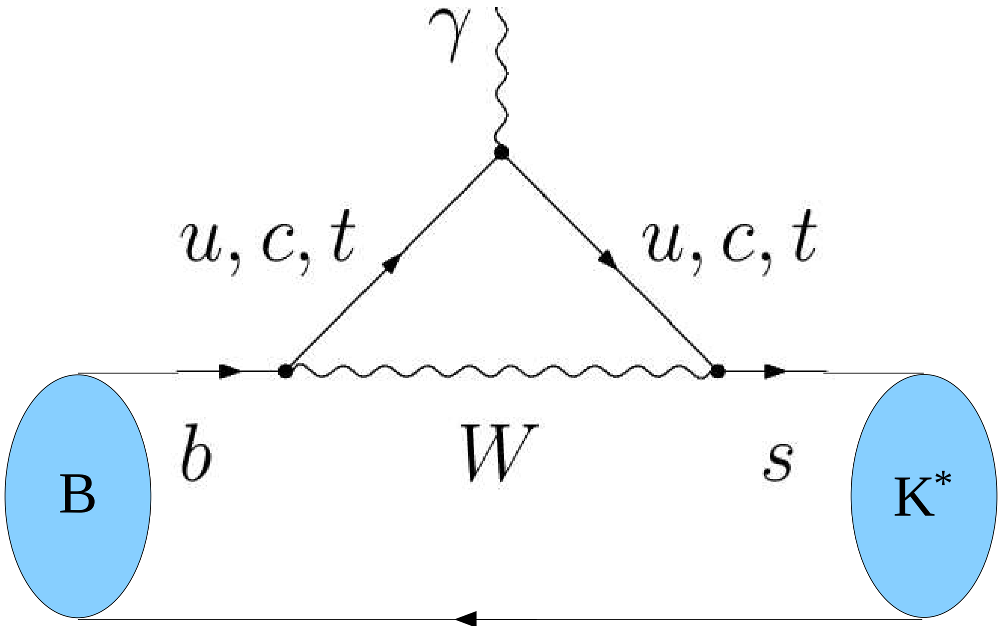
$\phi_s^{\rm NP} = -(10 \pm 3)^\circ$ and HPQCD lattice results

# $|V_{td}/V_{ts}|$ & UT angle $\gamma$ from $B \to (\rho, K^*)\gamma$

**Ball/Jones/Zwicky, hep-ph/0612081**

# Radiative Penguins






$$B \to K^*\gamma \quad \longleftrightarrow \quad b \to s\gamma$$

$$B \to (\rho,\omega)\gamma \quad \longleftrightarrow \quad b \to d\gamma$$

# Theory Framework

- QCD factorisation: (Bosch/Buchalla 01)

$$A(B \to V\gamma) = \sum_{i=1}^{8} \sum_{U=u,c} \lambda_U C_i \langle V\gamma | Q_i^U | B\rangle$$

$$\langle V\gamma | Q_i^U | B\rangle = \left[ T_1^{B\to V}(0)\, T_i^I + \int_0^1 d\xi\, du\, T_i^{II}(\xi, u)\, \phi_B(\xi)\, \phi_{2;V}^{\perp}(u) \right] \cdot e$$

- $\lambda_U$: CKM factors
- $C_i, T_i^{I,II}$: perturbative QCD quantities
- $T_1, \phi_B, \phi_{2;V}^{\perp}$: non-perturbative QCD quantities

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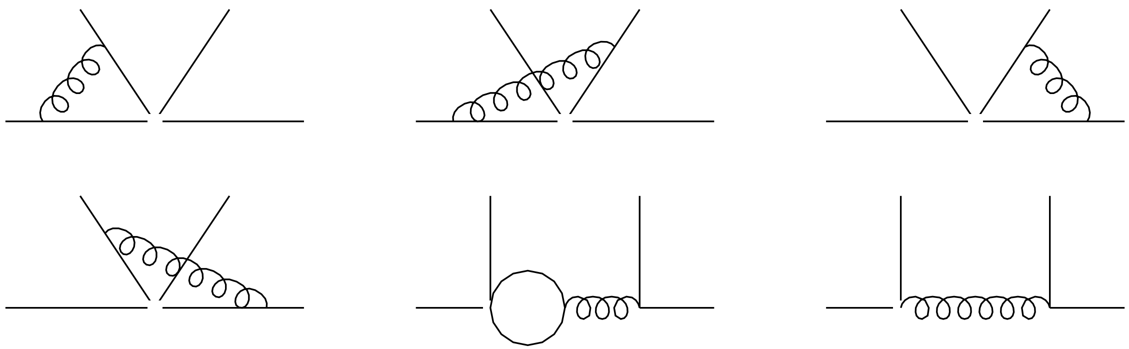
$T_i^I =$



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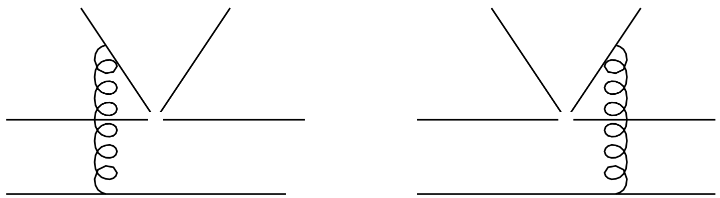

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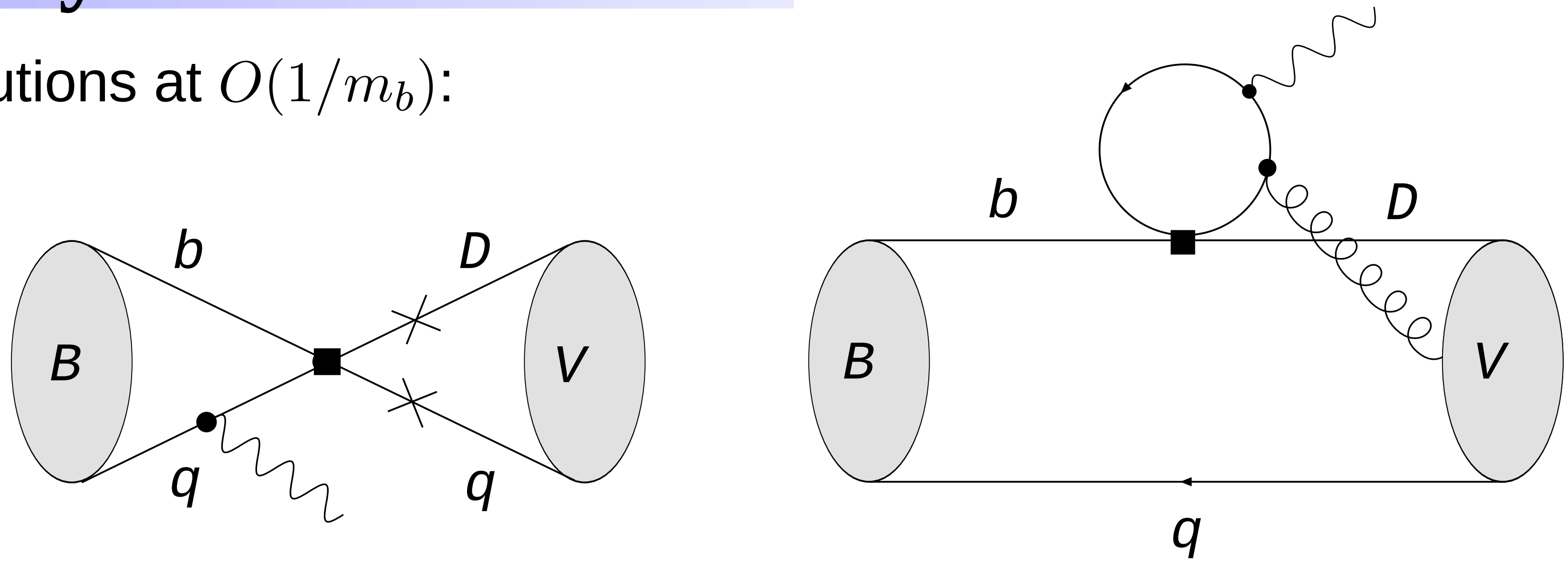
Contributions at $O(1/m_b)$:




(a) (b)

- weak annihilation
- can be treated in QCDF
- relevant for $\mathcal{B}(B \to \rho\gamma)$ and isospin asymmetries
- long-distance photon emission, beyond QCDF, relevant for $\mathcal{B}(B^\pm \to \rho^\pm\gamma)$

- soft gluon emission
- beyond QCDF, new method developed by Ball/Jones/Zwicky 06
- relevant for $\mathcal{B}(B \to V\gamma)$ and time-dependent CP asymmetry

# Form Factors

- state-of-the-art results from QCD sum rules on the light-cone: (Ball/Zwicky 04)

| $T_1^\rho(0)$ | $T_1^\omega(0)$ | $T_1^{K^*}(0)$ |
|---|---|---|
| $0.27 \pm 0.04$ | $0.25 \pm 0.04$ | $0.31 \pm 0.04$ |

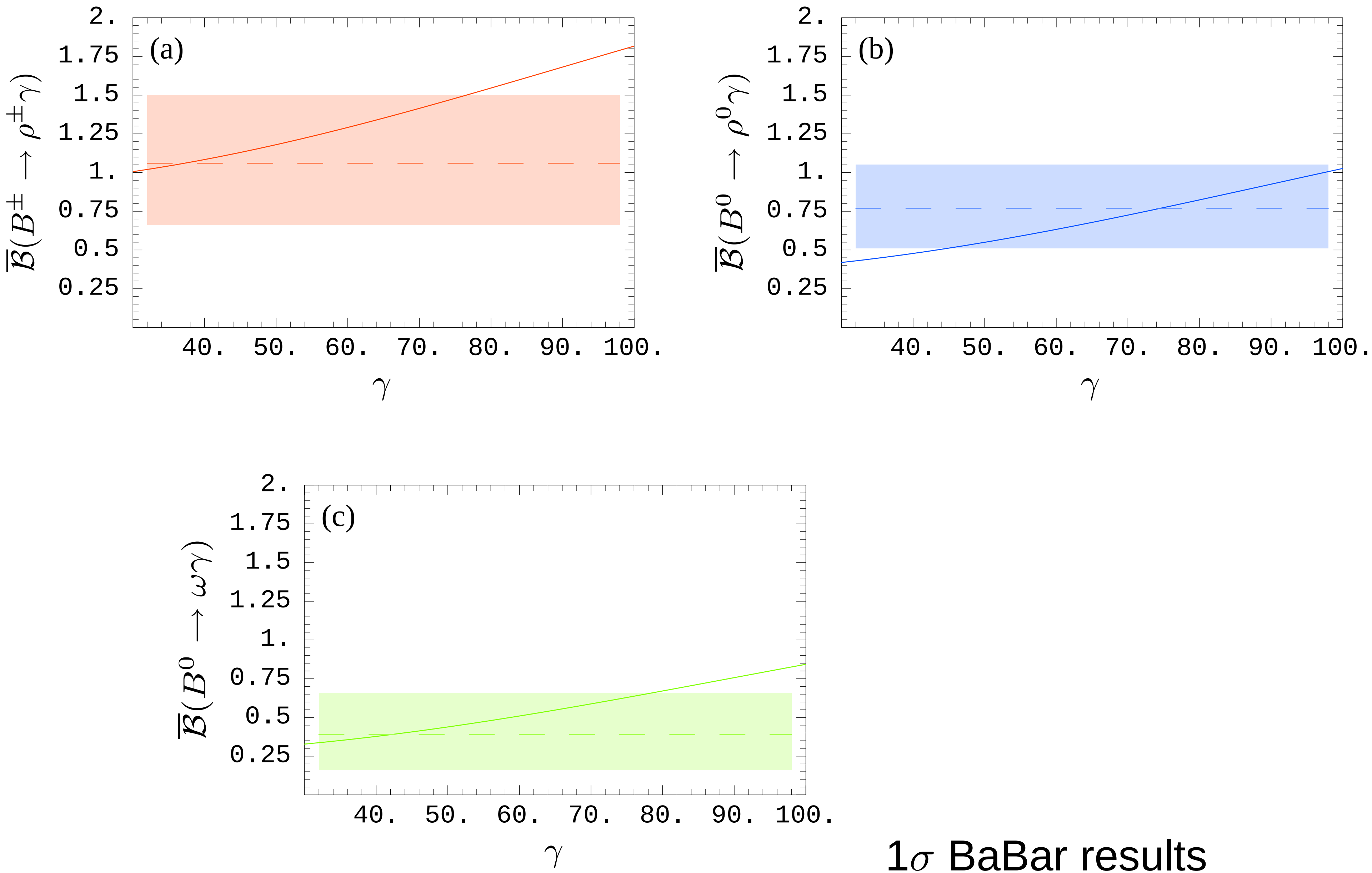
- better accuracy for ratios:

$$\xi_\rho \equiv \frac{T_1^{K^*}}{T_1^\rho} = 1.17 \pm 0.09 \qquad \xi_\omega \equiv \frac{T_1^{K^*}}{T_1^\omega} = 1.30 \pm 0.10$$

- strategy for predicting branching ratios:

$$\overline{\mathcal{B}}(B \to V\gamma)\Big|_{\rm th} = \left[\frac{\overline{\mathcal{B}}(B \to V\gamma)}{\overline{\mathcal{B}}(B \to K^*\gamma)}\right]_{{\rm th},\, \boxed{\xi_V}} \overline{\mathcal{B}}(B \to K^*\gamma)\Big|_{\rm exp}$$

# Theory Predictions for $B \to (\rho, \omega)\gamma$




$1\sigma$ BaBar results

# $|V_{td}/V_{ts}|$

$$\frac{\overline{\mathcal{B}}(B\to(\rho,\omega)\gamma)}{\overline{\mathcal{B}}(B\to K^*\gamma)} \equiv R_{\rho/\omega} = \left|\frac{V_{td}}{V_{ts}}\right|^2 \left(\frac{1-m_\rho^2/m_B^2}{1-m_{K^*}^2/m_B^2}\right)^3 \frac{1}{\xi_\rho^2}\,[1+\Delta R]$$

BaBar 06: $R_{\rho/\omega} = 0.030 \pm 0.006$, Belle 05: $0.032 \pm 0.008$

Ball/Zwicky 06: $\xi_\rho = 1.17 \pm 0.09$

Ball/Jones/Zwicky 06: $\Delta R \sim 0 - 0.15$

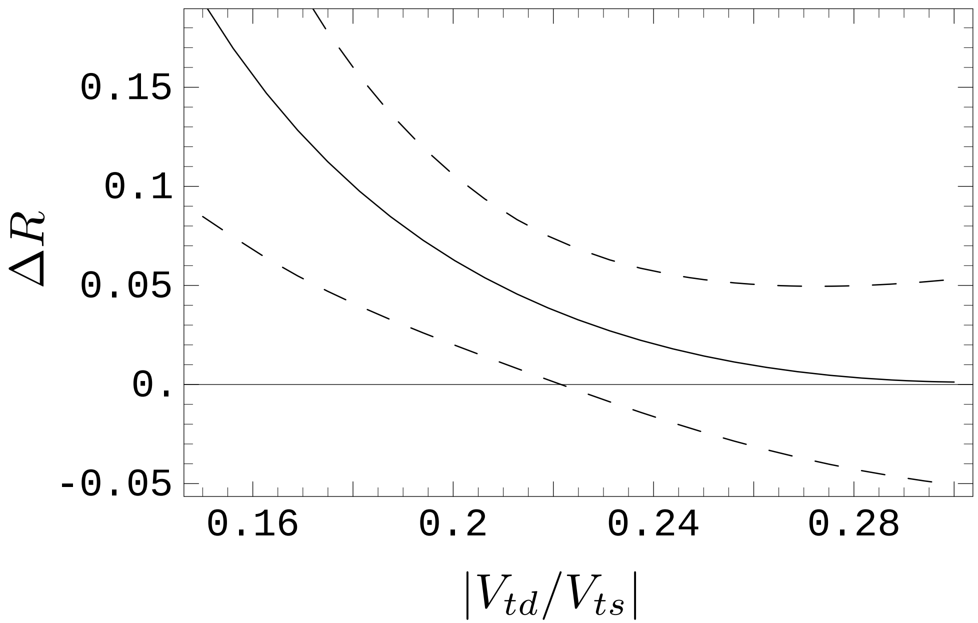
# $|V_{td}/V_{ts}|$

$$\frac{\overline{\mathcal{B}}(B\to(\rho,\omega)\gamma)}{\overline{\mathcal{B}}(B\to K^*\gamma)} \equiv R_{\rho/\omega} = \left|\frac{V_{td}}{V_{ts}}\right|^2 \left(\frac{1-m_\rho^2/m_B^2}{1-m_{K^*}^2/m_B^2}\right)^3 \frac{1}{\xi_\rho^2}\,[1+\Delta R]$$

BaBar 06: $R_{\rho/\omega} = 0.030 \pm 0.006$, Belle 05: $0.032 \pm 0.008$

Ball/Zwicky 06: $\xi_\rho = 1.17 \pm 0.09$

Ball/Jones/Zwicky 06: $\Delta R \sim 0 - 0.15$



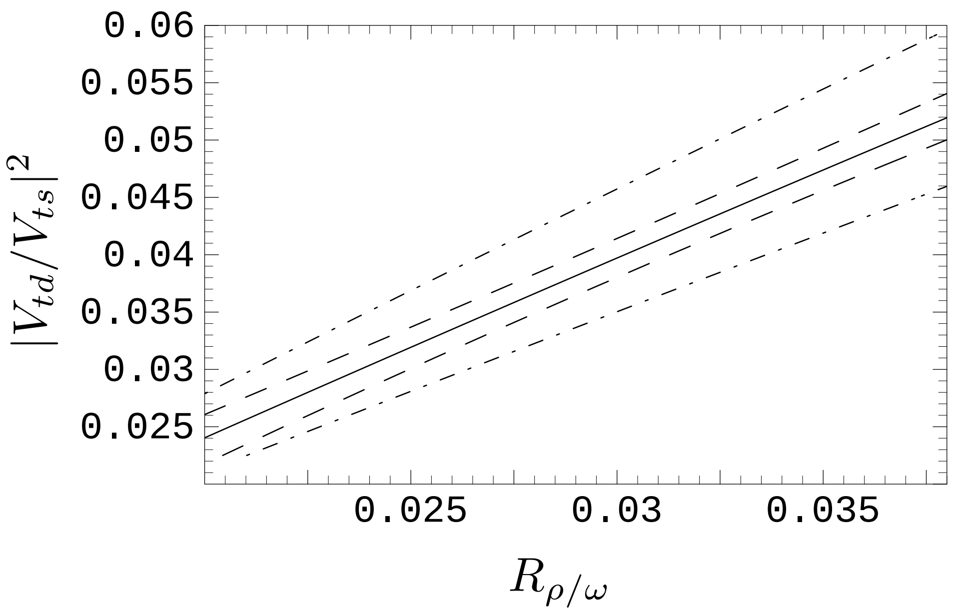

$\Delta R$ depends on $|V_{td}/V_{ts}|$ itself!

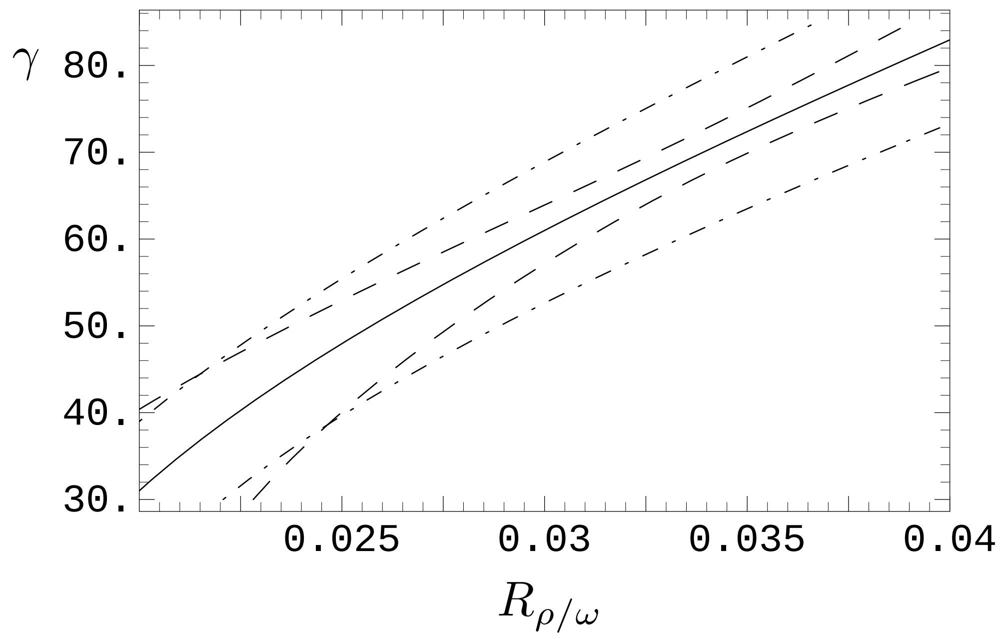
# $\Delta R$

Solution: use truly independent set of CKM parameters:

$$\boxed{\lambda,\ R_b,\ |V_{td}/V_{ts}|} \quad \text{or} \quad \boxed{\lambda,\ R_b,\ \gamma}$$

$\Rightarrow$ determine either $\boxed{|V_{td}/V_{ts}|}$ or $\boxed{\gamma}$ from experimental $R_{\rho/\omega}$



# Results

From 2006 BaBar data:

$$\left|\frac{V_{td}}{V_{ts}}\right| = 0.199^{+0.022}_{-0.025}(\mathrm{exp}) \pm 0.014(\mathrm{th}) \longleftrightarrow \gamma = (61.0^{+13.5}_{-16.0}(\mathrm{exp})^{+8.9}_{-9.3}(\mathrm{th}))^\circ$$

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Results from other methods:

- from $B$ mixing: $\Delta M_s/\Delta M_d$:

$$\left|\frac{V_{td}}{V_{ts}}\right| = 0.206^{+0.0081}_{-0.0060}(\mathrm{th}) \pm 0.0007(\mathrm{syst})$$

- depends on lattice input: $f_{B_s}\sqrt{B_{B_s}}/f_{B_d}\sqrt{B_{B_d}} = 1.21^{+0.047}_{-0.035}$ (Okamoto, Lattice 2005)

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Results from other methods:

- theory independent: Dalitz plot analysis of CP asymmetry in $B^- \to D^0 K^-$ with $(D^0, \bar{D}^0) \to K_S \pi^+ \pi^-$:

  BaBar : $\boxed{\gamma = (92 \pm 41 \pm 11 \pm 12)^\circ}$ , Belle: $\boxed{\gamma = (53^{+15}_{-18} \pm 3 \pm 9)^\circ}$

- SU(3) fits ($B \to \pi\pi$ and $B \to \pi K$): $\boxed{\gamma = (70.0^{+3.8}_{-4.3})^\circ}$ (Fleischer 06)

- QCD factorisation in $B \to PV$: $\boxed{\gamma = (62 \pm 8)^\circ}$ (Beneke/Neubert 03)

- SCET in $B \to \pi\pi$: $\boxed{\gamma = (73.9^{+7.4}_{-10.7})^\circ}$ (Stewart 06)

# Time-dependent CP Asymmetry in $B \to K^*\gamma$

**Ball/Zwicky, hep-ph/0609037**

# $A_{\rm CP}(B \to K^*\gamma)$

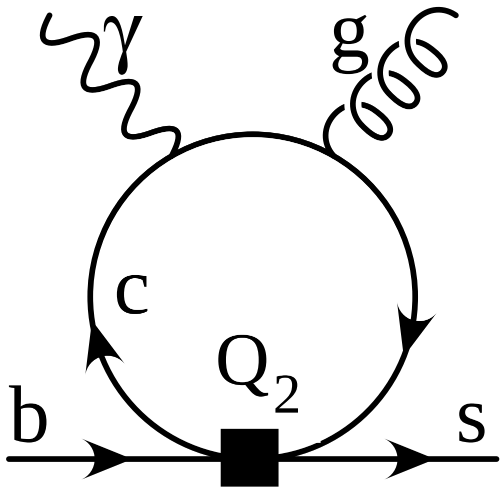
- $b \to s\gamma$ is actually either
  - $b_R \to s_L\gamma_L$ (with helicity factor $m_b$) or
  - $b_L \to s_R\gamma_R$ (with helicity factor $m_s$)
- $\gamma$ dominantly left-polarised, $\gamma_R$ suppressed by $m_s/m_b$
- entails a small time-dependent CP asymmetry (interference of $\gamma_L/\gamma_R$ amplitudes):

$$
\begin{aligned}
A_{\rm CP} &= \frac{\Gamma(\bar{B}^0(t) \to \bar{K}^{*0}\gamma) - \Gamma(B^0(t) \to K^{*0}\gamma)}{\Gamma(\bar{B}^0(t) \to \bar{K}^{*0}\gamma) + \Gamma(B^0(t) \to K^{*0}\gamma)} \\
&\approx -2\,\frac{m_s}{m_b}\,\sin(2\beta)\sin(\Delta M_d t) \approx -3\%
\end{aligned}
$$

- null-test of the SM! (Gershon/Soni 06)
- helicity suppression removed by new physics if splin flip can occur on internal line (e.g. in left-right symmetric models)

# $A_{\rm CP}(B \to K^*\gamma)$

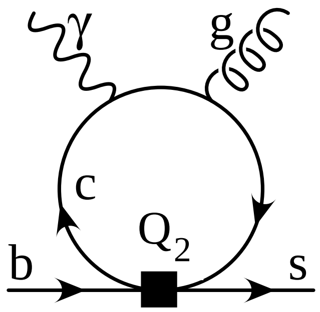
- helicity suppression removed by new physics if splin flip can occur on internal line (e.g. in left-right symmetric models)
- caveat emptor! No helicity suppression in 3-parton process $b \to s\gamma g$:




- all contributions $b \to s\gamma_R g \sim O(1/m_b)$
- dominant contribution from charm loop (with large Wilson coefficient $\sim 1$)

- contributes to $B \to K^*\gamma$ if $B$ or $K^*$ in 3-particle quark-antiquark-gluon state
- previous estimate: c loop increases $|A_{\rm CP}|$ to 10% with large uncertainties, up from 3% (Grinstein/Pirjol 05)

Can one do better?




- calculate effective operator for soft-gluon emission in $1/m_c$ expansion
- calculate matrix element from QCD sum rules on the light-cone
- contribution $A_{\rm CP}^{\rm c\ loop} = +(0.5 \pm 1)\%$
- all together: $\boxed{A_{\rm CP}(B \to K^*\gamma) = -(2.2 \pm 1.5^{+1}_{-0})\%}$
- experimental result: $\boxed{-(28 \pm 26)\%}$
- $B \to K^*\gamma$ difficult for LHC; $B_s \to \phi\gamma$ better suited;

  SM prediction of CP asymmetry: $\boxed{A_{\rm CP}(B_s \to \phi\gamma) = (0.1 \pm 0.1)\%}$
- any measured CP violation larger than a few percent unambiguous signal for new physics with non-standard weak couplings (not $V - A$)!

# Summary

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- in order to fully explore (both old and new) flavour physics in B decays, need to understand strong interaction physics
- QCD enters at all scales ($m_W$, $m_b$, $\sqrt{m_b \Lambda_{\rm QCD}}$, $\Lambda_{\rm QCD}$)
- the perturbative treatment of QCD effects is organised in terms of short-distance coefficients in effective field theories and scattering amplitudes in factorisation formulas; they are well under control
- nonperturbative QCD effects are organised in terms of matrix elements of effective local or nonlocal (light-cone) operators and are under good to reasonable control
- determination of CKM matrix elements fine except for possible tension between $|V_{ub}|$ from UTangles and inclusive $b \to ue\nu$ (2.5$\sigma$)
- for new physics searches, identify observables sensitive to new physics which are zero or near zero in the SM: null tests of the SM
  - Example: time-dependent CP asymmetry in $B \to K^*\gamma$

# Happy Penguins. . .

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Who would have thought it would be a Little Higgs?

I only hope his gluinos won't be too heavy!