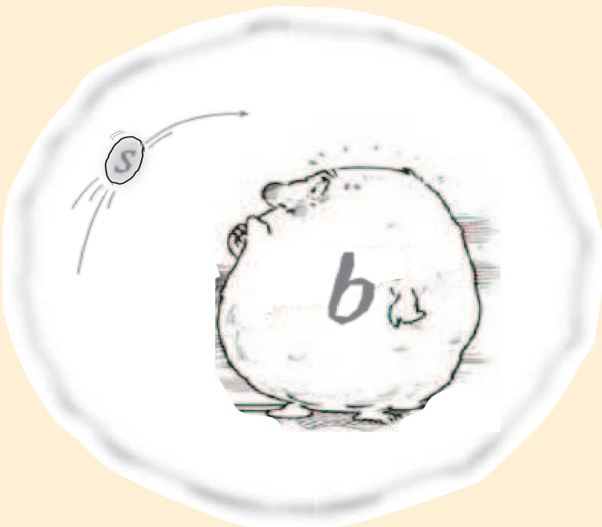
$B_s \longrightarrow KK$ Decays in Standard Model and Supersymmetry

Javier Virto

Vienna, December 2006



Universitat Autònoma de Barcelona
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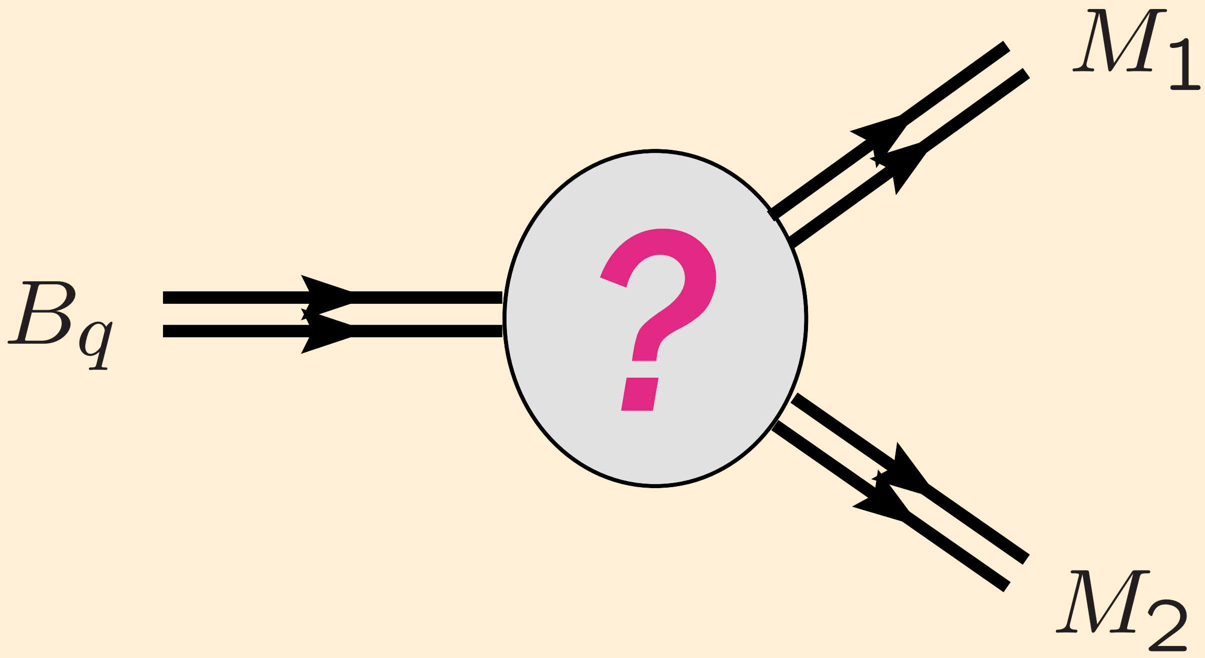
Grup de Física Teòrica

$B_q \to M_1 M_2$



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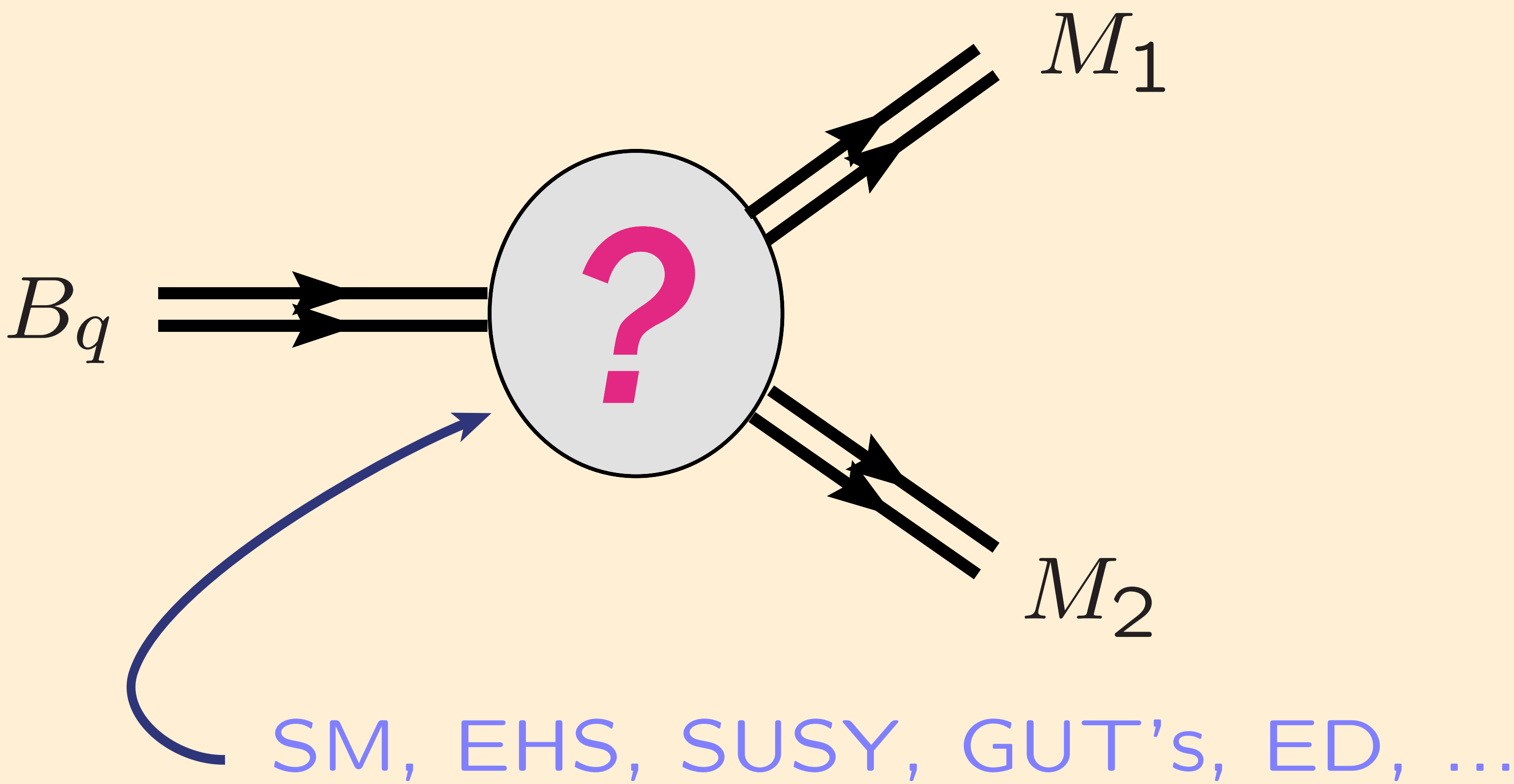

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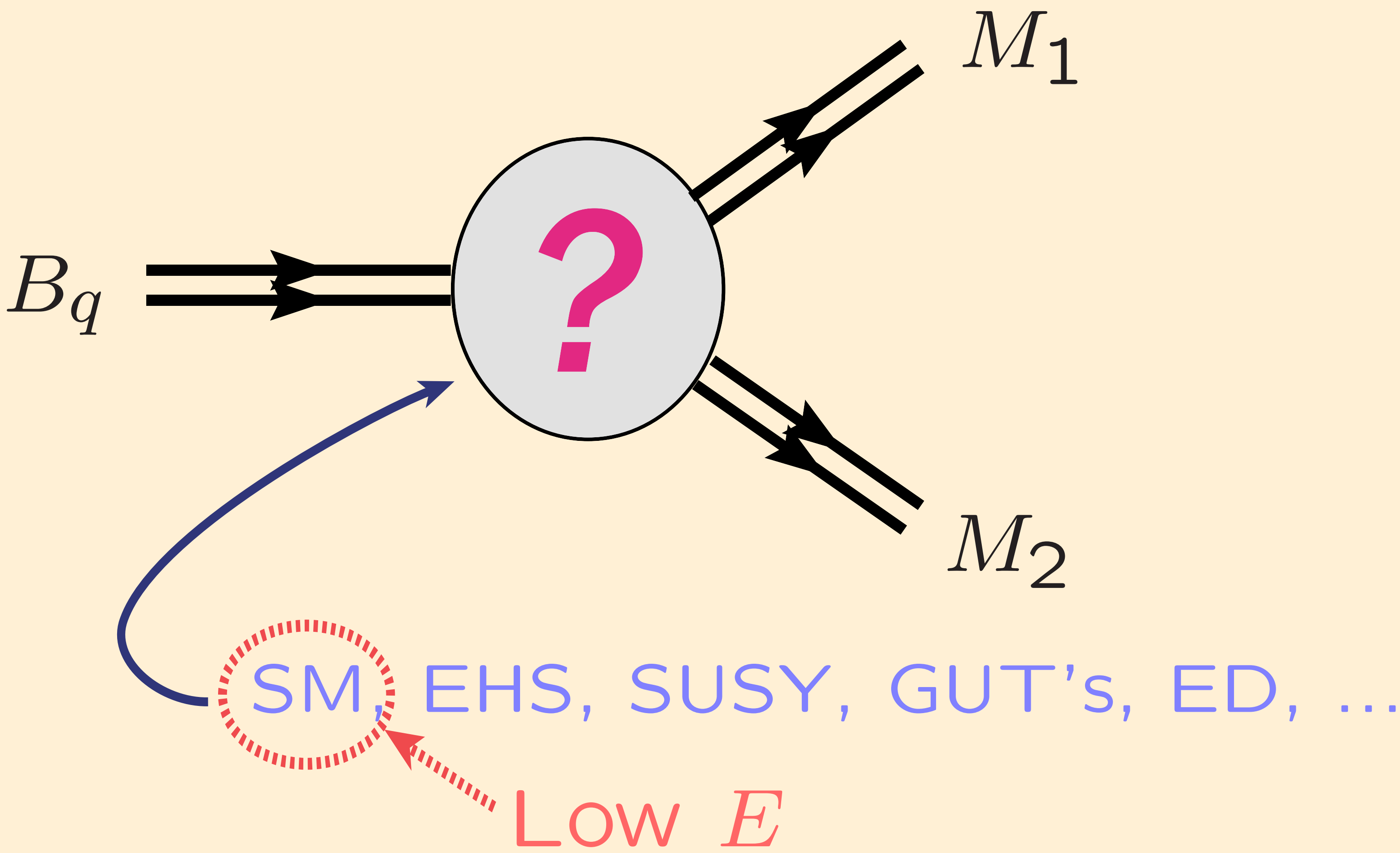
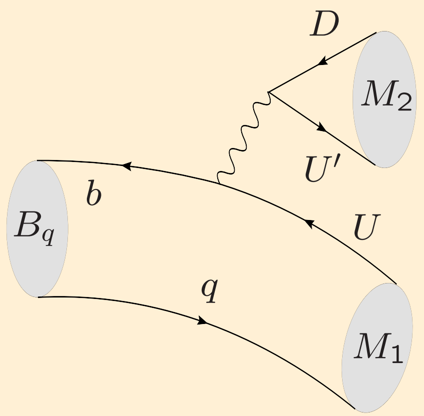
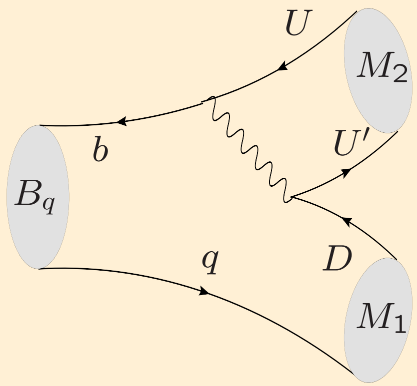


$B_q \to M_1 M_2$ in SM (up to $\mathcal{O}(G_F)$)



$\propto V_{U'D}V^*_{Ub}$



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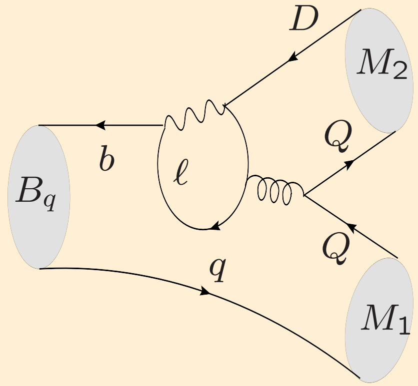
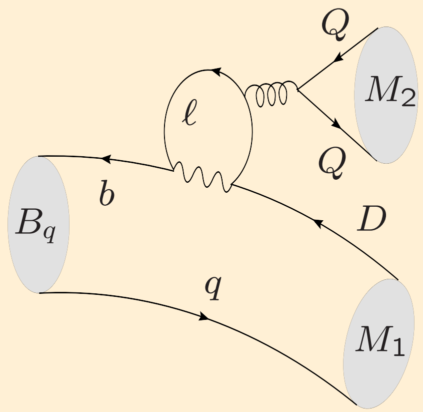


$\propto V_{\ell D}V^*_{\ell b}$



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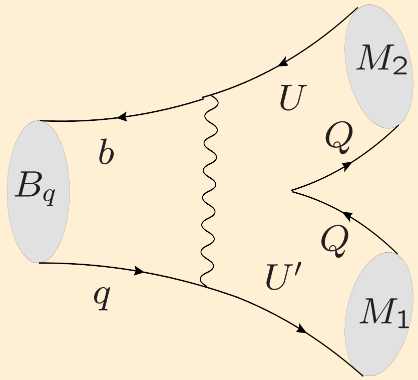

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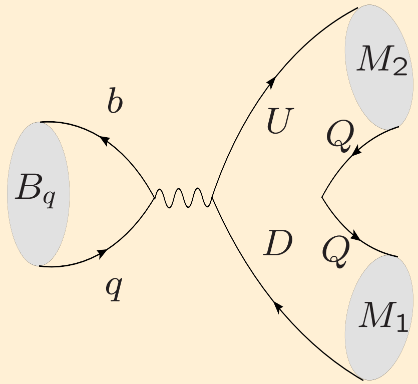
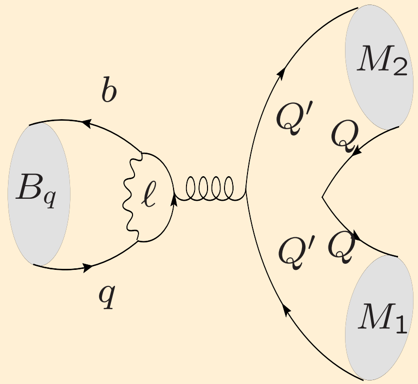


$\propto V_{UD}V^*_{qb}$



$\propto V_{\ell q}V^*_{\ell b}$

$B_q \to M_1 M_2$ in SM (up to $\mathcal{O}(G_F)$)

$\Delta C = 0$ Decays $\Rightarrow$

$$A_{SM}(B_q \to M_1 M_2) \propto V_{uD}V_{ub}^*,\ \ V_{cD}V_{cb}^*,\ \ V_{tD}V_{tb}^*$$

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- Notation: $\lambda_\ell^{(D)} \equiv V_{\ell D}V_{\ell b}^*$

$$\lambda_u^{(d)} = 0.0038 e^{i\gamma} = |\lambda_u^{(d)}| e^{i\gamma} \qquad \lambda_c^{(d)} = -0.0094 = -|\lambda_c^{(d)}|$$
$$\lambda_u^{(s)} = 0.00088 e^{i\gamma} = |\lambda_u^{(s)}| e^{i\gamma} \qquad \lambda_c^{(s)} = 0.04 = |\lambda_c^{(s)}|$$

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- CKM unitarity $\Rightarrow$ $\lambda_u^{(D)} + \lambda_c^{(D)} + \lambda_t^{(D)} = 0$

$B_q \to M_1 M_2$ in SM (up to $\mathcal{O}(G_F)$)

"Tree" and "Penguin" contributions:

$$\mathcal{A}_{SM} \equiv A_{SM}(B_q \to M_1 M_2) = \lambda_u^{(D)} T^q_{M_1 M_2} + \lambda_c^{(D)} P^q_{M_1 M_2}$$

$$\bar{\mathcal{A}}_{SM} \equiv A_{SM}(\bar{B}_q \to \bar{M}_1 \bar{M}_2) = \lambda_u^{(D)*} T^q_{M_1 M_2} + \lambda_c^{(D)*} P^q_{M_1 M_2}$$

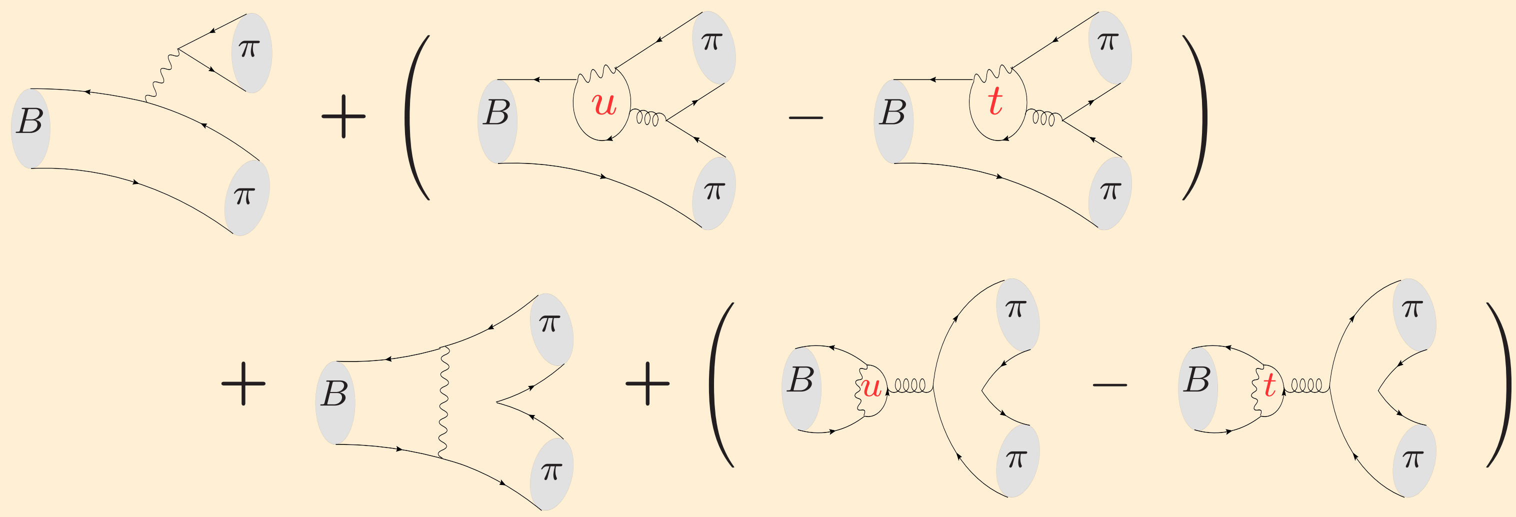
Hadronic Parameters:

$$|T^q_{M_1 M_2}|,\ |P^q_{M_1 M_2}|,\ \text{arg}\left(\frac{P^q_{M_1 M_2}}{T^q_{M_1 M_2}}\right)$$

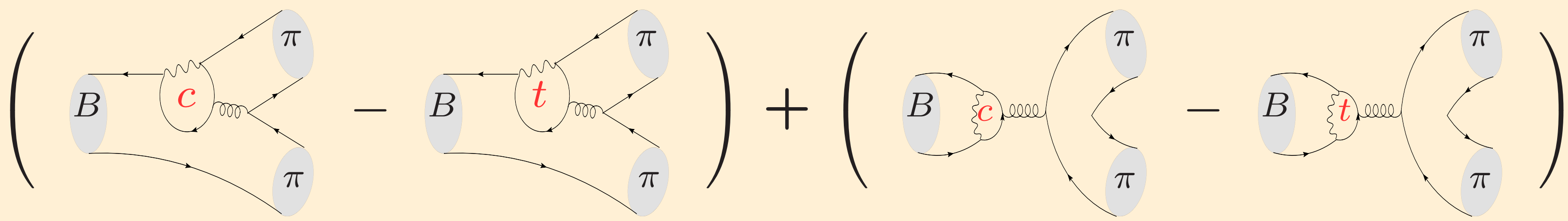
Example: $B^0 \to \pi^+\pi^-$

$$A_{SM}(B^0 \to \pi^+\pi^-) = \lambda_u^{(d)}\, T_{\pi\pi} + \lambda_c^{(d)}\, P_{\pi\pi}$$

$$\lambda_u^{(d)}\, T_{\pi\pi} =$$



$$\lambda_c^{(d)}\, P_{\pi\pi} =$$

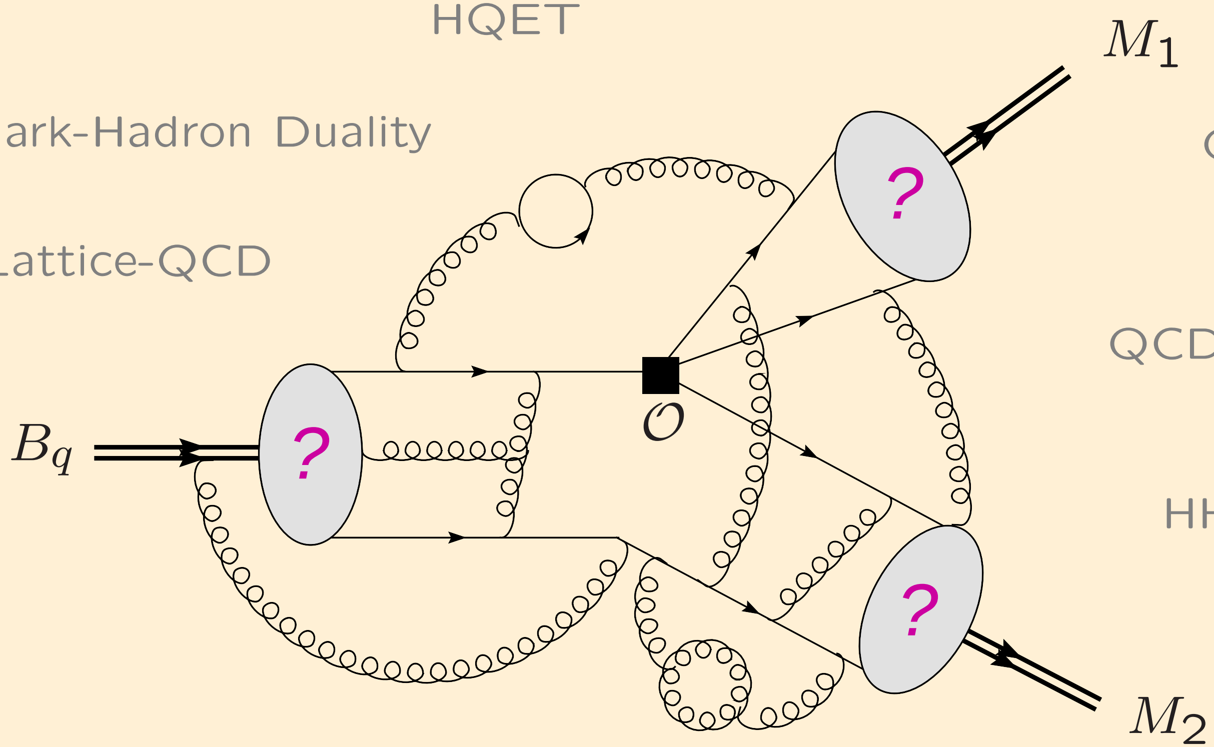


The QCD Jungle

HQET

Quark-Hadron Duality

Lattice-QCD



QCD Sum-rules

QCD-Factorization

HHChPT

Colour Transparency

SCET

Large-N_c

Quark Models

Motivation

- Without theoretical control over long-distance dynamics $\Rightarrow$

  Impossible to extract $T^q_{M_1 M_2}$, $P^q_{M_1 M_2}$ from first principles.

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  Impossible to extract $T^q_{M_1M_2}$, $P^q_{M_1M_2}$ from first principles.

- B-physics entering a *precision era.*

$\Rightarrow$ We need smart strategies to predict $T^q_{M_1M_2}$, $P^q_{M_1M_2}$

precisely and in a reliable way

(Before attempting to solve QCD, no time for that yet)

SM Hadronic Parameters from Data

– Only valid for decays that receive negligible NP contributions!!

$$BR \equiv \tau_{\mathrm{B}} f_{\mathrm{PS}} \frac{|A|^2 + |\bar{A}|^2}{2} = f(|T|, |P|, \arg(P/T))$$

$$A_{dir} \equiv \frac{|A|^2 - |\bar{A}|^2}{|A|^2 + |\bar{A}|^2} = f'(|T|, |P|, \arg(P/T))$$

$$A_{mix} \equiv -2 \frac{\mathrm{Im}(e^{-i\phi_M} A^* \bar{A})}{|A|^2 + |\bar{A}|^2} = f''(|T|, |P|, \arg(P/T))$$

SM Hadronic Parameters from Data

Example: $B_d^0 \to \pi^+\pi^-$

$$
\begin{aligned}
BR(B_d^0 \to \pi^+\pi^-)_{\text{exp}} &= (5.0 \pm 0.4) \times 10^{-6} \\
A_{dir}(B_d^0 \to \pi^+\pi^-)_{\text{exp}} &= -0.33 \pm 0.11 \\
A_{mix}(B_d^0 \to \pi^+\pi^-)_{\text{exp}} &= 0.49 \pm 0.12
\end{aligned}
$$

	$\gamma = 61^\circ$	$\gamma = (61^{+7}_{-5})^\circ$
$\lvert T_{\pi\pi}\rvert$ (10^{-6}GeV)	$(4.87, 6.11)$	$(4.60, 6.45)$
$\lvert P_{\pi\pi}/T_{\pi\pi}\rvert$	$(0.07, 0.20)$	$(0.06, 0.25)$
$\arg(P_{\pi\pi}/T_{\pi\pi})$	$(107, 150)^\circ$	$(88, 158)^\circ$

SM Hadronic Parameters from QCDF

$$A(B_q \to M_1 M_2) = \sum_{p=u,c} \lambda_p^{(D)} \langle M_1 M_2 | \mathcal{T}_A^p + \mathcal{T}_B^p | B_q \rangle$$

$$\Rightarrow \begin{cases} T^q_{M_1 M_2} & = \langle M_1 M_2 | \mathcal{T}_A^u + \mathcal{T}_B^u | B_q \rangle \\ P^q_{M_1 M_2} & = \langle M_1 M_2 | \mathcal{T}_A^c + \mathcal{T}_B^c | B_q \rangle \end{cases}$$

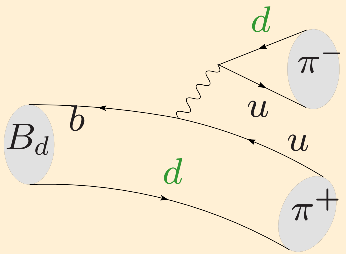
	Theory	S2	S3	S4
$\lvert T_{\pi\pi} \rvert$ (10^{-6}GeV)	$7.7^{+0.04}_{-0.06}$	6.3	7.8	6.8
$\lvert P_{\pi\pi}/T_{\pi\pi} \rvert$	$0.32^{+0.16}_{-0.09}$	0.49	0.37	0.48

$$\Rightarrow \quad BR(B_d^0 \to \pi^+\pi^-)^{\mathrm{QCDF}} = 8.9^{+4.0+3.6+0.6+1.2}_{-3.4-3.0-1.0-0.8} \times 10^{-6}$$

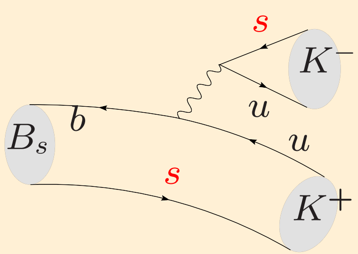
SM Hadr.Pars.from Flavor Symmetries

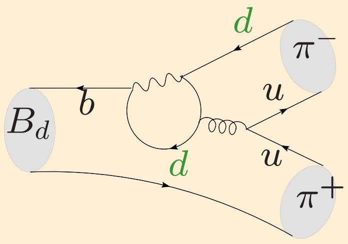
Example: $B_s^0 \to K^+K^-$

$B_d^0 \to \pi^+\pi^- \quad \longleftrightarrow \quad B_s^0 \to K^+K^-$



$\longleftrightarrow$





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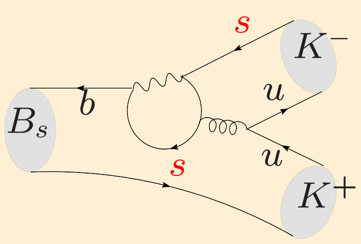

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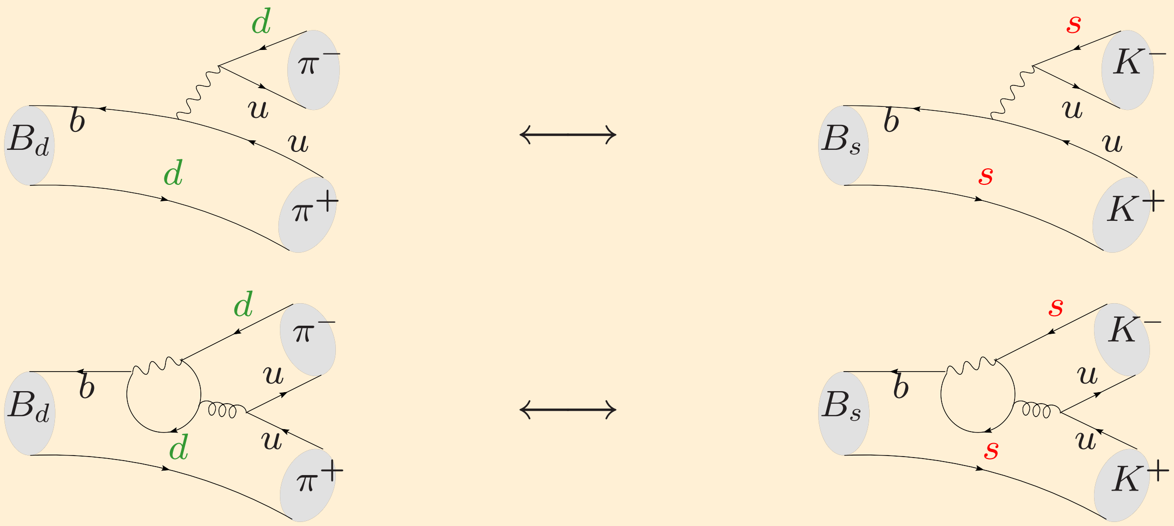


$\Rightarrow$ $SU(3)$ limit : $|T_{\pi\pi}| = |T_{KK}|$ & $\left|\frac{P_{\pi\pi}}{T_{\pi\pi}}\right| = \left|\frac{P_{KK}}{T_{KK}}\right|$ & $\arg\left(\frac{P_{\pi\pi}}{T_{\pi\pi}}\right) = \arg\left(\frac{P_{KK}}{T_{KK}}\right)$

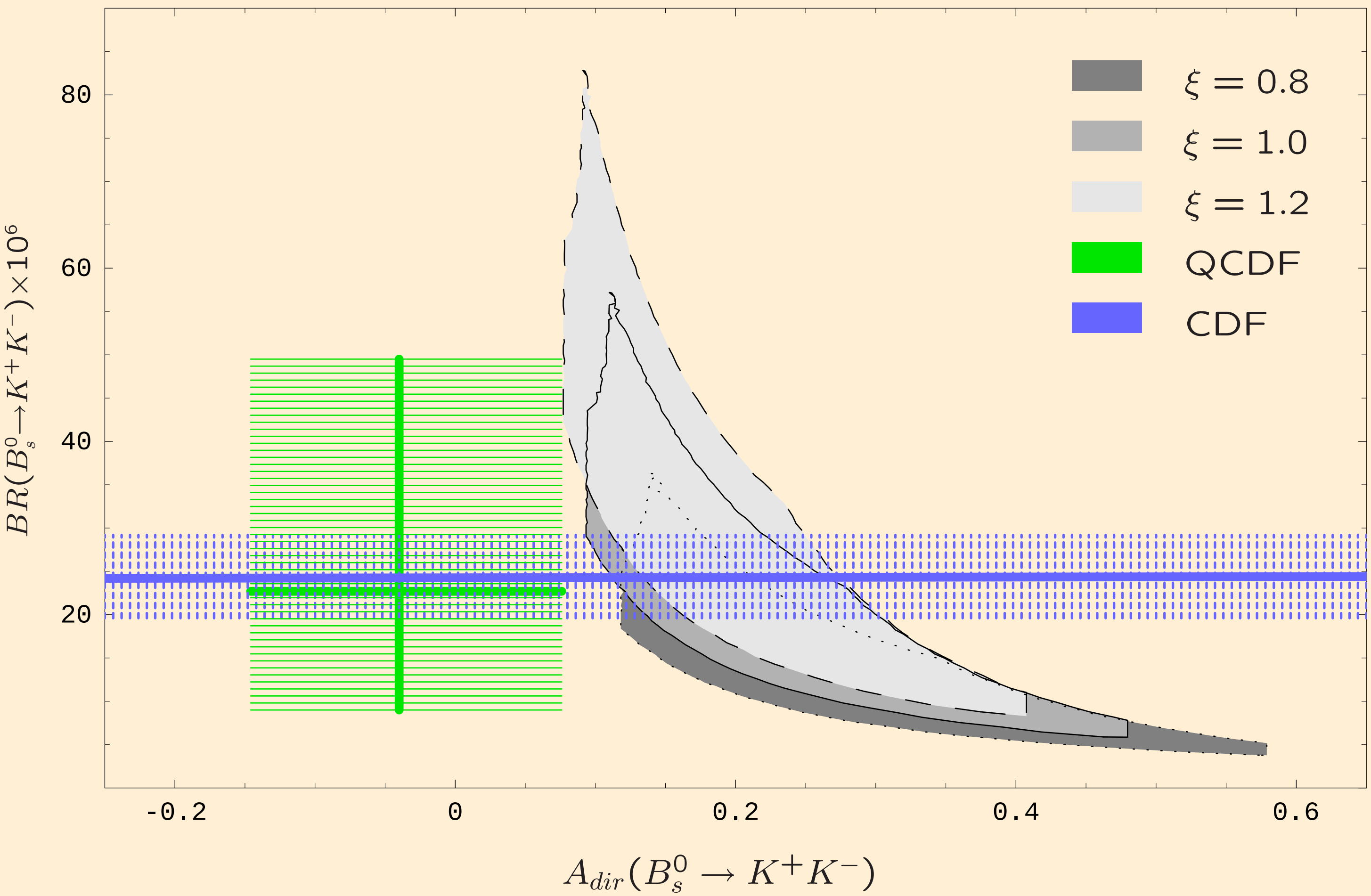
SM Hadr.Pars.from Flavor Symmetries

SU(3) breaking:

- $\mathcal{R}_{\mathcal{C}} \equiv \left|\frac{T_{KK}}{T_{\pi\pi}}\right| = 1.52^{+0.18}_{-0.14}$ [Khodjamirian, Mannel & Melcher (2004)]
- $\xi \equiv \left|\frac{P_{KK}/T_{KK}}{P_{\pi\pi}/T_{\pi\pi}}\right| = 1.0 \pm 0.2$
- $\arg(P/T) \longrightarrow$ Little sensitivity [Fleischer & Matias (2002)]

	$\lvert T_{KK}\rvert$ (10^{-6}GeV)	$\lvert P_{KK}/T_{KK}\rvert$
$\gamma = 61^\circ$, $\xi = 1$	$(8.57, 10.75)$	$(0.07, 0.20)$
$\gamma = 61^\circ$, $\xi = 1 \pm 0.2$	$(8.57, 10.75)$	$(0.06, 0.24)$
$\gamma = (61^{+7}_{-5})^\circ$, $\xi = 1$	$(8.10, 11.35)$	$(0.06, 0.25)$

A Comparative View through $B \to KK$



But...

Can we do better?

Analyzing Flavor-Symmetries

- All hadronic effects included naturally
- Mostly model independent
- Large uncertainties $\longrightarrow$ can improve experimentally
- SU(3) breaking is guessed (ξ)

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Solutions:

$\longrightarrow$ Reliable estimates of SU(3) breaking
$\longrightarrow$ More accurate exp data

Analyzing QCDF: A & B Operators

$$A(B_q \to M_1 M_2) = \sum_{p=u,c} \lambda_p^{(D)} \langle M_1 M_2 | \mathcal{T}_A^p + \mathcal{T}_B^p | B_q \rangle$$

$$\Rightarrow \begin{cases} T^q_{M_1 M_2} &= \langle M_1 M_2 | \mathcal{T}_A^u + \mathcal{T}_B^u | B_q \rangle \\ P^q_{M_1 M_2} &= \langle M_1 M_2 | \mathcal{T}_A^c + \mathcal{T}_B^c | B_q \rangle \end{cases}$$

$$\langle M_1 M_2 | \mathcal{T}_A^p | B_q \rangle = c_1\, \delta_{pu}\, \alpha_1 + c_2\, \delta_{pu}\, \alpha_2 + c_3\, \alpha_3^p + c_4\, \alpha_4^p + c_5\, \alpha_{3,\mathrm{EW}}^p + c_6\, \alpha_{4,\mathrm{EW}}^p$$

$$\langle M_1 M_2 | \mathcal{T}_B^p | B_q \rangle = d_1\, \delta_{pu}\, \beta_1 + d_2\, \delta_{pu}\, \beta_2 + d_3\, \beta_3^p + d_4\, \beta_4^p + d_5\, \beta_{3,\mathrm{EW}}^p + d_6\, \beta_{4,\mathrm{EW}}^p$$

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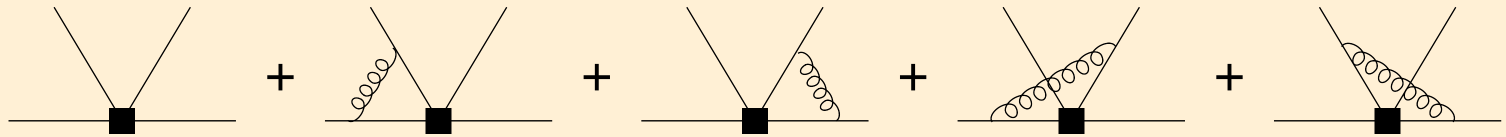
Example: $B_s^0 \to K^+ K^-$ $\left(A_{KK}^q = \frac{G_F}{\sqrt{2}} M_{B_q}^2 F^{B_q \to K} f_K \right)$

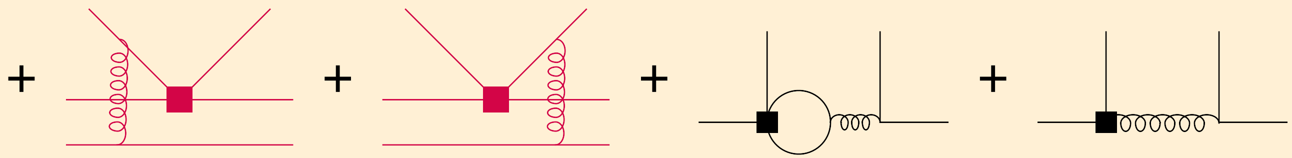
$$T^{s\pm} = A_{KK}^s (\bar{\alpha}_1 + \bar{\beta}_1 + \bar{\alpha}_4^u + \bar{\alpha}_{4,\mathrm{EW}}^u + \bar{\beta}_3^u + 2\bar{\beta}_4^u - \tfrac{1}{2}\bar{\beta}_{3,\mathrm{EW}}^u + \tfrac{1}{2}\bar{\beta}_{4,\mathrm{EW}}^u)$$

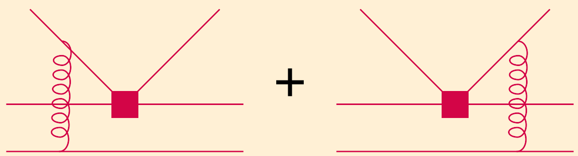
$$P^{s\pm} = A_{KK}^s (\bar{\alpha}_4^c + \bar{\alpha}_{4,\mathrm{EW}}^c + \bar{\beta}_3^c + 2\bar{\beta}_4^c - \tfrac{1}{2}\bar{\beta}_{3,\mathrm{EW}}^c + \tfrac{1}{2}\bar{\beta}_{4,\mathrm{EW}}^c)$$

Analyzing QCDF: α-coefficients

$\alpha_i^p(M_1 M_2)$ =





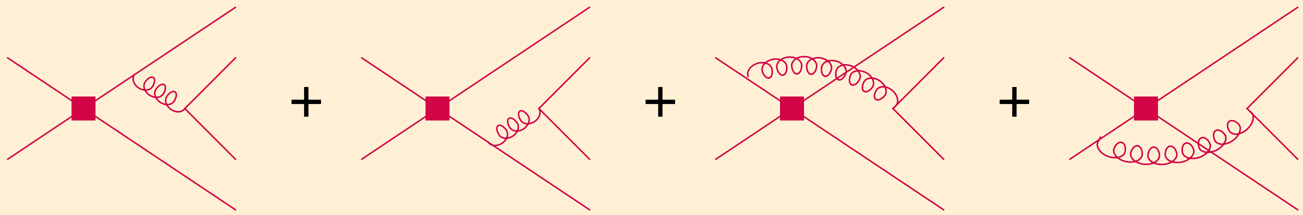


$$\supset \int_0^1 \frac{dy}{\bar{y}} \Phi_{m_1}(y) = \Phi_{m_1}(1) X_H^{M_1} + \text{finite}$$

$X_H^{M_1} \longrightarrow$ Model dependence

Analyzing QCDF: β-coefficients

$\beta_i^p(M_1 M_2)$ =



$$\supset \int_0^1 \frac{dx dy}{\bar{x} y} \Phi_{m_2}(x) \Phi_{m_1}(y)$$

– Divergent subtractions: $\int_0^1 \frac{dy}{y} \to X_A^{M_1}, \quad \int_0^1 dy \frac{\ln y}{y} \to -\frac{1}{2}(X_A^{M_1})^2$

$X_A^{M_1}, X_A^{M_2} \longrightarrow$ Model dependence

Analyzing QCDF

- Theoretical framework
- Can predict most hadronic parameters
- $1/m_b$ - I.R. divergencies $\rightarrow$ Model dependence
- Cannot give large A_{dir}

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Solutions:

$\longrightarrow$ Control over the I.R. divergencies
$\longrightarrow$ Mechanism for large strong phases

Concilia et vinces

S.Descotes, J.Matias, J.Virto. *Phys. Rev. Lett* **97** *061801 (2006)*

Δ_d : A solid quantity in QCDF

- Consider the decay $B_d \to K^0 \bar{K}^0$. We define:

$$\boxed{\Delta_d \equiv T^{d0} - P^{d0}}$$

$\longrightarrow$ I.R. divergencies X_A, X_H CANCEL in Δ_d

$$\Delta_d = A^d_{KK}[\alpha_4^u - \alpha_4^c + \beta_3^u - \beta_3^c + 2\beta_4^u - 2\beta_4^c]$$

- Including QCDF input uncertainties:

$$\boxed{\Delta_d = (1.09 \pm 0.43) \times 10^{-7} + i(-3.02 \pm 0.97) \times 10^{-7}}$$

SM Hadr.Parameters from FS+QCDF

- Extract the hadronic parameters: $|T^{d0}|$, $|P^{d0}|$, $\arg\left(\frac{P^{d0}}{T^{d0}}\right)$, from:

$$BR^{d0} \equiv BR(B_d \to K^0 \bar{K}^0)\ ,\ A_{dir}^{d0} \equiv A_{dir}(B_d \to K^0 \bar{K}^0) \ \text{and} \ \Delta_d$$

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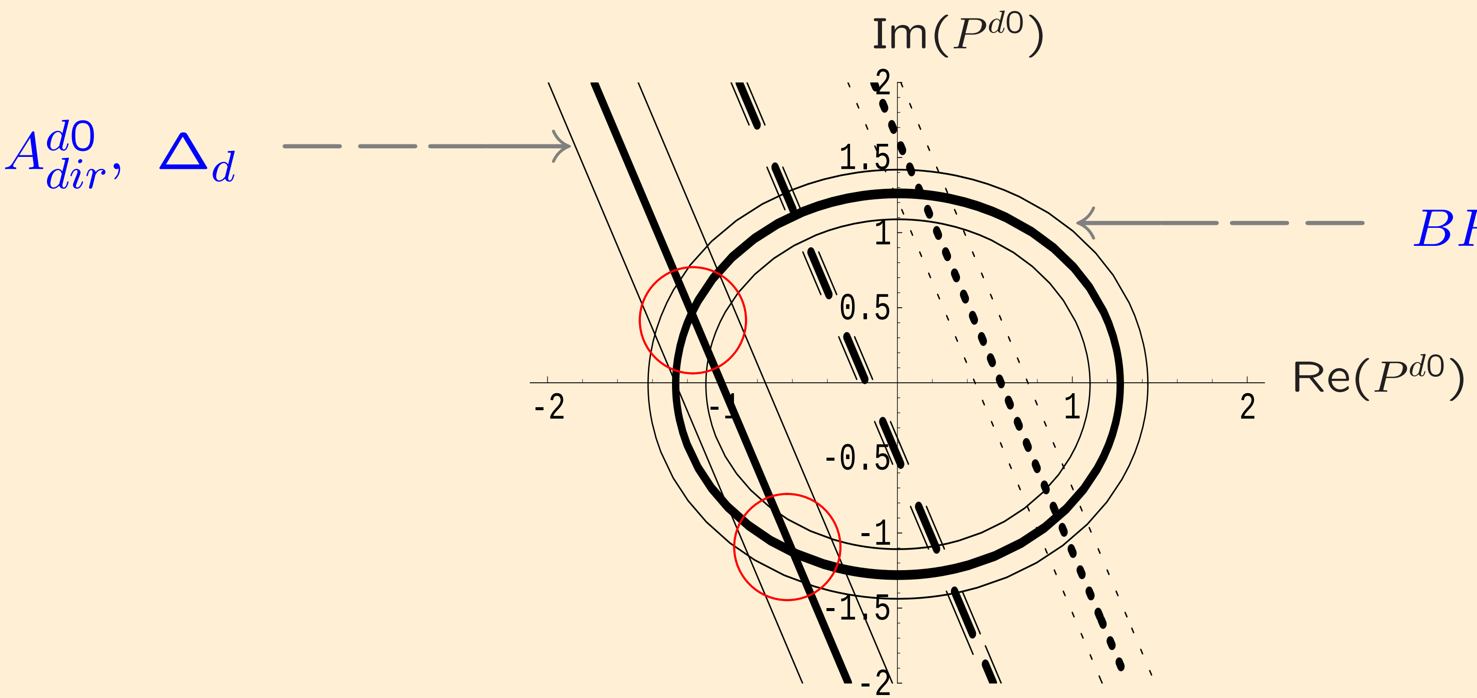
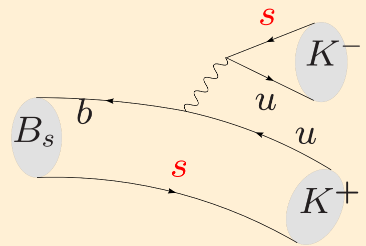


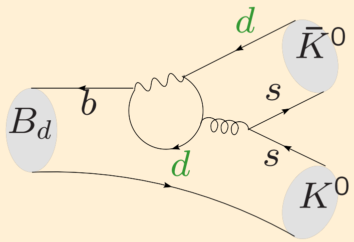
SM Hadr.Parameters from FS+QCDF

- From $B_d \to K^0\bar{K}^0$ to $B_s \to KK$:

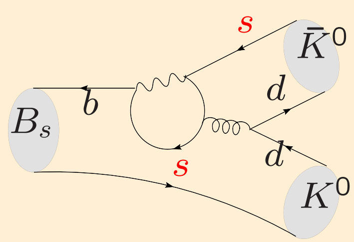
$B_d^0 \to K^0\bar{K}^0 \quad \longleftrightarrow \quad B_s^0 \to K^0\bar{K}^0 \quad \longleftrightarrow \quad B_s^0 \to K^+K^-$

Nothing $\longleftrightarrow$ Nothing $\longleftrightarrow$





$\longleftrightarrow$



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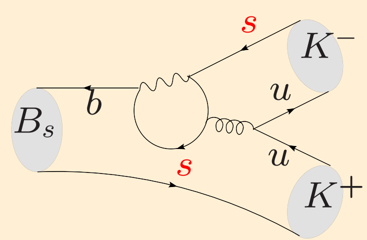


SM Hadr.Parameters from FS+QCDF

- From $B_d \to K^0\bar{K}^0$ to $B_s \to KK$ (SU(3) breaking):

- $|P^{s0}/(f P^{d0}) - 1| \leq 3\%$
- $|T^{s0}/(f T^{d0}) - 1| \leq 3\%$
- $|P^{s\pm}/(f P^{d0}) - 1| \leq 2\%$
- $|T^{s\pm}/(A^s_{KK}\bar{\alpha}_1) - 1 - T^{d0}/(A^d_{KK}\bar{\alpha}_1)| \leq 4\%$

$$\left(f \equiv \frac{A^s_{KK}}{A^d_{KK}}; \quad A^q_{KK} \equiv \frac{G_F}{\sqrt{2}} M^2_{B_q} f_K F^{B_q \to K} \right)$$

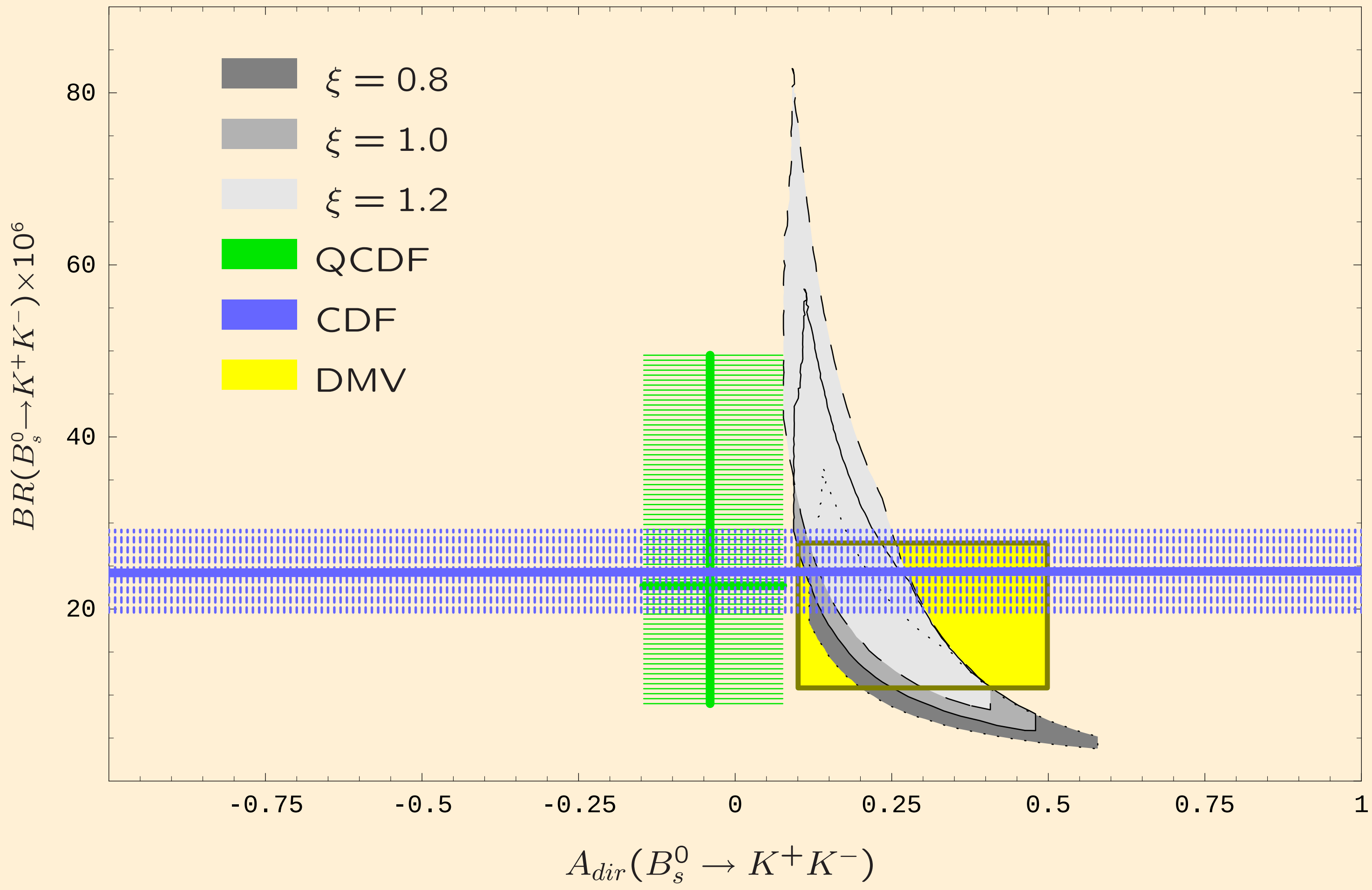
Final Results

	$BR^{s0} \times 10^6$	$A_{dir}^{s0} \times 10^2$	$A_{mix}^{s0} \times 10^2$	$BR^{s\pm} \times 10^6$	$A_{dir}^{s\pm} \times 10^2$	$A_{mix}^{s\pm} \times 10^2$
$A_{dir}^{d0} = -0.2$	$18.4 \pm 6.5 \pm 3.6$	0.8 ± 0.3	-0.3 ± 0.8	$21.9 \pm 7.9 \pm 4.3$	24.3 ± 18.4	24.7 ± 15.5
$A_{dir}^{d0} = -0.1$	$18.2 \pm 6.4 \pm 3.6$	0.4 ± 0.3	-0.7 ± 0.7	$19.6 \pm 7.3 \pm 4.2$	35.7 ± 14.4	7.7 ± 15.7
$A_{dir}^{d0} = 0$	$18.1 \pm 6.3 \pm 3.6$	0 ± 0.3	-0.8 ± 0.7	$17.8 \pm 6.0 \pm 3.7$	37.0 ± 12.3	-9.3 ± 10.6
$A_{dir}^{d0} = 0.1$	$18.2 \pm 6.4 \pm 3.6$	-0.4 ± 0.3	-0.7 ± 0.7	$16.4 \pm 5.7 \pm 3.3$	29.7 ± 19.9	-26.3 ± 15.6
$A_{dir}^{d0} = 0.2$	$18.4 \pm 6.5 \pm 3.6$	-0.8 ± 0.3	-0.3 ± 0.8	$15.4 \pm 5.6 \pm 3.1$	6.8 ± 28.9	-40.2 ± 14.6

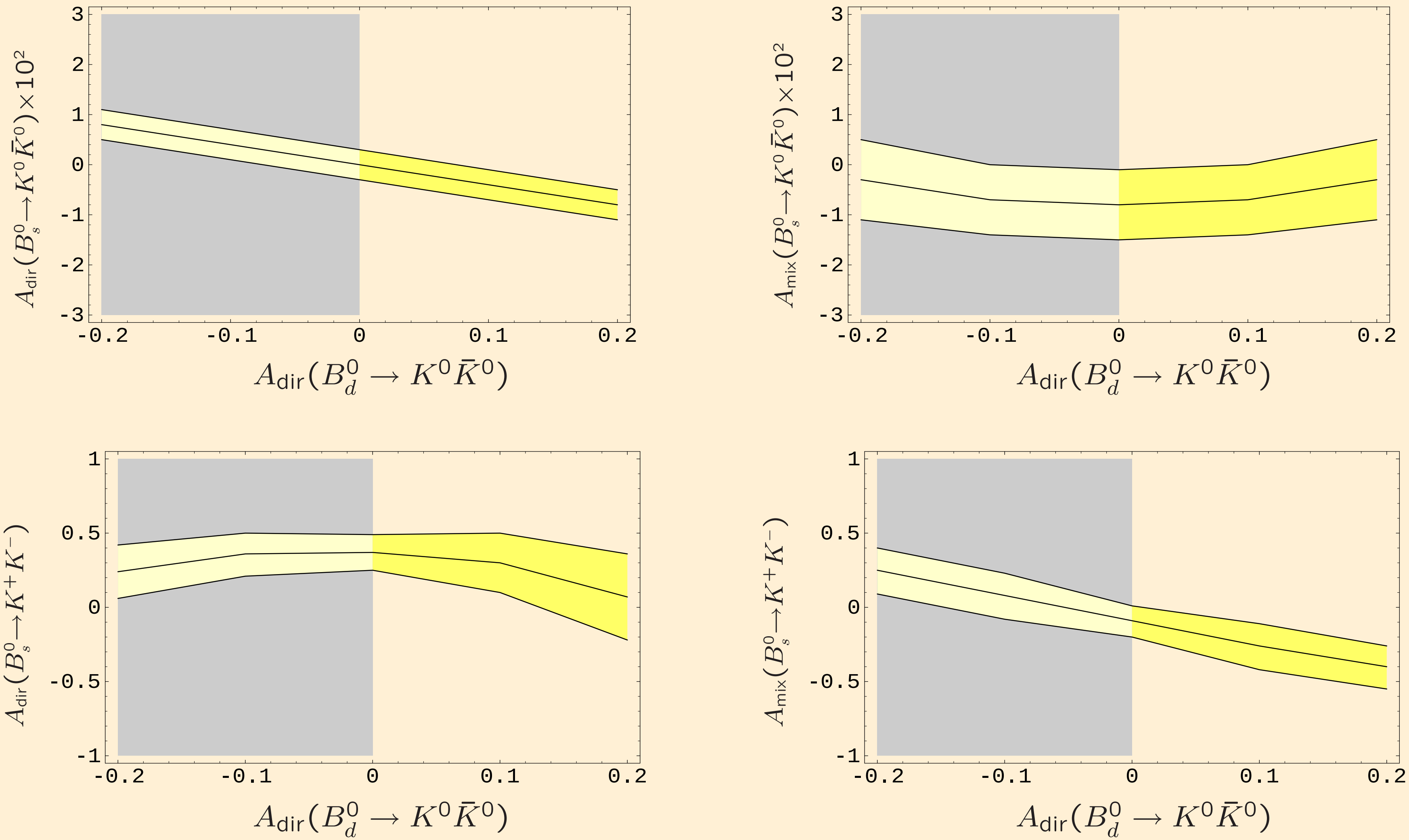
	$\lvert T^{s\pm}\rvert \times 10^6$	$\lvert P^{s\pm}/T^{s\pm}\rvert$	$\arg(P^{s\pm}/T^{s\pm})$	$\mathcal{R}_{\mathcal{C}}$	ξ	$\arg(P^{s\pm}/T^{s\pm})_{\rm rej}$
$A_{dir}^{d0} = -0.2$	12.7 ± 2.8	0.09 ± 0.03	$(45 \pm 33)^\circ$	2.3 ± 0.7	0.71 ± 0.24	$(-9 \pm 31)^\circ$
$A_{dir}^{d0} = -0.1$	12.1 ± 2.7	0.10 ± 0.03	$(78 \pm 27)^\circ$	2.2 ± 0.7	0.75 ± 0.27	$(-41 \pm 23)^\circ$
$A_{dir}^{d0} = 0$	11.5 ± 2.6	0.10 ± 0.03	$(105 \pm 15)^\circ$	2.1 ± 0.6	0.78 ± 0.31	$(-65 \pm 14)^\circ$
$A_{dir}^{d0} = 0.1$	11.1 ± 2.6	0.11 ± 0.03	$(137 \pm 27)^\circ$	2.0 ± 0.6	0.82 ± 0.35	$(-90 \pm 28)^\circ$
$A_{dir}^{d0} = 0.2$	10.8 ± 2.6	0.11 ± 0.03	$(180 \pm 10)^\circ$	2.0 ± 0.6	0.84 ± 0.35	$(-126 \pm 37)^\circ$

⋆ First testable prediction: $BR(B_s^0 \to K^+K^-) = (17 \pm 6 \pm 3) \times 10^{-6}$

Final Results



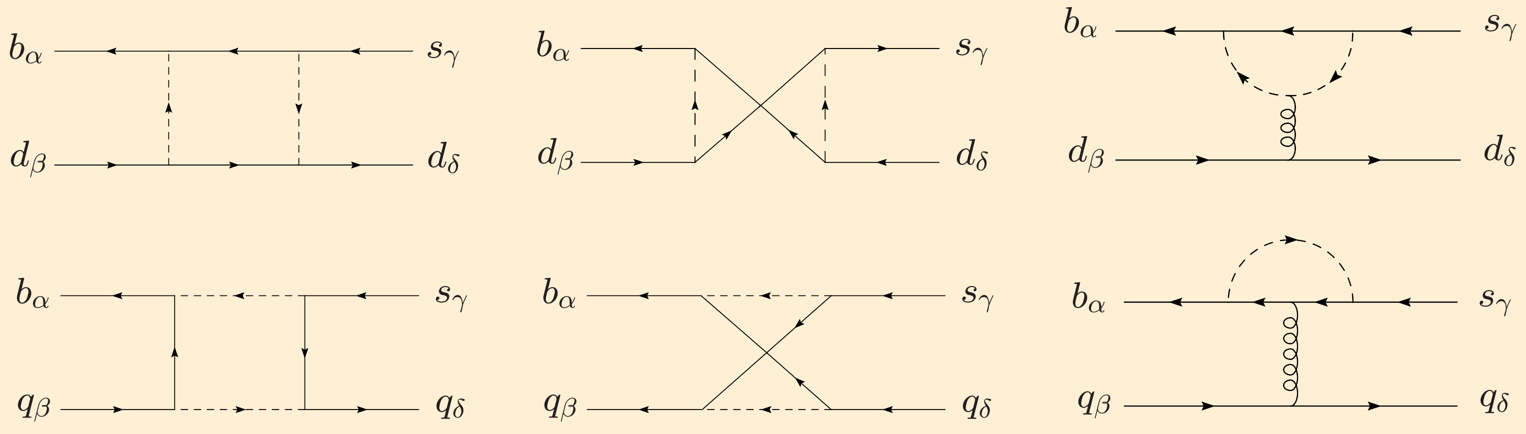
Final Results



The lamb's mother

Will we see NP in $B_s \to KK$?

SUSY Contributions to $B_s \to KK$

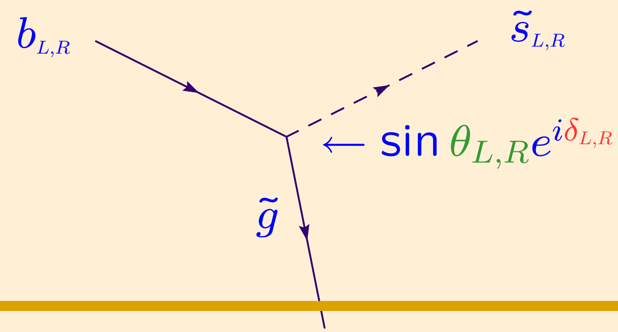


- BIG SUSY contributions: Boxes and penguins with squark-gluino loops.

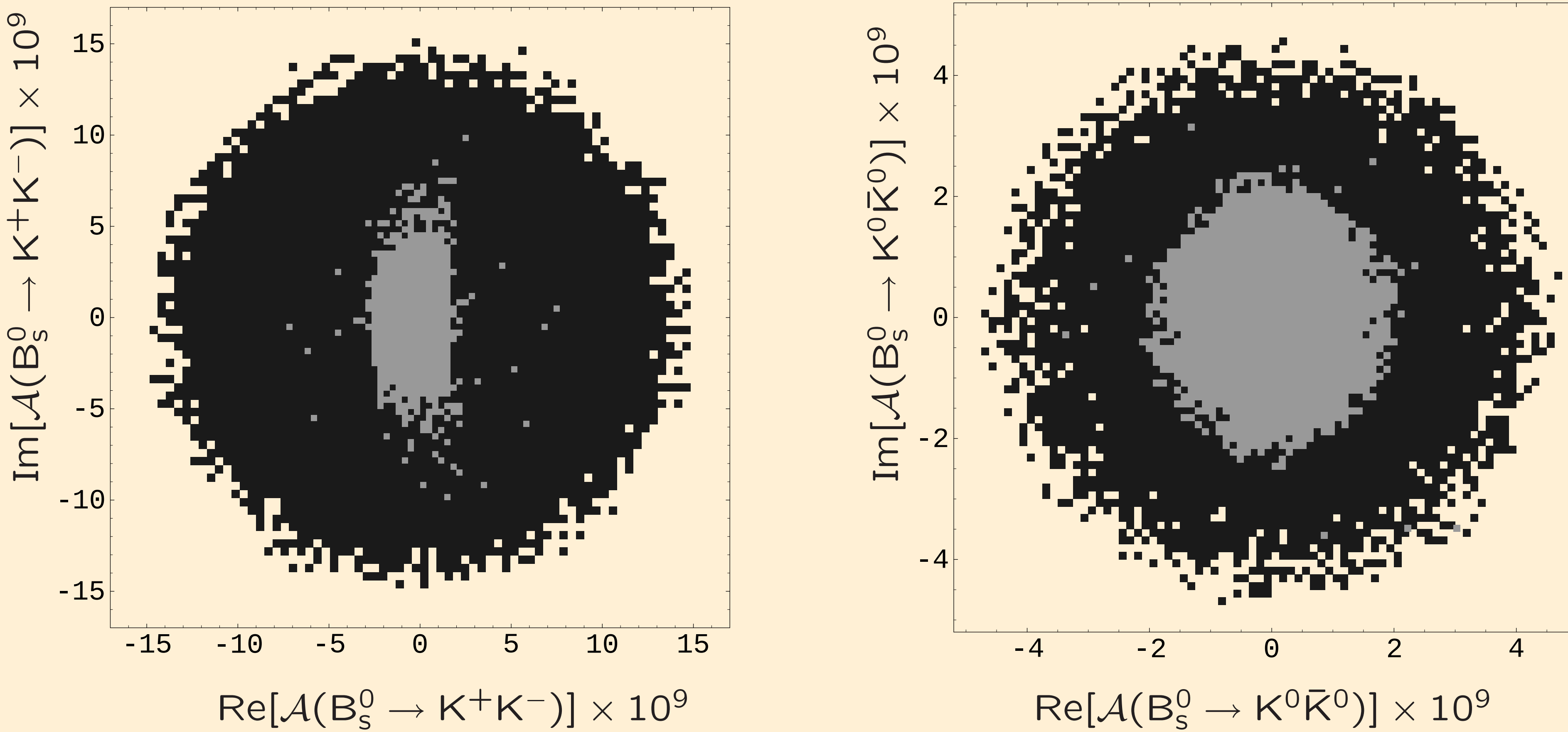
$$\frac{SUSY}{EW\,\text{pengs}} \sim \frac{\alpha_s/M_{NP}^2}{\alpha/M_W^2} \sim 1$$

- Constraints due to $b \to s\gamma$, $B-B$, $K-K$ and $D-D$ mixing:

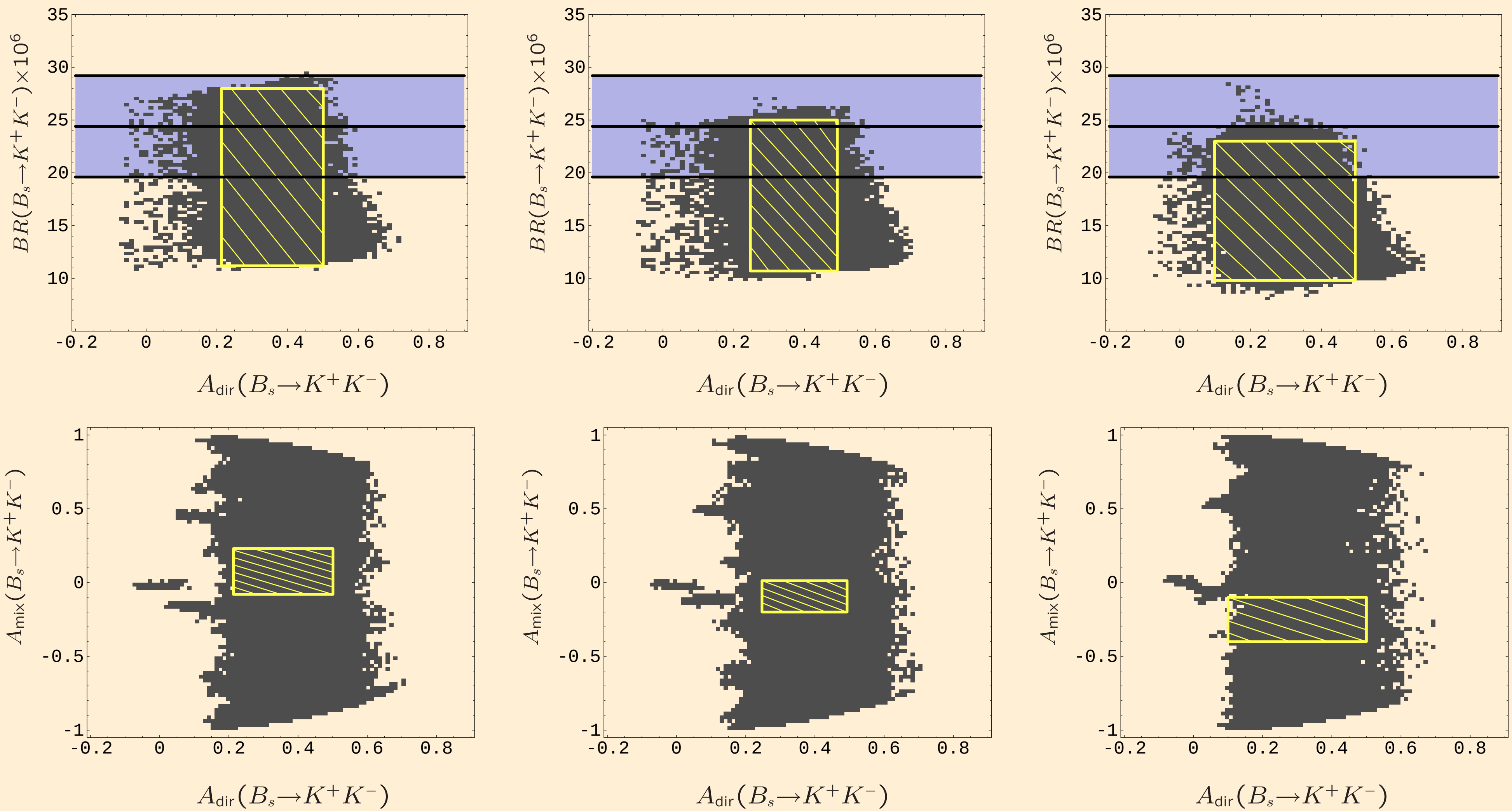
$$\Gamma^D \simeq \left(\begin{array}{ccc|ccc} 1 & 0 & 0 & & & \\ 0 & \cos\theta_L & \sin\theta_L e^{i\delta_L} & & & \\ 0 & -\sin\theta_L e^{-i\delta_L} & \cos\theta_L & & & \\ \hline & & & 1 & 0 & 0 \\ & & & 0 & \cos\theta_R & \sin\theta_R e^{i\delta_R} \\ & & & 0 & -\sin\theta_R e^{-i\delta_R} & \cos\theta_R \end{array}\right)$$



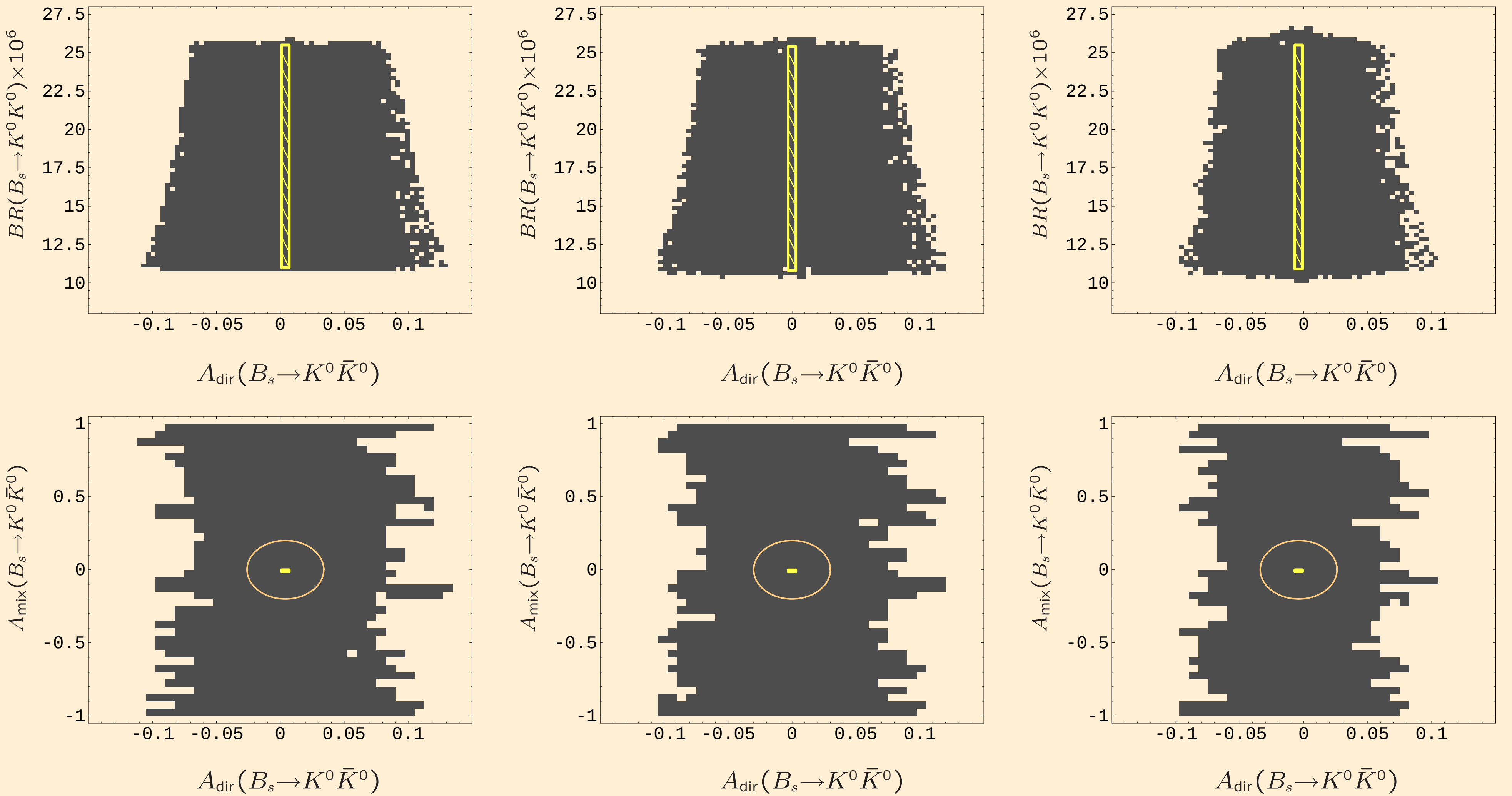
SUSY Amplitudes



SUSY Contributions to $B_s^0 \to K^+K^-$



SUSY Contributions to $B_s^0 \to K^0\bar{K}^0$



To Summarize...

- ⋆ A combination of QCDF and Flavour Symmetries, through the quantity Δ_d allows for a clean extraction of the hadronic parameters (the best so far for $B_s \to KK$ modes).

- ⋆ $BR(B_s^0 \to K^+K^-)$ OK with SM. Necessary to reduce uncertainties to be used as a constraint.

- ⋆ No relevant deviations from SM expected for $BR(B_s^0 \to K^0\bar{K}^0)$ within this SUSY framework.

- ⋆ CP asymmetries in $BR(B_s^0 \to K^+K^-)$: the next test.

- ⋆ CP asymmetries in $BR(B_s^0 \to K^0\bar{K}^0)$: the hard test.