HADRONIC B DECAYS

My Ph.D. work

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Outline

Description of my Ph.D. work : 4 research projects

- Wick contractions and hadronic decays
- Extraction of CKM angle α from $B^0 \to K^0\bar{K}^0$ decay
- SUSY and $B \to \pi K$ puzzle
- New physics (NP) and $B \to \phi K_s$ and $B \to \phi K^*$ decays

Project 1 : Wick contractions and hadronic decays

Thanks to my collaborators:
Alakabha Datta
David London

Work published in the Journal of Modern Physics (2007)

Concept of the project

Sum over all possible

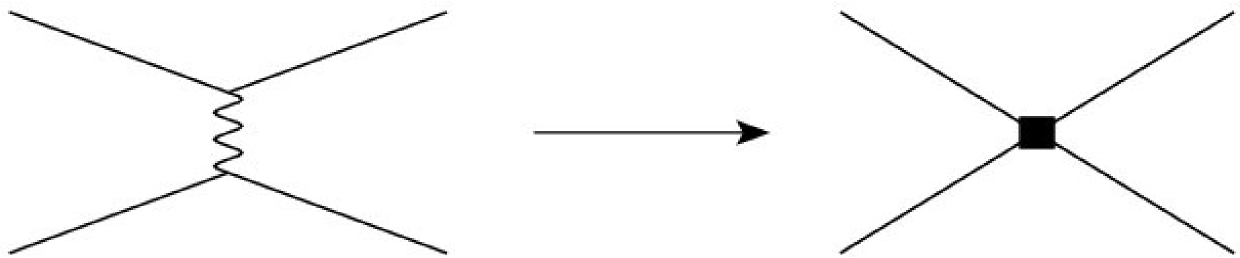
Wick contractions

of the effective hamiltonian

and see what happens...

Reminder :
The effective hamiltonian

- **Operator product expansion :**
  Replace a complicated operator by a linear combination of simple operators



Wilson coefficients : short distances (can be calculated perturbatively)

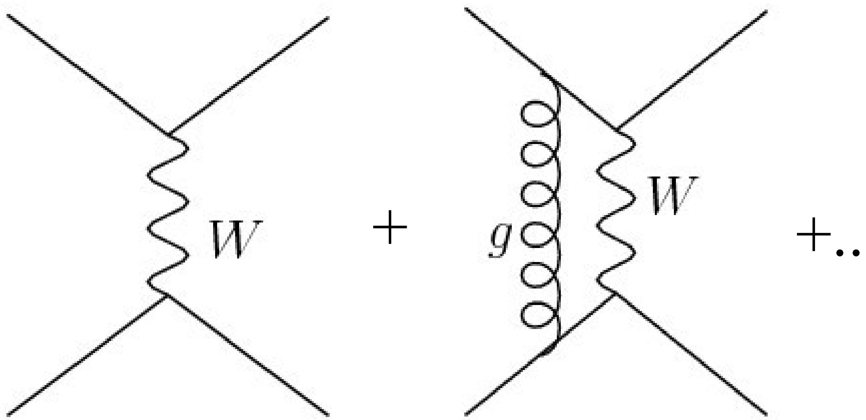
$$\mathcal{H} = \sum_i c_i(\mu) O_i(\mu)$$

Renormalization scale (unknown value ~ m_b)

Operators : long distances

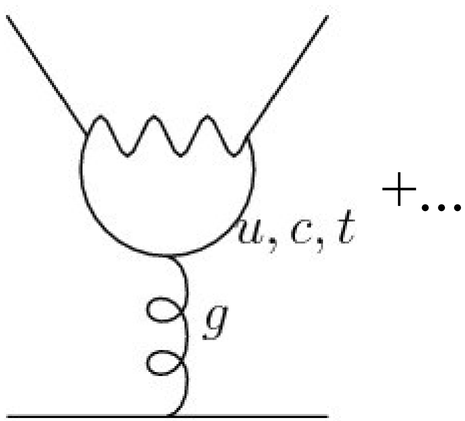
3 families of operators:

- Trees



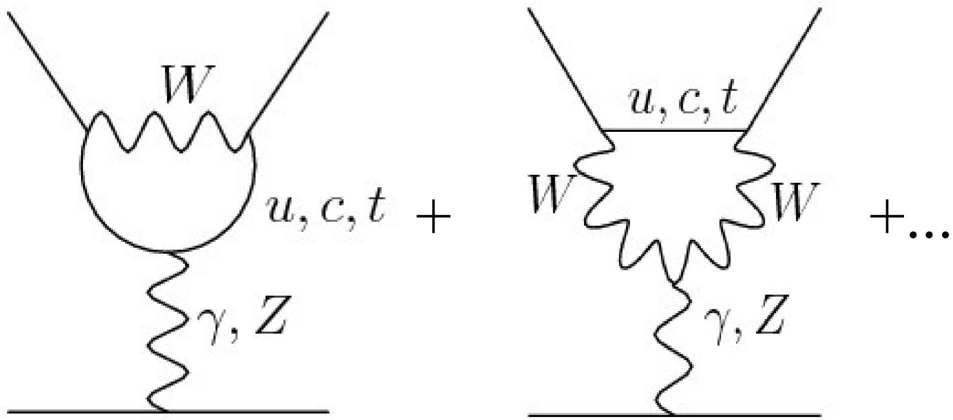
$\Rightarrow O_{1-2}$

- Gluonic penguins



$\Rightarrow O_{3-6}$

- Electroweak penguins



$\Rightarrow O_{7-10}$

Form of operators :

$$\begin{aligned} O_i &= (\bar{q}_i \gamma_\mu (1-\gamma_5) q_{i(j)})(\bar{q}_j \gamma_\mu (1 \pm \gamma_5) q_{j(i)}) \\ &= (\bar{q}_i q_{i(j)})_{V-A} (\bar{q}_j q_{j(i)})_{V \pm A} \end{aligned}$$

- Quarks content
- Lorentz structure
- Color Structure

Basic idea

1) Apply initial state $|B\rangle$ and final state $\langle M_1 M_2|$ to the effective hamiltonian
2) Apply basic rules of QFT by taking the sum over all possible Wick contractions of the effective hamiltonian

$$\langle \bar{q}_1 q_2 \bar{q}_3 q_4 | \bar{q}_5 q_6 \bar{b} q_7 | \bar{q}_8 b \rangle \Rightarrow$$

24 possible forms of Wick contractions

24 contractions : A – X

$$\underline{A} = \langle \bar{q}_1 q_2 \bar{q}_3 q_4 | \bar{q}_5 b \bar{q}_6 q_7 | \bar{q}_8 b \rangle \ , \qquad \underline{B} = \langle \bar{q}_1 q_2 \bar{q}_3 q_4 | \bar{q}_5 b \bar{q}_6 q_7 | \bar{q}_8 b \rangle \ ,$$

$$\underline{C} = \langle \bar{q}_1 q_2 \bar{q}_3 q_4 | \bar{q}_5 b \bar{q}_6 q_7 | \bar{q}_8 b \rangle \ , \qquad \underline{D} = \langle \bar{q}_1 q_2 \bar{q}_3 q_4 | \bar{q}_5 b \bar{q}_6 q_7 | \bar{q}_8 b \rangle \ ,$$

$$\underline{E} = \langle \bar{q}_1 q_2 \bar{q}_3 q_4 | \bar{q}_5 b \bar{q}_6 q_7 | \bar{q}_8 b \rangle \ , \qquad \underline{F} = \langle \bar{q}_1 q_2 \bar{q}_3 q_4 | \bar{q}_5 b \bar{q}_6 q_7 | \bar{q}_8 b \rangle \ ,$$

...

Not all independent!

Example :

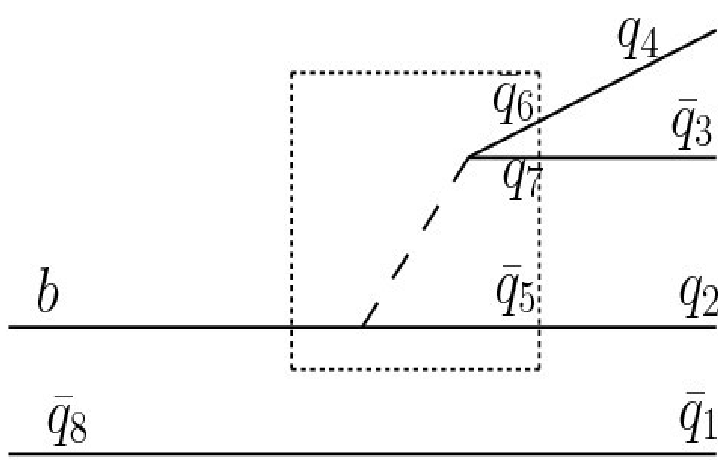
$\underline{E} \leftrightarrow \underline{F}$ with exchange $\bar{q}_1 q_2 \leftrightarrow \bar{q}_3 q_4$

Do not change the physics!

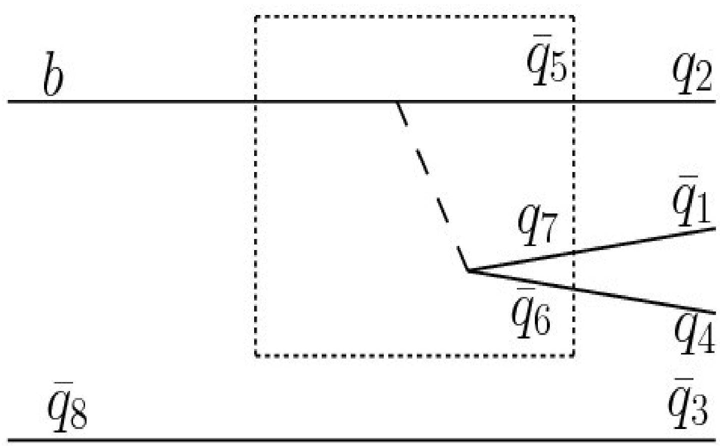
→ Only 14 independent contractions

Classification of contractions

- Class I : Emission

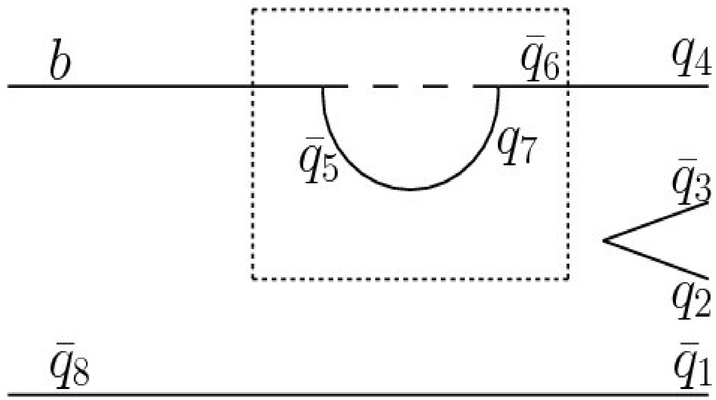


$\underline{E} \rightarrow EM$

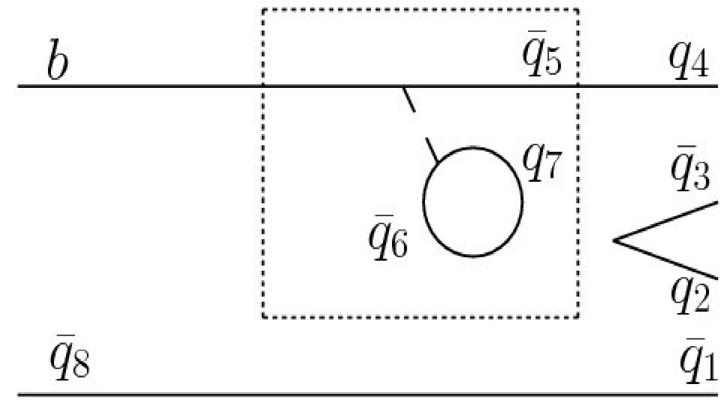


$\underline{F} \rightarrow EM_C$

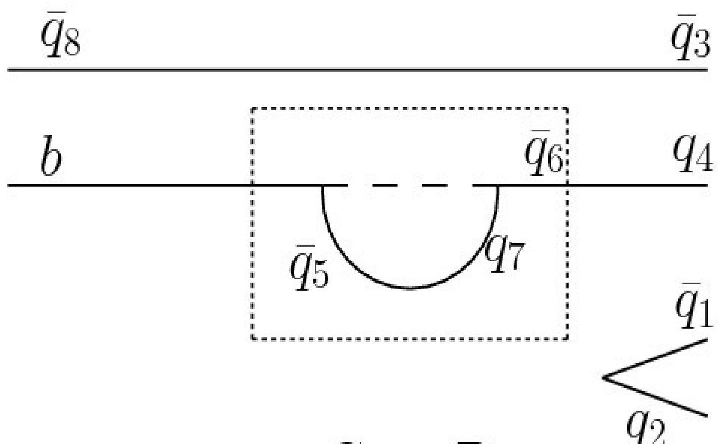
Class II : Rescattering



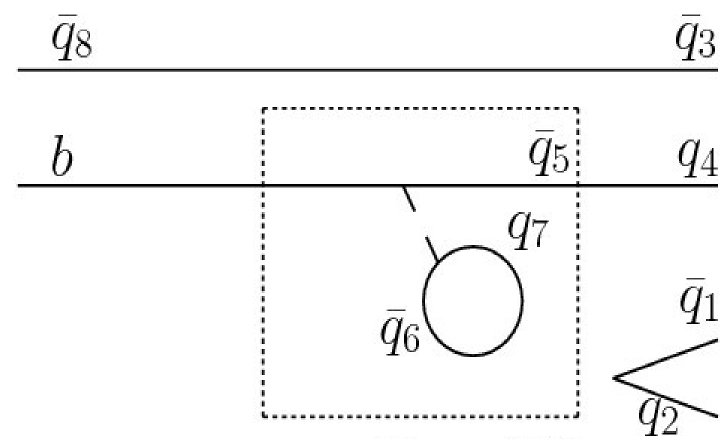
$\underline{A} \to P$



$\underline{G} \to PF$

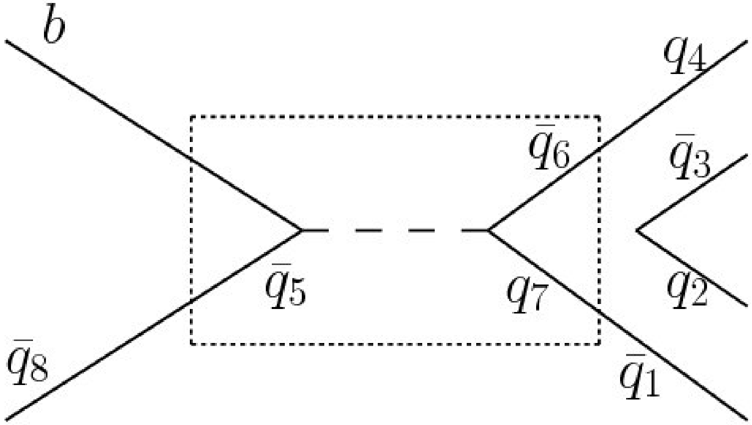


$\underline{C} \to P_{OZI}$

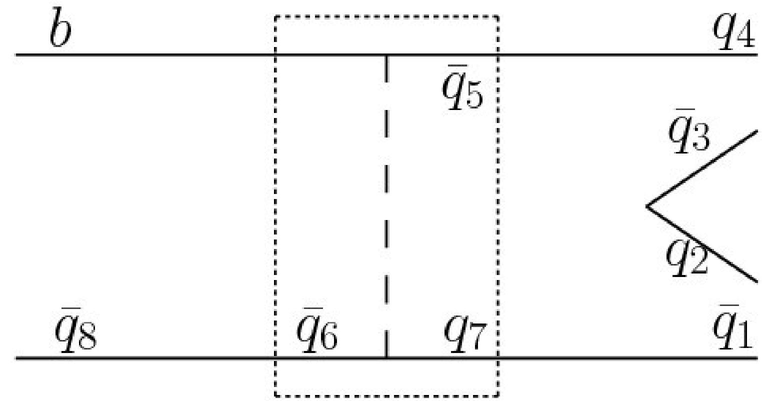


$\underline{K} \to PF_{OZI}$

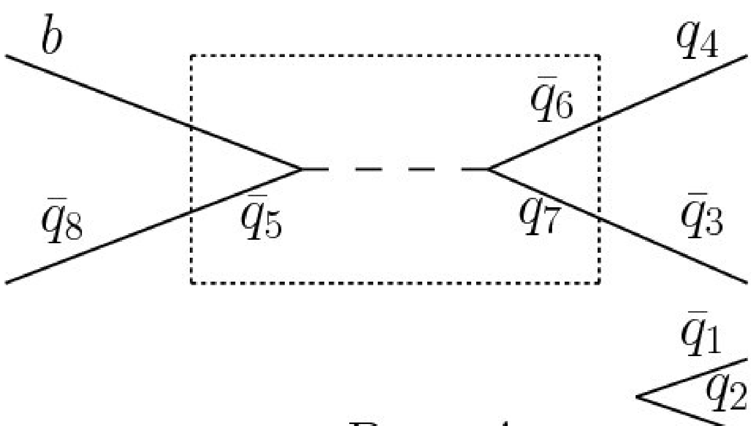
Class III : Annihilation / exchange



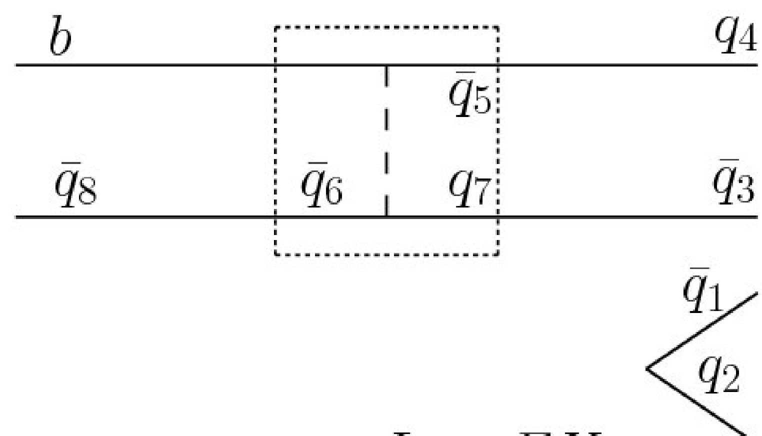
$\underline{B} \to A$



$\underline{H} \to EX$

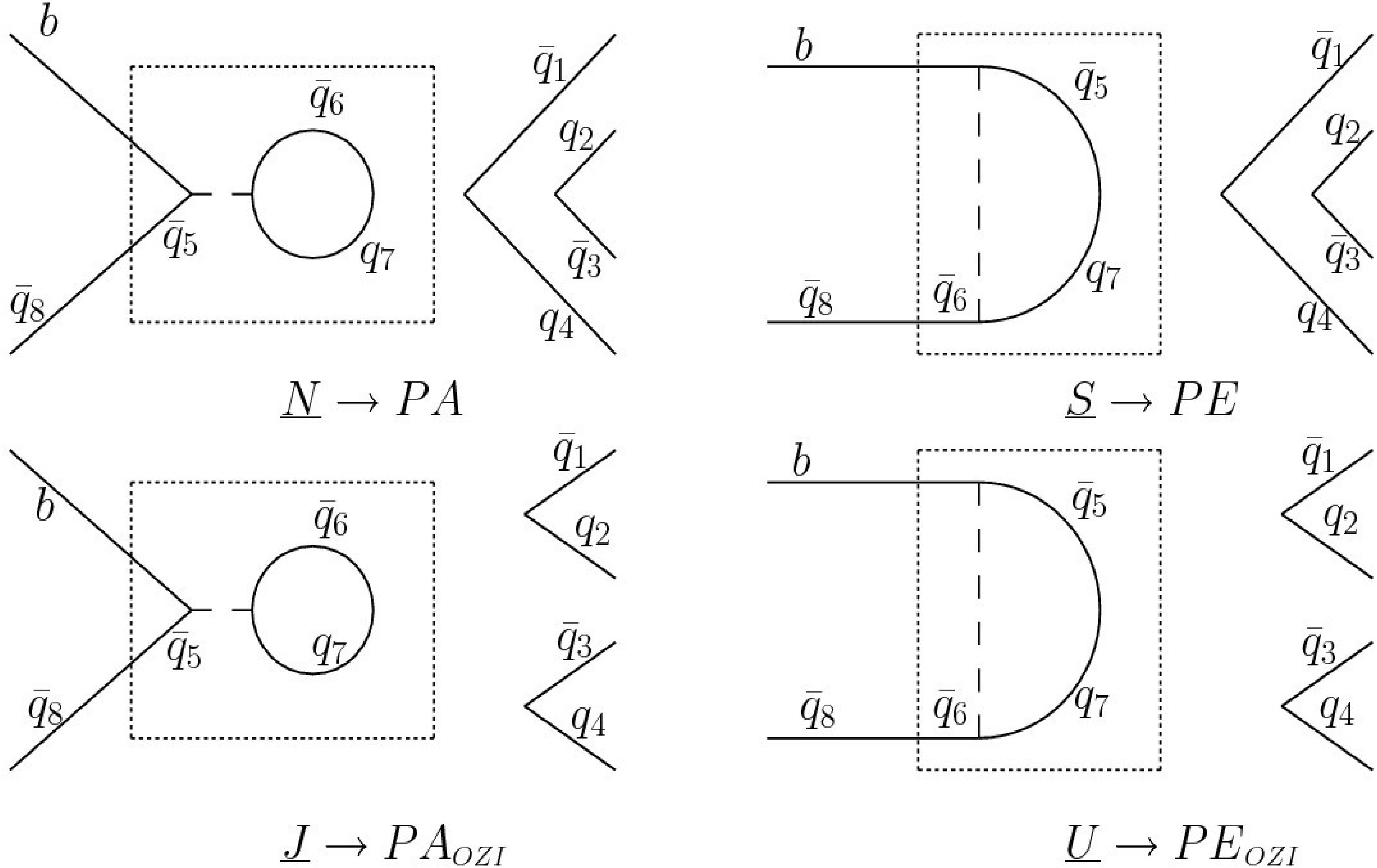


$\underline{D} \to A_{OZI}$



$\underline{L} \to EX_{OZI}$

Class IV : Annihilation / exchange with rescattering



Parametrization of decay amplitudes

Trivially...

Sum over all

Wick contractions

↓

Parametrization of

decay amplitudes

This is the first result of the approach with contractions

Example : Trees of B $\to \pi$ K decays ($O_{1,2}$)

$$
\begin{aligned}
T^{-0} &= \sqrt{2}c_i[\lambda_u^{(s)}(P_i'^u + A_i'^u) + \lambda_c^{(s)} P_i'^c] \,, \\
T^{0-} &= c_i[-\lambda_u^{(s)}(P_i'^u + A_i'^u + EM_i'^u + EM_{Ci}'^u) - \lambda_c^{(s)} P_i'^c] \,, \\
T^{+-} &= \sqrt{2}c_i[-\lambda_u^{(s)}(P_i'^u + EM_i'^u) - \lambda_c^{(s)} P_i'^c] \,, \\
T^{00} &= c_i[\lambda_u^{(s)}(P_i'^u - EM_{Ci}'^u) + \lambda_c^{(s)} P_i'^c] \,.
\end{aligned}
$$

Compare with parametrization with the "language of diagrams":

$$
\begin{aligned}
T^{-0} &= P_u' + A' + P_c' \,, \\
\sqrt{2}T^{0-} &= -P_u' - A' - T' - C' - P_c' \,, \\
T^{+-} &= -P_u' - T' - P_c' \\
\sqrt{2}T^{00} &= P_u' - C' + P_c' \,,
\end{aligned}
$$

We can write **diagrams** in terms of **Wick contractions**!

$$
\begin{aligned}
P'_u &= \sqrt{2}\lambda_u^{(s)} c_i P_i'^{u} \, , \\
P'_c &= \sqrt{2}\lambda_c^{(s)} c_i P_i'^{c} \, , \\
T' &= \sqrt{2}\lambda_u^{(s)} c_i EM_i'^{u} \, , \\
C' &= \sqrt{2}\lambda_u^{(s)} c_i EM_{Ci}'^{u} \, , \\
A' &= \sqrt{2}\lambda_u^{(s)} c_i A_i'^{u} \, ,
\end{aligned}
$$

We can use Wick contractions to formalize the language of diagrams

This is the second result of the approach of Wick contractions

Application of flavor symmetries

Example of 2 contractions within isospin:

$$C_1 = \langle \bar{q}_1 u \bar{q}_3 q_4 | \bar{u} b \bar{q}_6 q_7 | \bar{q}_8 b \rangle \; ,$$

$$C_2 = \langle \bar{q}_1 d \bar{q}_3 q_4 | \bar{d} b \bar{q}_6 q_7 | \bar{q}_8 b \rangle \; .$$

The contraction of u or d quark field is a propagator
→ It depends only on the mass of u or d.

Trivially...
$C_1 = C_2$ because $m_u = m_d$ under isospin.

The same idea is applied for SU(3) symmetry.

Example of SU(3) for $B \to \pi K$

Confirm independently Gronau-Pirjol-Yan relations

(relate tree and EWP diagrams)

Third result of the approach of contractions

ADVANTAGES

- Simplicity :
  - Group theory : Wigner-Eckart theorem with Clebsch-Gordan coefficients
  - Wick Contractions : Linear algebra!
- Approach of Wick contractions allows to keep track of the physics

QCD expansion of Wick contractions

Analogy with effective theories (QCDF, perturbative QCD, SCET) : $\alpha_s(m_b)$ expansion of hadronic matrix elements for the $m_b \to \infty$ limit.

QCD expansion of Wick contraction by considering gluons explicitly

$$X \to X_0 + \alpha_s X_1 + \ldots$$

Basic example for the LO of the expansion:

$$
\begin{aligned}
\sum_{i=1,2} c_i EM_i' &= c_1 \delta_{xz}\delta_{x\alpha}\delta_{y\beta}\delta_{y\beta}\delta_{\alpha z}\langle \bar{q}_1 q_2 \bar{q}_3 q_4 | \bar{q}_5 b \bar{q}_6 q_7 | \bar{q}_8 b\rangle \\
&\quad + c_2 \delta_{xz}\delta_{x\alpha}\delta_{y\alpha}\delta_{y\beta}\delta_{\beta z}\langle \bar{q}_1 q_2 \bar{q}_3 q_4 | \bar{q}_5 b \bar{q}_6 q_7 | \bar{q}_8 b\rangle \\
&= c_1 N_c^2 \langle \bar{q}_1 q_2 \bar{q}_3 q_4 | \bar{q}_5 b \bar{q}_6 q_7 | \bar{q}_8 b\rangle + c_2 N_c \langle \bar{q}_1 q_2 \bar{q}_3 q_4 | \bar{q}_5 b \bar{q}_6 q_7 | \bar{q}_8 b\rangle \\
&= c_1 N_c^2 \overline{EM}' + c_2 N_c \overline{EM}' \\
&= (c_1 + \frac{c_2}{N_c}) N_c^2 \overline{EM}' \ .
\end{aligned}
$$

2 unknowns VS 1 unknown → less parameters

Approximative relations between diagrams!

Fourth result of contractions

Examples of results :

- "Crossed isospin relations" at LO

$$\frac{P'^{C}_{EW}}{T'} = -\frac{3}{2}\frac{\lambda_t^{(s)}}{\lambda_u^{(s)}}\left[\frac{c_9/N_c + c_{10}}{c_1 + c_2/N_c}\right][1+\mathcal{O}(\alpha_s(m_b))]$$

$$\frac{P'_{EW}}{C'} = -\frac{3}{2}\frac{\lambda_t^{(s)}}{\lambda_u^{(s)}}\left[\frac{c_9 + c_{10}/N_c}{c_1/N_c + c_2}\right][1+\mathcal{O}(\alpha_s(m_b))]$$

- SU(3) ratio C'/T' at LO

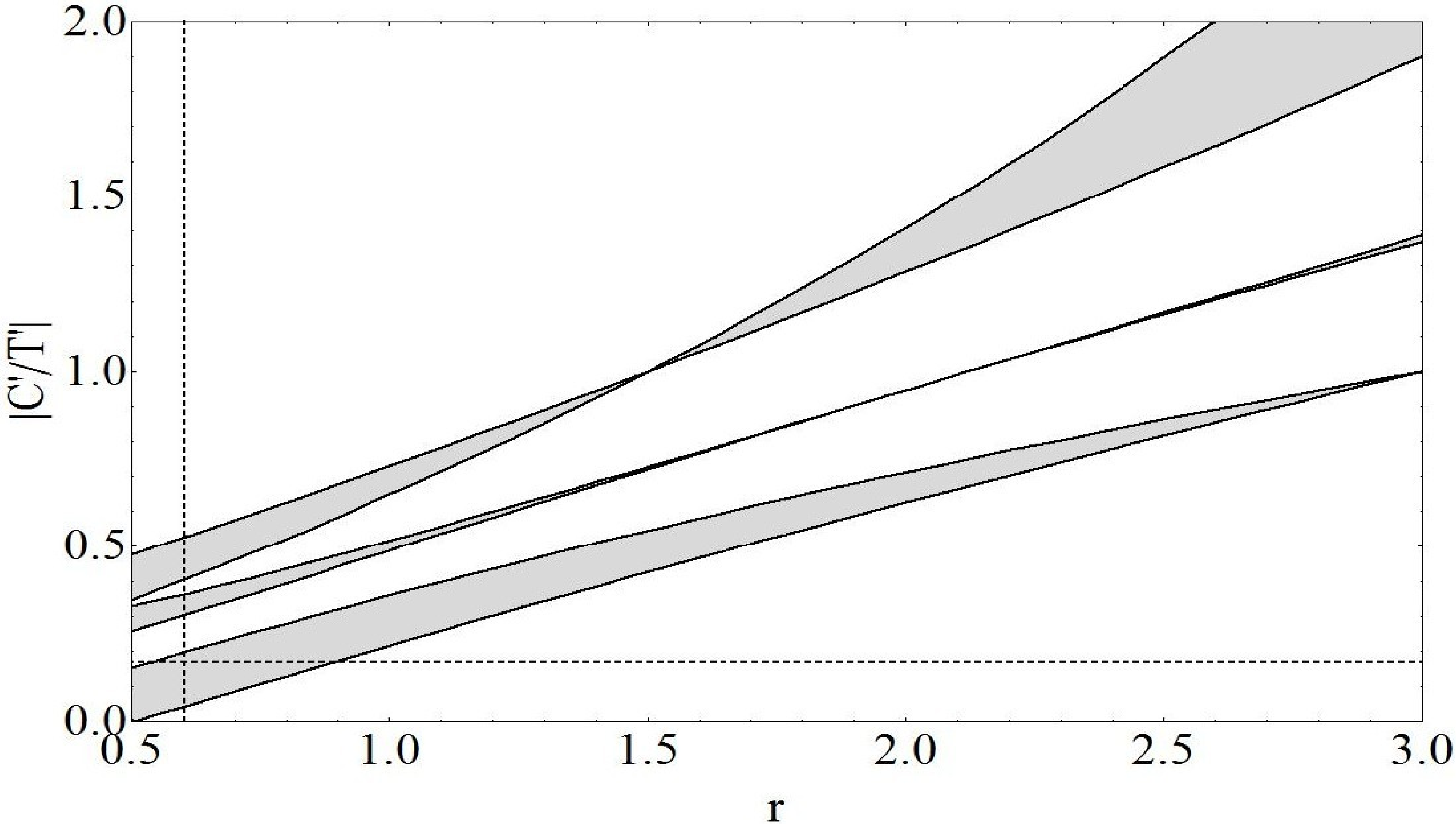
$$\frac{C'}{T'} = \frac{c_1/N_c + c_2}{c_1 + c_2/N_c}[1+\mathcal{O}(\alpha_s(m_b))] < \frac{1}{3}$$

(but numerical fits say |C'/T'|>1)

★ Very sensitive to exact values of Wilson coefficients... not very useful in practice.

SU(3) ratio of C'/T' at NLO

$$\frac{C'}{T'}(r,\delta_r) = \frac{\left(\frac{c_1}{N_c}+c_2\right)+\frac{c_1}{2}\left(1-\frac{1}{N_c^2}\right)re^{i\delta_r}}{\left(c_1+\frac{c_2}{N_c}\right)+\frac{c_2}{2}\left(1-\frac{1}{N_c^2}\right)re^{i\delta_r}}$$



Summary of main results

- Parametrization of decay amplitudes
- Formalize the language of diagrams
- Simple framework for flavor symmetries
  - Independent derivation of GPY relations
- QCD expansion of contractions :
  - Matching with effective theories
  - Approximative relations between diagrams

Project 2 : Extraction of CKM angle α from $B^0 \to K^0 \bar{K}^0$ decay

Thanks to my collaborators:
Alakabha Datta
David London
Joaquim Matias

Work published in the Physical Review D (2007)

Concept of the project

There are 3 experimental values
There are 4 theoretical parameters

$$\mathcal{A}(B_d^0 \to K^0 \bar{K}^0) = V_{ub}^* V_{us} (T - P) + V_{tb}^* V_{ts} P$$

We need more information...

The calculation of |T-P| within QCD factorization is free of divergence

Using this, we have enough of information to extract α !

Reminder : QCD factorization

- Naive factorization :

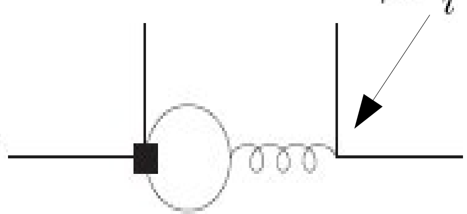
$$\begin{aligned}\langle \pi^0 K^+ | (\bar{b}u)_{V-A} (\bar{u}s)_{V-A} | B^+ \rangle &= \langle K^+ | (\bar{u}s)_{V-A} | 0 \rangle \langle \pi^0 | (\bar{b}u)_{V-A} | B^+ \rangle \\ &+ \frac{1}{N_c} \langle \pi^0 | (\bar{u}u)_{V-A} | 0 \rangle \langle K^+ | (\bar{b}s)_{V-A} | B^+ \rangle\end{aligned}$$

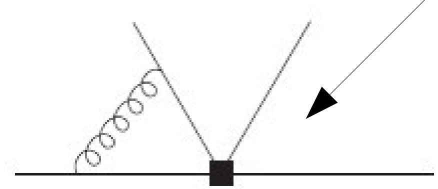
Form factor (known)

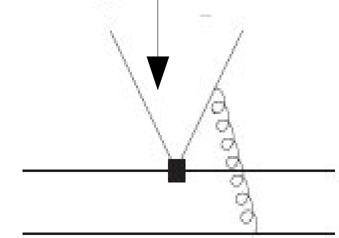
Decay constant (known)

- QCD factorization : add QCD corrections!

$$\begin{aligned}a_i^p(M_1 M_2) &= \left(c_i + \frac{c_{i\pm1}}{N_c}\right) N_i(M_2) + \frac{c'_{i\pm1}}{N_c} \frac{C_F \alpha'_s}{4\pi} \left[V_i(M_2) + \frac{4\pi^2}{N_c} H_i(M_1 M_2) \right] \\ &+ P_i^p(M_2) \,,\end{aligned}$$







Divergences!

Calculation of |T-P|

$$\frac{T}{A_d^0} = \alpha_4^u - \frac{1}{2}\alpha_{4EF}^u + \beta_3^u + 2\beta_4^u - \frac{1}{2}\beta_{3EF}^u - \beta_{4EF}^u$$

$$\frac{P}{A_d^0} = \alpha_4^c - \frac{1}{2}\alpha_{4EF}^c + \beta_3^c + 2\beta_4^c - \frac{1}{2}\beta_{3EF}^c - \beta_{4EF}^c$$

$$T - P \propto P_i^u - P_i^c$$

$$|T - P| = (2.96 \pm 0.97) \times 10^{-7}\mathrm{GeV}$$

Sources of errors

- Renormalization scale (19.7 %)
- Gegenbauer coefficients (4.1 % and 0.9 %)
- Form factor $B \to K$ (15.8 %)
- s quark mass (5.7 %)
- Ratio of quark masses m_c/m_b (53.7 %)

Constraint on α with current experimental data

$$0 \leqslant \sin^2\alpha \leqslant 1$$

This constraint can potentially be improved with more precise calculation of |T-P| and more precise experimental data.

Constraint on experimental data from the current value of α

We can invert equations and use the current experimental average on α to constrain measurements of $B^0 \rightarrow K^0\bar{K}^0$:

$$0.02 \leqslant A_{dir}^2 + A_{mix}^2 \leqslant 0.125$$

Current experimental data

	BaBar	Belle
A_{dir}	$-0.40^{+0.41}_{-0.06}$	$0.38^{+0.38}_{-0.05}$
A_{mix}	$1.28^{+0.80+0.11}_{-0.73-0.16}$	$0.38^{+0.69}_{-0.77} \pm 0.09$

Implications

If the constraint on asymmetries is not respected :

- The calculated value of |T-P| is incorrect (imply large long distance rescattering effects? Large penguin-c contributions? ...)

OR

- Hint of new physics!

Summary

- New method for extracting the CKM angle α from experimental data of $B^0 \to K^0\bar{K}^0$ decay. Not applicable with current data.

- New constraint on CP asymmetries of $B^0 \to K^0\bar{K}^0$ decay. Test for the calculation of $|T\text{-}P|$ and the SM itself.
Not applicable with current data.

Project 3 : SUSY and $B \rightarrow \pi K$ puzzle

Thanks to my collaborators:
Seungwon Baek
David London

Work published in the
Physics Letters B ***(2008)***

Question?

Can the

GNK model (SUSY)

solves the

$B \to \pi K$ *puzzle ?*

$B \to \pi K$ *decays*

- 4 decay modes :

$$B^+ \to \pi^+ K^0 \ , \qquad B^+ \to \pi^0 K^+ \ ,$$

$$B_d^0 \to \pi^- K^+ \ , \qquad B_d^0 \to \pi^0 K^0 \ ,$$

and their CP-conjugated.

- 9 experimental measurements :
  - 4 mean branching ratios
  - 4 time-independent CP asymmetries
  - 1 time-dependent CP asymmetry

The "$B \to \pi K$ puzzle"

- <u>Ratios of branching ratios</u> :

$$
\begin{aligned}
R &= \left[\frac{\mathrm{BR}(B_d^0 \to \pi^- K^+) + \mathrm{BR}(\bar{B}_d^0 \to \pi^+ K^-)}{\mathrm{BR}(B^+ \to \pi^+ K^0) + \mathrm{BR}(B^- \to \pi^- \bar{K}^0)}\right] \frac{\tau_{B^+}}{\tau_{B_d^0}}, \\
R_c &= 2\left[\frac{\mathrm{BR}(B^+ \to \pi^0 K^+) + \mathrm{BR}(B^- \to \pi^0 K^-)}{\mathrm{BR}(B^+ \to \pi^+ K^0) + \mathrm{BR}(B^- \to \pi^- \bar{K}^0)}\right], \\
R_n &= \frac{1}{2}\left[\frac{\mathrm{BR}(B_d^0 \to \pi^- K^+) + \mathrm{BR}(\bar{B}_d^0 \to \pi^+ K^-)}{\mathrm{BR}(B_d^0 \to \pi^0 K^0) + \mathrm{BR}(\bar{B}_d^0 \to \pi^0 \bar{K}^0)}\right],
\end{aligned}
$$

  - To a <u>good</u> approximation : $R \simeq R_c \simeq R_n \simeq 1$
  - To a <u>very good</u> approximation : $R_c \simeq R_n$

Experimental data

	Automne 2005	Automne 2007	Automne 2008
R	0.84 ± 0.05	0.90 ± 0.05	0.90 ± 0.05
R_c	1.00 ± 0.09	1.12 ± 0.07	1.12 ± 0.07
R_n	0.82 ± 0.08	0.98 ± 0.07	0.99 ± 0.07

- Sum rules of CP asymmetries :

To a very good approximation :

$$A_{CP}(\pi^- K^+) + A_{CP}(\pi^+ K^0) = A_{CP}(\pi^0 K^+) + A_{CP}(\pi^0 K^0)$$

with 2008 data :

- Prediction : $A_{CP}(\pi^0 K^0) = -0.139 \pm 0.037$
- Measurement : $A_{CP}(\pi^0 K^0) = -0.01 \pm 0.10$

- Global fits on all 9 experimental data :

We can perform a χ^2 fit to adjust theoretical parameters (Baek-London 2007)

- 3 magnitudes |P'|, |T'|, |C'| (EWP → GPY rel.)
- +2 relative strong phases
- +1 CKM angle γ

---

6 theoretical parameters

Results :

$$\boxed{\begin{array}{l}\chi^2_{min}/d.o.f. = 1.0/3(80\%) \\ |C'/T'| = 1.6 \pm 0.3\end{array}}$$

Theory : $|C'/T'| < 0.6$

B → π K puzzle !

General NP in $B \to \pi K$ decays

If we neglect new physics strong phase differences, only 4 NP amplitudes in general:

$$\boxed{\mathcal{A}'^{u}, \mathcal{A}'^{d},} \mathcal{A}'^{C,u} \text{ and } \mathcal{A}'^{C,d}$$

$$\mathcal{A}'^{comb} = \mathcal{A}'^{d} - \mathcal{A}'^{u}$$

(always the same linear combination)

A solution to the $B \to \pi K$ puzzle (Baek-London)

$$\left\{ \begin{array}{rcl} |\mathcal{A}'^{comb}| & = & 14.4 \pm 4.2 \text{ eV} \\ |\mathcal{A}'^{C,u}| & \simeq & 0 \text{ eV} \\ |\mathcal{A}'^{C,d}| & \simeq & 0 \text{ eV} \end{array} \right.$$

Can GNK reproduces this pattern ?

SUSY : The GNK model

- Only contributions from gluino/squark loops (box and penguin diagrams)
- *Down* squark decoupled from *strange* and *bottom* squarks (this affect b $\rightarrow$ s without affecting b $\rightarrow$ d transitions)
- Mixing matrix :

$$\Gamma_L = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_L & \sin\theta_L \, e^{i\delta_L} \\ 0 & -\sin\theta_L \, e^{-i\delta_L} & \cos\theta_L \end{pmatrix}$$

Explicit weak phase

New source of CP violation for b $\rightarrow$ s

Effective hamiltonian of GNK:

$$\mathcal{H}_{NP} = \frac{G_F}{\sqrt{2}} \left[\sum_{i=1}^{6} \sum_{q=u,d} \left(c_i^q(\mu) O_i^q + \tilde{c}_i^q(\mu) \tilde{O}_i^q \right) + c_{8g} O_{8g} + \tilde{c}_{8g} \tilde{O}_{8g} \right]$$

<u>Operators</u> : Can be treated within factorization

<u>Wilson coefficients</u> : Depend on GNK parameters

Parameters of GNK model:

- Mass of gluino
- Masses of squarks
- Mixing angles $\theta_{L,R}$
- Phases $\delta_{L,R}$

Unknown values...
How to calculate GNK contributions ?
Let's scan!

$\rightarrow$ Lots of free parameters!

Scan the parameters space

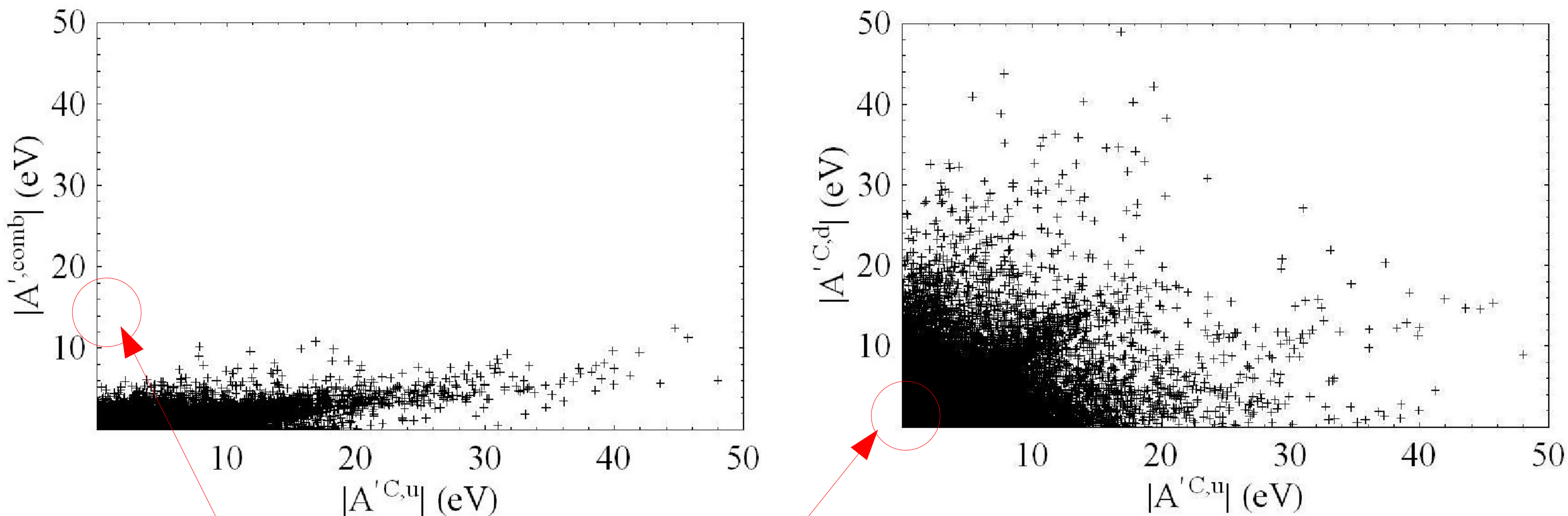
We seek for the solution : $\left\{ \begin{array}{rcl} |\mathcal{A}'^{comb}| & = & 14.4 \pm 4.2 \text{ eV} \\ |\mathcal{A}'^{C,u}| & \simeq & 0 \text{ eV} \\ |\mathcal{A}'^{C,d}| & \simeq & 0 \text{ eV} \end{array} \right.$

By scanning randomly the parameters space:

$$\begin{array}{rcl} 100 \text{ GeV} < & \text{masses} & < 2000 \text{ GeV} \\ -\pi/4 < & \theta_{L,R} & < \pi/4 \\ -\pi < & \delta_{L,R} & < \pi \end{array}$$

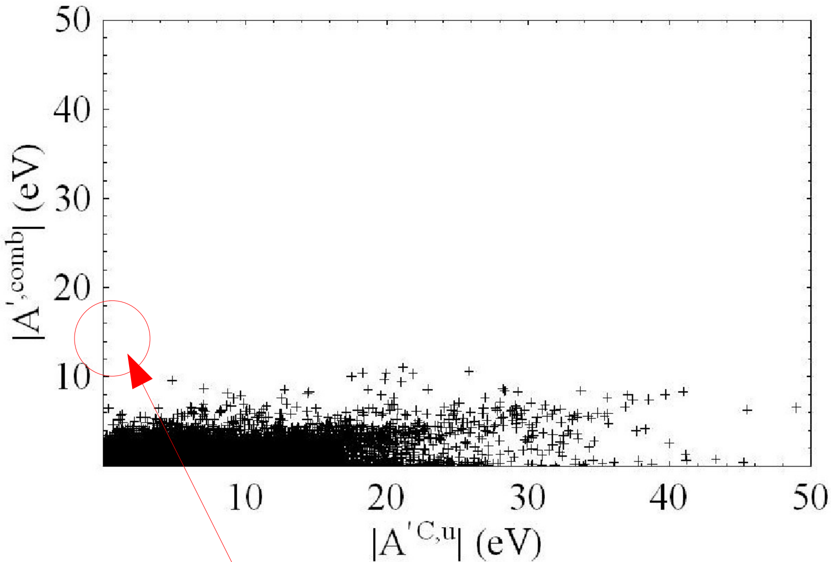
and calculate $|\mathcal{A}'^{comb}|, |\mathcal{A}'^{C,u}|,$ and $|\mathcal{A}'^{C,d}|$
for all scanned points of the parameters space.

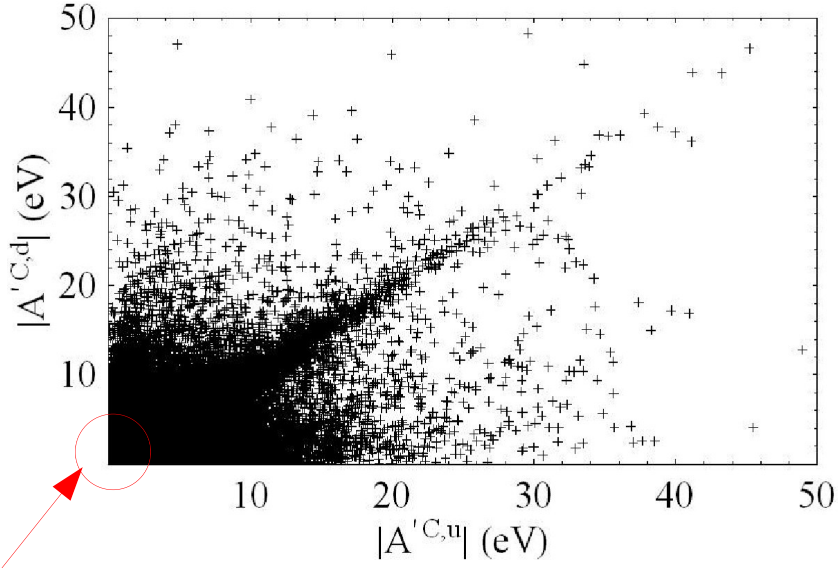
Results for LL mixing



Not a single point in the solution area!

Results for LL and RR mixing





Not a single point in the solution area!

GNK model is not excluded but doesn't seem to be a natural solution

Search for a more general solution...

Instead of seeking for $\left\{ \begin{array}{rcl} |\mathcal{A}'^{comb}| & = & 14.4 \pm 4.2 \text{ eV} \\ |\mathcal{A}'^{C,u}| & \simeq & 0 \text{ eV} \\ |\mathcal{A}'^{C,d}| & \simeq & 0 \text{ eV} \end{array} \right.$

1) Scan the parameters space (500 000 points)

2) Calculate $|\mathcal{A}'^{comb}|, |\mathcal{A}'^{C,u}|, \text{ et } |\mathcal{A}'^{C,d}|$ for all points

3) Do a χ^2 fit for all points to adjust SM parameters (with C' fixed to zero)

4) Calculate the effect of GNK on Δm_s

Results

critère	#
$\chi^2_{min} < 11.31$	74
Δm_s	414357
combinés	15

LL mixing only

critère	#
$\chi^2_{min} < 11.31$	102
Δm_s	92844
combinés	1

LL/RR mixing

Summary

- The GNK model is not excluded but it is not a natural solution to the $B \to \pi K$ puzzle
- If we insist to solve the puzzle with GNK, the only constraint on GNK parameters is : mass of gluino < 1.3 TeV
- There are implications for SUSY in general...
- Will the puzzle survive...?

Project 4 : New physics for $B \to \phi K_s$ and $B \to \phi K^*$ decays

Thanks to my collaborators:
Alakabha Datta
David London

Work published in the
Physics Letters B (2009)

Concept of the project

To seek for a single

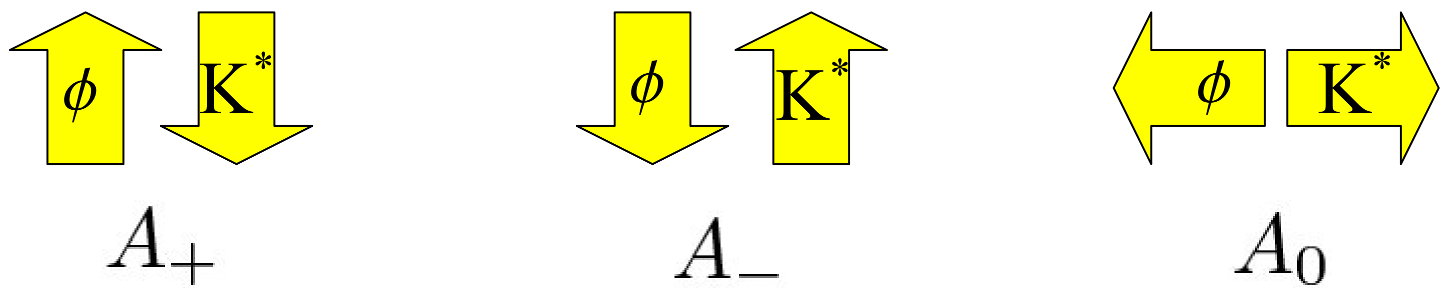
explanation for both

$B^0 \rightarrow \phi K_s$ *and* $B^0 \rightarrow \phi K^*$

puzzles...

*Polarizations of B → ϕ K**

ϕ and K* mesons are vectors → 3 states of spin



We can measure all polarizations individually!

$$f_L = \frac{|A_0|^2}{|A_+|^2 + |A_0|^2 + |A_-|^2} = 1 - \mathcal{O}(1/m_b^2)$$

factorization

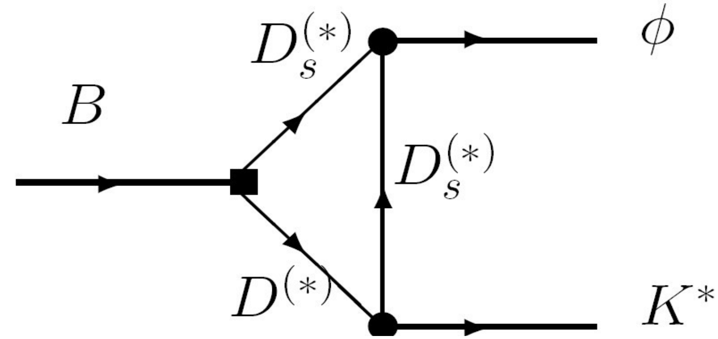
BaBar and Belle :
(averages)

$$\begin{cases} f_L(B^+ \to \phi K^{*+}) &= 0.50 \pm 0.05 \\ f_L(B^0 \to \phi K^{*0}) &= 0.480 \pm 0.030 \end{cases}$$

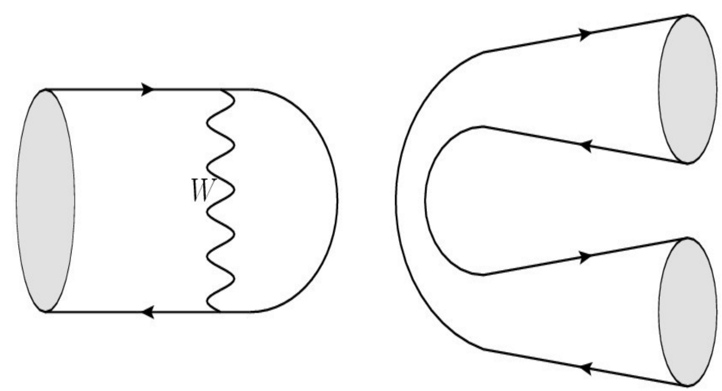
SM explanations of the $B \to \phi K^*$ puzzle

Some "small" SM contribution **CAN** be enhanced dynamically for + and - polarizations

- Long distance rescattering effects



- Enhanced penguin-annihilation in BBNS



But cannot solve both $B^0 \to \phi K^*$ and $B^0 \to \phi K_s$!

CP asymmetries of $B^0 \to \phi K_s$

Within SM : No CP violation in $B^0 \to \phi K_s$!

THEORY	$C_{CP} = 0$ $S_{CP} \simeq 0.68$ (sin2β from B^0 - $\bar{B}^0$ mixing)
EXPERIMENT	(BaBar and Belle averages) $C_{CP} = -0.23 \pm 0.15$ $S_{CP} = 0.44\ ^{+0.17}_{-0.18}$

The context is...

There's a problem with $B^0 \to \phi K^*$*...*

There's a problem with $B^0 \to \phi K_s$ *...*

Identical at level of quarks...

There is no single explanation
to both problems within SM...

Let's try with new physics!

General operators of NP

10 general operators :

$$\left.\begin{aligned}
O_{LL}^{V/A} &= \bar{s}\gamma_\mu(1-\gamma_5)b\,\bar{s}\gamma^\mu(1-\gamma_5)s\ , \\
O_{LR}^{V/A} &= \bar{s}\gamma_\mu(1-\gamma_5)b\,\bar{s}\gamma^\mu(1+\gamma_5)s\ , \\
O_{RL}^{V/A} &= \bar{s}\gamma_\mu(1+\gamma_5)b\,\bar{s}\gamma^\mu(1-\gamma_5)s\ , \\
O_{RR}^{V/A} &= \bar{s}\gamma_\mu(1+\gamma_5)b\,\bar{s}\gamma^\mu(1+\gamma_5)s\ ,
\end{aligned}\right\}\ \text{Vectors/Axial vectors}$$

$$\left.\begin{aligned}
O_{LL}^{S/P} &= \bar{s}(1-\gamma_5)b\,\bar{s}(1-\gamma_5)s\ , \\
O_{LR}^{S/P} &= \bar{s}(1-\gamma_5)b\,\bar{s}(1+\gamma_5)s\ , \\
O_{RL}^{S/P} &= \bar{s}(1+\gamma_5)b\,\bar{s}(1-\gamma_5)s\ , \\
O_{RR}^{S/P} &= \bar{s}(1+\gamma_5)b\,\bar{s}(1+\gamma_5)s\ ,
\end{aligned}\right\}\ \text{Scalars/Pseudoscalars}$$

$$\left.\begin{aligned}
O_{L}^{T} &= \bar{s}\sigma_{\mu\nu}(1-\gamma_5)b\,\bar{s}\sigma^{\mu\nu}(1-\gamma_5)s\ , \\
O_{R}^{T} &= \bar{s}\sigma_{\mu\nu}(1+\gamma_5)b\,\bar{s}\sigma^{\mu\nu}(1+\gamma_5)s\ .
\end{aligned}\right\}\ \text{Tensors}$$

Unknown complex coefficients c :

$|c_i|e^{i\delta}e^{i\Phi} \rightarrow |c_i|e^{i\Phi}$ (neglect NP strong phases)

Scenarios

- Cannot add all operators... too many free parameters
- Let's consider 2 scenarios:
  - All possibilities to add a single NP operator
  - All “realistic” possibilities to add pairs of NP operators

Case of single NP operator

By calculating hadronic matrix elements with factorization, we know the relative contributions of NP operators to B → ϕ K_s and B → ϕ K* polarizations ($\xi \sim \Lambda_{QCD}/m_b$).

	ϕK_S	$\phi K^*(\mathrm{L})$	$\phi K^*(-)$	$\phi K^*(+)$
$O_{LL}^{V/A}, O_{LR}^{V/A}$	1	1	ξ^2	ξ
$O_{RL}^{V/A}, O_{RR}^{V/A}$	1	1	ξ	ξ^2
$O_{LL}^{S/P}$	ξ^2	ξ	1	ξ^2
$O_{LR}^{S/P}$	1	1	ξ^2	ξ
$O_{RL}^{S/P}$	1	1	ξ	ξ^2
$O_{RR}^{S/P}$	ξ^2	ξ	ξ^2	1
O_L^T	ξ	ξ	1	ξ^2
O_R^T	ξ	ξ	ξ^2	1

No single operator can give simultaneously a large contribution to ϕK_s and $\phi K^*(\pm)$

Case of pairs of NP operators

- 6 operators can accommodate ϕK_s
- 4 operators can accommodate $\phi K^*(\pm)$
- Thus, 24 pairs of operators can accommodate both ϕK_s and $\phi K^*(\pm)$
- If we restrict this to "realistic pairs" of operators, 4 pairs remain:
$$(O_{LL}^{S/P}, O_{LR}^{S/P}), (O_{LL}^{S/P}, O_{RL}^{S/P}), (O_{RR}^{S/P}, O_{LR}^{S/P}), (O_{RR}^{S/P}, O_{RL}^{S/P})$$
- As a comparison :
$$(O_{LL(LR)}^{V/A}, O_{RL(RR)}^{V/A}) \text{ and } (O_L^T, O_R^T)$$

Numerical analysis

- We tested those pairs numerically
  - SM calculated with QCD factorization (neglect PA)
  - NP coefficients are adjusted with χ^2 fits
    - 4 free parameters
    - 7 measurements (BR's, CP asym. polarization fractions)

Numerical results

- With current data :

Operateurs	Minimal	Central	Maximal
$(O^{S/P}_{LL}, O^{S/P}_{RL})$	2.6 (45.7%)	2.8 (42.4%)	3.1 (37.6%)
$(O^{S/P}_{LL}, O^{S/P}_{LR})$	1.4 (70.6%)	1.3 (72.9%)	1.3 (72.9%)
$(O^{S/P}_{RR}, O^{S/P}_{RL})$	1.9 (59.3%)	1.7 (63.7%)	1.6 (65.9%)
$(O^{S/P}_{RR}, O^{S/P}_{LR})$	1.7 (63.7%)	1.7 (63.7%)	1.6 (65.9%)
$(O^{V/A}_{LL(LR)}, O^{V/A}_{RL(RR)})$	15.7 (0.13%)	10.6 (1.4%)	7.1 (6.9%)
(O^{T}_{R}, O^{T}_{L})	3.6 (30.8%)	3.6 (30.8%)	3.9 (27.2%)

(Three sets of theoretical parameters)

- Theoretical errors doesn't influence a lot
- S/P operators can satisfy data
- V/A excluded and T disfavored

Future scenario...

- Error bars for ϕK_s reduced by a factor of 2 :

Operateurs	Minimal	Central	Maximal
$(O^{S/P}_{LL}, O^{S/P}_{RL})$	6.3 (9.8%)	7.4 (6.0%)	8.6 (3.5%)
$(O^{S/P}_{LL}, O^{S/P}_{LR})$	4.3 (23.1%)	4.0 (26.1%)	3.9 (27.2%)
$(O^{S/P}_{RR}, O^{S/P}_{RL})$	5.2 (15.8%)	5.8 (12.2%)	5.6 (13.3%)
$(O^{S/P}_{RR}, O^{S/P}_{LR})$	4.9 (17.9%)	4.7 (19.5%)	4.5 (21.2%)
$(O^{V/A}_{LL(RR)}, O^{V/A}_{RL(LR)})$	20.3 (0.01%)	15.9 (0.12%)	10.9 (1.2%)
(O^{T}_{R}, O^{T}_{L})	13.7 (0.33%)	13.5 (0.37%)	14.0 (0.29%)

(Three sets of theoretical parameters)

- Hard for S/P operators → suggests smallest central value of C_{CP} in future...
- V/A and T are totally excluded

Implications for NP models

We cannot exclude any concrete NP model from this but...

S/P dominated models are favored

V/A dominated models are disfavored or excluded

2 Higgs doublets like models are favored

SUSY, Extra Z' boson, ... are disfavored

Sensitivity of triple products

- Triple products:

$$A_T^{(1)} \equiv \frac{\mathrm{Im}(A_\perp A_0^*)}{|A_0|^2 + |A_{||}|^2 + |A_\perp|^2}\,, \qquad A_T^{(2)} \equiv \frac{\mathrm{Im}(A_\perp A_{||}^*)}{|A_0|^2 + |A_{||}|^2 + |A_\perp|^2}\,,$$

Directly related with NP phases
→ Potentially very sensitive to NP

- Prediction of TP's for NP pairs (central values):

Operators	$A_T^{(1)}$	$\tilde{A}_T^{(1)}$	$A_T^{(2)}$	$\tilde{A}_T^{(2)}$
$(O_{LL}^{S/P}, O_{RL}^{S/P})$	$[-0.30, -0.27]$	$[0.030, 0.062]$	$[0.16, 0.22]$	$[-0.006, -0.004]$
$(O_{LL}^{S/P}, O_{LR}^{S/P})$	$[0.29, 0.32]$	$[-0.008, 0.014]$	$[-0.17, -0.14]$	$[-0.003, 0.000]$
$(O_{RR}^{S/P}, O_{RL}^{S/P})$	$[0.26, 0.28]$	$[-0.099, 0.056]$	$[-0.037, 0.090]$	$[-0.004, 0.001]$
$(O_{RR}^{S/P}, O_{LR}^{S/P})$	$[-0.33, -0.31]$	$[-0.036, -0.011]$	$[-0.001, 0.000]$	0.000

(Ranges represent the 3 sets: minimal, central and maximal)

Very different patterns of TP for different operators → Very interesting to measure them!

Summary

- Important not to forget "<u>single explanation</u>"
- Test general NP operators with numerical fits on $B \to \phi K_s$ and $B \to \phi K^*$ decays measurements
- Single NP operators are excluded
- Pairs of S/P operators can satisfy data
- Pairs of V/A operators are excluded and pairs of T operators are disfavored
- Great potential to distinguish between different model with TP's

The bottom line...

Current data do not allow

sharp conclusions

but

maybe an exciting era

is beginning...