$B_{(c)} \to \tau\nu$: Complementarity at SuperB, LHC and LC

(+ issues in $B \to \pi K$)

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(+ issues in $B \rightarrow \pi K$)

Stefan Recksiegel

from: TU München

speaking at: KEK

R Parity violating enhancement of $B_u^+ \to \ell^+\nu$ and $B_c^+ \to \ell^+\nu$

Stefan Recksiegel

KEK Theory Group

LMU München

July 17th, 2002


賞状
第三位
テニス大会の部
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Recksiegel Stefan
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あなたはKEKトライアスロン2002に於て頭書の成績を収めたのでこれを賞します
2002年9月21日
トライアスロン実行委員
川合将義
佐藤昌史
これを賞します
平成 年 月 日
高エネルギー物理学研究所
所長 菅原寛孝

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- R. Fleischer, S.R. and F. Schwab, Eur. Phys. J. C **51**, 55 (2007)

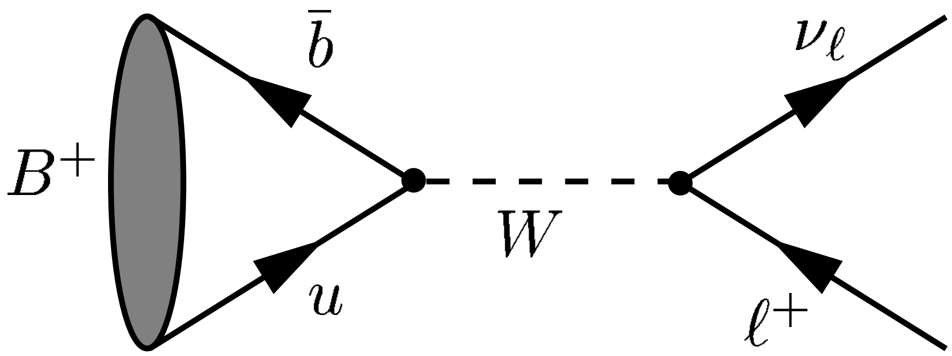
Why study $B \to \tau\nu$?

$\to$ Suppressed in SM and clean (only f_B appears, no FFs).

Processes that are suppressed in the SM are excellent probes to look for New Physics, because they are not necessarily also suppressed in NP !

(This is why $b \to s\gamma$, B_0-$\bar{B}_0$ mixing, $K \to \pi\nu\bar{\nu}$, etc. draw so much attention and why they are so good in constraining NP models.)

$B_q^+ \to \ell^+ \nu_\ell$



$B \to \tau\nu$ is suppressed so much because coupling to W is left-handed $\to$ need spin-flip for the lepton $\to$ factor m_ℓ

Standard Model rate for $B_q^+ \to \ell^+ \nu_\ell$:

$$\Gamma(B_q^+ \to \ell^+ \nu_\ell) = \frac{G_F^2 m_{B_q} m_l^2 f_{B_q}^2}{8\pi} |V_{qb}|^2 \left(1 - \frac{m_l^2}{m_{B_q}^2}\right)^2$$

Helicity suppression: BR is proportional to m_l^2, expect:

$$BR(B_q^+ \to \tau^+ \nu_\tau) : BR(B_q^+ \to \mu^+ \nu_\mu) : BR(B_q^+ \to e^+ \nu_e) = m_\tau^2 : m_\mu^2 : m_e^2$$

Experimentally,

$$\begin{aligned} \mathrm{BR}(B^\pm \to \tau^\pm \nu_\tau) &= (1.70 \pm +0.42) \times 10^{-4} \quad &\text{(BELLE-CONF-0840)} \\ &= (1.20 \pm 0.40 \pm 0.36) \times 10^{-4} \quad &\text{(BaBar)} \end{aligned}$$

In agreement with the SM expectations, central values are
(τ) 1.23×10^{-4} : (μ) 5.51×10^{-7} : (e) 1.29×10^{-11}

(Experimental imits on e, μ channels are 1, 1.3×10^{-6}, respectively.)

New Physics: 2HDM

The SM has only one Higgs doublet

$\rightarrow$ masses for the gauge bosons and quarks, one physical particle.

Many other theories have two Higgs doublets (2HDM)

(SUSY needs two to provide masses to up- and down-quarks)

$\rightarrow$ not one but four extra particles

h^0 has SM-like couplings m_f/v, H^0, A^0 and $H^\pm$ couplings are scaled by $\tan\beta$ for down-type fermions (type-II 2HDM)

($\tan\beta$ is ratio of Higgs VEVs)

Let's look at this in a bit more detail:

Fermion Mass terms in the SM

$$\mathcal{L}_{\text{Yukawa}} = -\Gamma_u^{ij}\bar{Q}_L^i \phi^c\, u_R^j - \Gamma_d^{ij}\bar{Q}_L^i \phi\, d_R^j - \Gamma_e^{ij}\bar{L}_L^i \phi\, l_R^j \quad + \text{h.c.}$$

(Γ_f are coupling matrices, Q_L^i and L_L^i are left-handed doublets, u_R^j, d_R^j, l_R^j are right-handed singlets)

The same scalar field gives the masses to u-type and d-type fermions

2HDM models:

$$\mathcal{L}_{\text{Yukawa}} = -\sum_{k=1,2}\Gamma_u^{ij,k}\bar{Q}_L^i \phi_k^c\, u_R^j - \sum_{k=1,2}\Gamma_d^{ij,k}\bar{Q}_L^i \phi_k\, d_R^j \quad +\text{leptons} \quad +\text{h.c.}$$

(ϕ_1 and ϕ_2 are the two Higgs fields)

Generally, arbitrary couplings to the two Higgs fields possible ! ("type-III 2HDM model")

Problem: FCNC

Solution: Either u-type and d-type quarks both couple to same ϕ
$\rightarrow$ "type-I 2HDM"

or u-type couple to ϕ_1 and d-type couple to ϕ_2 (e.g. SUSY)
$\rightarrow$ "type-II 2HDM"

SUSY: Several more relations, among them: $M_h^2 \leq M_Z^2$ at tree level
$\rightarrow$ obviously broken.
Loop corrections can relax bound to $M_h^{\max} \approx 135\text{GeV}$.

Important parameter: Ratio of VEVs of the two doublets

$$\tan\beta = v_1/v_2$$

Remember: In type-II, $\phi_1 \to u$-type masses, $\phi_2 \to d$-type masses
Large $\tan\beta \sim m_t/m_b$ allows top and bottom Yukawa coupling unification !

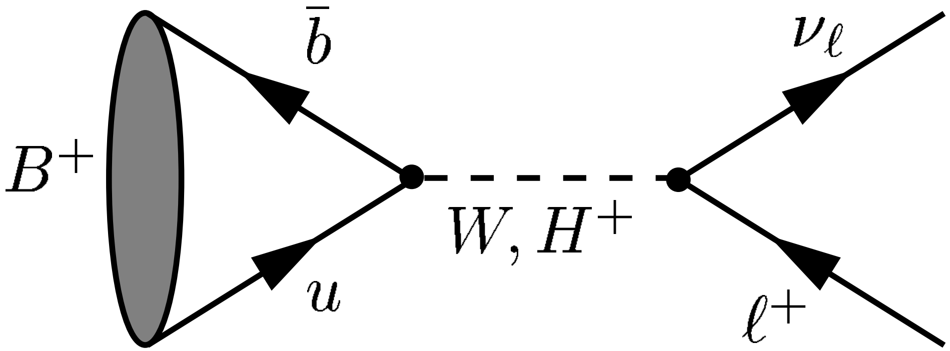
Isidori/Mescia/Paradisi/Temes 2007

MSSM at large $\tan\beta$:

- Interesting effects on $B \to \tau\nu$
- Enhancement of $(g-2)_\mu$ in accordence with exp
- No large non-SM effects is ΔM_{B_s} and $b \to s\gamma$
- $b \to s\,\ell^+\ell^-$ can be strongly enhanced, but can be made compatible with experiment in parts of MSSM parameter space

$B_q^+ \to \ell^+ \nu_\ell$ in 2HDMs

Why are there interesting effects in $B^\pm \to \ell^+ \nu_\ell$?



$H^\pm$ can mediate $B^\pm \to \ell^+ \nu_\ell$!

Factor m_ℓ also present, but now Yukawa, not helicity-flip.

$\to \tan\beta$ enhancement

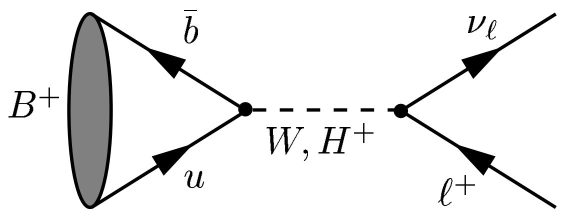
Hou 1992, Du/Jin/Yang 1997

Effect of $H^\pm$ on $B^\pm \to \ell^+ \nu_\ell$ modifies SM expression by factor r_H^q

$$r_H^q = \left[1 - \tan^2\beta \, \frac{M_{B_q}^2}{M_{H^\pm}^2} \right]^2 \equiv [1 - R^2 M_{B_q}]^2$$

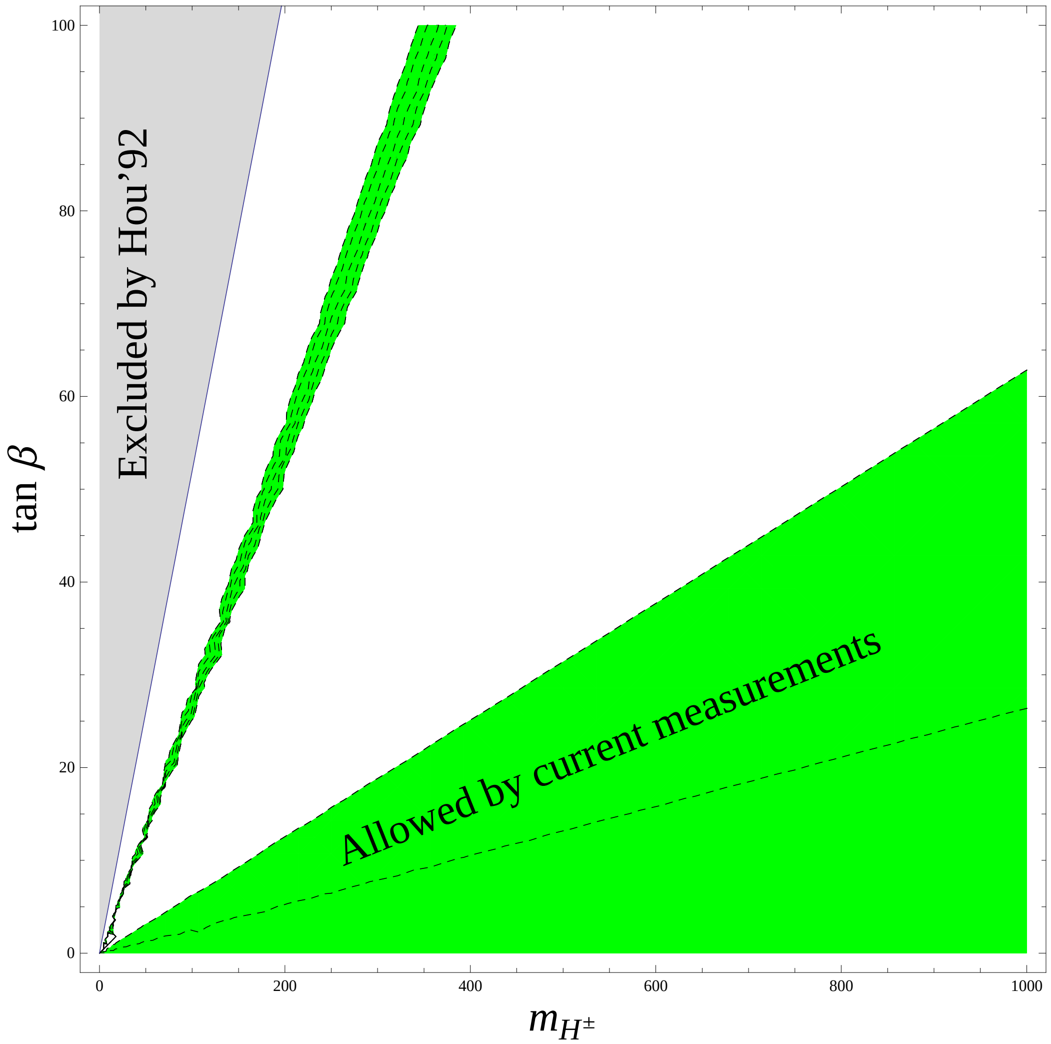
$\tan\beta \gg 1$ phenomenologically attractive,
significant contribution possible !

But: destructive interference, decreasing BR for small NP contribution.



(Hou: $\tan\beta < 0.52\, m_{H^-}/1\text{GeV}$ for $BR(B \to \mu\nu) < 10^{-5}$ in 1992)

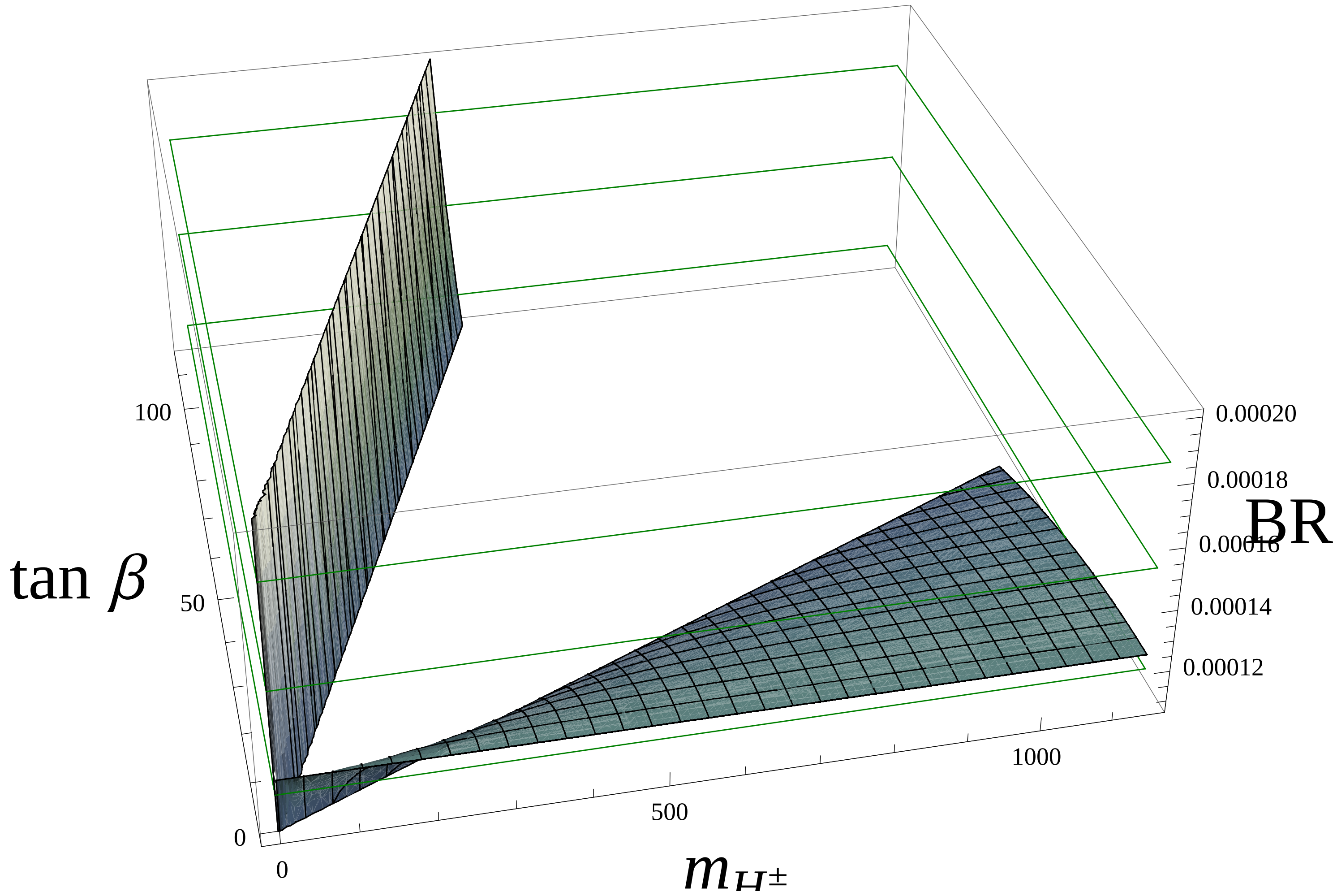
We plot the $M_{H^\pm}$–$\tan\beta$ plane:



Green: Allowed with 1-σ experimental range, f_B, $\mathrm{BR}_{\mathrm{exp}}$ are varied in their 1-σ ranges (multiple lines)

(For clarity, we do not show areas excluded due to direct Higgs searches)

Why two allowed areas ? Let's look at this in 3D !



Green lines: 1-σ experimental range → allowed area

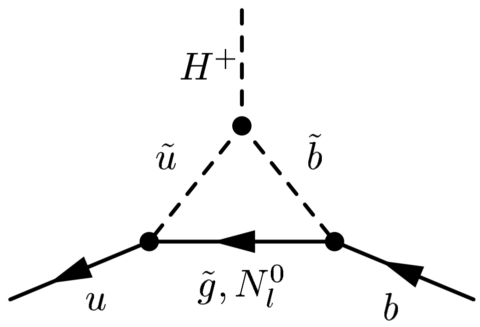
Buras/Chankowski/Rosiek/Slawianowska 2002

D'Ambrosio/Giudice/Isidori/Strumia 2002

Akeroyd/SR 2003

Additional modification: vertex corrections, mainly gluino

$$r_H = \left(1 - \frac{\tan^2\beta}{1+\tilde{\epsilon}_0\,\tan\beta}\,\frac{m_B^2}{m_{H^\pm}^2}\right)^2$$



(A similar correction term can be generated at tree-level in type-III 2HDMs)

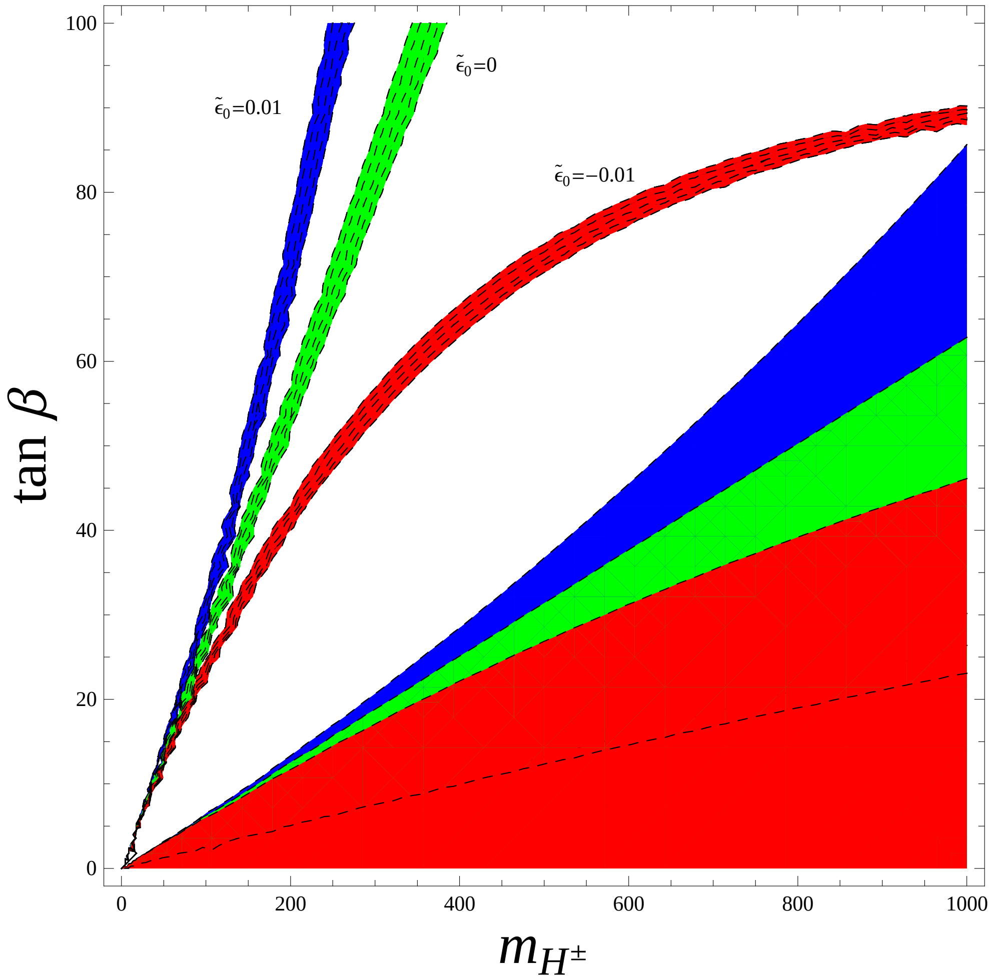
Itoh/Komine/Okada 2005

Isidori/Paradisi 2006, Chen/Geng 2006

$\tilde{\epsilon}_0 \sim 10^{-2}$ is expected in MSSM

$\tilde{\epsilon}_0 < 0$ would be possible, but would involve $\mu < 0$ which moves $g-2$ into the wrong direction

Still, let's look at what $\tilde{\epsilon}_0 = (0, \pm 10^{-2})$ does ...



$\tilde{\epsilon}_0 = (-10^{-2}, 0, 10^{-2})$

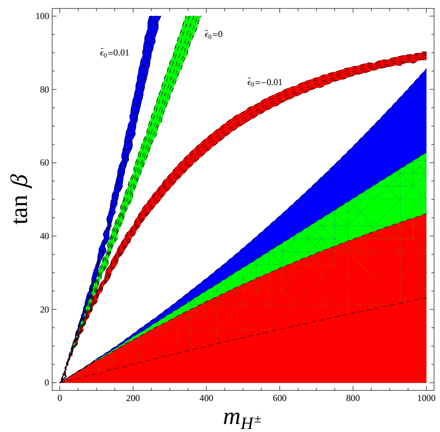
f_B, $\mathrm{BR}_{\mathrm{exp}}$ are varied in their 1-σ ranges (multiple lines)

$\rightarrow$ very moderate dependence on f_B, $\mathrm{BR}_{\mathrm{exp}}$,

but $\tilde{\epsilon}_0$ very important !

$B_u \to \tau\nu$ and 2HDMs

- We finally have a measurement of $B_u \to \tau\nu$
- In 2HDMs, H^+ contributions strongly modify $B \to \tau\nu$
  $\to$ $B_u \to \tau\nu$ constrains parameter space of 2HDMs !
- Loop corrections (or even tree in type-III) can break the clean constraints in the $M_{H^\pm}$–$\tan\beta$ plane
- Careful when relating measurement $\leftrightarrow$ constraints!



$B_c \to \tau\nu$

B_c not studied too well, cannot be produced in B factories

LEP had B_c in their samples $\to$ how many ?

$\Rightarrow$ do they influence the $\tan\beta/M_H$-limits ?

Transition probability: $\approx 38\%$ of b–quarks hadronize into $B_u^\pm$,

$$\boxed{2 \cdot 10^{-4} - 5 \cdot 10^{-3} \text{ hadronize into } B_c^\pm}$$

$\to$ let us look a bit closer at that number

$F_{b\to B_c}$

Lisignoli/Masetti/Petrarca 1991

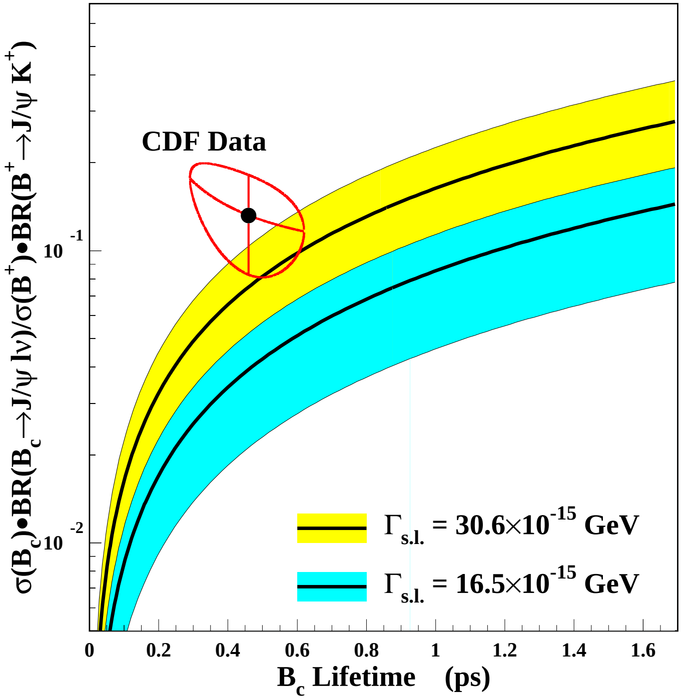
HERWIG Monte Carlo study:

$$F_{b\to B_c} \sim \begin{array}{ll} 0.2 - 1.0 \cdot 10^{-3} & \text{@LEP} \\ 1.3 \cdot 10^{-3} & \text{@Tevatron} \end{array}$$

CDF 1998

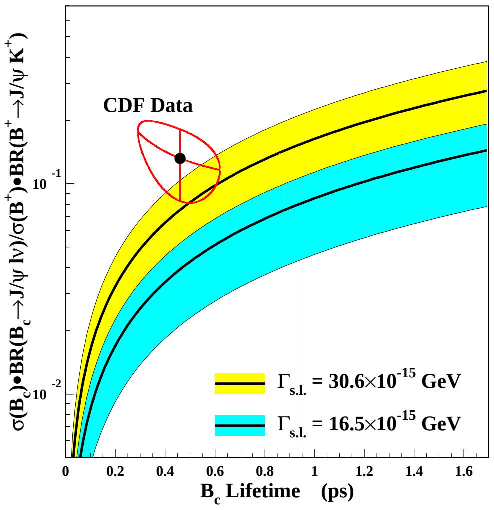
CDF: "Observation of B_c in $p\bar{p}$": $F_{b\to B_c} = 1.3 \cdot 10^{-3}$

Data still significantly on the high side of theoretical predictions



CDF 1998:

$$\frac{\sigma(B_c^+)\cdot \mathrm{BR}(B_c \to J/\psi e^\pm \nu)}{\sigma(B^+)\cdot \mathrm{BR}(B \to J/\psi K^+)} = 0.13 \pm 0.05$$



CDF/D0 2006:

$$\frac{\sigma(B_c^+)\cdot \mathrm{BR}(B_c \to J/\psi e^\pm \nu)}{\sigma(B^+)\cdot \mathrm{BR}(B \to J/\psi K^+)} = 0.28 \pm 0.07$$

Gershtein/Likhoded 07

Using CDF/D0 branching fractions for $B \to J/\psi K^\pm$ and $B_c \to J/\psi e^\pm \nu$, G/L claim that B_c production is "an order of magnitude higher" than theoretical predictions

$$\boxed{F_{b\to B_c} = 1\cdot 10^{-3} - 5\cdot 10^{-3}}$$

Analyses of $B \to \tau\nu$ before B_u channel measurement

L3 97

L3 gave a limit on $B_u \to \tau\nu$: (actually: $B_u \to \tau\nu + B_c \to \tau\nu$)
$\mathrm{BR}(B_u \to \tau\nu) < 5.7 \cdot 10^{-4}$ @ 90 % CL (i.e. ≈ 3.5 SM).

With this result, they improved Hou's '93 limit
($\tan\beta \leq 0.52 m_{H^-}/1\mathrm{GeV}$) to $\tan\beta \leq 0.38 m_{H^-}/1\mathrm{GeV}$

Mangano/Slabopitsky 97

took into account B_c contribution in L3 analysis !
Assumed $2 \cdot 10^{-4} - 1 \cdot 10^{-3}$ for $F_{b \to B_c}$, studied limits on $\tan\beta / M_H$.

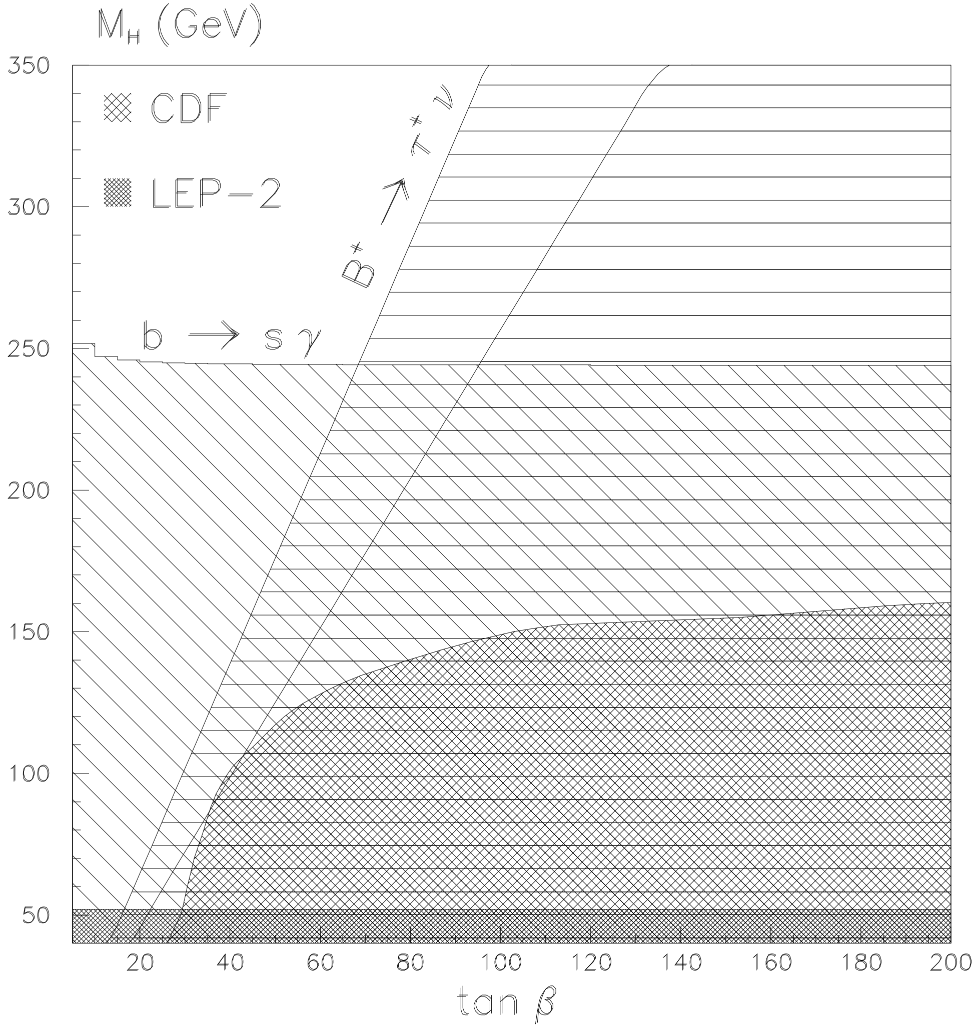
$$\to \quad \tan\beta \leq 0.3x \; m_{H^-}/1\mathrm{GeV}, \quad 0 \leq x \leq 7$$

$\to$ slightly better than original L3 analysis (0.38)
$\to$ better than original Hou '92 (0.52)

right line: L3 original ($\tan\beta \leq 0.38 m_{H^-}/1\text{GeV}$)

left line: Mangano/Slabopitsky very optimistic: $\tan\beta \leq 0.27 m_{H^-}/1\text{GeV}$

Hou limit would be almost exactly diagonal. (NB: flipped w.r.t. my plots)



Mangano/Slabopitsky 97

What does the $B_u \to \tau\nu$ measurement change ?

- We now have a measurement of $B_u \to \tau\nu$ from the B factories, therefore L3 result not interesting anymore for $\tan\beta/M_H$-limits
- But: $B_{u/c} \to \tau\nu$ at Z peak still interesting ?
- What does L3 (or any other experiment at the Z peak) actually measure ?

$$\mathrm{BR}_{\mathrm{eff}} = \mathrm{BR}(B^\pm \to \tau^\pm \nu) \left(1 + \frac{N_c}{N_u}\right)$$

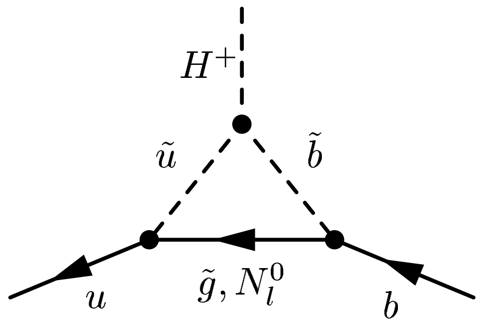
$$\frac{N_c}{N_u} = \left|\frac{V_{cb}}{V_{ub}}\right|^2 \frac{F_{b\to B_c^\pm}}{F_{b\to B^\pm}} \left(\frac{f_{B_c}}{f_B}\right)^2 \frac{M_{B_c}}{M_B} \frac{\tau_{B_c}}{\tau_B} = 0.35 - 1.0 \cdot \frac{F_{b\to B_c}}{10^{-3}}$$

$\to$ For $F_{b\to B_c} \sim 10^{-3}$, there can be one B_c event for each B_u event!

Significant B_c contribution to $B \to \tau\nu$ at Z peak!

- There is a surprisingly large number of $B_c^+ \to \tau^+\nu$ in the $B^+ \to \tau^+\nu$ signal at the Z peak!

- Also important: "ϵ–corrections":



- Different corrections for B_u and B_c are possible, important to know both $B_u^+ \to \tau^+\nu$ and $B_c^+ \to \tau^+\nu$ rate !

- If SM is assumed: Use Z peak measurement to determine $F_{b\to B_c}$!
$\to$ Understand B_c production

Conclusions ($B \to \tau\nu$)

- $B \to \tau\nu$ is a very interesting decay channel, small in the SM, strongly modified by New Physics
- 2HDMs modify $B \to \tau\nu \Rightarrow B \to \tau\nu$ constrains 2HDMs (and other NP models)
- Very good complementarity between $\Upsilon(4S)$ and Z peak ($B_c \to \tau\nu$) !
- Need to know both channels (ϵ–corrections)
- Please measure $B \to \mu\,\nu$! BaBar's limit is 30% better . . .

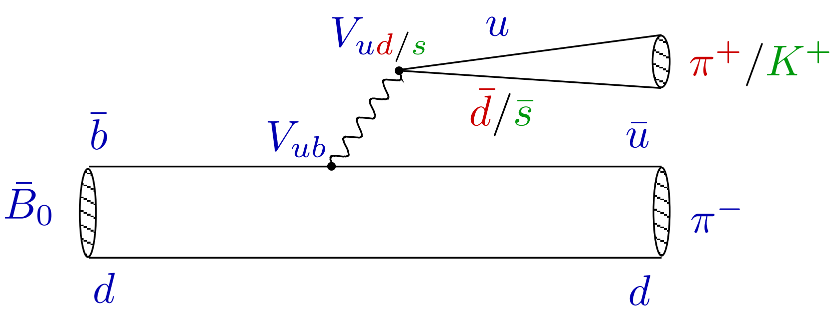
$$B \to \pi K$$

Why $B \to \pi K$?

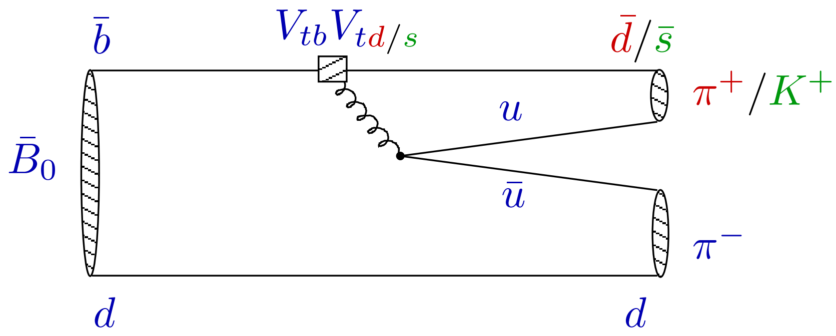
The thing that intrigued the theorists:

- Those observables that had small electroweak (EW) contributions were as expected
- Observables with large EW corrections did not agree with expectations
- EW sector is where new physics would be expected !

Feynman diagrams for $B \to \pi\pi$, $B \to \pi K$



tree diagram



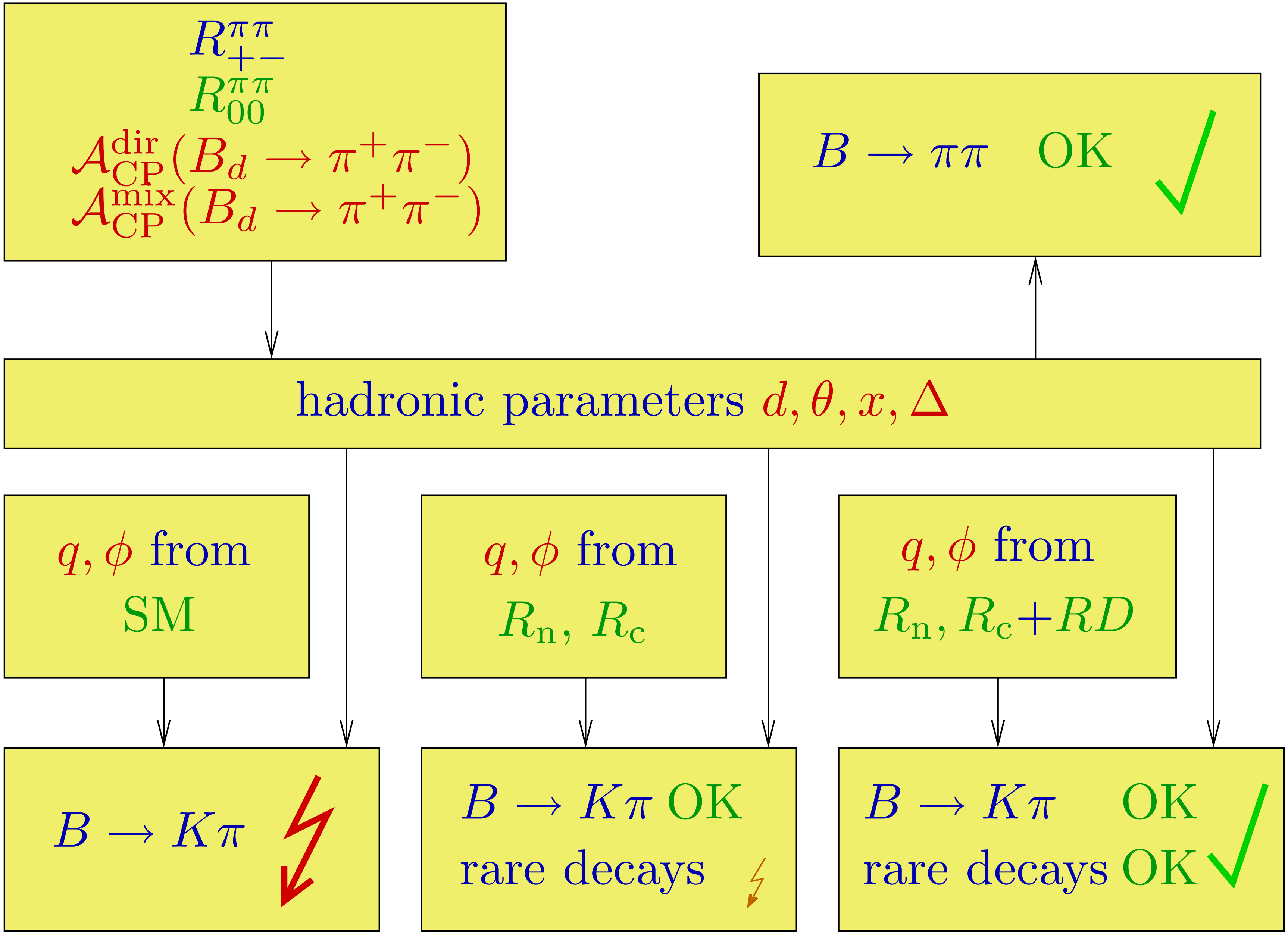
penguin diagram

Colour-suppressed tree diagrams have the same topology as the QCD penguin diagrams, electroweak penguin diagrams have the same topology as tree diagrams.

$(P/T)_{K\pi}/(P/T)_{\pi\pi} \sim (V_{cs}/V_{us})/(V_{cd}/V_{ud})_{\pi\pi} \sim 1/\lambda^2$.

$\Longrightarrow$ $B \to \pi\pi$ is tree-dominated, $B \to K\pi$ is penguin-dominated.

2004



$R_{+-}^{\pi\pi}$
$R_{00}^{\pi\pi}$
$\mathcal{A}_{\rm CP}^{\rm dir}(B_d \to \pi^+\pi^-)$
$\mathcal{A}_{\rm CP}^{\rm mix}(B_d \to \pi^+\pi^-)$
$B \to \pi\pi$ OK
hadronic parameters d, θ, x, Δ
q, ϕ from SM
q, ϕ from $R_{\rm n}$, $R_{\rm c}$
q, ϕ from $R_{\rm n}, R_{\rm c}$+RD
$B \to K\pi$
$B \to K\pi$ OK
rare decays
$B \to K\pi$ OK
rare decays OK

The approach:

i) *$SU(3)$ flavour symmetry*
$SU(3)$-breaking effects are, however, included through ratios of decay constants and form factors. Also: sensitivity of the numerical results on non-factorizable $SU(3)$-breaking effects is explored.

ii) *Neglect of the penguin annihilation and exchange topologies*

Strategy:

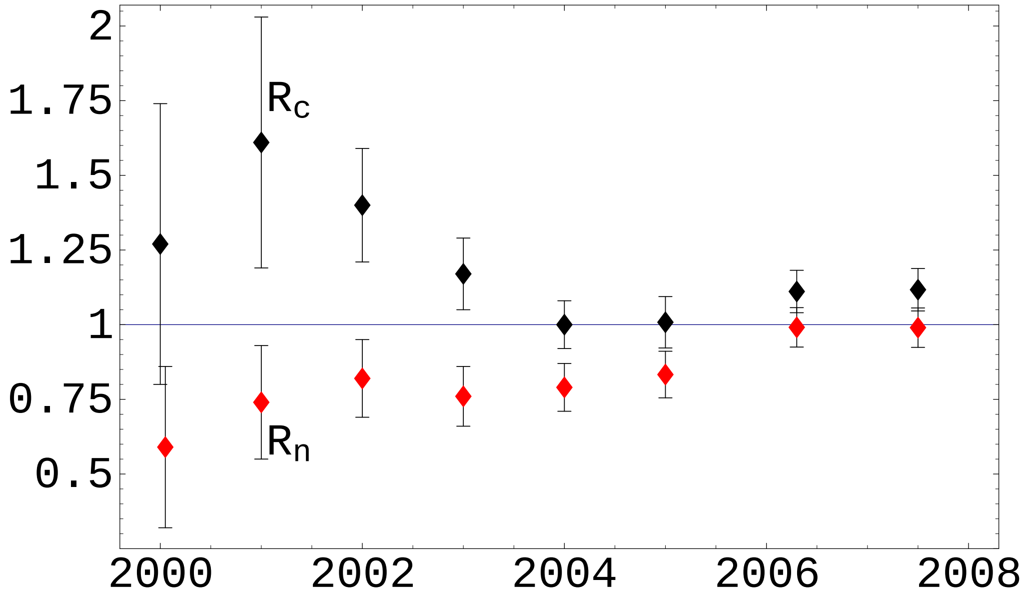
i) Use experimental data on BRs and asymmetries in $B \to \pi\pi$ to determine $\pi\pi$ hadronic parameters

ii) With $SU(3)$, transform these to πK hadronic parameters

iii) Calculate all πK observables, compare with experiment

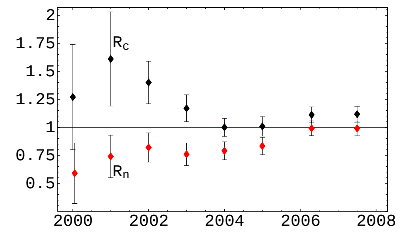
Buras/Fleischer 00

The $B \to \pi K$ puzzle has been around for a while, already in 2000 it was observed that the CLEO data exhibited a puzzling pattern.

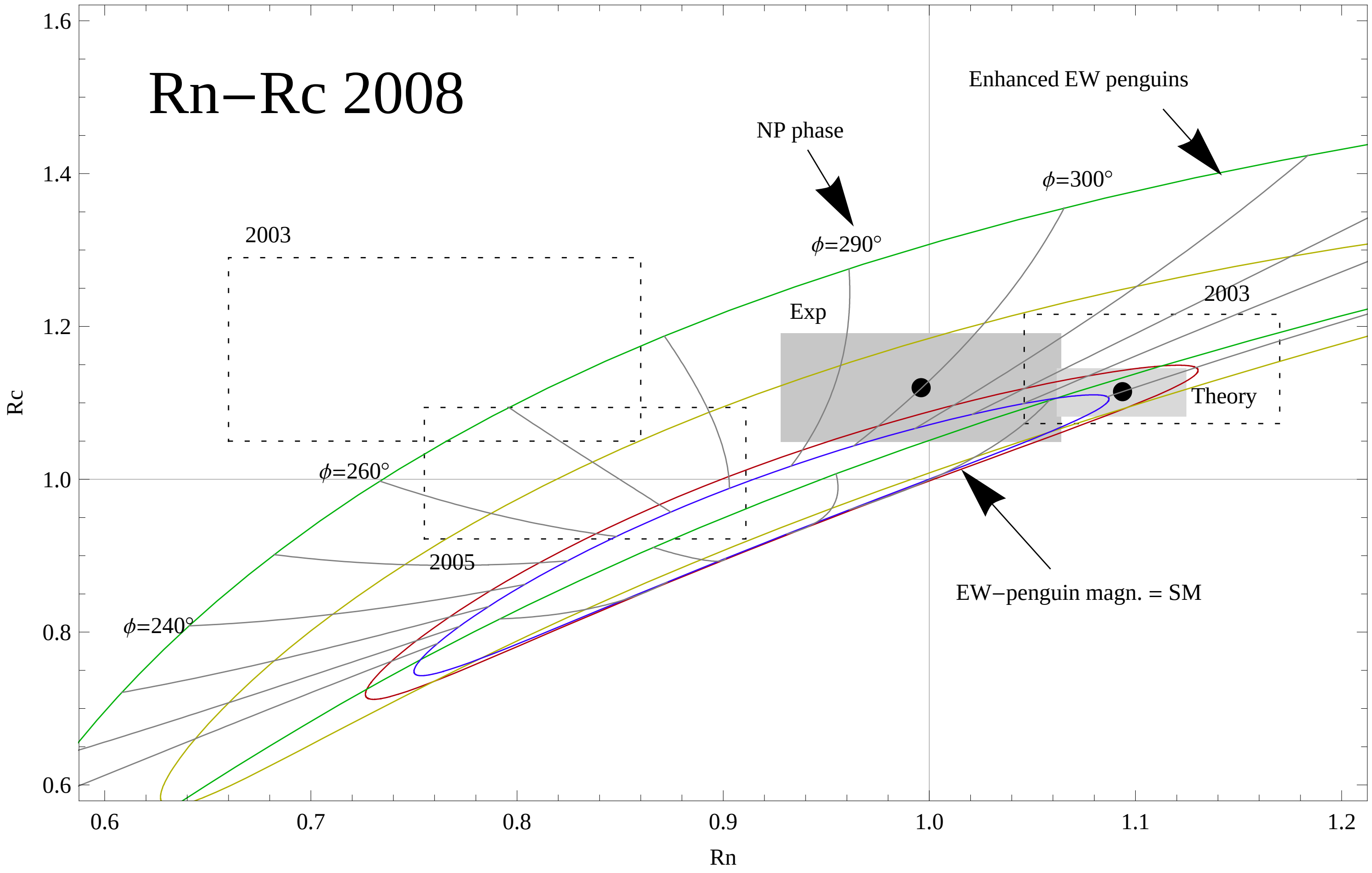


$$R_c \equiv 2\left[\frac{\mathrm{BR}(B^\pm \to \pi^0 K^\pm)}{\mathrm{BR}(B^\pm \to \pi^\pm K^0)}\right] \qquad R_n \equiv \frac{1}{2}\left[\frac{\mathrm{BR}(B_d \to \pi^\mp K^\pm)}{\mathrm{BR}(B_d \to \pi^0 K^0)}\right]$$

The first $B \to \pi K$ puzzle was the R_c-R_n puzzle.



Situation in the R_c and R_n plane:

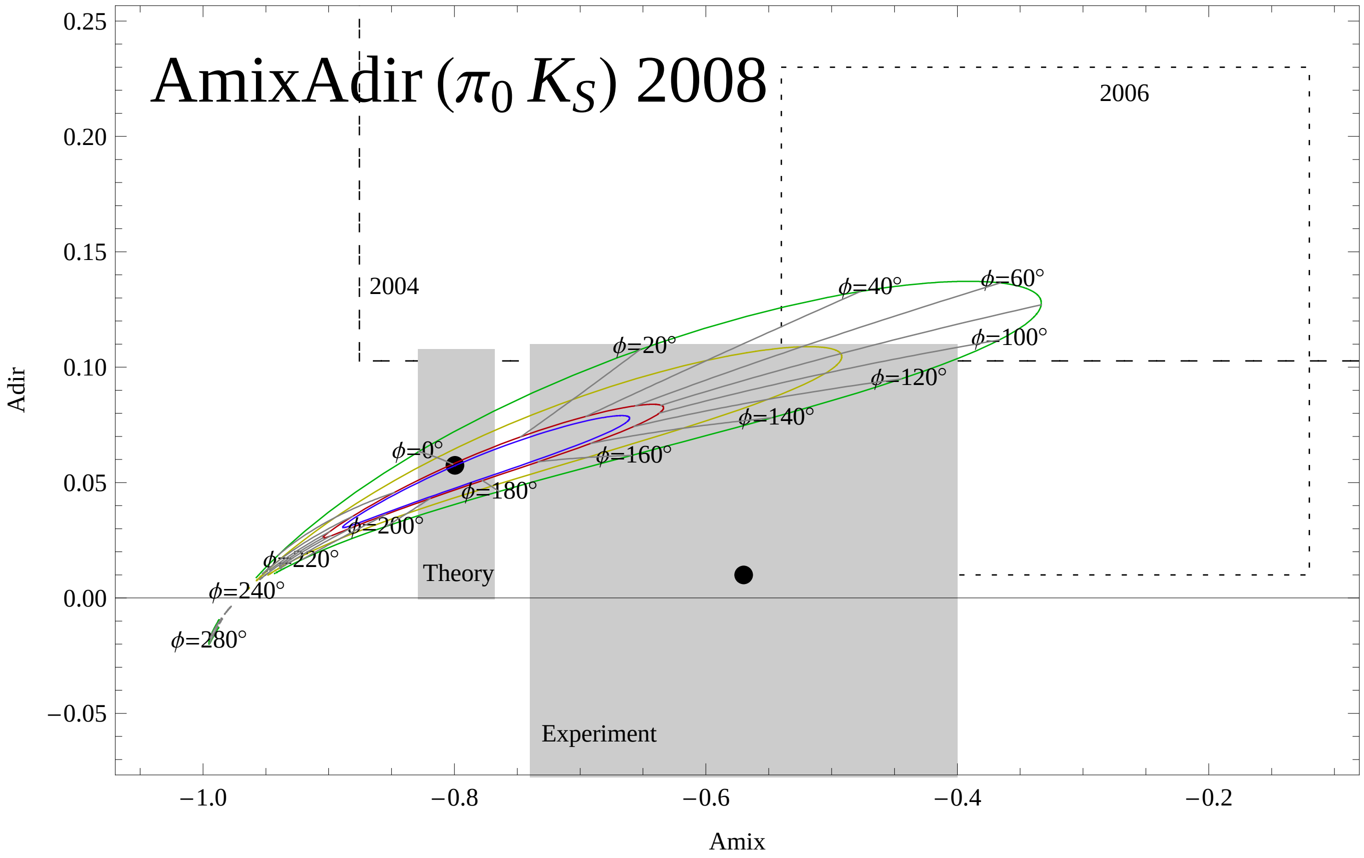


Experimental data has moved towards theory, no more puzzle.

Later ($\sim$ 2006):

R_c-R_n puzzle almost solved, but some asymmetries still puzzling.

E.g.: $\mathcal{A}_{CP}^{mix}(B_d \to \pi^0 K_S)$ predicted ~ -0.9 but experiment ~ -0.3.



Also (almost) resolved, both theory and experiment have moved !

($\Delta A \equiv \mathcal{A}_{CP}^{dir}(B^\pm \to \pi^0 K^\pm) - \mathcal{A}_{CP}^{dir}(B_d \to \pi^\mp K^\pm) \neq 0$ is a hadronic effect.)

Conclusions ($B \to \pi K$ puzzle)

- $B \to \pi K$ is very interesting because (unlike $B \to \pi\pi$) it is penguin dominated ($\to$ room for New Physics)
- People were excited about the $B \to \pi K$ puzzle because the observables with large EW contributions (where new physics would be expected were peculiar. Also, QCD factorisation does not work as well as originally assumed.
- Improved experimental data and improved theory now give a consistent picture.