$K \to \pi^+ \nu\bar{\nu}$ and $K_L \to \pi^0 \nu\bar{\nu}$
Minimal Flavour Violation and Beyond

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Flavour at the LHC
CERN, November 6-10, 2005

Declaration

$$K_L \to \pi^0 \nu \bar{\nu}$$

$$K^+ \to \pi^+ \nu \bar{\nu}$$

Master Formula for Weak Decays

AJB (2001)
hep-ph/0101336
hep-ph/0109197

Non-Perturbative Factors in the SM	QCD RG Factors	Short Distance Loop Functions (Penguins, Boxes)	New Flavour-Changing Parameters

Represent different Dirac and Colour Stuctures

$$A(\text{Decay}) = B_i \; \eta^i_{QCD} \; V^i_{CKM} \left[F^i_{SM} + F^i_{New}\right] + B^{New}_i \left[\eta^i_{QCD}\right]^{New} V^i_{New} \left[G^i_{New}\right]$$

(Summation over i)

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(Summation over i)

$$A\left(K^+ \to \pi^+ \nu\bar{\nu}\right) = B_+ \left[\lambda_c \tilde{P}_c + \lambda_t X(v)\right]$$
$$A\left(K_L \to \pi^0 \nu\bar{\nu}\right) = B_L \,\text{Im}\left(\lambda_t X(v)\right)$$

$$\lambda_c = V^*_{cs} V_{cd}$$
$$\lambda_t = V^*_{ts} V_{td}$$

B_+, B_L from $K^+ \to \pi^0 e^+ \nu$

$$X(v) = |X(v)| e^{i\theta_x}$$

v = parameters (m_t, ...)

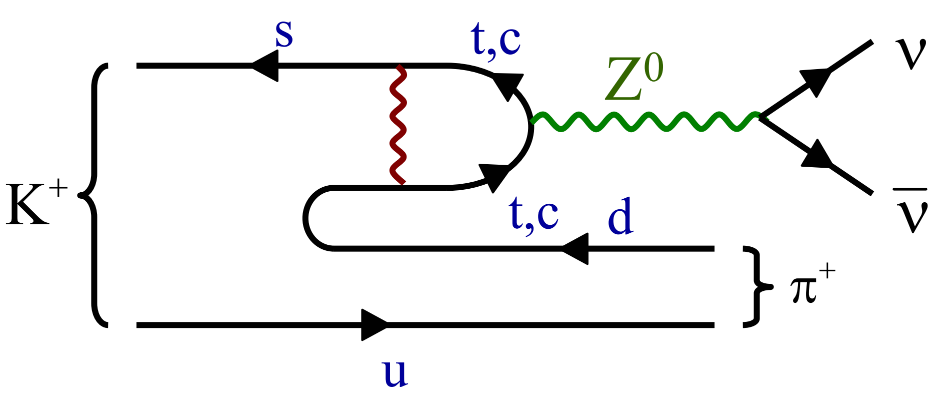
Pure Short Distance Dynamics

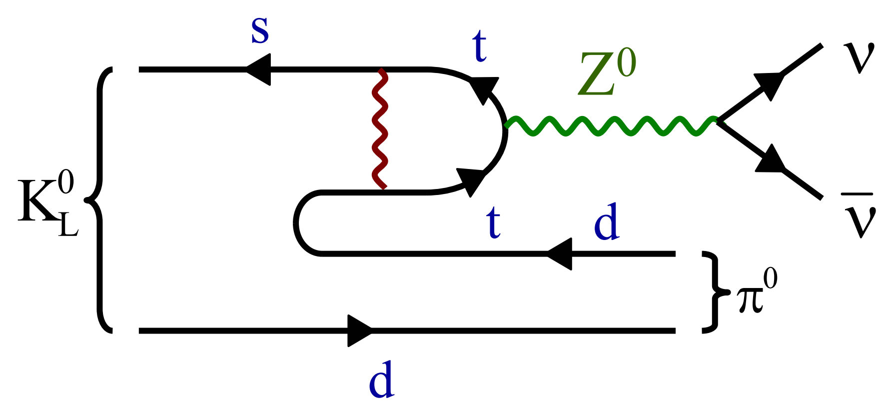
AJB, Romanino, Silvestrini (98)

$$\theta_x = \begin{cases} 0 & \text{SM} \\ 0, \pi & \text{MFV} \end{cases}$$

(AJB, Fleischer)

Decays $K \to \pi\nu\bar{\nu}$





Isospin Symmetry

$$\left\langle \pi^+ \middle| (\bar{s}d)_{V-A} \middle| K^+ \right\rangle = \sqrt{2}\left\langle \pi^0 \middle| (\bar{s}u)_{V-A} \middle| K^+ \right\rangle$$

$$\left\langle \pi^0 \middle| (\bar{s}d)_{V-A} \middle| K^0 \right\rangle = \left\langle \pi^0 \middle| (\bar{s}u)_{V-A} \middle| K^+ \right\rangle$$

Leading Decay: $K^+ \to \pi^0 e^+ \nu$

Isospin Breaking:

Marciano, Parsa (Suppression)

K^+(10%) K_L(5%)

Long Distance:

K^+: +(6±2)% Isidori, Mescia, Smith (2005)

K_L: ≤1% Buchalla, Isidori

The Rest of this Talk

1. Express Review of $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ (NNLO)

2. UT from $K \rightarrow \pi\nu\bar{\nu}$ $\left(\beta, \gamma, |V_{td}|\right)$

3. $K \rightarrow \pi\nu\bar{\nu}$ and MFV (upper bounds)

4. $K \rightarrow \pi\nu\bar{\nu}$ beyond MFV

5. $\Delta M_{s,d}$ and $B_{s,d} \rightarrow \mu\bar{\mu}$ (MFV and beyond)

6. Two final Messages

Express Review of $K^+ \to \pi^+ \nu\bar{\nu}$ and $K_L \to \pi^0 \nu\bar{\nu}$

AJB
Schwab
Uhlig
hep-ph/0405132

NLO: Buchalla + AJB (94); NNLO: AJB, Gorbahn, Haisch, Nierste (05)

SM: $\mathrm{Br}\left(K^+ \to \pi^+ \nu\bar{\nu}\right) = (8.0 \pm 1.1) \cdot 10^{-11}$ | $\mathrm{Br}\left(K_L \to \pi^0 \nu\bar{\nu}\right) = (2.8 \pm 0.6) \cdot 10^{-11}$

Exp: $\mathrm{Br}\left(K^+ \to \pi^+ \nu\bar{\nu}\right) = \left(14.7 {}^{+13.0}_{-8.9}\right) \cdot 10^{-11}$ | $\mathrm{Br}\left(K_L \to \pi^0 \nu\bar{\nu}\right) < 5.9 \cdot 10^{-7}$ (KTeV)

Brookhaven: E787, E949
(CKM, NA48, JPARC, ..)

Soon improved by E391a !!!
(J-PARC, ...)

$2.9 \cdot 10^{-7}$
90% C.L.

TH very clean : (With improved CKM parameters ~ 2008) ⇒

$\sigma\left(\mathrm{Br}\left(K^+ \to \pi^+ \nu\bar{\nu}\right)\right) < 5\%$

$\sigma\left(\mathrm{Br}\left(K_L \to \pi^0 \nu\bar{\nu}\right)\right) < 5\%$

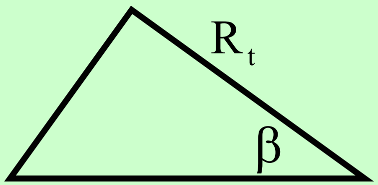
Very clean determination of Unitarity Triangle

$\sigma(\mathrm{Br}) \cong 10\%$	$\sigma(\sin 2\beta \cong 0.04)$	$\sigma(\gamma) = 9^\circ$	$\sigma(\lvert V_{td}\rvert) = 7\%$
$\sigma(\mathrm{Br}) \cong 5\%$	$\sigma(\sin 2\beta \cong 0.025)$	$\sigma(\gamma) = 5^\circ$	$\sigma(\lvert V_{td}\rvert) = 4\%$

Basic Formulae for $K^+ \to \pi^+ \nu\bar{\nu}$ (SM)

$$Br\left(K^+ \to \pi^+ \nu\bar{\nu}\right) = 4.8 \cdot 10^{-11}\left[A^4 R_t^2 X^2 + 2 P_c A^2 R_t X \cos\beta + P_c^2\right]$$

$X \equiv X(m_t)$



$$= 10^{-11}\left[\ \underset{\text{(top)}}{4.2} + \underset{\text{(top-charm)}}{3.1} + \underset{\text{(charm)}}{0.7}\ \right]$$

$$A = \frac{|V_{cb}|}{\lambda^2} \cong 0.83$$

Buchalla AJB (94) NLO)

$$P_c = 0.367 \pm \underbrace{0.033}_{\Delta m_c = 50\,\text{MeV}} \pm \underbrace{0.037}_{\text{theory}} \pm \underbrace{0.009}_{\alpha_s} \cong 0.37 \pm 0.07$$

BGHN NNLO (05)

$$P_c = 0.371 \pm 0.031_{m_c} \pm \underbrace{0.009}_{\text{theory}} \pm \underbrace{0.009}_{\alpha_s} = 0.37 \pm 0.04$$

$$Br\left(K^+ \to \pi^+ \nu\bar{\nu}\right)_{SM} = \left[8.0 \pm \underbrace{0.5}_{P_c} \pm \underbrace{0.8}_{\text{CKM}}\right] 10^{-11} \cong (8.0 \pm 1.1) 10^{-11}$$

$$Br\left(K^+ \to \pi^+ \nu\bar{\nu}\right) = \left[14.7\ {}^{+13.0}_{-8.9}\right] 10^{-11}$$

E787 (2)
E949 (1)
3 Events

QCD Corrections to $K \to \pi\nu\bar{\nu}$

LO | NLO | NNLO

Charm Part

$$P_c = \frac{4\pi}{\alpha_s(\mu_c)} P_c^{(0)} + P_c^{(1)} + \frac{\alpha_s(\mu_c)}{4\pi} P_c^{(3)}$$

$\mu_c = 0(m_c)$

Vainshtein, Zakharov, Novikov
Shifman (1977)
Ellis, Hagelin (1983)
Dib, Dunietz, Gilman (1991)

Buchalla
AJB
(1994)

AJB
Gorbahn
Haisch
Nierste
(2005)

$$x_t = \frac{m_t^2(\mu_t)}{M_W^2}$$

Top Part

$$X^{SM}(x_t) = X_0(x_t) + \frac{\alpha_s(\mu_t)}{4\pi} X_1(x_t)$$

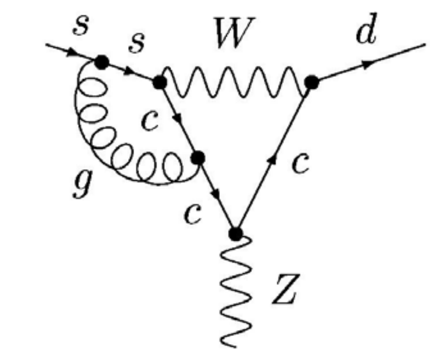
Inami, Lim (81)
AJB (81)

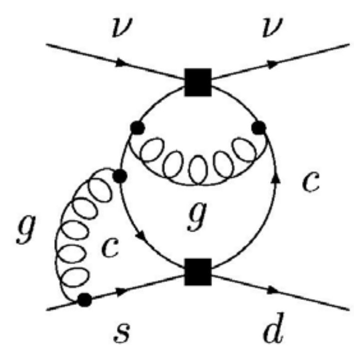
Buchalla, AJB (93)
Misiak, Urban (98)

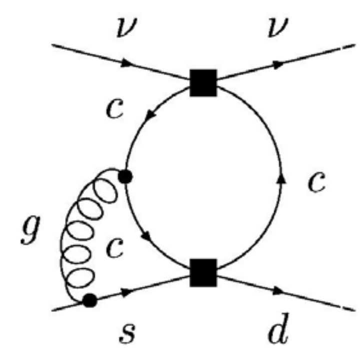
$C_i (\mu_w)$

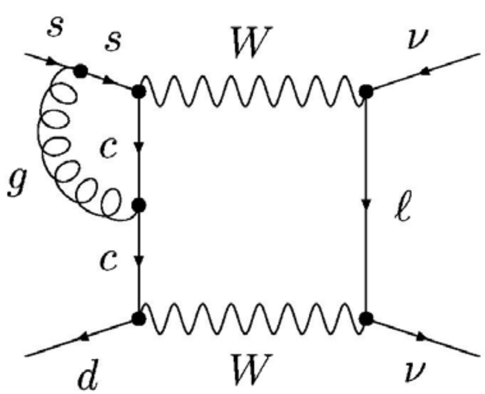
3-Loop Anomalous Dimensions

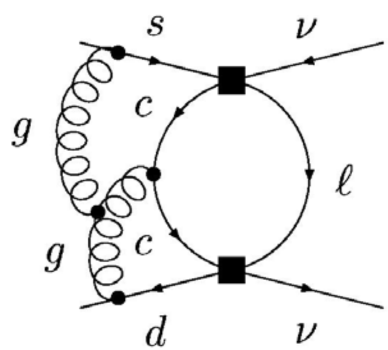
Matrix Elements

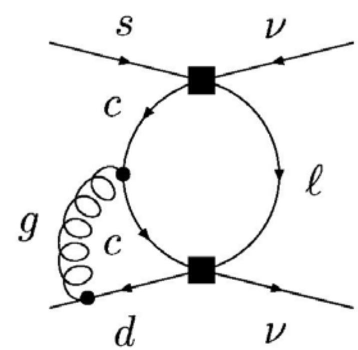




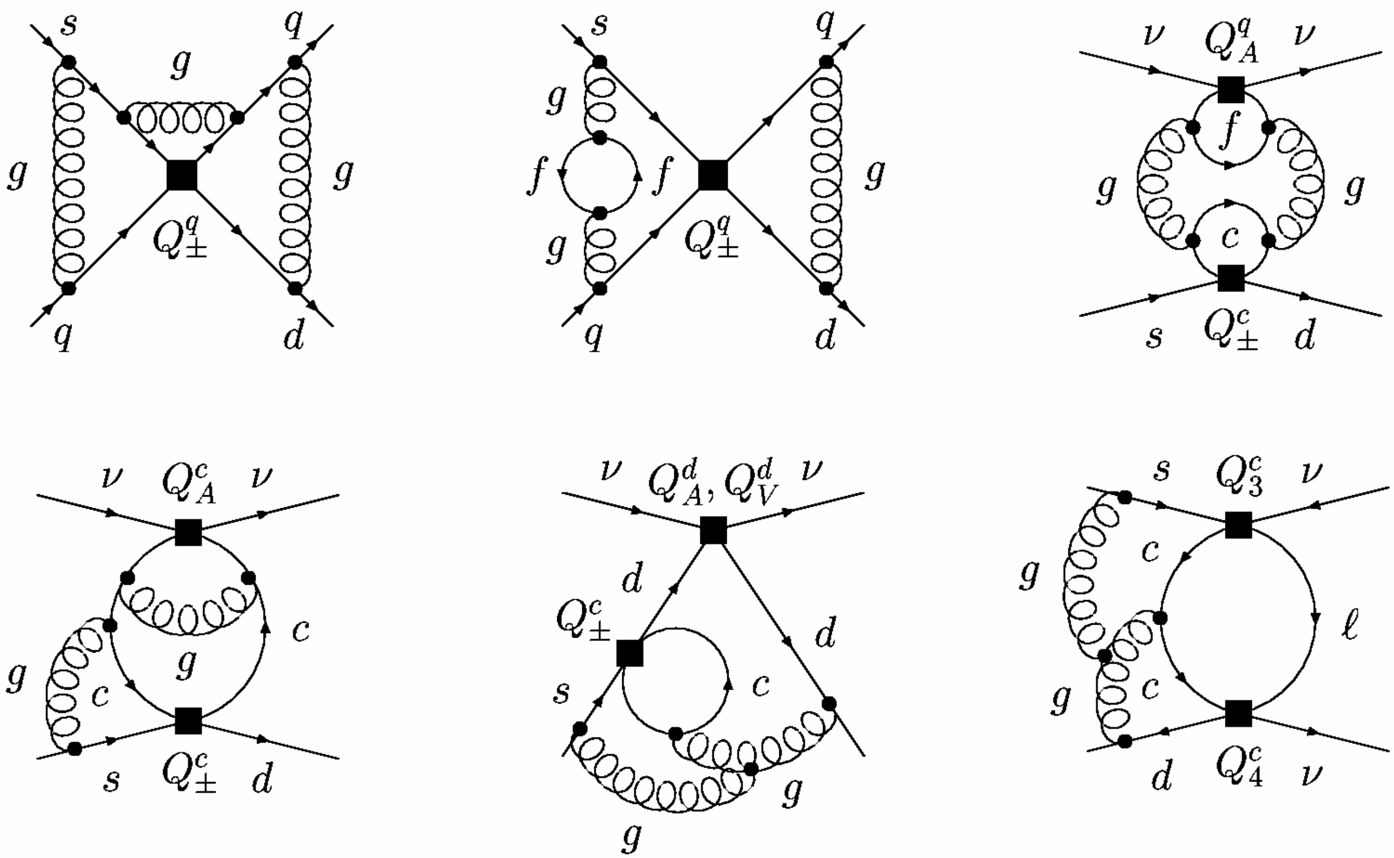






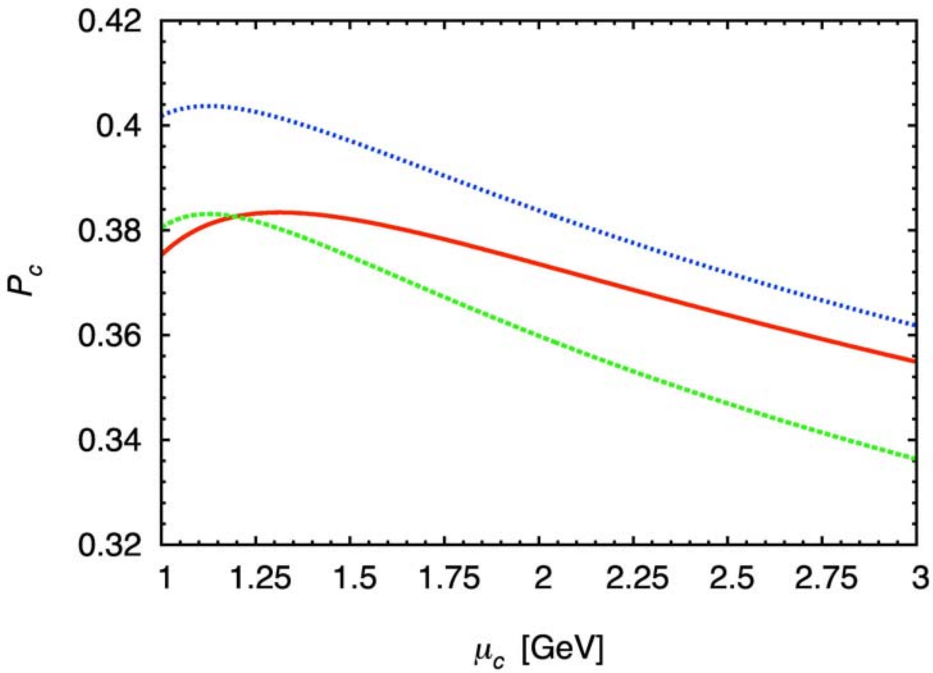


No Comments

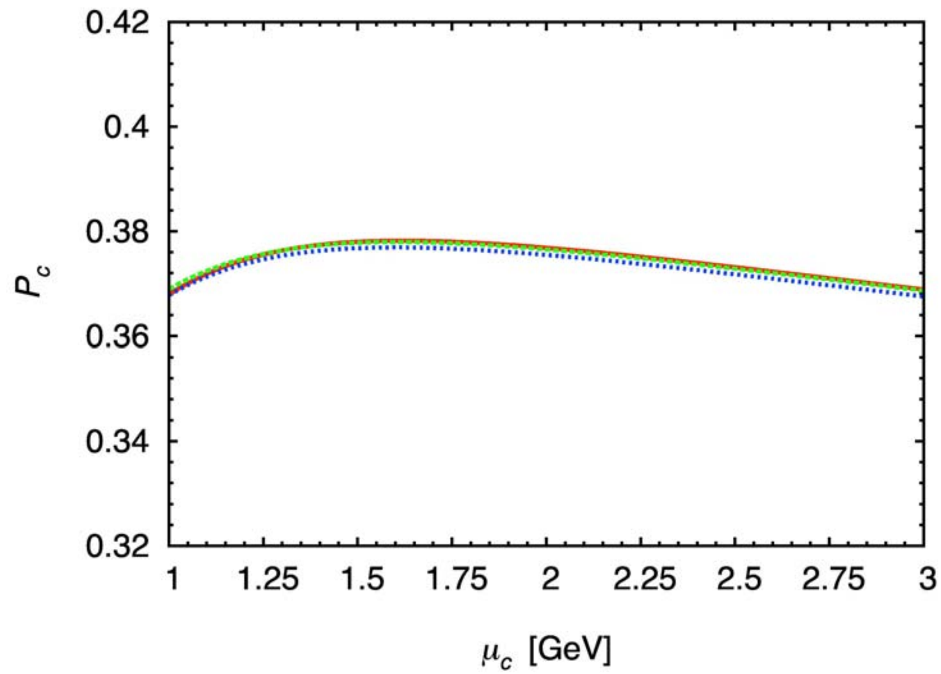


s q g g g $Q^q_\pm$ q d
s q g f f g g $Q^q_\pm$ q d
ν Q^q_A ν f g g c s $Q^c_\pm$ d
ν Q^c_A ν c g g c s $Q^c_\pm$ d
ν Q^d_A, Q^d_V ν d $Q^c_\pm$ d s c g g
s Q^c_3 ν g c ℓ g c d Q^c_4 ν

$P_c(\mu_c)$ for various calculations of $\alpha_s(\mu_c)$ from $\alpha_s(M_Z)$

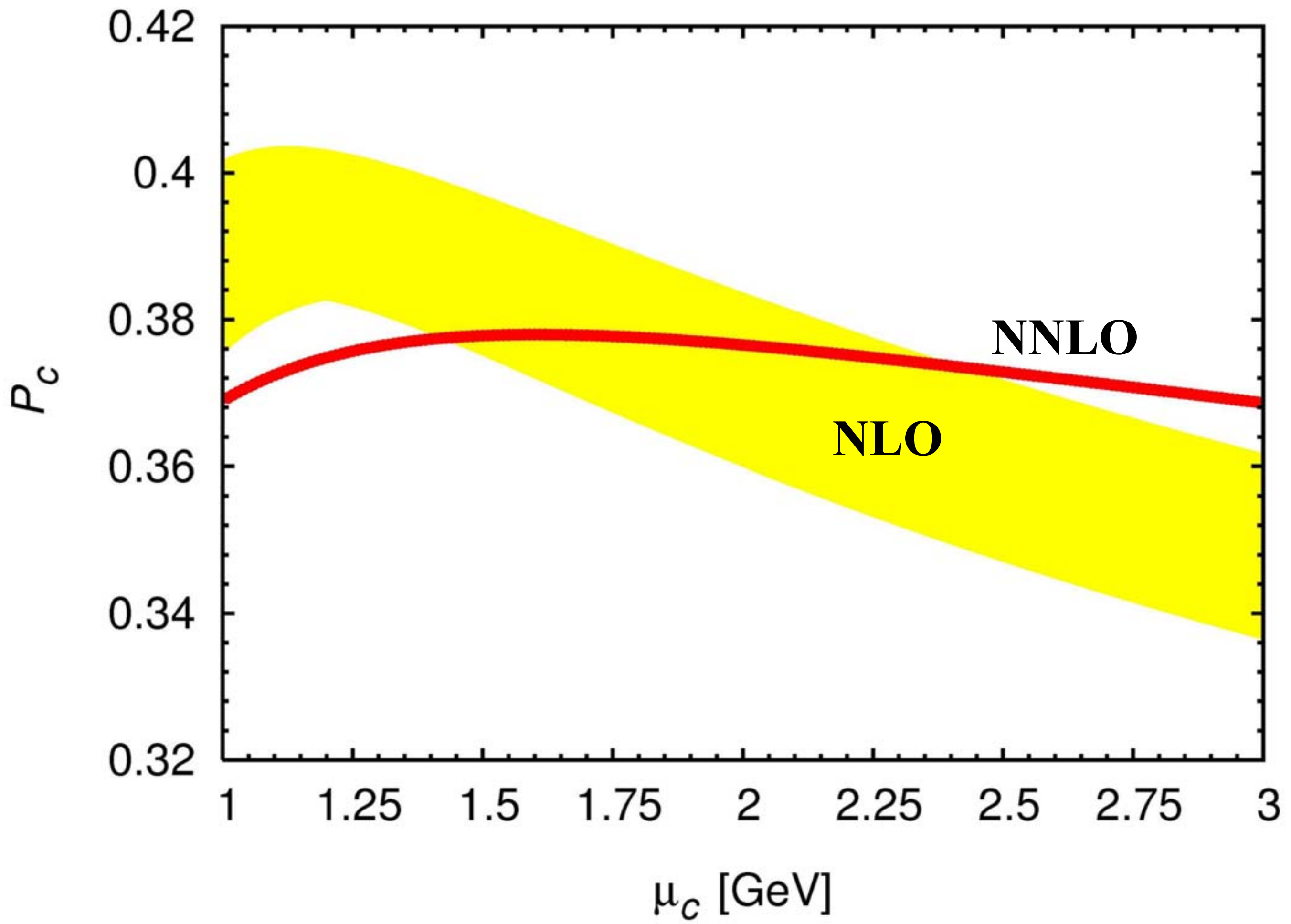


NLO

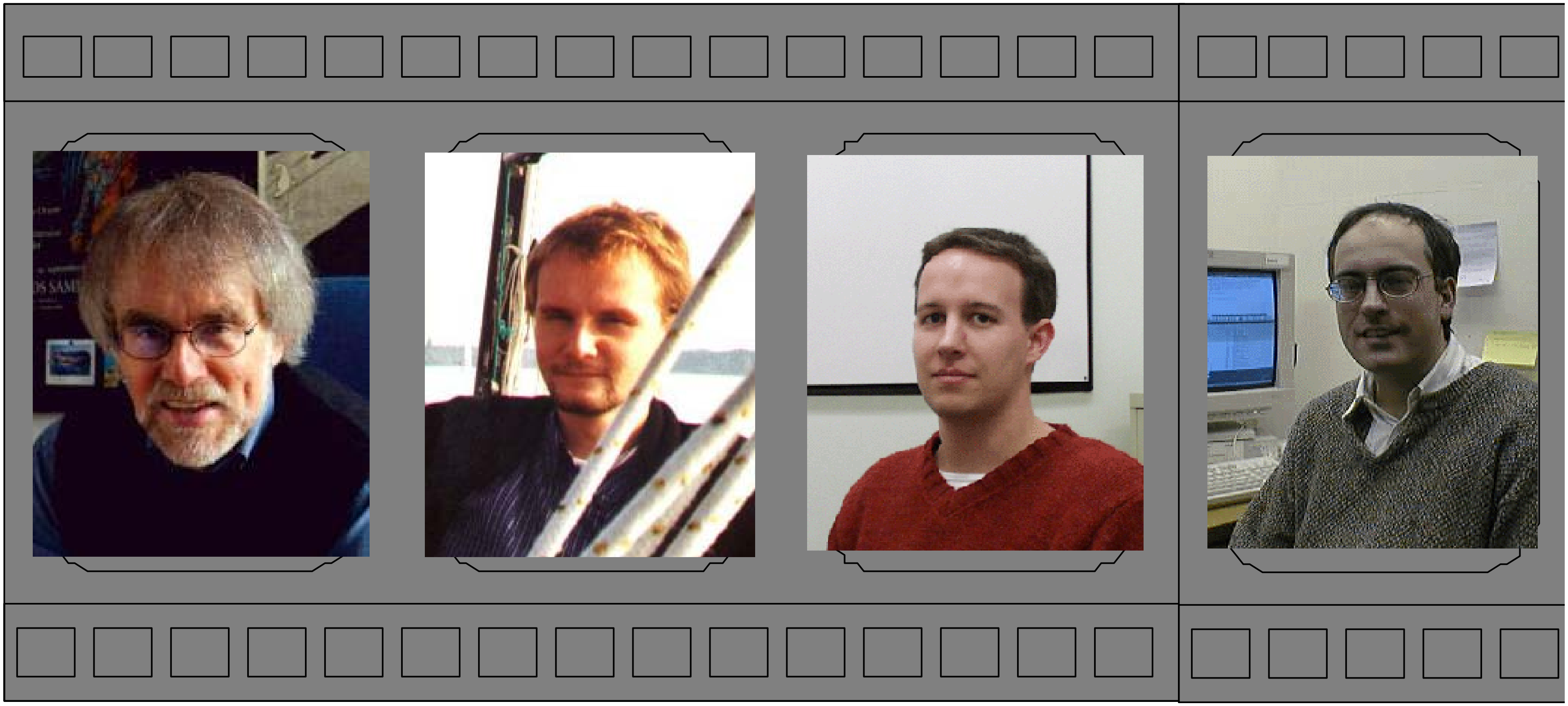


NNLO

Reduction of TH Error in P_c



Four Musketeers



AJB **Martin Gorbahn** **Ulrich Haisch** **Ulrich Nierste**

Anatomy of $|V_{td}|$ from $K^+ \to \pi^+ \nu\bar{\nu}$

AJB
Schwab
Uhlig

$$\frac{\sigma(|V_{td}|)}{|V_{td}|} = 0.39\frac{\sigma(P_c)}{P_c} + 0.70\frac{\sigma(Br(K^+))}{Br(K^+)} + \frac{\sigma(|V_{cb}|)}{|V_{cb}|}$$

Present:	$\pm$ 4%	$\pm$ (Very Large)	$\pm$ 2%	
$\sigma(Br(K^+)) = 10\%$, $\sigma(P_c) = 0.03$	$\pm$ 3%	$\pm$ 7%	$\pm$ 1.4%	(Scenario I)
$\sigma(Br(K^+)) = 5\%$, $\sigma(P_c) = 0.02$	$\pm$ 2%	$\pm$ 3.5%	$\pm$ 1%	(Scenario II)

Determination
at 4-5% possible

Theoretically clean Relations

D´Ambrosio + Isidori (02)

$$\mathrm{Br}\left(K^{+}\to\pi^{+}\nu\bar{\nu}\right)=\bar{\kappa}_{+}\left|V_{cb}\right|^{4}X^{2}\left[R_t^2\sin^2\beta+\left(R_t\cos^2\beta+\frac{\lambda^4P_c}{\left|V_{cb}\right|^2X}\right)^2\right]$$

$$R_t\sim\xi\frac{\sqrt{\Delta M_d}}{\sqrt{\Delta M_s}}\qquad\bar{\kappa}_{+}=7.64\cdot10^{-6}\qquad P_c=0.37\pm0.04$$

AJB, Schwab, Uhlig (04)

$$\mathrm{Br}\left(K^{+}\to\pi^{+}\nu\bar{\nu}\right)=\bar{\kappa}_{+}\left|V_{cb}\right|^{4}X^{2}\left[T_1^2+\left(T_2+\frac{\lambda^4P_c}{\left|V_{cb}\right|^2X}\right)^2\right]$$

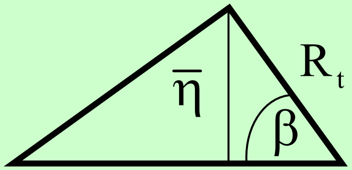
$$T_1=\frac{\sin\beta\sin\gamma}{\sin\left(\beta+\gamma\right)}\qquad T_2=\frac{\cos\beta\sin\gamma}{\sin\left(\beta+\gamma\right)}$$

(Direct $\not{C}\not{P}$)

Basic Formulae for $K_L \to \pi^o \nu \bar{\nu}$

(SM) Buchalla AJB (NLO)

$$Br\left(K_L \to \pi^o \nu\bar{\nu}\right) = 2.8 \cdot 10^{-11} \left[\frac{\bar{\eta}}{0.35}\right]^2 \left[\frac{|V_{cb}|}{41.5 \cdot 10^{-3}}\right]^4 \left[\frac{X}{1.48}\right]^2$$



$$= \left(2.8 \pm \underbrace{0.6}_{\text{CKM}}\right) \cdot 10^{-11}$$

(AJB Schwab Uhlig)

E391a : $Br\left(K_L \to \pi^o \nu\bar{\nu}\right) < 2.9 \cdot 10^{-7}$

Future: E391a, JHF

Model independent bound (Grossman, Nir)

$$Br\left(K_L \to \pi^o \nu\bar{\nu}\right) \le 4.4\, Br\left(K^+ \to \pi^+ \nu\bar{\nu}\right) \le 1.4 \cdot 10^{-9} \left(90\% C.L.\right)$$

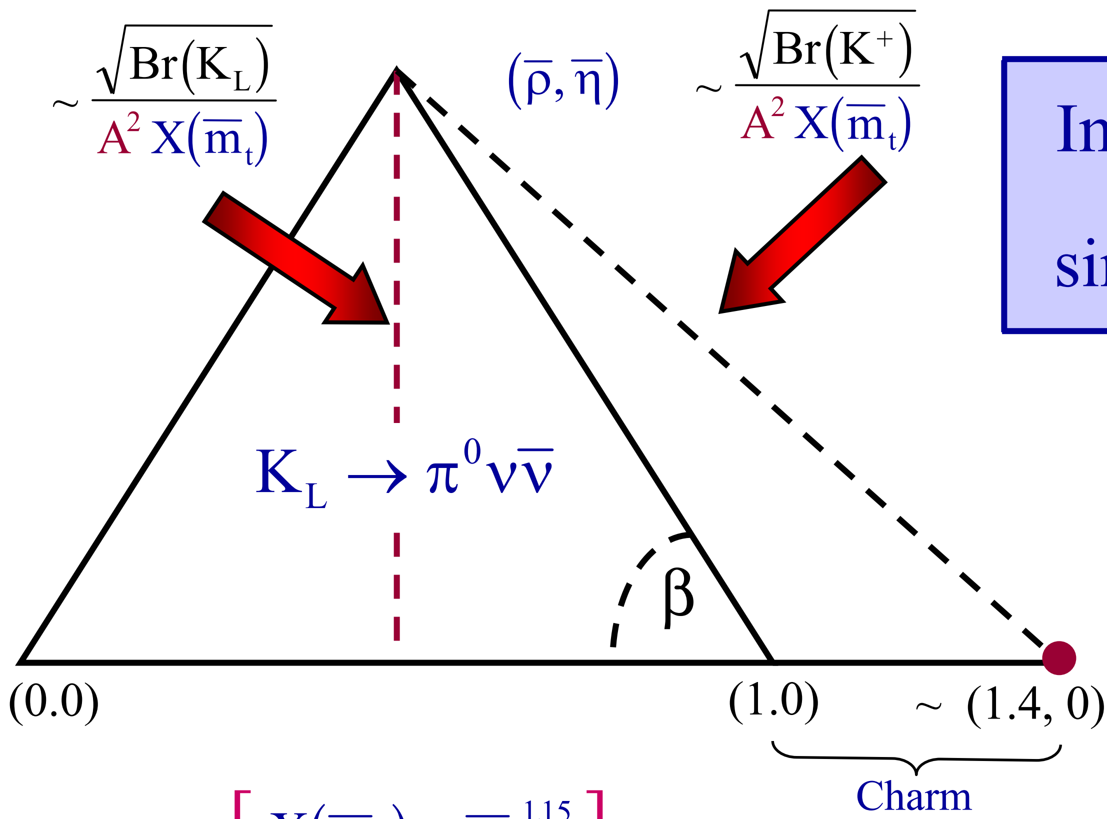
E391a could get the first non-trivial upper bound.

$$\bar{\eta} = R_t \sin\beta$$

E391 (JHF): ~ 1000 Events

UT from $K \to \pi\nu\bar{\nu}$

Buchalla
AJB



$$\operatorname{Im}\lambda_t = F_1(\bar{m}_t, Br(K_L))$$

$$\sin 2\beta = F_2(P_c, Br(K_L), Br(K^+))$$

$$\lambda_t = V_{ts}^* V_{td}$$

$\sin 2\beta$ $(K \to \pi\nu\bar{\nu})$ ⟷ $\sin 2\beta$ $(B \to J/\psi, K_s)$ $\to \varphi K_s$

K-Physics ⟷ B - Physics

$[\ X(\bar{m}_t) \sim \bar{m}_t^{1.15}\ ]$

(0.37 ± 0.04) ⟶ P_c

$$\sim \frac{P_c}{A^2 X(\bar{m}_t)}$$

Test of SM and Beyond

Golden Relations

(All involving $K_L \to \pi^0 \nu\bar{\nu}$)

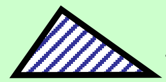
Buchalla, AJB (94)

$$\cot\beta = \frac{\sqrt{B_1 - B_2 - P_c}}{\sqrt{B_2}}$$

$$B_1 \sim Br\left(K^+ \to \pi^+ \nu\bar{\nu}\right)$$

$$B_2 \sim Br\left(K_L \to \pi^0 \nu\bar{\nu}\right)$$

$$\left(\sin 2\beta\right)_{\pi\nu\bar{\nu}} = \left(\sin 2\beta\right)_{\psi K_S}$$

$J_{CP} \sim$  $\sim \dfrac{\sqrt{Br\left(K_L \to \pi^0 \nu\bar{\nu}\right)}}{X\left(m_t\right)}$

AJB, Schwab, Uhlig (04)

$$\frac{\sin\beta\sin\gamma}{\sin\left(\beta+\gamma\right)} = 0.35\left[\frac{1.53}{X\left(m_t\right)}\right]\left[\frac{0.0415}{\left|V_{cb}\right|}\right]^2\sqrt{\frac{Br\left(K_L \to \pi^0 \nu\bar{\nu}\right)}{3\cdot 10^{-11}}}$$

β from $a_{\psi K_S}$

γ from $\begin{matrix} B_s^0 \to D_s^\pm K^\mp \\ B_d^0 \to D^\pm \pi^\mp \end{matrix}$

X

Reduction of TH Error: NLO → NNLO

AJB, Gorbahn, Haisch, Nierste (2005)

$$\sigma(|V_{td}|) \quad : \pm 4.1\% \rightarrow \pm 1\%$$

$$\sigma(\sin 2\beta) : \pm 0.025 \rightarrow \pm 0.006$$

$$\sigma(\gamma) \quad : \pm 4.9^{\circ} \rightarrow \pm 1.2^{\circ}$$

CKM from

$$K^{+} \rightarrow \pi^{+}\nu\bar{\nu}$$

$$K_{L} \rightarrow \pi^{0}\nu\bar{\nu}$$

Main parametric uncertainties : $m_c(m_c)$, $|V_{cb}|$

$$\sigma(P_c)_{m_c} = \left[\frac{0.67}{\mathrm{GeV}}\right] \sigma(m_c(m_c))$$

The Angle β from $K \to \pi\nu\bar{\nu}$

Buchalla, AJB (94)
AJB, Schwab, Uhlig (04)

BSU:

$$\frac{\sigma(\sin 2\beta)}{\sin 2\beta} = 0.31\frac{\sigma(P_c)}{P_c} + 0.55\frac{\sigma(Br(K^+))}{Br(K^+)} \pm 0.39\frac{\sigma(Br(K_L))}{Br(K_L)}$$

$\sigma(\sin 2\beta) =$	± 0.034	$\pm ?$	$\pm ?$	(Present)
$\sigma(\sin 2\beta) =$	0.017	± 0.039	± 0.028	(Scenario I) Br´s at 10%
$\sigma(\sin 2\beta) =$	0.011	± 0.020	± 0.014	(Scenario II) Br´s at 5%

TH very clean

$\sigma(\sin 2\beta) \approx 0.02 - 0.03$ requires $\sigma(Br´s) \leq 5\%$

The Angle γ from $K \to \pi\nu\bar{\nu}$

AJB, Schwab, Uhlig (04)

$$\frac{\sigma(\gamma)}{\gamma} = 0.75\frac{\sigma(P_c)}{P_c} + 1.32\frac{\sigma(Br(K^+))}{Br(K^+)} + 0.07\frac{\sigma(Br(K_L))}{Br(K_L)} + 4.1\frac{\sigma(|V_{cb}|)}{|V_{cb}|}$$

$\sigma(\gamma) =$	$\pm 4.9^\circ$	$\pm ?$	$\pm ?$	$\pm 4.9^\circ$	(Present)
$\sigma(\gamma) =$	$\pm 3.7^\circ$	$\pm 8.5^\circ$	$\pm 0.4^\circ$	$\pm 3.8^\circ$	(Scenario I) Br´s at 10%
$\sigma(\gamma) =$	$\pm 2.5^\circ$	$\pm 4.2^\circ$	$\pm 0.2^\circ$	$\pm 2.5^\circ$	(Scenario II) Br´s at 5%

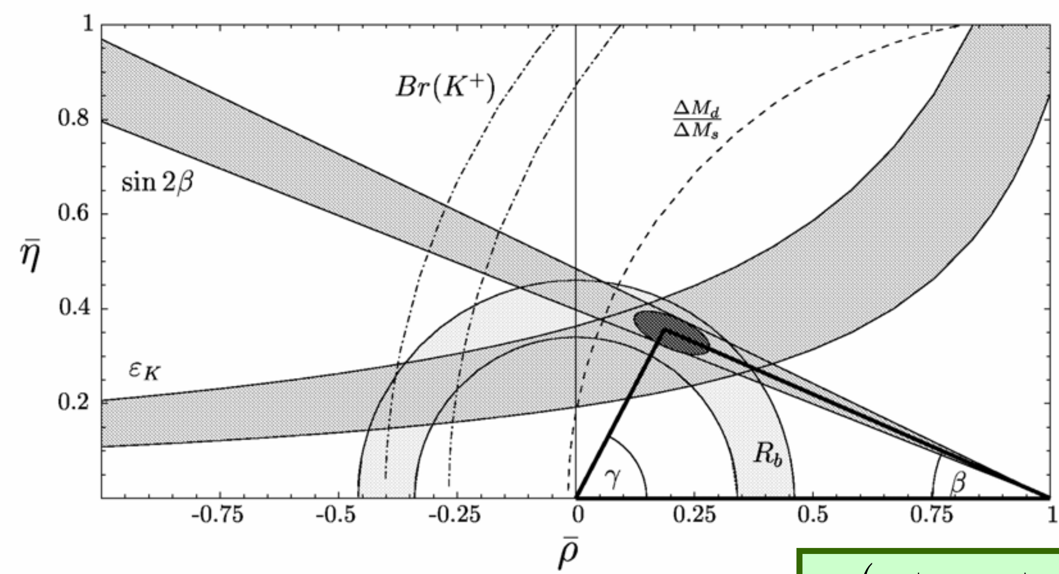
TH very clean

$\sigma(\gamma) \approx \pm 5^\circ$ requires $\sigma(Br(K^+)) \leq 5\%$

Unitarity Triangle 2004

(AJB, Schwab, Uhlig)

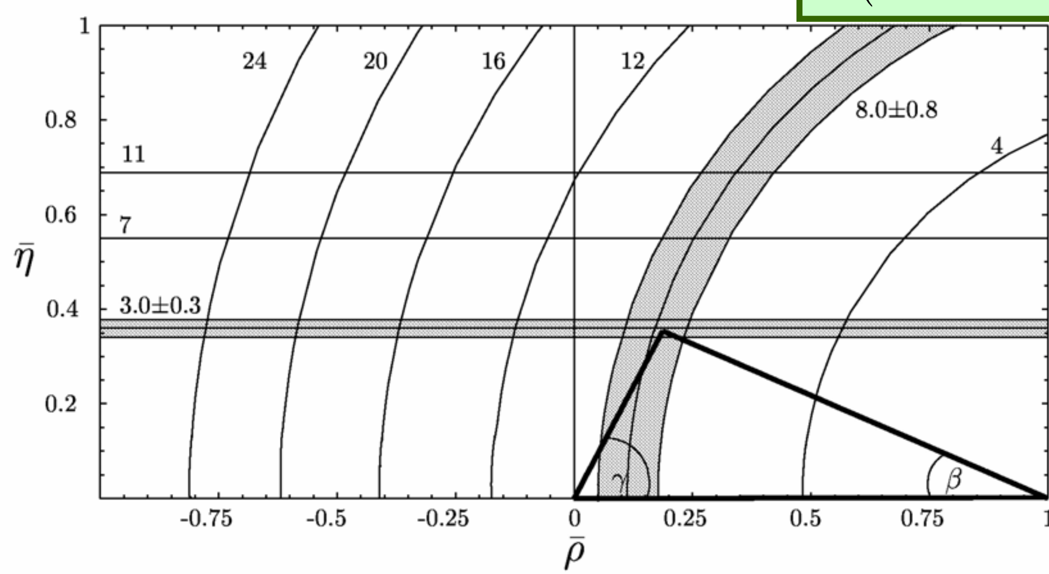
$$Br(K^+) \equiv Br(K^+ \to \pi^+ \nu\bar{\nu}) = 14.7 \cdot 10^{-11}$$



$P_c = \underline{\underline{0.37}} \pm 0.04$

$m_c,\ V_{cb},\ \mu_c$

$Br(K^+ \to \pi^+ \nu\bar{\nu})$



$Br(K_L \to \pi^0 \nu\bar{\nu})$

Unitarity Triangle from $K \to \pi\nu\bar{\nu}$

(2012)

Minimal Flavour Violation (MFV)

$$A(\text{Decay}) = \sum_i B_i \eta^i_{QCD} V^i_{CKM} \overbrace{\underbrace{\left[F^i_{SM} + F^i_{New}\right]}_{\text{real}}}^{F_i(v)}$$

AJB, Gambino, Gorbahn, Jäger, Silvestrini
D'Ambrosio, Giudice, Isidori, Strumia

K and B Physics related to each other

SM: $v = x_t$

1. All flavour changing processes governed by V^i_{CKM} .
2. Only SM Operators are relevant.
3. New Physics enters only through 7 Master Functions

$$F_i(v) = S(v), X(v), Y(v), Z(v), D'(v), E'(v), E(v)$$

$v =$ collects parameters specific to a given MFV model.

Review: AJB hep-ph/0310208

MFV "Sum Rules"

Relations that do not involve the Master Functions X, Y, Z, S, etc.

Violation of these relations signals new flavour (CP) violating interactions beyond CKM or new operators that are strongly suppressed in SM

Examples

$$(\sin 2\beta)_{\pi\nu\bar{\nu}} = (\sin 2\beta)_{\psi K_s}$$

$$\frac{Br(B_s \to \mu^+\mu^-)}{Br(B_d \to \mu^+\mu^-)} = \frac{\tau(B_s)}{\tau(B_d)} \frac{m_{B_s}}{m_{B_d}} \left[\frac{F_{B_s}}{F_{B_d}}\right]^2 \left[\frac{|V_{ts}|}{|V_{td}|}\right]^2$$

$$\frac{\Delta M_d}{\Delta M_s} = \frac{m_{B_d}}{m_{B_s}} \frac{\hat{B}_d}{\hat{B}_s} \frac{F_{B_d}^2}{F_{B_s}^2} \frac{|V_{td}|^2}{|V_{ts}|^2}$$

$$\frac{Br(B \to X_d \nu\bar{\nu})}{Br(B \to X_s \nu\bar{\nu})} = \frac{|V_{td}|^2}{|V_{ts}|^2}$$

Universal Unitarity Triangle (UUT) can be constructed

Intriguing Property of Models with Minimal Flavour Violation

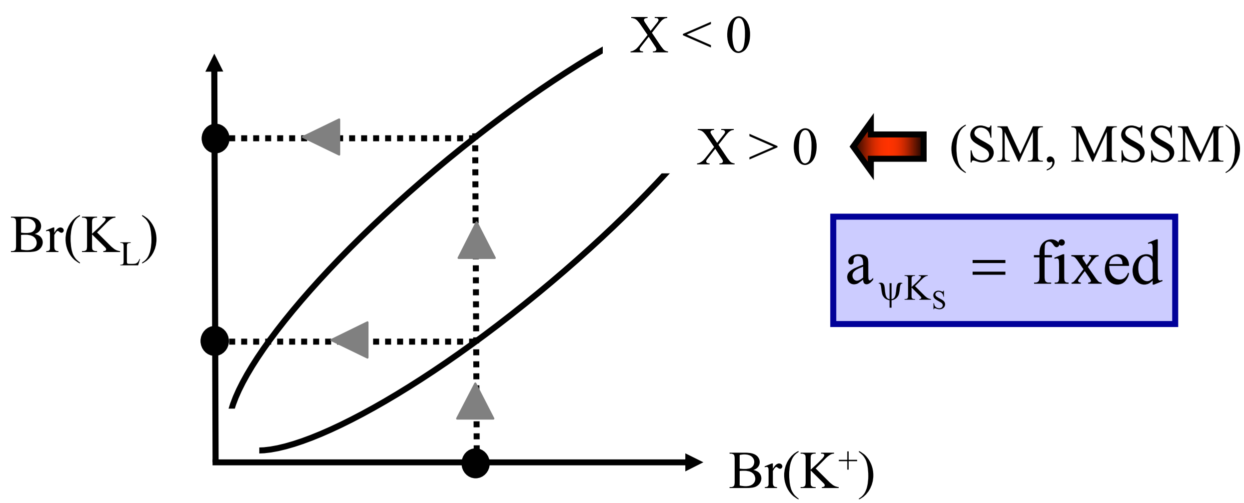
AJB, Fleischer (01)

$$Br(K_L) = F\left(Br(K^+),\ a_{\psi K_S},\ sgn(X)\right)$$

TH very clean

Independently of any parameters, for given $Br(K^+)$ and $a_{\psi K_S}$ only <u>two values</u> of $Br(K_L)$ possible.

X < 0 very unlikely



$a_{\psi K_S}$ = fixed

MFVfit Collaboration

(BBBEPSW)
hep-ph/0505110

Use the existing results for

1. UUTfit
2. $B \rightarrow X_s \gamma$
3. $B \rightarrow X_s l^+ l^-$
4. $K^+ \rightarrow \pi^+ \nu \bar{\nu}$

⇒

$X_{max}(v) = 1.95$ $\quad$ $Y_{max}(v) = 1.43$

$(X_{SM} \cong 1.48)$ $\quad$ $(Y_{SM} \cong 0.98)$

⇓

Model Independent Upper Bounds within MFV Scenario

Conclusion : Large Departures from SM within MFV not possible

Upper Bounds on Rare K and B Decays from MFV

Bobeth, Bona, AJB, Ewerth, Pierini, Silvestrini, Weiler hep-ph/0505110

Branching Ratios	MFV (95%)	SM (95%)	SM (68%)	Exp
$Br(K^+ \to \pi^+ \nu\bar{\nu}) \cdot 10^{11}$	<11.9	<10.9	8.3 ± 1.2	$14.7^{+13.0}_{-8.9}$
$Br(K_L \to \pi^0 \nu\bar{\nu}) \cdot 10^{11}$	<4.6	<4.2	3.1 ± 0.6	$<5.9 \cdot 10^4$
$Br(B \to X_s \nu\bar{\nu}) \cdot 10^{5}$	<5.2	<4.1	3.7 ± 0.2	<64
$Br(B_s \to \mu^+ \mu^-) \cdot 10^{9}$	<7.4	<5.9	3.7 ± 1.0	$<5.0 \cdot 10^2$
$Br(B_d \to \mu^+ \mu^-) \cdot 10^{10}$	<2.2	<1.8	1.1 ± 0.4	$<1.6 \cdot 10^3$

Magnificent Seven







$K^+ \rightarrow \pi^+ \nu\bar{\nu}$ and $K_L \rightarrow \pi^0 \nu\bar{\nu}$ beyond MFV

1. $\{\text{Real } X\} \rightarrow |X| e^{i\theta_x} \qquad \theta_x \neq 0$

2. Relation to other K decays and in particular to B decays not necessarily present.

3. CP conserving contributions to $K_L \rightarrow \pi^0 \nu\bar{\nu}$ in models with Lepton mixing (Grossman, Nir, Perez, Isidori, Murayama)

Scenario with New Physics Contributions dominated by enhanced EW-Penguins with a new complex weak phase

Colangelo, Isidori (98); AJB, Silvestrini (99); AJB, Romanino Silvestrini (99); AJB, Colangelo, Isidori, Romanino, Silvestrini (00); Buchalla, Hiller, Isidori (01); Atwood, Hiller (02)

AJB, Fleischer, Recksiegel, Schwab (03, 04, 05)

↓

Enhanced EW-Penguins with $\theta_x \approx -90^o$ signaled by $B \to \pi K$ anomalies

→

Spectacular Modifications of $K \to \pi \nu \bar{\nu}$ relative to SM and MFV

Implications for $K^+ \to \pi^+ \nu\bar{\nu}$ and $K_L \to \pi^o \nu\bar{\nu}$

(BFRS)

$$Br(K^+ \to \pi^+ \nu\bar{\nu})_{SM} = (7.8 \pm 1.2) \cdot 10^{-11} \Rightarrow (7.5 \pm 2.1) \cdot 10^{-11}$$

Enhancement of |X| compensated by destructive "top-charm" interference

$$Br(K_L \to \pi^o \nu\bar{\nu})_{SM} = (3.0 \pm 0.6) \cdot 10^{-11} \Rightarrow (3.1 \pm 1.0) \cdot 10^{-10}$$

Strong Violation of the "Golden" Relation :

Buchalla, AJB (94)

SM: $(\sin 2\beta)_{\pi\nu\bar{\nu}} = (\sin 2\beta)_{\psi K_S}$

Here: $-\left(0.69 \begin{smallmatrix}+0.23 \\ -0.41\end{smallmatrix}\right) \neq 0.72 \pm 0.03$

$\sin 2\beta_X$

$$\beta_X = \beta - \theta_X$$

$$X = |X| e^{i\theta_X}$$

$\beta_X \cong 110^o$

FIG

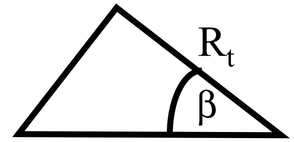
Saturation of the model-independent Grossman-Nir bound :

$$Br(K_L \to \pi^o \nu\bar{\nu}) \leq 4.4 \; Br(K^+ \to \pi^+ \nu\bar{\nu})$$

Here:

$$\frac{Br(K_L \to \pi^o \nu\bar{\nu})}{Br(K^+ \to \pi^+ \nu\bar{\nu})} \approx 4.4 \; \sin^2(\beta_X) \approx 4.2 \pm 0.2$$

Impact of $X = |X| e^{i\theta_X}$ on $K^+ \to \pi^+ \nu\bar{\nu}$



$(A \approx 0.83)$

$(P_c \approx 0.39)$

$$Br\left(K^+ \to \pi^+ \nu\bar{\nu}\right) = 4.8 \cdot 10^{-11} \left[A^4 R_t^2 |X|^2 + 2 P_c A^2 R_t |X| \cos \overbrace{(\beta - \theta_X)}^{\beta_X} + P_c^2 \right]$$

SM:	=	10^{-11} [4.1	+	3.0	+	0.7]	X= 1.53
Here:	=	10^{-11} [8.5	−	1.7	+	0.7]	$X = 2.2 e^{-i86^o}$
		(top)		(charm-top)		(charm)	$\beta\text{-}\theta_X \approx 110^o$

$$Br\left(K^+ \to \pi^+ \nu\bar{\nu}\right) = (7.8 \pm 1.2) \cdot 10^{-11} \Rightarrow (7.5 \pm 2.1) \cdot 10^{-11}$$

(SM)

Impact of $X = |X| e^{i\theta_X}$ on $K_L \to \pi^o \nu\bar{\nu}$ (BFRS)

$$\frac{Br(K_L \to \pi^o \nu\bar{\nu})}{Br(K_L \to \pi^o \nu\bar{\nu})_{SM}} = \underbrace{\left|\frac{X}{X_{SM}}\right|^2}_{\approx 2} \underbrace{\left[\frac{\sin(\beta - \theta_X)}{\sin\beta}\right]^2}_{\approx 5}$$

$\beta\text{-}\theta_X \approx 110^o$
$\beta \cong 24^o$

$$Br(K_L \to \pi^o \nu\bar{\nu}) = (3.0 \pm 0.6) \cdot 10^{-11} \Rightarrow (3.1 \pm 1.0) \cdot 10^{-10}$$

(SM) (Here)

$$\frac{Br(K_L \to \pi^o \nu\bar{\nu})}{Br(K^+ \to \pi^+ \nu\bar{\nu})} = \underset{(SM)}{0.4} \Rightarrow 4.2$$

< 4.4 Grossman-Nir bound

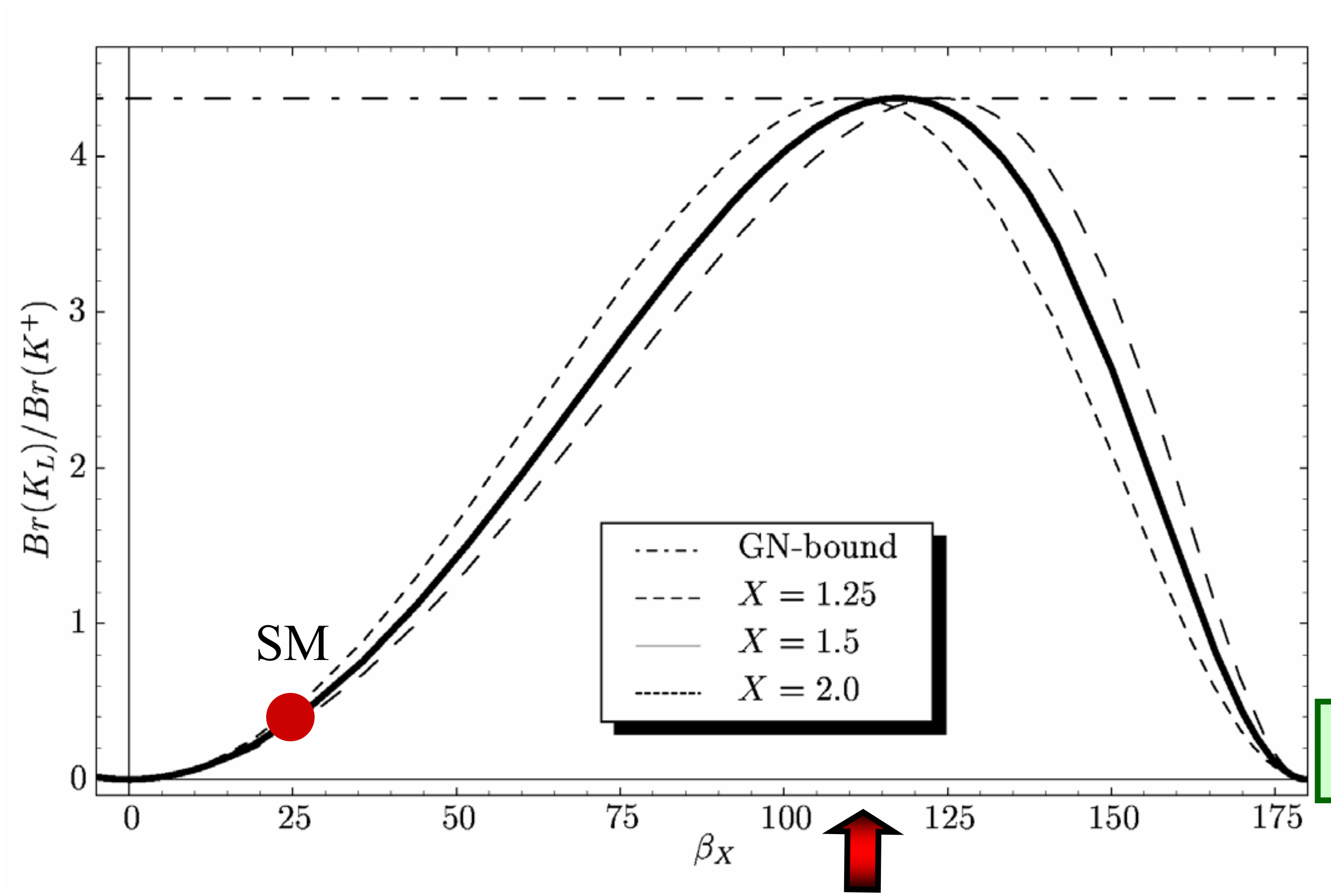
Order of magnitude enhancement !!

$$\frac{Br\left(K_L \to \pi^0 \nu\bar{\nu}\right)}{Br\left(K^+ \to \pi^+ \nu\bar{\nu}\right)} \text{ versus } \beta_X$$

BSU (04)

$$\beta_x = \beta - \theta_X$$

New Phase in EWP

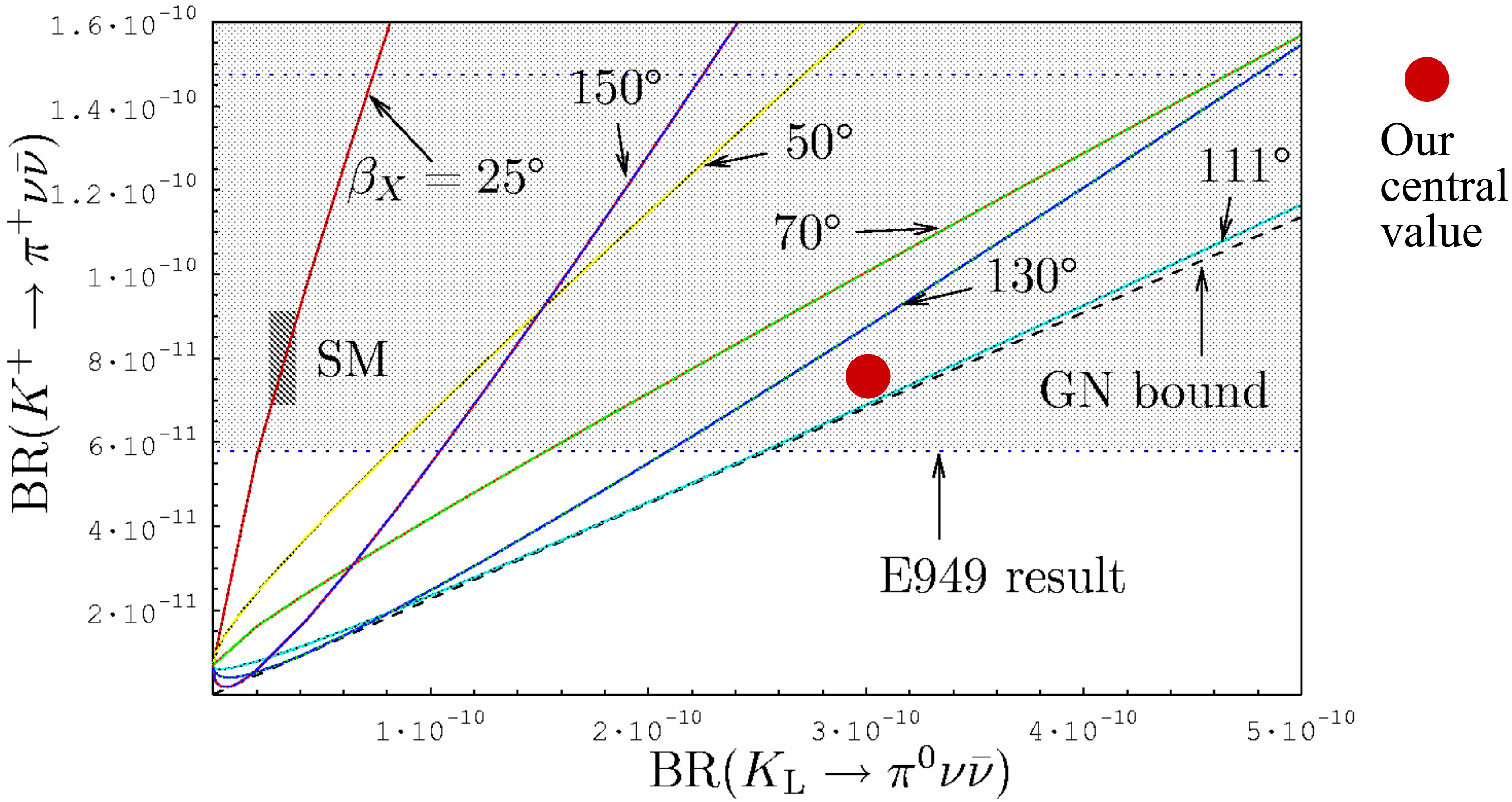


$\theta_X \approx -90^o$

Necessary to fit B→πK data (BFRS)

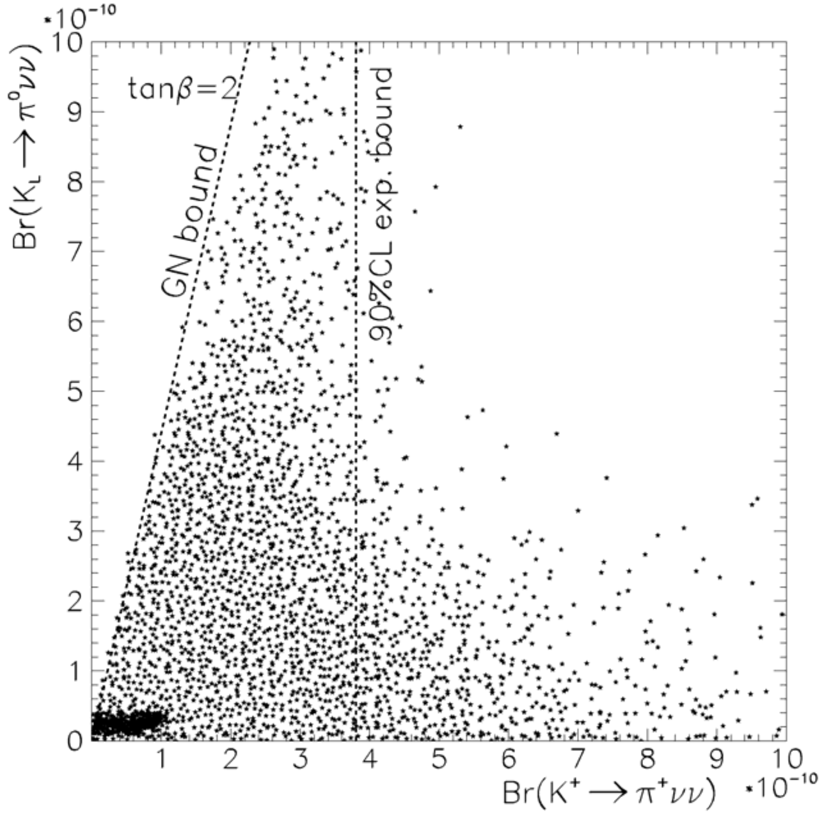
$K^+ \to \pi^+ \nu\bar{\nu}$ and $K_L \to \pi^0 \nu\bar{\nu}$ with $X = |X| e^{i\theta_x}$ (BFRS)

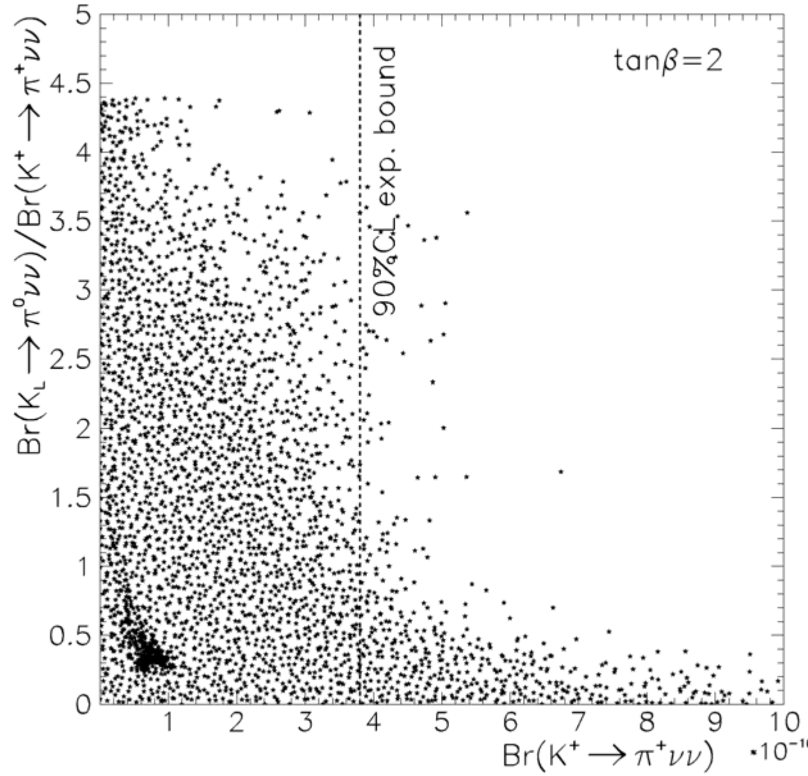
$$\beta_x = \beta - \theta_x$$



$K_L \rightarrow \pi^0 \nu\bar{\nu}$ and $K^+ \rightarrow \pi^0 \nu\bar{\nu}$ from a general MSSM

AJB, Ewerth, Jäger, Rosiek (04)





Relations between $\Delta M_{s,d}$ and $B_{s,d} \to \mu\bar{\mu}$ in Models with Minimal Flavour Violation

(AJB, hep-ph/0303060)

$$\Delta M_q \sim \hat{B}_q F_{B_q}^2 \left|V_{tq}\right|^2 S(x_t, x_{new})$$

$$Br(B_q \to \mu\bar{\mu}) \sim F_{B_q}^2 \left|V_{tq}\right|^2 Y^2(x_t, \bar{x}_{new})$$

Large hadronic uncertainties due to $F_{B_q}^2$

$$F_{B_d}\sqrt{\hat{B}_d} = \left(235 \pm 33 \begin{matrix} +0 \\ -24 \end{matrix}\right) \mathrm{MeV} \qquad F_{B_d} = (189 \pm 27)\ \mathrm{MeV}$$

$$F_{B_s}\sqrt{\hat{B}_d} = (276 \pm 38)\,\mathrm{MeV} \qquad F_{B_s} = (230 \pm 30)\ \mathrm{MeV}$$

$$\hat{B}_d = 1.34 \pm 0.12$$

$$\hat{B}_s = 1.34 \pm 0.12 \qquad \frac{\hat{B}_s}{\hat{B}_d} = 1.00 \pm 0.03$$

(No problems with chiral logs and quenching)

$Br(B_{s,d} \to \mu\bar{\mu})$ from $\Delta M_{s,d}$

$$Br(B_q \to \mu\bar{\mu}) = 4.36 \cdot 10^{-10} \frac{\tau(B_q)}{\hat{B}_q} \frac{Y^2(x_t, \bar{x}_{new})}{S(x_t, x_{new})} \Delta M_q$$

No dependence on $F^2_{B_q}$

SM:

$$Br(B_s \to \mu\bar{\mu}) = 3.42 \cdot 10^{-9} \left[\frac{\tau(B_s)}{1.46\mathrm{ps}}\right] \left[\frac{1.34}{\hat{B}_s}\right] \left[\frac{\bar{m}_t(m_t)}{167\ \mathrm{GeV}}\right]^{1.6} \left[\frac{\Delta M_s}{18.0/\mathrm{ps}}\right]$$

$$Br(B_d \to \mu\bar{\mu}) = 1.00 \cdot 10^{-10} \left[\frac{\tau(B_d)}{1.54\mathrm{ps}}\right] \left[\frac{1.34}{\hat{B}_d}\right] \left[\frac{\bar{m}_t(m_t)}{167\ \mathrm{GeV}}\right]^{1.6} \left[\frac{\Delta M_d}{0.50/\mathrm{ps}}\right]$$

(Example)

$\Delta M_s = (18.0 \pm 0.5/\mathrm{ps})$ ⇒ $Br(B_s \to \mu\bar{\mu}) = (3.42 \pm 0.54) \cdot 10^{-9}$

$\Delta M_d = (0.503 \pm 0.006/\mathrm{ps})$ ⇒ $Br(B_d \to \mu\bar{\mu}) = (1.00 \pm 0.14) \cdot 10^{-10}$

Moreover new Physics Effects can be easier seen

Testing MFV through $B_{s,d} \to \mu\bar{\mu}$ and $\Delta M_{s,d}$

$$\frac{Br(B_s \to \mu\bar{\mu})}{Br(B_d \to \mu\bar{\mu})} = \underbrace{\frac{\hat{B}_d}{\hat{B}_s}}_{(1.00\pm 0.03)} \underbrace{\frac{\tau(B_s)}{\tau(B_d)} \frac{\Delta M_s}{\Delta M_d}}_{\text{Experiment}}$$

Valid in MFV models in which only SM operators relevant.

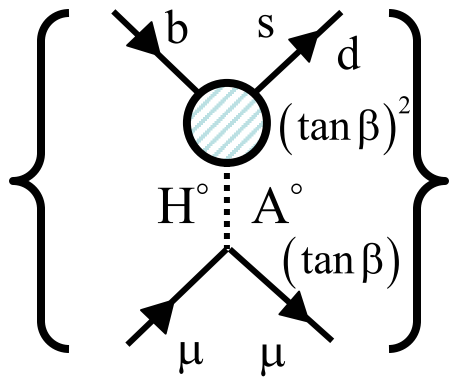
Violation of this relation would indicate the presence of new operators and generally of non-minimal flavour violation.

MSSM at large tanβ

$\left(B_{s,d} \to \mu^+\mu^-\right)$

In MSSM at large tanβ
(CKM still the only source of Flavour and CP Violation)

Strong Enhancement



$$\mathrm{Br}\left(B_{s,d} \to \mu\bar{\mu}\right) \sim (\tan\beta)^6$$

$10^{-6}\left(10^{-7}\right)$ possible

SM ~ 10^{-9}

Babu, Kolda
Chankowski, Slawianowska
Bobeth, Ewerth, Krüger, Urban
Huang, Liao, Yan, Zhu
Isidori, Retico
Dedes, Dreiner, Nierste
Dedes, Pilaftis
Chankowski, Rosiek
Foster, Okumura, Roszkowski

$$\mathrm{Br}\left(B_s \to \mu\bar{\mu}\right) < 1.5 \cdot 10^{-7}$$

$$\mathrm{Br}\left(B_d \to \mu\bar{\mu}\right) < 4.0 \cdot 10^{-8}$$

CDF, D∅

95% C.L.

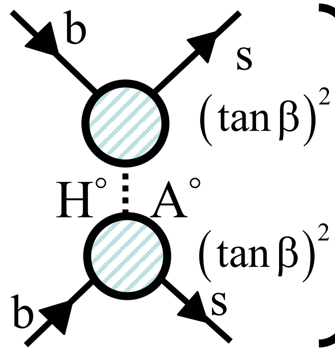
MSSM at large tanβ (cont.)

(ΔM_s)

$B_s^0 - \bar{B}_s^0$ Mixing

(Double-Higgs Peguin)

Suppression



$$\Rightarrow \left\{ \Delta M_s \approx (\Delta M_s)^{SM} - c(\tan\beta)^4 \right\}$$

AJB, Chankowski, Rosiek
Slawianowska (2001, 2002)

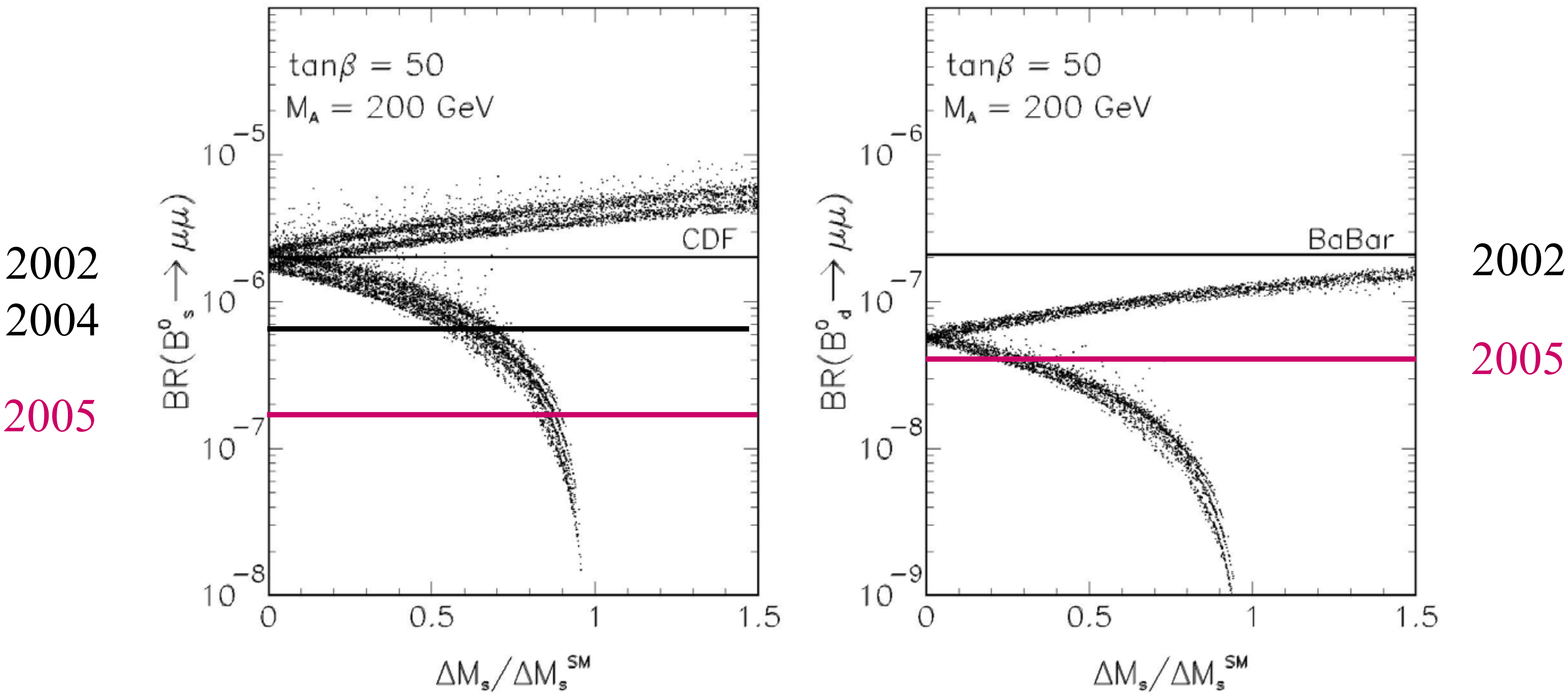
Correction between
SUSY effects in
$Br(B_{s,d} \to \mu\bar{\mu})$ and ΔM_s

Negligible contributions to ΔM_d, ε_K ⇐ Clear violation of K↔B MFV relations

Subsequent analyses: D'Ambrosio, Giudice, Isidori, Stumia
Dedes, Pilaftis

$Br\left(B_{s,d} \to \mu^+\mu^-\right)$ vs $(\Delta M_s)^{exp}/(\Delta M_s)^{SM}$ in SUSY at Large $\tan\beta$

AJB, Chankowski, Rosiek, Slawianowska, hep-ph/0207241



Comparison of different Models

	universal extra dimensions	MSSM (CKM) large tanβ	MSSM (CKM) low tanβ	Littlest Higgs
$Br(K^+ \to \pi^+ \nu\bar{\nu})$	⇧	No effect	⇩	⇩
$Br(K_L \to \pi^0 \nu\bar{\nu})$	⇧	No effect	⇩	⇩
$Br(B_s \to \mu\bar{\mu})$	⇧	⇧⇧⇧	⇧⇩	⇧
ΔM_s	⇧	⇩	⇧	⇧
Collaboration with:	Spranger Weiler (02)	see previous refs.	Gambino Gorbahn Jäger Silvestrini (01)	Poschenrieder Uhlig (04)

Please !! Measure !! (Before 2012)

$$Br\left(K^+ \to \pi^+ \nu\bar{\nu}\right) \qquad Br\left(K_L \to \pi^0 \nu\bar{\nu}\right)$$

$$Br\left(B_{s,d} \to \mu\bar{\mu}\right) \qquad \Delta M_S$$

and γ independently of NP

⇒ We will know much more about flavour physics