Constraints on R-parity violating interactions in MSSM from leptonic decays of pseudoscalar mesons

Hikaru Matsuo
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ICEPP

Aida, Asakawa, Cho, HM, PRD82, 115008(2010)
Cho, HM, PLB703, 318(2011)

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  - $B^+ \to \tau\nu$
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Leptonic decays of Ds-meson

- decay rate of a pseudoscalar meson

$$\Gamma(P \to l_i \nu_j) = \frac{1}{8\pi} G_F^2 |V_{u_a d_b}|^2 f_P^2 m_{l_i}^2 m_P \left(1 - \frac{m_{l_i}^2}{m_P^2}\right)^2$$

Dec/2010

CLEO,BaBar,Belle

$$f_{D_s} = 259.0 \pm 6.9 \ [\text{MeV}]$$

PRD80, 112004 (2009),...

HPQCD+UKQCD

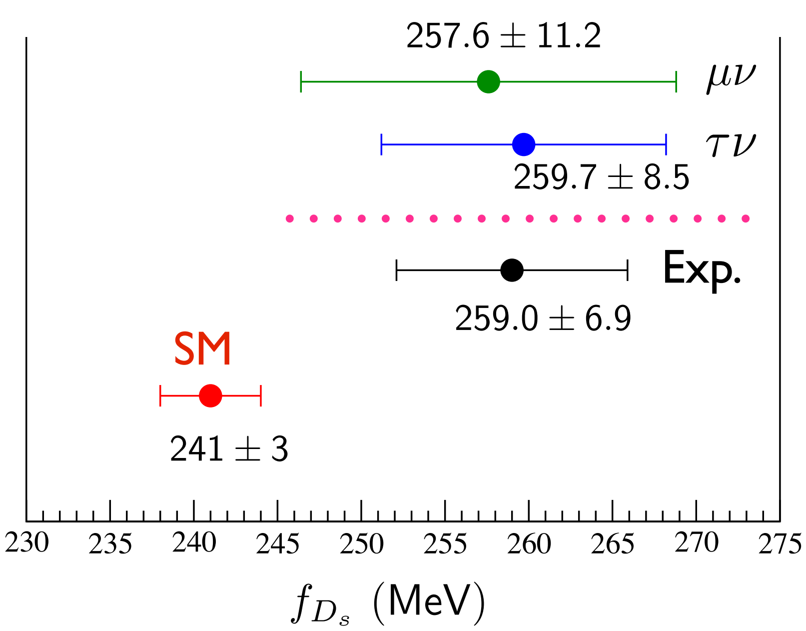
$$f_{D_s} = 241 \pm 3 \ [\text{MeV}]$$

PRL100, 062002 (2008)

2.4-sigma deviation

New Physiscs ... !?

$D_s \to \tau\nu, \mu\nu$



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CLEO,BaBar,Belle

$$f_{D_s}^{\rm exp} = 257.3 \pm 5.3 \text{ [MeV]}$$

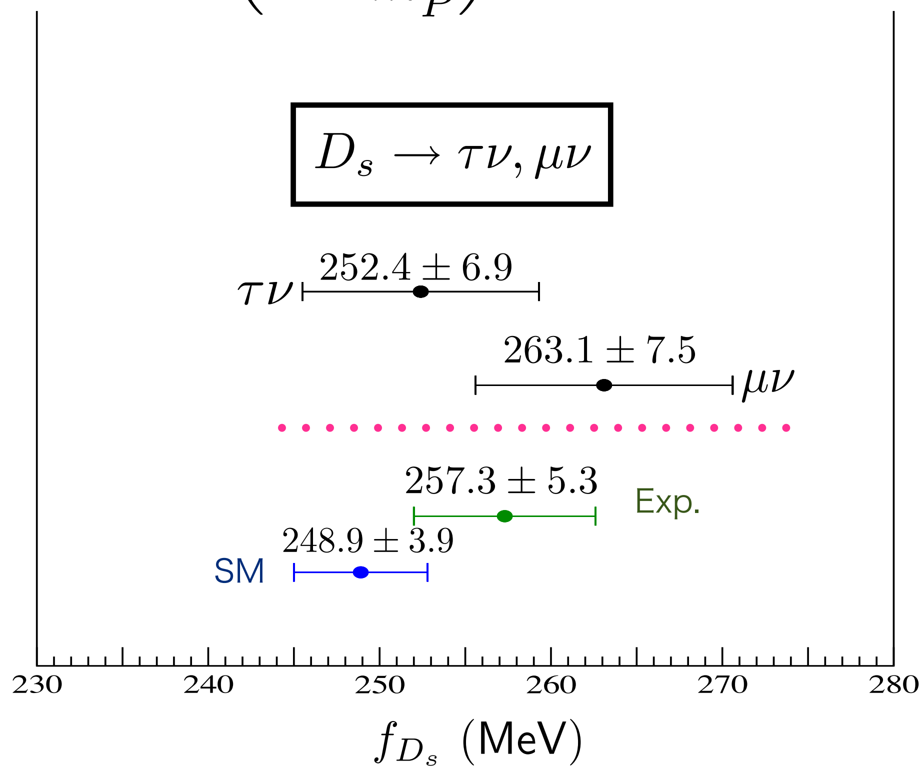
PRD82, 091103; PRD79,052001;
PRL100,241801, ...

FNAL,MILC,HPQCD

$$f_{D_s}^{SM} = 248.9 \pm 3.9 \text{ [MeV]}$$

Pos LATTICE2010, 317(2010);
arXiv: 1008.4018[hep-latt].

1.3-sigma deviaton



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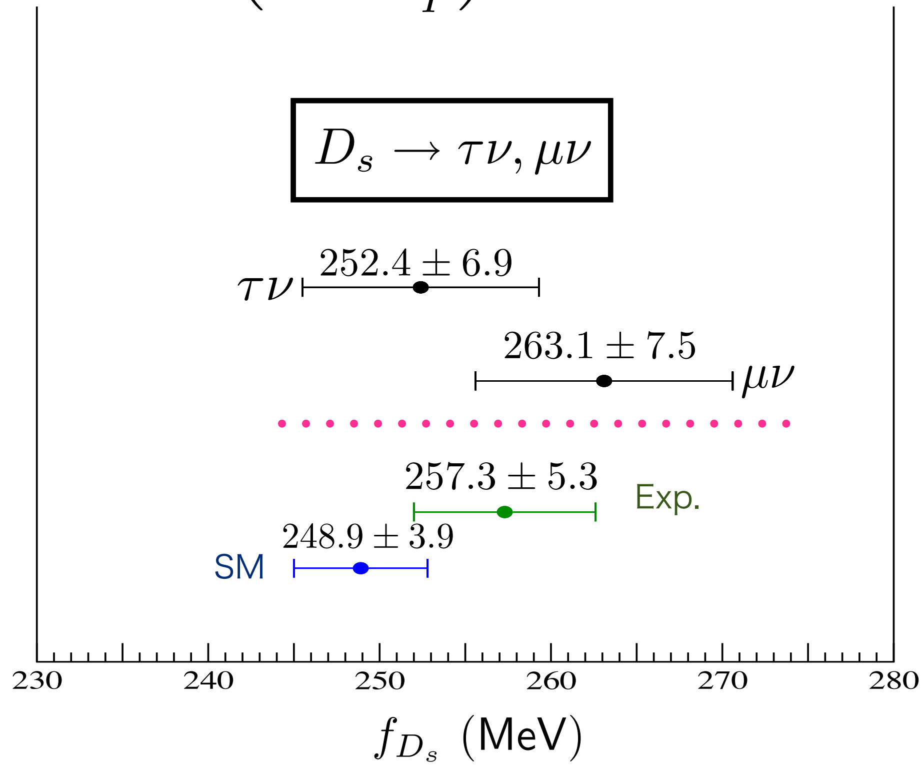


The "f_{Ds}-puzzle" has disappeared.

However, this result constrains NP contributions.

→ "interference effect of multi channels in NP" is important.

Leptonic decays of B-meson

BaBar,Belle

$$\mathrm{Br}(B^+ \to \tau\nu)_{\mathrm{exp}} = (1.64 \pm 0.34) \times 10^{-4}$$

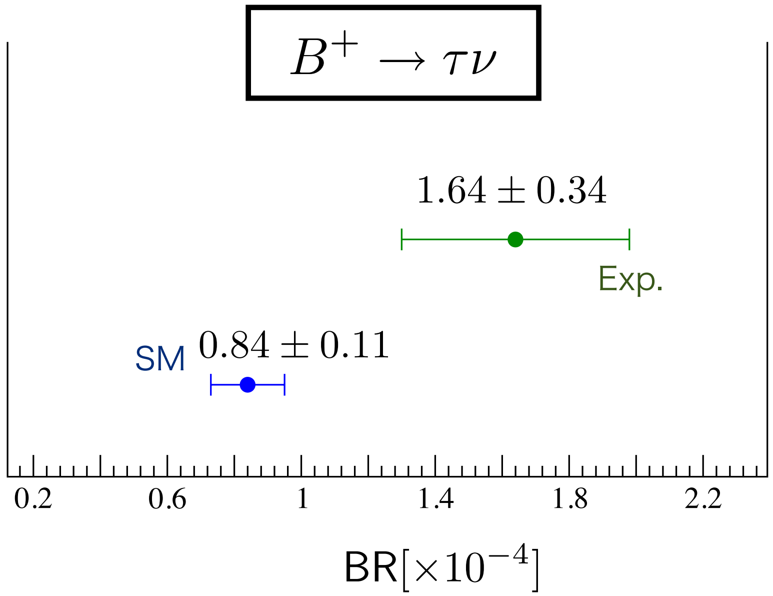
arXiv:1008.0104 [hep-ex], PRD82, 071101(2010)

UTfit

$$\mathrm{Br}(B^+ \to \tau\nu)_{\mathrm{SM}} = (0.805 \pm 0.071) \times 10^{-4}$$

ICHEP2010

2.4-sigma deviation



our purpose

- possibilities of New physics to these processes:
  - Two-Higgs doublet models (THDM) Ahn etal ('10), Akeroyed etal (09), Akeroyd etal ('07)...
  - Leptoquark models Dobrescu etal ('08), Benbrik etal (09), ...
  - R-parity violating SUSY (w/ "single coupling dominant hypothesis")

    Beak etal ('99), Dreiner etal ('02), ... Bhattacharrya etal ('10)

- investigate possibilities of by R-parity violating SUSY-SM
  beyond the single coupling hypothesis

R-parity

- R-parity

$$R_P \equiv (-1)^{3(B-L)+2S}$$

- B: baryon number, L: lepton number, S: spin quantum number
- SM particle : R-even (+1), SUSY particle : R-odd (-1)
  - as a consequence, even number of SUSY particles should appear in interaction vertices
    - proton is stable
    - lightest SUSY particle (LSP) is stable --> could be a candidate of cold dark matter
- R-parity violating interaction (RPV)
  - as a consequence, there are lepton- & baryon- number violating operators
  - phenomenological interests
    - neutrino mass w/o ultra-heavy Majorana neutrinos **Hall, Suzuki ('84)**
    - LSP is unstable, but gravitino could be dark matter **Buchmuller etal ('07)**

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set up (I)

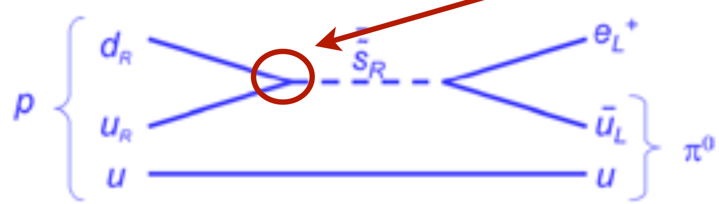
R-parity violating superpotential (trilinear int.)

$$W_{\not R} = \frac{1}{2}\lambda_{ijk}L_iL_jE_k + \lambda'_{ijk}L_iQ_jD_k + \frac{1}{2}\lambda''_{ijk}U_iD_jD_k \quad (i,j,k=1,2,3)$$

$\lambda, \lambda', \lambda''$: RPV couplings

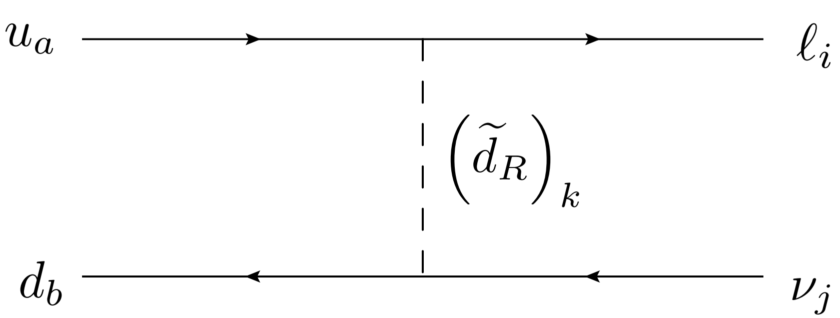
	SU(3)$_C$	SU(2)$_L$	U(1)$_Y$
Q	$\mathbf{3}$	$\mathbf{2}$	$1/6$
U	$\mathbf{3}^*$	$\mathbf{1}$	$-2/3$
D	$\mathbf{3}^*$	$\mathbf{1}$	$1/3$
L	$\mathbf{1}$	$\mathbf{2}$	$-1/2$
E	$\mathbf{1}$	$\mathbf{1}$	1

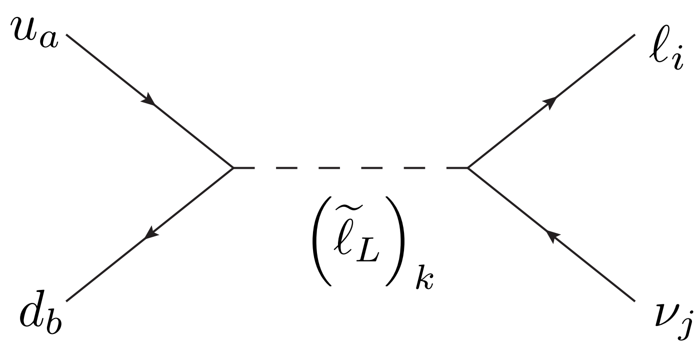
we set the baryon number violating coupling $\lambda''_{ijk} = 0$



previous studies on RPV couplings: ...Barger etal('89), Bhattacharyya ('97), Allanach etal('99), Dreiner ('07)...

Feyman diagrams of decay $P(u_a\bar{d}_b) \to \ell_i\nu_j$





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set up (2)

- The new physics contribution is parametrized by

$$r_P^2 \equiv \frac{\left|G_F V^*_{u_a d_b} + A^P_{ii}\right|^2}{G_F^2 \left|V^*_{u_a d_b}\right|^2} + \sum_{j(\neq i)} \frac{\left|A^P_{ij}\right|^2}{G_F^2 \left|V^*_{u_a d_b}\right|^2}$$

  - second term in r.h.s. → leptons in final state are flavor off-diagonal

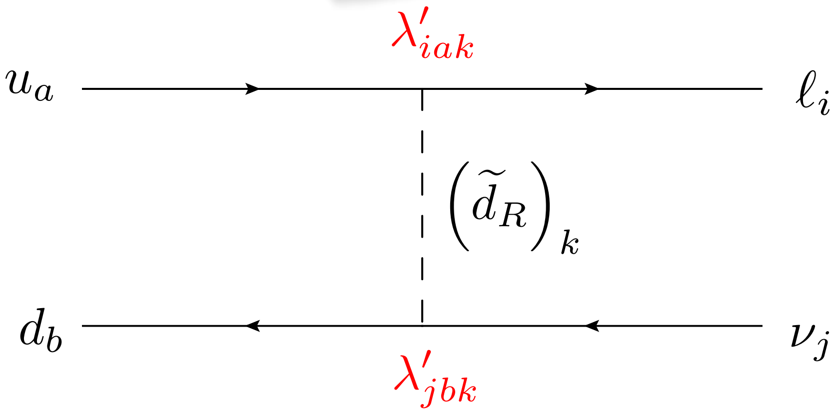
- Decay rate:

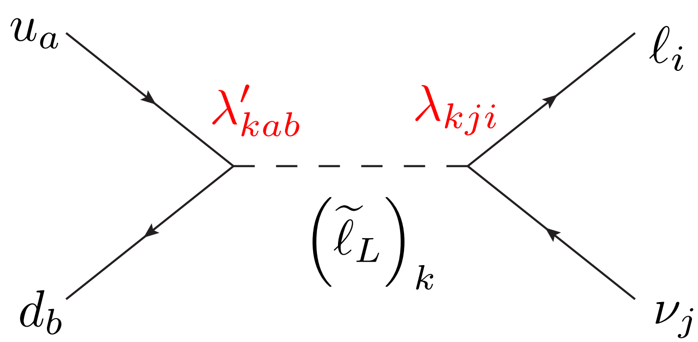
$$\Gamma(P \to l_i \nu_j) = \frac{1}{8\pi} \underline{r_P^2} G_F^2 |V^*_{u_a d_b}|^2 f_P^2 m_{l_i}^2 m_P \left(1 - \frac{m_{l_i}^2}{m_P^2}\right)^2$$

set up(3) : RPV processes

$$r_P^2 \equiv \frac{\left|G_F V_{u_a d_b}^* + A_{ii}^P\right|^2}{G_F^2 \left|V_{u_a d_b}^*\right|^2} + \sum_{j(\neq i)} \frac{\left|A_{ij}^P\right|^2}{G_F^2 \left|V_{u_a d_b}^*\right|^2}$$

$$W_{\not R} = \frac{1}{2}\lambda_{ijk} L_i L_j E_k + \lambda'_{ijk} L_i Q_j D_k$$



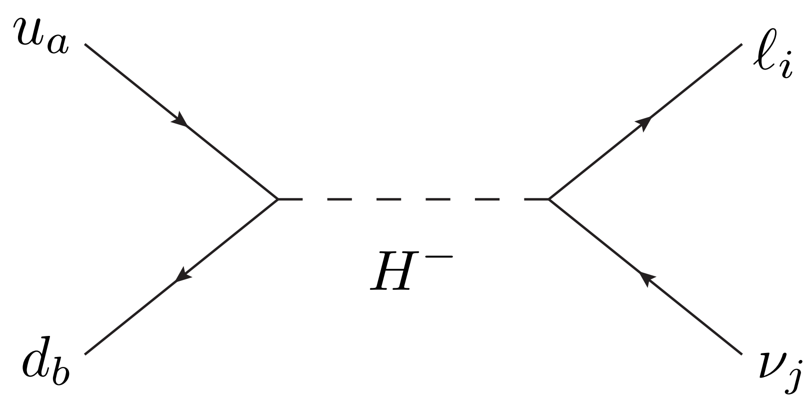


$$(A_t^P)_{ij} = \frac{1}{4\sqrt{2}} \sum_{k=1}^{3} \frac{\lambda'_{iak}\lambda'^*_{jbk}}{m^2_{\widetilde{d}_{Rk}}}$$

$$(A_s^P)_{ij} = -\frac{1}{2\sqrt{2} m_{l_i}} \frac{m_P^2}{m_{u_a} + m_{d_b}} \sum_{k=1}^{3} \frac{\lambda^*_{kji}\lambda'_{kab}}{m^2_{\widetilde{l}_{Lk}}}$$

set up(4) : MSSM process

$$r_P^2 \equiv \frac{\left|G_F V^*_{u_a d_b} + A^P_{ii}\right|^2}{G_F^2 \left|V^*_{u_a d_b}\right|^2} + \sum_{j(\neq i)} \frac{\left|A^P_{ij}\right|^2}{G_F^2 \left|V^*_{u_a d_b}\right|^2}$$

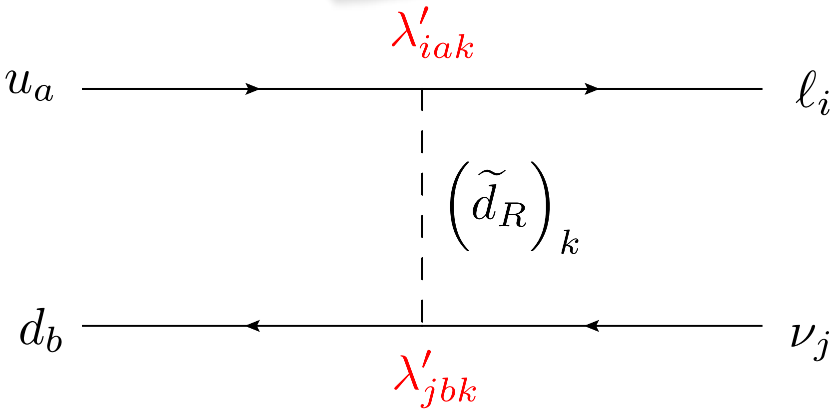


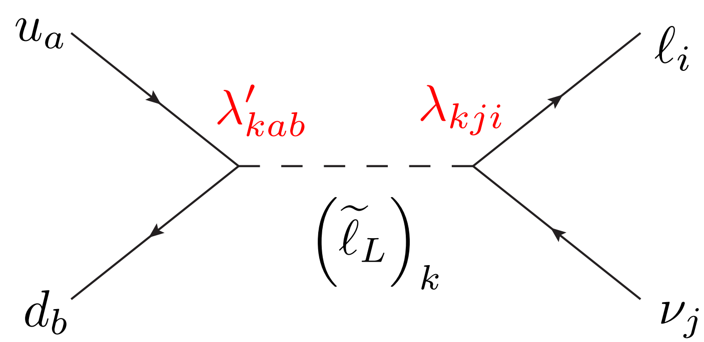
$$A^P_H = -G_F V^*_{u_a d_b} \frac{m_{d_b}}{m_{u_a} + m_{d_b}} \frac{m_P^2}{m_{H^-}^2} \left(\tan^2\beta - \frac{m_{u_a}}{m_{d_b}}\right)$$

set up(3) : RPV processes

$$r_P^2 \equiv \frac{\left|G_F V^*_{u_a d_b} + A^P_{ii}\right|^2}{G_F^2 \left|V^*_{u_a d_b}\right|^2} + \sum_{j(\neq i)} \frac{\left|A^P_{ij}\right|^2}{G_F^2 \left|V^*_{u_a d_b}\right|^2}$$

$$W_{\not R} = \frac{1}{2}\lambda_{ijk} L_i L_j E_k + \lambda'_{ijk} L_i Q_j D_k$$





$$(A_t^P)_{ij} = \frac{1}{4\sqrt{2}} \sum_{k=1}^{3} \frac{\lambda'_{iak}\lambda'^*_{jbk}}{m^2_{\widetilde{d}_{Rk}}}$$

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Numerical Study (1)

inputs

$$|V_{cs}| = 1.023 \pm 0.036, \quad |V_{ub}| = (3.89 \pm 0.44) \times 10^{-3},$$

$$m_{D_s} = 1968.47 \pm 0.33 \text{ MeV}, \quad m_{B^+} = 5279.17 \pm 0.29 \text{ MeV},$$

adopt the central values as references

$$r_P^2 \equiv \frac{\left|G_F V^*_{u_a d_b} + A^P_{ii}\right|^2}{G_F^2 \left|V^*_{u_a d_b}\right|^2} + \sum_{j(\neq i)} \frac{\left|A^P_{ij}\right|^2}{G_F^2 \left|V^*_{u_a d_b}\right|^2}$$

assumptions

- final state: $\tau \nu_\tau$
- we set $A^P_{ij} = 0$ for $i \neq j$ (constraints from LFV)
- t-channel: sbottom exchange
- s-channel: smuon exchange $(\lambda_{k33}, \quad k \neq 3)$

$$\Gamma(P \to l_i \nu_j) = \frac{1}{8\pi} r_P^2 G_F^2 |V^*_{u_a d_b}|^2 f_P^2 m_{l_i}^2 m_P \left(1 - \frac{m_{l_i}^2}{m_P^2}\right)^2$$

$$\longrightarrow f_P^{\text{EXP}} = r f_P^{\text{SM}}$$

constraints on new physics

$$r_{D_s} = 1.03 \pm 0.04$$

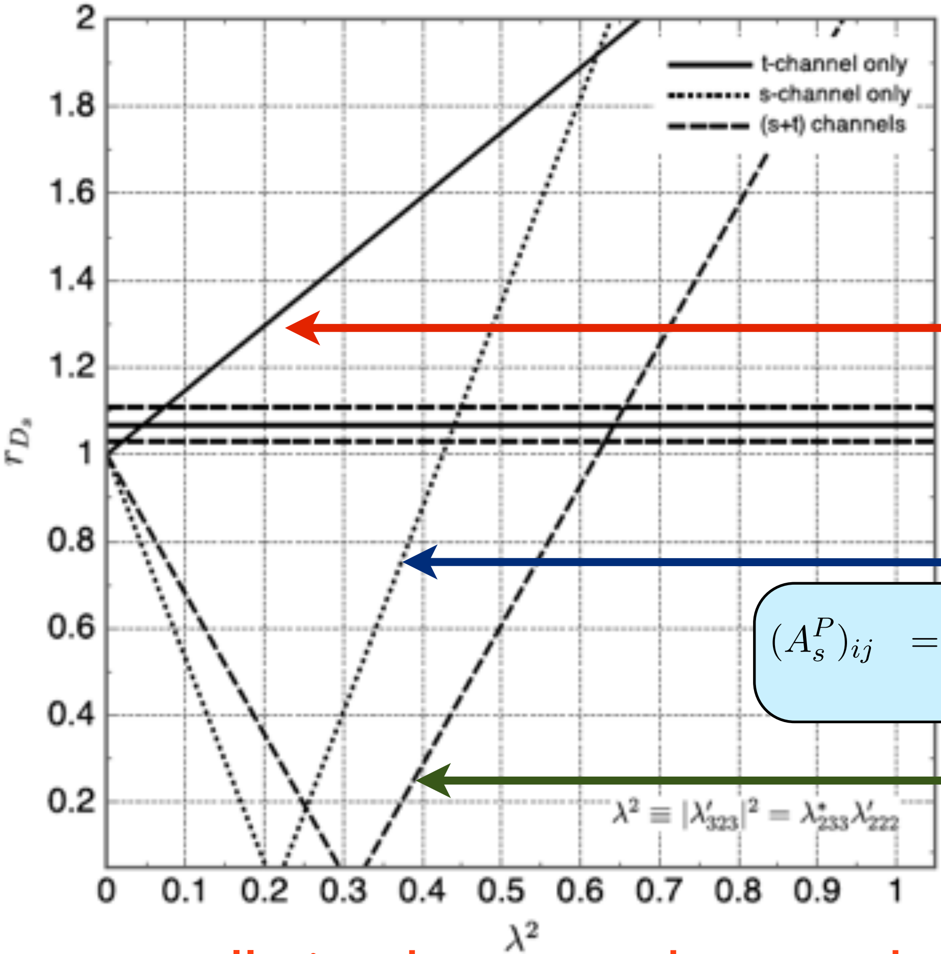
$$r_{B^+} = 1.43 \pm 0.21$$

Numerical Study (2)

[assumptions]

- $\lambda^2 \equiv |\lambda'_{323}|^2 = \lambda'_{222}\lambda^*_{233}$
- squark/slepton masses: $\tilde{m} = 100$ GeV

$D_s \to \tau\nu$



$$r_P = \frac{|G_F V^*_{u_a d_b} + A^P_{ii}|}{G_F |V^*_{u_a d_b}|}$$

t-channel only

$$(A^P_t)_{ij} = \frac{1}{4\sqrt{2}} \sum_{k=1}^{3} \frac{\lambda'_{iak}\lambda'^*_{jbk}}{m^2_{\tilde{d}_{Rk}}}$$

s-channel only

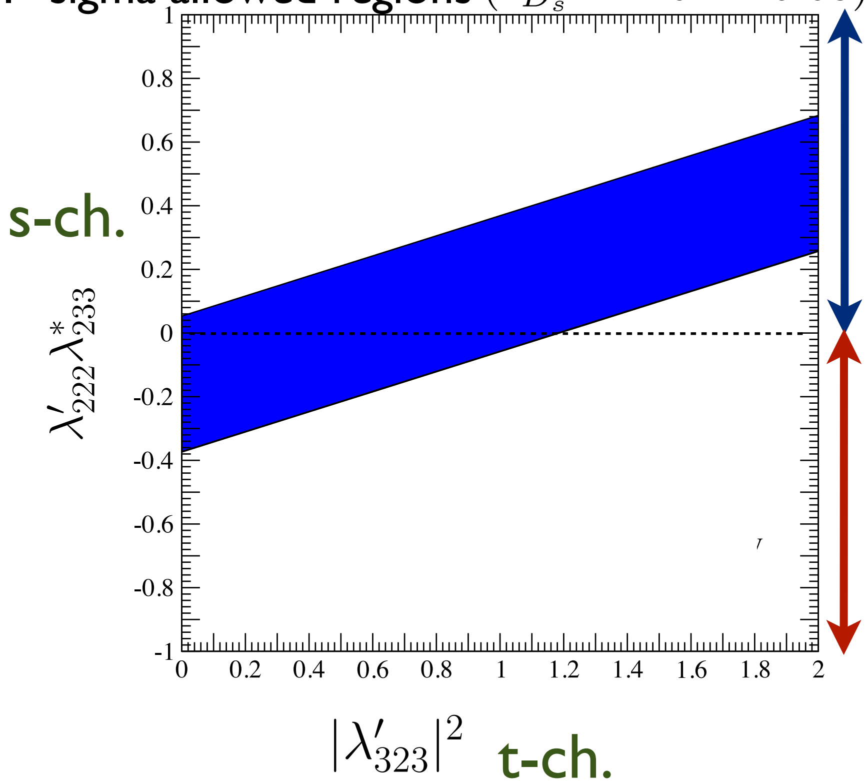
$$(A^P_s)_{ij} = -\frac{1}{2\sqrt{2} m_{l_i}} \frac{m^2_P}{m_{u_a} + m_{d_b}} \sum_{k=1}^{3} \frac{\lambda^*_{kji}\lambda'_{kab}}{m^2_{\tilde{l}_{Lk}}}$$

(s+t) channels

cancellation between the s- and t-channel amplitudes!

$D_s \longrightarrow \tau\nu$

1- sigma allowed regions $(r_{D_s} = 1.04 \pm 0.03)$



- squark/slepton masses: $\widetilde{m} = 500$ GeV
- $\lambda'\lambda'$(t-ch.) of Ds -> always positive
- signs of $\lambda'\lambda'$(t-ch.) and $\lambda\lambda'$(s-ch.)

  - same :
    due to **destructive** interference between s-ch and t-ch, RPV couplings can be large

  - opposite :
    due to **constructive** interference between s-ch and t-ch, RPV couplings are constrainded

-> $0 < |\lambda'_{323}|^2 < 1.2$ (t-ch)

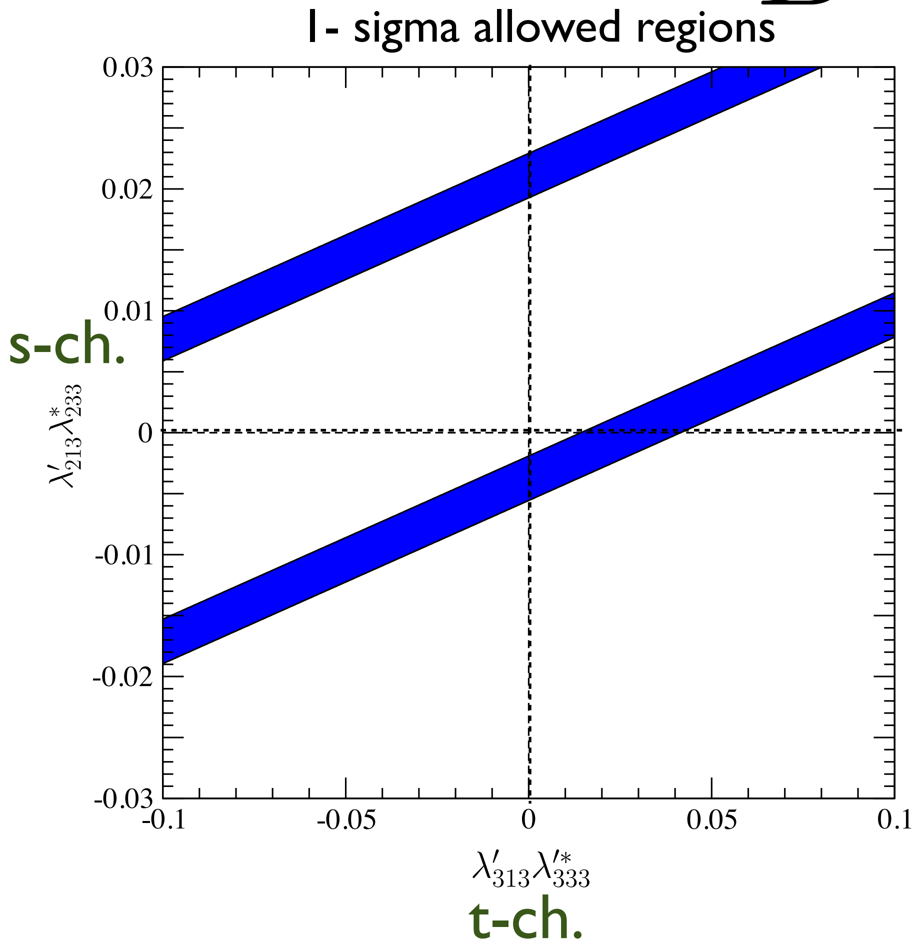
$-0.4 < \lambda^*_{233}\lambda'_{222} < 0$ (s-ch)

$$(A_t^P)_{ij} = \frac{1}{4\sqrt{2}} \sum_{k=1}^{3} \frac{\lambda'_{iak}\lambda'^*_{jbk}}{m^2_{\tilde{d}_{Rk}}}$$

$$(A_s^P)_{ij} = -\frac{1}{2\sqrt{2}m_{l_i}} \frac{m_P^2}{m_{u_a} + m_{d_b}} \sum_{k=1}^{3} \frac{\lambda^*_{kji}\lambda'_{kab}}{m^2_{\tilde{l}_{Lk}}}$$

$$r_{D_s} = |G_F V^*_{cs} + A_{\rm t} + A_{\rm s}/G_F V^*_{cs}|$$

$B^+ \to \tau\nu$



- combination of opposite sign of s, t-channel couplings is constrained

$$(A_t^P)_{ij} = \frac{1}{4\sqrt{2}}\sum_{k=1}^{3}\frac{\lambda'_{iak}\lambda'^*_{jbk}}{m^2_{\tilde{d}_{Rk}}}$$

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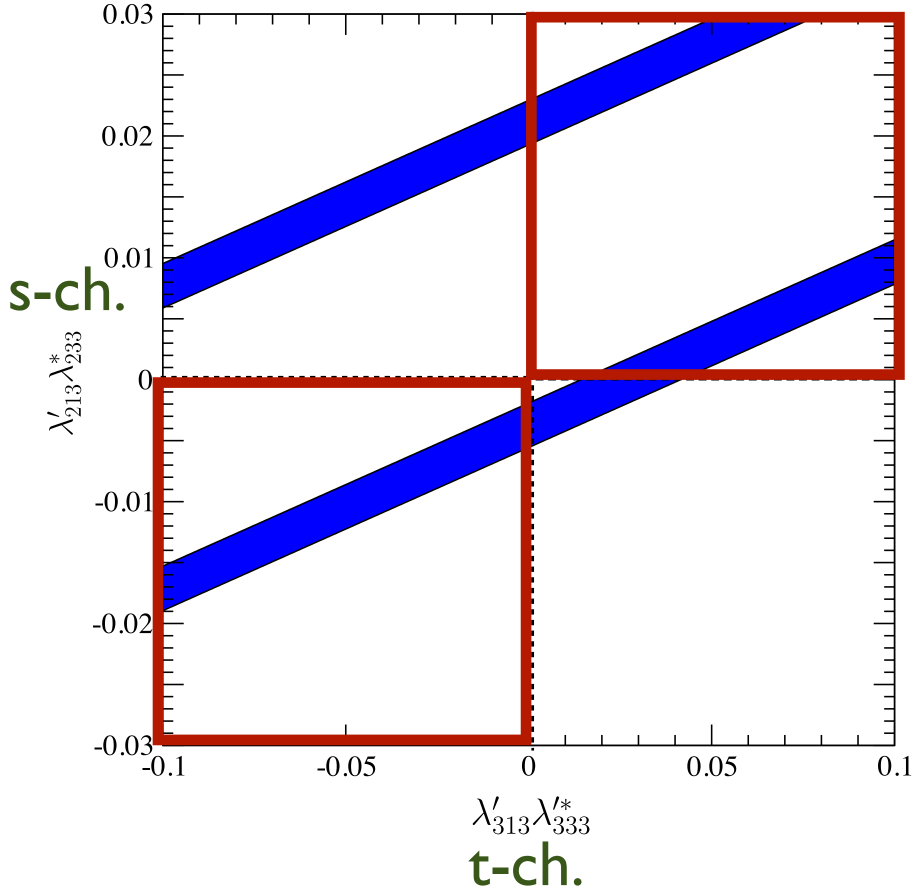
$B^+ \to \tau\nu$

1- sigma allowed regions



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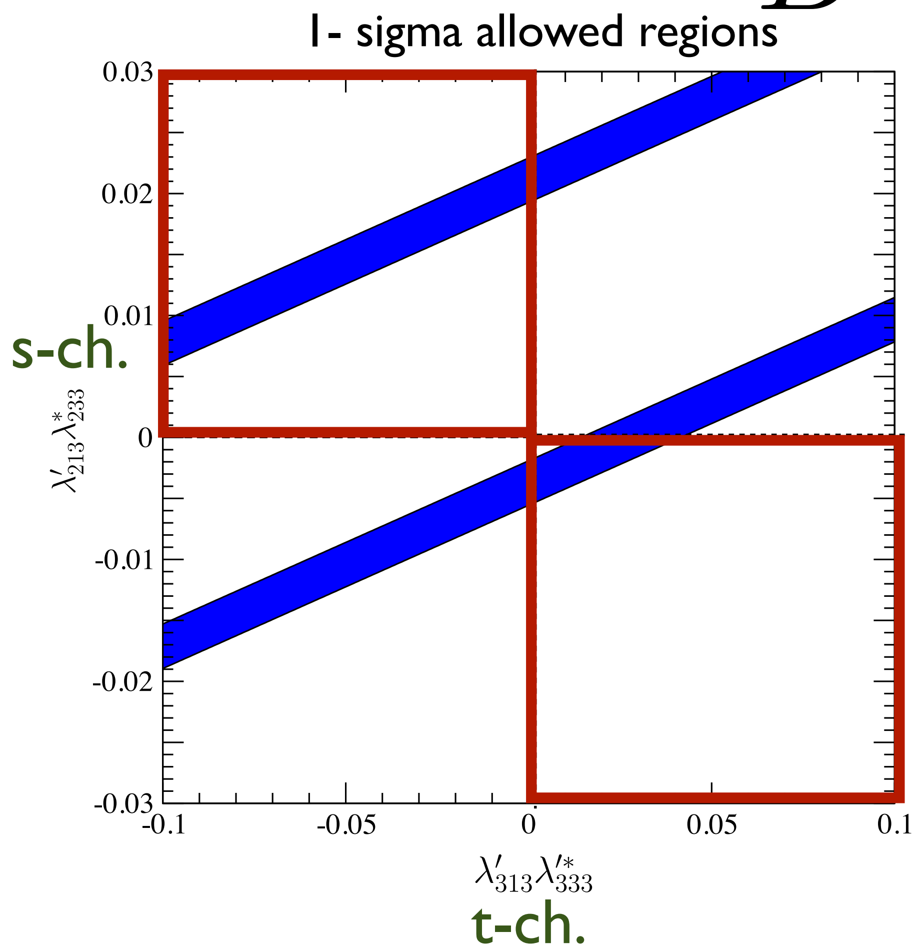
$B^+ \to \tau\nu$



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$$(A_s^P)_{ij} = -\frac{1}{2\sqrt{2}m_{l_i}} \frac{m_P^2}{m_{u_a}+m_{d_b}} \sum_{k=1}^{3} \frac{\lambda^*_{kji}\lambda'_{kab}}{m^2_{\tilde{l}_{Lk}}}$$

$$r_{D_s} = |G_F V^*_{cs} + A_t + A_s / G_F V^*_{cs}|$$

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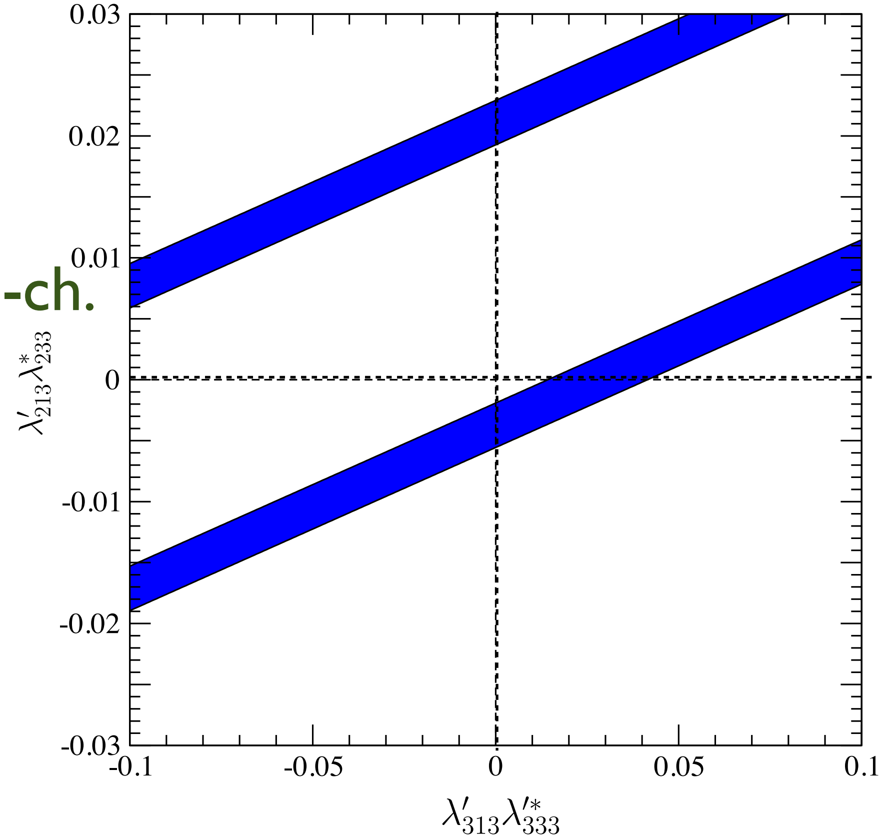
$B^+ \rightarrow \tau\nu$

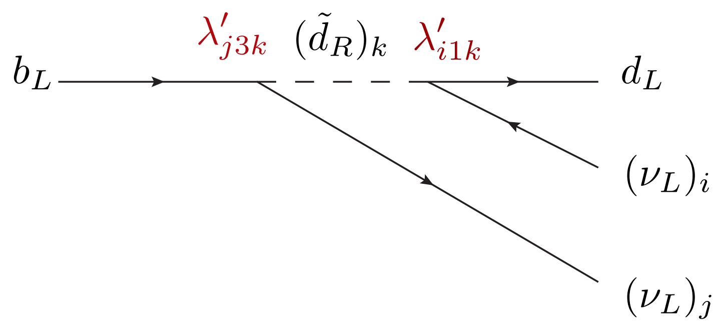
1- sigma allowed regions



s-ch.

t-ch.

- combination of opposite sign of s, t-channel couplings is constrained
- t-channel coupling is constrained by $B^+ \rightarrow \pi^+ \nu\bar{\nu}$



$\lambda'_{313}\lambda'^*_{333} < 2.5 \times 10^{-2}$ PLB681,44 (2009)

for BR<1 x 10[-4] @BaBar,(PRL94, 101801 (2005))

$$(A_t^P)_{ij} = \frac{1}{4\sqrt{2}} \sum_{k=1}^{3} \frac{\lambda'_{iak}\lambda'^*_{jbk}}{m^2_{\tilde{d}_{Rk}}}$$

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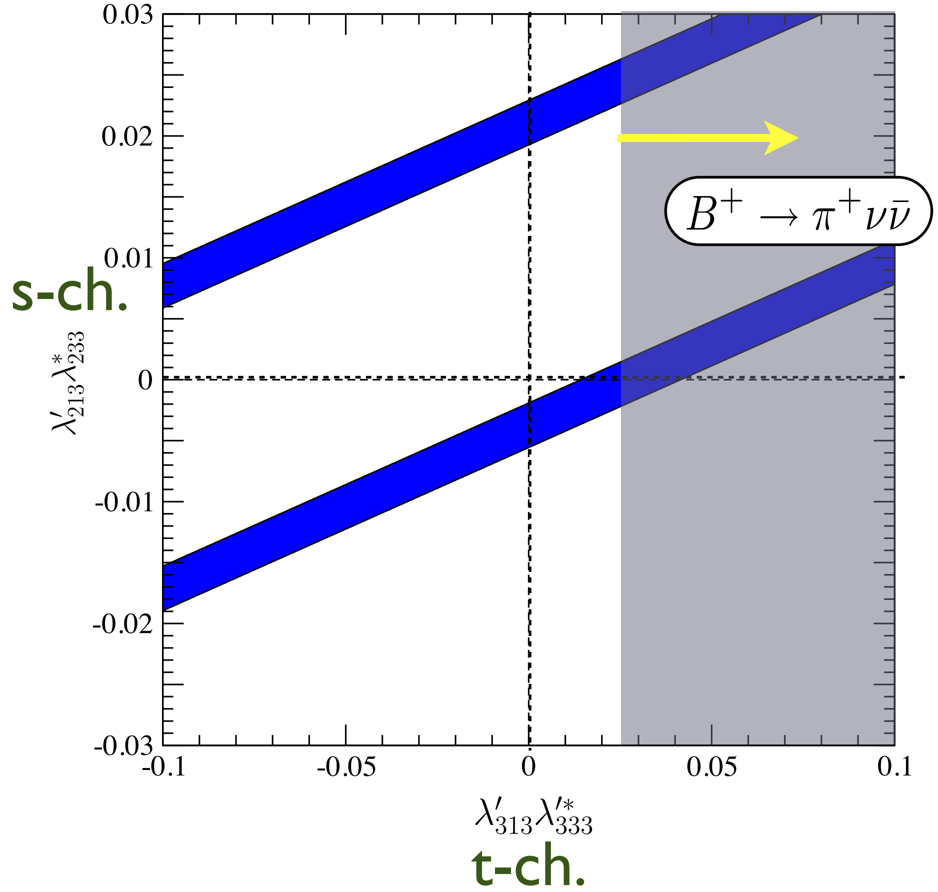
$$r_{D_s} = |G_F V^*_{cs} + A_t + A_s / G_F V^*_{cs}|$$

$B^+ \to \tau\nu$

1- sigma allowed regions



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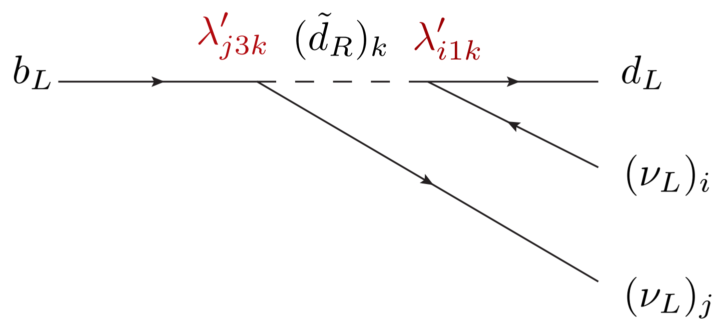
$$(A_s^P)_{ij} = -\frac{1}{2\sqrt{2}m_{l_i}} \frac{m_P^2}{m_{u_a} + m_{d_b}} \sum_{k=1}^{3} \frac{\lambda^*_{kji}\lambda'_{kab}}{m^2_{\tilde{l}_{Lk}}}$$

$$r_{D_s} = |G_F V^*_{cs} + A_t + A_s / G_F V^*_{cs}|$$

- combination of opposite sign of s, t-channel couplings is constrained
- t-channel coupling is constrained by $B^+ \to \pi^+ \nu\bar{\nu}$



$\lambda'_{313}\lambda'^*_{333} < 2.5 \times 10^{-2}$ PLB681,44 (2009)

for BR<1 x 10^{-4} @BaBar,(PRL94, 101801 (2005))

-> for positive t-ch coupling,

$$1.9 \times 10^{-2} < \lambda'_{213}\lambda^*_{233} < 2.6 \times 10^{-2}$$

$$-0.5 \times 10^{-2} < \lambda'_{213}\lambda^*_{233} < 0.1 \times 10^{-2}$$

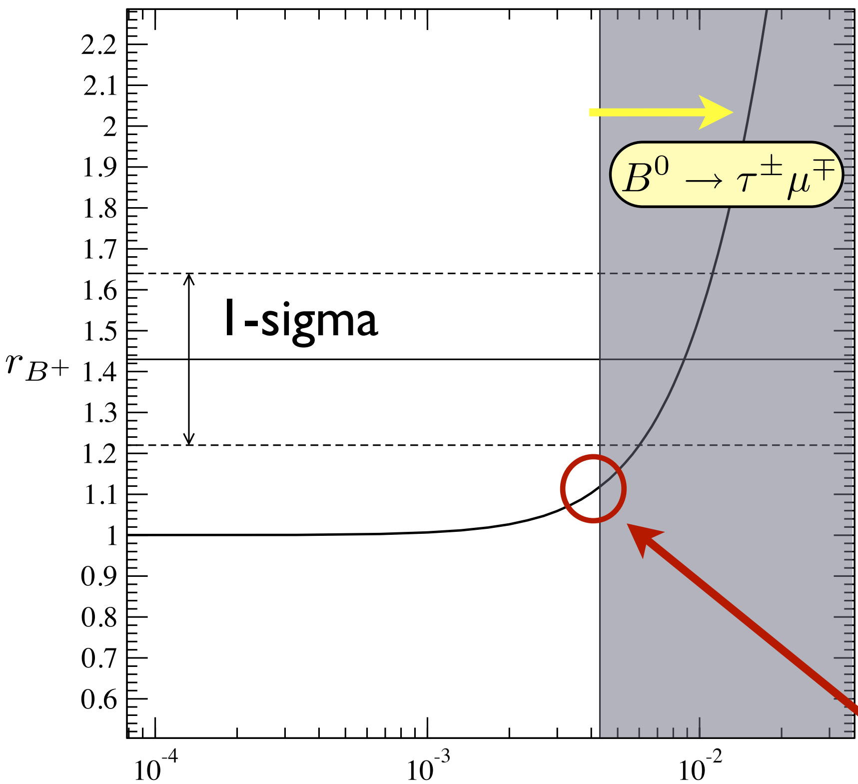
RPV-LFV interactions

$$r_P^2 \equiv \frac{\left|G_F V^*_{u_a d_b} + A^P_{ii}\right|^2}{G_F^2 \left|V^*_{u_a d_b}\right|^2} + \sum_{j(\neq i)} \frac{\left|A^P_{ij}\right|^2}{G_F^2 \left|V^*_{u_a d_b}\right|^2}$$

assumptions

- final state: $\tau\nu_j \ (j = e, \mu)$
- we set $(r_P^2)_{ii}=1$
- squark/slepton masses: $\widetilde{m} = 500$ GeV

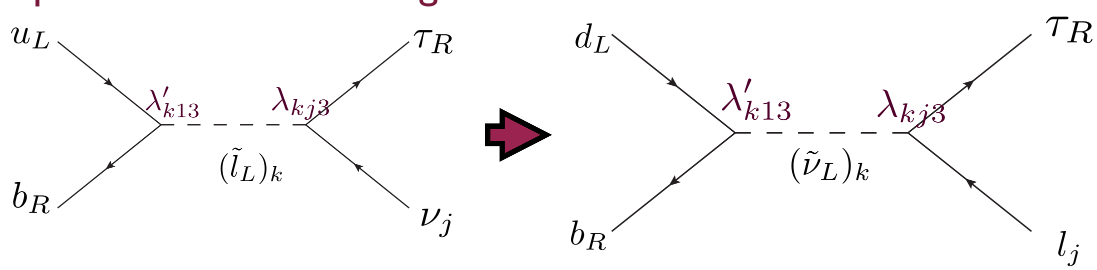
RPV-LFV process : $B^+ \to \tau\nu$



s-ch.

$B^0 \to \tau + l_j$

slepton s-channel exchange



$$\lambda_{k23}\lambda'_{k13}\ (B^0 \to \tau\mu) < 4.3 \times 10^{-3}$$

for BR < 28 x 10^-6 @BaBar(PRD77, 091104(2008))

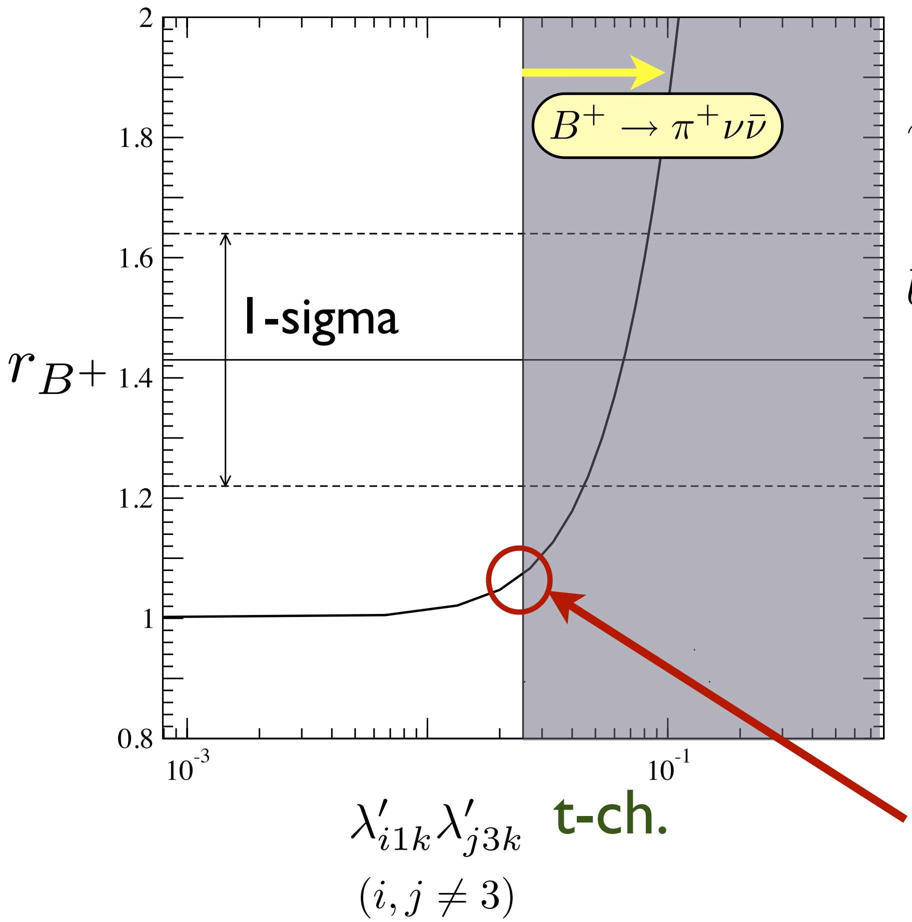
$$\lambda_{k13}\lambda'_{k13}\ (B^0 \to \tau e) < 4.9 \times 10^{-3}$$

for BR<22 x 10^-6 @BaBar(PRD77,091104(2008))

$r_{B^+} \sim 1.1$

taking account of contributions from $\lambda_{k13}\lambda'_{k13}\ (B^0 \to \tau e)$ and $\lambda_{k23}\lambda'_{k13}\ (B^0 \to \tau\mu)$, r_{B^+}~1.3.

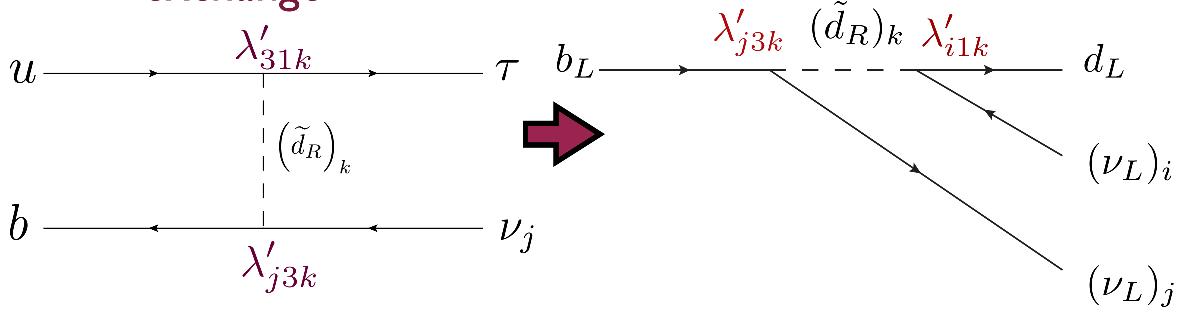
RPV-LFV process : $B^+ \to \tau\nu$



$r_{B^+} \sim 1.1$

sdown t-channel exchange

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



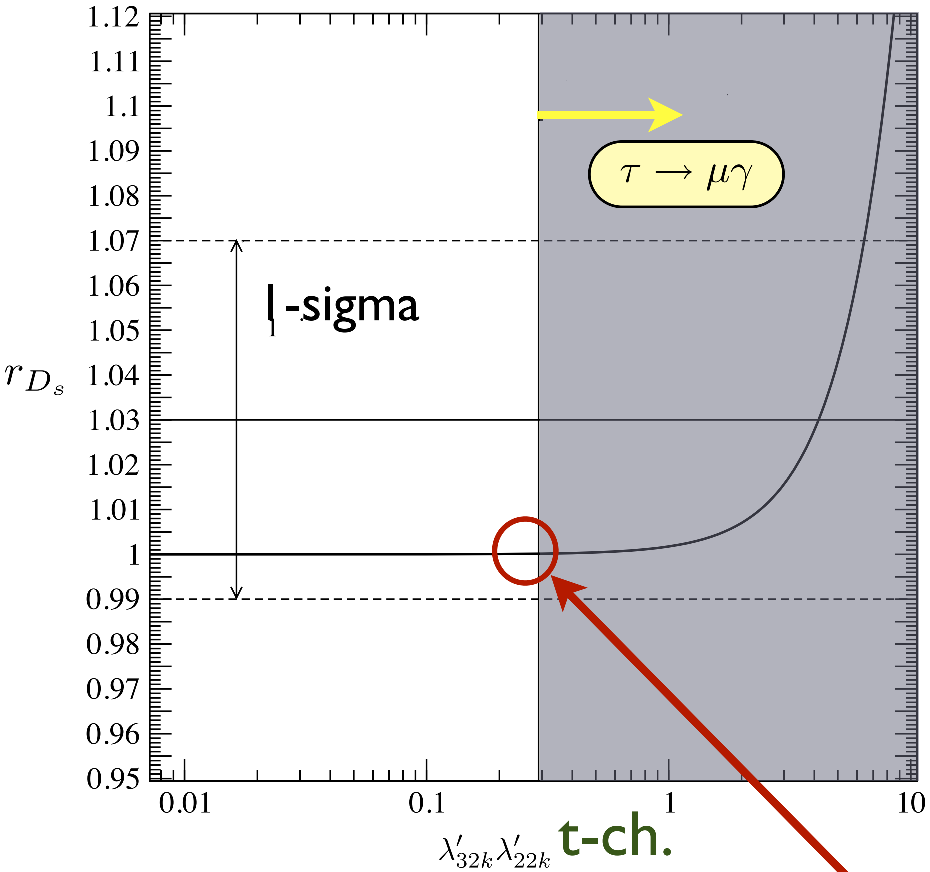
B. Aubert et al. [BABAR Collaboration], Phys. Rev. Lett. 94, 101801 (2005)

$$\lambda'_{i1k}\lambda'_{j3k} < 2.5 \times 10^{-2}$$

for BR<1 x 10^{-4} @BaBar(PRL94, 101801 (2005))

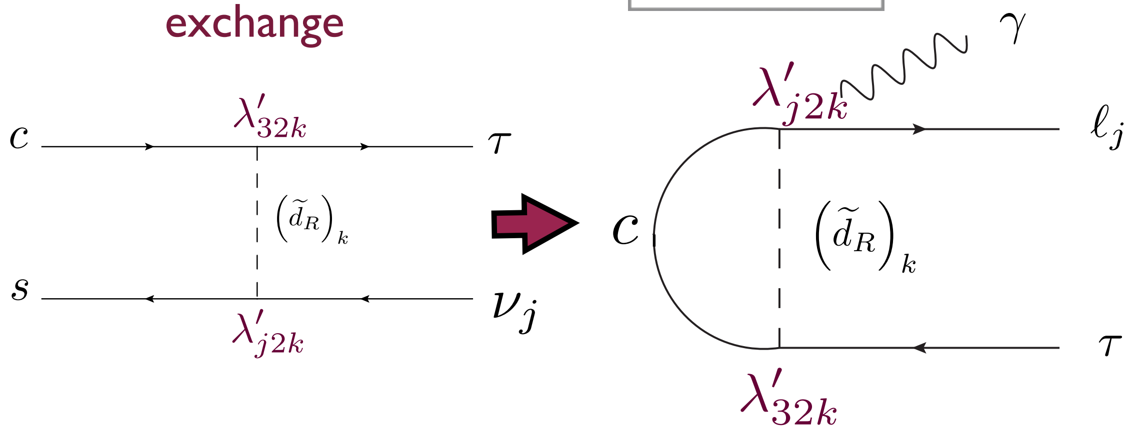
PLB681,44 (2009)

RPV-LFV process : $D_s \to \tau\nu$



sdown t-channel exchange

$\tau \to l_j + \gamma$



$\lambda'_{32k}\lambda'_{12k}\ (\tau \to e\gamma)$

for $Br < 3.3 \times 10^{-8}$ @ BABAR (PRL104 ,021802(2010))

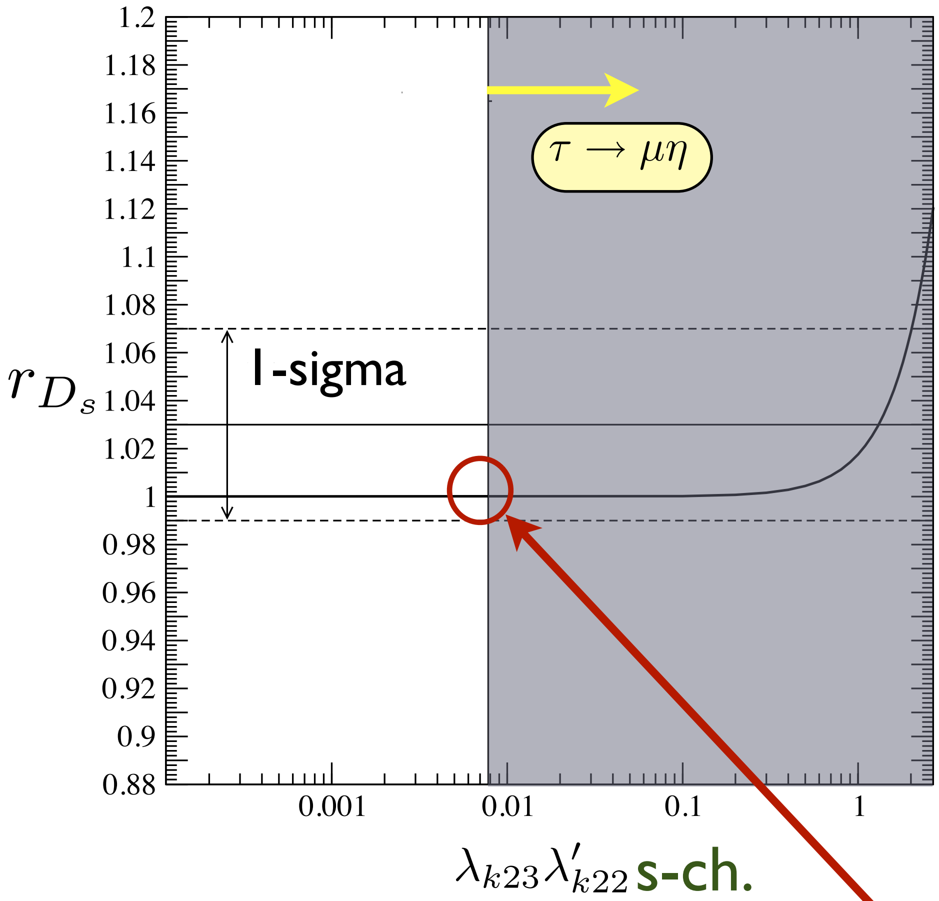
$\lambda'_{32k}\lambda'_{22k}\ (\tau \to \mu\gamma) < 0.29$

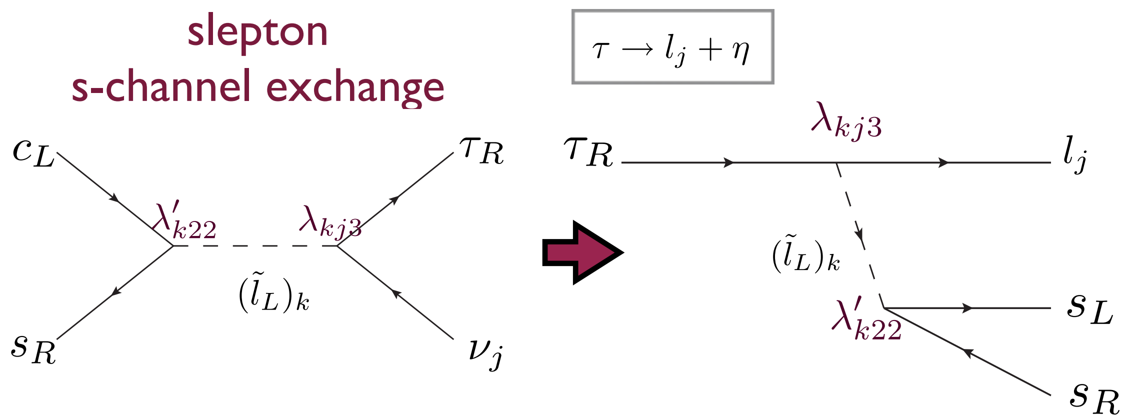
for $Br < 4.4 \times 10^{-8}$ @ BABAR (PRL104 ,021802(2010))

Bhattacharyya etal, NPB831,344('10)

$r_{D_s} \sim 1.0 + \mathcal{O}(10^{-4})$

RPV-LFV process : $D_s \to \tau\nu$





$\lambda_{k13}\lambda'_{k22}\ (\tau \to e\eta)$

for $Br < 4.4 \times 10^{-8}$ @ BELLE (ICHEP2010)

$\lambda_{k23}\lambda'_{k22}\ (\tau \to \mu\eta) < 7.8 \times 10^{-3}$

for $Br < 2.3 \times 10^{-8}$ @ BELLE (ICHEP2010)

Li etal, PRD73,073005

$$r_{D_s} \sim 1.0 + \mathcal{O}(10^{-6})$$

summary

- leptonic decays of Ds and B^+ mesons are studied in SUSY-SM with RPV interactions (beyond "single coupling dominance hypothesis")
- both constructive and destructive interference between s- and t-channel amplitudes are possible
- because of cancellation between s- and t-channels, size of RPV couplings cannot be restricted so that production/decay of SUSY particles through RPV interactions may be enhanced without conflicting the data of leptonic decays
- contributions from the flavor off-diagonal interactions are discussed under constraints from LFV experiments

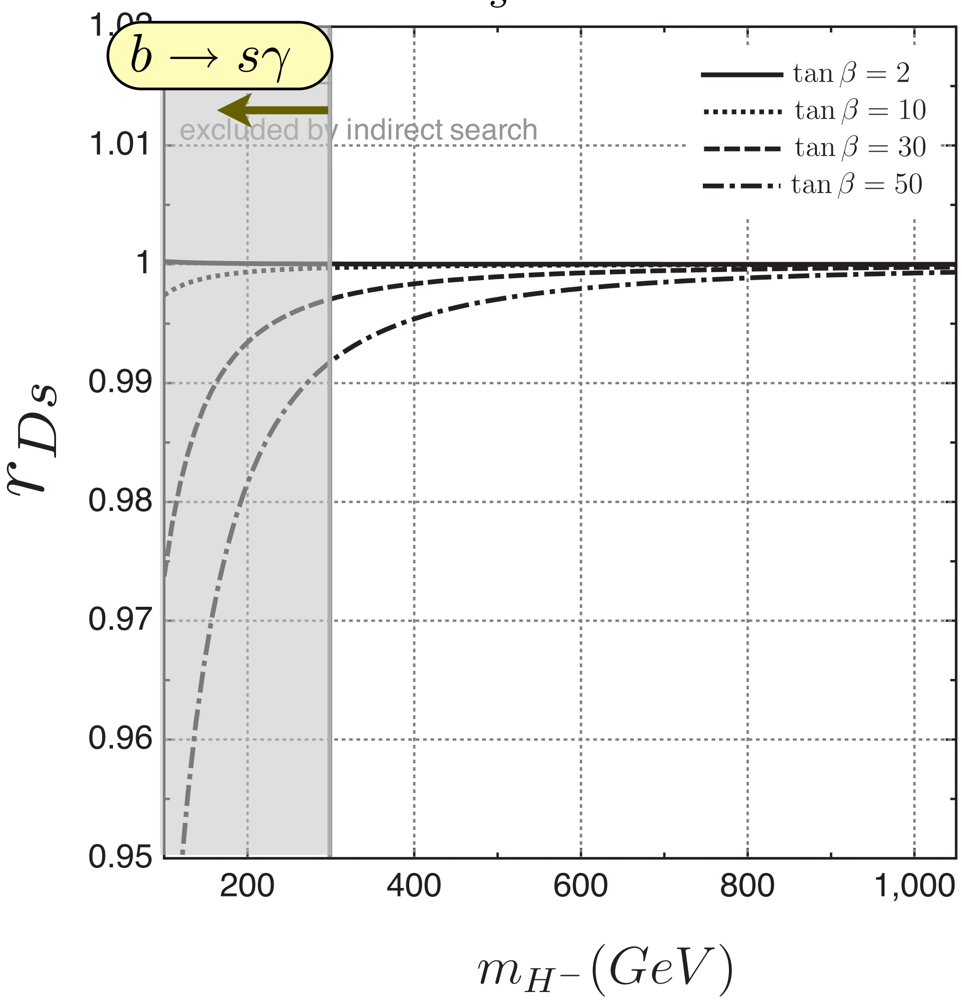
back up

x

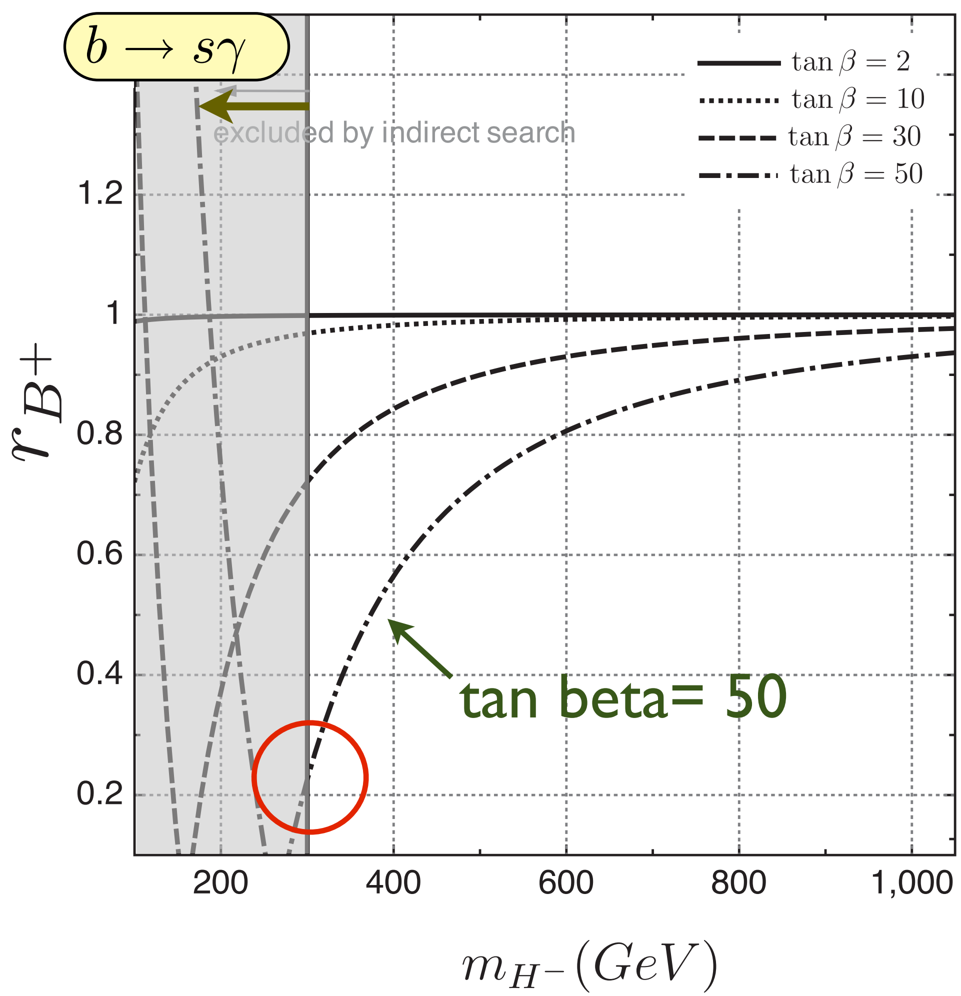
charged higgs

$$A_H^P = -G_F V^*_{u_a d_b} \frac{m_{d_b}}{m_{u_a} + m_{d_b}} \frac{m_P^2}{m_{H^-}^2} \left(\tan^2\beta - \frac{m_{u_a}}{m_{d_b}} \right)$$

$D_s \rightarrow \tau\nu$



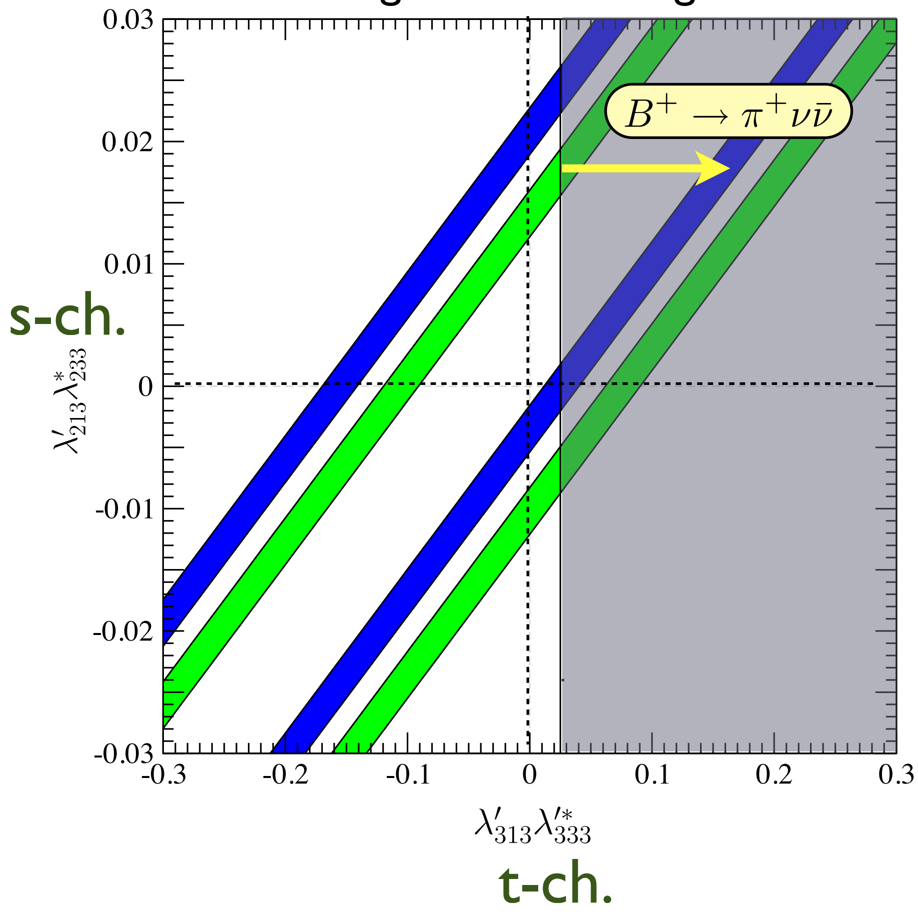
$B^+ \rightarrow \tau\nu$



x

chrged higgs : $B^+ \to \tau\nu$

1- sigma allowed regions



blue : RPV only

green : RPV + charged Higgs

input $m_{H^-} = 300\text{GeV}$

$\tan\beta = 50$

•taking account of (RPV + charged Higgs) contributions,

$$0.5 \times 10^{-2} < \lambda'_{213}\lambda^*_{233} < 2.0 \times 10^{-2}$$

$$-1.2 \times 10^{-2} < \lambda'_{213}\lambda^*_{233} < -0.5 \times 10^{-2}$$

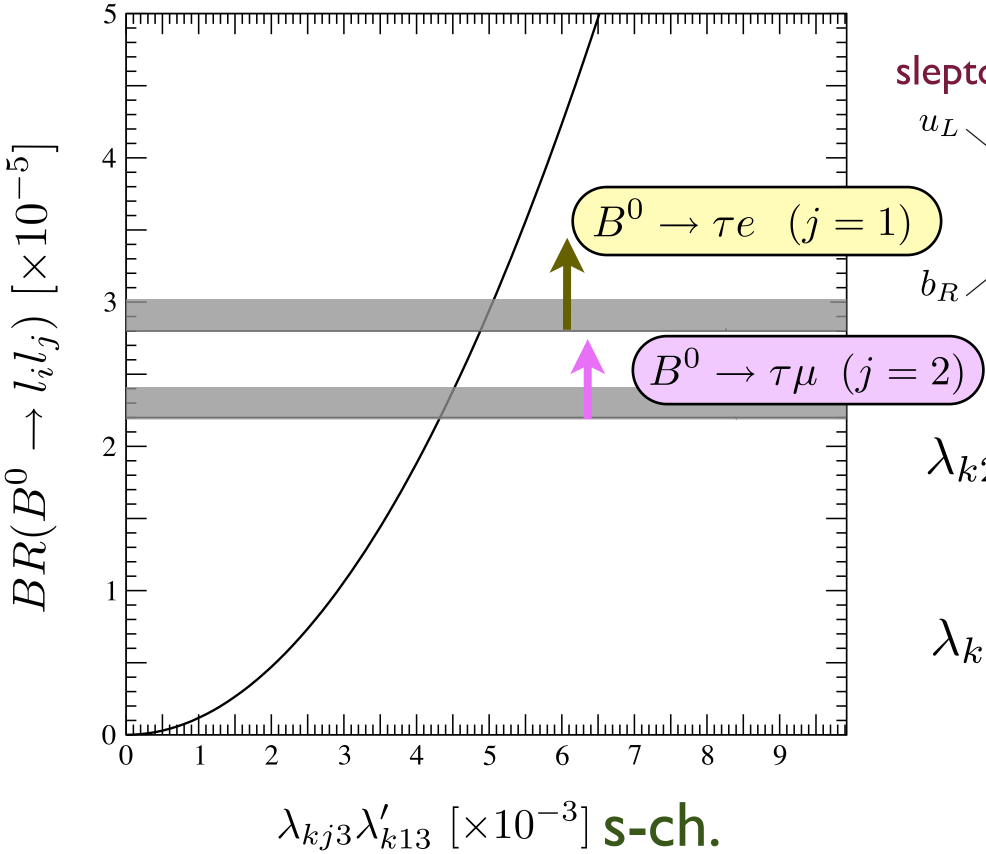
for positive t-ch. coupling

$$A_H^P = -G_F V^*_{u_a d_b} \frac{m_{d_b}}{m_{u_a} + m_{d_b}} \frac{m_P^2}{m_{H^-}^2} \cdot \left(\tan^2\beta - \frac{m_{u_a}}{m_{d_b}}\right)$$

$$r_P = |G_F V^*_{u_i d_j} + A_t + A_s + A_H / G_F V^*_{u_i d_j}|$$

x

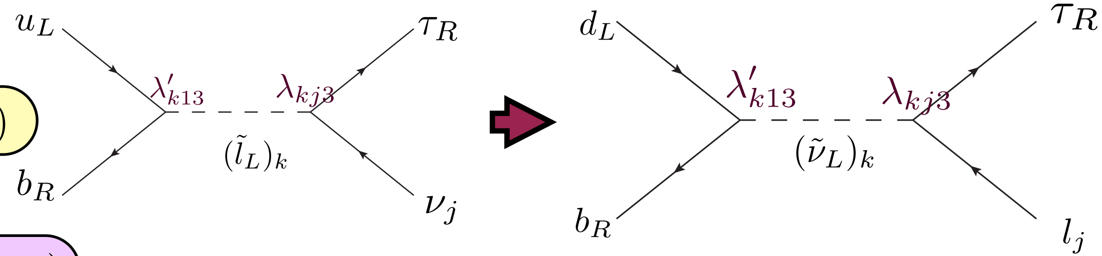
RPV-LFV process : $B^+ \to \tau\nu$



s-ch.

slepton s-channel exchange

$B^0 \to \tau + l_j$



$$\lambda_{k23}\lambda'_{k13} \ (B^0 \to \tau\mu) < 4.3 \times 10^{-3}$$

for BR < 28 x 10^-6 @BaBar(PRD77, 091104)

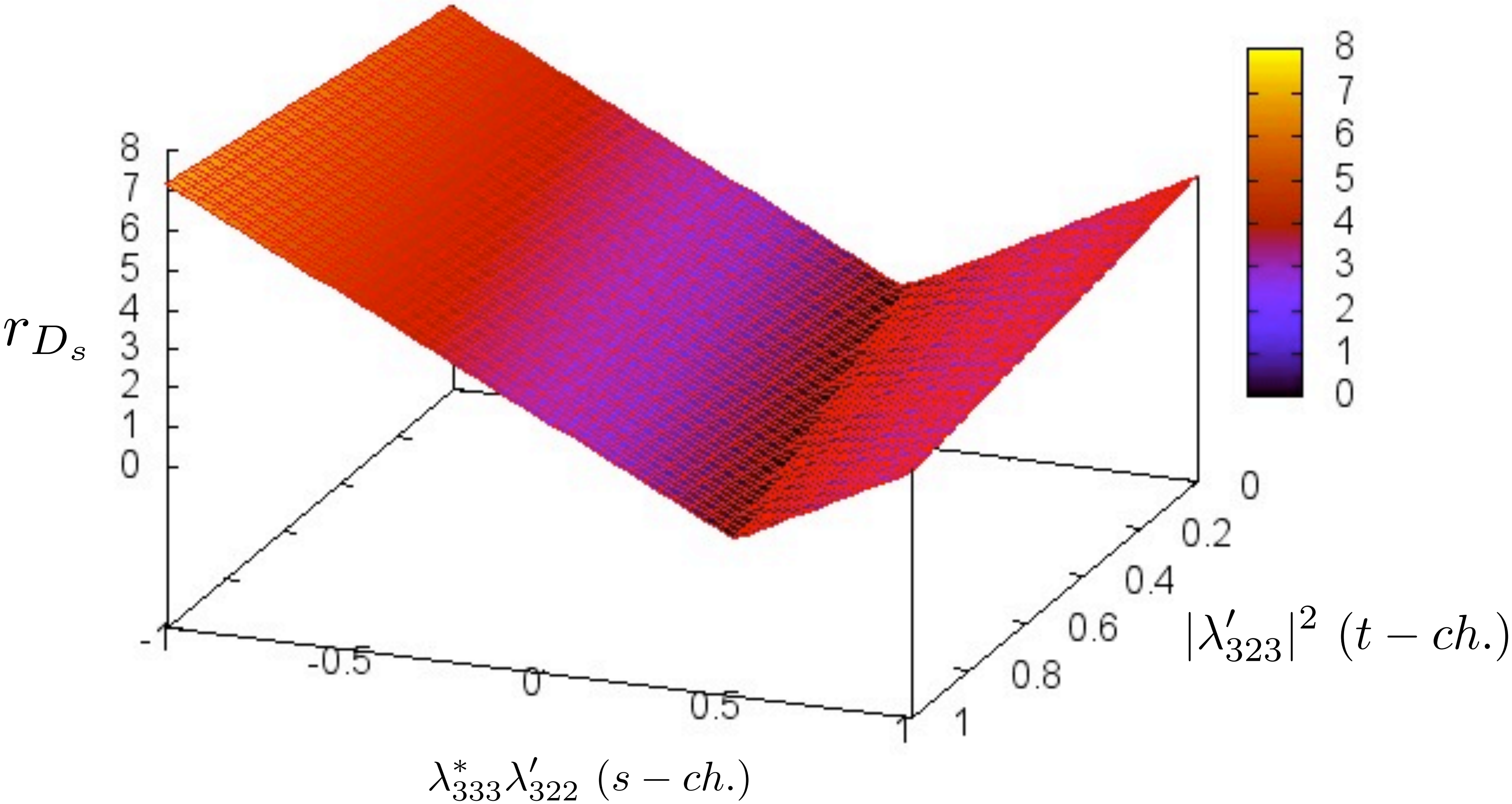
$$\lambda_{k13}\lambda'_{k13} \ (B^0 \to \tau e) < 4.9 \times 10^{-3}$$

for BR<22 x 10^-6 @BaBar(PRD77,091104)

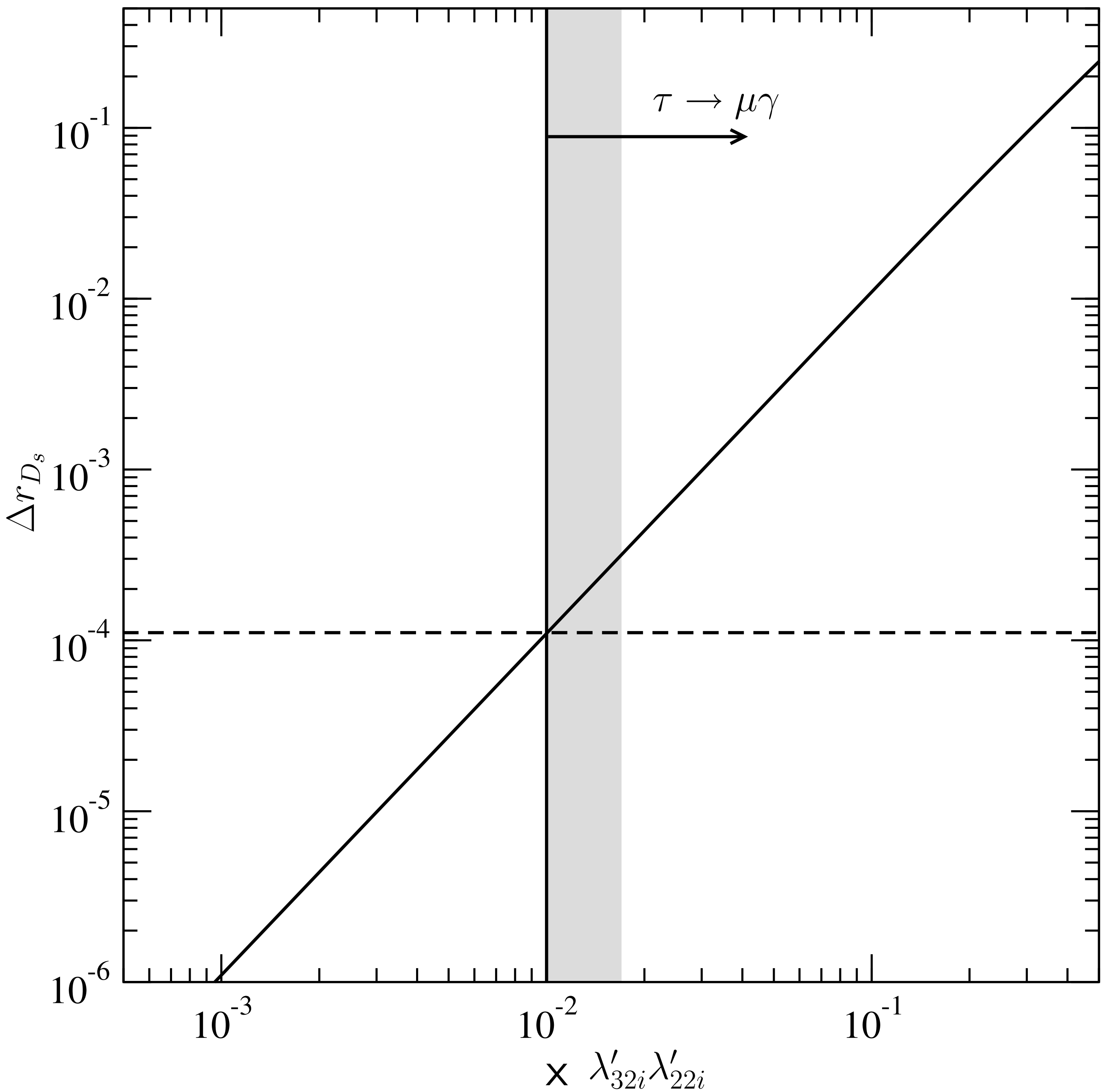
x

result

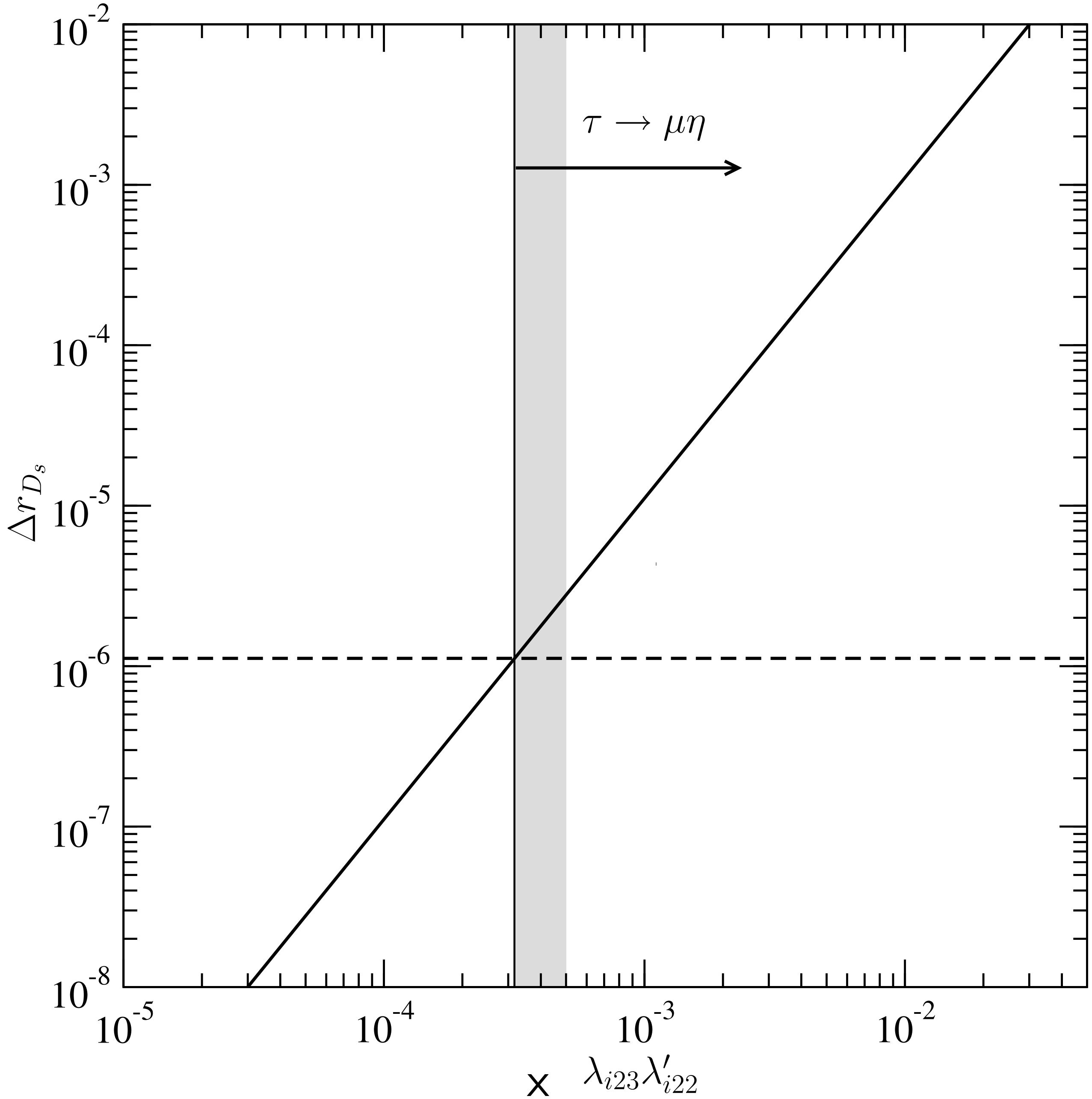
$D_s \to \tau\nu_\tau$ s—tの干渉



$r_{D_s} = 1.07 \pm 0.04$ の領域に等高線をひく



$\tau \to \mu\gamma$
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
Δr_{D_s}
10^{-3}
10^{-2}
10^{-1}
x $\lambda'_{32i}\lambda'_{22i}$


10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
Δr_{D_s}
$\tau \to \mu\eta$
10^{-5}
10^{-4}
10^{-3}
10^{-2}
x $\lambda_{i23}\lambda'_{i22}$

Back up slides

$$\Gamma(Q \to q\bar{e}\nu_e) = \frac{G_F^2 m_Q^5}{192\pi^3}|V_Q q|^2 f(m_q^2/m_Q^2)$$

$$f(r) = 1 - 8r + 8r^3 - r^4 - 12r^2 \ln r$$

$$\mathrm{Br}(\mathrm{b} \to \mathrm{ce}\nu_\mathrm{e}) = 0.11$$

$$\Gamma(b \to d l_i^+ l_j^-) = \frac{1}{12}\frac{m_b^5}{512\pi^3}\left(\frac{\lambda'_{k13}\lambda_{k23}}{m_{\widetilde{\nu}_k}^2}\right)^2$$

$$\mathrm{Br}(\mathrm{b} \to \mathrm{dl_i^+ l_j^-}) = \frac{\Gamma(b \to d l_i^+ l_j^-)}{\Gamma(b \to c e \nu_e)} \mathrm{Br}(\mathrm{b} \to \mathrm{ce}\nu_\mathrm{e})$$

$$\mathrm{Br}(B^+ \to \pi^+ e^\pm \mu^\mp) < 0.17 \times 10^{-6}$$

HFAG

X

Back up slides

$$\mathrm{Br}(\mathrm{b} \to \mathrm{d l_i^+ l_j^-}) = \frac{\Gamma(b \to d l_i^+ l_j^-)}{\Gamma(b \to c e \nu_e)} \mathrm{Br}(\mathrm{b} \to \mathrm{c e} \nu_\mathrm{e})$$

$$= \frac{1}{32 G_F^2} \frac{\left(\frac{\lambda'_{k13}\lambda_{k23}}{m^2_{\tilde{\nu}_k}}\right)^2}{|V_{cb}|^2 f(m_c^2/m_b^2)} \quad \approx 3.7 \times 10^2 \times \left(\frac{\lambda'_{k13}\lambda_{k23}}{(m_{\tilde{\nu}_k}/100\mathrm{GeV})^2}\right)^2$$

$$\to \lambda'_{k13}\lambda_{k23} < 2.1 \times 10^{-5}$$

$$f(m_c^2/m_b^2) \approx 0.484$$

$$V_{cb} = (40.6 \pm 1.3) \times 10^{-3}$$

$$\mathrm{Br}(B^+ \to \pi^+ e^\pm \mu^\mp) < 0.17 \times 10^{-6}$$

HFAG

X