Rare Decays and Supersymmetry (SUSY)

Tomáš Blažek
Comenius Univ, Bratislava

25 June 2015, ATLAS Cz-Sk, Olomouc

Contents

1) Hot Rare Decays

$B_s \rightarrow \mu^+ \mu^-$ with P.Maták, Nucl.Phys. 2010

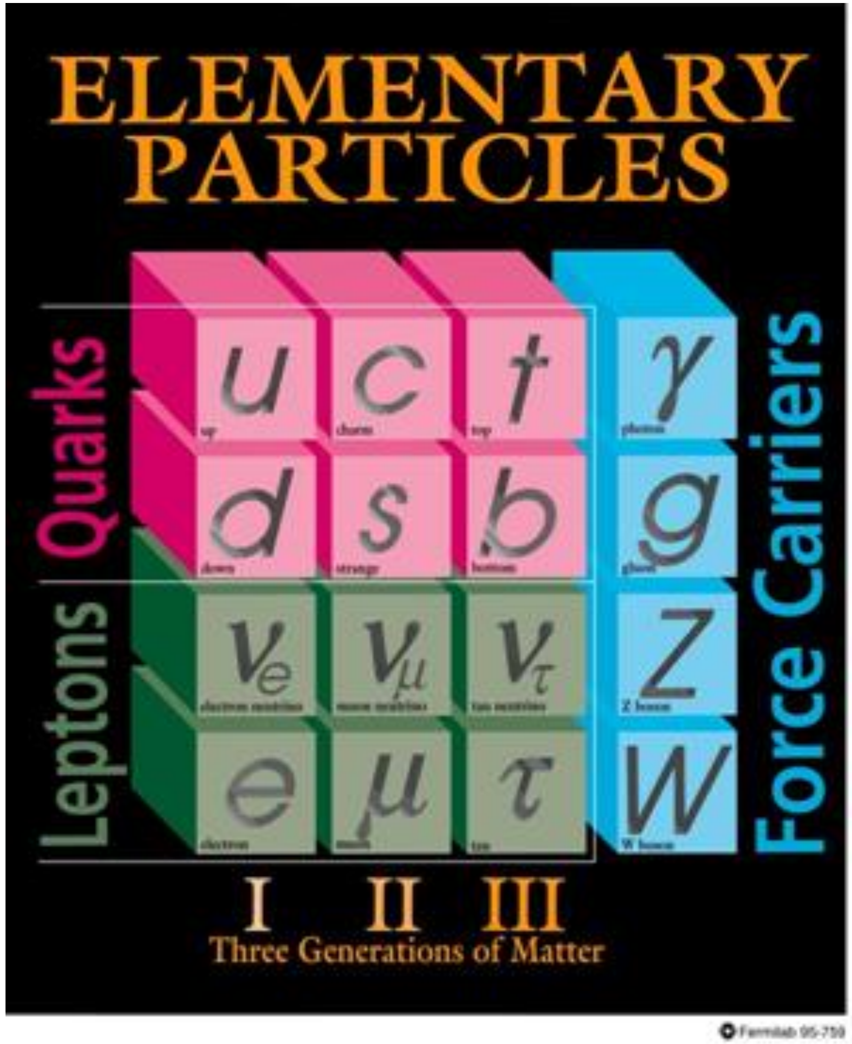
$K^+ \rightarrow \pi^+ \nu$ vbar with P.Maták, Intl. J. Phys. 2014, PhD Thesis 2015

$R_K = \Gamma(K^+ \rightarrow e^+ \nu_e) \,/\, \Gamma(K^+ \rightarrow \mu^+ \nu_\mu)$ with Z.Kučerová, M.S. Thesis 2015

2) Supersymmetry

3) Results, Prospects – Experiment, Theory

Standard Model – revisited



Despite its popularity, the picture is missing significant points, from theoretical perspective, more than just missing the higgs boson

Standard Model – revisited

E » 100 GeV

symmetry $SU(3)_c \times SU(2)_L \times U(1)_Y$

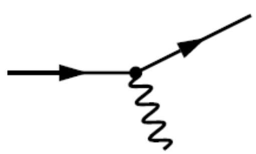
chiral theory
(the left and right transform differently)

particle states	representations		hypercharge Y ($Y=Q_{el} - T_3$)
$Q_1=\binom{u_L}{d_L}$, $Q_2=\binom{c_L}{s_L}$, $Q_3=\binom{t_L}{b_L}$	triplet	doublet	+1/6
u_R^*, c_R^*, t_R^*	antitriplet	singlet	- 2/3
d_R^*, s_R^*, b_R^*	antitriplet	singlet	+1/3
$L_1=\binom{e_L}{\nu_{eL}}$, $L_2=\binom{\mu_L}{\nu_{\mu L}}$, $L_3=\binom{\tau_L}{\nu_{\tau L}}$	singlet	doublet	- 1/2
e_R^*, μ_R^*, τ_R^*	singlet	singlet	+1
higgs boson	singlet	doublet	- 1/2

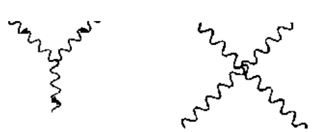
interactions strong electroweak
dynamics from symmetry

f_1f_2H, HH, $(HH)^2$ yukawa & higgs int's
introduce new parameters

ffg, ff**W**, ff**B**

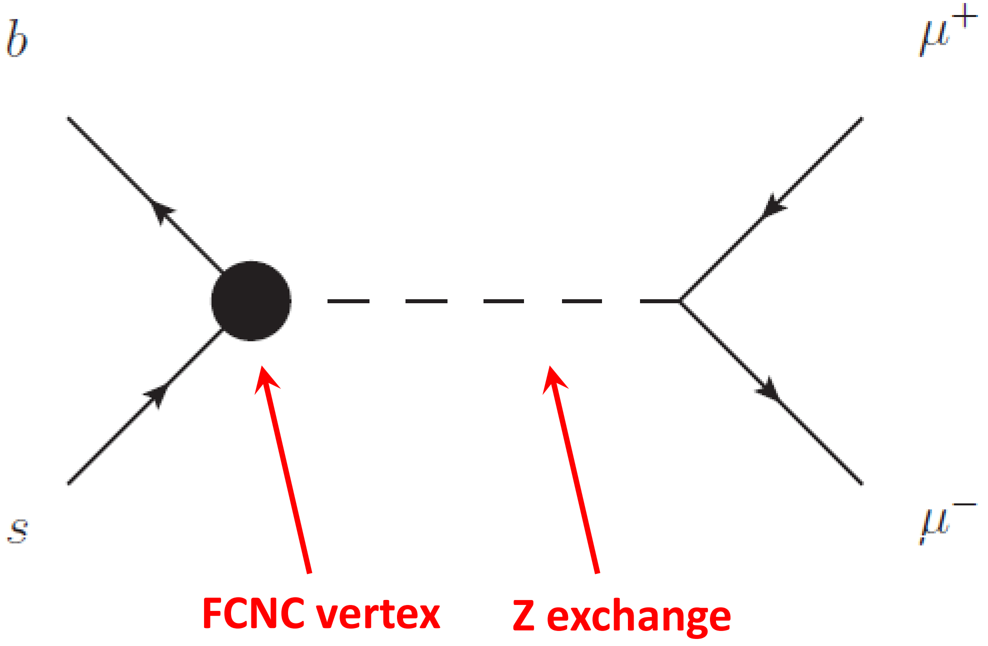


3g, 4g,
3W, **4W**



After Electroweak Symmetry Breaking
ffH generates fermion masses
ff**W** generates CKM Matrix
W^0, B replaced by physical Z, γ
HH and $(HH)^2$ determine physical higgs mass

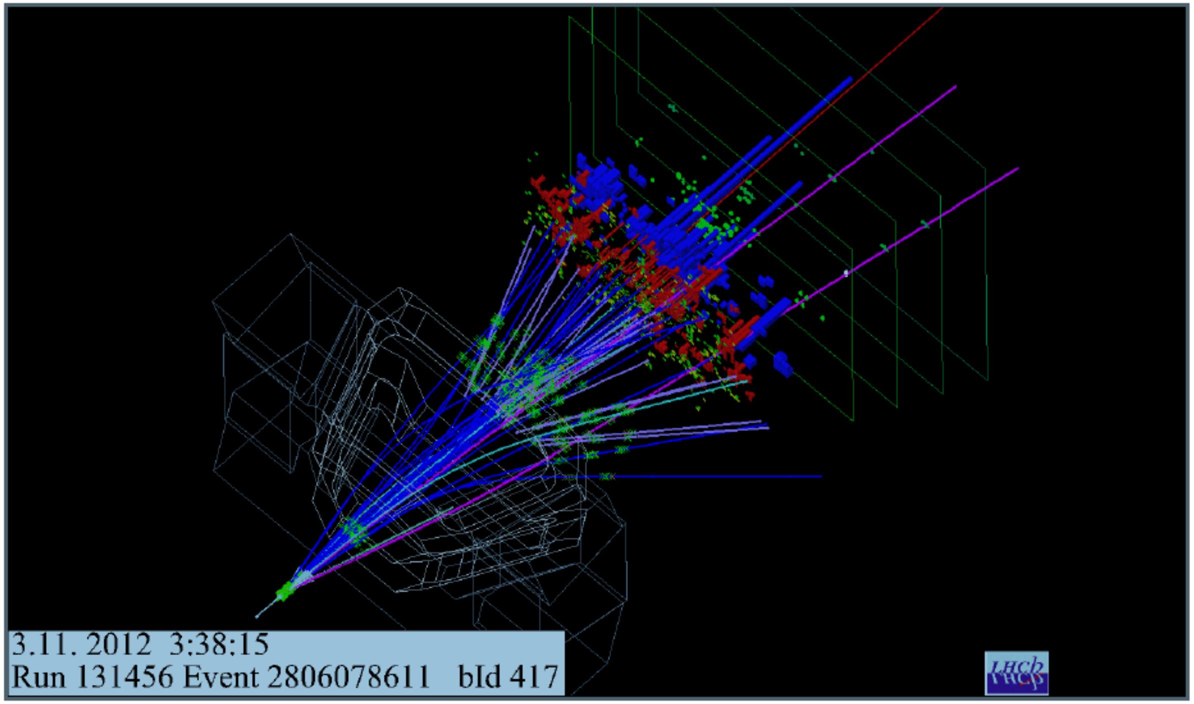
$B_s \longrightarrow \mu^+ \mu^-$



Standard Model: $Br(B_s \longrightarrow \mu^+ \mu^-) = 3.1 \pm 1.4 \times 10^{-9}$

$B_s \rightarrow \mu^+ \mu^-$

Experiment:



August 6th 2013, CERN

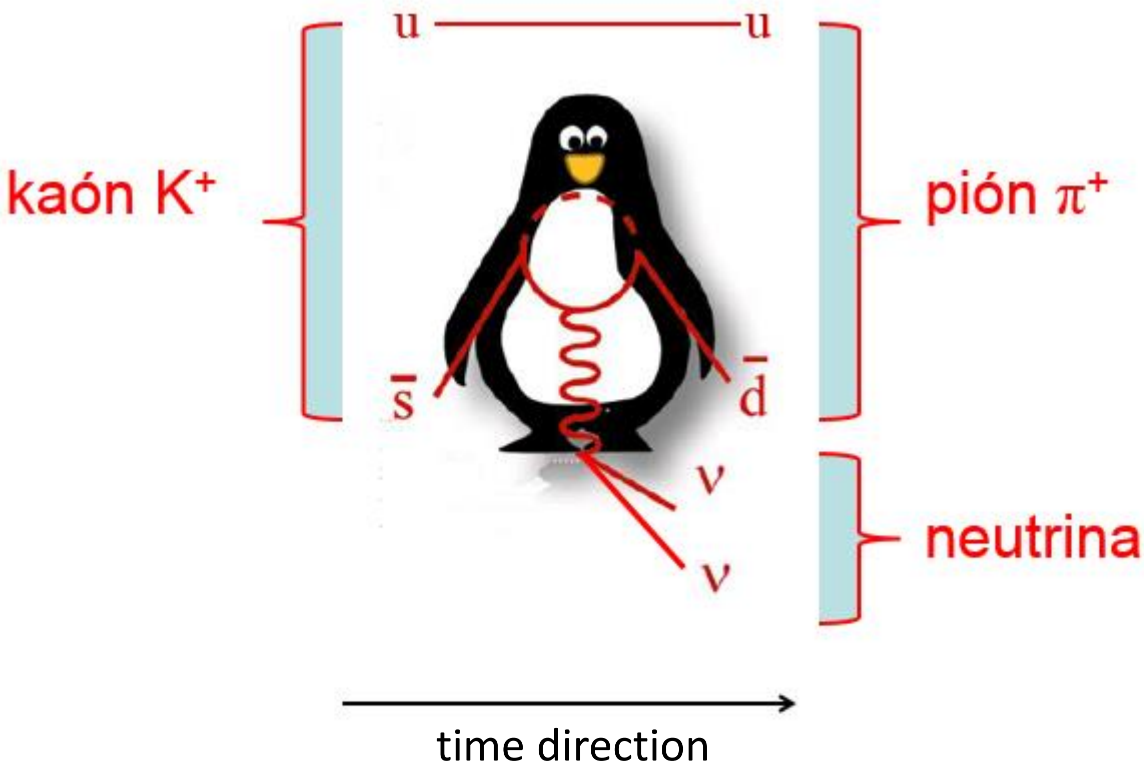
Standard Model: $Br\ (B_s \rightarrow \mu^+ \mu^-) = 3.1 \pm 1.4 \times 10^{-9}$

LHCb $3fb^{-1}$: $Br\ (B_s \rightarrow \mu^+ \mu^-) = 2.9 \pm 1.0 \times 10^{-9}$

CMS $25fb^{-1}$: $Br\ (B_s \rightarrow \mu^+ \mu^-) = 3.0 \pm 1.0 \times 10^{-9}$

ATLAS conf $4.9fb^{-1}$ 2013 $Br\ (B_s \rightarrow \mu^+ \mu^-) < 15\ (\pm 12) \times 10^{-9}$

$K^+ \longrightarrow \pi^+ \nu$ νbar



Standard Model: Br ($K^+ \longrightarrow \pi^+ \nu$ νbar) = $7.8 \pm 0.85 \times 10^{-11}$

$K^+ \longrightarrow \pi^+ \nu\, \nu bar$

Standard Model: $Br\,(K^+ \longrightarrow \pi^+ \nu\, \nu bar) = 7.8 \pm 0.85 \times 10^{-11}$

Experiment:

BNL E-787 and E-949 altogether seven events only:

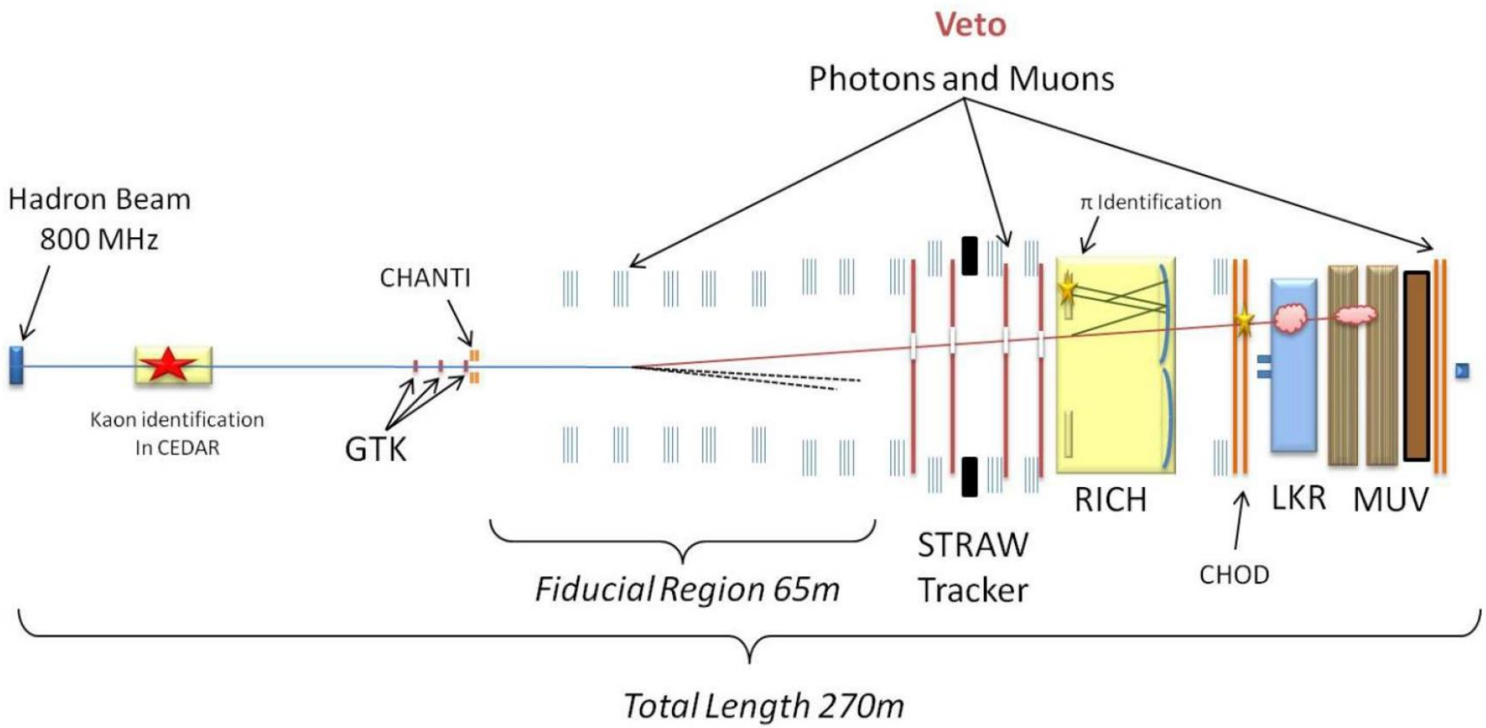
$$Br\,(K^+ \longrightarrow \pi^+ \nu\, \nu bar) = 17.3 \pm 11 \times 10^{-11}$$

NA62 Experiment will improve this measurement

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

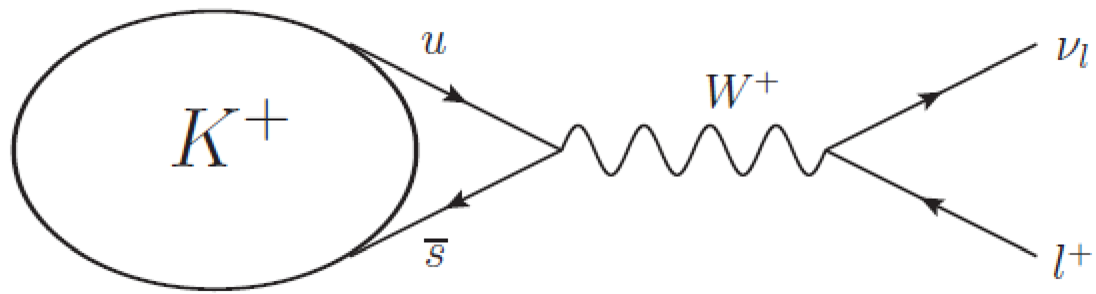
Standard Model: Br ($K^+ \rightarrow \pi^+ \nu \bar{\nu}$) = $7.8 \pm 0.85 \times 10^{-11}$

NA62 Experiment: in-flight kaon decays
running since October 2014, will finish in 2018
goal: 10% error in this "golden" decay channel



$$R_K = \frac{\Gamma(K^+ \to e^+\nu)}{\Gamma(K^+ \to \mu^+\nu)}$$

Standard Model:



$$\Gamma = \frac{1}{4\pi} G_F^2 F_0^2 |V_{us}|^2 m_e^2 m_K \left(1 - \frac{m_e^2}{m_K^2}\right)^2$$

$$R_K^{tree} = \left(\frac{m_e}{m_\mu}\right)^2 \left(\frac{m_K^2 - m_e^2}{m_K^2 - m_\mu^2}\right)^2$$

$$R_K^{SM} = (2.477 \pm 0.001) \times 10^{-5}$$

$$R_K = \frac{\Gamma(K^+ \to e^+\nu)}{\Gamma(K^+ \to \mu^+\nu)}$$

Standard Model: $R_K^{SM} = (2.477 \pm 0.001) \times 10^{-5}$

Experiment:

NA62, 2007: $R_K^{SM} = (2.488 \pm 0.010) \times 10^{-5}$

10 times more than theory

Supersymmetry

- Minimal Supersymmetric extension of the Standard Model (MSSM)
- Economic SUSY breaking

MSSM SUSY partners

E » 100 GeV

symmetry SU(3)c x SU(2)L x U(1)Y **chiral** theory

particle states	representations		hypercharge Y ($Y=Q-T_3$)		
$Q_{1,2,3}$	triplet	doublet	+1/6	→ **($\tilde{Q}_i$, Q_i)**	squarks and quarks
u_1^c, u_2^c, u_3^c	antitriplet	singlet	- 2/3	→ **($\tilde{u}^c_i$, u^c_i)**	
d_1^c, d_2^c, d_3^c	antitriplet	singlet	+1/3	→ **($\tilde{d}^c_i$, d^c_i)**	
$L_{1,2,3}$	singlet	doublet	- 1/2	→ **($\tilde{L}_i$, L_i)**	sleptons and leptons
e_1^c, e_2^c, e_3^c	singlet	singlet	+1	→ **($\tilde{e}^c_i$, e^c_i)**	
H	singlet	doublet	- 1/2	→ **(H_u , $\tilde{H}_u$) + (H_d , $\tilde{H}_d$)**	

TWO higgs doublets
each with its own higgsinos

No SUSY partners among the SM particle states

MSSM: $SU(2)_L \times U(1)_Y \rightarrow U(1)_{em}$

Electroweak Symmetry Breaking

Neutral components of H_u and H_d both get independent vacuum expectation values

$$\langle H_u^0 \rangle = v_u \neq 0 \qquad \langle H_d^0 \rangle = v_d \neq 0$$

Ratio $v_u / v_d = \tan\beta$ could be as high as 50 !

Note: $v_u / v_d = \tan\beta \gg 1$ *may explain heavy top quark*

MSSM Potential Magic:

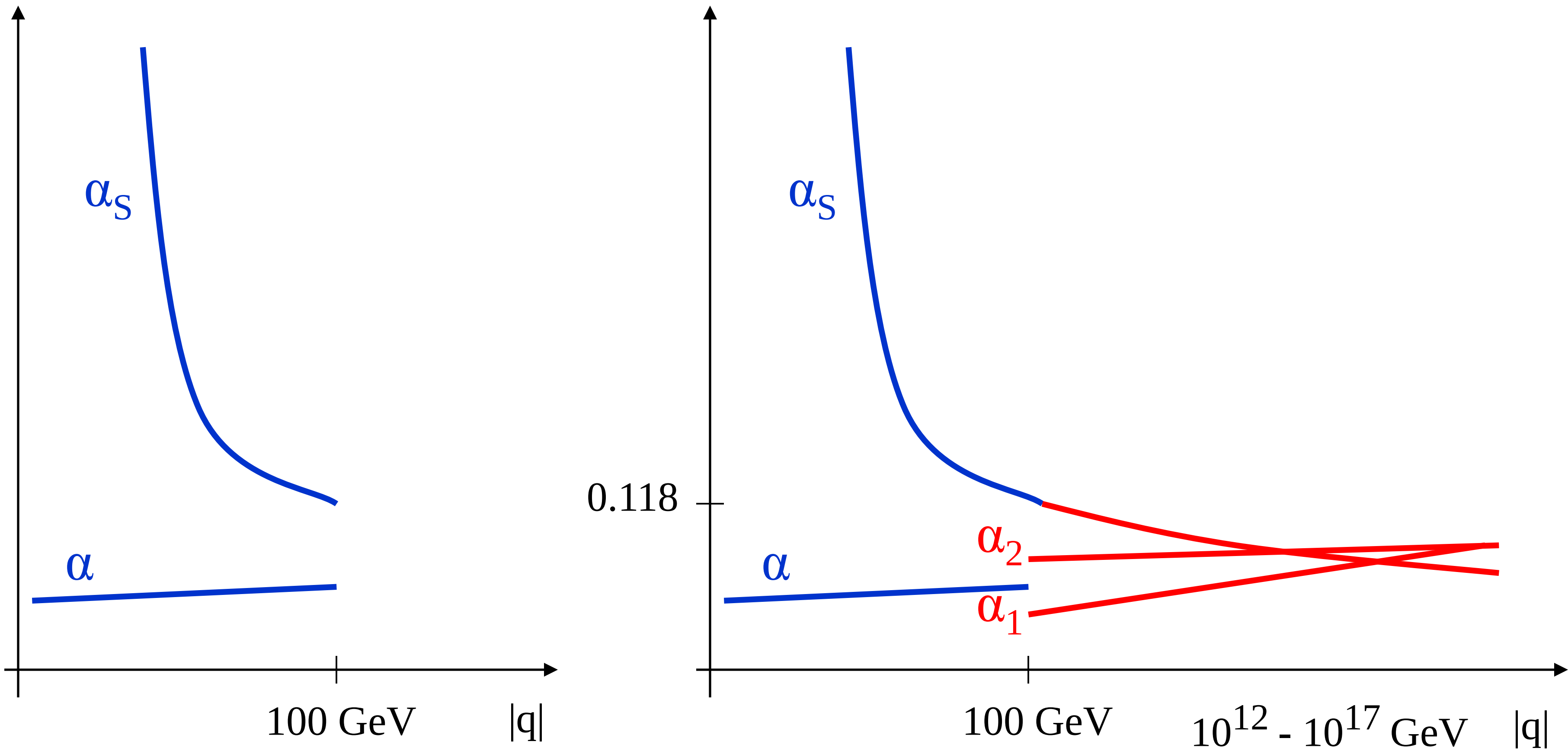
large $\tan\beta$ means y_d and y_e yukawa couplings
are 50 times greater than what we think they are in SM

Indeed: $m_d = y_d v_d$, $m_e = y_e v_d$ *with* $v_d = 3$ *GeV instead of 170 GeV requires compensation in the yukawas by a factor 50 !*

Väzbové konštanty (= náboje) v závislosti na prenesenej hybnosti

Štandardný model pod 100 GeV
zvyšková kalibračná symetria
$SU(3)_c \times U(1)_{em}$

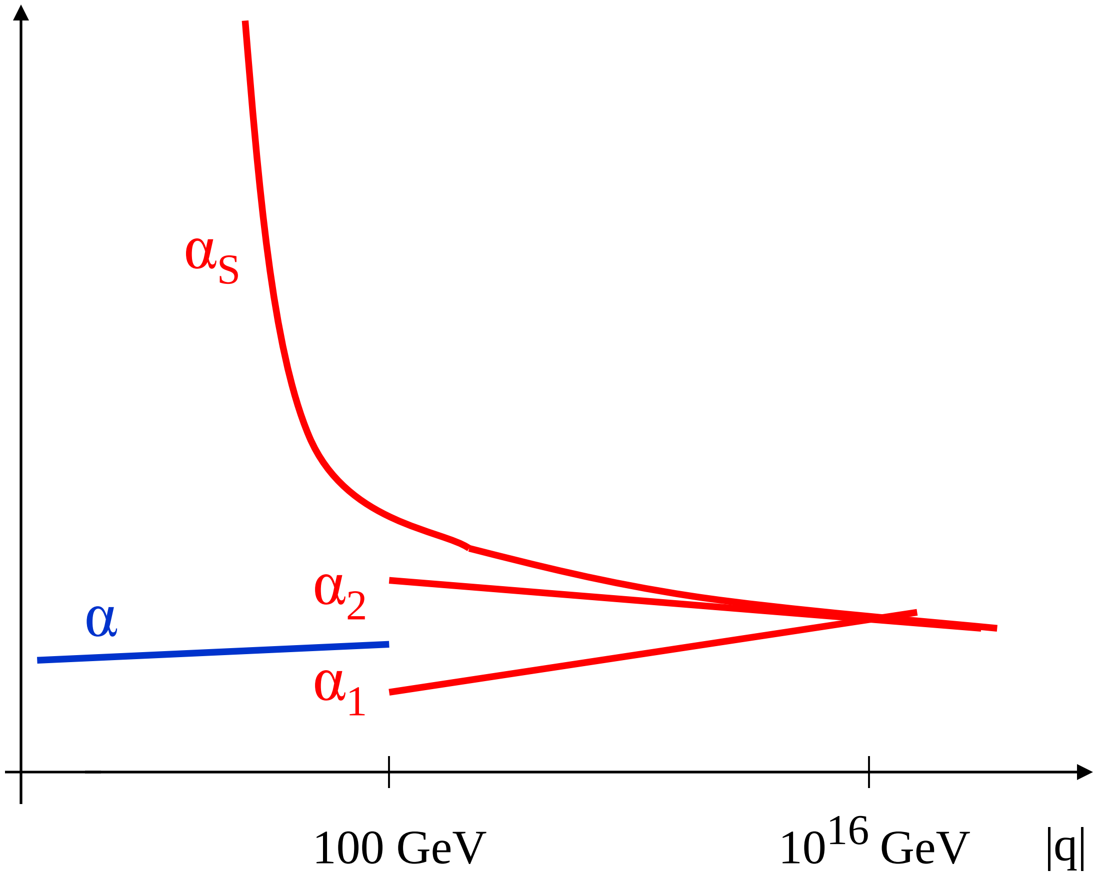
Štandardný model nad škálou 100 GeV:
kalibračná symetria
$SU(3)_c \times SU(2)_L \times U(1)_Y$



q = prenesená hybnosť

MSSM Motivation

gauge coupling unification



q = prenesená hybnosť

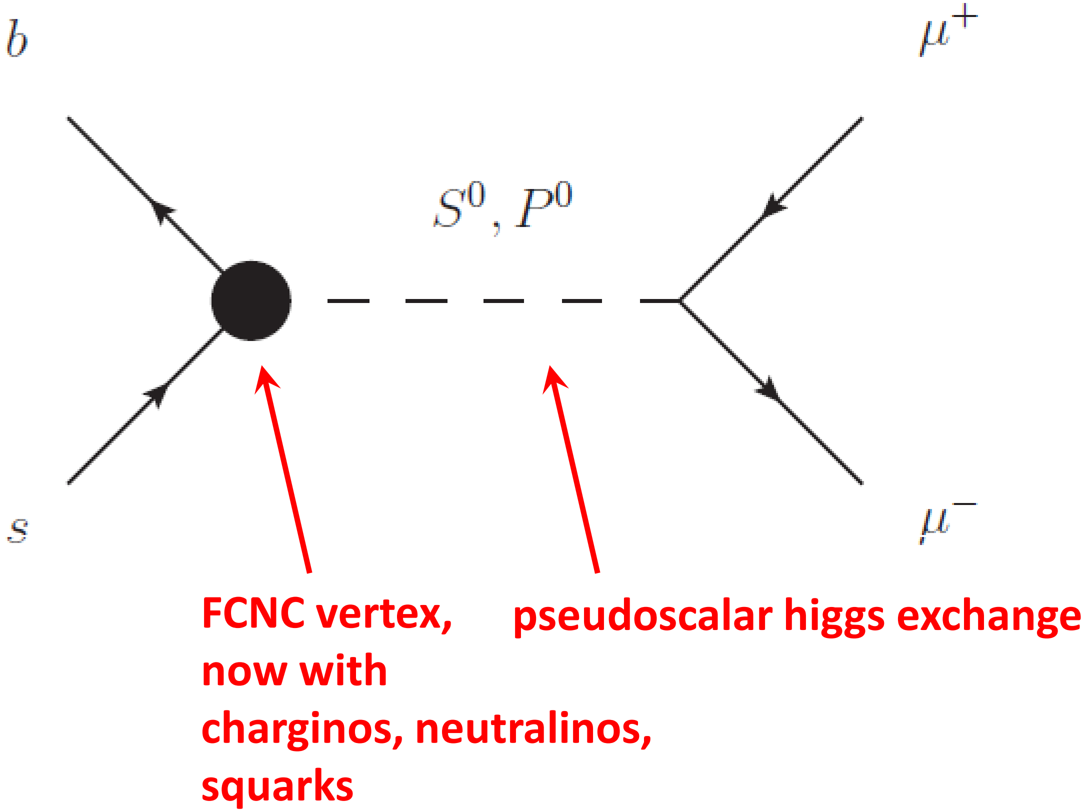
So Where Are the MSSM superpartners?

Optimistic Answer: just behind the corner !

Pessimistic Answer: we'll never know

Realistic Answer: LHC will tell ....
and, maybe, rare decays will point us
in the right direction

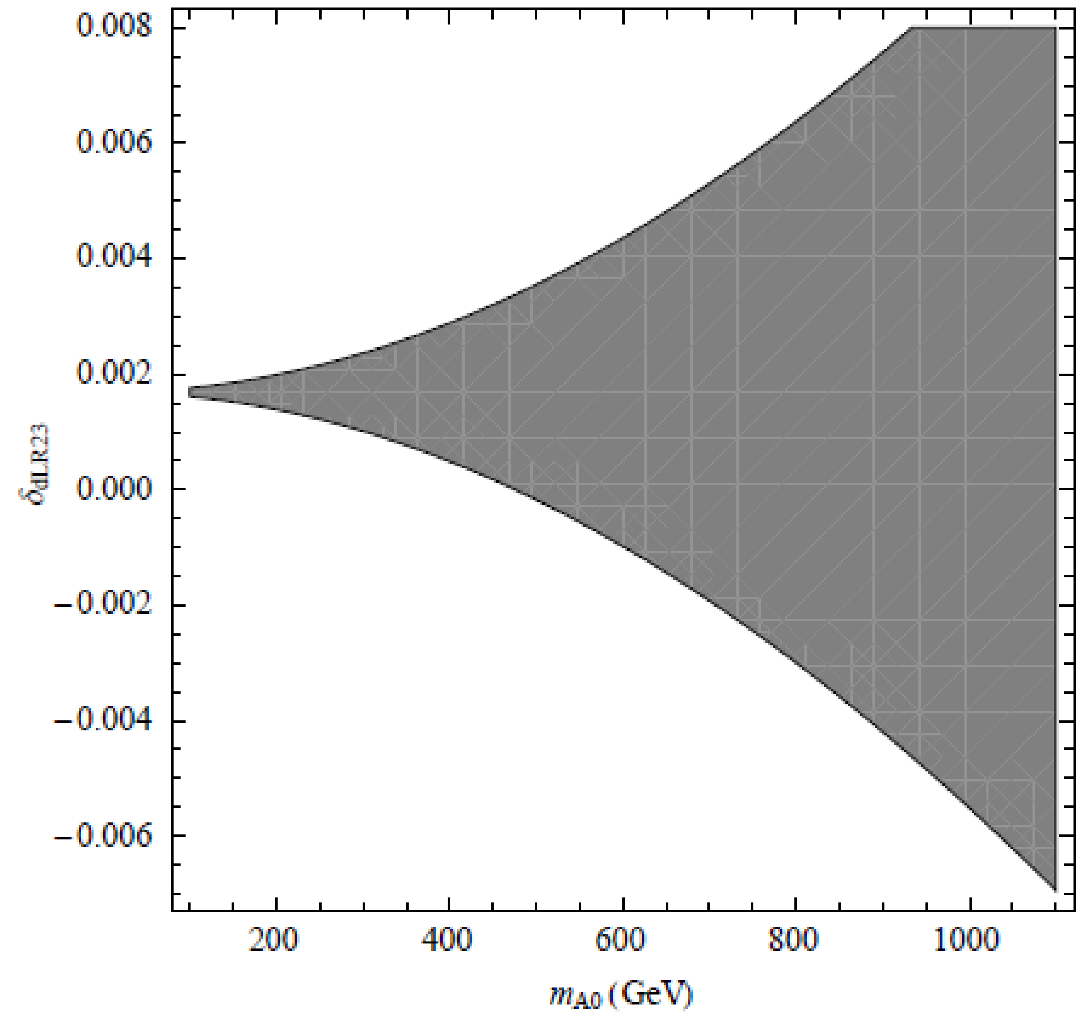
$B_s \rightarrow \mu^+ \mu^-$



MSSM: $Br(B_s \rightarrow \mu^+ \mu^-) \sim (\tan\beta)^6$

MSSM: $B_s \longrightarrow \mu^+ \mu^-$ sample analysis

$$(\delta_{\tilde{q},XY})^{JI} = \frac{(\Delta \mathcal{M}^2_{\tilde{q},XY})^{JI}}{\bar{m}^2_{\tilde{q}}}$$



Blazek, Matak, 2010

$K^+ \rightarrow \pi^+ \nu$ νbar

T. Blažek, P. Maták

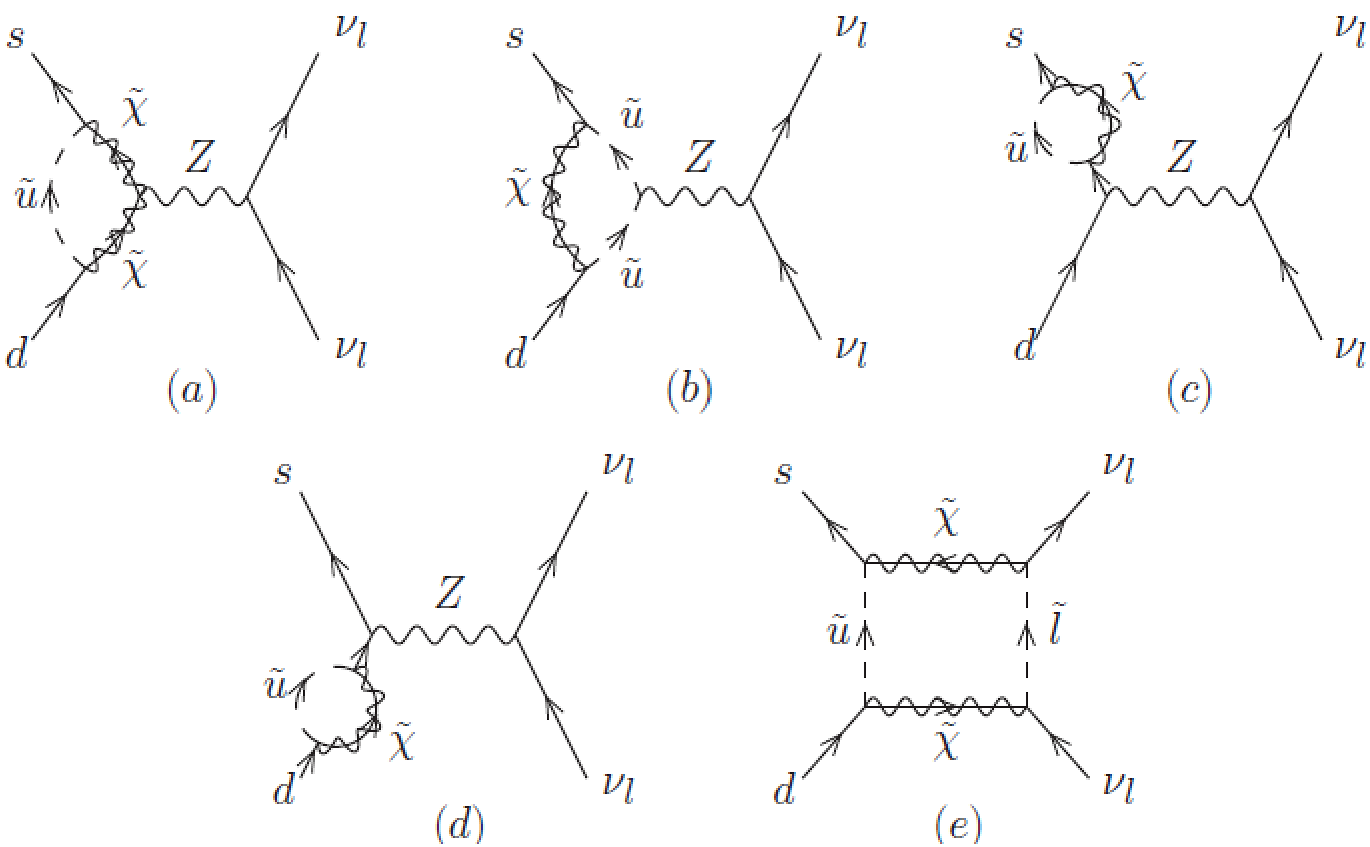
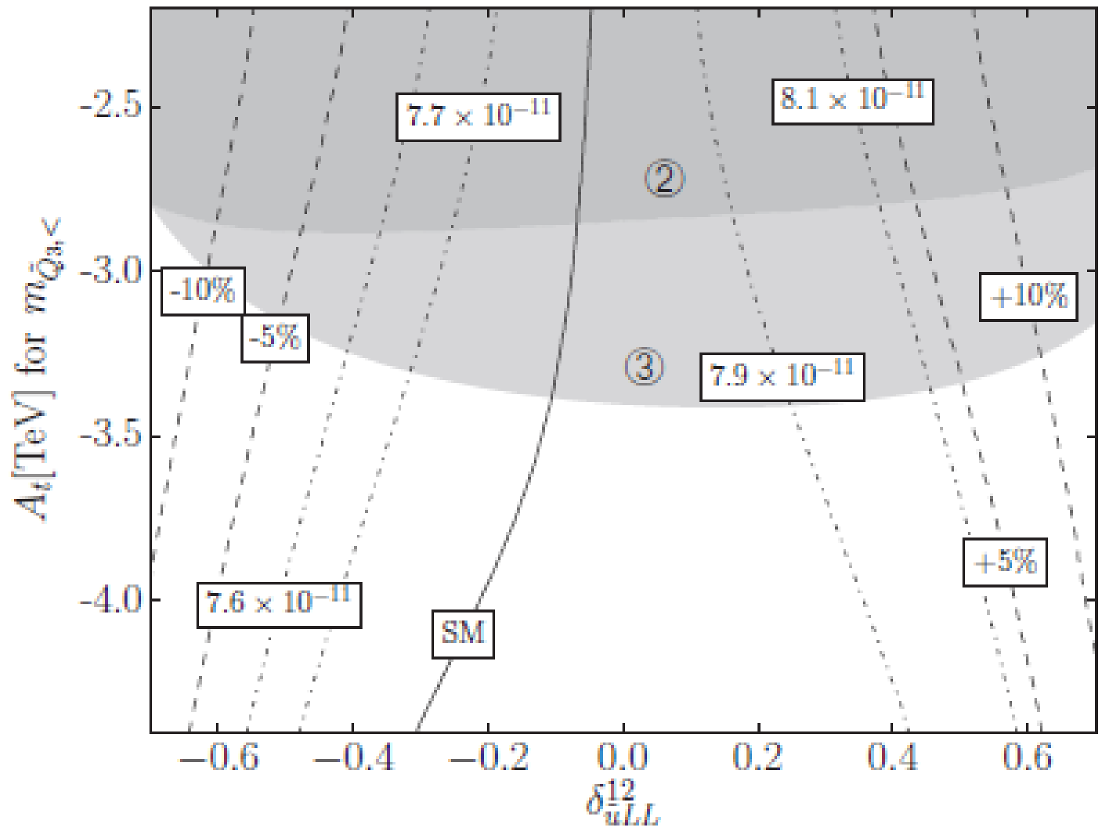


Fig. 1. MSSM chargino diagrams for the $K^+ \rightarrow \pi^+ \nu \bar{\nu}$.

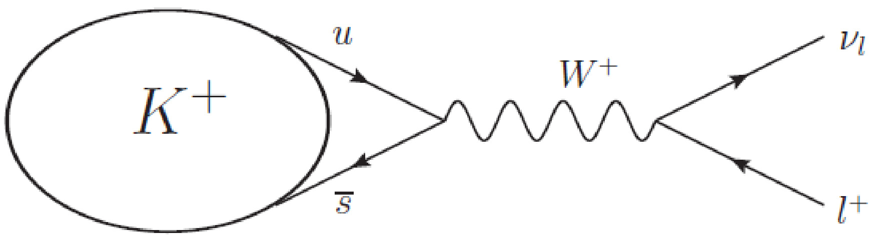
$K^+ \rightarrow \pi^+ \nu$ νbar

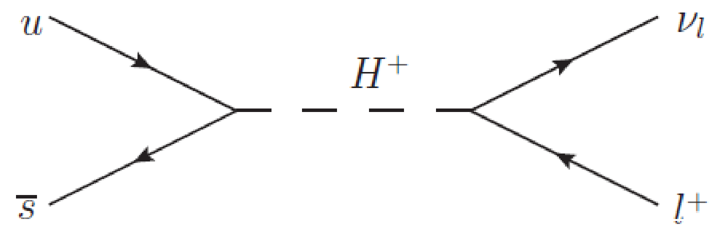
T. Blažek, P. Maták



$$R_K = \frac{\Gamma(K^+ \to e^+\nu)}{\Gamma(K^+ \to \mu^+\nu)}$$

MSSM constribution:





$$\Gamma = \frac{1}{4\pi} G_F^2 F_0^2 |V_{us}|^2 m_e^2 m_K \left(1 - \frac{m_e^2}{m_K^2}\right)^2 \left(1 - \frac{m_K^2}{M_H^2}(\tan\beta)^2\right)^2$$

does not depend on lepton flavour

MSSM constribution to R_K
cancels out at tree level ☹

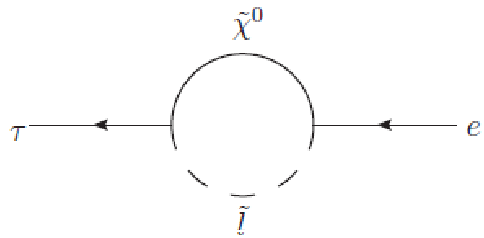
$$R_K = \frac{\Gamma(K^+ \to e^+\nu)}{\Gamma(K^+ \to \mu^+\nu)}$$

1-loop MSSM correction

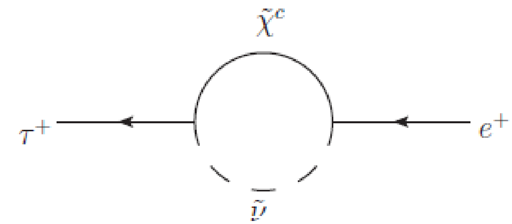
$$\Gamma(K^+ \to l^+\nu) = \Gamma^{SM}(K^+ \to l^+\nu)\left|\left[1 - \tan^2\beta\left(\frac{m_K}{m_H}\right)^2 + \Delta_l\right]\right|^2$$

$$R_K = R_K^{SM}\frac{\left|1 - \tan^2\beta\left(\frac{m_K}{m_H}\right)^2 + \Delta_e\right|^2}{\left|1 - \tan^2\beta\left(\frac{m_K}{m_H}\right)^2 + \Delta_\mu\right|^2} \approx R_K^{SM}(1 + \underbrace{2\,\mathrm{Re}(\Delta_e) + |\Delta_e|^2}_{\approx\Delta r})$$

$$R_K = \frac{\Gamma(K^+ \to e^+\nu)}{\Gamma(K^+ \to \mu^+\nu)}$$



(a) Nloop



(b) CHloop

$$\Delta_e = \tan^2\beta \left(\frac{m_K}{m_H}\right)^2 \eta^e_m(m_e)^{-1}$$

$$(\eta^e_m)_{31} = -\frac{1}{(4\pi)^2}\left[\underbrace{\mathcal{N}^R_{3AX}\mathcal{N}^{L*}_{1AX}\, m_{\tilde{\chi}^0_A}\mathcal{B}_0\left(0, m^2_{\tilde{\chi}^0_A}, m^2_{\tilde{l}_X}\right)}_{\text{Nloop}} + \right.$$

$$\left. + \underbrace{\mathcal{C}^R_{3AX}\mathcal{C}^{L*}_{1AX}\, m_{\tilde{\chi}^+_A}\mathcal{B}_0\left(0, m^2_{\tilde{\chi}^+_A}, m^2_{\tilde{\nu}_X}\right)}_{\text{CHloop}}\right]$$

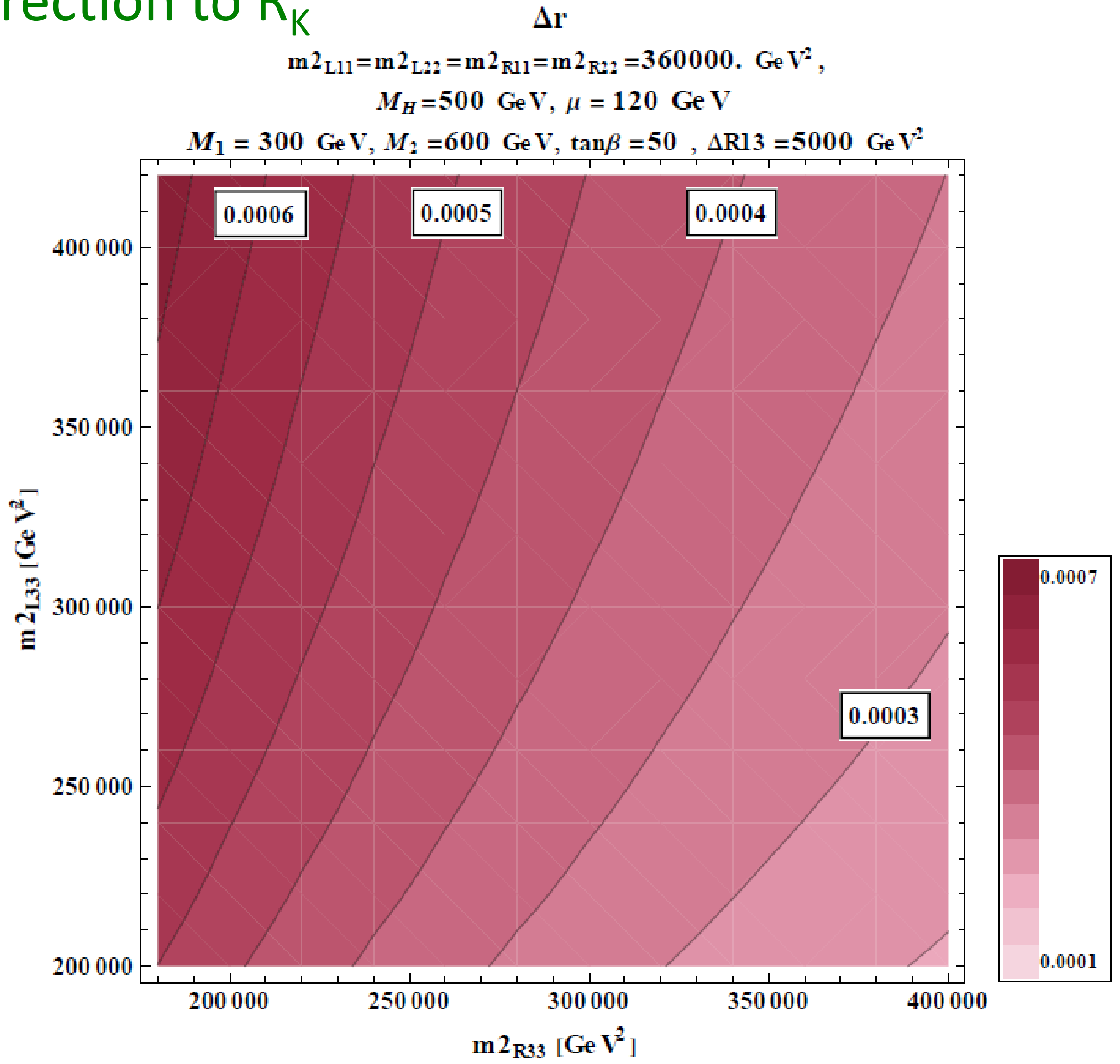
Sneutrínová hmotnostná matica a báza interakčných stavov:

$$M^2_{\tilde{\nu}} = \begin{pmatrix} m2_{L11} & 0 & \Delta L13 \\ 0 & m2_{L22} & 0 \\ \Delta L13 & 0 & m2_{L33} \end{pmatrix} \begin{pmatrix} \tilde{\nu}_e \\ \tilde{\nu}_\mu \\ \tilde{\nu}_\tau \end{pmatrix}$$

Sleptónová hmotnostná matica a báza interakčných stavov:

$$M^2_{\tilde{l}} = \begin{pmatrix} m2_{L11} & 0 & \Delta L13 & 0 & 0 & 0 \\ 0 & m2_{L22} & 0 & 0 & 0 & 0 \\ \Delta L13 & 0 & m2_{L33} & 0 & 0 & -\mu v_u Y_\tau \\ 0 & 0 & 0 & m2_{R11} & 0 & \Delta R13 \\ 0 & 0 & 0 & 0 & m2_{R22} & 0 \\ 0 & 0 & -\mu v_u Y_\tau & \Delta R13 & 0 & m2_{R33} \end{pmatrix} \begin{pmatrix} \tilde{e}_L \\ \tilde{\mu}_L \\ \tilde{\tau}_L \\ \tilde{e}_R \\ \tilde{\mu}_R \\ \tilde{\tau}_R \end{pmatrix}$$

1-loop MSSM correction to R_K



Kučerová, M.S.Diploma Thesis 2015

1-loop MSSM correction could barely show up in the NA62 measurement

Summary

- SUSY remains the best candidate we have for Beyond Standard Model (BSM) Physics

- if MSSM is a theory of nature,
  its signals should be seen fast after crossing the mass thresholds ... squark, gluino jets
  OR neutralino / chargino decays,
  however, it may take years to confirm with certainty it is the MSSM

- **once the experiment suggests we see SUSY, the most pressing issue will immediately become the mechanism of SUSY breaking**

- **unless there is no direct BSM observation, rare decays are a great opportunity at spotting BSM Physics**

- Here we scratched three of them, all dependent on large yukawa couplings due to large $\tan\beta \approx 50$, motivated by simple SO(10) SUSY Unified theories

- good news: we have the experiments going on and will know soon

Invitation to the Svit Summer School

6 – 13 September 2015

Theoretical Physics Group,
Faculty of Mathematics, Physics and Informatics, Comenius University Bratislava

MODELS OF MODERN PHYSICS

Theoretical Physics Workshop and Summer School

Svit, Slovakia 6 – 13 September 2015

- **Anderson Localisation** (P.MARKOŠ, *Comenius U, Bratislava*)
- **Topological Superconductivity** (L.KOMENDOVÁ, *Uppsala Uni.*)
- **Dynkin Magic for Simple Groups** (T.BLAŽEK, *Comenius U, Bratislava*)

… and more, for program details see the School's web page

Slovenská fyzikálna spoločnosť

http://sophia.dtp.fmph.uniba.sk/~blazek/Schools/2015S/2015S.php

Contact: blazek@fmph.uniba.sk