SUSY in rare K decays

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Outline

1. K->pi nu nubar: generalities
2. K->pi nu nubar: MSSM
3. Beyond K->pi nu nubar
4. Conclusions

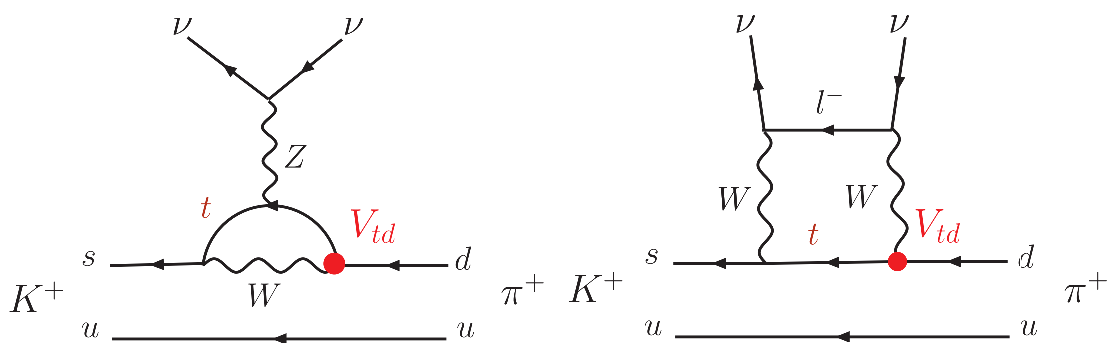
Non-supersymmetric scenarios covered by M Blanke (also A Buras)

Warning: I have not published on rare K decays for more than 10 years. This may be apparent at times in this talk.

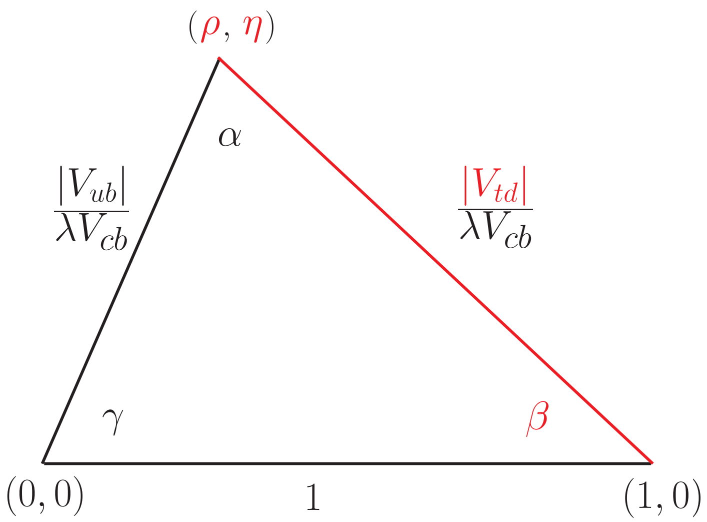
1. K->pi nu nubar: generalities

What can $K \to \pi\nu\bar{\nu}$ tell us?

FCNC process, sensitive to heavy particles & their couplings



QCD matrix elements: form factors, extracted from leading semileptonic K decays or calculated on the lattice



Charm, light quark, pQCD effects well understood

see talk by Gorbahn

Standard Model: theoretically cleanest UT determination

BSM effects

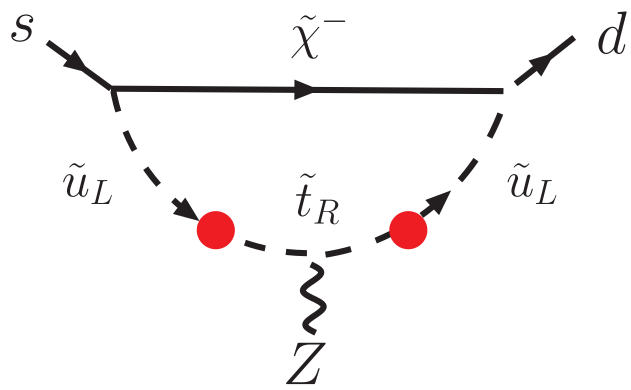
Modified Z-penguin or direct contributions to the semileptonic 4-fermion operators

e.g. heavy new physics affects the Z coupling to left-handed quarks through a single operator

$(\bar{D}\,\gamma_\mu\,S)\,(H^\dagger D_\mu H) \rightarrow d_L\,\gamma_\mu\,Z^\mu\,s_L + u_L\,\gamma_\mu\,Z^\mu\,c_L\, + \ldots$

dimension-six operator, will decouple as $1/M^2$, as expected from decoupling thm

in SUSY this operator can arise, primarily due to chargino-squark loops



parameterize coefficient by Inami-Lim function C

SM: $\lambda_t\ C$; NP: $\lambda_t\ C \rightarrow \lambda_t\ C + C_{NP}$

with QCD corrections

see talk by Gorbahn

internal charm
SM-dominated

local operators

$$\langle \pi\nu\bar{\nu}|(\bar{s}d)_{V\mp A}(\bar{\nu}_l\nu_l)_{V-A}|K\rangle =$$
$$\langle(\bar{s}d)_V\rangle\langle(\bar{\nu}_l\nu_l)\rangle \propto F^{K\to\pi}$$

$$\mathcal{H}_{\text{eff}} = \frac{G_F}{\sqrt{2}}\frac{\alpha}{2\pi\sin^2\theta_W}\sum_{l=e,\mu,\tau} V_{cs}^{*}V_{cd}X_{NL}^{l}(\bar{s}d)_{V-A}(\bar{\nu}_l\nu_l)_{V-A}$$

$$+\frac{G_F}{\sqrt{2}}\frac{\alpha}{2\pi\sin^2\theta_W}\sum_{l=e,\mu,\tau}\left[\tilde{X}_L(\bar{s}d)_{V-A}+\tilde{X}_R(\bar{s}d)_{V+A}\right](\bar{\nu}_l\nu_l)_{V-A}$$

talk by Gorbahn

Z-penguins,boxes with heavy particles.
V_{td}, new physics (masses & couplings) enter only here

Observables

$$BR_+ \equiv BR(K^+ \to \pi^+ \nu\bar{\nu}) = \kappa_+ \Big[\Big(\frac{\tilde{P}_c}{\lambda} + \frac{\mathrm{Re}\tilde{X}}{\lambda^5}\Big)^2 + \Big(\frac{\mathrm{Im}\tilde{X}}{\lambda^5}\Big)^2\Big]$$

$$BR_L \equiv BR(K_L \to \pi^0 \nu\bar{\nu}) = \kappa_L \Big(\frac{\mathrm{Im}\tilde{X}}{\lambda^5}\Big)^2$$

$\kappa_+ = 0.5173(25) \times 10^{-10}$

$\kappa_L = 2.231(13) \times 10^{-10}$

(form factors) Mescia, Smitch 2007

$\tilde{P}_c \equiv \mathrm{Re}\lambda_c P_c$ $\quad P_c = 0.372 \pm 0.015$ (charm) Brod, Gorbahn, Stamou 2010

ca +10% shift due to long-distance charm, up Isidori, Mescia, Smith 2005

$\tilde{X} \equiv \tilde{X}_L + \tilde{X}_R \equiv \lambda_t X$ $\quad \lambda_t = V_{ts}^* V_{td}$ $\quad X_{\mathrm{SM}} = 1.53 \pm 0.04$

$$\frac{BR_L}{BR_+} \leq \frac{\kappa_L}{\kappa_+} = 4.4$$

model-independent bound Grossman, Nir (1997)

SM: $BR_L/BR_+ \sim 0.4$

$K \to \pi\nu\bar{\nu}$ beyond the SM

$$BR_+ = 7.81(75)(29) \times 10^{-11}$$
$$BR_L = 2.43(39)(6) \times 10^{-11}$$

SM prediction

Brod, Gorbahn, Stamou 2011

$$BR_+^{\mathrm{exp}} = (1.73^{+1.15}_{-1.05}) \times 10^{-10}$$

BNL AGS E787,E949

$$BR_L^{\mathrm{exp}} < 2.6 \times 10^{-8} \quad (90\%\ \mathrm{CL})$$

E391a

Ongoing measurements at NA62 (BR_+) and KOTO (BR_L)

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Ongoing measurements at NA62 (BR_+) and KOTO (BR_L)

In general, saturating Grossman-Nir would allow
BR_L up to $\sim 10^{-9}$ given the experimental upper bound on BR_+

to saturate would need to suppress $\left(\frac{\tilde{P}_c}{\lambda} + \frac{\text{Re}\tilde{X}}{\lambda^5}\right)^2$

modify $|\tilde{X}|$ (only possibility for minimal flavor violation)
and/or change arg $\tilde{X}$ (requires non-minimal flavour violation)

2. K->pi nu nubar: MSSM

Flavour violation in the MSSM

MSSM has plentiful sources of flavour violation.
In fact, flavour physics imposes the most stringent constraints on the SUSY scale, or alternatively on the SUSY breaking.

6x6 squark mass matrices have flavor structure (most of it parameterising soft SUSY breaking)

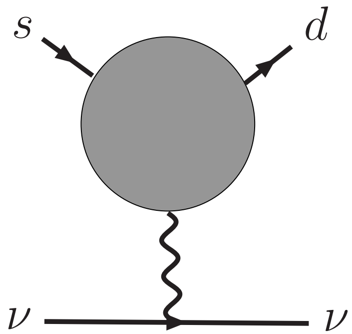
3x3 matrices

$$M^2_{(\tilde{u},\tilde{d})} = \begin{pmatrix} M^2_{\tilde{q}\,LL} & M^2_{(\tilde{u},\tilde{d})LR} \\ (M^2_{(\tilde{u},\tilde{d})LR})^\dagger & M^2_{(\tilde{u},\tilde{d})RR} \end{pmatrix}$$

LR,RL SU(2) breaking

LL, RR gauge invariant

Anatomy of SUSY contribution



$$\propto \frac{1}{M_Z^2} V_{Z\bar{s}d}$$

req. SU(2)-breaking (cf general discussion part)

$$\Rightarrow V_{Z\bar{s}d} = \mathcal{O}\Big(\frac{M_Z^2}{M_{\rm SUSY}^2}\Big)$$

Nir & Worah (1997)
Buras, Romanino, Silvestrini (1997)
Colangelo & Isidori (1998)

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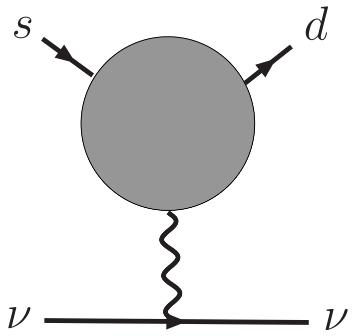

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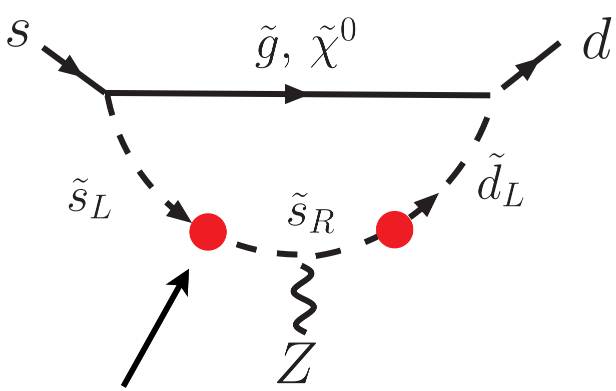
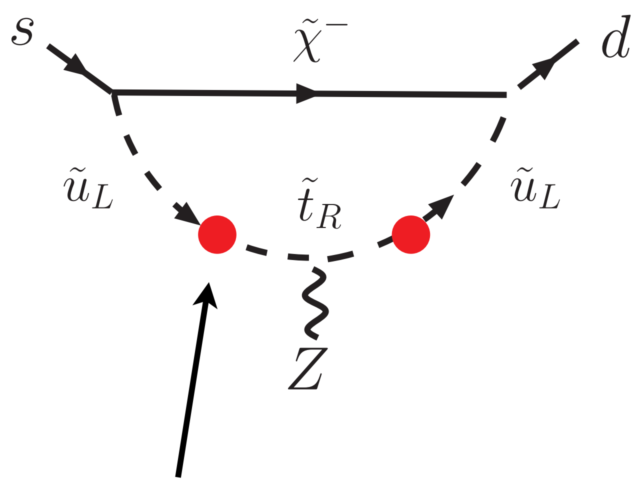
sources of SU(2) breaking include



constrained by KK, BB mixing



weakly constrained

SUSY contributions (2)

Penguins $$\tilde{X}_{\mathrm{SUSY}}^{(\mathrm{peng})} \propto \frac{(M_{LR}^2)_{d't}\,(M_{LR}^2)_{s't}^*}{M_{\mathrm{SUSY}}^4}$$ Colangelo & Isidori (1998)

Boxes require no SU(2) breaking (+)

suppressed by additional SUSY propagator (-)

SUSY contributions (2)

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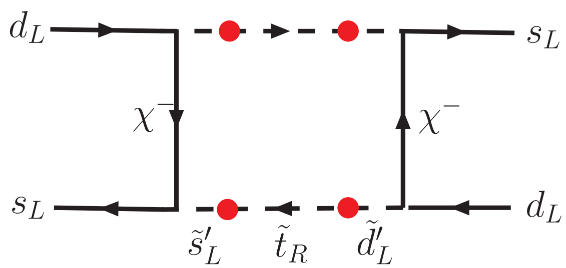
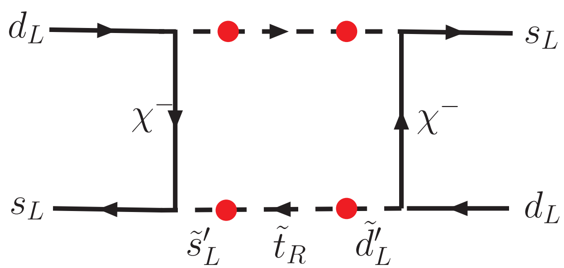
impact on other observables, e.g. KK mixing?

conventionally, require individually



$< \Delta M_K^{\text{exp}}$

desirable: (SM) +



+ ... $\approx \Delta M_K^{\text{exp}}$

Complex X plane, BR_L vs BR_+

Scan over 16 most relevant MSSM parameters

Buras, Ewerth, SJ, Rosiek 2004

Complex X plane, BR_L vs BR_+

Scan over 16 most relevant MSSM parameters

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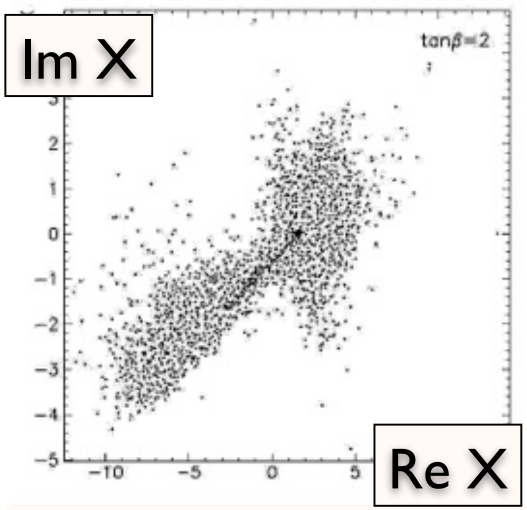

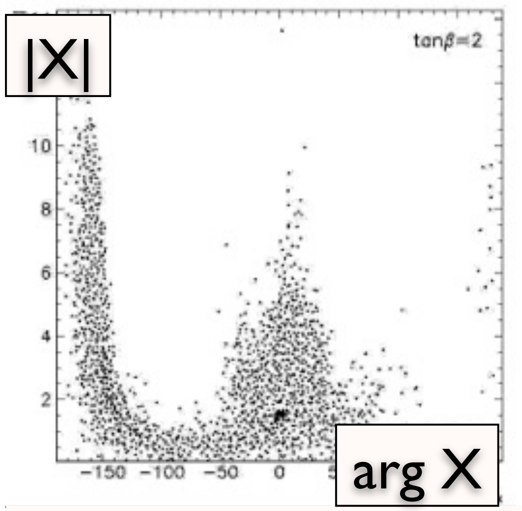

Complex X plane, BR_L vs BR_+

Scan over 16 most relevant MSSM parameters

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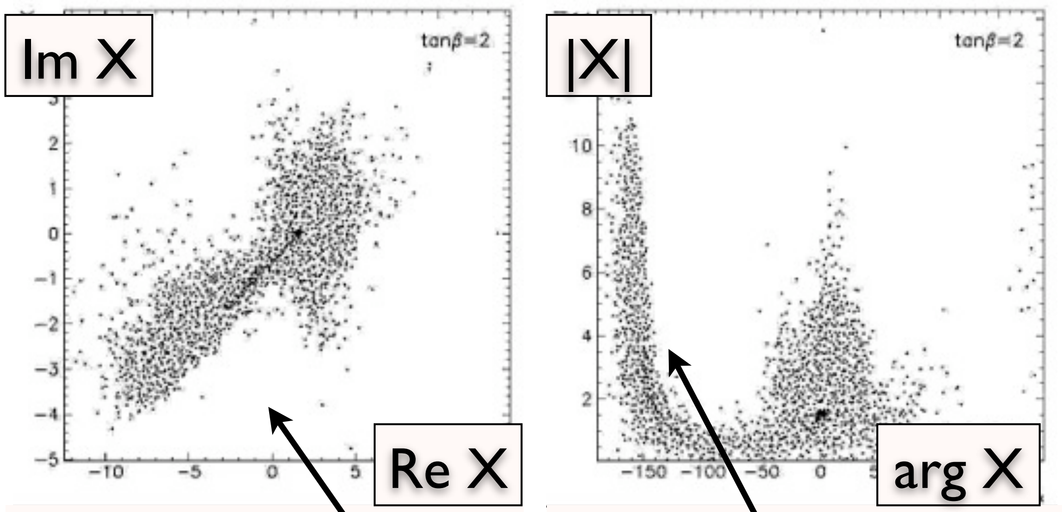

observe clear boundaries

Complex X plane, BR_L vs BR_+

Scan over 16 most relevant MSSM parameters

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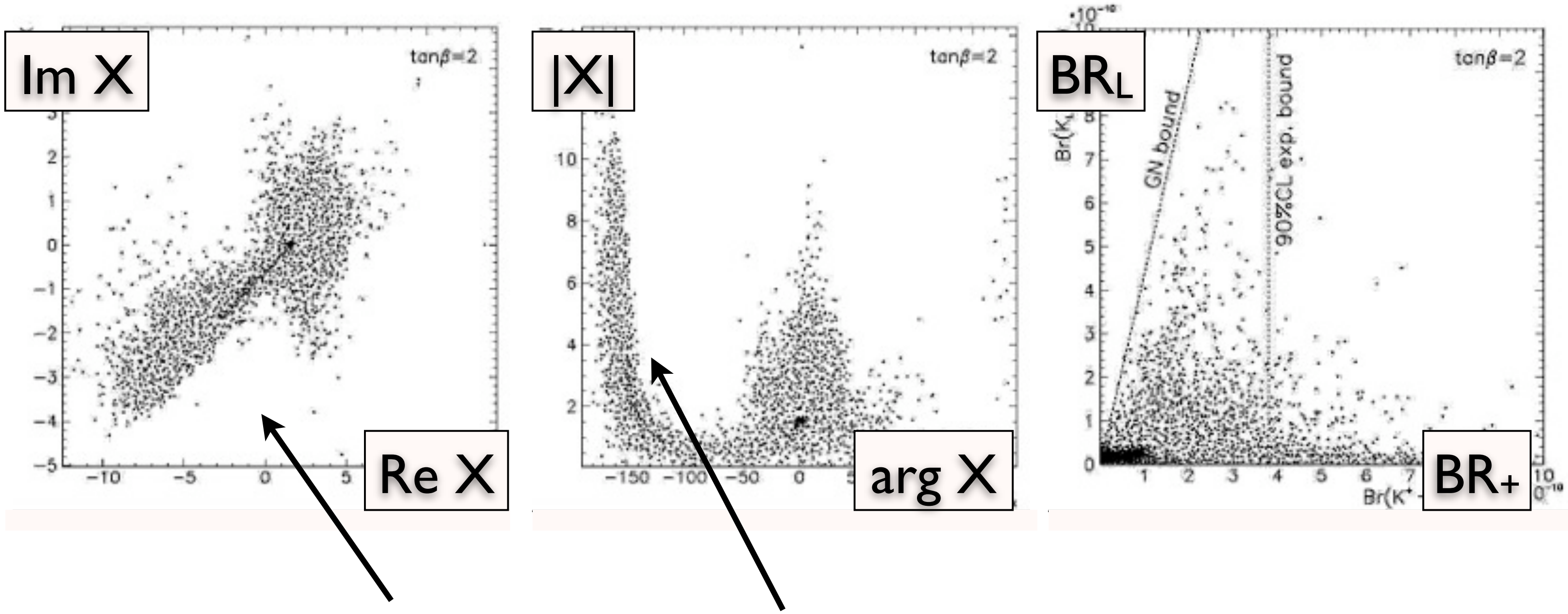

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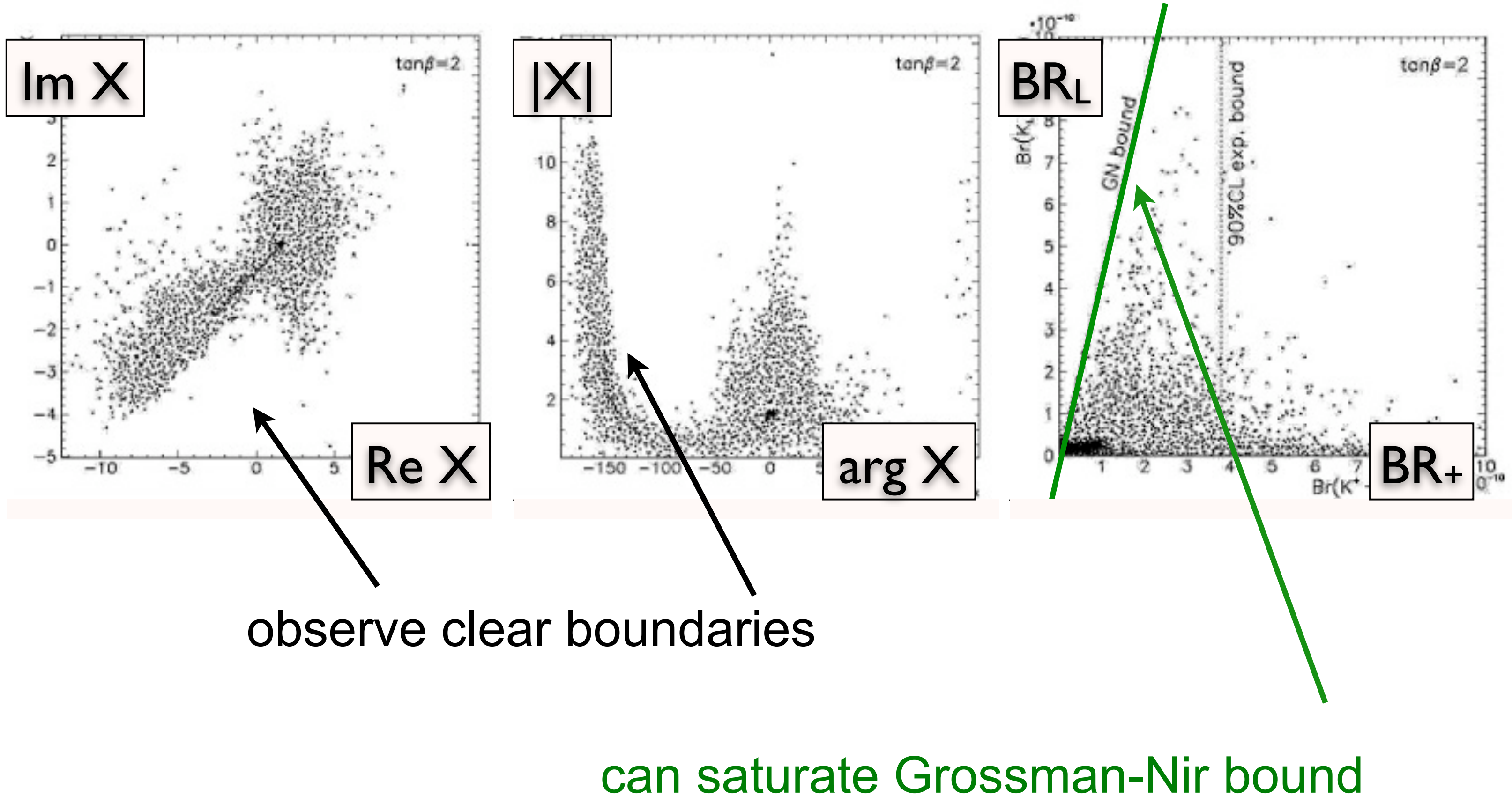
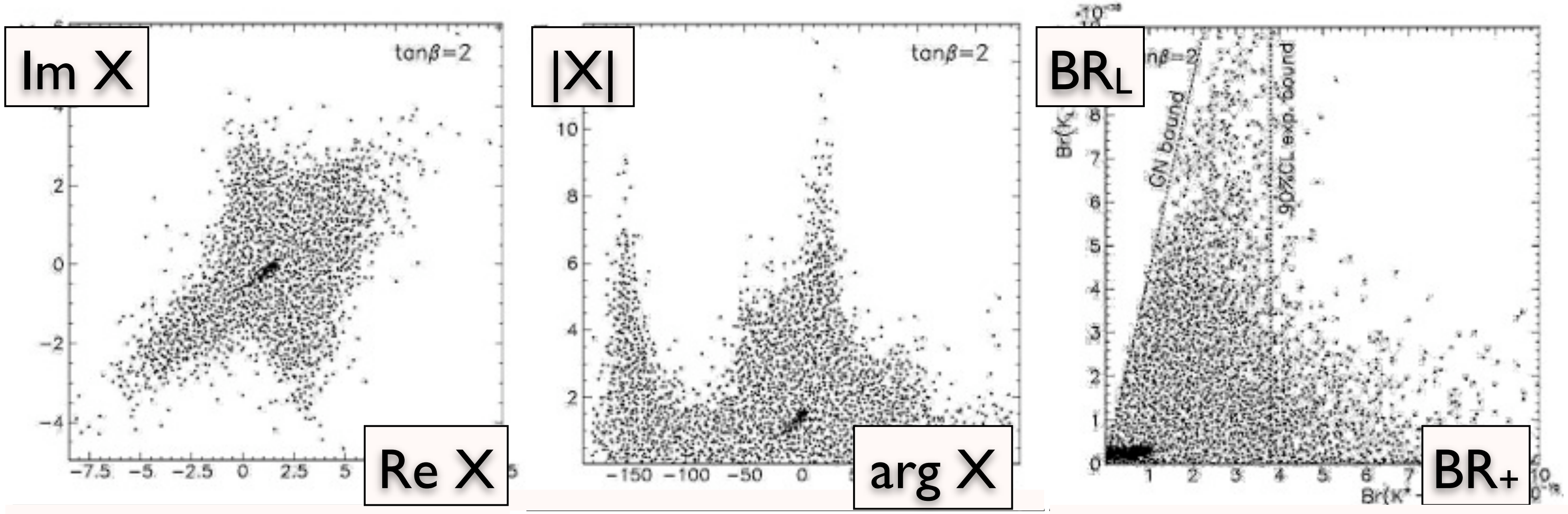


nb - 2004 analysis, substantial parts of parameter space now in conflict with LHC direct searches

66 parameters - all that enter amplitudes

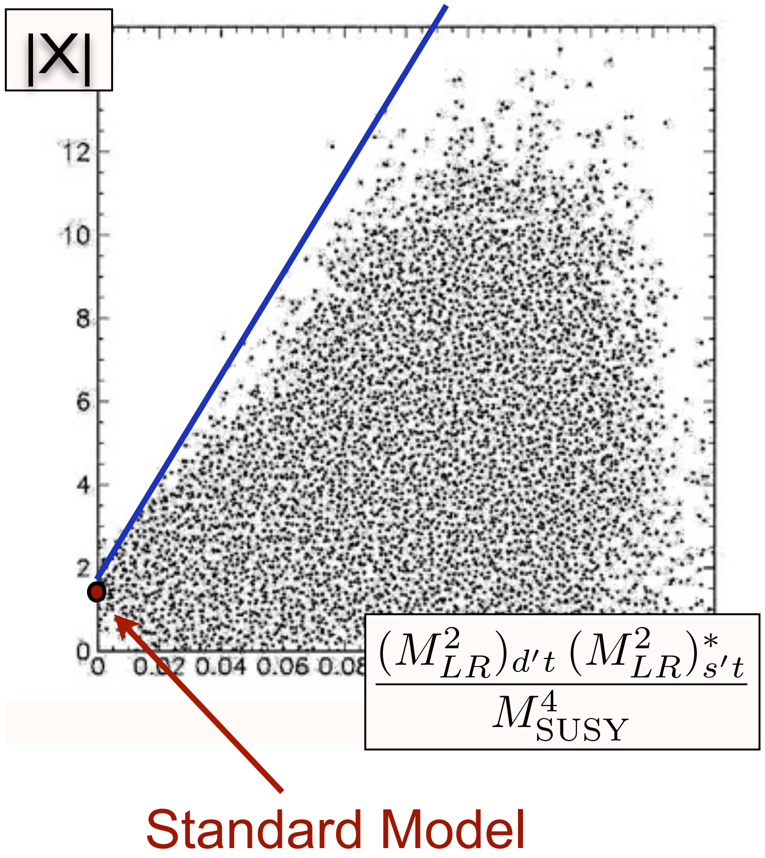
Buras, Ewerth, SJ, Rosiek 2004



minor changes - confirms expectations of hierarchies of contributions/importance of parameters

Probing the anatomy numerically

Buras, Ewerth, SJ, Rosiek 2004



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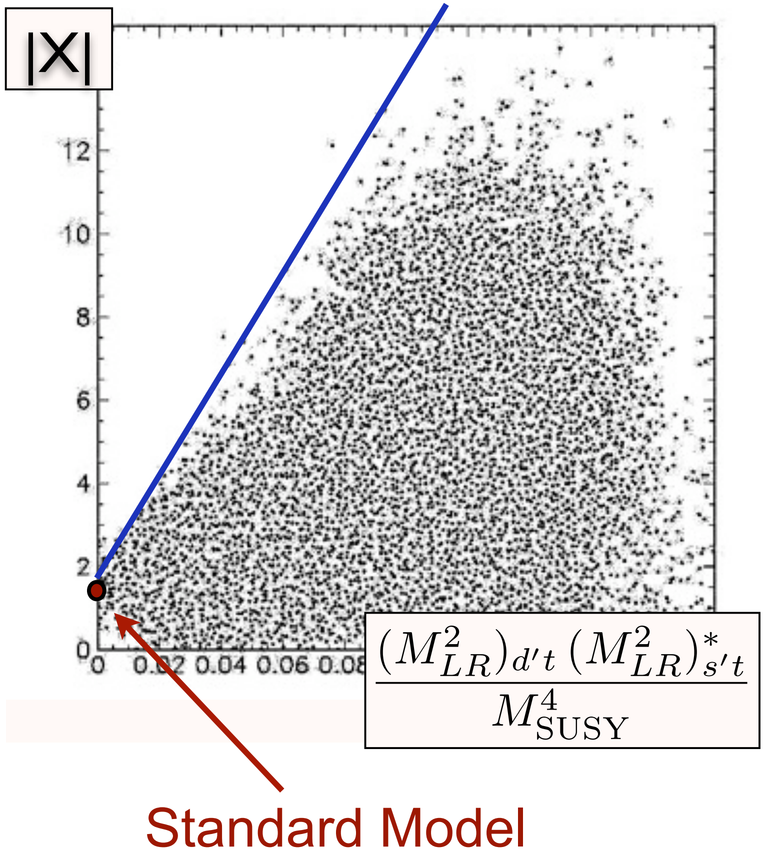

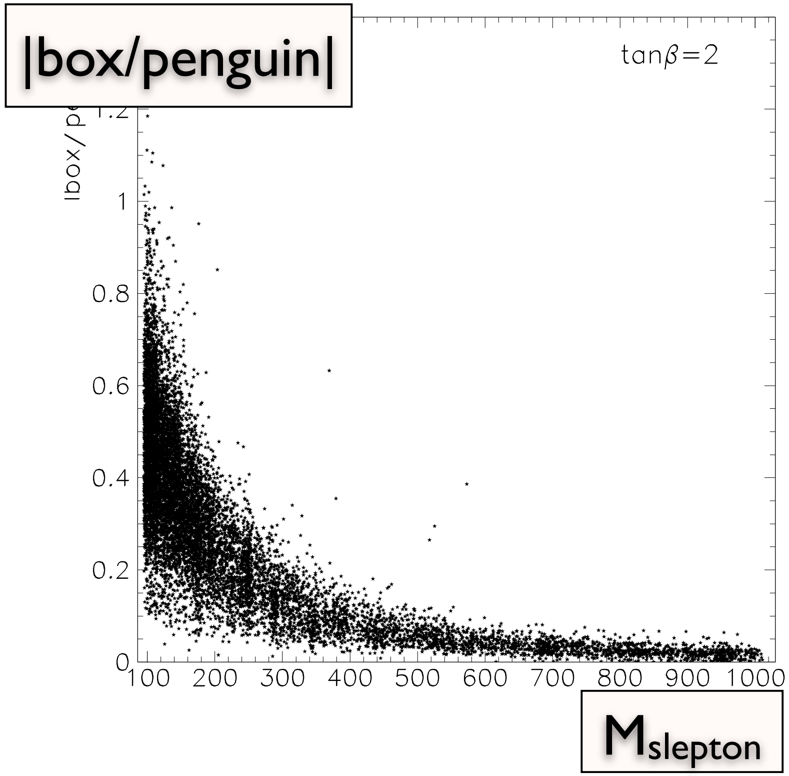

boxes not negligible!

Probing the anatomy numerically

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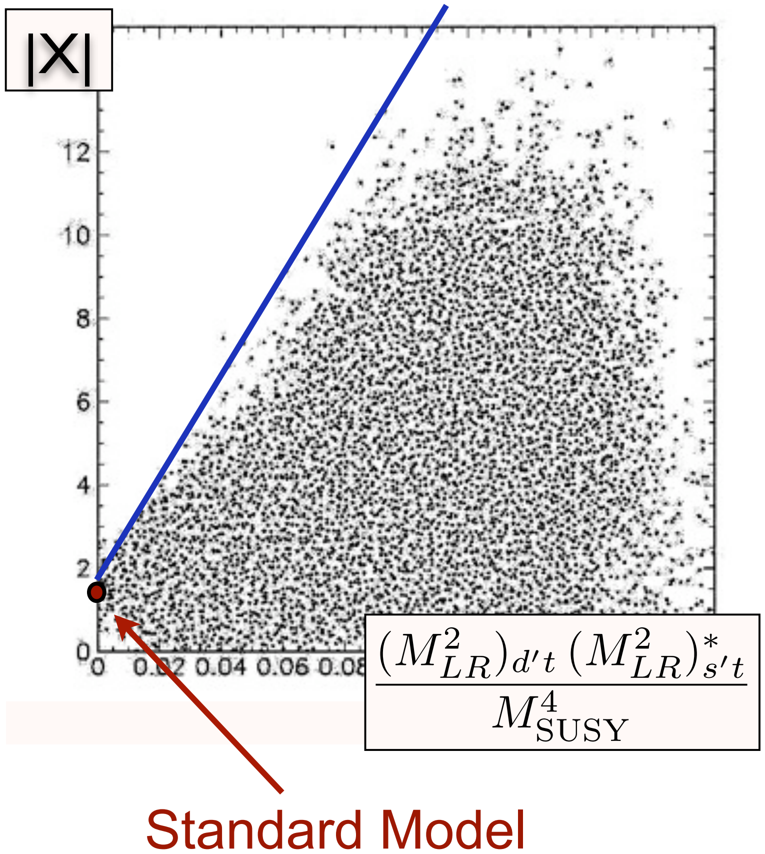

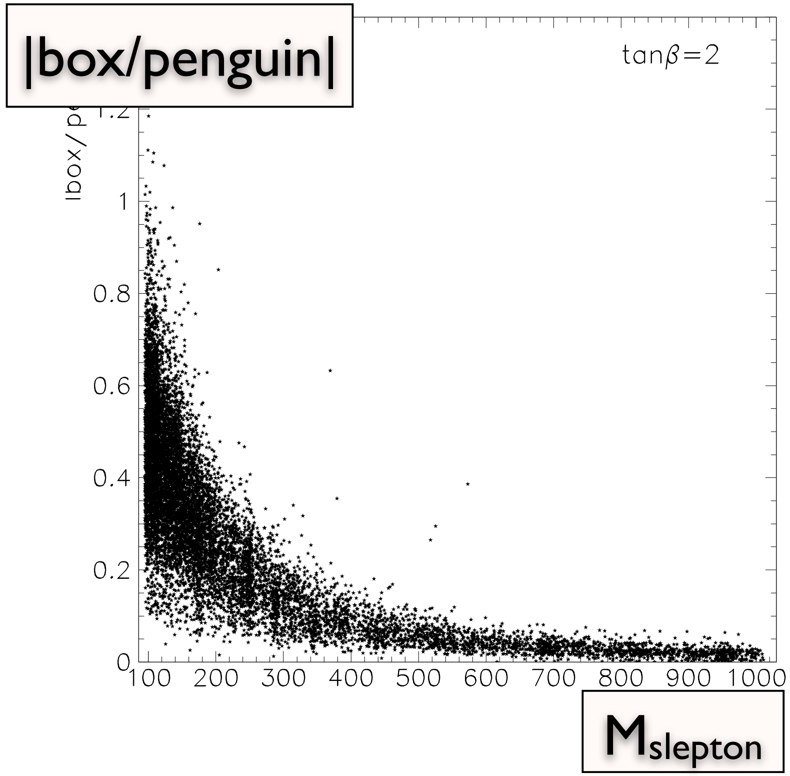

boxes not negligible!

strong sensitivity to just one parameter combination in general MSSM - holds even for boxes. Note boxes not covered by the Colangelo-Isidori argument.

Probing the anatomy numerically

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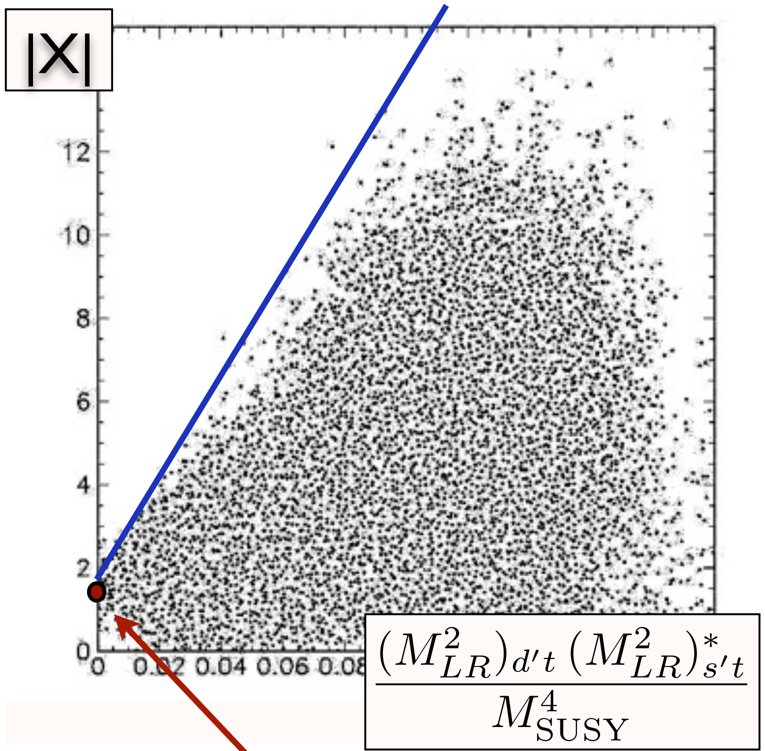
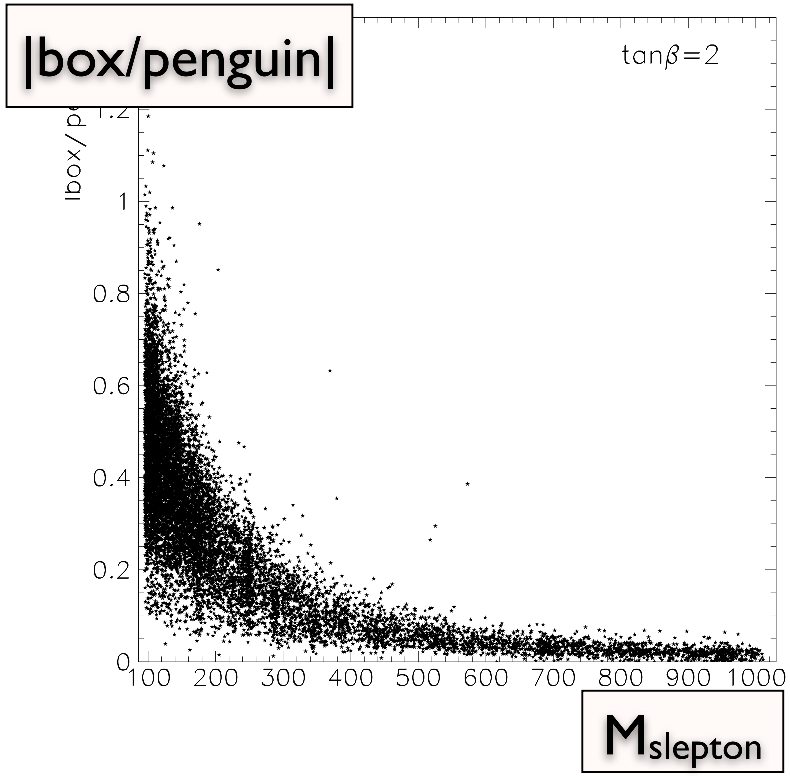




Standard Model

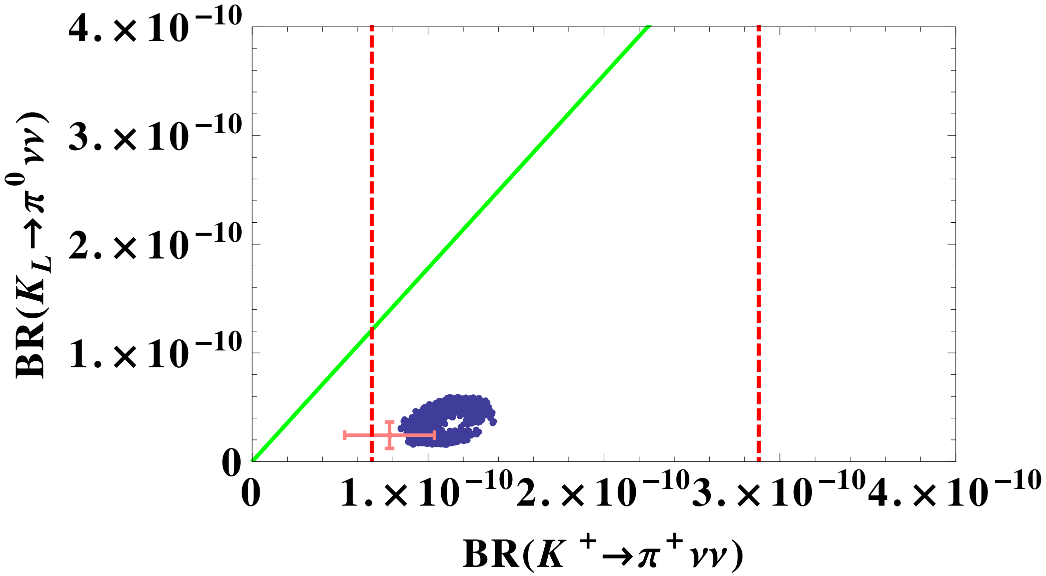
boxes not negligible!

strong sensitivity to just one parameter combination in general MSSM - holds even for boxes. Note boxes not covered by the Colangelo-Isidori argument.

Boxes (when large) are dominated by the same flavour structure simply because that structure is weakly constrained by KK mixing (ie can be large).

LHC era

Direct LHC searches exclude parts of the parameter space.



Tanimoto, Yamamoto 2015

O(1) effects still possible in both BR_+ and BR_L

also work on large tan(beta) with LL mixing
effects of O(10%) in BR_+

Blazek, Matak 2015

3. Beyond K->pi nu nubar

Other rare modes and their correlations

from: SJ, talk at NA62 Handbook workshop 2009

Operator		$K^+\to\pi^+\nu\bar\nu$	$K_L\to\pi^0\nu\bar\nu$	$K_L\to\pi^0\ell^+\ell^-$	$K_L\to\ell^+\ell^-$	$K^+\to\ell^+\nu$	$P_T(K^+\to\pi^0\mu^+\nu)$	$\Delta_{\rm CKM}$	ϵ'/ϵ	ϵ_K	in MSSM?
$O_{lq}^{(1)}$	$(\bar D_L\gamma^\mu S_L)(\bar L_L\gamma_\mu L_L)$	✓	✓	✓	hs	–	–	–	–	–	✓
$O_{lq}^{(3)}$	$(\bar D_L\gamma^\mu\sigma^i S_L)(\bar L_L\gamma_\mu\sigma^i L_L)$	✓	✓	✓	hs	hs	✓	✓	–	–	✓
O_{qe}	$(\bar D_L\gamma^\mu S_L)(\bar l_R\gamma_\mu l_R)$	–	–	✓	hs	–	–	–	–	–	small
O_{ld}	$(\bar d_R\gamma^\mu s_R)(\bar L_L\gamma_\mu L_L)$	✓	✓	✓	hs	–	–	–	–	–	small
O_{ed}	$(\bar d_R\gamma^\mu s_R)(\bar l_R\gamma_\mu l_R)$	–	–	✓	hs	–	–	–	–	–	small
$O_{lq}^\dagger$	$(\bar u_R S_L)\cdot(\bar l_R L_L)$	–	–	–	–	✓	✓	✓	–	–	tiny
$(O_{lq}^t)^\dagger$	$(\bar u_R\sigma_{\mu\nu}S_L)\cdot(\bar l_R\sigma^{\mu\nu}L_L)$	–	–	–	–	–	?	?	–	–	tiny
O_{qde}	$(\bar d_R S_L)(\bar L_L l_R)$	–	–	✓	✓	–	–	–	–	–	tiny
$O_{qde}^\dagger$	$(\bar D_L s_R)(\bar l_R L_L)$	–	–	✓	✓	✓	✓	✓	–	–	large $\tan\beta$
$O_{\varphi q}^{(1)}$	$(\bar D_L\gamma^\mu S_L)(H^\dagger D_\mu H)$	✓	✓	✓	hs	–	–	–	✓	(✓)	✓
$O_{\varphi q}^{(3)}$	$(\bar D_L\gamma^\mu\sigma^i S_L)(H^\dagger D_\mu\sigma^i H)$	✓	✓	✓	hs	hs	✓	✓	✓	(✓)	✓
$O_{\varphi d}$	$(\bar d_R\gamma^\mu s_R)(H^\dagger D_\mu H)$	✓	✓	✓	hs	–	–	–	✓	(✓)	large $\tan\beta$ (non-MFV)

Other rare modes and their correlations

from: SJ, talk at NA62 Handbook workshop 2009

Operator		Observable: $K^+ \to \pi^+ \nu\bar\nu$	$K_L \to \pi^0 \nu\bar\nu$	$K_L \to \pi^0 \ell^+\ell^-$	$K_L \to \ell^+\ell^-$	$K^+ \to \ell^+\nu$	$P_T(K^+ \to \pi^0\mu^+\nu)$	$\Delta_{\rm CKM}$	ϵ'/ϵ	ϵ_K	in MSSM?
$O_{lq}^{(1)}$	$(\bar D_L \gamma^\mu S_L)(\bar L_L \gamma_\mu L_L)$	✓	✓	✓	hs	–	–	–	–	–	✓
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O_{ed}	$(\bar d_R \gamma^\mu s_R)(\bar l_R \gamma_\mu l_R)$	–	–	✓	hs	–	–	–	–	–	small
$O_{lq}^{\dagger}$	$(\bar u_R S_L) \cdot (\bar l_R L_L)$	–	–	–	–	✓	✓	✓	–	–	tiny
$(O_{lq}^{t})^{\dagger}$	$(\bar u_R \sigma_{\mu\nu} S_L) \cdot (\bar l_R \sigma^{\mu\nu} L_L)$	–	–	–	–	–	?	?	–	–	tiny
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$O_{qde}^{\dagger}$	$(\bar D_L s_R)(\bar l_R L_L)$	–	–	✓	✓	✓	✓	✓	–	–	large $\tan\beta$
$O_{\varphi q}^{(1)}$	$(\bar D_L \gamma^\mu S_L)(H^\dagger D_\mu H)$	✓	✓	✓	hs	–	–	–	✓	(✓)	✓
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O_{ed}	$(d_R\gamma^\mu s_R)(l_R\gamma_\mu l_R)$	–	–	✓	hs	–	–	–	–	–	small
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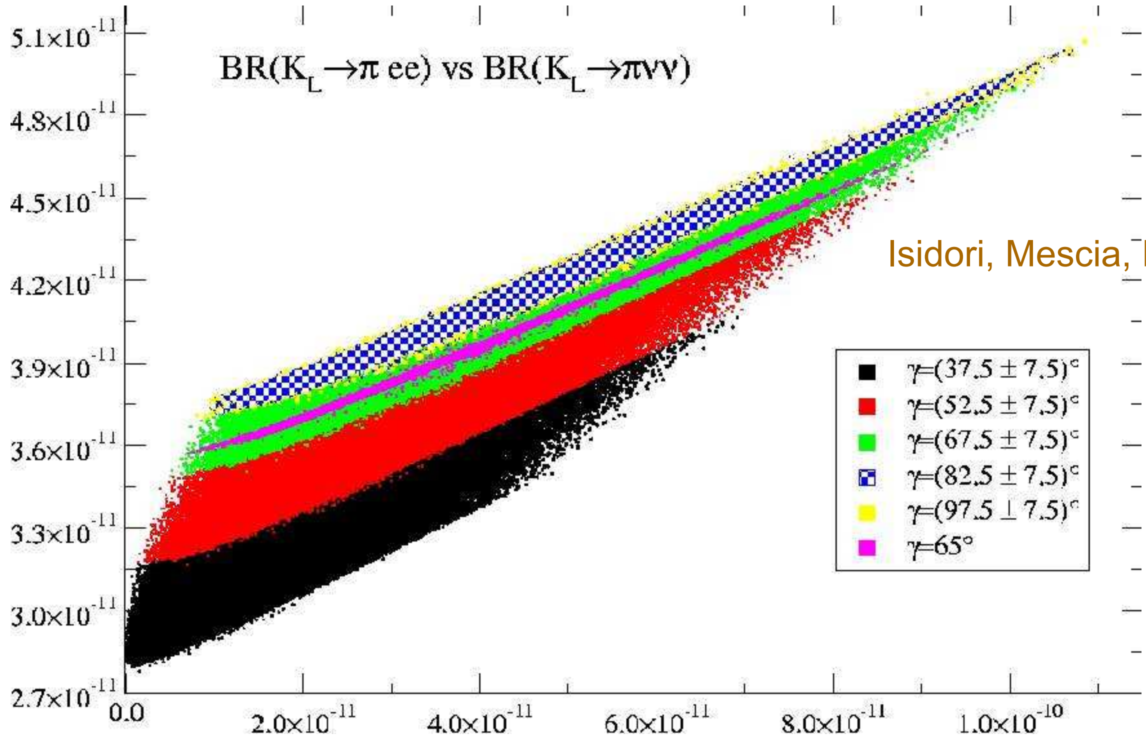
$O_{lq}^{(1)}$	$(\bar{D}_L\gamma^\mu S_L)(\bar{L}_L\gamma_\mu L_L)$	✓	✓	✓	hs	–	–	–	–	–	✓
$O_{lq}^{(3)}$	$(\bar{D}_L\gamma^\mu\sigma^i S_L)(\bar{L}_L\gamma_\mu\sigma^i L_L)$	✓	✓	✓	hs	hs	✓	✓	–	–	✓
O_{qe}	$(\bar{D}_L\gamma^\mu S_L)(\bar{l}_R\gamma_\mu l_R)$	–	–	✓	hs	–	–	–	–	–	small
O_{ld}	$(\bar{d}_R\gamma^\mu s_R)(\bar{L}_L\gamma_\mu L_L)$	✓	✓	✓	hs	–	–	–	–	–	small
O_{ed}	$(\bar{d}_R\gamma^\mu s_R)(\bar{l}_R\gamma_\mu l_R)$	–	–	✓	hs	–	–	–	–	–	small
$O_{lq}^{\dagger}$	$(\bar{u}_R S_L)\cdot(\bar{l}_R L_L)$	–	–	–	–	✓	✓	✓	–	–	tiny
$(O_{lq}^{t})^{\dagger}$	$(\bar{u}_R\sigma_{\mu\nu} S_L)\cdot(\bar{l}_R\sigma^{\mu\nu} L_L)$	–	–	–	–	–	?	?	–	–	tiny
O_{qde}	$(\bar{d}_R S_L)(\bar{L}_L l_R)$	–	–	✓	✓	–	–	–	–	–	tiny
$O_{qde}^{\dagger}$	$(\bar{D}_L s_R)(\bar{l}_R L_L)$	–	–	✓	✓	✓	✓	✓	–	–	large $\tan\beta$
$O_{\varphi q}^{(1)}$	$(D_L\gamma^\mu S_L)(H^\dagger D_\mu H)$	✓	✓	✓	hs	–	–	–	✓	(✓)	✓
$O_{\varphi q}^{(3)}$	$(\bar{D}_L\gamma^\mu\sigma^i S_L)(H^\dagger D_\mu\sigma^i H)$	✓	✓	✓	hs	hs	✓	✓	✓	(✓)	✓
$O_{\varphi d}$	$(\bar{d}_R\gamma^\mu s_R)(H^\dagger D_\mu H)$	✓	✓	✓	hs	–	–	–	✓	(✓)	large $\tan\beta$ (non-MFV)

Rare leptonic charged

Interference of short- and long-distance contributions (discussed at this conference from lattice, dispersive, chiral Lagrangian perspectives)



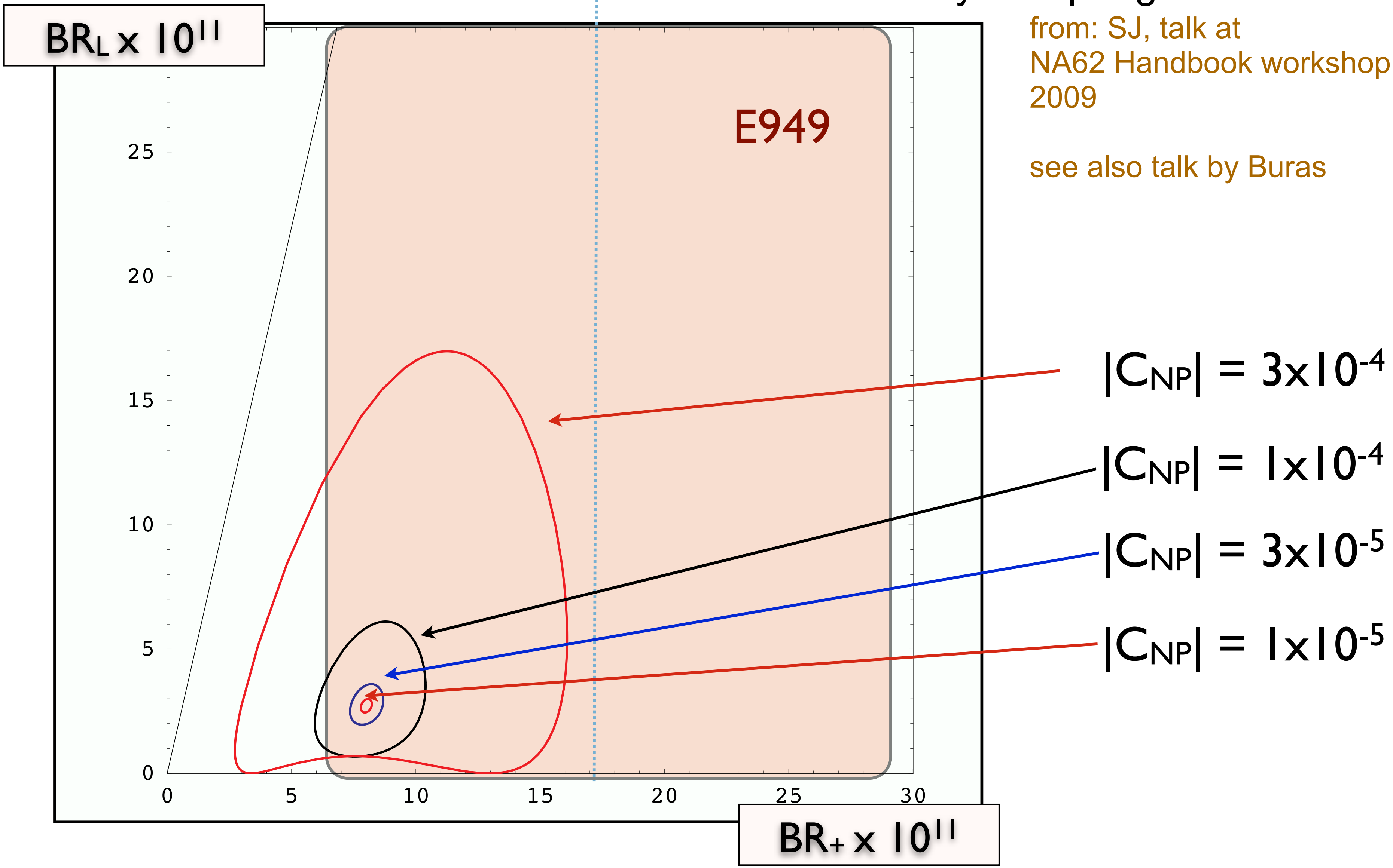
Isidori, Mescia, Paradisi, Smith, Trine 2006

Correlation with ε'

assumes BSM only in Z-penguin

from: SJ, talk at
NA62 Handbook workshop
2009

see also talk by Buras



Correlation with ε’

assumes BSM only in Z-penguin

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NA62 Handbook workshop
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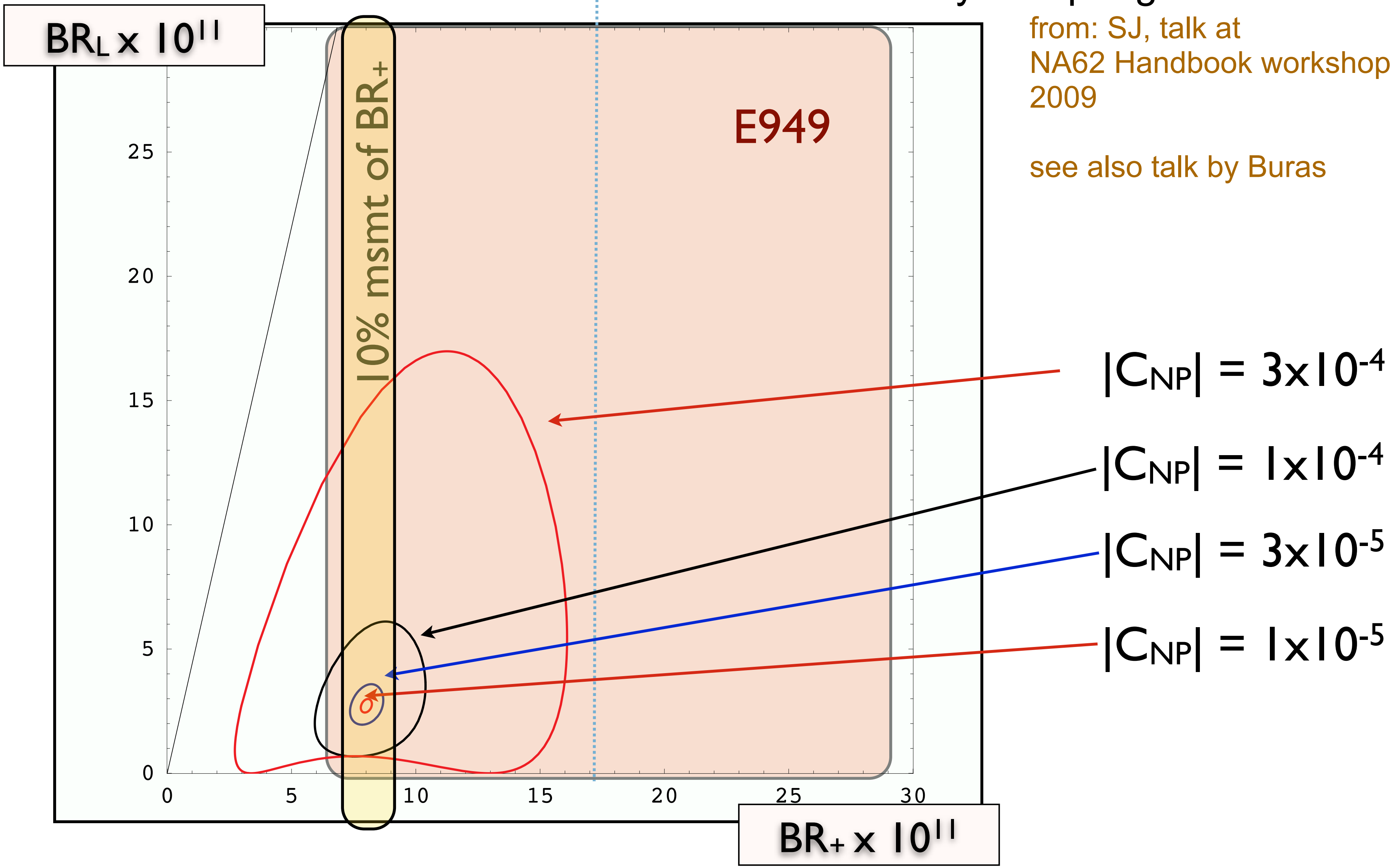

Correlation with ε'

assumes BSM only in Z-penguin

from: SJ, talk at
NA62 Handbook workshop
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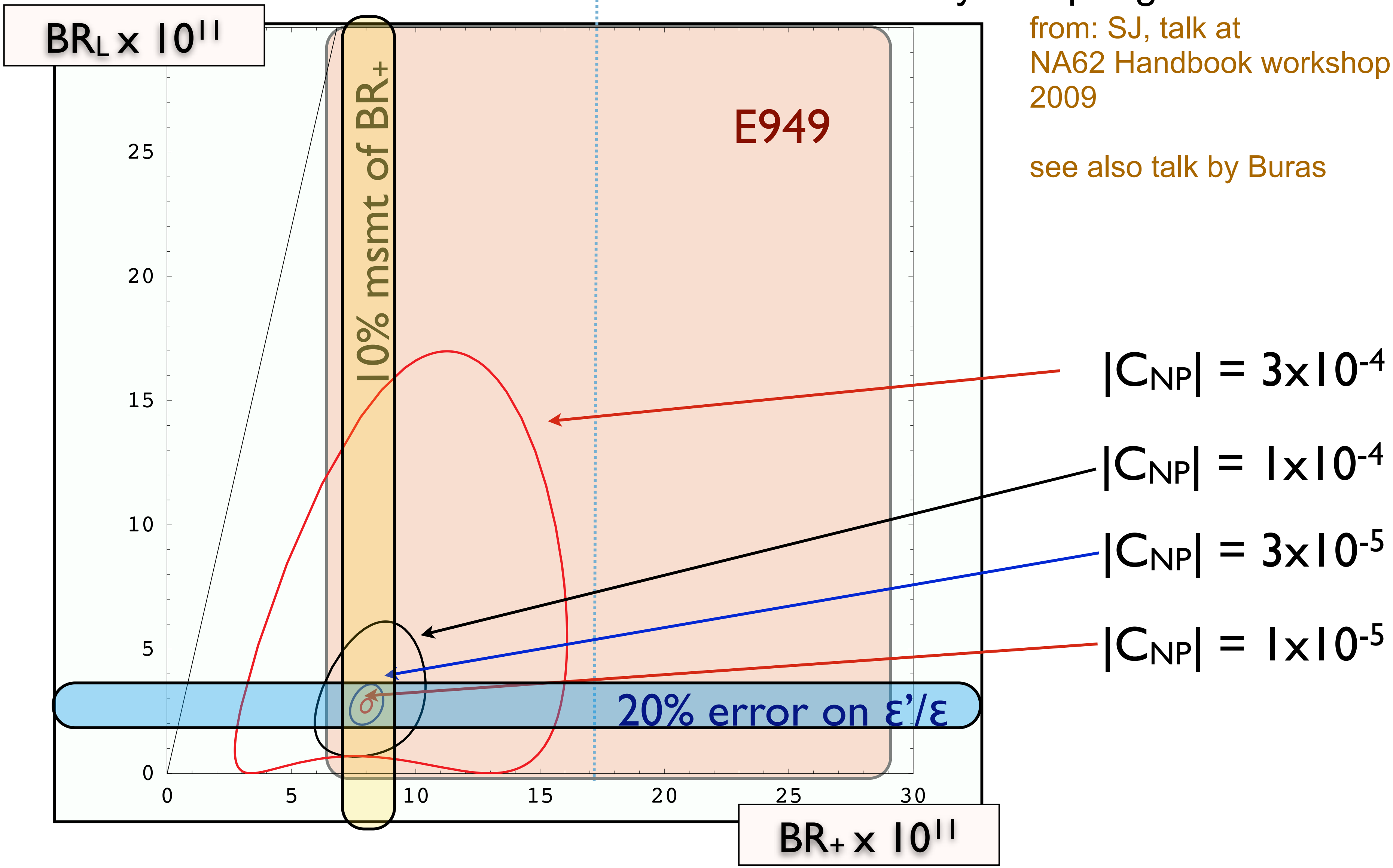
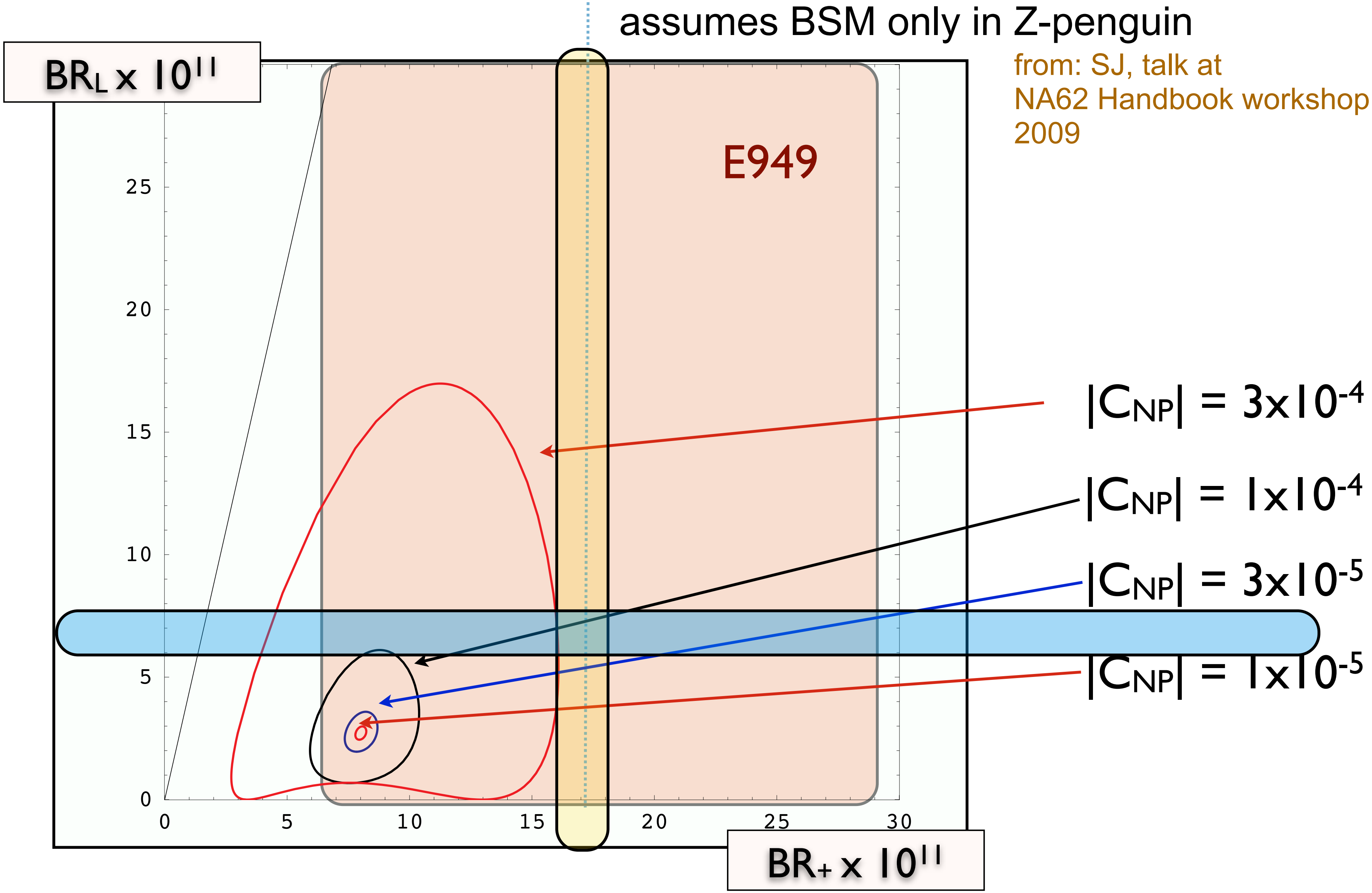
see also talk by Buras



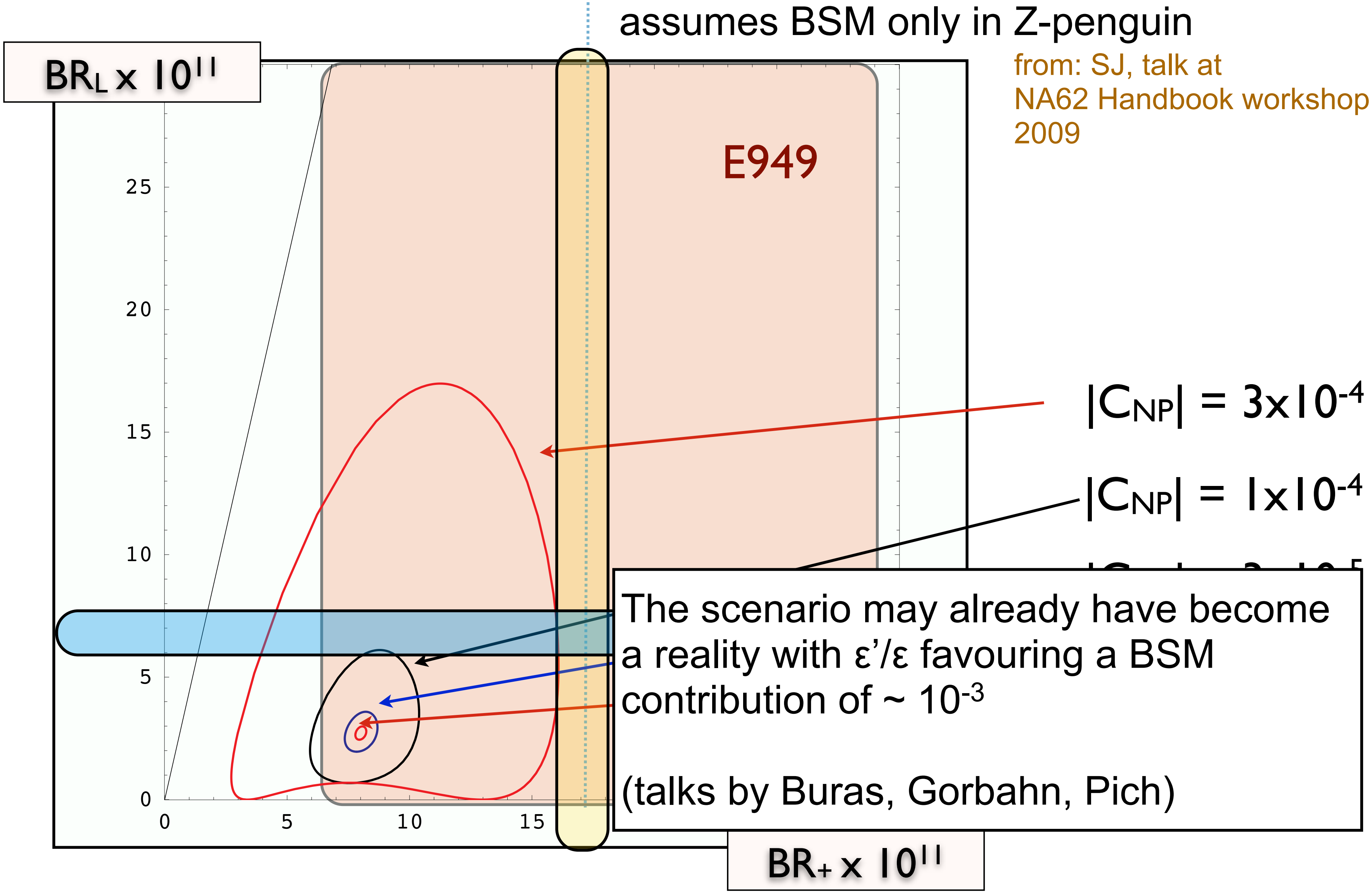
“exciting” scenario envisioned in 2009

assumes BSM only in Z-penguin

from: SJ, talk at
NA62 Handbook workshop
2009



“exciting” scenario envisioned in 2009



The scenario may already have become a reality with ε’/ε favouring a BSM contribution of ~ 10^{-3}

(talks by Buras, Gorbahn, Pich)

4. Conclusions

Supersymmetry, like other natural BSM candidate frameworks, has long been facing its greatest challenges from Kaon physics, primarily through ε_K

Recent progress in experiment (NA62, KOTO, ...) as well as theory (lattice, perturbative, ...) makes new precision observables accessible. Rare K decays may well play a (very) prominent role in the next 10 years for BSM searches, in a SUSY context and beyond.