The Discovery Potential of rare K and B decays

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Indirect measurements

Lessons from the past:
rare low energy processes like ΔM_K (charm), B_d - B_d osc. and EWPT (top), can tell us a lot about heavy particles prior to their discovery

'60 ΔM_K

'87 ARGUS at Desy ΔM_{Bd}

'9x LEP

'99-now Belle/Babar

Present
SM works remarkably well, surprisingly also in the least understood sector: the flavor sector

Future
In order to test NP indirectly we need theoretically very clean observables, preferably with small SM contribution.

Flavour in the SM

Yukawas are responsible for flavour transitions

$$\mathscr{L}_{\text{Yukawa}} = \bar{Q}_L Y_D D_R H + \bar{Q}_L Y_U U_R (H)_c$$

$$Y_D = (m_d, m_s, m_b)/v$$

$$Y_U = V_{\text{CKM}}^{\dagger}(m_u, m_c, m_t)/v$$

$m_t >> m_i$ and V_{CKM} has a hierarchical structure

There are no FCNCs on tree level.

Flavour change is small

$$Y_D = (m_d, m_s, m_b)/v$$

$$Y_U = V^\dagger_{\rm CKM}(m_u, m_c, m_t)/v$$

$$Y_U \approx \begin{pmatrix} 10^{-5} & -0.002 & 0.007 + 0.004i \\ 10^{-6} & 0.007 & -0.04 + 0.0008i \\ 10^{-8} + 10^{-7}i & 0.0003 & 0.96 \end{pmatrix}$$

We have no idea why Y_U and Y_D are the way they are.

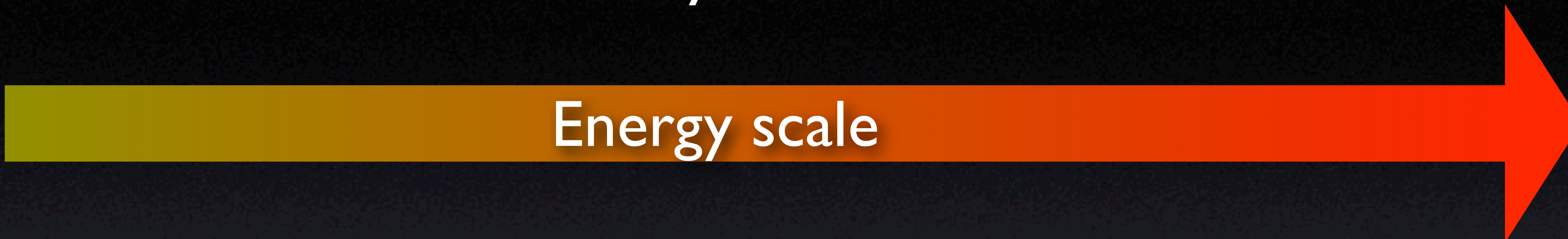
Generally, NP models are struggling since we have no theory of flavour.

We want NP to show up at around a TeV (Higgs stabilization).

K-K mixing e.g. shows no generic flavour violation up to 10^3 TeV.

Flavour precision tests

General structure of a decay rate



Γ = (non-pert. QCD) x QCD RG x (V_{ckm} SM short dist.+ NP)

Three strategies for precision tests:

1) hadronic uncertainties cancel in asymmetries $A_{\rm CP}^{\rm mix}(B_s \to \psi\phi)$
   partial cancelation: $Br(B_q \to \mu^+\mu^-)/\Delta M_q$
2) hadronic matrix element from Experiment ($K \to \pi\bar{\nu}\nu$)
3) inclusive, non-perturbative ~ $(\Lambda_{QCD}/m_b)^2$ ($B \to X_s\gamma$)

FCNCs in the SM

interesting Flavour channels

$s \to d \sim \lambda^5$ ΔM_K, ϵ_K, ϵ'/ϵ, $K_L \to \pi^0 \bar{l} l, K \to \pi \bar{\nu} \nu$

$b \to d \sim \lambda^3$ ΔM_d, $B_d \to \mu^+ \mu^-$, $B \to X_d \gamma$

$b \to s \sim \lambda^2$ ΔM_s, $B_s \to \mu^+ \mu^-$, $B \to X_s l^+ l^-$,
$B \to X_s \gamma$ $A_{FB}(B \to X_s l^+ l^-)$
$B \to K^* \gamma$

increasing
SM contribution

theoretical error

< 15 % < 10% < 5%

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b→s ~ λ[2] ΔM_s, $B_s \to \mu^+ \mu^-, B \to X_s l^+ l^-,$

$B \to X_s \gamma \;\; A_{FB}(B \to X_s l^+ l^-)$

$B \to K^* \gamma$

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< 15 % < 10% < 5%

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SM contribution

FCNCs in the SM

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s→d ~ λ[5] ΔM$_K$, ε$_K$, ε'/ε, $K_L \to \pi^0 \bar{l} l, K \to \pi \bar{\nu} \nu$

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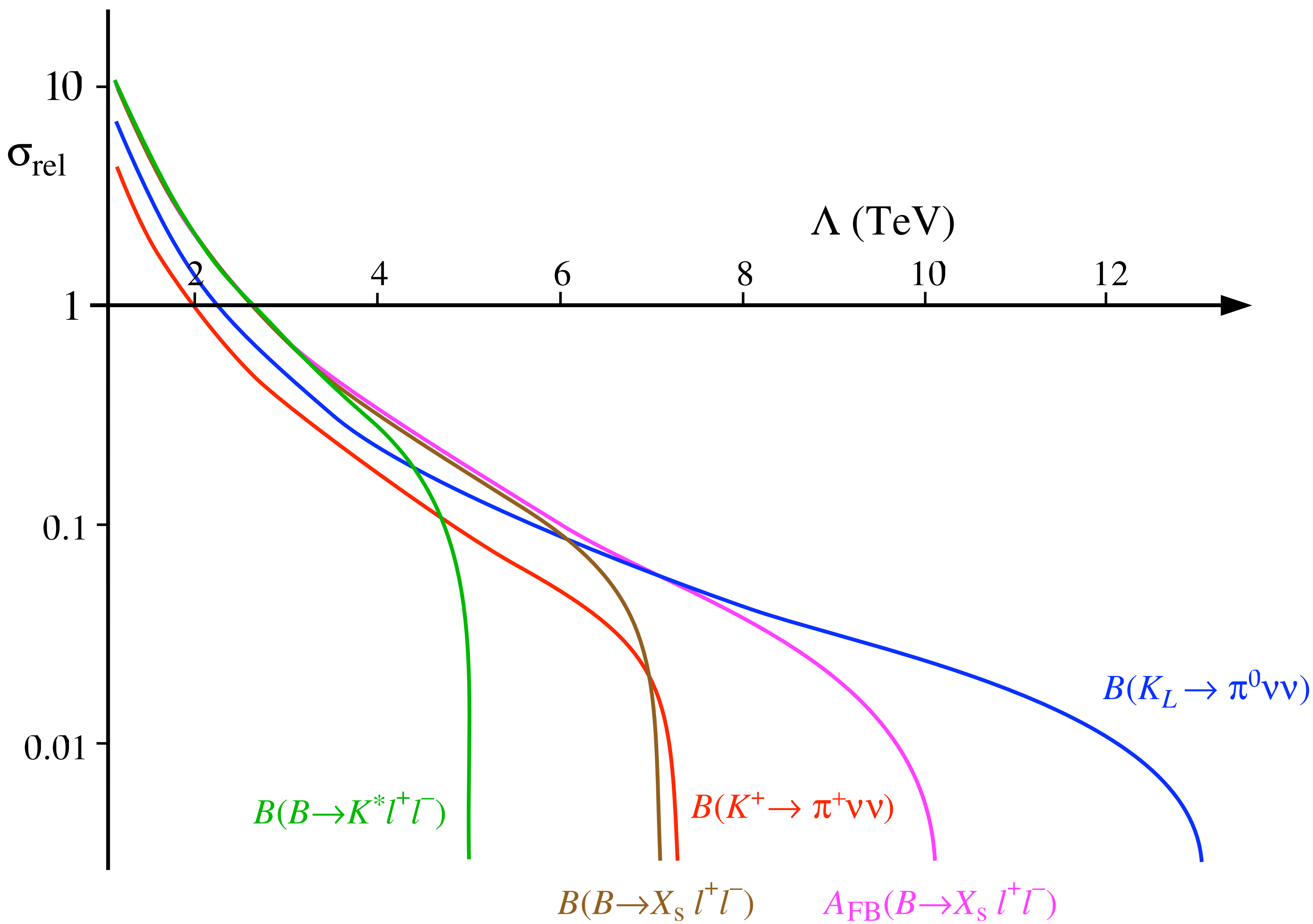
increasing
SM contribution

theoretical error

< 15 % < 10% < 5%

Comparison of sensitivities

D'Ambrosio, Giudice, Isidori, Strumia '02; Buras,Bryman, Isidori, Littenberg '05



plan of the talk

- Interesting NP flavour observables of the future
- rare Kaon decays: the four golden modes, status of the SM calculation, NP searches
- $B \to X_s \gamma$ (new result)
- rare B decays and large tanß
- Conclusions

4 golden modes

$$Br(K_L \to \pi^0 \mu^+ \mu^-)$$

$$Br(K_L \to \pi^0 e^+ e^-)$$

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

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

4 golden modes

$$Br(K_L \to \pi^0 \mu^+ \mu^-)$$

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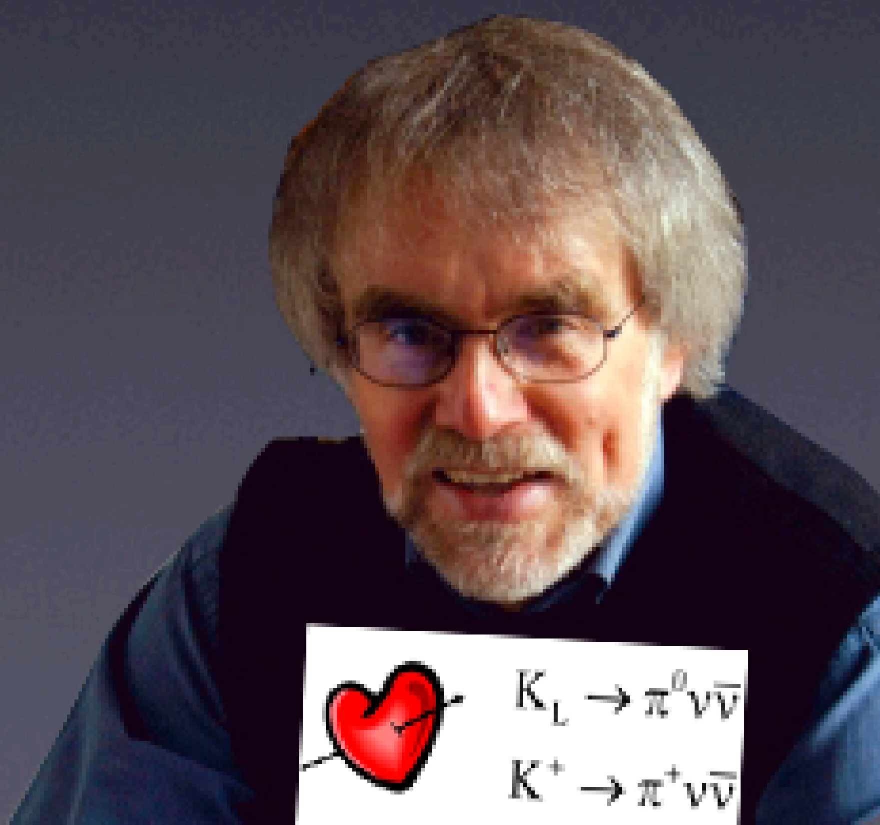
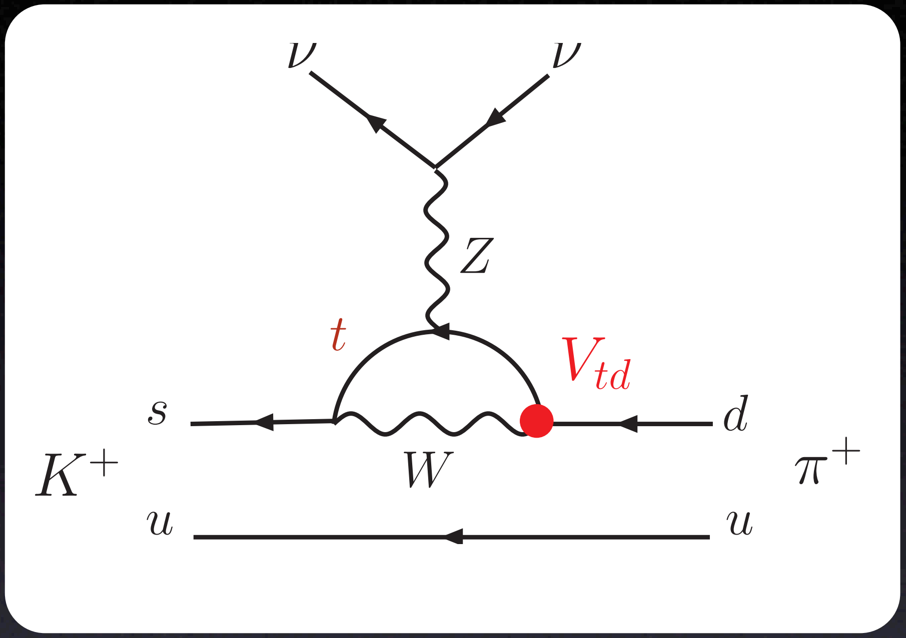
$$Br(K^+ \to \pi^+ \nu \bar{\nu})$$

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

60-ϵ!



Potential of $K \rightarrow \pi\nu\bar{\nu}$



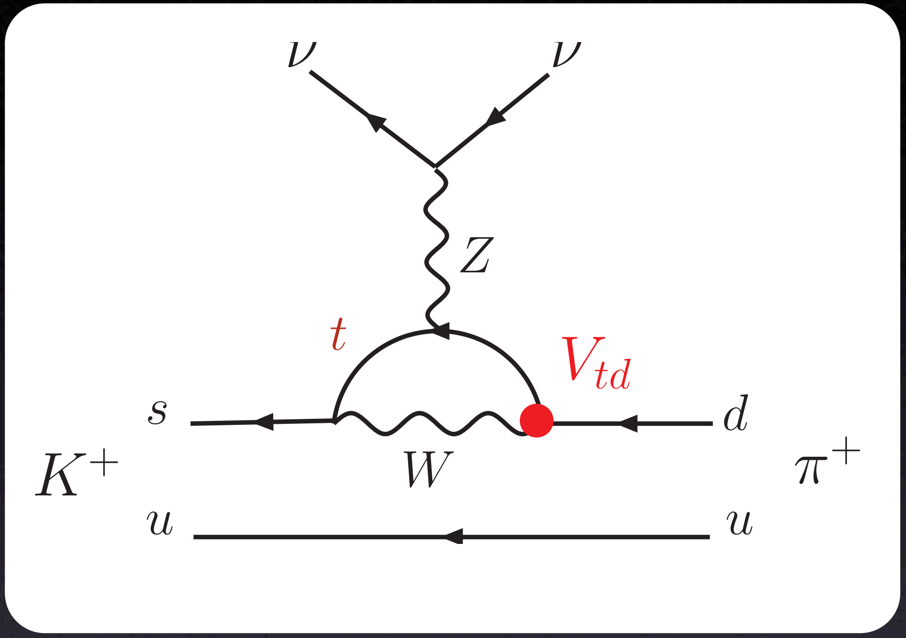
+ box

Dominated by short distance contributions

o sigma$(K^+)_{theory}$ ~ 4%

o sigma$(K_L)_{theory}$ ~ 2%

Potential of $K \to \pi\nu\bar{\nu}$



+ box

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

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

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

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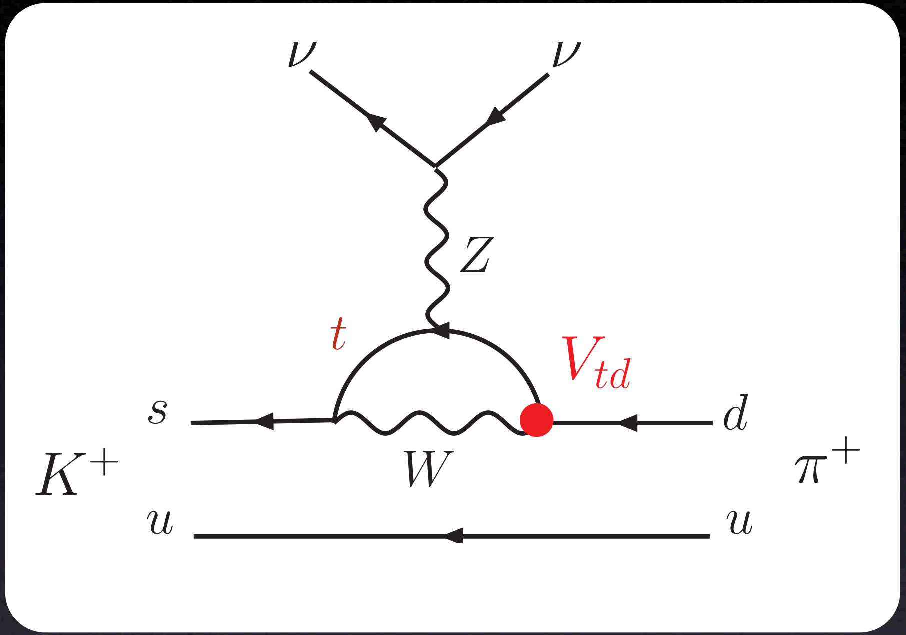

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$\lambda_t = V_{\rm ts}^* V_{\rm td} \quad \lambda_c = V_{\rm cs}^* V_{\rm cd}$

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

pure short-distance

Dominated by short distance contributions

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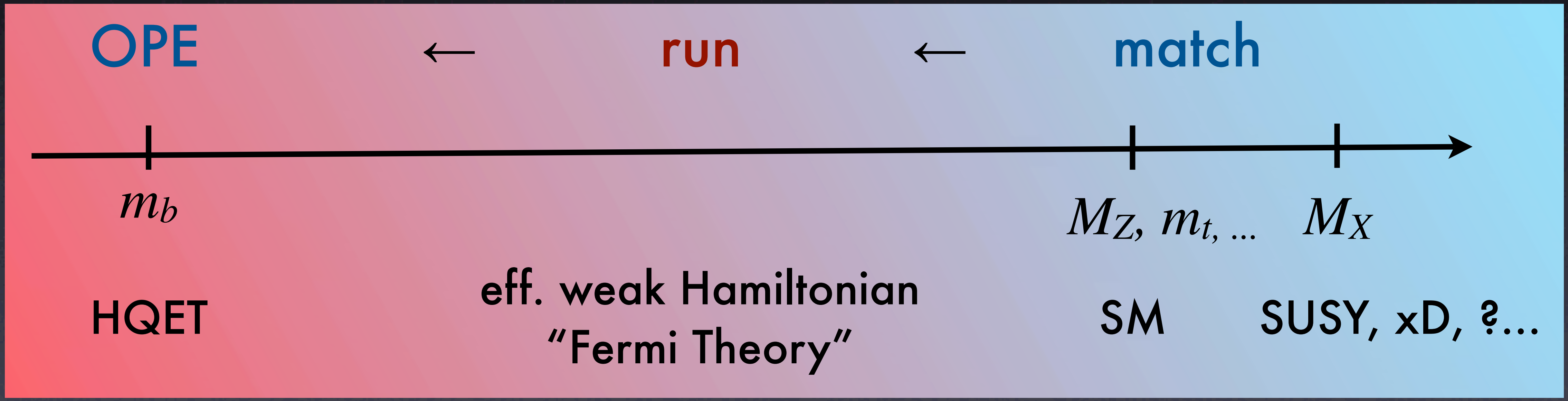
o sigma(K_L)$_{\rm theory}$ ~ 2%

SM Calculation



General properties

$$\mathcal{L}_{\text{eff}}^{(6)} = \frac{4G_F}{\sqrt{2}} \frac{\alpha}{2\pi s_W^2} \sum_{i=u,c,t} C^i(\mu) Q_\nu^{(6)}$$

$$Q_\nu^{(6)} = \sum_{l=e,\mu,\tau} (\bar{s}_L \gamma_\mu d_L)(\bar{\nu}_{lL} \gamma^\mu \nu_{lL})$$

$$C^i(M_W) \propto m_i^2 V_{is}^* V_{id} \propto \begin{cases} \Lambda_{\text{QCD}}^2 \lambda & \text{u} \\ m_c^2(\lambda + i\lambda^5) & \text{c} \\ m_t^2(\lambda^5 + i\lambda^5) & \text{t} \end{cases}$$

* Z penguin is $SU(2)_L$ breaking: powerlike GIM
* large CPV phase in dominant top contribution

* charm effects:
1) negligible in K_L: $O(m_c^2/m_t^2) << 1$ for dominant direct CPV-Amplitude
2) small in $K^+ \sim 30\%$ (→ next to next slide)

SM prediction of $K_L \to \pi^0 \nu\bar{\nu}$

$$\mathcal{B}(K_L \to \pi^0 \nu\bar{\nu}) = \kappa_L \left[\frac{\mathrm{Im}\,(V_{ts}^* V_{td})}{\lambda^5} X \right]^2$$

$$\kappa_L = r_{K_L} \frac{3\alpha^2 \mathcal{B}(K^+ \to \pi^0 e^+ \nu_e)}{2\pi^2 s_W^4} \frac{\tau(K_L)}{\tau(K^+)}$$

* short distance dominated (>99%)
* very small theoretical error ~ 2%
* 85% of total error CKM input
* precise and direct measurement of amount of CPV in SM

$$\mathcal{B}(K_L \to \pi^0 \nu\bar{\nu}) = (2.93 \pm 0.44) \times 10^{-11}$$

Buras, Gorbahn, Haisch, Nierste '06

$Br_{exp} / Br_{SM} < 2.86\ 10^4$ (90% C.L.) E391

KTEV, E391a (soon to be improved!)

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$$X = 1.46 \pm 0.04 \quad (\mathrm{NLO})$$

t

Buchalla & Buras '93, '99;
Misiak & Urban '99

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Buchalla & Buras ‘93, ‘99;
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$$r_{K_L} = 0.944 \pm 0.028$$ ~~isospin~~

Marciano & Parsa ‘96

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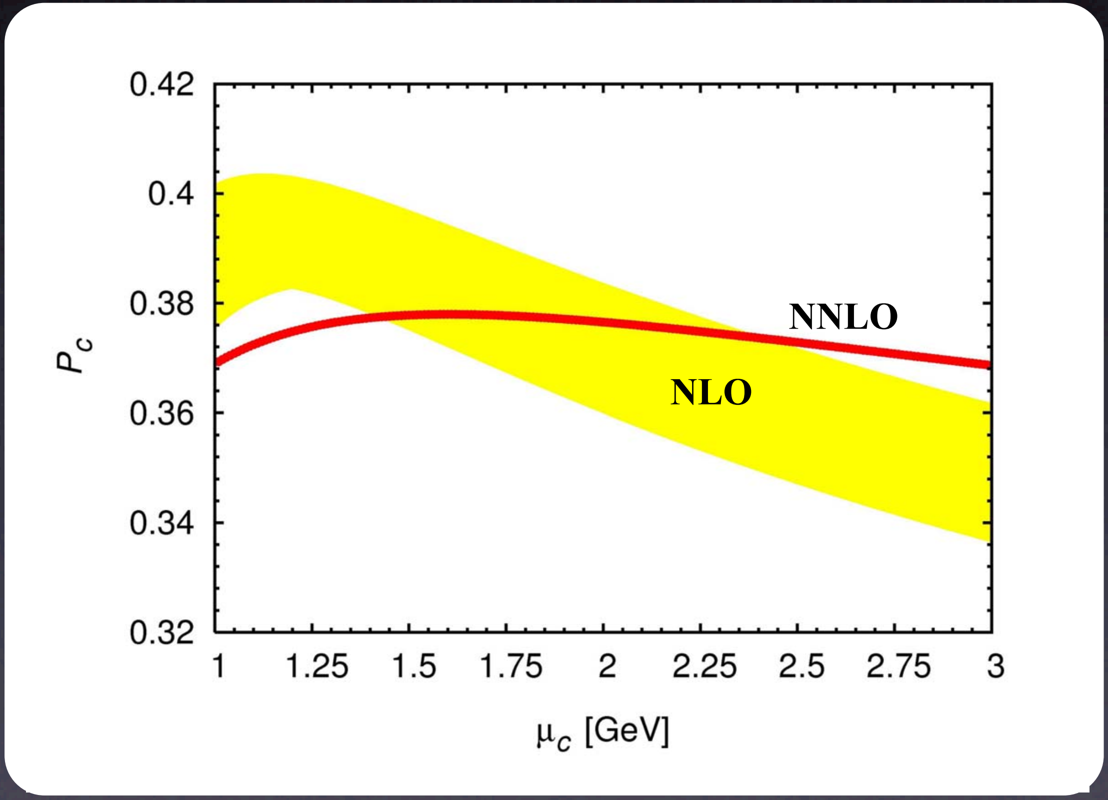
* theoretical error of QCD corrections to the charm contribution P_c factor ~4 smaller thanks to NNLO calculation
* P_c error now dominated by Δm_c

Buras, Gorbahn, Haisch, Nierste '05



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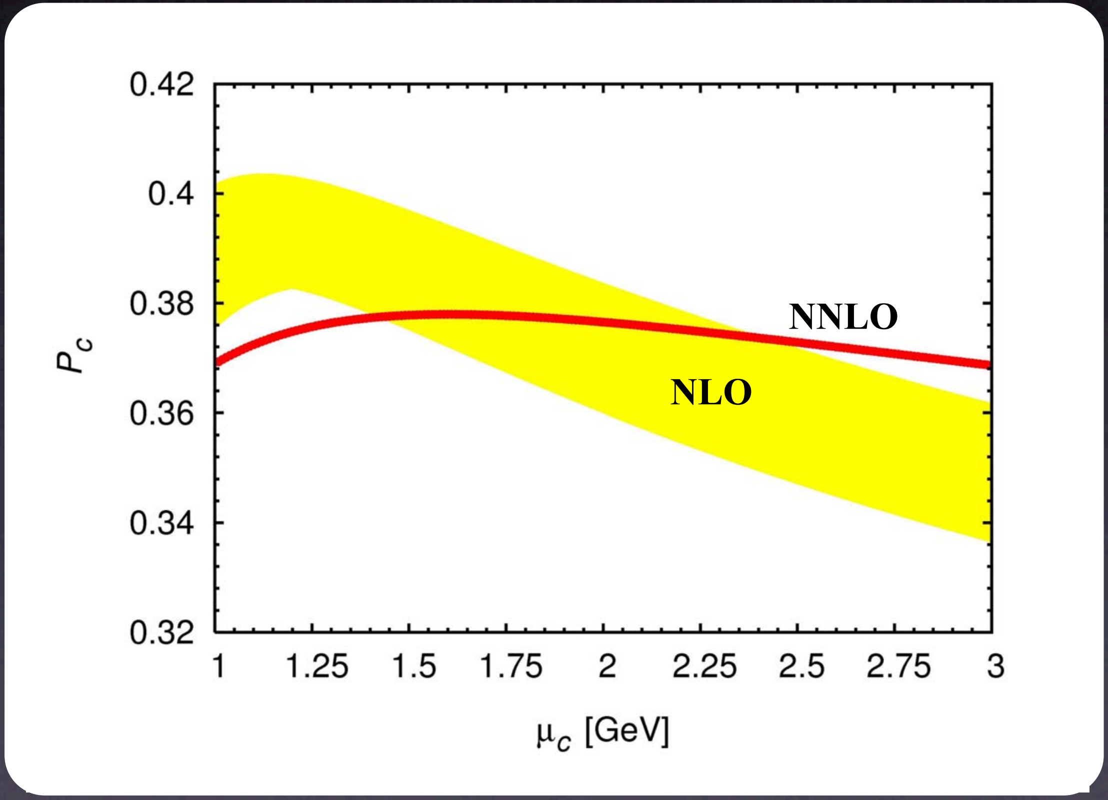

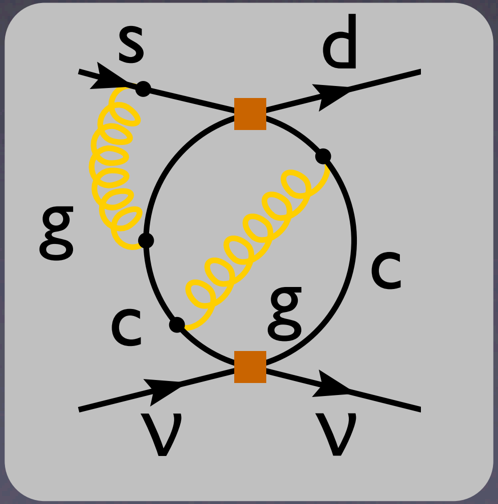

	Δm_c	theory	α_s	
P_c^{NLO} = 0.369	±0.033	±0.037	±0.009	≈ 0.37±0.07
P_c^{NNLO} = 0.375	±0.031	±0.009	±0.009	≈ 0.38±0.04

Buchalla, Buras '94 (NLO)

Buras, Gorbahn, Haisch, Nierste '05 (NNLO)

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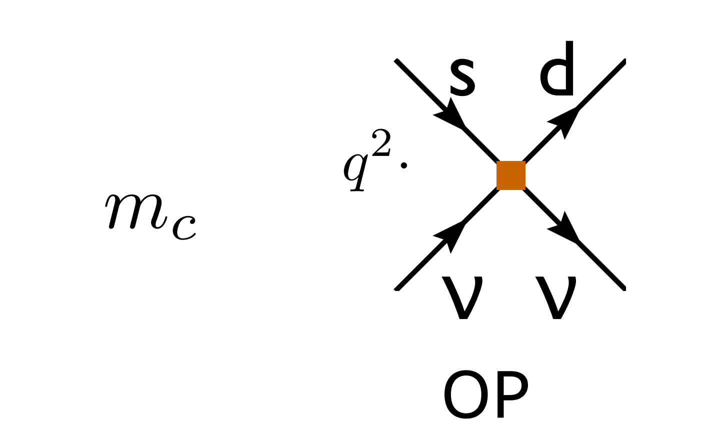
Buras, Gorbahn, Haisch, Nierste '05

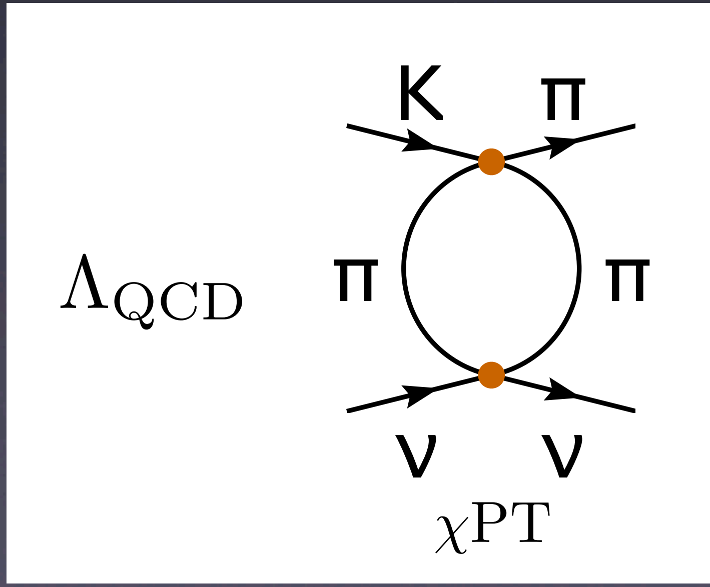
* LD and dim8 effects in δP_c are ~ $\pi^2 F_\pi^2/m_c^2$ ~10% of charm contribution, 6% enhancement of Br_{K^+}

Isidori, Mescia & Smith '05

* LQCD could improve accuracy to 1-2%

Isidori, Martinelli & Turchetti '05





$\delta P_c = 0.04 \pm 0.02$

SM prediction for $K^+ \to \pi^+ \nu\bar{\nu}$

$$\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu}) = (8.0 \pm 1.1) \times 10^{11}$$

Buras, Gorbahn, Haisch, Nierste ‘05

$$\mathcal{B}^+_{\text{exp}} = \left(14.7^{+13.0}_{-8.9}\right) \times 10^{11}$$

E787 (2), E949 (1)

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MFV

SM Yukawa couplings are the only source of flavour violation.

All flavour violation is proportional to V_{CKM}.

Strong correlations between K and B physics.

K^+ and K_L in specific MFV models

- Littlest Higgs: slight suppression

Buras, Uhlig, Poschenrieder ’05

- Universal ED: <9-10% enhancement

Buras, AW, Spranger ’03

- CMFV MSSM: 0...40% suppression

Buras, Gambino, Gorbahn, Jäger, Silvestrini ’00

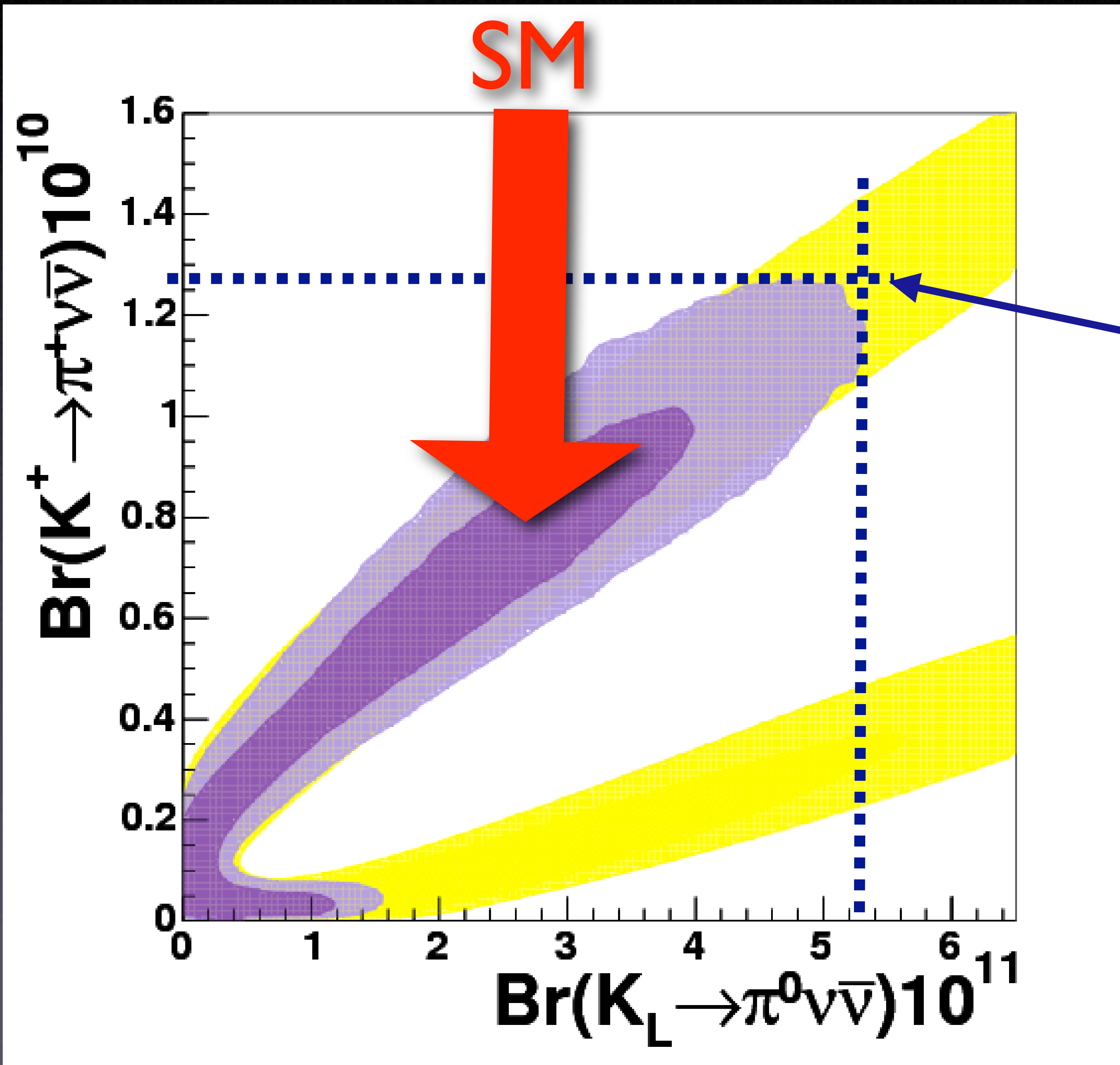
Buras, Blanke ‘06

General pattern:
NP contribution to ΔM_d interferes constructively with SM $\Delta F=2$ Amplitude S in the above models and

$$\left(\frac{V_{\rm td}^{\rm NP}}{V_{\rm td}^{\rm SM}}\right)^2 = \frac{S^{\rm SM}}{S^{\rm SM}+|\Delta S^{\rm NP}|} < 1$$

$Br(K)_{exp} > Br(K)_{SM}$ immediately falsifies most MFV models!

MFV upper bound



model independent

95%C.L. upper bound

Bona, Buras, Bobeth, Ewerth, Pierini, Silvestrini, AW '05

Universal CKM fit from UTfit Bona et. al '05

using universal UTfit + $B \to X_s \gamma$ + $B \to X_s l^+ l^-$

MFV upper bounds

Bona, Buras, Bobeth, Ewerth, Pierini, Silvestrini, AW (05)

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	<2.86 10^4 (90% C.L.) E391
$Br(B \to X_S \nu\bar{\nu}) \cdot 10^5$	<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	<80 (90% C.L.) CDF
$Br(B_d \to \mu^+\mu^-) \cdot 10^{10}$	<2.2	<1.8	1.1±0.4	$<1.6 \cdot 10^3$

BNL AGS E787, E949

low/moderate tanß !

Beyond MFV

rare K decays are a very sensitive probe
for non-MFV flavour violation since

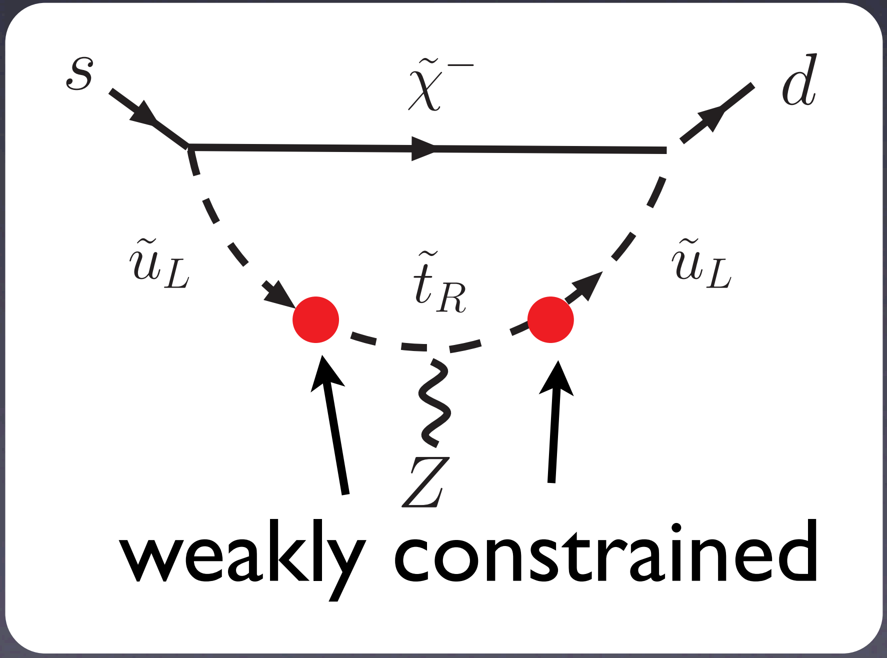
$(s \to d) \sim \lambda^5$

suppression is not built in the model anymore.

Generic MSSM

Nir & Worah '97
Buras, Romanino, Silvestrini '97
Colangelo & Isidori '98
Buras, Ewerth, Jäger, Rosiek '04
Isidori, Mescia, Paradisi, Smith , Trine '06

- Flavor structure probes Susy breaking mechanism
- Room for sizable deviations even if ΔF=2 sector agrees well with SM
- very sensitive to new sources of flavor symmetry breaking due to λ^5 suppression of SM amplitude

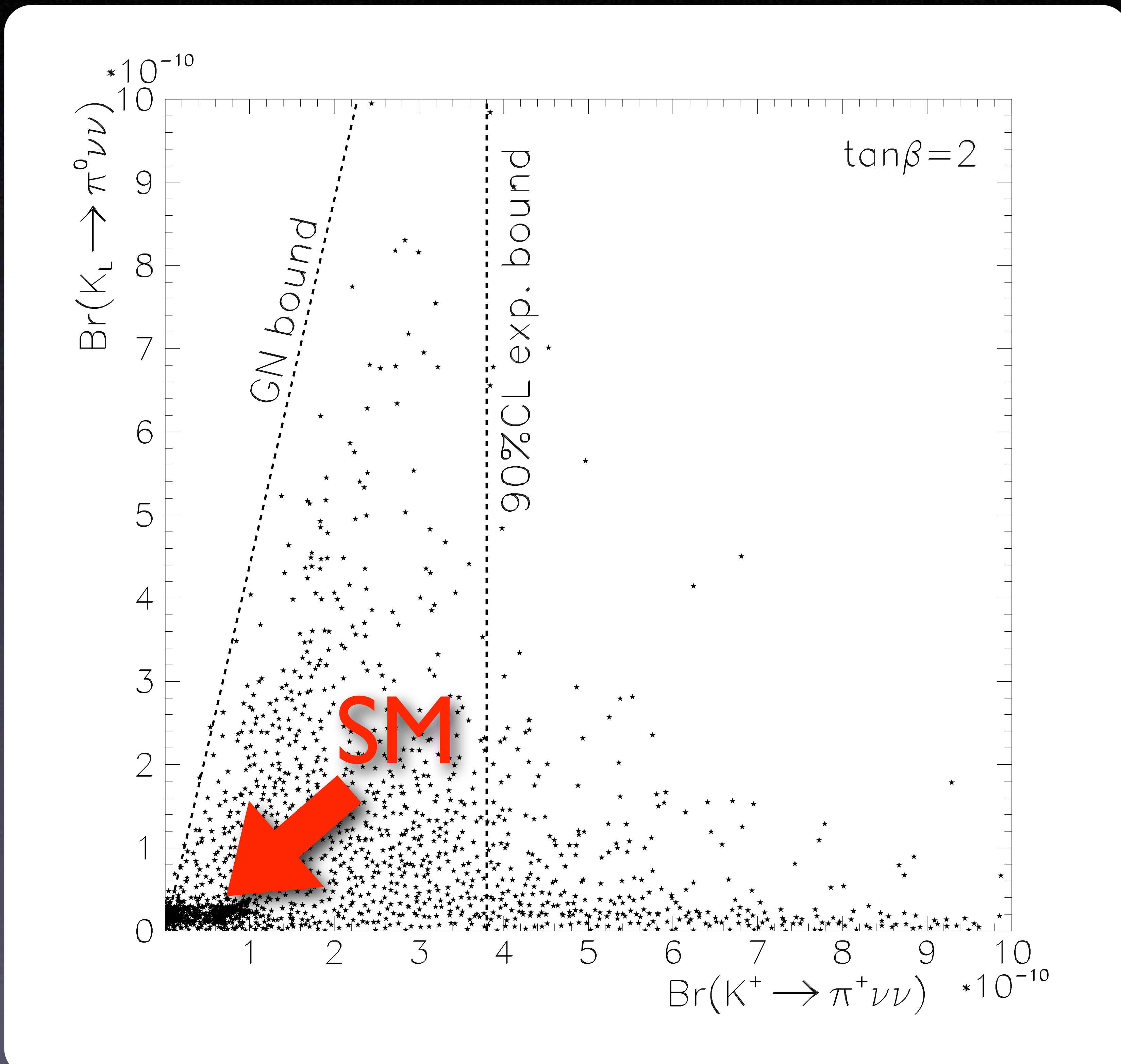


Amplitude ~~SU(2)~~$_L$ $\propto \frac{1}{M_Z^2} V_{Z\bar{s}d}$

$$\tilde{X}^{(\text{peng})}_{\text{SUSY}} \propto \frac{(M^2_{LR})_{d't}\,(M^2_{LR})^*_{s't}}{M^4_{\text{SUSY}}}$$

small tanß

Generic MSSM



Buras, Ewerth, Jäger, Rosiek '04

includes all present constraints
ΔM_K, ϵ_K, $b \to s\gamma$,...

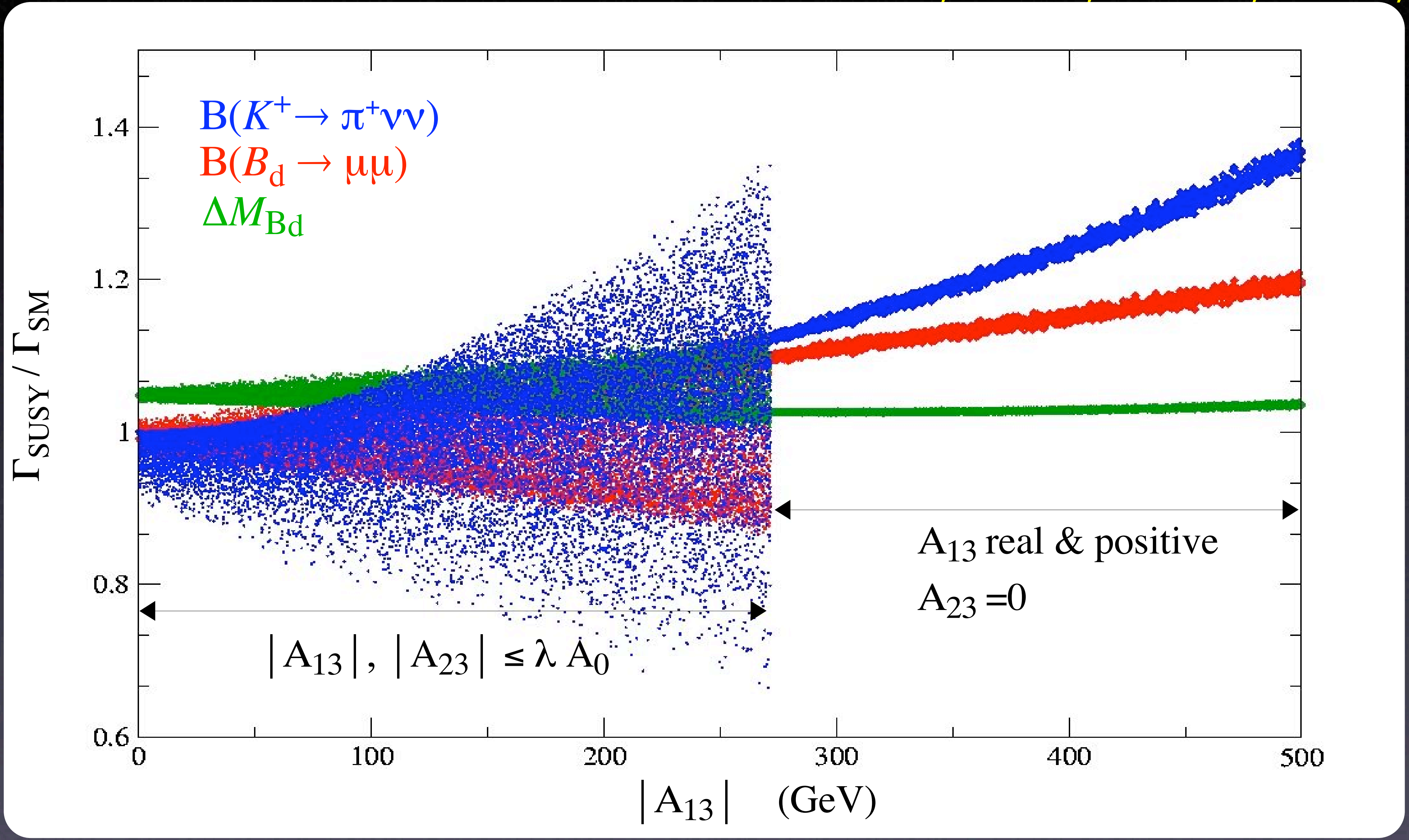
saturation of Grossman-Nir bound

K_L could be 20-30x enhanced

in reach of E391a

Generic MSSM II

Isidori, Mescia, Paradisi, Smith , Trine '06



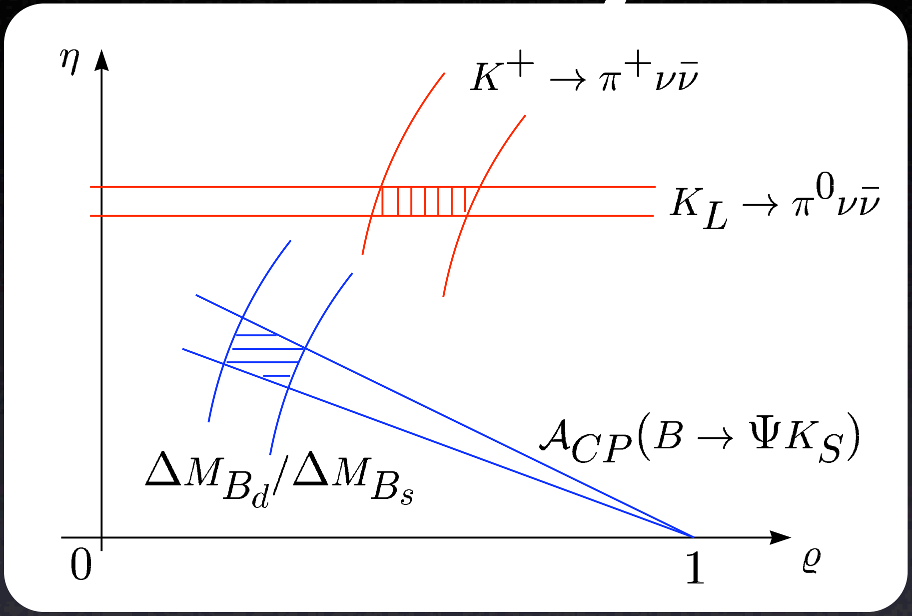
K⁺ best probe of up-type trilinear soft Susy breaking terms

$$\mathcal{L}_{\rm soft} \subset (A^U Y^U)_{ij} Q_L^i U_R^j \phi$$

CKM and rare K decays

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

test of the 'golden relation'



Could help improve the knowledge of CKM parameters

However, more interesting is the 201x scenario:

* CKM known to great precision independent of NP from Belle, BaBar, LHCb, SuperB, ...
* SM prediction for K^+, K_L together with a 10% measurement allows precision test of the flavor structure of NP

Status of $K_L \to \pi^0 l^+ l^-$

Buchalla, D'Ambrosio, Isidori; Isidori, Smith, Unterdorfer '04, Smith, Mescia, Trine '06

$$Br(K_L \to \pi^0 l^+ l^-) = \left[C^l_{\rm mix} + C^l_{\rm int} \left(\frac{{\rm Im}\lambda_t}{10^{-4}} \right) + C^l_{\rm dir} \left(\frac{{\rm Im}\lambda_t}{10^{-4}} \right)^2 + C^l_{\rm CPC} \right] \cdot 10^{-12}$$

indirect CPV	interference of direct and indirect	direct CPV	CP conserving

substantial progress in theory precision associated with light quark loops

experimental input from NA48

$C^e_{\rm dir} = (4.62 \pm 0.24)(\omega^2_{7V} + \omega^2_{7A})$ $C^\mu_{\rm dir} = (1.09 \pm 0.05)(\omega^2_{7V} + 2.32\omega^2_{7A})$

$C^e_{\rm int} = (11.3 \pm 0.3)\omega_{7V}\,,$ $C^\mu_{\rm int} = (2.63 \pm 0.06)\omega_{7V}\,,$

$C^e_{\rm mix} = 14.5 \pm 0.05\,,$ $C^\mu_{\rm mix} = 3.36 \pm 0.20\,,$

$C^e_{\rm CPC} \simeq 0\,,$ $C^\mu_{\rm CPC} = 5.2 \pm 1.6\,,$

$$Br(K_L \to \pi^0 \mu^+ \mu^-) = (1.5 \pm 0.3) \cdot 10^{-11}$$

$$Br(K_L \to \pi^0 e^+ e^-) = (3.7^{+1.1}_{-0.9}) \cdot 10^{-11}$$

Exp: @ 90% C.L.

$< 2.8 \cdot 10^{-10}$ KTEV '00

$< 3.8 \cdot 10^{-10}$ KTEV '03

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Direct CPV amplitude:

* clean probe of independent NP structures and CPV beyond SM
* important if beyond-MFV NP is found

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NP

Direct CPV amplitude:

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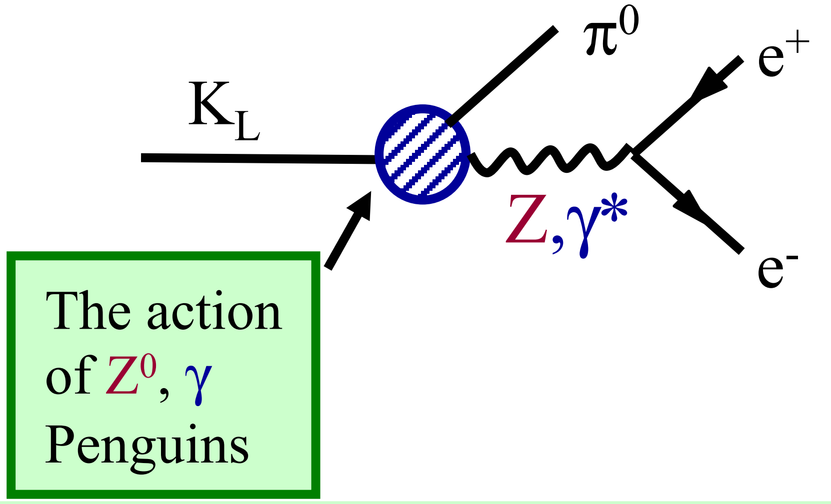
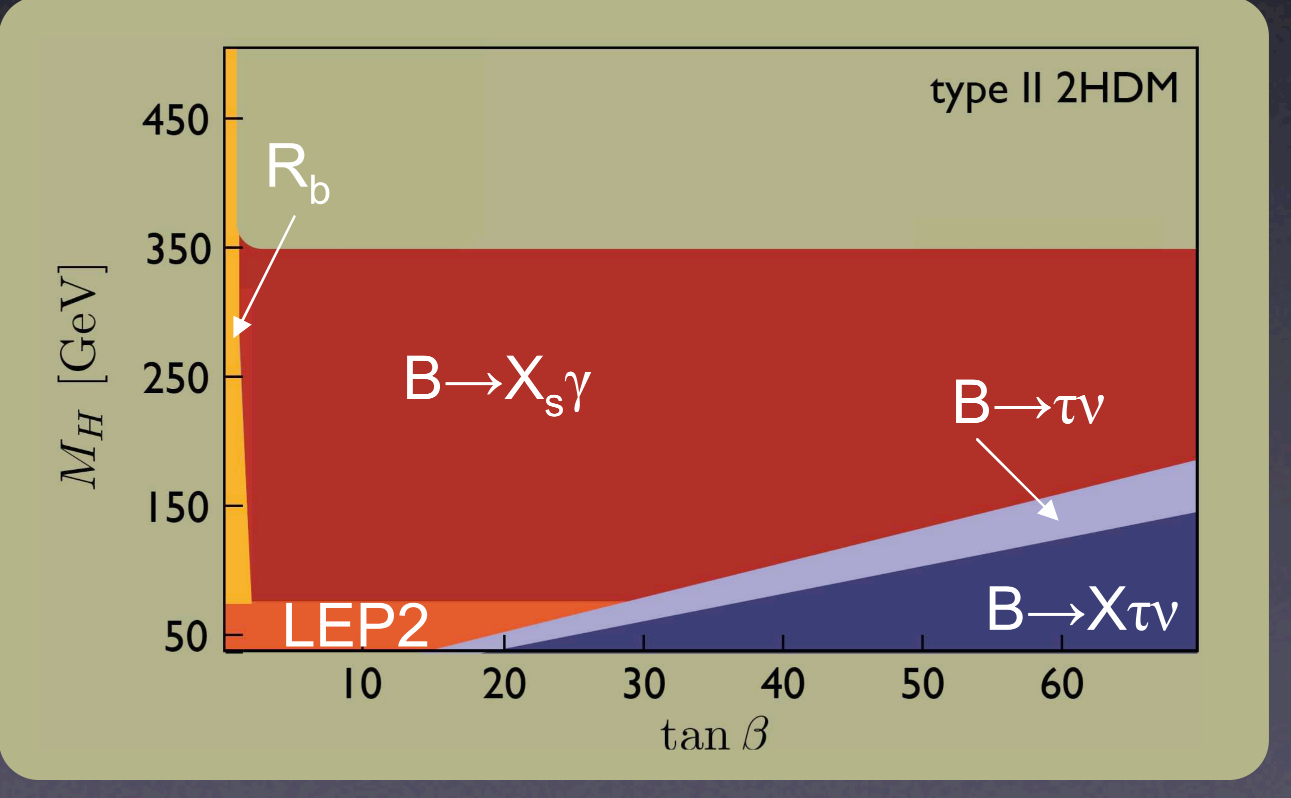


$$Q_\nu\,, Q_{9V}\,, Q_{10A}$$

$$B \to X_s \gamma$$

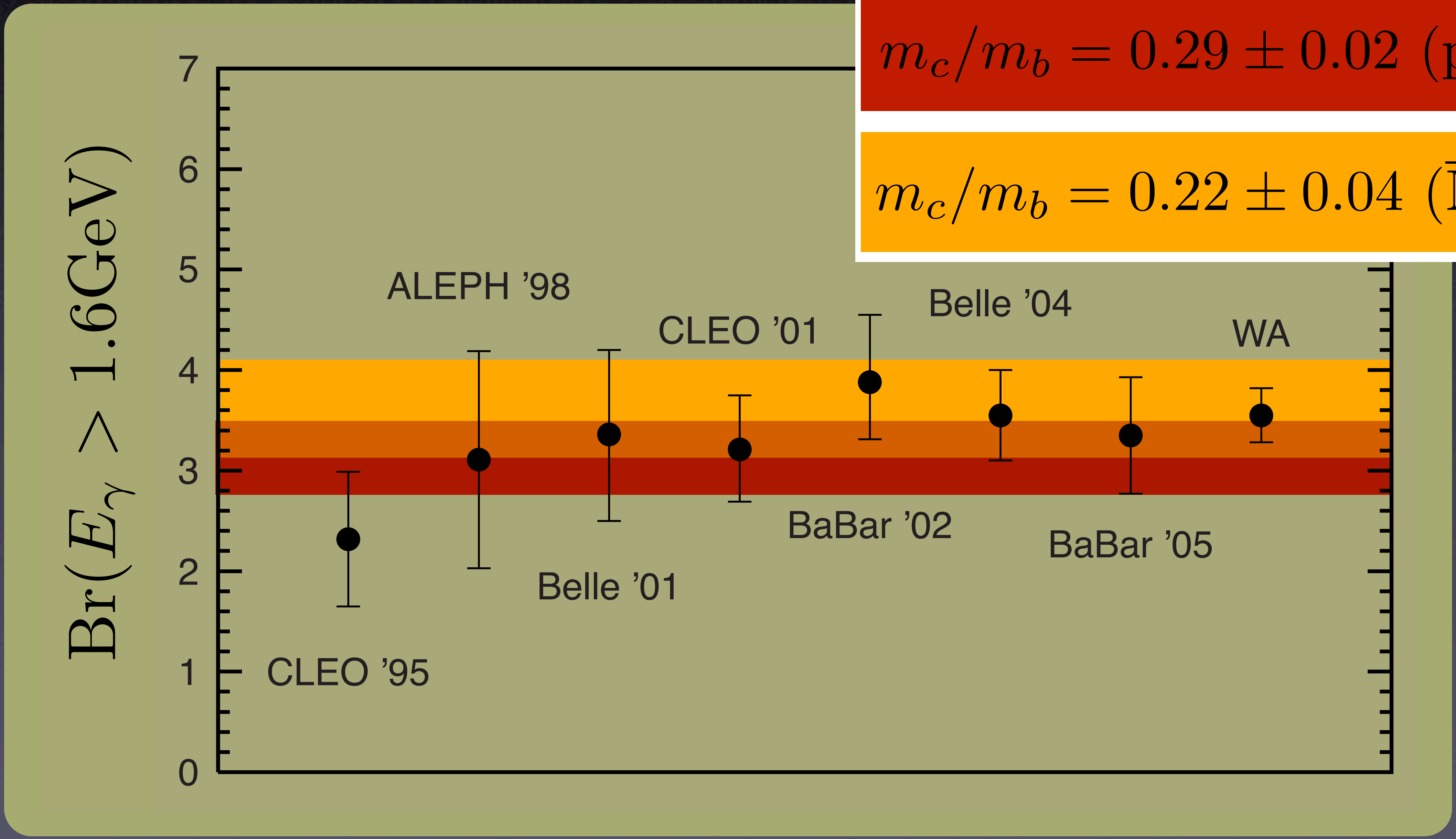
new NNLO results



$$B \to X_s \gamma$$

Charm mass dependence enters first at NLO:

Strong scheme ambiguity in m_c/m_b only be resolved at NNLO



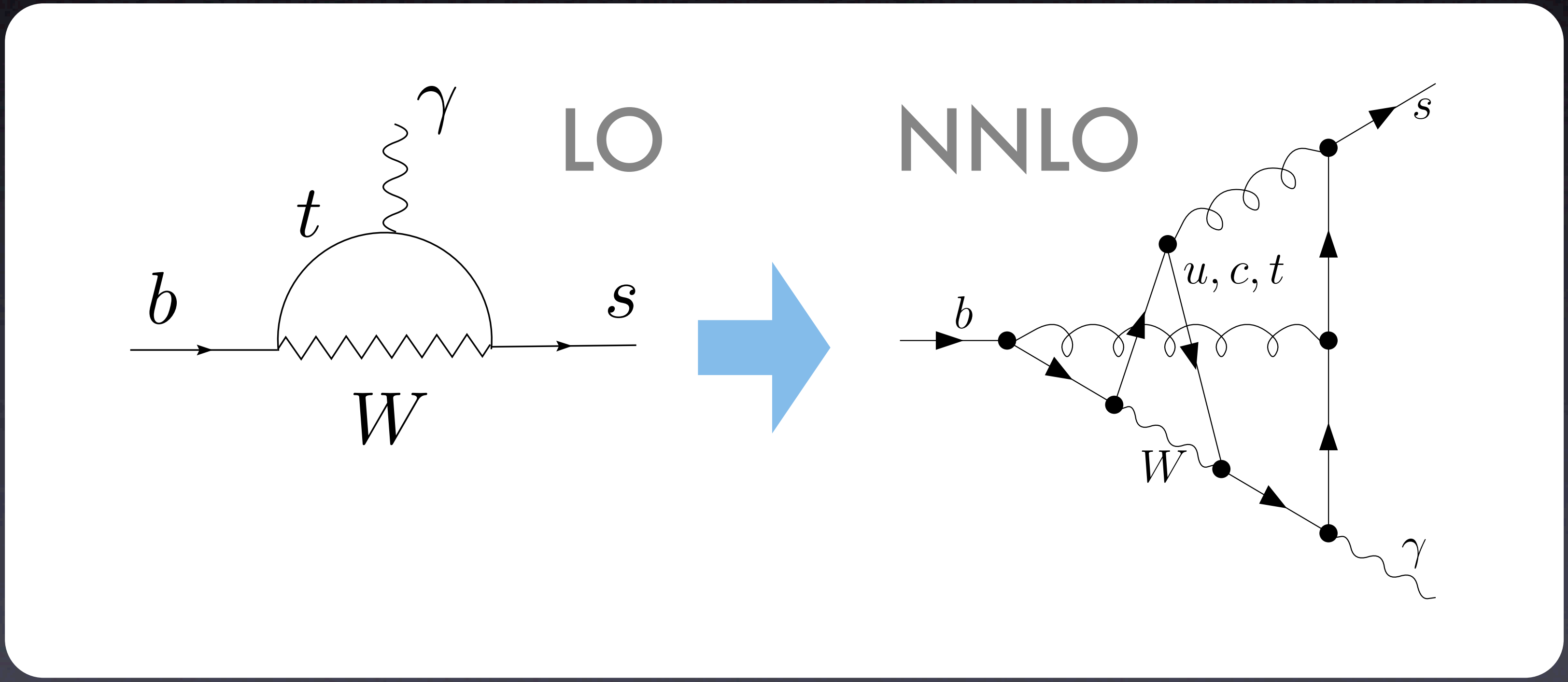
$m_c/m_b = 0.29 \pm 0.02$ (pole mass)

$m_c/m_b = 0.22 \pm 0.04$ ($\overline{\mathrm{MS}}$)

(old NLO)

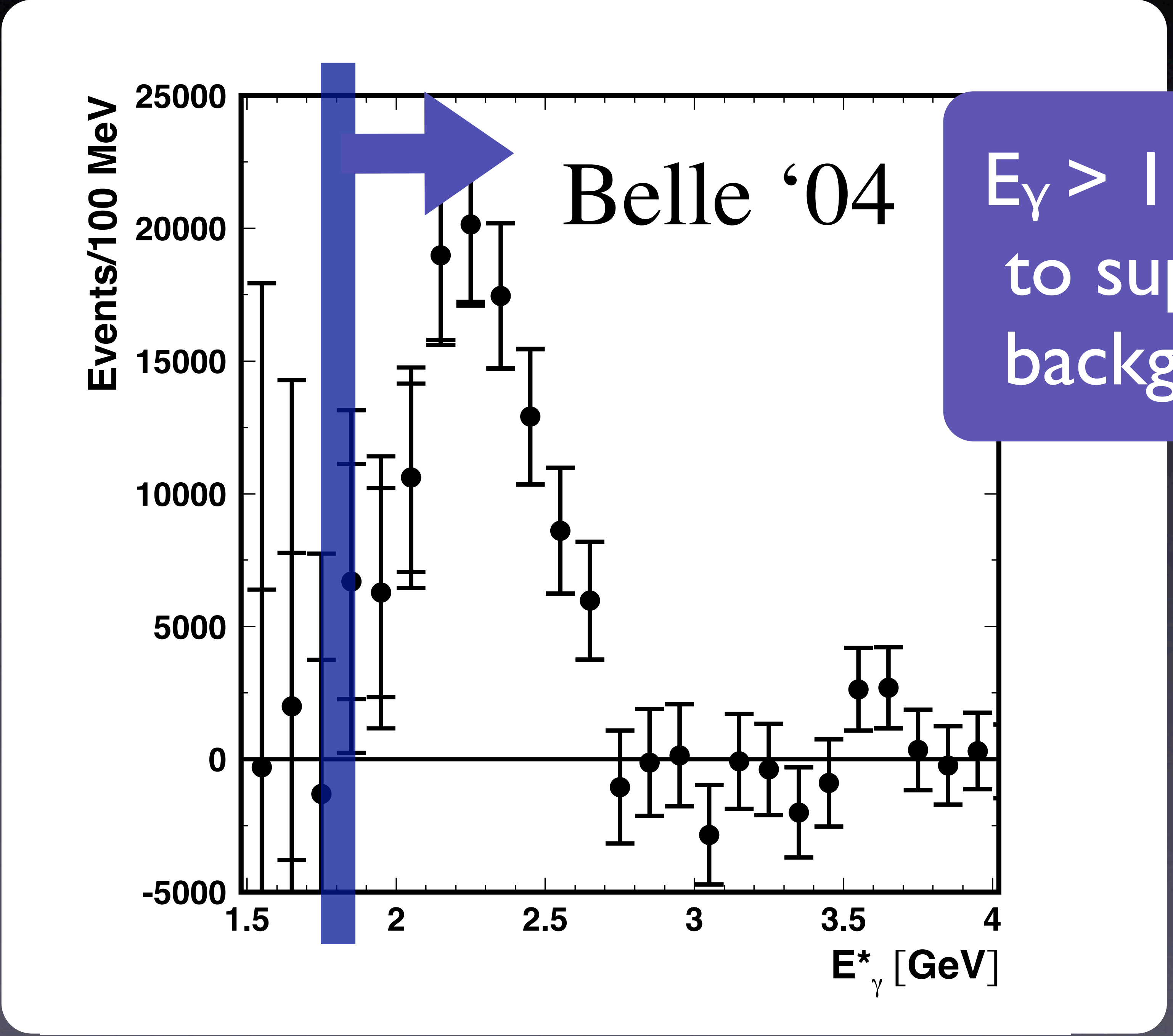
very involved calculation

M. Misiak,[1,2] H. M. Asatrian,[3] K. Bieri,[4] M. Czakon,[5] A. Czarnecki,[6] T. Ewerth,[4] A. Ferroglia,[7] P. Gambino,[8] M. Gorbahn,[9] C. Greub,[4] U. Haisch,[10] A. Hovhannisyan,[3] T. Hurth,[2,11] A. Mitov,[12] V. Poghosyan,[3] M. Ślusarczyk,[6] and M. Steinhauser[9]



1) 3-loop matching (complete)
2) 3 and 4-loop mixing (almost)
3) most difficult: 3-loop matrix element (interpolation between m_c/m_b>>1 and $\alpha_s^2 n_F$ approximation)

Cut in photon energy



$E_\gamma > 1.8$ GeV to suppress background

BaBar $E_\gamma > 1.9$ GeV, CLEO $E_\gamma > 2.0$ GeV

Cut in photon energy

with cut $E_0 > E_\gamma$ three relevant scales:

Neubert '04; Becher, Neubert '06

(hard) m_b

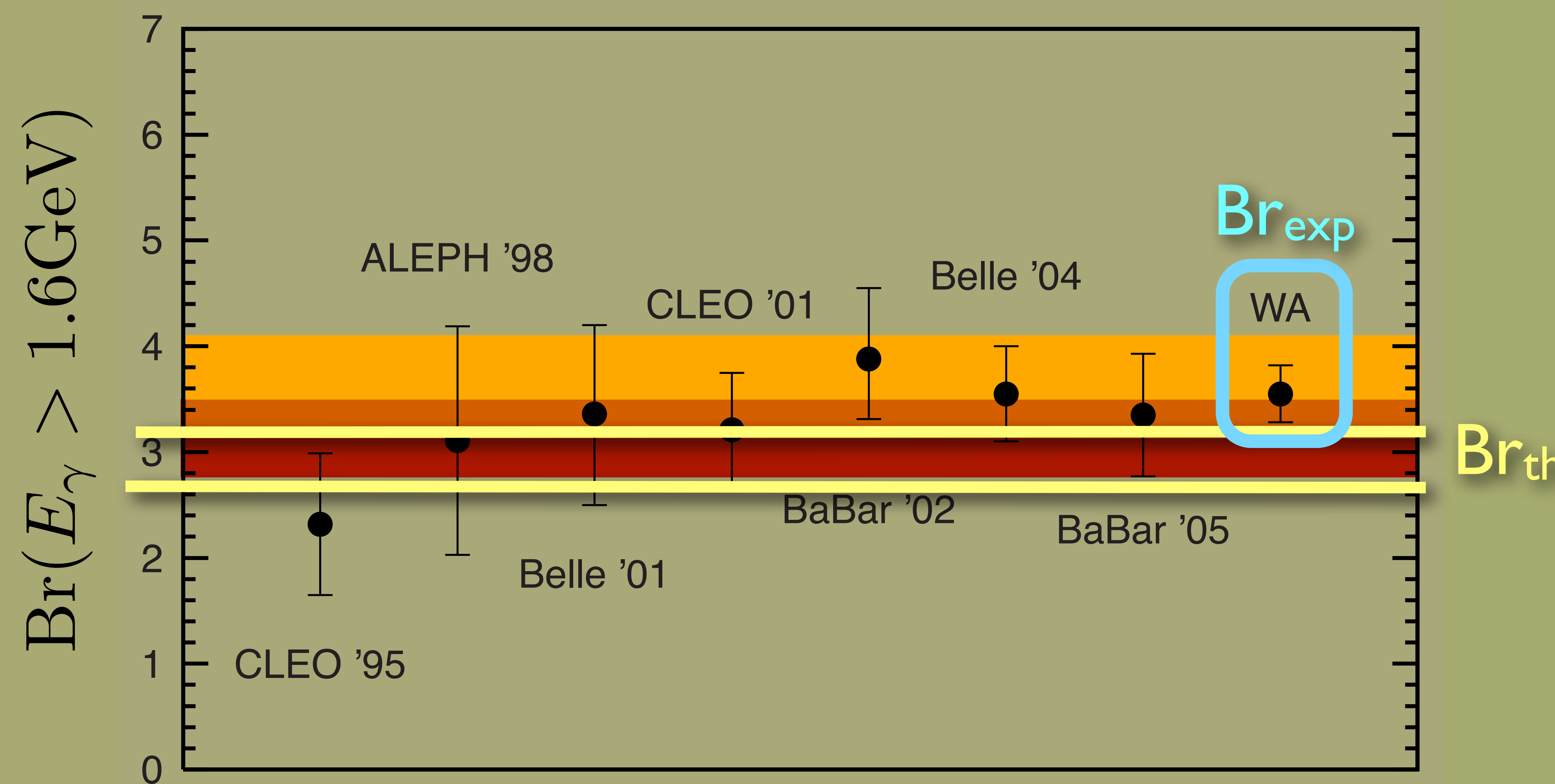
(jet) $(\Delta\, m_b)^{1/2}$

(soft) $\Delta = m_b - 2E_0 \approx 1\,\text{GeV}$

OPE in terms of $(\Lambda_{QCD}/\Delta)^n$ and $\alpha_S(\Delta)$

$$\Gamma \sim \underbrace{H^2}_{\text{hard}} \underbrace{J}_{\text{jet}} \otimes \underbrace{S}_{\text{soft}}$$

calculate NNLO corrections to multiscale OPE to resum large logarithms



$$\frac{\mathrm{Br}(\bar{B} \to X_s\gamma)_{\mathrm{exp}}}{\mathrm{Br}(\bar{B} \to X_s\gamma)_{\mathrm{th}}} = 1.19 \pm 0.09_{\mathrm{exp}} \pm 0.10_{\mathrm{th}}$$

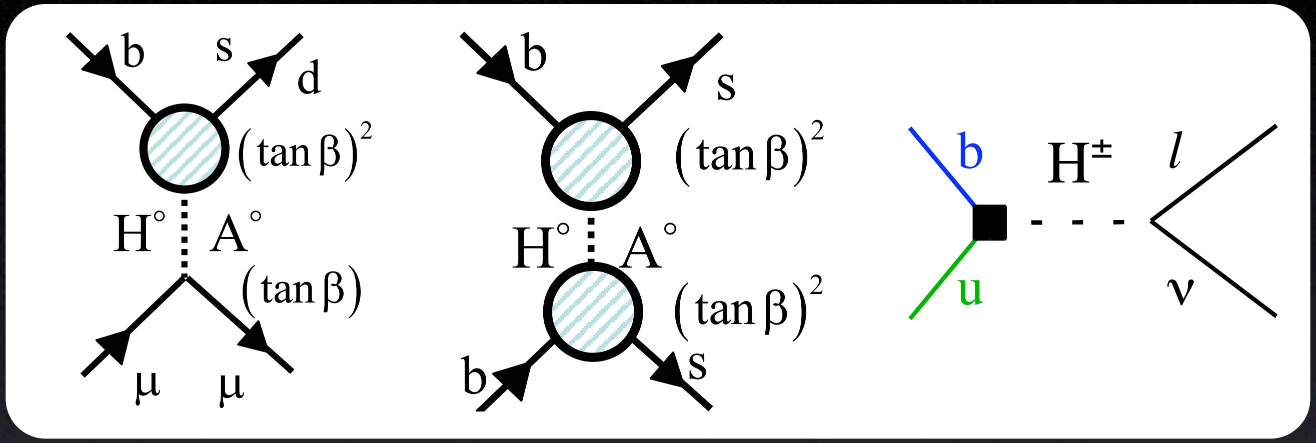
NNLO estimate of Becher/Neubert '06 including effect of photon energy cut using the recent NNLO result of Misiak et. al '06

MFV MSSM at large tanß

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

Key players

Specific pattern:



Babu, Kolda '02

$Br(B_s \to \mu^+\mu^-) \sim (\tan\beta)^6$

$\Delta M_s \sim (\Delta M_s)^{SM} - c\,(\tan\beta)^4$

Buras, Chankowski, Rosiek, Slawianowska '02

$Br(B_u \to \tau\nu) \sim Br(B_u \to \tau\nu)^{SM} - d\,(\tan\beta)^2$ Isidori, Paradisi '06

$Br(B \to X_s\gamma)$ chargino and H± contributions tend to cancel for $A_U<0$.

using UTfit '05 and CDF/D0 result; UTfit '06 -> 0.96

$(\Delta M_s)^{exp}/(\Delta M_s)^{SM} = 0.8 \pm 0.12$

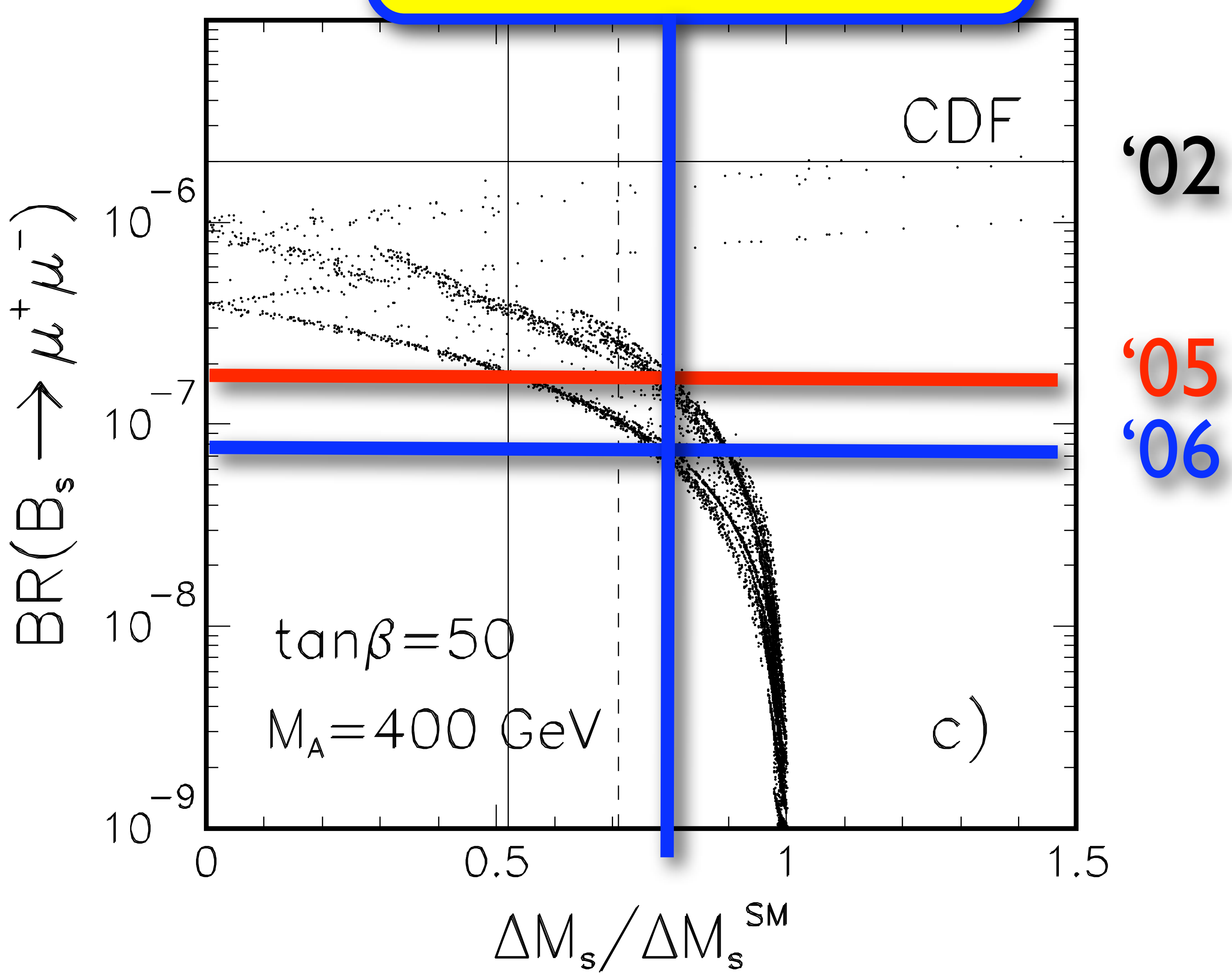
$R_{B\tau\nu}=(Br(B_u \to \tau\nu))^{exp}/(Br(B_u \to \tau\nu))^{SM} = 0.7 \pm 0.3$

pre-ICHEP 06, post-ICHEP -> R=0.85

$B_s \to \mu^+\mu^-$ vs. ΔM_s

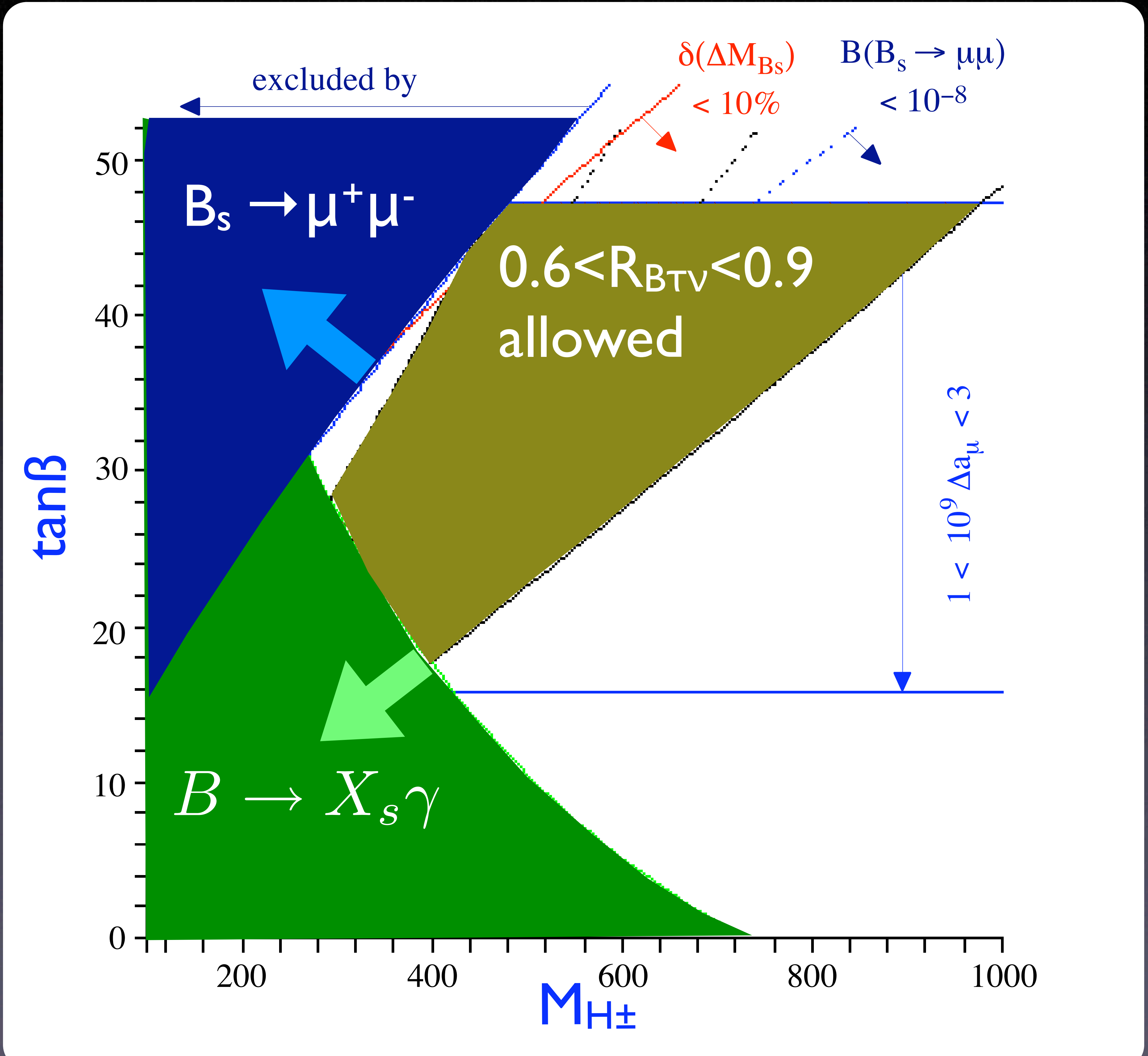
Buras, Chankowski, Rosiek, Slawianowska '02

$(\Delta M_s)^{exp}/(\Delta M_s)^{SM}$



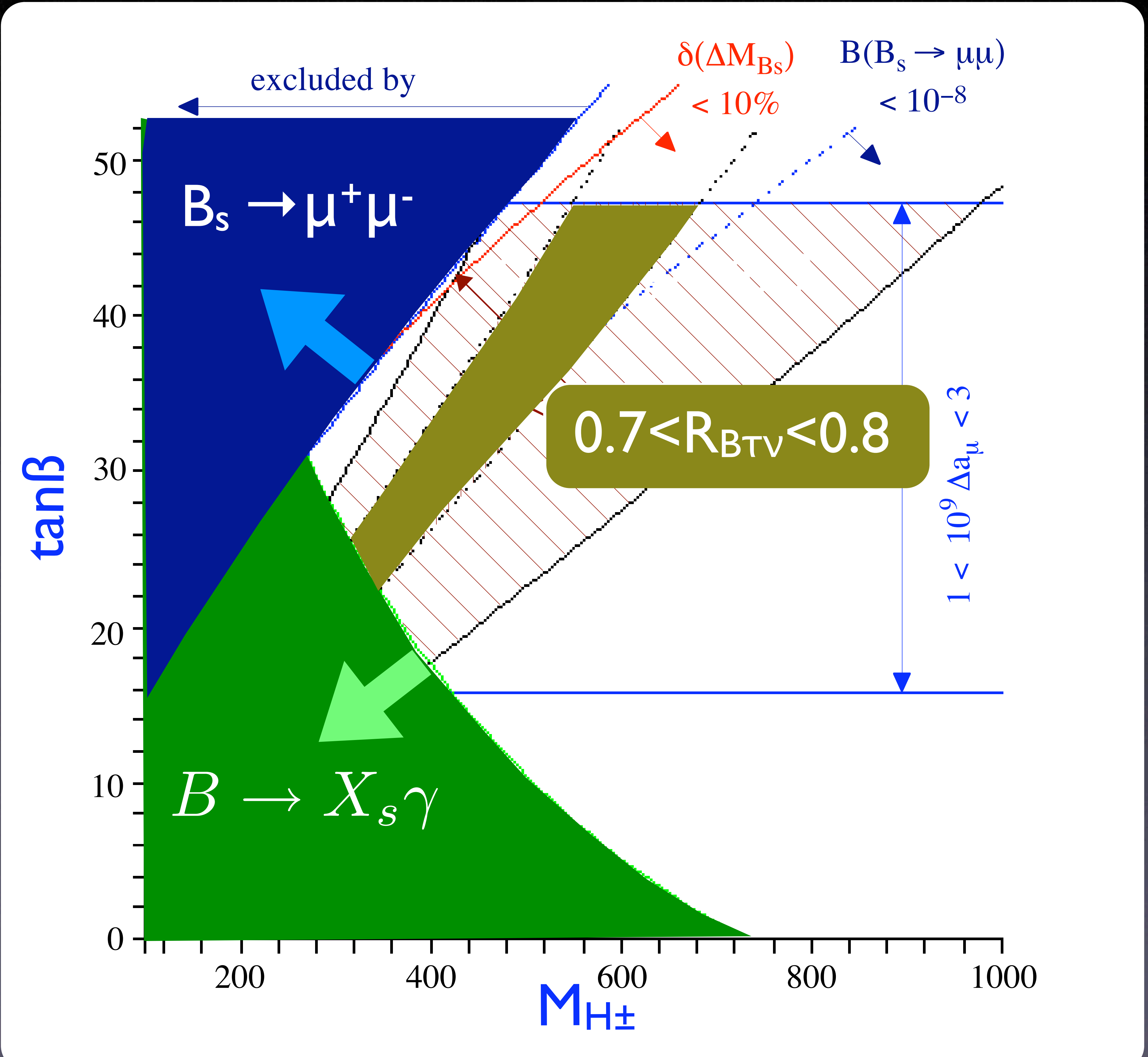
MFV-MSSM and large tanβ

Isidori, Paradisi '06



MFV-MSSM and large tanβ

Isidori, Paradisi '06



Outlook and conclusions

- We are puzzled by the flavour problem
- Rare K decays are very sensitive probe into TeV scale flavour violation. Best test of MFV and generically expect large deviations in non-MFV scenarios.
- Beginning of the era of precision flavour tests of NP
- Very interesting NP scenario Little Higgs with T parity: see C. Tarantino's talk for a discussion of the signatures.
- Theorist's nirvana: measure $K \to \pi\bar{\nu}\nu$ and $B_s \to \mu^+\mu^-$