# The Future of Flavor Physics

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**“ The aim of physics is to find new terms in the Lagrangian of the universe.**

**Everything else is chemistry.”**

M. Schwartz

By this stringent yardstick, most of us, while we strive to do physics, wind up doing chemistry

Nonetheless, flavor physics has historically been a rich source of physics, even by Mel’s criterion

Does flavor physics in the LHC era meet this rigorous criterion?

What are the crucial experiments in the search for new terms in the flavor Lagrangian (New Physics)?

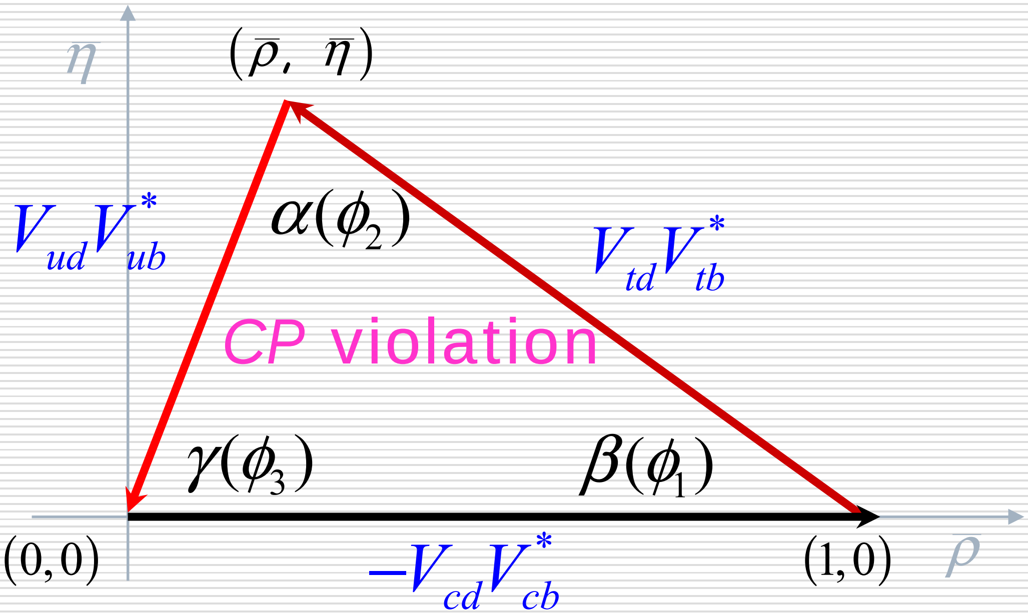
# Where is flavor physics now?

- The PEP-II/*BaBar* and KEKB/Belle $B$ Factories, together with CLEO$c$ and modern $K$ decay experiments, have brought us to the precision measurement regime for many heavy quark and heavy lepton measurements
- CDF and DØ at Tevatron Run II are now producing physics and have unique capabilities in $B_s$ mixing, rare decays and $b$ baryon studies
- Bottom line: the CKM phase is consistent with being the source for all observed $CP$-violating phenomena
  - There must, however, be additional sources of $CP$ violation
- Over the next few years, $CP$ violation and rare decays in the flavor sector will be pursued with improved precision, and, equally important, with improved sophistication
  - *e.g.*, the best current methods for measurement of $\alpha\,(\phi_2)$ and $\gamma\,(\phi_1)$ were not those put forward in the initial phase

## The Unitarity Triangle summarizes the salient features of Standard Model heavy flavor physics

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \cong \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\bar{\rho}-i\bar{\eta}) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\bar{\rho}-i\bar{\eta}) & -A\lambda^2 & 1 \end{pmatrix}$$

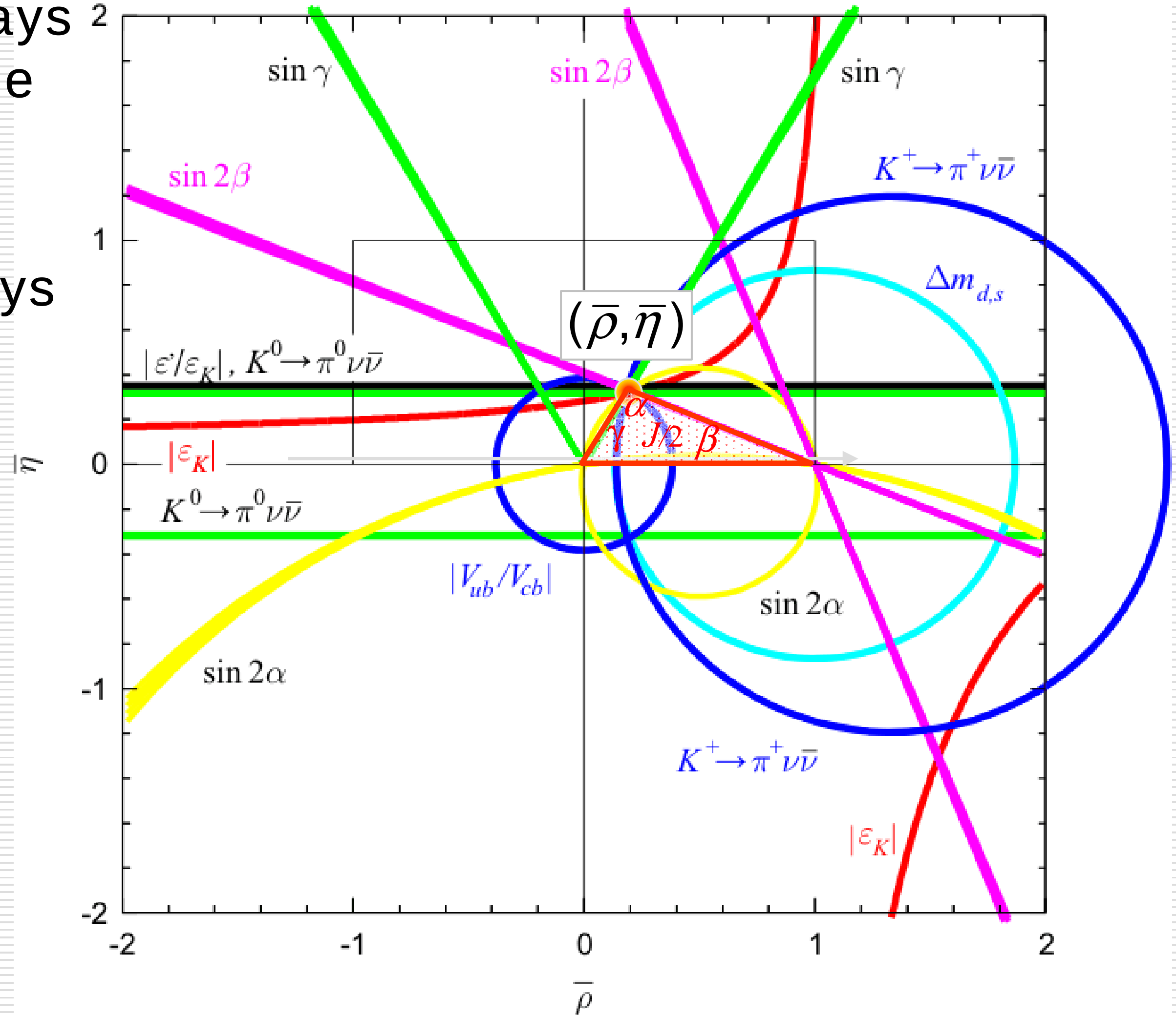
Unitarity : $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$



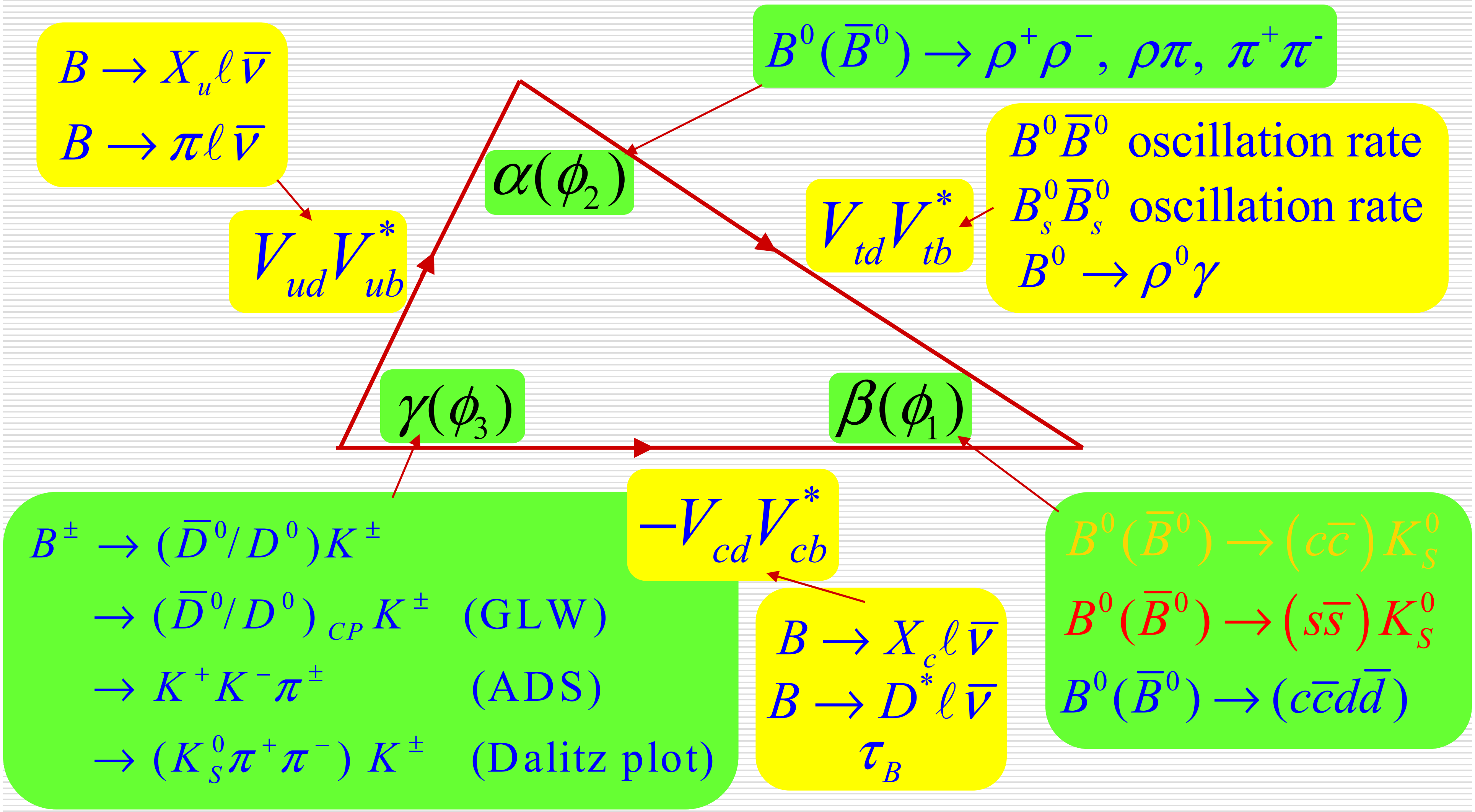

*CP violation* $\propto J = \mathfrak{Im}\left[V_{ud}V_{cs}V_{us}^*V_{cd}^*\right] \simeq A^2\lambda^6\eta \sim 10^{-5}$ *, the Jarlskog invariant:*

# Let me count the ways

- There are many ways to overconstrain the Unitarity Triangle
- Useful constraints from $B$ and $K$ decays

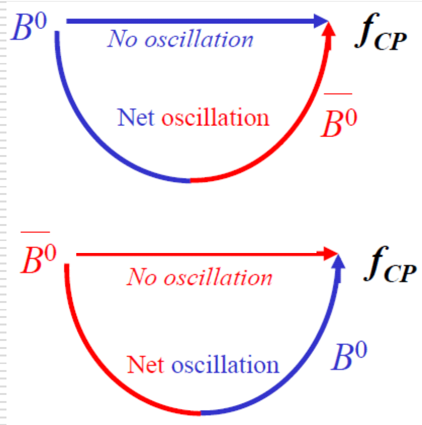


# Overconstraining the Unitarity Triangle



## $CP$ asymmetry from the interference between mixing and decay

$$A_{f_{CP}}(t) = \frac{\Gamma\left(\overline{B}^0(t) \to f_{CP}\right) - \Gamma\left(B^0(t) \to f_{CP}\right)}{\Gamma\left(\overline{B}^0(t) \to f_{CP}\right) + \Gamma\left(B^0(t) \to f_{CP}\right)}$$




$$A_{f_{CP}}(t) = S \cdot \sin(\Delta m \cdot t) \text{ - } C \cdot \cos(\Delta m \cdot t)$$

$$S = \frac{2 \cdot \mathrm{Im}(\lambda)}{1 + |\lambda|^2} \qquad C = \frac{1 - |\lambda|^2}{1 + |\lambda|^2}$$

$$\lambda = \sqrt{\frac{M_{12}^* - \frac{i}{2}\Gamma_{12}^*}{M_{12} - \frac{i}{2}\Gamma_{12}}} \cdot \frac{\langle f_{CP} | H | \overline{B}^0 \rangle}{\langle f_{CP} | H | B^0 \rangle} = \frac{q}{p} \cdot \frac{\overline{A}_f}{A_f}$$

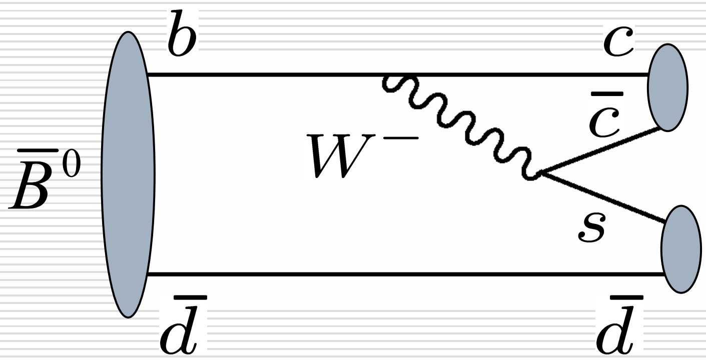
For a single decay amplitude: $|q/p|=1$

$$|\lambda| = 1 \quad \Rightarrow \quad S = \mathrm{Im}(\lambda), \ \ C = 0$$

$$A_{f_{CP}}(t) = \mathrm{Im}(\lambda) \cdot \sin(\Delta m \cdot t)$$

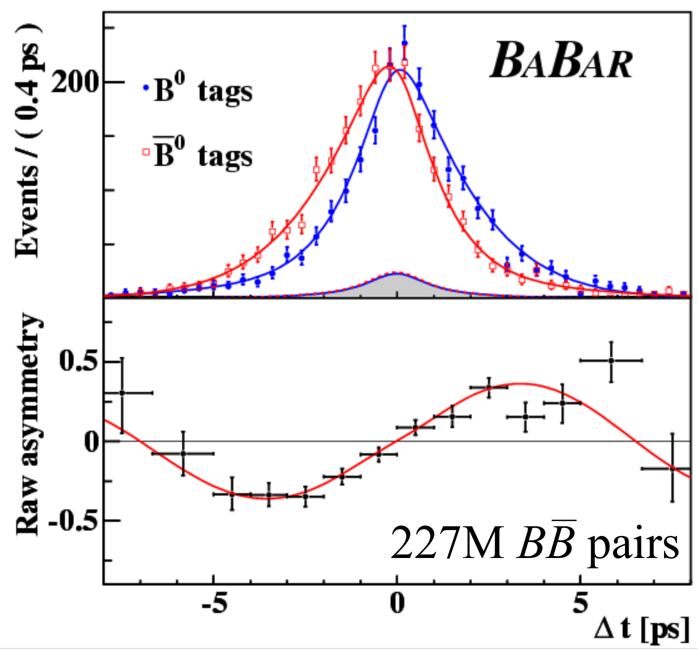
If there is New Physics it could be in the decay amplitude or the mixing amplitude

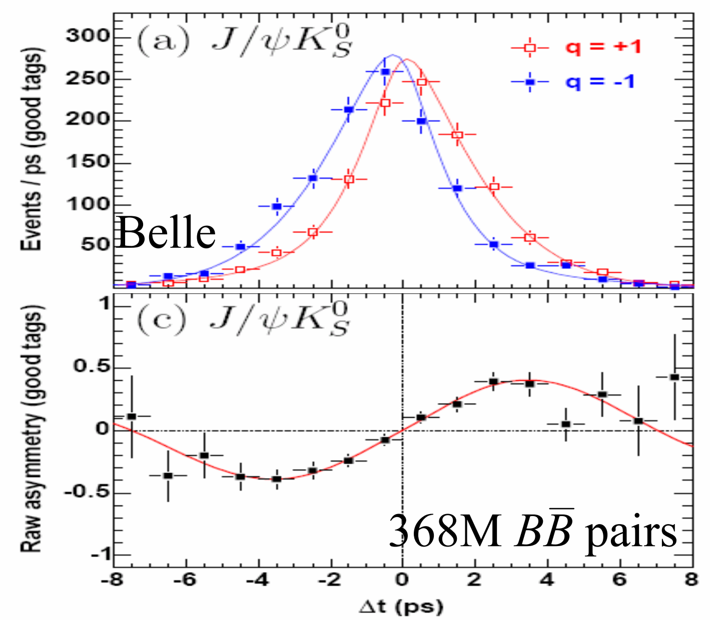
# $\sin 2\beta$ is now a precision measurement




$J/\psi,\ \psi(2S),\ \chi_{c1},\ \eta_c$

$\overline{K}^0 \rightarrow K_S^0, K_L^0$
$\overline{K}^{*0} \rightarrow K_S^0 \pi^0$

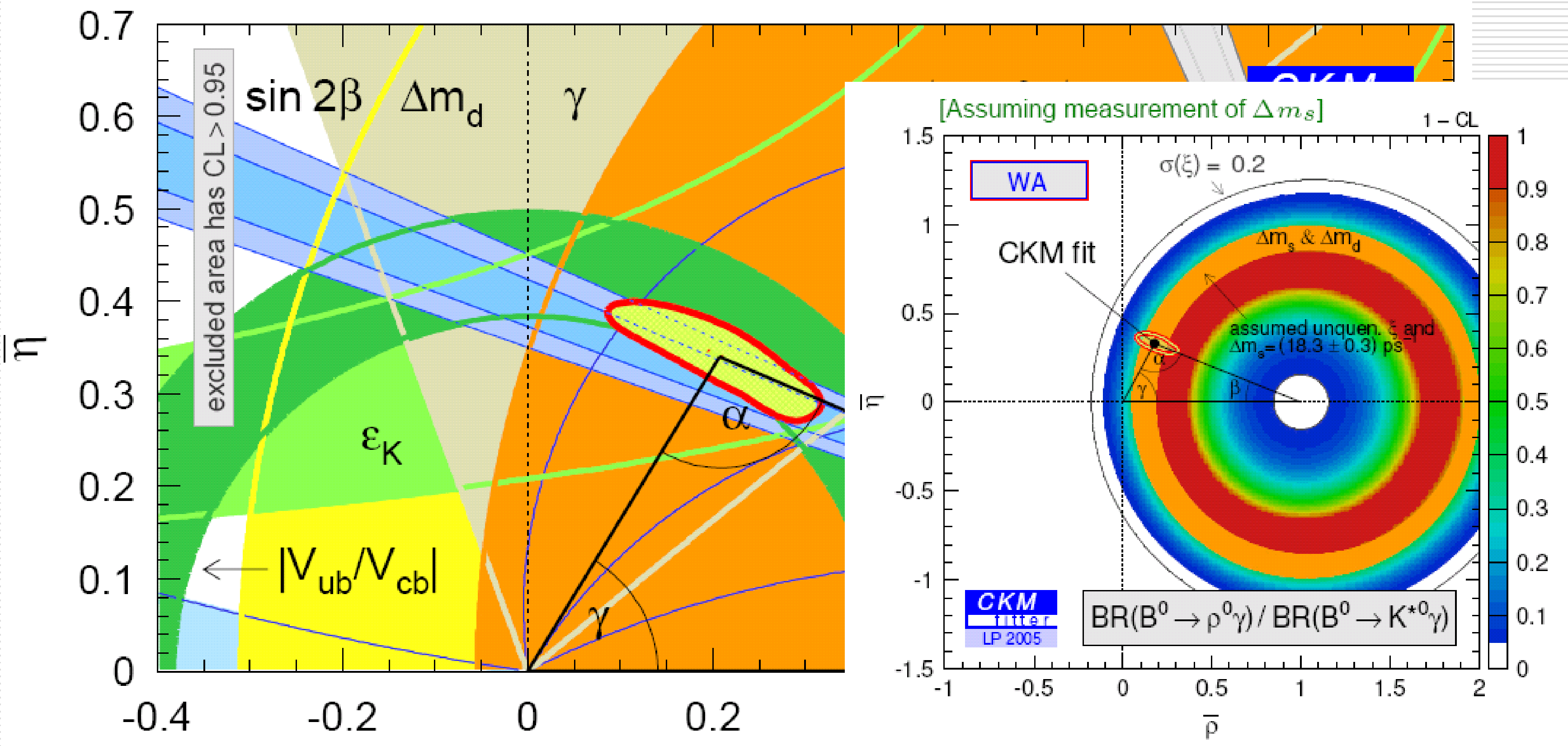



$\sin 2\beta = +0.722 \pm 0.040 \pm 0.023$

$\sin 2\phi_1 = +0.652 \pm 0.039 \pm 0.020$

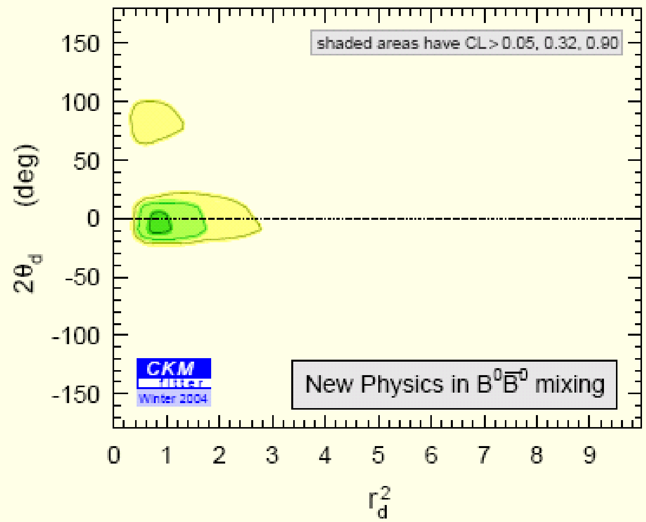
# Unitary Triangle 2005



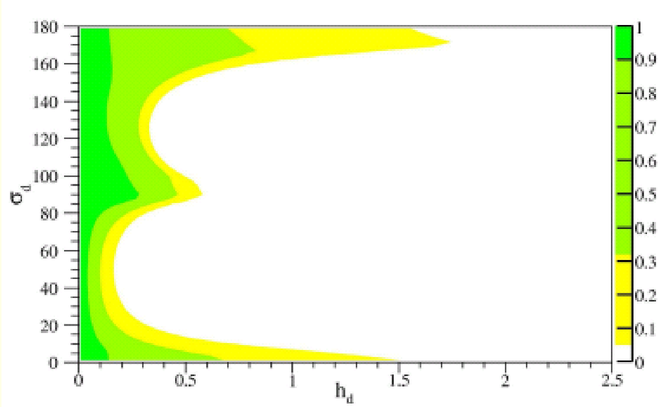

$|V_{td}/V_{ts}|$ **from** $B \to \rho\gamma$ **vs.** $B \to K^*\gamma$

# Is there New Physics in $B^0\overline{B}^0$ mixing?

- Assume: New Physics in tree decays - negligible
- Define $r_d^2 \exp(2i\theta_d) \equiv 1 + he^{i\sigma} \equiv \langle B^0|\mathcal{H}^{\rm full}|\overline{B}^0\rangle / \langle B^0|\mathcal{H}^{\rm SM}|\overline{B}^0\rangle$
- Use $|V_{ub}/V_{cb}|$, $\mathcal{A}_{DK}$, $S_{\psi K}$, $S_{\rho\rho}$, $\Delta m_{B_d}$, $\mathcal{A}_{\rm SL}$
- Fit to $\eta$, $\rho$, $\boxed{r_d}$, $\theta_d$ (or $\boxed{h}$, $\sigma$)
- Find whether $h \neq 0$ ($r_d \neq 1$) is allowed




Nir

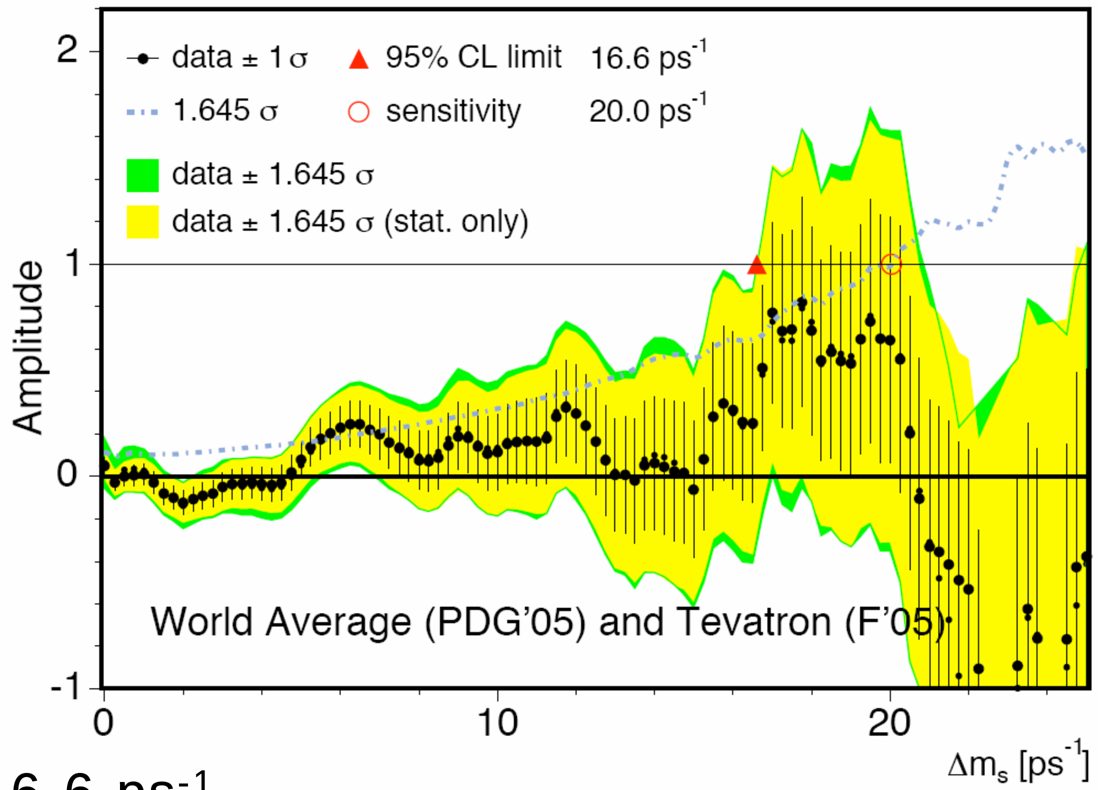



Agashe, et al.

For arbitrary phase, $h = |A_{\rm NP}/A_{\rm SM}| \sim 0.2 \pm 0.2$

# $B_s$ mixing limits

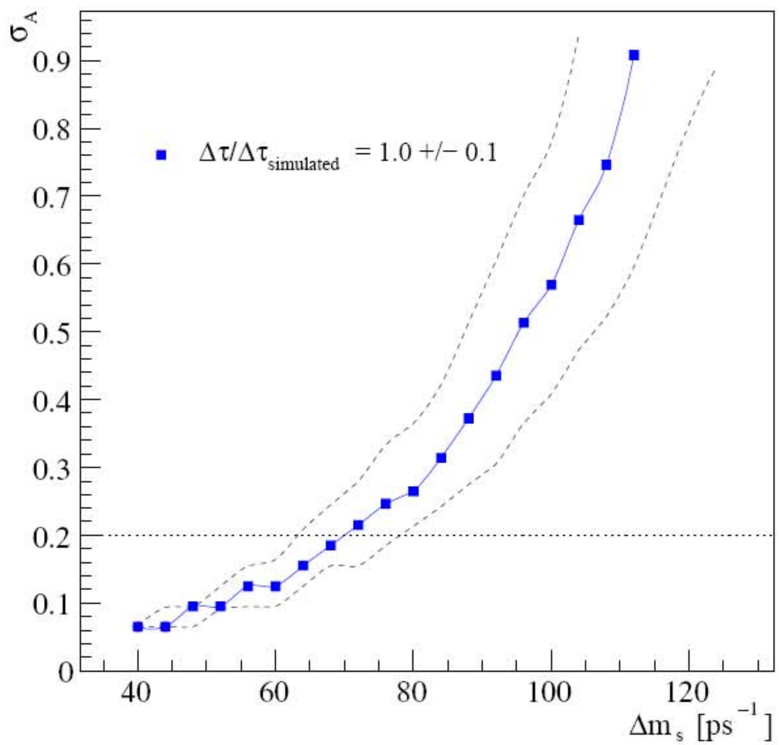
- New CDF/DØ results

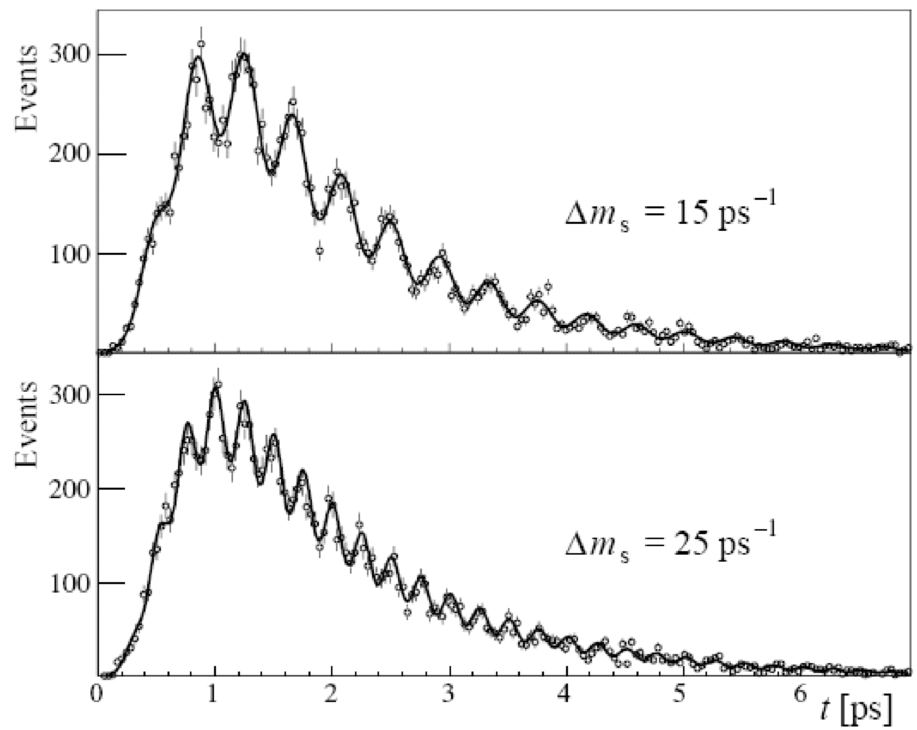



Limit $14.5 \rightarrow 16.6$ ps$^{-1}$

sensitivity $18.3 \rightarrow 20.0$ ps$^{-1}$

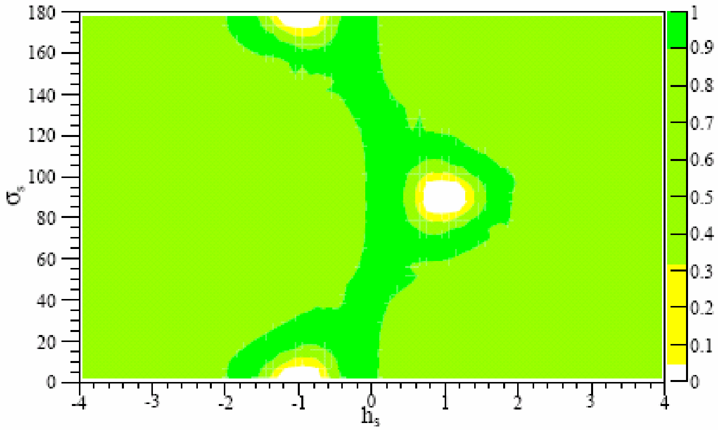
# LHCb sensitivity to $B_s^0 \overline{B}_s^0$ mixing



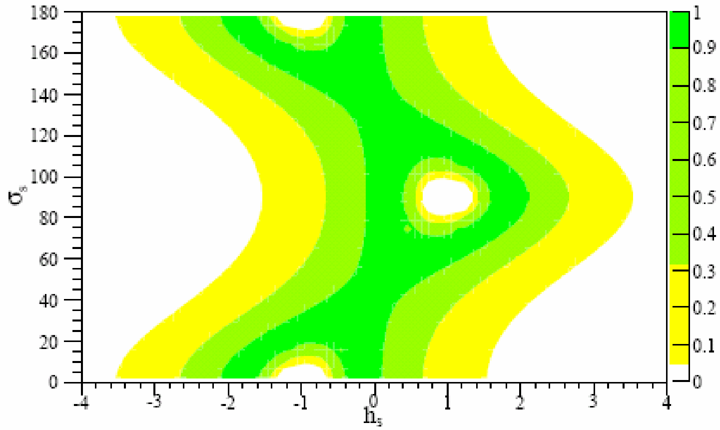




In 1 year, $\geq 5\sigma$ observation of $B_s^0$ oscillations up to $\Delta M_s = 68\ \mathrm{ps}^{-1}$

# Is there New Physics in $B_s^0 \overline{B}_s^0$ mixing?




Current



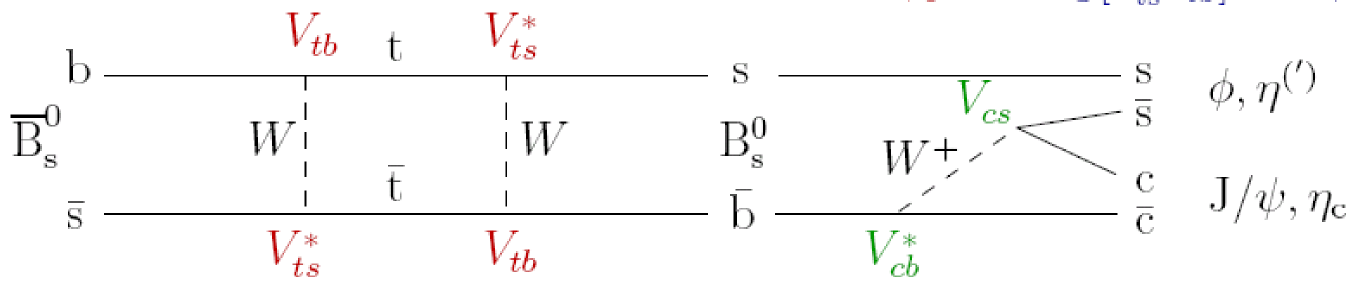

If $\Delta m_s = (18.3 \pm 0.3)\,\mathrm{ps}^{-1}$

Agashe, Papucci, Perez, Pirjol

# $\phi_s$

Mixing-induced CP violation: phase mismatch $\phi_s - 2\phi_D \approx \phi_s \neq 0, \pi$

"first mix, then decay" • $\phi_s \stackrel{\text{SM}}{\equiv} 2\arg[V_{ts}^* V_{tb}] \approx -2\beta_s = \mathcal{O}(-0.04)$ rad




→ CP-asymmetry directly measures $\phi_s = \mathcal{O}(-0.04)$ rad (for given $\eta_{f_{CP}}$)

$$\mathcal{A}_{CP}(t) = \frac{-\eta_{f_{CP}} \sin(\phi_s) \sin(\Delta M_s t)}{\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) - \eta_{f_{CP}} \cos(\phi_s) \sinh\left(\frac{\Delta\Gamma_s t}{2}\right)}$$

| Channels | $\sigma(\phi_s)$ [rad] | Weight $(\sigma/\sigma_i)^2$ [%] |
|---|---|---|
| $B_s^0 \to J/\psi\ \eta(\gamma\ \gamma)$ | 0.112 | 6.4 |
| $B_s^0 \to J/\psi\ \eta(\pi^+\ \pi^-\ \pi^0)$ | 0.148 | 3.6 |
| $B_s^0 \to \eta_c\ \phi$ | 0.106 | 7.1 |
| Combined three pure CP eigenstates channels | 0.068 | 17.1 |
| $B_s^0 \to J/\psi\ \phi$ | 0.031 | 82.9 |
| Combined all four CP eigenstates channels | 0.028 | 100.0 |

With 10 fb$^{-1}$ (5 years): $\sigma(\phi_s) \sim 0.013$ rad ⟶ $\sim 3\sigma$ for $\phi_s = -0.04$ rad (SM)

# Constraints on New Physics

- Even at current precision, the *grosso modo* agreement of flavor physics experimental results with Standard Model predictions places very meaningful limits on physics beyond the Standard Model
- In the presence of New Physics, many of these simple relations can be modified
- This has spawned a minor phenomenological industry that has provided guidance for the current experiments and a roadmap for future investigations
  - Where to look for New Physics?
    - *FCNC processes*
    - $b \to s$ vertices: $\Delta F=1$, $\Delta F=2$
      - $CP$ violation, mixing, rare $b$ and $\tau$ decays
    - Precision measurements in $K$, $D$ and $B$ decays

# The LHC era begins

- What will remain to be done in flavor physics when the current programs at *BABAR*, Belle, CDF and DØ are over?
  - Overconstrained tests of the CKM matrix to the level of precision warrented by theoretical uncertainties
  - Searches, and, quite likely, measurements of deviations from the Standard Model that will be crucial to an understanding of New Physics uncovered at the LHC
- What facilities will we have?
  - LHC: ATLAS, CMS, LHC$b$
  - Linear collider (ILC/CLIC)?
  - A Super $B$ Factory?
  - Rare kaon experiments?
  - $\tau$/charm collider
  - Fixed target charm experiment?
- Which facilities beyond the LHC are most crucial to flavor studies?

# An Endangered Species Act for heavy quarks in the US?

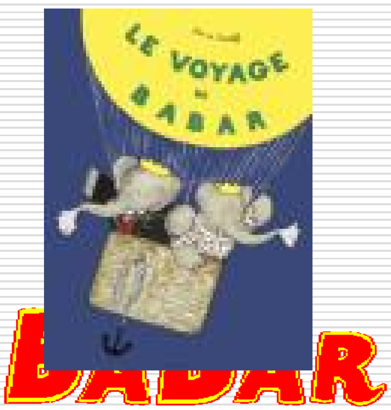
2003 — C / M (u c t / d s b) ✗

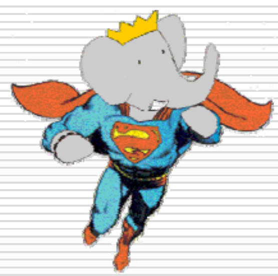
2005 — BTEV Co ✗

2005 — μe MECO ✗

2005 — K opio ✗

2006-2008



SUPERBABAR

# Data samples ($b$) at the start* of the LHC era

- *BABAR* and Belle will each have collected a total data sample of approximately 1 ab$^{-1}$ by ~2008
  - 2 ab$^{-1}$ = 2 x 10$^9$ produced $B\overline{B}$ pairs
- The Tevatron Run II experiments CDF and DØ will each have collected 4-8 fb$^{-1}$ by ~2009
  - Premier objective is a measurement of $B_s^0\overline{B}_s^0$ mixing

## How can flavor physics complement the LHC program?

- The Higgs will likely come first
- The search for evidence of physics beyond the Standard Model will then take center stage
  - There have been many exercises showing how, with sufficiently large data samples and concomitant improved precision, heavy quark and $\tau$ measurements can uniquely discriminate between SUSY breaking models, extra dimension scenarios, *etc*.
  - These need sharpening, on both sides: high $p_t$ and flavor physics
- It is possible that the LHC will find the Standard Model Higgs and nothing else
  - In this situation, the importance of precision flavor physics in searching for physics beyond the Standard Model may increase

# Strategies

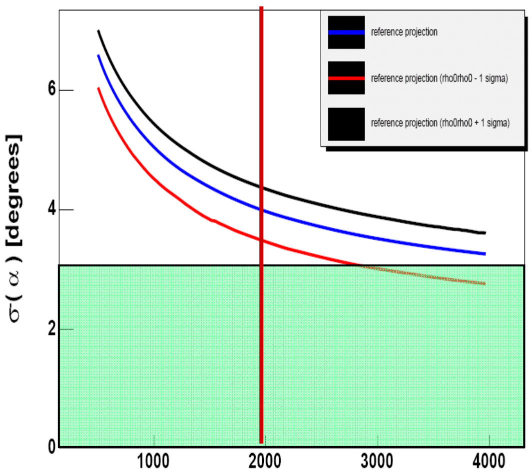
- Improve measurements of CKM unitarity triangle measurements to the precision warrented by theory
  - $CP$ asymmetries in tree-dominated processes
  - Differences in $CP$ asymmetries between tree and penguin-dominated processes

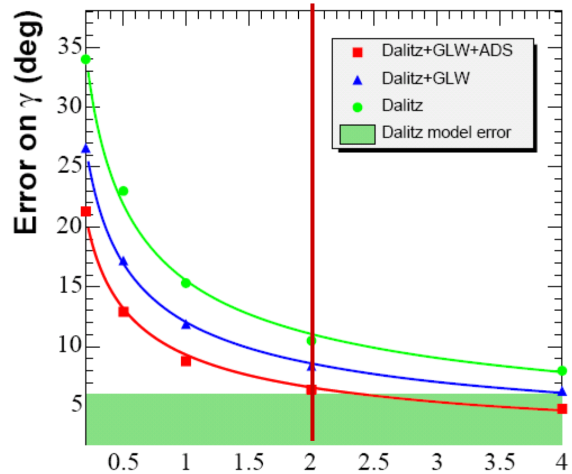
- Search for/measure FCNC processes, highly suppressed in the Standard Model, in which New Physics may show up
  - Generation 3 to generation 2 ($b\to s$, $\tau\to\mu$) transitions are especially promising
    - $B_s$ oscillations
    - $b\to s\gamma$ branching fraction, $A_{CP}$
    - $A_{\mathrm{FB}}(b\to s\ell^+\ell^-)$
    - $B_s\to\mu^+\mu^-$

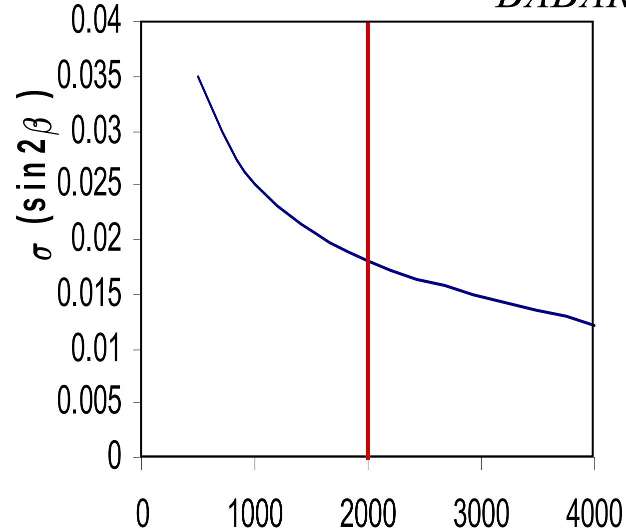
# Precision of $\alpha$, $\sin 2\beta$, $\gamma$ in this decade

- Through ~2008 (and beyond), precision of UT angle measurements will continue to be statistics limited

*BABAR*



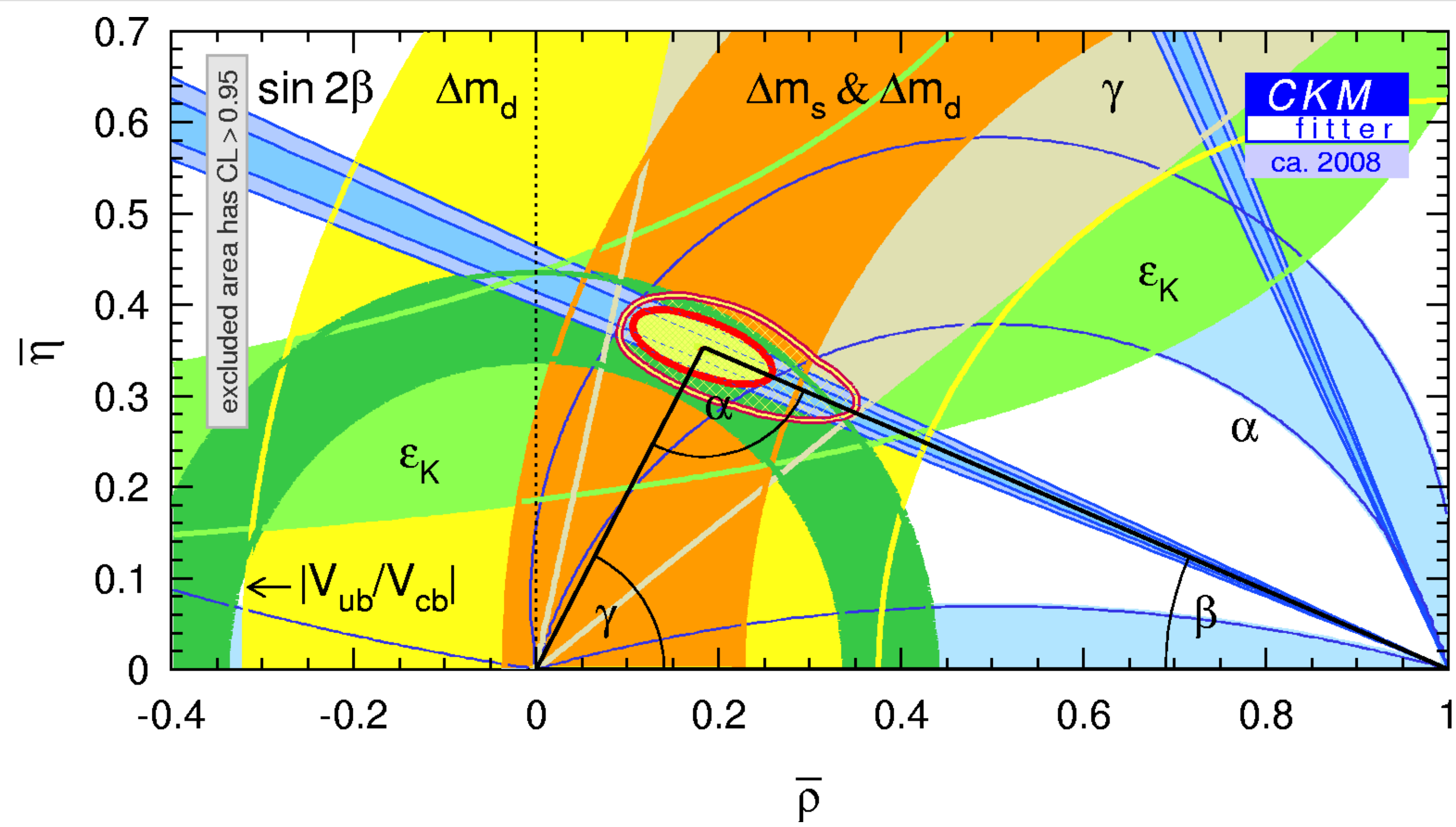




- $\alpha$, $\gamma$ methods shown run into model problems at 2 $ab^{-1}$ level
  - With higher statistics, other methods may be better
    *e.g.* for $\alpha$, use $B \to \pi\pi$ + isospin analysis instead of $B \to \rho\rho$

LHC*b* (1 year @ 2 x $10^{32}$) (Schneider)

$\sigma(\alpha) = 10^{o}$ $\qquad$ $\sigma(\gamma) = 5^{o}\left(B^{\pm} \to D^{0} K^{\pm}\right)$ $\qquad$ $\sigma(\sin 2\beta) = 0.02$

# Global CKM fit: 2008




$\sigma(V_{ub}) = 6.5\%$

$\sigma(\Delta m_s) = 5\%$

$\sigma(\sin 2\beta) = 0.019 \quad \sigma(\alpha) = 8^{\circ} \quad \sigma(\gamma) = 10^{\circ}$

# What is the ultimate possible UT precision?

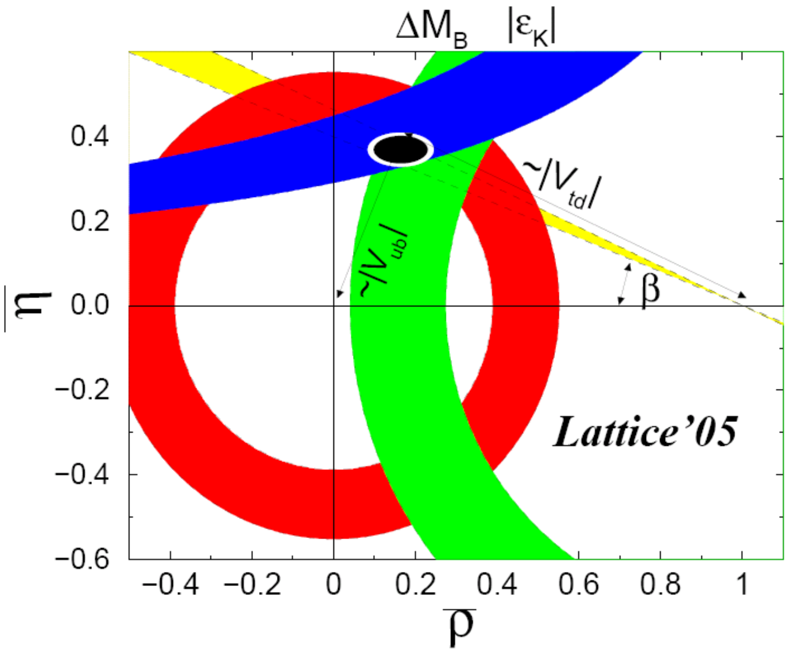
- Theoretical limits (continuum methods)
  - Many measurements will not be theory-limited for quite some time

Ligeti:

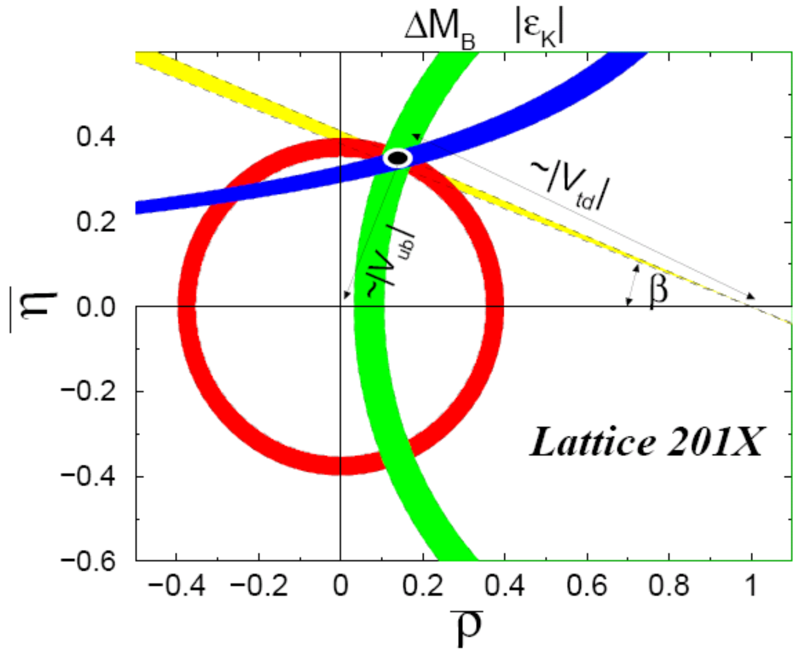
| Measurement (in SM) | Theoretical limit | Present error |
|---|---|---|
| $B \to \psi K_S \ (\beta)$ | $\sim 0.2^\circ$ | $1.6^\circ$ |
| $B \to \phi K_S,\ \eta^{(\prime)} K_S, \ldots\ (\beta)$ | $\sim 2^\circ$ | $\sim 10^\circ$ |
| $B \to \pi\pi,\ \rho\rho,\ \rho\pi \ (\alpha)$ | $\sim 1^\circ$ | $\sim 15^\circ$ |
| $B \to DK \ (\gamma)$ | $\ll 1^\circ$ | $\sim 25^\circ$ |
| $B_s \to \psi\phi \ (\beta_s)$ | $\sim 0.2^\circ$ | — |
| $B_s \to D_s K \ (\gamma - 2\beta_s)$ | $\ll 1^\circ$ | — |
| $\lvert V_{cb}\rvert$ | $\sim 1\%$ | $\sim 3\%$ |
| $\lvert V_{ub}\rvert$ | $\sim 5\%$ | $\sim 15\%$ |
| $B \to X \ell^+ \ell^-$ | $\sim 5\%$ | $\sim 20\%$ |
| $B \to K^{(*)} \nu\bar{\nu}$ | $\sim 5\%$ | — |
| $K^+ \to \pi^+ \nu\bar{\nu}$ | $\sim 5\%$ | $\sim 70\%$ |
| $K_L \to \pi^0 \nu\bar{\nu}$ | $< 1\%$ | — |

# Ultimate UT precision - II

- Unitarity triangle using unquenched lattice results




Current precision

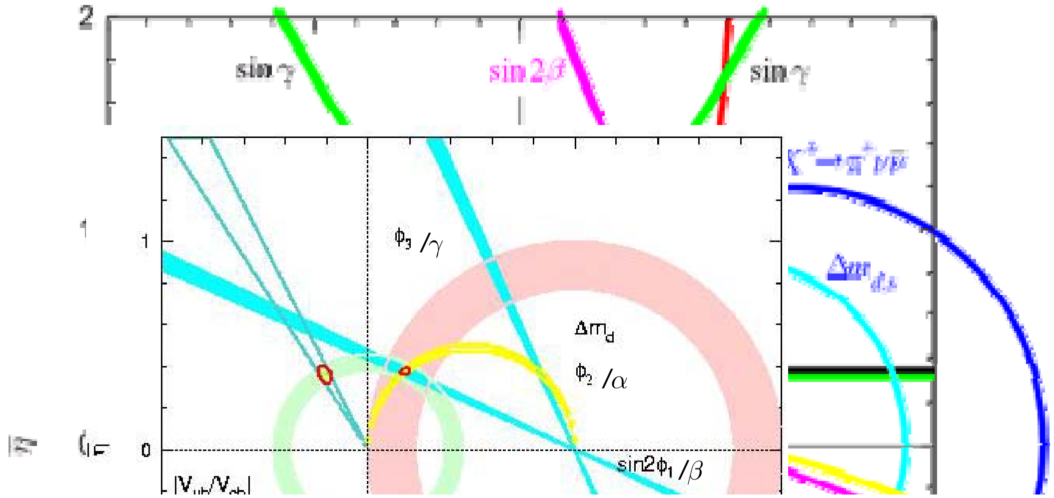



"Ultimate" precision

Okamoto

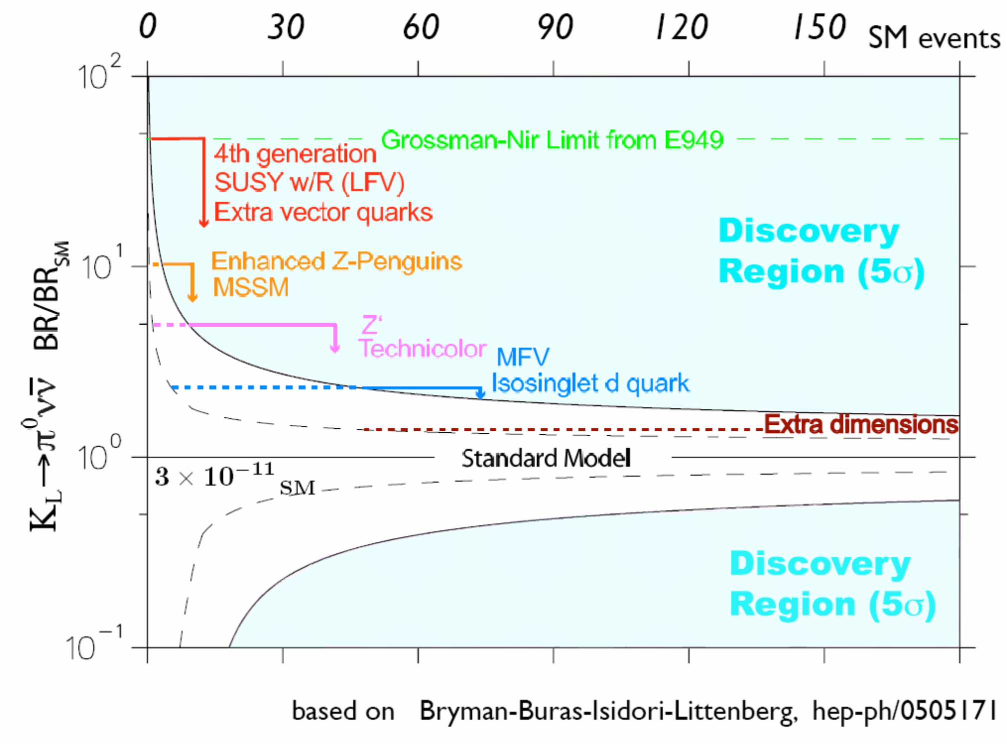
# Ultimate UT precision - III

- Prediction for SuperKEK*B* at 50 ab$^{-1}$ (~2020)
- LHC*b* measurements will also be pertinent (or, they may be the only measurements)
- Rare $K$ decay constraints




| | short-distance (e.w.) contrib. to the total rate $(\Gamma - \Gamma_{no\ s.d.})/\Gamma$ | present irreducible th. error on the s.d. amplitude extracted from BR only | total BR withinSM (central value) |
|---|---|---|---|
| $K_L \to \pi^0 \nu\nu$ | $> 99\%$ | 1% | $8\times10^{-11}$ |
| $K^+ \to \pi^+ \nu\nu$ | 88% | 3% | $3\times10^{-11}$ |
| $K_L \to \pi^0 e^+e^-$ | 38% | 15% Dalitz → ~ 10% | $3.5\times10^{-11}$ |
| $K_L \to \pi^0 \mu^+\mu^-$ | 28% | 30% Dalitz → ~ 15% | $1.5\times10^{-11}$ |

- The **real** motivation for precision measurements of rare $K$ decay branching fractions is the sensitivity to New Physics

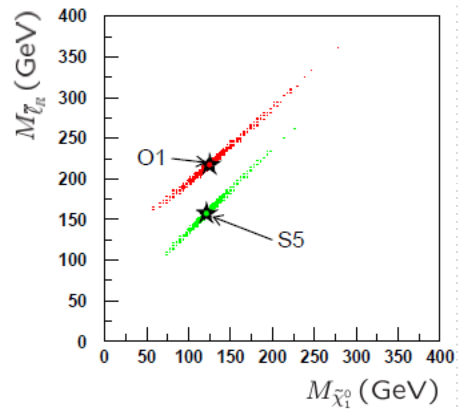



- The same is true for high precision $B$ and $\tau$ decay studies

# After the LHC finds New Physics

- LHC, by the mass difference and threshold methods, will measure SUSY masses to a precision of 5 to 10 GeV
- ILC or CLIC, a decade later, will dramatically improve errors, by, e.g., measuring slepton masses with a threshold scan to a precision ~100 MeV with 10 fb-1 per point

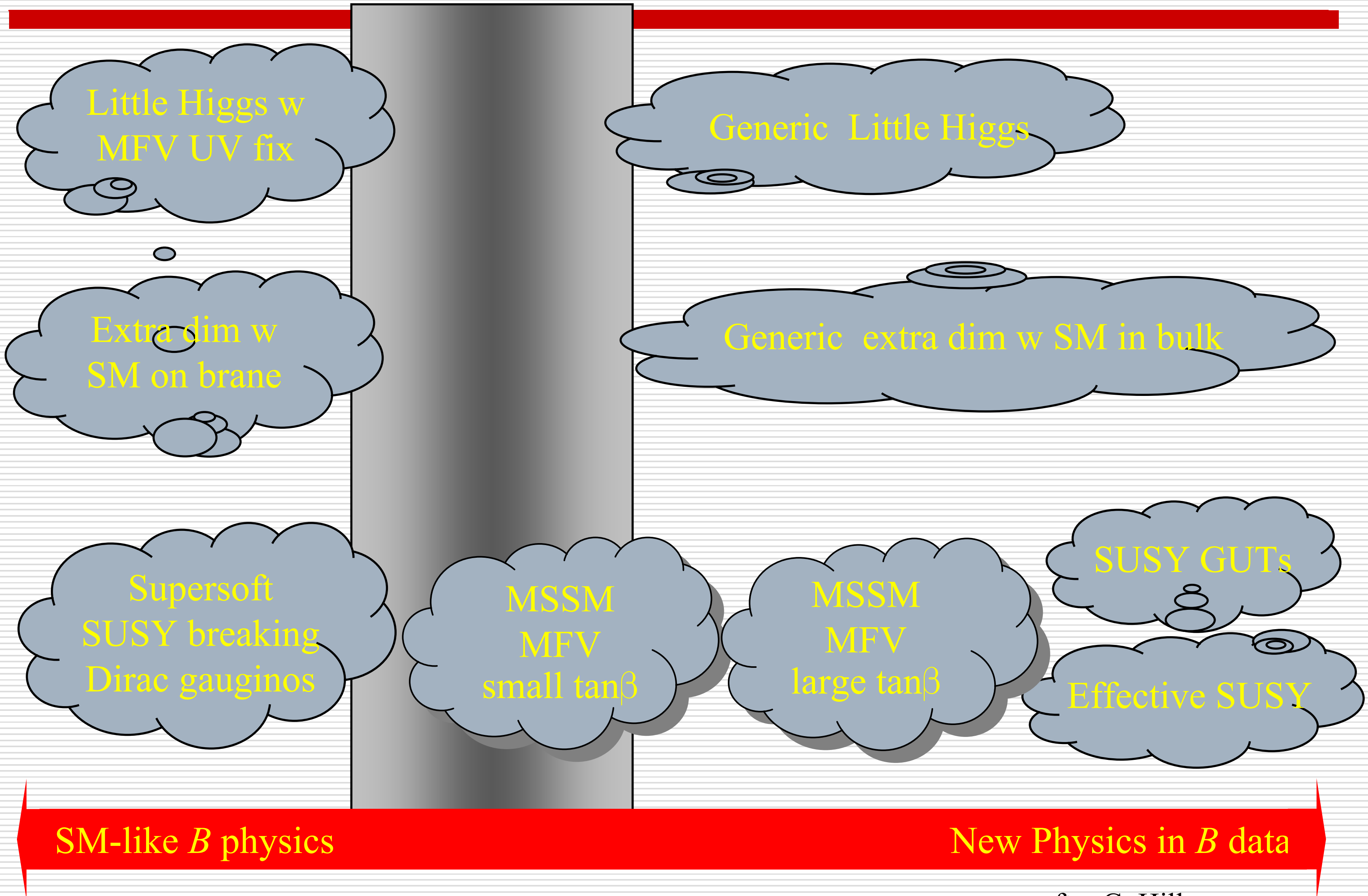
| | LHC | LHC+ILC |
|---|---|---|
| $\Delta m_{\tilde{\chi}_1^0}$ | 4.8 | 0.19 |
| $\Delta m_{\tilde{l}_R}$ | 4.8 | 0.34 |
| $\Delta m_{\tilde{\chi}_2^0}$ | 4.7 | 0.24 |
| $\Delta m_{\tilde{q}_L}$ | 8.7 | 4.9 |
| $\Delta m_{\tilde{b}_1}$ | 13.2 | 10.5 |




Correlations allow model discrimination (without ILC)

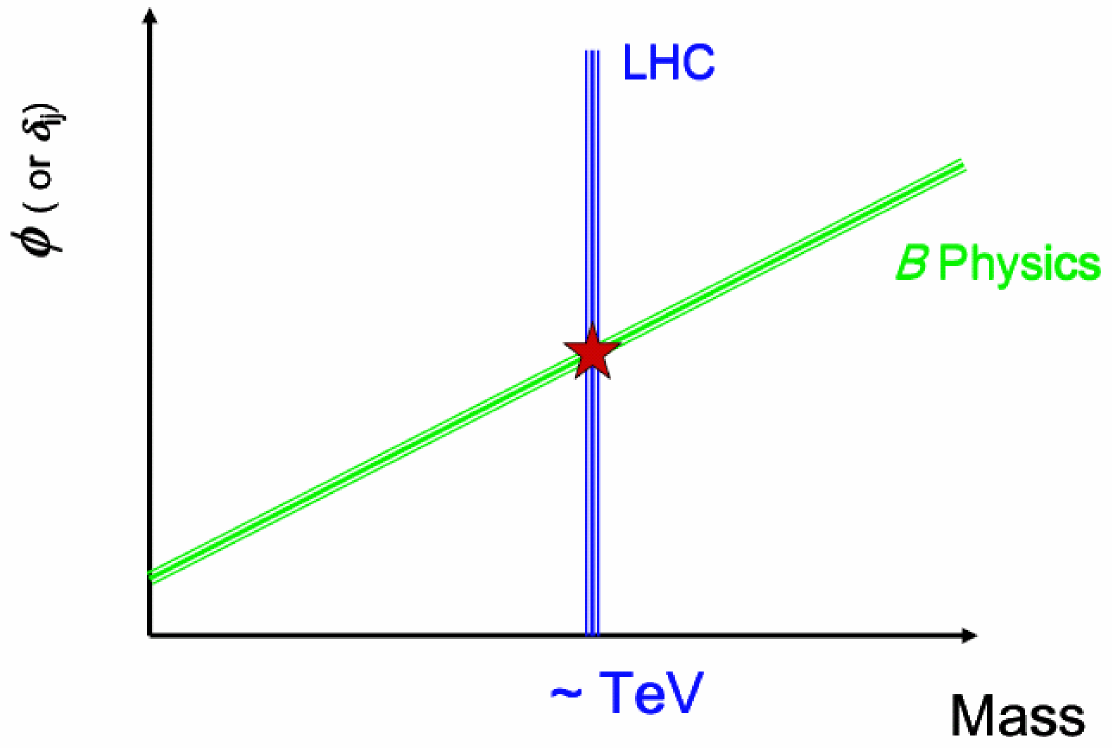
- In the meantime it is important to clarify the flavor structure of New Physics discoveries with high statistics $K$, $B$ and $\tau$ experiments
- These studies can uniquely discriminate between SUSY models

# Many SM extensions yield measurable effects in *B* physics




after G. Hiller

# Heavy flavor studies complement LHC direct searches



# Experimental signatures of extended flavor structure

- FCNC processes, LFV processes and CPV in loop decays
- There are many clean measurements that are diagnostic of models
  - New $CP$ violating phase in $b \to sq\bar{q}$ : $CPV(t)$ in $B^0 \to \phi K_s$, $\eta' K_s$, $K_sK_sK_s$
  - Right-handed current in $b \to s\gamma$ : $CPV(t)$ in $B^0 \to K_s\pi^0\gamma$
  - Lepton flavor violation in $\tau$ decays : $\mathcal{B}(\tau \to \mu\gamma)$
  - Charged Higgs in tree diagram : $\mathcal{B}(B \to D\tau\nu)/\mathcal{B}(B \to D\mu\nu)$
  - $b \to d\gamma$, $A_{FB}$ in $b \to s\ell^+\ell^-$, $B \to K^*\nu\nu$, $B \to \ell\nu$, .........
  - $B_s$ mixing

  - Some measurements are unique to hadron experiments, some to $e^+e^-$, and some can be done in both environments

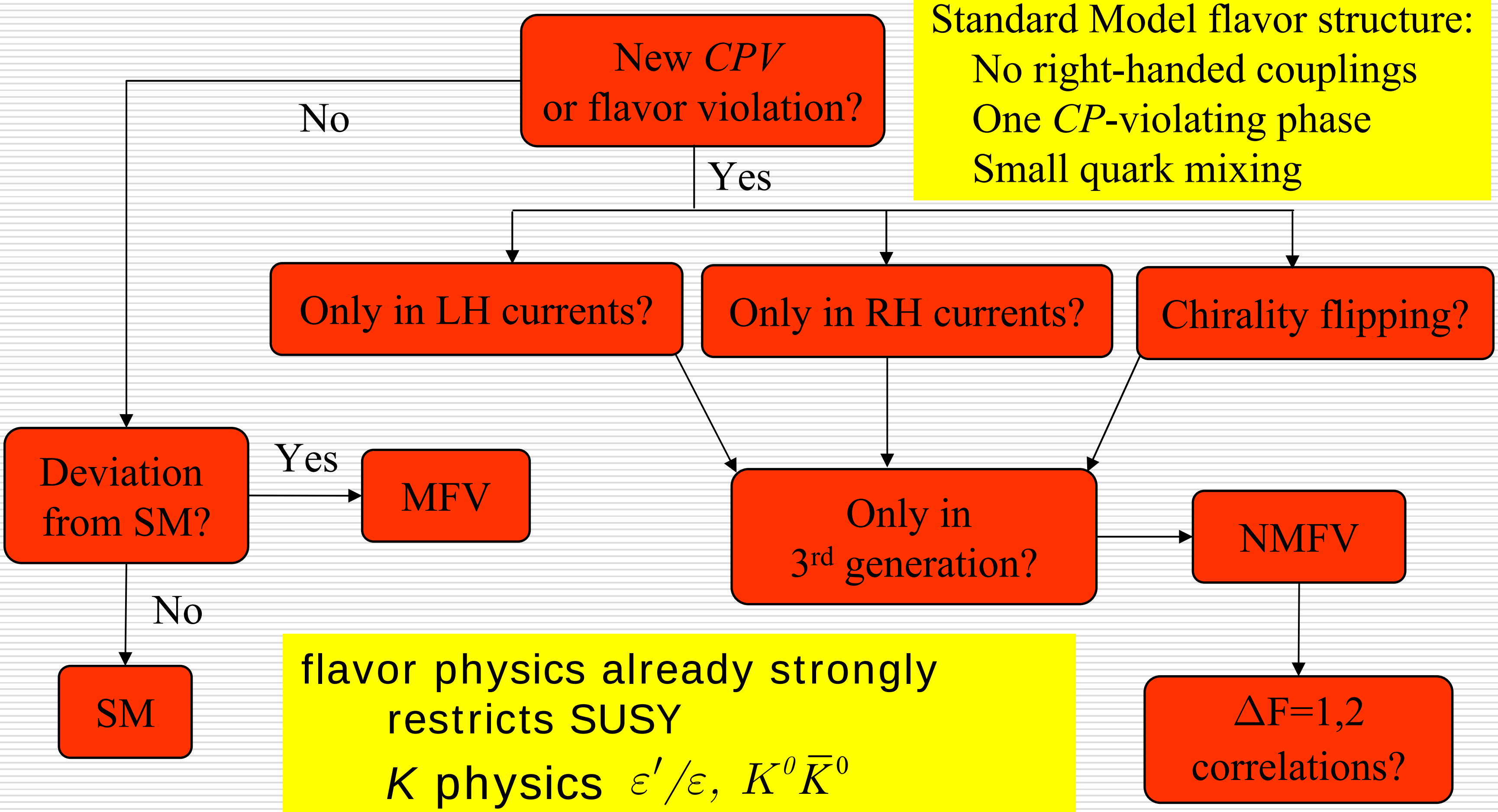
# Many rare processes are sensitive to New Physics

| Mode | Standard Model Branching Fraction $\mathcal{B}$ | New Physics Effects |
|---|---|---|
| $b \to s\gamma$ | $\sim 3 \times 10^{-4}$ | $\mathcal{B}$, $A_{CP}$, $A_{\rm FB}$ |
| $b \to sg$ | $\sim 10^{-5}$ per mode | $A_{CP}$ |
| $B \to X\ell\ell$ | $\sim 10^{-6}$ per mode | $\mathcal{B}$, $A_{CP}$, $A_{\rm FB}$ |
| $B \to X\nu\nu$ | $\sim 10^{-6}$ per mode | $\mathcal{B}$ up to $10^{-5}$/mode |
| $D \to X\ell\ell$ | $\sim 10^{-6}$ per mode | $\mathcal{B}$ up to $10^{-5}$/mode |
| $B \to \tau\nu$ | $\sim 10^{-4}$ | Close to SM sensitivity |
| $\tau \to \ell\gamma$ | $\sim 10^{-40}$ | $\mathcal{B}$ up to $10^{-8}$ |
| $B \to \ell\ell$ | $< 10^{-11}$ | $\mathcal{B}$ up to $10^{-5}$ |
| $D \to \ell\ell$ | $< 10^{-9}$ | $\mathcal{B}$ up to $10^{-6}$ |

The observed pattern of effects is diagnostic of the mechanism of SUSY breaking or the type of extra dimension model

# flavor physics provides a roadmap

Standard Model flavor structure:
- No right-handed couplings
- One *CP*-violating phase
- Small quark mixing




flavor physics already strongly restricts SUSY

- *K* physics $\varepsilon'/\varepsilon,\ K^0\bar{K}^0$
- Hg EDM
- *B* physics $\mathcal{B}(b\to s\gamma),\ \Delta m_{B_s},\ldots\ldots$

Perez

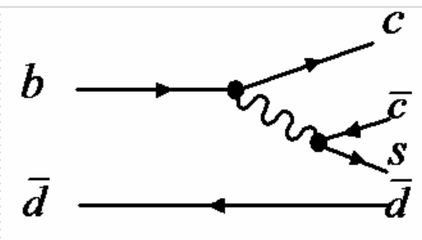
# What can a Super $B$ Factory bring to the party?

- flavor physics, whether $b$, $c$ or $\tau$ decays, provides
  - Sensitivity to New Physics (SUSY, extra dimensions, ......)
    - New $CP$ phases, non-Standard Wilson coefficients, ......
  - Strong and unique constraints on models of SUSY breaking
    - $\mathcal{B}(b\to s\gamma)$ has already ruled out a host of New Physics models
  - Super $B$ specific measurements
    - $CP$V in $b\to s$
    - FCNC ($K\ell\ell$, $K\nu\nu$ ......)
    - LFV ($\tau$ decays)
    - Higgs mediation ($B\to\tau\nu$, $B\to D\tau\nu$, etc.)
    - Precision CKM Unitarity Triangle parameters
      - Measure $\alpha, \beta, \gamma, V_{ub}, V_{cb}, \Delta m_d$ to the limit of theoretical precision (see above)
  - There is, of course, some overlap with LHC*b*

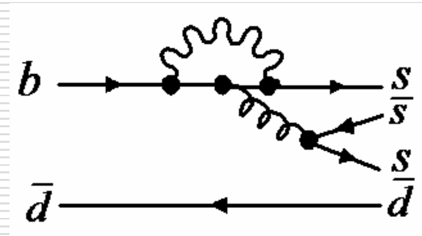
# Probes of new physics

- In the Standard Model we expect the same value for "$\sin 2\beta$" in $b \to c\bar{c}s$, $b \to c\bar{c}d$, $b \to s\bar{s}s$, $b \to d\bar{d}s$ modes, but different SUSY models can produce different asymmetries
- Since the penguin modes have branching fractions one or two orders of magnitude less than tree modes, great deal of luminosity is required to make these measurements to meaningful precision

$B^0 \to J/\psi K_S^0$

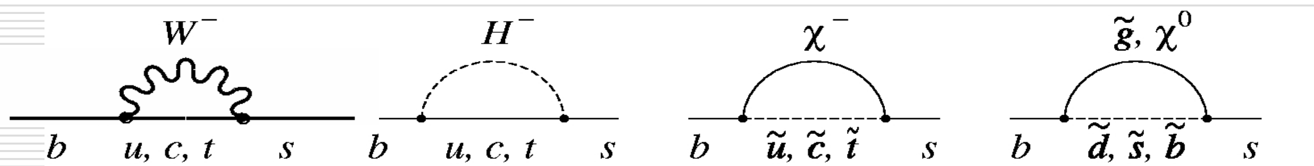



$B^0 \to \phi K_S^0$




$$\lambda_{tree} = \frac{q}{p}\frac{\bar{A}}{A} = \eta \frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*}\frac{V_{cb} V_{cs}^*}{V_{cb}^* V_{cs}} = (-1)e^{-2i\beta}$$

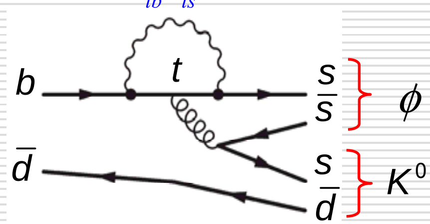
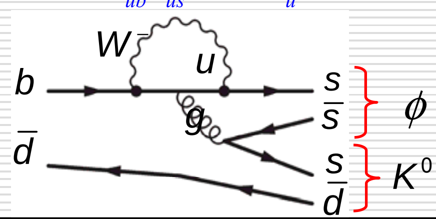
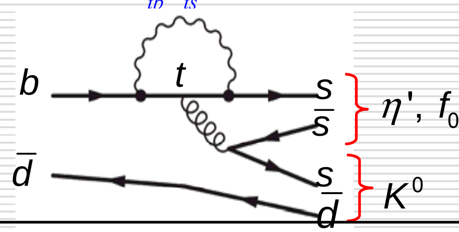
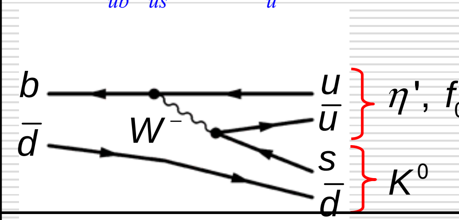
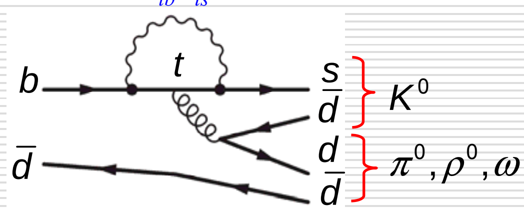
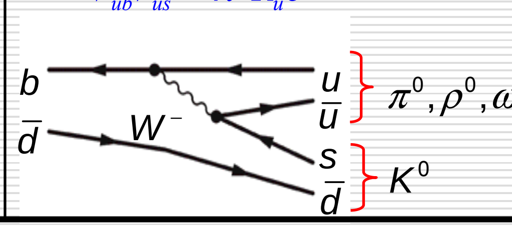
$$\lambda_{penguin} = \frac{q}{p}\frac{\bar{A}}{A} = \eta \frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*}\frac{V_{tb} V_{ts}^*}{V_{tb}^* V_{ts}} = (-1)e^{-2i\beta}$$




$$\lambda = e^{i(2\beta+\phi^{SUSY})}\frac{|\bar{A}|}{|A|} \Rightarrow S_{\phi K} = \sin(2\beta + \phi^{SUSY})$$

In general $S_{J/\psi K_S} \neq S_{\phi K_S}$; $C_{J/\psi K_S} \neq C_{\phi K_S}$

# There are penguin and tree corrections to $b \to s s \bar{s},\ s d \bar{d}$ modes

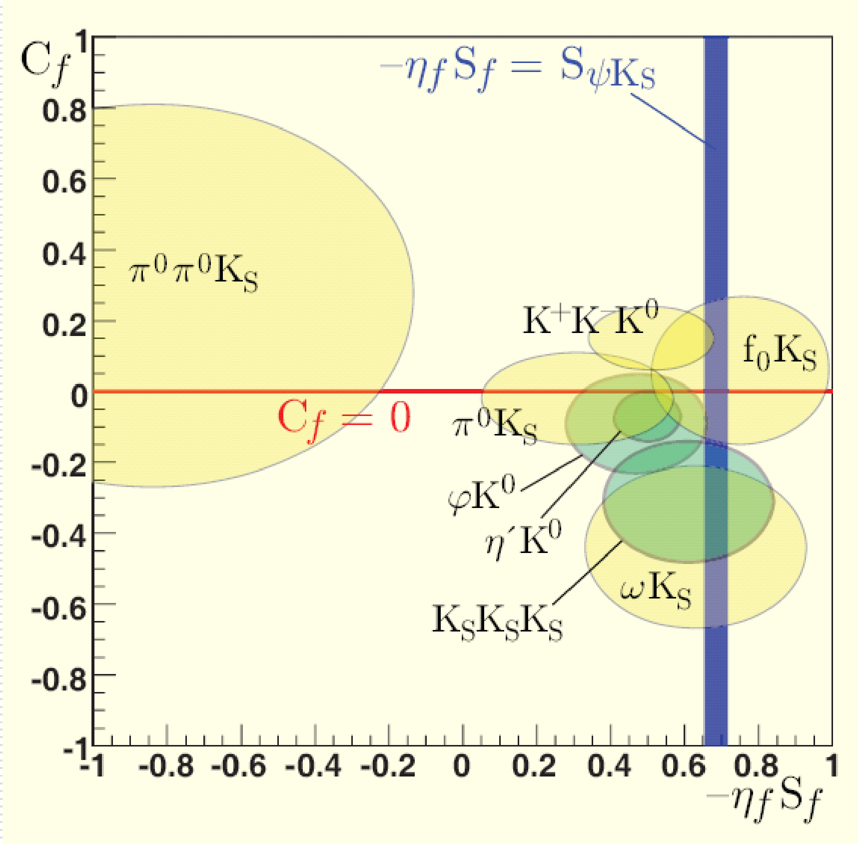
| $b \to s s \bar{s},\ s d \bar{d}$ mode | $\mathcal{B}$ x$10^{-6}$ | | |
|---|---|---|---|
| $B^0 \to \phi K^0_S$ | 4 | $\propto V_{tb}V^*_{ts} \sim \lambda^2$   | $\propto V_{ub}V^*_{us} \sim \lambda^4 R_u e^{-i\gamma}$   |
| $B^0 \to \eta' K^0_S$ | 29 | $\propto V_{tb}V^*_{ts} \sim \lambda^2$   | $\propto V_{ub}V^*_{us} \sim \lambda^4 R_u e^{-i\gamma}$   |
| $B^0 \to \pi^0 K^0_S$ | 20 | $\propto V_{tb}V^*_{ts} \sim \lambda^2$   | $\propto V_{ub}V^*_{us} \sim \lambda^4 R_u e^{-i\gamma}$   |

| $B^0 \to J/\psi K^0_S$ | 440 |
|---|---|

Issues: triggering, charged/neutral vertexing, ….

# There is as yet no evidence for New Physics

## from $CP$ asymmetry measurements in $b \to s$ transitions

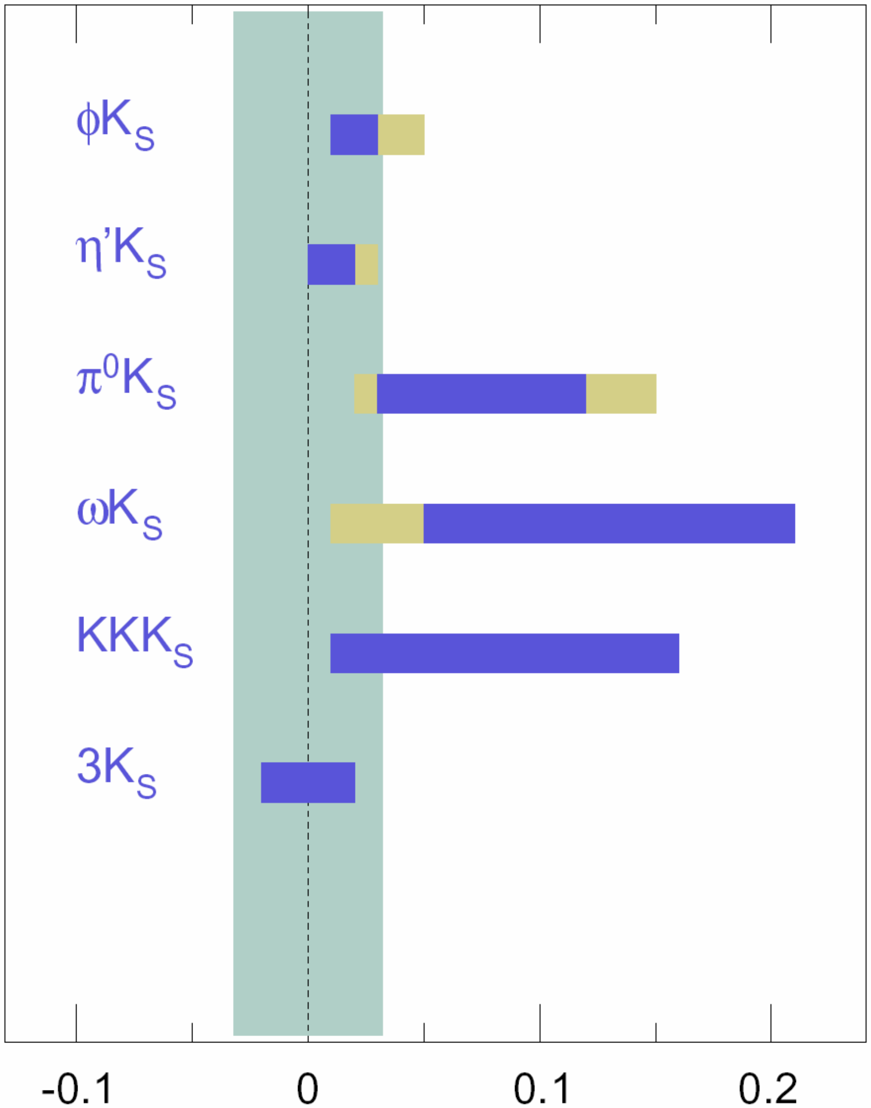



Kirkby and Nir, PDG

As we press the search, we must understand

- The required and achievable experimental precision
- The reliability of theoretical calculations

# How good are the SM predictions?




Two body:
Beneke, PLB 620 (2005) 143

blue = ±1 sigma
grey = full range

Calculations within framework of QCD factorization

Three body:
Cheng, Chua & Soni,
hep-ph/0506268

$$\Delta = S_{penguin} - \sin 2\beta$$

# squark mass matrix ($d$ sector)

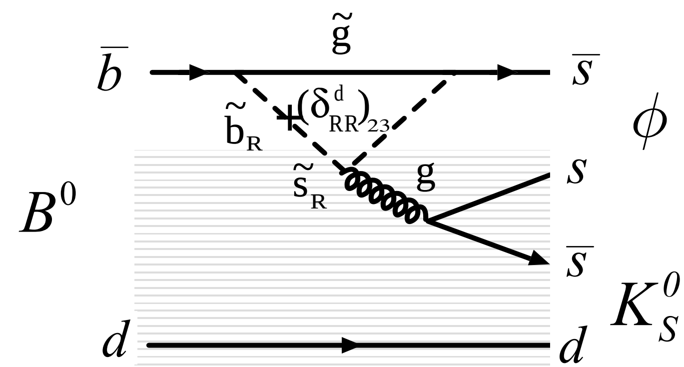
flavor structure: Super$B$, LHC$b$

$$\begin{pmatrix} m^2_{\tilde d_L} & m_d(A_d-\mu\tan\beta) & (\Delta^d_{12})_{LL} & (\Delta^d_{12})_{LR} & (\Delta^d_{13})_{LL} & (\Delta^d_{13})_{LR} \\ & m^2_{\tilde d_R} & (\Delta^d_{12})_{RL} & (\Delta^d_{12})_{RR} & (\Delta^d_{13})_{RL} & (\Delta^d_{13})_{RR} \\ & & m^2_{\tilde s_L} & m_s(A_s-\mu\tan\beta) & (\Delta^d_{23})_{LL} & (\Delta^d_{23})_{LR} \\ & & & m^2_{\tilde s_R} & (\Delta^d_{23})_{RL} & (\Delta^d_{23})_{RR} \\ & & & & m^2_{\tilde b_L} & m_b(A_b-\mu\tan\beta) \\ & & & & & m^2_{\tilde b_R} \end{pmatrix}$$

Mass spectrum: LHC, LC

Assuming all $\Delta$'s small and squarks nearly degenerate, we can use mass insertion approximation (MIA):

$$\left(\delta^d_{ij}\right)_{AB} = \frac{\left(\Delta^d_{ij}\right)_{AB}}{\tilde m^2}$$



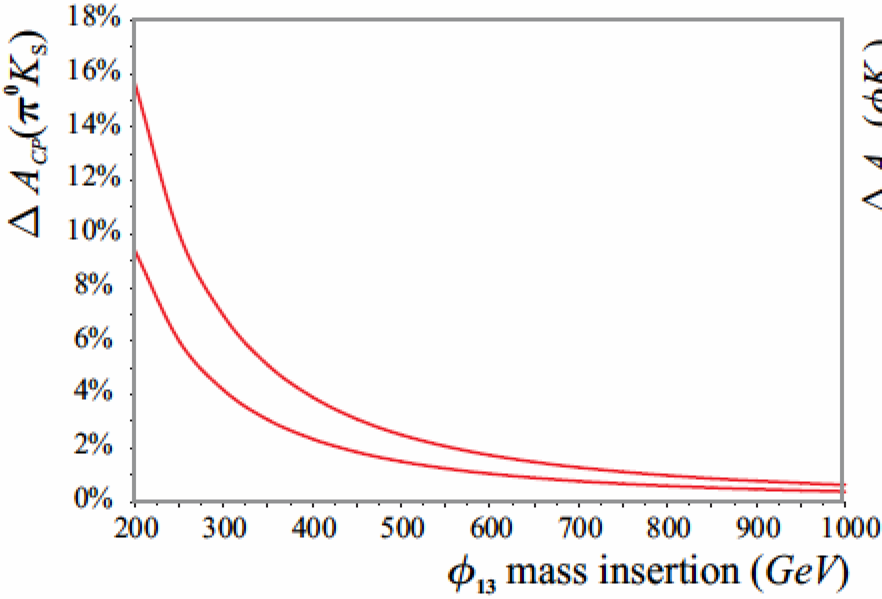

flavor mixing parametrization
$b \to s\ (23), \quad b \to d\ (13)$

Off diagonal terms can provide unique information on *CP* phases

# The scale of New Physics

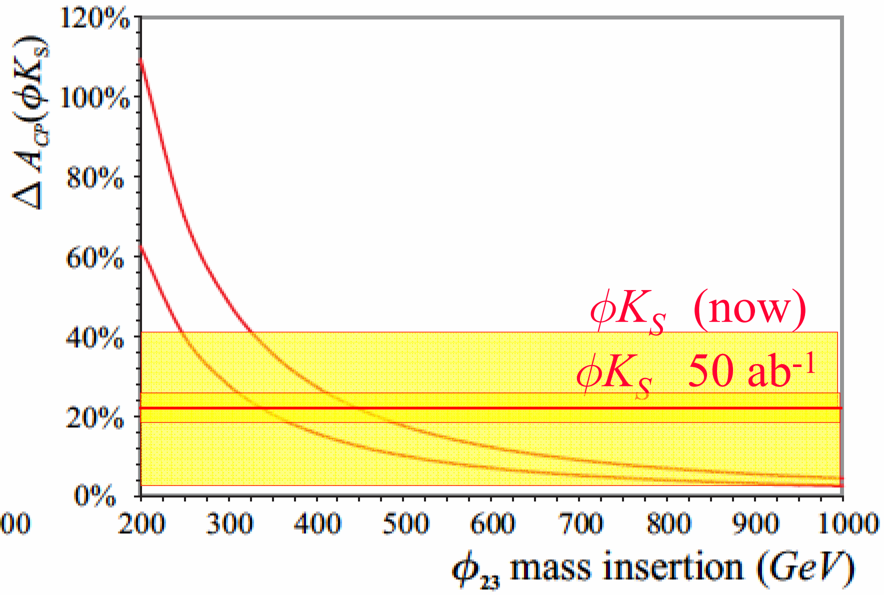
- Mass insertion approximation: model-independent ($\delta_{LL,RR}$)

$\phi_{13}$ mass insertion




$\Delta A_{CP}(J/\psi K_S\text{-}\pi^0 K_S)$

$\phi_{23}$ mass insertion

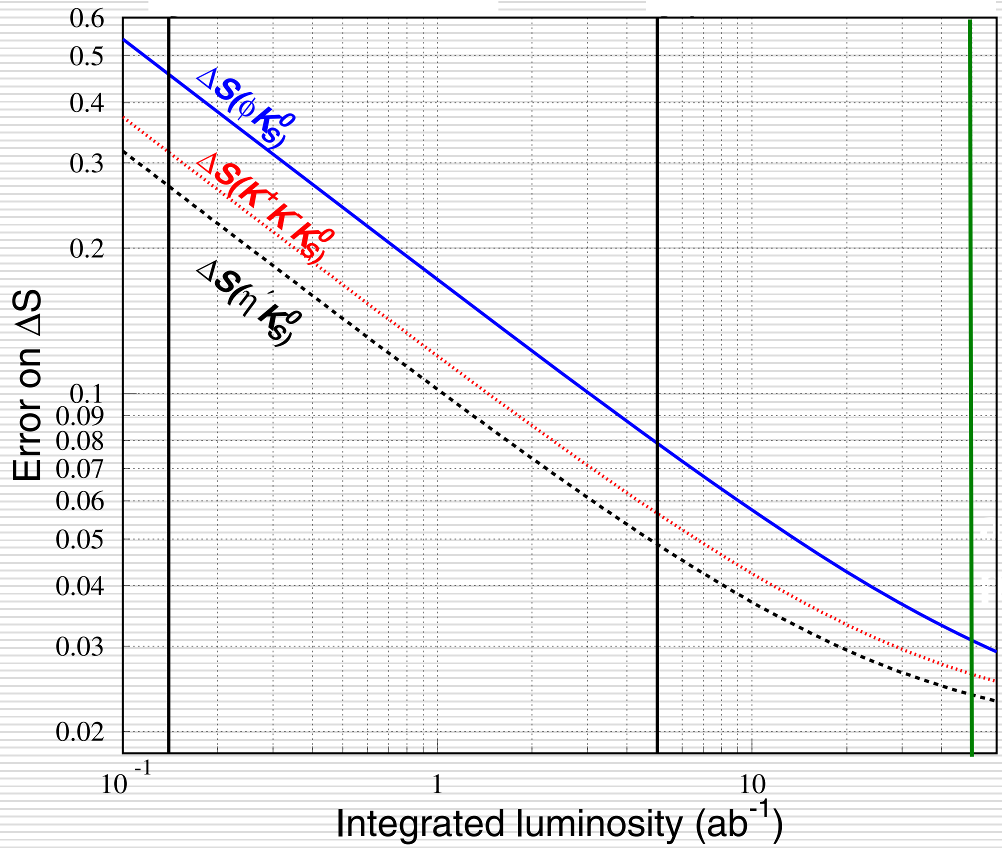



$\Delta A_{CP}(J/\psi K_S\text{-}\phi K_S)$

after Ciuchini, Franco, Martinelli, Masiero, & Silvestrini

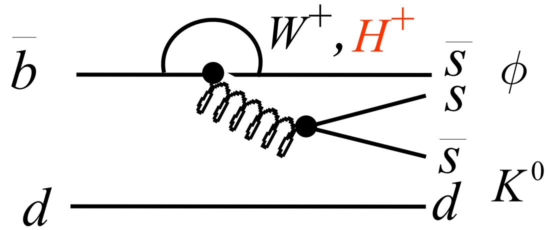
# How much integrated luminosity ?

- 50 $ab^{-1}$ is required for $CP$ asymmetry measurements in rare penguin modes and for rare branching fractions

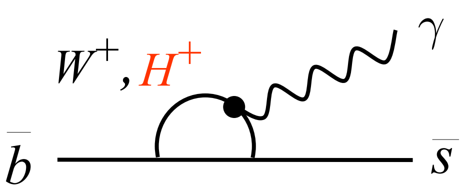


# New Physics effects in the MMSM/THDM

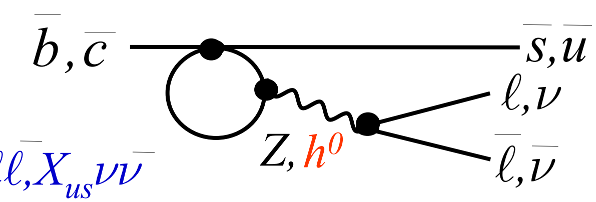
*b→sg penguins*



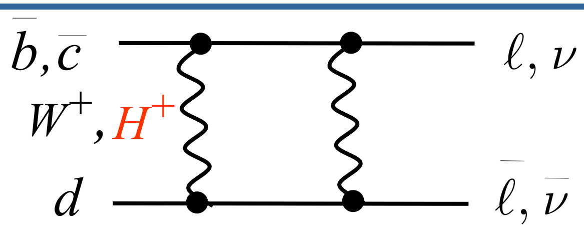

*b→sγ penguins*



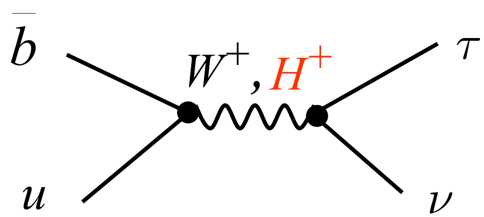

$B,D \to X_{us}\ell\bar{\ell}, X_{us}\nu\bar{\nu}$




$B,D \to \ell\bar{\ell}, \nu\bar{\nu}$

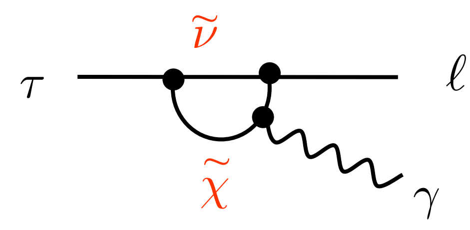



$B \to \tau\nu$



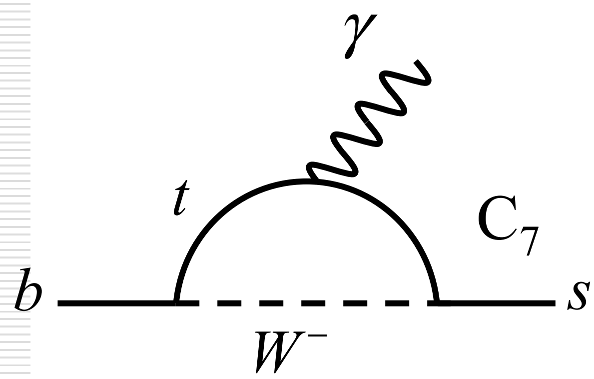

**LFV**

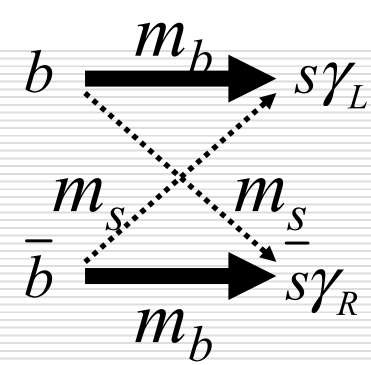
$\tau \to \ell\gamma$



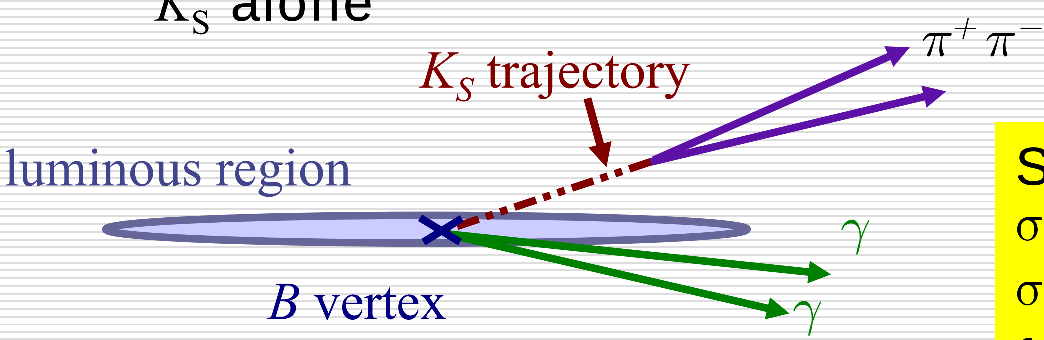
# Time dependent $CP$ asymmetry in $B \to X_s \gamma$

- Theoretically clean, but $A_{CP}$ is very small in the Standard Model, since the photon is polarized, and the final state is almost flavor specific
  $\Rightarrow$ Helicity suppresion:
  $$\sim m_s/m_b$$




- Requires vertex reconstruction with $K_S$ alone



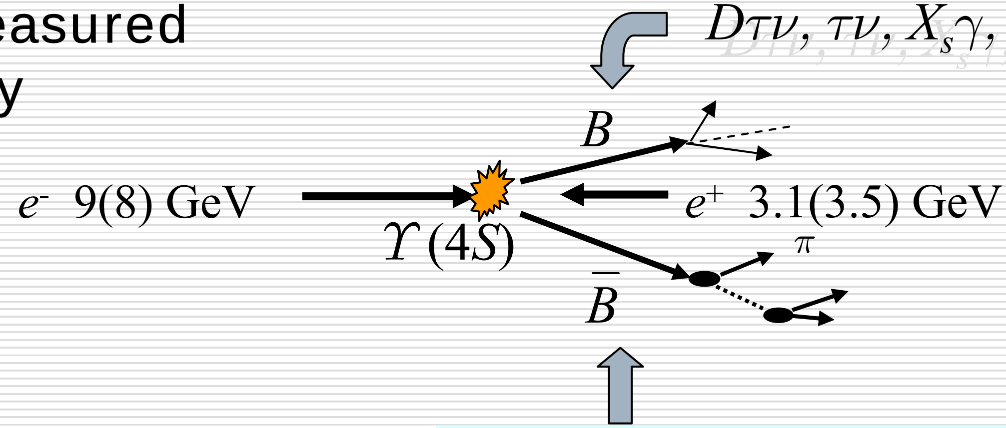

**SuperKEKB study:**
$\sigma(A_{CP}^{mix}(B \to K^*\gamma, K^* \to K_S\pi^0)) = 0.04$
$\sigma(A_{CP}^{dir}(B \to X_s\gamma)) = 0.005$
for 50 $ab^{-1}$

# Asymmetric $B$ factories provide a uniquely clean environment

- High (30%) and well-measured flavour-tagging efficiency
- $B$ decays with neutrinos

  $B \to D\tau\nu,\ \tau\nu,\ u\ell\nu,\ \ldots\ldots$

  Charged Higgs    $V_{ub}$




Coherent production: reconstructing one $B$ meson yields the four-momentum of the recoiling $B$ – a "$B$ beam"

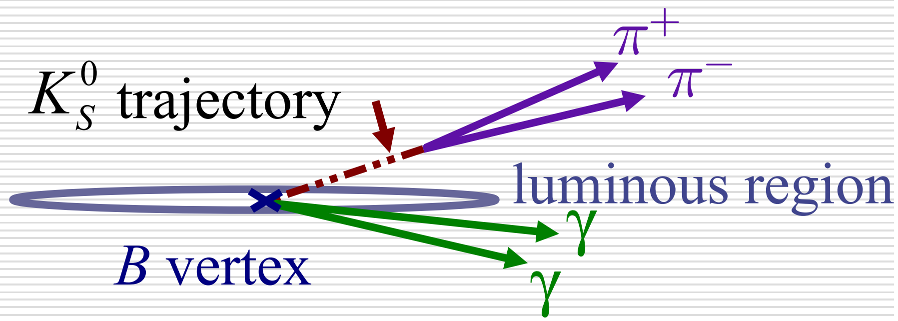
- $B$ decays with $\gamma,\ \pi^0$

  $B \to X_s\gamma,\ \pi^0\pi^0,\ \ldots\ldots$

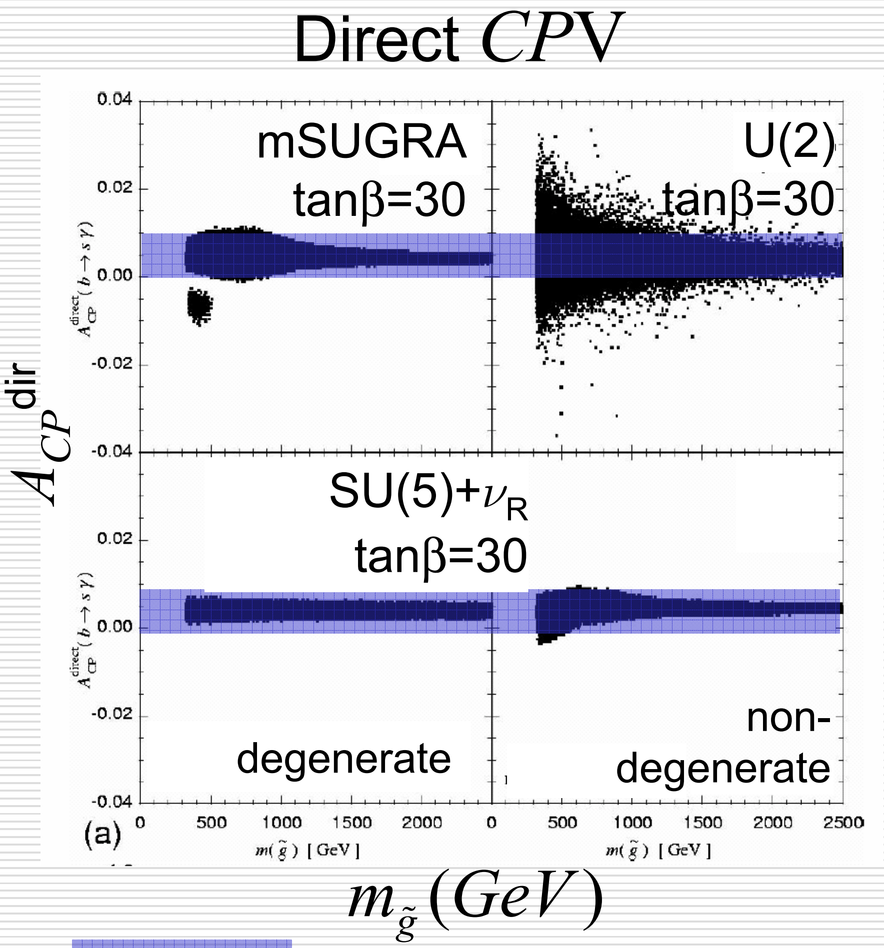
- $B$ vertex reconstruction with $K_S^0$ alone

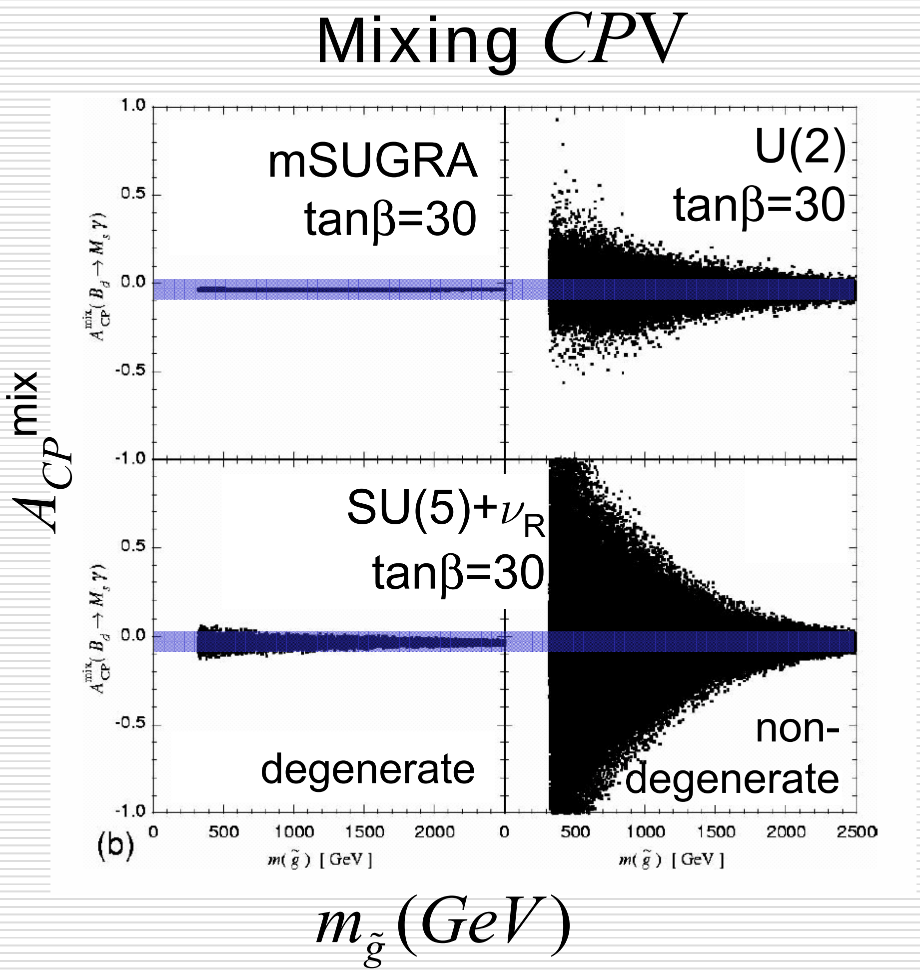
  $B \to K_S^0\pi^0,\ \to K_S^0\pi^0\gamma,\ \ldots\ldots$

  direct $CPV$    $\alpha\,(\phi_2)$ isospin analysis



# $A_{CP}^{mix}$ in four SUSY models



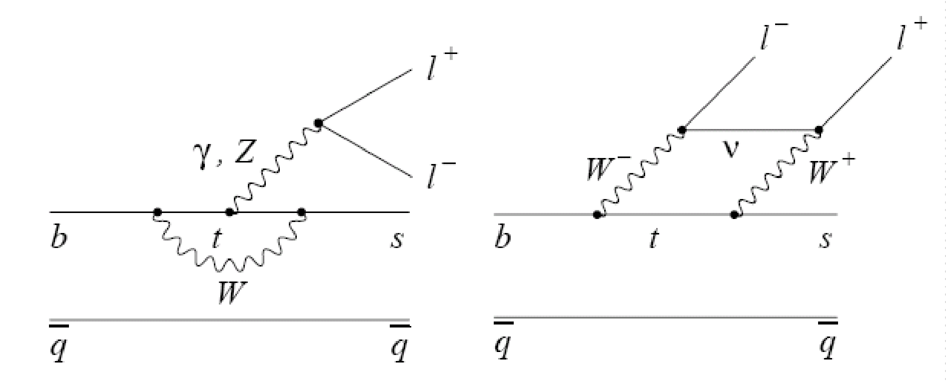



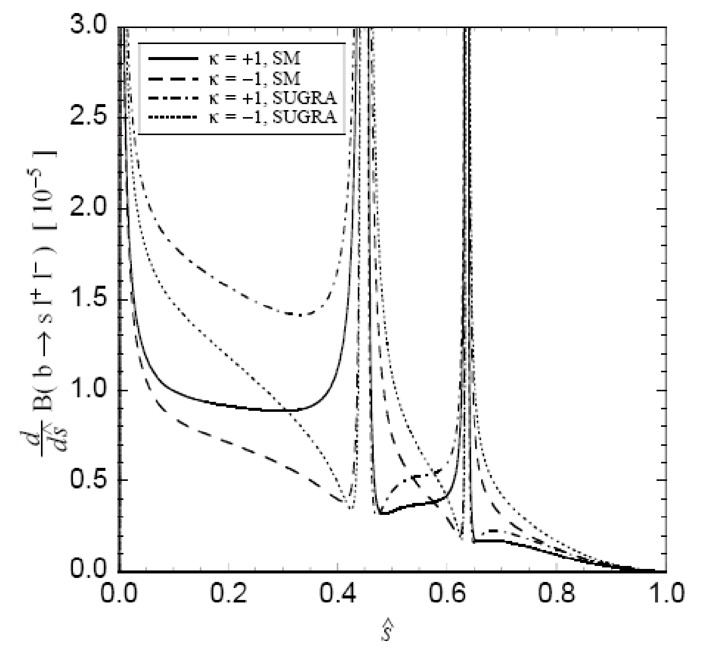

50ab$^{-1}$

Goto, Okada, Shimizu, Shindou, Tanaka

# $b \to s\ell^+\ell^-, B \to K\ell^+\ell^-, B \to K^*\ell^+\ell^-$

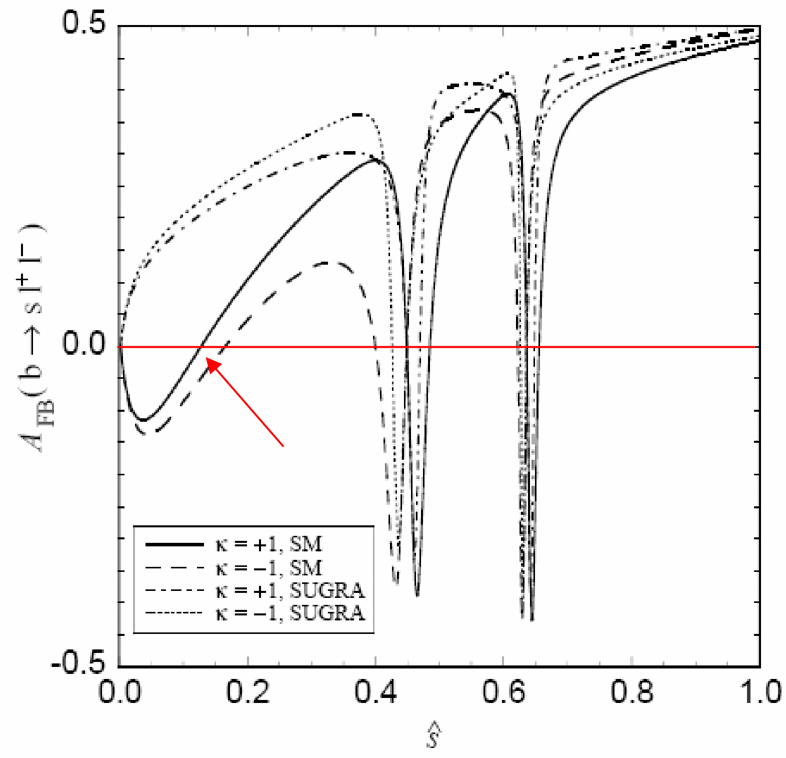
- Uniquely sensive tests of Wilson coefficients

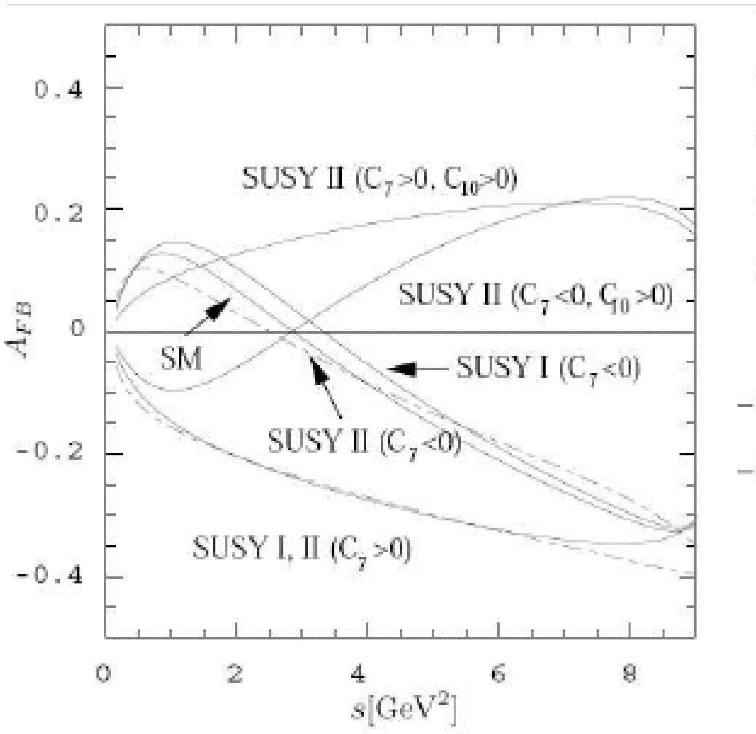


# $b \to s\ell^+\ell^-, B \to K\ell^+\ell^-, B \to K^*\ell^+\ell^-$

- Exclusive decays affected by larger uncertainties
- Inclusive decays are better: only in $e^+e^-$
- Use of ratios: AFB, ACP, $e^+e^- / \mu^+\mu^-$

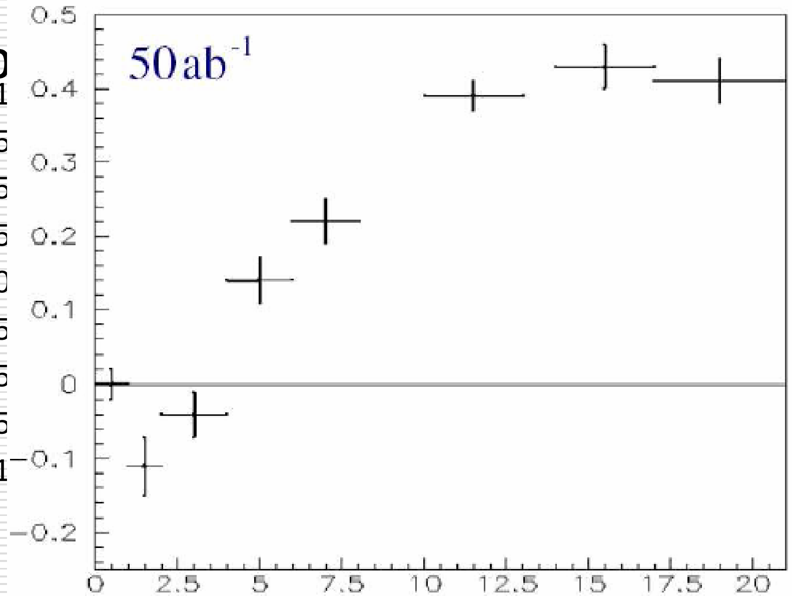


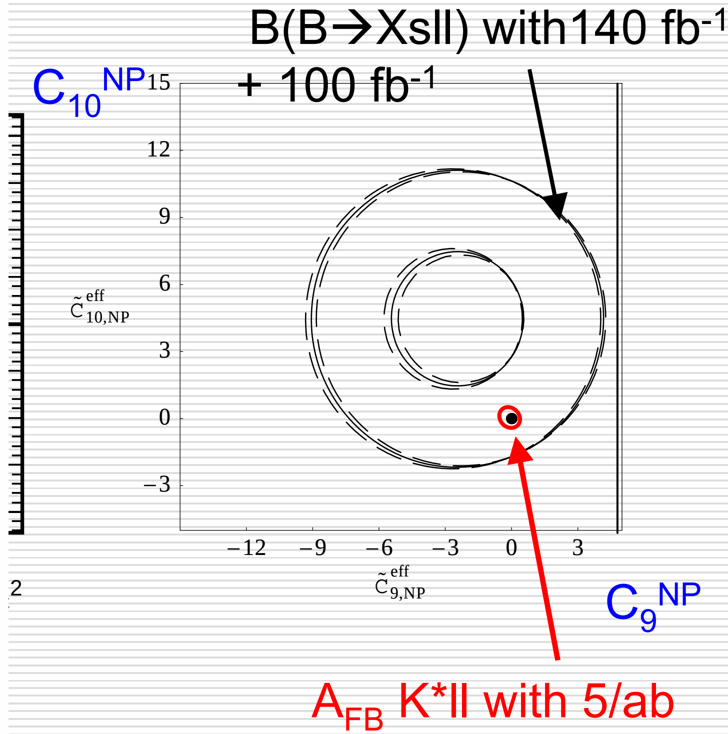



# $b \to s\ell^+\ell^-, B \to K\ell^+\ell^-, B \to K^*\ell^+\ell^-$

Precision

- Sup

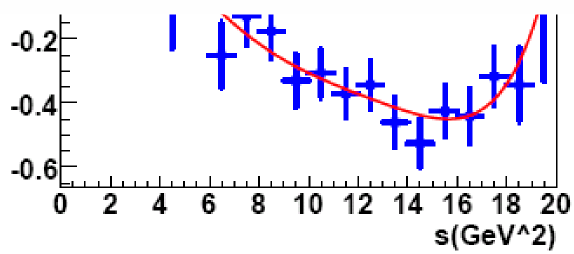



- LHC

$-A_{FB}$ vs $q^2$

SuperB factory with 50

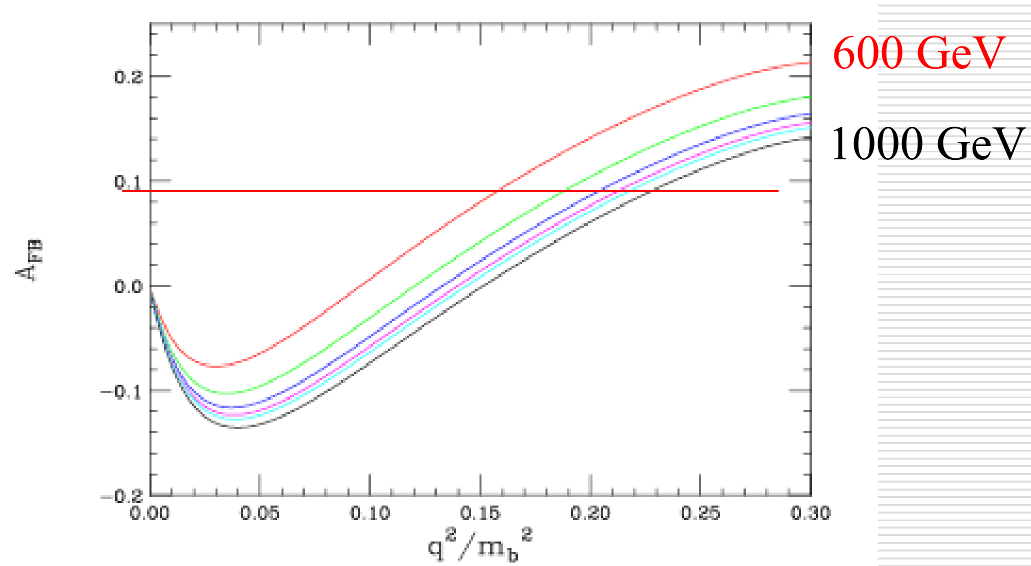



- 2 $\text{fb}^{-1}$: $(4.0 \pm 1.2)$ GeV$^2$ with
- 10 $\text{fb}^{-1}$: $(4.0 \pm 0.5)$ GeV$^2$

$\Rightarrow$ 13% error on $C_7^{\text{Eff}}/C_9^{\text{Eff}}$

# $b \to s\ell^+\ell^-, B \to K\ell^+\ell^-, B \to K^*\ell^+\ell^-$

- Extra dimension models
  - Randall-Sundrum example (Rizzo)
    - Zero crossing moves with mass of lightest KK graviton



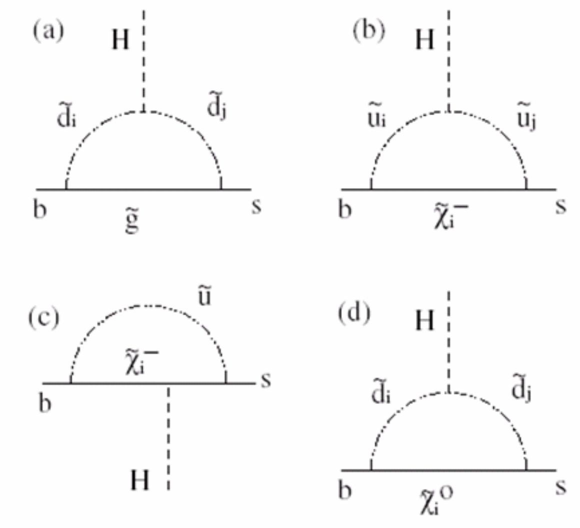
# (More) model-independent analysis of NP couplings

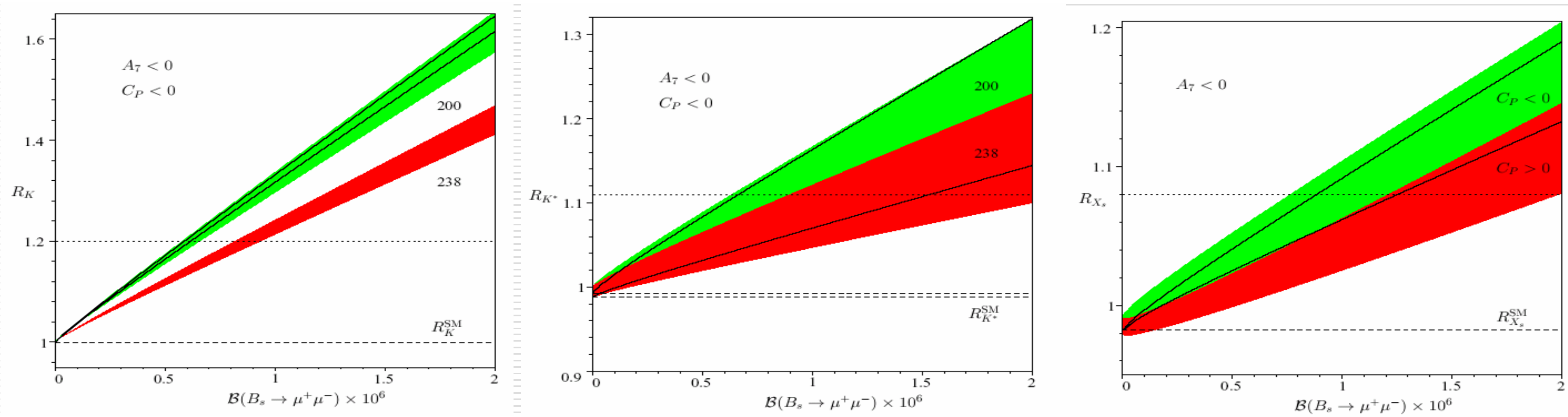
New Physics scalar and pseudoscalar couplings can result in a difference in

$$R_{K,K^*,x_s} = \frac{\mathcal{B}(B \to (K, K^*, x_s) e^+ e^-)}{\mathcal{B}(B \to (K, K^*, x_s) \mu^+ \mu^-)}$$

from unity

$R_{K,K^*,x_s}$ is correlated with the (unobserved) rate $\mathcal{B}(B_s \to \mu^+ \mu^-)$




Hiller and Krüger

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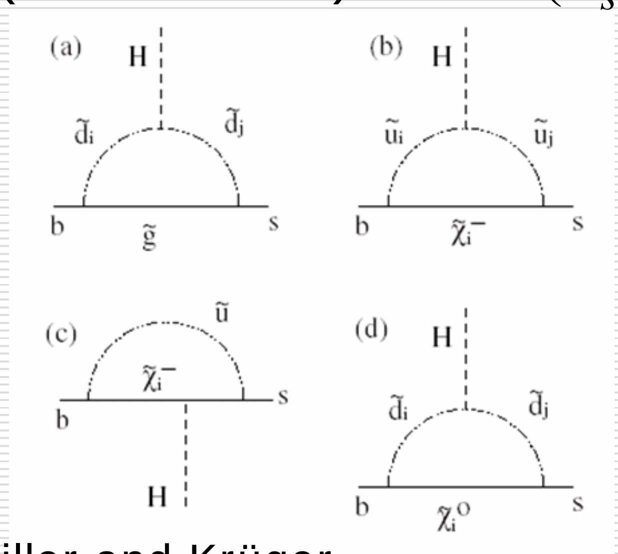
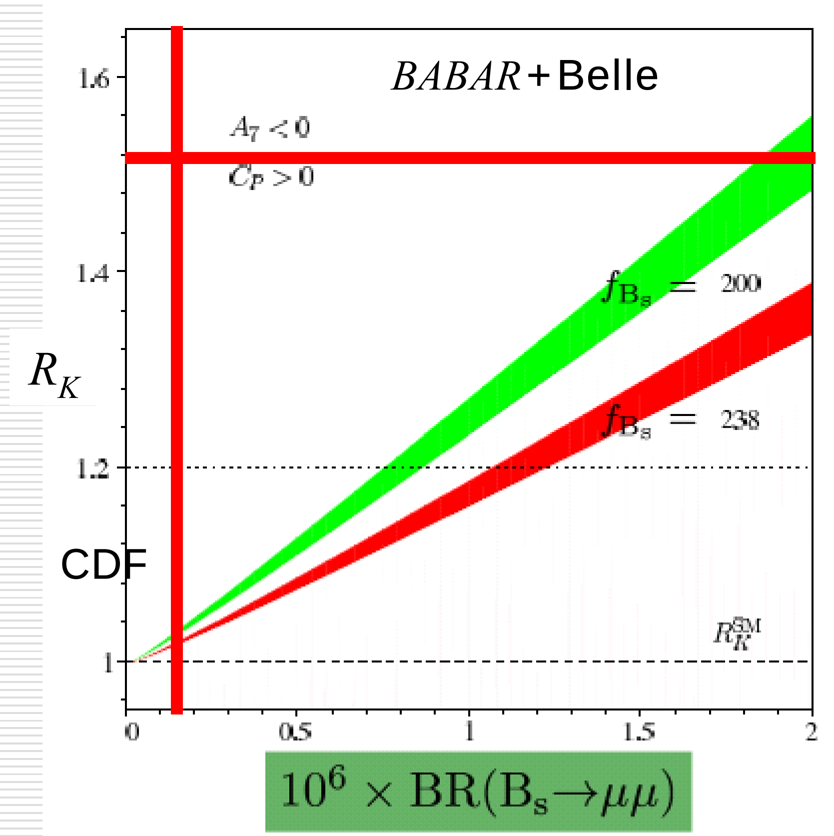


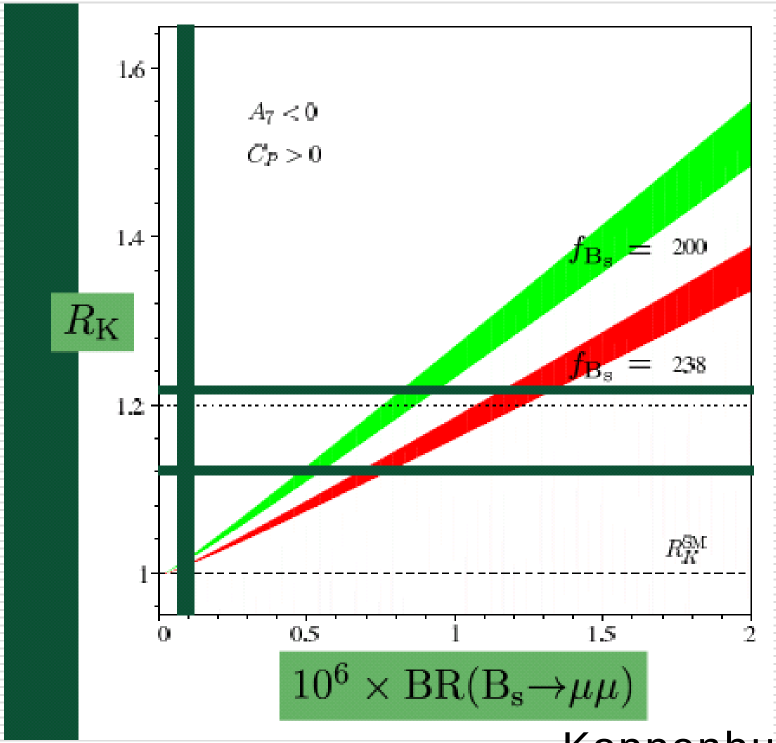

Hiller and Krüger




Koppenburg

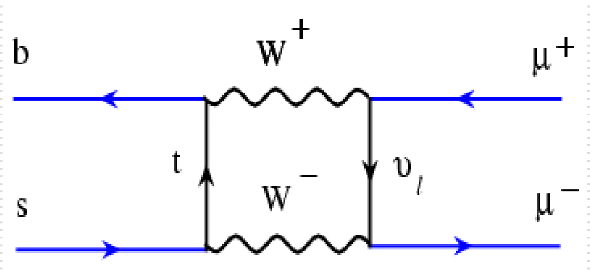
# Prospects

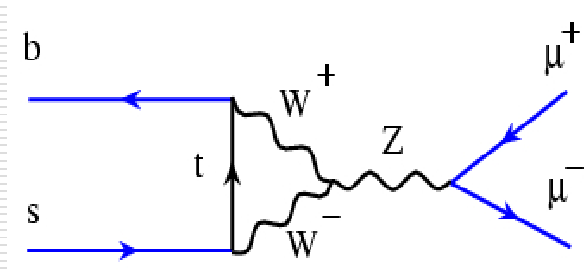
- $R_K$ can be measured very well at a Super $B$ factory
- It would appear to be difficult at LHC*b* due to difficulty with triggering on electrons, but a new study indicates that if the trigger can be modified, there is good sensitivity
- A 10% measurement of $R_K$ is possible with 2.5 $ab^{-1}$ at a Super B factory or with 2 $fb^{-1}$ at LHCb with an electron trigger

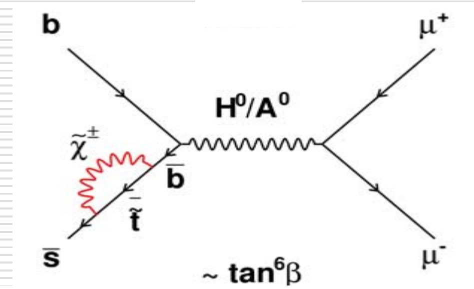



Koppenburg

# Rare $B$ decays: $B_s^0 \to \mu^+\mu^-$

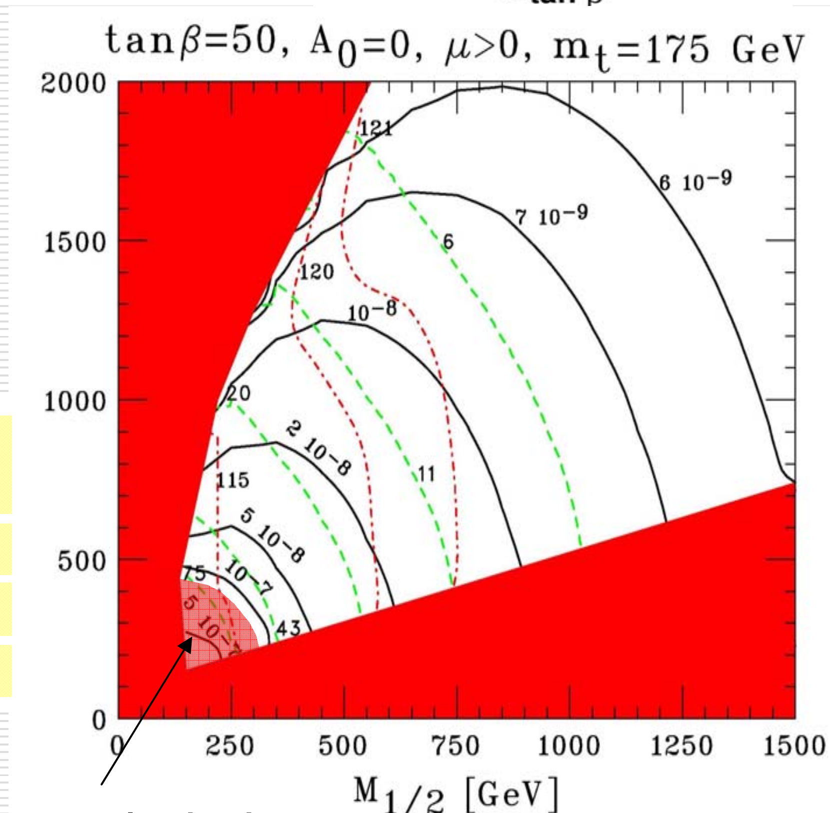



- Standard Model $\mathcal{B}$ ~ 3.5 x $10^{-9}$
  - Current limit (CDF+DØ) < 1.5 x $10^{-7}$ @ 95% CL
- Should be observed at LHC

| | 1 year | $B_s \to \mu^+\mu^-$ signal (SM) | $b \to \mu$, $b \to \mu$ background | Inclusive bb background |
|---|---|---|---|---|
| LHCb | 2 $fb^{-1}$ | 17 | < 100 | < 7500 |
| ATLAS | 10 $fb^{-1}$ | 7 | < 20 | |
| CMS (1999) | 10 $fb^{-1}$ | 7 | < 1 | |



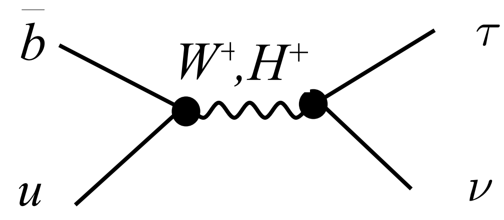

Excluded!

# $B\to\tau\nu$

Standard Model prediction:

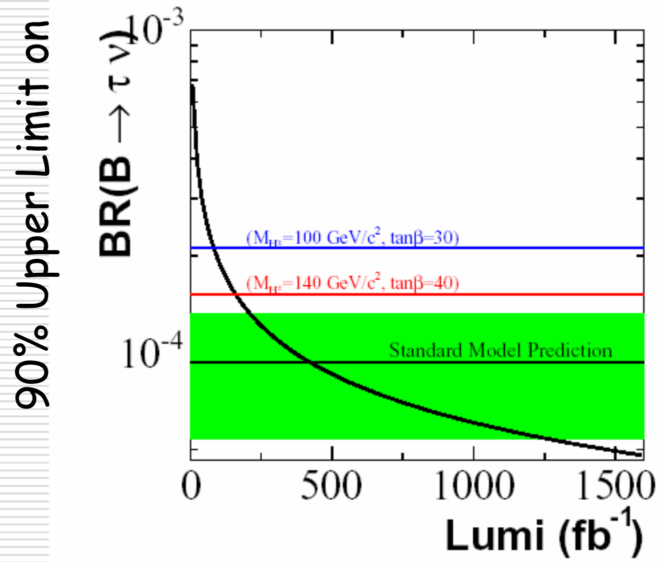
$$BF(B^+\to\tau^+\nu_\tau) = 1.2\times10^{-4}\left(\frac{f_B}{200MeV}\right)^2\left(\frac{V_{ub}}{0.004}\right)^2$$

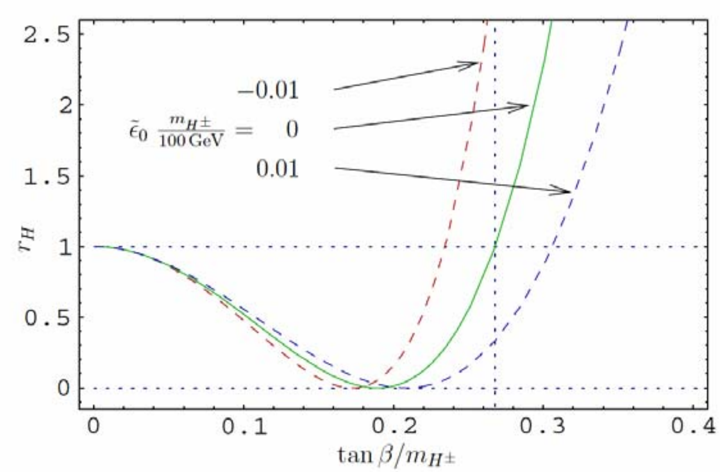
can be modified by an $H^+$ at large $\tan\beta$




$$BF(B^+\to\tau^+\nu_\tau) = 1.3^{+1.0}_{-0.9}\times10^{-4}$$

$$(< 2.6\times10^{-4} \text{ at } 90\% \text{ C.L.})$$



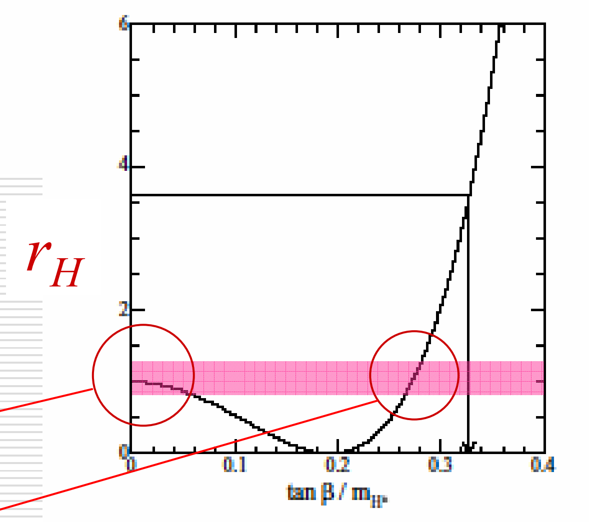



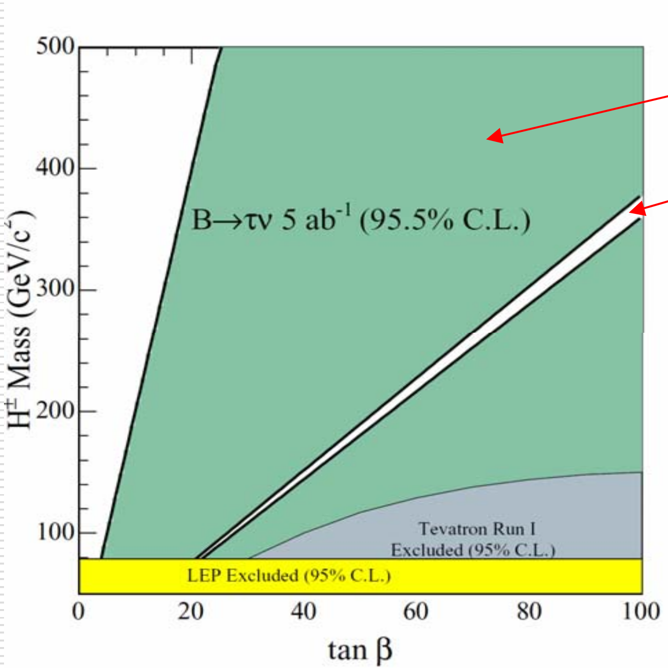
# $B \to \tau\nu$ limit on $H^+$ mass

$$\mathcal{B}(B \to \tau\nu) = \mathcal{B}(B \to \tau\nu)_{\rm SM} \times r_H,$$

$$r_H = \left(1 - \frac{m_B^2}{m_H^2}\tan^2\beta\right)^2$$

95% CL excluded region at 5ab$^{-1}$ (if $\mathcal{B}_{obs} = \mathcal{B}_{SM}$)

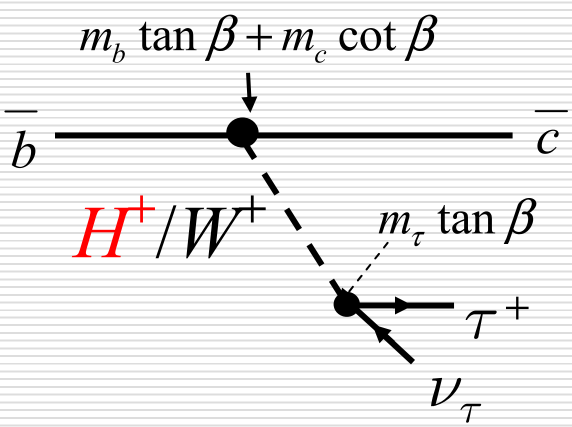


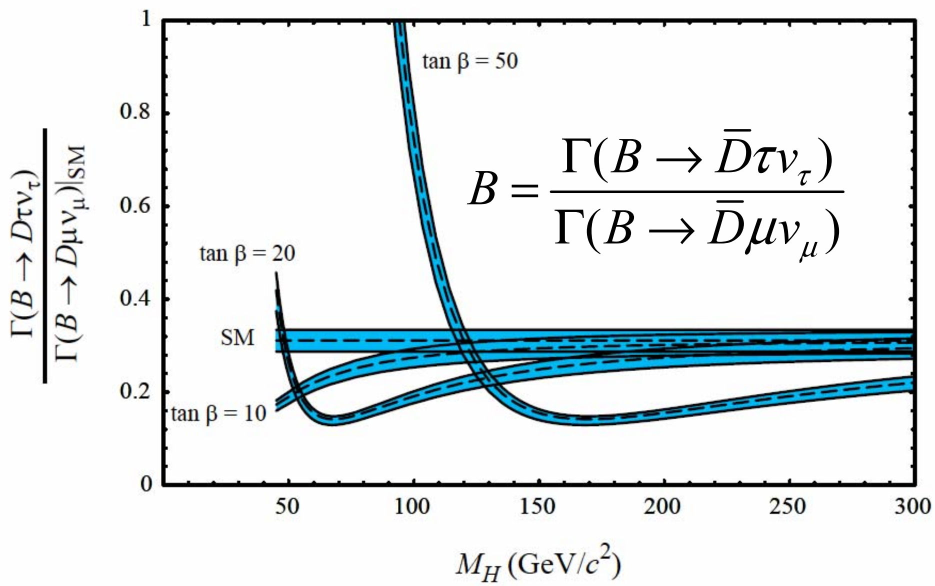




Iijima

# $B^+ \to \bar{D}^0 \tau \nu_\tau$

- Standard Model: $\mathcal{B}$= 8 x $10^{-3}$

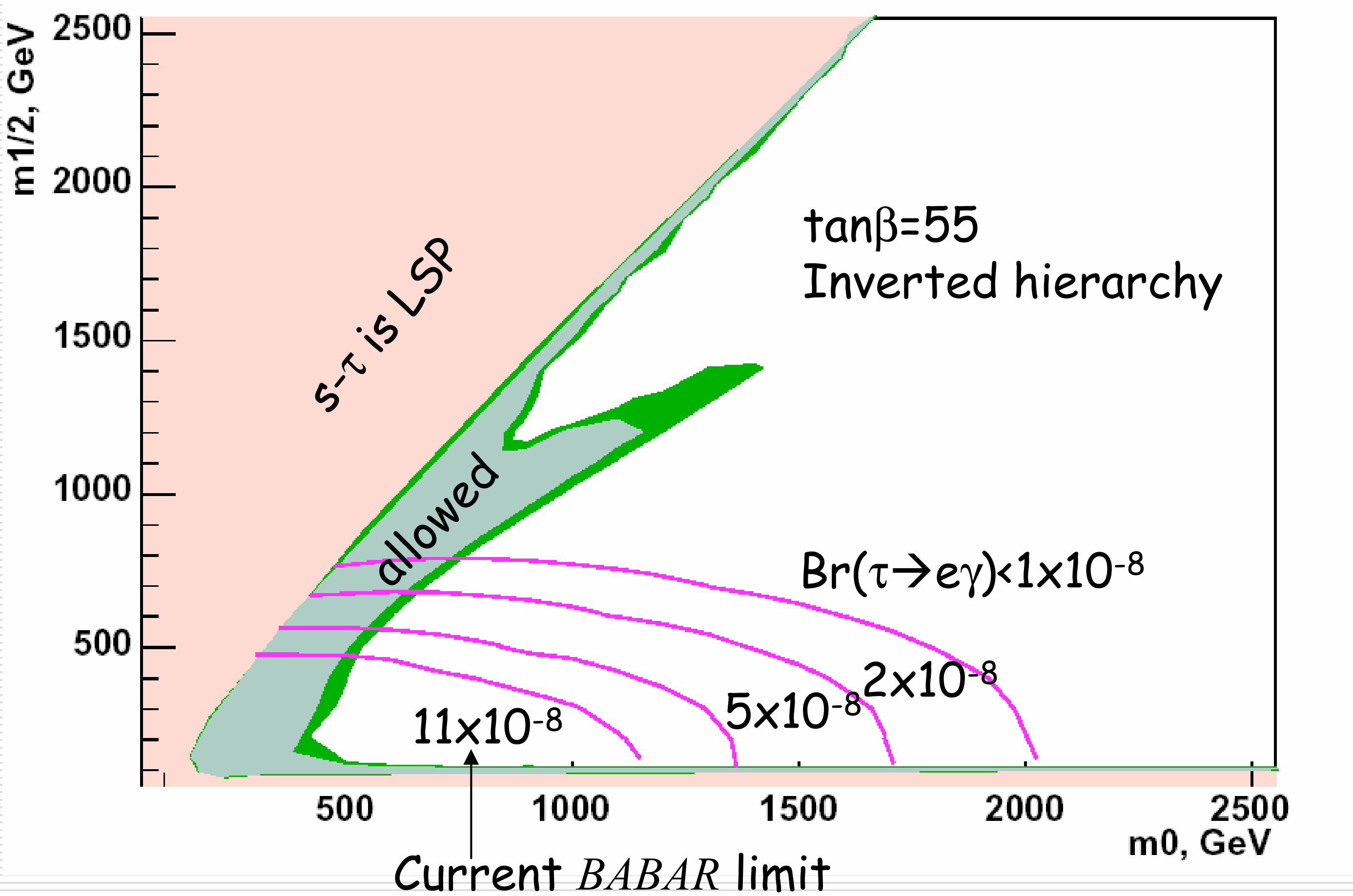



- For 50 $ab^{-1}$: $\sigma\mathcal{B}/\mathcal{B}$=2.5%

SuperKEKB

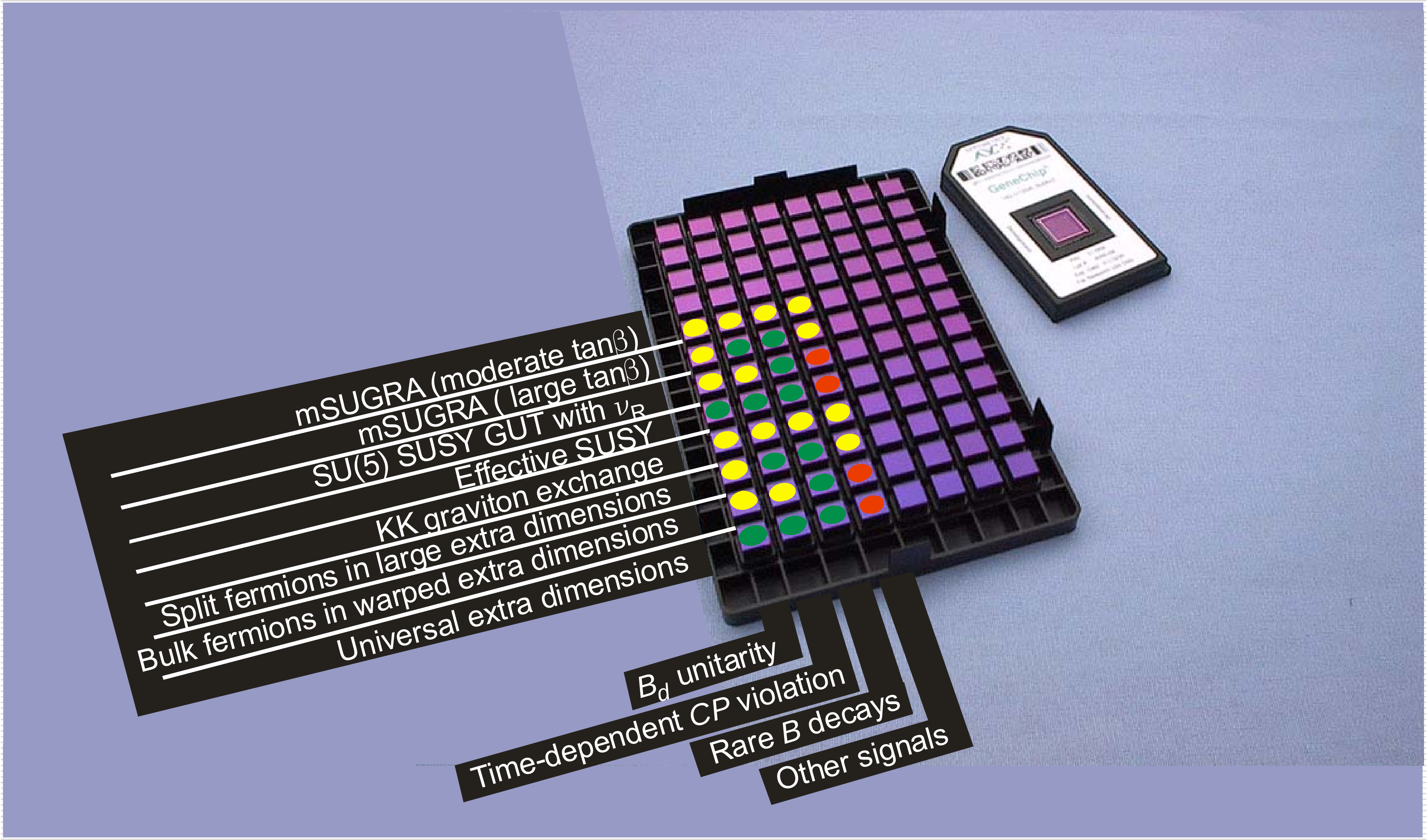
# $\tau \rightarrow \ell\gamma$ and mSUGRA



# The pattern of deviation from the SM values is diagnostic

| Model | $B_d$ Unitarity | Time-dep. $CPV$ | Rare $B$ decay | Other signals |
|---|---|---|---|---|
| mSUGRA (moderate tan $\beta$) | - | - | - | - |
| mSUGRA (large tan $\beta$) | $B_d$ mixing | - | $B \to (D)^* \tau\nu$ <br> $b \to s\ell^+\ell^-$ | $B_s \to \mu\mu$ <br> $B_s$ mixing |
| SUSY GUT with $\nu_R$ | - | $B \to \phi K_S$ <br> $B \to K^*\gamma$ | - | $B_s$ mixing <br> $\tau$ LFV, $n$ EDM |
| Effective SUSY | $B_d$ mixing | $B \to \phi K_S$ | $A_{CP}\,(b \to s\gamma)$ <br> $b \to s\ell^+\ell^-$ | $B_s$ mixing |
| KK graviton exchange | - | - | $b \to s\ell^+\ell^-$ | - |
| Split fermions in large extra dimensions | $B_d$ mixing | - | $b \to s\ell^+\ell^-$ | $K^0 \bar{K}^0$ mixing <br> $D^0 \bar{D}^0$ mixing |
| Bulk fermions in warped extra dimensions | $B_d$ mixing | $B \to \phi K_S$ | $b \to s\ell^+\ell^-$ | $B_s$ mixing <br> $D^0 \bar{D}^0$ mixing |
| Universal extra dimensions | - | - | $b \to s\ell^+\ell^-$ <br> $b \to s\gamma$ | $K \to \pi\nu\nu$ |

# flavor physics is a DNA chip for New Physics



# The role of hadronic experiments

- Measure $\mathcal{B}(K^+ \rightarrow \pi^+ \nu\bar{\nu})$ and $\mathcal{B}(K_L^0 \rightarrow \pi^0 \nu\bar{\nu})$
- Search for LFV in $\mu$ to $e$ conversion, $\mu \rightarrow e\gamma$

- Measure $B_s$ mixing
- Measure $CPV$ in $J/\psi\phi$
- Measure $\mathcal{B}(B_s \rightarrow \mu\mu)$ at SM level or above
- Measure $A_{\mathrm{FB}}$ in exclusive $b \rightarrow s\ell\ell$
- Measure $\mathcal{B}(B \rightarrow Kee)/\mathcal{B}(B \rightarrow K\mu\mu)$ ?
- Improve measurements of $\alpha, \beta, \gamma$

# The role of a Super $B$ Factory (if one exists)

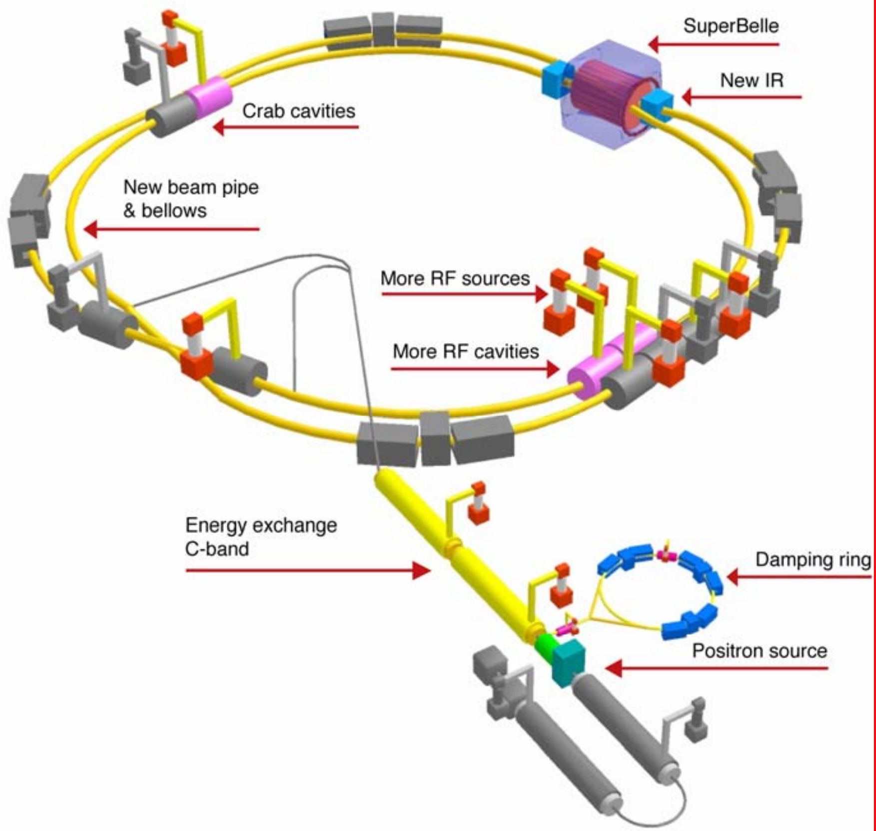
- Measure $\alpha, \beta, \gamma, V_{ub}, V_{cb}, \Delta m_d$ to the limit of theoretical precision
- Measure $CPV$ in $b \to sss$ decays to sufficient precision to ascertain a pattern
- Measure $A_{\mathrm{FB}}$ in inclusive and exclusive $b \to s\ell\ell$ decays
- Measure $\mathcal{B}(B \to Kee)/\mathcal{B}(B \to K\mu\mu)$
- Measure $B \to \tau\nu$
- Search for right handed couplings in $b \to s\gamma$
- Search for NP effects in $B \to VV$ decay
- Search for $CPV$ in $b \to s\gamma$ and $b \to s\ell\ell$ decays
- Search for LFV: $\tau \to \mu\gamma$ decay
- Search for charged Higgs in $B \to D\tau\nu$ decay

# Will there be a Super $B$ Factory?

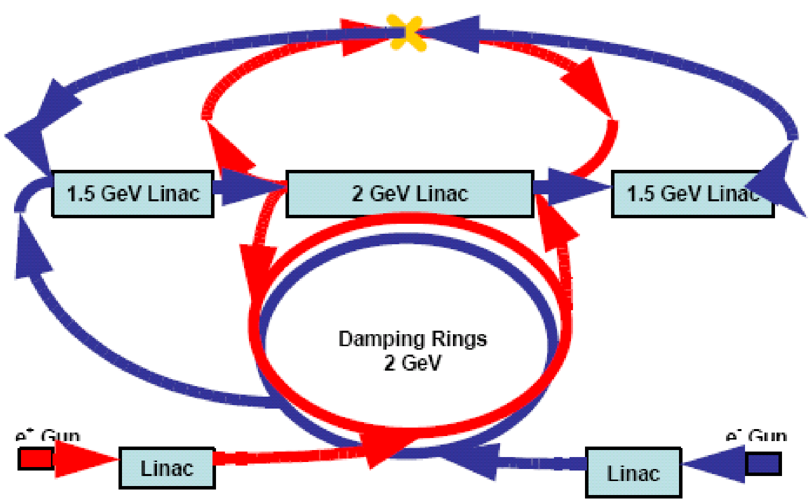
- Potential upgrades of PEP-II, KEKB
  - SuperPEP-II design aimed at $\mathcal{L}$=7 x $10^{35}$
    - SLAC is now out of the local HEP accelerator business
  - SuperKEKB design has $\mathcal{L}$=4 x $10^{35}$ with 50 $ab^{-1}$ by 2020
    - Proposed to ministry; awaits a decision
- Another approach is being considered
  - Raimondi has suggested revisiting the recirculating linear collider scheme proposed in the '80's by Amaldi and Coignet, in the light of modern accelerator physics techniques
  - The luminosity goal is $\mathcal{L}$~$10^{36}$
  - The idea appears quite promising
    - Linear collider-related R&D over the past two decades has addressed many of the technical issues
  - INFN is actively considering an LCSuper*B* based on an international collaborative effort
  - A workshop was held on Nov 11/12 at Frascati

http://www.lnf.infn.it/conference/superbf05/

# One and one half Super B Factory concepts




Conceptual design of INFN
Super*B* Factory
(Raimondi, Biagini, Seeman, ...)



# Conclusions

- Heavy flavor physics, in all its guises, can play a significant role in deepening our understanding of the Standard Model, and, should New Physics be found at LHC, it provides unique tools for probing the flavor structure of the new particles (squarks?)
- If the scale of New Physics is < 1 TeV, as motivated by our current understanding of the Higgs mechanism, there will be measurable effects in the heavy quark/heavy lepton sector
  - LHC will yield information on masses and couplings of new particles by direct production
  - Information on squark off-diagonal couplings requires detailed studies of heavy quark decays at Super $B$ Factories or dedicated hadronic experiments
- The effects of new physics loops can be seen in rare decay branching fractions and kinematic distributions and in $CP$-violating asymmetries in channels with very small branching fractions

# Conclusions - II

- The new generation of experiments at hadronic accelerators will doubtless extend the fruitful programs of the current $B$ Factories
- It is important that other approaches be followed as well:
  - A Super $B$ Factory can, in the next decade, provide unique high precision measurements as well as results complementary to those of hadronic experiments
  - Rare $K$ decay experiments
  - Searches for lepton flavor violation
- Flavor physics has a glorious history and remains relevant as a tool for understanding New Physics at the LHC
- A year-long series of workshops on flavor physics in the LHC era is currently underway at CERN. Let us hope that this effort can contribute to a sustained future for flavor physics over the next decade or more