Moriond QCD
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Flavour physics in the LHC era

An introduction

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Contents

1. The flavor structure of the Standard Model

2. Tests of the Standard Model: where do we stand

3. Flavour Physics beyond 2009 : where to go ?

The flavour structure of the Standard Model

M. Kobayashi, T.Maskawa, 1974:
theoretical mechanism for
CP-violation in the SM

$$\begin{pmatrix} u \\ d \end{pmatrix} \quad \begin{pmatrix} c \\ s \end{pmatrix} \quad \begin{pmatrix} t \\ b \end{pmatrix}$$

Idea: nontrivial superposition of non-interacting particles
forms flavor eigenstate that interacts weakly

$$\begin{pmatrix} e \\ \nu_e \end{pmatrix} \quad \begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix} \quad \begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix}$$

$$L_{\text{int}} = \frac{g_2}{\sqrt{2}} \left(\bar{u}_L \, , \; \bar{c}_L \, , \; \bar{t}_L \right) \gamma^\mu \hat{V}_{CKM} \begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix} W_\mu^+ + h.c.$$

The flavour structure of the Standard Model

Weak eigenstates of quarks are "rotated" combination of flavour states

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \underbrace{\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}}_{V_{CKM}} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

CKM matrix

Wolfenstein parametrization

$$V_{CKM} = \begin{matrix} & d & s & b \\ u & 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ c & -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ t & A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{matrix} + O(\lambda^4)$$

4 parameters: λ, A, ρ, η

$$\lambda = |V_{us}| + O(\lambda^7) = 0.2272 \pm 0.0010$$

↓

the Cabibbo angle

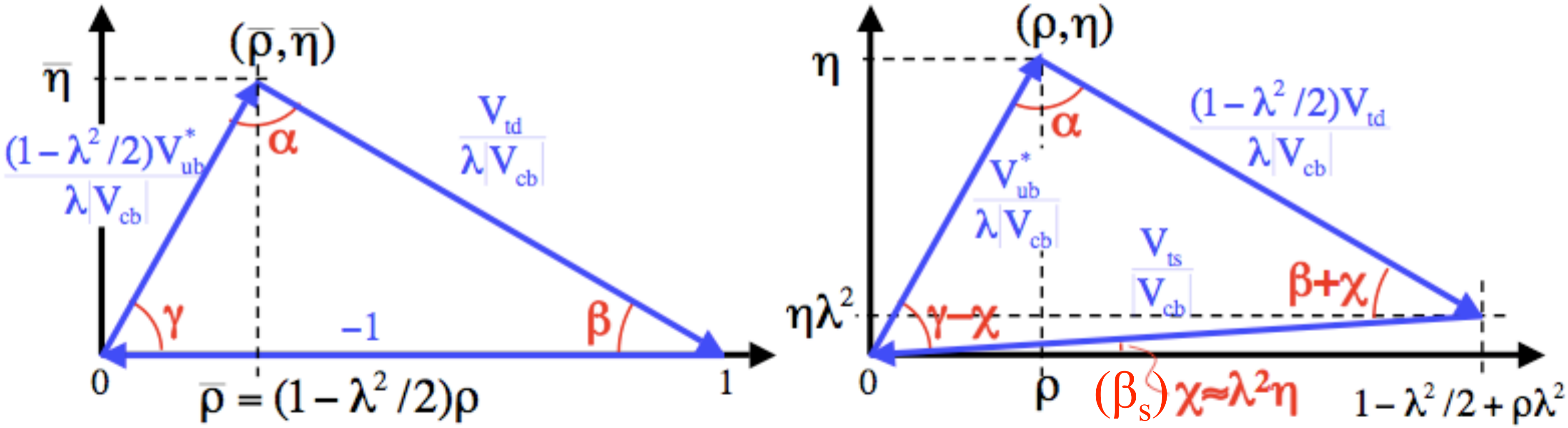
(*Measured by* KLOE)

CP violation arises from the presence of phase factors in some of the *V*'s, i.e. from a non-vanishing value of η.

CKM Unitarity Triangles

b d **t u**

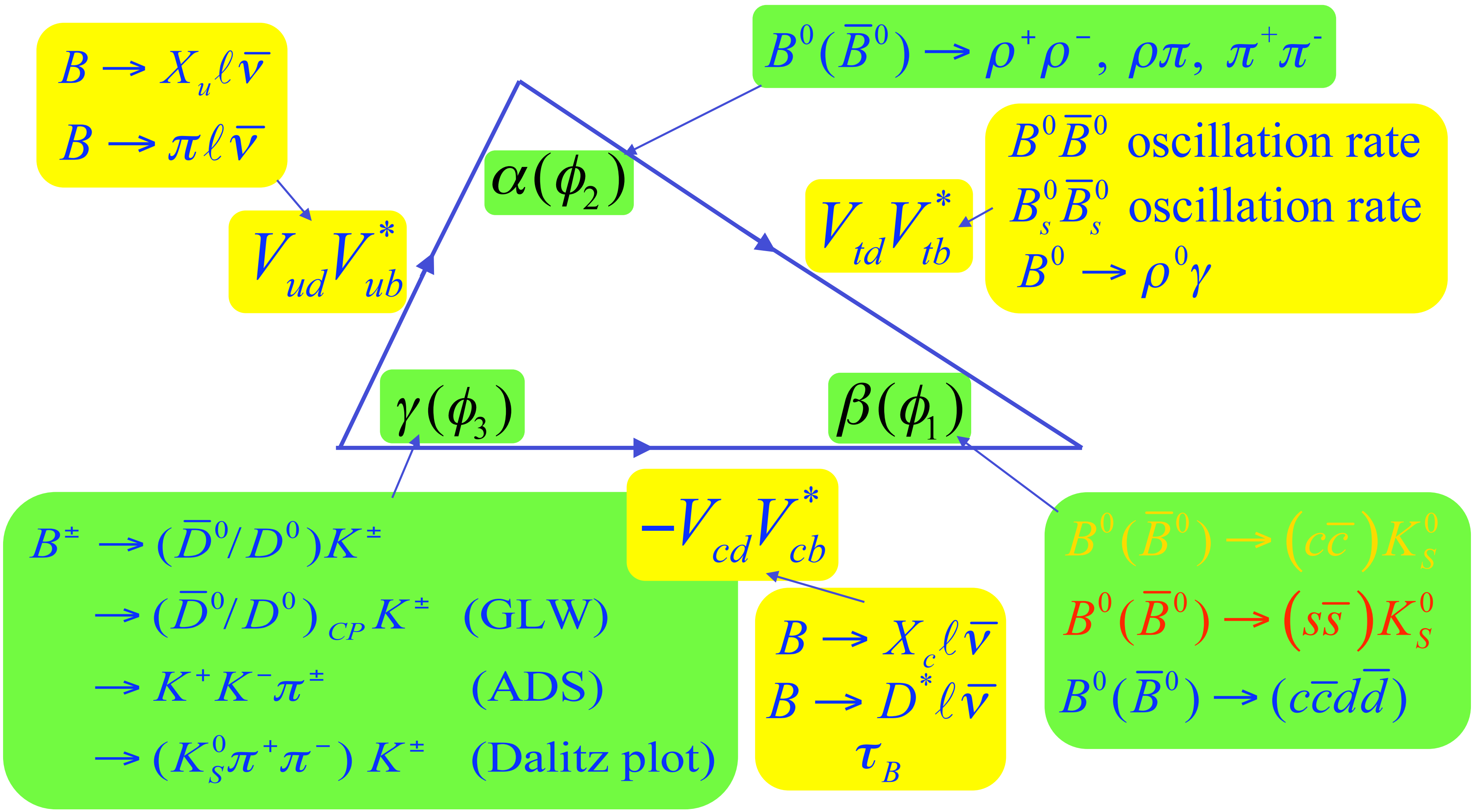
$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0 \quad \leftarrow \text{keep terms up to } O(\lambda^5) \rightarrow \quad V_{tb}V_{ub}^* + V_{ts}V_{us}^* + V_{td}V_{ud}^* = 0$$



$$\arg(V_{ub}) = -\gamma, \quad \arg(V_{td}) = -\beta, \quad \arg(V_{ts}) = \chi + \pi$$

Tests of the standard model: where do we stand ?

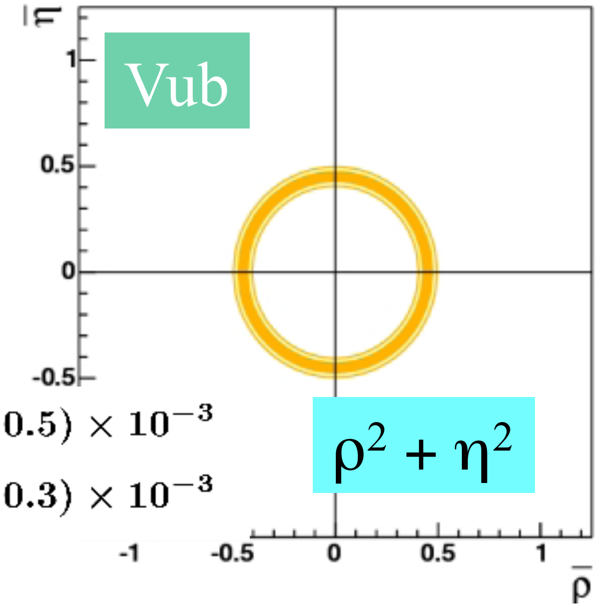
Overconstraining the Unitarity triangle



Precise determination of parameters through B-decays study.

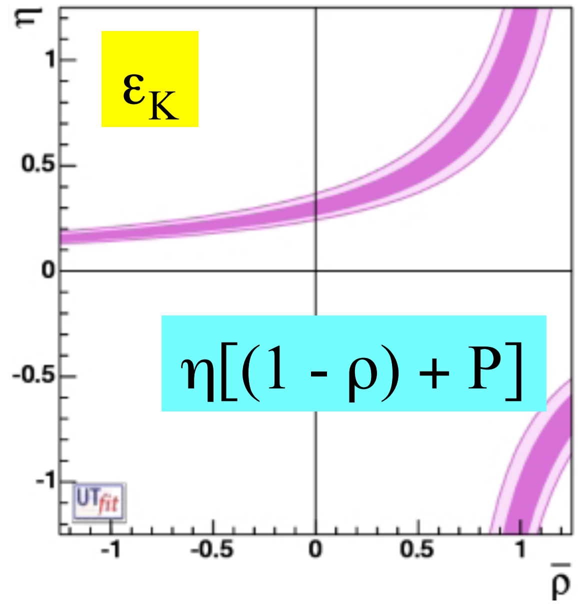
Overconstraining the Unitarity triangle

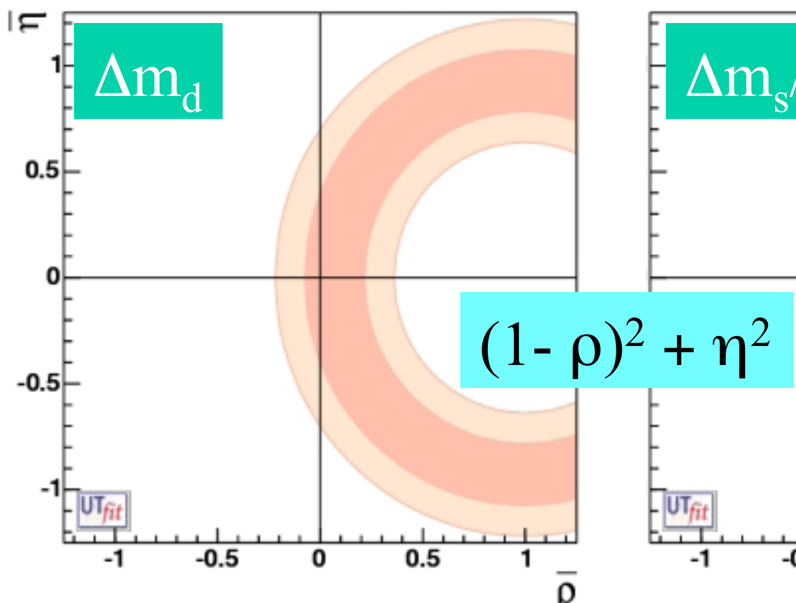
(Plots from Utfit)

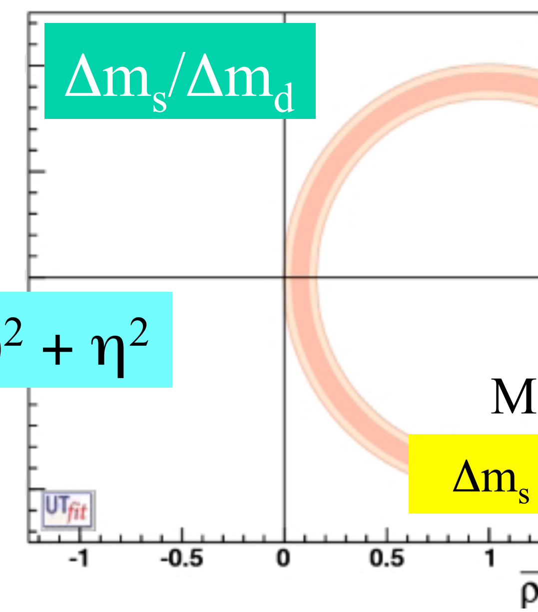


Exclusive: $V_{ub} = (3.7 \pm 0.2 \pm 0.5) \times 10^{-3}$

Inclusive: $V_{ub} = (4.3 \pm 0.2 \pm 0.3) \times 10^{-3}$





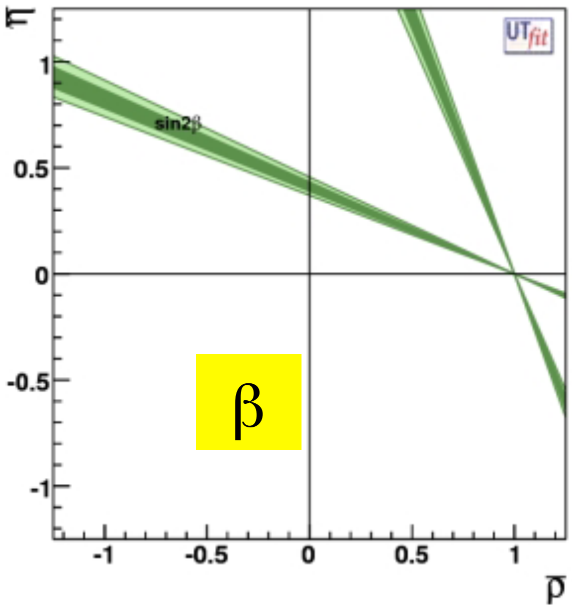


Measurement from CDF and DO:

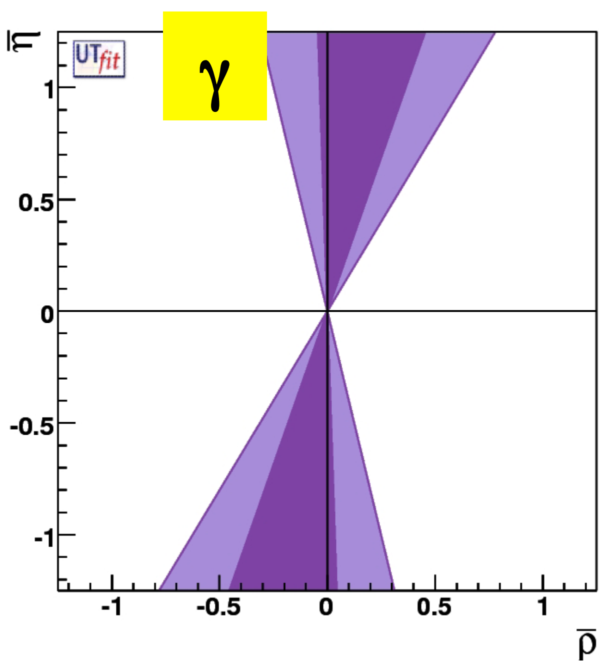
$\Delta m_s = 17.77 \pm 0.10(\text{stat}) \pm 0.07(\text{syst})\ ps^{-1}$

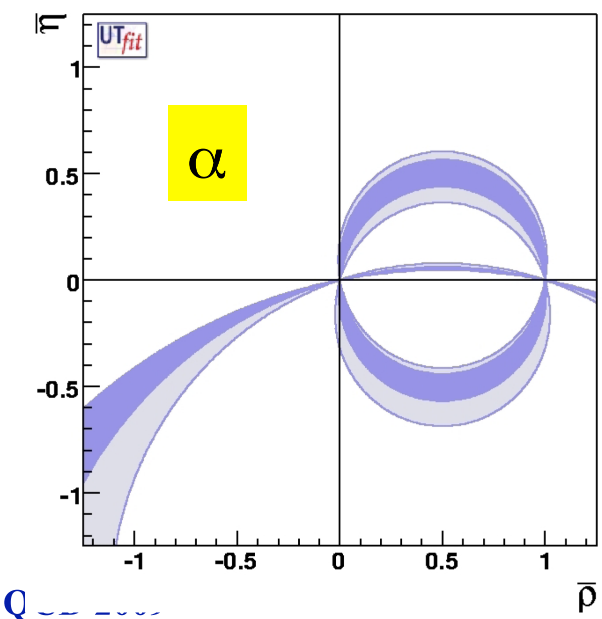
Overconstraining the Unitarity triangle

(Plots from Utfit)



β most precise measured angle
(sin2β masured at B-factories:
sin2β= 0.668 ± 0.028)





Overconstraining the Unitarity triangle

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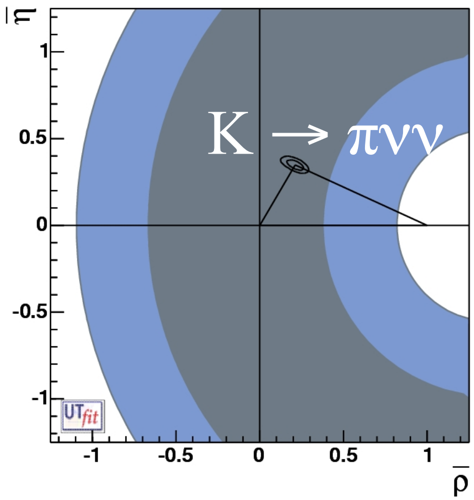
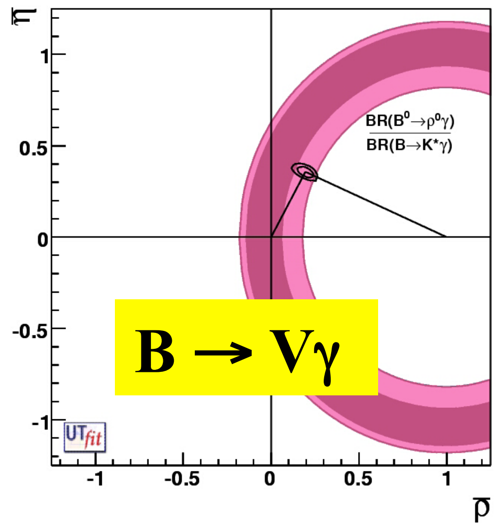
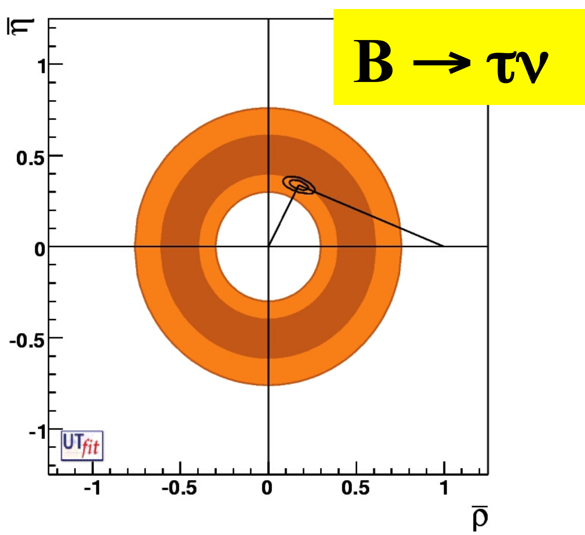






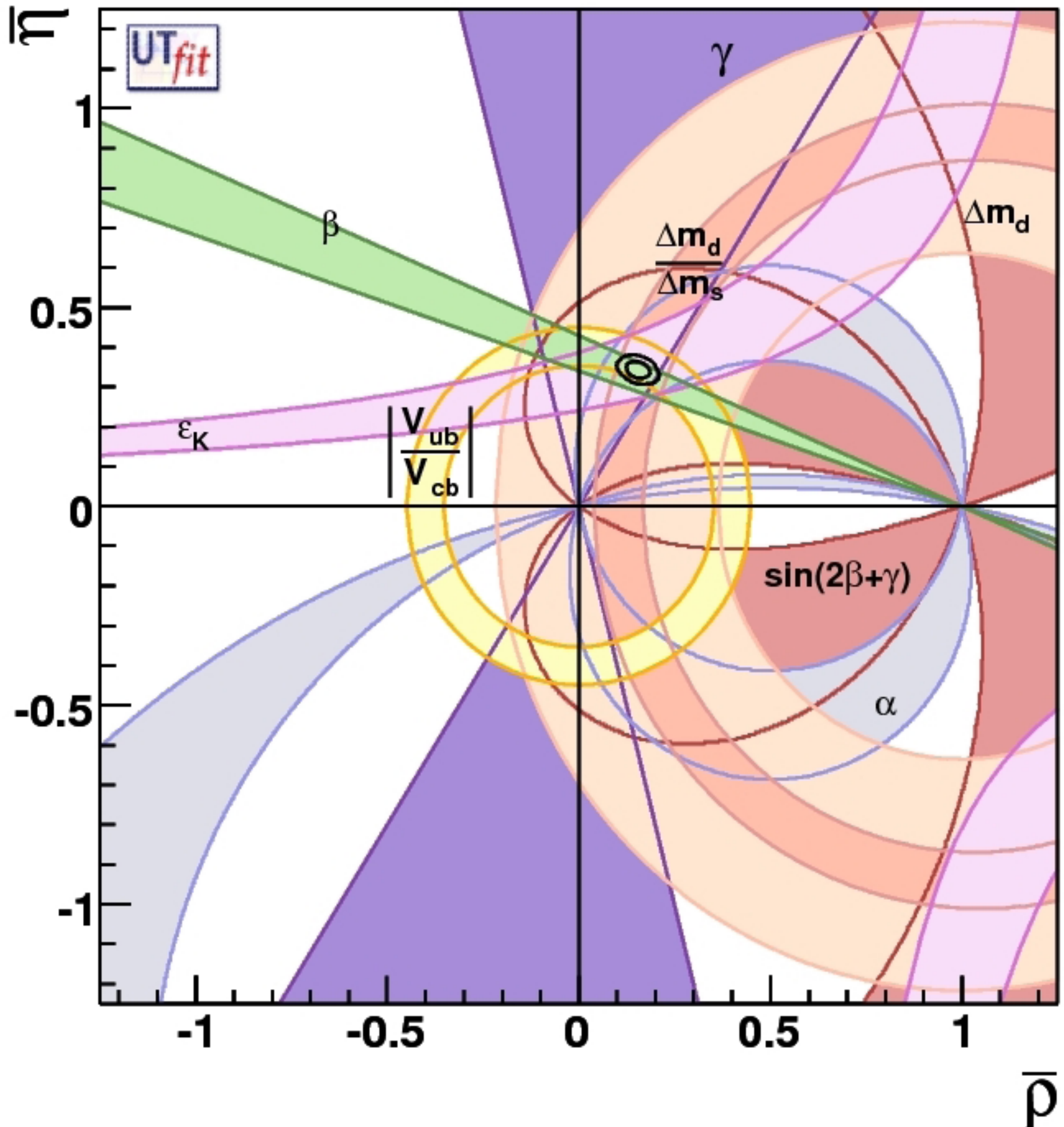
BELLE (2008) :

$$\mathcal{B}(B \rightarrow \tau\nu) = (1.65^{+0.38+0.35}_{-0.37-0.37}) \times 10^{-4}$$

BaBar (2008) :

$$\mathcal{B}(B \rightarrow \tau\nu) = (1.8 \pm 0.8 \pm 0.1) \times 10^{-4}$$

Current status of CKM parameters



λ= 0.2258±0.0011

A = 0.83±0.02

$\bar{\rho}$ = 0.154±0.022

$\bar{\eta}$ = 0.342±0.014

Accuracy of angles is limited by experiment:

$\alpha \sim \pm 7°$

$\beta < \pm 1°$

$\gamma \sim \pm 13°$

χ measured by Tevatron

Accuracy of sides is limited by theoretical uncertainty (*extraction of Vub , lattice calculation of ξ²,..)*

Where is Flavour Physics now

- The PEP-II/*BABAR* and KEKB/Belle B-Factories, together with CLEO-*c* and recent *K* decay experiments, have reached the precision measurement regime for many parameters
- CDF and DØ at Tevatron Run II are producing beautiful results on B_s mixing, rare decays and *b*-baryon studies.

  The experiments CDF and DØ will each have collected ~ 8 fb^{-1} by 2010 with well understood detectors

Also results on D^0 oscillations, charm and beauty spectroscopy, ….and many others

→ *talks of today*

The flavour stage

- ☆ All measurements related with electroweak quark transitions are coherent with the CKM picture of the Standard Model
- ☆ **Overconstrained tests of the CKM matrix to the level of precision warrented by theoretical uncertainties** *(will theory be able to calculate hadronic parameters with 1% precision in few years?)*
- ☆ **The CKM phase is consistent with being the source for all observed CP-violating phenomena in the laboratory.**

There must, however, be additional sources of CP violation

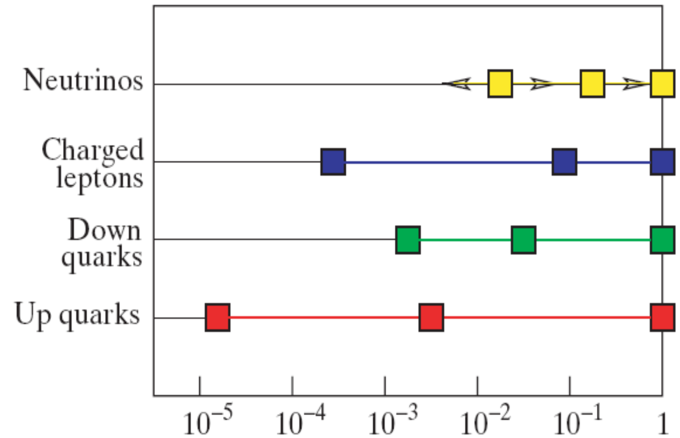
The SM fails to explain the cosmic matter-antimatter asymmetry

↓

Need New Physics (NP) beyond the SM

The flavour problems

➔ The fermion masses:
why 6 orders of magnitude?



Mass hierarchies (from *hep-ph/0603118*). The heaviest fermion of a given type has unit mass.

➔ Why so many physical parameters
(6 masses,3 mixing angles,1 CP phase)

➔ Absence of FCNC in the SM (explained by GIM mechanism and structure of CKM mixing matrix)

NP flavour blind or must keep FCNC very small

Flavour Physics beyond 2009 :

where to go

The flavour stage

Goal of heavy flavour physics is now shifting from understanding of CKM in the Standard Model (SM)

to

probing new physics Beyond the Standard Model (BSM) through virtual effects in loops.

After all CHARM and TOP quarks were first seen not because produced directly, but via their effects in FCNC processes in K and B physics respectively

Strengths of indirect approach

Can in principle access higher scales and therefore see effect earlier:

Third quark family inferred by Kobayashi and Maskawa (1973) to explain small CP violation measured in kaon mixing (1964), but only directly observed in 1977 (b) and 1995 (t)

Neutral currents (ν+N→ ν+N) discovered in 1973, but real Z discovered in 1983

Can in principle also access the phases of the new couplings:

NP at TeV scale needs to have a "flavour structure" to provide the suppression mechanism for already observed FCNC processes → once NP is discovered, it is important to measure this structure, including new phases

Complementary to the "direct" approach:

If NP found in direct searches at LHC, B (as well as D, K) physics measurements will help understanding its nature and flavour structure

Is there New Physics in B decays ?

FCNC very sensitive to NP (because highly suppressed in SM)

Examples

1. **$\beta_s \cong \arg(V_{ts})-\pi$** via **phase of B_s mixing**
   - CKM fit prediction is very precise
2. **Measurement of $Br(B_{s,d} \rightarrow \mu\mu)$** of rare decays
   - Expect large contributions from NP models
3. **Angular distributions and other observables (*ex:* in $B_d \rightarrow K^*\mu\mu$)**
   - Sensitive to non-SM operators in interactions
4. **$\gamma \cong -\arg(V_{ub})$**
   - Comparison of tree processes with measurements from loop processes can reveal NP

But also: ✳ lepton flavor violation in charged leptons FCNC,

$\tau \rightarrow \mu+\gamma$, $\mu \rightarrow e+\gamma$

✳ deviation from μ-e universality (in $R_{K,\pi,B}$)

$R_K = \Gamma(K\rightarrow e\nu)/\Gamma(K\rightarrow\mu\nu)$, $R_B = (B\rightarrow K^*ee) / (B\rightarrow K^*\mu\mu)$

Φ_s from $B_s \rightarrow J/\psi\ \phi$ decays

SU(3) counterpart of $B_d \rightarrow J/\psi K_s$ and measures the B_s- B_s mixing phase

The phase of the oscillation in the SM is given by:

$$\phi_s^{SM} \cong -2 \cdot \arg(V_{ts}\ V^*_{tb}/V_{cs}\ V^*_{cb}) \cong -2\beta_s = -2\lambda^2\eta \sim -0.04$$

very small , so very sensitive to NP

Prediction from a global fit to CKM measurements (UT fit):

$$\phi_s = -0.037 \pm 0.002$$

2008 CDF/D0 measurement:

$$\phi_s = (-2.37\ ^{+0.38}_{-0.27})\ \text{rad} \quad , \quad (-0.75\ ^{+0.27}_{-0.38})\ \text{rad}$$

ATLAS and CMS: $\sigma_{stat}(\phi_s) \sim 0.04$ with $\int L\, dt = 30$ fb^{-1} data

LHCb: $\sigma_{stat}(\phi_s) \sim 0.01$ with $\int L\, dt = 10$ fb^{-1}

SM prediction of ϕ_s tested to a level of ~4σ

Φ_s : sensitivity to New Physics

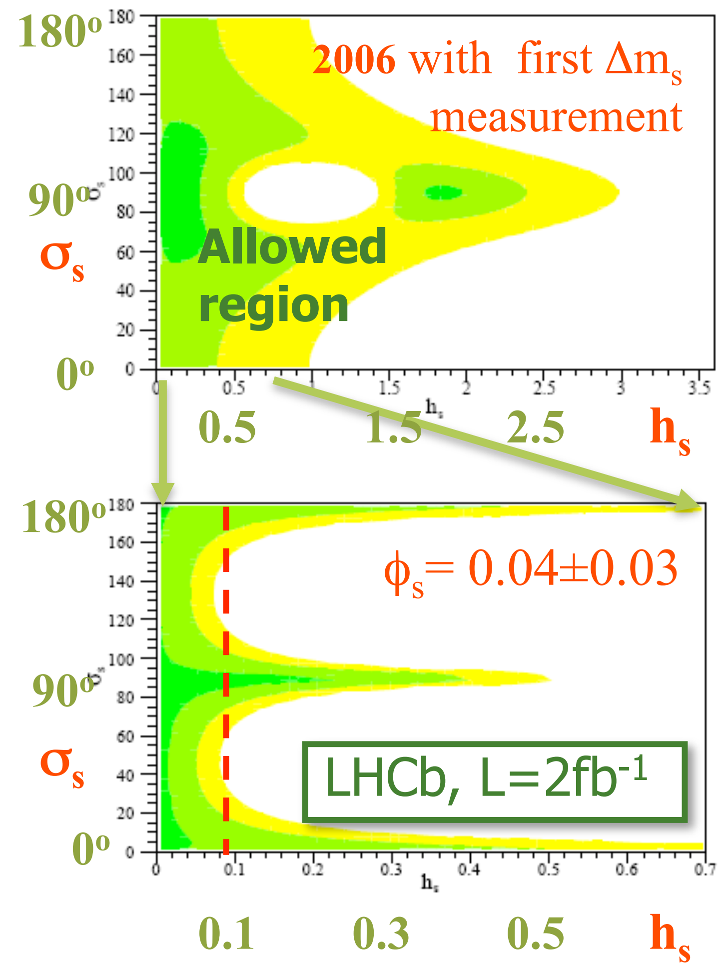
- **One nominal LHCb year (2 fb^{-1}):**
  $\sigma(\phi_s)$= 0.023 (UT fit value: -0.037)

- The measurement can be interpreted via a parametrization of NP effects
  Then $\mathbf{\Delta m_s}$ and $\boldsymbol{\phi_s}$ can be written:

$$\Delta m_s = \Delta m_s^{SM} \left| 1 + h_s \exp(2i)\sigma_s \right|$$

$$\Phi_s = \Phi_s^{SM} + \arg\left(1 + h_s \exp\left(2i\sigma_s\right)\right)$$

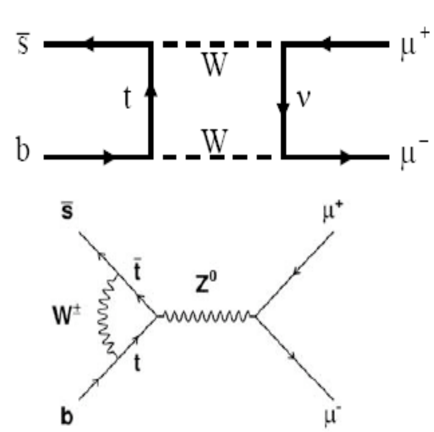
From Z. Ligeti et al hep-ph/0604112
Allowed regions CL > 0.90, 0.32, 0.05



Search for rare decay $B_s \to \mu^+\mu^-$

SM expectation:

$BR(B_s \to \mu^+\mu^-) = (3.4 \pm 0.4) \times 10^{-9}$
$BR(B_d \to \mu^+\mu^-) = (1.0 \pm 0.5) \times 10^{-10}$



SM

Best limit by CDF and DØ :

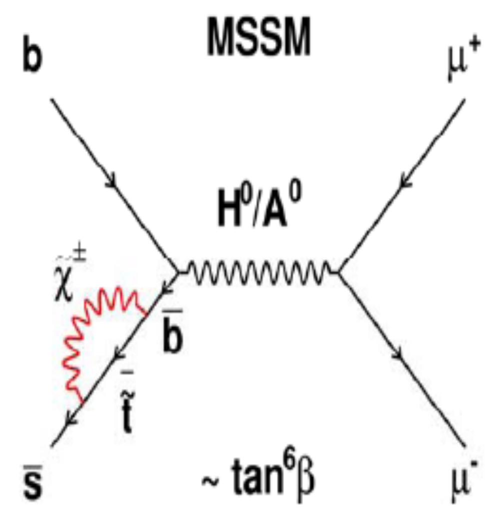
$BR(B_s \to \mu^+\mu^-) < 6 \times 10^{-8}$ @95%CL
$BR(B_d \to \mu^+\mu^-) < 2 \times 10^{-8}$ @95%CL

In Supersymmetry:

Large contributions in some SUSY models

$BR(B_{d,s} \to \mu+\mu-)$ very sensitive if high values of $\tan\beta$

$$BR(B_s \to \mu^+\mu^-) \propto \tan^6\beta / m_A^4$$

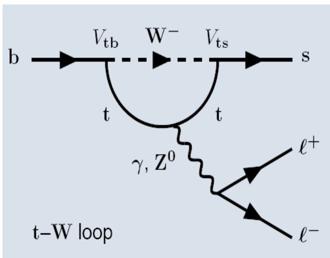


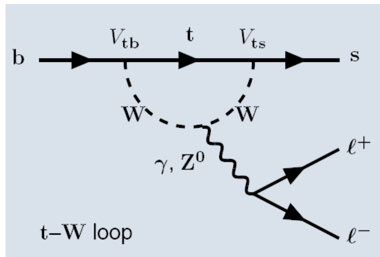
ATLAS and CMS: $\int L\,dt = 30\ fb^{-1}$, <~6×10^{-9} (90%CL)

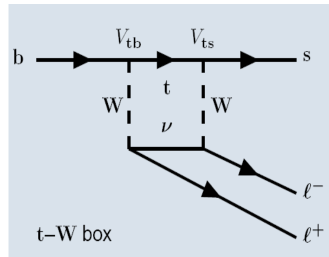
LHCb: $\int L\,dt = 10\ fb^{-1}$, >5σ observation for SM Br

Search for $B^0 \to K^{*0}\mu^+\mu^-$ decay

SM processes contributing to decay:





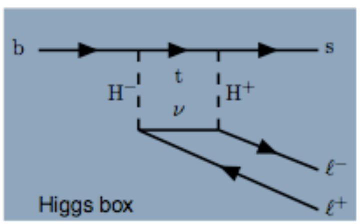


$BR(B^0 \to lls) = 4.5x10^{-6}$

$BR(B^0 \to llK) = 0.5x10^{-6}$

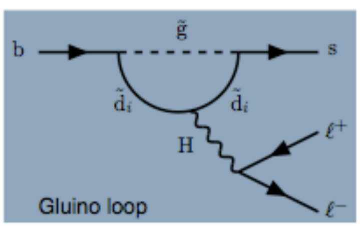
$BR(B^0 \to K^*\mu+\mu-) = \sim\mathbf{1.2} \text{ x } 10^{-6}$

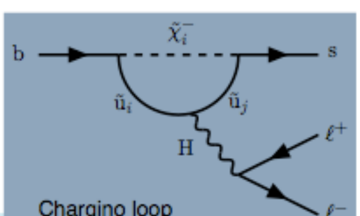
Decay seen in B factories, ~ no NP in BR

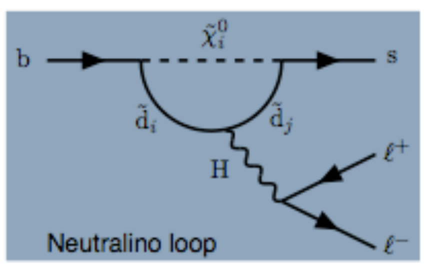


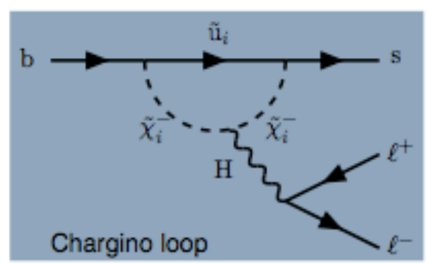
Decay is very sensitive to extensions of SM :

Analysis of angular distributions allow to extract information about New Physics (SUSY, graviton exchange,extra dimension)

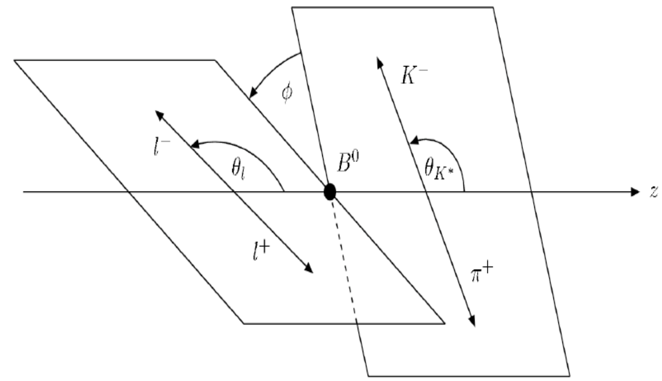








Observables in $B^0 \rightarrow K^{*0}\mu^+\mu^-$ decay



Forward-backward asymmetry $A_{FB}(s)$ in the μμ rest-frame is sensitive probe of New Physics:

- Predicted zero of $A_{FB}(s)$ depends on Wilson coefficients C_7^{eff}/C_9^{eff}

$$A_{FB}(s) = \frac{\int_0^1 \frac{d^2\Gamma}{ds\,dcos\theta} dcos\theta - \int_{-1}^0 \frac{d^2\Gamma}{ds\,dcos\theta} dcos\theta}{\int_0^1 \frac{d^2\Gamma}{ds\,dcos\theta} dcos\theta + \int_{-1}^0 \frac{d^2\Gamma}{ds\,dcos\theta} dcos\theta}$$

s = μμ mass squared (= $\mathbf{q^2}$)
θ_l = angle between μ and B in μμ rest frame (A_{FB} angle)

Transverse Asymmetry:
(asymmetry in the spin amplitude of the K*)

$$A_T^{(2)}(s) = \frac{|A_\perp|^2 - |A_\parallel|^2}{|A_\perp|^2 + |A_\parallel|^2}.$$

K^{*0} polarisation can be measured

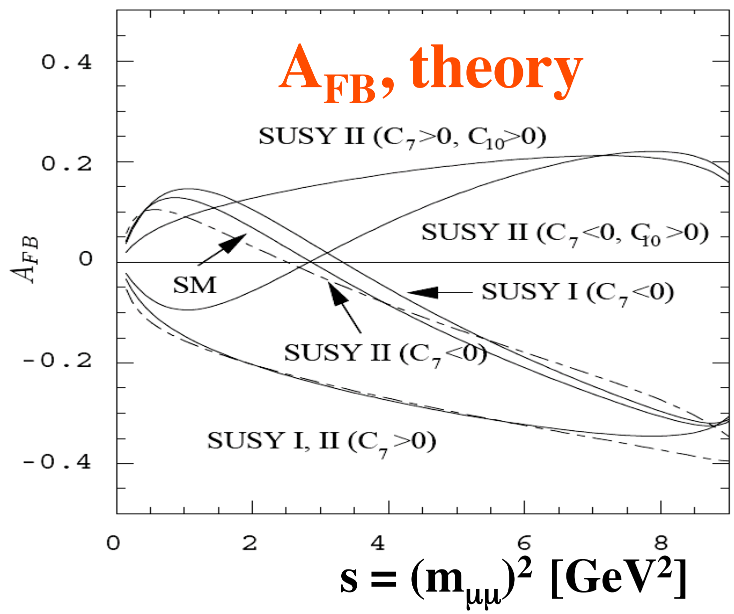
New Physics in $B_d \to K^{0*}\mu\mu$

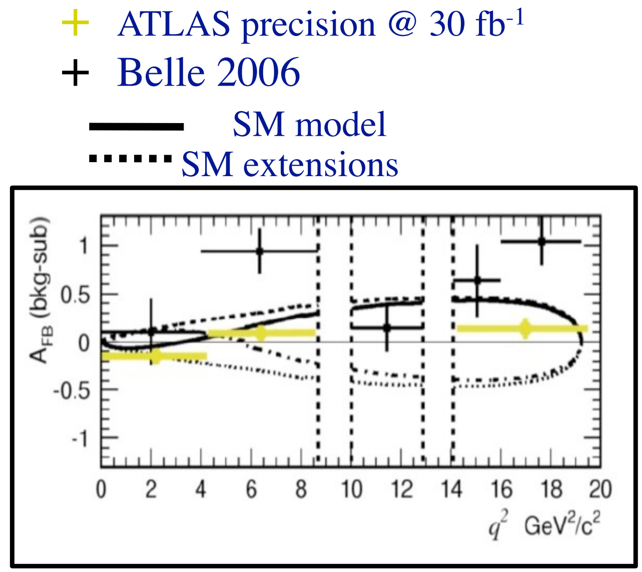
$A_{FB}(s)$ in SM and different SUSY models:

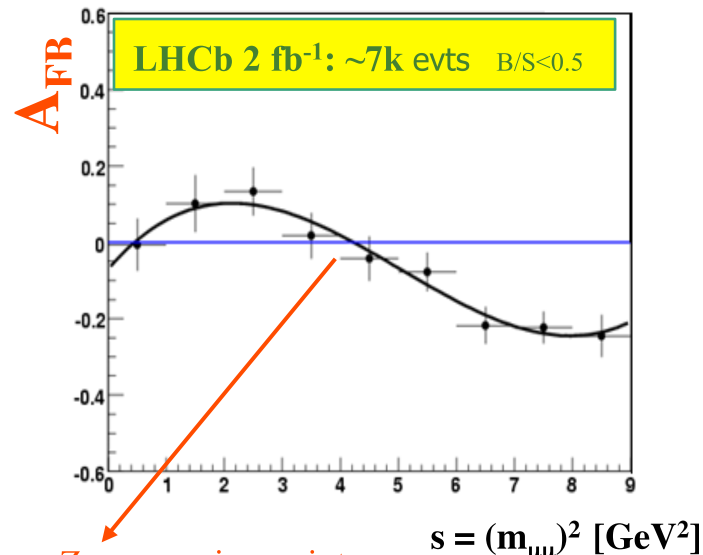
SUSY I = SUGRA

SUSY II = MIA MSSM

(from Phys.Rev.D61 (2000) 074024)







Zero crossing point

$\sigma_{A_{FB}}$ (2fb^{-1})=1.2 GeV ^{2} (= 0.28 with 10 fb^{-1})

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Conclusions

Flavor Physics can give informations on some major open problems of physics today.

- The effects of New Physics loops can be seen in rare decay branching fractions (B, τ), kinematic distributions and in *CP*-violating asymmetries in channels with small (10^{-5}- 10^{-6}) Branching Fractions

- Heavy flavour physics will 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 flavour structure of the new particles

Conclusions

- It is important that , in parallel to LHC data (mainly LHCb, other approaches be followed as well:

1. A Super *B*-Factory can, in the next decade, provide high precision measurements (→ leptonic decays, τ rare decays) complementary to those of hadronic experiments (→ B_s, and B_d /B_s very rare decays)

2. Rare K decay experiments

   ($K \to \pi\nu\nu$, $K \to \pi l^+ l^-$ *Br ~*10^{-10} , 10^{-11})

3. Searches for lepton flavor violation

Better theoretical understanding and predictions will be fundamental for the achievement of this program