The Flavour of Rare Decays

Indirect Tests of the Standard Model

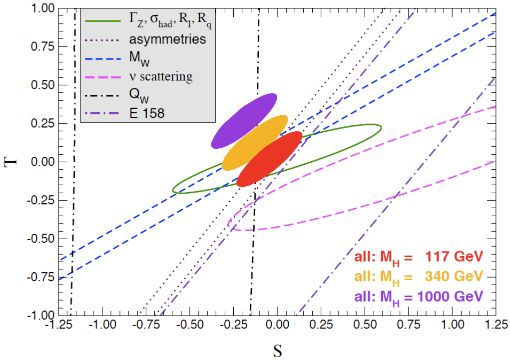
Thomas Mannel, Uni. Siegen

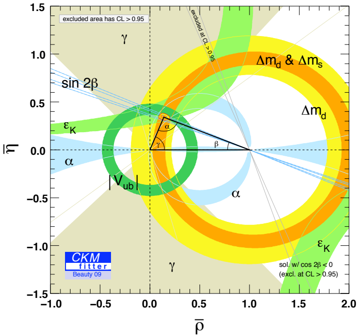
Ahmed Ali's Fest, June 21$^{\text{st}}$, 2011

Contents

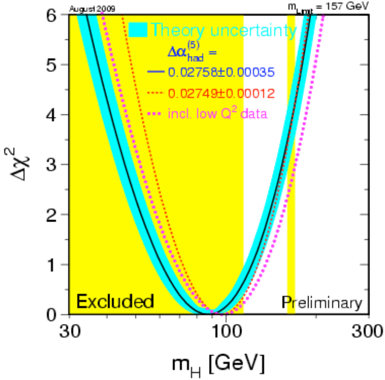
Why Study Rare Decays?

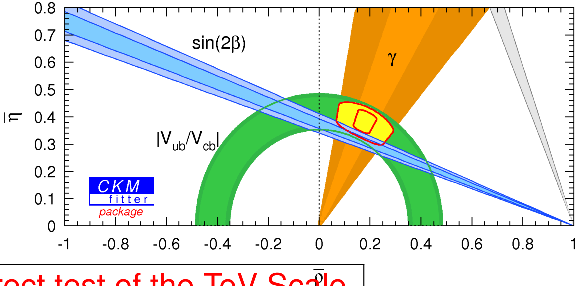
- The Standard Model passed all tests
  up to the 100 GeV Scale:
- LEP: test of the gauge Structure
- Flavour factories: test of the Flavour Sector





- No siginicant deviation has been found (yet)!
- ... only a few “tensions” (= Observables off by $\sim 2\sigma$)

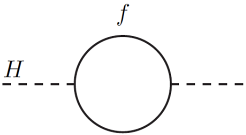




LHC will perform a direct test of the TeV Scale

Why do we believe in TeV Physics?

- Theoretical argument:
- Stabilization of the electroweak scale:

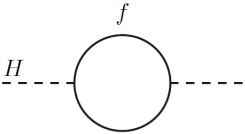


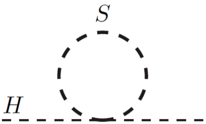
- Quadratic Dependence on the cut-off

$$\Delta m_H^2 = -\frac{\lambda_f^2}{8\pi^2}\Lambda_{\mathrm{UV}}^2$$

- Drives the Higgs mass up to the UV cut off $\Lambda_{\mathrm{UV}} \sim M_{\mathrm{PL}}$

- Stabilization at the TeV scale: e.g. through SUSY:





- Only logarithmic divergence

$$\Delta m_H^2 = m_{\text{soft}}^2 \frac{\lambda}{16\pi^2} \ln\left(\frac{\Lambda_{\text{UV}}}{m_{\text{soft}}}\right)$$

- $m_{\text{soft}} \sim \mathcal{O}(\text{TeV})$:
  Splitting between particles and particles

- How strong are these arguments?
- Could there something be wrong with our understanding of
  - electroweak symmetry breaking?
  - scale and conformal invariance? (c.f. Lee Wick Model)
  - ...
- Does flavour tell us something about this? .... and what?

What can Flavour tell us?

- Flavour Physics $\leftrightarrow$ No new physics at the TeV scale with a generic flavour structure
- Parametrization of new physics:
  Higher Dimensional Operators:

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda}\mathcal{L}^{(5)} + \frac{1}{\Lambda^2}\mathcal{L}^{(6)} + \cdots \qquad \mathcal{L}^{(n)} = \sum_j C_j O_j^{(n)}$$

- Λ: New Physics scale
- $O_j^{(n)}$: Local Operators of dimension n

- Some of the $O_j^{(n)}$ may mediate flavour transitions: e.g.

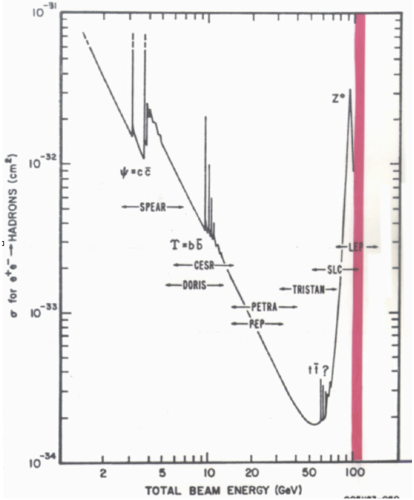
$$O_1^{(6)} = (\bar{s}_L \gamma_\mu d)(\bar{s}_L \gamma^\mu d) \qquad \text{(Kaon Mixing)}$$
$$O_2^{(6)} = (\bar{b}_L \gamma_\mu d)(\bar{b}_L \gamma^\mu d) \qquad (B_d \text{ Mixing})$$
$$O_3^{(6)} = (\bar{b}_L \gamma_\mu 2)(\bar{b}_L \gamma^\mu s) \qquad (B_s \text{ Mixing})$$
$$O_4^{(6)} = (\bar{c}_L \gamma_\mu u)(\bar{c}_L \gamma^\mu u) \qquad (D \text{ Mixing})$$

- $\Lambda \sim 1000$ TeV from Kaon mixing ($C_i = 1$)
- $\Lambda \sim 1000$ TeV from D mixing
- $\Lambda \sim 400$ TeV from B_d mixing
- $\Lambda \sim 70$ TeV from B_s mixing

- “New physics” is around the corner??
- Are the flavour data a hint at a new physics scale well above the TeV scale?
- ... there are a few corners where $\mathcal{O}(1)$ flavour effects are still possible
- Are there lessons from history?

The Top Quark Story

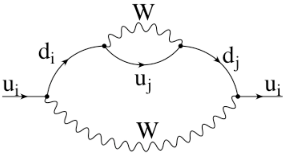
- First indirect hint to a heavy top quark:
  $B - \overline{B}$ Oscillation of ARGUS (1987)
- The world in 1987 (“PETRA Days”):
  The top was believed to be at $\sim$ 25 GeV
  ... based on good theoretical arguments
- ARGUS could not have seen anything with a 25 GeV Top (within SM)



- The consequences:
  - (–) No Toponium
  - (–) No Top quark discovery at LEP and SLC
  - (–) No “New Physcis $\mathcal{O}(30 \text{ GeV})$” just around the corner
  - (+) CP violation in the B sector may become observable
  - (+) GIM is weak for bottom quarks
- This was actually good for Flavour Physics at that time ...
- GIM Suppressed rare decays as a ‘telescope” to see large scales
- From current data: TeV “New Physics” must have a flavour structure close to the one of the SM
- $\rightarrow$ Concept of “Minimal Flavour Violation” (MFV)

Peculiarities of SM Flavour Parametrization

- Strong CP remains mysterious
- Flavour diagonal CP Violation is well hidden:
  e.g electric dipole moment of the neutron:
  At least three loops (Shabalin)



$$d_e \sim e \frac{\alpha_s}{\pi} \frac{G_F^2}{(16\pi^2)^2} \frac{m_t^2}{M_W^2} \mathrm{Im}\Delta\, \mu^3$$

$$\sim 10^{-32} e\, cm \quad \text{with } \mu \sim 0.3\,\mathrm{GeV}$$

$$d_{\mathrm{exp}} \leq 3.0 \times 10^{-26} e\, cm$$

- Pattern of mixing and mixing induced CP violation determined by GIM: Tiny effects in the up quark sector
    - $\Delta C = 2$ is very small
    - Mixing with third generation is small: charm physics basically “two family”
    - $\to$ CP violation in charm is small in the SM
- Fully consistent with particle physics observations
- ... but inconsistent with matter-antimatter asymmetry

??? Many Open Questions ???

- Our Understanding of Flavour is unsatisfactory:
  - 22 (out of 27) free Parameters of the SM originate from the Yukawa Sector (including Lepton Mixing)
  - Why is the CKM Matrix hierarchical?
  - Why is CKM so different from the PMNS?
  - Why are the quark masses (except the top mass) so small compared with the electroweak VEV?
  - Why do we have three families?
- Why is CP Violation in Flavour-diagonal Processes not observed? (e.g. z.B. electric dipolmoments of electron and neutron)
- Where is the CP violation needed to explain the matter-antimatter asymmetry of the Universe?

Rare Decays as a Telescope

The “stargazers” of the “rare decays telescope” ...

Effective Weak Hamiltonian

- At the scale of the b quark:
  Integrate out the weak bosons and the top:

$$H_{\rm eff} = \frac{4G_F}{\sqrt{2}} \lambda_{\rm CKM} \sum_k \hat{C}_k(\mu) \mathcal{O}_k(\mu)$$

$$\begin{aligned}
\mathcal{O}_1 &= \left(\bar{c}_{L,i}\gamma_\mu s_{L,j}\right)\left(\bar{d}_{L,j}\gamma_\mu u_{L,i}\right) \ , \quad \mathcal{O}_2 = \left(\bar{c}_{L,i}\gamma_\mu s_{L,i}\right)\left(\bar{d}_{L,j}\gamma_\mu u_{L,j}\right) \ , \\
\mathcal{O}_3 &= (\bar{s}_{\rm L,\it i}\gamma_\mu b_{\rm L,\it i}) \sum_{q=u,d,s,c,b} (\bar{q}_{\rm L,\it j}\gamma^\mu q_{\rm L,\it j}) \ , \quad \mathcal{O}_4 = (\bar{s}_{\rm L,\it i}\gamma_\mu b_{\rm L,\it j}) \sum_{q=u,d,s,c,b} (\bar{q}_{\rm L,\it j}\gamma^\mu q_{\rm L,\it i}) \ , \\
\mathcal{O}_5 &= (\bar{s}_{\rm L,\it i}\gamma_\mu b_{\rm L,\it i}) \sum_{q=u,d,s,c,b} (\bar{q}_{\rm R,\it j}\gamma^\mu q_{\rm R,\it j}) \ , \quad \mathcal{O}_6 = (\bar{s}_{\rm L,\it i}\gamma_\mu b_{\rm L,\it j}) \sum_{q=u,d,s,c,b} (\bar{q}_{\rm R,\it j}\gamma^\mu q_{\rm R,\it i}) \ . \\
\mathcal{O}_7 &= \frac{e}{16\pi^2} m_b (\bar{s}_{\rm L,\alpha}\sigma_{\mu\nu} b_{\rm R,\alpha}) F^{\mu\nu} \ , \quad \mathcal{O}_8 = \frac{g}{16\pi^2} m_b (\bar{s}_{\rm L,\alpha} T^a_{\alpha\beta}\sigma_{\mu\nu} b_{\rm R,\alpha}) G^{a\mu\nu} \ , \\
\mathcal{O}_9 &= \frac{1}{2}(\bar{s}_{\rm L}\gamma_\mu b_{\rm L})(\bar{\ell}\gamma^\mu \ell) \ , \quad \mathcal{O}_{10} = \frac{1}{2}(\bar{s}_{\rm L}\gamma_\mu b_{\rm L})(\bar{\ell}\gamma^\mu \gamma_5 \ell)
\end{aligned}$$

- Coefficients in the SM are known to NLO!

- All physics at high scales larger than μ is encoded in the Coefficients $\hat{C}_k(\mu)$
- $\to$ need to measure / constrain these coefficients
- Opens the possibility to perform a model independent check of the SM (Ali et al., 1994)

Towards a model-independent analysis of rare *B* decays

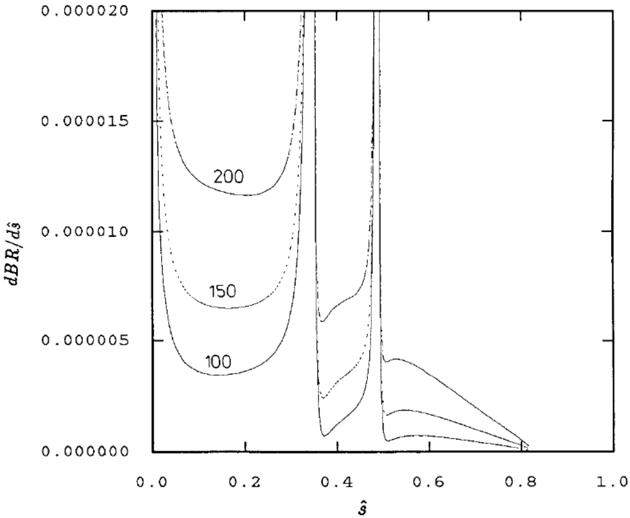
A. Ali★, G.F. Giudice★★, T. Mannel

Theory Division, CERN, CH-1211 Geneva 23, Switzerland

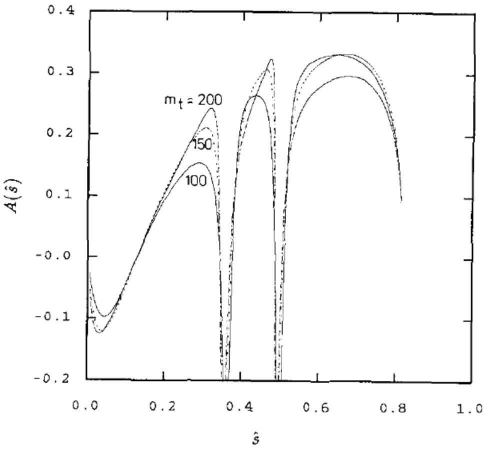
Received: 6 September 1994/Revised version: 13 January 1995

- At that time: First measurement of $B \to X_s\gamma$ by CLEO
- Identify observables with sensitivity to the coefficients

Differential rate



Forward backward asymmetry



There is a zero in the forward backward asymmetry in the SM!

- 1994: CLEO measurements mainly constrained $|C_7|$
- C_7 still could be grossly off the SM by $C_7 = -C_{7,SM}$

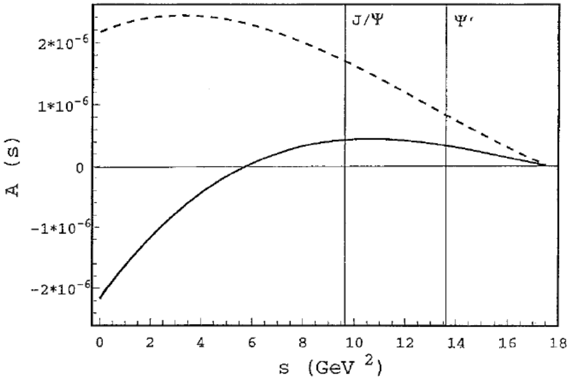
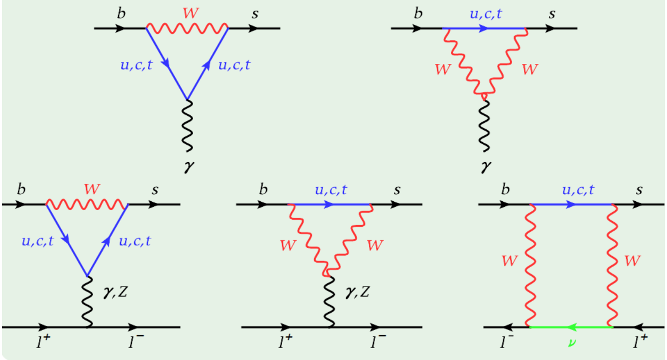


Fig. 7. The dependence of the differential FB asymmetry on the Wilson coefficients. Solid line: SM. Long-dashed line: $C_7 \to -C_7$, with the other parameters retaining their SM values. The vertical lines indicate the location of the J/Ψ and Ψ' resonances

- Observables: Integrated rate below and above the $c\bar{c}$ resonances
- Forward backward Asymmetry, integrated below and above the $c\bar{c}$ resonances
- More recently: Angular distributions of leptons and K^* polarizations

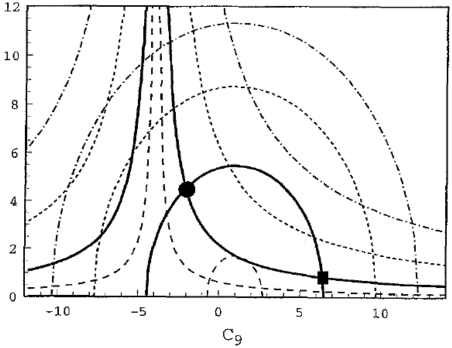
(Hiller et al.)

- Assumptions
  - Only the coefficients C_9 and C_{10} induced by loop diagrams contain "new physics"

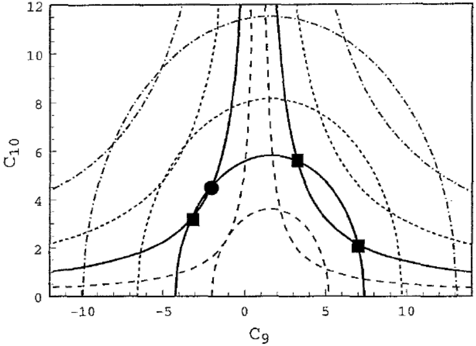


  - $\to C_1 \dots C_6$ are fixed to their SM values
  - $|C_7|$ is fixed by the measurement of $B \to X_s\gamma$

$C_9 - C_{10}$ Contours for $C_7 = C_{7,SM}$

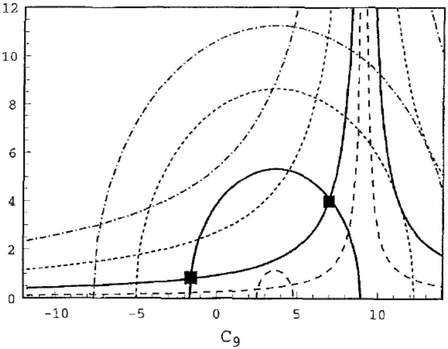


low q^2 region

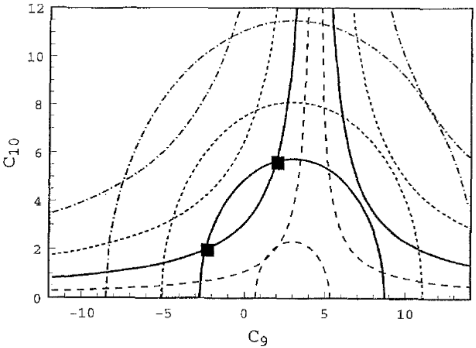


high q^2 region

$C_9 - C_{10}$ Contours for $C_7 = -C_{7,SM}$



low q^2 region



high q^2 region

$B \to X_s\gamma$ and $B \to K^*\gamma$

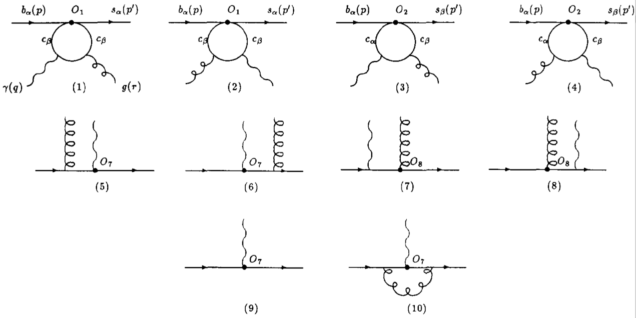
- Continuous work since the CLEO discovery
- More data from different experiments ...
- More theory needed as well
- Calculations up to NLO
- Exclusive decays: Form factors needed

- Early work by Ahmed and Collaborators

A profile of the final states in $B \to X_s + \gamma$ and an estimate of the branching ratio $BR(B \to K^* + \gamma)$

A. Ali and C. Greub
Deutsches Elektronen Synchrotron DESY, W-2000 Hamburg, FRG

Received 11 January 1991; revised manuscript received 7 February 1991



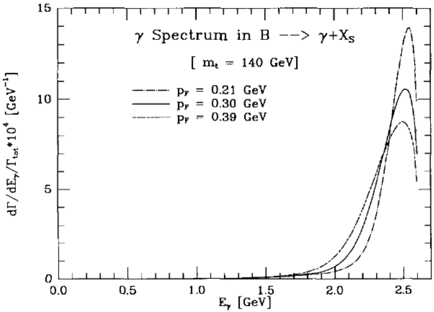


Fig. 3. Inclusive photon energy spectrum for the process $B \to X_s + \gamma$ using perturbative QCD and the B-meson wave function model described in the text, and $m_t = 140$ GeV. The three indicated values of the parameter p_F bracket the recent ($\pm 1\sigma$)-fits of the CLEO data from the lepton energy spectrum in B-decays [16].

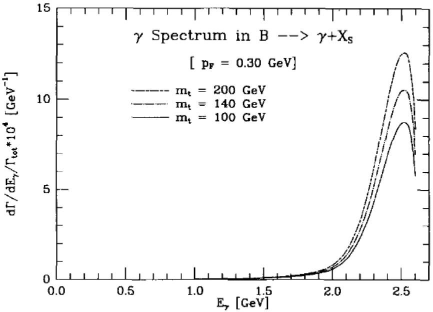
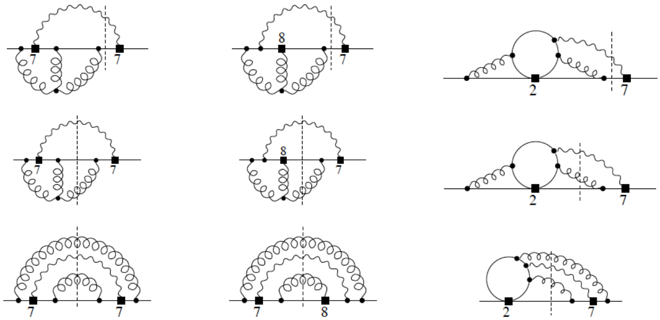


Fig. 4. Inclusive photon energy spectrum for the process $B \to X_s + \gamma$ using perturbative QCD and the B-meson wave function model described in the text, with the parameter p_F set to 0.3 GeV, and three representative values of the top quark mass as indicated.

Status of $b \to s\gamma$

- Higher orders in the perturbative calculation: Full NLO
- Estimate of the non-perturbative contributions: Still some controversy



- Theoretical prediction: (Misiak 2010)

$$\mathcal{B}(\bar{B} \to X_s\gamma) = (3.15 \pm 0.23) \times 10^{-4}$$

- Experimental value (HFAG):

$$\mathcal{B}(\bar{B} \to X_s\gamma) = (3.55 \pm 0.24_{\rm exp} \pm 0.09_{\rm model}) \times 10^{-4}$$

- Can we calculate more precisely?
- ... will be a challenge ...

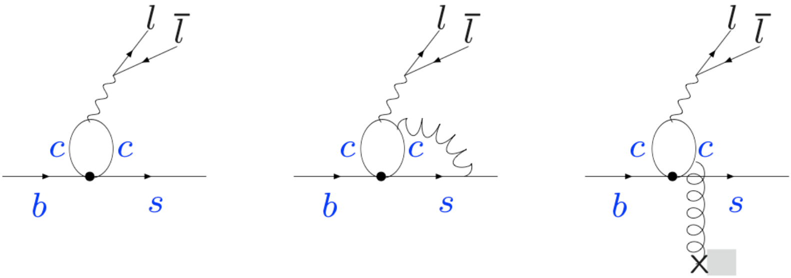
More Recent Developments in $b \to s\ell\ell$

- Model independent analysis has been refined by Ahmed and his Co-workers
  - by also including the information from $b \to s\gamma$
  - by working it out for exclusive decays
  - by using more refined form factors
  - by enlarging the operator basis (e.g. by right handed currents)
- Still problems remain: Hadronic matrix elements
- ... some of which are not just form factors ...

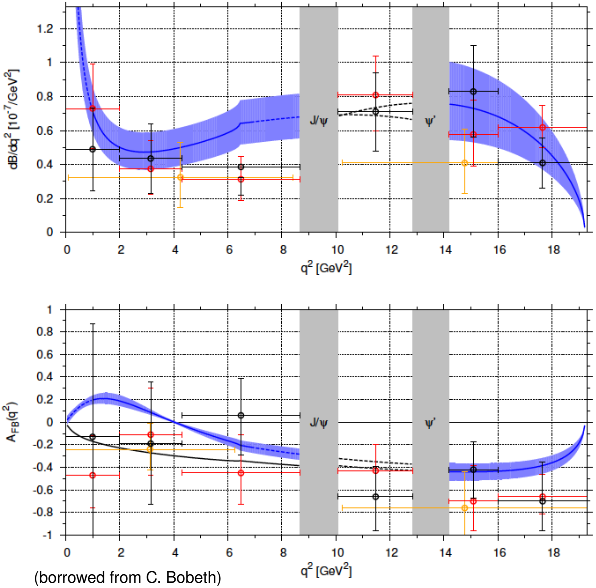
Charm Loops

Buchalla, Isidori, recently: Khodjamirian, TM, Pivovarov, Wang

- Charm-loop effect: a combination of the $(\bar{s}c)(\bar{c}b)$ weak interaction ($O_{1,2}$) and e.m.interaction $(\bar{c}c)(\bar{\ell}\ell)$



- new hadronic matrix elements, not a form factor



Br and A_{FB}

SM prediction + unc.
@ low- and high-q^2

Data points from

[Babar '08]

[Belle '09]

[CDF '10]

(borrowed from C. Bobeth)

- For $q^2 < 4m_c^2$: Light cone expansion of the charm loop
- Expansion parameter $\frac{\Lambda_{\rm QCD}^2}{(4m_c^2 - q^2)}$
- Leads to a non-local operator (“shape-function-like” operator)

$$\widetilde{\mathcal{O}}_\mu(q) = \int d\omega \, I_{\mu\rho\alpha\beta}(q, m_c, \omega) \bar{s}_L \gamma^\rho \left(\delta[\omega - \frac{(in_+\mathcal{D})}{2}] \widetilde{G}_{\alpha\beta} \right) b_L \ ,$$

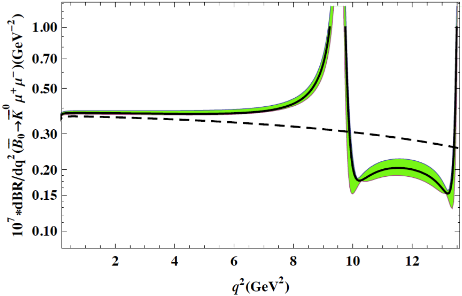
- Matrix element for the exclusive decays can be calculated in a LCSR for $q^2 \leq 4m_c^2$

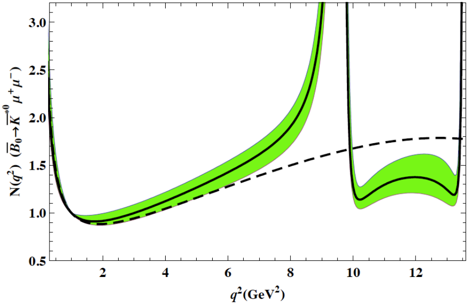
- Use dispersion relations to extrapolate into the resonance region:

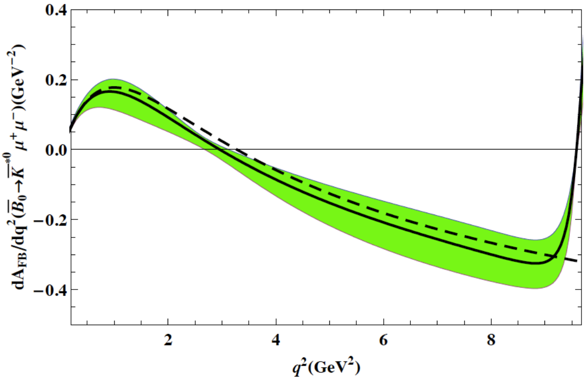
$$\mathcal{H}^{(B\to K)}(q^2) = \mathcal{H}^{(B\to K)}(0) + q^2 \left[\sum_{\psi=\psi(1S),\psi(2S),\ldots} \frac{f_\psi A_{B\psi K}}{m_\psi^2 (m_\psi^2 - q^2 - i m_\psi \Gamma_\psi)} + \int_{4m_D^2}^{\infty} ds \frac{\rho(s)}{s(s - q^2 - i\epsilon)} \right]$$

- $|A_{B\psi K}|$ and f_ψ are determined from data.
- Phases of $A_{B\psi K}$ may lead to destructive interference
- alternating signs possible ...

Results on $B \to K^{(*)}\ell^+\ell^-$





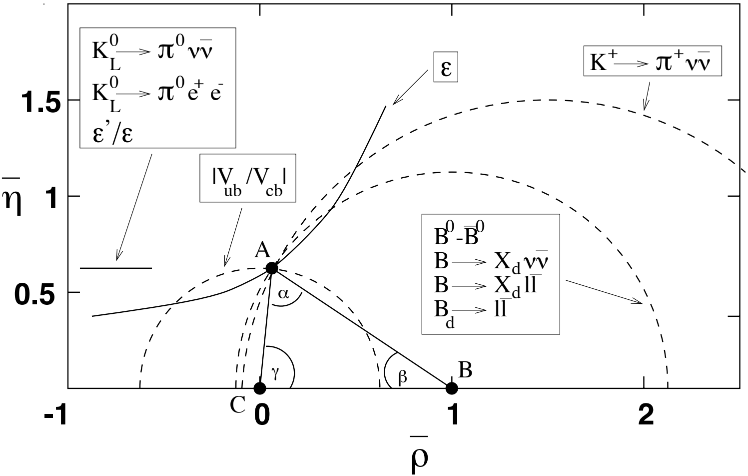


Problem to compute at large q^2?
... still a good predicton of the zero in A_{FB},
This is a good "telescope"

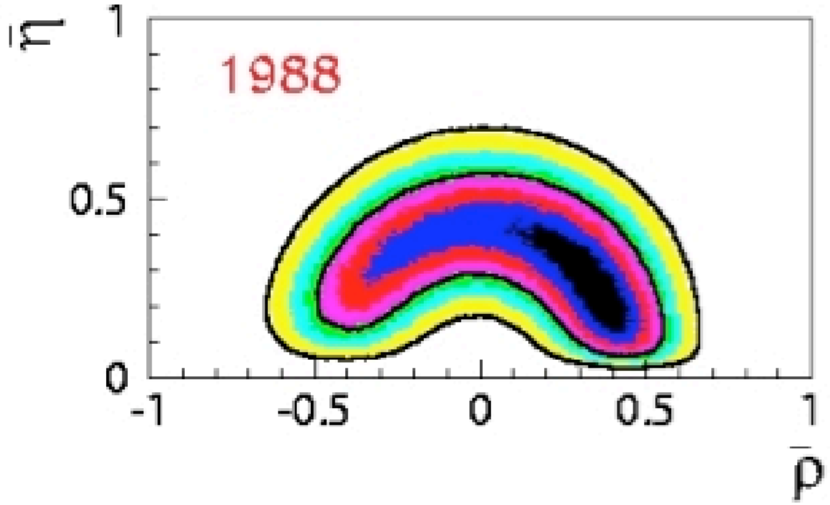
- Region of large q^2: Difficult due to resonances
- For very large q^2: Duality will work again ...
- Ongoing work ...

Impact on our knowledge about Flavour

CKM Unitarity



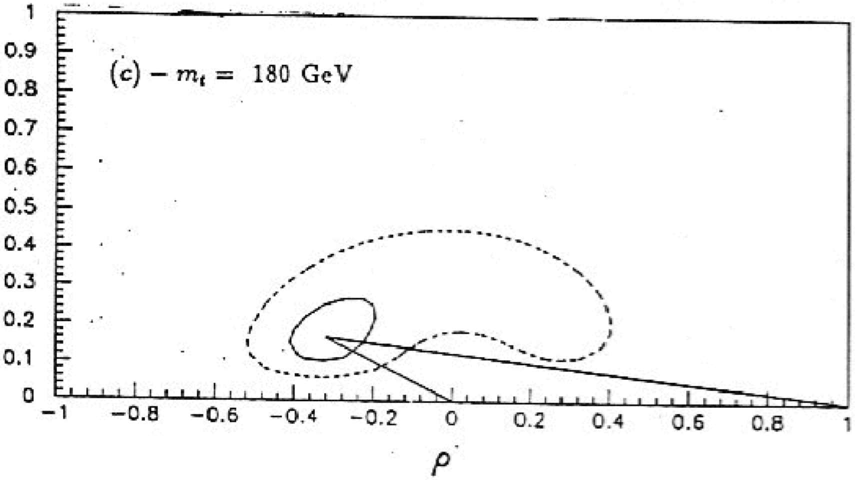
The situation $\sim$ 88



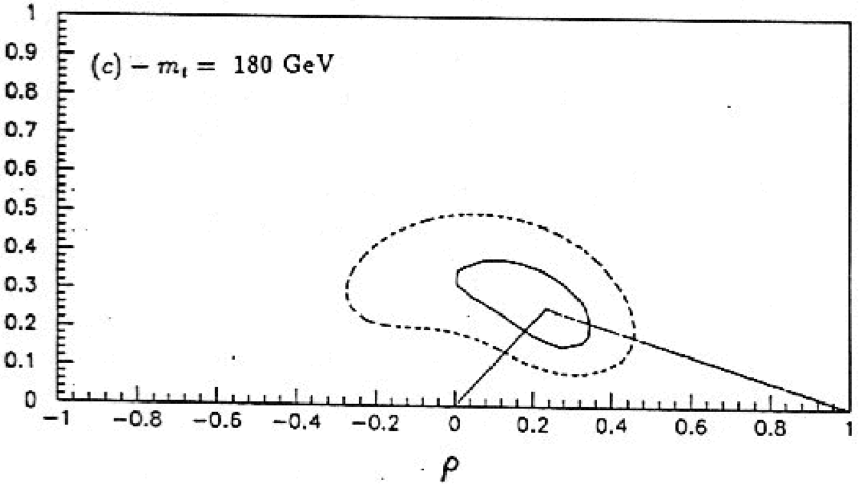
The history of the UT since $\sim$ 1993

- Situation in 1993:
  - HQET was still young ($\sim$ 3 years)
  - Hadronic Matrix elements for $\Delta m_d \sim f_B^2$ were quite uncertain
  - V_{ub}/V_{cb} was known at the level of $\sim$ 20%
  - The top quark mass was still $m_t \sim (140 \pm 40)$ GeV
  - No CP violation has been observed except ϵ_K
- The UT still could have been “flat”

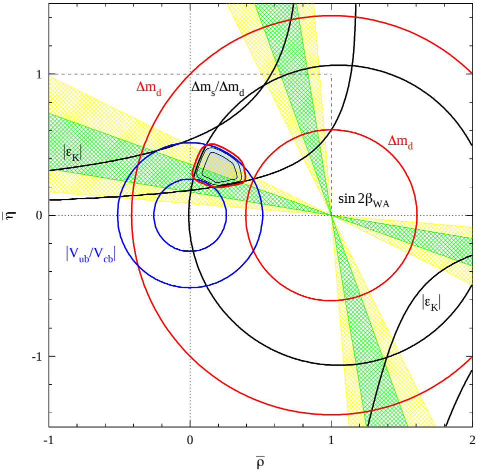
Unitarity triangle 1993: $f_B = 135 \pm 25$ MeV

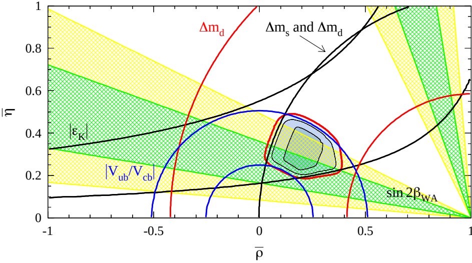


Unitarity triangle 1993: $f_B = 200 \pm 30$ MeV

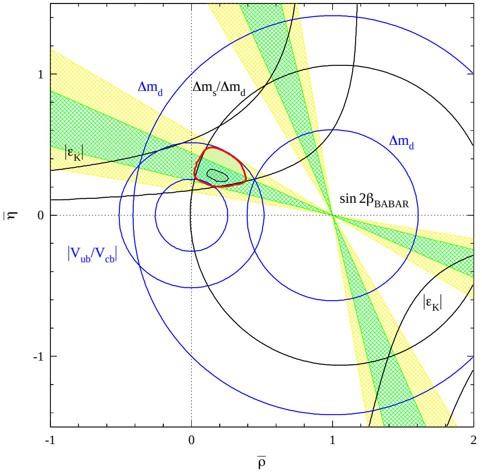


2001: First observation of "Non-Kaon CPV"

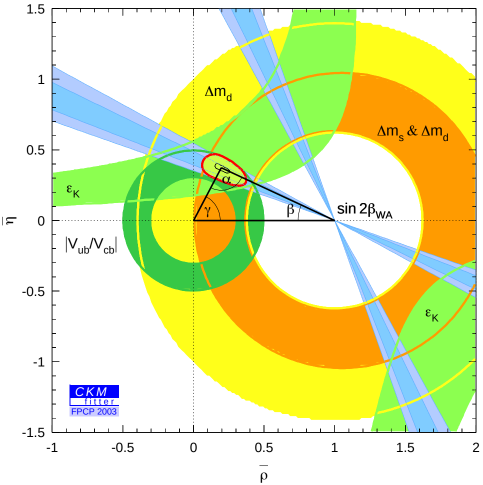




Unitarity Triangle 2001

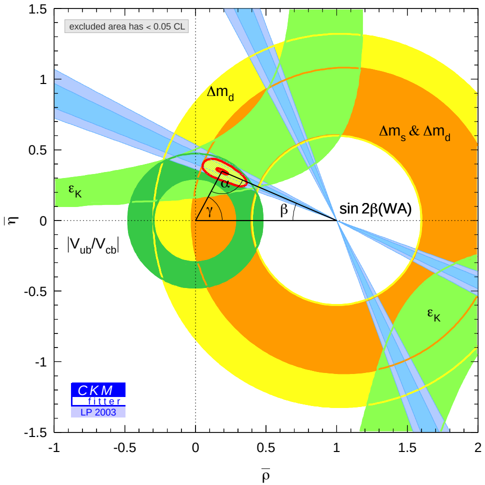


Unitarity Triangle 2002



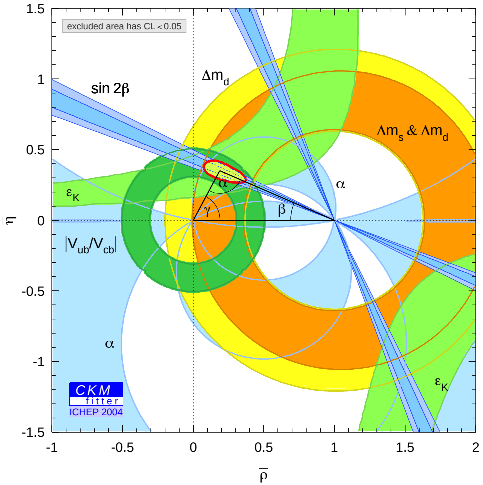
- Some improvement of V_{ub}/V_{cb} through the Heavy Quark Expansion
- More data on $\mathcal{A}_{\mathrm{CP}}(B \to J/\Psi K_s)$

Unitarity Triangle 2003



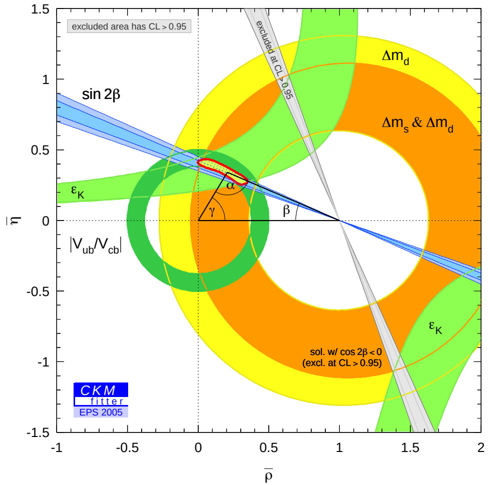
- Slight improvement of $f_B^2 B_B$ from lattice calculations
- Still more data on $\mathcal{A}_{\mathrm{CP}}(B \to J/\Psi K_s)$
- Central value of V_{ub}/V_{cb} slightly moved

Unitarity Triangle 2004



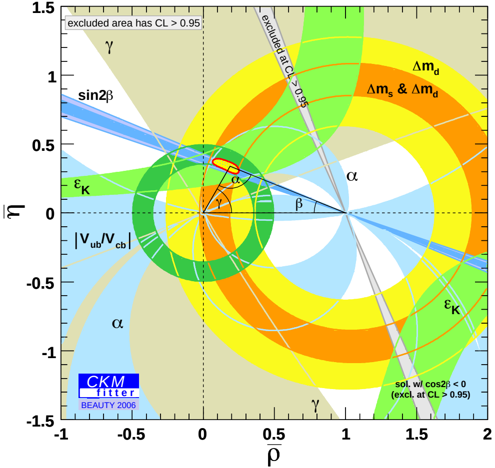
- More improvement of $f_B^2 B_B$ from lattice calculations
- Still more data on $\mathcal{A}_{\rm CP}(B \to J/\Psi K_s)$
- First constraints on the angle α from $B \to \rho\rho$

Unitarity Triangle 2005



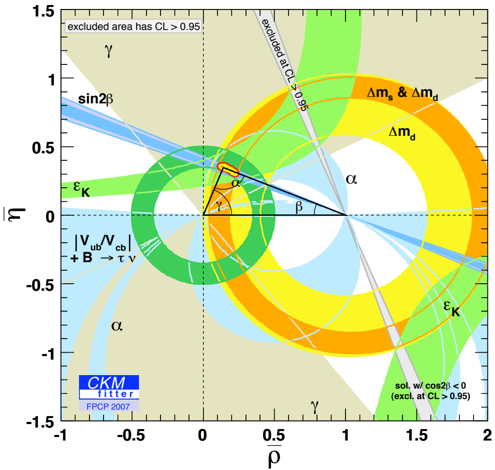
- Still more data on $\mathcal{A}_{\mathrm{CP}}(B \to J/\Psi K_s)$
- Exclusion of the “wrong branch” of β
- Dramatic Improvement of V_{ub} from the HQE

Unitarity Triangle 2006



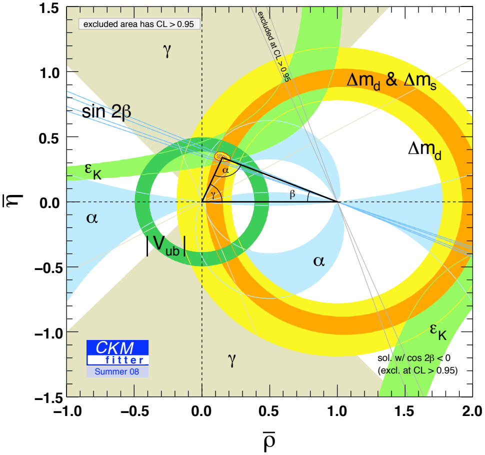
- TEVATRON measurement of Δm_s
- Tighter constraints on α
- First constraints on γ from CPV in $B \to K\pi$

Unitarity Triangle 2007



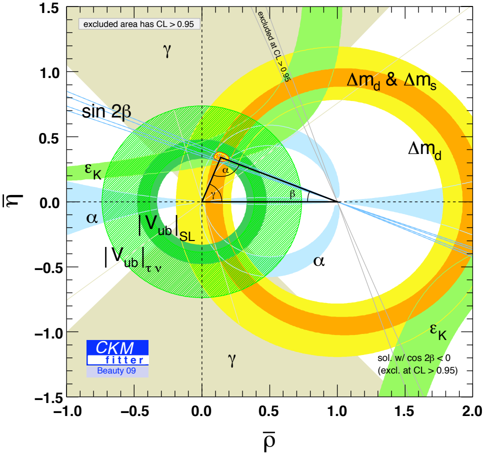
- First input from $B \to \tau \bar{\nu}$

Unitarity Triangle 2008



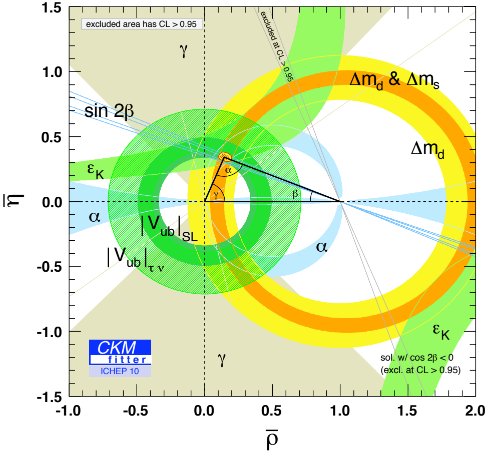
- Improved Δm_s
- We thought we knew V_{ub} quite well
- Tensions become visible ....

Unitarity Triangle 2009



- $B \to \tau \bar{\nu}$?

Current Unitarity Triangle



- Some clarifications needed!
- First hint to something new?

NO Conclusions ....

... since the story will go on

NO Conclusions ....

... since the story will go on

! This was last week at the bsll2011 workshop !

NO Conclusions ....

... since the story will go on

! This was last week at the bsll2011 workshop !

Best wishes for the future