

Flavor Theory

→ *Zoltan Ligeti*

Hawaii, DPF/JPS meeting, Nov. 2, 2006

- Introduction

The flavor problems

- Mixing in the B_d and B_s systems

Impact of measurement of Δm_s

Bounds on non-SM contributions

- Selected recent developments

CP violation ($b \rightarrow s$ penguins, angles α and γ)

Progress with inclusive decays ($|V_{xb}|$, rare decays, τ_{Λ_b})

Some exclusive processes ($B \rightarrow \tau\nu$, $\rho\gamma$, 2-body nonleptonic)

- Conclusions

Why is flavor physics and CPV interesting?

- SM flavor problem: hierarchy of masses and mixing angles
- NP flavor problem: TeV scale (hierarchy problem) \ll flavor & CPV scale

$$\epsilon_K: \frac{(s\bar{d})^2}{\Lambda^2} \Rightarrow \Lambda \gtrsim 10^4 \text{ TeV}, \quad B_d \text{ mixing: } \frac{(b\bar{d})^2}{\Lambda^2} \Rightarrow \Lambda \gtrsim 10^3 \text{ TeV}$$

-
- Almost all extensions of the SM have new sources of CPV & flavor conversion (e.g., 43 new CPV phases in SUSY)
 - A major constraint for model building (flavor structure: universality, heavy squarks, squark-quark alignment, ...)
 - The observed baryon asymmetry of the Universe requires CPV beyond the SM (not necessarily in flavor changing processes, nor in the quark sector)

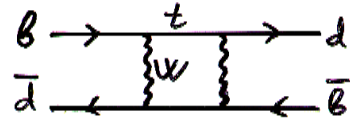


What are we after?

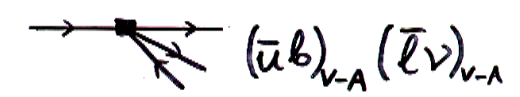
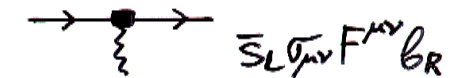
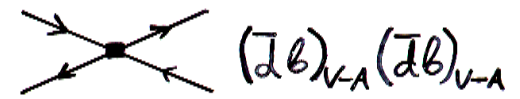
- At scale m_b , flavor changing processes are mediated by $\mathcal{O}(100)$ higher dimension operators

Depend only on a few parameters in the SM \Rightarrow correlations between s, c, b, t decays

weak / NP scale



$\sim 5 \text{ GeV}$



E.g.: in SM $\frac{\Delta m_d}{\Delta m_s}, \frac{b \rightarrow d\gamma}{b \rightarrow s\gamma}, \frac{b \rightarrow dl^+\ell^-}{b \rightarrow sl^+\ell^-} \propto \left| \frac{V_{td}}{V_{ts}} \right|$, but test different short dist. physics

- Does the SM (i.e., integrating out virtual W, Z , and quarks in tree and loop diagrams) explain all flavor changing interactions? Right coefficients and operators?

Study SM loops (mixing, rare decays), interference (CPV), tree vs. loop processes



Spectacular track record

- Flavor and CP violation are excellent probes of New Physics
 - β -decay predicted neutrino
 - Absence of $K_L \rightarrow \mu\mu$ predicted charm
 - ϵ_K predicted 3rd generation
 - Δm_K predicted charm mass
 - Δm_B predicted heavy top
- If there is NP at the TEV scale, it must have a very special flavor / CP structure
- Or will the LHC find just a SM-like Higgs?



SM tests with K and D mesons

- CPV in K system is at the right level (ϵ_K accommodated with $\mathcal{O}(1)$ CKM phase)
 - Hadronic uncertainties preclude precision tests (ϵ'_K notoriously hard to calculate)
 - $K \rightarrow \pi\nu\bar{\nu}$: Theoretically clean, but rates small $\mathcal{B} \sim 10^{-10}(K^\pm), 10^{-11}(K_L)$
- Observation (3 events): $\mathcal{B}(K^+ \rightarrow \pi^+\nu\bar{\nu}) = (1.5^{+1.3}_{-0.9}) \times 10^{-10}$ — need more data
-

- D system: complementary to K and B

Only meson where mixing is generated by down type quarks (SUSY: up squarks)

CPV, FCNC both GIM and CKM suppressed \Rightarrow tiny in SM and not yet observed

$$y_{CP} = \frac{\Gamma(CP \text{ even}) - \Gamma(CP \text{ odd})}{\Gamma(CP \text{ even}) + \Gamma(CP \text{ odd})} = (0.9 \pm 0.4)\%$$

No mixing also disfavored by $> 2\sigma$ in 2-d fit to $(\Delta m, \Delta\Gamma)$ at Babar & Belle

- At the present sensitivity, CPV would be the only clean signal of NP in D mixing
- Could also discover NP via FCNC, e.g., $D \rightarrow \pi\ell^+\ell^-$

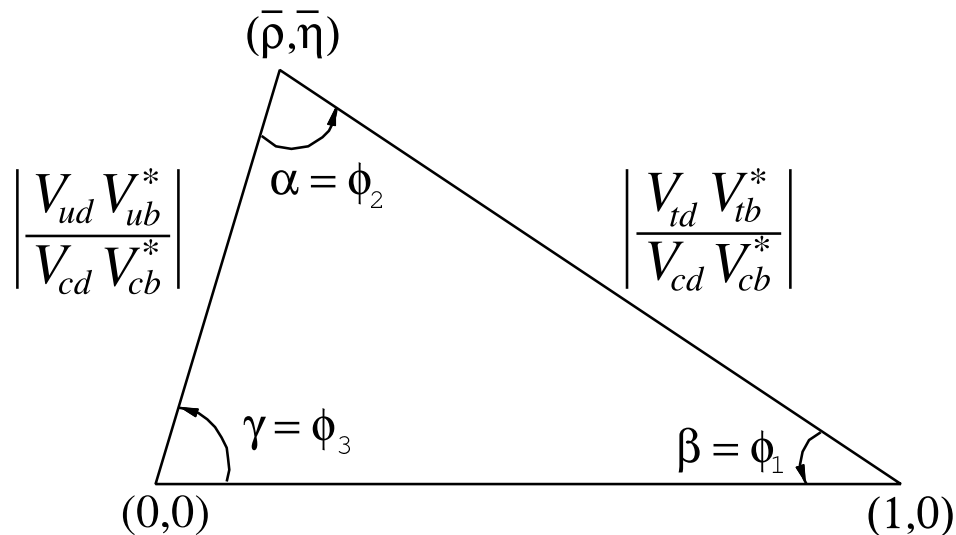


CKM matrix and unitarity triangle

- Exhibit hierarchical structure of CKM ($\lambda \simeq 0.23$)

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1 - \frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\bar{\rho} - i\bar{\eta}) \\ -\lambda & 1 - \frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1 - \bar{\rho} - i\bar{\eta}) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

- Results often shown in $(\bar{\rho}, \bar{\eta})$ plane — a “language” to compare measurements



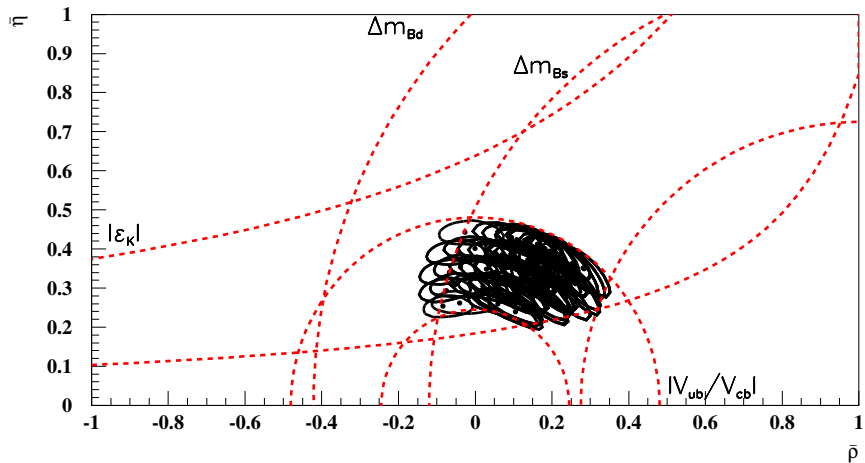
$$V_{ud} V_{ub}^* + V_{cd} V_{cb}^* + V_{td} V_{tb}^* = 0$$

Angles and sides are directly measurable in numerous different processes

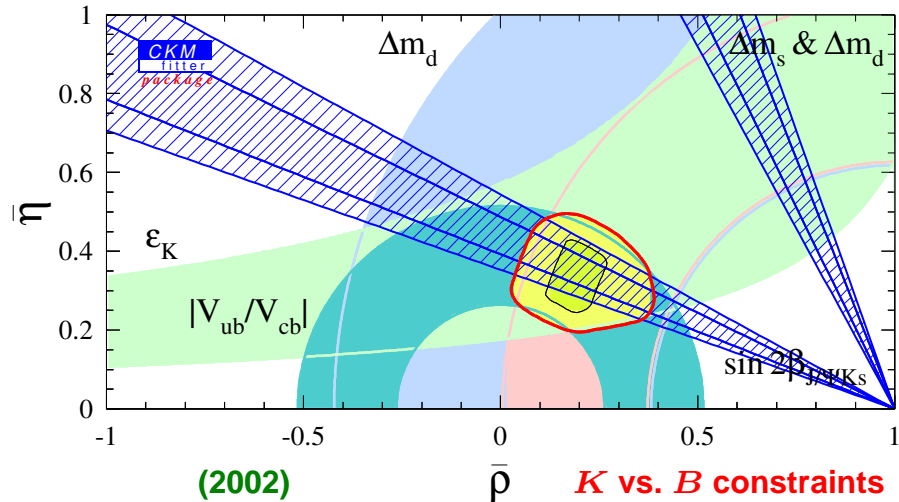
Goal: overconstraining measurements sensitive to different short dist. phys.



Remarkable progress at B factories

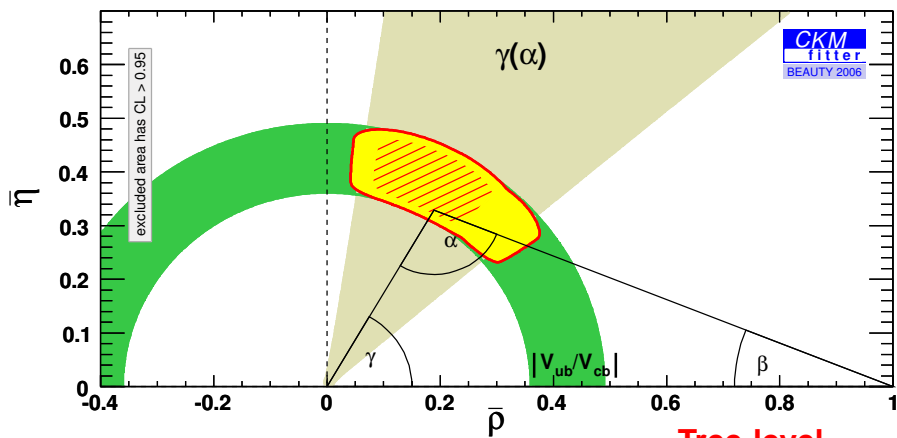


(1998)



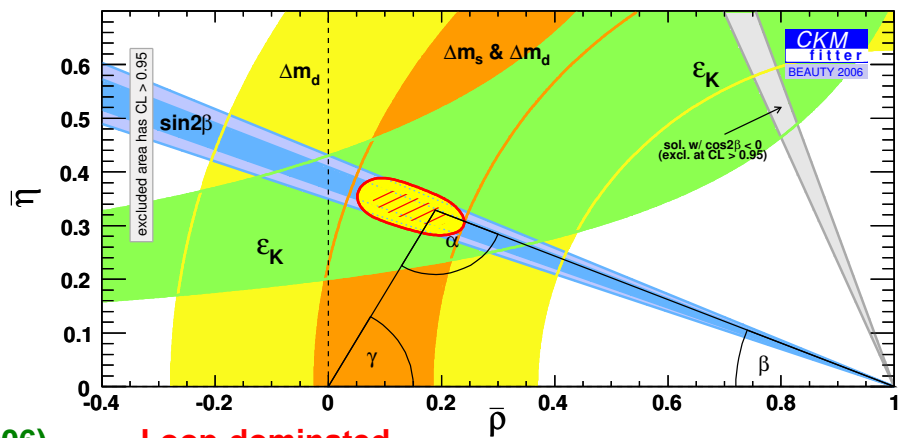
(2002)

K vs. B constraints



Tree-level

(2006)

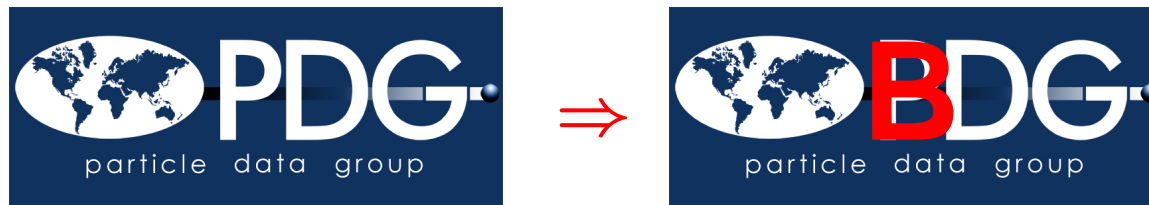


Loop-dominated

- The CKM picture is verified \Rightarrow looking for corrections rather than alternatives



The *B* factory era



The B factory era

- Q: How many CP violating quantities have been measured with 3σ significance?



The B factory era

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A: 6? 9? 12? 15?



The B factory era

- Q: How many CP violating quantities have been measured with 3σ significance?

A: 12

$\epsilon_K, \epsilon'_K,$

$S_{\psi K}, S_{\eta' K}, S_{K^+ K^- K^0}, S_{D^{*+} D^{*-}}, S_{\pi^+ \pi^-},$

$A_{K^- \pi^+}, A_{\eta' K^* 0}, A_{\pi^+ \pi^-}, A_{\rho \pi}^{-+}, a_{D^{*\pm} \pi^\mp}$

- Just because a measurement determines a CP violating quantity, it no longer automatically implies that it is interesting

(If $S_{\eta' K}$ was still consistent with 0, it would be a clear discovery of new physics!)

- It does not matter whether one measures a side or an angle — what matters are experimental precision and clean theoretical interpretation for short dist. physics



Mixing in the $B_{d,s}$ systems

$B\bar{B}$ mixing: matter – antimatter oscillation

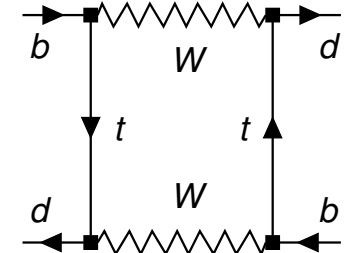
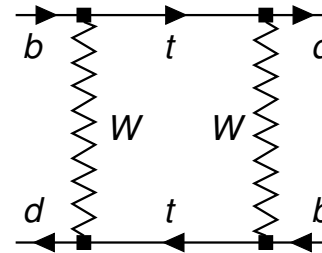
- Two flavor eigenstates: $|B^0\rangle = |\bar{b}d\rangle$, $|\bar{B}^0\rangle = |b\bar{d}\rangle$

Time evolution:
$$i \frac{d}{dt} \begin{pmatrix} |B^0(t)\rangle \\ |\bar{B}^0(t)\rangle \end{pmatrix} = \left(M - \frac{i}{2} \Gamma \right) \begin{pmatrix} |B^0(t)\rangle \\ |\bar{B}^0(t)\rangle \end{pmatrix}$$

M, Γ are 2×2 Hermitian matrices; $CPT \Rightarrow M_{11} = M_{22}, \Gamma_{11} = \Gamma_{22}$

- Mixing due to box diagrams dominated by top quarks \Rightarrow sensitive to high scales

Mass eigenstates: $|B_{H,L}\rangle = p|B^0\rangle \mp q|\bar{B}^0\rangle$



Time dependence: $|B_{H,L}(t)\rangle = e^{-(iM_{H,L} + \Gamma_{H,L}/2)t} |B_{H,L}\rangle$ involve mixing and decay



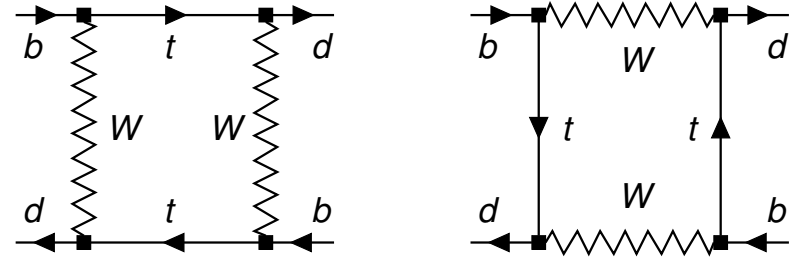
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- In $|\Gamma_{12}| \ll |M_{12}|$ limit, which holds for both $B_{d,s}$ within and beyond the SM

$$\Delta m = 2|M_{12}|, \quad \Delta\Gamma = 2|\Gamma_{12}| \cos \phi_{12}, \quad \phi_{12} = \arg\left(-\frac{M_{12}}{\Gamma_{12}}\right) \Rightarrow \text{NP cannot enhance } \Delta\Gamma_s$$



Parameterize new physics in mixing

- Assume: (i) 3×3 CKM matrix is unitary; (ii) Tree-level decays dominated by SM

Concentrate on NP in mixing amplitude; two parameters for each neutral meson:

$$M_{12} = \underbrace{M_{12}^{\text{SM}} r^2 e^{2i\theta}}_{\text{easy to relate to data}} \equiv \underbrace{M_{12}^{\text{SM}} (1 + h e^{2i\sigma})}_{\text{easy to relate to models}}$$

- Tree-level CKM constraints unaffected: $|V_{ub}/V_{cb}|$ and γ (or $\pi - \beta - \alpha$)
- $B\bar{B}$ mixing dependent observables sensitive to NP: $\Delta m_{d,s}$, S_{f_i} , $A_{\text{SL}}^{d,s}$, $\Delta\Gamma_s$



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$$\Delta m_{B_q} = r_q^2 \Delta m_{B_q}^{\text{SM}} = |1 + h_q e^{2i\sigma_q}| \Delta m_q^{\text{SM}}$$

$$S_{\psi K} = \sin(2\beta + 2\theta_d) = \sin[2\beta + \arg(1 + h_d e^{2i\sigma_d})] \quad S_{\rho\rho} = \sin(2\alpha - 2\theta_d)$$

$$S_{\psi\phi} = \sin(2\beta_s - 2\theta_s) = \sin[2\beta_s - \arg(1 + h_s e^{2i\sigma_s})]$$

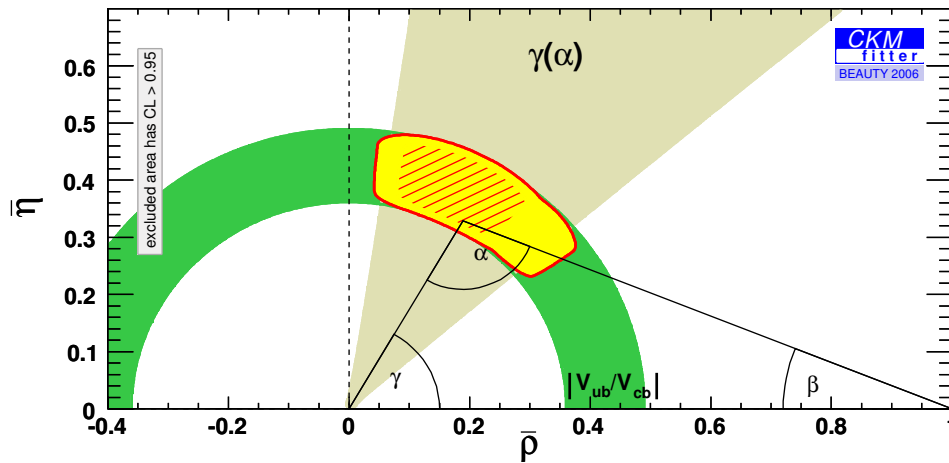
$$A_{\text{SL}}^q = \text{Im}\left(\frac{\Gamma_{12}^q}{M_{12}^q r_q^2 e^{2i\theta_q}}\right) = \text{Im}\left[\frac{\Gamma_{12}^q}{M_{12}^q (1 + h_q e^{2i\sigma_q})}\right] \quad \Delta\Gamma_s = \Delta\Gamma_s^{\text{SM}} \cos^2 2\theta_s$$



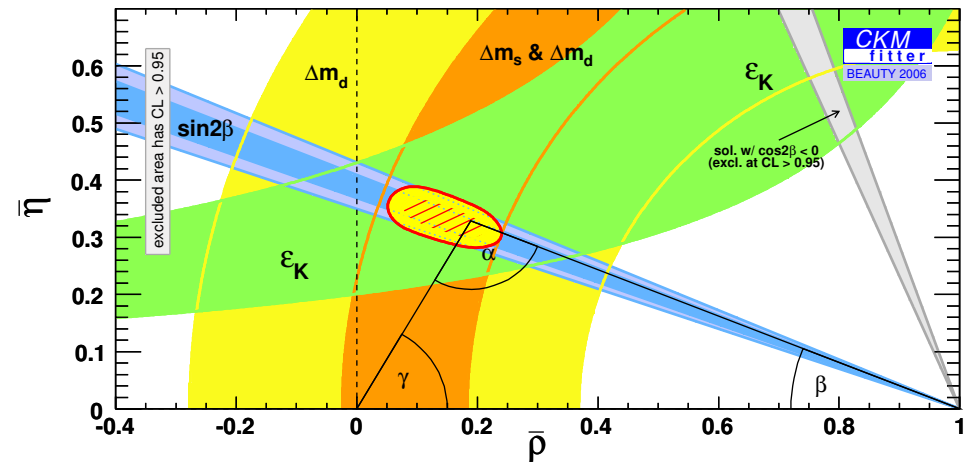
Constraining new physics in loops

- B factories determined $\bar{\rho}, \bar{\eta}$ from (effectively) tree-level & loop-induced processes

Tree-level



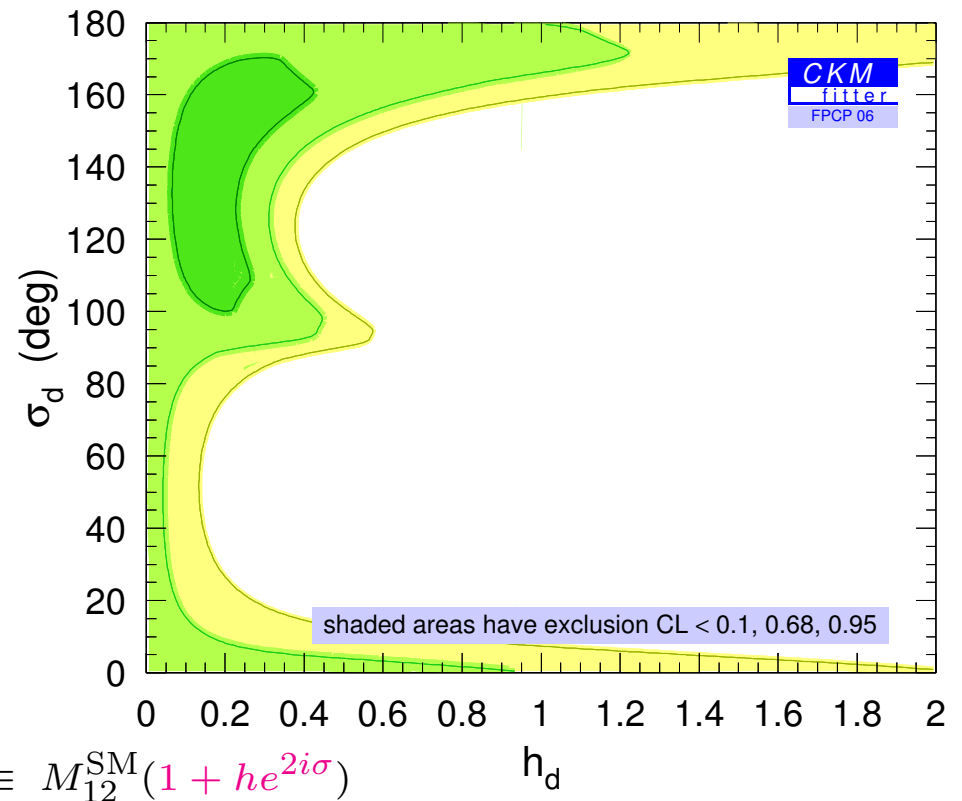
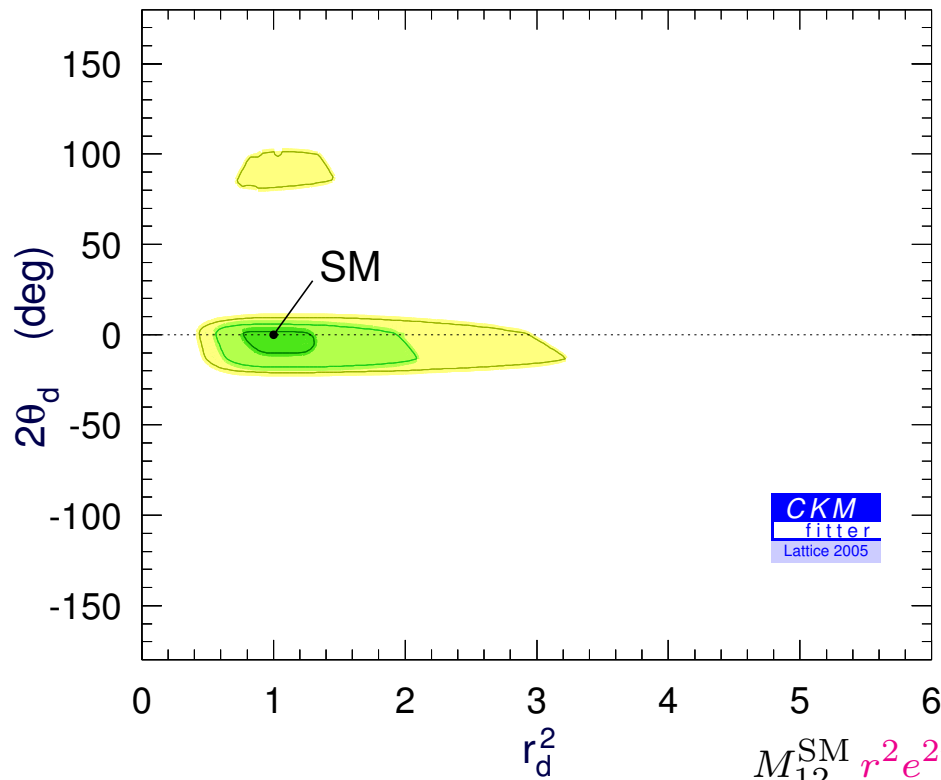
Loop-induced



- $\bar{\rho}, \bar{\eta}$ constrained to SM region even in the presence of NP in loops
 - $\epsilon_K, \Delta m_d, \Delta m_s$, etc., can be used to overconstrain the SM and test for NP
- NP: more parameters \Rightarrow independent measurements critical



The parameters r_d^2 , θ_d and h_d , σ_d



r_d^2, θ_d : $|M_{12}/M_{12}^{\text{SM}}|$ can only differ significantly from 1 if $\arg(M_{12}/M_{12}^{\text{SM}}) \sim 0$

h_d, σ_d : NP may still be comparable to SM: $h_d = 0.23^{+0.57}_{-0.23}$, i.e., $h_d < 1.7$ (95% CL)

- $\mathcal{O}(20\%)$ non-SM contributions to most loop-mediated transitions are still allowed

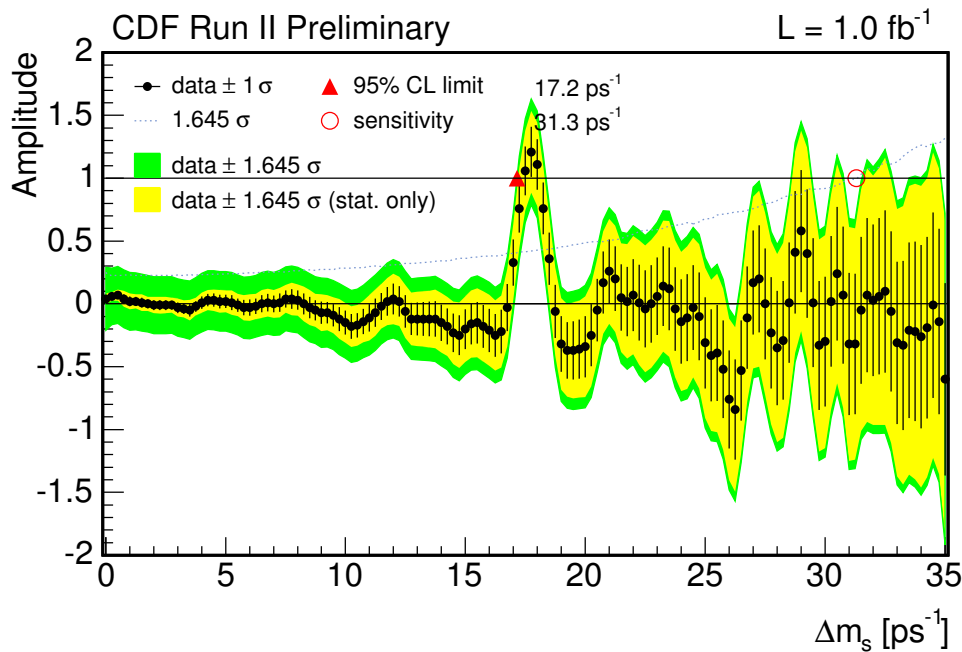


The news of the year: Δm_s

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

A 5.4σ measurement

[CDF, hep-ex/0609040]



Uncertainty $\sigma(\Delta m_s) = 0.7\%$ is already smaller than $\sigma(\Delta m_d) = 0.8\%$!

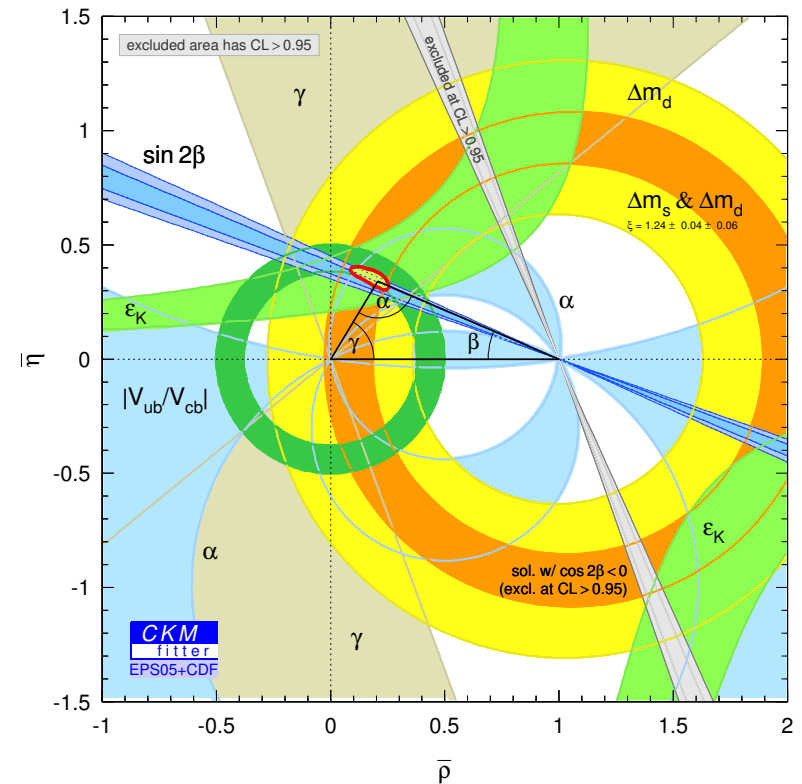
- Largest uncertainty: $\xi = \frac{f_{B_s} \sqrt{B_s}}{f_{B_d} \sqrt{B_d}}$ [Grinstein et al., '92]

Chiral logs: $\xi \sim 1.2$

[Grinstein et al., '92]

SM CKM fit: $\xi = 1.158^{+0.096}_{-0.064}$

Using $\xi_{\text{LQCD}} = 1.24 \pm 0.04 \pm 0.06$

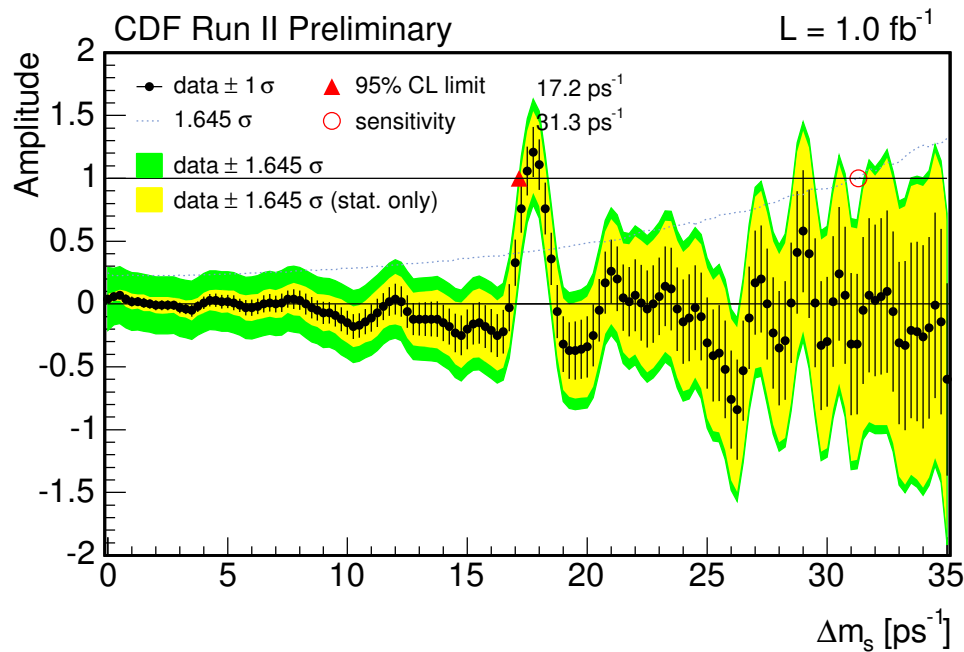


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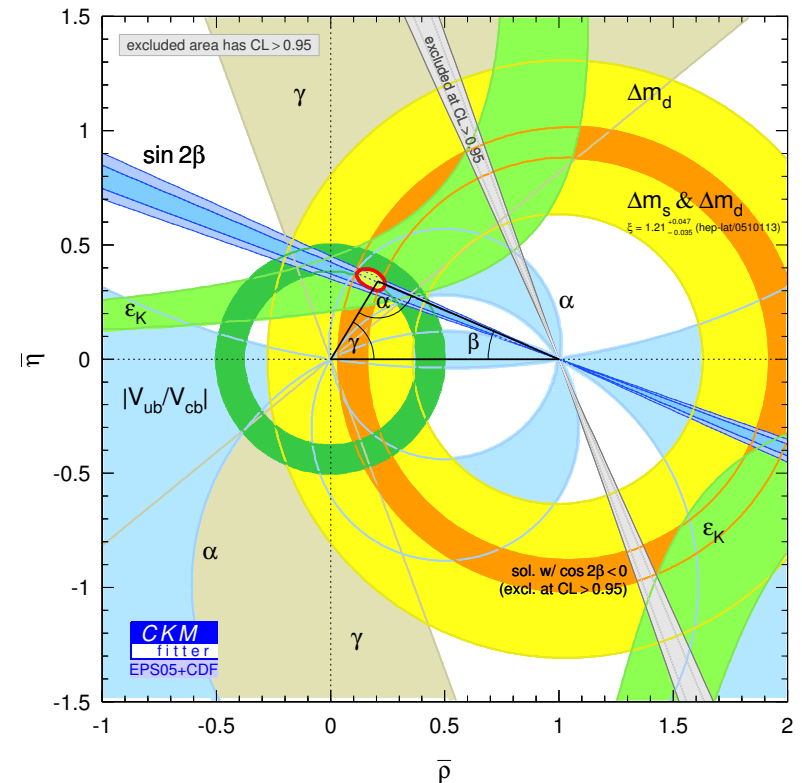
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Chiral logs: $\xi \sim 1.2$

[Grinstein et al., '92]

SM CKM fit: $\xi = 1.158^{+0.096}_{-0.064}$

Using $\xi_{\text{LQCD}} = 1.21^{+0.047}_{-0.035}$ [HPQCD+JLQCD]

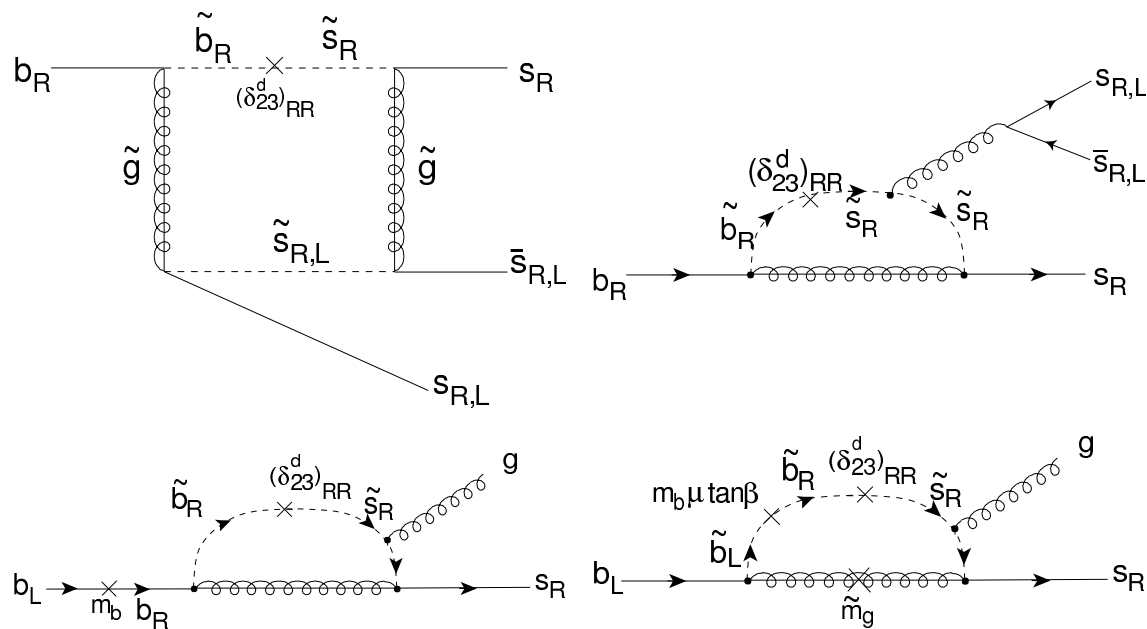


E.g.: models to enhance Δm_s

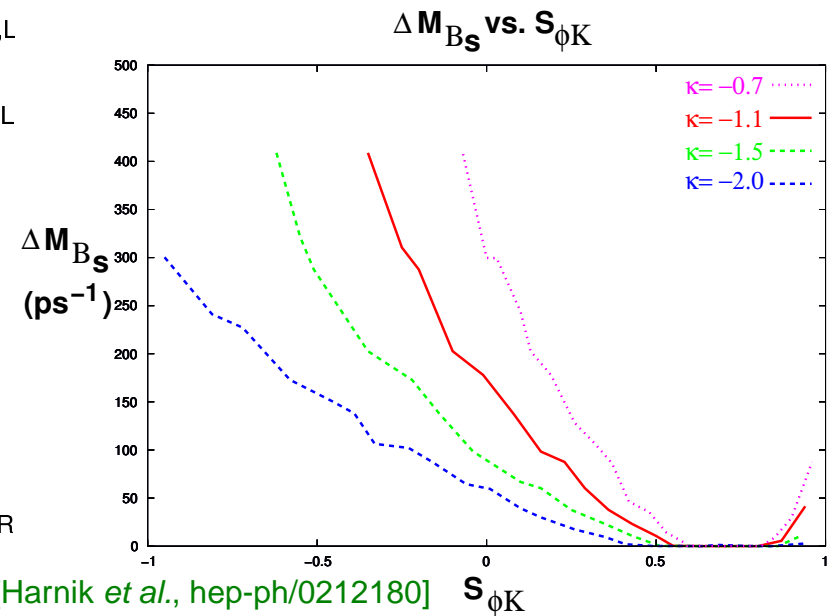
- SUSY GUTs: near maximal $\nu_\mu - \nu_\tau$ mixing may imply large mixing between s_R and b_R , and between \tilde{s}_R and \tilde{b}_R

Mixing among right-handed quarks drop out from CKM matrix, but among right-handed squarks it is physical

$$\begin{pmatrix} \tilde{s}_R \\ \tilde{s}_R \\ \tilde{s}_R \\ \tilde{\nu}_\mu \\ \tilde{\mu} \end{pmatrix} \longleftrightarrow \begin{pmatrix} \tilde{b}_R \\ \tilde{b}_R \\ \tilde{b}_R \\ \tilde{\nu}_\tau \\ \tilde{\tau} \end{pmatrix}$$



$\mathcal{O}(1)$ effects in $b \rightarrow s$ possible



E.g.: models to suppress Δm_s

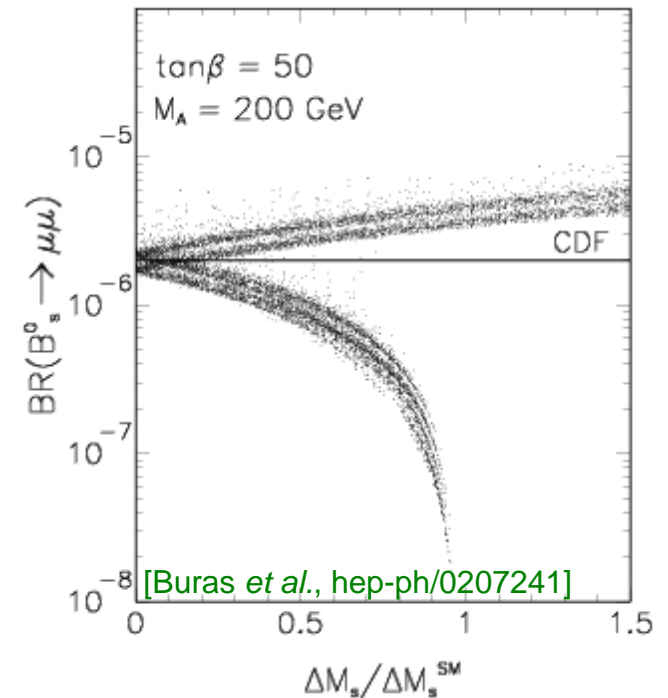
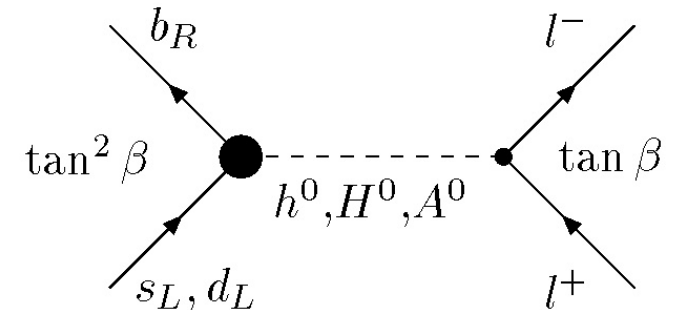
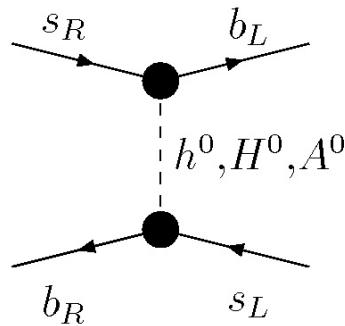
- Neutral Higgs mediated FCNC in the large $\tan \beta$ region:

Enhancement of $\mathcal{B}(B_{d,s} \rightarrow \mu^+ \mu^-) \propto \tan^6 \beta$ up to two orders of magnitude above the SM

CDF: $\mathcal{B}(B_s \rightarrow \mu^+ \mu^-) < 8 \times 10^{-8}$ (90% CL)

SM: 3.4×10^{-9} — measurable at LHC

Suppression of $\Delta m_s \propto \tan^4 \beta$ in a correlated way

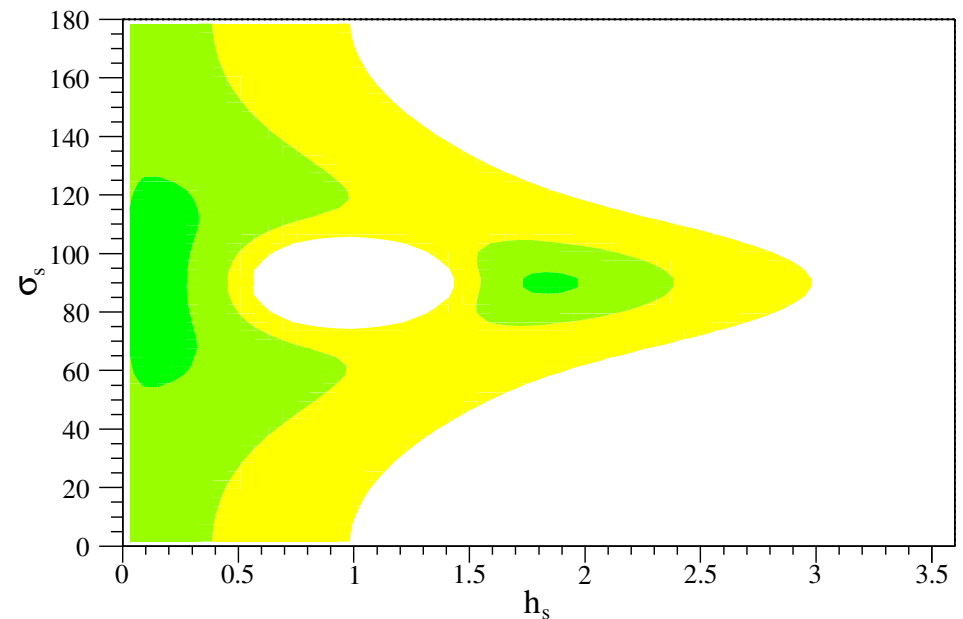
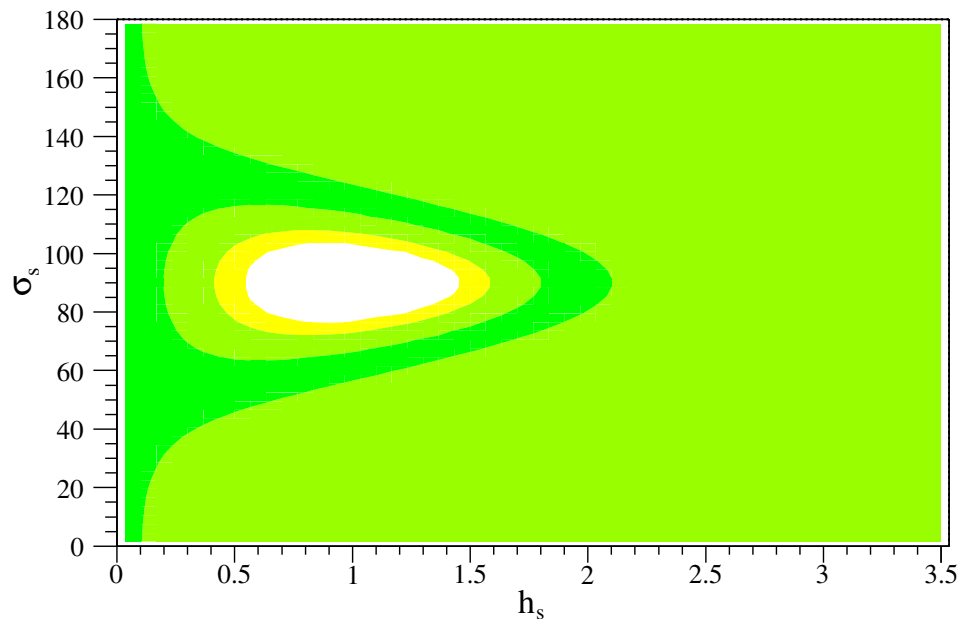


New physics in $B_s^0 \bar{B}_s^0$ mixing

- Constraints before (left) and after (right) measurement of Δm_s (and $\Delta \Gamma_s$)

Recall parameterization: $M_{12} = M_{12}^{\text{SM}} (1 + h_s e^{2i\sigma_s})$

[ZL, Papucci, Perez, hep-ph/0604112]



- To learn more about the B_s system, need data on CP asymmetry in $B_s \rightarrow J/\psi \phi$

and better constraint on $A_{\text{SL}}^s = \frac{\Gamma[\bar{B}_s^0(t) \rightarrow \ell^+ X] - \Gamma[B_s^0(t) \rightarrow \ell^- X]}{\Gamma[\bar{B}_s^0(t) \rightarrow \ell^+ X] + \Gamma[B_s^0(t) \rightarrow \ell^- X]}$

[see also: Buras *et al.*, hep-ph/0604057; Grossman, Nir, Raz, hep-ph/0605028]



Next milestone: $S_{B_s \rightarrow \psi\phi}$

- Plot $S_{\psi\phi} = \text{its SM value} \pm 0.10 / \pm 0.03$

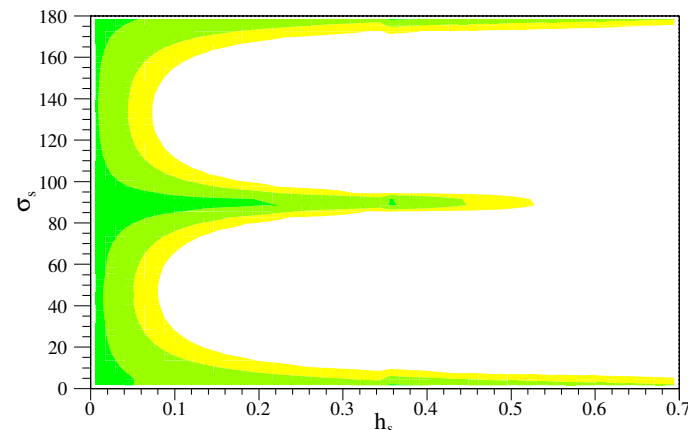
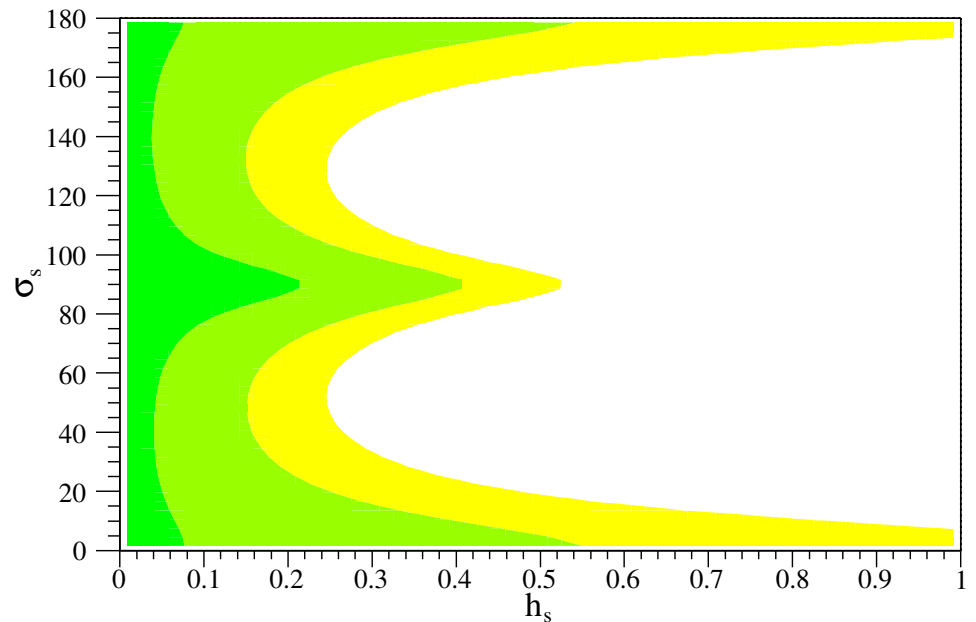
0.1/1 yr of nominal LHCb data \Rightarrow

- $S_{\psi\phi}$ ($\sin 2\beta_s$ for CP -even) is analog of $S_{\psi K}$, similarly clean theoretically

SM: $\beta_s = \arg(-V_{ts}V_{tb}^*/V_{cs}V_{cb}^*) = \mathcal{O}(\lambda^2)$

CKM fit predicts: $\sin 2\beta_s = 0.0346^{+0.0026}_{-0.0020}$

- Unless there is an easy-to-find narrow resonance at ATLAS & CMS, this could be one of the most interesting early measurements



[ZL, Papucci, Perez, hep-ph/0604112]



Some recent developments

(Go from theoretically simpler to more complex)

Important features of the SM

- The SM flavor structure is very special:
 - Single source of CP violation in CC interactions
 - Suppressions due to hierarchy of mixing angles
 - Suppression of FCNC processes (loops)
 - Suppression of FCNC chirality flips by quark masses (e.g., $S_{K^*\gamma}$)

Many suppressions that NP might not respect \Rightarrow sensitivity to very high scales

- It is interesting / worthwhile / possible to test all of these
-

- Need broad program — there isn't just a single critical measurement

Challenging field theory — many energy scales / expansions



CPV in $b \rightarrow s$ penguin decays

- Measuring same angle in decays sensitive to different short distance physics
 \Rightarrow Good sensitivity to NP ($f_s = \phi K_S, \eta' K_S, \text{etc.}$)

- Amplitudes with one weak phase dominate — theor. clean:

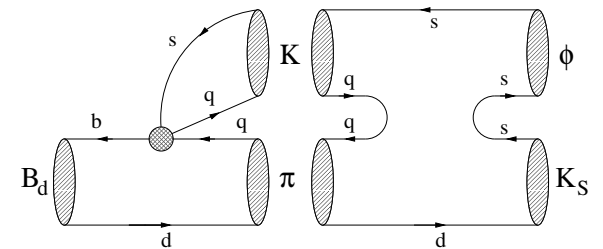
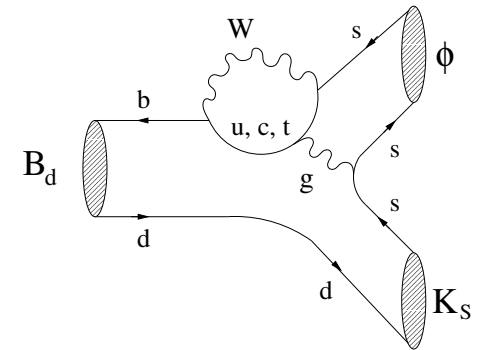
$$\bar{A} = \underbrace{V_{cb}V_{cs}^*}_{\mathcal{O}(\lambda^2)} \underbrace{\langle \text{“P”} \rangle}_1 + \underbrace{V_{ub}V_{us}^*}_{\mathcal{O}(\lambda^4)} \underbrace{\langle \text{“P} + T_u \text{”} \rangle}_{\mathcal{O}(1)}$$

SM: expect: $S_{f_s} - S_{\psi K}$ and $C_{f_s} (= -A_{f_s}) \lesssim 0.05$
 How small? Calculate $\langle \text{“P”} \rangle / \langle \text{“P} + T_u \text{”} \rangle$

NP: $S_{f_s} \neq S_{\psi K}$ possible; expect mode-dependent S_f
 Depend on size & phase of SM and NP amplitude

NP could enter $S_{\psi K}$ mainly in mixing, while S_{f_s} through both mixing and decay

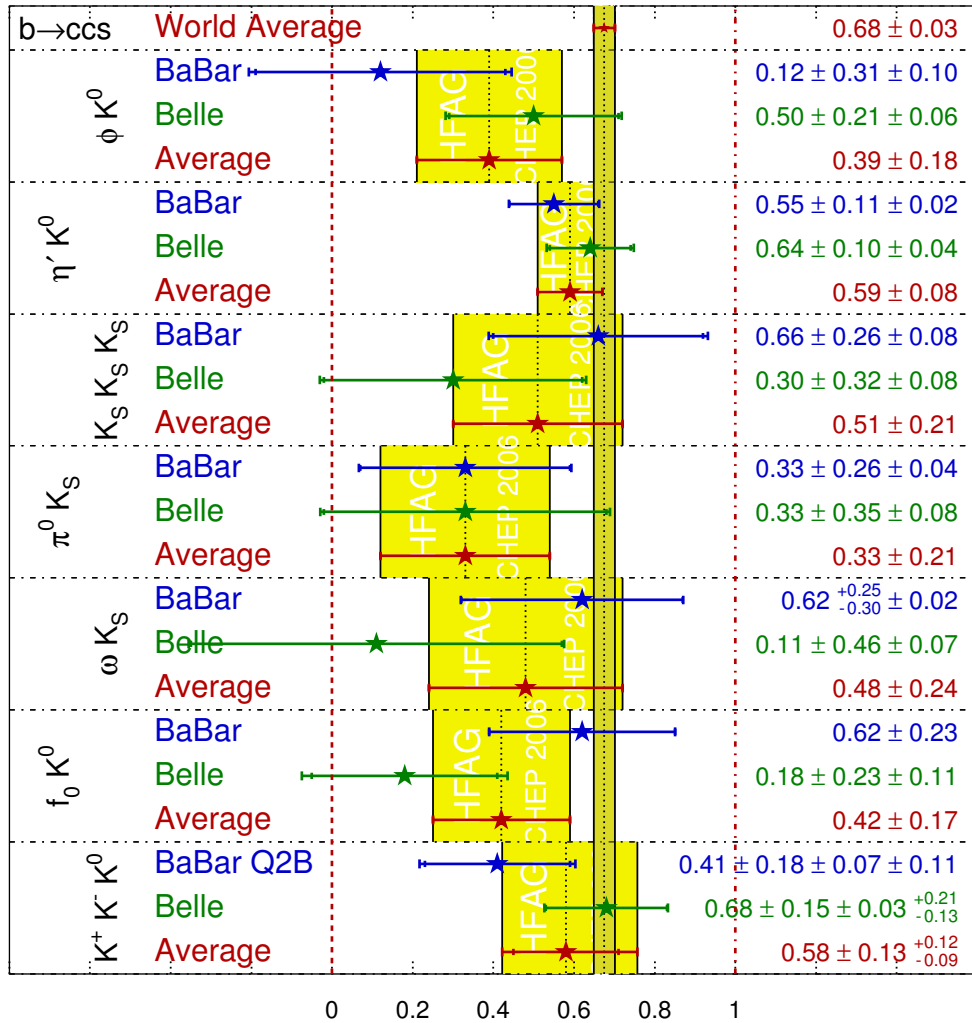
- Interesting to pursue independent of present results — there is room for NP



Is there NP in $b \rightarrow s$ transitions?

$\sin(2\beta^{\text{eff}}) \equiv \sin(2\phi_1^{\text{eff}})$

ICHEP 2006 PRELIMINARY



- SM: expect $S_{f_s} - S_{\psi K} \lesssim 0.05$
- NP: $S_{f_s} \neq S_{\psi K}$ possible (mode-dep.)
- Smallest exp. errors: $\eta' K_S$ and ϕK_S
- All calculations find < few % SM pollution [Buchalla *et al.*; Beneke; Williamson & Zupan]
- Will significance of deviations from $S_{\psi K}$ (all below) increase / decrease?
- Improved theory may allow in future to constrain specific NP models / parameters via pattern of deviations



α from $B \rightarrow \rho\rho, \rho\pi, \pi\pi$

- $S_{\rho^+\rho^-} = \sin[(B\text{-mix} = -2\beta) + (\bar{A}/A = -2\gamma + \dots) + \dots] = \sin(2\alpha) + \text{small}$

(1) Longitudinal polarization (CP -even) dominates

(2) Small rate: $\mathcal{B}(B \rightarrow \rho^0\rho^0) = (1.16 \pm 0.46) \times 10^{-6} \Rightarrow \text{small } \Delta\alpha$

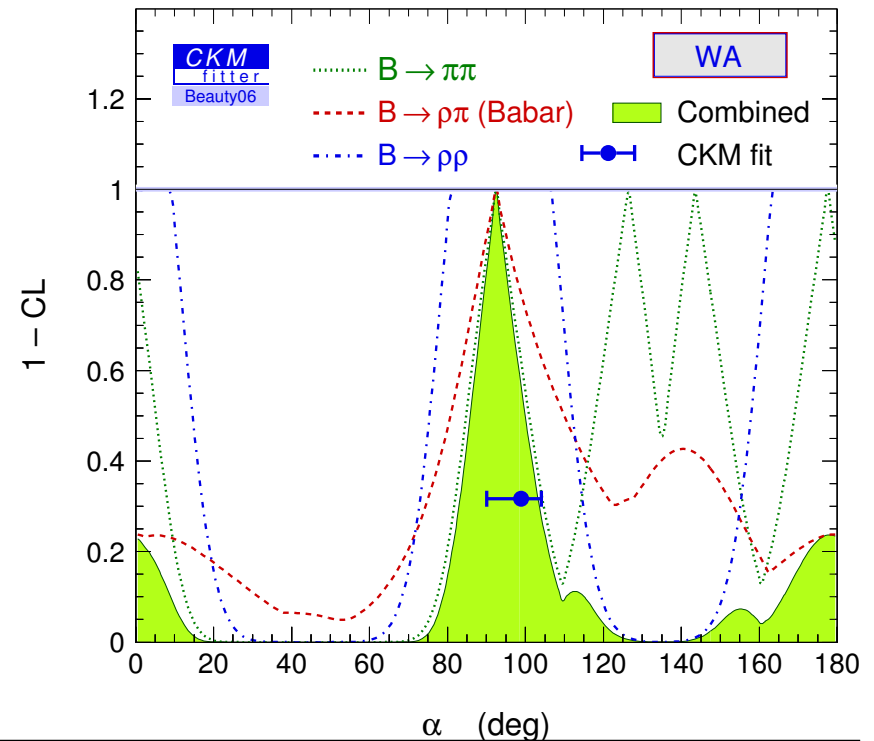
$$\frac{\mathcal{B}(B \rightarrow \pi^0\pi^0)}{\mathcal{B}(B \rightarrow \pi^+\pi^0)} = 0.23 \pm 0.04 \text{ vs. } \frac{\mathcal{B}(B \rightarrow \rho^0\rho^0)}{\mathcal{B}(B \rightarrow \rho^+\rho^0)} = 0.06 \pm 0.03 \text{ — observed in 2006}$$

- Before 2006 $B \rightarrow \rho\rho$ dominated

All three modes important now

$\rho\rho$ is more complicated than $\pi\pi$, $I = 1$ possible due to $\Gamma_\rho \neq 0$; its $\mathcal{O}(\Gamma_\rho^2/m_\rho^2)$ effects can be constrained with more data [Falk *et al.*]

- All measurements combined: $\alpha = (93_{-9}^{+11})^\circ$



γ from $B^\pm \rightarrow DK^\pm$

- Tree level: interfere $b \rightarrow c$ ($B^- \rightarrow D^0 K^-$) and $b \rightarrow u$ ($B^- \rightarrow \bar{D}^0 K^-$)
 Need $D^0, \bar{D}^0 \rightarrow$ same final state; determine B and D decay amplitudes from data

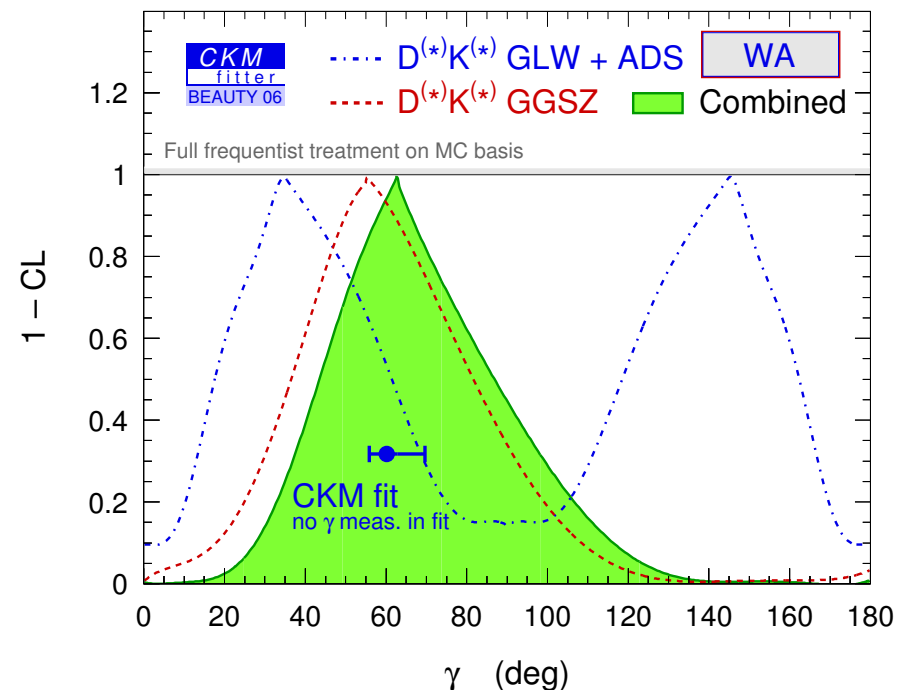
Sensitivity driven by: $r_B = |A(B^- \rightarrow \bar{D}^0 K^-)/A(B^- \rightarrow D^0 K^-)| \sim 0.1 - 0.2$

Central value of r_B decreased in 2006

- Before 2006 Dalitz plot analysis in $D^0, \bar{D}^0 \rightarrow K_S \pi^+ \pi^-$ dominated [Giri *et al.*; Bondar]

Variants according to D decay; comparable results now

- All measurements combined: $\gamma = (62^{+38}_{-24})^\circ$
 \Rightarrow Need a lot more data



inclusive processes

B physics has been fertile ground for theoretical developments:

HQET, ChPT, SCET, Lattice QCD, ...

Remark: hadronic uncertainties

- To believe **discrepancy = new physics**, need model independent predictions:

$$\text{Quantity of interest} = (\text{calculable prefactor}) \times \left[1 + \sum_k (\text{small parameters})^k \right]$$

Theoretical uncertainty is parametrically suppressed by $\sim (\text{small parameter})^N$, but models may be used to estimate the uncertainty

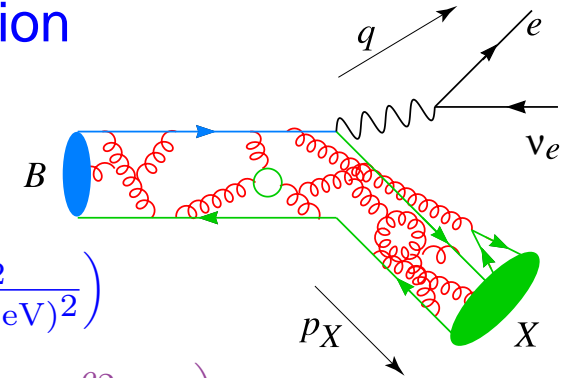
- Most of the recent progress comes from expanding in powers of $\Lambda/m_Q, \alpha_s(m_Q)$
... a priori not known whether $\Lambda \sim 200\text{MeV}$ or $\sim 2\text{GeV}$ ($f_\pi, m_\rho, m_K^2/m_s$)
... need experimental guidance to see which cases work how well



Determination of $|V_{cb}|$ from inclusive decays

- Theoretically cleanest application of heavy quark expansion

$$\Gamma(B \rightarrow X_c \ell \bar{\nu}) = \frac{G_F^2 |V_{cb}|^2}{192\pi^3} \left(\frac{m_Y}{2}\right)^5 (0.534) \times \left[1 \right. \\ - 0.22 \left(\frac{\Lambda_{1S}}{500 \text{ MeV}}\right) - 0.011 \left(\frac{\Lambda_{1S}}{500 \text{ MeV}}\right)^2 - 0.052 \left(\frac{\lambda_1}{(500 \text{ MeV})^2}\right) - 0.071 \left(\frac{\lambda_2}{(500 \text{ MeV})^2}\right) \\ - 0.006 \left(\frac{\lambda_1 \Lambda_{1S}}{(500 \text{ MeV})^3}\right) + 0.011 \left(\frac{\lambda_2 \Lambda_{1S}}{(500 \text{ MeV})^3}\right) - 0.006 \left(\frac{\rho_1}{(500 \text{ MeV})^3}\right) + 0.008 \left(\frac{\rho_2}{(500 \text{ MeV})^3}\right) \\ + 0.011 \left(\frac{T_1}{(500 \text{ MeV})^3}\right) + 0.002 \left(\frac{T_2}{(500 \text{ MeV})^3}\right) - 0.017 \left(\frac{T_3}{(500 \text{ MeV})^3}\right) - 0.008 \left(\frac{T_4}{(500 \text{ MeV})^3}\right) \\ \left. + 0.096\epsilon - 0.030\epsilon_{\text{BLM}}^2 + 0.015\epsilon \left(\frac{\Lambda_{1S}}{500 \text{ MeV}}\right) + \dots \right]$$



[Trott *et al.*; Buchmüller & Flacher]

Corrections: $\mathcal{O}(\Lambda/m)$: $\sim 20\%$, $\mathcal{O}(\Lambda^2/m^2)$: $\sim 5\%$, $\mathcal{O}(\Lambda^3/m^3)$: $\sim 1 - 2\%$,
 $\mathcal{O}(\alpha_s)$: $\sim 10\%$, Unknown terms: $< 2\%$

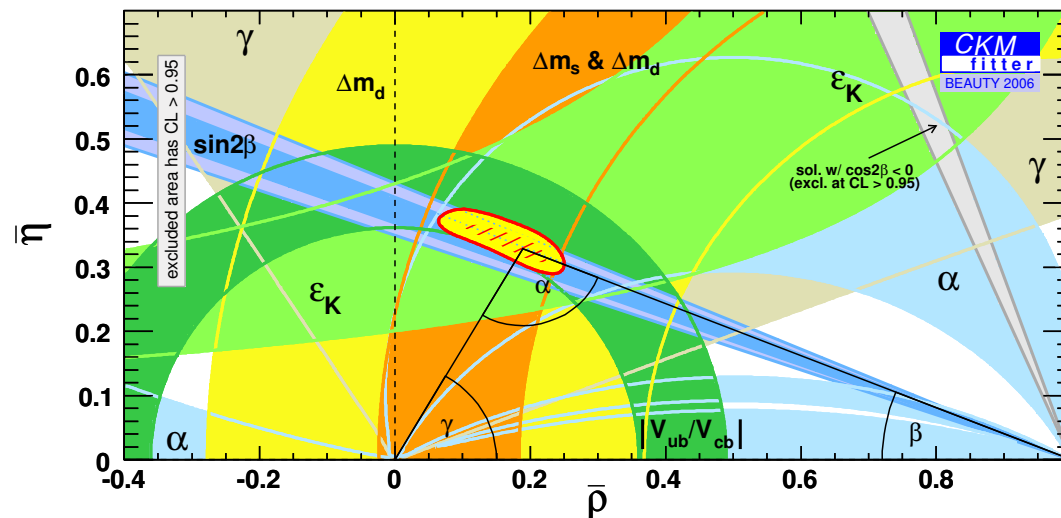
~ 90 observables: consistent fit to hadronic matrix elements and $|V_{cb}|$; test theory

- $|V_{cb}| = (41.7 \pm 0.7) \times 10^{-3}$, $< 2\%$ error, important for ϵ_K (error $\propto |V_{cb}|^4$) & $K \rightarrow \pi \nu \bar{\nu}$



$|V_{ub}|$ from inclusive $B \rightarrow X_u \ell \bar{\nu}$

- Phase space cuts required to suppress $b \rightarrow c \ell \bar{\nu}$ background complicate theory:
Lower scales, dependence on nonperturbative functions (rather than numbers)
Renormalization of shape function and structure of subleading terms complicated
[Bauer & Manohar; Bosch, Lange, Neubert, Paz; Lee & Stewart; etc.]
- “B-beam” technique + use of several kinematic variables: E_ℓ, m_X, q^2, P_+
- Inclusive average $|V_{ub}| = (4.49 \pm 0.19 \pm 0.27) \times 10^{-3} > \text{CKM fit } (3.7 \pm 0.1) \times 10^{-3}$



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- Exclusive determinations from $B \rightarrow \pi \ell \nu$ lower (larger errors)

– Lattice QCD ($q^2 > 16 \text{ GeV}^2$): $|V_{ub}| = (3.7 \pm 0.3_{-0.4}^{+0.6}) \times 10^{-3}$

[HPQCD & FNAL]

– Lattice & dispersion relation: $|V_{ub}| = (4.0 \pm 0.5) \times 10^{-3}$

[Arnesen et al.; Becher & Hill]

– Light-cone SR: $|V_{ub}| = (3.4 \pm 0.1_{-0.4}^{+0.6}) \times 10^{-3}$

[Ball, Zwicky; Braun et al.; Colangelo, Khodjamirian]

- Statistical fluctuation? Inclusive average optimistic? Something more interesting?

Understanding the $B \rightarrow \pi \ell \bar{\nu}$ form factor also important for $B \rightarrow \pi\pi, K\pi$ decays



Inclusive $B \rightarrow X_s \gamma$

- One (if not “the”) most elaborate SM calculations
Constrains many models: 2HDM, SUSY, LRSM, etc.
- NNLO practically completed [Misiak et al., hep-ph/0609232]
4-loop running, 3-loop matching and matrix elements

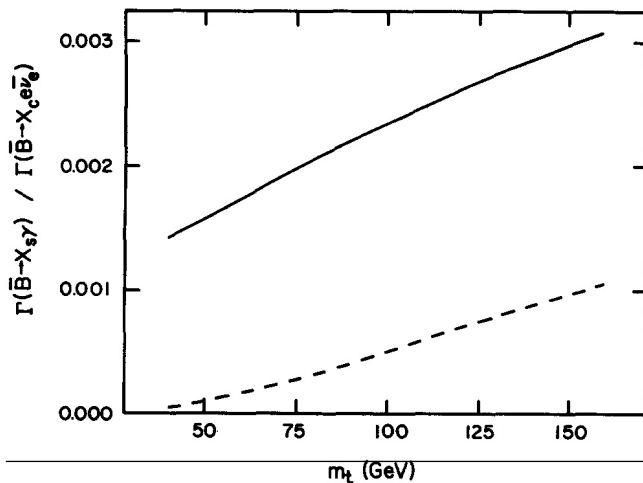
Scale dependences significantly reduced \Rightarrow

measurement: $(3.55 \pm 0.26) \times 10^{-4}$

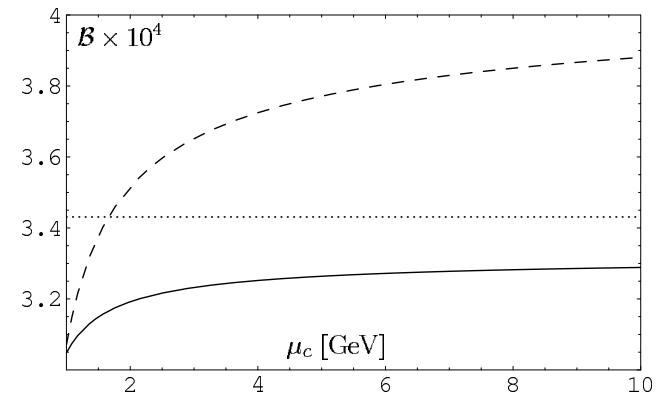
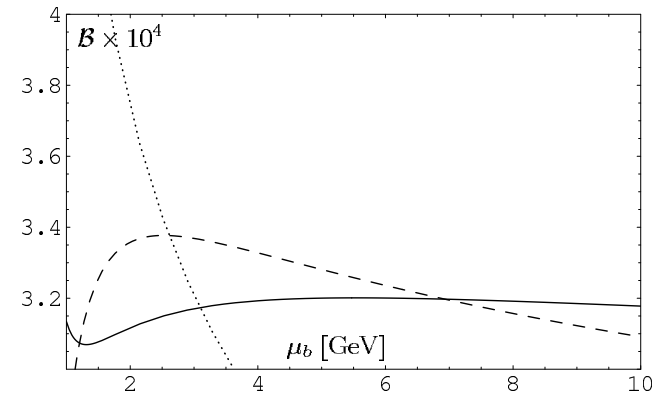
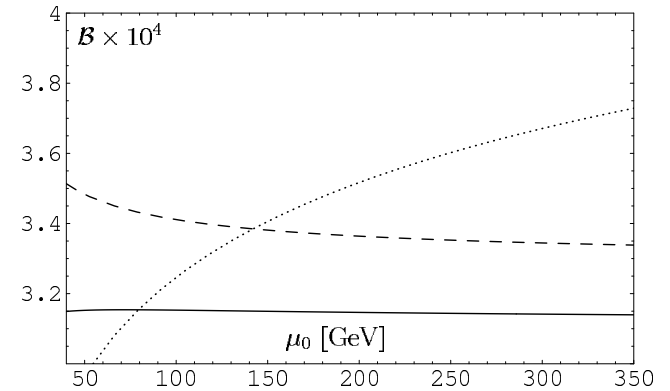
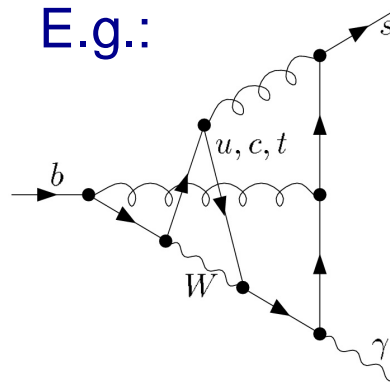
- $\mathcal{B}(B \rightarrow X_s \gamma) \Big|_{E_\gamma > 1.6 \text{ GeV}} = (3.15 \pm 0.23) \times 10^{-4}$

[Effect of E_γ cut: talk by Becher]

B. Grinstein et al. / \bar{B} -meson decay [1990]

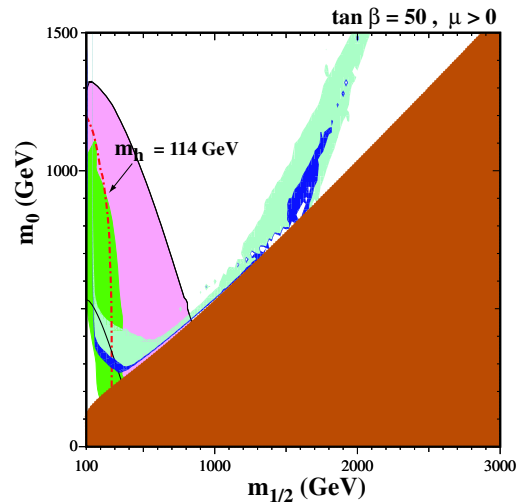
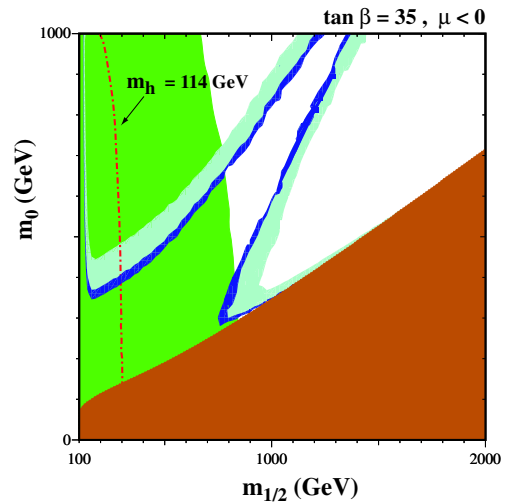
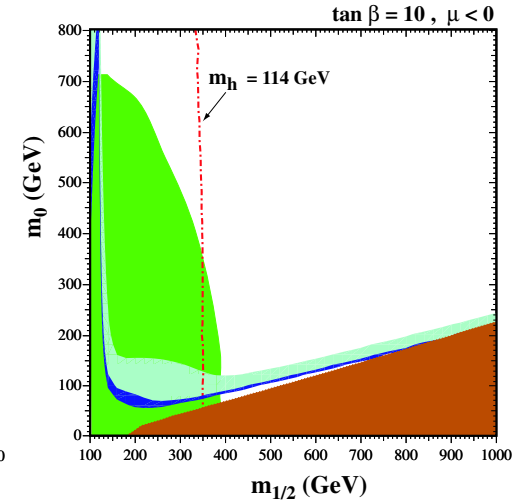
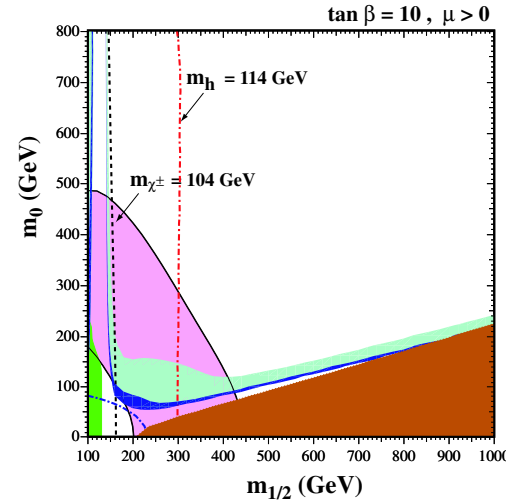


E.g.:



$B \rightarrow X_s \gamma$ and neutralino dark matter

- **Green:** excluded by $B \rightarrow X_s \gamma$
- Brown:** excluded (charged LSP)
- Magenta:** favored by $g_\mu - 2$
- Blue:** favored by $\Omega_\chi h^2$ from WMAP
- **Analyses assume constrained MSSM**
- If either $S_{\eta'K} \neq \sin 2\beta$ or $S_{K^*\gamma} \neq 0$, then has to be redone
- Then $B \rightarrow X_s \ell^+ \ell^-$ and $B_s \rightarrow \mu\mu$ may give complementary constraints



[Ellis, Olive, Santoso, Spanos]



Inclusive $B \rightarrow X_s \ell^+ \ell^-$

- Rate depends on

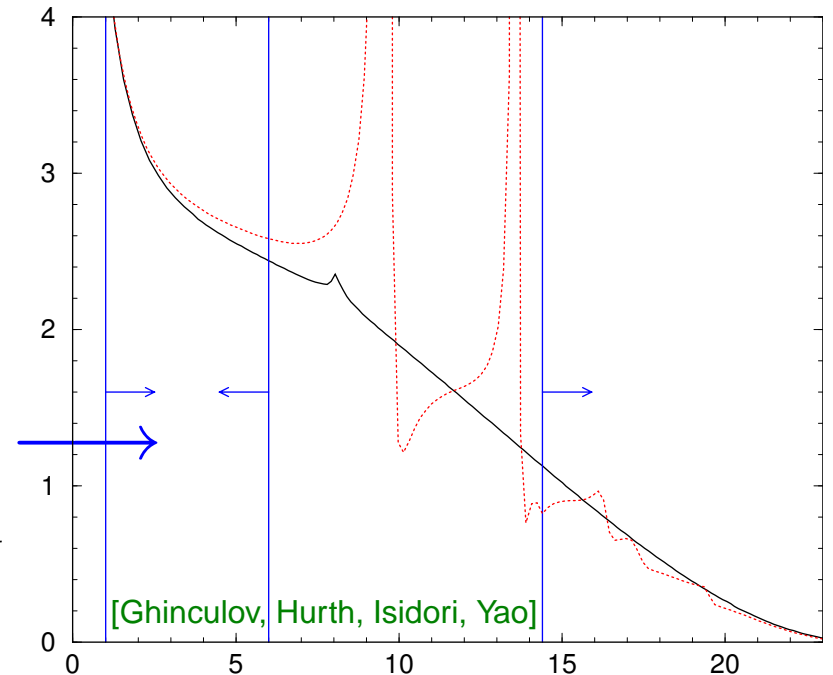
$$O_7 = m_b \bar{s} \sigma_{\mu\nu} e F^{\mu\nu} P_R b,$$

$$O_9 = e^2 (\bar{s} \gamma_\mu P_L b) (\bar{\ell} \gamma^\mu \ell),$$

$$O_{10} = e^2 (\bar{s} \gamma_\mu P_L b) (\bar{\ell} \gamma^\mu \gamma_5 \ell)$$

Theory most precise for $1 \text{ GeV}^2 < q^2 < 6 \text{ GeV}^2$

Experiments need additional cut $m_{X_s} \lesssim 2 \text{ GeV}$
to suppress $b \rightarrow c(\rightarrow s \ell^+ \nu) \ell^- \bar{\nu}$ background



- Rate in this region is determined by B light-cone distribution function (“shape fn”)
Theory similar to measurement of $|V_{ub}|$ from $B \rightarrow X_u \ell \bar{\nu}$ (and related to $B \rightarrow X_s \gamma$)

[Lee, ZL, Stewart, Tackmann]

- Sensitivity to NP survives after taking into account hadronic effects



Many other interesting rare B decays

- Important probes of new physics

- $B \rightarrow K^* \gamma$ or $X_s \gamma$: Best m_{H^\pm} limits in 2HDM — in SUSY many param's
- $B \rightarrow K^{(*)} \ell^+ \ell^-$ or $X_s \ell^+ \ell^-$: bsZ penguins, SUSY, right handed couplings

A crude guide ($\ell = e$ or μ)

Decay	\sim SM rate	physics examples
$B \rightarrow s \gamma$	3×10^{-4}	$ V_{ts} , H^\pm, \text{SUSY}$
$B \rightarrow \tau \nu$	1×10^{-4}	$f_B V_{ub} , H^\pm$
$B \rightarrow s \nu \nu$	4×10^{-5}	new physics
$B \rightarrow s \ell^+ \ell^-$	5×10^{-6}	new physics
$B_s \rightarrow \tau^+ \tau^-$	1×10^{-6}	
$B \rightarrow s \tau^+ \tau^-$	5×10^{-7}	⋮
$B \rightarrow \mu \nu$	5×10^{-7}	
$B_s \rightarrow \mu^+ \mu^-$	4×10^{-9}	
$B \rightarrow \mu^+ \mu^-$	2×10^{-10}	

Replacing $b \rightarrow s$ by $b \rightarrow d$ costs a factor ~ 20 (in SM); interesting to test in both: rates, CP asymmetries, etc.

In $B \rightarrow q l_1 l_2$ decays expect 10–20% K^*/ρ , and 5–10% K/π (model dept)

Many of these (cleanest inclusive ones) impossible at hadron colliders



Nonleptonic decays: the Λ_b lifetime

- OPE has been thought to be less reliable in non-leptonic than semileptonic decay (local duality)

Prediction

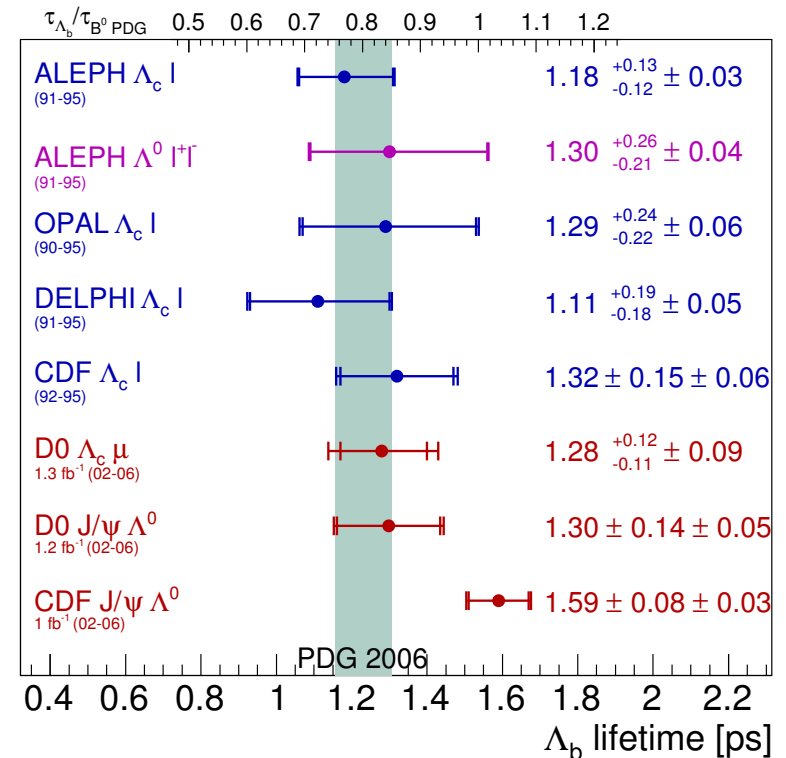
Data (PDG)

$$\frac{\tau_{\Lambda_b}}{\tau_{B^0}} = 1 + \mathcal{O}\left(\frac{\Lambda^2}{m_b^2}, 16\pi^2 \frac{\Lambda^3}{m_b^3}\right) = 0.80 \pm 0.05$$

Hard to accommodate $\tau_{\Lambda_b}/\tau_{B^0}$ much below 0.9

[Bigi *et al.*; Neubert & Sachrajda; Gabbiani, Onishchenko, Petrov, ...]

Recent CDF measurement 3σ from PDG



- How this settles will affect our estimate of the uncertainty of the calculation of $\Delta\Gamma_s$ (In addition to perturbative uncertainty and that in matrix elements [from LQCD])



exclusive processes

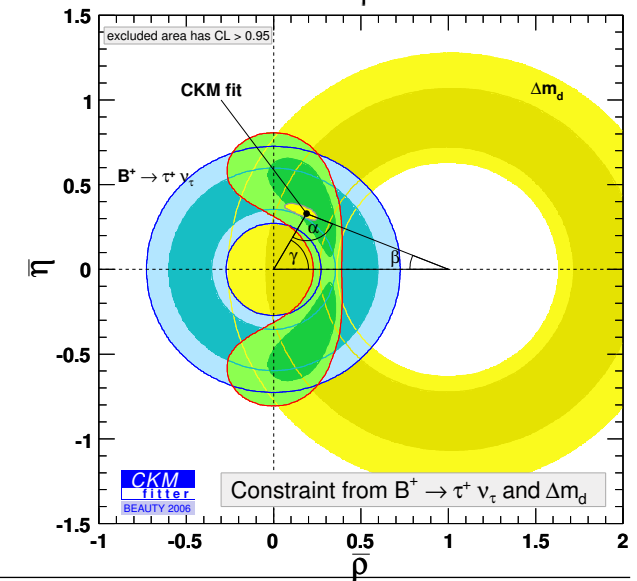
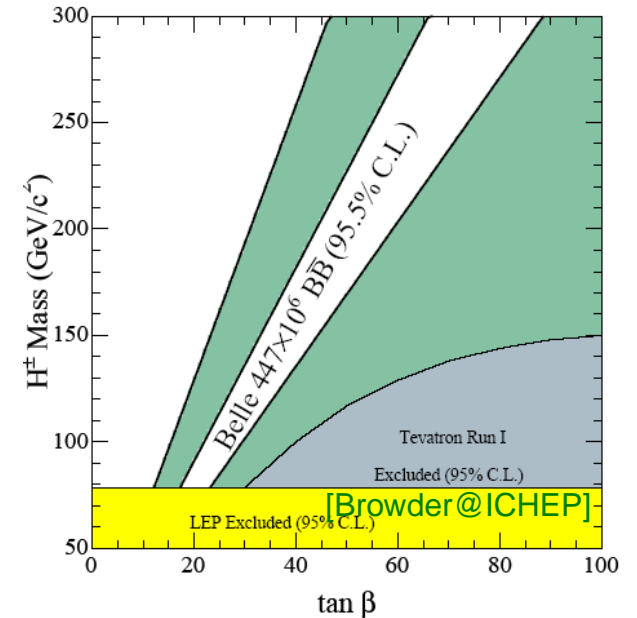
Discovery of $B \rightarrow \tau \nu$

- A new operator not previously constrained
- Sensitive to tree-level charged Higgs contribution

Data: $\mathcal{B}(B^+ \rightarrow \tau^+ \nu) = (1.34 \pm 0.48) \times 10^{-4}$

- If experimental error small: $\Gamma(B \rightarrow \tau \nu) / \Delta m_d$ determines $|V_{ub}/V_{td}|$ independent of f_B (left with B_d error)
- If error of f_B small: two circles that intersect at $\alpha \sim 90^\circ$
- Error of $\Gamma(B \rightarrow \tau \nu)$ will improve incrementally
- With a super B factory (+LHCb+CLEO-c), a Grinstein-type double ratio can minimize uncertainties:

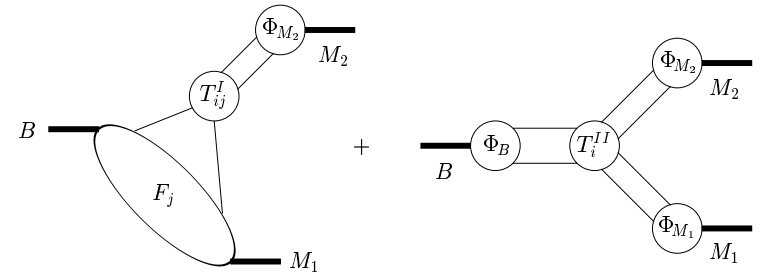
$$\frac{\mathcal{B}(B \rightarrow \ell \bar{\nu})}{\mathcal{B}(B_s \rightarrow \ell^+ \ell^-)} \times \frac{\mathcal{B}(D_s \rightarrow \ell \bar{\nu})}{\mathcal{B}(D \rightarrow \ell \bar{\nu})} = \text{calculable to few \%}$$



Factorization in charmless $B \rightarrow M_1 M_2$

- BBNS (QCDF) proposal [Beneke, Buchalla, Neubert, Sachrajda]

$$\langle \pi\pi | O_i | B \rangle \sim F_{B \rightarrow \pi} T(x) \otimes \phi_\pi(x) + T(\xi, x, y) \otimes \phi_B(\xi) \otimes \phi_\pi(x) \otimes \phi_\pi(y)$$



- KLS (pQCD) proposal involve only ϕ_B & $\phi_{M_{1,2}}$, with k_\perp dependence [Keum, Li, Sanda]

- SCET: $\langle \pi\pi | O_i | B \rangle \sim A_{c\bar{c}} + \sum_{ij} T(x, y) \otimes \left[J_{ij}(x, z_k, k_\ell^+) \otimes \phi_\pi^i(z_k) \phi_B^j(k_\ell^+) \right] \otimes \phi_\pi(y)$

- In practice, relate some convolutions to the measurable $B \rightarrow M_{1,2}$ form factors
Selfconsistency between many nonleptonic (and/or semileptonic) rates

Open issues — theoretical challenges:

- Is the second term suppressed by α_s compared to the first one?
- Are charm penguins perturbatively calculable?
- Role and regularization of certain seemingly divergent convolutions?



SCET in a nutshell

- Effective field theory for processes involving energetic hadrons, $E \gg \Lambda$

[Bauer, Fleming, Luke, Pirjol, Stewart, + ...]

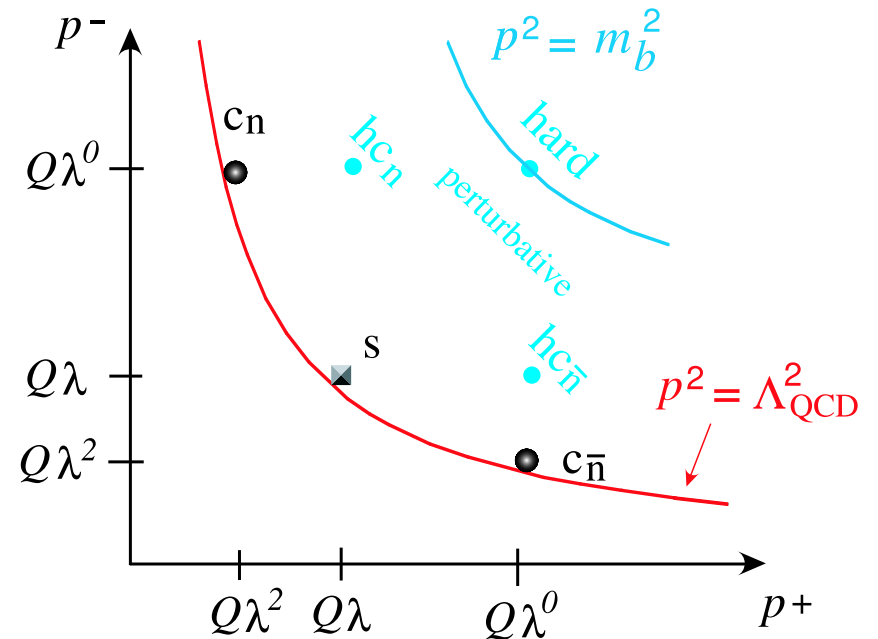
- Expand in $\Lambda^2 \ll \Lambda E \ll E^2$, separate scales
[light-cone variables: (p_-, p_+, p_\perp)]

Introduce distinct fields for relevant degrees of freedom; power counting in λ

SCET_I: $\lambda = \sqrt{\Lambda/E}$ — jets ($m \sim \Lambda E$)

SCET_{II}: $\lambda = \Lambda/E$ — hadrons ($m \sim \Lambda$)

New symmetries: collinear / soft gauge inv.



- Simplified / new ($B \rightarrow D\pi, \pi\ell\bar{\nu}$) proofs of factorization theorems

[Bauer, Pirjol, Stewart]

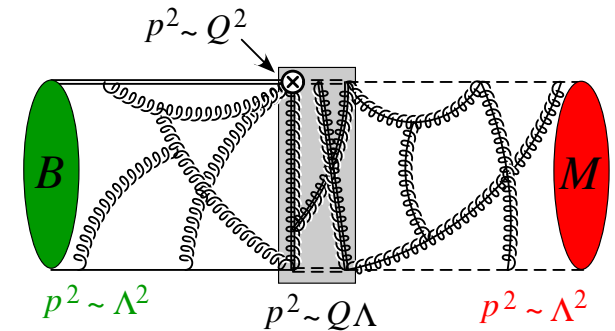
- Subleading order untractable before: factorization in $B \rightarrow D^0\pi^0$ [Mantry, Pirjol, Stewart], CPV in $B \rightarrow K^*\gamma$, weak annihilation, etc.



Semileptonic $B \rightarrow \pi, K$ form factors

- At leading order in Λ/Q , to all orders in α_s , two contributions at $q^2 \ll m_B^2$: soft form factor & hard scattering (Separation scheme dependent; $Q = E, m_b$, omit μ 's)

[Beneke & Feldmann; Bauer, Pirjol, Stewart; Becher, Hill, Lange, Neubert]



$$F(Q) = C_i(Q) \zeta_i(Q) + \frac{m_B f_B f_M}{4E^2} \int dz dx dk_+ T(z, Q) J(z, x, k_+, Q) \phi_M(x) \phi_B(k_+)$$

- Symmetries \Rightarrow nonfactorizable (1st) term obey form factor relations [Charles et al.]
 $3 B \rightarrow P$ and $7 B \rightarrow V$ form factors related to 3 universal functions

- Relative size? QCDF: 2nd $\sim \alpha_s \times$ (1st), PQCD: 1st \ll 2nd, SCET: 1st \sim 2nd
- Whether first term factorizes (involves $\alpha_s(\mu_i)$, as 2nd term does) involves same physics issues as hard scattering, annihilation, etc., contributions to $B \rightarrow M_1 M_2$



An application: $B \rightarrow \rho\gamma$

- Determines $|V_{td}/V_{ts}|$ independent of $B\bar{B}$ mixing (a new operator!)

Hadronic physics: form factor at $q^2 = 0$ [Bosch, Buchalla; Beneke, Feldman, Seidel; Ali, Lunghi, Parkhomenko]

$$\frac{\mathcal{B}(B \rightarrow \rho\gamma)}{\mathcal{B}(B \rightarrow K^*\gamma)} = \left| \frac{V_{td}}{V_{ts}} \right|^2 \left(\frac{m_B - m_\rho}{m_B - m_{K^*}} \right)^3 \begin{cases} \frac{1}{2}(\xi_{V^0\gamma})^{-2} \\ (\xi_{V^\pm\gamma})^{-2} \end{cases}$$

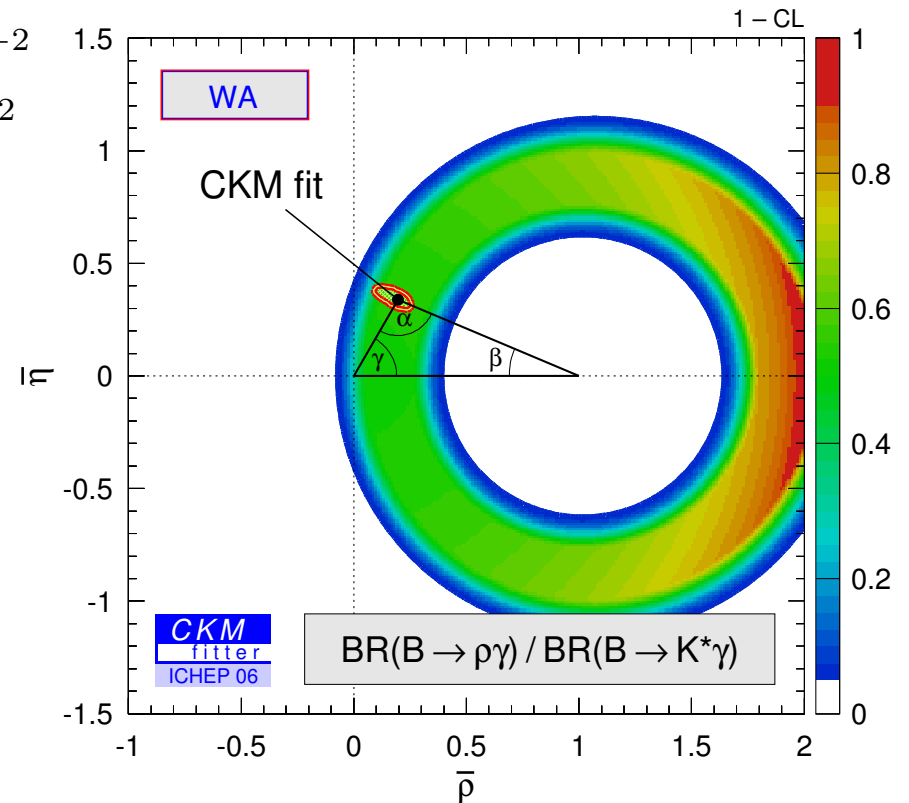
No weak annihilation in B^0 , cleaner than B^\pm
(Please don't average $\rho\gamma$ and $\omega\gamma$!)

$SU(3)$ breaking: $\xi = 1.2 \pm 0.1$ (CKM '05)

[Ball, Zwicky; Becirevic; Mescia]

Conservative? $\xi - 1$ is model dependent

Could LQCD help? Moving NRQCD?



- More data: control some theoretical errors by comparing ratios in B^0 vs. B^\pm decay



Meet the “zero-bin”

- Encounter singular integrals $\int_0^1 dx \phi_\pi(x)/x^2 \sim \int dx/x$ in several calculations e.g., $B \rightarrow \pi$ form factor, weak annihilation, “chirally enhanced” terms, etc.

Divergences \sim one of the quarks become soft near $x = 0$ or 1 (p_i^- small), but derivations use that they are collinear (p_i^- large)

- Zero-bin: simple way to eliminate double counting between collinear & soft modes (collinear quark with $p_i^- = 0$ is not a collinear quark) [Manohar & Stewart, hep-ph/0605001]

Understand which singularities are physical, and how confinement effects them

- Zero-bin ensures there is no contribution from $x_i = p_i^- / (\bar{n} \cdot p_\pi) \sim 0$

Subtractions implied by zero-bin depend on the singularity of integrals, e.g.:

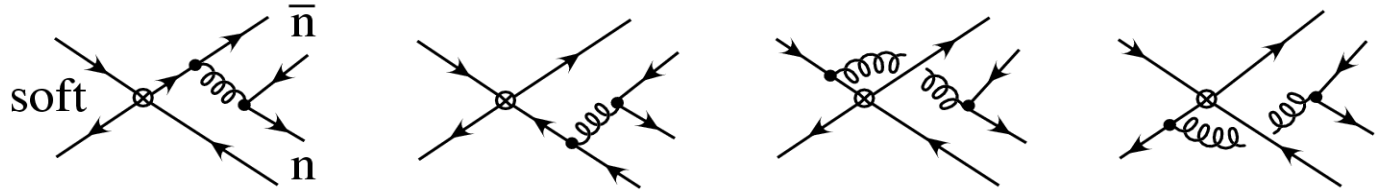
$$\int_0^1 \frac{dx}{x^2} \phi_\pi(x, \mu) \Rightarrow \int_0^1 dx \frac{\phi_\pi(x, \mu) - x \phi'_\pi(0, \mu)}{x^2} + \phi'_\pi(0, \mu) \ln \left(\frac{\bar{n} \cdot p_\pi}{\mu_-} \right) + \dots$$

= finite and real



Weak annihilation

- Power suppressed, order Λ/E corrections



Yields convolution integrals of the form: $\int_0^1 dx \phi_\pi(x)/x^2$, $\phi_\pi(x) \sim 6x(1-x)$

Singularity if gluon near on-shell — one of the pions near endpoint configuration

- **KLS**: first emphasized importance for strong phases and CPV

[Keum, Li, Sanda]

Divergence rendered finite by k_\perp , still sizable and complex contributions

- **BBNS**: interpret as IR sensitivity \Rightarrow model by complex parameters

$$“X_A” = \int_0^1 dx/x = (1 + \rho_A e^{i\varphi_A}) \ln(m_B/\Lambda)$$

[Beneke, Buchalla, Neubert, Sachrajda]

- **SCET**: Match onto six-quark operators of the form

$$O_{1d}^{(ann)} = \sum_q \underbrace{[\bar{d}_s \Gamma_s b_v]}_{\text{gives } f_B} \underbrace{[\bar{u}_{\bar{n}, \omega_2} \Gamma_{\bar{n}} q_{\bar{n}, \omega_3}]}_{\pi \text{ in } \bar{n} \text{ direction}} \underbrace{[\bar{q}_{n, \omega_1} \Gamma_n u_{n, \omega_4}]}_{\pi \text{ in } n \text{ direction}}$$

[Arnesen, ZL, Rothstein, Stewart]

At leading nonvanishing order in Λ/m_b and α_s : Real and calculable



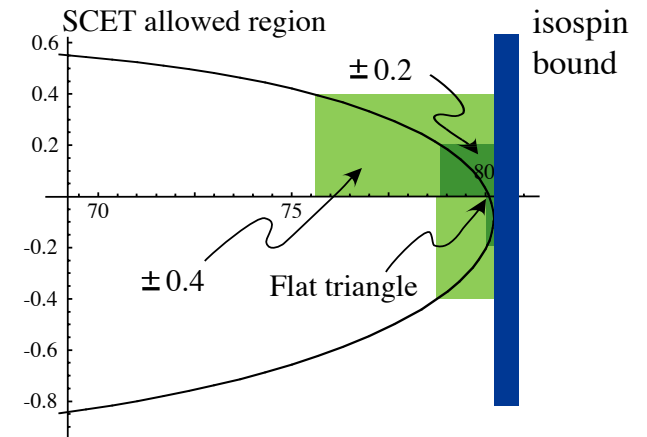
What the $B \rightarrow \pi\pi$ data tell us

- Theory predicts suppression of strong phase: $\arg(T/C) = \mathcal{O}(\alpha_s, \Lambda/m_h)$

- Use theory to extract weak phase [Bauer, Stewart, Rothstein]

SCET fit to data: $\gamma \sim 80^\circ$, about 2σ from CKM fit

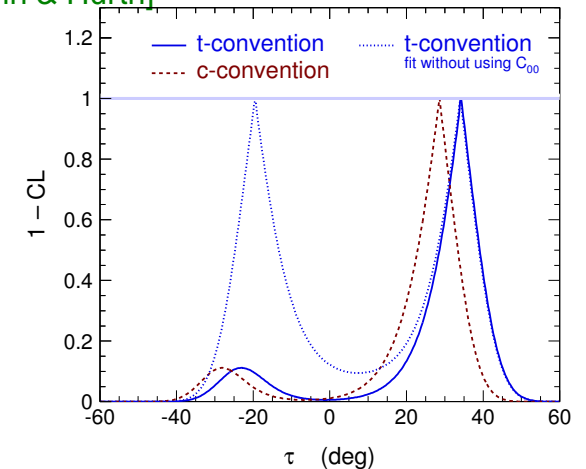
Statistics? Power corrections? New physics?



- Use CKM fit to learn about theory [Grossman, Hocker, ZL, Pirjol; Feldmann & Hurth]

- large power corrections to T, C ?
- large u penguins?
- large weak annihilation?
- conspiracy between several smaller effects?

Need to better understand $B \rightarrow \pi\pi$, $B \rightarrow \pi\ell\bar{\nu}$, $\alpha_{\rho\rho}$, γ_{DK}



- $K\pi$: hard to accommodate $A_{K^+\pi^0} = 0.047 \pm 0.026$, given $A_{K^+\pi^-} = -0.093 \pm 0.015$



More hints of possible surprises

- Theory of heavy-to-light decays is rapidly developing

More work and data needed to understand behavior of expansions

Why some predictions work at $\lesssim 10\%$ level, while others receive $\sim 30\%$ corrections

Open issues: role of charming penguins, chirally enhanced terms, annihilation, ...

We have the tools to try to address the questions

- Hope to clarify in the next 2–3 years (better data + refined theory)
 - $B \rightarrow \pi\pi$, $K\pi$ rates and CP asymmetries
 - α from $B \rightarrow \pi\pi$ using SCET vs. α from CKM fit
 - $B \rightarrow VV$ polarization
 - Robustness of predictions for $S_{K^*\gamma}$ and zero of A_{FB} in $B \rightarrow K^*\ell^+\ell^-$

Dozens, if not hundreds of papers on each...

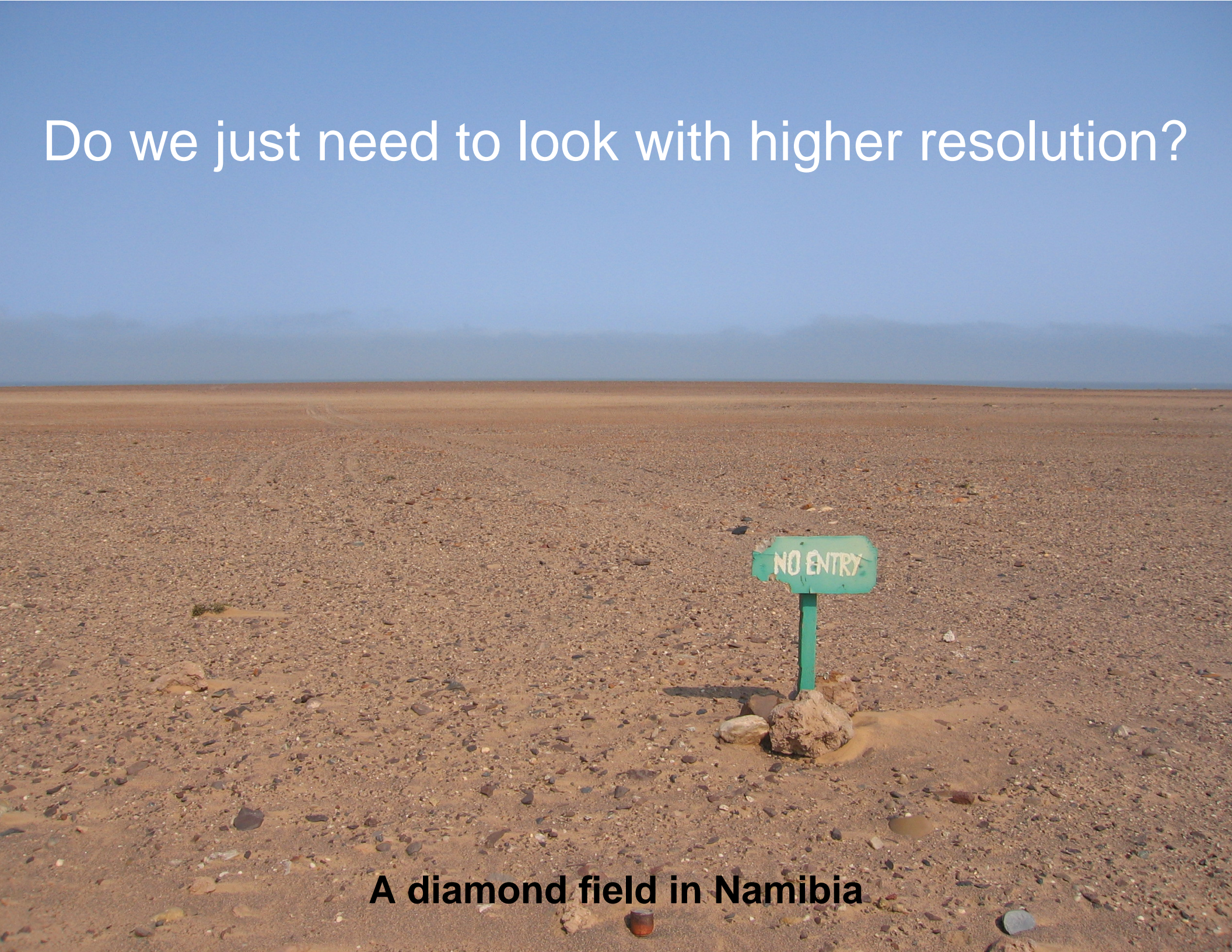


Final comments

Shall we see new physics in flavor physics?



Do we just need to look with higher resolution?



A diamond field in Namibia

Outlook

- If there are new particles at TeV scale, new flavor physics could show up any time

- Goal for further flavor physics experiments:

If NP is seen in flavor physics: study it in as many different operators as possible

If NP is not seen in flavor physics: achieve what is theoretically possible

could teach us a lot about the NP seen at LHC

The program as a whole is a lot more interesting than any single measurement

- Try to distinguish: One / many sources of CPV? Only in CC interactions?

NP couples mostly to up / down sector? 3rd / all generations? $\Delta(F) = 2$ or 1?

- Political and technical realities aside, compelling case for much larger datasets

Many interesting measurements, complementarity with high energy frontier

[Roodman, tomorrow]



Theoretical limitations (continuum methods)

- Many interesting decay modes will not be theory limited for a long time

Measurement (in SM)	Theoretical limit	Present error
$B \rightarrow \psi K$ (β)	$\sim 0.2^\circ$	1.0°
$B \rightarrow \eta' K, \phi K$ (β)	$\sim 2^\circ$	$6^\circ, 11^\circ$
$B \rightarrow \rho\rho, \rho\pi, \pi\pi$ (α)	$\sim 1^\circ$	$\sim 15^\circ$
$B \rightarrow DK$ (γ)	$\ll 1^\circ$	$\sim 25^\circ$
$B_s \rightarrow \psi\phi$ (β_s)	$\sim 0.2^\circ$	—
$B_s \rightarrow D_s K$ ($\gamma - 2\beta_s$)	$\ll 1^\circ$	—
$ V_{cb} $	$\sim 1\%$	$\sim 2\%$
$ V_{ub} $	$\sim 5\%$	$\sim 10\%$
$B \rightarrow X_s \gamma$	$\sim 5\%$	$\sim 10\%$
$B \rightarrow X_s \ell^+ \ell^-$	$\sim 5\%$	$\sim 20\%$
$B \rightarrow K^{(*)} \nu \bar{\nu}$	$\sim 5\%$	—

For some entries, the shown theoretical limits require more complicated analyses
 It would require major breakthroughs to go significantly below these theory limits



Conclusions

- Our knowledge of the flavor sector and CPV improved tremendously
CKM phase is the dominant source of CPV in flavor changing processes
- Deviations from SM in B_d mixing, $b \rightarrow s$ and even in $b \rightarrow d$ decays are constrained
NP in $B\bar{B}$ mixing may still be comparable to the SM (sensitive to scales \gg LHC)
- Progress in theory toward model independently understanding more observables:
Precision calculations for inclusive semileptonic and rare decays
Zero-bin \Rightarrow no divergent convolutions, annihilation real (novel ideas)
- Flavor physics may provide important clues to model building in the LHC era



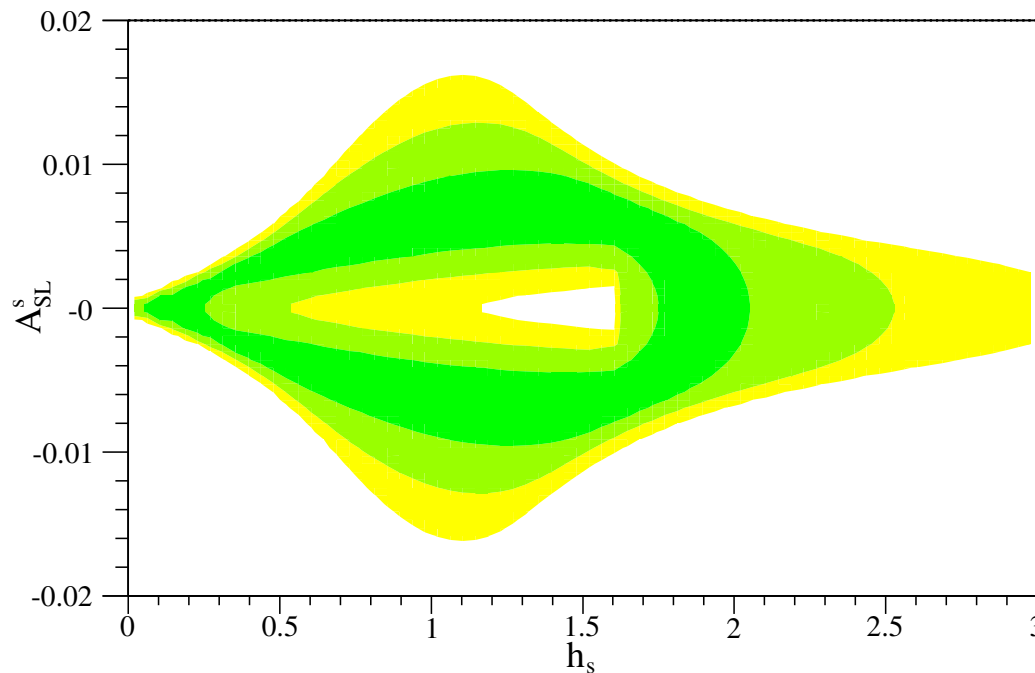


Backup slides

CP violation in B_s mixing: A_{SL}^s

- Difference of $B \rightarrow \bar{B}$ vs. $\bar{B} \rightarrow B$ transition probabilities

$$A_{\text{SL}}^s = \frac{\Gamma[\bar{B}_{\text{phys}}^0(t) \rightarrow \ell^+ X] - \Gamma[B_{\text{phys}}^0(t) \rightarrow \ell^- X]}{\Gamma[\bar{B}_{\text{phys}}^0(t) \rightarrow \ell^+ X] + \Gamma[B_{\text{phys}}^0(t) \rightarrow \ell^- X]} = -2 \left(\left| \frac{q}{p} \right| - 1 \right)$$



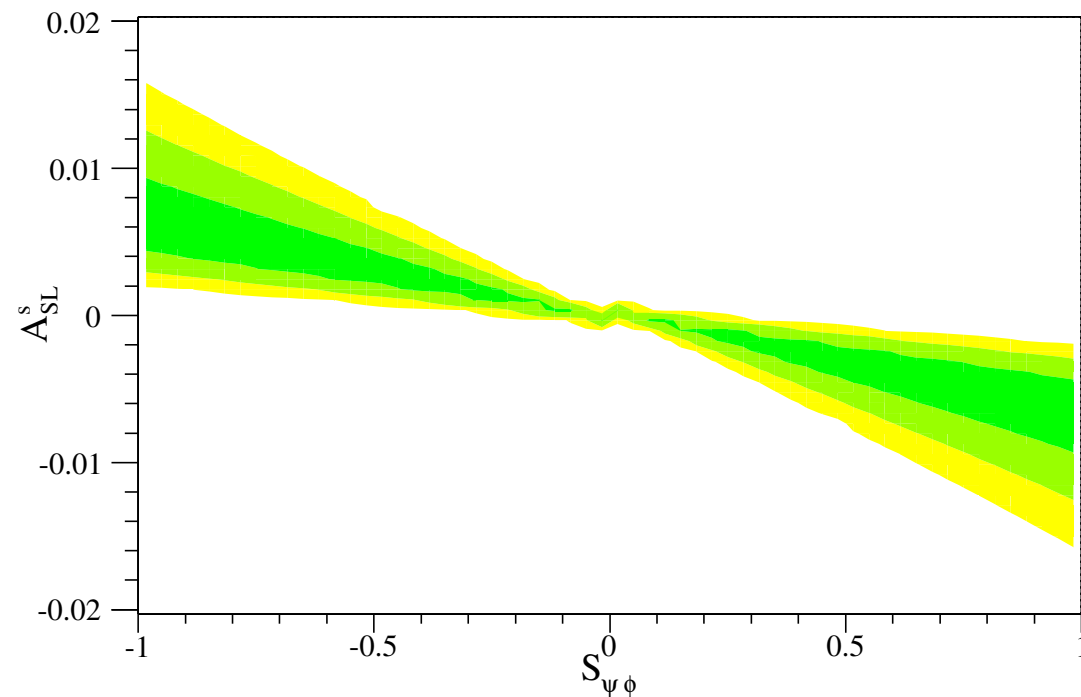
- Can be 3 orders of magnitude above SM; $|A_{\text{SL}}^s| > |A_{\text{SL}}^d|$ possible, contrary to SM



Correlation between $S_{\psi\phi}$ and A_{SL}^s

- In $h_s, \sigma_s \gg \beta_s$ region A_{SL}^s and $S_{\psi\phi}$ are highly correlated

$$A_{\text{SL}}^s = - \left| \frac{\Gamma_{12}^s}{M_{12}^s} \right|^{\text{SM}} S_{\psi\phi} + \mathcal{O}\left(h_s^2, \frac{m_c^2}{m_b^2}\right)$$



- Deviation would indicate violation of 3×3 unitarity or NP at tree level



One-page introduction to SCET

- Effective theory for processes involving energetic hadrons, $E \gg \Lambda$

[Bauer, Fleming, Luke, Pirjol, Stewart, + ...]

Introduce distinct fields for relevant degrees of freedom, power counting in λ

modes	fields	$p = (+, -, \perp)$	p^2	
collinear	$\xi_{n,p}, A_{n,q}^\mu$	$E(\lambda^2, 1, \lambda)$	$E^2\lambda^2$	SCET _I : $\lambda = \sqrt{\Lambda/E}$ — jets ($m \sim \Lambda E$)
soft	q_q, A_s^μ	$E(\lambda, \lambda, \lambda)$	$E^2\lambda^2$	SCET _{II} : $\lambda = \Lambda/E$ — hadrons ($m \sim \Lambda$)
usoft	q_{us}, A_{us}^μ	$E(\lambda^2, \lambda^2, \lambda^2)$	$E^2\lambda^4$	Match QCD \rightarrow SCET _I \rightarrow SCET _{II}

- Can decouple ultrasoft gluons from collinear Lagrangian at leading order in λ

$$\xi_{n,p} = Y_n \xi_{n,p}^{(0)} \quad A_{n,q} = Y_n A_{n,q}^{(0)} Y_n^\dagger \quad Y_n = \text{P exp} \left[ig \int_{-\infty}^x ds n \cdot A_{us}(ns) \right]$$

Nonperturbative usoft effects made explicit through factors of Y_n in operators

New symmetries: collinear / soft gauge invariance

- Simplified / new ($B \rightarrow D\pi, \pi\ell\bar{\nu}$) proofs of factorization theorems

[Bauer, Pirjol, Stewart]

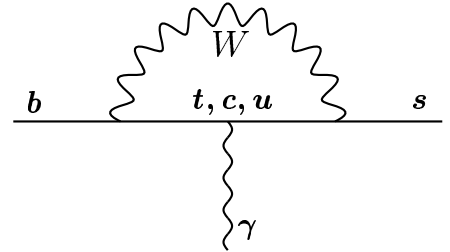


Photon polarization in $B \rightarrow X_s \gamma$

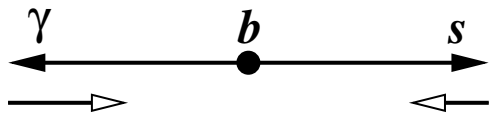
- Is $B \rightarrow X_s \gamma$ due to $O_7 \sim \bar{s} \sigma^{\mu\nu} F_{\mu\nu} (m_b P_R + m_s P_L) b$ or $\bar{s} \sigma^{\mu\nu} F_{\mu\nu} (m_b P_L + m_s P_R) b$?

SM: In $m_s \rightarrow 0$ limit, γ must be left-handed to conserve J_z

$O_7 \sim \bar{s} (m_b F_{\mu\nu}^L + m_s F_{\mu\nu}^R) b$, therefore $b \rightarrow s_L \gamma_L$ dominates



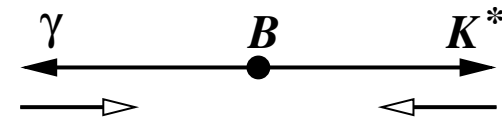
Inclusive $B \rightarrow X_s \gamma$



Assumption: 2-body decay

Does not apply for $b \rightarrow s \gamma g$

Exclusive $B \rightarrow K^* \gamma$



... quark model (s_L implies $J_z^{K^*} = -1$)

... higher K^* Fock states

- One measurement so far; had been expected to give $S_{K^* \gamma} = -2 (m_s/m_b) \sin 2\beta$

$$\frac{\Gamma[\bar{B}^0(t) \rightarrow K^* \gamma] - \Gamma[B^0(t) \rightarrow K^* \gamma]}{\Gamma[\bar{B}^0(t) \rightarrow K^* \gamma] + \Gamma[B^0(t) \rightarrow K^* \gamma]} = S_{K^* \gamma} \sin(\Delta m t) - C_{K^* \gamma} \cos(\Delta m t) \quad \text{[Atwood, Gronau, Soni]}$$

- What is the SM prediction? What limits the sensitivity to new physics?



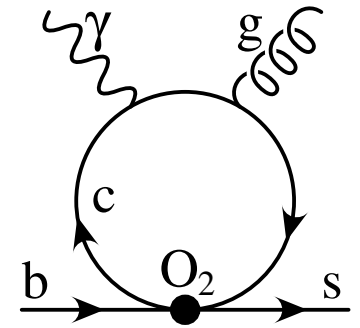
Right-handed photons in the SM

- Dominant source of “wrong-helicity” photons in the SM is O_2 [Grinstein, Grossman, ZL, Pirjol]

Equal $b \rightarrow s\gamma_L, s\gamma_R$ rates at $\mathcal{O}(\alpha_s)$; calculated to $\mathcal{O}(\alpha_s^2\beta_0)$

Inclusively only rates are calculable: $\Gamma_{22}^{(\text{brem})}/\Gamma_0 \simeq 0.025$

Suggests: $A(b \rightarrow s\gamma_R)/A(b \rightarrow s\gamma_L) \sim \sqrt{0.025/2} = 0.11$



- Exclusive $B \rightarrow K^*\gamma$: factorizable part contains an operator that could contribute at leading order in Λ_{QCD}/m_b , but its $B \rightarrow K^*\gamma$ matrix element vanishes

Subleading order: several contributions to $\bar{B}^0 \rightarrow \bar{K}^{0*}\gamma_R$, no complete study yet

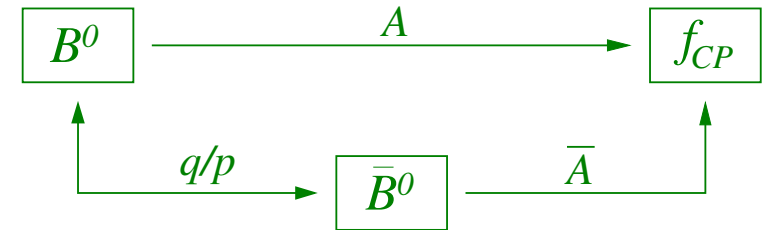
We estimate: $\frac{A(\bar{B}^0 \rightarrow \bar{K}^{0*}\gamma_R)}{A(\bar{B}^0 \rightarrow \bar{K}^{0*}\gamma_L)} = \mathcal{O}\left(\frac{C_2}{3C_7} \frac{\Lambda_{\text{QCD}}}{m_b}\right) \sim 0.1$

- Data: $S_{K^*\gamma} = -0.28 \pm 0.26$ — both the measurement and the theory can progress



CPV in interference between decay and mixing

- Can get theoretically clean information in some cases when B^0 and \bar{B}^0 decay to same final state



$$|B_{L,H}\rangle = p|B^0\rangle \pm q|\bar{B}^0\rangle \quad \lambda_{f_{CP}} = \frac{q}{p} \frac{\bar{A}_{f_{CP}}}{A_{f_{CP}}}$$

Time dependent CP asymmetry:

$$a_{f_{CP}} = \frac{\Gamma[\bar{B}^0(t) \rightarrow f] - \Gamma[B^0(t) \rightarrow f]}{\Gamma[\bar{B}^0(t) \rightarrow f] + \Gamma[B^0(t) \rightarrow f]} = \underbrace{\frac{2 \operatorname{Im} \lambda_f}{1 + |\lambda_f|^2}}_{S_f} \sin(\Delta m t) - \underbrace{\frac{1 - |\lambda_f|^2}{1 + |\lambda_f|^2}}_{C_f (-A_f)} \cos(\Delta m t)$$

- If amplitudes with one weak phase dominate a decay, hadronic physics drops out
Measure a phase in the Lagrangian theoretically cleanly:

$$a_{f_{CP}} = \eta_{f_{CP}} \sin(\text{phase difference between decay paths}) \sin(\Delta m t)$$



The cleanest case: $B \rightarrow J/\psi K_S$

- Interference of $\bar{B} \rightarrow \psi \bar{K}^0$ ($b \rightarrow c\bar{c}s$) with $\bar{B} \rightarrow B \rightarrow \psi K^0$ ($\bar{b} \rightarrow c\bar{c}\bar{s}$)

Amplitudes with a second weak phase strongly suppressed

(unitarity: $V_{tb}V_{ts}^* + V_{cb}V_{cs}^* + V_{ub}V_{us}^* = 0$)

$$\bar{A}_{\psi K_S} = \underbrace{V_{cb}V_{cs}^*}_{\mathcal{O}(\lambda^2)} \underbrace{\langle \text{"T"} \rangle}_{\text{"1"}} + \underbrace{V_{ub}V_{us}^*}_{\mathcal{O}(\lambda^4)} \underbrace{\langle \text{"P"} \rangle}_{\alpha_s(2m_c)}$$

First term \gg second term \Rightarrow theoretically very clean

$$S_{\psi K_S} = -\sin[(B\text{-mix} = -2\beta) + (\text{decay} = 0) + (K\text{-mix} = 0)]$$

Corrections: $|\bar{A}/A| \neq 1$ (main uncertainty), $\epsilon_K \neq 0$, $\Delta\Gamma_B \neq 0$

all are $\text{few} \times 10^{-3} \Rightarrow$ accuracy $< 1\%$

- World average: $\sin 2\beta = 0.675 \pm 0.026$ — a 4% measurement!

- Large deviations from CKM excluded (e.g., approximate CP in the sense that all CPV phases are small) \Rightarrow Look for corrections, rather than alternatives to CKM

