Determination of CKM matrix elements (mainly at the B-factories)

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SFB-Meeting

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The CKM matrix

1. Origin

Relation to the Yukawa sector:

$$L_{quark\ masses} = \bar{u}_L M_u u_R + \bar{d}_L M_d d_R + h.c., \quad u \equiv \begin{pmatrix} u \\ c \\ t \end{pmatrix}, d \equiv \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$$M_{u,diag} = U_L^+ M_u U_R$$

$$M_{d,diag} = D_L^+ M_d D_R$$

$$\rightarrow V_{CKM} = U_L^+ D_L$$

2. CP violation through the CKM Matrix

a) Beyond strong CP violation the only source of CP violation in SM

b) Extremely economic: Only 1 CP violating parameter for 3 generations

c)

#generations	Observed baryon asymmetry
3	CP violation & quark masses too small
4	CP violation & quark masses sufficiently large (Hou (2008)) e.w. Phase transition?

Why measuring CKM matrix elements ?

1. Fundamental parameters of the SM

Point to Beyond Standard Model (BSM) physics (like fermion mass values)

Metrology: Determine them as best as possible

=> Model building & model testing (link to e.g. neutrino sector)

2. Consistency/Unitarity

Any measured deviation from unitarity points to BSM physics

E.g.: * More generations

*** Additional particles & couplings beyond the SM ($H^{\pm}$, SUSY, ...)**

Consistency checks:

- **Compare observables constraining same CKM parameter (e.g. tree vs loop)**
- **directly measured CKM parameter with its prediction from global fit**
- **Overall unitarity of the matrix**

Parametrisation of the CKM matrix

Three Euler angles and one phase (Chau, Keung 1984):

$$V = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$= \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

$$c_{ij} = \cos\theta_{ij},\ s_{ij} = \sin\theta_{ij},\ i < j = 1,2,3 \qquad c_{ij} > 0, s_{ij} > 0\ \ (0 \le \theta_{ij} \le \pi/2)$$

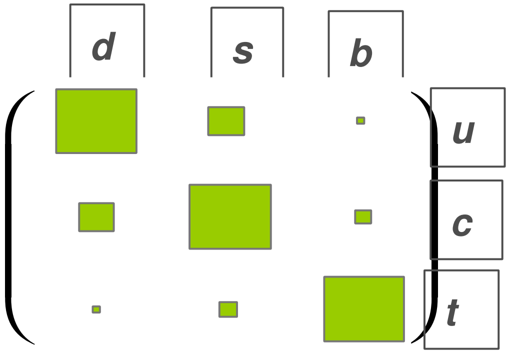
Freedom of phase re-definition => phase can appear at other places!

A statement like “The phase of the CKM matrix is 60°.”
only makes sense in a given phase convention.

Not always clearly specified in the literature.

Parametrisation of the CKM matrix

$V_{CKM} =$



***Wolfenstein** parametrisation*

(Expansion in $\lambda = \sin\theta_c (\approx V_{us}) \approx 0.225$):

$$V_{CKM} \approx \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

=> η=0 <=> No CP-violation in SM

Define to all orders in λ (Buras, Lautenbacher, Ostermaier, 1994):

$$s_{12} \equiv \lambda$$

$$s_{23} \equiv A\lambda^2$$

$$s_{13} e^{-i\delta} \equiv A\lambda^3(\rho - i\eta)$$

Unitary holds

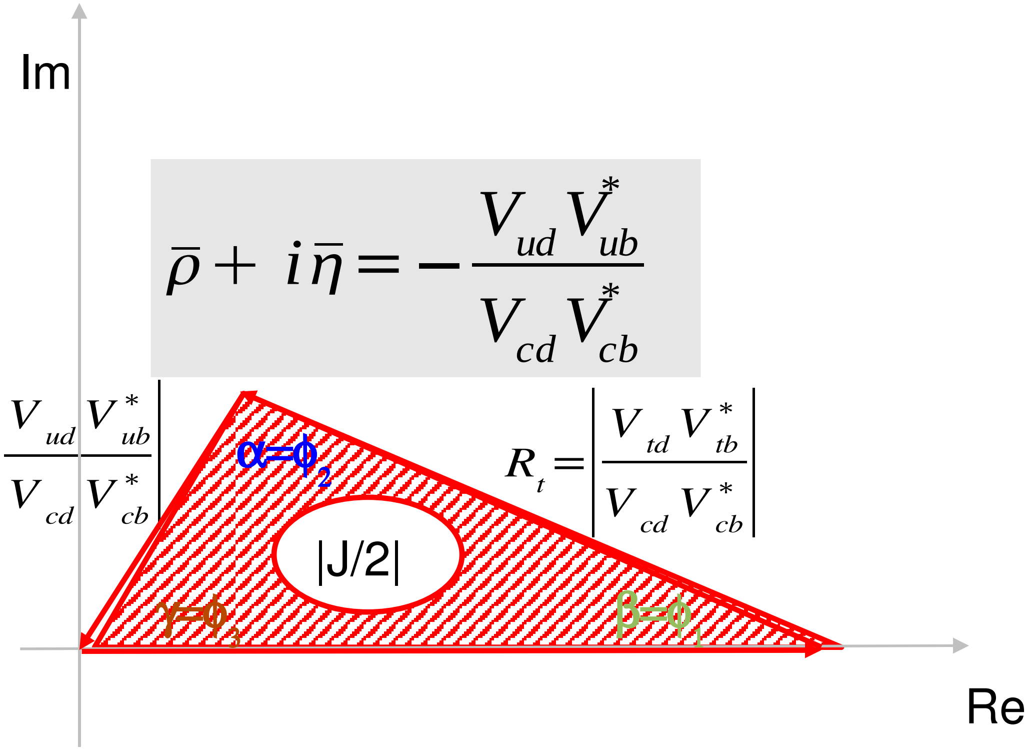
to all orders!

Unitarity Triangle

Unitary implies e.g. $$\frac{1}{V_{cd}V_{cb}^*}\left(V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^*\right) = 0$$

$$\bar{\rho} + i\bar{\eta} = -\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}$$

$$R_u = \left|\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right| \qquad R_t = \left|\frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*}\right|$$

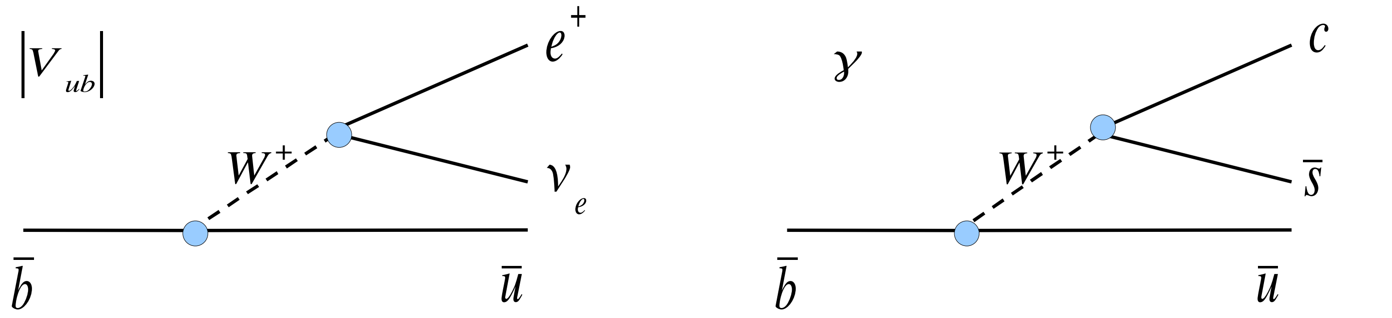


Phase-convention independent measure of CP-violation in SM:

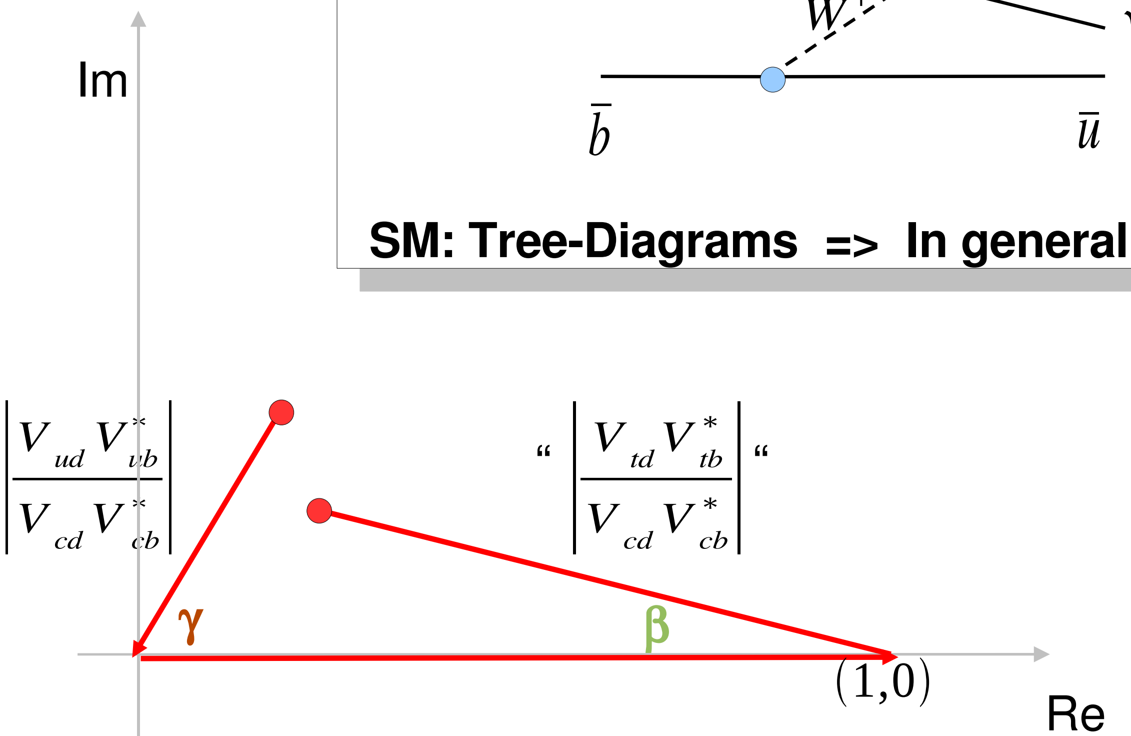
$$J \propto \bar{\eta}$$

All sides and angles can be determined from the B-meson system alone (but does not contain the full information)!

Hunting for New Physics in Loop-mediated processes

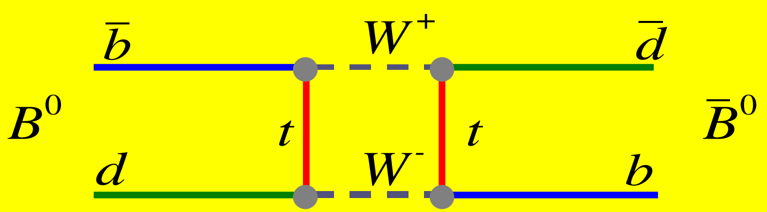


SM: Tree-Diagrams => In general: Sensitivity to BSM physics small



SM: Loop-Diagrams (higher order processes)

$V_{td}V^*_{tb}$



=> Enhanced sensitivity to BSM

λ from tree-level processes

$|V_{ud}|$: 1) Super-allowed nuclear β-decays (SFD)

2) Neutron β-decay

3) Pionic β-decay

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

$$\approx \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

$|V_{us}|$: 1) Semileptonic Kaon decays

2) Leptonic Kaon & Pion decay

3) τ-decays

4) Semileptonic Hyperon decays

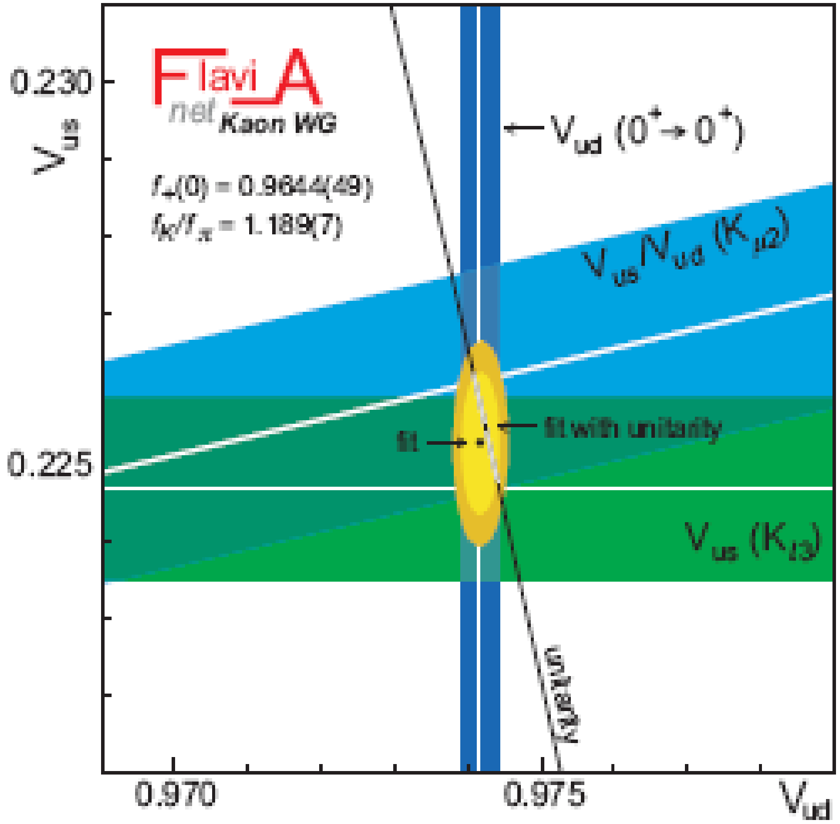
$|V_{cd}|$, $|V_{cs}|$: 1) Dimuon production from neutrinos on nuclei

2) Semileptonic D-meson decays

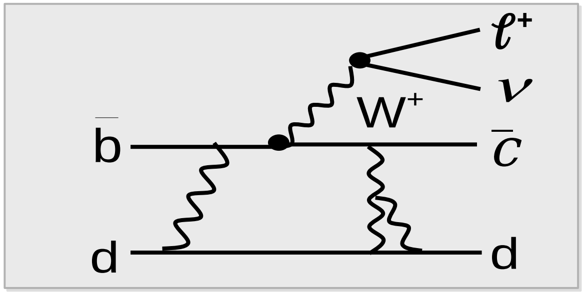
At present, the most stringent constraint on λ comes from $|V_{ud}|_{SFD}$!

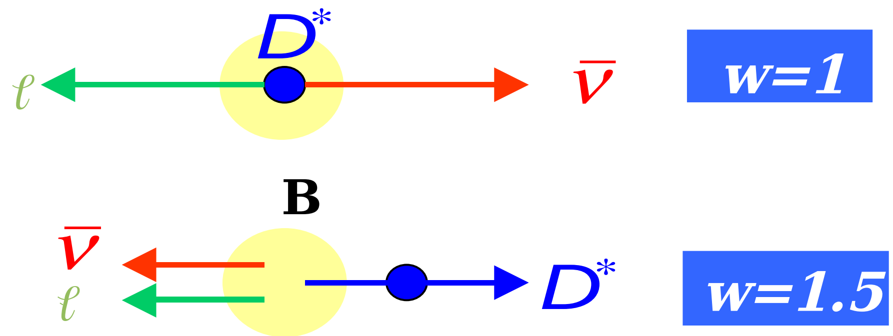
λ from tree-level processes

$$1 = |V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2$$



$|V_{cb}|$: Exclusive semileptonic B-decays





Heavy Quark-Limit: Only one FF (ξ)

For light degrees of freedom (q, g):

no change in interactions with Q for w=1

if m_Q is very large => $\xi(w=1)=1$

For finite masses:

Luke's theorem

$$B \to D^* l\nu:$$

$$F(w=1) = \eta_A \eta_{QED} \cdot \left(1 + 0 \cdot \frac{\Lambda_{QCD}}{m_Q} + b \cdot \frac{\Lambda_{QCD}^2}{m_Q^2} + \ldots\right)$$

$$B \to D l\nu:$$

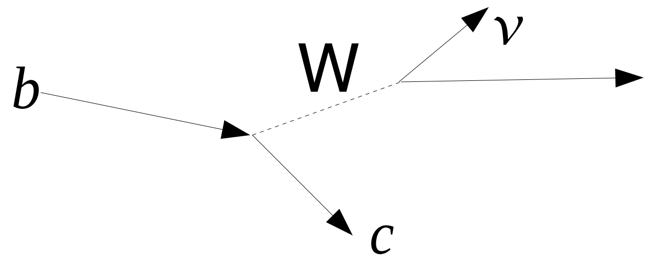
$$V_1(w=1) = \eta_A \eta_{QED} \cdot \left(1 + a \cdot \frac{\Lambda_{QCD}}{m_Q} + b' \cdot \frac{\Lambda_{QCD}^2}{m_Q^2} + \ldots\right)$$

$B \to D^* l\nu$ preferred:

* Theoretical uncertainties in FF calculation
* Phase space ($w \to 1$)
* Experimental Background

$|V_{cb}|$: Inclusive semileptonic B-decays

$$\Gamma(b\to c\,l\,\nu)=|V_{cb}|^2\frac{G_F^2\cdot m_b^5}{192\pi^3}\cdot\Phi\left(\frac{m_c}{m_b}\right)\cdot\left(1+c(\alpha,\alpha_s)\right)$$



Including non-perturbative effects (Heavy Quark Expansion):

'Kinetic Mass scheme' (there are others, e.g.: 'Y(1S) scheme'):

$$\Gamma(B\to X_c\,l\,\nu)=1.014\cdot|V_{cb}|^2\frac{G_F^2 m_b^5}{192\pi^3}A^{pert}\left(\frac{m_c}{m_b},\mu\right)\left[\Phi\left(\frac{m_c}{m_b}\right)\left(1-\frac{\mu_\pi^2-\mu_G^2}{2m_b^2}\right)-2\left(1-\frac{m_c^2}{m_b^2}\right)^4\frac{\mu_G^2}{m_b^2}+O\left(\frac{1}{m_b^3}\right)\right]$$

No contribution at order $1/m_b$ => Decay rate close to quark-level decay rate

For precision determination of V_{cb}: $1/m_b^2$ and $1/m_b^3$ to be taken into account

Lifetimes of B mesons

$\tau(B^0)$ = (1.530 ± 0.008) ps

$\tau(B^+)$ = (1.639 ± 0.009) ps

Semileptonic BF

BF($B^+/B^0 \to X\,l\,\nu$) = (10.74 ± 0.16)%

$|V_{cb}|$: Inclusive semileptonic B-decays

* Theory Error on $|V_{cb}|$ dominates: O(5%) !

* Reason: Theory parameters difficult to calculate

* Idea: Shape of differential spectrum is function of theory parameters

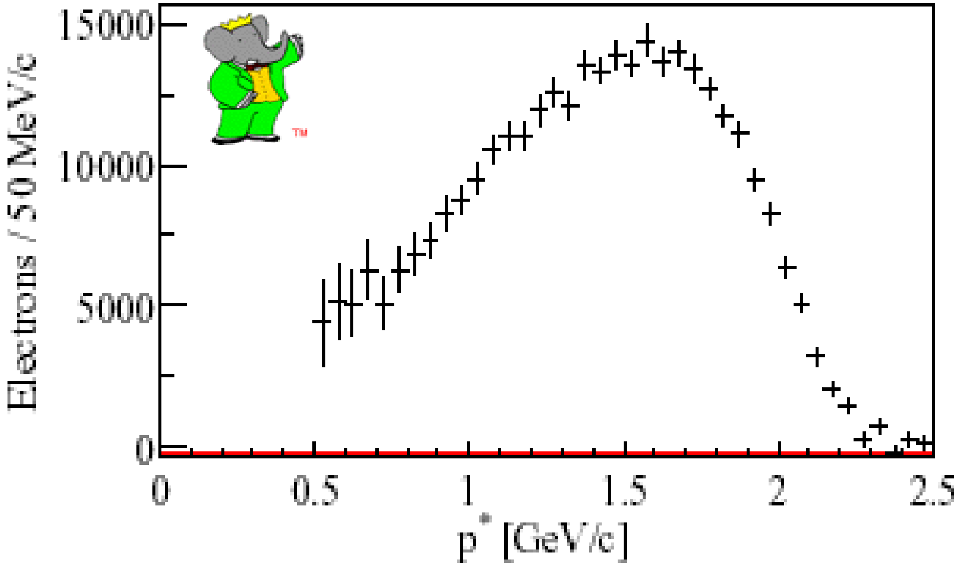
$$\frac{d\Gamma}{dE}(E) = f(E | m_b, m_c; \mu_\pi^2, \mu_G^2, \rho_D^3, \rho_{LS}^3, \ldots; \alpha_s)$$

* Measure Moments of differential spectra

=> Determine theory parameters from data

$$B \to X_c l \nu$$

$$M_n^l(E_0) = \frac{\int_{E_0} E_l^n \frac{d\Gamma}{dE_l}(E_l)\, dE_l}{\int_{E_0} \frac{d\Gamma}{dE_l}(E_l)\, dE_l}$$

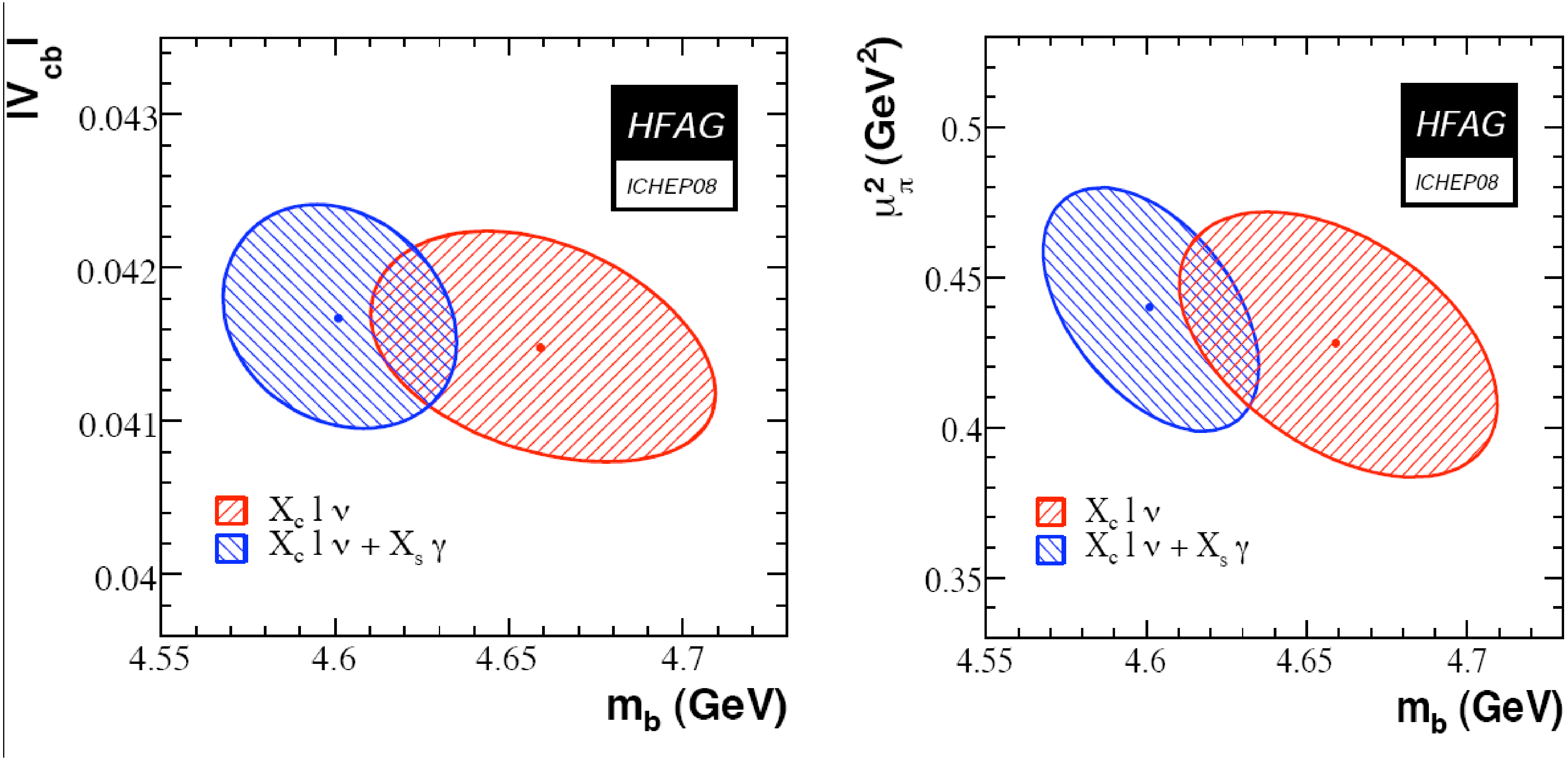


$|V_{cb}|$: Inclusive semileptonic B-decays

Experiments: **BABAR, BELLE, CDF, CLEO, DELPHI**

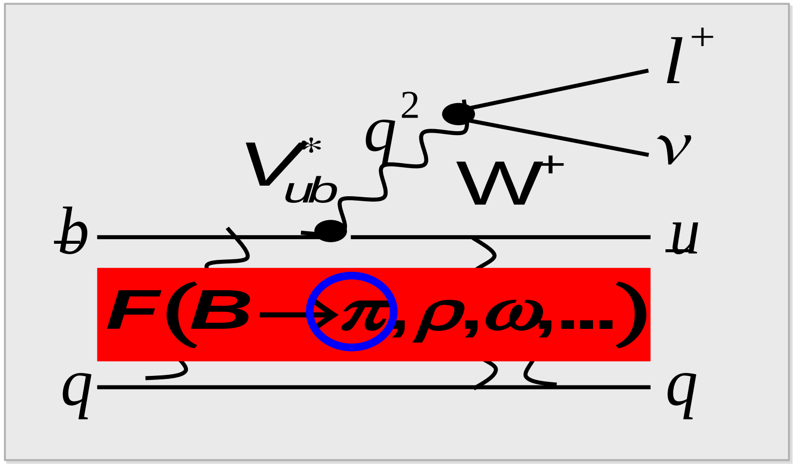
Hadronic mass and leptonic energy moments in $B \to X_c l \nu$

+ 1. and 2. photon energy moment in $B \to X_s \gamma$



$|V_{cb}|(incl) = (41.67 \pm 0.43 \pm 0.08 \pm 0.58) \times 10^{-3}$ Below 2% precision

$|V_{ub}|$: Exclusive semileptonic B-decays



$$BF(B\to h\,l\,\nu)\propto|V_{ub}|^2 F^2(q^2)$$

In contrast to $B\to D^{(*)}$ transitions:
No Heavy Quark Symmetry
providing form factor normalization

Form Factors from:

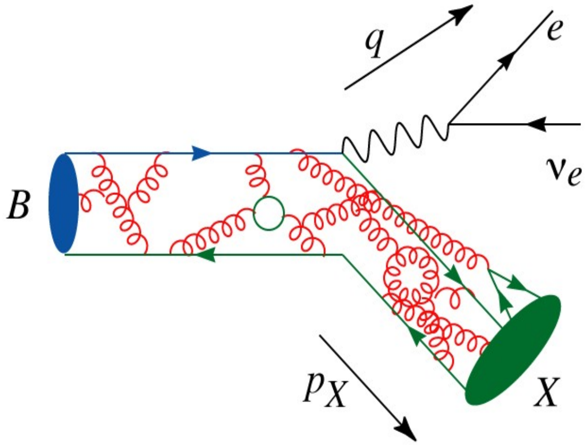
* Light-Cone Sum Rules (LCSR): only valid at small q^2
* Lattice QCD: only valid at high q^2

FF uncertainties enter at two different places:

1. FF shape => $BF(B\to h\,l\,\nu)=\frac{N_{sig}}{\epsilon N_{BB}}$

2. FF normalization => $|V_{ub}|=\sqrt{\frac{BF(B\to h\,l\,\nu)}{\tau_B \Gamma_{thy}}}$

$|V_{ub}|$: Inclusive semileptonic B-decays



Γ_{sl} theoretically well known (OPE)

$$|V_{ub}| = 0.00424 \sqrt{\frac{B(b \to u\, l^{-}\bar{\nu})}{0.002}\,\frac{1.61\,ps}{\tau_B}} \times \left(1.0 \pm 0.028_{OPE,pert} \pm 0.039_{m_b}\right)$$

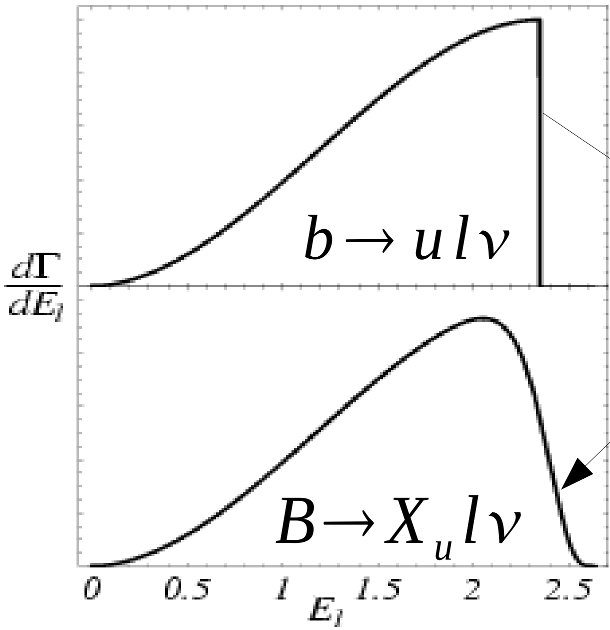
Background from $B \to X_c\, l\nu \quad \left(|V_{ub}| \approx 4\times10^{-3},\ |V_{cb}| \approx 4\times10^{-2}\right)$

Signal/BG ~1/50 !

$\Rightarrow$ **Kinematical Cuts**

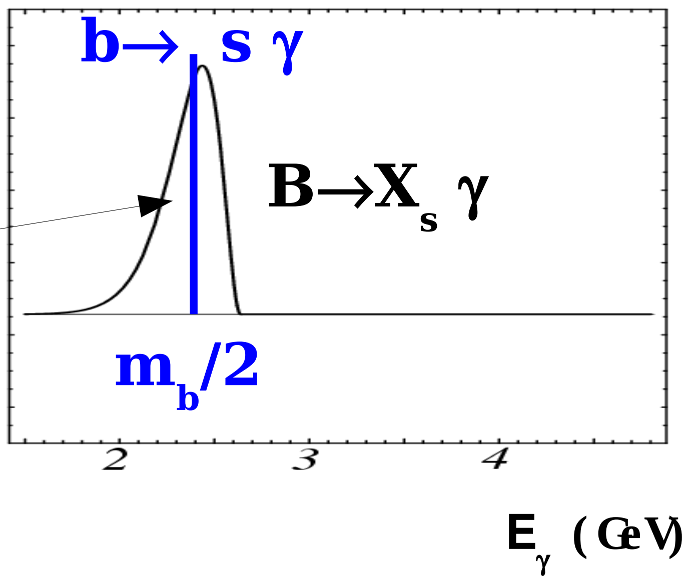
$\Rightarrow$ **Extrapolation: Fraction of accepted signal events?**

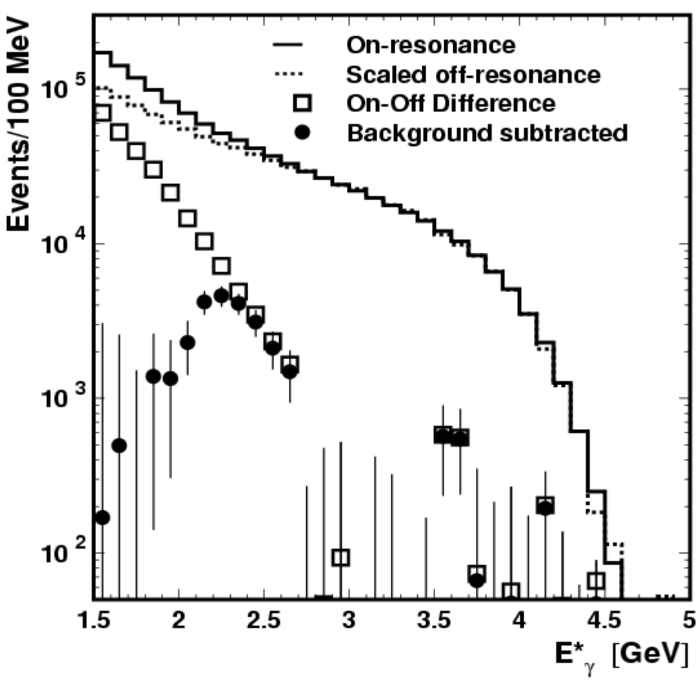
$|V_{ub}|$: Inclusive semileptonic B-decays

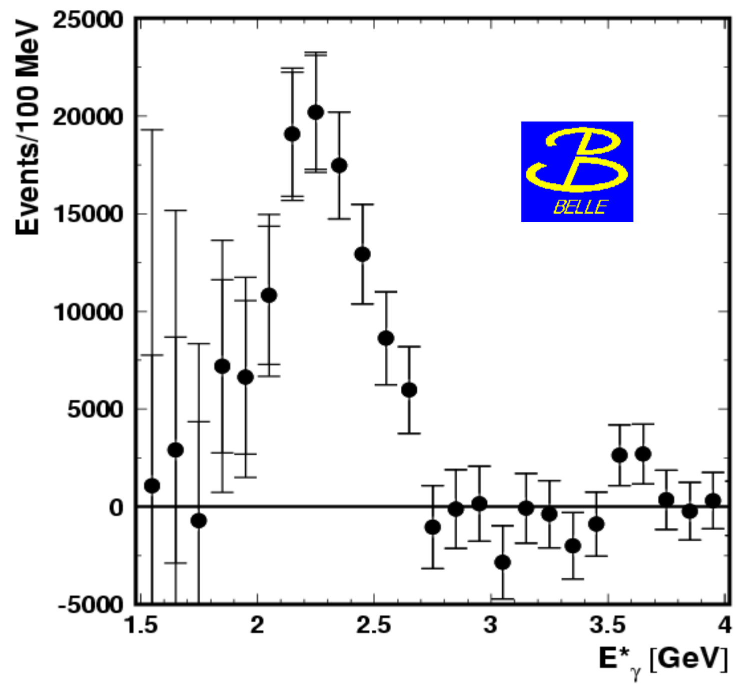


Shape Function *S*:

"Fermi-motion"
of b-quark
inside B-Meson



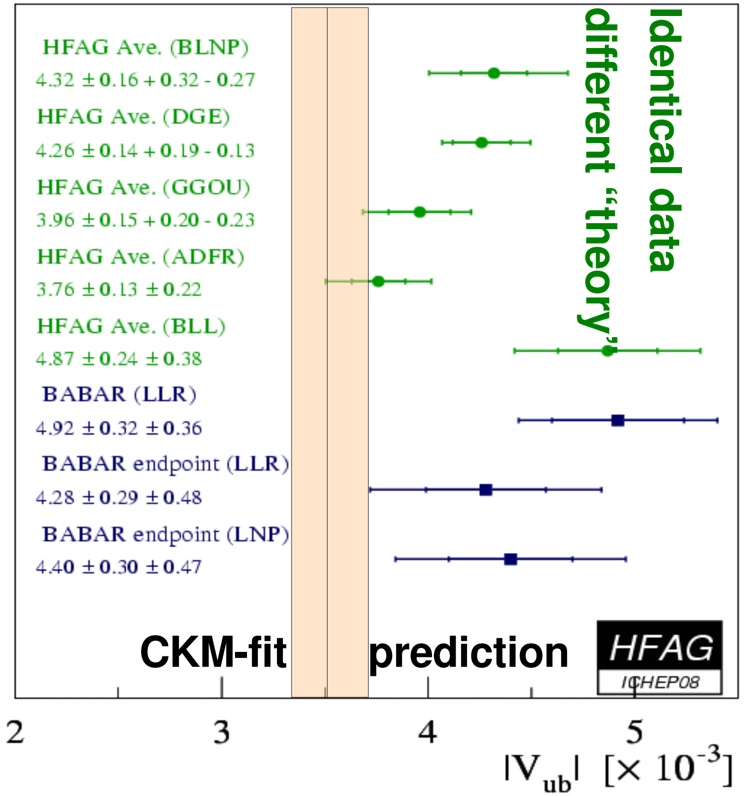


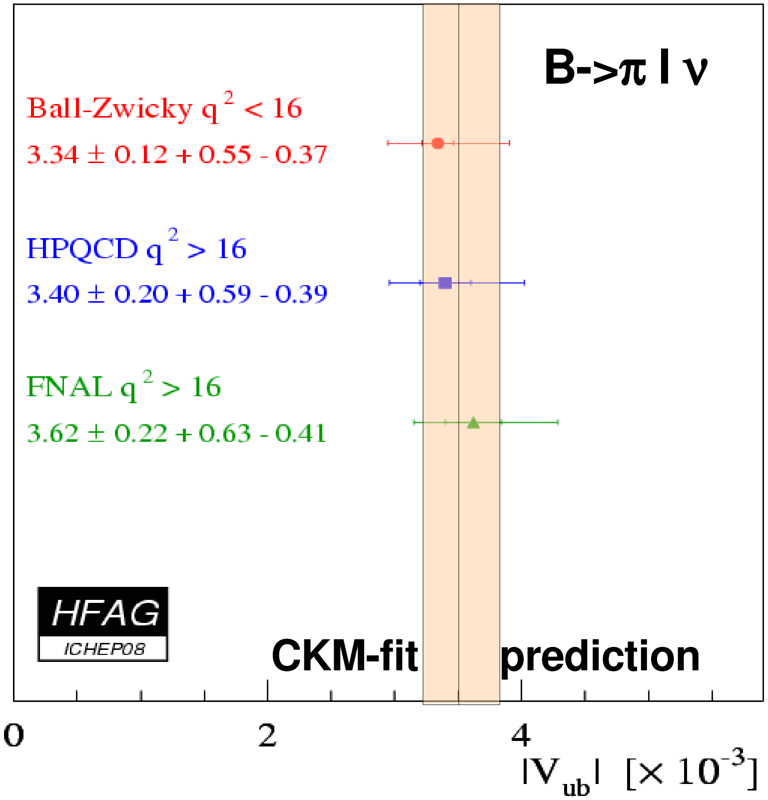


Summary: $|V_{ub}|$ and $|V_{cb}|$

	INCLUSIVE	EXCLUSIVE
$|V_{cb}|$	$(41.67\pm0.43\pm0.08\pm0.58)\times10^{-3}$	$(38.18\pm0.56_{exp}\pm0.54_{theostat}\pm0.83_{theosys})\times10^{-3}$
	moments in B->X_c l ν & B->X_s γ	**B->D*l ν using FF at zero recoil:** $0.921\pm0.013_{theostat}\pm0.020_{theosys}$ 0808.2519 [hep-lat]

$|V_{ub}|$

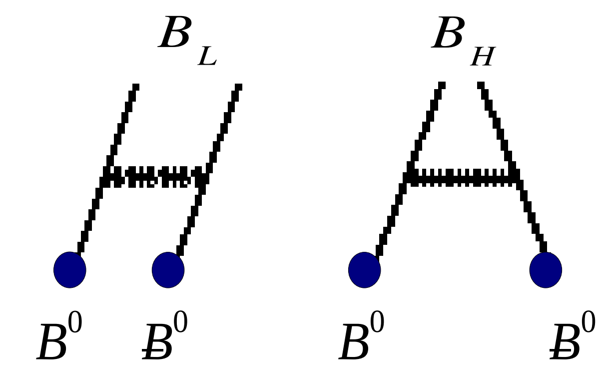




Mixing and CP violation: Observables

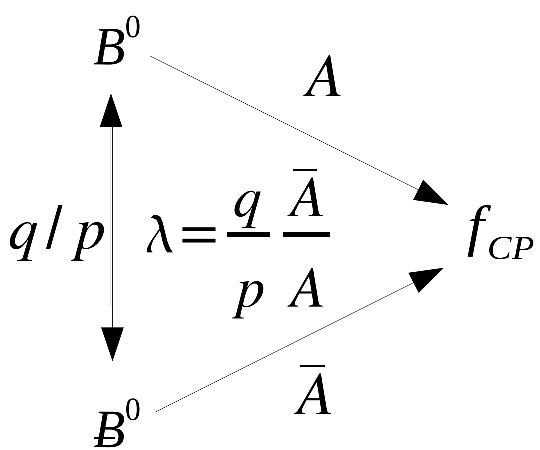
Mass eigenstates:

$$B_H = p\,B^0 + q\,\bar{B}^0$$
$$B_L = p\,B^0 - q\,\bar{B}^0$$



Oscillations: $B^0 \rightarrow \bar{B}^0 \rightarrow B^0$ with frequency

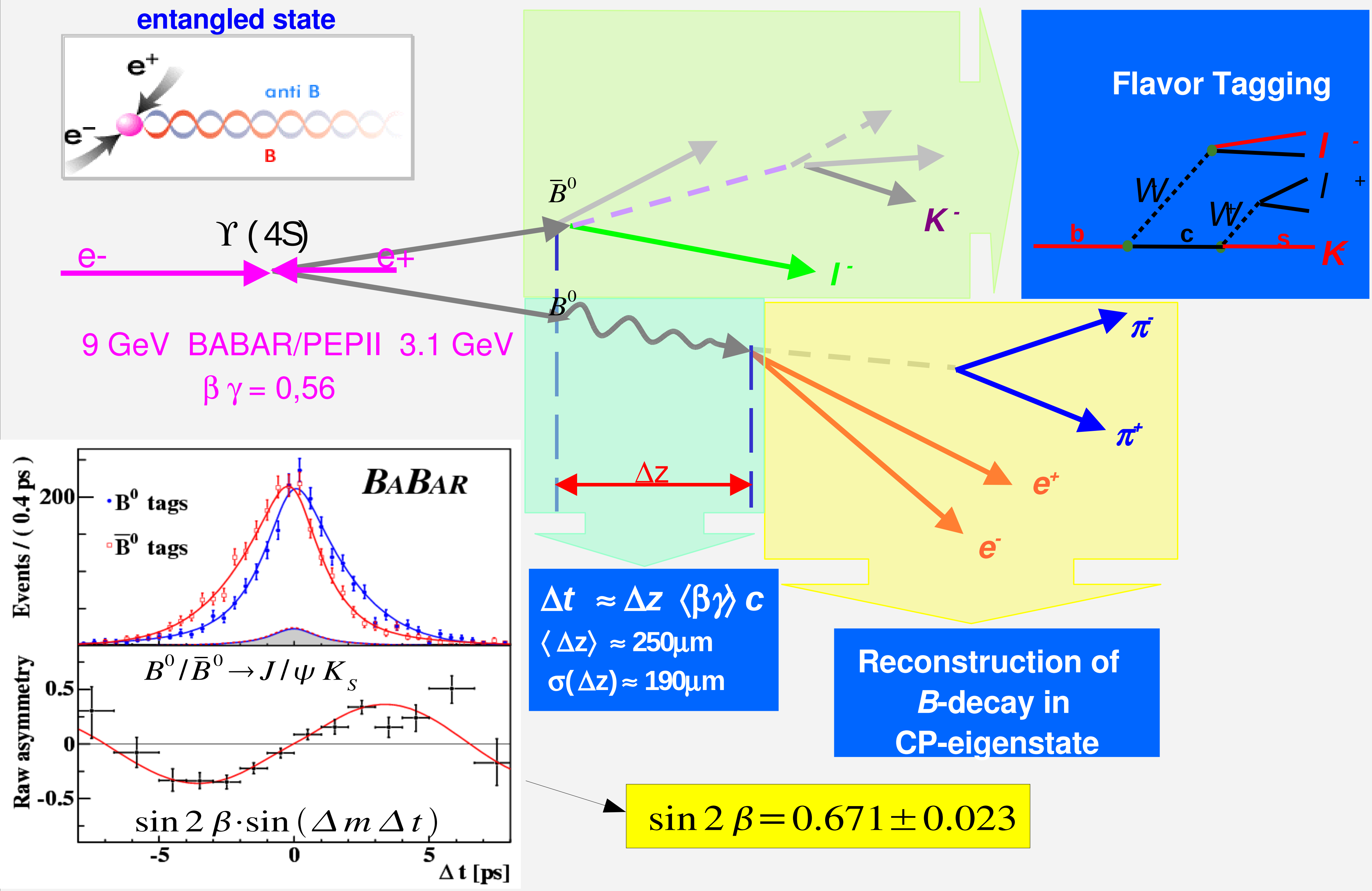
$$\Delta m \equiv M_H - M_L$$



$$A_{CP}(t) = \frac{\Gamma(\bar{B}^0(t) \rightarrow f_{CP}) - \Gamma(B^0(t) \rightarrow f_{CP})}{\Gamma(\bar{B}^0(t) \rightarrow f_{CP}) + \Gamma(B^0(t) \rightarrow f_{CP})}$$

$$= \frac{2\,Im\,\lambda}{1+|\lambda|^2}\sin(\Delta m \cdot t) - \frac{1-|\lambda|^2}{1+|\lambda|^2}\cos(\Delta m \cdot t)$$

Measurement of a time-dependent CP asymmetry

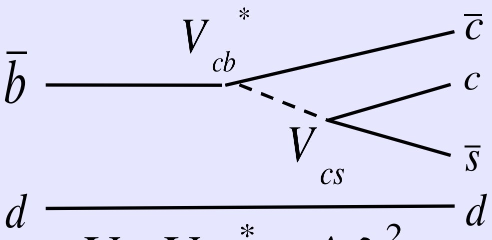


$$\sin 2\beta = 0.671 \pm 0.023$$

Experimental inputs with "no" theory machinery - β

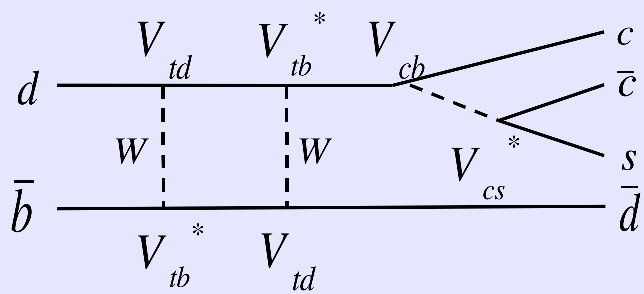
$$B^0 / \bar{B}^0 \to (c\,\bar{c})\,K^0_{CP}\;(e.g. \to \pi^+\pi^-)$$

$$\lambda_{CP} = \frac{q}{p}\frac{\bar{A}}{A} \approx e^{-2\cdot i\beta}$$

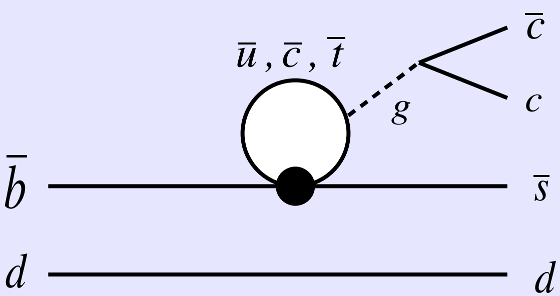


$$V_{cs}V_{cb}^* \propto A\lambda^2$$

$\oplus$



$$\frac{q}{p} \approx \frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*}$$



$$V_{cs}V_{cb}^* \propto A\lambda^2$$

$$V_{ts}V_{tb}^* \propto A\lambda^2$$

$$V_{us}V_{ub}^* \propto A\lambda^4$$

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$$B^0/\bar{B}^0 \rightarrow (c\bar{c})K^0_{CP}\,(e.g. \rightarrow \pi^+\pi^-)$$

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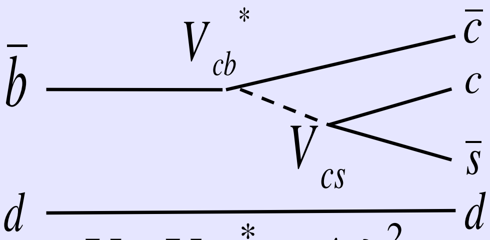

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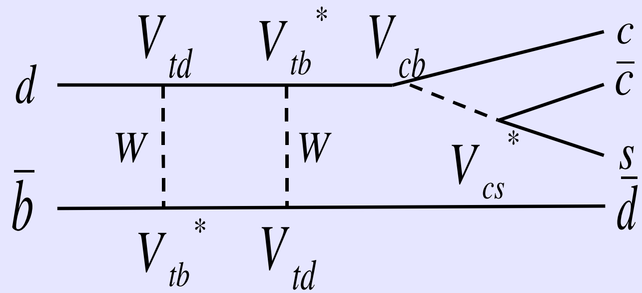

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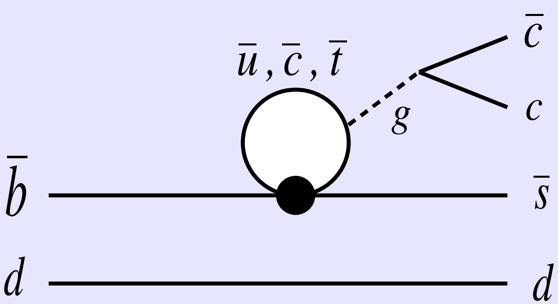

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$$A_{CP}(t) = \frac{2\,Im\lambda_{CP}}{1+|\lambda_{CP}|^2}\sin(\Delta m_d t) - \frac{1-|\lambda_{CP}|^2}{1+|\lambda_{CP}|^2}\cos(\Delta m_d t)$$

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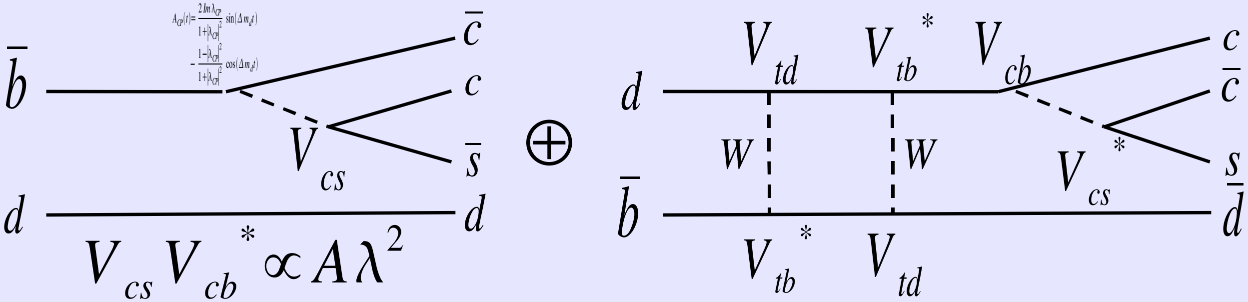

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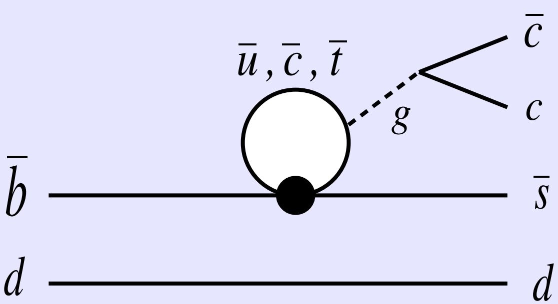

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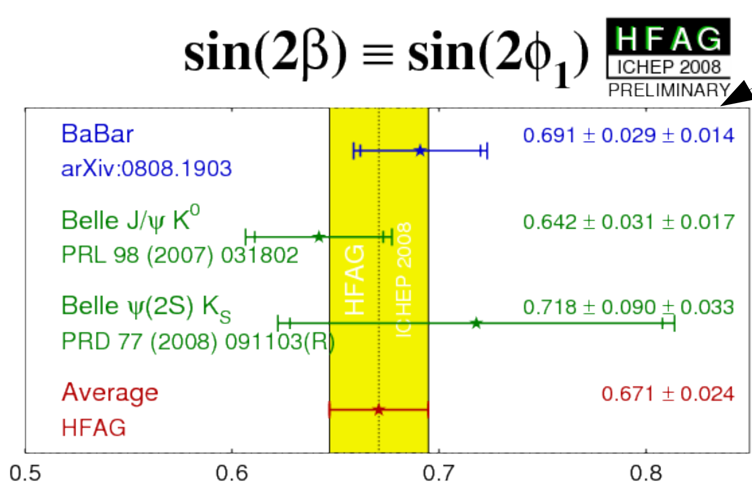
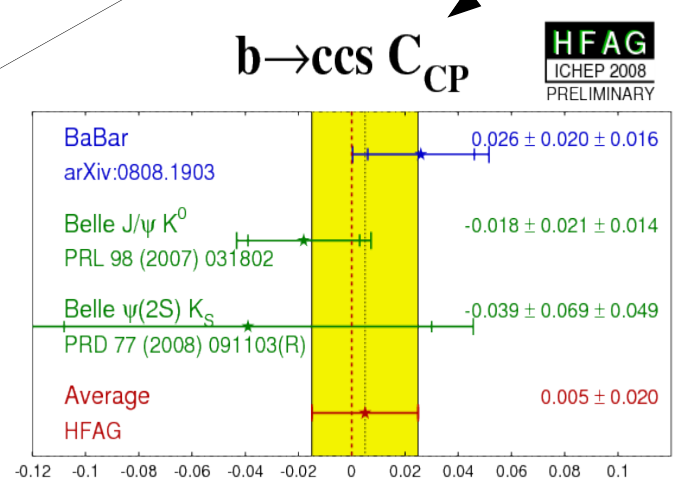
$\sin(2\beta) \equiv \sin(2\phi_1)$



$b \rightarrow ccs\ C_{CP}$



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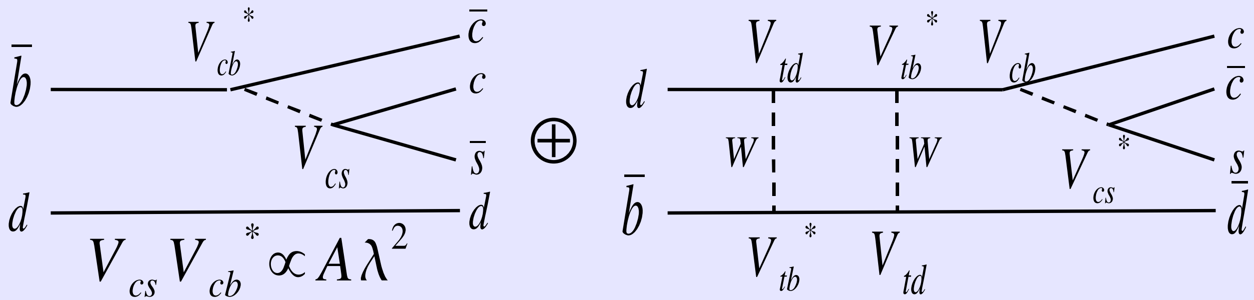
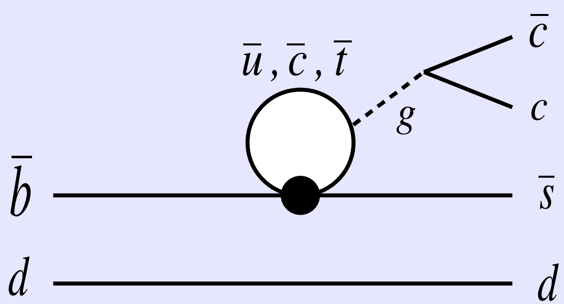


$$\frac{q}{p} \approx \frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*}$$

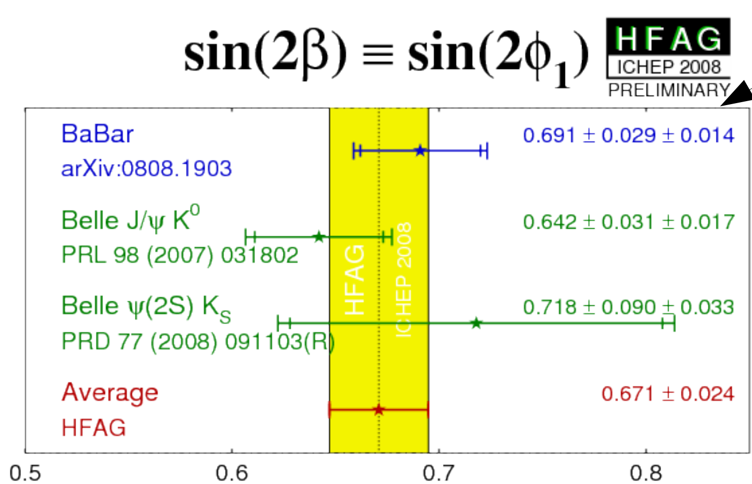


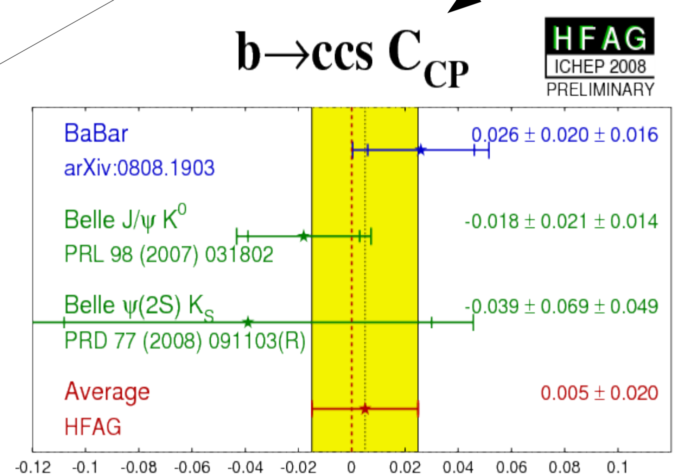
$$V_{cs}V_{cb}^* \propto A\lambda^2$$

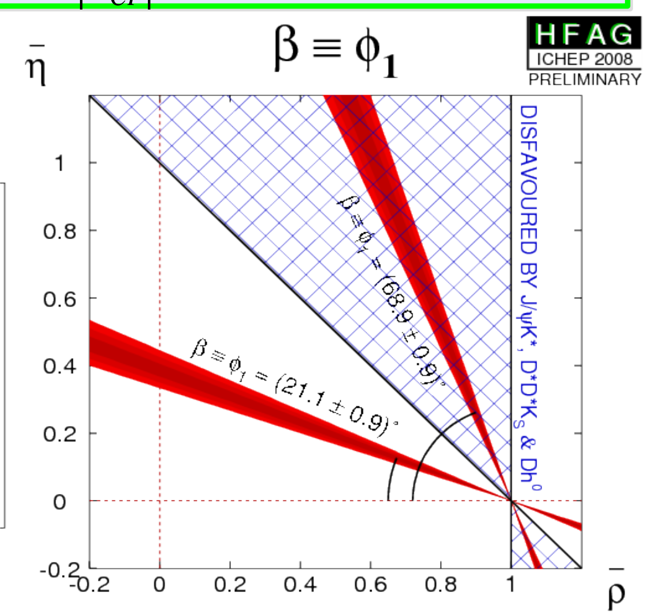
$$V_{ts}V_{tb}^* \propto A\lambda^2$$

$$V_{us}V_{ub}^* \propto A\lambda^4$$

$$A_{CP}(t) = \frac{2\,Im\,\lambda_{CP}}{1+|\lambda_{CP}|^2}\sin(\Delta m_d t) - \frac{1-|\lambda_{CP}|^2}{1+|\lambda_{CP}|^2}\cos(\Delta m_d t)$$

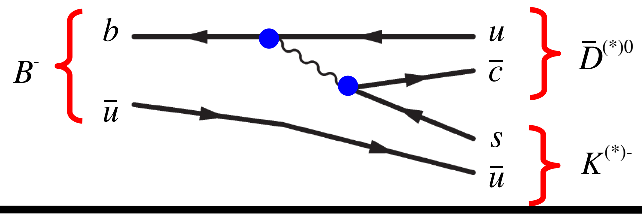




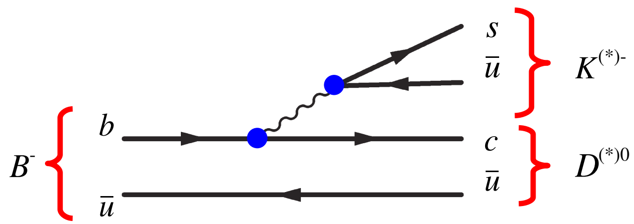


Experimental inputs with "no" theory machinery - γ

***CP* violation in charged B- decays:** $b \to c\bar{u}s,\, u\bar{c}s$



$$r_B = \frac{\propto V_{ub} V_{cs}^{*}}{\propto V_{cb} V_{us}^{*}} \approx 0.1 - 0.3$$



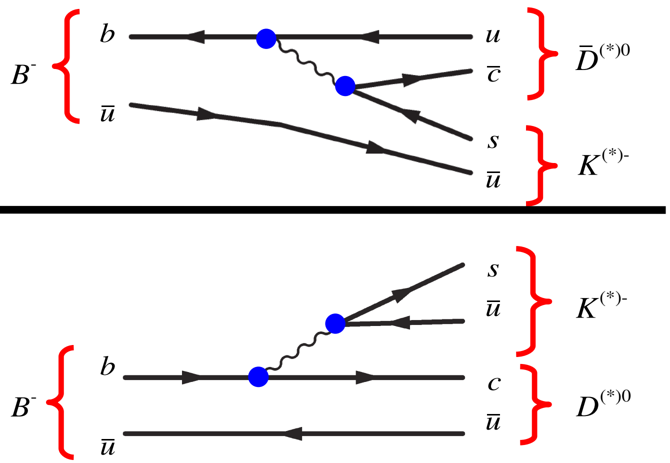
CKM phase difference: γ	strong phase difference: δ

r_B, δ : for each final state $D^{(*)}K^{(*)}$

Experimental inputs with "no" theory machinery - γ

CP violation in charged B- decays: $b \rightarrow c\,\bar{u}\,s\,,\,u\,\bar{c}\,s$

$r_B =$



$\propto V_{ub} V^*_{cs}$

$\approx 0.1 - 0.3$

$\propto V_{cb} V^*_{us}$

CKM phase difference: γ	strong phase difference: δ

r_B, δ : for each final state $D^{(*)}K^{(*)}$

«GLW» D^0-decay into CP-eigenstates

Gronau-London; Gronau-Wyler (1991)

«ADS» $\bar{D}^0 \rightarrow K^+ \pi$ (fav.) & $D^0 \rightarrow K^+ \pi$ (disfav.)

Atwood-Dunietz-Soni (1997)

«GGSZ» $D^0 \rightarrow K_S \pi^+ \pi^-$ (Dalitz plot)

Bondar (Belle, 2002)

Giri-Grossman-Soffer-Zupan (2003)

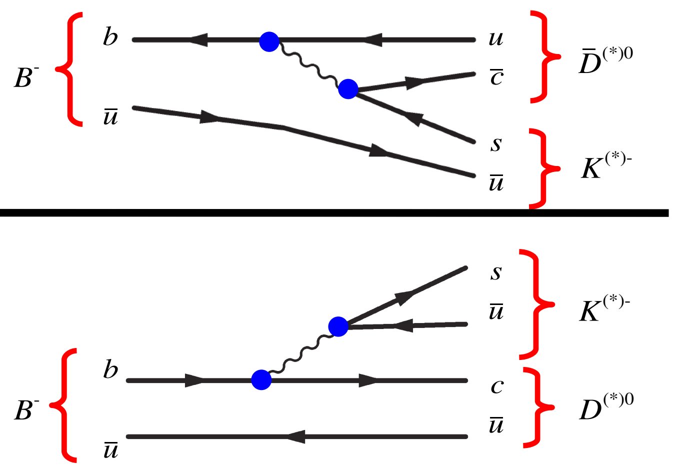
=> Syst. in Dalitz model; $\not{C}P$ in D-decays

Experimental inputs with “no” theory machinery - γ

***CP* violation in charged B- decays:** $b \to c\,\bar{u}\,s\,,\,u\,\bar{c}\,s$

CKM phase difference: γ	strong phase difference: δ

$r_B =$



$\propto V_{ub} V^*_{cs}$

$\approx 0.1 - 0.3$

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r_B, δ : for each final state $D^{(*)}K^{(*)}$

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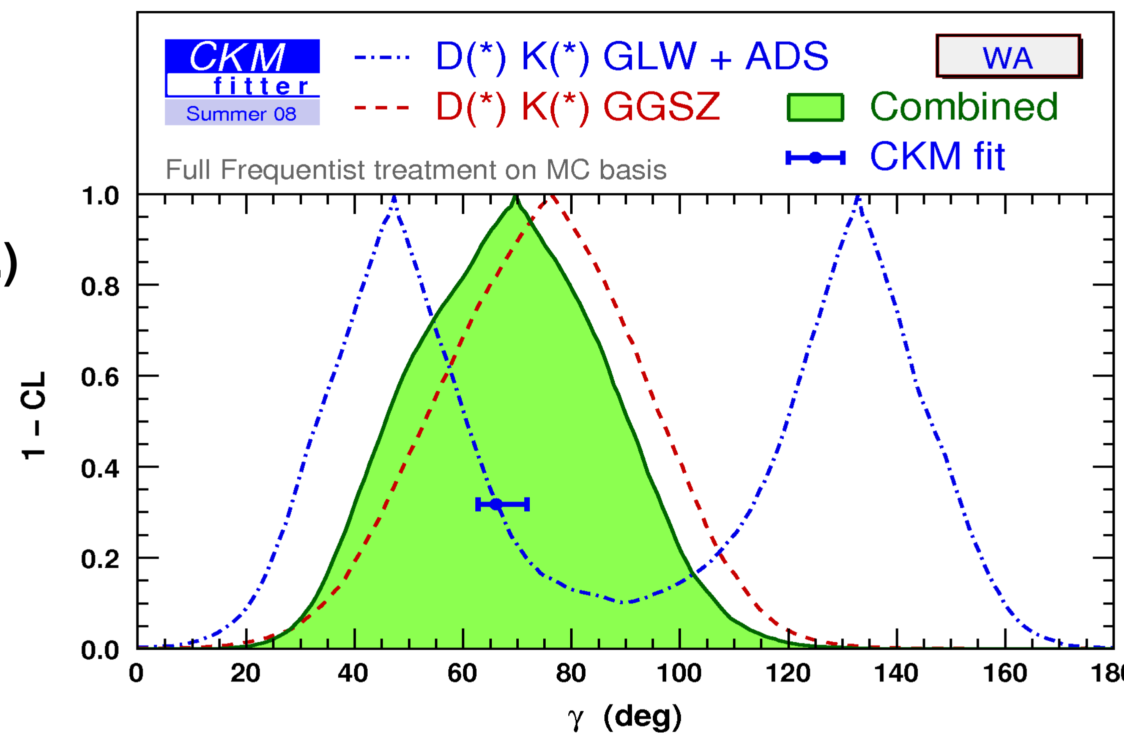
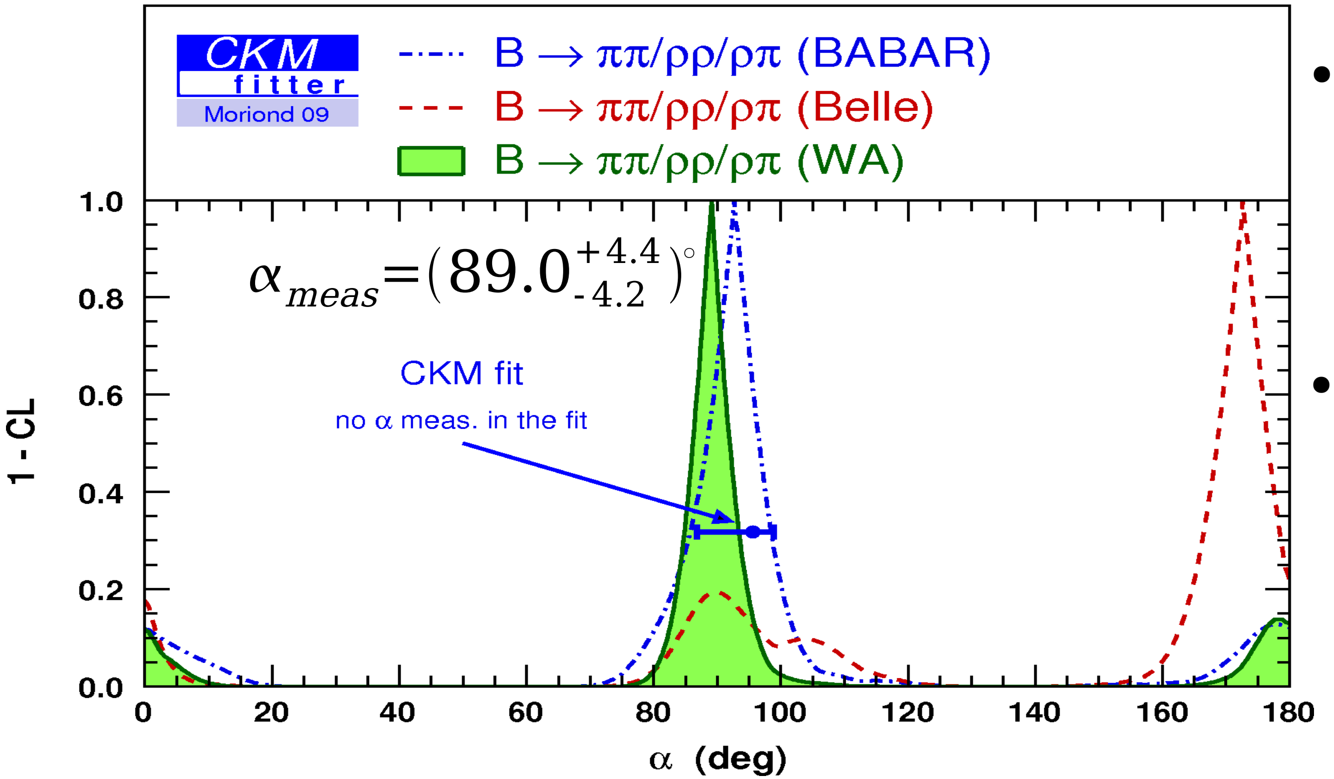


Experimental inputs with modest theory machinery - α

Assumption: Isospin symmetry of strong interactions in B → $\pi\pi$, $\rho\rho$, $\rho\pi/\pi\pi\pi$



- **Current precision dominated by B → $\rho\rho$**
- **β measured: α determines γ (if no NP in $\Delta I=3/2$-amplitude)**

Issues:

*** e.w. penguins, π-$\eta^{(\prime)}$-/ρ-ω-Mixing, other isospin violations, finite ρ-width**

*** Control of charmless BG, Dalitz plot structure ($\pi\pi\pi$)**

=> Difficult to go below a few degrees precision

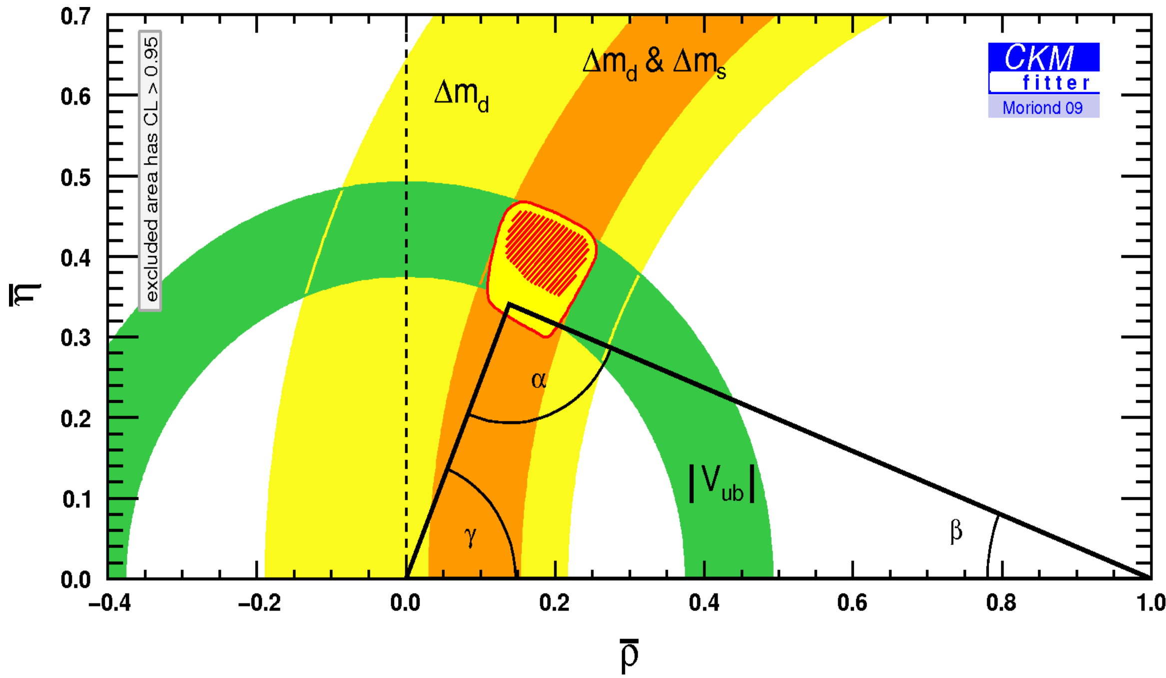
Experimental Inputs relying heavily on theory machinery

$$\Delta m_d \propto \left|V_{td} V_{tb}^*\right|^2 f_{B_d}^2 B_d$$

$$\Delta m_s \propto \left|V_{ts} V_{tb}^*\right|^2 f_{B_s}^2 B_s$$

$$\propto \left|V_{ts} V_{tb}^*\right|^2 \frac{f_{B_s}^2 B_s}{f_{B_d}^2 B_d} f_{B_d}^2 B_d$$

$$\propto \left|V_{ts} V_{tb}^*\right|^2 \xi^2 f_{B_d}^2 B_d$$



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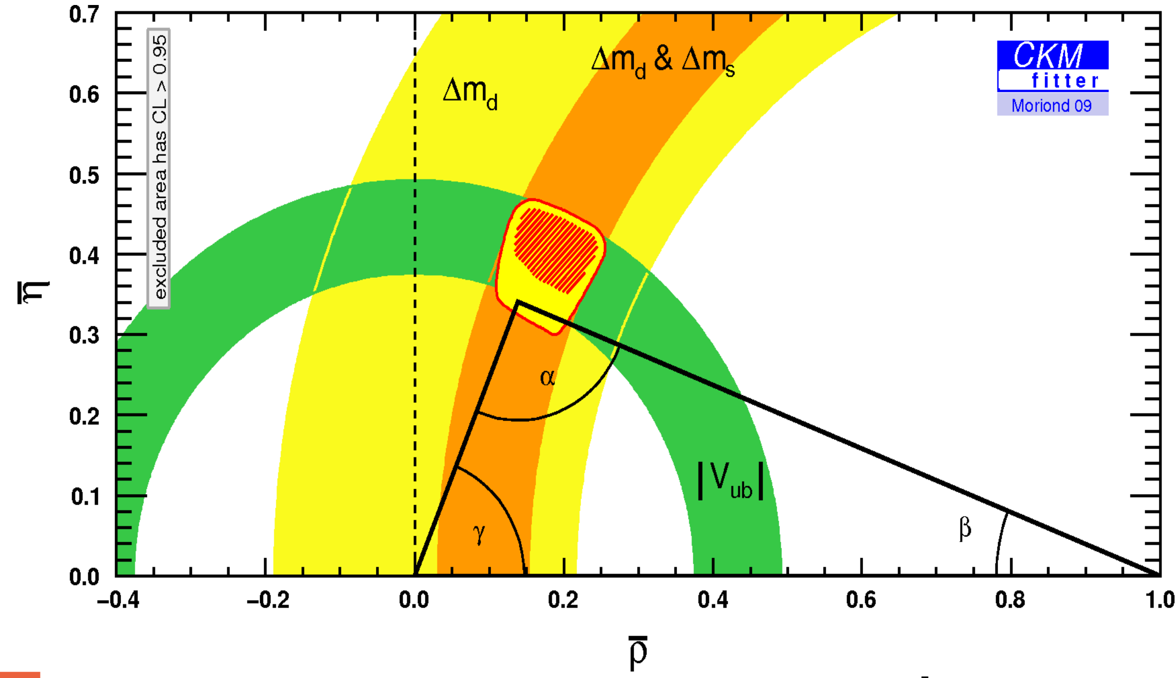
$$\Delta m_d \propto \left|V_{td} V_{tb}^*\right|^2 f_{B_d}^2 B_d$$

$$\Delta m_s \propto \left|V_{ts} V_{tb}^*\right|^2 f_{B_s}^2 B_s$$

$$\propto \left|V_{ts} V_{tb}^*\right|^2 \frac{f_{B_s}^2 B_s}{f_{B_d}^2 B_d} f_{B_d}^2 B_d$$

$$\propto \left|V_{ts} V_{tb}^*\right|^2 \xi^2 f_{B_d}^2 B_d$$



$$|\epsilon_K| \approx C\, B_K\, |V_{cb}|^2 \lambda^2 \bar{\eta} \left[(1-\bar{\rho}) |V_{cb}|^2 \eta_{tt} S(x_t^2) + \eta_{ct} S(x_c, x_t) - \eta_{cc} S(x_c^2) \right]$$

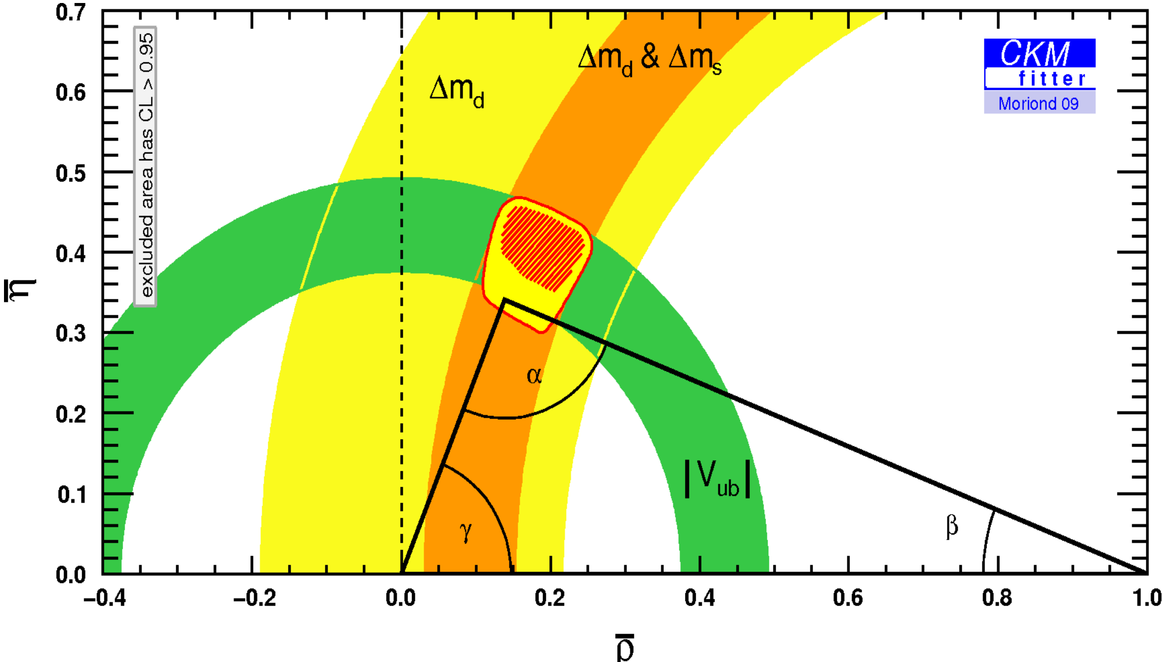
Experimental Inputs relying heavily on theory machinery

$$\Delta m_d \propto \left|V_{td} V_{tb}^*\right|^2 f_{B_d}^2 B_d$$

$$\Delta m_s \propto \left|V_{ts} V_{tb}^*\right|^2 f_{B_s}^2 B_s$$

$$\propto \left|V_{ts} V_{tb}^*\right|^2 \frac{f_{B_s}^2 B_s}{f_{B_d}^2 B_d} f_{B_d}^2 B_d$$

$$\propto \left|V_{ts} V_{tb}^*\right|^2 \xi^2 f_{B_d}^2 B_d$$



$$|\epsilon_K| \approx C\, B_K\, |V_{cb}|^2 \lambda^2 \bar{\eta} \left[(1-\bar{\rho}) |V_{cb}|^2 \eta_{tt} S(x_t^2) + \eta_{ct} S(x_c, x_t) - \eta_{cc} S(x_c^2) \right]$$

Need for consistent "averages" for LQCD parameters

However:

1. Not clear how to do it

2. Subjective

3. Meaning of errors not clear

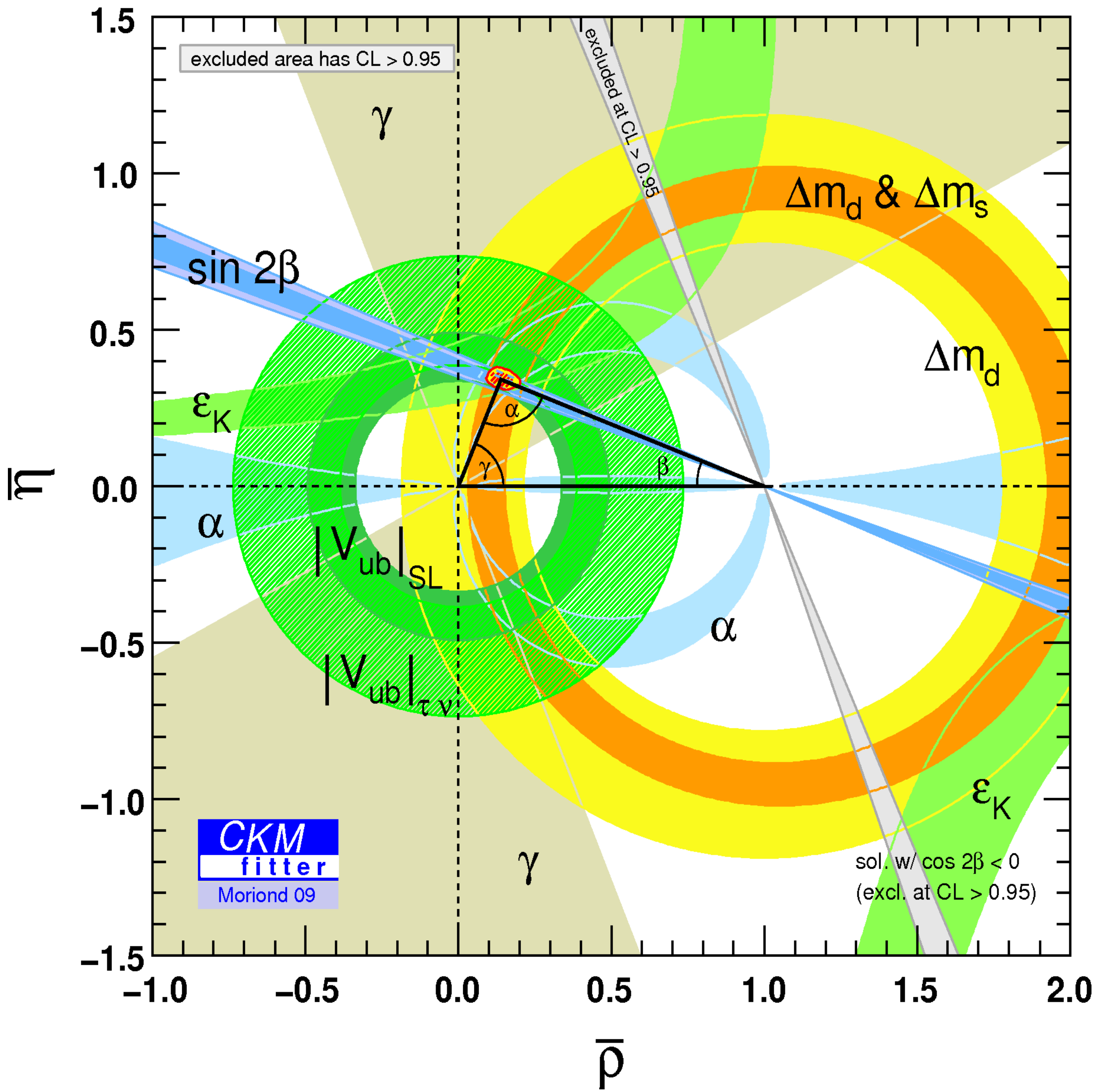
f_{B_s}	$(228 \pm 3 \pm 17)\, MeV$
f_{B_s}/f_{B_d}	$1.196 \pm 0.008 \pm 0.023$
B_s	$1.23 \pm 0.03 \pm 0.05$
B_s/B_d	$1.05 \pm 0.02 \pm 0.05$
$\hat{B}_K$	$0.721 \pm 0.005 \pm 0.040$

Here:

only 2 & (1+1) unquenched calculations

"Algorithmic average" preserving smallest systematic uncertainty

The overall picture



- Good agreement on 2σ-level
- Big success for:
  - * B-factories
  - * Tevatron (Δm_s)
  - * KM mechanism

- NP can still be around due to sizeable non-perturbative QCD uncertainties

The role of leptonic B-decays, esp. B→τν

1. **Helicity suppression** => B→eν, B→μν not measurable at B-factories

=> B→τν (10^{-4}): Evidence at B-factories (first @ Belle)

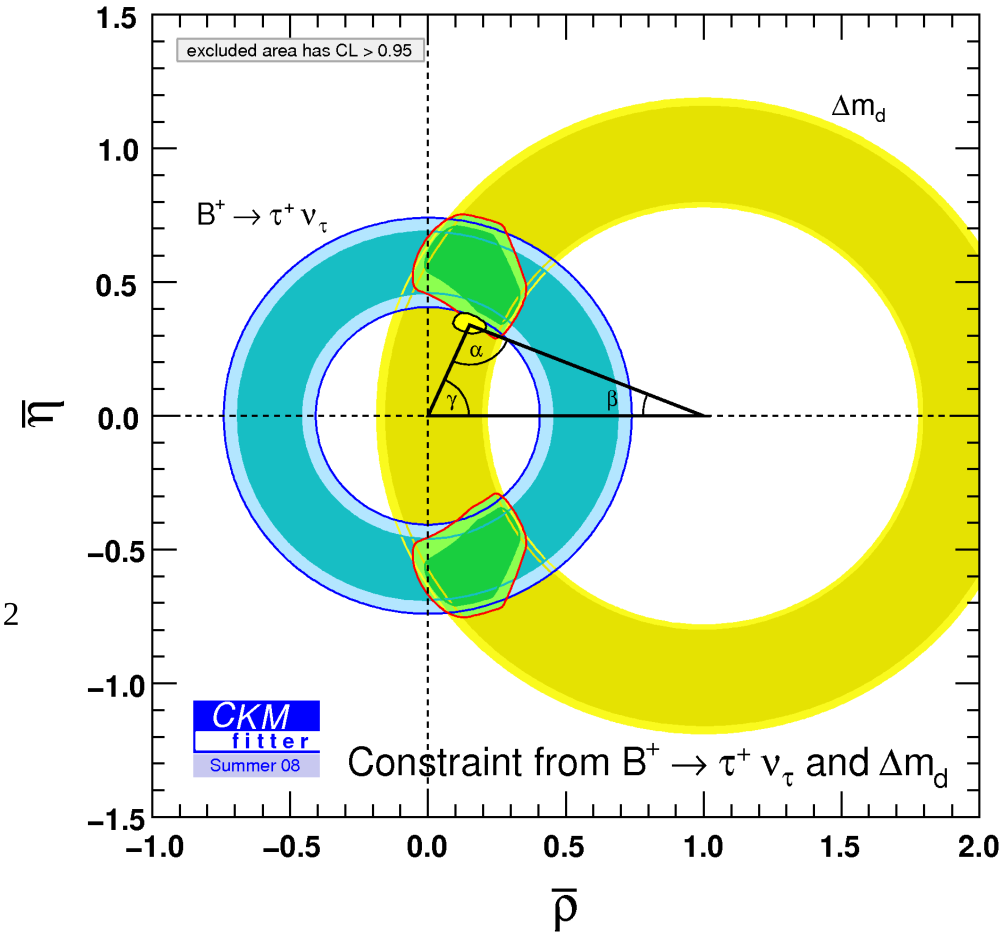
$$\mathcal{B}(B^- \to \ell^- \bar{\nu}) = \frac{G_F^2 m_B}{8\pi} m_l^2 \left(1 - \frac{m_l^2}{m_B^2}\right)^2 f_B^2 |V_{ub}|^2 \tau_B$$

2. **Uncertainties in prediction:** f_B **and** $|V_{ub}|$

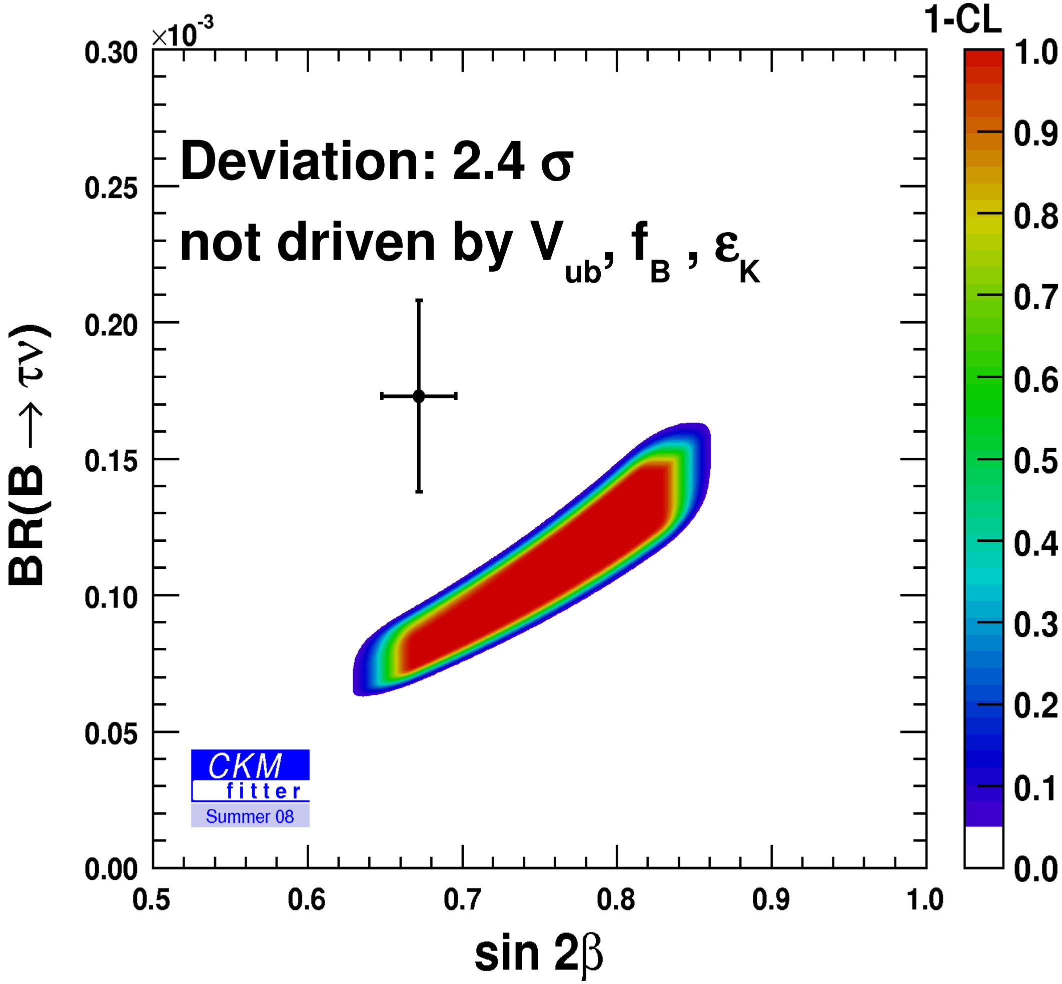
3. Δm_d **& BF(B→τν) removes dependence on** f_B **(but not on** B_d **):** $\Delta m_d \propto f_B^2 B_d$

4. **Sensitive to H± contributions**

$$B(B^- \to \tau^- \bar{\nu}_\tau) = B_{SM}(B^- \to \tau^- \bar{\nu}_\tau) \times \left(1 - \tan^2\beta \frac{m_B^2}{m_{H^\pm}^2}\right)^2$$



Interesting effect in B→τν (or in sin2β)?



CKM08	BF $[10^{-4}]$ BABAR	Belle
Hadr. Tags	1.8 ± 1.0	1.79 ± 0.72
SL Tags	1.8 ± 0.9	1.65 ± 0.52

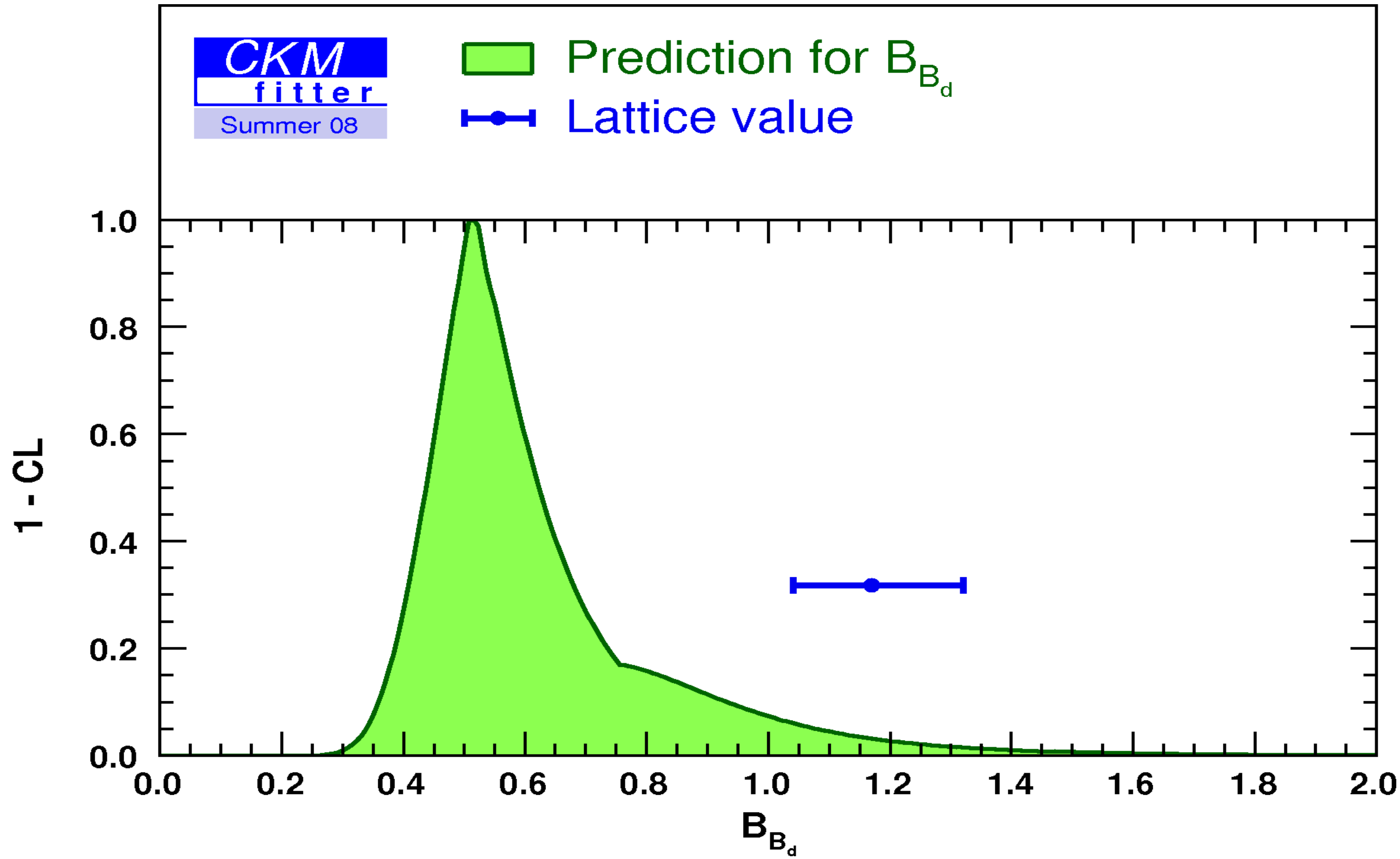
SM prediction (using V_{ub} from SM fit):

$0.80^{+0.26}_{-0.13} \times 10^{-4}$ (2σ-level)

$$\frac{BR(B \to \tau\nu)}{\Delta m_d} = \frac{3\pi}{4} \frac{m_\tau^2}{m_W^2 S(x_t)} \left(1 - \frac{m_\tau^2}{m_B^2}\right)^2 \tau_{B^+} \frac{1}{B_{Bd}} \frac{1}{|V_{ud}|^2} \left(\frac{\sin\beta}{\sin\gamma}\right)^2$$

$B\to\tau\nu$ & Δm_d: B_d prediction

Deviation may be caused by:
1. Statistical fluctuation or
2. NP ($H^\pm$, $\sin 2\beta$) or
3. Problem in B_d-value

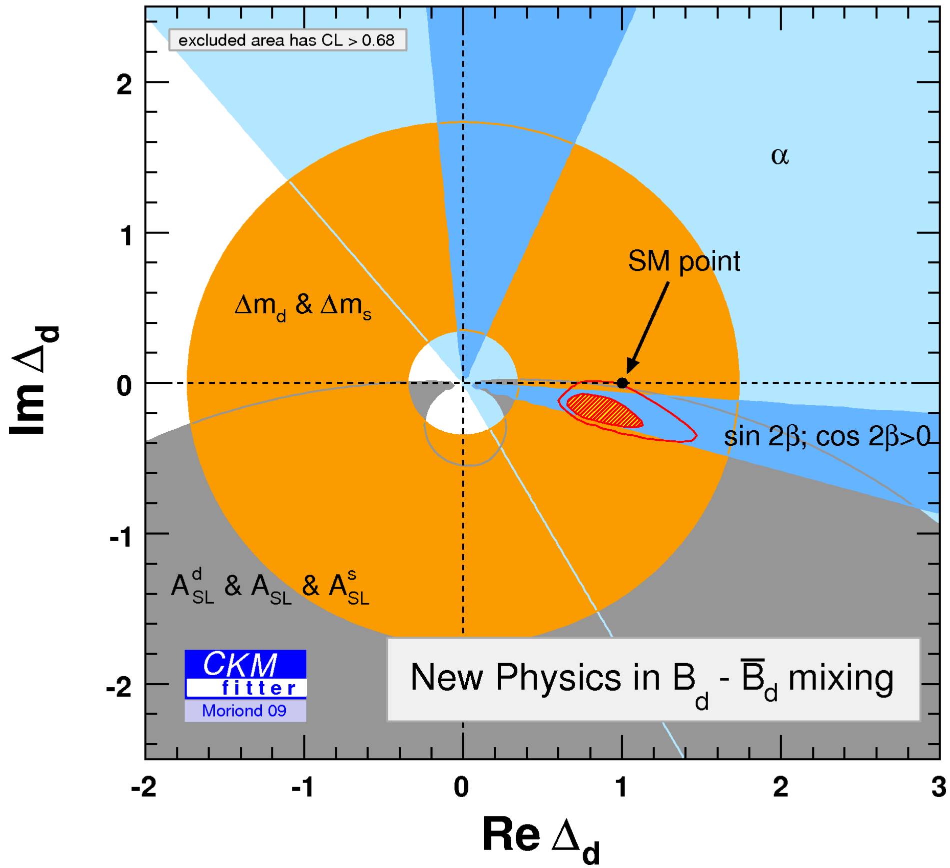


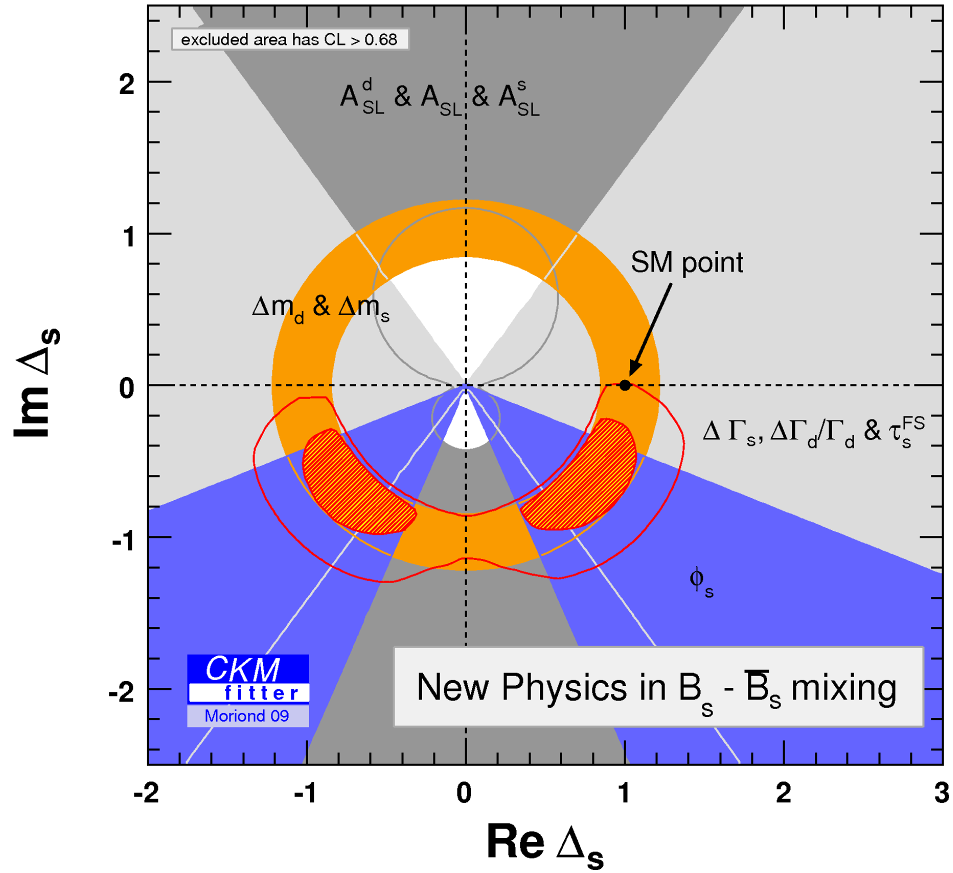
NP in B_d-Mixing ?

$$\langle B_q^0 | M_{12}^{SM+NP} | \overline{B}_q^0 \rangle \equiv \Delta_q^{NP} . \langle B_q^0 | M_{12}^{SM} | \overline{B}_q^0 \rangle$$

$$\Delta_q^{NP} = \mathrm{Re}(\Delta_q) + i\, \mathrm{Im}(\Delta_q)$$

Lenz, Nierste





- **NP space still considerably large**
- **Deviation from SM:** 2.1σ

- **Deviation from SM:** 1.9σ **(driven by CP violation in Bs mixing: Tevatron)**

Conclusion & Outlook

- KM mechanism dominant source of observed CP violation but: significant NP effects may hide behind non-perturbative QCD uncertainties (Δm_d, Δm_s, ε_K, V_{ub}, V_{cb})
  Important improvements have to come from theory

- β, α & γ can be significantly improved @ a Super-B-factory; there are limitations (α) or dependence on external input (γ: Dalitz plot $\rightarrow$ charm factory (CLEO-c, Super-F?))

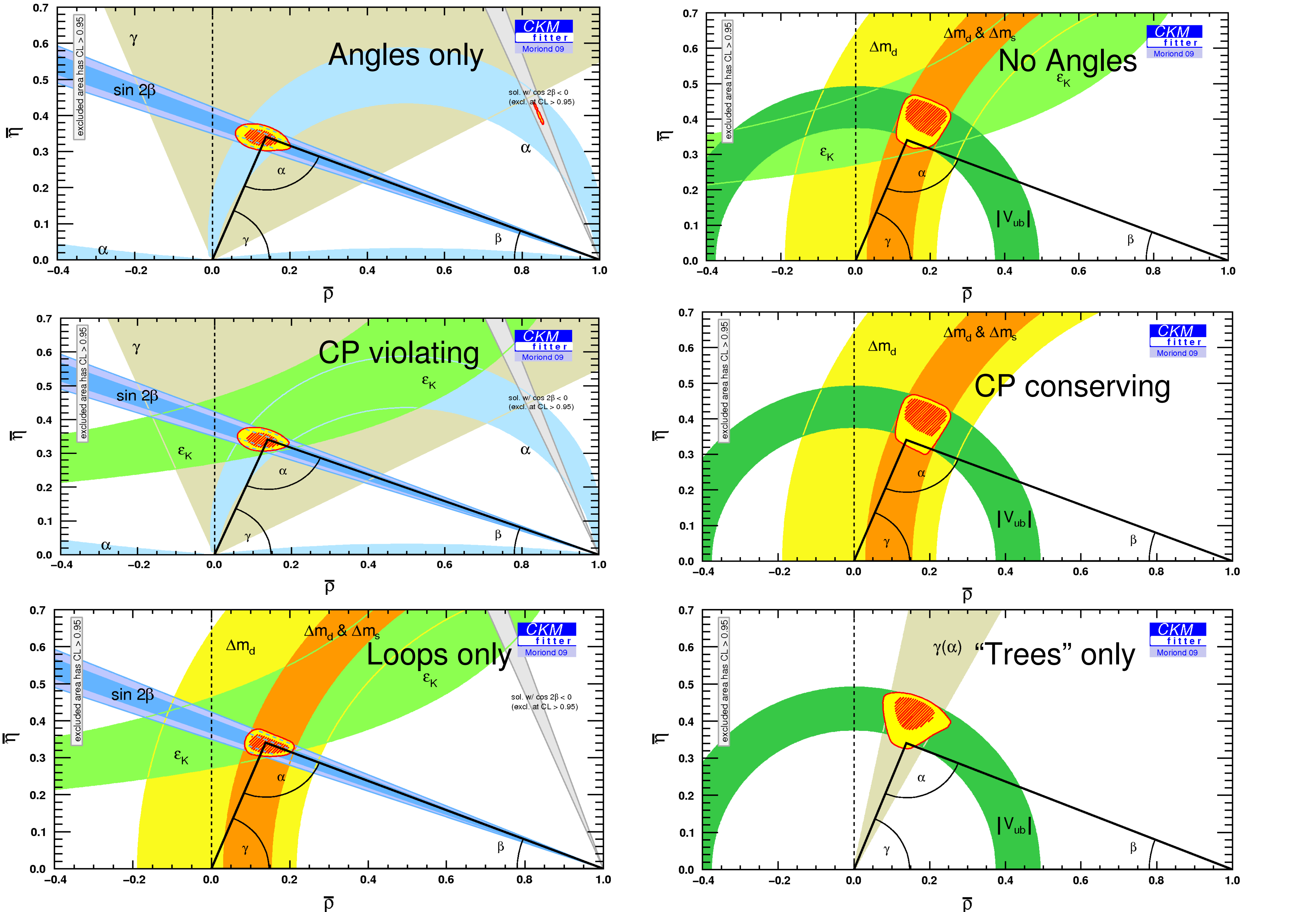
- Rare decays @ a Super-B-factory: e.g. $B\rightarrow l\nu$, sin2β($b\rightarrow s$ peng), $B\rightarrow V\gamma$, , $B\rightarrow X_d\gamma$

- Charm-/B-/Super-F-factory: V_{cd} & V_{cs} from (semi)leptonic D and D_s-decays; D-mixing

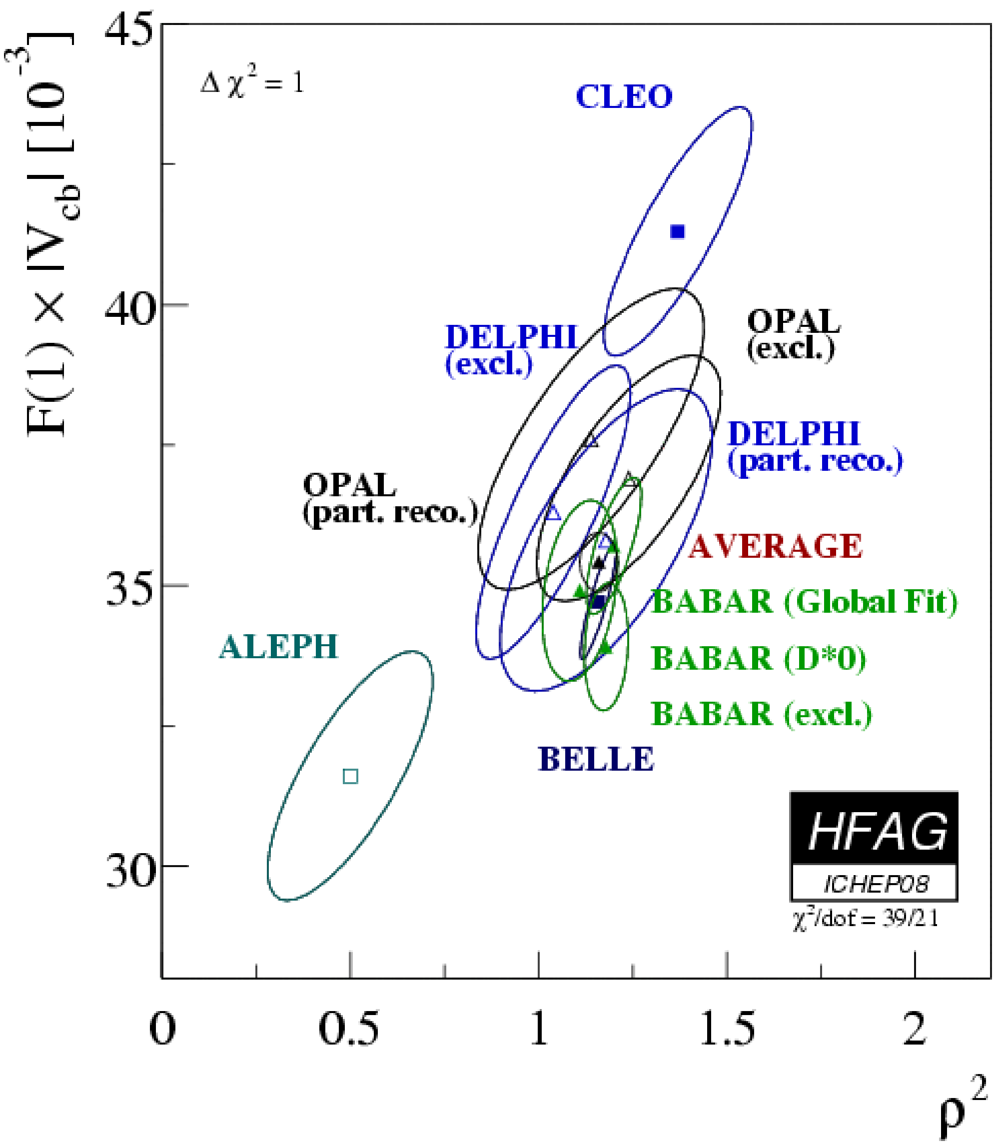
- LHCb: * improvements in the area of angle measurements (β, esp. γ; α challenging)
  * B_s-sector (β_s from $B_s\rightarrow\psi\phi$, $B_s\rightarrow\phi\phi$ ($b\rightarrow s$ penguin), rare decays like $B_s\rightarrow\mu\mu$)

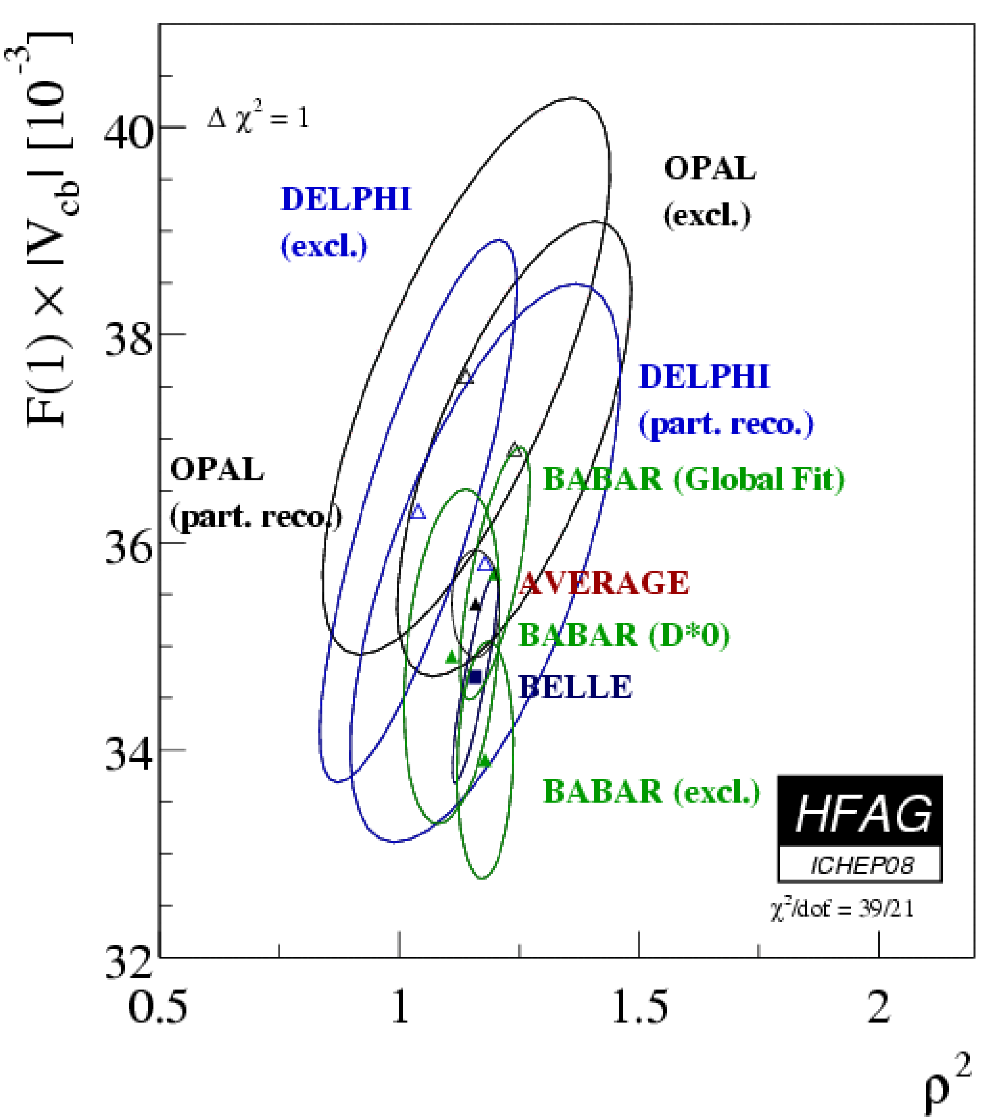
BACKUP

Detailed comparisons (incl. B→τν, not shown)



$|V_{cb}|$: Exclusive semileptonic B-decays

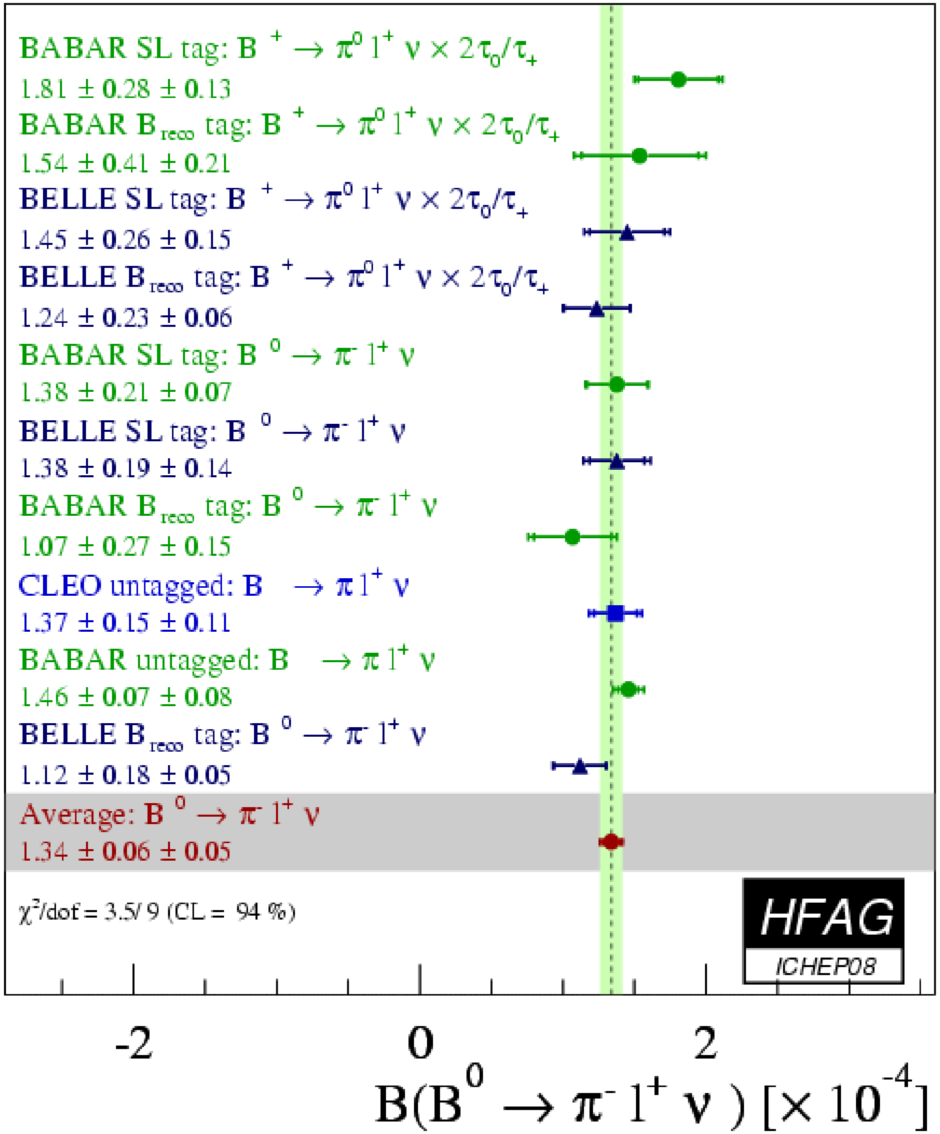


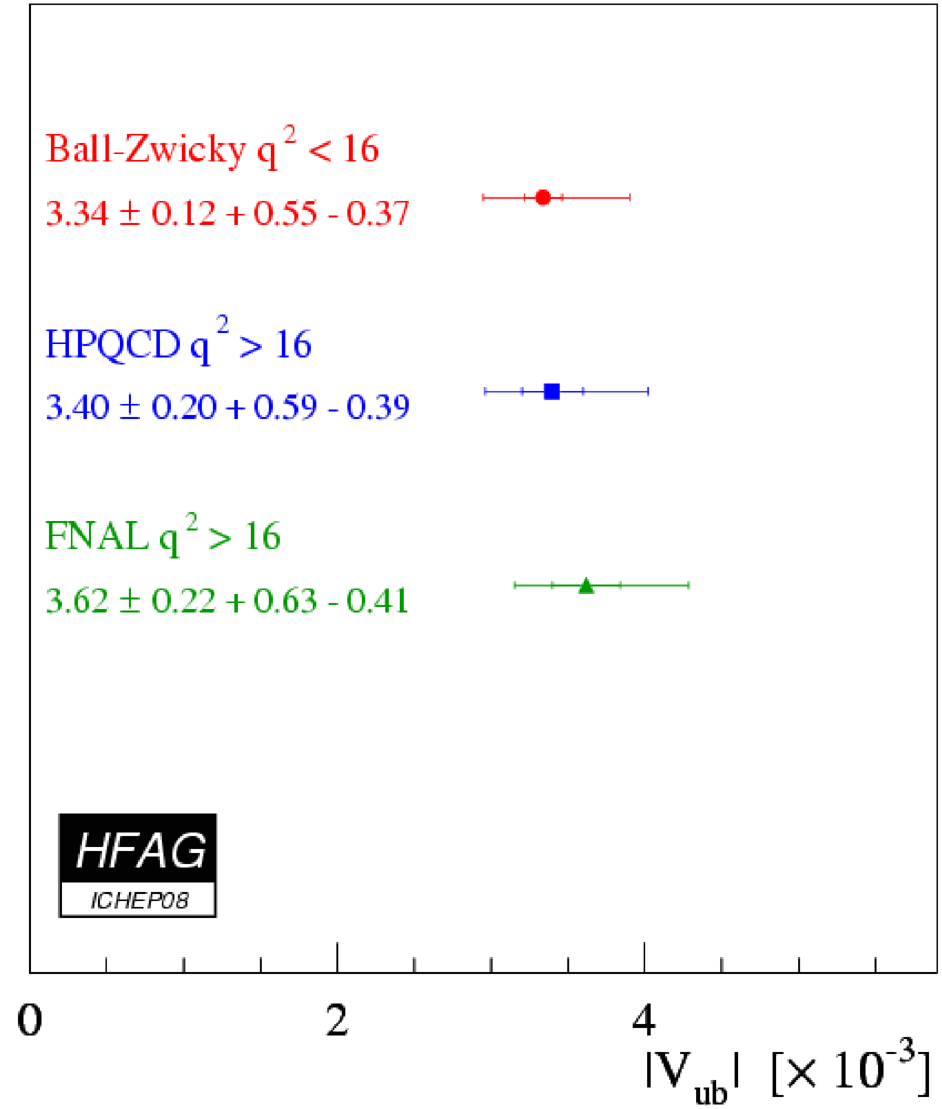


$$|V_{cb}| = (38.18 \pm 0.56_{exp} \pm 0.54_{theostat} \pm 0.83_{theosys}) \times 10^{-3}$$

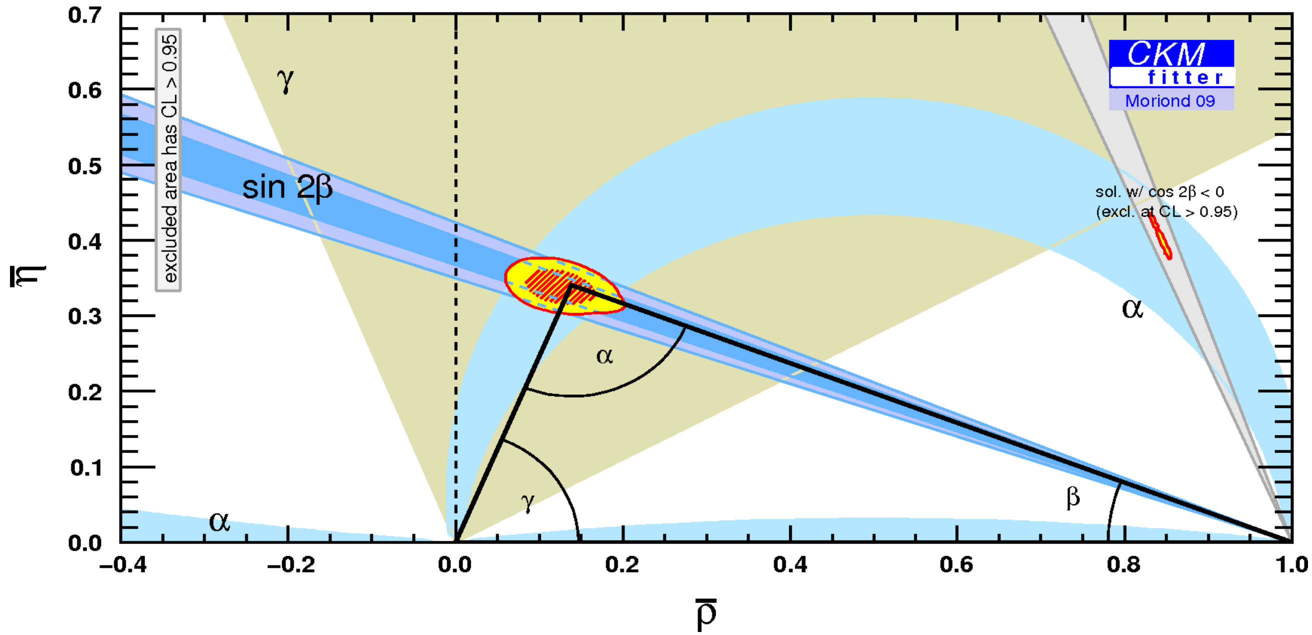
$$F(1) = 0.921 \pm 0.013_{theostat} \pm 0.020_{theosys}$$ 0808.2519 [hep-lat]

$|V_{ub}|$: Exclusive semileptonic B-decays

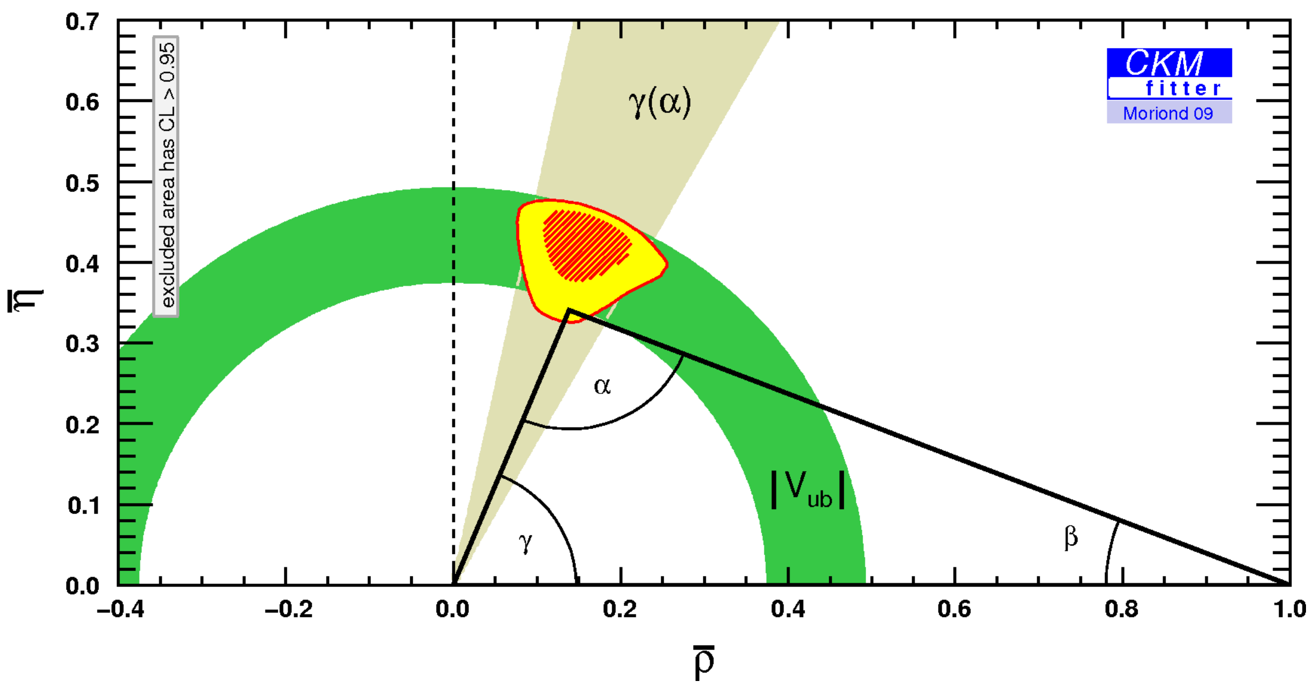




Experimental inputs with modest theory machinery - α



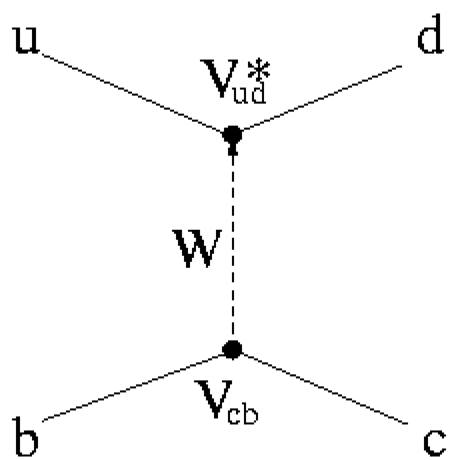
- β measured: α determines γ (if no NP in ΔI=3/2-amplitude)

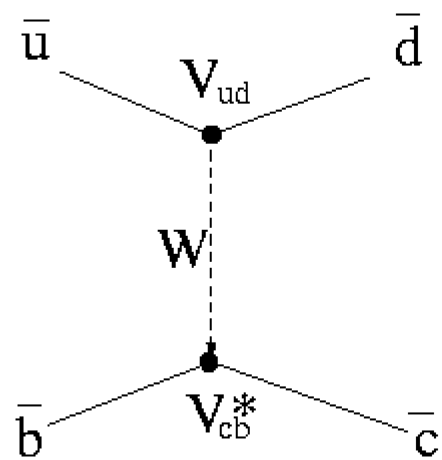


- Together with $|V_{ub}|$: apex of UT fixed independent of NP in mixing
- Consider next observables sensitive to NP in mixing: Same apex?

1.4.4 CP violation generated by the CKM matrix

$$L_{weak} \propto W_\mu^+ \left(\bar{u}\;\bar{c}\;\bar{t}\right) \gamma^\mu (1-\gamma^5) \begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} \qquad \begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = V_{CKM} \cdot \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$





$u\, b \rightarrow d\, c$ $\qquad$ $\bar{u}\, \bar{b} \rightarrow \bar{d}\, \bar{c}$

$$M \propto V_{ud}^* V_{cb} (\bar{u}_d \Gamma^\mu u_u)(\bar{u}_c \Gamma_\mu u_b) \qquad M^+ \propto V_{ud} V_{cb}^* (\bar{u}_u \Gamma^\mu u_d)(\bar{u}_b \Gamma_\mu u_c) \qquad \Gamma^\mu \equiv \gamma^\mu (1-\gamma^5)$$

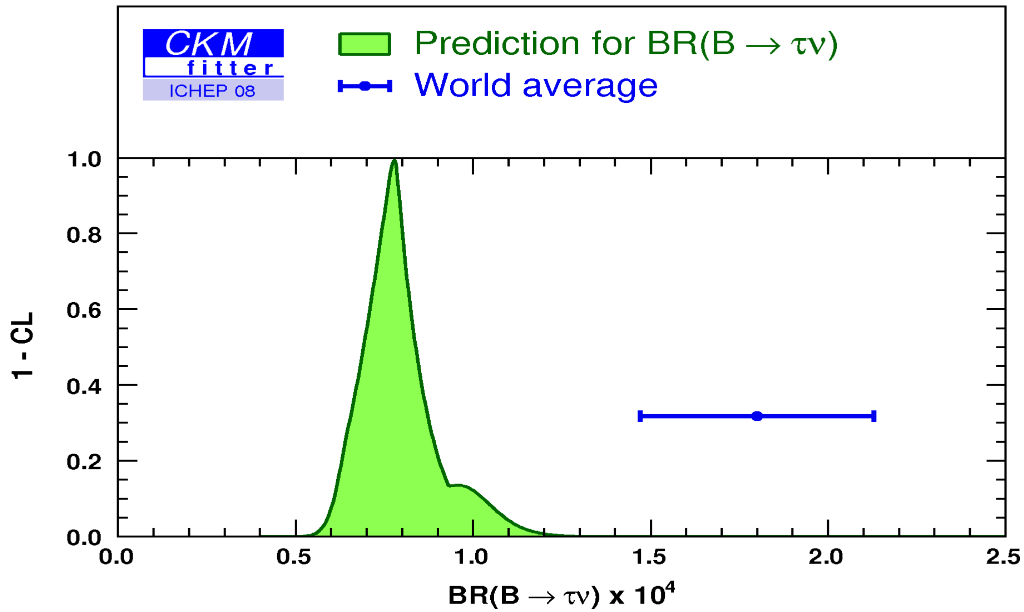
|| ?

CP

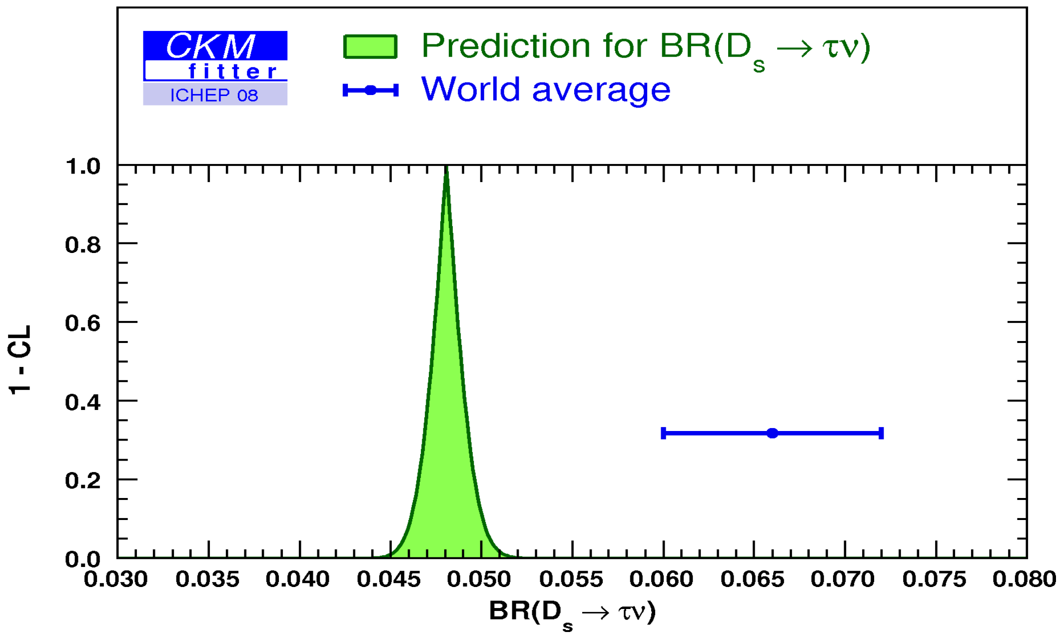
$$M_{CP} \propto V_{ud}^* V_{cb} (\bar{u}_u \Gamma^\mu u_d)(\bar{u}_b \Gamma_\mu u_c)$$

CP invariance: $M^+ = M_{CP} \Rightarrow V_{CKM}$ real

Interesting effects in leptonic decays?



- Deviation: 2.9 σ
- Prediction driven by angles (not V_{ub})
- Either hint for
  1. NP ($H^\pm$, in sin2β, ...) or
  2. problem in B_d-value



- Deviation: 2.9 σ
- Prediction driven by one LQCD result for f_{Ds} ((241±3) MeV, 0706.1726)
- If LQCD value confirmed by other calculations with similar errors:

  Hint for NP, but not: $H^\pm$ or 4th gen. (Kronfeld & Dobrescu, 2008)

sin2β(b→s penguin)

Theoretical interpretation rather clean