B-THEORY IN THE LHC ERA
AN OVERVIEW

Blaženka Melić

Rudjer Boskovic Institute
Zagreb

2010 LHC Days in Split, Oct 4-9th

OVERVIEW

- WHY B PHYSICS ?
- STATUS OF B PHYSICS
- OUTLOOK

INTRODUCTION:

- ❑ b-quark – member of the third generation quark doublet

- ❑ decays into quarks of first two generations:

  - mostly b $\rightarrow$ c
  - rearly b $\rightarrow$ s, d, u

[u d'] [c s'] [t b']

relatively LONG lifetime → TEST OF SM

EXPERIMENTS

Experiments providing most of analyses today	Experiments that just started collecting data	Planned facilities
TEVATRON (Fermilab)	LHCb, **ATLAS, CMS**	SuperB, Belle II, **ILC**

BaBar (SLAC)

3.1 GeV e^+
9 GeV e^-
468M BB pairs

BELLE (KEK)

3.5 GeV e^+
8 GeV e^-
657M BB pairs

- weak eigenstates and mass eigenstates are connected through the unitary transformation → CKM MATRIX

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

loop diagrams

THREE angles and ONE PHASE :

$$\hat{V}_{\mathrm{CKM}} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{13}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{13}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{13}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{13}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{13}} & c_{23}c_{13} \end{pmatrix}$$

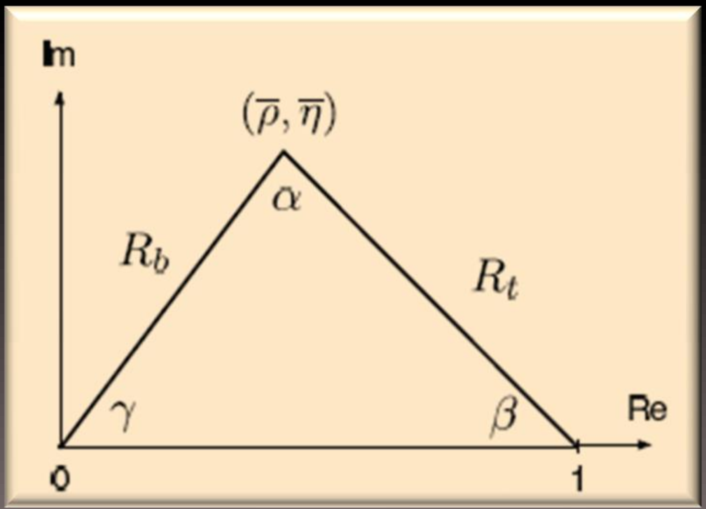
$c_{ij} = \cos\Theta_{ij}$, $s_{ij} = \sin\Theta_{ij}$

CP VIOLATION

UNITARY TRIANGLES OF CKM MATRIX:

$$\hat{V}_{\rm CKM}^{\dagger} \cdot \hat{V}_{\rm CKM} = \hat{1} = \hat{V}_{\rm CKM} \cdot \hat{V}_{\rm CKM}^{\dagger}$$

visualization of the relation: $\sum V_{dj} V_{jb}^{*} = 0$ as a triangle in a complex plane (2 nonsquashed)



$$\underbrace{V_{ud}V_{ub}^{*}}_{(\rho+i\eta)A\lambda^3} + \underbrace{V_{cd}V_{cb}^{*}}_{-A\lambda^3} + \underbrace{V_{td}V_{tb}^{*}}_{(1-\rho-i\eta)A\lambda^3} = 0$$

$$\bar{\rho} \equiv \rho \left(1 - \frac{1}{2}\lambda^2\right), \quad \bar{\eta} \equiv \eta \left(1 - \frac{1}{2}\lambda^2\right)$$

$$s_{12} \equiv \lambda = 0.22, \quad s_{23} \equiv A\lambda^2, \quad s_{13}e^{-i\delta_{13}} \equiv A\lambda^3(\rho - i\eta)$$

e.g. $V_{ub} = A\,\lambda^3\,(\rho - i\,\eta)$ $\rightarrow$ arg (V_{ub}) = - γ

$V_{cb} = A\,\lambda^2$

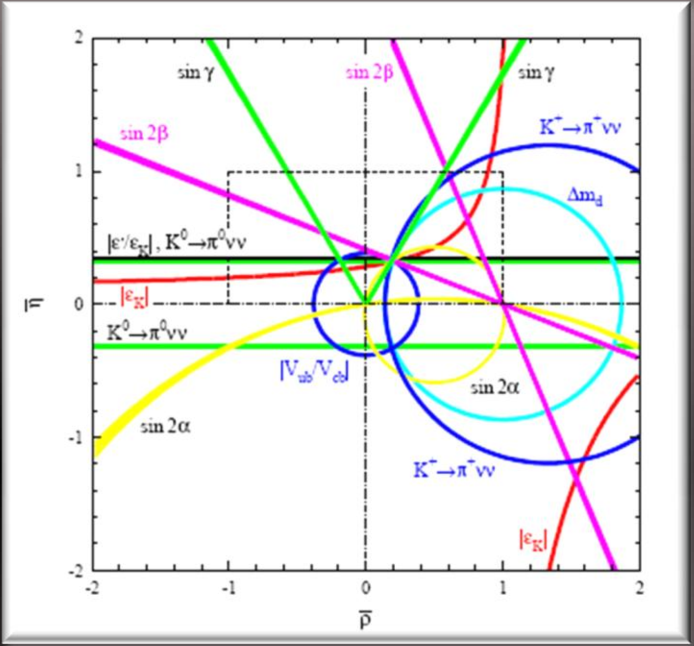
$V_{td} = A\,\lambda^3\,(1 - \rho - i\,\eta)$ $\rightarrow$ arg (V_{td}) = - β_d

$V_{ts} \approx - A\,\lambda^2\,(1 + i\,\lambda^2\,\eta)$ $\rightarrow$ arg (V_{ts}) = β_s

CKM fits – theory is used to convert experimental data into contours in ρ-η plane

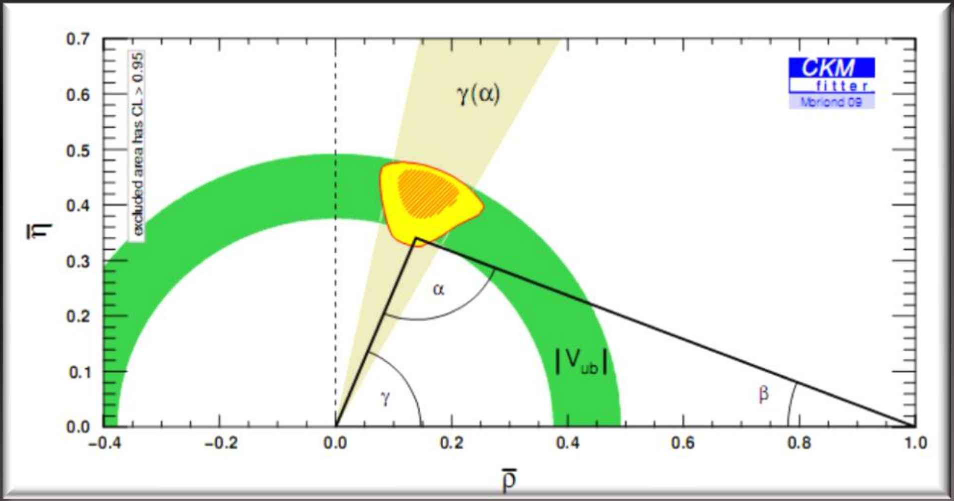
Global analysis of data - HFAG & CKMfitter, UT fit

THE IDEAL …

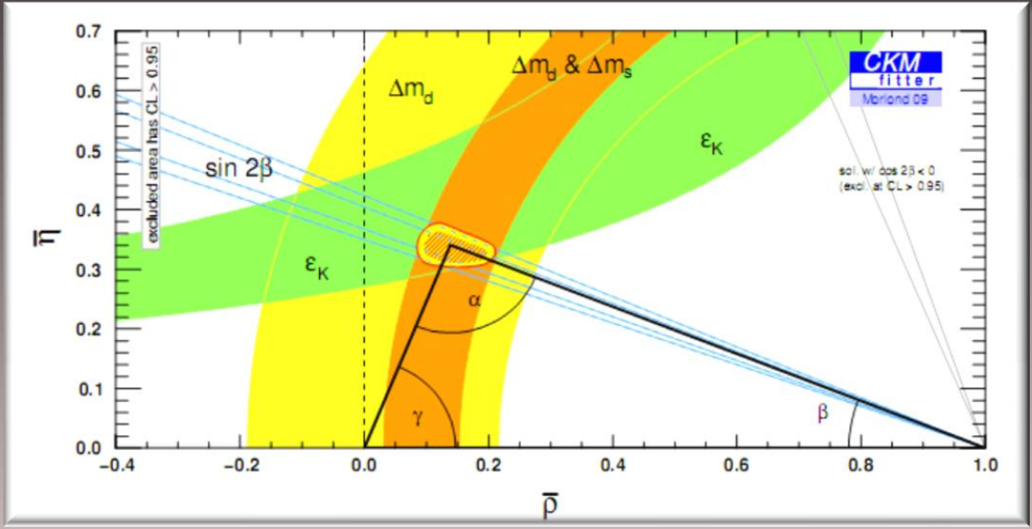


THE REALITY …

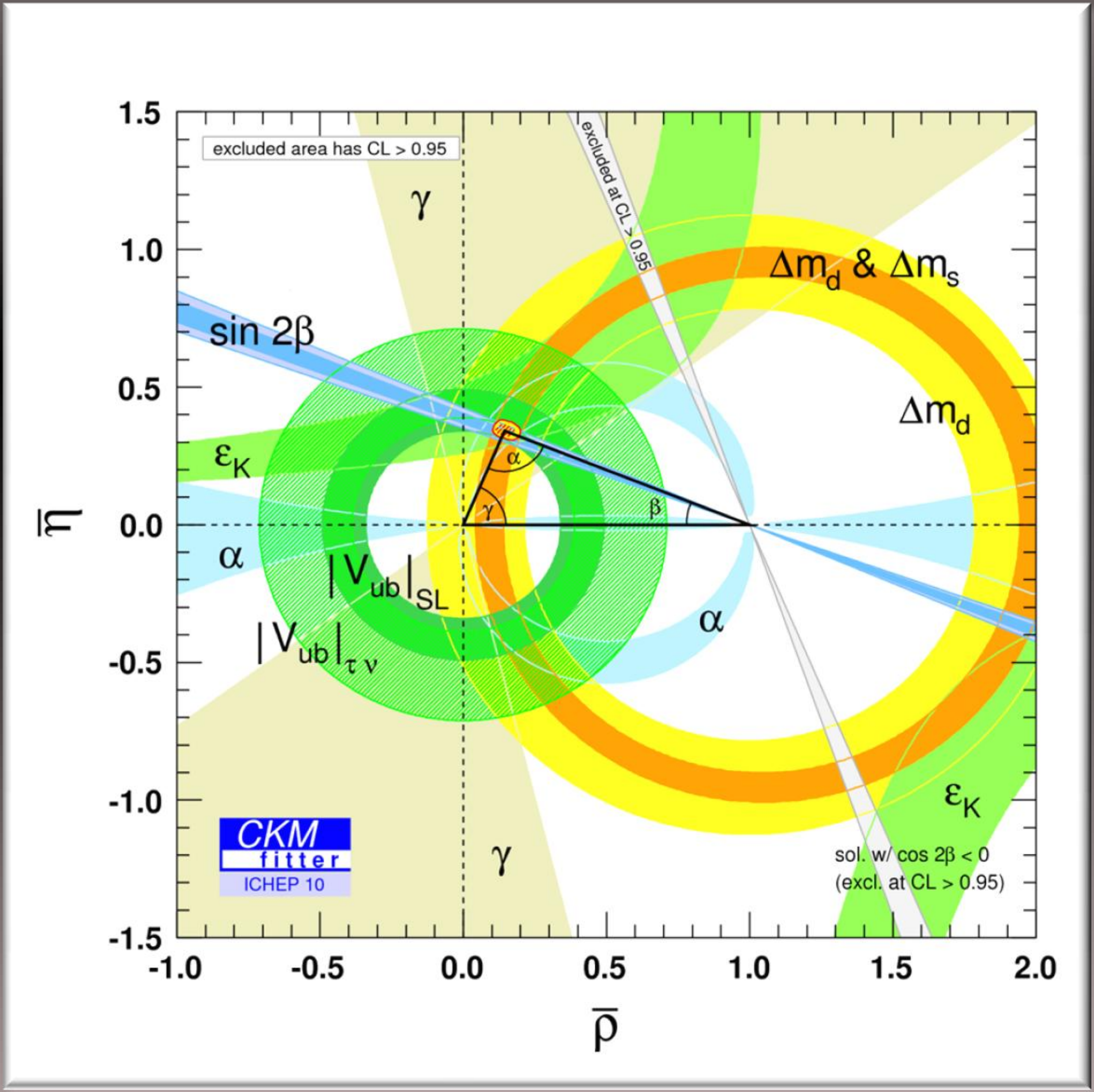
constraints from TREE decays:



constraints from LOOP decays:



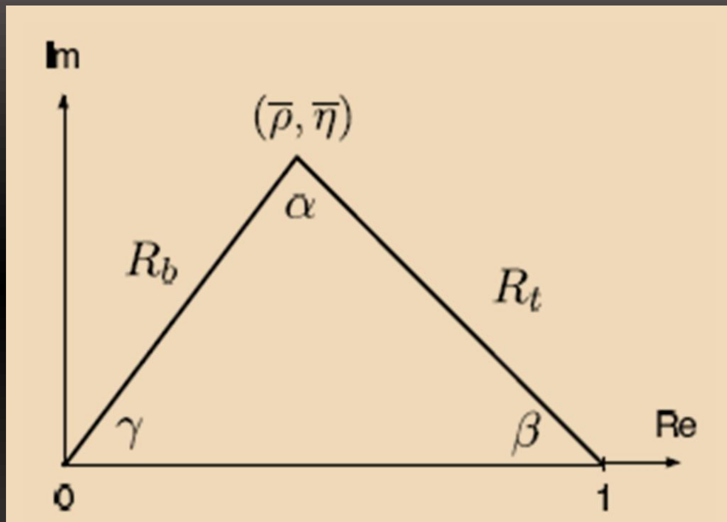
ALTOGETHER …..

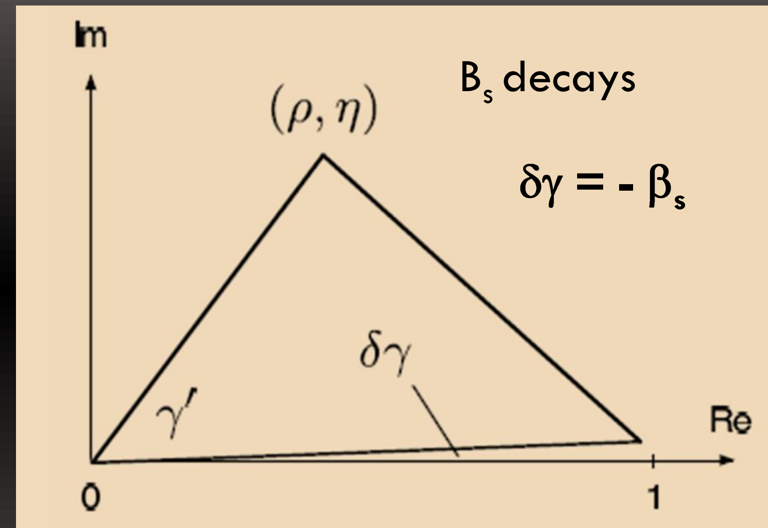


THE GOAL is to OVERCONSTRAIN CKM matrix as much as possible

→ **NEW PHYSICS**

two non-squashed triangles in a complex plane:





$$\underbrace{V_{ud}V_{ub}^*}_{(\rho+i\eta)A\lambda^3} + \underbrace{V_{cd}V_{cb}^*}_{-A\lambda^3} + \underbrace{V_{td}V_{tb}^*}_{(1-\rho-i\eta)A\lambda^3} = 0$$

$$\underbrace{V_{ud}^*V_{td}}_{(1-\rho-i\eta)A\lambda^3} + \underbrace{V_{us}^*V_{ts}}_{-A\lambda^3} + \underbrace{V_{ub}^*V_{tb}}_{(\rho+i\eta)A\lambda^3} = 0.$$

these triangles coincide at the λ^3 level

LHC will reach precision for exploring both triangles at λ^5 level

B_s decays, loop proceses !

good overall consistency of experimental constraints in CKM fits

$\longrightarrow$ there is not much room for new sources of flavour symmetry breaking

MINIMAL FLAVOUR VIOLATION (MVF) PARADIGM:

The large quark-flavour symmetry of gauge SM is
BROKEN ONLY BY THE TWO QUARK YUKAWA COUPLINGS Y_u & Y_d

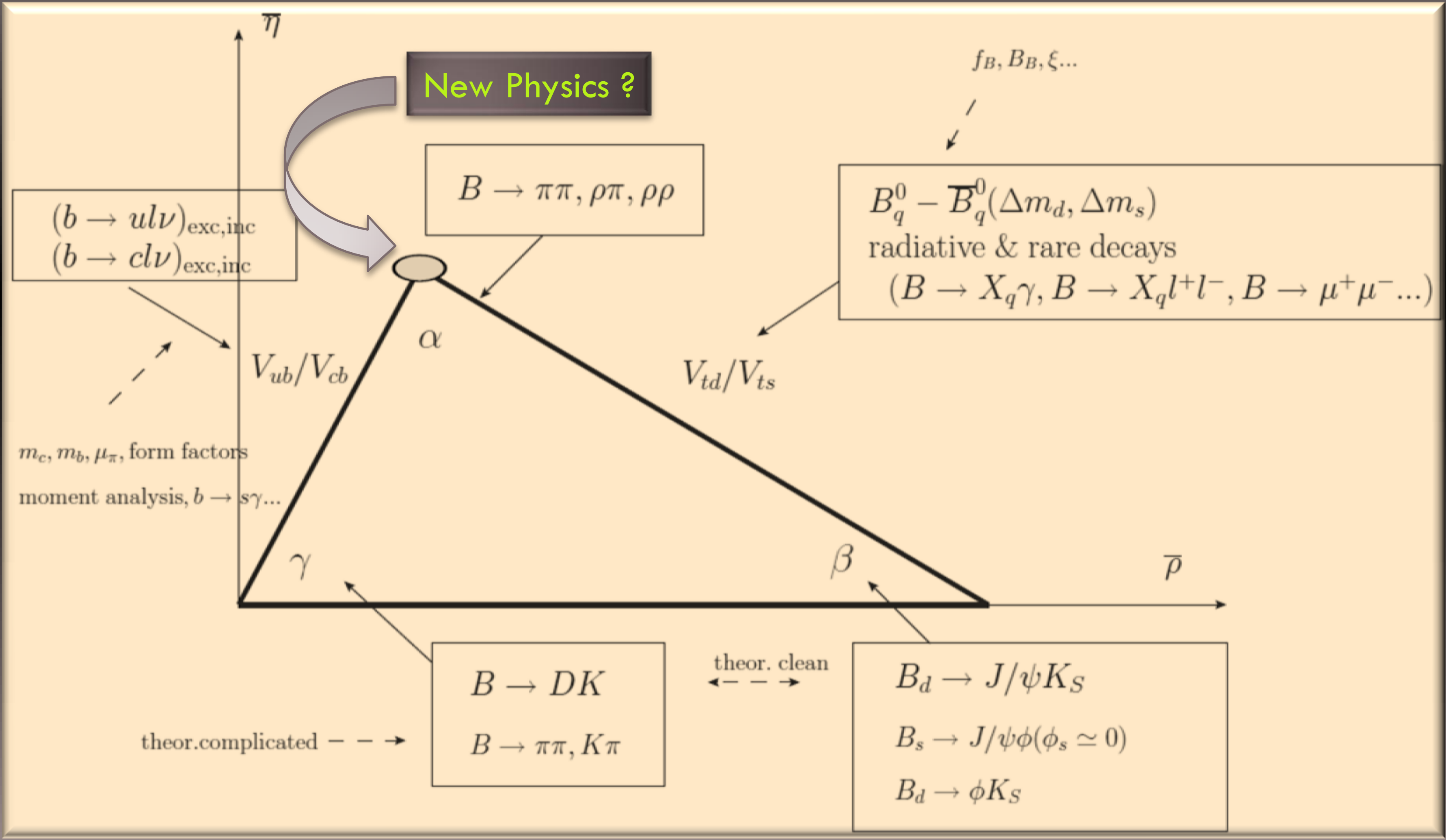
$\longrightarrow$ CKM matrix controls all flavour-changing phenomena, also beyond SM !

MFV : $Y_u \sim (3, \bar{3}, 1)$ & $Y_d \sim (3, 1, \bar{3})$ are non-dynamical fields now !

- background values of these fields are ordinary SM Yukawa couplings

$$-\mathcal{L}^{\rm SM}_{\rm Yukawa} = Y_d^{ij}\bar{Q}_L^i \phi D_R^j + Y_u^{ij}\bar{Q}_L^i \tilde{\phi} U_R^j + Y_e^{ij}\bar{L}_L^i \phi E_R^j + {\rm h.c.} \qquad (\tilde{\phi} = i\tau_2\phi^\dagger)$$

UNITARY TRIANGLE FROM B-PHYSICS



- ❑ large number of different decay channels, sensitive to different weak phases
- ❑ expected large CP asymmetries due to the non-squashed unitary triangles
- ❑ GIM suppression largely relaxed due to $m_t \gg m_{u,d}$, m_c

MANIFESTATIONS OF CP VIOLATION:

- CP violation in the decay (direct CP violation):

  $$|\mathcal{A}(B \rightarrow F)| \neq |\mathcal{A}(\bar{B} \rightarrow \bar{F})|$$

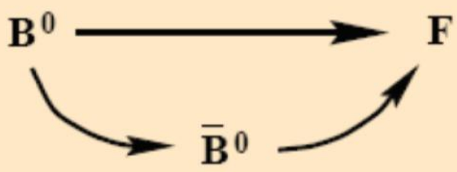
- CP violation in mixing:

  mass eigenstates $\neq$ CP eigenstates

- CP violation in the

  interference of decays with and without mixing

  $$\mathcal{A}(B \rightarrow F) \neq \mathcal{A}(\bar{B} \rightarrow F)$$

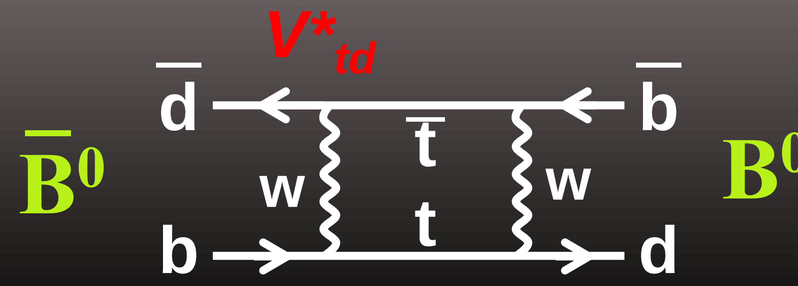


CKM angle β/ϕ_1

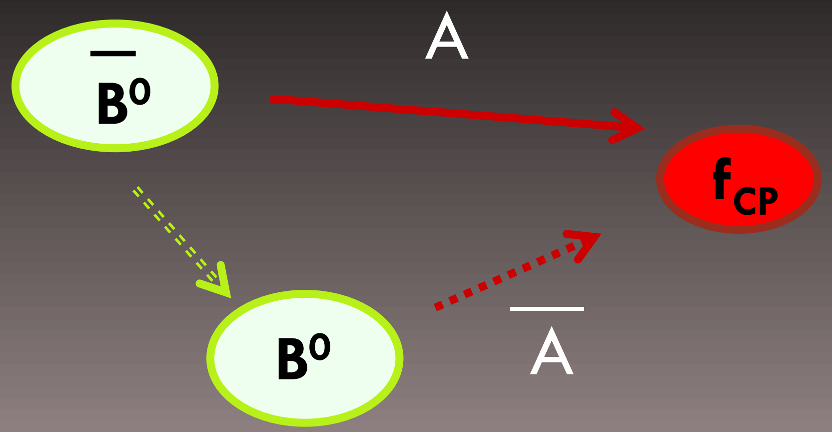
$\arg(-V_{cb}^{*}V_{cd}/V_{tb}^{*}V_{td})$

CKM fitter: β [deg] = 21.76. [+0.92 –0.82]

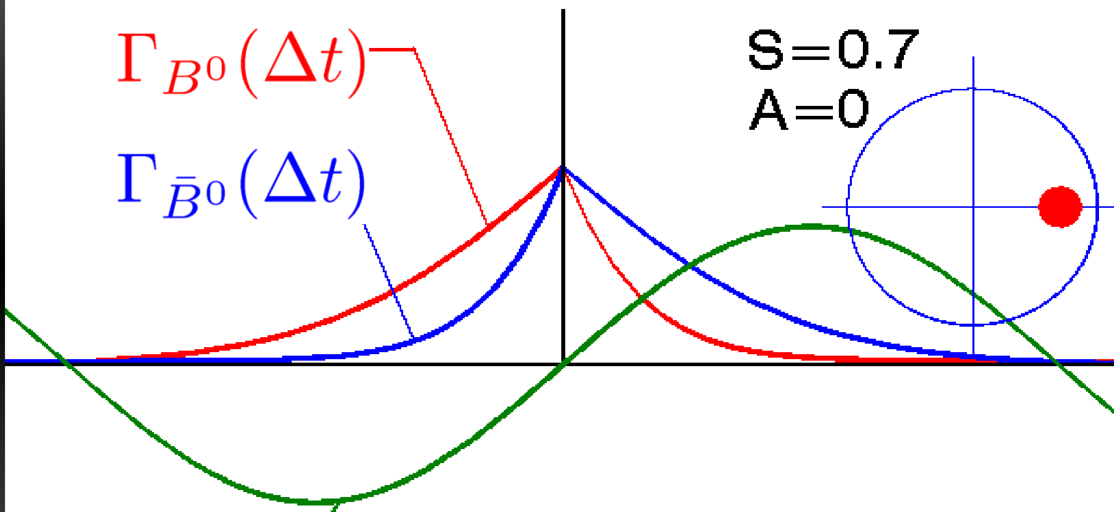
$B^0 - \bar{B}^0$ MIXING



$V^*_{td} = |V_{td}|e^{i\beta}$



CPV as a function of proper time diff (Δt)



$$A_{CP}(\Delta t) \equiv \frac{\Gamma_{\bar{B}^0}(\Delta t) - \Gamma_{B^0}(\Delta t)}{\Gamma_{\bar{B}^0}(\Delta t) + \Gamma_{B^0}(\Delta t)} = \mathcal{S}\sin\Delta m\Delta t + \mathcal{A}\cos\Delta m\Delta t$$

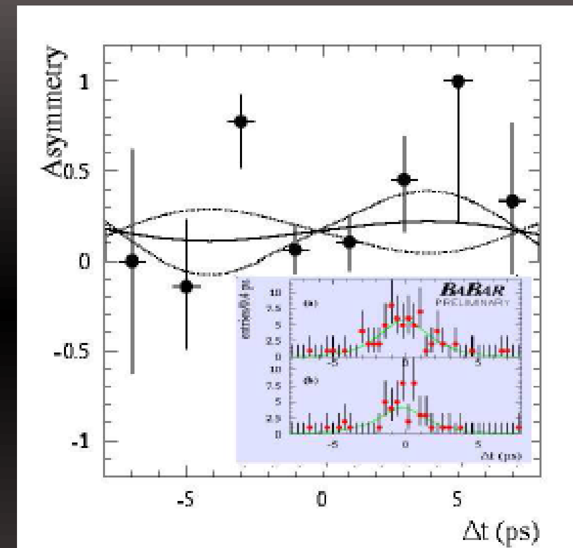
K.Sumisawa (KEK)

Mixing-induced CPV

Direct CPV

$$S = \frac{2\,\mathrm{Im}\left(q/p\,\bar{A}A^*\right)}{|\bar{A}|^2 + |A|^2}, \qquad A = \frac{|\bar{A}|^2 - |A|^2}{|\bar{A}|^2 + |A|^2}$$

Δt = decay time difference between B meson pairs



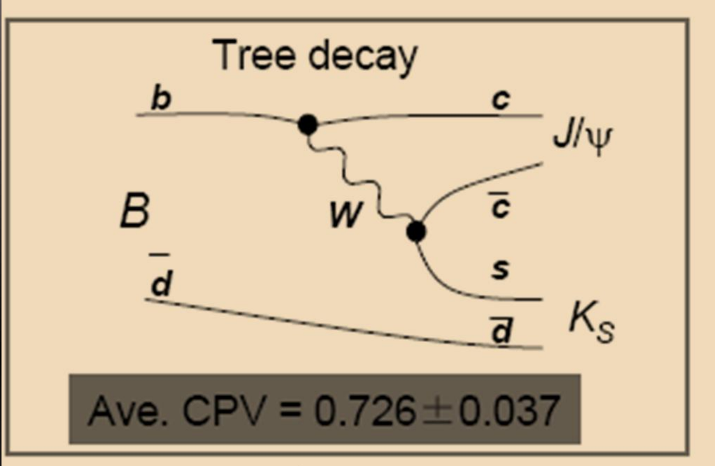
e.g. for $B^0 \rightarrow J/\psi\, K_s$

$S = -\xi_{CP}\sin 2a = +\sin 2a$

$A \sim 0 \quad (A = -C)$

(ξ_{CP} : CP eigenvalue ±1)

Why is $B \to J/\Psi K$ gold plated ?



and other $\bar{b} \to \bar{c}\, c\, \bar{s}$ decays

$$A(B_d^0 \to J/\psi K^0) = \frac{G_F}{\sqrt{2}}\left(1-\frac{\lambda^2}{2}\right)\lambda^2 A\left\{A_c^{(0)} + A_c^{(1)}\right\}\left[1 + \frac{\lambda^2 R_b}{1-\lambda^2/2}\left\{\frac{A_u^{(0)} + A_u^{(1)}}{A_c^{(0)} + A_c^{(1)}}\right\} e^{i\gamma}\right]$$

only one amplitude dominates!

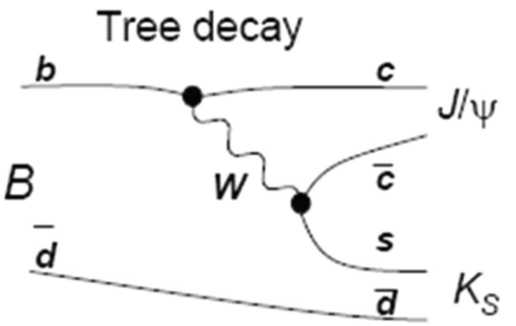
EW penguins are **negligible** $\mathcal{O}(\bar{\lambda}^3)$

Any measurable deviation from $a_{CP}(t) = -\sin(2\beta)\sin(\Delta m\, t)$

is the sign of New Physics

CKM fitter: β [deg] = 21.76 [+0.92 –0.82]

TESTING SM IN $B_d \to \phi K_S$ DECAY



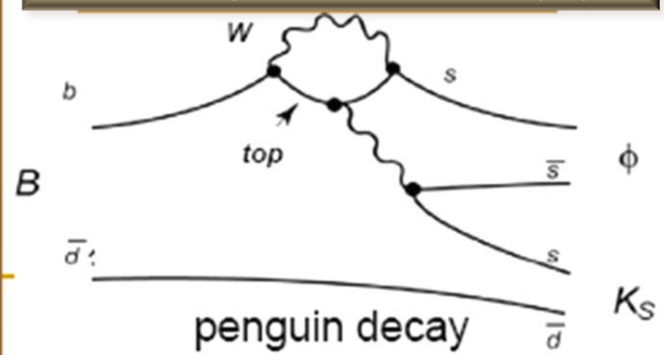
HFAG $a_{CP} = 0.655 \pm 0.0244$

penguins can be neglected

a_{CP} (all charmonium K_S) $= 0.672 \pm 0.023$

SM physics: equal asymmetries $\to$ some tension observed

HFAG $a_{CP} = 0.56^{+0.16}_{-0.18}$



pure penguin process (gluonic and EW penguins)

$\to$ can be affected by NEW PHYSICS

CKM angle γ/ϕ_3

$$\arg(-V_{ub}^* V_{ud} / V_{cb}^* V_{cd})$$

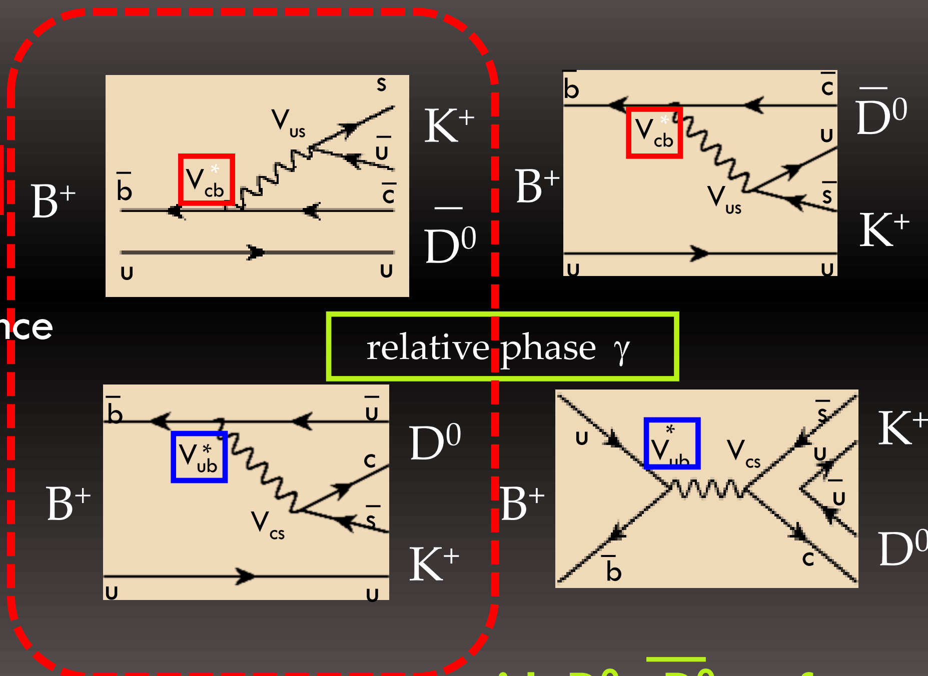
CKM fitter: $\gamma\,[\mathrm{deg}] = 67.2\ [+3.9 - 3.9]$

γ measurements from $B \to D^{(*)}K^{(*)}$

A(b→c)

interference

A(b→u)



with D^0 , $\overline{D^0} \to f_D$

and similar for $B^0 \to D^0K^*$

advantages:

- only tree decays
- largely unaffected by the New Physics scenarios
- clear theoretical interpretation

disadvantages:

- rare decays and low r_B

↓

Experimentally not easy to measure

Related variables (depend on the *B* meson decay channel):

$$r_B = \frac{|A_{b\to u}|}{|A_{b\to c}|} \rightarrow \quad r_B \sim 0.1 \text{ for charged } B \text{ mesons}, \quad r_B \sim 0.3 \text{ for neutral } B \text{ mesons}$$

d_B strong phase (*CP* conserving)

Three ways to extract the information:

- GLW
- ADS
- Dalitz — depending on the CP-tagged final state f_D

D. Derkach

Amplitude relations:

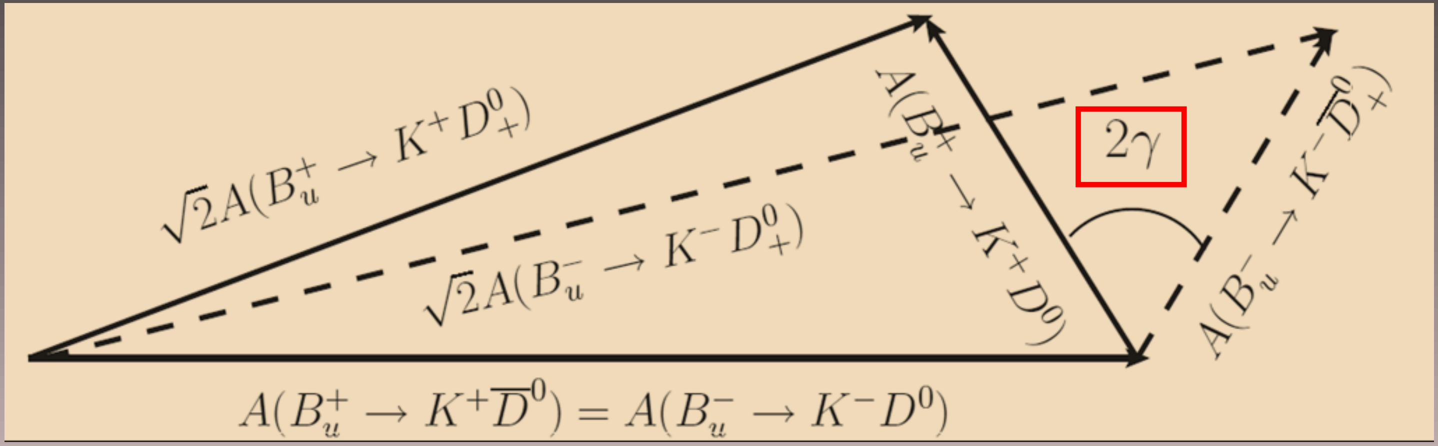
$$A(B^+ \to K^+ \bar{D}^0) = A(B^- \to K^- D^0)$$
$$A(B^+ \to K^+ D^0) = A(B^- \to K^- \bar{D}^0) \times e^{2i\gamma}$$

CP = +1 eigenstate: $|D^0_+\rangle = \frac{1}{\sqrt{2}}\left[|D^0\rangle + |\bar{D}^0\rangle\right]$

ISOSPIN ANALYSIS in the complex plane to combine all amplitudes and extract γ:

$$\sqrt{2}A(B^+ \to K^+ D^0_+) = A(B^+ \to K^+ D^0) + A(B^+ \to K^+ \bar{D}^0)$$
$$\sqrt{2}A(B^- \to K^- D^0_+) = A(B^- \to K^- \bar{D}^0) + A(B^- \to K^- D^0)$$

precise measurement of all 6 amplitudes is needed:

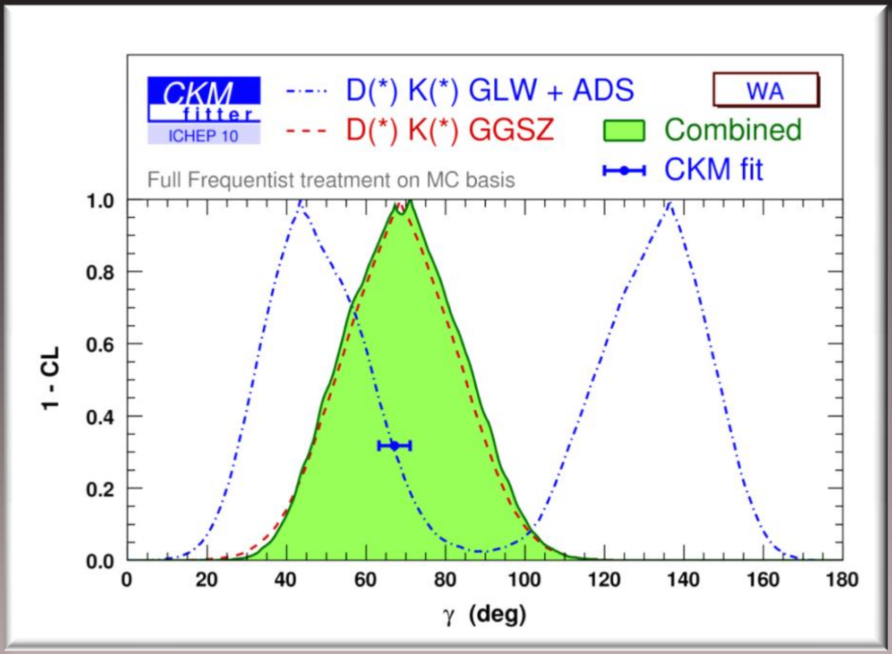


similarly one can use $B_c \to D_s\, D$ to extract $\gamma \to$ favorable (non-squashed triangles)

LHCb ?

$\Delta\gamma$ (LHCb) = 1.9 – 2.7 [deg]

also $B \to \pi\,\pi$, $B \to \pi\, K$ can be used, but with larger theoretical uncertainties



$\gamma\,[\text{deg}] = 67.2\ [+3.9 - 3.9]$

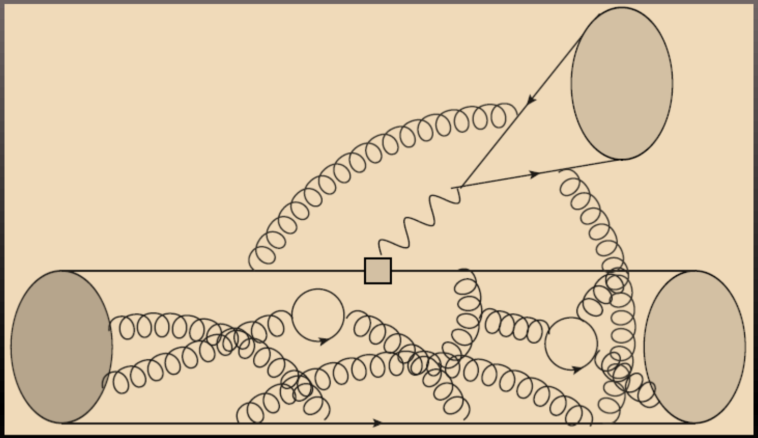
CKM angle α/ϕ_2

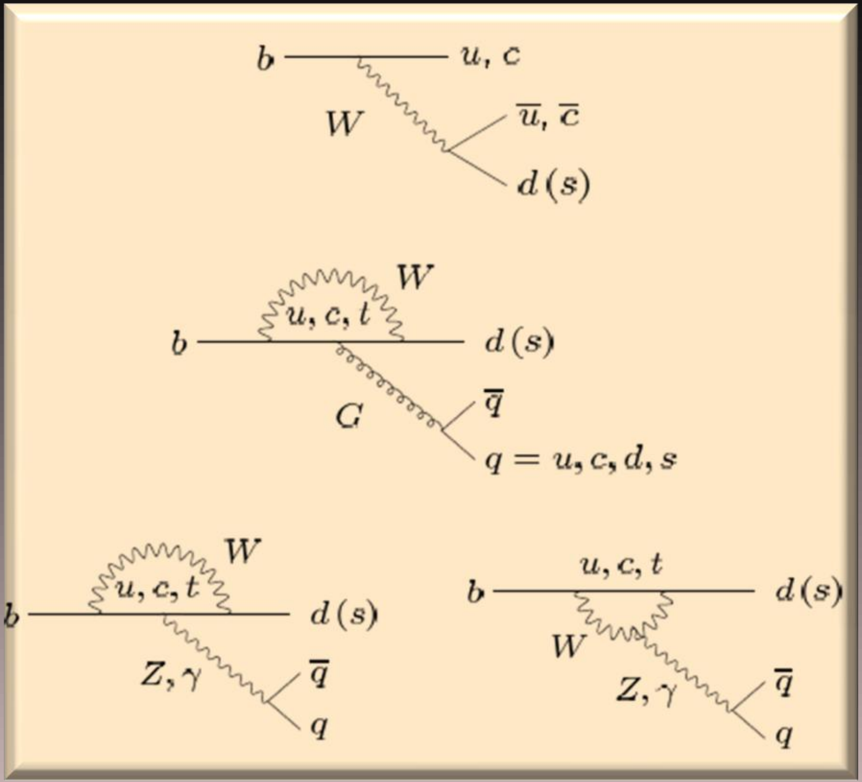
$$\arg(-V_{tb}^* V_{td}/V_{ub}^* V_{ud})$$

CKM fitter: $\alpha\,[\mathrm{deg}] = 91.0\ [+3.9 - 3.9]$

NONLEPTONIC DECAYS

THEORETICALLY the most complicated decays:





tree diagrams

QCD penguin diagrams

EW penguin diagrams

$$\mathcal{H}_{weak} = \frac{G_F}{\sqrt{2}} \sum_{p=u,c} V_{pb} V_{pd}^* \left\{ C_1(\mu) \mathcal{O}_1^p + C_2(\mu) \mathcal{O}_2^p + \sum_{i=3,..,10} C_i(\mu) \mathcal{O}_i + C_{7\gamma} \mathcal{O}_{7\gamma} + C_{8g} \mathcal{O}_{8g} \right\}$$

C_i =Wilson coeff. - perturbative

O_i =four quark operators

$O_{1,2}$ = tree operators

$O_{3\text{-}6}$ = QCD penguin operators

$O_{7\text{-}10}$ = EW penguin operators

$$|A| e^{i\delta} \sim \langle \bar{f} | \mathcal{H}_{weak} | \bar{B} \rangle = \sum_k \underbrace{C_k(\mu)}_{\text{pert. QCD}} \times \underbrace{\langle \bar{f} | \mathcal{O}_k(\mu) | \bar{B} \rangle}_{\text{non-pert. QCD}}$$

How to calculate ?

$$\langle \pi\pi | \mathcal{O}_1 | B \rangle = \underbrace{\langle \pi | \bar{d} \Gamma_\mu u | 0 \rangle \langle \pi | \bar{u} \Gamma^\mu b | B \rangle}_{'naive'\ factorization} \left[1 + \mathcal{O}(\alpha_s) + \mathcal{O}(\Lambda_{QCD}/m_b) \right]$$

$$= i m_b^2 f_\pi F^+_{B\to\pi}(m_\pi^2) \left[1 + \mathcal{O}(\alpha_s) + \mathcal{O}(\Lambda_{QCD}/m_b) \right]$$

Models for calculating matrix elements of four quark operators beyond naïve factorization:

- **QCD FACTORIZATION** – at the zeroth order of a Λ_{QCD}/m_b expansion (Beneke, Buchalla, Neubert, Sachrajda)
- **PERTURBATIVE QCD approach** – nonfactorizable corrections are small (Keum, Li, Sanda)
- **LCSR** (light-cone sum rule approach) – $O(\alpha_s)$ and $O(\Lambda_{QCD}/m_b)$ corrections are calculable (Khodjamirian)
- **USE OF ISOSPIN SYMMETRIES** (Gronau,Rosner et al)
- **SCET**(soft-collinear effective theory) – for B -> light particle decays (Bauer, Fleming, Luke, Stewart)

α measurements from $B^0 \to \pi^+ \pi^-$

- problems with neutral B decays :

$$A(B^0 \to \pi^+\pi^-) \equiv A_{\pi^+\pi^-} = Te^{i\gamma} + Pe^{i\delta}$$

tree ampl.

penguin ampl.

- amplitude:

$$\Gamma(B^0(t) \to \pi^+\pi^-) \propto \Gamma_{\pi^+\pi^-}\,[1+ \\ + C_{\pi^+\pi^-}\cos\Delta mt - S_{\pi^+\pi^-}\sin\Delta mt]$$

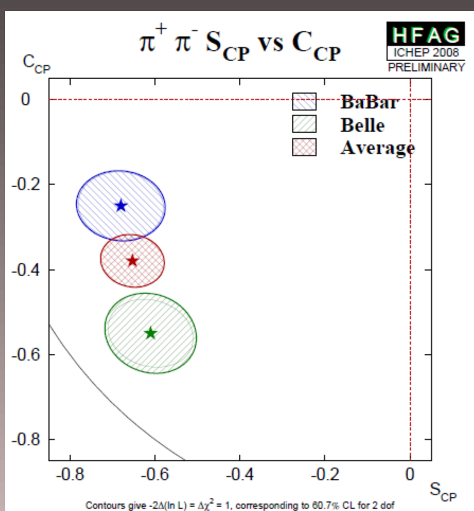
$$S_{\pi^+\pi^-} = -2\frac{\Im(\lambda)}{1+|\lambda|^2}, \qquad \lambda = e^{-2i\beta}\frac{\bar{A}_{\pi^+\pi^-}}{A_{\pi^+\pi^-}}$$

$$S_{\pi^+\pi^-} = \sin 2\alpha + 2r\cos\delta\sin(\beta+\alpha)\cos 2\alpha.$$

$r = P/T$

if penguins would be negligible

penguin amplitudes enter at Cabibbo allowed level
$\rightarrow$ PENGUIN POLLUTION



MEASURED

$$\sin(2\alpha_{\text{eff}}) = S_{\pi^+\pi^-}/\sqrt{1 - C^2_{\pi^+\pi^-}}$$

How to extract α ?

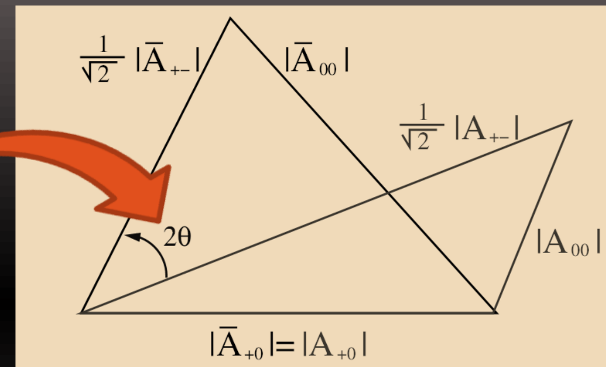
USE OF ISOSPIN RELATIONS (asumme that EW penguins are negligible)

- theoretical uncertainty due to the GLUONIC penguin contributions is eliminated :

$$\frac{1}{\sqrt{2}}\overline{A}(\overline{B} \to \pi^+\pi^-) = A_{I=2} - A_{I=0}$$

$$\overline{A}(\overline{B} \to \pi^0\pi^0) = 2A_{I=2} + A_{I=0}$$

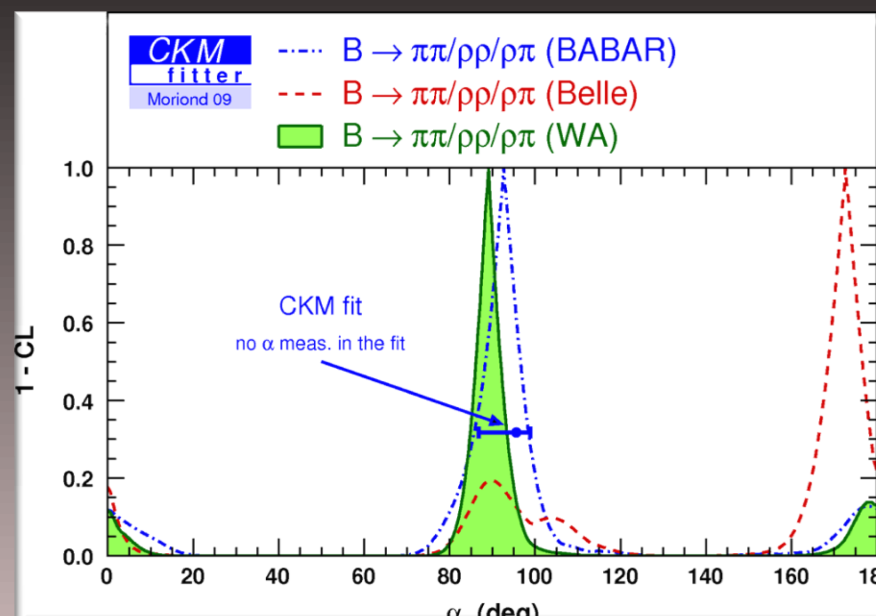
$$\overline{A}(B^- \to \pi^-\pi^0) = 3A_{I=2}$$



eg. $A_{+-} = \langle \pi^+\pi^- | H | B^0 \rangle$

$$2\alpha = 2\alpha_{\rm eff} - 2\theta$$

Similarly one can use B → ρπ, ρρ



α [deg] = 91.0 [+3.9 − 3.9]

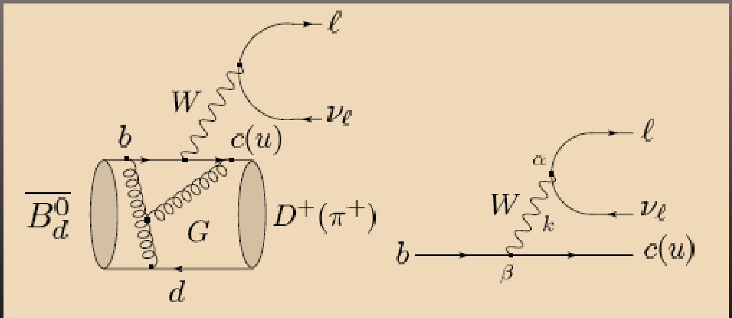
$|V_{ub}|$ & $|V_{cb}|$ matrix elements

CKM fitter:

$|V_{ub}| = 3.54\ [+0.16\ -0.14]\ 10^{-3}$

$|V_{cb}| = 41.28\ [+0.58 -1.29]\ 10^{-3}$

SEMILEPTONIC B-DECAYS



exclusive:

$$T_{fi} = \frac{G_F}{\sqrt{2}} V_{cb} \left[\bar{u}_\ell \gamma^\alpha (1-\gamma_5) v_\nu\right] \langle D^+ | \bar{c}\gamma_\alpha (1-\gamma_5) b | \bar{B}^0_d \rangle$$

$$\langle D^+(k)|\bar{c}\gamma_\alpha b|\bar{B}^0_d(p)\rangle = F_1(q^2)\left[(p+k)_\alpha - \left(\frac{M_B^2 - M_D^2}{q^2}\right) q_\alpha\right] + F_0(q^2)\left(\frac{M_B^2 - M_D^2}{q^2}\right) q_\alpha$$

B⟶ D : HQE & HEAVY QUARK EFFECTIVE THEORY: heavy quark symmetry - $\Lambda_{QCD}/m_{b,c} \to 0$

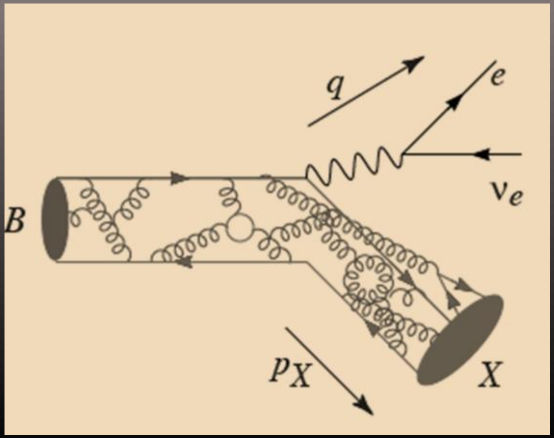
$$\frac{1}{\sqrt{M_D M_B}} \langle D(v')|\bar{c}_{v'}\gamma_\alpha b_v|\bar{B}(v)\rangle = \xi(v' \cdot v)(v + v')_\alpha$$

$F_1(q^2)$, $F_0(q^2)$ ~ ξ (ω = v'v)

only one function

ISGUR-WISE FUNCTION $\xi(1) = 1$

B⟶ π : form factors $F_1(q^2)$, $F_0(q^2)$ from LATTICE QCD or LIGHT-CONE SUM RULES inclusive:



OPE in α_s and $1/m_b$

averaged properties of b quark interactions with light quarks

$$\Gamma(B \to X_u \ell \bar{\nu}_\ell) = \frac{G_F^2 |V_{ub}|^2 m_b^5}{192\pi^3} \left(1 - 2.41\frac{\alpha_s}{\pi} - 21.3\left(\frac{\alpha_s}{\pi}\right)^2 + \frac{\lambda_1 - 9\lambda_2}{2m_b^2} + O\left(\alpha_s^2, \frac{\Lambda_{QCD}^3}{m_b^3}\right)\right)$$

problems with large backgrounds which originate from $b \to c\ell\bar{\nu}$

→ CUTS – large theor. ucertainties !

there is a need for precise determination of $|V_{ub}|$ to check consistency with sin2β

extraction of $|V_{cb}|$ from $B \to X_c \ell \bar{\nu}$ is more favorable

Inclusive b $\rightarrow$ u l ν decays

$$\mathcal{H}_{\rm eff} = -\frac{G_F}{\sqrt{2}} V_{ts}^* V_{tb} \left(\sum_{i=1}^{16} C_i(\mu) Q_i + C_7^\gamma(\mu) Q_7^\gamma + C_8^g(\mu) Q_8^g \right)$$

$B \rightarrow X_s \gamma$:

$$\frac{d\Gamma}{dE_\gamma} = \frac{G_F^2 |V_{tb} V_{ts}^*|^2 \alpha |C_7^{\rm eff}|^2 m_b^5}{32\pi^4} f(E_\gamma)$$

B-meson light-cone function – "shape function"

- unknown

$$f(\omega) = \frac{1}{2m_B} \langle B | \bar{h}\, \delta(in \cdot D + \omega)\, h | B \rangle$$

$B \rightarrow X_u l \nu$:

$$\frac{d\Gamma}{dE_\ell} = \frac{G_F^2 |V_{ub}|^2 m_b^4}{96\pi^3} \int d\omega\, \theta(m_b - 2E_\ell - \omega) f(\omega)$$

$$\left| \frac{V_{ub}}{V_{tb} V_{ts}^*} \right|^2 = \frac{3\alpha}{\pi} |C_7^{\rm eff}|^2 \frac{\Gamma_u(E_c)}{\Gamma_s(E_c)} + O(\alpha_s) + O\left(\frac{\Lambda_{\rm QCD}}{m_B} \right)$$

Bauer, Luke, Mannel , hep-ph/0205150

So, what is the problem?

- we have to exclude large CHARMED BACKGROUND in $b \to u$ *decay*
- maximal at $E_\gamma = 0$ and MINIMAL at the end point of photon energy spectrum $E_\gamma = 2.7$ GeV

BUT:

- OPE breaks down near the end point $\to$ SHAPE FUNCTIONS of photon spectrum are neeeded

$$\left|\frac{V_{ub}}{V_{tb}V_{ts}^*}\right|^2 = \frac{3\alpha}{\pi}|C_7^{\rm eff}|^2\frac{\Gamma_u(E_c)}{\Gamma_s(E_c)} + O(\alpha_s) + O\left(\frac{\Lambda_{\rm QCD}}{m_B}\right)$$

$$\Gamma_u(E_c) \equiv \int_{E_c}^{m_B/2} dE_\ell \frac{d\Gamma_u}{dE_\ell}$$

$$\Gamma_s(E_c) \equiv \frac{2}{m_b}\int_{E_c}^{m_B/2} dE_\gamma (E_\gamma - E_c)\frac{d\Gamma_s}{dE_\gamma}$$

This help us to extract $f(\omega)$ from $B \to X_s\gamma$ and use it in analysis of data in $B \to X_u l\nu$

NNLO SM calculation:

$$B_{SM}(B \to X_s \gamma) = (3.15 \pm 0.23)\times 10^{-4} \quad (\text{for } E_\gamma > 1.6 \text{ GeV})$$

HFAG:

$$B(B \to X_s \gamma) = (3.55 \pm 0.26)\times 10^{-4} \quad (\text{for } E_\gamma > 1.6 \text{ GeV})$$

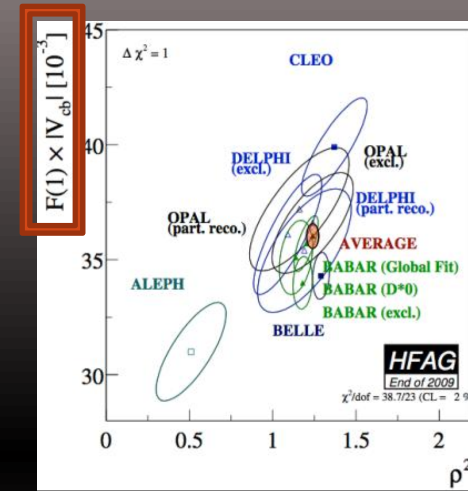
$\Rightarrow$ $|V_{ub}| = (4.37 \pm 0.16_{exp} \pm 0.20_{th} \pm 0.30_{NNLO})*10^{-3}$

$|V_{cb}|$

Exclusive B → $D^* l\nu$ decays

Using unquenched lattice result : F(1)= 0.927 (13) (20) (PRD79:014506(2009))

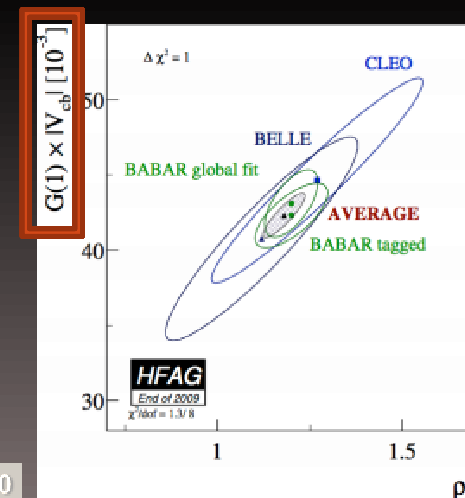
⇨ $|V_{cb}|$ = (38.8 +/- 0.8_{exp} +/- 1.0_{th})* 10-3



Exclusive B → $Dl\nu$ decays

Using unquenched lattice result : G(1)= 1.074 (18) (16) (hep-lat/0510113)

⇨ $|V_{cb}|$ = (39.1 +/- 1.4_{exp} +/- 1.3_{th})* 10-3



Inclusive b → $cl\nu$ decays

■ Global fit to moments from all experiments (HFAG, kinetic scheme):

Input	$|V_{cb}|(10^{-3})$	m_b^{kin} (GeV)	μ_π^2 (GeV^2)	χ^2 / ndf
all moments	41.85±0.42±0.59	4.591±0.031	0.454±0.038	29.7 / (66-7)
only b→cℓν	41.68±0.44±0.58	4.646±0.047	0.439±0.042	24.2 / (55-7)

Kowalewski - FPCP2010

⇨ $|V_{cb}|$ exc. vs inc ~ 2.3σ apart ⇨

$|V_{cb}|$*10^3

D*ℓν: 38.8±0.8±1.0

D ℓν: 39.1±1.4±1.3

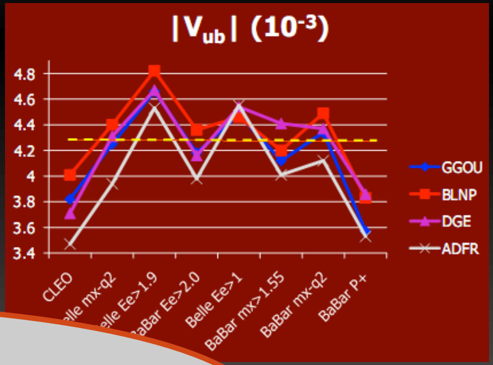
inclusive: 41.9±0.4±0.6

average: 40.9±1.0 (scaled)

$|V_{ub}|$

Exclusive $B \rightarrow \pi l \nu$ decays $|V_{ub}| = (2.95 \pm 0.31) \cdot 10^{-3}$

Inclusive $b \rightarrow u l \nu$ decays $|V_{ub}| = (4.37 \pm 0.16_{exp} \pm 0.20_{th} \pm 0.30_{NNLO}) \cdot 10^{-3}$



Source	$|V_{ub}| \cdot 10^3$	comments
$B \rightarrow \pi \ell \nu$	2.95 ± 0.31	Latest combined fit to data, lattice
$b \rightarrow u \ell \nu$	4.37 ± 0.39	PDG2010 average; error inflated to account for NNLO result
UTFit	3.48 ± 0.16	(ICHEP 2008) Predictions from CKM fits
CKMFitter	$3.51\ ^{+0.15}_{-0.16}$	(Beauty 2009) Predictions from CKM fits

2.7σ apart

the average agrees

Rare and radiative decays
→ NEW PHYSICS ?

WHY NEW PHYSICS AT TEV SCALE ?

- Source of the EW symmetry breaking:
  Higgs ? - the Higgs mechanism of $SU(2)_L \times U(1)_Y$ breaking and generation of fermion masses IS NOT (YET) VERIFIED $\longrightarrow$ problem of gauge symmetry breaking
  - new strong interactions?

- Dark matter problem

- Baryon asymmetry problem

- CP violation is confirmed:
  size and origin of CP phases are UNKNOWN

Two possible solutions :

Pesimistic: Λ_{NP} > 100 TeV
- we cannot learn much from FCNC processes, and it will be difficult to find evidences of NP at LHC….

Optimistic: Λ_{NP} ~ 1 TeV
- there will be a lot of things to learn from B (in particular rare) decays

ELECTROWEAK SYMMETRY BREAKING

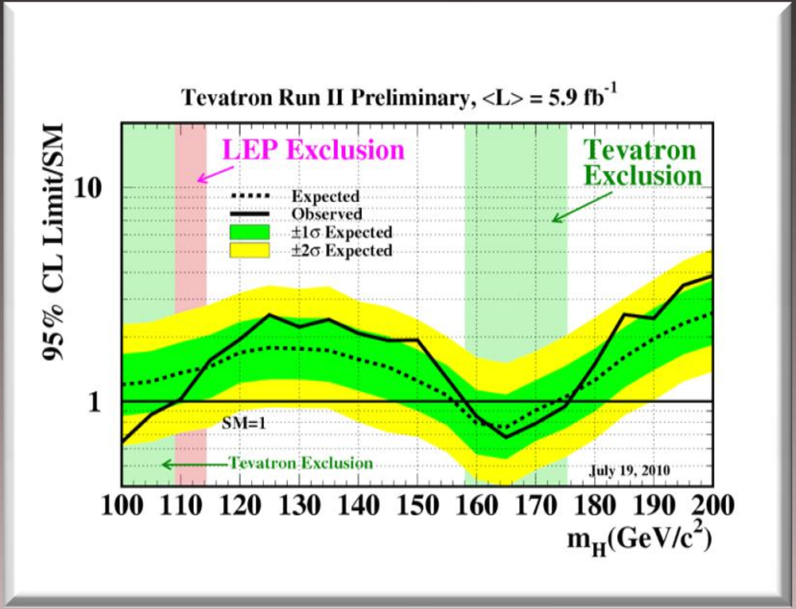
SM : **HIGGS**

$SU(3)_c \times Su(2)_L \times U(1)_Y \longrightarrow SU(3)_c \times U(1)_{em}$

$$V_{\text{Higgs}} = m_H^2 |H|^2 + \frac{\lambda}{2}|H|^4$$ minimum at $$\langle H \rangle = \begin{pmatrix} 0 \\ v \end{pmatrix}$$ $$v = \sqrt{\frac{-m_H^2}{\lambda}}$$

EW measurements: v = 174 GeV

there is physical Higgs boson H with a mass $m_H = \sqrt{2\lambda}\, v$

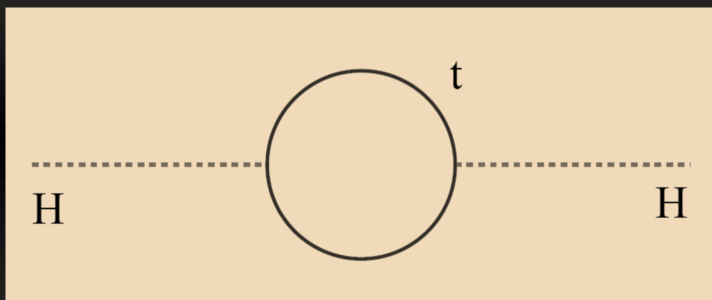


exp. constraints

GAUGE HIERARCHY PROBLEM:

v = 174 GeV   vs $M_{pl} = 2.4 \times 10^{18}$

quantum loops generate large corrections to the Higgs mass:



$$m_H^2 = (m_H^2)_0 + \frac{kg^2\Lambda^2}{16\pi^2}$$

Λ = cut-off

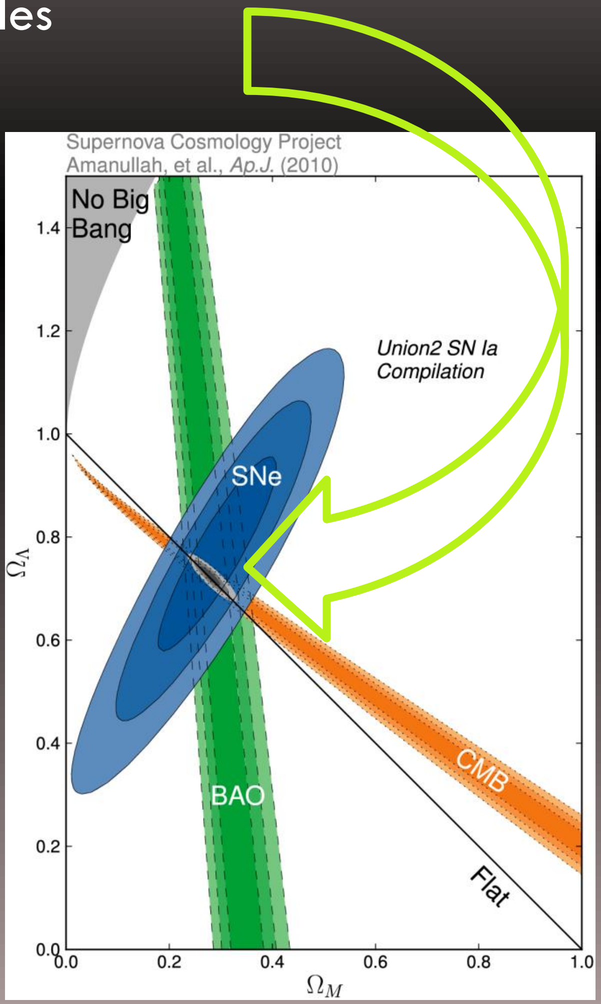
to have small corrections (that the perturbation theory makes sense) we need

$v << \Lambda/(4\pi)$ → FINE TUNING

Solution: NEW PARTICLES WITH MASSES BELOW 4π v ~ 1 TeV to cancel the divergences (eg. SUSY particles)

DARK MATTER

there is overwhelming evidence that the most of the matter in our Universe is composed of nonrelativistic particles
interacting only feebly with SM particles



SM has no suitable DM candidate:

- weakly interacting particles are too light (photons, neutrinos)
- or have too short lifetimes (Higgs, Z)

BARYON ASYMMETRY

$$\rho_b/\rho_{tot} = 0.0456 \pm 0.0015$$

Saharov's conditions:

- violation of B
- departure from the thermodynamic equilibrium
- violation of C and CP

$$(m_t^2 - m_c^2)(m_t^2 - m_u^2)(m_c^2 - m_u^2)(m_b^2 - m_s^2)(m_b^2 - m_d^2)(m_s^2 - m_d^2) \times J_{\rm CP} \neq 0,$$

$$J_{\rm CP} = |{\rm Im}(V_{i\alpha} V_{j\beta} V_{i\beta}^* V_{j\alpha}^*)| \quad (i \neq j,\, \alpha \neq \beta)\,.$$

If two quark would have the same mass → CP-violating phase could be eliminated !

→ CP –violation is related to the FLAVOUR PROBLEM – understanding of quark mass hierarchy and the number of fermion generations

JARLSKOG PARAMETER J_{CP} = measure of the strength of CP violation in SM

$J_{CP} = O(10^{-5})$ → TOO SMALL

How could new physics enter ?

- NP may modify the strength of SM operators through new short-distance effects depending on the masses of new particles

  NP enters at the loop level
  – box diagrams and penguin topologies – and may be integrated out like the W-boson and top quark in SM

$$C_i \rightarrow C_i^{SM} + C_i^{NP}$$

- NP may introduce new operators

$$\{O_i\} \rightarrow \{O_i^{SM}, O_i^{NP}\}$$

Non-MFV SCENARIOS:

- SUSY
- left-right symmetric models
- extra dimensions
- models with an extra Z'
- 'little' Higgs
- fourth generation …

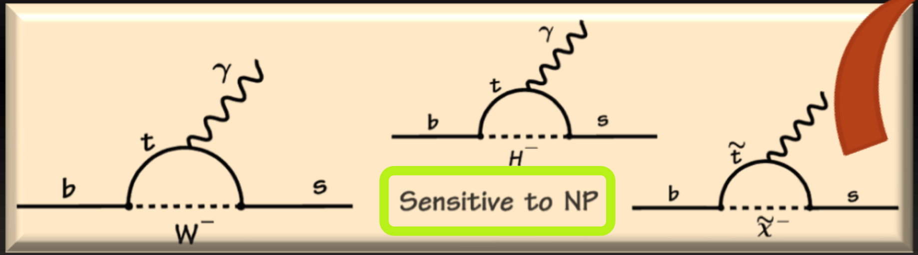
CRUTIAL PROBLEM –
to distingush NP from
hadronic uncertainties in SM !

$B \to X_s \gamma$ & $B \to X_s l \nu$ & $B \to X_s l^+ l^-$

direct probe of SM at one loop level - LOOP DECAYS:

- $b \to s\gamma$ BR(10%) ~ $3\ 10^{-4}$ → $|V_{ts}|$
  $b \to d\gamma$ BR(10%) ~ 10^{-6} → $|V_{td}|$

Up to now: agreement with SM



SENSITIVE TO NEW PHYSICS

- Exclusive $b \to s\gamma$ decays:

  $B \to \rho\gamma$ / $B \to K^*\gamma$ allow determination of $|V_{td} / V_{ts}|$ independent of form factors:

$$|V_{td} / V_{ts}| = 0.199 \pm 0.022_{stat} \pm 0.012_{syst} \pm 0.027_{extrap} \pm 0.002_{th}$$

theor. error ~ 1 %

- $B \to X_s l^+ l^-$ decays: - new operators – forward-backward asymmetries to constrain Wil. coeff.
  - problems: charmed resonances $J/\psi, \psi', \psi'' \to l^+l^-$ → low q^2 region CUTS

$$BR(B \to X_s e^+e^-)_{SM} \approx BR(B \to X_s \mu^+\mu^-)_{SM} \approx (4.2 \pm 0.7)\ 10^{-6}$$

$B \to K^{(*)} l^+ l^-$ $BR(B \to K^{(*)} l^+ l^-)_{SM} \sim 10^{-7(-6)}$ - sizable !

- sensitive to right handed currents
- forward-backward asymmetry in $B \to K^*$ decay - in SM: $A_{FB}(s) = 0$ for $s_0 = 4.4 +/- 0.3$ GeV
- 3-body decay → more observables - q^2 distribution, K^* polarization

$B \to K^{(*)} \nu\nu$

experimental signature is $B \to K^{(*)} + E_{miss}$

→ measured decay rate is sensitive to exotic source of missing energy

→ light dark mather, unparticles , etc.

a probe for NP in Z^0 penguins in $b \to s \nu \nu$ *decay*

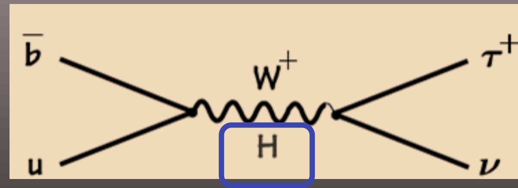
$$\mathcal{H}_{\rm eff} = -\frac{4\,G_F}{\sqrt{2}} V_{tb} V_{ts}^* \left(C_L^\nu \mathcal{O}_L^\nu + C_R^\nu \mathcal{O}_R^\nu \right)$$

$$\mathcal{O}_{L,R}^\nu = \frac{e^2}{8\pi^2} (\bar{s}\gamma_\mu P_{L,R} b)(\bar{\nu} P_L \nu)$$

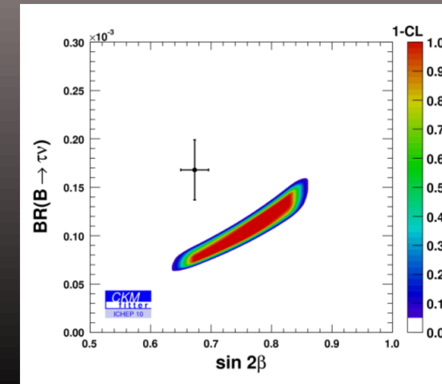
Observable	SM prediction	Experiment
$\mathcal{B}(B^0 \to K^{*0}\nu\bar{\nu})$	$(6.8^{+1.0}_{-1.1}) \times 10^{-6}$ [63]	$< 80 \times 10^{-6}$ [65]
$\mathcal{B}(B^+ \to K^+\nu\bar{\nu})$	$(3.6 \pm 0.5) \times 10^{-6}$ [66]	$< 14 \times 10^{-6}$ [67]
$\mathcal{B}(\bar{B} \to X_s\nu\bar{\nu})$	$(2.7 \pm 0.2) \times 10^{-5}$ [63]	$< 64 \times 10^{-5}$ [68]

arXiv:1008.1541v1

BR(B→τ ν)



TENSION between the new world average for sin2β, which is smaller than before, and the new world average for BR(B→τν) !



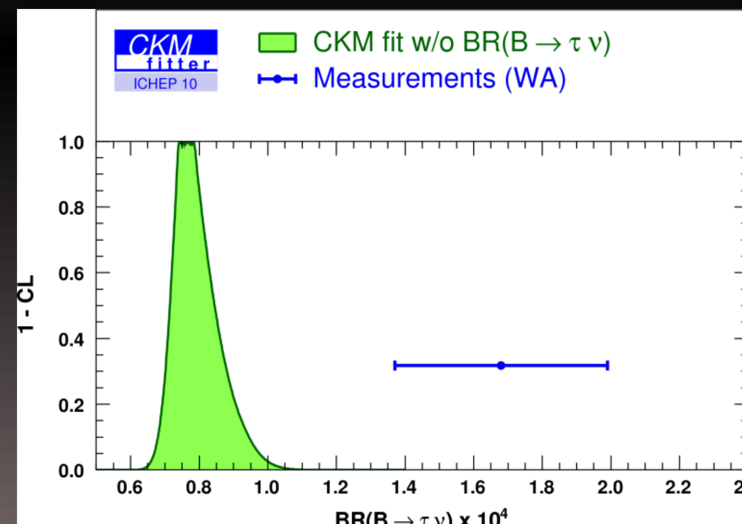
Naïve world average

$$Br(\tau\nu) = [1.73 \pm 0.35] \times 10^{-4}$$

⇕

$$Br(\tau\nu)_{CKM\ fit} = \left[0.786\ ^{+0.179}_{-0.083}\right] \times 10^{-4}$$

fit without including BR(B→τ ν)

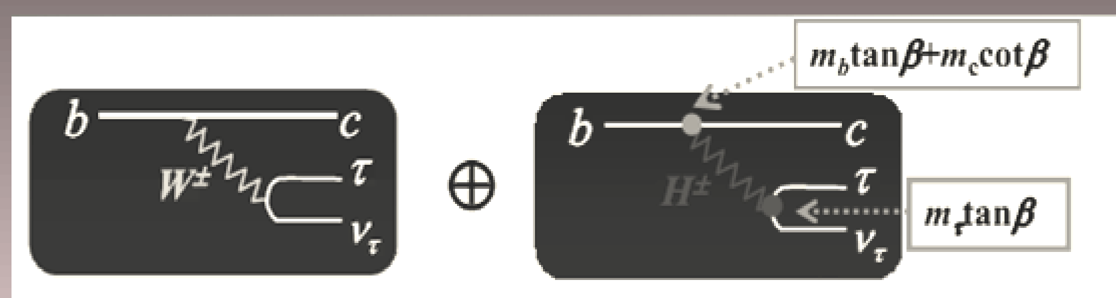


2HDM :

$$BF(B^+ \to \tau^+ \nu_\tau) = BF(B^+ \to \tau^+ \nu_\tau)_{SM} \times r_H$$

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

BR(B→ D$^{(*)}$ τ ν)



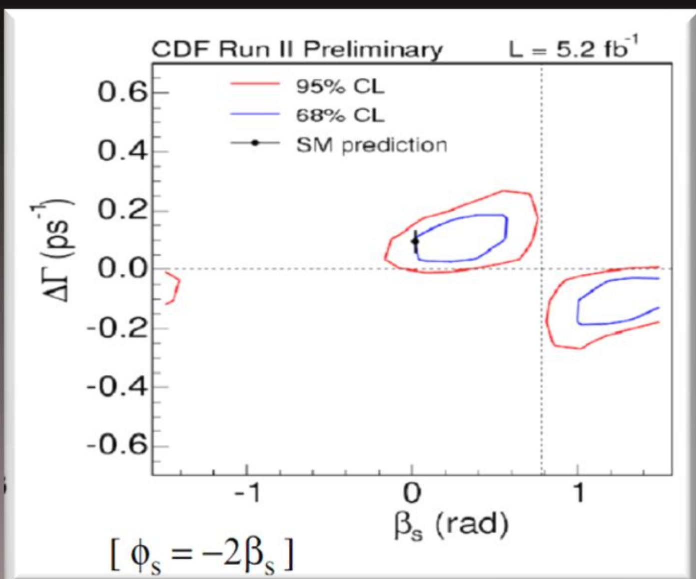
NEW ERA – EXPLORING B_s SYSTEM

- $B_s - B_s$ MIXING

- similar like $B_q - B_q$ MIXING, but the frequency of oscillation is higher:

$$\Delta m_d = 0.5/ps \rightarrow \Delta m_s = 17.9/ps$$

$\rightarrow$ proper time resolution



- $B_s \rightarrow J/\psi\, \phi$ DECAY

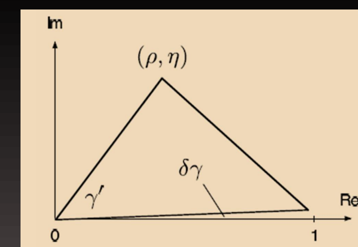
- similar like $B_q \rightarrow J/\psi\, K_s$ decay, but the CP asymmetry is tiny in SM:

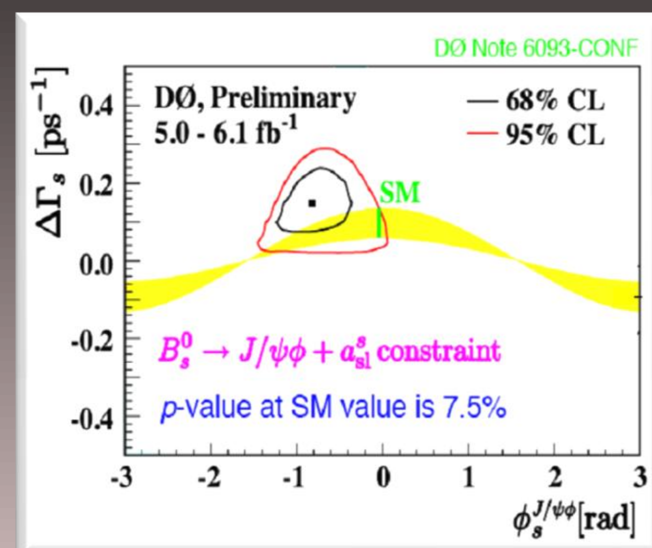
$$\sin(2\beta)_{SM} = 0.69 \rightarrow \sin(\phi_s^{\,J/\psi\,\phi})_{SM} = -0.04$$

- this decay measures

$$\phi_s = -2\,\delta\gamma = -2\,\lambda^2\,\eta$$

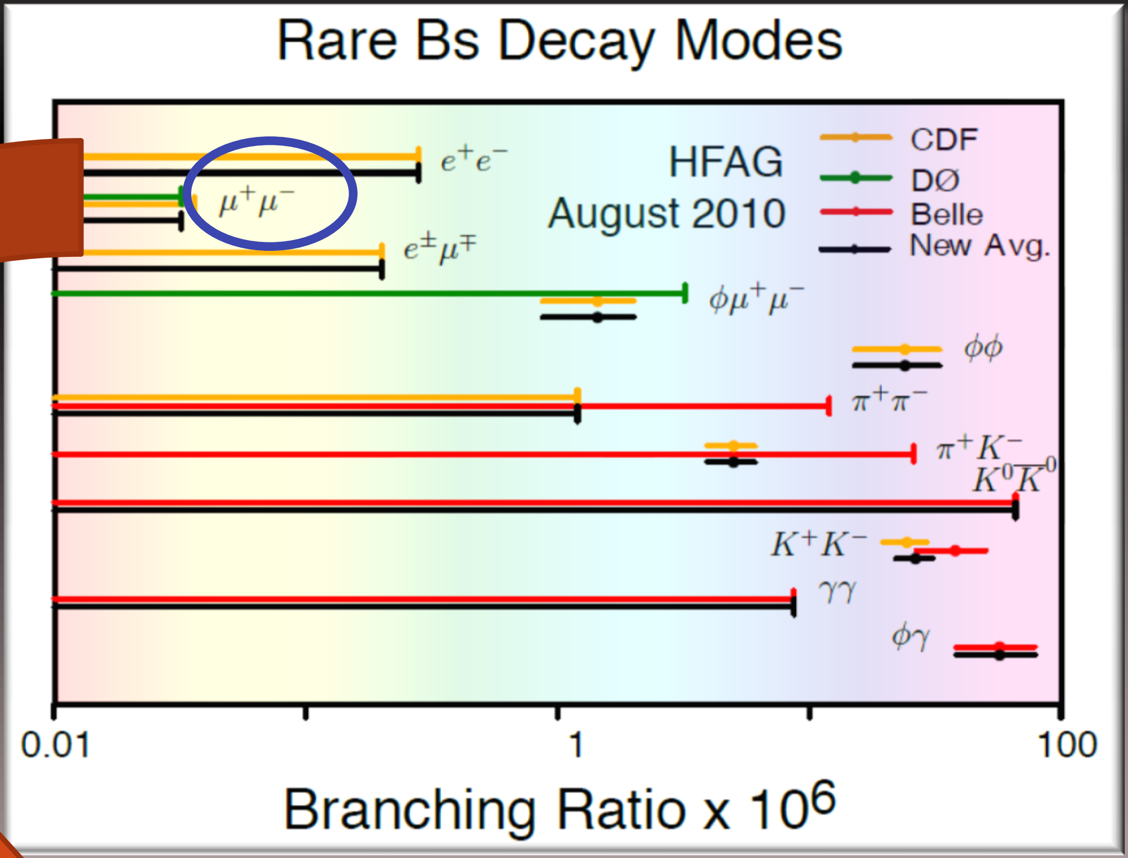
$\sim -2°$





- MANY B_s DECAY CHANNELS TO D, π AND K etc. - similar analysis like for $B_{u,d}$ decays, but BR are small

- FORBIDEN DECAYS $B_s \to e\,\mu$



LEPTONIC DECAYS -VERY CLEAN

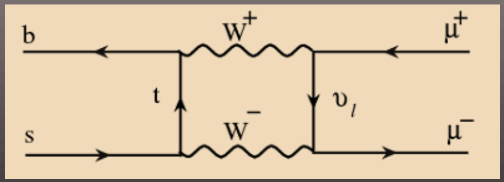
→ EXCELENT PROBE FOR NEW PHYSICS

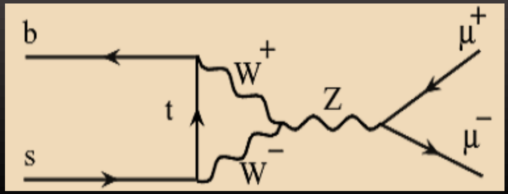
$B_s \to \mu^+ \mu^-$

- helicity suppressed:

$$\mathrm{BR}(B_s \to \mu^+\mu^-) = 4.1 \times 10^{-9} \times \left[\frac{f_{B_s}}{0.24\,\mathrm{GeV}}\right]^2 \left[\frac{|V_{ts}|}{0.040}\right]^2 \left[\frac{\tau_{B_s}}{1.5\,\mathrm{ps}}\right] \left[\frac{m_t}{167\,\mathrm{GeV}}\right]^{3.12}$$

$$\mathrm{BR}(B_d \to \mu^+\mu^-) = 1.1 \times 10^{-10} \times \left[\frac{f_{B_d}}{0.20\,\mathrm{GeV}}\right]^2 \left[\frac{|V_{td}|}{0.008}\right]^2 \left[\frac{\tau_{B_d}}{1.5\,\mathrm{ps}}\right] \left[\frac{m_t}{167\,\mathrm{GeV}}\right]^{3.12}$$





using recent experiments would allow for extraction of $|V_{td}|^2/|V_{ts}|^2$:

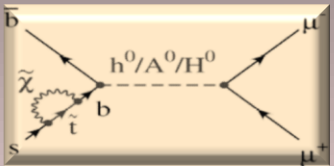
$$\frac{\mathrm{BR}(B_d \to \mu^+\mu^-)}{\mathrm{BR}(B_s \to \mu^+\mu^-)} = \left[\frac{\tau_{B_d}}{\tau_{B_s}}\right] \left[\frac{M_{B_d}}{M_{B_s}}\right] \left[\frac{f_{B_d}}{f_{B_s}}\right]^2 \left|\frac{V_{td}}{V_{ts}}\right|^2$$

another way around:

$$\frac{\mathrm{BR}(B_s \to \mu^+\mu^-)}{\mathrm{BR}(B_d \to \mu^+\mu^-)} = \left[\frac{\tau_{B_s}}{\tau_{B_d}}\right] \left[\frac{\hat{B}_{B_d}}{\hat{B}_{B_s}}\right] \left[\frac{\Delta M_s}{\Delta M_d}\right]$$

$B(B_s \to \mu\mu) < 4.3 \times 10^{-8}$ (95%CL) $\qquad B(B_s \to \mu\mu)_{SM} = 3.2(2) \times 10^{-9}$

$B(B_d \to \mu\mu) < 7.6 \times 10^{-9}$ (95%CL) $\qquad B(B_d \to \mu\mu)_{SM} = 1.0(1) \times 10^{-10}$



SUMMARY - B PHYSICS AT LHC

– CHALLENGE FOR BOTH, EXPERIMENTALISTS AND THEORISTS

- ❑ CKM ANGLES - especially γ

  $B \to D K$, $B_s \to D_s K$,
  $B \to \pi \pi$, $B_s \to K K$,...

- ❑ CP VIOLATION - overconstraining UT

  $B \to \phi K_s$, $B_s \to \phi \phi$,...
  $B \to \pi \rho$, $B \to \rho \rho$,...

- ❑ B_s MIXING AND B_s DECAYS

  $B_s \to D_s \pi$, $B_s \to D_s K$, ...
  $B_s \to J/\psi\phi$, $B_s \to J/\psi\eta^{(')}$, $B_s \to J/\psi K_s$, ...

- ❑ SEARCH FOR NEW PHYSICS IN RARE DECAYS

  $B_s \to \mu^+ \mu^-$, $b \to s\, l^+ l^-$
  $B \to K^* \gamma$, $B \to K^* l^+ l^-$,...

- ❑ AND MUCH MORE ....