Flavor and BSM

Known fundamental matter comes in generations $\psi \to \psi_i$, $i = 1, 2, 3$, living in the same gauge multiplet of

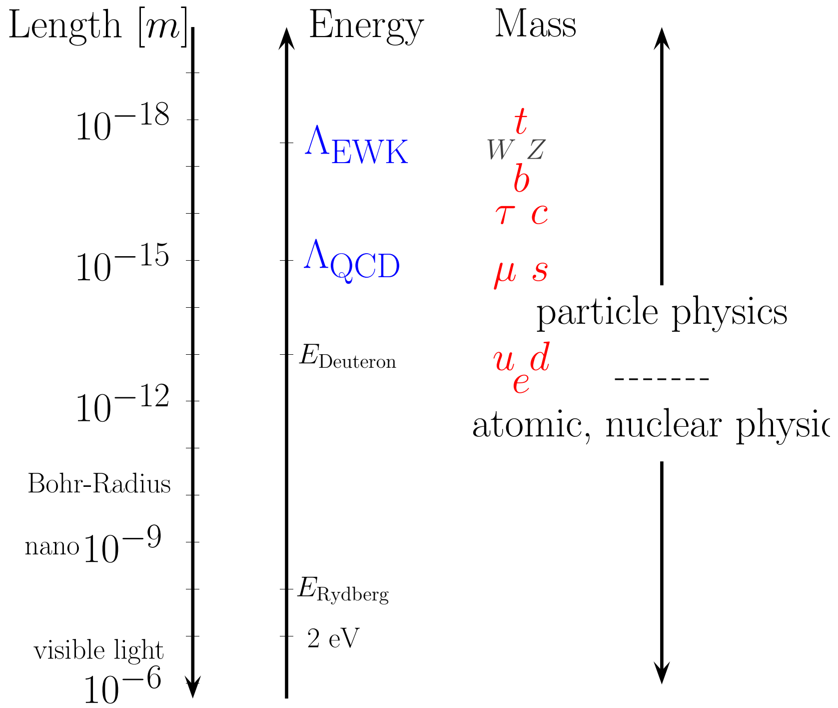
$$SU(3)_C \times SU(2)_L \times U(1)_Y \to SU(3)_C \times U(1)_{em}$$

The gauge interactions are generation-independent.

quarks: $\begin{pmatrix} u \\ d \end{pmatrix}, \begin{pmatrix} c \\ s \end{pmatrix}, \begin{pmatrix} t \\ b \end{pmatrix}$

and leptons: $\begin{pmatrix} \nu_e \\ e \end{pmatrix}, \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}, \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}$

Lots of phenomenological consequences.



$m_u\,(2\text{ GeV})$	$m_d\,(2\text{ GeV})$	$m_s\,(2\text{ GeV})$
2.8 ± 0.6 MeV	5.0 ± 1.0 MeV	95 ± 15 MeV
$m_c\,(m_c)$	$m_b\,(m_b)$	$m_t\,(m_t)$
1.28 ± 0.05 GeV	4.22 ± 0.05 GeV	163 ± 3 GeV

hierarchical! Spectrum spans five orders of magnitude.

Quarks mix and change flavor in weak interaction:

$$V_{\mathrm{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \sim \begin{pmatrix} 1 & \lambda & \lambda^3 \\ \lambda & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix} \; ; \quad \lambda \simeq 0.2$$

$$\vartheta_{13} \sim \lambda^3 \ll \vartheta_{23} \sim \lambda^2 \ll \vartheta_{12} \sim \lambda \ll 1$$

hierarchical!

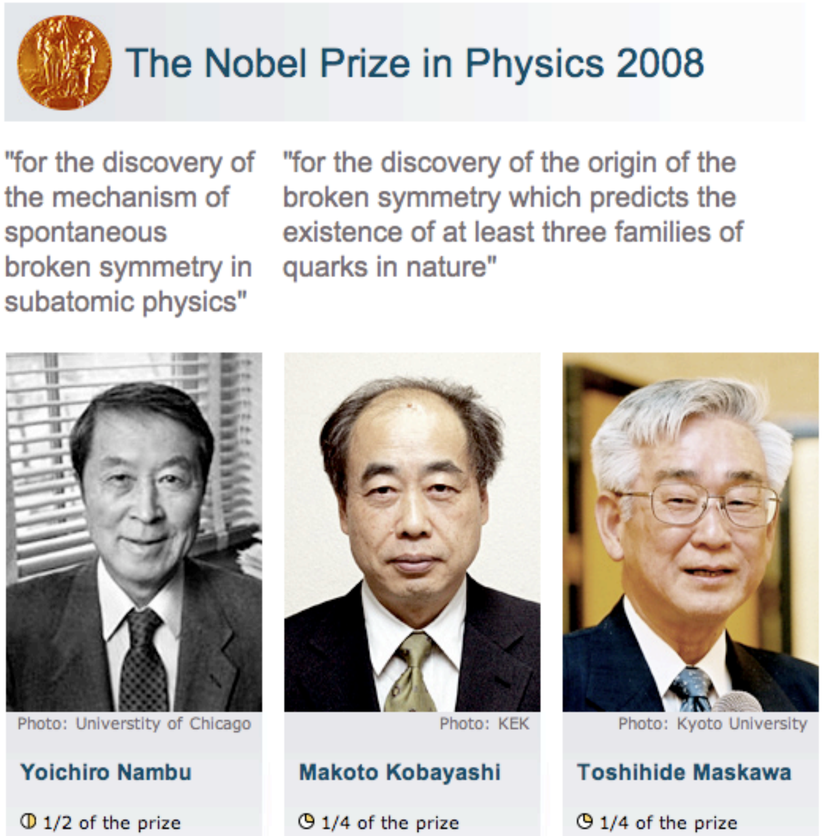
Large mixing angles for leptons (PMNS-Matrix):

$\vartheta_{23} \sim 45^\circ$, $\vartheta_{12} \sim 35^\circ$, $\vartheta_{13} \sim O(10^\circ)$ all O(1) – anarchy?

CP is violated!.. together with Quark Flavor

Quark mixing matrix has 1 physical CP violating phase δ_{CKM}.

(with 3 generations)

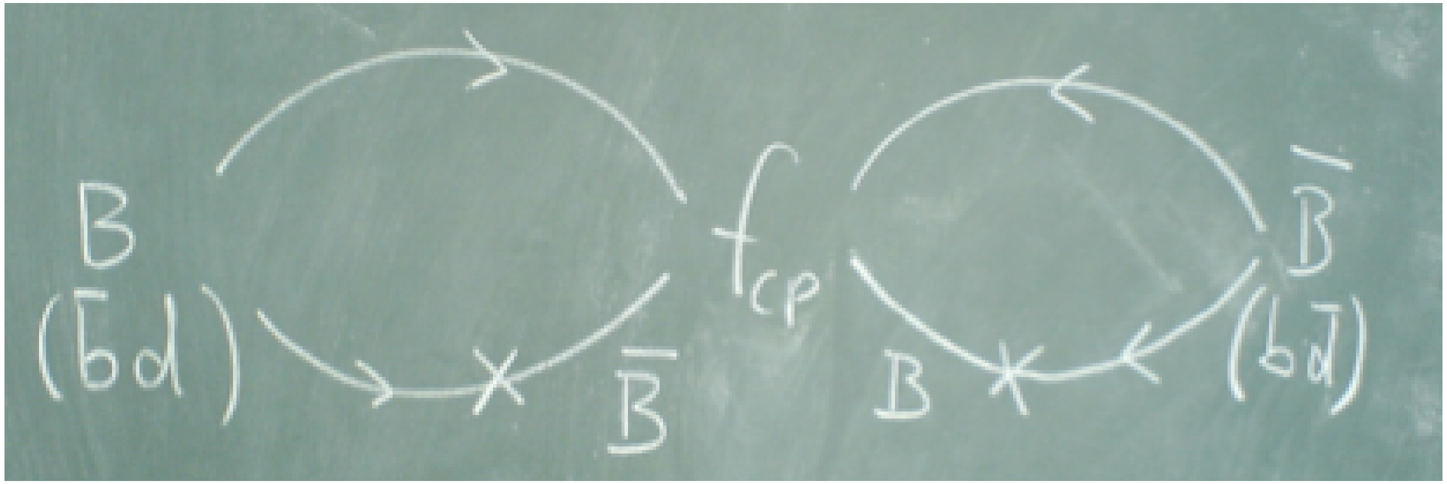


Kobayashi and Maskawa, Prog.Theor.Phys 49 (1973) 652

CP is violated!.. together with Quark Flavor

Quark mixing matrix has 1 physical CP violating phase δ_{CKM}.

Verified in $B\bar{B}$ mixing $\quad \sin 2\beta = 0.672 \pm 0.023$ HFAG Aug 2010



δ_{CKM} is large, $O(1)$!

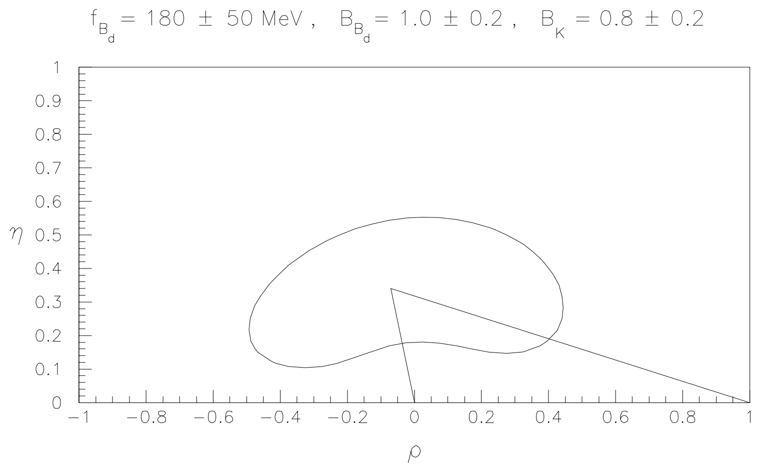
CPX also observed in B-decay $A_{CP}(B \to K^{\pm}\pi^{\mp}) = -0.098 \pm 0.013$

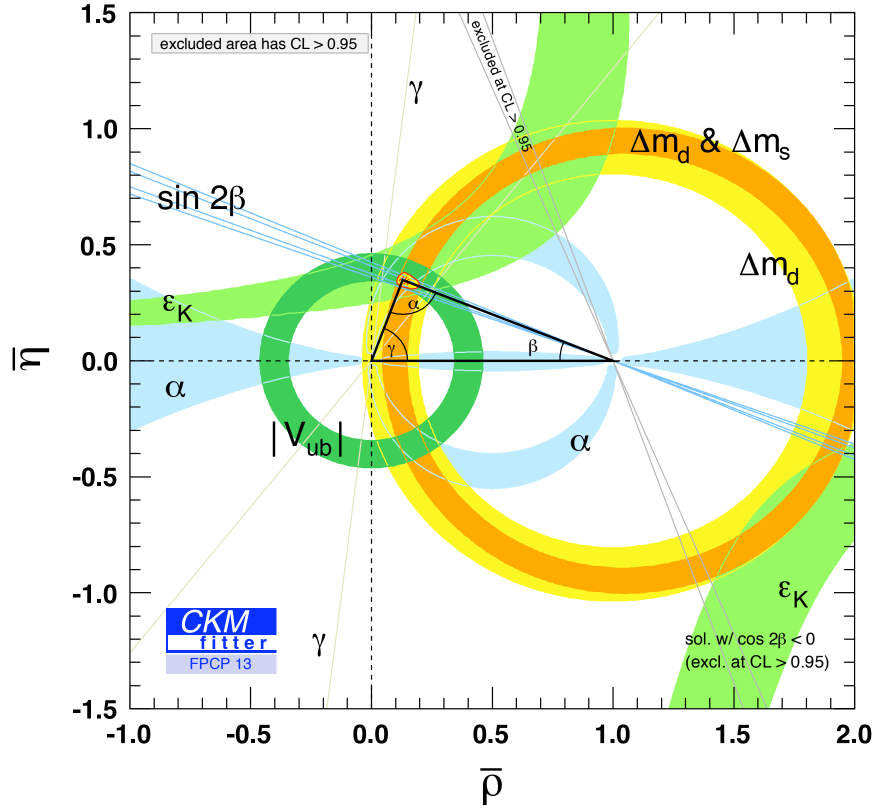
HFAG Aug 2010

$$\Gamma(B \to K^+\pi^-) \neq \Gamma(\bar{B} \to K^-\pi^+)$$

SM tests with Quark flavor/CKM 1995 vs today

The CKM-picture of flavor and CP violation is currently consistent with all – and quite different – laboratory observations, although some tensions exist.





$$V_{CKM}V_{CKM}^{\dagger} = 1$$

The Flavor of Matter $\psi \rightarrow \psi_i$, $i = 1, 2, 3$

(Parametric) source of flavor are the Yukawa couplings $Y_{u,d,l}$ – 3×3 matrices:

$$\mathcal{L}_Y = -\bar{Q} Y_u \Phi^C U - \bar{Q} Y_d \Phi D - \bar{L} Y_l \Phi E + h.c.$$

$Y_{u,d,l} \neq 0$: 10=6+3+1 parameters for quarks and 10 (12) parameters for leptons (two additional phases if neutrinos are majorana).

– absolute mass scale of neutrinos

– majorana ?

– lepton CP phases

– number of sterile neutrinos

– more precision

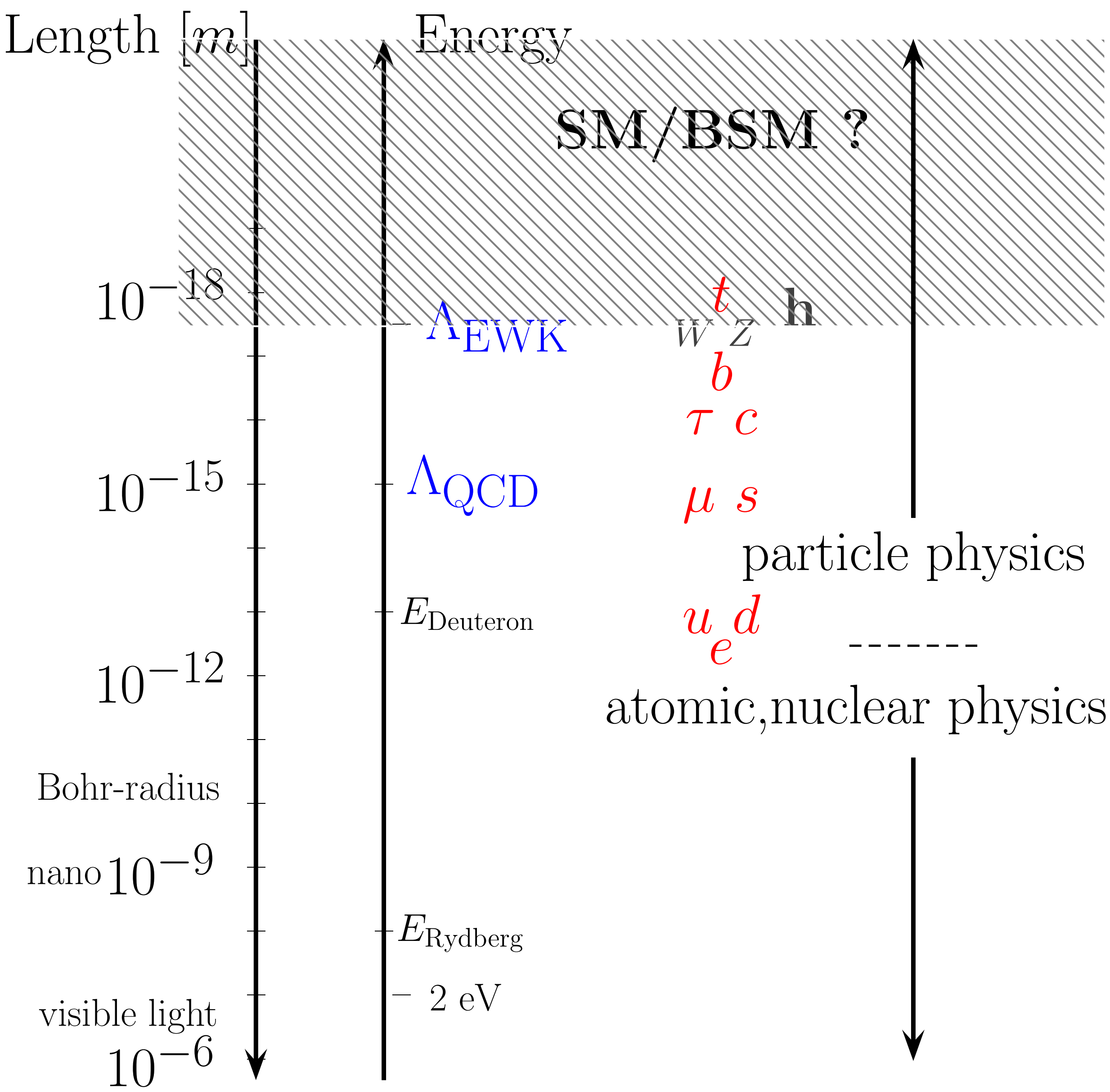
Main goals:

- Test the SM, explore its borders and the physics beyond.
- Towards understanding the origin of flavor (structure of $Y_{u,d,l}$).

$$
\begin{aligned}
Y_u &\sim \begin{pmatrix} 10^{-5} & -0.002 & 0.008 + i\,0.003 \\ 10^{-6} & 0.007 & -0.04 \\ 10^{-8} + i\,10^{-7} & 0.0003 & 0.94 \end{pmatrix} \\
Y_d &\sim \mathrm{diag}\left(10^{-5}, 5 \cdot 10^{-4}, 0.025\right) \quad (\cdot \frac{\langle H_u \rangle}{\langle H_d \rangle}) \\
Y_l &\sim \mathrm{diag}\left(10^{-6}, 6 \cdot 10^{-4}, 0.01\right) \quad (\cdot \frac{\langle H_u \rangle}{\langle H_d \rangle})
\end{aligned}
$$

Exploring Physics at Highest Energies

here we are again:



The Higgs-flavor arena

With observation of scalar boson with mass 126 GeV scalar new arena for flavor physics.

In SM, $f = q, l$:

– $hf\bar{f}'$ couplings are strictly flavor diagonal $\propto \delta_{ff'}$.

– $hf\bar{f}'$ couplings are strictly $\propto m_f$, $\mu(h \to \tau\tau)/\mu(h \to \mu\mu)|_{SM} = \frac{m_\tau^2}{m_\mu^2}$.

$\mu(h \to f\bar{f})$: signal strength

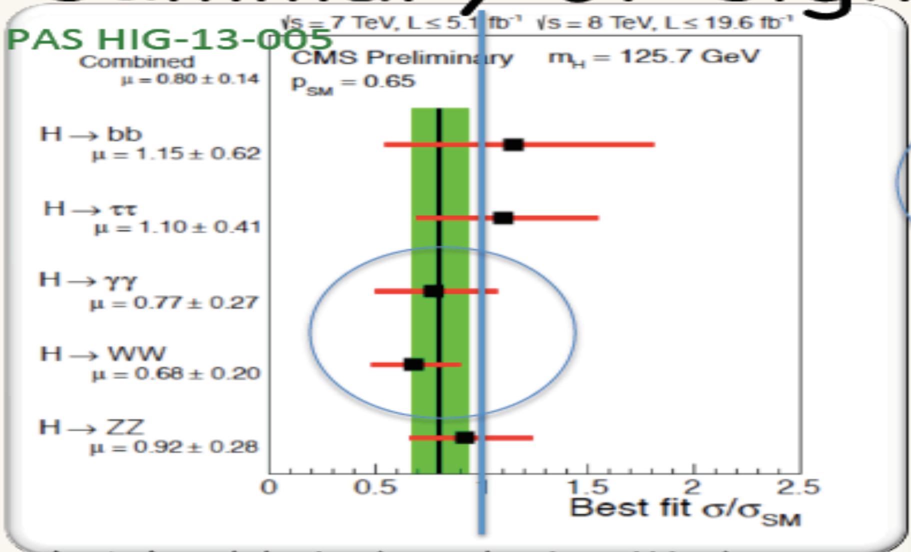
Already in 2 Higgs Doublet models, this doesnt have to be the case.
Important test of SM and flavor physics. e.g. arXiv: :1302.3229,1304.6727

Some (still) Rare Decay Channels

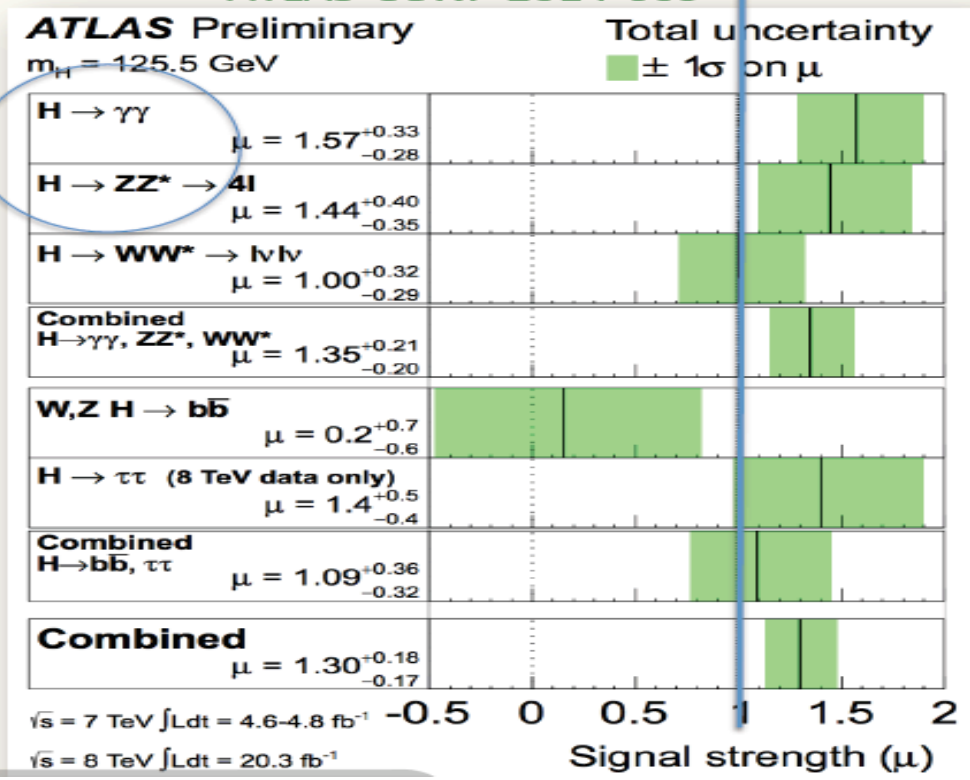
	$Z\gamma$	$\gamma\gamma^* \to \gamma\mu\mu$	$\mu\mu$
ATLAS	$\mu_{up} < 11(9)$		$\mu_{up} < 9.8(8.2)$
CMS	$\mu_{up} < \sim 10(10)$	$\mu_{up} < \sim 11(8)$	$\mu_{up} < 7.4(5.1)$

Summary of Signal Strength

CMS PAS HIG-13-005



ATLAS-CONF-2014-009



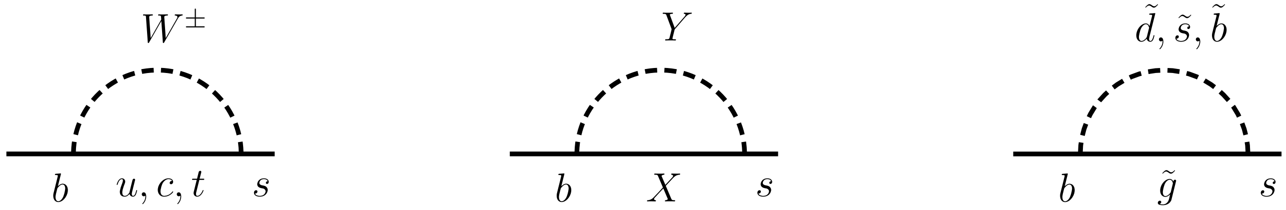
ATLAS bb is low but with large error.

$$k_\gamma^2 = |1.28 k_W - 0.28 k_t|^2$$

From Eilam Gross, talk Moriond EWK'14

Terascale Flavor facing todays FCNC Data

$$\mathcal{A}_{FCNC} \sim \underbrace{K_{ij}K^*_{kj}}_{mixing} \times \underbrace{\Delta m^2_{ik}}_{splitting(GIM)} \times \underbrace{(1/\Lambda_{\rm NP})^n}_{decoupling}$$



With no suppression from flavor (mixing nor splitting) at 95 % C.L:

	$K^0\bar{K}^0$	$D^0\bar{D}^0$	$B^0_d\bar{B}^0_d$	$B^0_s\bar{B}^0_s$
$\Lambda_{\rm NP}$ [TeV]	$2 \cdot 10^5$	$5 \cdot 10^3$	$2 \cdot 10^3$	$3 \cdot 10^2$

Bona et al, 0707.0636 [hep-ph]

Connection to TeV-scale is lost, or TeV-scale flavor non-generic!

Different sectors and different couplings presently probed:

$s \to d$: $K^0 - \bar{K}^0$, $K \to \pi\nu\bar{\nu}$

$c \to u$: $D^0 - \bar{D}^0$, ΔA_{CP}

$b \to d$: $B^0 - \bar{B}^0$, $B \to \rho\gamma$, $b \to d\gamma$, $B \to \pi\mu\mu$

$b \to s$: $B_s - \bar{B}_s$, $b \to s\gamma$, $B \to K_s\pi^0\gamma$, $b \to sll$, $B \to K^{(*)}ll$, $B_s \to \Phi ll$ (precision, angular analysis), $B_s \to \mu\mu$, $\Lambda_b \to \Lambda\mu\mu$

$t \to c, u$, $l \to l'$: not observed

Most experimental contributions from e^+e^--machines (CLEO, SLAC, KEK) and hadron colliders (Tevatron, LHC). Current program dominated by LHC(b). Belle II at horizon ($\sim 2016/17$).

Topics Moriond 14:

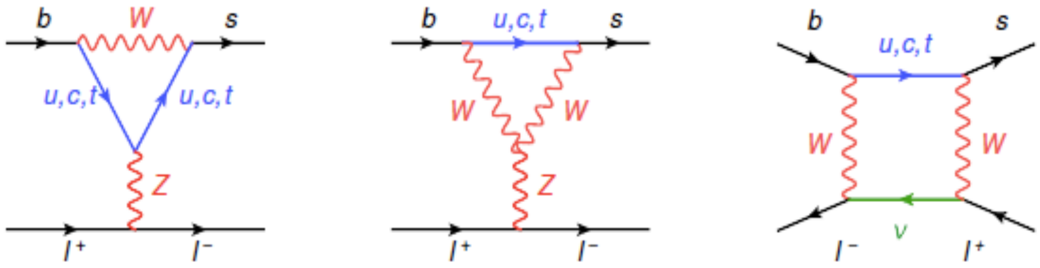
–$B_s \to \mu\mu$ precision; Talks by Bobeth, Gorbahn

–$b \to s\ell\ell$ global fits; Talks by Descotes-Genon, Altmannshofer

– CP violation in charm (Belle measuremet of $D \to \pi^0\pi^0$; Talk by Ritter

Motivation to study $B_q \to \ell^+\ell^-$

- test of the SM at loop-level (FCNC decay) $\Rightarrow$ loop-suppressed



$\Rightarrow$ @ LO in QED, hadronic uncertainty only from $B_{d,s}$ decay constant

- in addition helicity suppressed

  $\Rightarrow$ sensitive to non-SM (pseudo-) scalar interactions

- important B-decay @ LHCb, CMS & ATLAS $\Rightarrow$ first measurements from 2013:

$$\overline{\mathcal{B}}(B_s \to \mu^+\mu^-) = (2.9 \pm 0.7) \times 10^{-9}$$
$$\overline{\mathcal{B}}(B_d \to \mu^+\mu^-) = (3.6^{+1.6}_{-1.4}) \times 10^{-10}$$

LHCb (3/fb) + CMS (25/fb)

[LHCb arXiv:1307.5024]
[CMS arXiv:1307.5025]

- exp. prospects for $B_s \to \mu^+\mu^-$:

  @ LHCb with 50 fb^{-1} : $\sim 0.15 \times 10^{-9}$ = 5% error of SM (only stat. err) [LHCb arXiv:1208.3355]
  @ CMS with 100 fb^{-1} : 15% error of SM [Kai-Feng Chen, KEK Flavor Factory WS, 2014]

Very rare FCNCs $B_s \to \mu\mu$ – Theory precision

NEW: SM branching ratio prediction at NNLO QCD and NLO EWK, Bobeth et al arXiv:1311.0903.

$$\overline{\mathcal{B}}(B_s \to \mu^+\mu^-) = (3.65 \pm 0.23) \times 10^{-9}$$

$$\overline{\mathcal{B}}(B_d \to \mu^+\mu^-) = (1.06 \pm 0.09) \times 10^{-10}$$

$$\overline{\mathcal{B}}(B_s \to e^+e^-) = (8.54 \pm 0.55) \times 10^{-14}, \quad \overline{\mathcal{B}}(B_s \to \tau^+\tau^-) = (7.73 \pm 0.49) \times 10^{-7},$$

$$\overline{\mathcal{B}}(B_d \to e^+e^-) = (2.48 \pm 0.21) \times 10^{-15}, \quad \overline{\mathcal{B}}(B_d \to \tau^+\tau^-) = (2.22 \pm 0.19) \times 10^{-8}$$

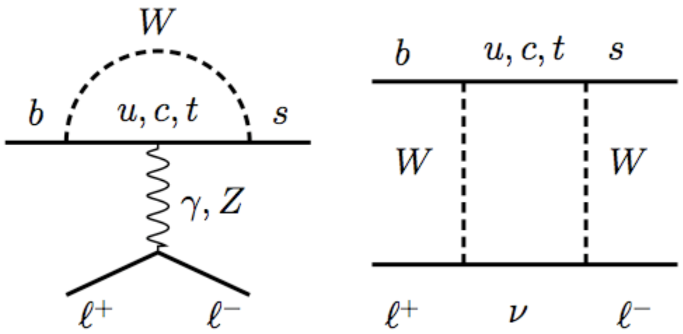
[CB/Gorbahn/Hermann/Misiak/Stamou/Steinhauser arXiv:1311.0903]

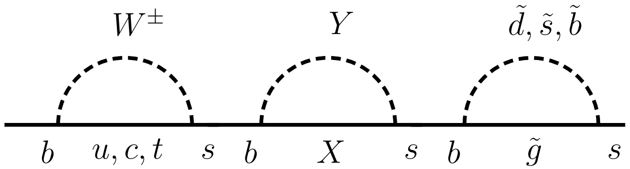
Residual largest uncertainties are parametric: Each f_{Bs} and V_{CKM} $\sim 4\%$ th uncertainty

$\langle 0|\bar{b}\gamma_\mu\gamma_5 s|B_s(p)\rangle = ip_\mu f_{B_s}$, with $f_{Bs} = 227.7 \pm 4.5$MeV (FLAG lattice averages)

Exclusive semileptonic FCNC $b \to s\mu^+\mu^-$ decays

$Br_{\mathrm{SM}} \sim 10^{-6} - 10^{-7}$





observed (at SM level):

$B \to K^{(*)}\mu^+\mu^-$ BaBar, Belle, CDF 6.8 fb^{-1} and LHCb 1 fb^{-1} LHCb-CONF-2012-008

$B_s \to \Phi\mu^+\mu^-$ CDF 2011 1101.1028 [hep-ex] LHCb 2012 LHCb-CONF-2012-008

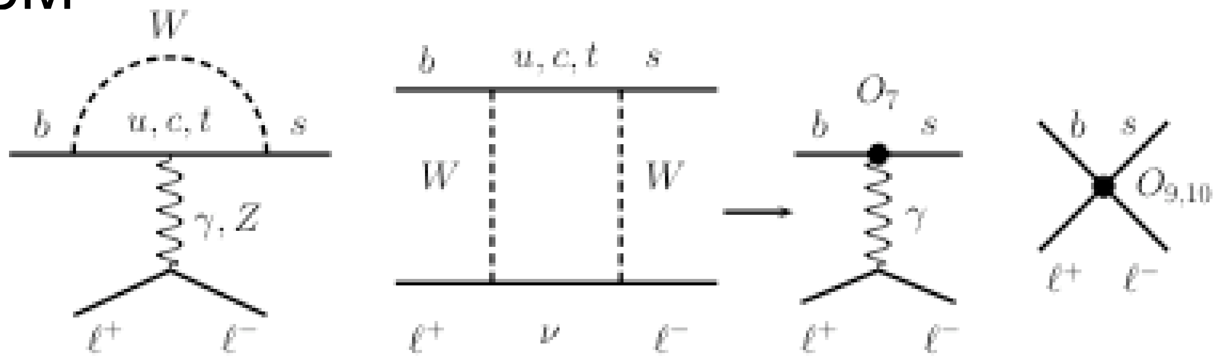
$\Lambda_b \to \Lambda\mu^+\mu^-$ CDF 2011 1107.3753 [hep-ex]

distributions measured. precision physics started.

Aim: Test the SM and BSM with quantum loop effects. Framework:

$$\mathcal{H}_{\rm eff} = -4\frac{G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i C_i(\mu) O_i(\mu).$$

Diagrams in SM



NP is in Wilson coefficients $C_i = C_i^{SM} + C_i^{NP}$ or new operators O_i.
Eff. theory framework allows for model-independent analysis to determine C_i from multi-observables/multi-processes. AGM hep-ph/9408213

Couplings for $b \to s l^+ l^-$

	description	SM	enhancement in models
$O_{1,2}$	charged current	YES	
$O_{3,..,6}$	QCD penguins	YES	SUSY
$O_{7,8}$	γ, g-dipole	YES	SUSY, large $\tan\beta$
$O_{9,10}$	(axial-)vector	YES	SUSY
$O_{S,P}$	(pseudo-)scalar	$\sim m_l m_b / m_W^2$	SUSY, large $\tan\beta$, R-parity viol.
$O'_{S,P}$	(pseudo-)scalar flipped	$\sim m_l m_s / m_W^2$	SUSY, R-parity viol.
$O'_{3,..,6}$	QCD peng. flipped	$\sim m_s / m_b$	SUSY
$O'_{7,8}$	γ, g-dipole flipped	$\sim m_s / m_b$	SUSY, esp. large $\tan\beta$
$O'_{9,10}$	(axial-)vector flipped	$\sim m_s / m_b$	SUSY
$O_{T,T5}$	tensor	negligible	leptoquarks

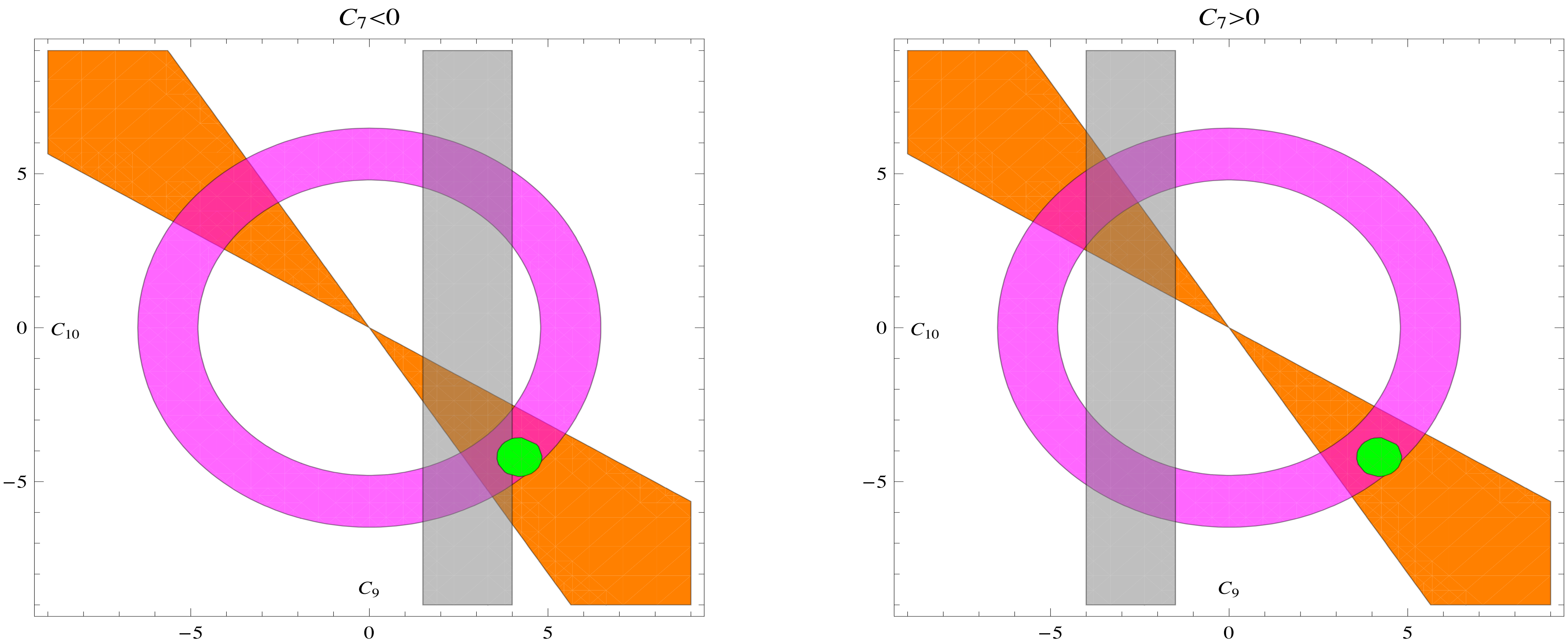
flipped: chiralities interchanged $L \leftrightarrow R$; for example, V-A changes to V+A

SM: 10 operators, all Wilson coefficients C_i real.

General NP: 22 O_i, C_i complex; additional ones with LFV ($O_i \to O_i^l$).

Need many orthogonal observables even in constrained frameworks such as MFV. Learn a lot about chirality, Dirac, CP-structure of BSM.

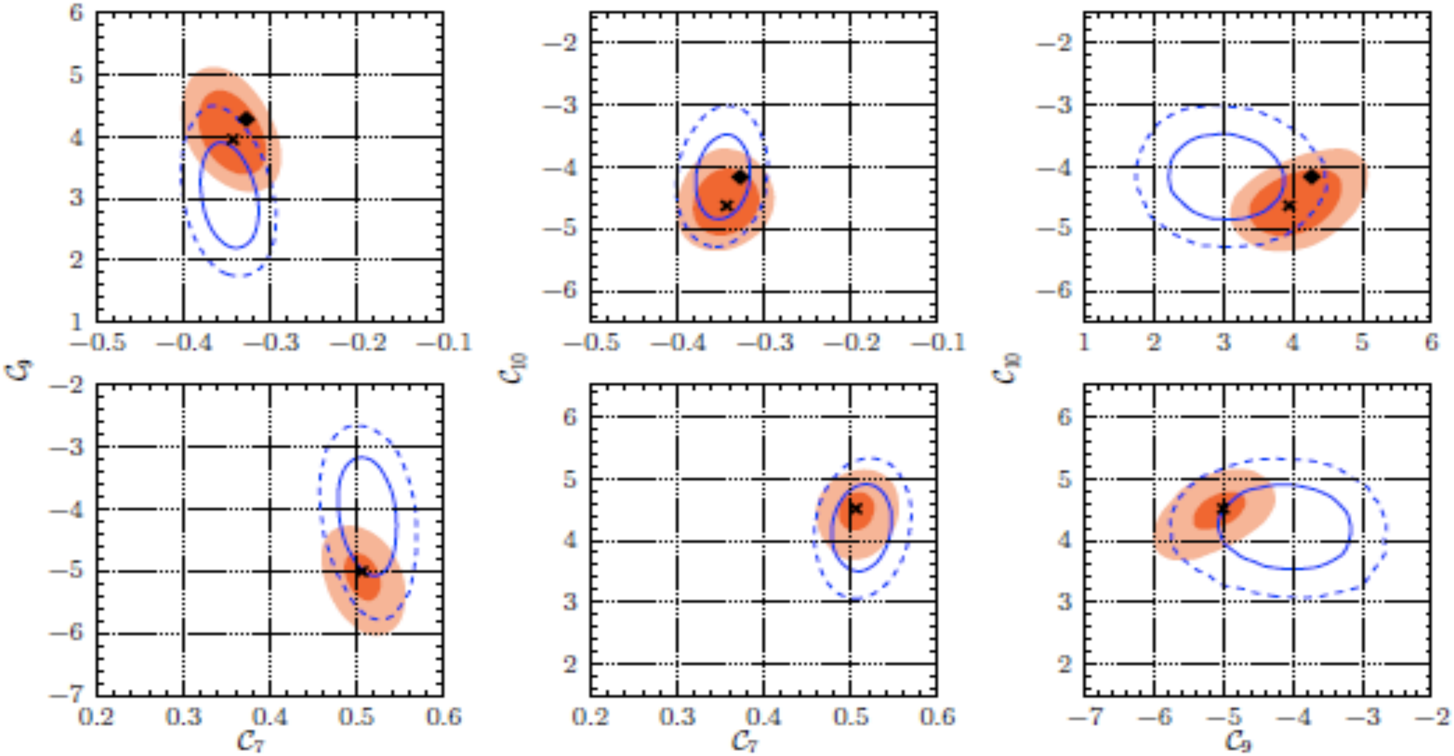
Model-independent analysis



$O_9 \sim \bar{s}\gamma_\mu P_L b \bar{l}\gamma^\mu l$, $O_{10} \sim \bar{s}\gamma_\mu P_L b \bar{l}\gamma^\mu \gamma_5 l$

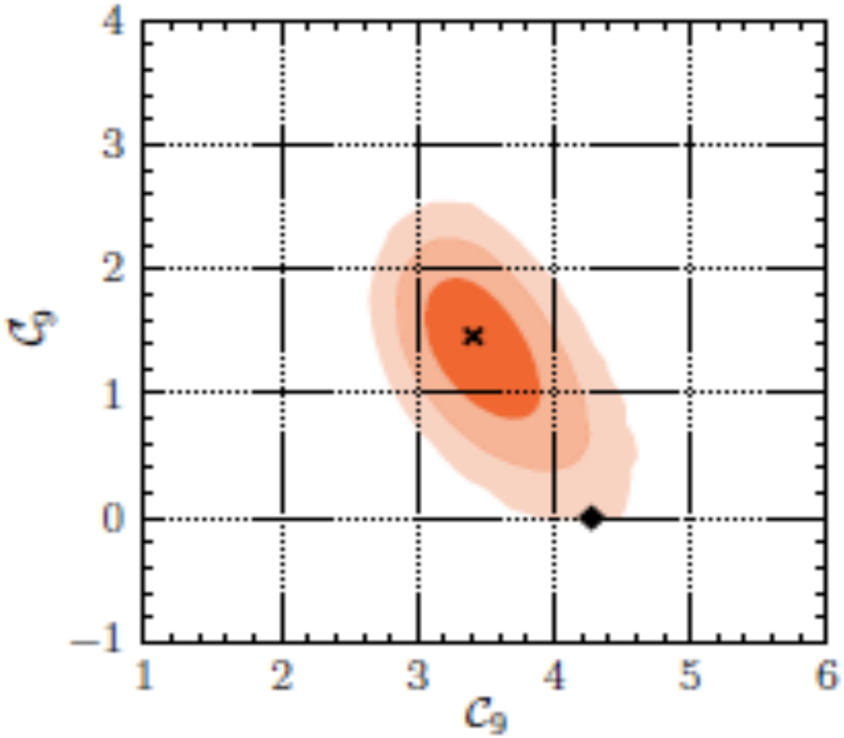
$B(b \to s l^+ l^-) \sim |C_9|^2 + |C_{10}|^2$, $A_{FB} \sim Re(C_9 C_{10}^*)$, $B(b \to s\gamma) \sim |C_7|^2$

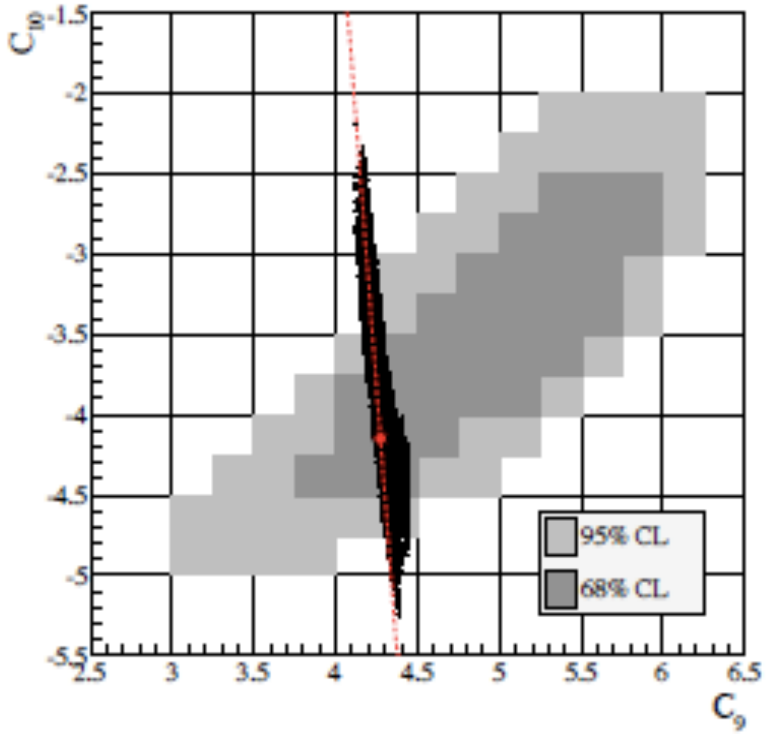
Model-independent analysis today



From 1310.2478 Beaujean et al, based on EOS tool
http://project.het.physik.tu-dortmund.de/eos/

SM global fits work.





From 1310.2478. 'Tuned' BSM fits do work, too. $O_9 \sim \bar{s}\gamma_\mu P_L b \bar{l}\gamma^\mu l$, $O_9' \sim \bar{s}\gamma_\mu P_R b \bar{l}\gamma^\mu l$; $\Delta C_9 \sim -\Delta C_9' \sim O(1)$. Difficult for most models incl. MSSM. $C_9^Z / C_{10}^Z \sim 4\sin\Theta_W^2 - 1 \ll 1$ Fig from 1205.1500 [hep-ph]

Z' model with $\Delta C_9 \sim -\Delta C_9'$.

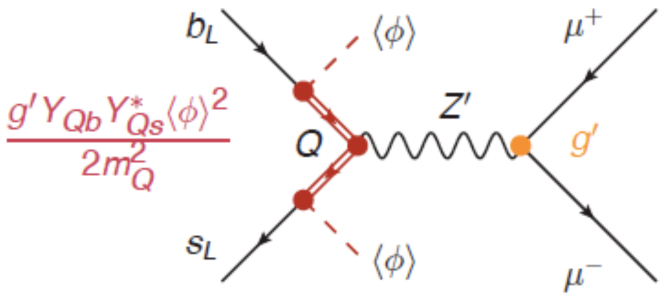
A Simple Model Based on Gauged $L_\mu - L_\tau$

muon number - tau number
is anomaly free
gauging it leads to the wanted
vector couplings with muons

$$\mathcal{L} \supset g'(\bar{\mu}\gamma^\mu\mu - \bar{\tau}\gamma^\mu\tau)Z'_\mu$$

couple the Z' to quarks only
indirectly, by mixing with
heavy vector-like fermions
charged under $U(1)'$

e.g. Fox, Liu, Tucker-Smith, Weiner 1104.4127



contributions to $B \to K^*\mu^+\mu^-$ are
independent of the $U(1)'$ gauge
coupling and the Z' mass

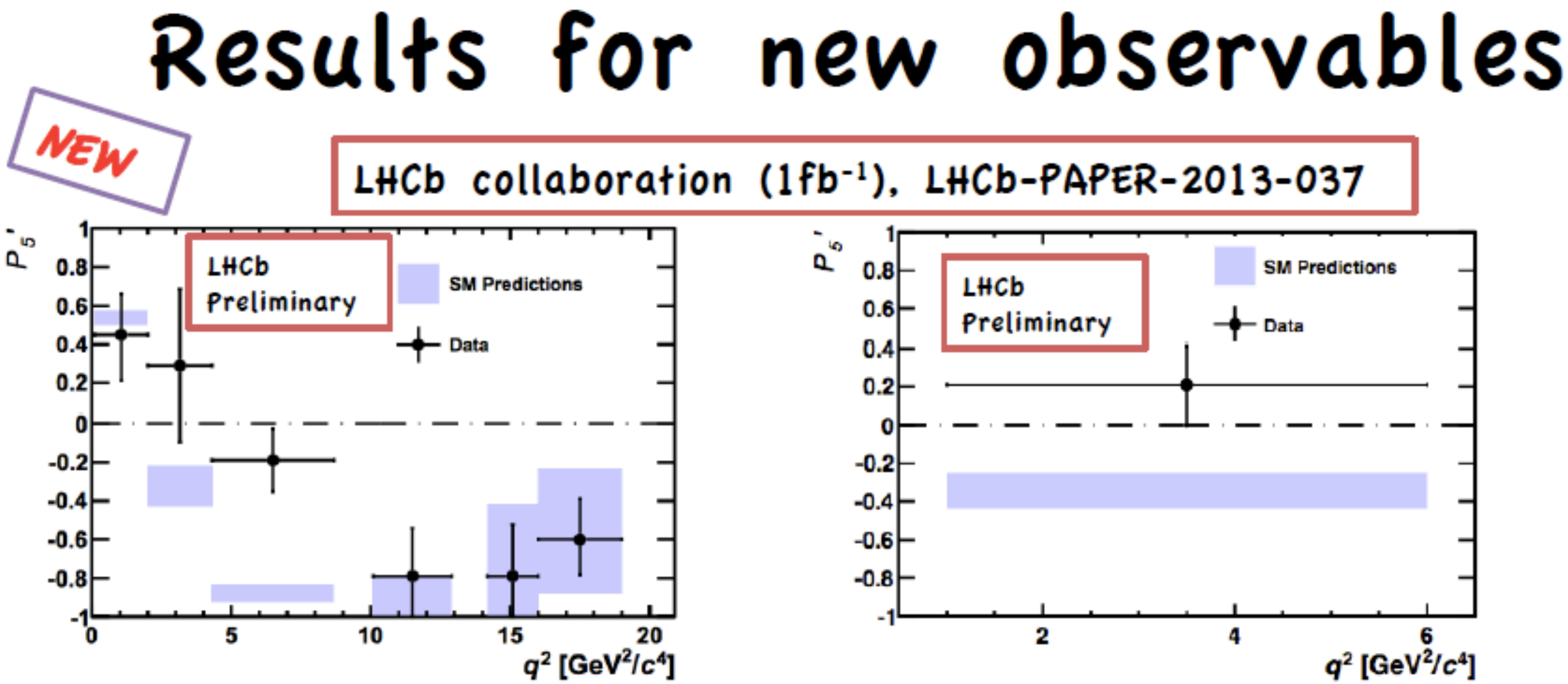
$$C_9 \simeq \frac{Y_{Qb} Y^*_{Qs}}{2m_Q^2} \quad , \quad C_9' \simeq -\frac{Y_{Db} Y^*_{Ds}}{2m_D^2}$$

Altmannshofer Moriond EWK 14

(note: opposite effect in the $\tau^+\tau^-$ final state, no effect in e^+e^-)

Wolfgang Altmannshofer (PI) | New Physics in $B \to K^*\mu^+\mu^-$? | March 16, 2014 | 13 / 16

$B \to K^*(\to K\pi)\mu\mu$, $Br \sim 10^{-7}$ **angular distributions**



There are many more measurements on this mode, also from ATLAS and CMS. This is the one with a lot of discussions. SM from 1303.5794 Descotes-Genon etal.

Note: LHCb's 3 fb^{-1} data set collected in 2012 not analyzed yet.

Generic SM FCNC $c \to u$ amplitude

$$\mathcal{A}(c \to u)_{\rm SM} = V_{cd}^* V_{ud} A_d + V_{cs}^* V_{us} A_s + V_{cb}^* V_{ub} A_b, \qquad A_q = A(m_q^2/m_W^2).$$

with CKM unitarity $VV^\dagger = 1$:

$$\mathcal{A}(c \to u)_{\rm SM} = \underbrace{V_{cd}^* V_{ud}}_{-\lambda}(A_d - A_b) + \underbrace{V_{cs}^* V_{us}}_{+\lambda}(A_s - A_b)$$

Amplitude is GIM-suppressed and CP violation is suppressed by $\frac{V_{cb}^* V_{ub}}{V_{cd}^* V_{ud}} \sim \lambda^4$.

Very sensitive to corrections beyond the SM.

$$\Delta A_{\mathrm{CP}} = A_{CP}(D^0 \to K^+K^-) - A_{CP}(D^0 \to \pi^+\pi^-)$$

$\Delta A_{\mathrm{CP}}^{wa} = -0.00678 \pm 0.00147$ (pre-Moriond QCD 2013)

$\Delta A_{\mathrm{CP}}^{\mathrm{SM}} \sim \lambda^4 \times P/T \simeq 10^{-3} \times P/T$; $P/T \sim$ "$0.x$";

"$\Delta A_{\mathrm{CP}}^{\mathrm{SM}}$ is below permille " (traditional)

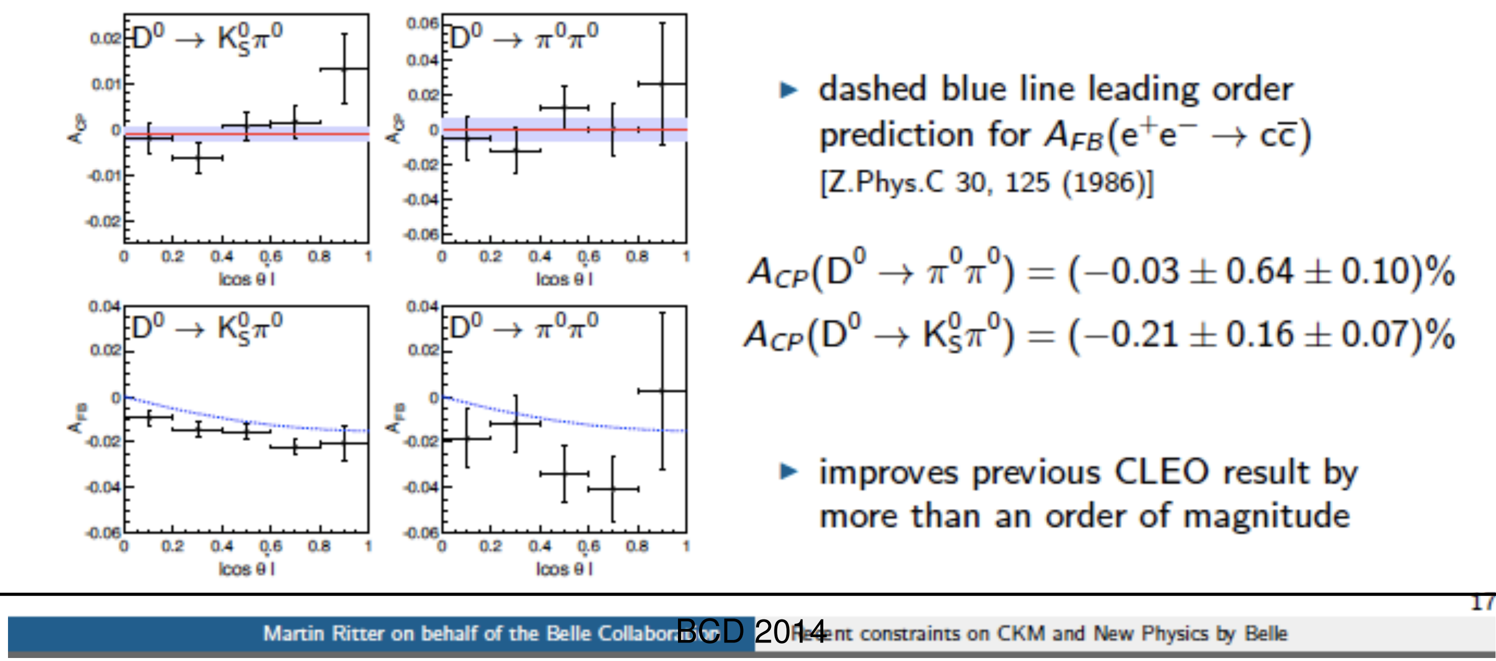
Are the data consistent with the SM? (large number of th papers)

Which model accommodates the data? (large number of th papers)

CP Violation in Charm

Status: $\Delta A_{\rm CP}^{HFAG} = 0.253 \pm 0.104)\%$ (May 2014, 2.4σ)
Taken at face value, penguins still need to be anhanced.

Many other modes $D \to P_1 P_2$, $P = \pi, K$ measured. If New physics in $c \to u$, then not only in $\Delta A_{\rm CP}$. Pattern in data, notably improved CP asymmetries can help to disentangle contributions within and beyond the SM. Improved measurement by Belle of $A_{CP}(D \to \pi^0 \pi^0)$:



The Moriond Conference: counting experiment - P2

- Let's have an overview on the Conference contents.

Rencontres de Moriond EW 2014

15-22 mars 2014

Europe/Paris timezone

- Overview
- Scientific Programme
- Preliminary Program [PDF]
- Timetable with slides (slides visible only upon completion)
- Timetable (compact version)
- Preparing contributions to the proceedings **(NEW)**

Programme scientifique

Electroweak Interactions and Unified Theories.

The Standard Model: precision tests. Search for the Higgs Boson.
Beyond the Standard Model: searches, supersymmetry, rare processes, extradimensions, ...
Flavour physics and CP violation (in the hadronic and leptonic sectors).
Neutrino physics.
Axions. Dark matter searches and Dark energy candidates.
Astroparticles and cosmological observations and their implications.

Part II

Motivations

The detailed outline

1. Gauge bosons, Standard Model (SM) tests and beyond:
   Shaking the first pillar of the SM.

   - Introduction to the LHC Physics Case from previous machines.
   - The top quark properties.
   - The 126 GeV boson particle and its properties.
   - The searches for New Physics.

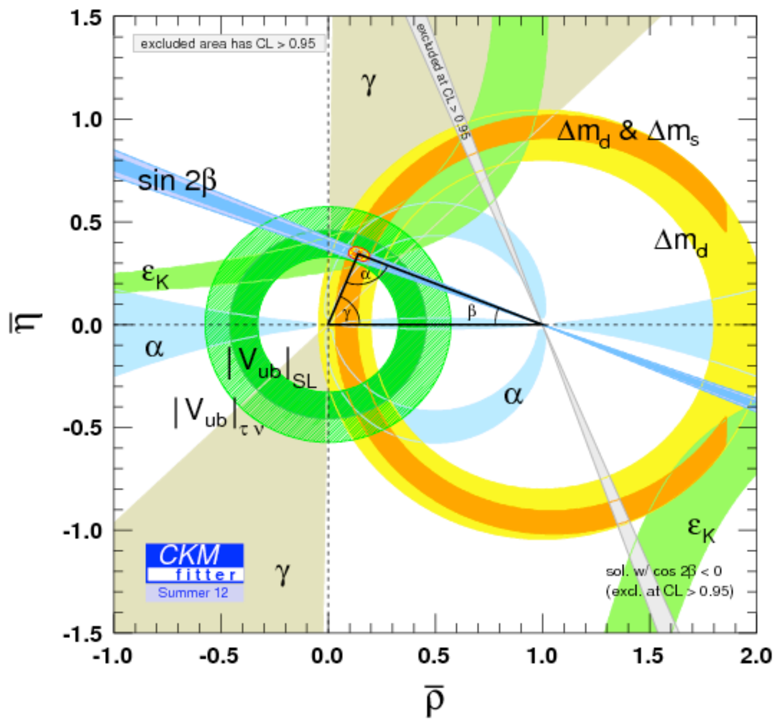
2. Quark Flavour Physics:
   Shaking the second pillar of the SM.

   - State of the art of the CKM matrix consistency checks.
   - Searches for deviations.

3. The other frontiers: neutrinos, cosmology etc...
   What if the quake comes from them?

Motivation for Part II

- The figure below illustrates the second pillar of the SM.



- What is behind and beyond this plot will be examined in the second part.

1. Flavour Physics and CP violation

The electroweak core of the flavour physics case is all about the understanding of the ElectroWeak Symmetry Breaking, just as the gauge physics we explored.

Within the Standard Model, you've been tought that after spontaneous symmetry breaking by the introduction of a scalar doublet and mass matrix diagonalisation:

$$\mathcal{L}_{cc}^{\text{quarks}} = \frac{g}{2\sqrt{2}} W_\mu^\dagger [\sum_{ij} \bar{u}_i(q_2)\gamma^\mu(1-\gamma^5) V_{ij} d_j] + \text{h.c}$$

The CKM matrix elements relates the mass and the weak eigenstates and controls the strength of flavour changing charged currents between quark generations.

The CKM matrix is described by four unknown parameters, one being a phase allowing for CP violation. Overconstraining these parameters makes possible a global consistency test of the SM hypothesis.

1. The unitarity triangle. One parametrization.

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

Consider the Wolfenstein parametrization as in EPJ C41:1-131,2005 : unitary-exact and phase convention independent:

$$\lambda^2 = \frac{|V_{us}|^2}{|V_{ud}|^2 + |V_{us}|^2}, \quad A^2\lambda^4 = \frac{|V_{cb}|^2}{|V_{ud}|^2 + |V_{us}|^2} \quad \text{and} \quad \bar{\rho} + i\bar{\eta} = -\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}$$

- λ is measured from $|V_{ud}|$ and $|V_{us}|$ in superallowed beta decays and semileptonic kaon decays, respectively.

- A is further determined from $|V_{cb}|$, measured from semileptonic charmed B decays.

- The last two parameters are to be determined from angles and sides measurements of the CKM unitarity triangle.

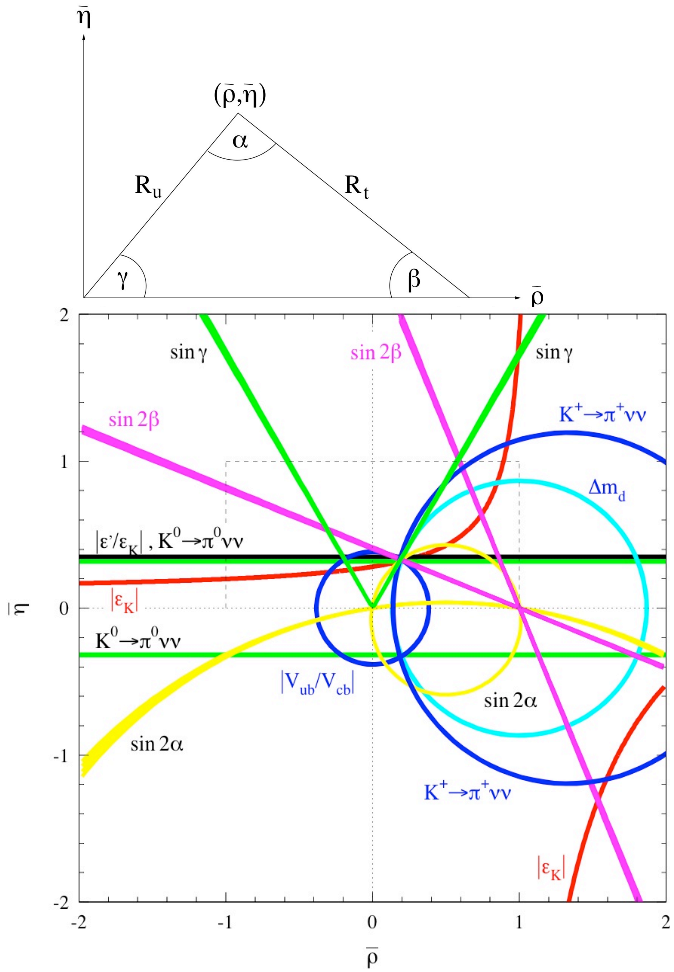
1. The unitarity triangle. Representation.

• An elegant way to represent the unitarity relations is to display them in the complex plane.

• The area of the triangle is half the Jarlkog invariant and measures the magnitude of the CP violation:

$$J \sum_{\sigma\gamma=1}^{3} \epsilon_{\mu\nu\sigma}\epsilon_{\alpha\beta\gamma} = \mathrm{Im}(V_{\mu\alpha}V_{\nu\beta}V^*_{\mu\beta}V^*_{\nu\alpha}) \; ,$$

$$J = A^2\lambda^6\eta(1-\lambda^2/2) \simeq 10^{-5}$$



1. The unitarity triangle. Angles and Sides.

- Let's continue the description of the CKM matrix by defining the angles and the sides from the matrix elements:

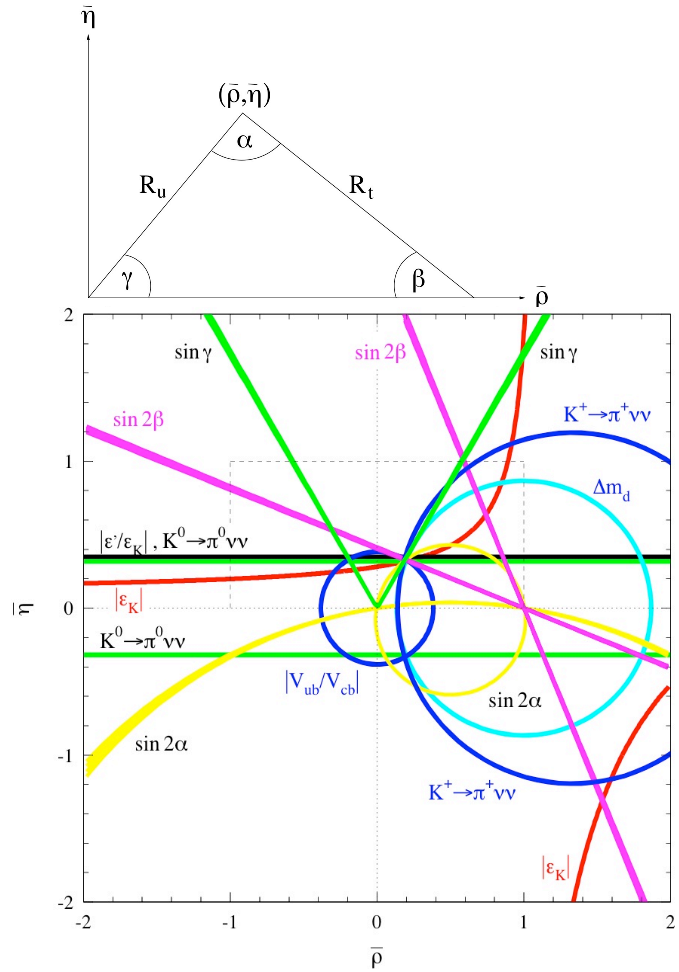
$$\alpha = \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right),$$

$$\beta = \pi - \arg\left(\frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*}\right),$$

$$\gamma = \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right).$$

$$R_u = \left|\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb*}}\right| = \sqrt{\bar\rho^2+\bar\eta^2}\,,$$

$$R_t = \left|\frac{V_{td}V_{tb}^*}{V_{cd}V_{cb*}}\right| = \sqrt{(1-\bar\rho)^2+\bar\eta^2}\,.$$



1. Main concluding messages about CKM.

- KM phase is the unique CP-violating phase of the SM.

- A non-vanishing η parameter of the Wolfenstein parameterization means CP violation in the SM (or the triangle is not flat).

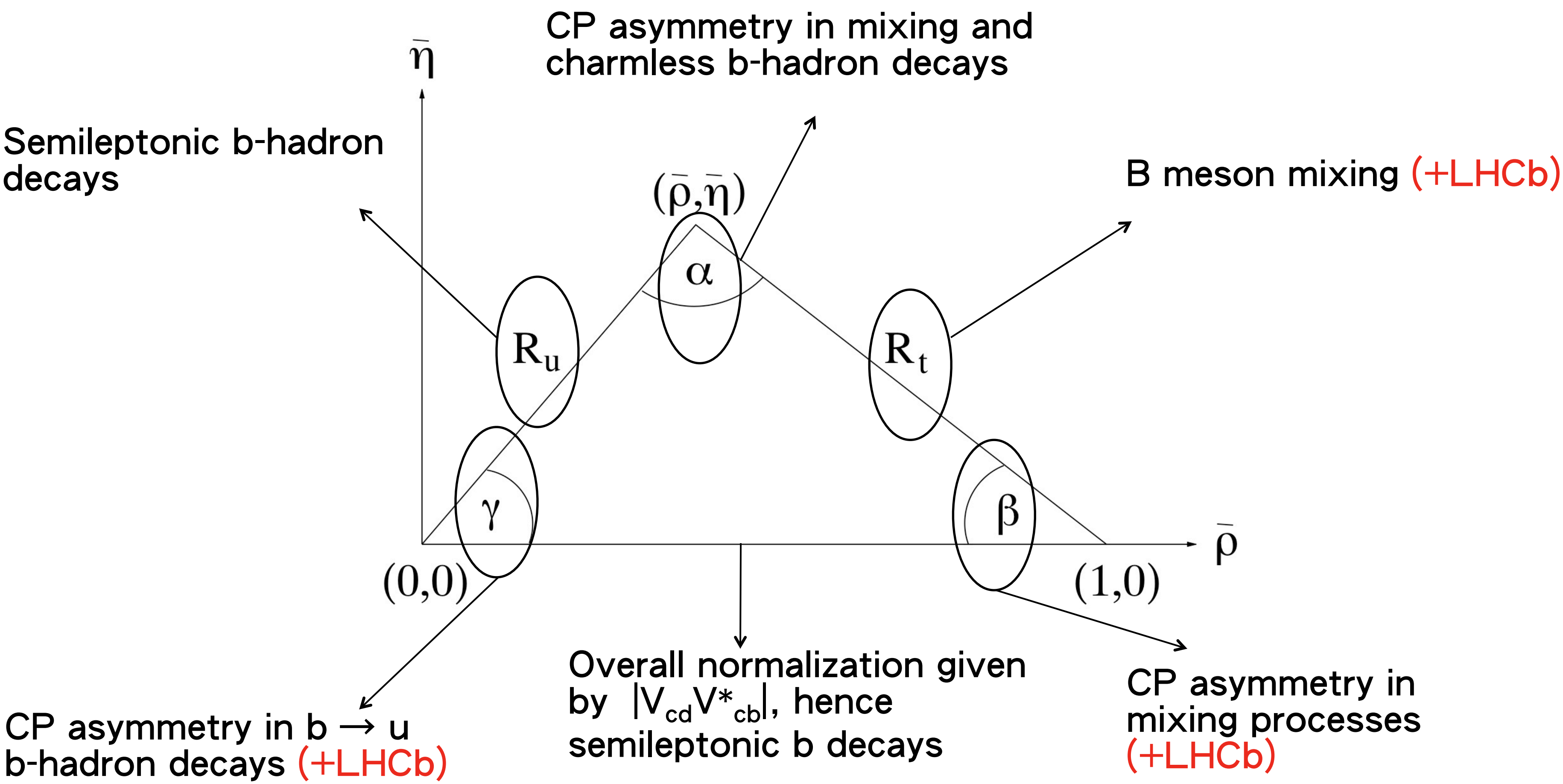
- None of the parameters of the matrix are fixed by first principles. It is necessary, as was done for the EW fit, to overconstrain the free parameters with redundant measurements.

- These ensures to produce a consistency check, out of which, if successful, the metrology of the parameters can be made.

- We're dealing with quarks here. Strong interaction theoretical uncertainties are a key element when interpreting the EWK content.

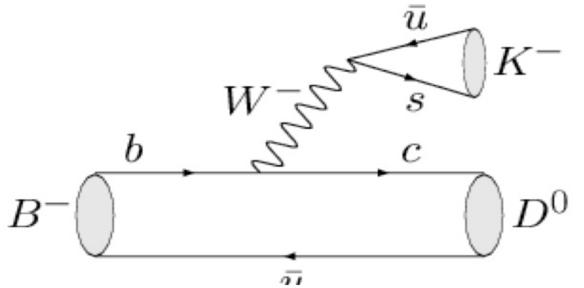
2. Machines, experiments and measurements.

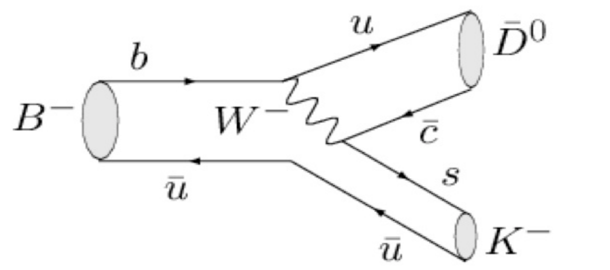
- *B* factories: contribute everywhere!



3. The γ angle at LHCb: principle.

• The determination of the angle γ requires interferences between charmless b→u transition and another weak phase, say for instance b→c. This interference is realized in decays B→DK.





$$
\begin{aligned}
A(B^- \to D^0 K^-) &= a \\
&\downarrow CP \\
\bar{A}(B^+ \to \bar{D}^0 K^+) &= a
\end{aligned}
\qquad
\begin{aligned}
A(B^- \to \bar{D}^0 K^-) &= a e^{-i\gamma} r_B e^{i\delta_B} \\
&\downarrow CP \\
\bar{A}(B^+ \to D^0 K^+) &= a e^{+i\gamma} r_B e^{i\delta_B}
\end{aligned}
$$

• The interference level between b→u and b→c transitions is controlled by the parameter r_B:

$$r_B = \left| \frac{A(B^- \to \bar{D}^0 K^-)}{A(B^- \to D^0 K^-)} \right|$$

• No penguin: theoretically clean. But one has to reach through undistinguishable paths the same final state !

3. The γ angle at LHCb: methods.

- We hence have to reconstruct the *D* mesons in final states accessible to both D^0 and *anti*-D^0. There are three main techniques which have been undertaken at *B* factories:

1. GLW (Gronau, London, Wyler): search for *D* mesons decays into 2-body CP eigenstates, e.g K^+K^-, $\pi^+\pi^-$ (CP=+) or $K_S\pi^0$, ϕK_S (CP=-). Somehow natural but very low branching fractions.

2. ADS (Atwood, Dunietz, Soni): Use *anti*-$D^0 \rightarrow K^-\pi^+$ for $b \rightarrow u$ transitions (Cabibbo allowed) and $D^0 \rightarrow K^-\pi^+$ (Doubly Cabibbo suppressed) for $b \rightarrow c$ transitions. Again low branching fractions and additionally one has to know the strong phase of the *D* decay.

3. GGSZ (Giri, Grossman, Sofer, Zupan): use quasi 2-body CP eigenstates of the *D* to be resolved in the Dalitz plane. $D \rightarrow K_S\pi^+\pi^-$. So far the most precise gamma determination.

   Note: I used D^0K for illustration. The same stands for D^*K and DK^*. The hadronic factors (r_B, δ_B) are however different in each case.

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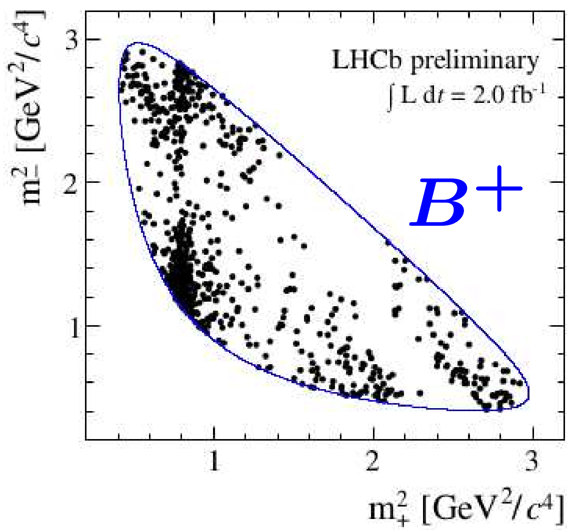
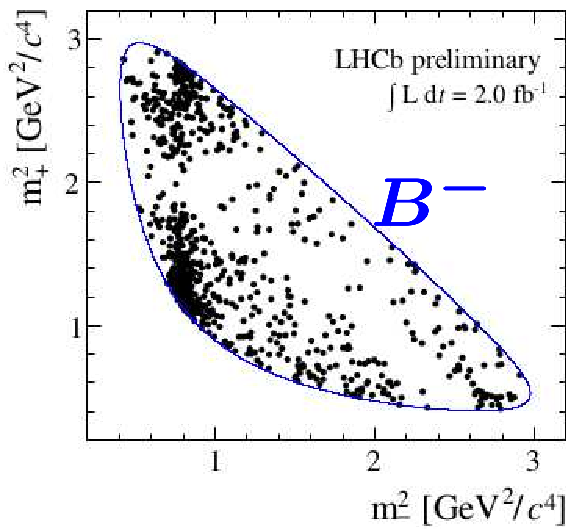
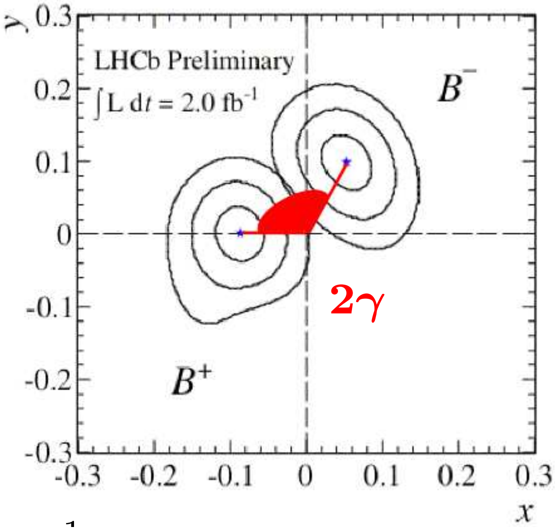
3. The γ angle at LHCb: one result GGSZ.



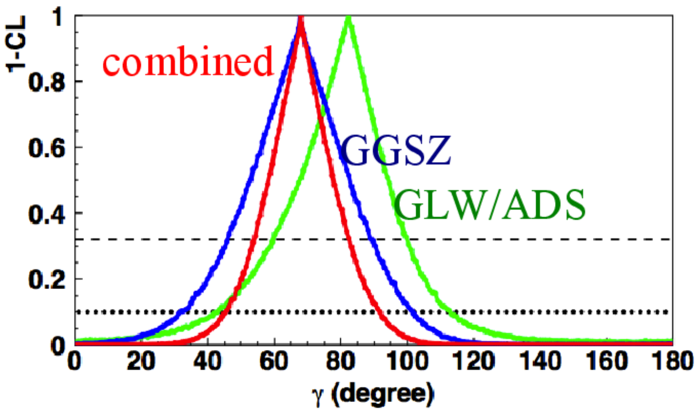




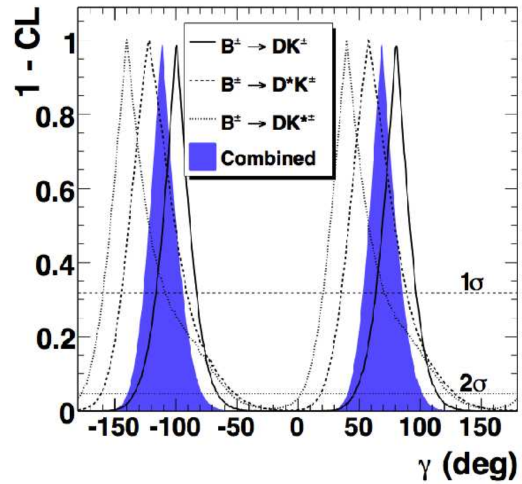
$$
\begin{aligned}
r_B &= (8.8^{+2.3}_{-2.4})10^{-2}, \\
\gamma &= (57 \pm 16)^\circ
\end{aligned}
$$

- Best precision for *DK* mode.

3. The γ angle: WA.



arXiv:1301.2033



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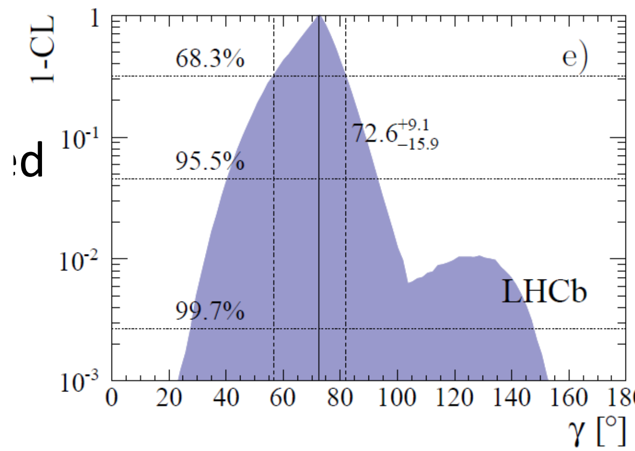
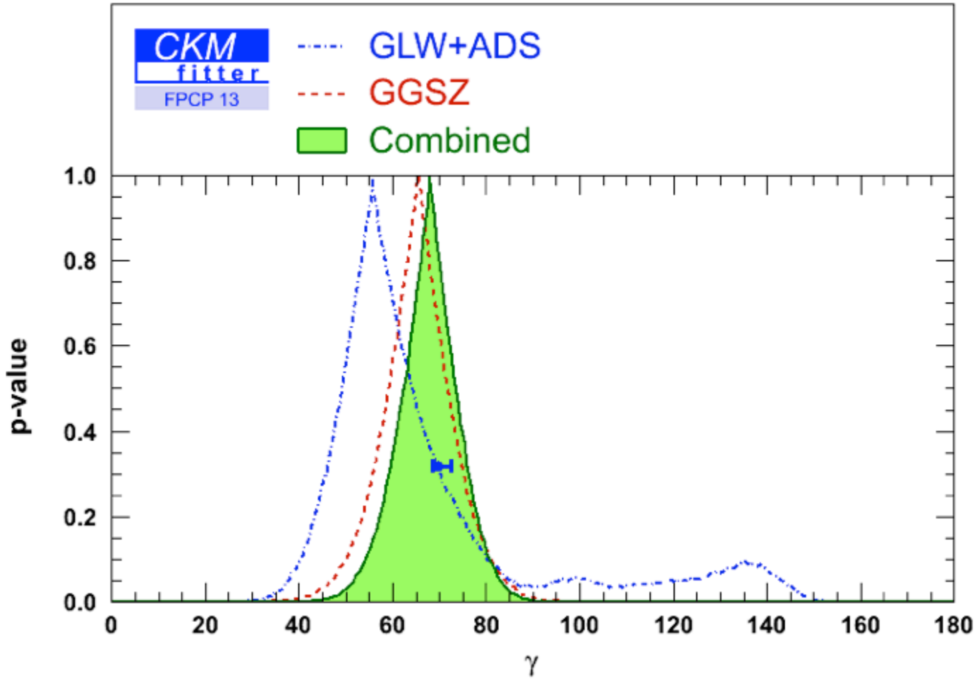


L. Carson @ Moriond

$$\begin{aligned}\gamma(\mathrm{Belle}) &= (68^{+15}_{-14})^\circ \\ \gamma(\mathrm{BaBar}) &= (69^{+17}_{-16})^\circ \\ \gamma(\mathrm{LHC}b) &= (67 \pm 12)^\circ\end{aligned}$$

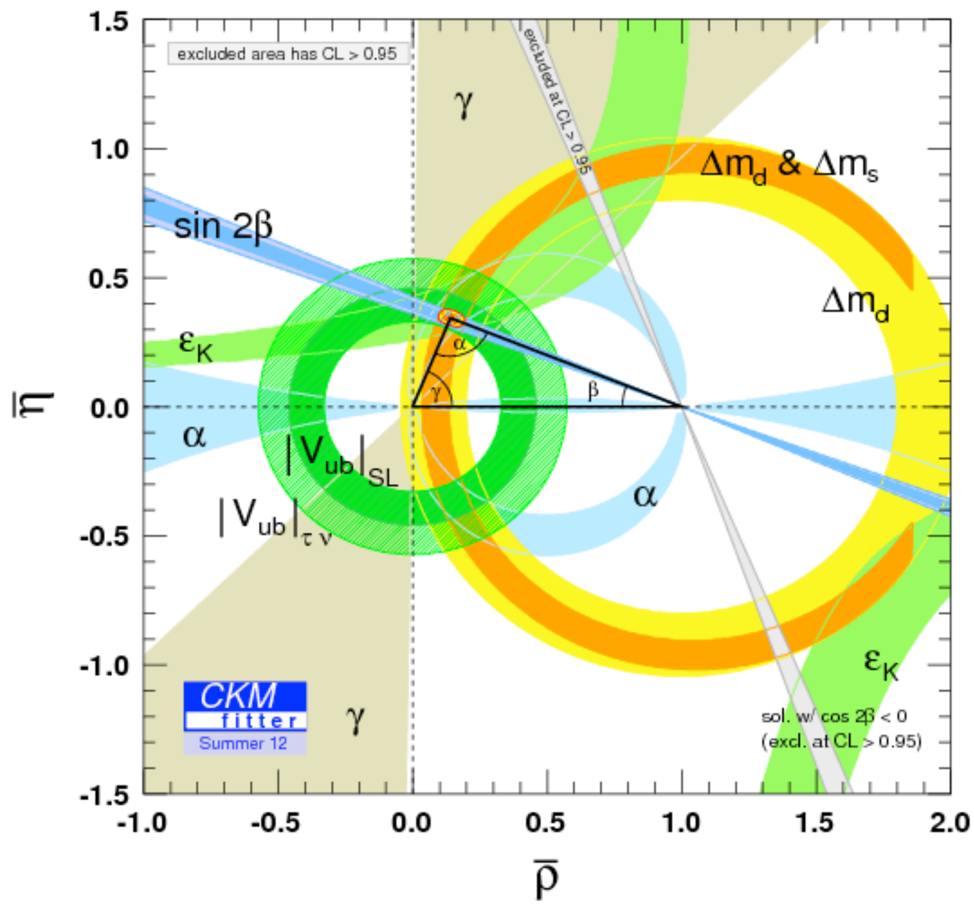
3. The γ angle: WA (grand combination).



$$\gamma(\mathrm{WA}) = \left(68.0^{+8.0}_{-8.5}\right)^\circ .$$

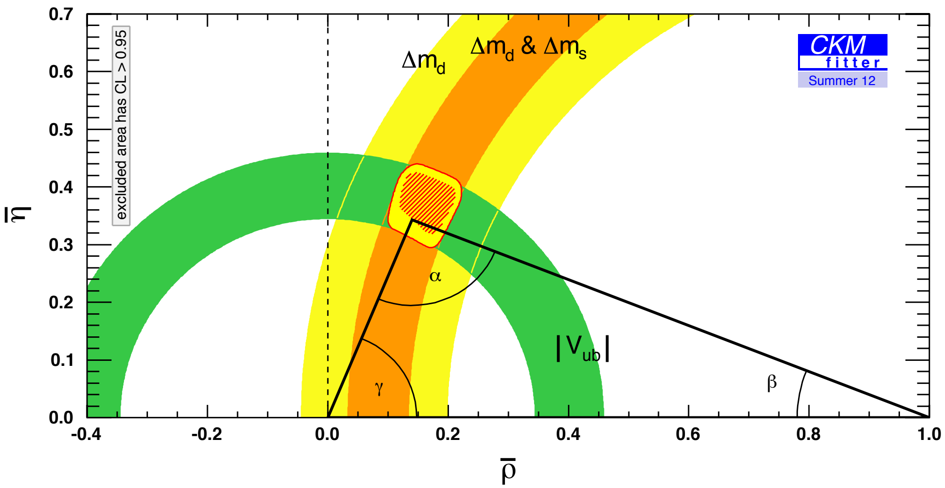
3. The global picture.

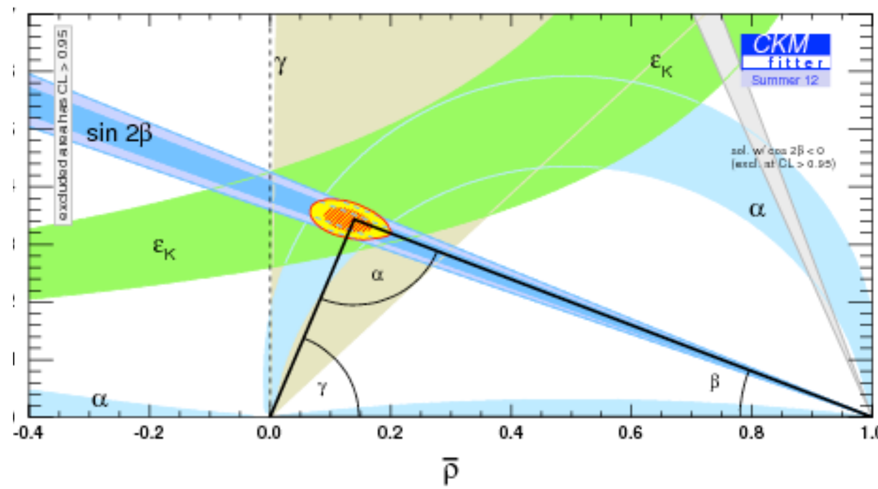
- Notes to read the picture: regions outside the coloured area are excluded at 95 % Confidence Level.
- If there is a region of the Wolfenstein parameter space which is common to all the constraints, the region not excluded at 95% C.L. is shown. This is the yellow bean.



3. The global picture.

- The global picture: comparison of observables constraints.
- CP-conserving against CP violating.

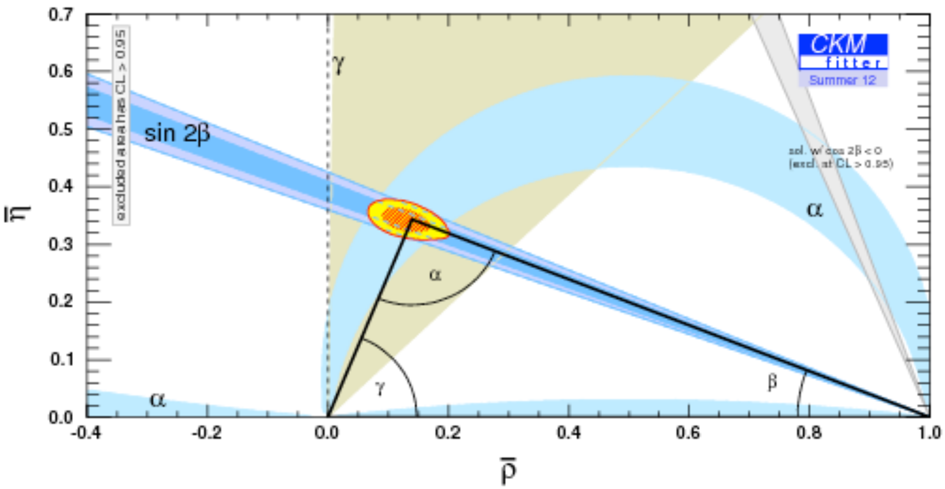


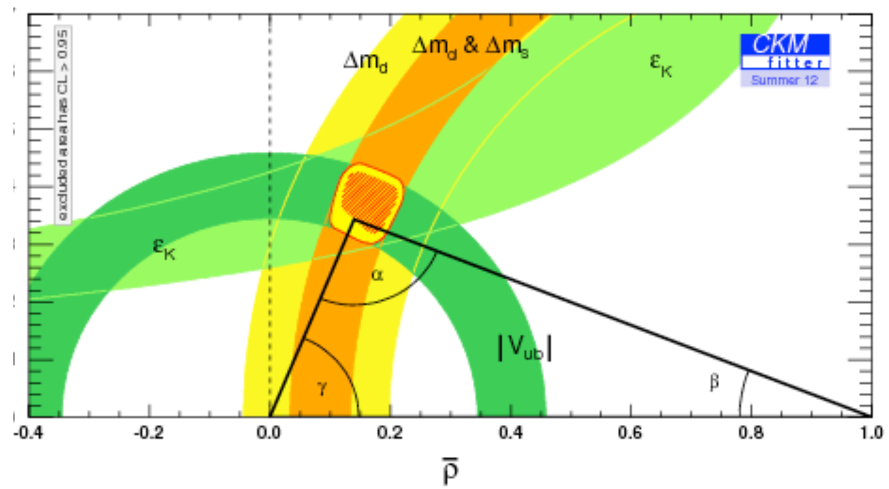


- Correct agreement. CP-conserving observables can quantify CP violation.

3. The global picture.

- The global picture: comparison of observables constraints.
- Angles (No theory uncert.) against No angles (Hadronic uncert.).

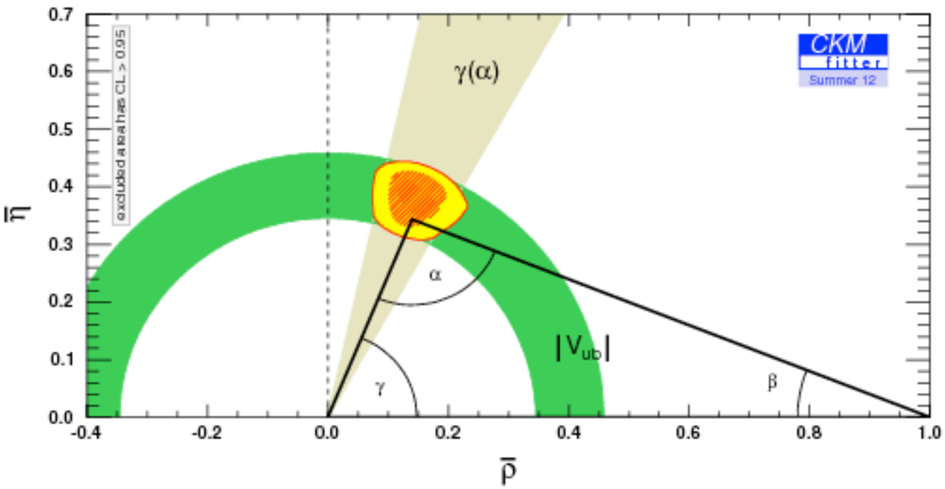


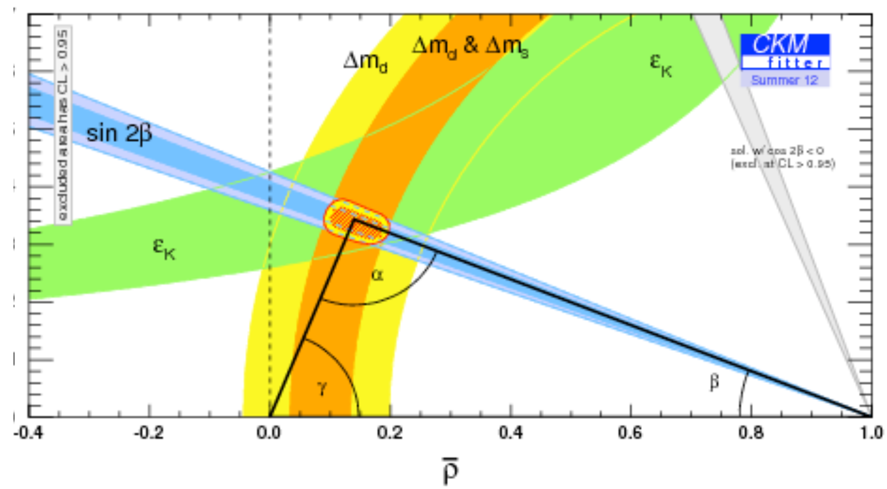


- Correct agreement. Only observables with a good theoretical control are considered in the global fit.

3. The global picture.

- The global picture: comparison of observables constraints.
- Trees against Loops.

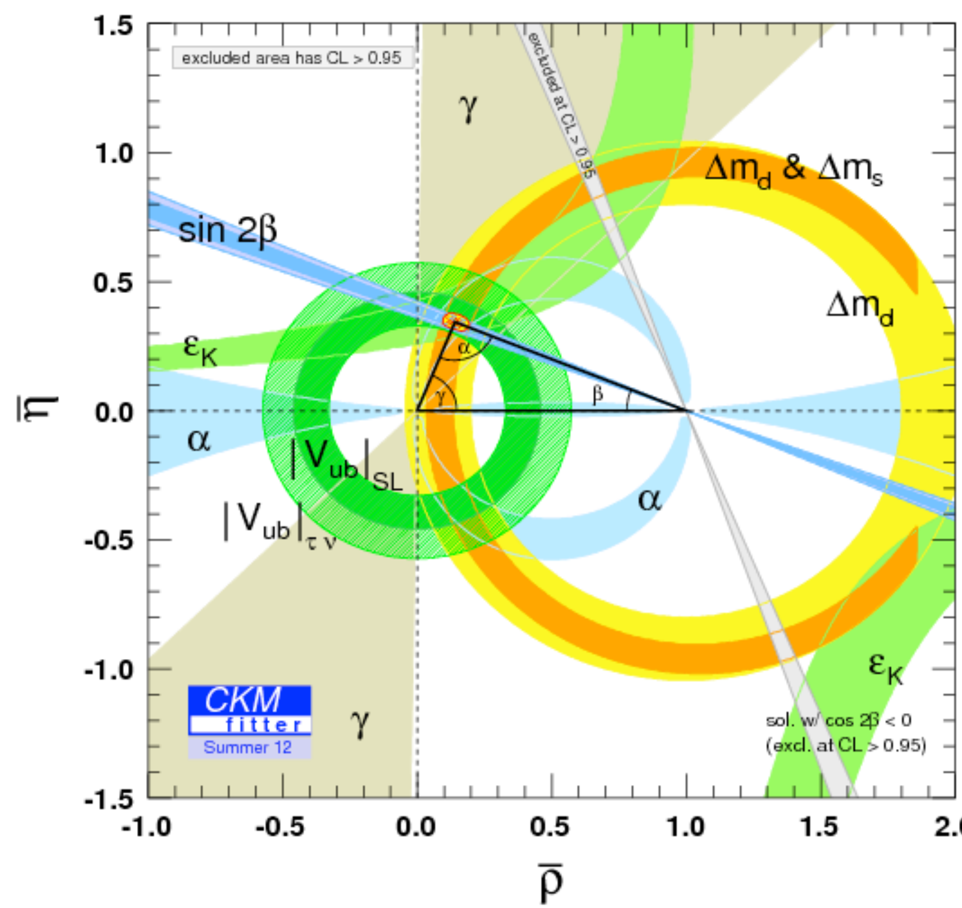




- Trees are thought to be SM-dominated. Loops on the contrary are excellent laboratories to exhibit New Physics. Well, same player shoots again.

3. The global picture.

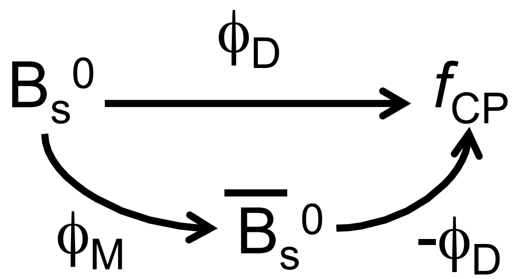
- This is a tremendous success of the Standard Model and especially the Kobayashi-Maskawa mechanism. This is simultaneously an outstanding experimental achievement by the B factories.
- CKM is at work in weak charged currents.
- The KM phase IS the dominant source of CP violation in K and B system.
- High precision γ angle measurement is the next goal, CKM-wise. It constrains also NP exploration.



5. One example of null test of the SM hypothesis

- Study the CP violation in interference between decay and mixing in B_s decays in $B_s^0 \to J/\psi\ (\mu^+\mu^-)\ \phi\ (K^+K^-)$ decays: CP violating phase $\phi_S = \phi_M - 2\phi_D$

- From the global CKM fit, ϕ_S is well determined: $\phi_S = -2\beta_S = -0.0363 \pm 0.0017$ rad, up to penguin diagram phase contributions (10^{-4}–10^{-3}). Null test of the SM hypothesis.

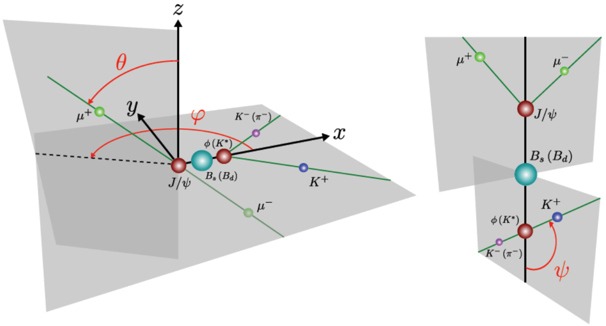


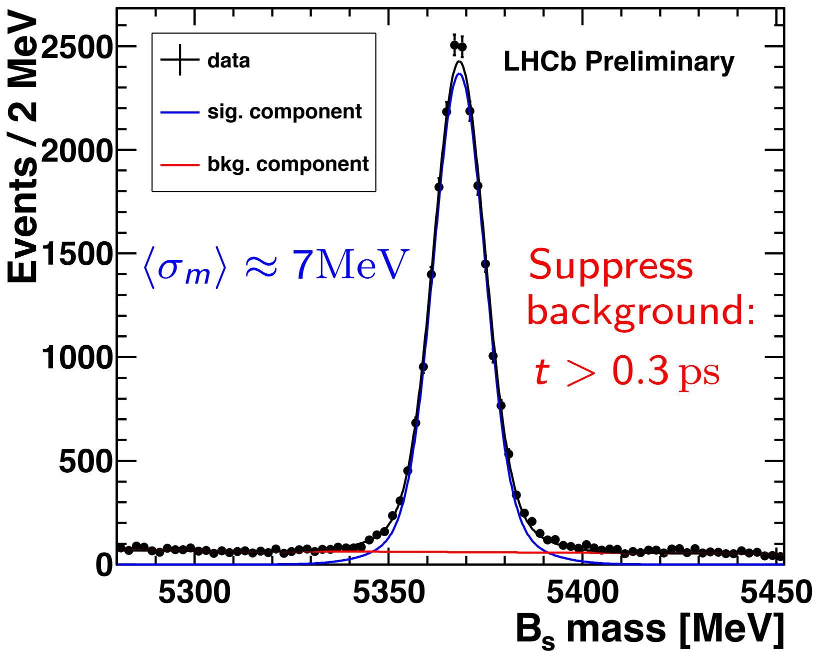
- The mixing phase, $\phi_M \approx 0$ in Standard Model can be modified by New Physics and hence measured by ϕ_S.

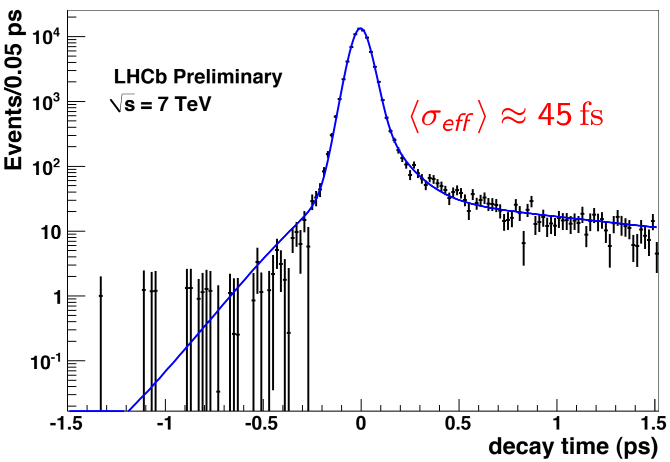
- Since the decay is $P \to VV$, the final state is superposition of states with different CP value: the measurement requires a tagged, time-dependent angular analysis.

5. One example of null test of the SM hypothesis

- It requires a simultaneous fit to *m, t, φ, ψ, θ*.
- Let's start with mass and propertime.

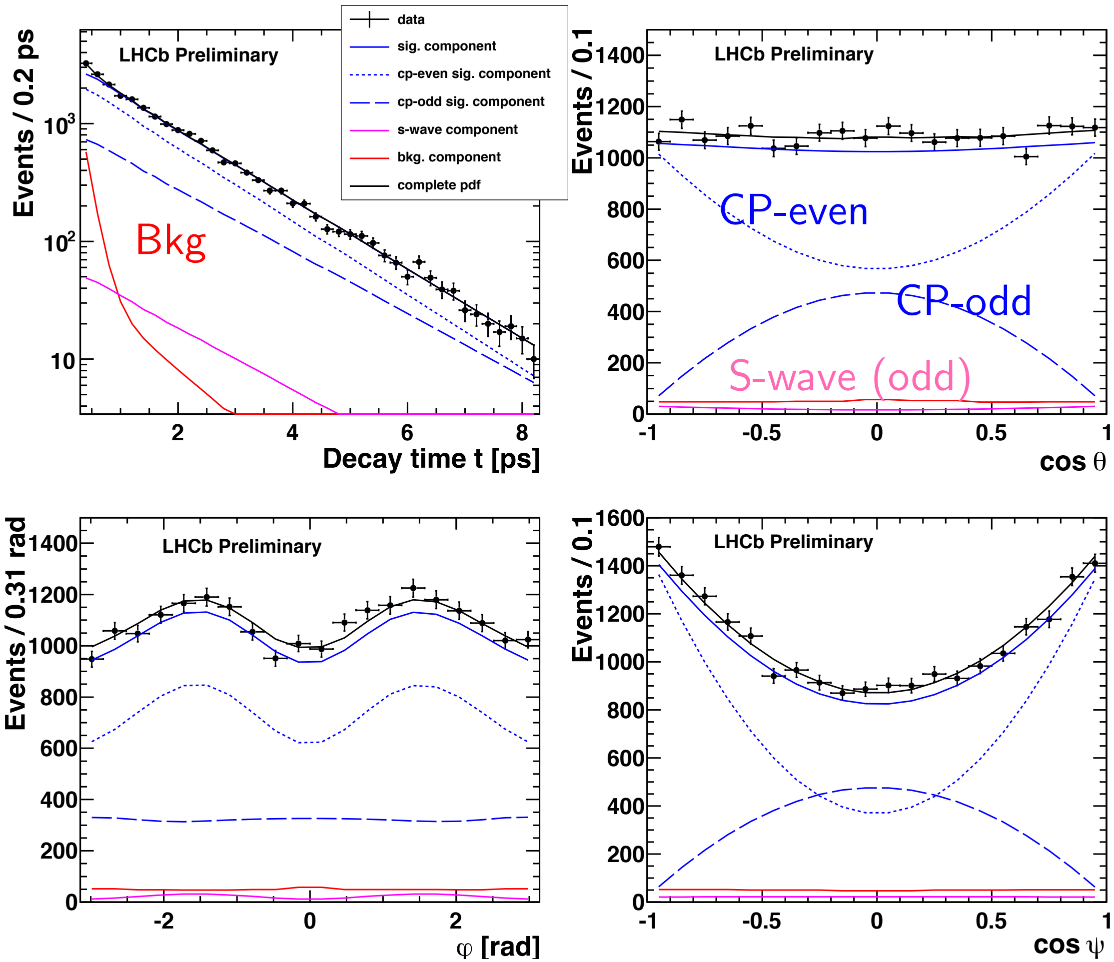






5. One example of null test of the SM hypothesis

- Results:

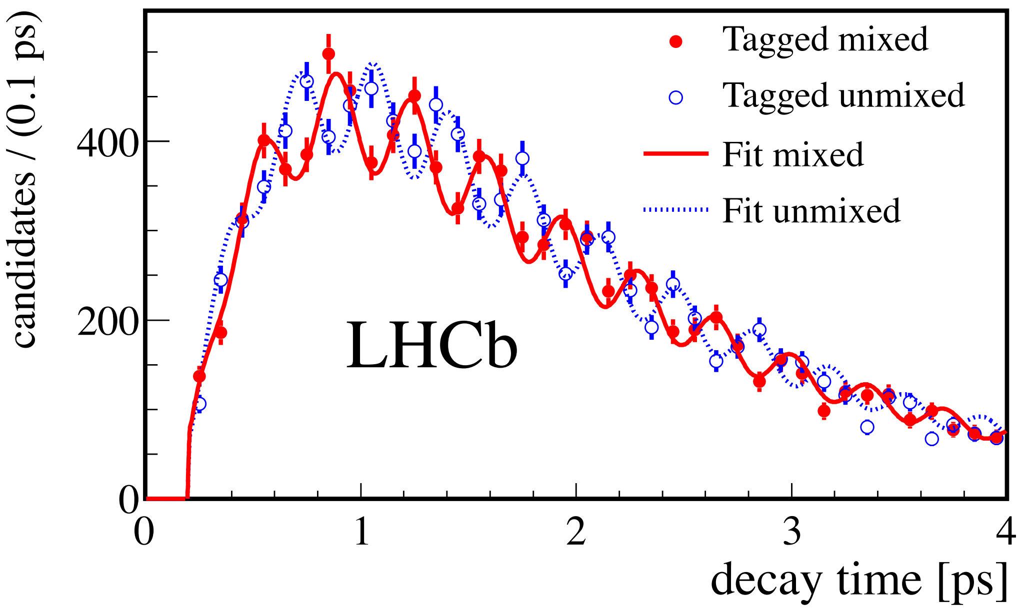


$$\Phi_s = 0.01 \pm 0.07 \text{ rad [LHCb 1/fb]}$$
$$\Phi_s = 0.0363 \pm 0.0017 \text{ rad [CKM fit]}$$

- Very much SM...
- Search for new *CP*-violating phases in many *c*- and *b*-hadron decays.
- Techniques and systematics controls are installed.
- The LHC Run II and beyond will give a breakthrough in precision.

6. A flavour of precision: oscillation frequencies of : Δm_s

- The mixing of neutral mesons is a two-level system in quantum mechanics. The particle and the antiparticle are indistinguishable under weak interaction and hence mixes giving rise to two mass eigenstates. In the measurement below (2013) the oscillation time is resolved at few 10^{-13} s! $B_s \rightarrow D_s\pi$ decays.



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7. Outlook for experimental quark flavours.
Beyond the current CKM profile...

- Improve the precision of the global fit observables (don't forget to improve simultaneously the theoretical errors)

- Rare decays (FCNC processes) are excellent laboratories to find a deviation to the SM prediction.

- We are entering in a precision era. Both the LHC (LHCb) and the SuperKEKB project at Japan will provide a breakthrough in precision.

- Precision measurements are an indispensable way to set an energy scale for new phenomena in absence of direct observation. True for the gauge and flavour sector of the electroweak theory.