HEAVY FLAVOUR 2016
Quo Vadis?

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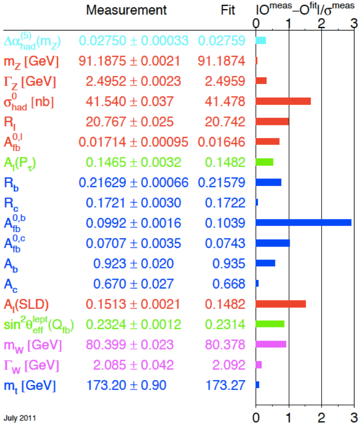
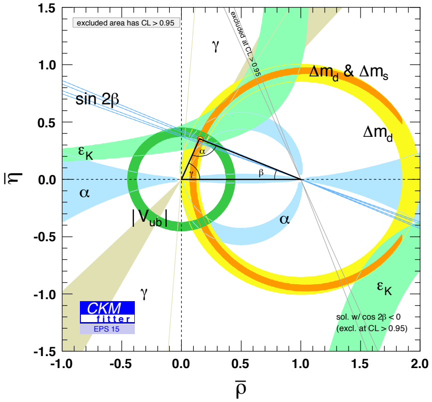
Contents

Where do we stand?

- Standard Model passed all tests up to $\mathcal{O}(100\ \text{GeV})$
- LEP: test of the gauge Structure
- Flavour factories: test of the Flavour Sector



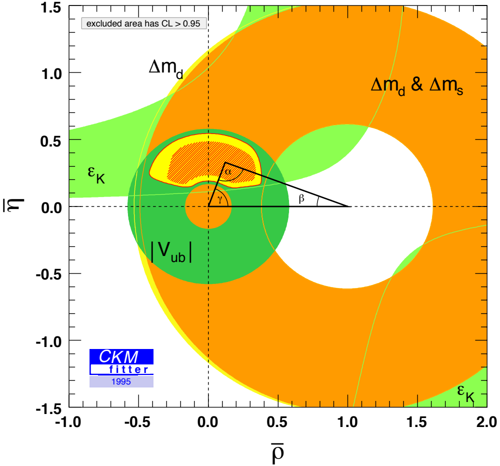
	Measurement	Fit
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02750 ± 0.00033	0.02759
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959
σ^0_{had} [nb]	41.540 ± 0.037	41.478
R_l	20.767 ± 0.025	20.742
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.01646
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1482
R_b	0.21629 ± 0.00066	0.21579
R_c	0.1721 ± 0.0030	0.1722
$A^{0,b}_{fb}$	0.0992 ± 0.0016	0.1039
$A^{0,c}_{fb}$	0.0707 ± 0.0035	0.0743
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1482
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.399 ± 0.023	80.378
Γ_W [GeV]	2.085 ± 0.042	2.092
m_t [GeV]	173.20 ± 0.90	173.27



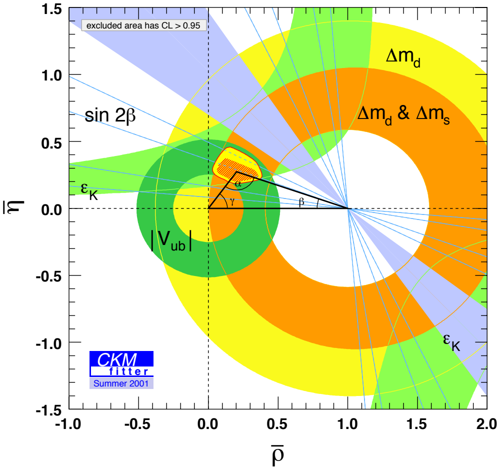
There has been tremendous progress in Flavour Physics

- Experimental facilities for precision measurements in strange, charm and bottom
- Theoretical methods have been refined to the precision level:
    - Lattice
    - Effective Field Theories
    - QCD sum rules
    - (Models)
- Close cooperation between experiment and theory!

Progress is best documented by the “CKM movie”: (CKM Fitter)



1995 (pre-B factory era)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CKM fitter
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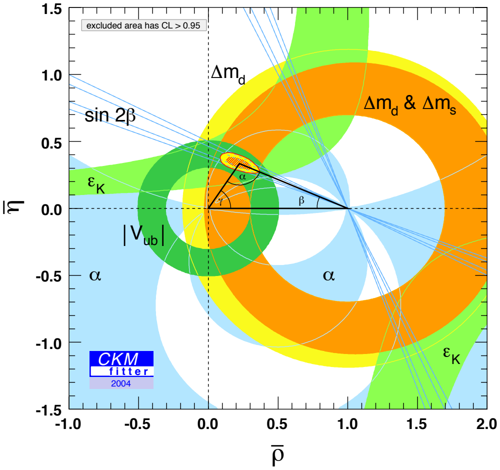
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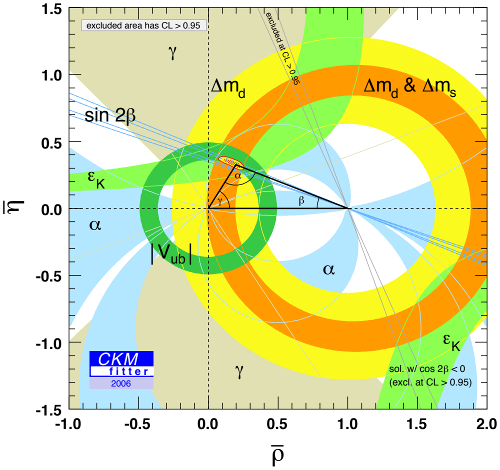
2004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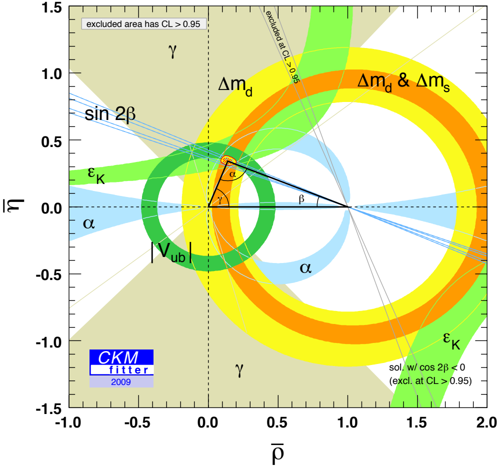
2006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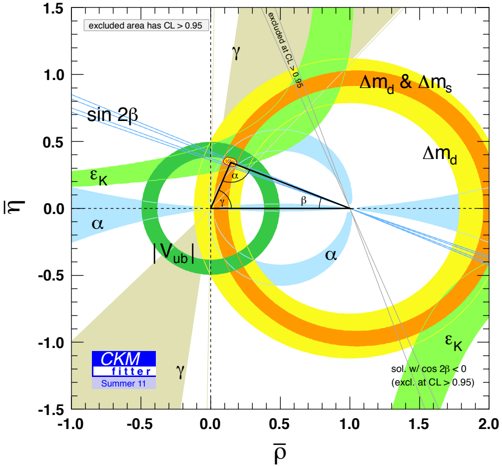
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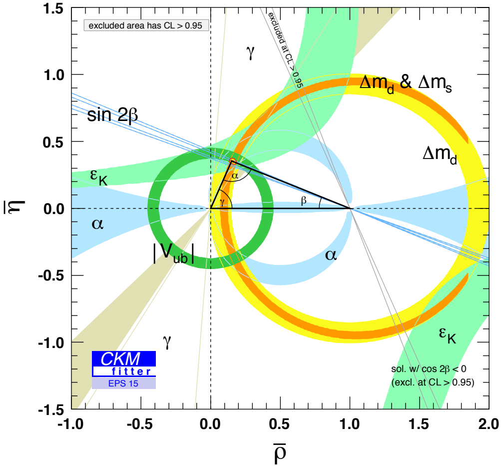
2011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CKM fitter
EPS 15
sol. w/ cos 2β < 0
(excl. at CL > 0.95)
$\bar\eta$
$\bar\rho$

2015

Triumph of the Standard model (?)

- LHC discovered a Higgs:
  - It has non-universal (i.e. mass dependent) couplings!
  - Is it THE Higgs? It looks pretty SM like!
  - ... or is ewk. symmetry breaking more complicated?
  - 750 GeV anomaly: the first hint at something new?
- Nevertheless, the Higgs discovery completes the SM, Despite of naturalness
- The SM could be valid up to extremely high scales
- No significant(!) hint at "new physics" yet

Particle Physics at the crossroads

LHC finds New Particles

- Find our what it is!
- How does this become compatible with the precision data?
- Why do we have MFV?
- ... and where does it come from?

LHC finds no New Particles

- Era of indirect searches
- Quark and Lepton Flavor Physics
- Indirect searches at highest energies
- "Precision Colllider Physics" at LHC

We will know soon! (at least about the 750 GeV bump)

- (Ubiquitous) effective field theory picture

$$\mathcal{L} = \mathcal{L}_{\rm dim\,4}^{SM} + \mathcal{L}_{\rm dim\,5} + \mathcal{L}_{\rm dim\,6} + \cdots$$

- $\mathcal{L}_{\rm dim\,n}$ are suppressed by large mass scales

$$\mathcal{L}_{\rm dim\,n} = \frac{1}{\Lambda^{n-4}} \sum_i C_n^{(i)} O_n^{(i)}$$

$O_n^{(i)}$: Operators of dimension n,
$SU(3)_C \times SU(2)_W \times U(1)_Y$ gauge invariant
$C_n^{(i)}$: dimensionless couplings

- What can we know about this mass scale?

From neutrino physics:

- Majorana masses for the ν's are generated by a unique dim-5 operator:

$$\mathcal{L}_{\rm dim\,5} = \frac{1}{\Lambda_{\rm LNV}} \sum_{ij} C_5^{ij} (\bar{L}_j H^c)^c (H^{c,\dagger} L_i)$$

- Generates a mixing matrix for the leptons (PMNS Matrix), analogous to the CKM Matrix
- This term is Lepton Number Violating, related to the scale $\Lambda_{\rm LNV}$
- Small Neutrino masses: $\Lambda_{\rm LNV} \sim 10^{14}$ GeV , almost as big as the GUT scale?
- Hopefully $\Lambda_{\rm QFV}$ and $\Lambda_{\rm LFV}$ is not that high!

From Quark Flavour Physics:

- For Quarks there is no contribution to $\mathcal{L}_{\dim 5}$
- Look at $\Delta F = 2$ flavour transitions:

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

- With generic couplings $\mathcal{O}(1)$:
  - $\Lambda \sim 1000$ TeV from Kaon mixing ($C_i = 1$)
  - $\Lambda \sim 1000$ TeV from D mixing
  - $\Lambda \sim 400$ TeV from B_d mixing
  - $\Lambda \sim 70$ TeV from B_s mixing

How to get TeV Scale new physics?

Concept of "Minimal Flavour Violation" (MFV)

- In the SM:
  The only source of Flavour (and CP) violation is the non-alignement of the mass matrices.
- This generates the (hierarchical) CKM structure
- This also generates a supression of FCNC processes

MFV: Assume that this is true also for new physics models

(Ali, Buras)

- Implemented by a spurion analysis
  D'Ambrosio at al., Zupan et al., Feldmann et al.
- Generates a supression of the dim-6 couplings in $\mathcal{L}_{\rm eff}$.

MFV is NOT a Theory of Flavour

??? Many Open Questions ???

- Our Understanding of Flavour is unsatisfactory:
  - 22 (out of 27) free Parameters of the SM originate from the Yukawa Sector (including Lepton Mixing)
  - Why is the CKM Matrix hierarchical?
  - Why is CKM so different from the PMNS?
  - Why are the quark masses (except the top mass) so small compared with the electroweak VEV?
  - Why do we have three families?
- Underlying principle for the flavor structure?
  like the gauge principle for the fundamental forces?
  - ... a broken (how?) flavour symmetry
  - ... extra dimensions
  - ... new gauge interactions

The Current “Tensions”

The current tensions

For the time being,
let's get excited about the current “tensions”

- $b \to s\ell\ell$ Anomalies:
  - R_K: Lepton non-universality in $B \to K\ell\ell$
  - P_5': Angular distribution in $B \to K^*\ell\ell$
  - Rates for $B \to K\mu\mu$ and $B_s \to \phi\mu\mu$
- $R(D)$ and $R(D^*)$: Rates for $B \to D^{(*)}\ell\bar{\nu}$
- $V_{xb}^{\rm incl}$ vs. $V_{xb}^{\rm excl}$: $b \to q\ell\bar{\nu}$ transitions

Step 1: Scrutinize the Standard Model
Step 2: Invent a New Physics Model

The current tensions

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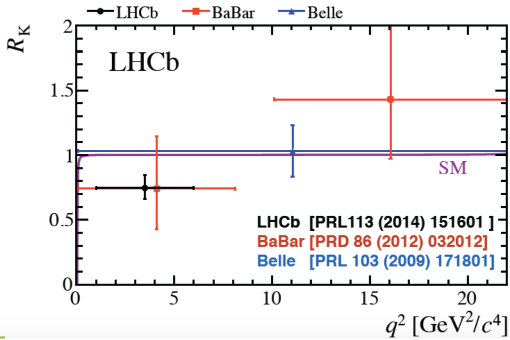
- V_{xb}^{incl} vs. V_{xb}^{excl}: $b \to q\ell\bar{\nu}$ transitions

Step 1: Scrutinize the Standard Model (work)
Step 2: Invent a New Physics Model (fun)

$b \to s\ell\ell$ anomalies: Lepton non-universality in $B \to K\ell\ell$

$$R_K = \frac{BR(B^+ \to K^+\mu^+\mu^-)}{BR(B^+ \to K^+e^+e^-)} = 0.745 \begin{array}{l} +0.090 \\ -0.074 \end{array} (stat) \pm 0.036(syst)$$

(SM: R_k=1.00, consistent at 2.6σ)



(taken from J. Albrecht, Moriond 2016)

However

- There is a violation of lepton universality through the masses of the leptons
- QED Effects come with

$$\frac{\alpha_{\rm em}}{\pi} \ln \left(\frac{m_\mu^2}{m_e^2} \right)$$

- These depend on the experimental set-up
- Major part is included by PHOTOS
- QED effect: $\Delta R_K = +3\%$ (Isidori, 2016)
- Check other, related channels: $B \to K^* \ell\ell$, $B_s \to \phi\ell\ell$

What could be explanations in terms of BSM Physics?

- Leptoquarks with family-specific couplings
- Gauge extensions with e.g. gauged $L_\mu - L_\tau$
- Extended Higgs Sectors

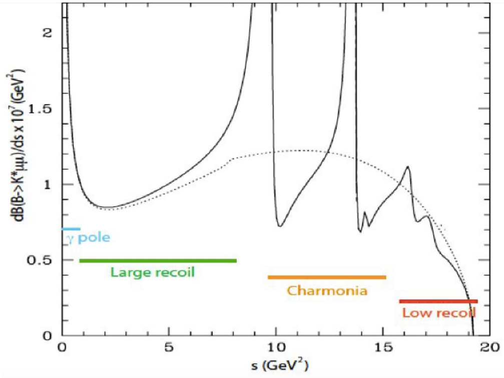
Attempts to explain all anomalies with a single model!

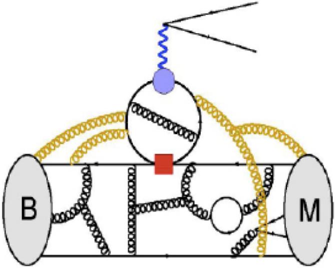
New Player: $B^+ \to K^+\tau\tau$

$$\mathrm{Br}(B^+ \to K^+\tau\tau) \leq 2.25 \times 10^{-3}$$

$b \to s\ell\ell$ anomalies: Angular distribution in $B \to K^*\ell\ell$

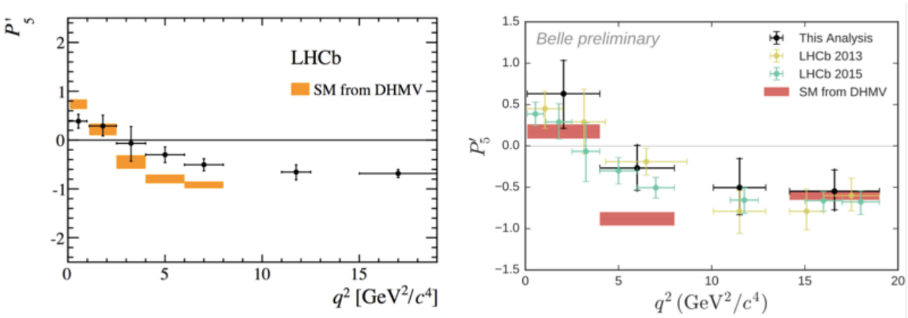
- $B \to K^*\ell\ell \to K\pi\ell\ell$ contains a lot of information
- Angular distributions in the final state
- Set up clever ratios to reduce form-factor uncertainties





- Photon pole: Dominance of O_7
- Large Recoil: $c\bar{c}$ loop contribution below threshold
- Charmonia: $B \to J/\Psi K^* \to (\ell\ell)K^*$
- Low Recoil: Duality fo the $c\bar{c}$ loop
- The $c\bar{c}$ loop brings a non-local / non-form-factor like contribution into the game!

Anomalies in the angular distributions:

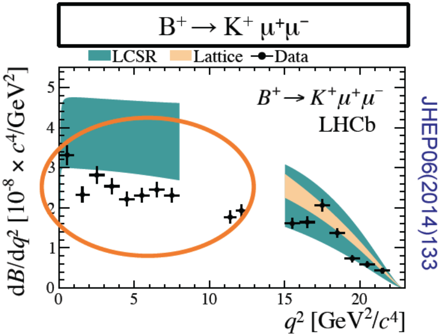


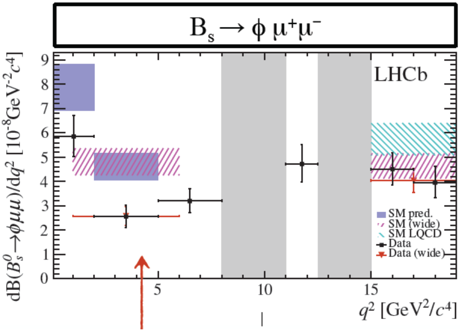
However, how well can we compute this?

- Form factor uncertainties (can be / is already fixed)
- Charm Loop contribution (????)

Needs additional scrutiny within the Standard Model!

$b \to s\ell\ell$ anomalies: Rates in $B \to K\mu\mu$ and $B_s \to \phi\mu\mu$





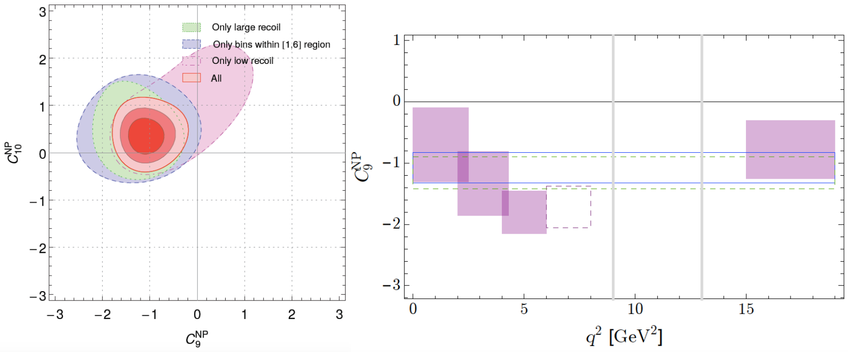
3.3σ from SM

Rates at low q^2 seem to be lower than the SM prediction!

Fit of the data to the Wilson coeff. of H_{eff}

(Descotes-Gennon et al., Altmannshofer, Straub)

$$H_{\text{eff}} = \cdots + C_9 (\bar{s}_L\gamma_\mu b_L)(\bar{\ell}\gamma^\mu \ell) + C_{10} (\bar{s}_L\gamma_\mu b_L)(\bar{\ell}\gamma^\mu\gamma_5 \ell)$$
$$+ C_9' (\bar{s}_R\gamma_\mu b_R)(\bar{\ell}\gamma^\mu \ell) + C_{10}' (\bar{s}_R\gamma_\mu b_R)(\bar{\ell}\gamma^\mu\gamma_5 \ell)$$



(from S. Descotes-Genon at FPCP2016)

		R_K	$\langle P_5' \rangle_{[4,6],[6,8]}$	$BR(B_s \to \phi\mu\mu)$	low recoil BR	Best fit now
$\mathcal{C}_9^{\text{NP}}$	$+$					
	$-$	✓	✓	✓	✓	X
$\mathcal{C}_{10}^{\text{NP}}$	$+$	✓		✓	✓	X
	$-$		✓			
$\mathcal{C}_{9'}^{\text{NP}}$	$+$			✓	✓	X
	$-$	✓	✓			
$\mathcal{C}_{10'}^{\text{NP}}$	$+$	✓	✓			
	$-$			✓	✓	X

- $\mathcal{C}_9^{\text{NP}} < 0$ consistent with all anomalies

Also consistent with different treatments of the charm loop

Note: $\mathcal{C}_9^{\text{NP}} \sim \mathcal{O}\left(\frac{v^2}{\Lambda^2}\right)$: Hints at a low NP scale

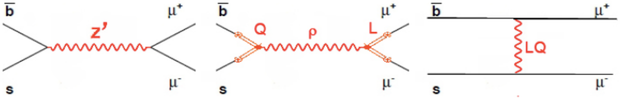
NP interpretations

SM explanations seem contrived

- hadronic effects (for $B \to K^*\mu\mu$, $B_s \to \phi\mu\mu$)
- statistical fluctuation (for R_K)
- bad luck ($\mathcal{C}_9$ can accomodate all discrepancies by chance)

NP models quite successful with new scale around TeV

- Z' boson (larger gauge group, e..g, $SU_C(3) \otimes SU_L(3) \otimes U_Y(1)$)
- Partial compositeness (mixing between known and extra fermions transforming under $SU_C(3) \otimes SU_L(2) \otimes SU_R(2) \otimes U_Y(1)$)
- Leptoquarks (coupling to a quark and a lepton, like $(3, 2, 1/6)$)
- MSSM susy definitely not favoured ...



[Buras, De Fazio, Girrbach, Blanke, Altmannshofer, Straub, Crivellin, D'Ambrosio, Becirevic, Sumensari...

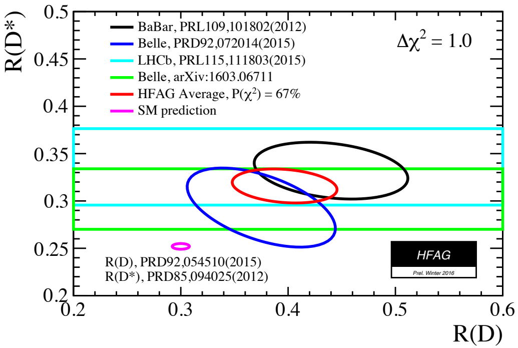
...Neubert, Bauer, Mahmoudi, Boucenna, Celis, Fuentes-Martin, Vicente, Virto...]

(from S. Descotes-Genon @ FPCP2016)

$B \to D^{(*)}\tau\bar{\nu}$

Tension in the exclusive semileptonic $B \to D^{(*)}\tau\bar{\nu}$ decays

$$R(D) = \frac{\Gamma(B \to D\tau\bar{\nu})}{\Gamma(B \to D\ell\bar{\nu})} \qquad R(D^*) = \frac{\Gamma(B \to D^*\tau\bar{\nu})}{\Gamma(B \to D^*\ell\bar{\nu})}$$



- Theory predictions are quite precise:
- Heavy Quark Symmetry fixes the longitudinal form factor f_0
- in Addition, its contribution is supressed by m_τ^2/m_b^2

However:

- Inclusive rate $B \to X_c\tau\bar{\nu}$ can be calculated within OPE (Ligeti, Tackmann)

$$\mathrm{Br}(B \to X_c\tau\bar{\nu}) = (2.42 \pm 0.06)\%$$

- There is a measurement of the inclusive rate by LEP (B hadron admixture)

$$\mathrm{Br}(B \to X_c\tau\bar{\nu}) = (2.41 \pm 0.23)\%$$

- Theoretical predictions for the exclusive channels (Kamenik, Fajfer)

$$\mathrm{Br}_{\mathrm{th.}}(B \to D\tau\bar{\nu}) + \mathrm{Br}_{\mathrm{th.}}(B \to D^*\tau\bar{\nu}) = (2.01 \pm 0.07)\%$$

- On the other hand: (BaBar 2012, Compatible with LHCb 2015)

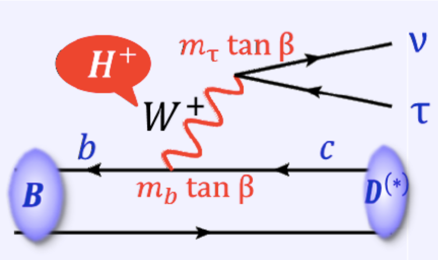
$$\mathrm{Br}_{\mathrm{expt.}}(B \to D\tau\bar{\nu}) + \mathrm{Br}_{\mathrm{expt.}}(B \to D^*\tau\bar{\nu}) = (2.78 \pm 0.25)\%$$

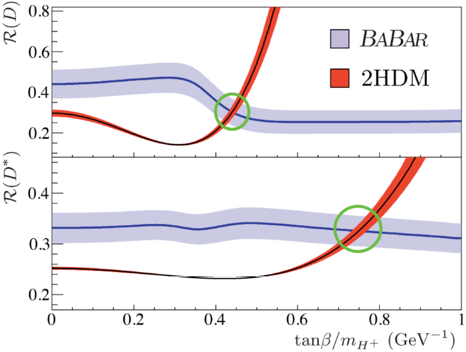
- ... and more recently: (Belle 2015)

$$\mathrm{Br}_{\mathrm{expt.}}(B \to D\tau\bar{\nu}) + \mathrm{Br}_{\mathrm{expt.}}(B \to D^*\tau\bar{\nu}) = (2.39 \pm 0.32)\%$$

Nevertheless, let's look into the fun part:
Possible interpretations in terms of new physics

- Two Higgs Doublet model (SUSY Type) excluded:





- Leptoquark Interpretations: (Tanaka, Watanabe, Sakaki)

  Operator Basis:

$$\mathcal{O}^l_{V_1} = (\bar{c}_L \gamma^\mu b_L)(\bar{\tau}_L \gamma_\mu \nu_{lL}), \quad \mathcal{O}^l_{V_2} = (\bar{c}_R \gamma^\mu b_R)(\bar{\tau}_L \gamma_\mu \nu_{lL}),$$

$$\mathcal{O}^l_{S_1} = (\bar{c}_L b_R)(\bar{\tau}_R \nu_{lL}), \quad \mathcal{O}^l_{S_2} = (\bar{c}_R b_L)(\bar{\tau}_R \nu_{lL}),$$

$$\mathcal{O}^l_T = (\bar{c}_R \sigma^{\mu\nu} b_L)(\bar{\tau}_R \sigma_{\mu\nu} \nu_{lL}). \qquad (7)$$

	S_1	S_3	V_2	R_2	U_1	U_3
spin	0	0	1	0	1	1
$F = 3B + L$	-2	-2	-2	0	0	0
$SU(3)_c$	3^*	3^*	3^*	3	3	3
$SU(2)_L$	1	3	2	2	1	3
$U(1)_{Y=Q-T_3}$	$1/3$	$1/3$	$5/6$	$7/6$	$2/3$	$2/3$

Six LQ Models

		$O^l_{V_1}$	$O^l_{V_2}$	$O^l_{S_1}$	$O^l_{S_2}$	O^l_T
Scalar	S_1	● (red)			● (blue)	$-$● (blue)$/4$
Scalar	S_3	● (red)				
Scalar	R_2				● (red)	● (red)$/4$
Vector	V_2^μ			● (red)		
Vector	U_1^μ	● (red)		● (blue)		
Vector	U_3^μ	● (red)				

- Single scalar Leptoquark explains R_K and $R(D^{(*)})$
- LUV proportional to the lepton masses?

$V_{cb}^{\rm incl}$ versus $V_{cb}^{\rm excl}$

- Inclusive V_{cb} from the Heavy Quark Expansion:
  Precision at the level of 1.5% theoretical uncertainty

$$|V_{cb}| = (42.09 \pm 0.79) \times 10^{-3}$$ (Gambino, Healy, Turczyk)

- Exclusive V_{cb} from $B \to D^*\ell\bar{\nu}$ endpoint:

$$|V_{cb}| = (39.04 \pm 0.75) \times 10^{-3}$$ (FNAL/MILC)

- Exclusive V_{cb} from $B \to D\ell\bar{\nu}$ rate

$$|V_{cb}| = (40.49 \pm 0.99) \times 10^{-3}$$ (Gambino)

- Tension with exclusive V_{cb} from $B \to D^*\ell\bar{\nu}$ endpoint

$V_{ub}^{\rm incl}$ versus $V_{ub}^{\rm excl}$

- Inclusive V_{ub} depends on non-perturbative functions:
  $\to$ Precision is less than in $b \to c$

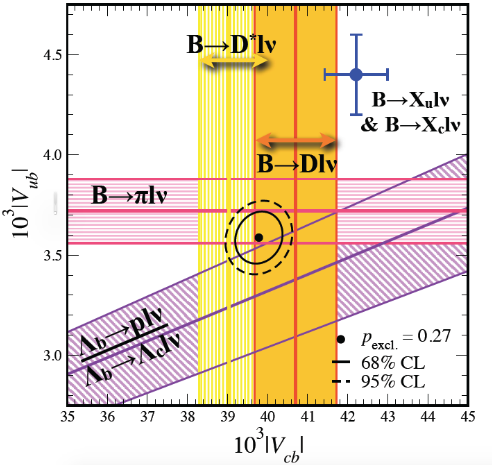
$$|V_{ub}| = (4.49 \pm 0.16^{+0.16}_{-0.18}) \times 10^{-3} \quad \text{(PDG)}$$
$$|V_{ub}| = (4.03^{+0.20}_{-0.22}) \times 10^{-3} \quad \text{(new BaBar result)}$$

- Exclusive V_{ub} from $B \to \pi\ell\bar{\nu}$

$$|V_{ub}| = (3.72 \pm 0.19) \times 10^{-3} \quad \text{(PDG)}$$

- Persistent tension in V_{ub},
  however, slightly receeding due to new data
- New Input from $\Lambda_b \to p\ell\bar{\nu}$ (LHCb)

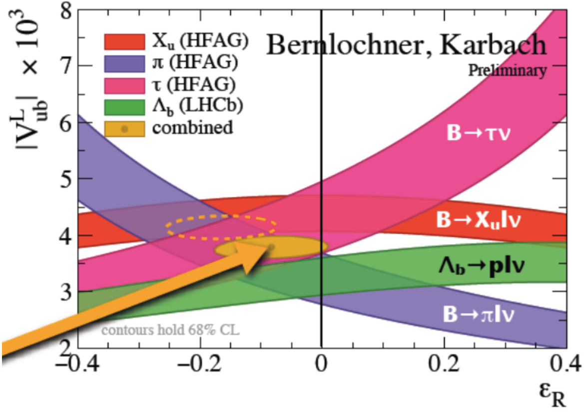
Summary of the current situation (Ruth van der Water @ FPCP2016)



(Fit by Andreas Kronfeld)

Interpretation in terms of new physics

Right-Handed Admixture



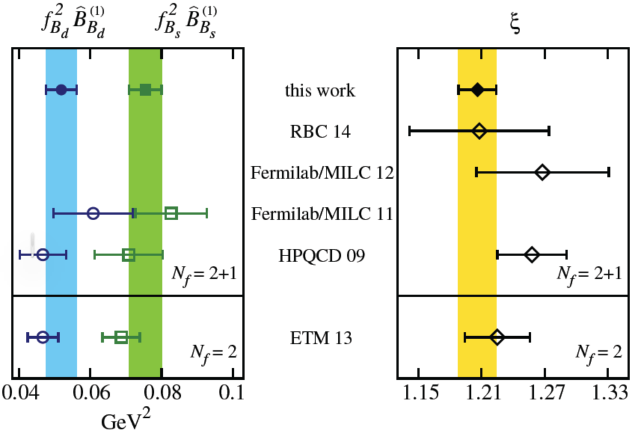
(From Paolo Gambino's talk at BEAUTY 2016)

More Stuff

Mixing, Top, Neutrinos, Charged Leptons

B-$\overline{B}$ Mixing

New lattice results for B-$\overline{B}$ Mixing (R. van der Water @ FPCP2016)



[Fermilab/MILC, 1602.03560]

New sum rule calculation for B-$\overline{B}$ Mixing

(Grozin, Klein, ThM, Pivovarov 2016)

- HQET Sum Rule for $\Delta B = B - 1$ (three loops)
  RG Invariant Bag factor $\hat{B}$:

$$\hat{B} = 1.34 \pm 0.06$$

- Latest Lattice calculation: (FERMILAB / MILC)

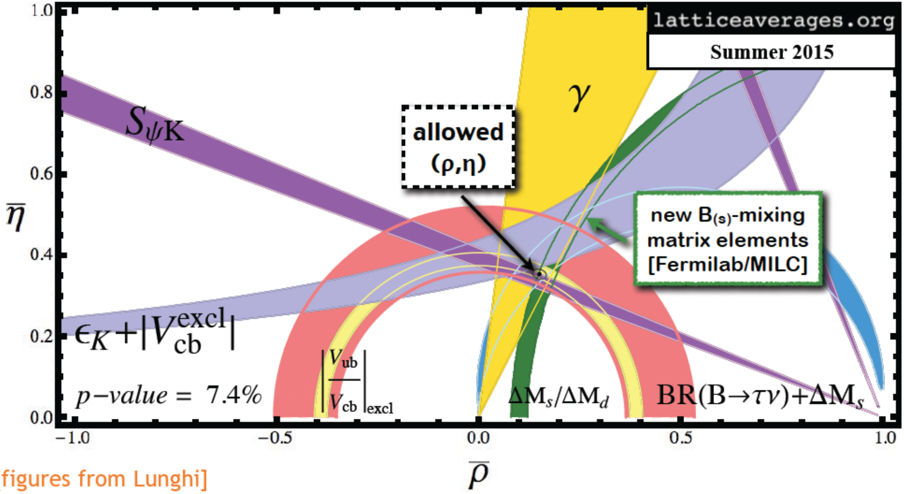
$$\hat{B} = 1.38 \pm 0.13$$

- FLAG Result

$$\hat{B} = 1.27 \pm 0.10$$

- QCD SR uncertainty is small,
  since the uncertainty is in $B(m_b) - 1$

February 2016



[figures from Lunghi]

(R. van der Water @ FPCP2016)

Top and Flavor

Flavour Topic: Top FCNC's
Small in the SM, but enhanced in many NP models

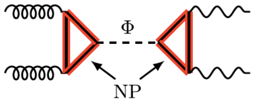
	SM	QS	2HDM	FC 2HDM	MSSM	$\not{R}$ SUSY
$t \to uZ$	8×10^{-17}	1.1×10^{-4}	$-$	$-$	2×10^{-6}	3×10^{-5}
$t \to u\gamma$	3.7×10^{-16}	7.5×10^{-9}	$-$	$-$	2×10^{-6}	1×10^{-6}
$t \to ug$	3.7×10^{-14}	1.5×10^{-7}	$-$	$-$	8×10^{-5}	2×10^{-4}
$t \to uH$	2×10^{-17}	4.1×10^{-5}	5.5×10^{-6}	$-$	10^{-5}	$\sim 10^{-6}$
$t \to cZ$	1×10^{-14}	1.1×10^{-4}	$\sim 10^{-7}$	$\sim 10^{-10}$	2×10^{-6}	3×10^{-5}
$t \to c\gamma$	4.6×10^{-14}	7.5×10^{-9}	$\sim 10^{-6}$	$\sim 10^{-9}$	2×10^{-6}	1×10^{-6}
$t \to cg$	4.6×10^{-12}	1.5×10^{-7}	$\sim 10^{-4}$	$\sim 10^{-8}$	8×10^{-5}	2×10^{-4}
$t \to cH$	3×10^{-15}	4.1×10^{-5}	1.5×10^{-3}	$\sim 10^{-5}$	10^{-5}	$\sim 10^{-6}$

750 GeV Bump

Summary of the various theory activities: (K. Zurek @ FPCP2016)

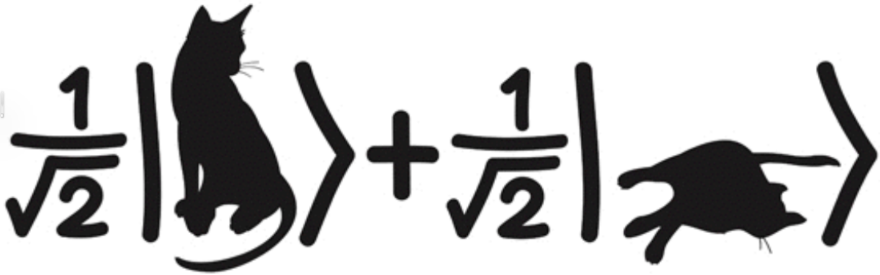
WHAT DO WE LEARN?

- Composite (pion) of new confining gauge group
- Or weakly coupled resonance + vector-like quarks



  - Both Work Well
  - Both predict extraordinary levels of activity in LHC Run II

Collapse of the wave function expected later this year:



Neutrinos

There is plenty of room form surprises: (A. de Gouvea @ FPCP2016)

In Conclusion

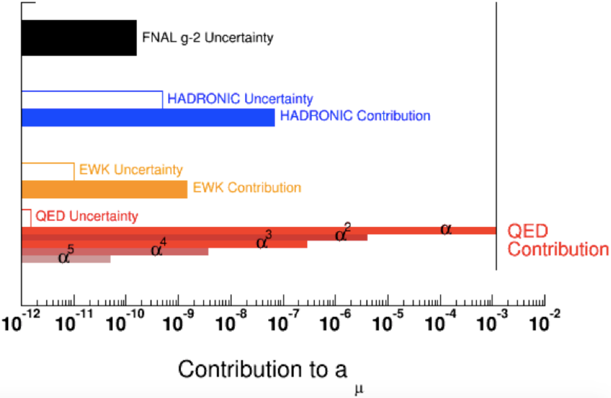
The venerable Standard Model sprung a leak in the end of the last century: neutrinos are not massless! (and we are still trying to patch it)

1. We still **know very little** about the new physics uncovered by neutrino oscillations.
2. **neutrino masses are very small** – we don't know why, but we think it means something important.
3. **neutrino mixing is "weird"** – we don't know why, but we think it means something important.
4. we need a minimal νSM Lagrangian. In order to decide which one is "correct" we **need to uncover the faith of baryon number minus lepton number** ($0\nu\beta\beta$ is the best [only?] bet).

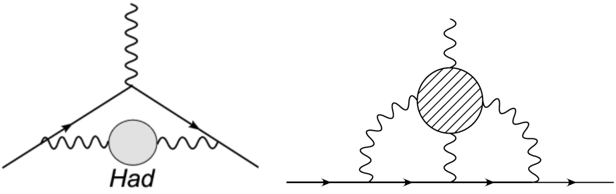
Charged Leptons I: $(g-2)_\mu$

Current status: (T. Bowcock, T. Izubuchi @ FPCP2016)

$$a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = 28.8(6.3)_{\text{exp}}(4.9)_{\text{SM}} \times 10^{-10} \qquad [3.6\sigma]$$



- hadronic vacuum polarization:
  - Extraction form experiment
  - New lattice calculations
- New lattice calculations of light-by-light scattering



- Further reduction of the uncertainties foreseen!

There is still a tension in $(g-2)_\mu$.

Charged Leptons II: Rare Processes

Good News:

- The presence of neutrino masses induces non-trivial charged lepton flavour physics
- The PMNS Matrix is not hierarchical
- LFV muon decays: $\mu \to e\gamma$, $\mu \to 3e$
- LFV τ decays: $\tau \to e/\mu\gamma$, $\tau \to 3\mu$, $\tau \to e2\mu$ ...

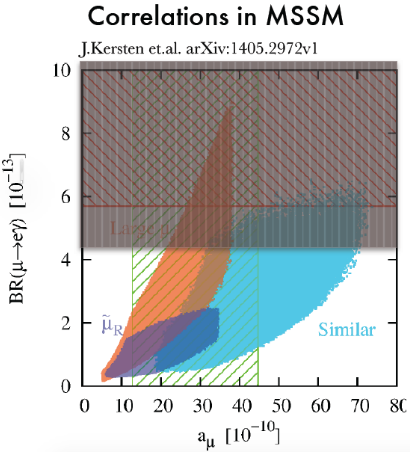
Bad News:

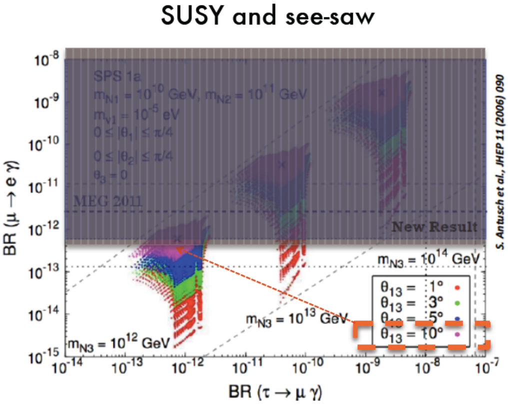
- If the dim-5 Operator is the only source of LFV (and LNV) these effects are super-small
- Naive counting

$$\mathcal{A}(\ell \to \ell'\gamma) \propto \frac{G_F}{16\pi^2} |V_{\rm PMNS}|^2 \frac{\Delta m_\nu^2}{M_W^2}$$

So we need new physics:

- This links to R_K and $R(D^{(*)})$
- Many models are thinkable,
  but need to enhance the amplitude tremendously!
- Such models exist:
  - Supersymmtry
  - Little Higgs
  - ...





(e.g. G. Cavoto @ FPCP2016)

News on CP Violation

Sources of CP violation in the SM:

- Strong CP violation:
  The QCD Vacuum generates the "θ term":

$$\mathcal{L}_{\text{strong CP}} = \theta \frac{\alpha_s}{8\pi} G^{\mu\nu,a} \tilde{G}^a_{\mu\nu}$$

  Natural size would be $\theta \sim 1$, Limit from Neutron EDM:

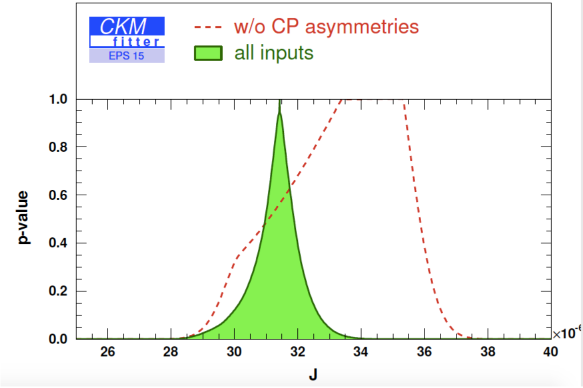
$$d_N \sim \theta \times 10^{-15} \text{e cm} \quad \text{thus} \quad \theta \leq 10^{-10}$$

- CKM CP Violation from the phase of the CKM matrix:

$$J = \text{Im}\, V^*_{cs} V_{us} V_{cd} V^*_{ud}$$

  There is only a single 4^{th} order rephasing invariant
- Leptons: PMNS Phases

- Strong CP remains a mystery, can be removed by an additional symmetry (Peccei Quinn Symmetry)
- CP Phases in the leptonic sector are still unexplored



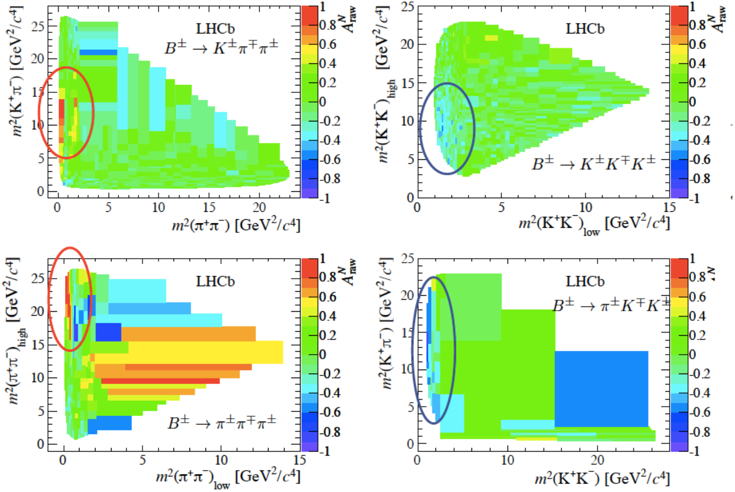
(Units are 10^{-6})

CPV in B Physics

Measurements get very precise!

Theory has (and will contiune to have) a hard time to keep up!

- Nonleptonic decays from QCD
  - Tackle the power corrections, but how?
  - Extension to three body decays
    Opens new roads to CPV studies



(R. Silva Coutihno @ FPCP2016)

CPV in Kaons

New Lattice calculations of Kaon CPV (C. Kelly @ FPCP2016)

- Method to treat moving pions (Lellouch. Lüscher)
- Towards a quantitative understanding of $\Delta I = 1/2$

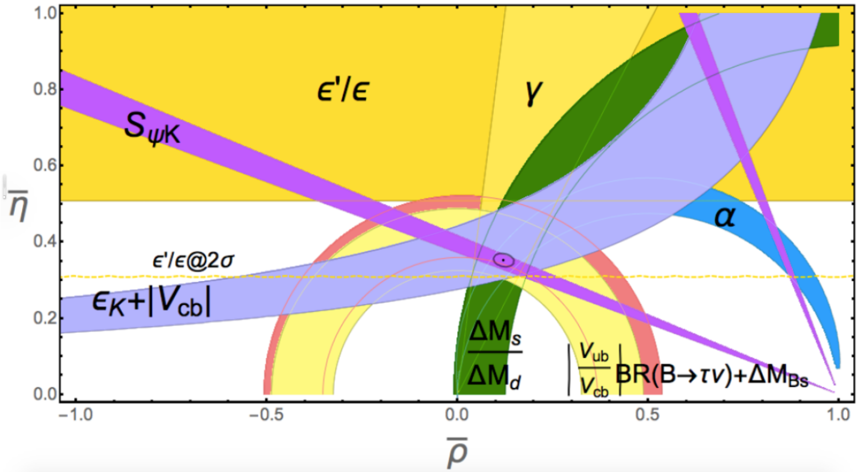
- $\mathrm{Re}(A_0)$ and $\mathrm{Re}(A_2)$ from expt.
- Lattice values for $\mathrm{Im}(A_0)$, $\mathrm{Im}(A_2)$ and the phase shifts,

$$\mathrm{Re}\left(\frac{\varepsilon'}{\varepsilon}\right) = \mathrm{Re}\left\{\frac{i\omega e^{i(\delta_2-\delta_0)}}{\sqrt{2}\varepsilon}\left[\frac{\mathrm{Im}A_2}{\mathrm{Re}A_2} - \frac{\mathrm{Im}A_0}{\mathrm{Re}A_0}\right]\right\}$$

$$= \quad 1.38(5.15)(4.43) \times 10^{-4}, \quad \text{(this work)}$$

$$16.6(2.3) \times 10^{-4} \quad \text{(experiment)}$$

[Lehner et al
arXiv:1508.01801



Instead of a Summary

Questions ot be discussed: See also the List sent by Alex

- What (if true) is the explanation of the 750 Gev bump?
- Can we gain control over non-leptonic (two and more body) decays?
  - QCD factorization: Power Corrections
  - Flavour Symmetries
- Is there a coherent NP model explaining all anomalies?
- Are there correlations between different flavor observables?
- How far can the non-perturbative methods be improved?
  - QCD Sum rules
  - Lattice QCD
- What can be learned from LFV and LNV in B decays?

Or, some more global questions:

- What can we do with 70 ab^{-1} of B factory data?
  There must be a B2TIP-reloaded at some point!
  addressing questions such as:
  - Very rare processes (e.g. LFV and LNV B decays)
  - Large data samples of "known" decays
  - How to improve theory?
- How do we exploit the full spectrum of ground state b hadrons produced at LHCb?

Are we getting towards a theory of flavour?


The Single Malt Whisky Flavour Map
Medicinal, dry smoke pepperyness
SMOKY
Pungent smoky, peaty richness
Leafy, stewed fruit ripeness
LIGHT
Fresh fruit, citrus crispness
Dried fruit, sherry richness
RICH
Spiced, woody complexity
Floral, herbal, grassy freshness
DELICATE
Nutty, barley, biscuity subtleness
Ardbeg 10
Laphroaig 10
Caol Ila 12
Talisker 10
Lagavulin 16
Lagavulin Distillers Edition
Bowmore 12
Talisker 18
Highland Park 12
Oban 14
Cragganmore 12
Cragganmore Distillers Edition
Bruichladdich 15
Dalwhinnie 15
Clynelish 14
Singleton of Dufftown 12
Cardhu 12
Glen Elgin 12
Macallan 10
Royal Lochnagar 12
Glenkinchie 12
Glenkinchie Distillers Edition
Glenmorangie 10
Glenlivet 12
Jura 10
Aberlour 10
Glenfiddich 12
Bunnahabhain 12
Knockando 12
Scapa 14
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