Flavor Physics and CP Violation

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(slides from CKM2016)

- Introduction
- Topics from CKM 2016
- Outlook

Topics to be looked at (coming years):

- SM looks to be complete
- KM mechanism established but NP???
- Hierarchy problem
- Neutrino mass/ parameters
- Dark Matter
- Baryon Asymmetry of the Universe (BAU)
- New Expt. Improve precision/sensitivity
- NP-sensitive/ Mod. independent observables

Flavor Factory/ LHCb/ Belle II

- Precision CKM (electron-positron collider)
- New Sources of CPV, huge data set
- Lepton Flavor Violation/ Lepton Universality
- Exotics/ Spectroscopy
- Better Tagging (better efficiency than LHCb)
- Clean environment to decipher NP
- Improve precision/sensitivity of Super-FF : 3-10
- Test CKM paradigm and determine V_{CKM}@ 1%

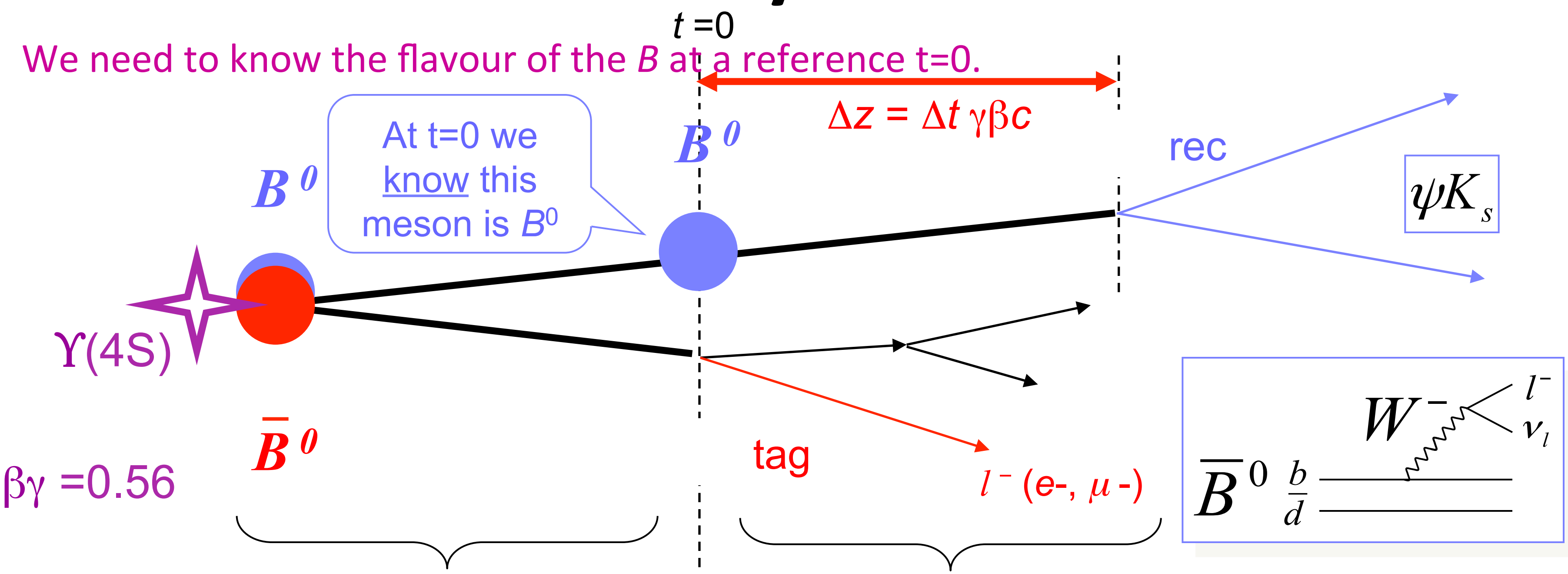
Belle II complimentary to LHCb

Flavor Physics & CP Violation

- Huge data with e^+ - e^- colliders + LHCb + Belle II
- Discrepancies/ puzzles
- $B \rightarrow K\pi$ (ΔA_{CP}) (hadronic modes)
- $B \rightarrow K^{(*)}ll$, $b \rightarrow sll$, R_K, P_5'
- **$B \rightarrow D^{(*)}\tau\nu$, $B \rightarrow \tau\nu$ and τ decays**
- $B \rightarrow \phi K_s$, $B \rightarrow \eta' K_0$, $B \rightarrow J/\psi K_s$
- **B_s** $\rightarrow \mu\mu$, $\phi\phi$, $J/\psi\phi$, $\phi\gamma$, $\gamma\gamma$
- Kaon, Charm, Tau and LFV decays
- Neutrino Physics
- Precision CKM $\rightarrow\rightarrow$ NP (?????)

How to Measure Time Dependent Decay Rates

We need to know the flavour of the *B* at a reference t=0.



The two mesons oscillate coherently : at any given time, if one is a B^0 the other is <u>necessarily</u> a $\bar{B}^0$

In this example, the tag-side meson decays first. It decays semi-leptonically and the charge of the lepton gives the flavour of the tag-side meson :
$l^- = \bar{B}^0 \qquad l^+ = B^0$.
Kaon tags also used.

Δt picoseconds later, the B^0 (or perhaps it is now a $\bar{B}^0$) decays.

- *CP* violation in decay: **direct**
  - can take place both for neutral and charged B's
  - can have time-dependent and -independent manifestations
  - Need two competing diagrams of different CP-violating and –conserving phases

$$\left|\frac{\bar{A}_{\bar{f}}}{A_f}\right| \neq 1$$

$$A_f = A(B \to f)$$
$$\bar{A}_{\bar{f}} = A(\bar{B} \to \bar{f})$$

$\rightarrow$ $|\lambda| \neq 1$, where $\lambda = \left(\frac{q}{p}\right)\left(\frac{\bar{A}_{\bar{f}}}{A_f}\right)$

- *CP* violation in mixing: **indirect**
  - only neutral B's are possibly affected
  - SM predicts very small effects

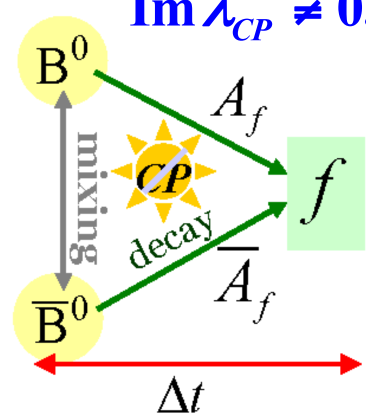
$$\left|\frac{q}{p}\right| \neq 1$$

$$\left|B_{H,L}\right\rangle = p\left|B^0\right\rangle \pm q\left|\bar{B}^0\right\rangle$$

$\rightarrow$ $\left|\frac{q}{p}\right|_{SM} - 1 \simeq 4\pi \frac{m_b^2}{m_t^2} \sin\beta \simeq 5 \times 10^{-4}$

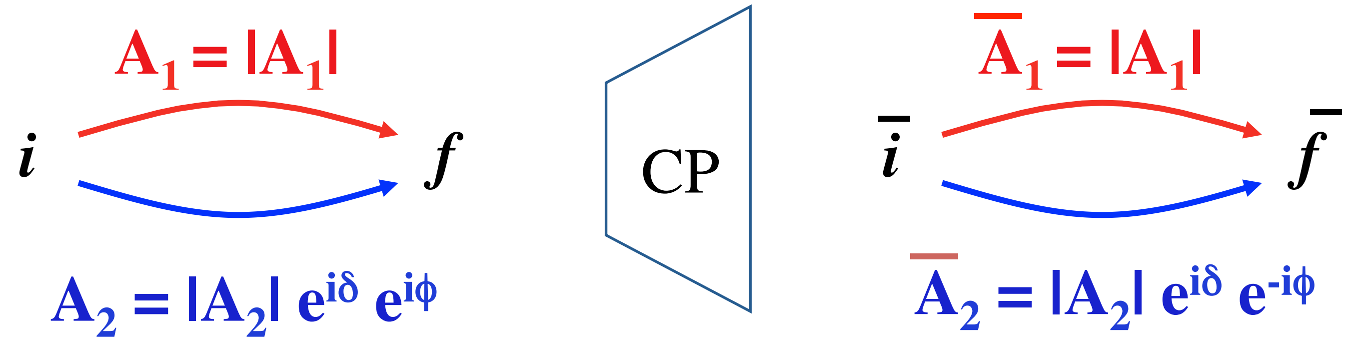
- violation from **mixing/decay interference**:
  - only neutral B's possibly affected
  - purely time-dependent effect
  - arises due to interference between decay with and without mixing

$$\mathrm{Im}\,\lambda_{CP} \neq 0, \quad |\lambda_{CP}| = 1$$



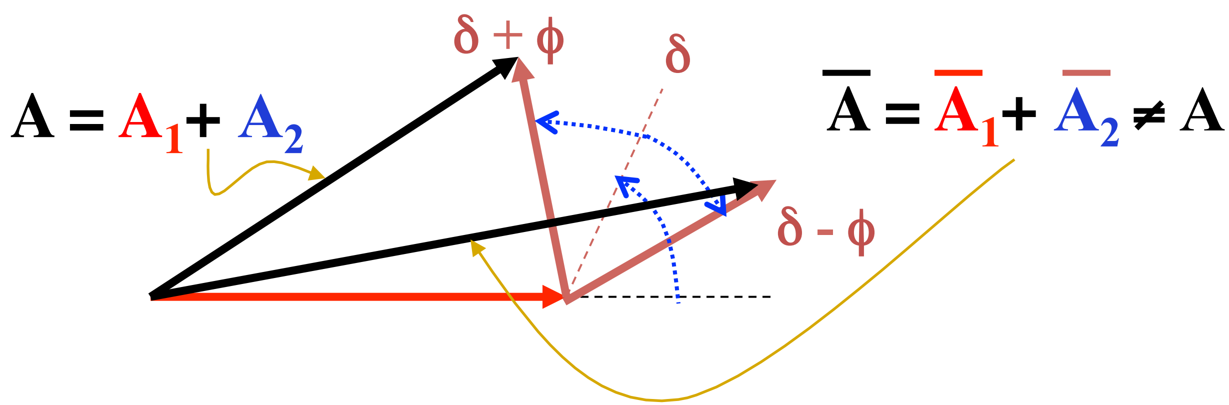
$$\lambda_{CP} = \eta_{CP}\frac{q}{p}\frac{\bar{A}_{\bar{f}}}{A_f}$$

$f \equiv$ CP eigen-state



$\delta \rightarrow \delta$ (*CP*-conserving)

$\phi \rightarrow -\phi$ (*CP*-violating)



The CKM model:

The 3 family scenario:

$$\begin{pmatrix} u \\ d \end{pmatrix} \quad \begin{pmatrix} c \\ s \end{pmatrix} \quad \begin{pmatrix} t \\ b \end{pmatrix} \qquad \begin{matrix} Q = 2/3|e| \\ Q = -1/3|e| \end{matrix}$$

The weak states d', s' and b' are related to flavor states d, s, b

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix} \equiv \hat{V}_{\rm CKM} \begin{pmatrix} d \\ s \\ b \end{pmatrix} .$$

where

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

- The mixing matrix V called the CKM (Cabibbo, Kobayashi and Maskawa) matrix contains three real parameters (Cabibbo-like mixing angles) and a phase factor δ . Due to the phase δ, the matrix is complex and this introduces the important possibility of CP violating amplitudes in the SM.

V is UNITARY

UNITARITY TRIANGLE :

The unitarity of CKM matrix implies various relations between its elements.

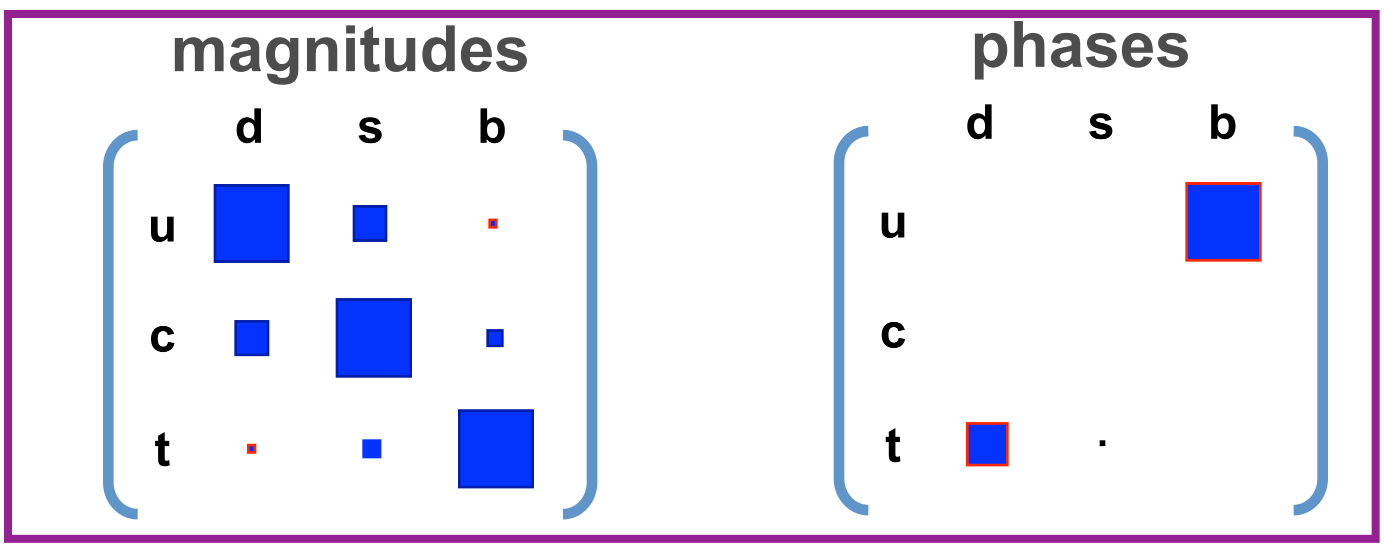
- Unitarity of CKM matrix: $V^{\dagger}V = V V^{\dagger} = 1$
- It gives 12 eqns (6 normalization and 6 orthogonal)
- Orthogonality cond^{n}s. can be represented by 6 triangles in the complex plane.
- The triangle which can be explored by B decays is

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

Wolfenstein parameterization of the CKM matrix V:

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

$$\lambda \quad \simeq \quad \sin\theta_c \simeq 0.22$$



The CKM matrix and the Unitarity Triangle

- **In SM, Mass states ≠ Weak states**
- **Flavour dynamics:** weak transitions which mix quarks of different generations

  ⇒ Encoded in unitary CKM matrix (V_{CKM})

Weak states — CKM matrix — Mass states

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

- **3 generations ⇒ 4 parameters describing V_{CKM}**
  - 3 real and 1 phase ⇒ only source of CPV in SM
  - Wolfenstein parametrisation, defined to hold in all orders in λ and rephasing invariant

    ⇒ Explicitly shows V_{CKM} generation hierarchy

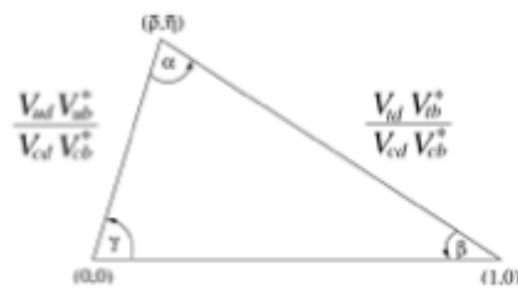
Wolfenstein parameterization:

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

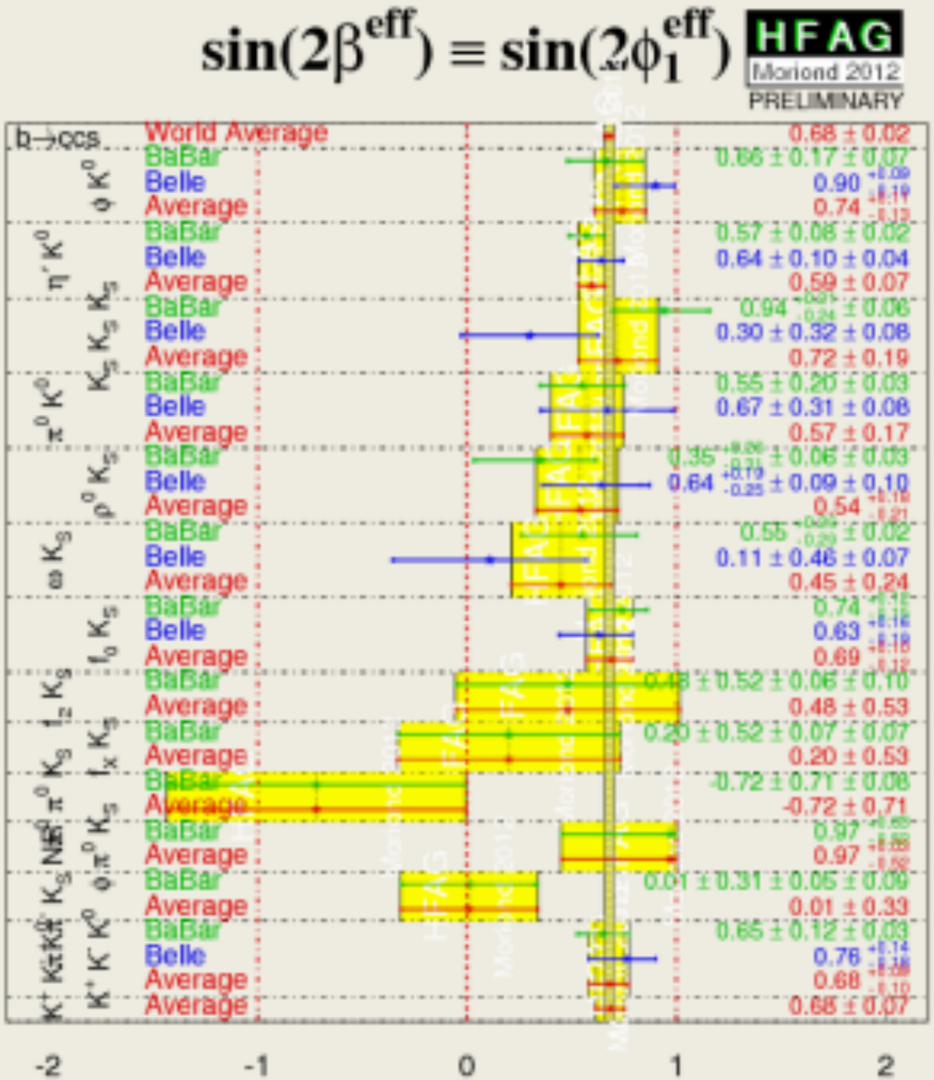
$O(\lambda^4)$, $\lambda = \sin(\theta_c) \approx 0.22$

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

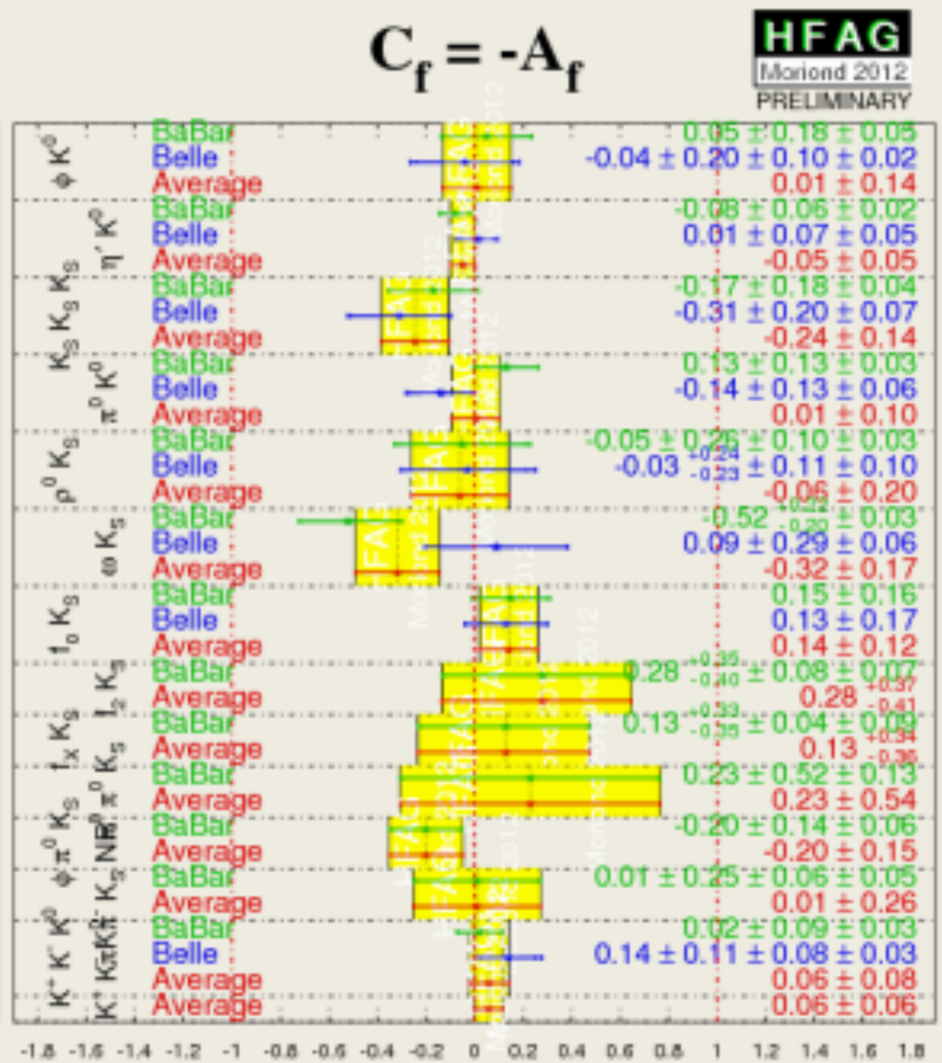
- **Unitarity triangles**
  - Graphical representation of V_{CKM} unitarity
  - B_d triangle: $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$



New Physics in Penguin Now



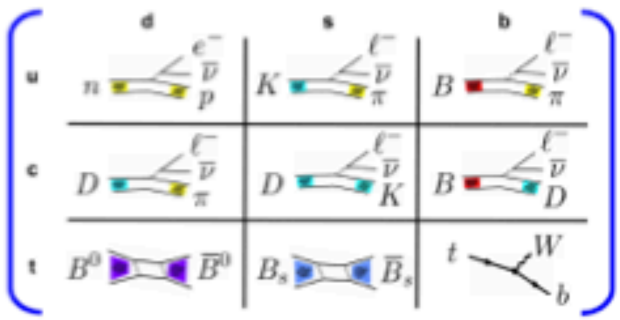
ΔS is consistent with 0.

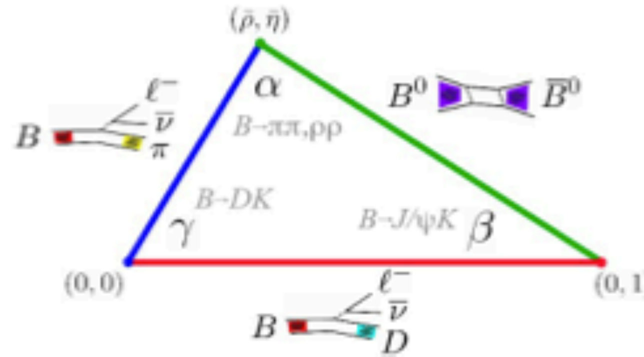


No evidence of direct CPV.

Extracting CKM parameters

V =





- **Observables**
  - Use QCD CP invariance to build hadronic independent CPV asymmetries
  - Or determine hadronic inputs from data
  - Observables double requirement
    - Good experimental accuracy
    - Satisfying control of attached theoretical uncertainty

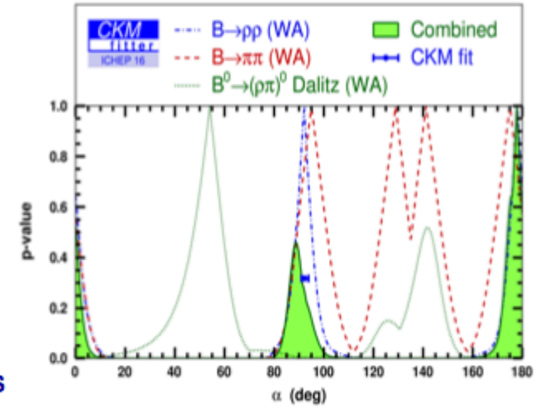
- **Statistical framework to combine data and assess theoretical uncertainties**

CKM fitter

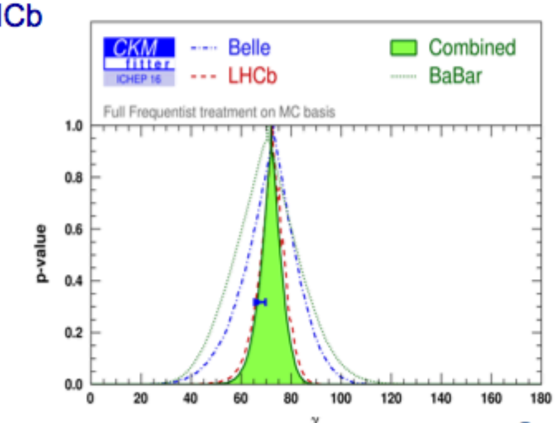
The global CKM fit inputs: Unitarity angles

CKM fitter ICHEP 16

- **α and the legacy of B-factories**
  - Combined analysis $B \to \pi\pi, \rho\pi, \rho\rho$
  - Using isospin to separate penguin and tree
  - $\alpha_{WA} = (88.9^{+2.3}_{-2.4})^{o} \cup (177.6^{+2.9}_{-4.8})^{o}$

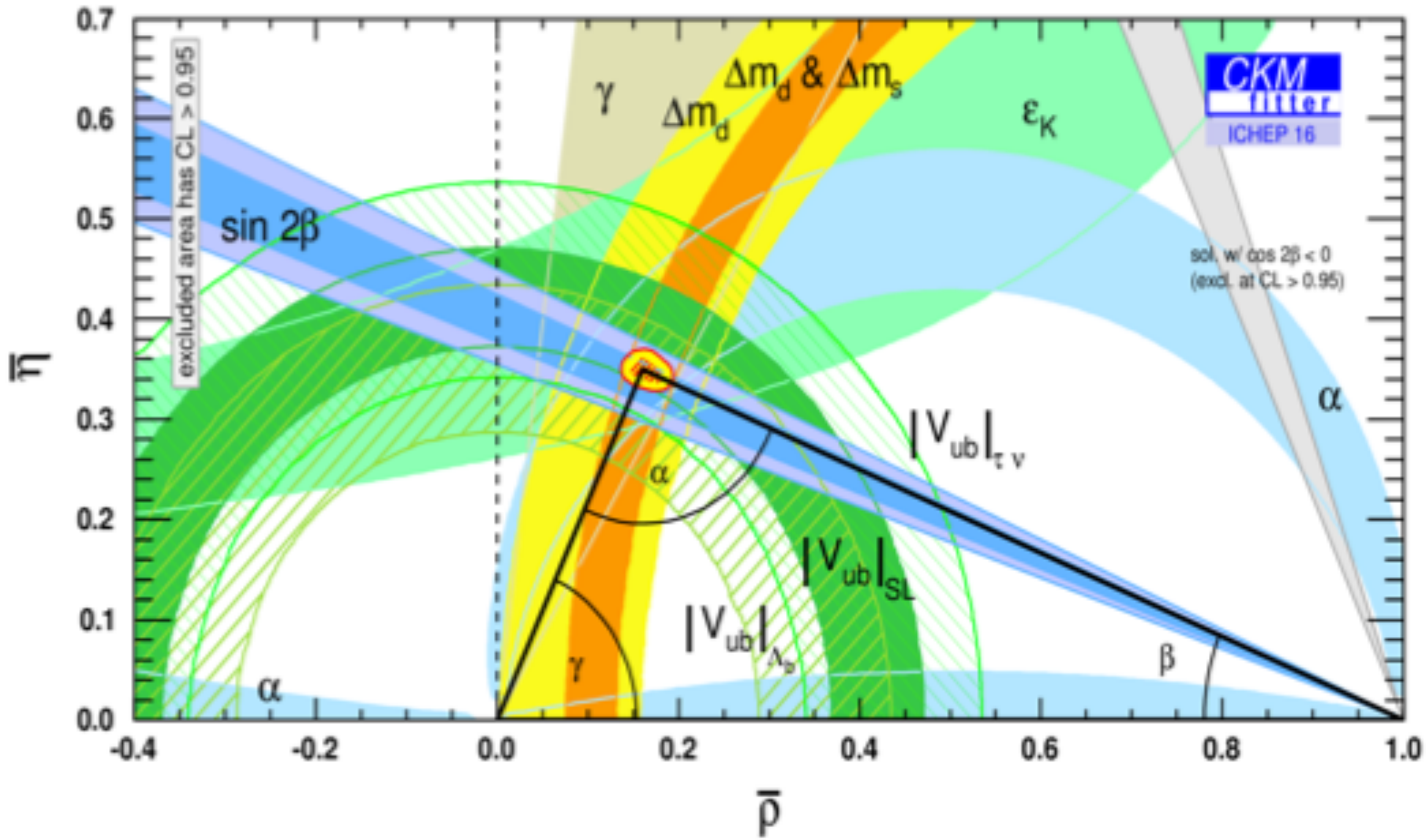


- **γ and a some help from LHCb**
  - $B^{-} \to D^{(*)0}K^{(*)-}$ vs $\overline{D}^{(*)0}K^{(*)-}$ with 3 diff. D^0 decay modes
  - Charm inputs: CLEO, BES *BABAR*, Belle, CDF, LHCb
  - $\gamma_{WA} = (72.2^{+5.3}_{-5.8})^{o}$



- **β in $B \to (c\bar{c})K$**
  - Interference between mixing and decay
  - $A_{CP}(t) = S \sin(\Delta m\, t) - C \cos(\Delta m\, t)$
  - $S = \eta_{CP} \sin(2\beta) = 0.691 \pm 0.017$ [HFAG]

The Unitarity Triangle: all constraints

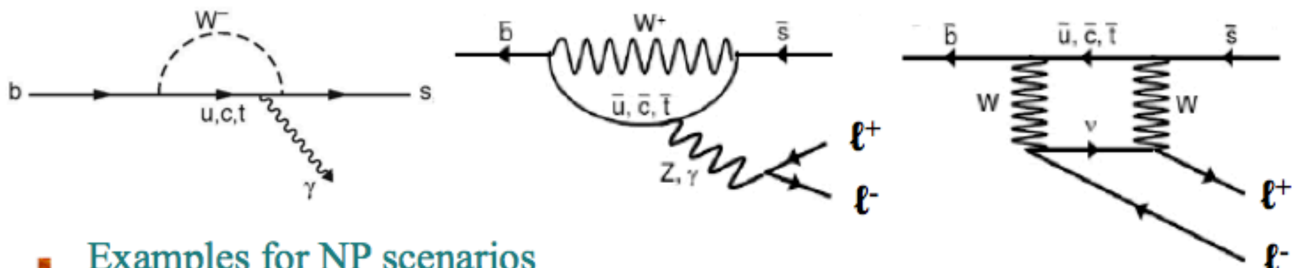


A consistent picture across a huge array of measurements

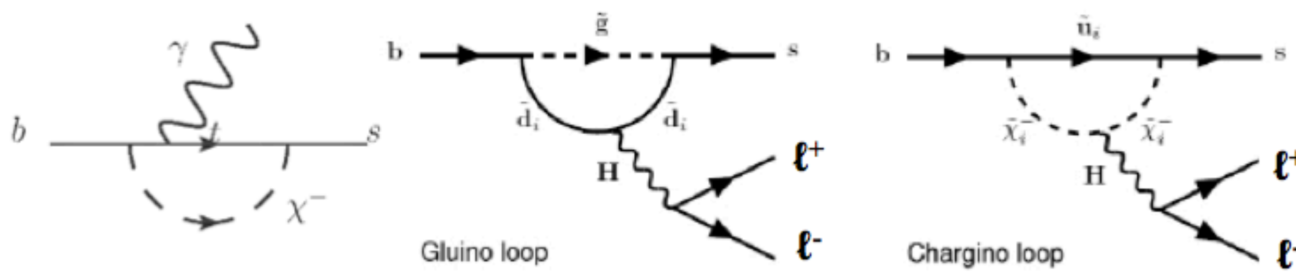
$b \rightarrow s\,\gamma(\ell\ell)$: FCNC processes

They provide, at relatively low energy, probes to NP at large mass scales

- Within the SM, these processes proceed via loop/box diagrams like

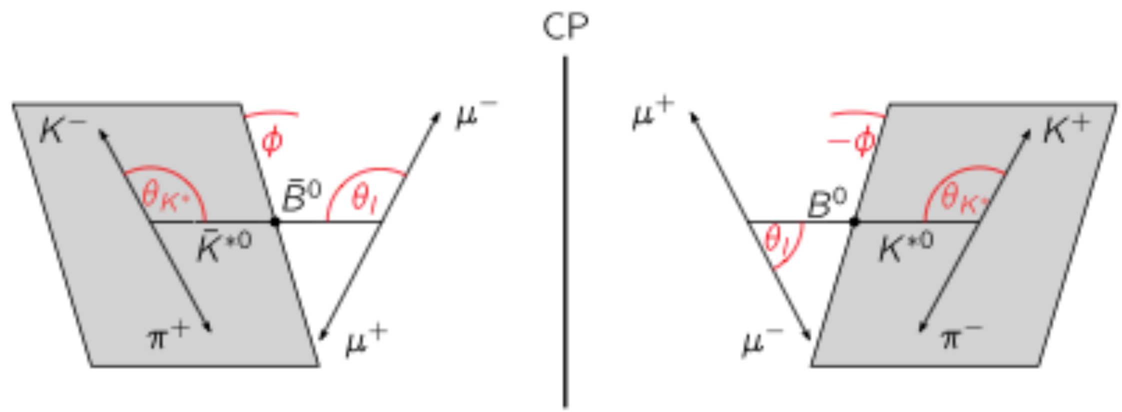


- Examples for NP scenarios



+ ?

$B \to K^* \mu^+ \mu^-$



- exclusive semi-leptonic decay probing the $b \to s$ transition
- 4-body decay: angular distribution with many observables sensitive to NP
- "self-tagging": sensitive to CP violation

$B \to K^*(\to K\pi)\mu^+\mu^-$ angular decay distribution

$$\frac{d^4\Gamma}{dq^2\, d\cos\theta_l\, d\cos\theta_{K^*}\, d\phi} = \frac{9}{32\pi}\times$$
$$\Big\{ I_1^s \sin^2\theta_{K^*} + I_1^c \cos^2\theta_{K^*} + (I_2^s \sin^2\theta_{K^*} + I_2^c \cos^2\theta_{K^*}) \cos 2\theta_l$$
$$+ I_3 \sin^2\theta_{K^*} \sin^2\theta_l \cos 2\phi + I_4 \sin 2\theta_{K^*} \sin 2\theta_l \cos\phi$$
$$+ I_5 \sin 2\theta_{K^*} \sin\theta_l \cos\phi + \left(I_6^s \sin^2\theta_{K^*} + I_6^c \cos^2\theta_{K^*}\right) \cos\theta_l$$
$$+ I_7 \sin 2\theta_{K^*} \sin\theta_l \sin\phi + I_8 \sin 2\theta_{K^*} \sin 2\theta_l \sin\phi + I_9 \sin^2\theta_{K^*} \sin^2\theta_l \sin 2\phi \Big\}$$

- Full set of observables: 12 angular coefficient functions $I_i(q^2)$

$B \to K^*(\to K\pi)\mu^+\mu^-$ angular decay distribution

$$\frac{d^4\Gamma}{dq^2\, d\cos\theta_l\, d\cos\theta_{K^*}\, d\phi} = \frac{9}{32\pi} \times$$

$$\Big\{ + I_2^s \sin^2\theta_{K^*}(3+\cos 2\theta_l) - I_2^c 2\cos^2\theta_{K^*} \sin^2\theta_l$$

$$+ I_3 \sin^2\theta_{K^*} \sin^2\theta_l \cos 2\phi + I_4 \sin 2\theta_{K^*} \sin 2\theta_l \cos\phi$$

$$+ I_5 \sin 2\theta_{K^*} \sin\theta_l \cos\phi + I_6 \sin^2\theta_{K^*} \cos\theta_l$$

$$+ I_7 \sin 2\theta_{K^*} \sin\theta_l \sin\phi + I_8 \sin 2\theta_{K^*} \sin 2\theta_l \sin\phi + I_9 \sin^2\theta_{K^*} \sin^2\theta_l \sin 2\phi \Big\}$$

- Full set of observables: 12 angular coefficient functions $I_i(q^2)$
- Neglecting lepton mass, scalar/tensor operators: 9 independent $I_i(q^2)$

$B \to K^*(\to K\pi)\mu^+\mu^-$ angular decay distribution

$$\frac{d^4\bar{\Gamma}}{dq^2\, d\cos\theta_l\, d\cos\theta_{K^*}\, d\phi} = \frac{9}{32\pi}\times$$

$$\Big\{ + \bar{I}_2^s \sin^2\theta_{K^*}(3+\cos 2\theta_l) - \bar{I}_2^c 2\cos^2\theta_{K^*}\sin^2\theta_l$$

$$+ \bar{I}_3 \sin^2\theta_{K^*}\sin^2\theta_l \cos 2\phi + \bar{I}_4 \sin 2\theta_{K^*}\sin 2\theta_l \cos\phi$$

$$- \bar{I}_5 \sin 2\theta_{K^*}\sin\theta_l \cos\phi - \bar{I}_6 \sin^2\theta_{K^*}\cos\theta_l$$

$$+ \bar{I}_7 \sin 2\theta_{K^*}\sin\theta_l \sin\phi - \bar{I}_8 \sin 2\theta_{K^*}\sin 2\theta_l \sin\phi - \bar{I}_9 \sin^2\theta_{K^*}\sin^2\theta_l \sin 2\phi \Big\}$$

- Full set of observables: 12 angular coefficient functions $I_i(q^2)$
- Neglecting lepton mass, scalar/tensor operators: 9 independent $I_i(q^2)$
- CP-conjugate decay: another 9 independent functions $\bar{I}_i(q^2)$

Basis of observables

- consider sums and differences of I_i, $\bar{I}_i$ to separate CP violating and CP conserving NP effects
- normalize to CP-averaged decay rate to reduce th. & exp. uncertainties

CP-averaged angular coefficients

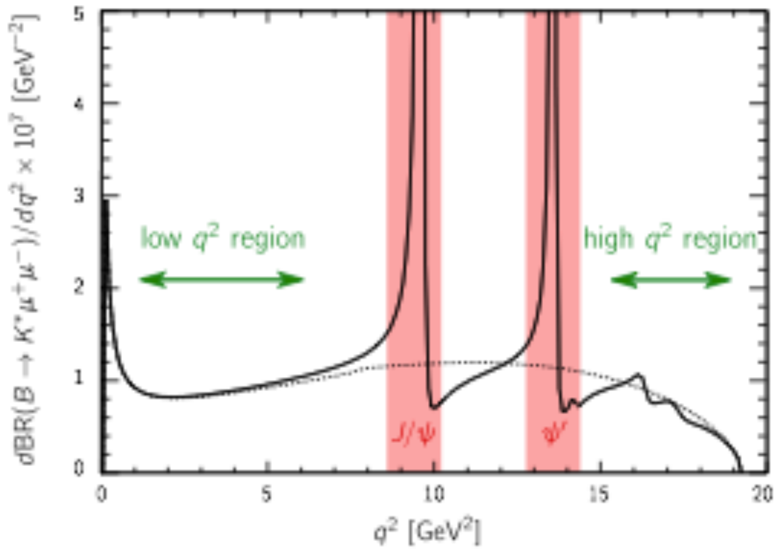
$$S_i^{(a)}(q^2) = \left(I_i^{(a)}(q^2) + \bar{I}_i^{(a)}(q^2)\right) \Bigg/ \frac{d(\Gamma + \bar{\Gamma})}{dq^2}$$

CP asymmetries

$$A_i^{(a)}(q^2) = \left(I_i^{(a)}(q^2) - \bar{I}_i^{(a)}(q^2)\right) \Bigg/ \frac{d(\Gamma + \bar{\Gamma})}{dq^2}$$

[Kruger et al. hep-ph/9907386, Bobeth et al. 0805.2525, Altmannshofer et al. 0811.1214]

Kinematical regions



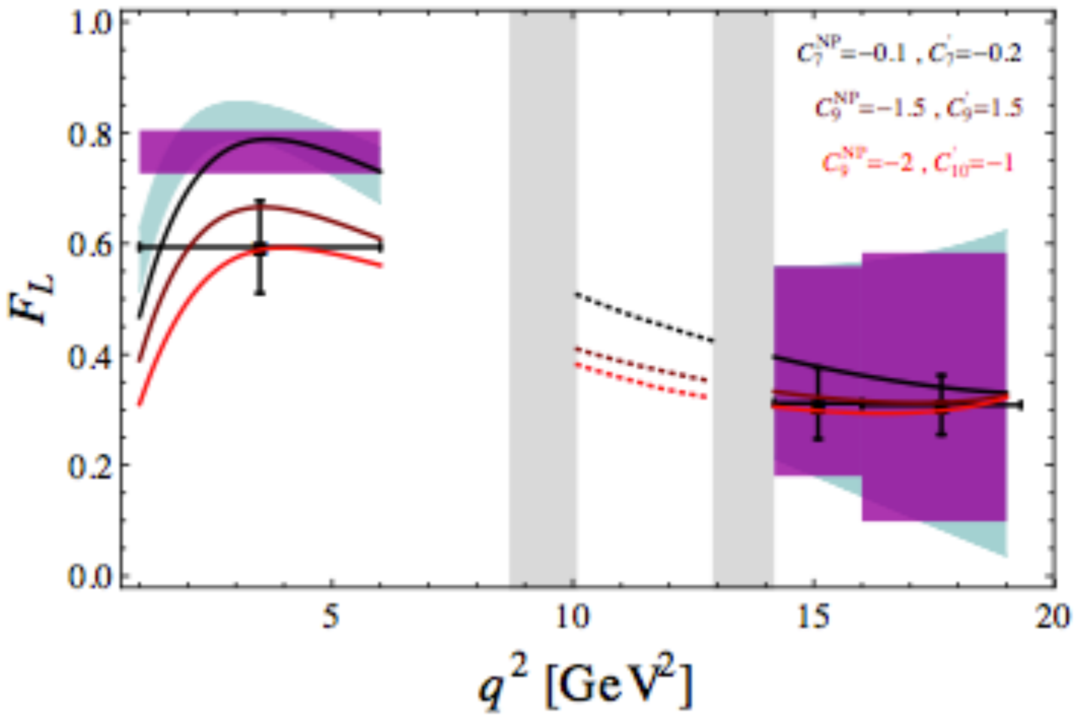
- low $q^2 \lesssim 6$ GeV^2: expansion in m_{K^*}/E_{K^*}
- intermediate $q^2 \in [6, 15]$ GeV^2: $c\bar{c}$ resonances, $B \to K^*\psi(\to \mu^+\mu^-)$
- high $q^2 \gtrsim 15$ GeV^2: expansion in $E_{K^*}/\sqrt{q^2}$

Alternative bases of observables

To reduce theory uncertainties related to form factors, one can change the normalization of the $S_i^{(a)}$ and $A_i^{(a)}$ and find "optimized" observables for low *or* high q^2

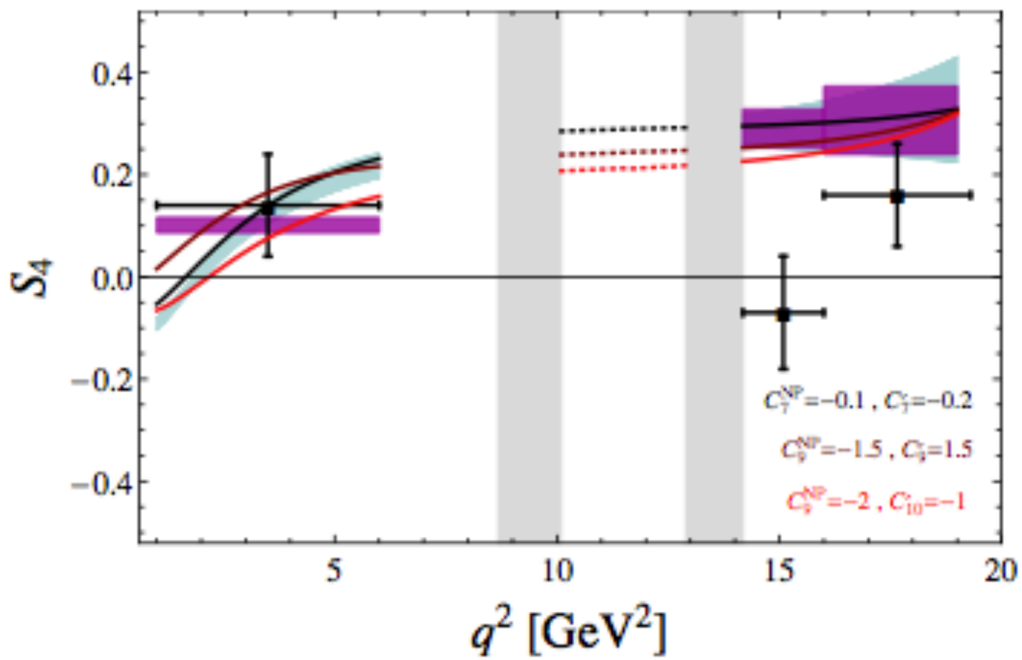
Low q^2	**High q^2**
$P'_4 = \frac{2\, S_4}{\sqrt{F_L(1 - F_L)}}$	$H_T^{(1)} = \frac{2\, S_4}{\sqrt{F_L(1 - F_L - S_3)}}$
$P'_5 = \frac{S_5}{\sqrt{F_L(1 - F_L)}}$	$H_T^{(2)} = \frac{S_5}{\sqrt{F_L(1 - F_L + S_3)}}$
$\dots$	$\dots$
[Descotes-Genon et al. 1303.5794]	[Bobeth et al. 1006.5013]

SM vs. data: F_L [Altmannshofer and DS 1308.1501]



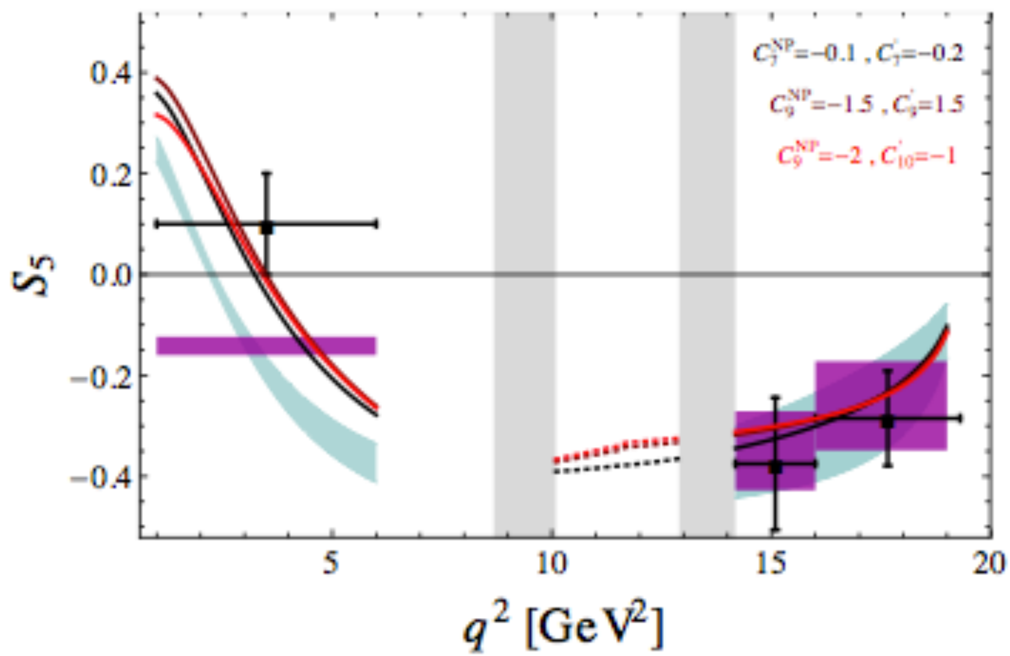
1.9σ tension at low q^2

SM vs. data: S_4 [Altmannshofer and DS 1308.1501]



2.8σ tension at high q^2

SM vs. data: S_5 [Altmannshofer and DS 1308.1501]

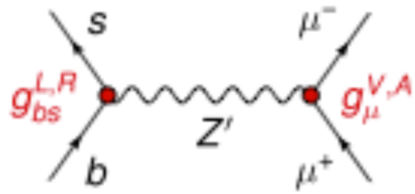


2.4σ tension at low q^2

The "$B \to K^* \mu^+ \mu^-$ anomaly"

- There is a tension in some angular observables $B \to K^* \mu^+ \mu^-$ that could be due to new physics (or statistical fluctuation, or underestimated theory errors)
- If due to NP, it requires a simultaneous contribution to the Wilson coefficients C_9 and C_9' in order not to violate constraints from other processes
- Which actual NP model could explain such an effect?

Solving the anomaly with a Z' boson

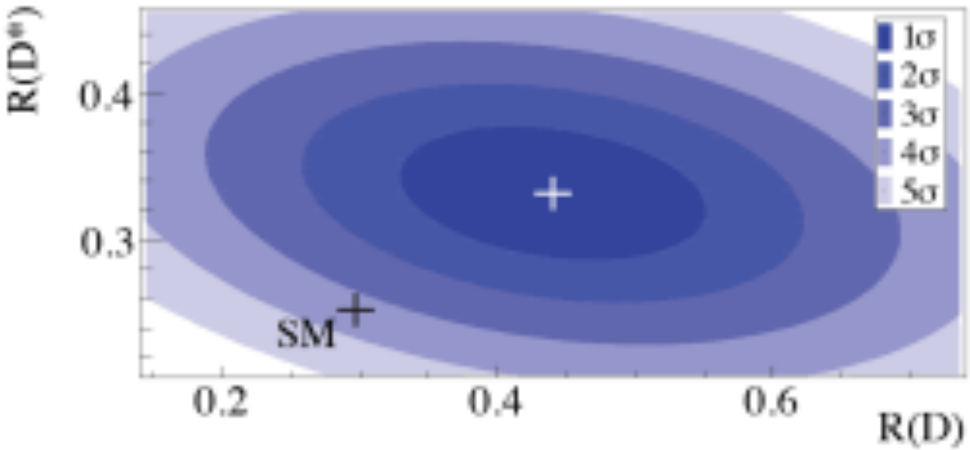


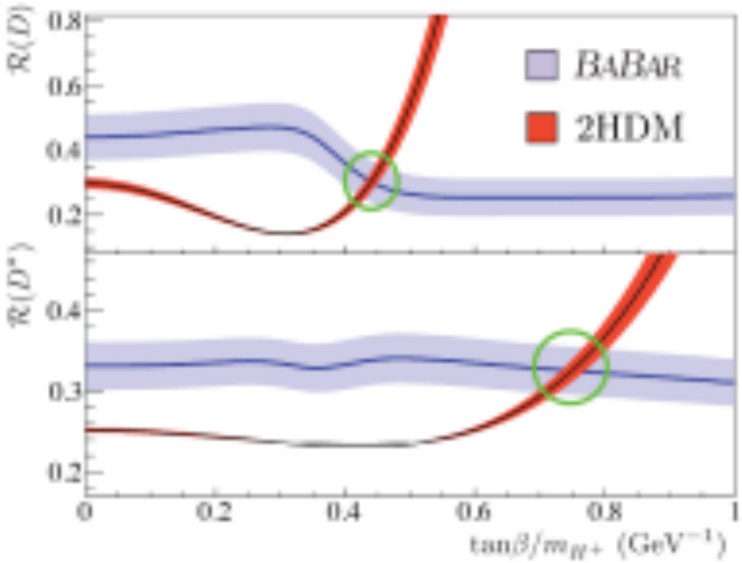
$$\mathcal{L} \supset \frac{g_2}{2c_W}\left[\bar{s}\gamma^\mu(g_{bs}^L P_L + g_{bs}^R P_R)b + \bar{\mu}\gamma^\mu(g_\mu^V + \gamma_5 g_\mu^A)\mu\right] Z'_\mu ,$$

$$\left\{C_9^{\mathrm{NP}}, C_9'\right\} \propto \frac{m_Z^2}{m_{Z'}^2}\left\{(g_{bs}^L)(g_\mu^V), (g_{bs}^R)(g_\mu^V)\right\}$$

[Descotes-Genon et al. 1307.5683, Altmannshofer and DS 1308.1501, Gauld et al. 1308.1959, Buras and Girrbach 1309.2466, Gauld et al. 1310.1082, Buras et al. 1311.6729]

• **Problem???**





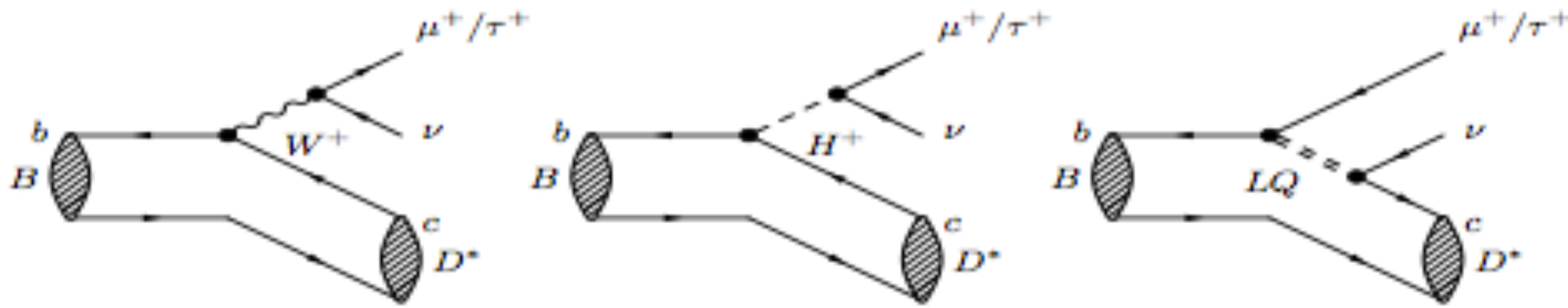
- Remains a puzzle
- Analysis in terms of general parametrizations
- More data

An effective theory approach to explain the problem:
RD, AB and AG , PRD, 88, 114023 (2013); JPG (2014)

Semi-tauonic decays

- B → D(*)τν are tree level decays mediated by a W in SM
- Lepton universality in SM, might be broken by mass-dependent couplings

→ Probe SM extensions to models with e.g. enlarged Higgs sector, leptoquarks



→ Test SM by measuring ratios

theoretically and experimentally cleaner

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

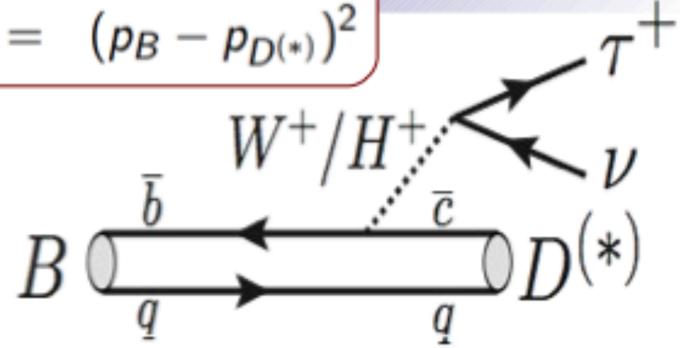
→ Renewed interest in this area, after anomalous result of Babar (next talk)

PRL109, 101802 (2012)

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

$$q^2 = (p_\ell + p_\nu)^2 = (p_B - p_{D^{(*)}})^2$$

- It is not a rare decay: BF~1-2%
- 3-body decay: many observables sensitive to NP can be exploited



Signal

$$\mathcal{R}(D^{(*)}) \equiv \frac{\mathcal{B}(B \to D^{(*)}\tau\nu)}{\mathcal{B}(B \to D^{(*)}\ell\nu)}$$

Normalization
(largest background)

Theoretically Clean

Cancellation of $|V_{cb}|$ and Form Factor uncertainties (partially: the helicity-suppressed amplitude estimated from HQET)

- Experimentally clean with leptonic tau decays
  - $\mathcal{B}(\tau \to \mu\nu\bar{\nu}), \mathcal{B}(\tau \to e\nu\bar{\nu}) \approx 17\%$
- Identical visible final state and direct access to *R*(D) and *R*(D*) ratios

- The effective Hamiltonian describing $b \to s l^+ l^-$ process is

$$\mathcal{H}_{eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \left[\sum_{i=1}^{6} C_i(\mu) O_i + \sum_{i=7,9,10}^{S,P} \left(C_i(\mu) O_i + C_i'(\mu) O_i' \right) \right],$$

$i = 1, 2$	Tree	$i = 9, 10$	Electroweak Penguin
$i = 3 - 6, 8$	Chromomagnetic Penguin	$i = S$	Scalar Penguin
$i = 7$	Electromagnetic Penguin	$i = P$	Pseudoscalar Penguin

- The effective Hamiltonian mediating the semileptonic decays $b \to c \bar{\tau} \nu_l$ is given by

$$\mathcal{H}_{eff} = \frac{4G_F}{\sqrt{2}} V_{cb} \left[\left(\delta_{l\tau} + C_{V_1}^l \right) \mathcal{O}_{V_1}^l + C_{V_2}^l \mathcal{O}_{V_2}^l + C_{S_1}^l \mathcal{O}_{S_1}^l + C_{S_2}^l \mathcal{O}_{S_2}^l \right],$$

- where the operators are

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

$$\mathcal{O}_{S_1}^l = (\bar{c}_L b_R)(\bar{\tau}_R \nu_{lL}), \qquad \mathcal{O}_{S_2}^l = (\bar{c}_R b_L)(\bar{\tau}_R \nu_{lL}).$$

- Recently LHCb and B factories have observed violation of lepton universality in $b \to s l^+ l^-$ and $b \to c l \nu_l$ processes.
- $\mathrm{Br}(B^+ \to K^+ ee)$ in agreement with SM.
- Can be explained if possible NP contributes to $b \to s\mu\mu$ not to $b \to see$.
- If same anomaly persists in R_{K^*}, it would be clear signature of NP.

Observables	Expt. value	SM prediction	Deviation
$R_K = \frac{Br(B^+ \to K^+ \mu^+ \mu^-)}{Br(B^+ \to K^+ e^+ e^-)}$	$0.745^{+0.090}_{-0.074} \pm 0.036$	1.0003 ± 0.0001	2.6σ
$R_D = \frac{Br(B \to D \tau \nu_l)}{Br(B \to D l \nu_l)}$	0.41 ± 0.05	0.286 ± 0.012	1.9σ
$R_{D^*} = \frac{Br(B \to D^* \tau \nu_l)}{Br(B \to D^* l \nu_l)}$	0.317 ± 0.017	0.252 ± 0.003	3.3σ

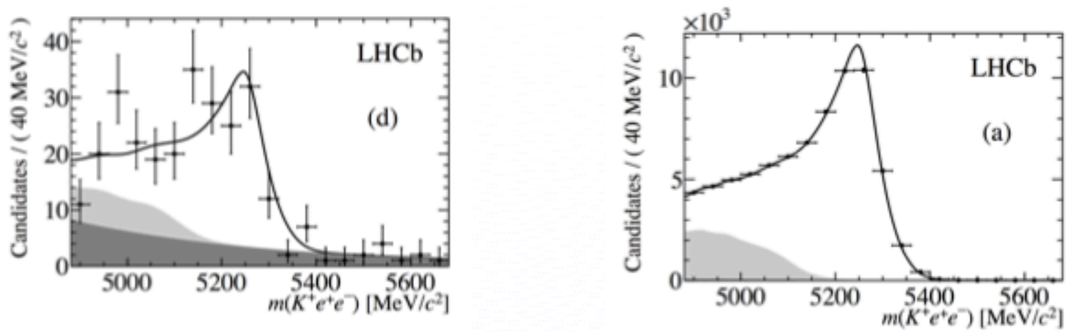
LFU in $B^+ \to K^+ l^+ l^-$

LHCb, PRL 113 (2014) 151601

$$R(K)^{SM} = \frac{BR(B^+ \to K^+ \mu^+ \mu^-)}{BR(B^+ \to K^+ e^+ e^-)} = 1 \pm \mathcal{O}(10^{-4})$$

[C. Bobeth et al., JHEP 07 (2007) 040]

- FCNC process, only ocurring at loop level in the SM
- Measured relative to $B^+ \to K^+ J/\psi(l^+ l^-)$ to cancel experimental systematic associated to differences between electrons and muons



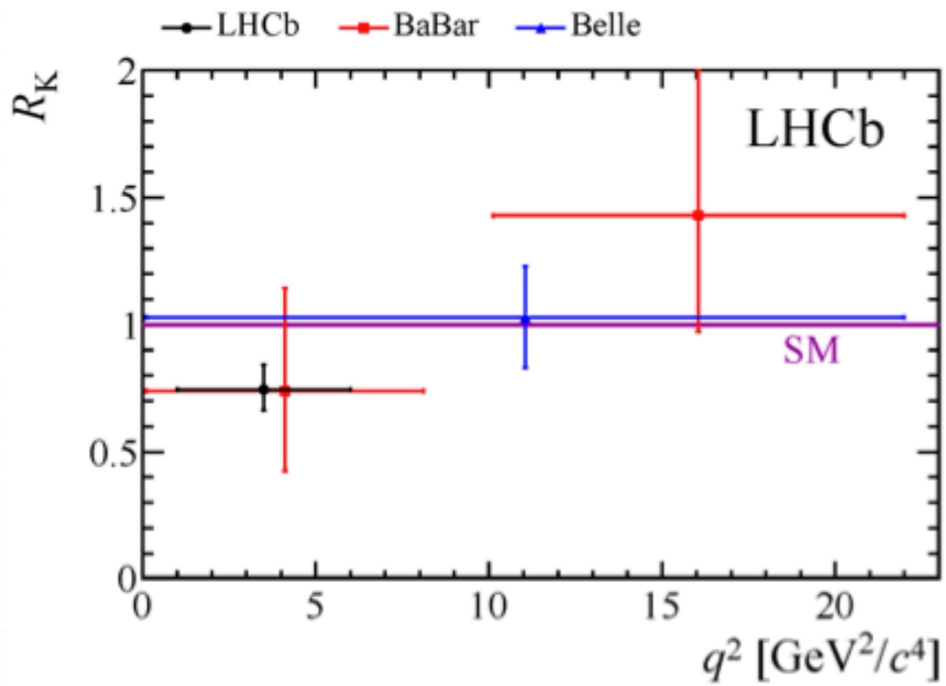
Note: FSR simulated using PHOTOS. Dominant effect to q^2 migration is Bremsstrahlung in the detector.

- Measurement performed with $3\,\mathrm{fb}^{-1}$ of data, in $1 < q^2 < 6\,\mathrm{GeV}/c^2$

$$R_K = 0.745\,^{+0.090}_{-0.074} \pm 0.036$$

Compatible with SM at 2.6σ

→ Consistent with $b \to s\mu\mu$ anomalies, if NP couples only to muons and not electrons



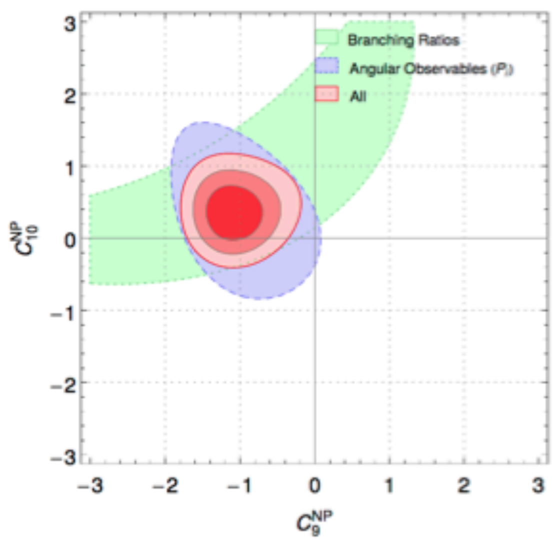
→ Clear motivation to explore related LFU ratios ($R_{K^{*0}}$, R_ϕ, ...)

Global fits to $b \to s\mu^+\mu^-$ observables

Model independent approach

$$\mathcal{H}^{\text{eff}} \sim \sum_i (C_i^{SM} + \Delta C_i^{NP})\mathcal{O}_i$$

where heavy fields are integrated out and *Wilson coefficients* (C_i) and *operators* ($\mathcal{O}_i$) encode coupling strength and Lorentz structure



[Descotes-Genon et al, 1510.04239v3]

→ Angular observables, BR's and R_K are compatible with a modified vector coupling $C_9^{\mu\mu} = -1$ and $\Delta C_9^{ee} = 0$

→ Best fit $\sim 4\sigma$ from the SM prediction

→ **LFU ratios free from QCD uncertainties that may affect other observables**

Conclusion

- First ever measurement of a $b \to \tau$ decay at a hadron collider
- R(D*) is the beginning of a vast exploration
  - Several channels
  - Two τ decay modes
- The addition of Run2 and Run3 data will eventually lead to samples of $O(10^5\text{-}10^6)$ events
  - Not only R, but also angles, polarizations, form factors…
  - …and charmless semi-tauonic decays!
- LHCb will compete with final Belle-II measurements

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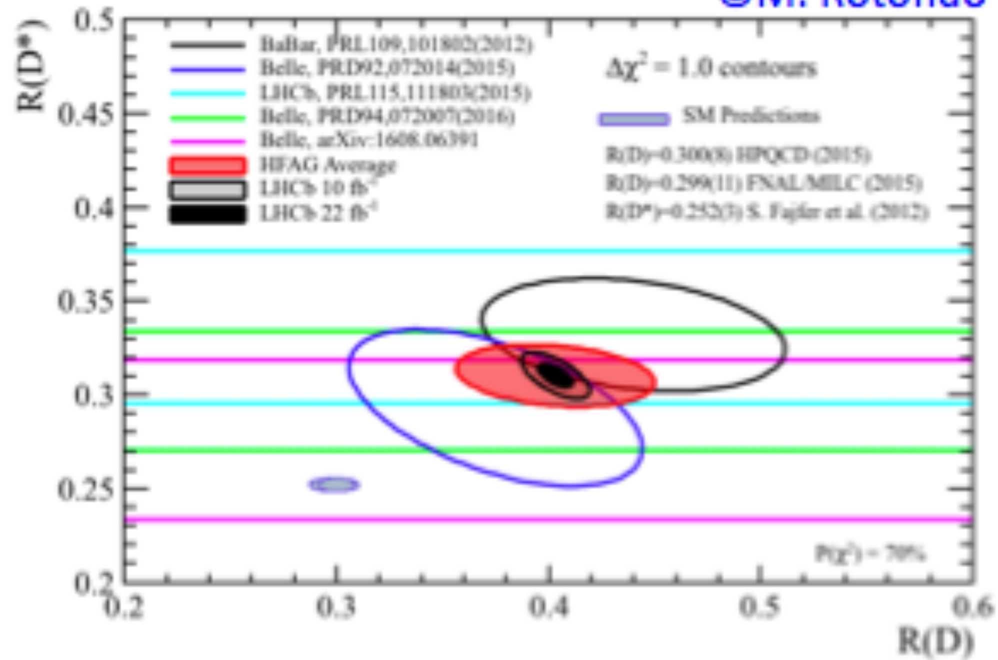


Tau Physics

LFV is severely suppressed in the SM

LFV τ decays, clean and unambiguous probes: NP

Deviation from V-A theory can originate:

a) CPV in lepton sector

b) Scalar contribution from H^{+-}

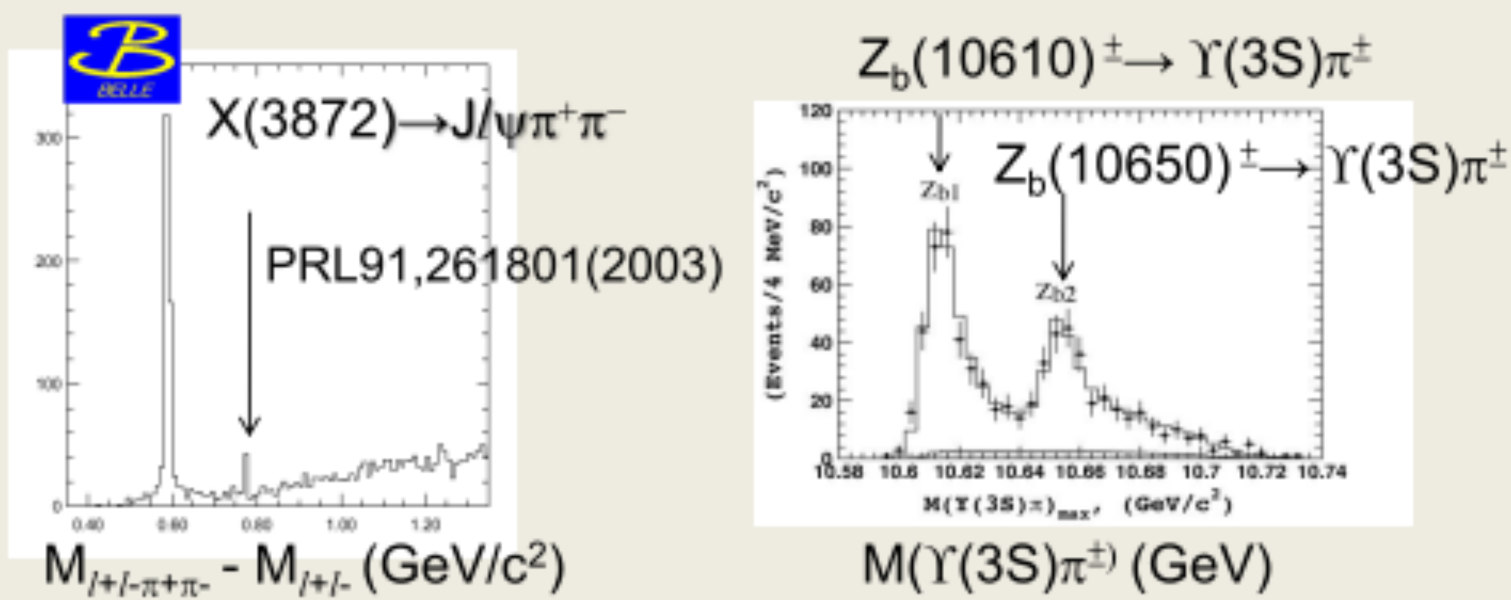
c) mixing of right and left hand current (W_L, W_R)

τ - > 3 l , τ -> l γ γ, τ -> l ν ν, τ -> l ν ν γ

$\tau^- \to K^- \pi^0 \nu_\tau$ (CP violation has tension with the experiment 2.8 sigma)

- **X Y Z and all that**
- Y (4260) → Dπ , Z (3900) → J/ψ pi
- Z (3885) → D D*, Z(4020)→ D* D*
- Z(4025) → h ππ, Y(4065)→ γ X(3872)
- Molecules, Hybrids, Tetra-quarks ……….

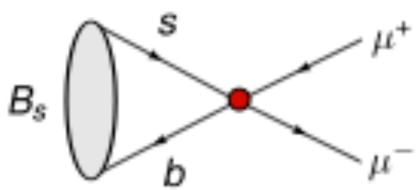
Observation of X(3872), Z_b(10610) and Z_b(10650).



$B_s \to \mu^+\mu^-$ in the SM

$$\mathcal{H}_{\text{eff}} = -\frac{4\,G_F}{\sqrt{2}}\frac{e^2}{16\pi^2} V_{tb}V_{ts}^{*}\, C_{10} O_{10} + \text{h.c.}$$

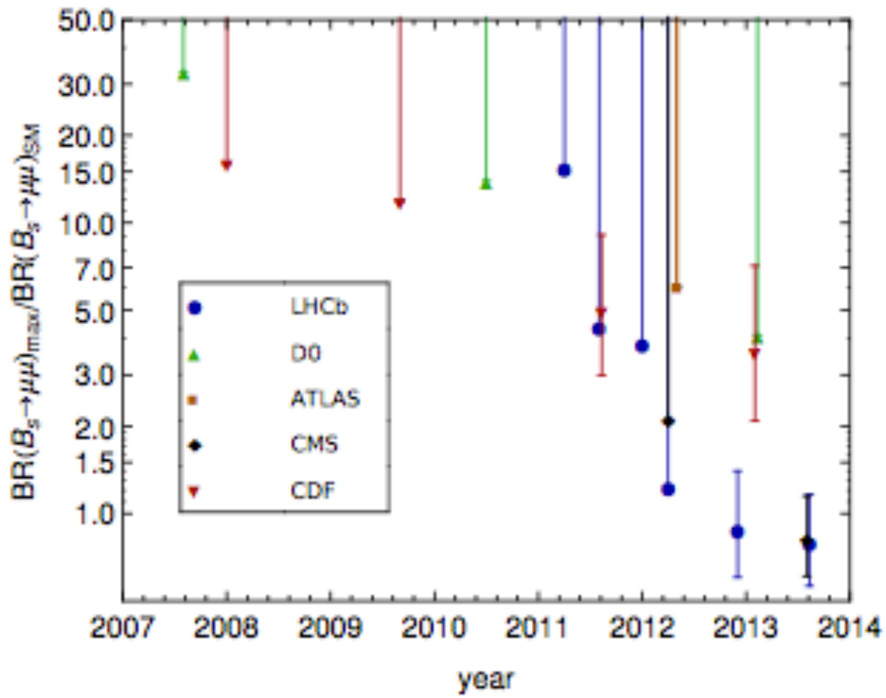
$$O_{10} = (\bar{s}_L \gamma_\mu b_L)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$$



- Flavour-changing neutral current
  - Loop suppresion
  - CKM suppresion
- B_s is a pseudoscalar
  - Helicity suppression, m_μ^2/m_B^2
  - Only 1 operator – no γ penguin or vector operator

$\Rightarrow$ One of the rarest B decays!

History: search for $B_s \to \mu^+\mu^-$

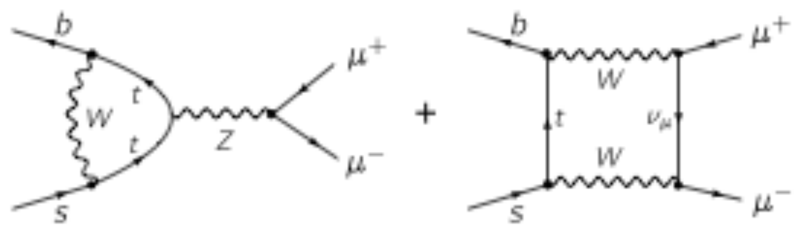


- Hope for order-of-magnitude enhancement was disappointed
- Precision of SM prediction becomes crucial

Computing the branching ratio

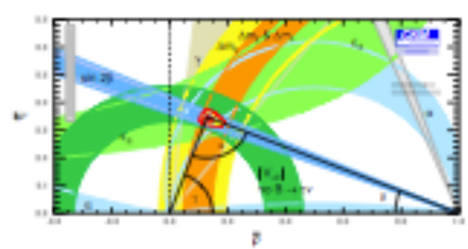
Schematically:

$$\mathrm{BR} \propto \tau_{B_s} \left| V_{tb} V_{ts}^* \, C_{10} \, \langle \mu\mu | O_{10} | B_s \rangle \right|^2$$

$C_{10}(\mu_W) =$ 

$+ \ldots$

$$\langle 0 | \bar{s}\gamma_\mu\gamma_5 b | \bar{B}_s(p) \rangle = i p_\mu f_{B_s}$$

$V_{tb} V_{ts}^* \Leftarrow$ 

State of the art [Bobeth et al. 1311.0903]

$$\overline{\text{BR}}(B_s \to \mu^+\mu^-)_{\text{SM}} = (3.65 \pm 0.23) \times 10^{-9}$$

$$\text{cf.:}\ \overline{\text{BR}}(B_s \to \mu^+\mu^-)_{\text{LHCb+CMS}} = (2.9 \pm 0.7) \times 10^{-9}$$

$B_s \to \mu\mu$ vs. $B_d \to \mu\mu$

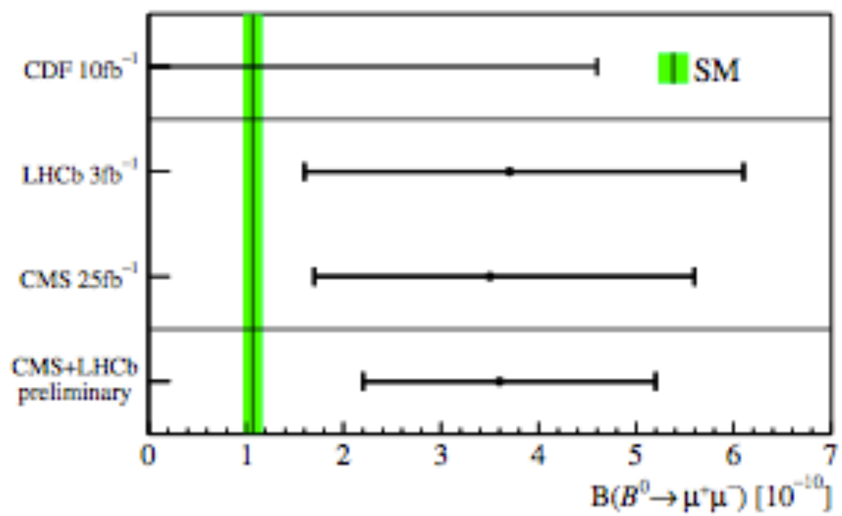
- In the SM (and all models with Minimal Flavour Violation), BRs differ only by CKM elements and overall factor

$$\frac{\text{BR}(B_s \to \mu^+\mu^-)}{\text{BR}(B_d \to \mu^+\mu^-)} = \frac{\tau_{B_s} f_{B_s}^2 m_{B_s} |V_{ts}|^2}{\tau_{B_d} f_{B_d}^2 m_{B_d} |V_{td}|^2}$$

$$\overline{\text{BR}}(B_d \to \mu^+\mu^-)_{\text{SM}} = (1.06 \pm 0.09) \times 10^{-10}$$

$$\text{cf.: } \overline{\text{BR}}(B_d \to \mu^+\mu^-)_{\text{LHCb+CMS}} = (3.3^{+1.6}_{-1.4}) \times 10^{-10}$$

$B_d \to \mu^+\mu^-$ experiment vs. SM



- 2.4σ above 0, 1.6σ above SM. If NP: no MFV!

$B_s \to \mu^+\mu^-$ beyond the SM

$$\mathcal{H}_{\text{eff}} = -\frac{4\,G_F}{\sqrt{2}}\frac{e^2}{16\pi^2}V_{tb}V_{ts}^* \sum_i C_i O_i + C_i' O_i' + \text{h.c.}$$

$$O_{10}^{(\prime)} = (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\ell}\gamma^\mu\gamma_5\ell)$$

$$O_S^{(\prime)} = \frac{m_b}{m_{B_s}}(\bar{s}P_{R(L)}b)(\bar{\ell}\ell)$$

$$O_P^{(\prime)} = \frac{m_b}{m_{B_s}}(\bar{s}P_{R(L)}b)(\bar{\ell}\gamma_5\ell)$$

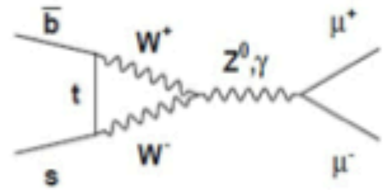
$$\text{BR}(B_s \to \mu^+\mu^-) \propto \left[|S|^2\left(1 - \frac{4m_\mu^2}{m_{B_s}^2}\right) + |P|^2\right]$$

$$S = \frac{m_{B_s}}{2}C_S \qquad P = \frac{m_{B_s}}{2}C_P + m_\mu C_{10}$$

FCNC $\Delta F = 1$: $B_{s,d} \to \mu^+\mu^-$

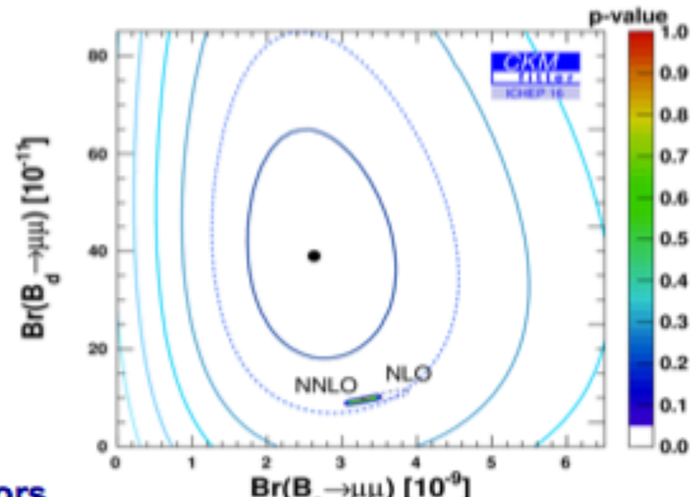
CKM fitter ICHEP 16

- **Measured by LHCb and CMS**
- **Sensitive to pseudo/scalar contributions**
- **Theoretical progress**
  - Inclusion of B_s mixing in experimental time-integrated rate $\langle Br(B_s \to \mu\mu)\rangle \simeq 1.1\, Br_{t=0}$
  - NLO+LO EW $\to$ NNLO + NLO EW



- **SM (and MFV) correlation between $Br(B_d \to \mu^+\mu^-)$ and $Br(B_s \to \mu^+\mu^-)$, driven by $\Delta m_d/\Delta m_s$**

$$Br(B_d \to \mu\mu)_{t=0}/Br(B_s \to \mu\mu)_{t=0} = 0.0298^{+0.0008}_{-0.0010}$$



- **Further tests of pseudo/scalar operators**

$$Br(B_d \to \tau\tau)_{t=0} \times 10^8 = 2.05^{+0.13}_{-0.15} \qquad Br(B_s \to \tau\tau)_{t=0} \times 10^7 = 6.98^{+0.38}_{-0.43}$$

Outlook

- No new physics signature
- Few deviations observed
- New physics models???
- Exciting time ahead

Thanks