FLAVOUR PHYSICS

Emi Kou (LAL/In2p3)

RPP 2013 LPCS/In2p3 Grenoble
16-18 January 2013

LABORATOIRE DE L'ACCÉLÉRATEUR LINÉAIRE

Outline

* Highlights of last year
* The status of the determination of the CKM unitarity triangle
* Prospect of the photon polarization determination of $b \to s\gamma$

Highlights of last year

LHCb revealing B_s: $B_{s/d} \to \mu^+\mu^-$

LHC search of signal BSM with $B_s \to \mu^+\mu^-$

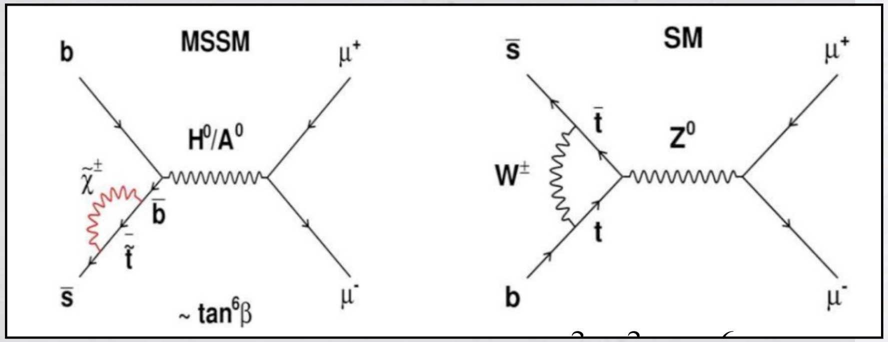
- $B_{s/d} \to \mu^+\mu^-$ is an extremely rare process in SM.

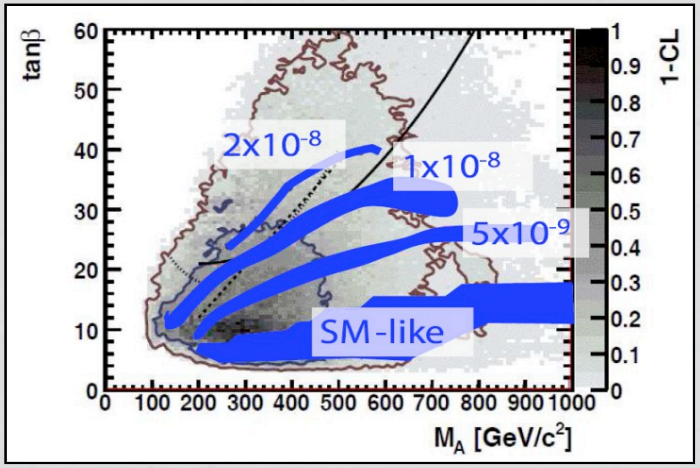
ArXive:1208.0934
Buras et al.

$$Br_{B_s \to \mu^+\mu^-} = (3.54 \pm 0.30) \times 10^{-9} \text{ SM}$$
$$Br_{B_d \to \mu^+\mu^-} = (0.107 \pm 0.01) \times 10^{-9} \text{ SM}$$

- In certain BSM model, it can be enhanced largely.

$$Br_{B_s \to \mu^+\mu^-} = \frac{m_b^2 m_\mu^2 \tan^6\beta}{m_{A_0}^4}$$





Highlights of last year

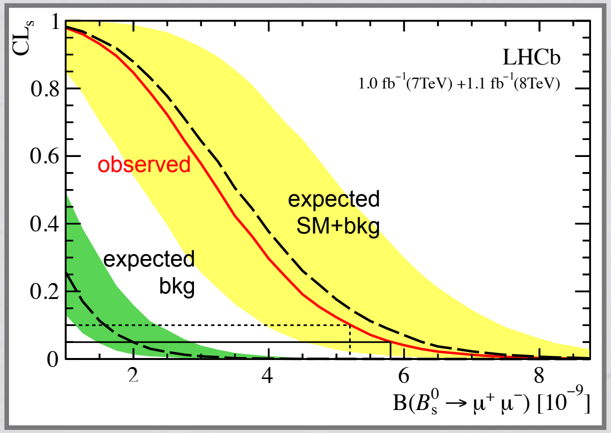
LHCb revealing B_s: $B_{s/d} \to \mu^+\mu^-$

First observation of $B_s \to \mu^+\mu^-$ turned out to be close to SM...

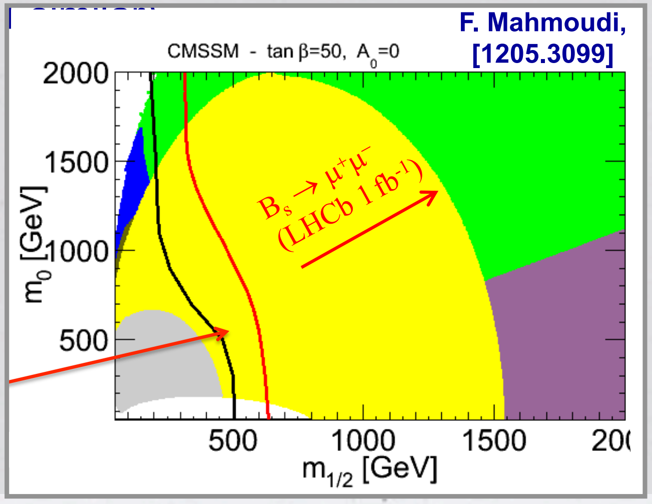
- LHCb found excess of $B_s \to \mu^+\mu^-$ candidate with signal significance of 3.5σ SD. ArXive:1211.2674

$$Br_{B_s \to \mu^+\mu^-} = (3.2^{+1.5}_{-1.2}) \times 10^{-9}$$

- Searches continue:
  - 6 fb^{-1} data required for 5σ discovery.
  - What about $B_d \to \mu^+\mu^-$?



Talk by Albrecht at HCP '12



$$Br_{B_s \to \mu^+\mu^-} = (3.54 \pm 0.30) \times 10^{-9} \text{ SM}$$

$$Br_{B_d \to \mu^+\mu^-} = (0.107 \pm 0.01) \times 10^{-9} \text{ SM}$$

Highlights of last year

LHCb revealing B_s: B_s oscillation

LHC search of signal BSM with B_s–$\overline{B}_s$ oscillation measurement

- In SM, there is only one complex phase which induces CP violation.

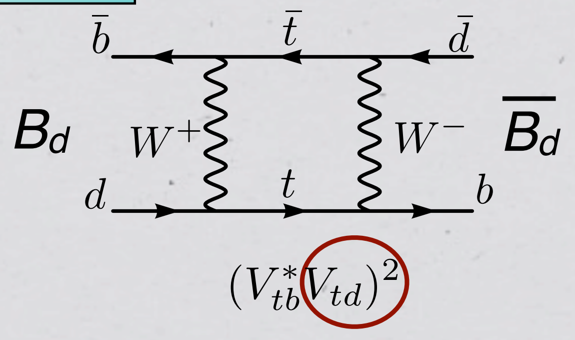
$$\sin 2\beta = 0.679 \pm 0.020$$

$$\sin 2\beta_s = 0.0363^{+0.0015}_{-0.0016} \quad \text{SM}$$

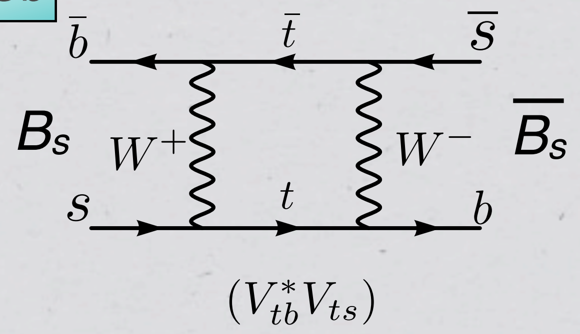
CKM fitter PRD84

- Many BSM predict more than one source of CP violation.
  - There are models which predict a large effect in the B_s sector.

B factories



LHCb



Highlights of last year

LHCb revealing B_s: B_s oscillation

LHC search of signal BSM with B_s–$\overline{B}_s$ oscillation measurement

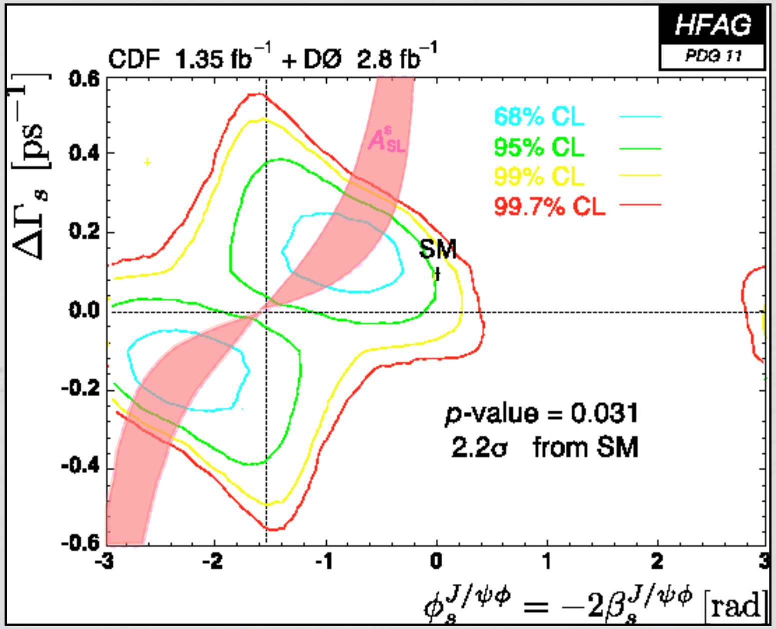
- In SM, there is only one complex phase which induces CP violation.

$$\sin 2\beta = 0.679 \pm 0.020$$

$$\sin 2\beta_s = 0.0363^{+0.0015}_{-0.0016} \text{ SM}$$

CKM fitter PRD84

- Many BSM predict more than one source of CP violation.
  - There are models which predict a large effect in the B_s sector.



Tevatron results (both Φ_s and A_{SL}) have been slightly off from the SM values

Highlights of last year

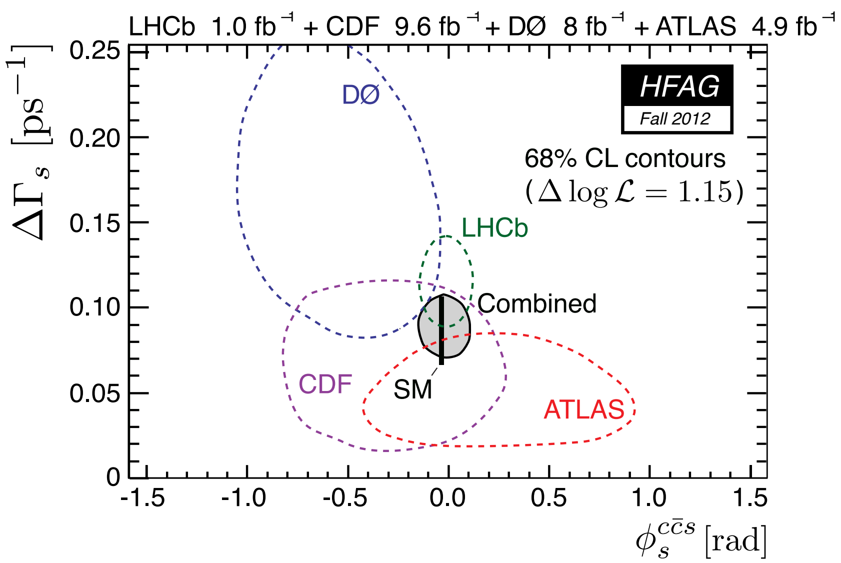
LHCb revealing B_s: B_s oscillation

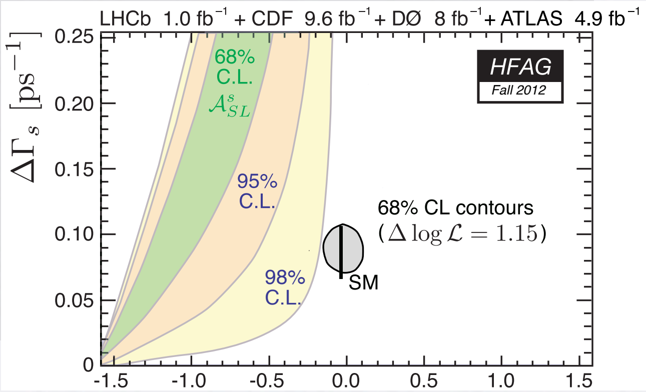
A higher precision achieved by LHCb on the B_s–$\overline{B}_s$ oscill. phase

- The latest combined value is:

$$\sin 2\beta_s = 0.013^{+0.083}_{-0.090}$$

- Order one deviation is excluded.
  - Impact on the BSM parameters are to be studied.
  - LHCb has an ability to reach to the SM value. Still some hope...





$$\sin 2\beta_s = 0.0363^{+0.0015}_{-0.0016} \ \text{SM}$$

Highlights of last year

Hint of new physics? : Direct CPV in D meson

Charm direct CP violation at LHCb: is it BSM or SM?

* The charm direct CP asymmetry:

$$A_{\rm CP}^{D^0\to h^+h^-} = \frac{\Gamma_{\overline{D}^0\to h^+h^-} - \Gamma_{D^0\to h^+h^-}}{\Gamma_{\overline{D}^0\to h^+h^-} + \Gamma_{D^0\to h^+h^-}}$$

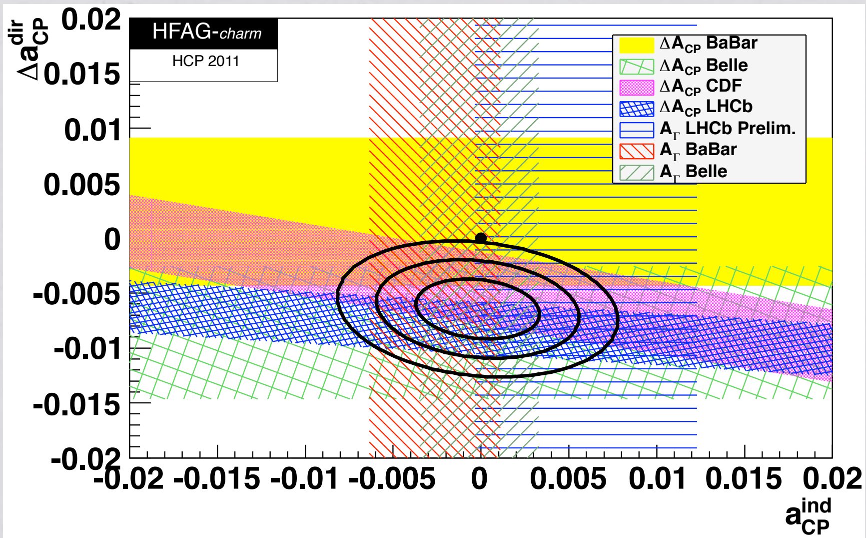
$$\Delta A_{\rm CP} = A_{\rm CP}^{D^0\to K^+K^-} - A_{\rm CP}^{D^0\to \pi^+\pi^-}$$

* In SM, the direct CP asymmetry *was* predicted to be of O(10^{-5} - $^{-3}$).

LHCb 2011

LHCb ArXive:1112.0938

$$\Delta A_{CP} = (-0.82 \pm 0.21 \pm 0.11)\%$$



World Average (HFAG)

$$\Delta A_{\rm CP} \simeq (-0.645 \pm 0.180)\%$$

Highlights of last year

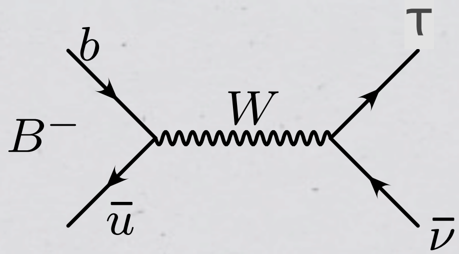
Hint of new physics? : Anomaly in $B_u \to \tau\nu$ (diminished...)

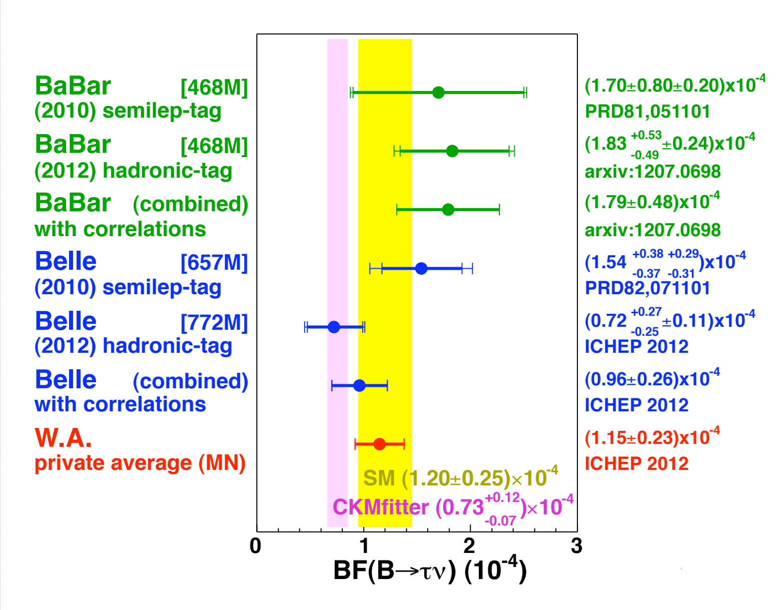
Branching ratio of B→τν

- Excess of events has been seen (charged Higgs contribution?):

$$Br(B \to \tau\nu)_{\rm SM}$$
$$= \frac{G_F^2 m_B m_\tau}{8\pi}\left(1 - \frac{m_\tau^2}{m_B^2}\right)^2 f_B^2 |V_{ub}|^2 \tau_B$$
$$Br(B \to \tau\nu)_{2HDM}$$
$$= Br(B \to \tau\nu)_{\rm SM}\left(1 - \tan^2\beta \frac{M_B^2}{m_{H^\pm}^2}\right)^2$$

- Latest Belle data has shifted to lower value...





Talk by Nakao at ICHEP'12

Highlights of last year

Hint of new physics? : Anomaly in $B_u \to \tau\nu$ (diminished...)

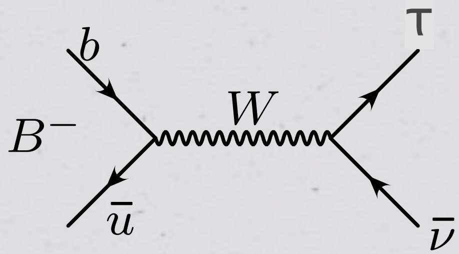
Branching ratio of B→τν

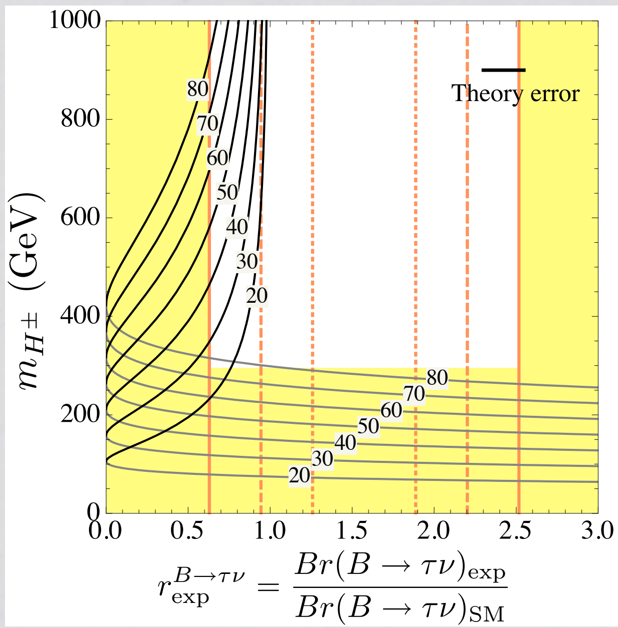
- Excess of events has been seen (charged Higgs contribution?):

$$Br(B \to \tau\nu)_{\rm SM} = \frac{G_F^2 m_B m_\tau}{8\pi}\left(1 - \frac{m_\tau^2}{m_B^2}\right)^2 f_B^2 |V_{ub}|^2 \tau_B$$

$$Br(B \to \tau\nu)_{2HDM} = Br(B \to \tau\nu)_{\rm SM}\left(1 - \tan^2\beta \frac{M_B^2}{m_{H^\pm}^2}\right)^2$$

- Latest Belle data has shifted to lower value...





EK & Zupan for PBFB

Highlights of last year

Hint of new physics? : B→D(*)τν decay rates

The ratio of B→D$^{(*)}$τν and B→D$^{(*)}$lν branching ratios

- The latest Babar measurements of:

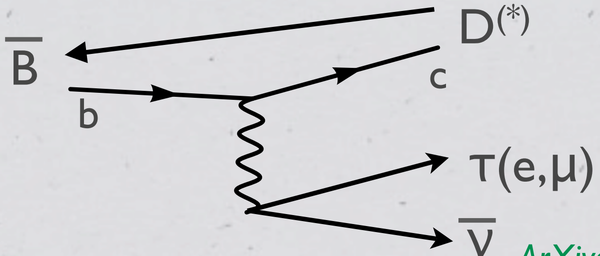
$$\mathcal{R}(D^{(*)}) = \frac{Br(\overline{B} \to D^{(*)}\tau\overline{\nu})}{Br(\overline{B} \to D^{(*)}l\overline{\nu})}$$

$$\mathcal{R}(D) = 0.440 \pm 0.058 \pm 0.042$$
$$\mathcal{R}(D^*) = 0.332 \pm 0.024 \pm 0.018 \ .$$

Babar ArXive:1205.5442

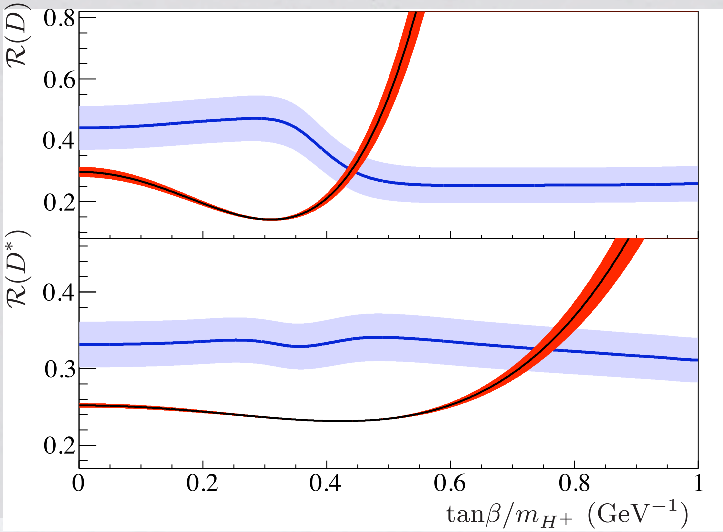
- Possible charged Higgs contribution? But it conflicts to Type II 2HDM… Or SM?

Becirevic et al. ArXive:1206.4977



Fajfer et al ArXive:1203.2654

$$\mathcal{R}(D)_{\rm SM} = 0.302 \pm 0.015$$
$$\mathcal{R}(D^*)_{\rm SM} = 0.252 \pm 0.003$$



The CKM unitarity triangle

What's new?

- SM is a very concise and extremely successful model:
  - ✓ Natural suppression of FCNC (i.e. GIM mechanism)
  - ✓ Only source of flavor and CP violation in the V_{CKM} matrix

The CKM unitarity triangle

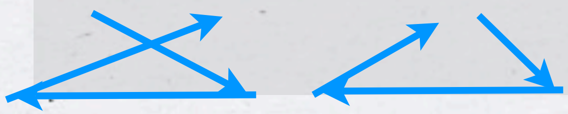
What's new?

$$V_{\rm CKM} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

$+A\lambda^4(1/2-\rho-i\eta)$

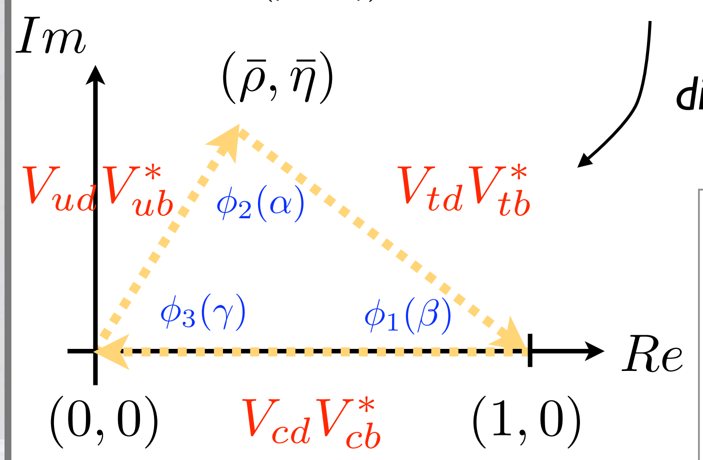
Test of Unitarity:

Verifying if the triangle closes at the apex by independently measuring the three sides and three angles!!



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

divide by $A\lambda^3$



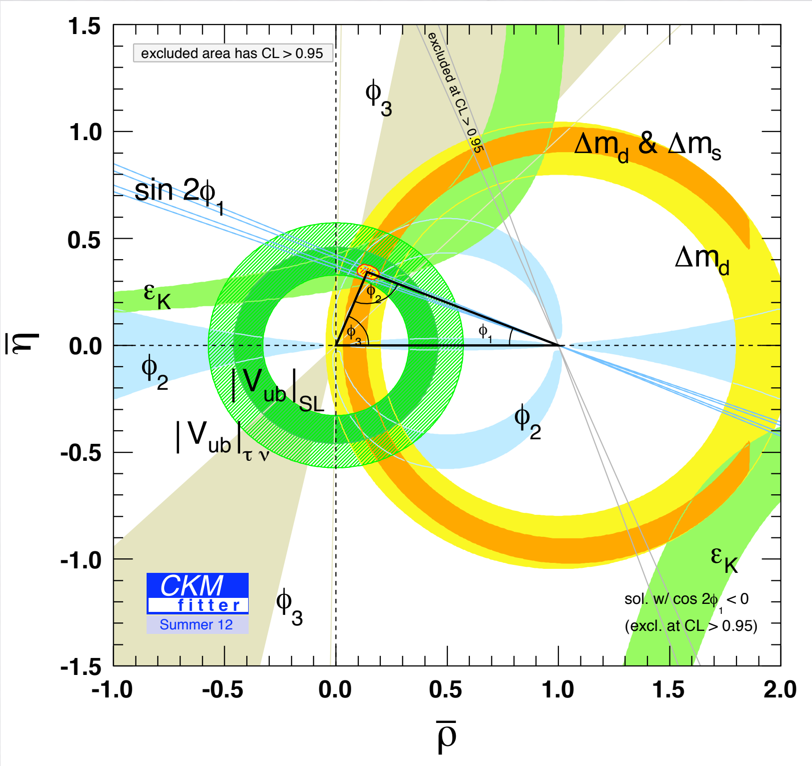
$$arg\left(\frac{V_{tb}^*V_{td}}{V_{cb}^*V_{cs}}\right) \equiv -\phi_1$$

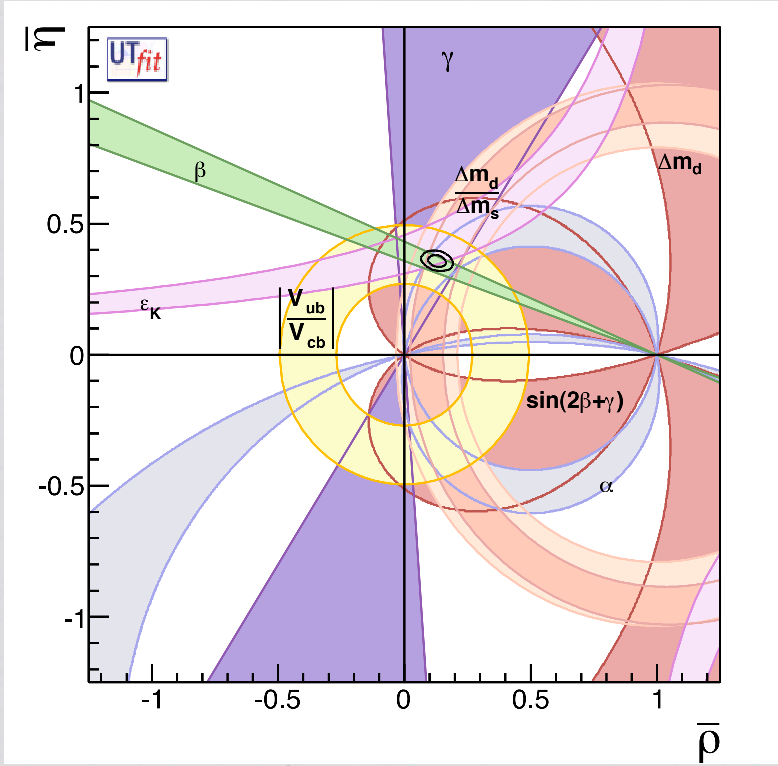
$$arg\left(\frac{V_{tb}^*V_{td}}{V_{ub}^*V_{ud}}\right) \equiv -\phi_2$$

$$arg\left(\frac{V_{cb}^*V_{cs}}{V_{ub}^*V_{ud}}\right) \equiv -\phi_3$$

The CKM unitarity triangle

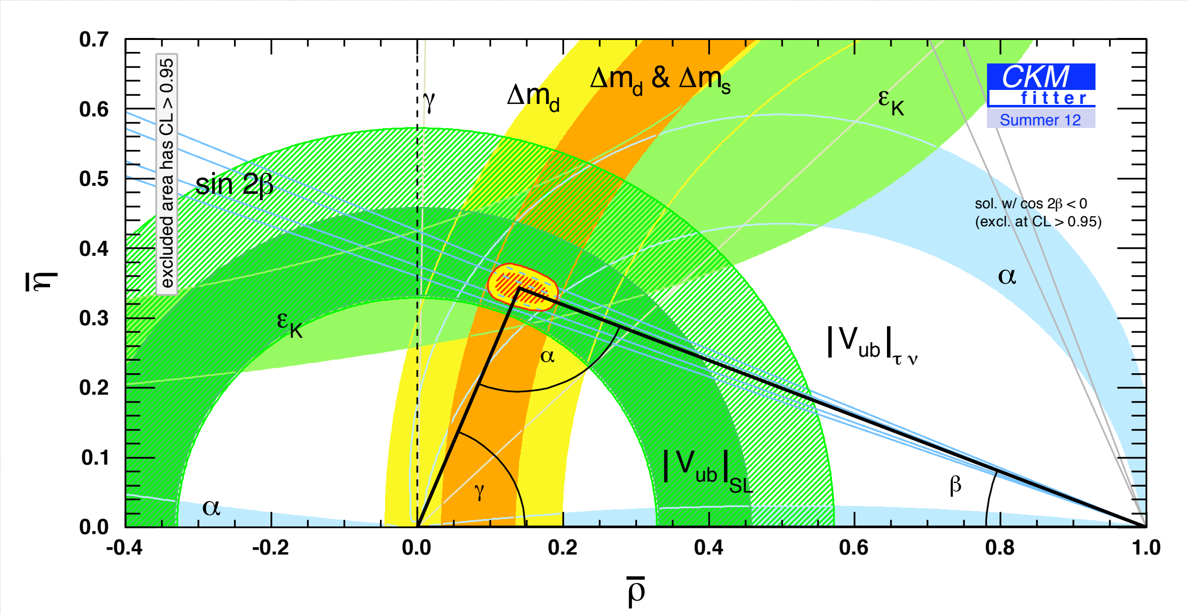
What's new?





The CKM unitarity triangle

What's new?



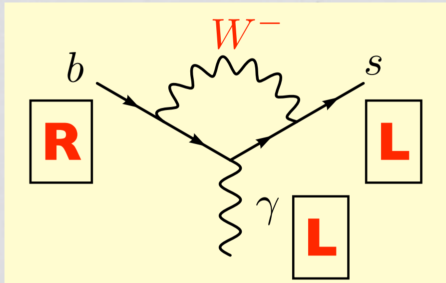
- The B factories measured β at a very high precision (21.7±0.64)°.
- The *main* source of CP violation comes from KM phase.
- For the side determination, the lattice input is crucial!
- Improvement in γ measurement important (LHCb, Belle II -> a few % in the future).

e,g,Vcb http://events.lal.in2p3.fr/WorkshopBdecays/

Prospect of γ polarization measurement

a future possibility for new physics search

- The b ➔sγ process is a good probe of fundamental properties of SM as well as BSM (CKM, top mass, new particle mass etc..)



- Especially, the b→sγ process has a particular structure in SM:

$$\bar{b}A_\mu s = -iV_{tb}V_{ts}^*\frac{G_F}{\sqrt{2}}\frac{e}{8\pi^2}\left[\underbrace{E_0(x_t)\bar{s}_L(q^2\gamma_\mu - q_\mu \not{q})b_L}_{O_{9\sim10}:\ \text{penguin operator}} - \underbrace{m_b E_0'(x_t)\bar{s}_L\sigma_{\mu\nu}q^\nu b_R}_{O_{7\gamma:}\ \text{magnetic operator}}\right]$$

photon off-shell (e.g. semi-leptonic)

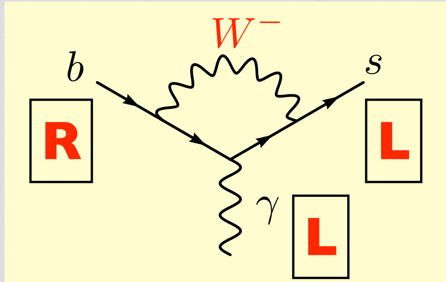
photon on-shell $b_R \rightarrow s_L\, \gamma_L$

W-boson couples only left-handedly ⟺

- $\bar{B}$ ➔s γ_L (left-handed polarization)
- B ➔s γ_R (right-handed polarization)

Prospect of γ polarization measurement

a future possibility for new physics search



- The b ➔sγ process is a good probe of fundamental properties of SM as well as BSM (CKM, top mass, new particle mass etc..)
- Especially, the b→sγ process has a particular structure in SM:

$\bar{b}$ … b_R … ator … *ell*

(e.g. semi-leptonic)

However, this left-handedness of the polarization of b ➔s γ has never been confirmed experimentally at a high precision yet!!

W-boson couples only left-handedly

$\bar{B}$ ➔s γ_L (left-handed polarization)

$\bar{B}$ ➔s γ_R (right-handed polarization)

Current constraints on $C_{7\gamma}$'

The constraint from B→Xs γ measurement?

We can write the amplitude including RH contribution as:

$$\mathcal{M}(b\to s\gamma)\simeq -\frac{4G_F}{\sqrt{2}}V_{ts}^*V_{tb}\left[\underbrace{(C^{\rm SM}_{2/7\gamma/8g}+C^{\rm NP}_{7\gamma})\langle\mathcal{O}_{7\gamma}\rangle}_{\propto\mathcal{M}_L}+\underbrace{C'^{\rm NP}_{7\gamma}\langle\mathcal{O}'_{7\gamma}\rangle}_{\propto\mathcal{M}_R}\right]$$

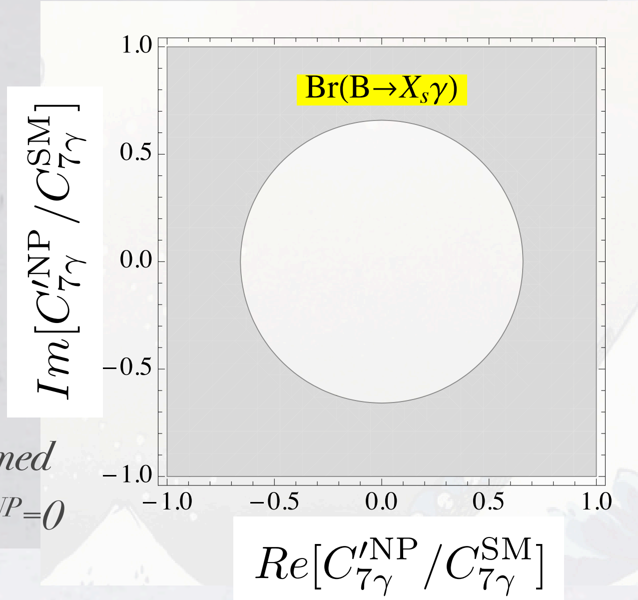
We have a constraint from inclusive branching ratio measurement

$$Br(B\to X_S\gamma)\propto|C^{\rm SM}_{2/7\gamma/8g}+C^{\rm NP}_{7\gamma}|^2+|C'^{\rm NP}_{7\gamma}|^2$$

HFAG $(3.55 \pm 0.24 \pm 0.09)\times 10^{-4}$

While the polarization measurement carries information on

$$\frac{\mathcal{M}_R}{\mathcal{M}_L}\simeq\frac{C'^{\rm NP}_{7\gamma}}{C^{\rm SM}_{7\gamma}+C^{\rm NP}_{7\gamma}}$$



Here we assumed $C'^{NP}_{7\gamma}\neq 0$, $C^{NP}_{7\gamma}=0$

How do we measure the polarization?!

proposed methods

- Method 1: Time dependent CP asymmetry in $B_d \to K_S \pi^0 \gamma$ $B_s \to K^+ K^- \gamma$ (called $S_{K_S \pi^0 \gamma}$, $S_{K^+ K^- \gamma}$)
- Method II: Transverse asymmetry in $B_d \to K^* l^+ l^-$ (called $A_T^{(2)}$, $A_T^{(im)}$)
- Method III: $B \to K_1 (\to K\pi\pi)\gamma$ (called λ_γ)
- Method IV: $\Lambda_b \to \Lambda^{(*)}\gamma$, $\Xi_b \to \Xi^* \gamma$ ...

Atwood et.al. PRL79

Kruger, Matias PRD71
Becirevic, Schneider, NPB854

Gronau et al PRL88
E.K. Le Yaouanc, Tayduganov PRD83

Gremm et al.'95, Mannel et al '97, Legger et al '07, Oliver et al '10

Comparison of the three methods

Becirevic, EK, Le Yaouanc, Tayduganov
arXive:1206.1502

proposed methods

- **Method 1:** Time dependent CP asymmetry in $B_d \to K_S \pi^0 \gamma$ $B_s \to K^+ K^- \gamma$ (called $S_{K_S\pi^0\gamma}$, $S_{K^+K^-\gamma}$)

$$S_{K_S\pi^0\gamma} = \frac{2|C_{7\gamma}^{\rm SM} C_{7\gamma}^{\prime\rm NP}|}{|C_{7\gamma}^{\rm SM}|^2 + |C_{7\gamma}^{\prime\rm NP}|^2} \sin(2\phi_1 - \phi_R) \qquad \phi_R = \arg\left[\frac{C_{7\gamma}^{\prime\rm NP}}{C_{7\gamma}^{\rm SM}}\right]$$

- **Method II:** Transverse asymmetry in $B_d \to K^* l^+ l^-$ (called $A_T^{(2)}$, $A_T^{(im)}$)

$$\mathcal{A}_T^{(2)}(q^2=0) = \frac{2Re[C_{7\gamma}^{\rm SM} C_{7\gamma}^{\prime\rm NP*}]}{|C_{7\gamma}^{\rm SM}|^2 + |C_{7\gamma}^{\prime\rm NP}|^2} \qquad \mathcal{A}_T^{(im)}(q^2=0) = \frac{2Im[C_{7\gamma}^{\rm SM} C_{7\gamma}^{\prime\rm NP*}]}{|C_{7\gamma}^{\rm SM}|^2 + |C_{7\gamma}^{\prime\rm NP}|^2}$$

- **Method III:** $B \to K_1^{1270} (\to K\pi\pi)\gamma$ (called λ_γ)

EK, Le Yaouanc, A.Tayduganov, PRD83 ('11)

$$\lambda = \frac{|C_{7\gamma}^{\prime\rm NP}|^2 - |C_{7\gamma}^{\rm SM}|^2}{|C_{7\gamma}^{\prime\rm NP}|^2 + |C_{7\gamma}^{\rm SM}|^2}$$

Comparison of the three methods

Becirevic, EK, Le Yaouanc, Tayduganov
arXive:1206.1502

proposed methods

▸ Method 1: Time dependent CP asymmetry in $B_d \rightarrow K_S\pi^0\gamma$ $B_s \rightarrow K^+K^-\gamma$ (called $S_{K_S\pi^0\gamma}$, $S_{K^+K^-\gamma}$)

$$S_{K_S\pi^0\gamma} = \frac{2|C_{7\gamma}^{SM} C_{7\gamma}^{\prime NP}|}{|C_{7\gamma}^{SM}|^2 + |C_{7\gamma}^{\prime NP}|^2} \, s\ldots \qquad \phi_R = \arg\left[\frac{C_{7\gamma}^{\prime NP}}{C_{7\gamma}^{SM}}\right]$$

BELLE II
$\sigma_{S_{K_S\pi\gamma}}(0.02)$

▸ Method II: Transverse asymmetry in $B_d \rightarrow K^* l^+ l^-$ (called $A_T^{(2)}$, $A_T^{(im)}$)

$$\mathcal{A}_T^{(2)}(q^2 = 0) = \frac{2Re[C_{7\gamma}^{SM} C_{7\gamma}^{\prime N\ldots}}{|C_{7\gamma}^{SM}|^2 + |C_{7\gamma}^{\prime N\ldots}} \ldots{}^2 = 0) = \frac{2Im[C_{7\gamma}^{SM} C_{7\gamma}^{\prime NP*}]}{|C_{7\gamma}^{SM}|^2 + |C_{7\gamma}^{\prime NP}|^2}$$

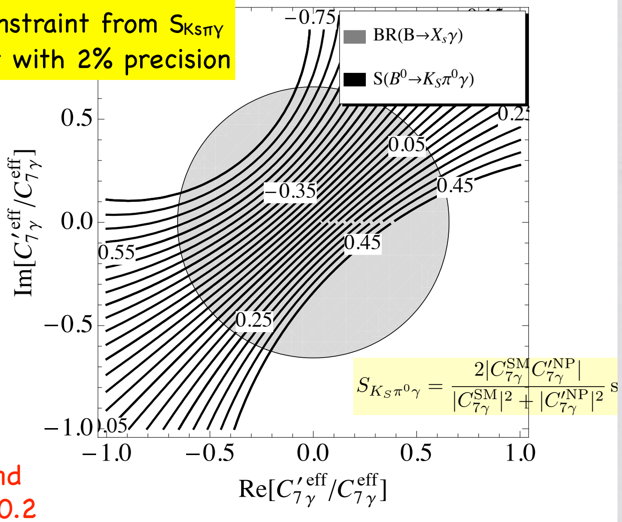
LHCb
$\sigma_{A_T^{2(im)}}(0.2)$

▸ Method III: $B \rightarrow K_1^{1270}(\rightarrow K\pi\pi)\gamma$ (called $\lambda_{\ldots}$) …, Le Yaouanc, A.Tayduganov, PRD83 ('11)

Super B Factory/LHCb
$\sigma_\lambda(0.1\text{-}0.2)$

Method I

Expected constraint from $S_{K_S\pi\gamma}$ measurement with 2% precision

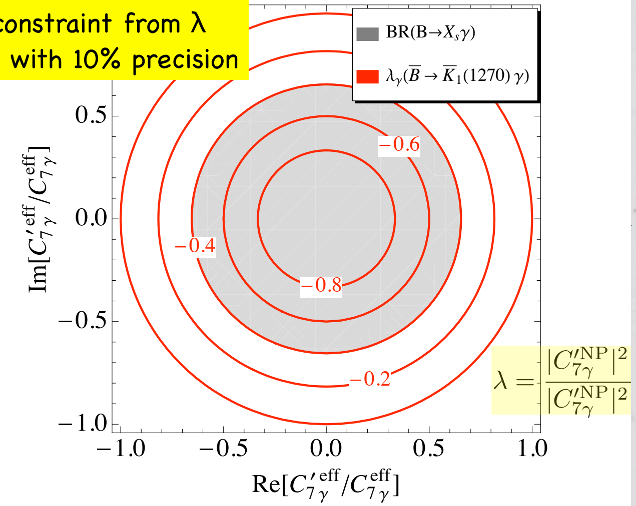


Current bound

$S_{K_S\pi^0\gamma} = -0.15 \pm 0.2$

Method III

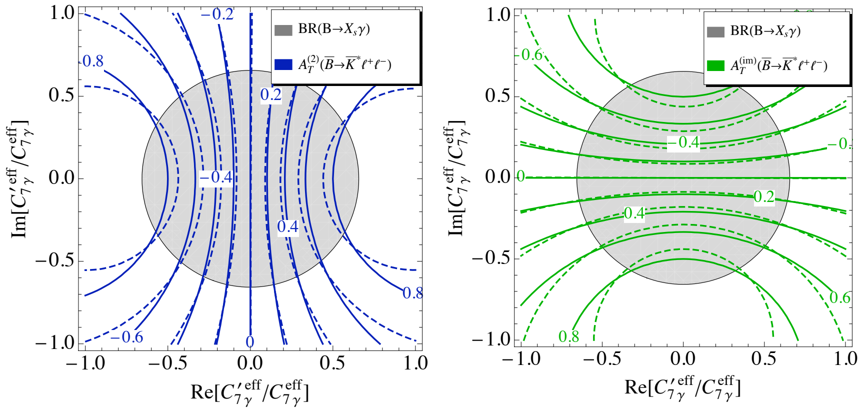
Expected constraint from λ measurement with 10% precision



Method II

Expected constraint from

$A_T^{(2)}$, $A_T^{(im)}$ measurement with 10% precision

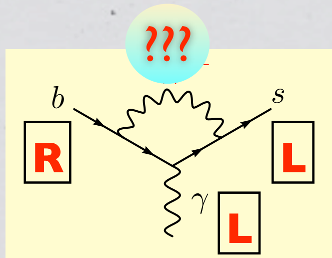


Assumption for γ^*/Z penguin (C_9,C_{10} contributions) necessary!

Becirevic, EK, Le Yaouanc, Tayduganov arXive: 1206.1502

Why right-handed contribution?

What types of new physics models?



What types of new physics models?

For example, models with right-handed neutrino, or custodial symmetry in general induces the right handed current.

Left-Right symmetric model (W_R)	SUSY GUT model δ_{RR} mass insertion
Blanke et al. JHEP1203	***Girrbach et al. JHEP1106***

Which flavour structure?

The models that contain new particles which change the chirality inside of the b➔sγ loop can induce a large chiral enhancement!

Left-Right symmetric model: mt/mb	SUSY with δ_{RL} mass insertions: m_{SUSY}/mb
Cho, Misiak, PRD49, '94 Babu et al PLB333 '94 EK, Lu and Yu, in preparation	***Gabbiani, et al. NPB477 '96 Ball, EK, Khalil, PRD69 '04***

NP signal beyond the constraints from Bs oscillation parameters possible.

Why right-handed contribution?

Left-right symmetric model

Left-Right symmetric model

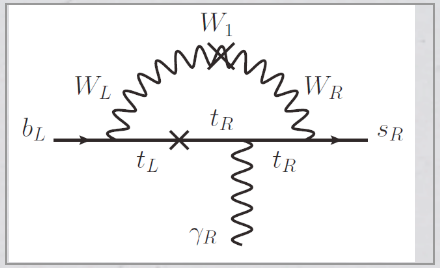
- Left-right symmetric model with general V_{CKM}^{R}:

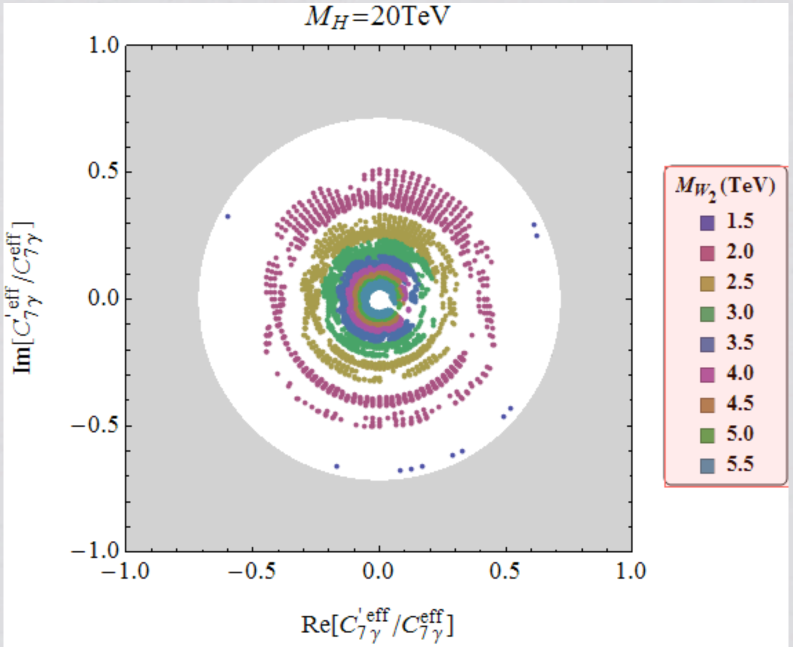
$$SU(2)_L \times SU(2)_R \times U(1)_{B-L}$$

- Chiral enhancement for $C_{7\gamma}'$ occurs with an enhancement factor:

$$(m_t/m_s) \times (V_{ts}^{R}/V_{ts}^{L})$$

- Constrained by various flavour phenomena and new LHC data.





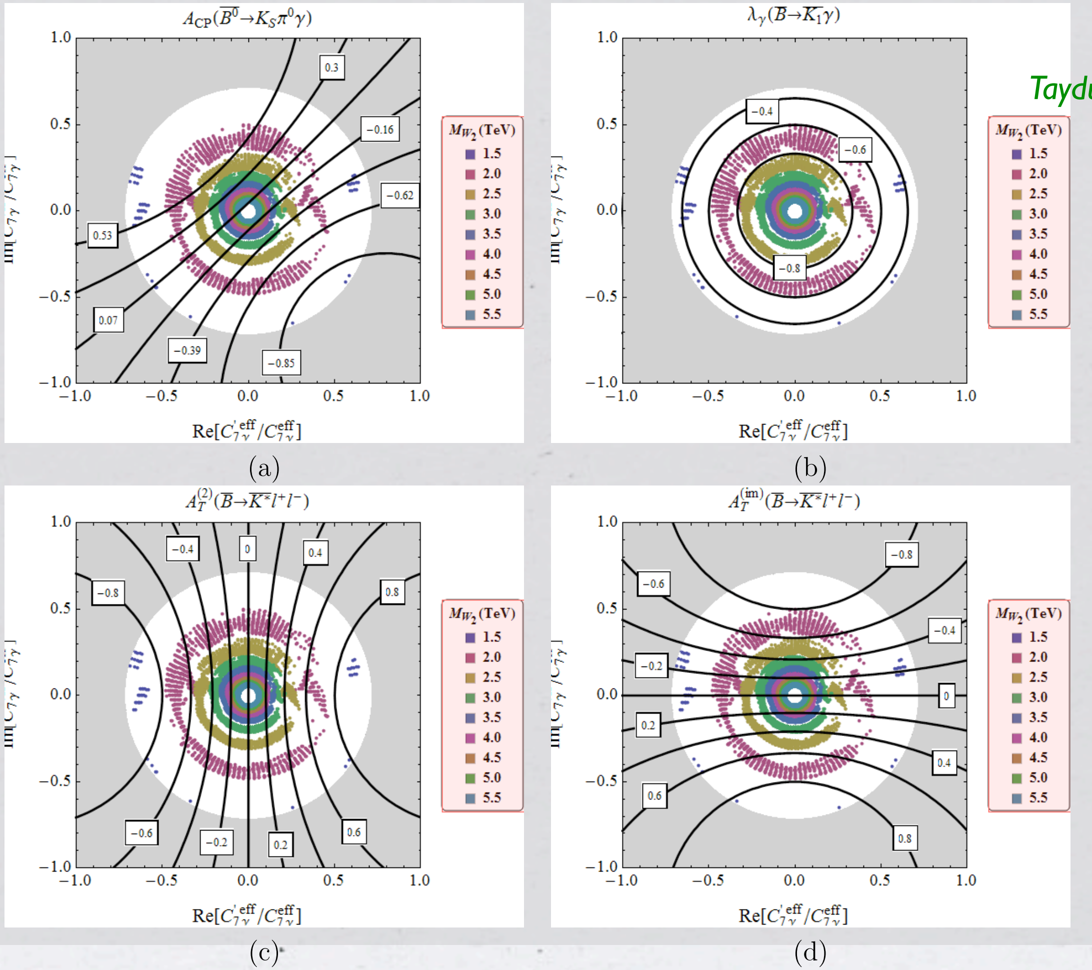
EK and Fusheng Yu in preparation

Why right-handed contribution?

Left-right symmetric model

Becirevic, EK, Le Yaouanc, Tayduganov arXive:1206.1502

EK and Fusheng Yu in preparation



Conclusions

- Highlights of last year: The results on the LHCb benchmark channels are SM-like so far. But future measurements can achieve a higher precision, which may reveal BSM.

- A very high precision in β measurement was achieved by the B factories. LHCb has an ability to significantly improve the precision in γ. For the side determination, progresses in the lattice QCD is essential.

- The photon polarization determination of $b \to s\gamma$ is a new observable which is sensitive to right-handed coupling. Investigation at LHCb has just started! Stay tuned!