CKM matrix and CP violation
~theory~

Emi KOU (LAL/IN2P3-Orsay)

Hadron Collider Physics Symposium 2011
Amphi des Cordeliers, Paris
14th-18th November 2011

Kobayashi-Maskawa mechanism at work!

- SM is a very concise model which incorporates:
  - ✓ Natural suppression of FCNC (i.e. GIM mechanism)
  - ✓ A source of CP violation in the V_{CKM} matrix (i.e. KM mechanism)

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

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

Kobayashi-Maskawa mechanism at work!

- SM is a very concise model which incorporates:
  - ✓ Natural suppression of FCNC (i.e. GIM mechanism)
  - ✓ A source of CP violation in the V_{CKM} matrix (i.e. KM mechanism)

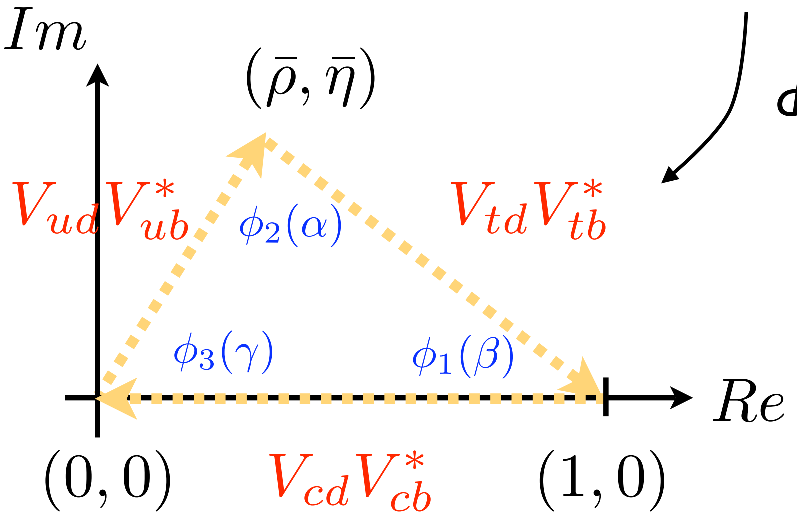
$$V_{\mathrm{CKM}} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

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

Unitarity Triangle

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

divide by $A\lambda^3$



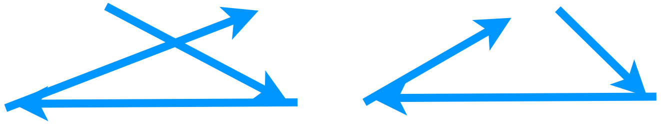
$$arg\left(\frac{V_{tb}^*V_{td}}{V_{cb}^*V_{cs}}\right) \equiv -\phi_1$$

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

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

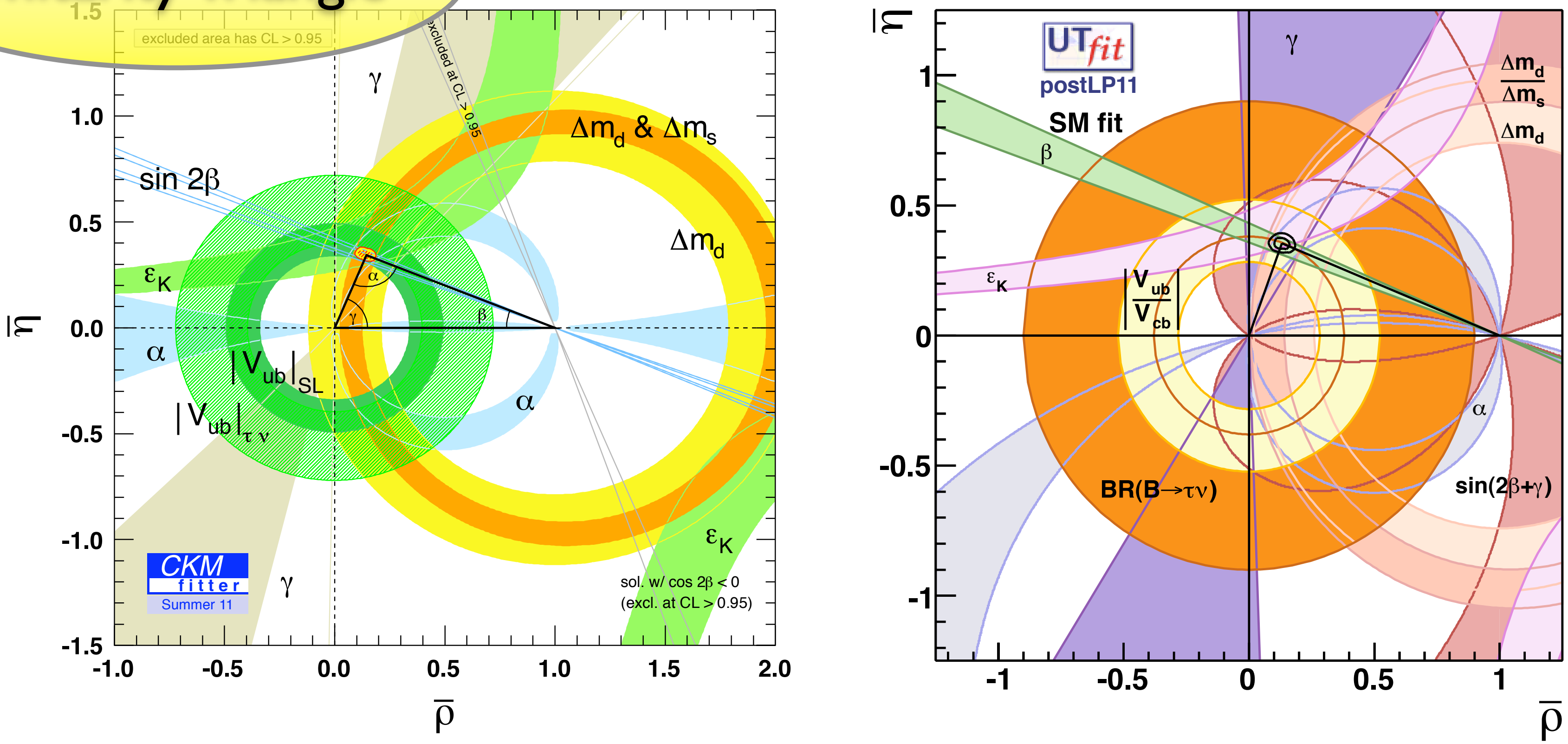
Test of Unitarity

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



Kobayashi-Maskawa mechanism at work!

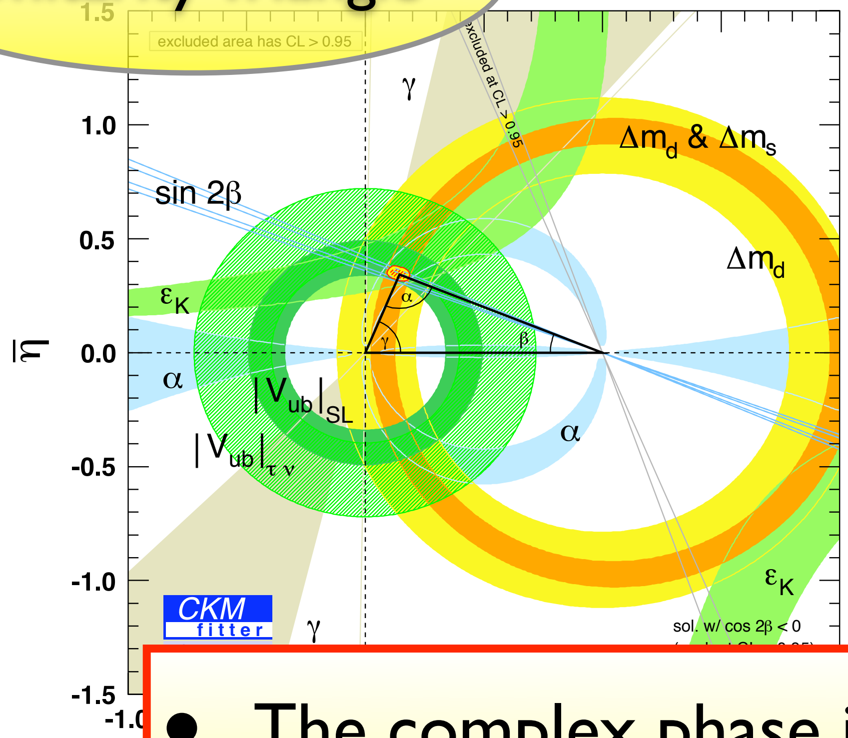
Unitarity Triangle

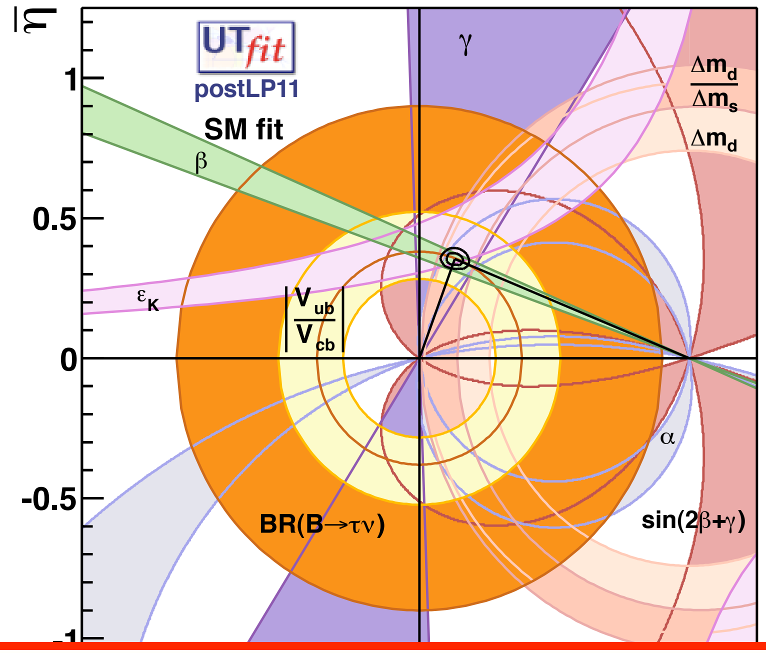


- β is measured to be around (21.7±0.64)° *HFAG*
- Improvement in γ measurement is on-going (B factories, LHCb).
- Issues in V_{ub} measurements. Improvement in the branching ratio measurement of B→τν can be done (SuperB factories).

Kobayashi-Maskawa mechanism at work!

Unitarity Triangle





- β is
- Impr
- Issu
meas

- The complex phase in the CKM matrix seems to be the dominant source of the CP violation in the flavour observable.
- On the other hand, we will show in this talk, there are still plenty of possibilities for new physics!

New physics contributions to the b→s transitions

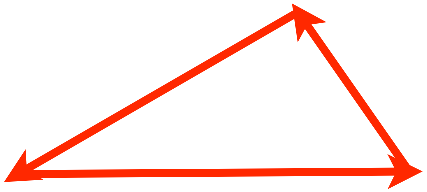
- ★B_s oscillation ($B_s \to J/\psi\Phi$ and A_{SL})
- ★CP measurement with b→sg penguin process
- ★CP and polarisation measurement of b→sγ

$$\underbrace{V_{ud}^* V_{ub}}_{\mathcal{O}(\lambda^3)} + \underbrace{V_{cd}^* V_{cb}}_{\mathcal{O}(\lambda^3)} + \underbrace{V_{td}^* V_{tb}}_{\mathcal{O}(\lambda^3)} = 0$$

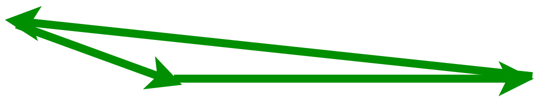
B_d

$$\underbrace{V_{us} V_{ub}^*}_{\mathcal{O}(\lambda^4)} + \underbrace{V_{cs} V_{cb}^*}_{\mathcal{O}(\lambda^2)} + \underbrace{V_{ts} V_{tb}^*}_{\mathcal{O}(\lambda^2)} = 0$$

B_s

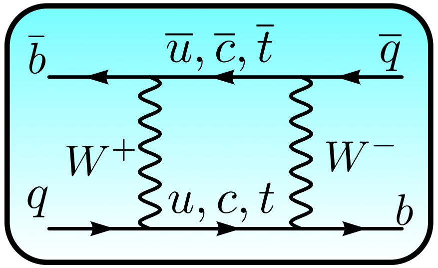


Bd unitarity triangle



Bs unitarity triangle

Oscillation in B_q System



Mass matrix of B_q system:

$$\mathcal{H} = \mathbf{M} - \frac{i}{2}\mathbf{\Gamma} = \begin{pmatrix} M_{11} - \frac{i}{2}\Gamma_{11} & M_{12} - \frac{i}{2}\Gamma_{12} \\ M_{21} - \frac{i}{2}\Gamma_{21} & M_{22} - \frac{i}{2}\Gamma_{22} \end{pmatrix}$$

$$\begin{aligned} \phi_q &\equiv arg[M_{12}] \\ \zeta_q &\equiv arg[\Gamma_{12}] - arg[M_{12}] \end{aligned}$$

When Γ_{12} is real, $\zeta_q = -\Phi_q$

Using CPT invariance, we find the mass eigenstate P_1 and P_2

$$\begin{aligned} |P_1\rangle &= p|P^0\rangle + q|\overline{P}^0\rangle \\ |P_2\rangle &= p|P^0\rangle - q|\overline{P}^0\rangle \end{aligned} \quad ; \qquad \frac{q}{p} = \pm\sqrt{\frac{M_{12}^* - \frac{i}{2}\Gamma_{12}^*}{M_{12} - \frac{i}{2}\Gamma_{12}}}$$

CP violation
$q/p \neq 1$

Experimental measurements are carried out for the observables

HFAG

$$\begin{aligned} \Delta M_q &\equiv M_2 - M_1 = -2|M_{12}| \\ \Delta\Gamma_q &\equiv \Gamma_1 - \Gamma_2 = 2|\Gamma_{12}|\cos\zeta_q \\ \frac{q}{p} &\simeq e^{-i\phi_q}\left(1 + \frac{\Delta\Gamma_q}{2\Delta M_q}\tan\zeta_q\right) \\ \left|\frac{q}{p}\right| &\simeq 1 + \frac{\Delta\Gamma_q}{2\Delta M_q}\tan\zeta_q \end{aligned}$$

ΔM_d=(0.507±0.004) ps^{-1},
ΔM_s=(17.77±0.19±0.07)ps^{-1}

Golden-Channels to measure q/p from time-dependent CP asymmery

$B_d \to c\bar{c}K_s$ ($\Phi_d=2\beta$): sin2β=0.676±0.020
$B_s \to J/\psi\Phi$ ($\Phi_d=2\beta_s$): Tevatron, LHCb
*$\Delta\Gamma/\Delta M$ is non-negligible for B_s

Di-lepton charge asymmetry

A_{SL}^d=-0.0049±0.0038
A_{SL}^s=-0.0089±0.0062

Recent measurements of B_s Oscillation

$$\begin{aligned} \Delta M_q &\equiv M_2 - M_1 = -2|M_{12}| \\ \Delta\Gamma_q &\equiv \Gamma_1 - \Gamma_2 = 2|\Gamma_{12}|\cos\zeta_q \\ \frac{q}{p} &\simeq e^{-i\phi_q}\left(1+\frac{\Delta\Gamma_q}{2\Delta M_q}\tan\zeta_q\right) \\ \left|\frac{q}{p}\right| &\simeq 1+\frac{\Delta\Gamma_q}{2\Delta M_q}\tan\zeta_q \end{aligned}$$

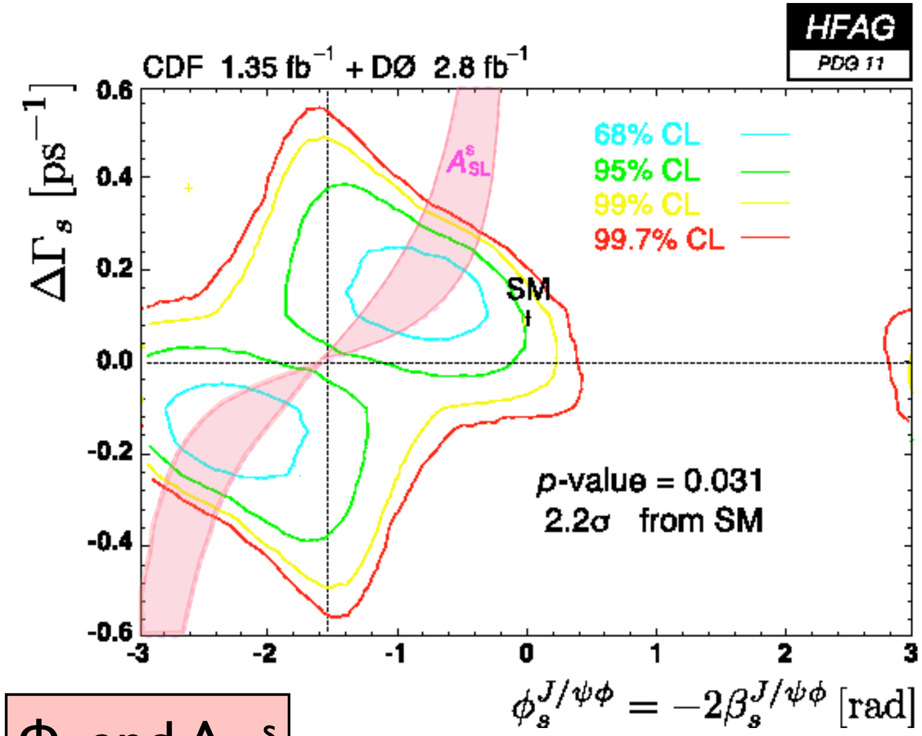
Golden-Channels to measure q/p from time-dependent CP asymmery

$B_s \to J/\psi\Phi$ ($\Phi_d = 2\beta_s$): Tevatron, LHCb

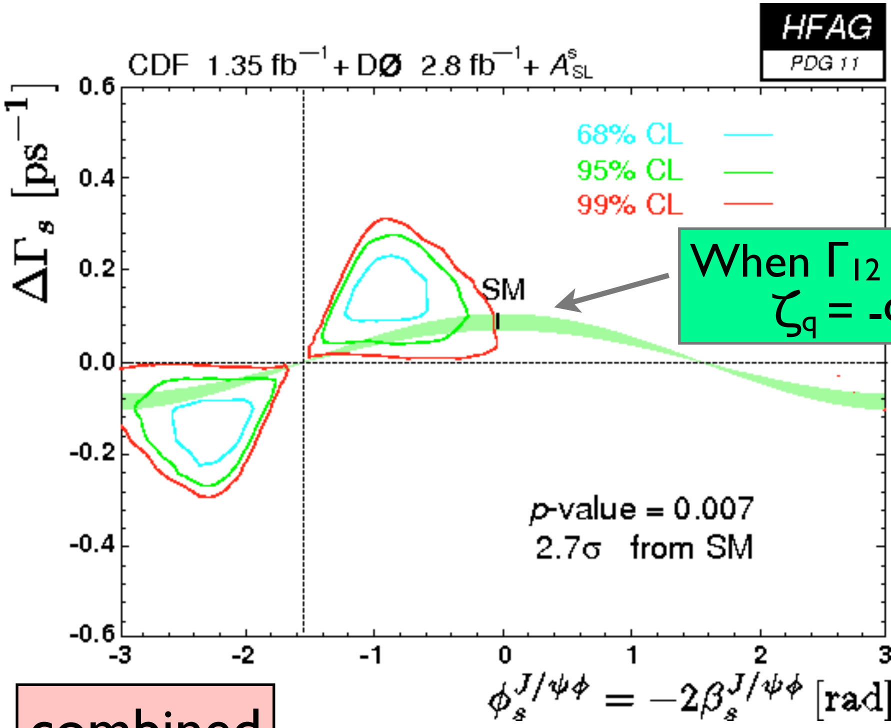
*$\Delta\Gamma/\Delta M$ is non-negligible for B_s

Di-lepton charge asymmetry

$A_{SL}{}^s = -0.0089 \pm 0.0062$



Φ_s and $A_{SL}{}^s$



When Γ_{12} is real, $\zeta_q = -\Phi_q$

combined

Recent measurements of B_s Oscillation

$$\Delta M_q \equiv M_2 - M_1 = -2|M_{12}|$$

$$\Delta\Gamma_q \equiv \Gamma_1 - \Gamma_2 = 2|\Gamma_{12}|\cos\zeta_q$$

$$\frac{q}{p} \simeq e^{-i\phi_q}\left(1 + \frac{\Delta\Gamma_q}{2\Delta M_q}\tan\zeta_q\right)$$

$$\left|\frac{q}{p}\right| \simeq 1 + \frac{\Delta\Gamma_q}{2\Delta M_q}\tan\zeta_q$$

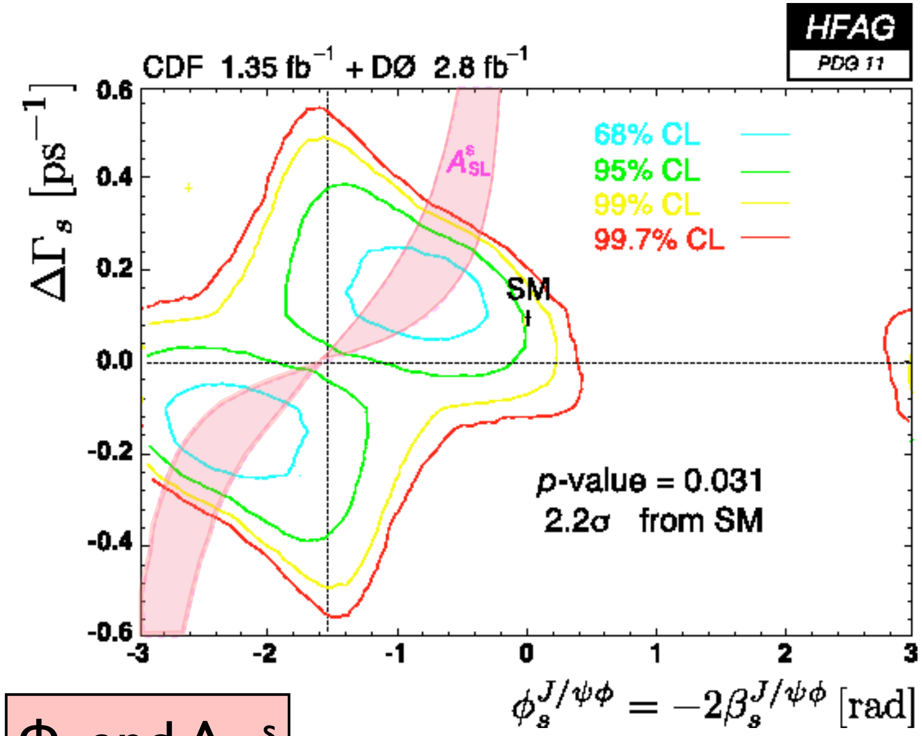
Golden-Channels to measure q/p from time-dependent CP asymmery

$B_s \rightarrow J/\psi\Phi$ ($\Phi_d=2\beta_s$): Tevatron, LHCb

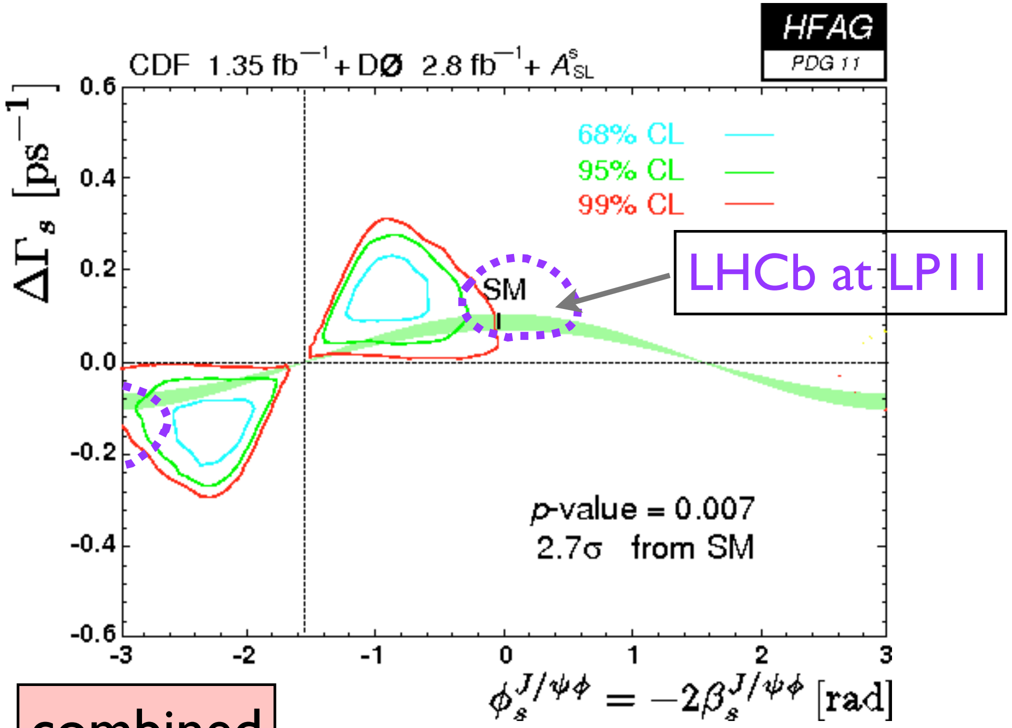
*$\Delta\Gamma/\Delta M$ is non-negligible for B_s

Di-lepton charge asymmetry

$A_{SL}{}^s$= -0.0089±0.0062



Φ_s and $A_{SL}{}^s$



LHCb at LP11

combined

Recent measurements of B_s Oscillation

$$\begin{aligned}
\Delta M_q &\equiv M_2 - M_1 = -2|M_{12}| \\
\Delta\Gamma_q &\equiv \Gamma_1 - \Gamma_2 = 2|\Gamma_{12}|\cos\zeta_q \\
\frac{q}{p} &\simeq e^{-i\phi_q}\left(1 + \frac{\Delta\Gamma_q}{2\Delta M_q}\tan\zeta_q\right) \\
\left|\frac{q}{p}\right| &\simeq 1 + \frac{\Delta\Gamma_q}{2\Delta M_q}\tan\zeta_q
\end{aligned}$$

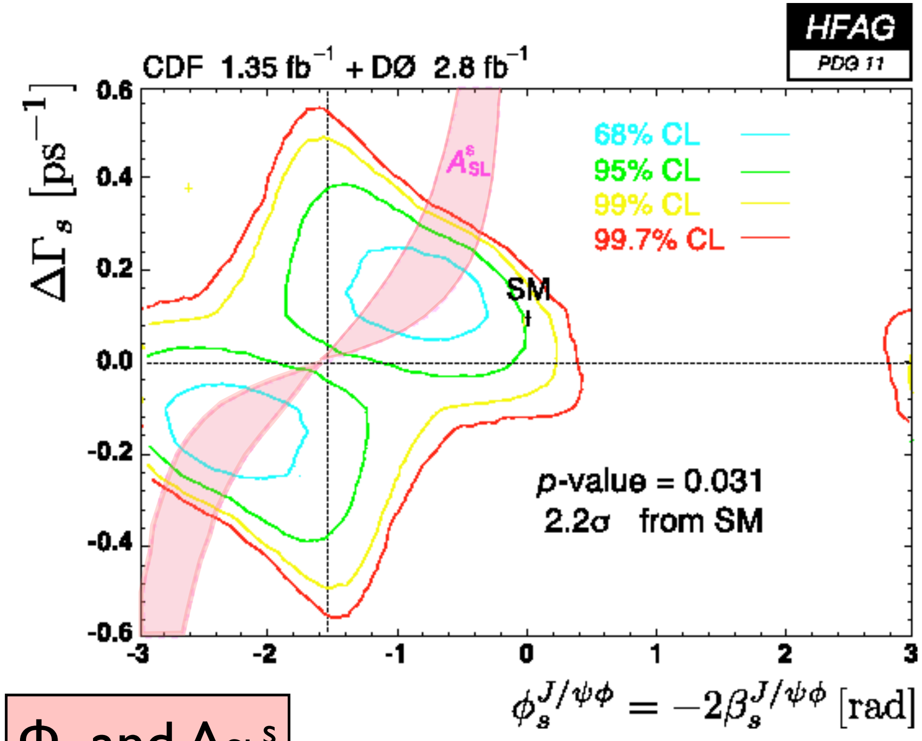
Golden-Channels to measure q/p from time-dependent CP asymmery

$B_s \to J/\psi\Phi$ ($\Phi_d = 2\beta_s$): Tevatron, LHCb

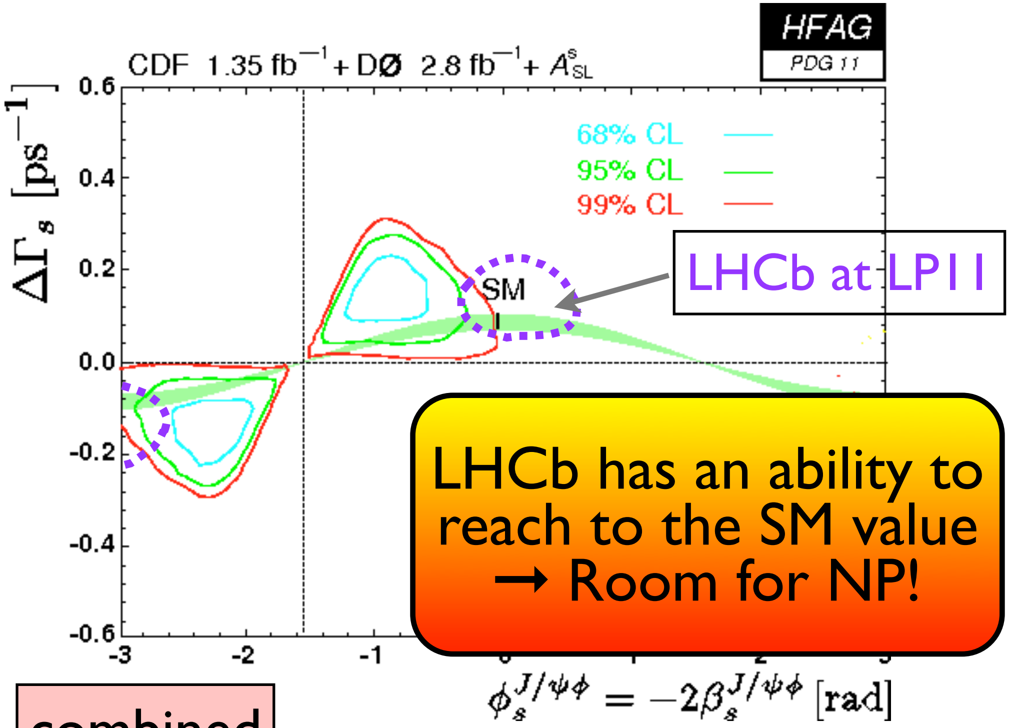
*$\Delta\Gamma/\Delta M$ is non-negligible for B_s

Di-lepton charge asymmetry

$A_{SL}{}^s = -0.0089 \pm 0.0062$



Φ_s and $A_{SL}{}^s$



LHCb at LP11

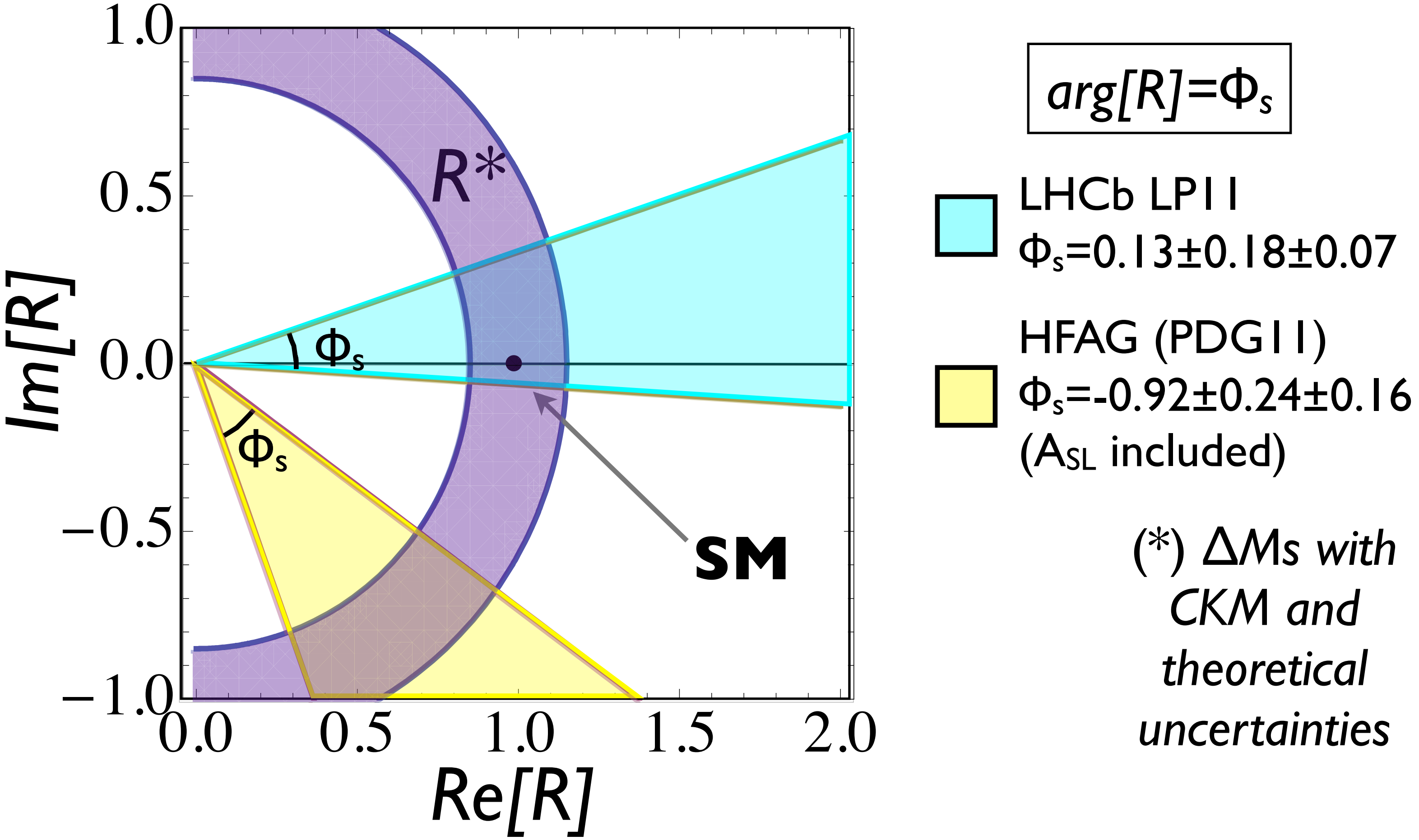
LHCb has an ability to reach to the SM value → Room for NP!

combined

New Physics contributions to Bs Oscillation

- Illustrating the remaining room for new physics

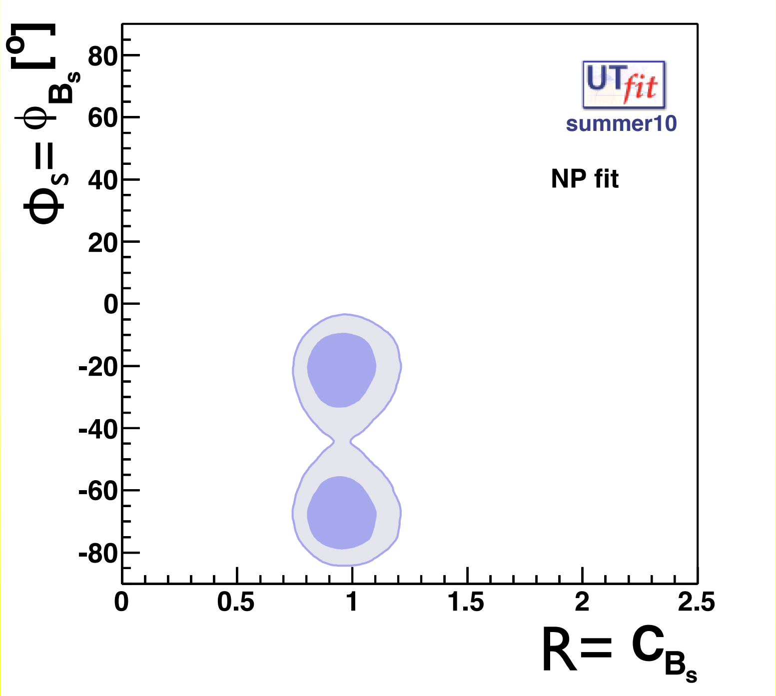
$$R \equiv \frac{\langle B_s^0|\mathcal{H}_{\rm eff}^{\rm SM}+\mathcal{H}_{\rm eff}^{\rm NP}|\overline{B}_s^0\rangle}{\langle B_s^0|\mathcal{H}_{\rm eff}^{\rm SM}|\overline{B}_s^0\rangle} = 1 + r^{\rm NP}e^{i\phi^{\rm NP}}$$

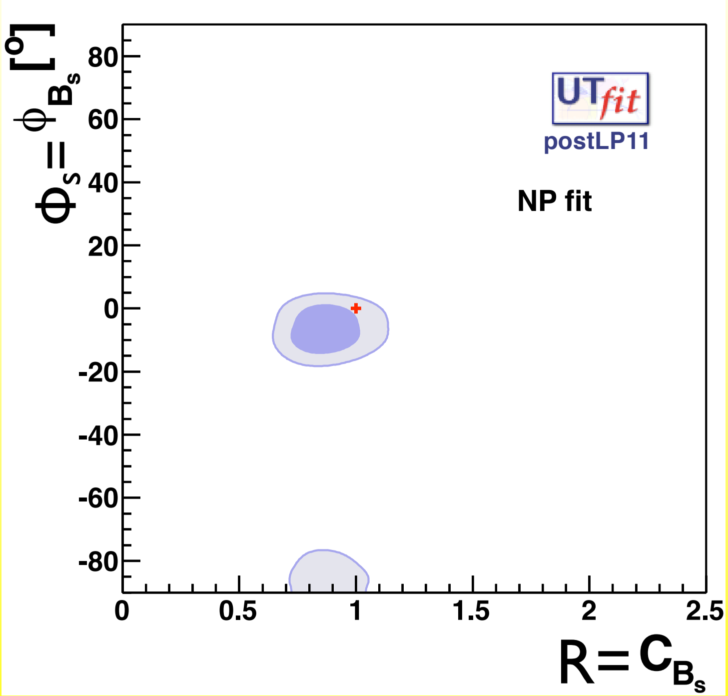


New Physics contributions to Bs Oscillation

- Illustrating the remaining room for new physics

$$R \equiv \frac{\langle B_s^0 | \mathcal{H}_{\mathrm{eff}}^{\mathrm{SM}} + \mathcal{H}_{\mathrm{eff}}^{\mathrm{NP}} | \overline{B}_s^0 \rangle}{\langle B_s^0 | \mathcal{H}_{\mathrm{eff}}^{\mathrm{SM}} | \overline{B}_s^0 \rangle} = 1 + r^{\mathrm{NP}} e^{i\phi^{\mathrm{NP}}}$$



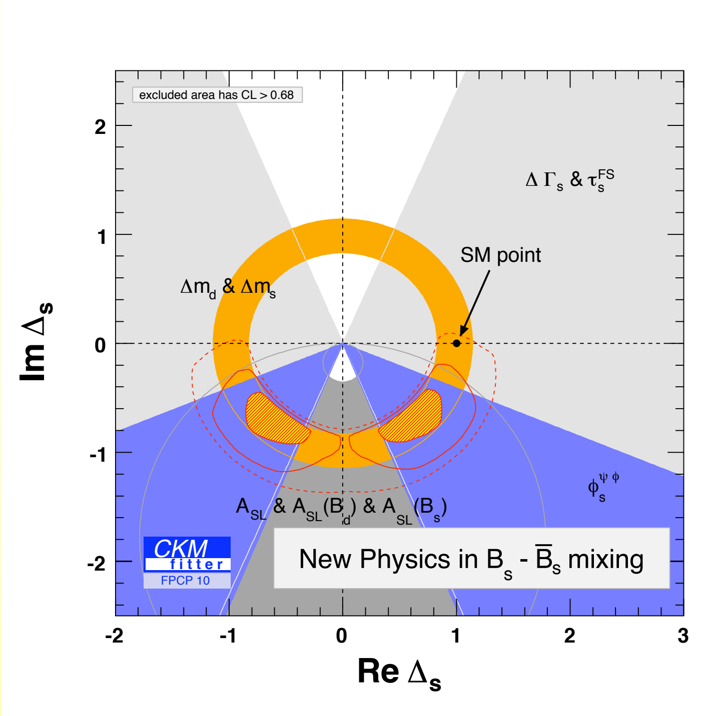


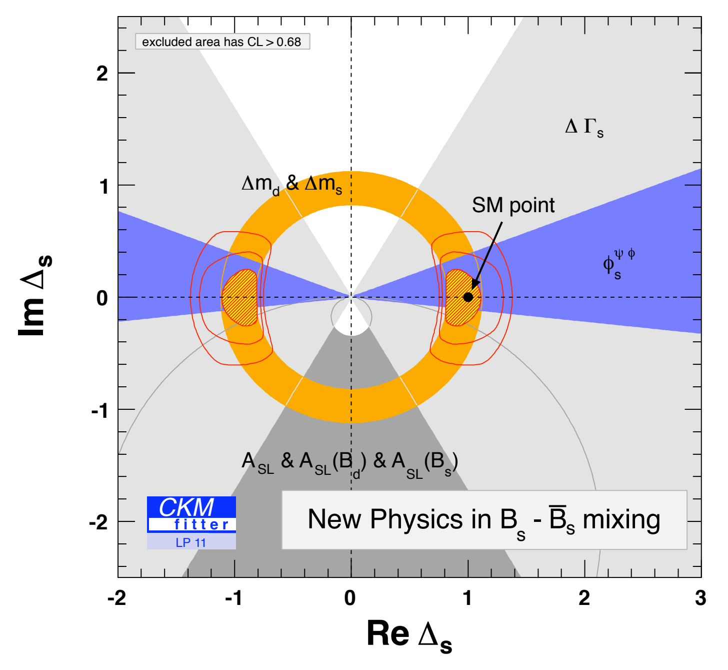
Thanks to D. Derkach for the figures!

New Physics contributions to Bs Oscillation

- Illustrating the remaining room for new physics

$$R \equiv \frac{\langle B_s^0 | \mathcal{H}_{\rm eff}^{\rm SM} + \mathcal{H}_{\rm eff}^{\rm NP} | \overline{B}_s^0 \rangle}{\langle B_s^0 | \mathcal{H}_{\rm eff}^{\rm SM} | \overline{B}_s^0 \rangle} = 1 + r^{\rm NP} e^{i\phi^{\rm NP}}$$

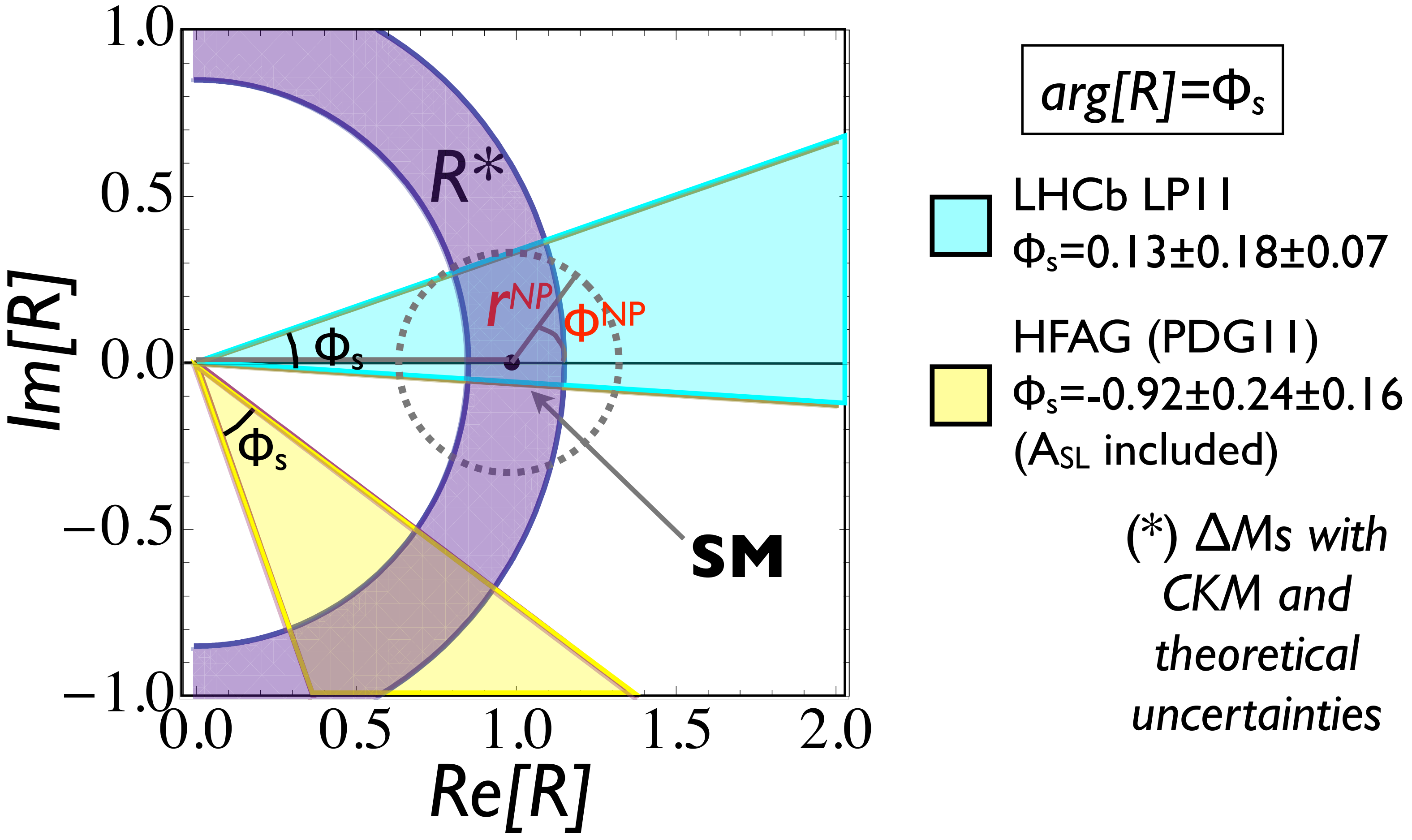




New Physics contributions to Bs Oscillation

- Illustrating the remaining room for new physics

$$R \equiv \frac{\langle B_s^0 | \mathcal{H}_{\rm eff}^{\rm SM} + \mathcal{H}_{\rm eff}^{\rm NP} | \overline{B}_s^0 \rangle}{\langle B_s^0 | \mathcal{H}_{\rm eff}^{\rm SM} | \overline{B}_s^0 \rangle} = 1 + r^{\rm NP} e^{i\phi^{\rm NP}}$$

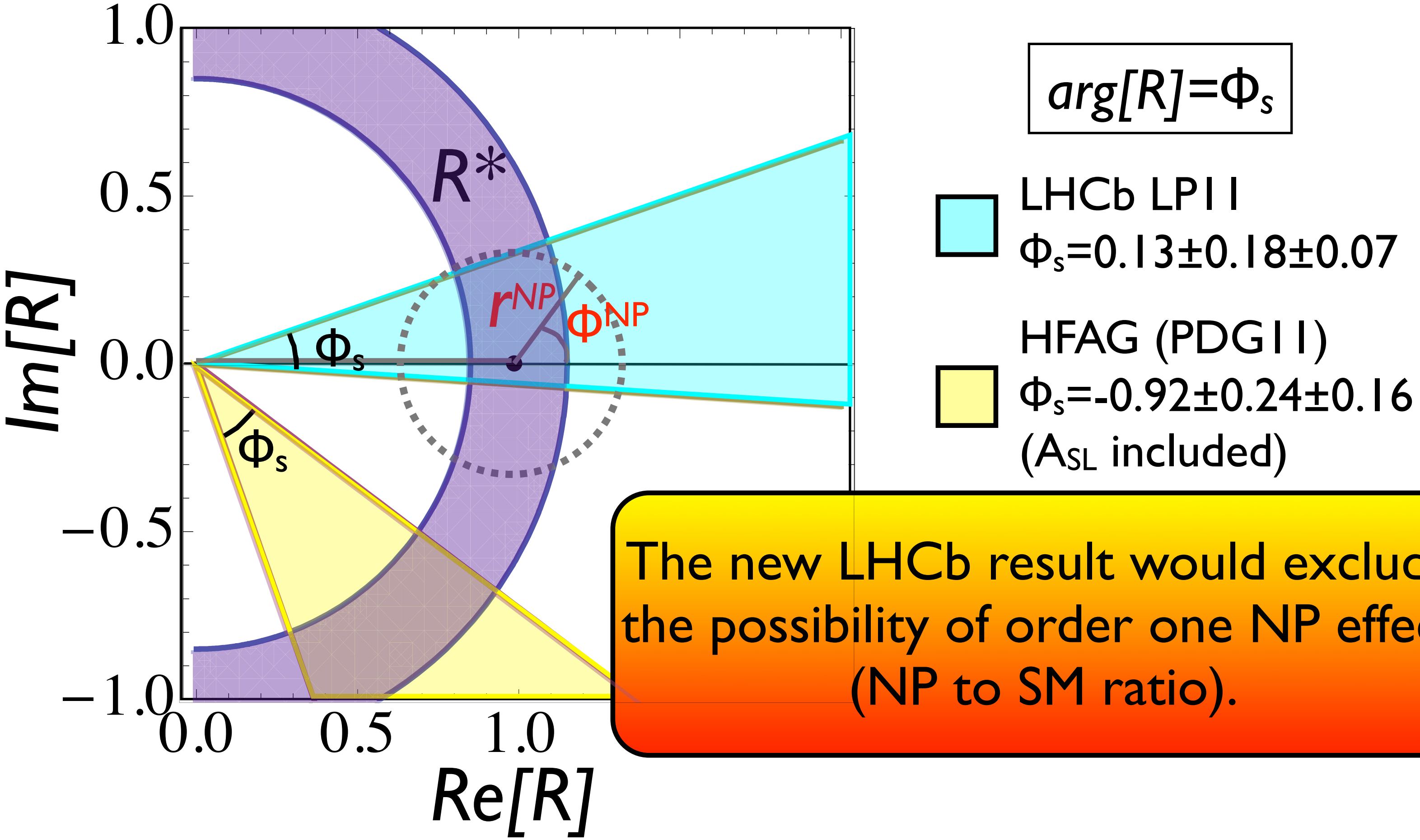


(*) ΔMs with CKM and theoretical uncertainties

New Physics contributions to Bs Oscillation

- Illustrating the remaining room for new physics

$$R \equiv \frac{\langle B_s^0|\mathcal{H}_{\rm eff}^{\rm SM}+\mathcal{H}_{\rm eff}^{\rm NP}|\overline{B}_s^0\rangle}{\langle B_s^0|\mathcal{H}_{\rm eff}^{\rm SM}|\overline{B}_s^0\rangle} = 1 + r^{\rm NP}e^{i\phi^{\rm NP}}$$



The new LHCb result would exclude the possibility of order one NP effect (NP to SM ratio).

New Physics contributions to Bs Oscillation

In the case of 4th generation

$$R \equiv \frac{\langle B_s^0|\mathcal{H}_{\rm eff}^{\rm SM}+\mathcal{H}_{\rm eff}^{\rm NP}|\overline{B}_s^0\rangle}{\langle B_s^0|\mathcal{H}_{\rm eff}^{\rm SM}|\overline{B}_s^0\rangle} = 1 + r^{\rm NP}e^{i\phi^{\rm NP}}$$

- t' contributions in the box
- SM value is modified due to the breaking of unitarity (e.g. $V_{tb} \neq 1$)

⋯⋯⋯

mt'=450GeV
$|V_{t's}|=1 \times \lambda^2$

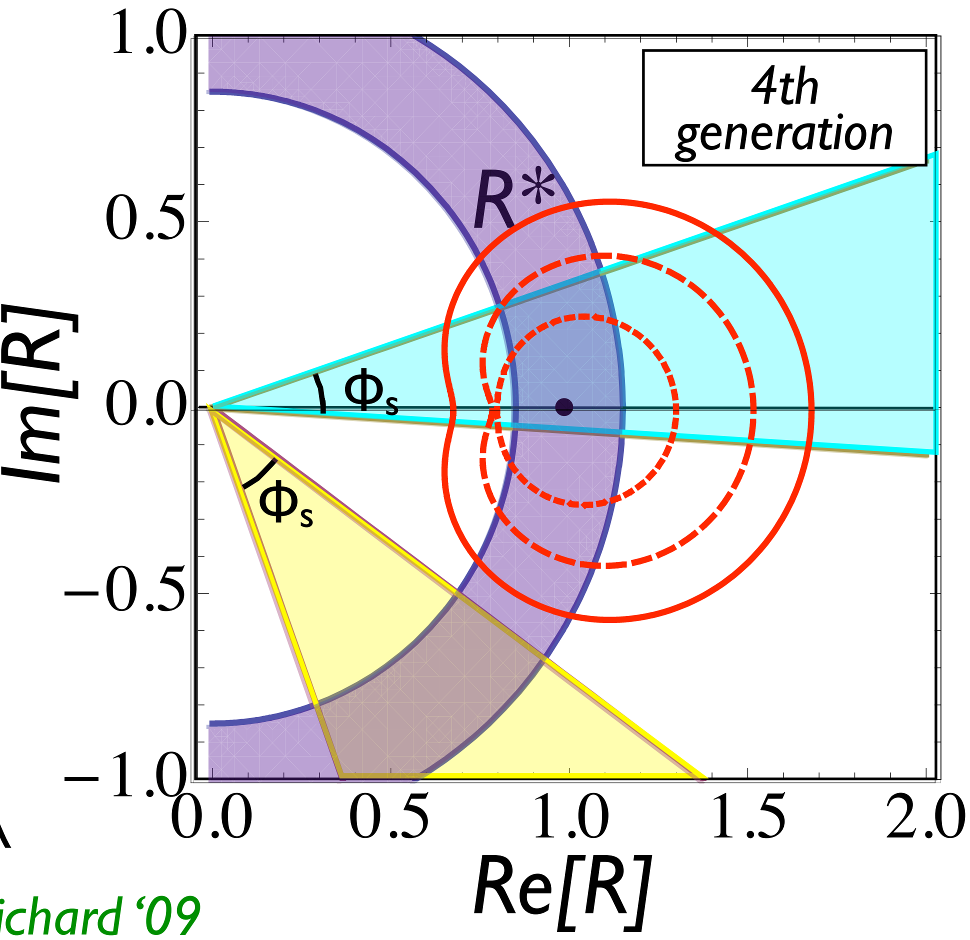
- - -

mt'=700GeV
$|V_{t's}|=1 \times \lambda^2$

———

mt'=450GeV
$|V_{t's}|=2 \times \lambda^2$

and $|V_{t'b}|=1/2 \times \lambda$



arg[R]=Φ_s

🟦 LHCb LP11
$\Phi_s=0.13\pm0.18\pm0.07$

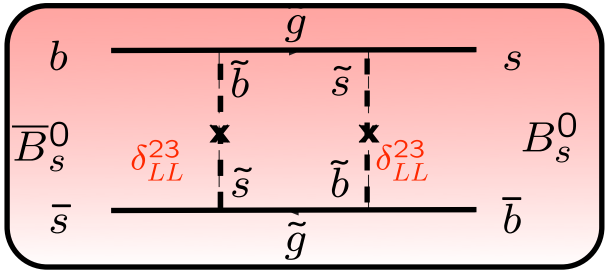
🟨 HFAG (PDG11)
$\Phi_s=-0.92\pm0.24\pm0.16$
(A_{SL} included)

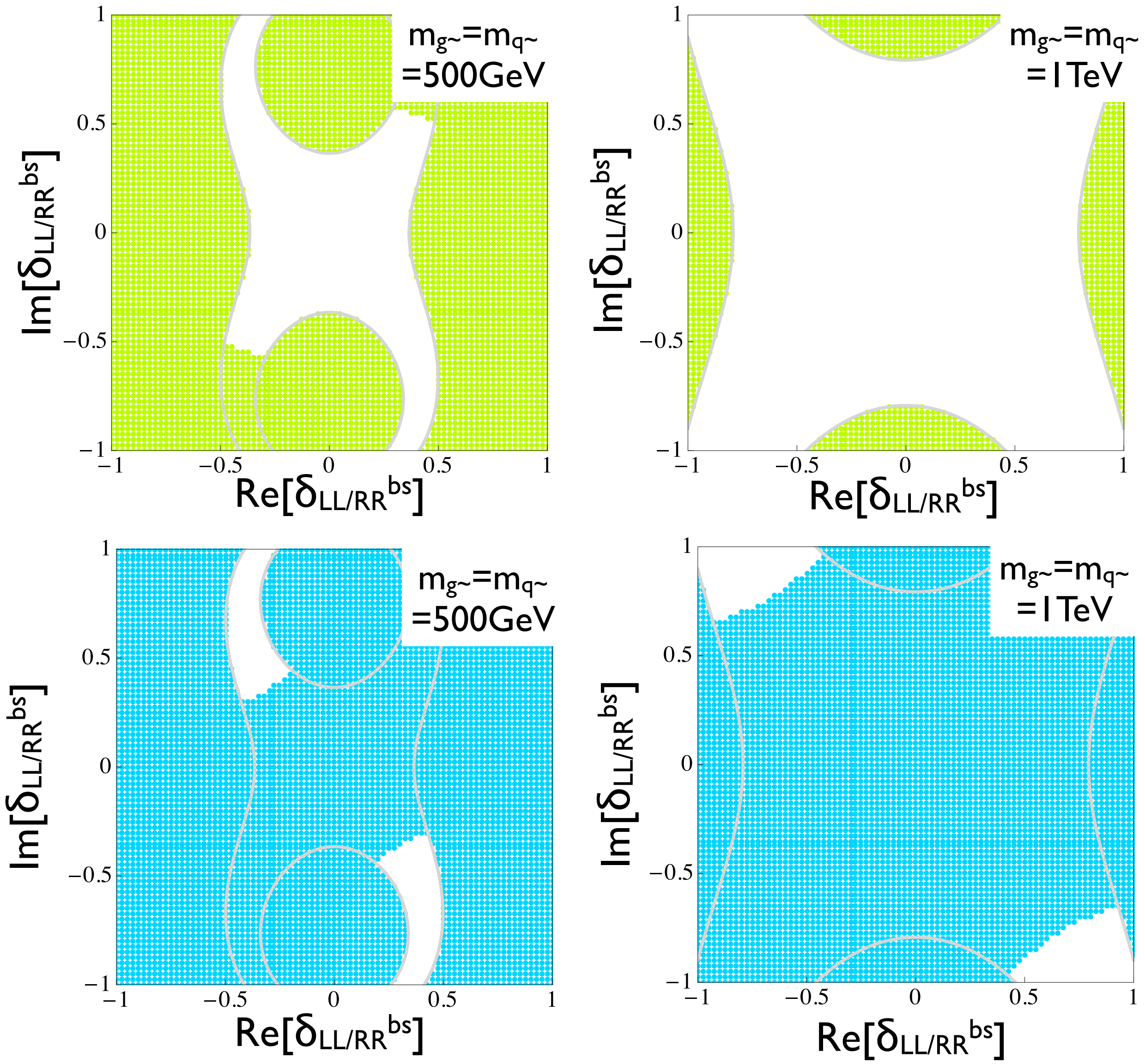
(*) ΔMs with CKM and theoretical uncertainties

E.K. & F. Richard '09

New Physics contributions to Bs Oscillation

In the case of SUSY (non-MFV)





🟩 LHCb LP11
$\Phi_s=0.13\pm0.18\pm0.07$

🟦 HFAG (PDG11)
$\Phi_s=-0.92\pm0.24\pm0.16$
(A_{SL} included)

☐ *ΔMs with CKM and theoretical uncertainties*

E.K. in preparation

β(Φ1) measurements with b→s gluon decay channels

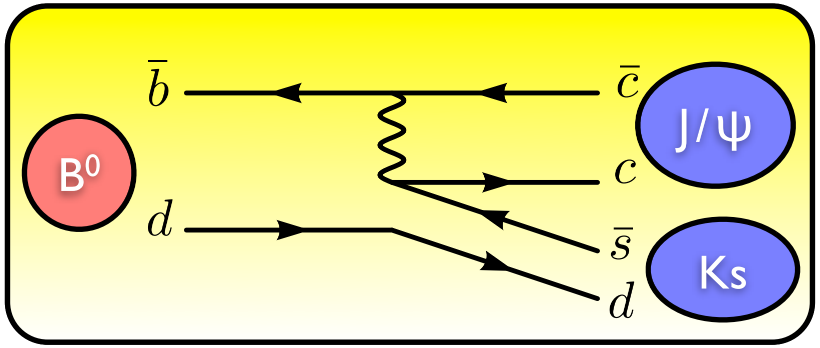
Time dependent CP asymmetry in the B_d system

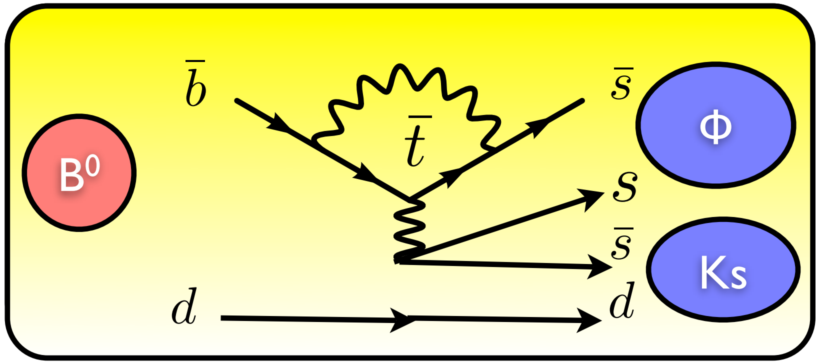
With tree process

$$\begin{aligned} S_{J/\psi K_s} &= Im\left[\underbrace{\frac{M_{12}}{M_{12}^*}}_{oscill.}\underbrace{\frac{A(\overline{B}\to J/\psi K_S)}{A(B\to J/\psi K_S)}}_{decay}\right] \\ &= Im\left[\underbrace{\frac{V_{tb}V_{td}^*}{V_{tb}^*V_{td}}}_{oscill.}\underbrace{\frac{V_{cb}V_{cs}^*}{V_{cb}^*V_{cs}}}_{decay}\right] \\ &= \sin 2\beta(2\phi_1) \end{aligned}$$

With penguin process

$$\begin{aligned} S_{\phi K_s} &= Im\left[\underbrace{\frac{M_{12}}{M_{12}^*}}_{oscill.}\underbrace{\frac{A(\overline{B}\to \phi K_S)}{A(B\to \phi K_S)}}_{decay}\right] \\ &= Im\left[\underbrace{\frac{V_{tb}V_{td}^*}{V_{tb}^*V_{td}}}_{oscill.}\underbrace{\frac{V_{tb}V_{ts}^*}{V_{tb}^*V_{ts}}}_{decay}\right] \\ &= \sin 2\beta(2\phi_1) \end{aligned}$$





β(Φ1) measurements with b→s gluon decay channels

Time dependent CP asymmetry in the B$_d$ system

With tree process

$$S_{J/\psi K_s} = Im\left[\underbrace{\frac{M_{12}}{M_{12}^*}}_{oscill.}\underbrace{\frac{A(\overline{B}\to J/\psi K_S)}{A(B\to J/\psi K_S)}}_{decay}\right]$$

$$= Im$$

$$= \sin 2\beta(2\phi_1)$$

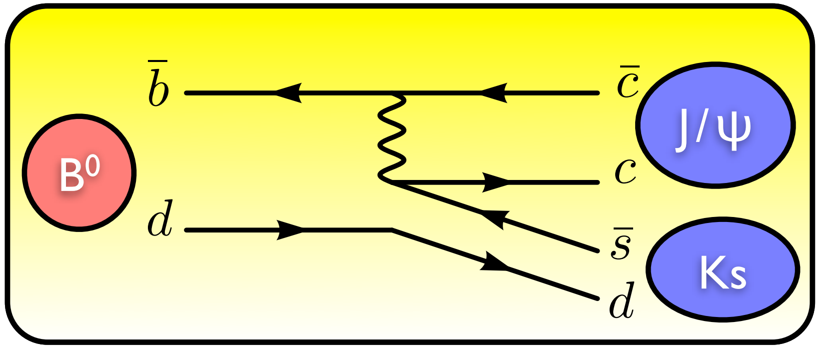
With penguin process

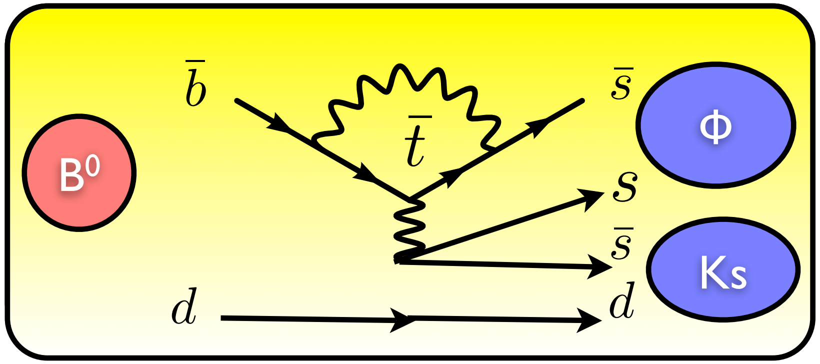
$$S_{\phi K_s} = Im\left[\underbrace{\frac{M_{12}}{M_{12}^*}}_{oscill.}\underbrace{\frac{A(\overline{B}\to \phi K_S)}{A(B\to \phi K_S)}}_{decay}\right]$$

$$\underbrace{\frac{{}_{tb}V_{td}^*}{{}^*_{tb}V_{td}}}_{scill.}\underbrace{\frac{V_{tb}V_{ts}^*}{V_{tb}^*V_{ts}}}_{decay}\Bigg]$$

$$2\beta(2\phi_1)$$

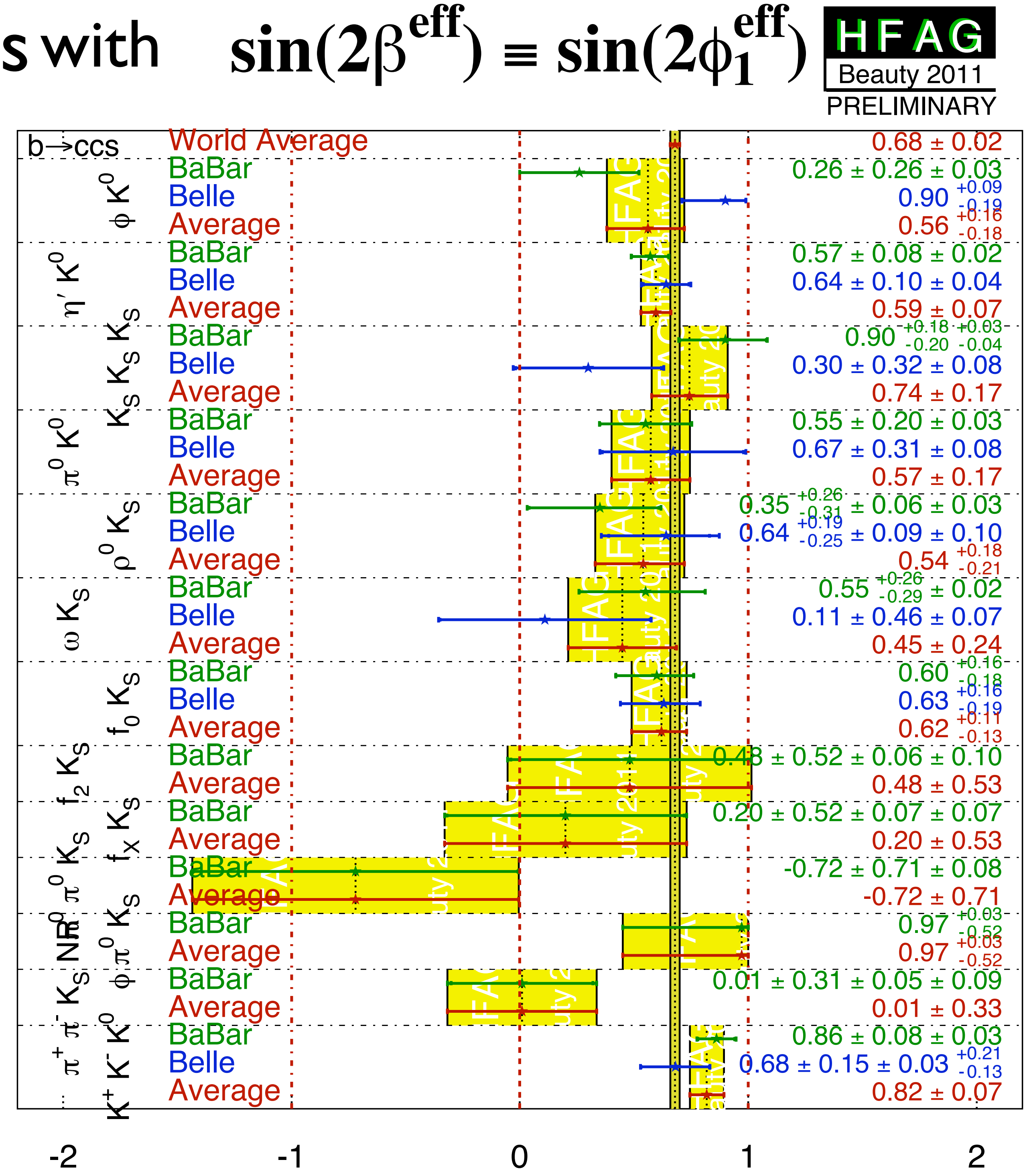
Difference in the measured β(Φ1) value is the indication of the new physics in the penguin loop!





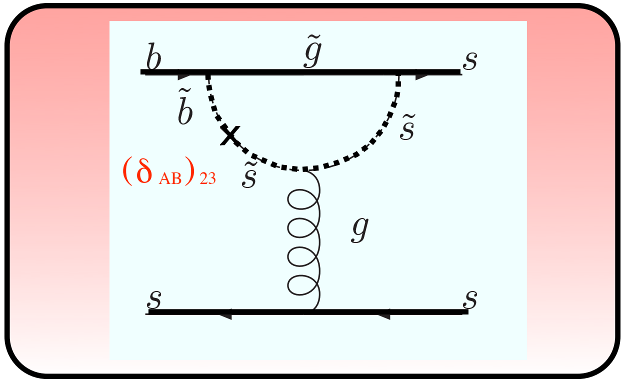
$\beta(\Phi_1)$ measurements with b→s gluon decay channels

- B factories measured various channels.
- The experimental errors are statistic dominant. Thus, SuperB factories can improve the measurement significantly.
- Theoretical errors for some of the channels are still under discussions.
- Similar study can be done for the B_s system with, e.g. $B_s \rightarrow \Phi\Phi$, $B_s \rightarrow \eta'\Phi$ etc.
- New physics contributions for box (B_q oscillation) and penguin can be significantly different.

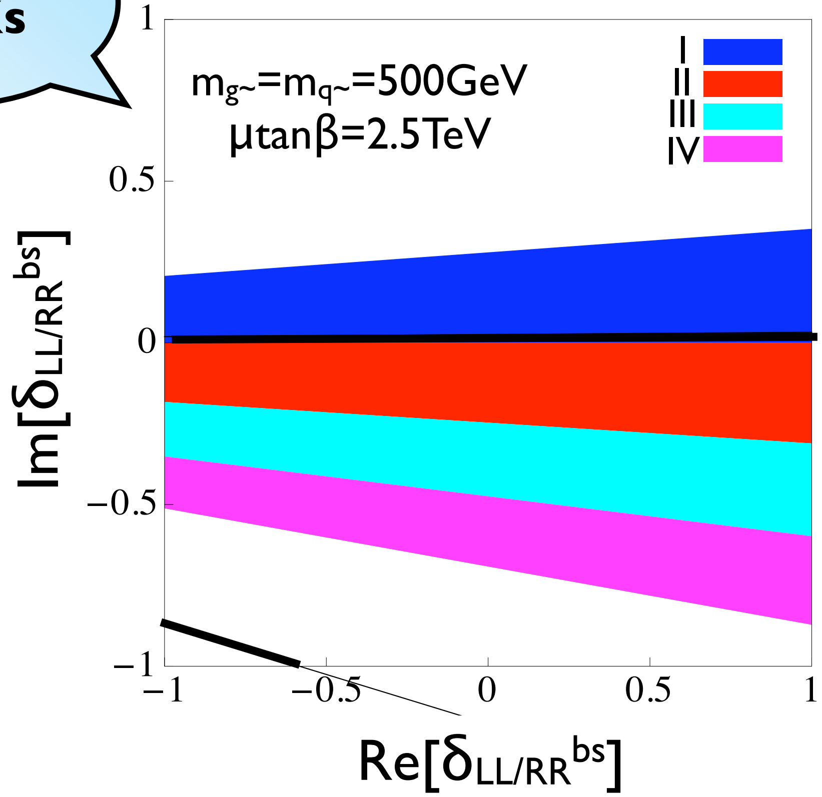


New Physics contributions to $\beta(\Phi_1)$ in $b \to s$ gluon decay channels

In the case of SUSY (non-MFV)



$S_{\phi K_S}$



The expected precision at the SuperB factories:

I: $0<\Delta S_{\phi K_S}<0.1$

II: $-0.1<\Delta S_{\phi K_S}<0$

III: $-0.2<\Delta S_{\phi K_S}<-0.1$

IV: $-0.3<\Delta S_{\phi K_S}<-0.2$

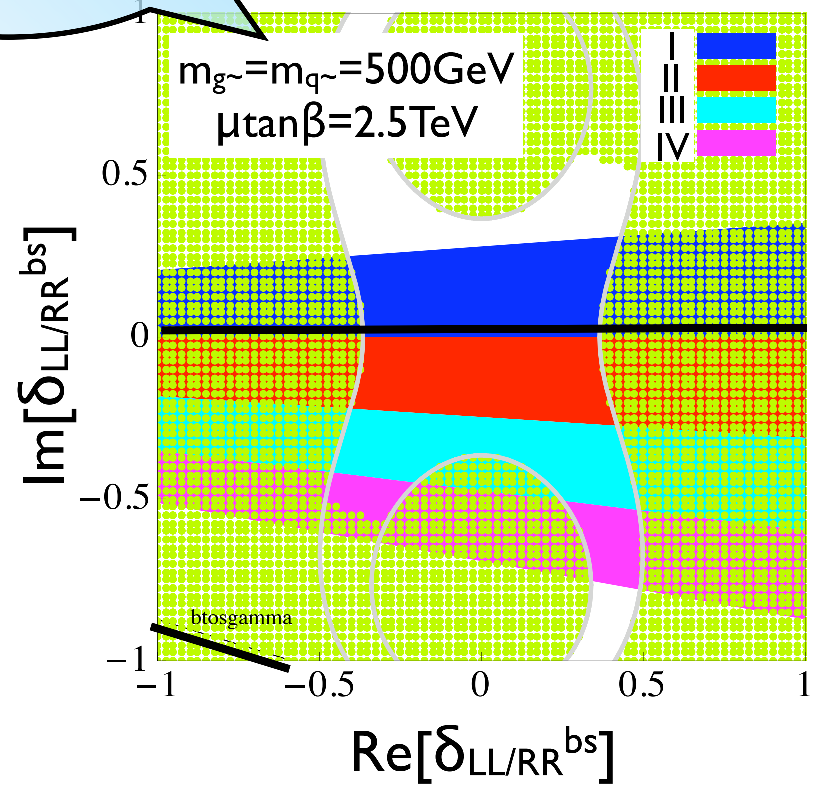
— Current limit $\Delta S_{\phi K_S}=-0.26\pm0.26$

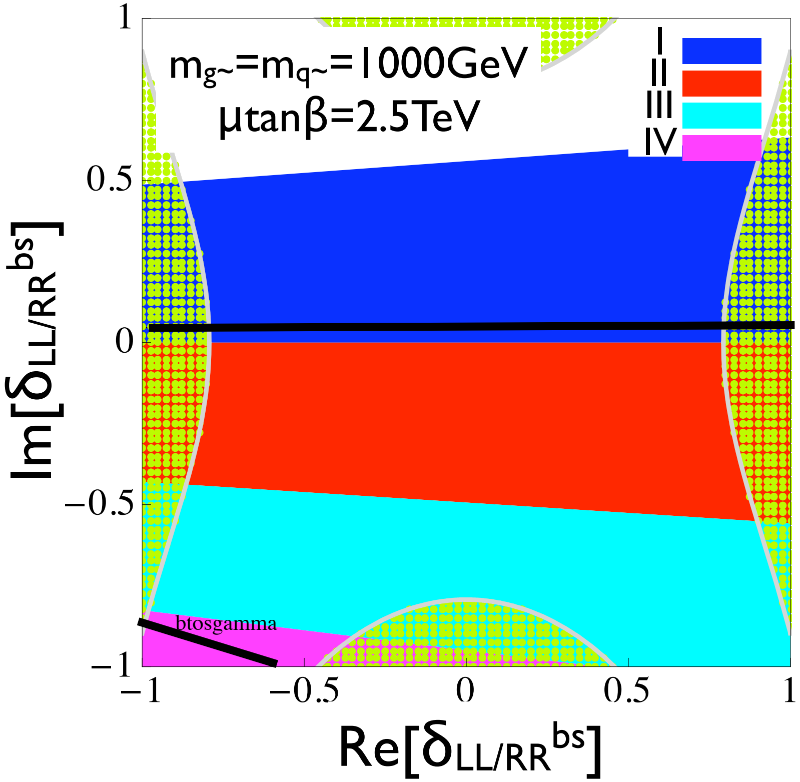
Khalil, E.K. PRD62

New Physics contributions to $\beta(\Phi_1)$ in $b \to s$ gluon decay channels

In the case of SUSY (non-MFV)

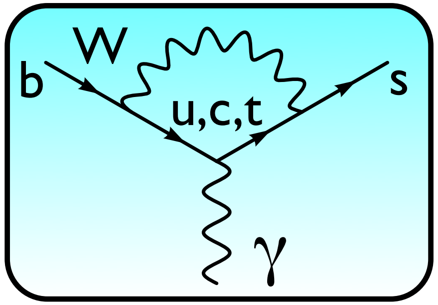
$S_{\phi K_s}$ with Bs Oscillation





Ball, Khalil, E.K. PRD69

New Physics contributions to $b \to s\gamma$



- The $b \to s\gamma$ process is a good probe of fundamental properties of SM as well as BSM (top mass, new particle mass etc...).
- However, this polarisation of $b \to s\ \gamma$ has never been confirmed at a high precision yet!!

W-boson couples only left-handed in SM

⇔

✍ $b \to s\ \gamma_L$ (left-handed polarisation)

✍ $\bar{b} \to \bar{s}\ \gamma_R$ (right-handed polarisation)

Proposed methods

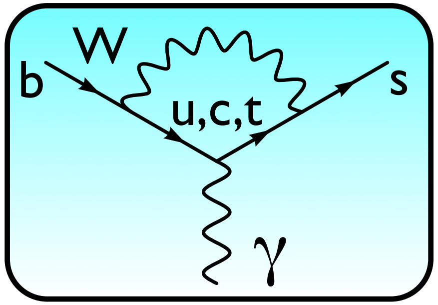
- Method I: Time dependent CP asymmetry in $B_d \to K_S\pi^0\gamma$ $B_s \to K^+K^-\gamma$ (called $S_{K_S\pi^0\gamma}$, S_{K+K-a})
- Method II: Transverse asymmetry in $B_d \to K^* l^+ l^-$ (called $A_T^{(2)}$, $A_T^{(im)}$)
- Method III: $B_d \to K_1(\to K\pi\pi)\gamma$ (called λ_γ)

Atwood et.al. PRL79

Kruger, Matias PRD71
Becirevic, Schneider, NPB854

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

New Physics contributions to b→sγ



- The b ➔sγ process is a good probe of fundamental properties of SM as well as BSM (top mass, new particle mass etc...).
- However, this polarisation of b ➔s γ has never been confirmed at a high precision yet!!

W-boson cou
only left-hand
in SM

handed polarisation)

t-handed polarisation)

Determination of the photon polarisation will be improved in the future!

Proposed methods

- **Method I**: 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-a})
- **Method II**: Transverse asymmetry in $B_d \to K^* l^+ l^-$ (called $A_T^{(2)}$, $A_T^{(im)}$)
- **Method III**: $B_d \to K_1 (\to K\pi\pi)\gamma$ (called λ_γ)

Atwood et.al. PRL79

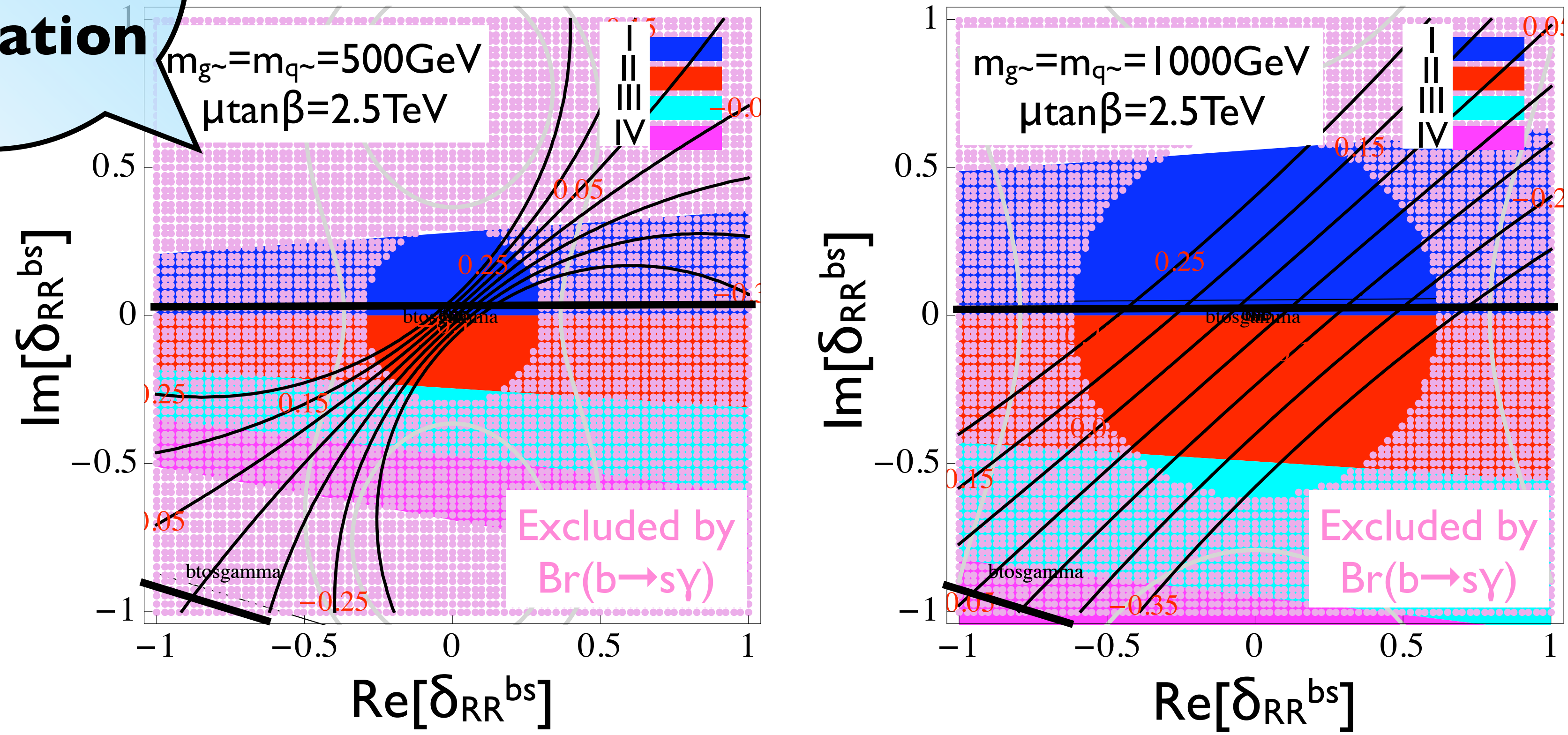
Kruger, Matias PRD71
Becirevic, Schneider, NPB854

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

New Physics contributions to b→sγ

$S_{K_S\pi\gamma}$ with $S_{\phi K_S}$ and Bs Oscillation

In the case of SUSY (non-MFV)



— Current limit $\Delta S_{K_S\pi\gamma}$=-0.15±0.20

Becirevic, E.K., Le Yaounc, Tayduganov in preparation

Conclusions

- The B factory measurements of $\sin 2\beta (2\Phi_1)$ showed that the complex phase in the CKM matrix seems to be the dominant source of the CP violation in the flavour observable.
- However, there are still plenty of room left for new physics!
- We discussed new physics contributions to the various b→s transitions.
  - ★B_s oscillation ($B_s \to J/\psi\Phi$ and A_{SL})
  - ★CP measurement with b→sg penguin process
  - ★CP and polarisation measurement of $b \to s\gamma$
- Combining these different measurements will be useful to pin down the new physics effects in flavour physics.

Backup

Polarisation determination of b→sγ

Photon polarization determination: 3 methods

There are 3 methods proposed to measure the ratio $\mathcal{M}_R/\mathcal{M}_L$ ($\simeq 0$ in the SM):

1. Method 1: time-dependent CP asymmetry in $B^0 \to K^{*0}(\to K_S\pi^0)\gamma$ *[Atwood et al., Phys.Rev.Lett.79 ('97)]*

$$S_{f\gamma} = -\xi_f \frac{2|\mathcal{M}_L\mathcal{M}_R|}{|\mathcal{M}_L|^2 + |\mathcal{M}_R|^2} \sin(\phi_M - \phi_L - \phi_R)$$

2. Method 2: transverse asymmetries in $B^0 \to K^{*0}(\to K^-\pi^+)\ell^+\ell^-$ *[Kruger&Matias, Phys.Rev.D71 ('05); Becirevic&Schneider, arXiv:1106.3283 ('11)]*

$$\mathcal{A}_T^{(2)} = -\frac{Re[\mathcal{M}_R\mathcal{M}_L^*]}{|\mathcal{M}_R|^2 + |\mathcal{M}_L|^2}, \quad \mathcal{A}_T^{(im)} = \frac{Im[\mathcal{M}_R\mathcal{M}_L^*]}{|\mathcal{M}_R|^2 + |\mathcal{M}_L|^2}$$

3. Method 3: K_1 three-body decay method in $B \to K_1(\to K\pi\pi)\gamma$ *[Gronau et al., Phys.Rev.Lett.88, Phys.Rev.D66 ('02)]*

$$\lambda_\gamma = \frac{|\mathcal{M}_R|^2 - |\mathcal{M}_L|^2}{|\mathcal{M}_R|^2 + |\mathcal{M}_L|^2}$$

Polarisation determination of b→sγ

Future constraints on right-handed currents

3 different methods give different constraints:

1. $\mathcal{A}_{CP}(B \to K_S \pi^0 \gamma)$:
   $S^{\text{exp}}_{K_S \pi^0 \gamma} = -0.15 \pm 0.2$
   [HFAG('10)]
   $\sigma(S_{K_S \pi^0 \gamma})^{\text{SuperB}} \approx 0.02$ at 75 ab^{-1}
2. λ_γ potential measurement from ω-distribution in $B \to K_1(1270)\gamma$: $\sigma(\lambda_\gamma)^{\text{th}} \sim 0.2$
3. $A_T^{(2)}$ and $A_T^{(im)}$ potential measurement from the angular analysis of $B^0 \to K^{*0}(\to K^- \pi^+)\ell^+\ell^-$: $\sigma(A_T^{(2)})^{\text{LHCb}} \approx 0.2$ at 2 fb^{-1}