Review on New Physics in Heavy Flavors: B-Meson Sector

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15 - 21 July 2012

Score After $1fb^{-1}$ of LHCb Data

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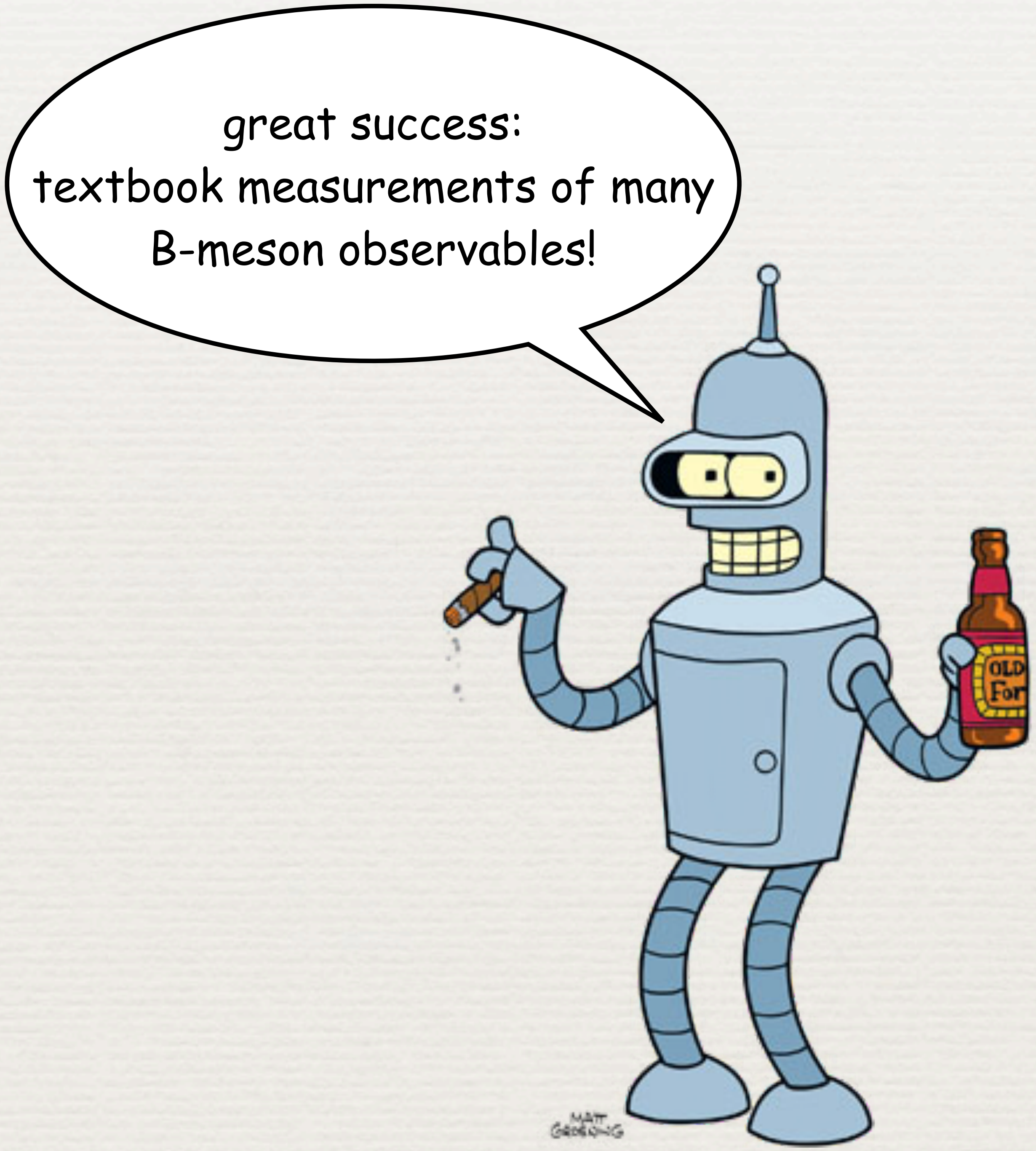

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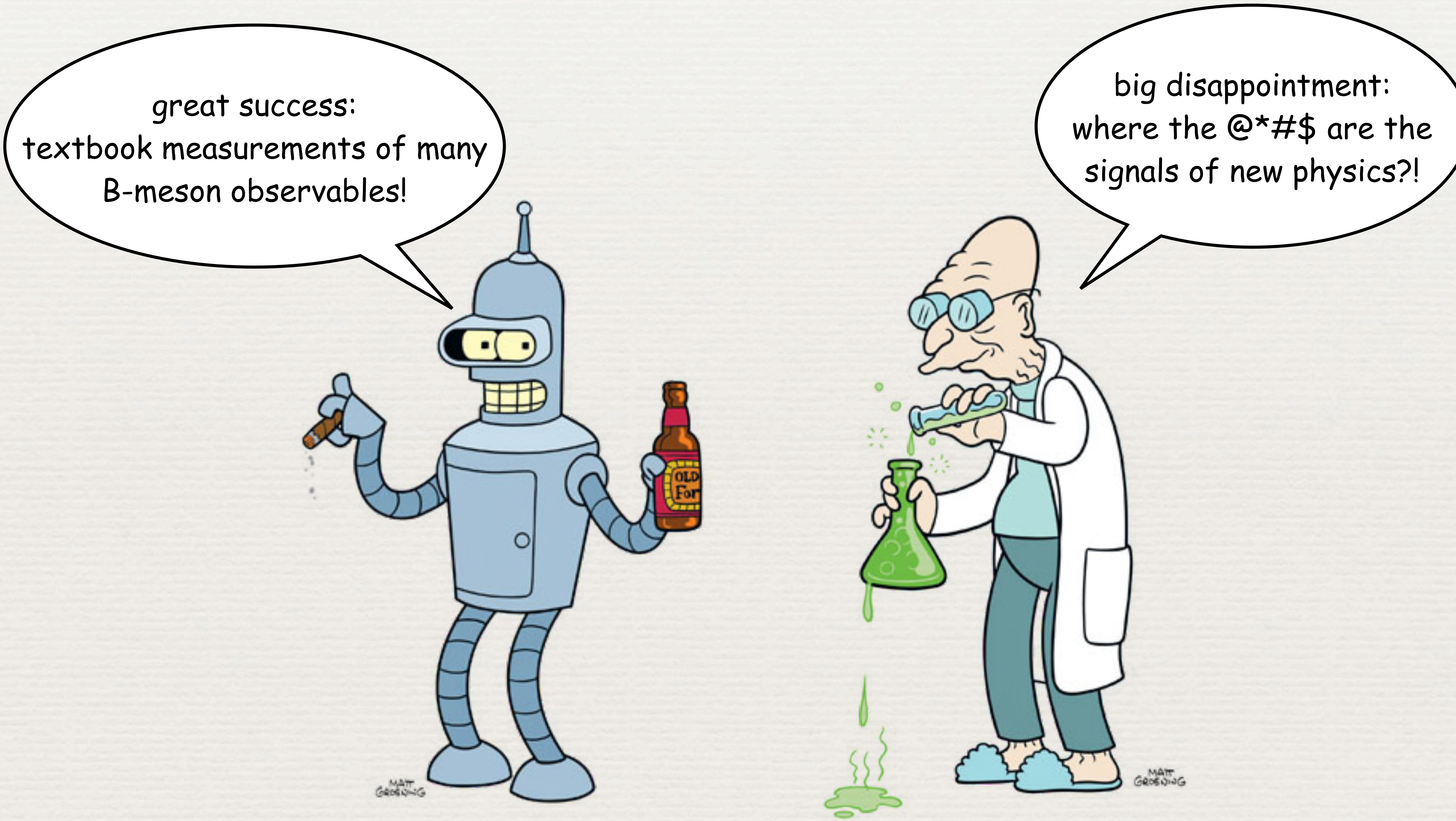
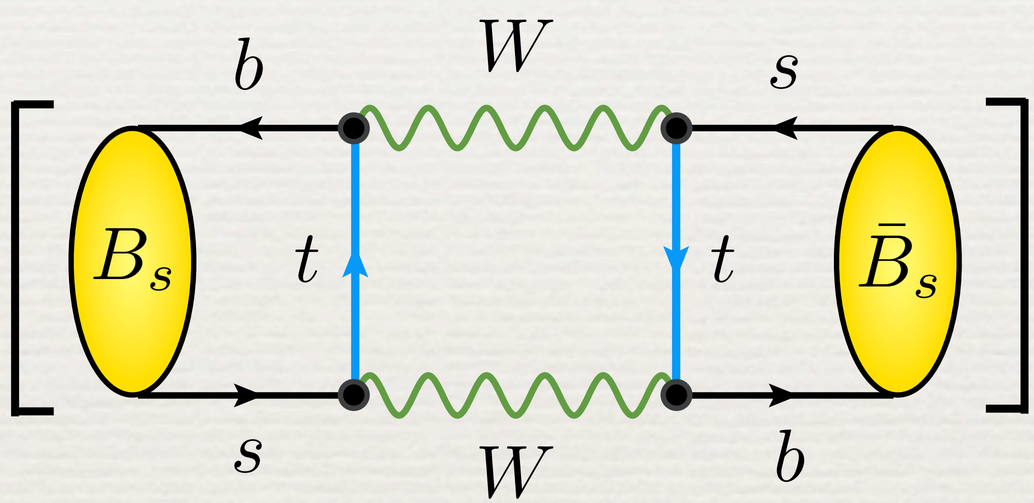


B-Meson Mixing

Standard Model & Beyond

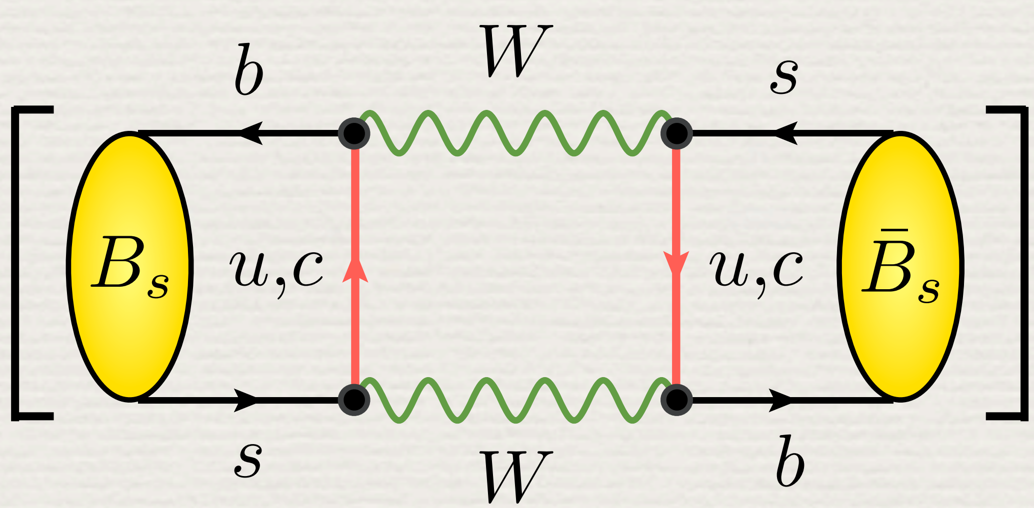
- B_s–$\bar{B}_s$ oscillations encoded in elements M_{12} & Γ_{12} of hermitian mass & decay rate matrices (CPT $\Rightarrow$ $M_{11} = M_{22}$, $\Gamma_{11} = \Gamma_{22}$). In Standard Model (SM) leading effects due to electroweak box diagrams:

$(M_{12})_{\mathrm{SM}} \propto \mathrm{Re}$



dispersive part arising from "off-shell" top quark

$(\Gamma_{12})_{\mathrm{SM}} \propto \mathrm{Im}$

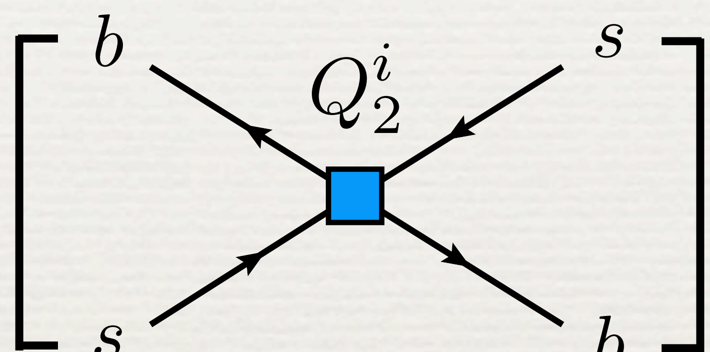


absorptive part related to "on-shell" light up-type quarks

Standard Model & Beyond

- Generic, sufficiently heavy new physics (NP) in M_{12} (Γ_{12}) can be described via effective $\Delta B = 2$ ($\Delta B = 1$) interactions:

$$(M_{12})_{\rm NP} \propto C_2^i$$

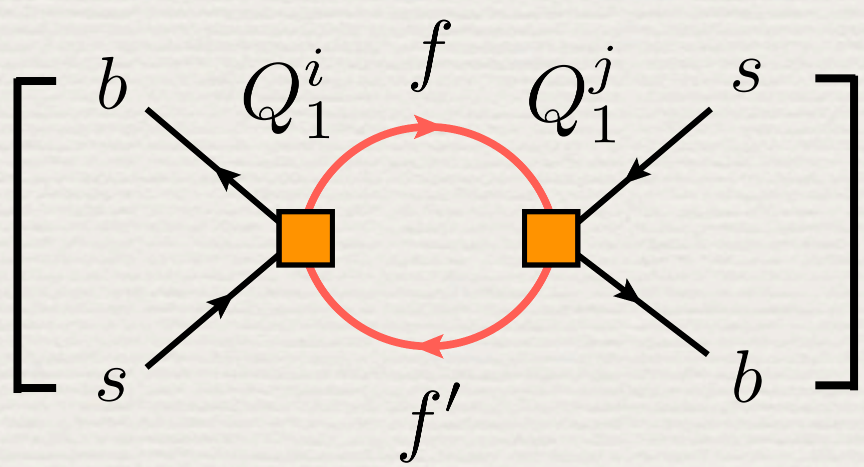


$$\sim \frac{1}{\Lambda_{\rm NP}^2}$$

NP scale

very sensitive to new particles:
SUSY, extra dimensions, ...

$$(\Gamma_{12})_{\rm NP} \propto C_1^i C_1^j \ {\rm Im}$$



$$\sim \frac{1}{(4\pi)^2}\frac{1}{\Lambda_{\rm NP}^4}$$

free of NP (?), since coefficients would also give B decays into light final states X ($M_X < m_b$)

loop factor

Parameters & Observables

- Model-independent parametrization of NP effects in B_s system:

$$M_{12} = (M_{12})_{\rm SM} + (M_{12})_{\rm NP} = (M_{12})_{\rm SM}\, R_M\, e^{i\phi_M}\ ,$$

$$\Gamma_{12} = (\Gamma_{12})_{\rm SM} + (\Gamma_{12})_{\rm NP} = (\Gamma_{12})_{\rm SM}\, R_\Gamma\, e^{i\phi_\Gamma}$$

Expressed through $R_{M,\Gamma}$, $\phi_{M,\Gamma}$ & $(\phi_s)_{\rm SM} = \arg(-(M_{12})_{\rm SM}/(\Gamma_{12})_{\rm SM})$, mass ΔM & width difference $\Delta\Gamma$, flavor-specific (e.g. semileptonic) CP asymmetry a^s_{fs} & CP-violating (CPV) phase $\phi_{\psi\phi}$ take form

$$\Delta M = (\Delta M)_{\rm SM}\, R_M\ ,$$

$$\Delta\Gamma \approx (\Delta\Gamma)_{\rm SM}\, R_\Gamma\, \cos(\phi_M - \phi_\Gamma)\ ,$$

$$a^s_{fs} \approx (a^s_{fs})_{\rm SM}\, \frac{R_\Gamma}{R_M}\, \frac{\sin(\phi_M - \phi_\Gamma)}{(\phi_s)_{\rm SM}}\ ,$$

$$\phi_{\psi\phi} = (\phi_{\psi\phi})_{\rm SM} + \phi_M$$

Parameters & Observables

- Besides $\phi_{\psi\phi}$ (from mixed-induced, time-dependent CP asymmetry in $B_s \to \psi\phi$) & a^s_{fs} (from tree-level $B_s \to \mu^+ D_s^- X$ decay), there is a 3rd relevant CPV quantity in B sector, i.e., like-sign dimuon charge asymmetry A^b_{SL}:

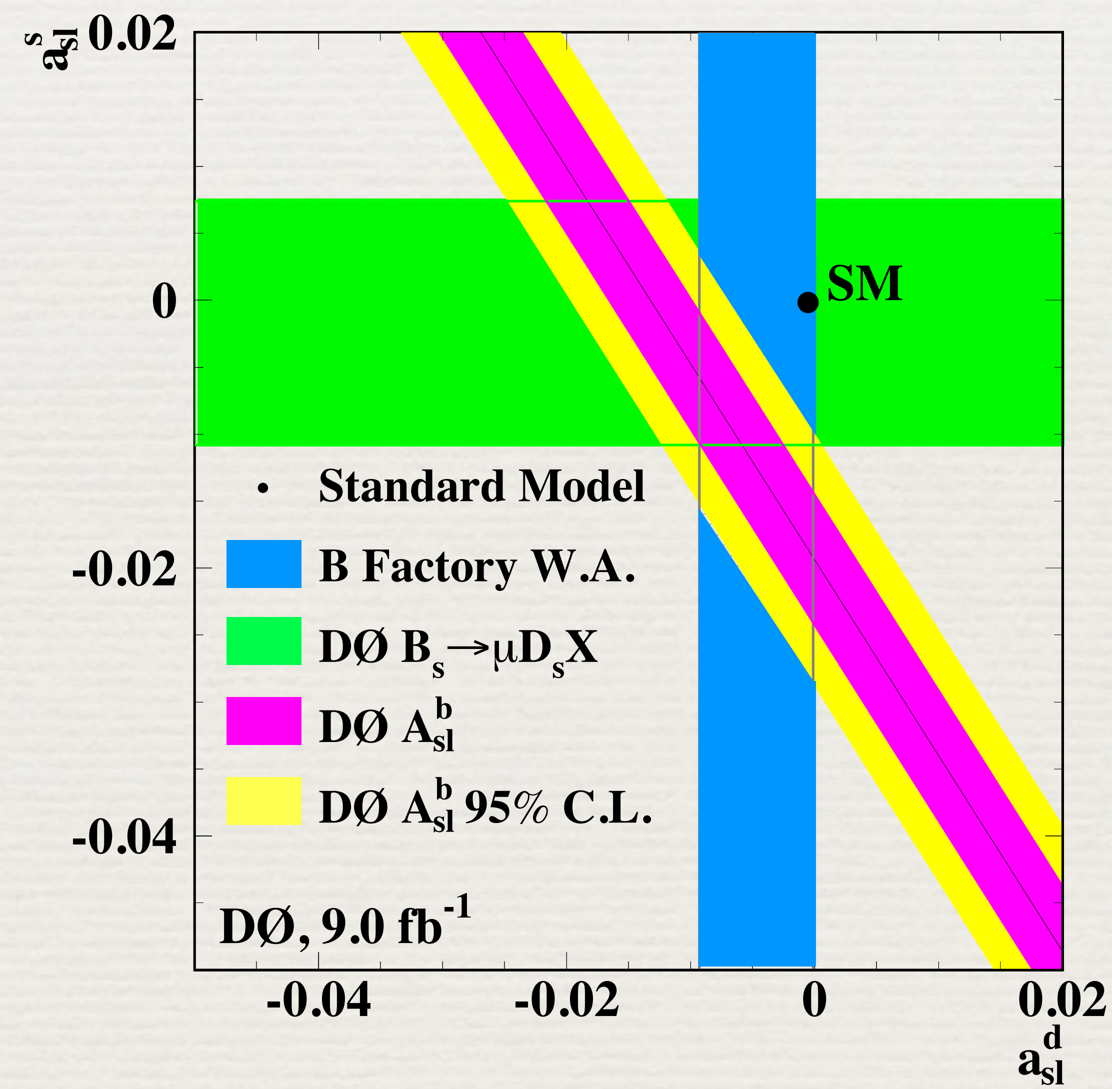
$$A^b_{\rm SL} = \frac{N_b^{++} - N_b^{--}}{N_b^{++} + N_b^{--}}$$

$$= C_d \, a^d_{fs} + (1 - C_d) \, a^s_{fs},$$

$N_b^{\pm\pm} = \#$ of events with $\mu^\pm\mu^\pm$,

$C_d \approx [0.5, 0.6] \propto$ production B_d/B_s

[DØ 1106.6308]



SM Predictions vs. Data

	SM predictions [Lenz & Nierste, 1106.6308]	data before 2011	data at present
ΔM [ps^{-1}]	17.3 ± 2.6	17.70 ± 0.08 [CDF]	17.73 ± 0.05 [CDF & LHCb]
$\Delta\Gamma$ [ps^{-1}]	0.087 ± 0.021	$0.154^{+0.054}_{-0.070}$ (0.9σ) [CDF & DØ]	0.116 ± 0.019 (1.0σ) [LHCb]
$\phi_{\psi\phi}$ [°]	-2.1 ± 0.1	-44^{+17}_{-21} (2.3σ) [CDF & DØ]	-0.11 ± 5.0 [LHCb]
A^b_{SL} [10^{-4}]	-2.1 ± 0.4	-85 ± 28 (3.0σ) [DØ]	-79 ± 20 (3.9σ) [DØ]
a^s_{fs} [10^{-5}]†	1.9 ± 0.3	-1200 ± 700 (1.7σ)	-1300 ± 800 (1.5σ)

†calculated from measured A^b_{SL} & $a^s_{fs} = (-4.7 \pm 4.6) \times 10^{-3}$ from BaBar & Belle

[HFAG, 1010.1589]

Implications of Present Data Set

- For $(M_{12})_{NP} \neq 0$, $(\Gamma_{12})_{NP} = 0$, fit to new data only slightly better than SM hypothesis (χ^2/dofs = 3.4/2 vs. χ^2/dofs = 3.5/2)

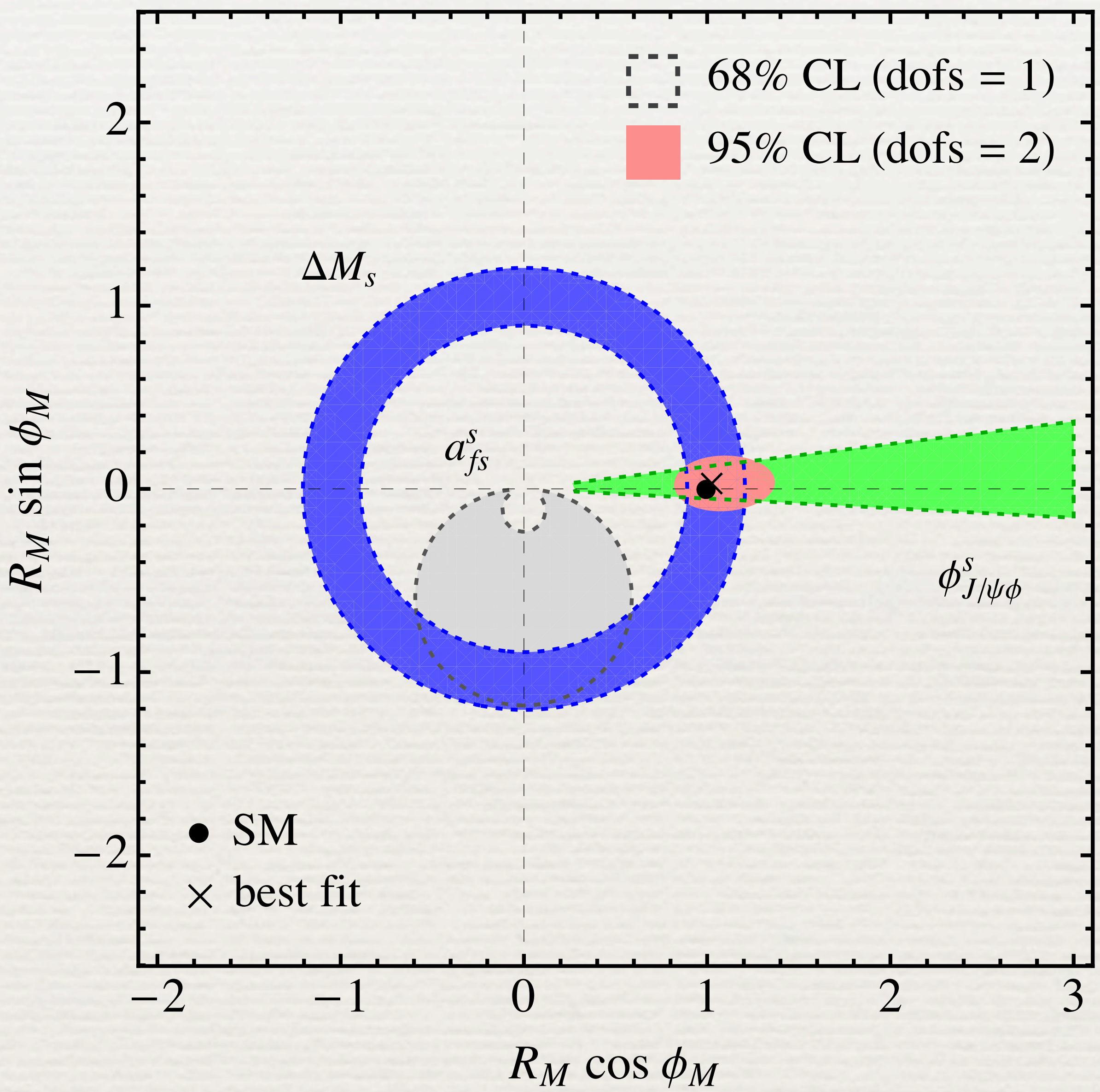
[Bobeth & UH, 1109.1826; also Lenz, Nierste & CKMfitter, 1203.0238]

- In fact, for NP in M_{12} only & $a^d_{fs} = (a^d_{fs})_{SM}$, A^b_{SL} measurement implies:

$$S_{\psi\phi} = \sin\phi_{\psi\phi} = -2.5 \pm 1.3$$

[see e.g. Dobrescu, Fox & Martin, 1005.4238; Ligeti et al., 1006.0432; ...]

[UH, 1206.1230]



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- In fact, scenario with NP in Γ_{12} only, allows for significantly better fit (χ^2/dofs = 0.2/2) than M_{12}-only assumption

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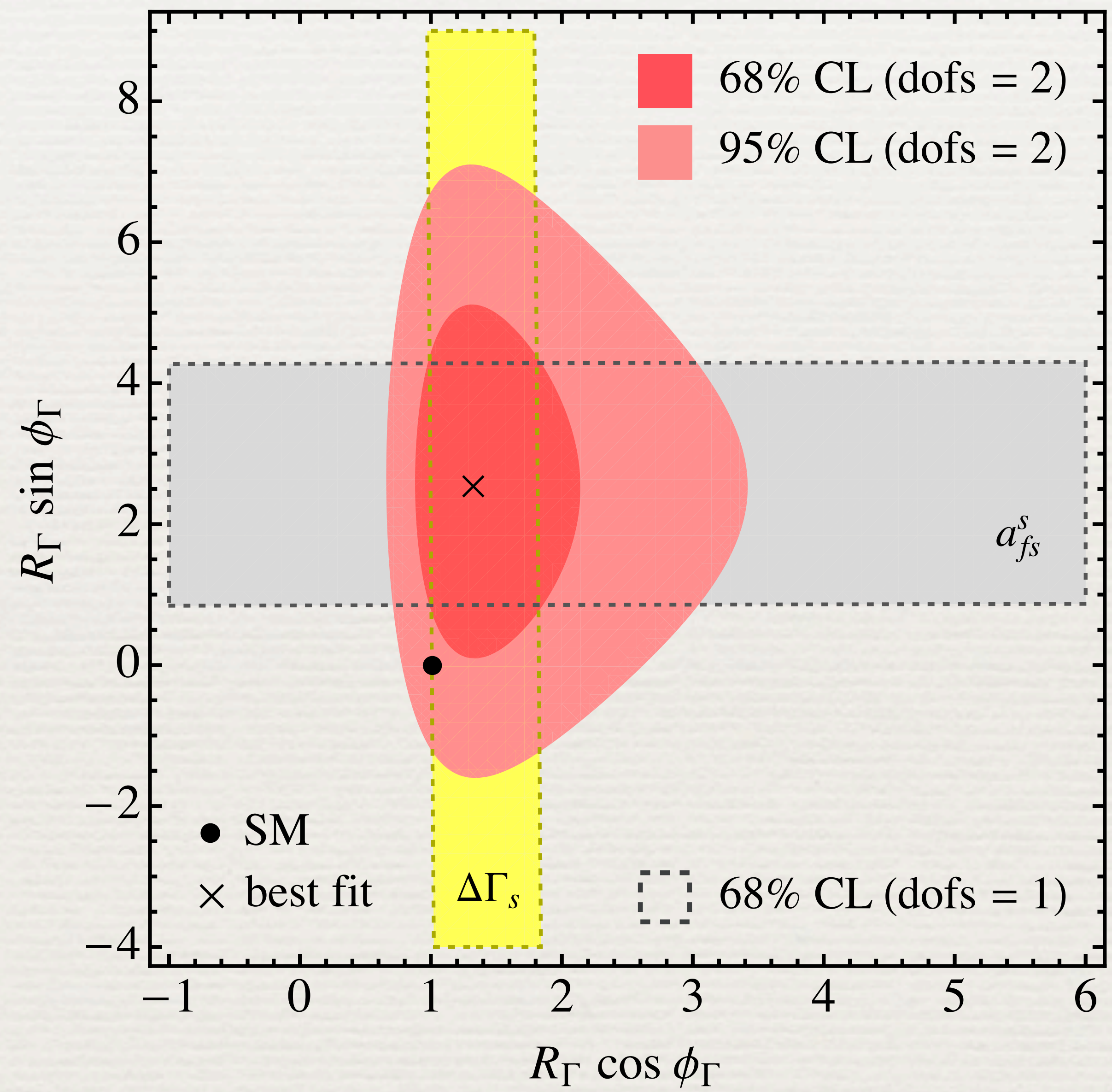

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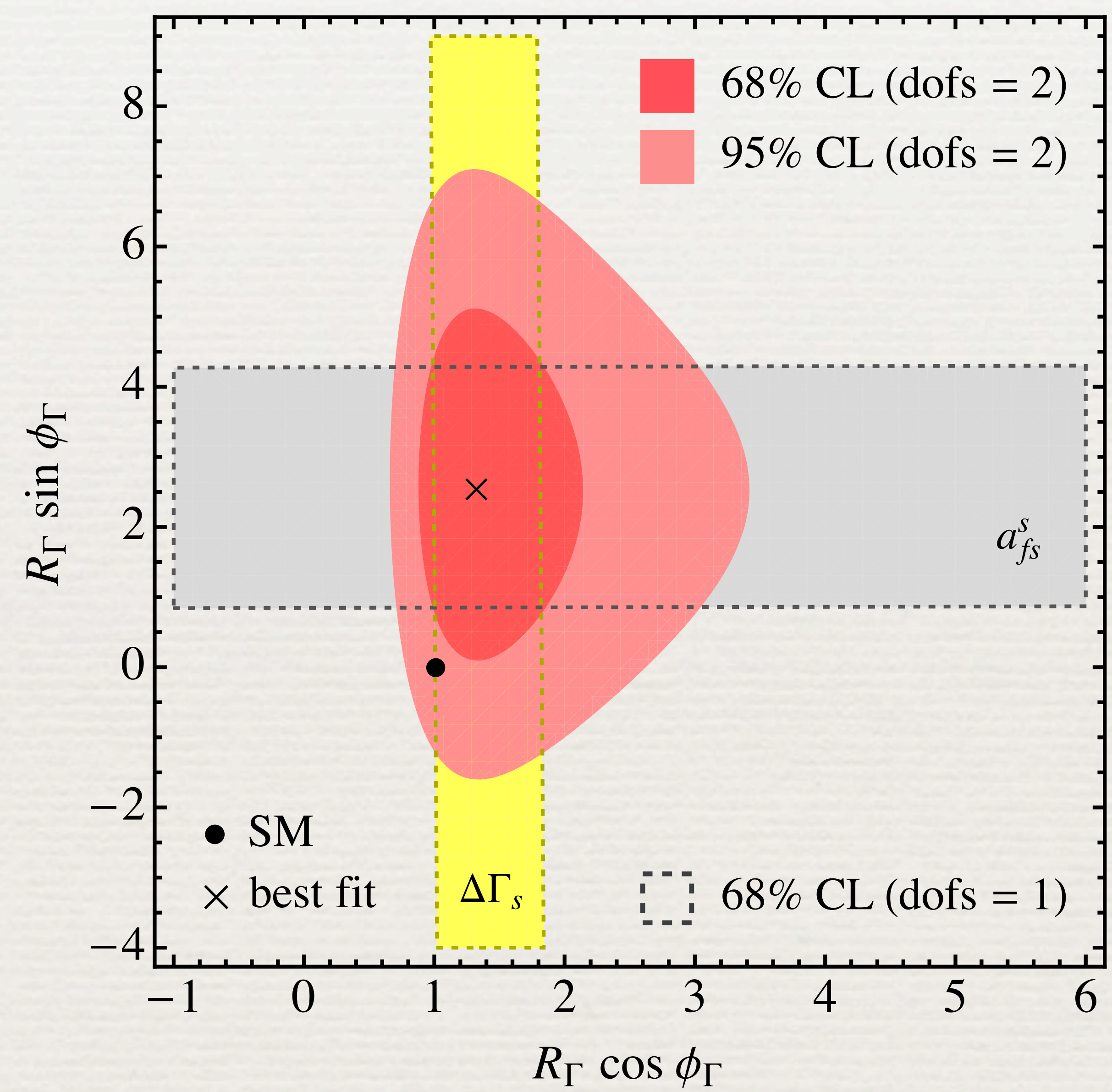

Given latter result, worthwhile to ask: how big can NP in Γ_{12} be?

NP in Γ_{12}: $(\bar{s}b)(\bar{\tau}\tau)$ Operators

- While any operator $(\bar{s}b)f$ with f leading to flavor-neutral final state of 2 or more fields & mass less than m_b can alter Γ_{12}, possible f's in practice limited, because $B_s \to f$ & $B_d \to X_s f$ modes involving light states in final state strongly constrained. A exception are B decays to tau pairs

**[see e.g. Dighe, Kundu & Nandi, 0705.4547, 1005.1629;
Bauer & Dunn, 1006.1629;
Alok, Baek & London, 1010.1333;
Kim, Seo & Shin, 1010.5123;
Bobeth & UH, 1109.1826; ...]**

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- Can study size of NP in Γ_{12} using an effective theory containing a complete set of $(\bar{s}b)(\tau\bar{\tau})$ operators (A, B = L, R):

$$\mathcal{L}_{\text{eff}}^{\text{NP}} = \frac{4G_F}{\sqrt{2}} V_{ts}^* V_{tb} \sum_i C_i Q_i \,,$$

$$P_{L,R} = (1 \mp \gamma_5)/2 \,,$$

$$Q_{S,AB} = (\bar{s} P_A b)(\bar{\tau} P_B \tau) \,,$$

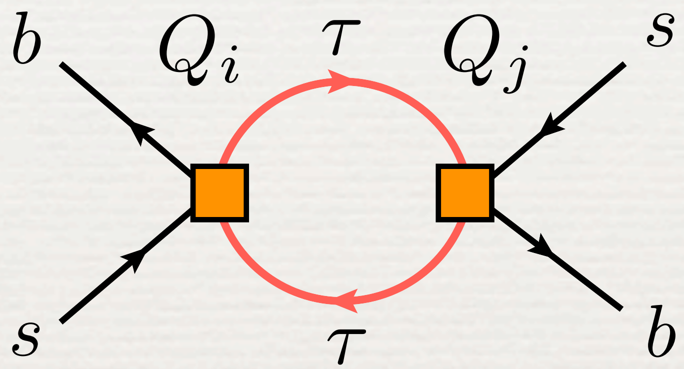
$$Q_{V,AB} = (\bar{s} \gamma_\mu P_A b)(\bar{\tau} \gamma^\mu P_B \tau) \,,$$

$$Q_{T,A} = (\bar{s} \sigma_{\mu\nu} P_A b)(\bar{\tau} \sigma^{\mu\nu} P_A \tau)$$

NP in Γ_{12}: $(\bar{s}b)(\bar{\tau}\tau)$ Operators

- Assuming single operator dominance, calculation of

$$(\Gamma_{12})_{\rm NP} \propto C_i C_j \; \mathrm{Im} \left[\quad \right]$$



translates into

$$(R_\Gamma)_{S,AB} < 1 + (0.4 \pm 0.1)\, |C_{S,AB}|^2 \,,$$

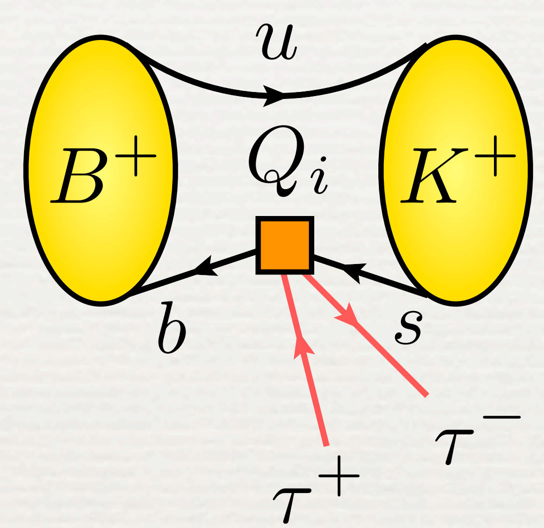
$$(R_\Gamma)_{V,AB} < 1 + (0.4 \pm 0.1)\, |C_{V,AB}|^2 \,,$$

$$(R_\Gamma)_{T,A} < 1 + (0.9 \pm 0.2)\, |C_{T,A}|^2$$

which implies that C_i's have to be around 1 (i.e., size of leading SM current-current coefficient) or larger to describe data well

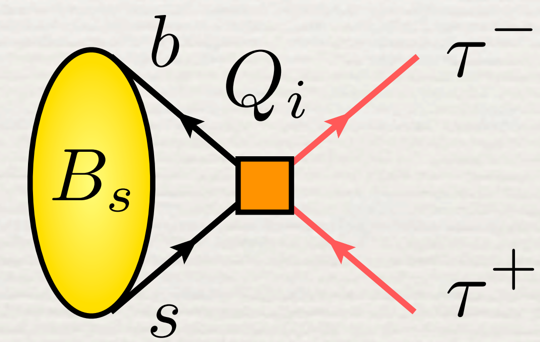
Bounds on $(\bar{s}b)(\bar{\tau}\tau)$ Operators

- Direct constraints arise from



  - $\text{Br}(B^+ \to K^+\tau^+\tau^-) < 3.3 \cdot 10^{-3}$ (90% CL)

    [Flood for BaBar, PoS ICHEP2010, 234 (2010)]



  - $\text{Br}(B_s \to \tau^+\tau^-) \lesssim 3\%$, $\text{Br}(B \to X_s\tau^+\tau^-) \lesssim 2.5\%$

    [see e.g. Grossman, Ligeti & Nardi, hep-ph/9607473; Dighe, Kundu & Nandi, 1005.4051; Bobeth & UH, 1109.1826]

  Bounds on purely leptonic & inclusive semileptonic Br's from $B_{d,s}$ lifetime ratio & contamination of $b \to cl\nu$ decays. LEP searches of $B \to X + E_{miss}$ & charm counting of comparable strength

- Indirect constraints from $b \to s\gamma$, l^+l^- relevant for tensor operators

Upper Bounds on Wilson Coefficients

	limit on $C_i(m_b)$	limit on Λ_{NP} for $C_i^\Lambda = 1$	process
S, AB	< 0.5	2.0 TeV	$B_s \to \tau^+\tau^-$
V, AB	< 0.8	1.0 TeV	$B^+ \to K^+\tau^+\tau^-$
T, L	< 0.06	3.2 TeV	$b \to s\gamma, l^+l^-$
T, R	< 0.09	2.8 TeV	$b \to s\gamma, l^+l^-$

- Assuming single operator dominance & complex C_i, one obtains quite loose bounds on scalar & vector operators, whereas tensor contributions are severely constrained, mostly due to $B \to X_s\gamma$

Present Data: $(\Gamma_{12})_{NP}$ Due to $b \to s\tau^+\tau^-$

- Upper limit on C_i translate into:

$$(R_\Gamma)_{S,AB} < 1.15\,,$$

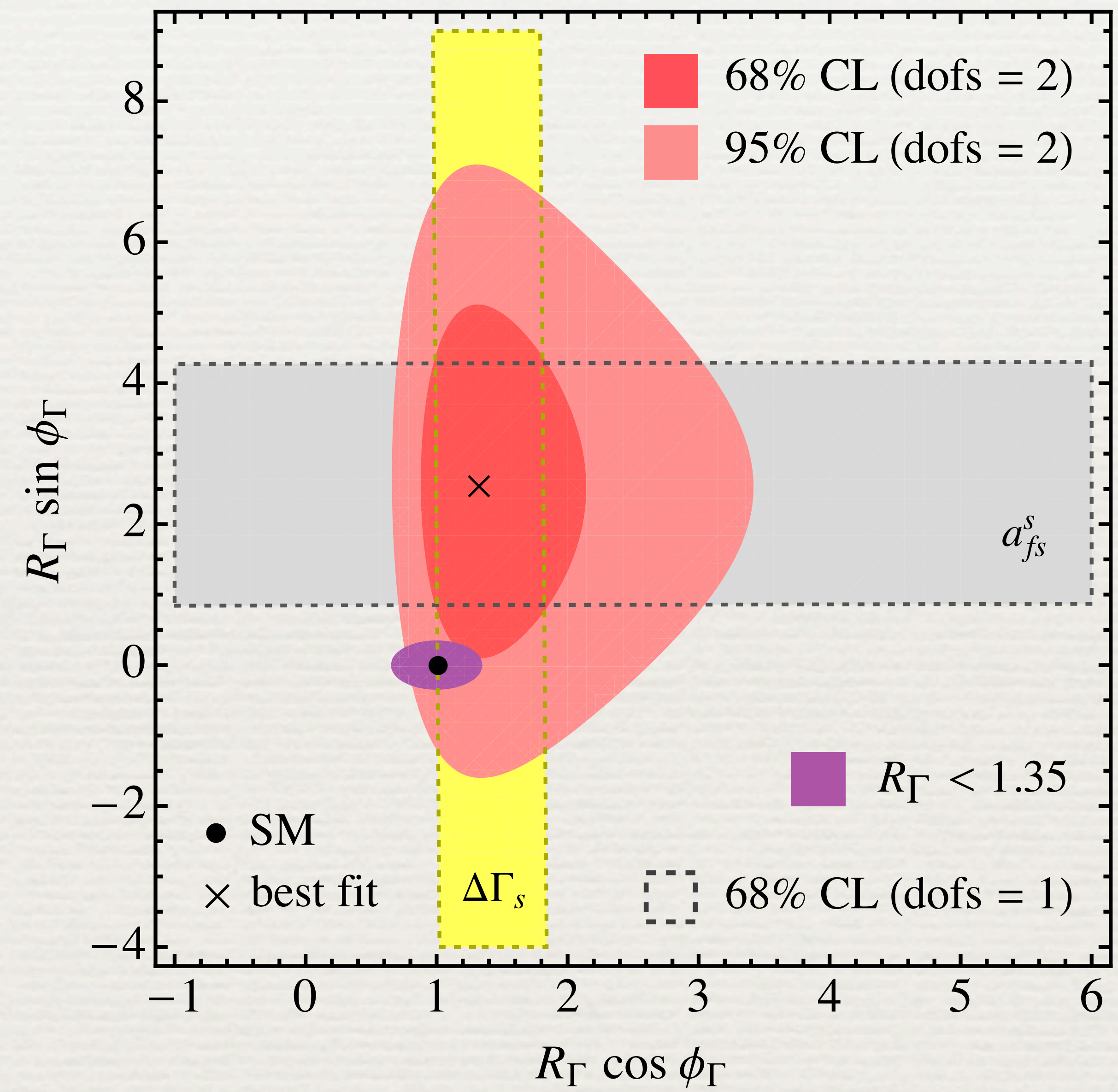
$$(R_\Gamma)_{V,AB} < 1.35\,,$$

$$(R_\Gamma)_{T,L} < 1.004\,,$$

$$(R_\Gamma)_{T,R} < 1.008$$

Largest correction due to vector operator can change $|\Gamma_{12}|_{SM}$ by 35%. Tension in B-meson sector can be relaxed, but effects are factor of around 10 too small to provide full explanation

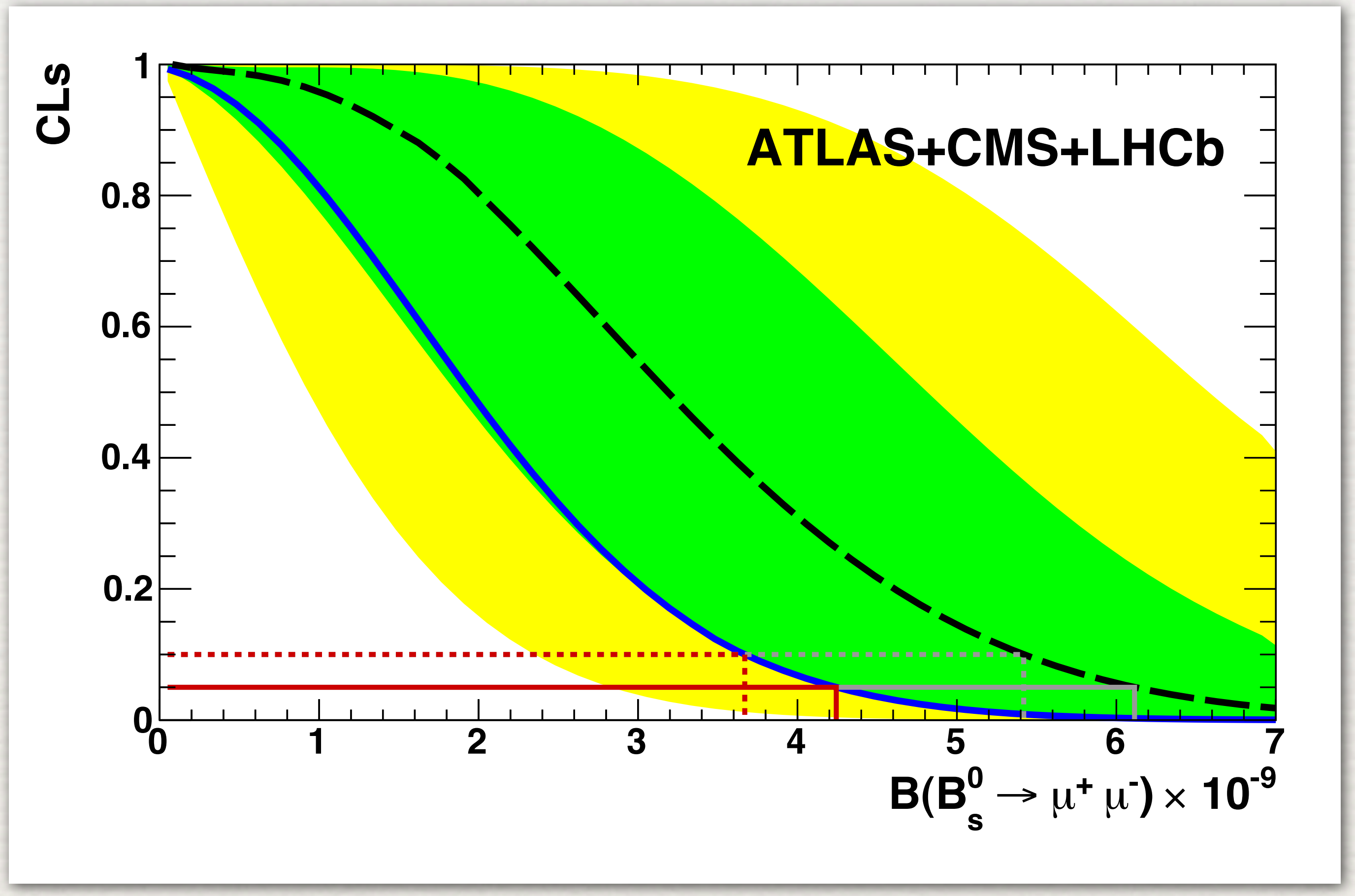
[UH, 1206.1230]



Rare B-Meson Decays

ATLAS, CMS & LHCb Cornering NP

[CMS-PAS-BPH-12-009]



95% CL bounds :

$$Br(B_s \to \mu^+\mu^-) < 4.2 \cdot 10^{-9}$$

$$Br(B_d \to \mu^+\mu^-) < 8.1 \cdot 10^{-10}$$

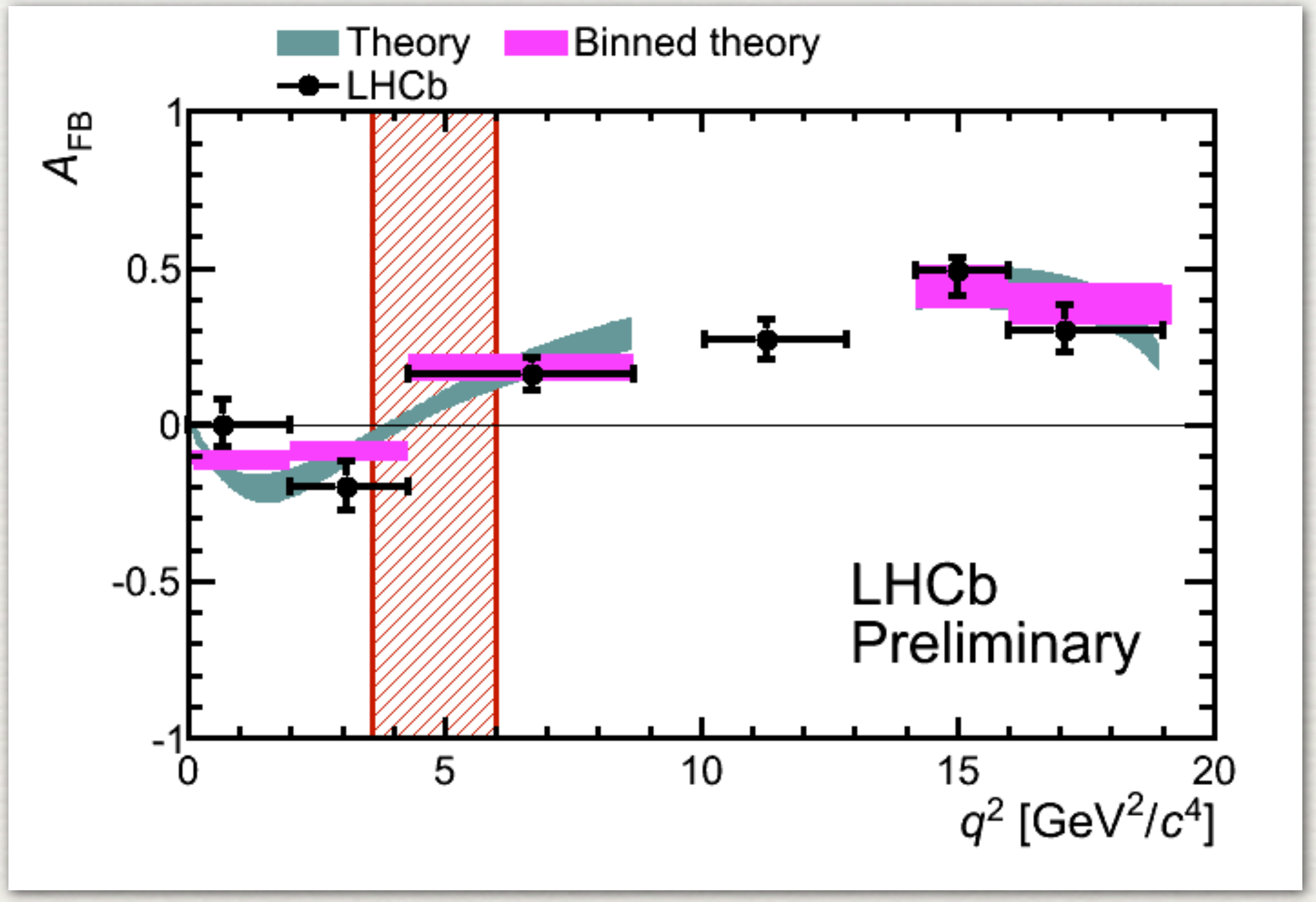
B_s B_d

+40% +900%

allowed relative to SM

LHCb Cornering NP

[LHCb-CONF-2011-038; LHCb-CONF-2012-008]



LHCb measurements of $B \to K^* \mu^+ \mu^-$ distributions show nice agreement with SM expectations

⬇

but O(50%) NP effects relative to SM amplitudes not ruled out yet

LHCb Cornering NP

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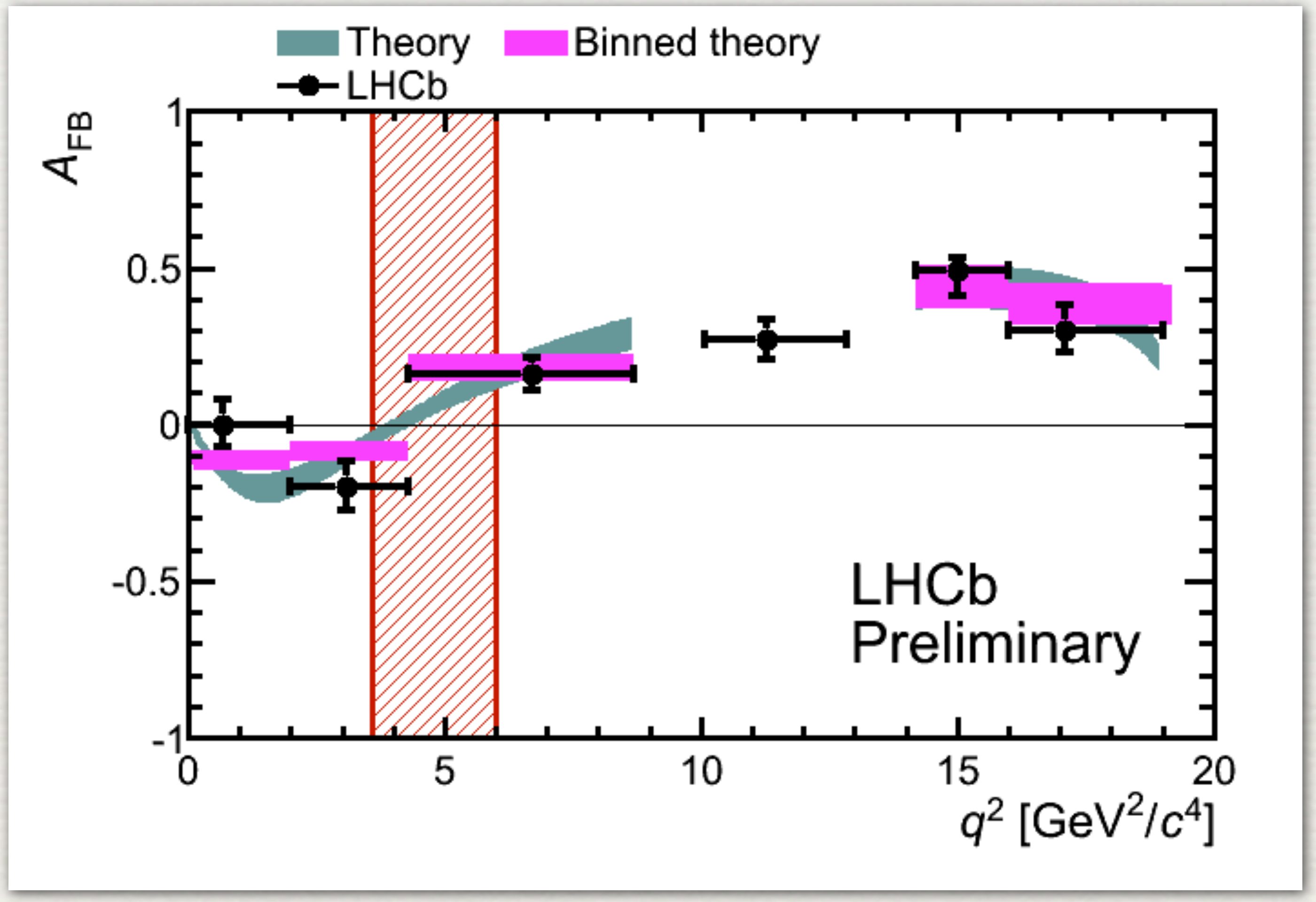


LHCb measurements of $B \to K^* \mu^+ \mu^-$ distributions show nice agreement with SM expectations

⬇

but O(50%) NP effects relative to SM amplitudes not ruled out yet

Spectacular NP effects excluded (unlikely), but in view of cleanness of rare B decays visible effects still possible

MSSM: Anatomy of Higgs Mass

- Tree-level mass of lightest CP-even Higgs maximized in decoupling limit $M_A >> M_Z$ with $\tan\beta = t_\beta >> 1$:

$$m_h^2 \approx M_Z^2 \, c_{2\beta}^2 \left(1 - \frac{M_Z^2}{M_A^2} \, s_{2\beta}^2\right) \leq M_Z^2$$

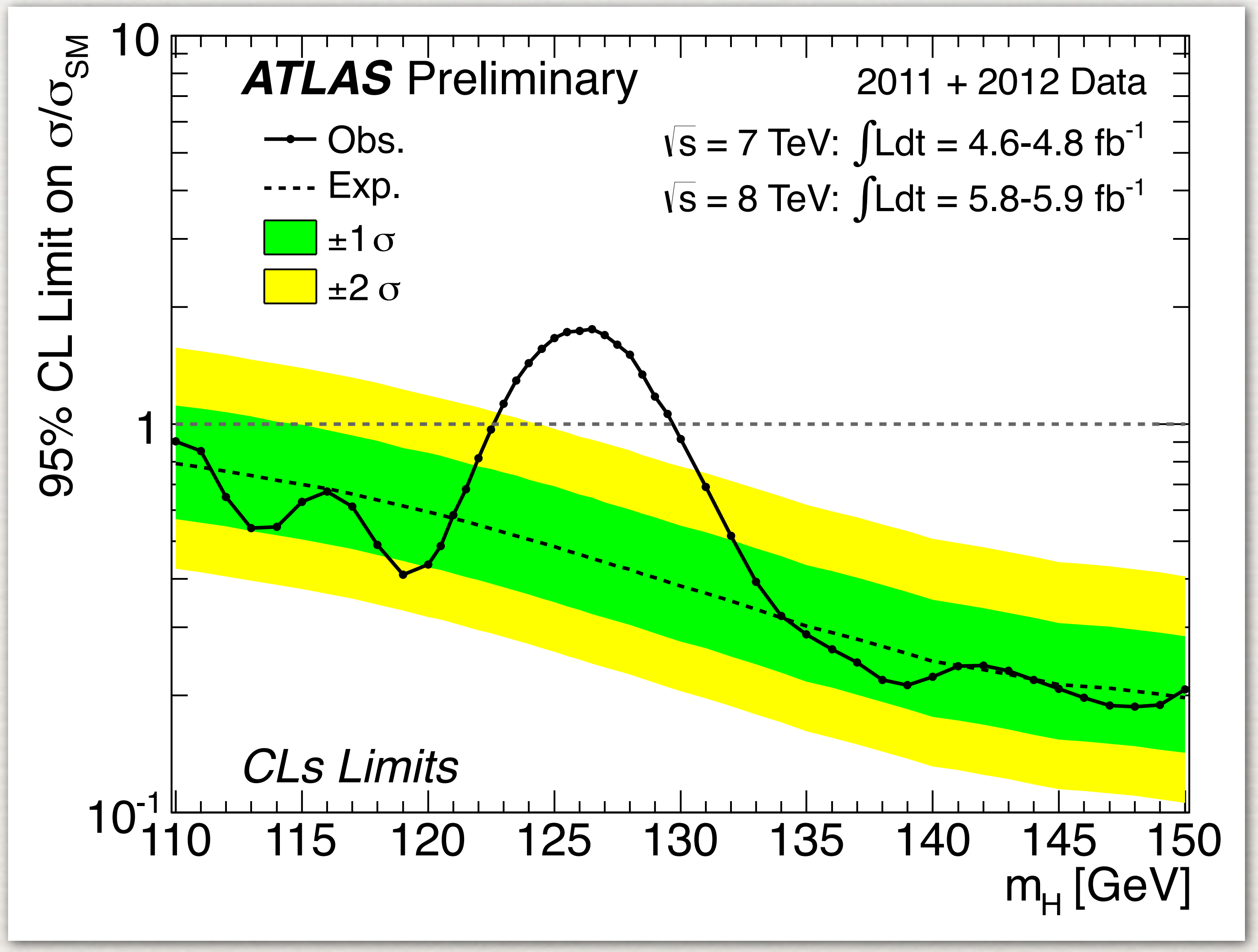
- Large one-loop contributions arise from incomplete cancellation of top-quark & -squark loop

$$(\Delta m_h^2)_{\tilde{t}} \approx \frac{3\sqrt{2} G_F}{2\pi^2} \, m_t^4 \left[- \ln\left(\frac{m_t^2}{m_{\tilde{t}}^2}\right) + \frac{X_t^2}{m_{\tilde{t}}^2} \left(1 - \frac{X_t^2}{12 m_{\tilde{t}}^2}\right)\right]$$

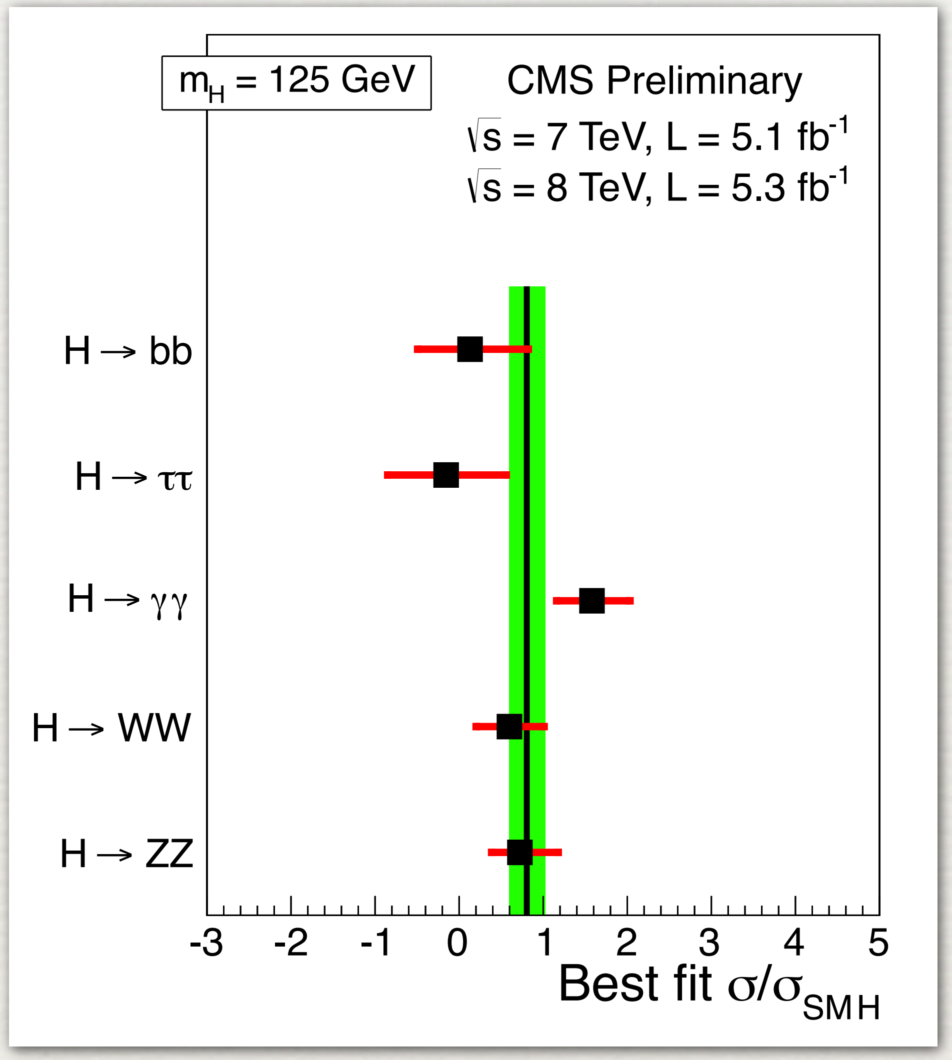
that can make m_h sufficiently heavy if $m_{\tilde{t}} = \sqrt{m_{\tilde{t}1} \, m_{\tilde{t}2}} >> m_t$ and/or $X_t = A_t - \mu/t_\beta$ close to maximal $|X_t| = \sqrt{6} \, m_{\tilde{t}}$. Two-loop effects break symmetry $X_t \leftrightarrow -X_t$ & allow larger value of m_h for $\mathrm{sgn}(X_t M_3) = +1$

MSSM: Anatomy of Higgs Mass

[ATLAS-CONF-2012-093]



[CMS-HIG-12-020]

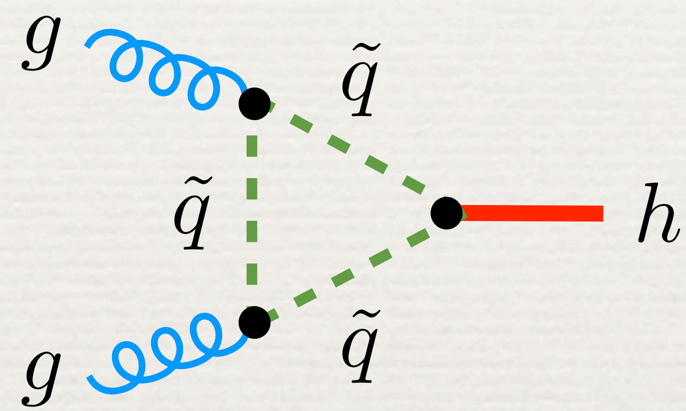


- In MSSM, Higgs with mass of around 125 GeV clearly not natural. Will be agnostic about issue & assume fine-tuned region of MSSM parameter space realized with $M_A >> M_Z$ & t_β & trilinear term A_t large. Are there other observable consequences?

MSSM: Dissecting Higgs Production

- Structure of MSSM corrections to gg → h & h → γγ can be easily understood by studying case of soft Higgs. In decoupling limit one finds for stop & sbottom contributions to hgg vertex:

$$\kappa_{\tilde{q}} \approx \frac{1}{4}\, m_q^2 \, \frac{\partial}{\partial m_q^2} \ln \left[\det \left(\mathcal{M}_{\tilde{q}}^2 \right) \right]$$



$$\approx \begin{cases} \dfrac{m_t^2}{4} \left(\dfrac{1}{m_{\tilde{t}_1}^2} + \dfrac{1}{m_{\tilde{t}_2}^2} - \dfrac{X_t^2}{m_{\tilde{t}_1}^2 m_{\tilde{t}_2}^2} \right), & \tilde{q} = \tilde{t} \\[2ex] -\dfrac{m_b^2 X_b^2}{4 m_{\tilde{b}_1}^2 m_{\tilde{b}_2}^2}, & \tilde{q} = \tilde{b} \end{cases}$$

MSSM: Dissecting Higgs Production

- Assuming degenerate stops & neglecting sbottom-loop effects, shift in Higgs production cross section hence approximately given by:

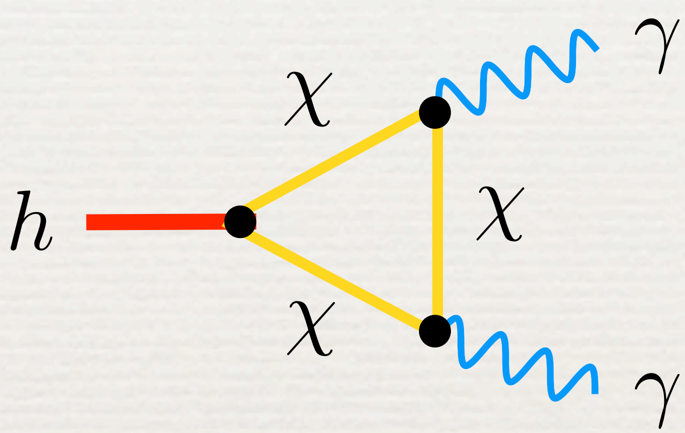
$$R_h \approx (1+\kappa_{\tilde{t}})^2 \approx \begin{cases} 1 + \dfrac{m_t^2}{m_{\tilde{t}}^2}\,, & X_t = 0 \\[2ex] 1 - 2\,\dfrac{m_t^2}{m_{\tilde{t}}^2}\,, & X_t = \sqrt{6}\,m_{\tilde{t}} \end{cases}$$

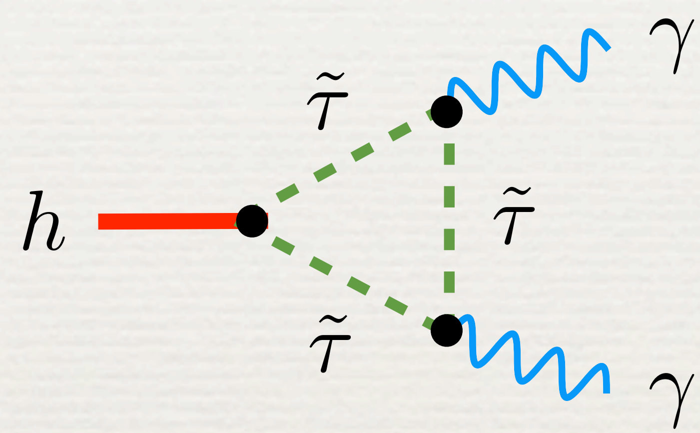
As Higgs-boson mass around 125 GeV calls for close to maximal mixing, natural to expect suppression of gg → h. In fact, this is exactly what happens in wide ranges of MSSM parameter space

[see for example Dermisek & Low, hep-ph/0701235; Cacciapaglia et al., 0901.0927]

MSSM: Dissecting Higgs Decay to Diphotons

- For $M_A >> M_Z$, charged Higgs effects are strongly suppressed, but chargino & stau loops can have notable impact on diphoton rate:





$$\kappa_\chi \approx \mathrm{sgn}\left[\det\left(\mathcal{M}_\chi\right)\right] \frac{2}{t_\beta}\frac{M_W^2}{m_\chi^2}$$

$$\kappa_{\tilde{\tau}} \approx -\frac{m_\tau^2 X_\tau^2}{4 m_{\tilde{\tau}_1}^2 m_{\tilde{\tau}_2}^2}$$

[see for example Djouadi et al., hep-ph/9612362; Carena et al., 1112.3336; 1205.5842]

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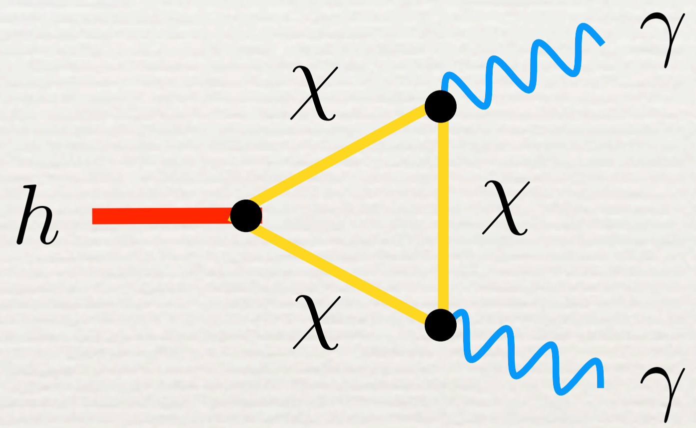

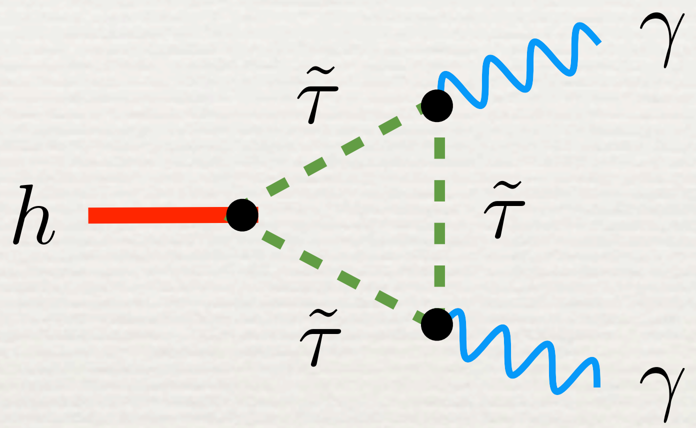

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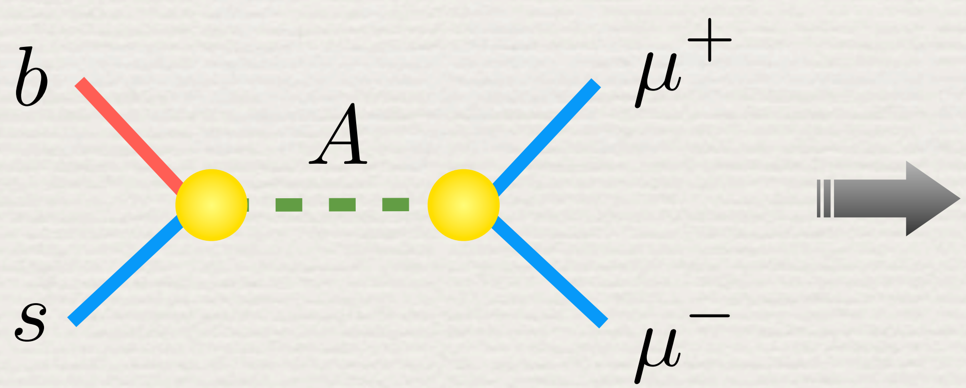
$$\kappa_{\tilde{\tau}} \approx -\frac{m_\tau^2 X_\tau^2}{4m_{\tilde{\tau}_1}^2 m_{\tilde{\tau}_2}^2}$$

Unlike chargino effects, stau loops not t_β suppressed. In fact, $R_\gamma > 1$ needs light stau with large mixing $X_\tau = A_\tau - \mu t_\beta$, which is most easily achieved for $t_\beta >> 1$ & μ significantly above weak scale

MSSM: Anatomy of $B_s \to \mu^+\mu^-$

- In large-t_β regime, rare purely leptonic B_s decay receives dominant corrections from neutral Higgs double penguins:

$$R_{\mu^+\mu^-} = \frac{\mathrm{Br}(B_s \to \mu^+\mu^-)}{\mathrm{Br}(B_s \to \mu^+\mu^-)_{\mathrm{SM}}} \approx 1 - 13.2\, C_P + 43.8 \left(C_S^2 + C_P^2\right)$$



$$C_S \approx C_P \propto \mu A_t\, t_\beta^3\, \frac{m_t^2}{m_{\tilde t}^2}\, \frac{m_b m_\mu}{M_W^2 M_A^2}$$

Term linear in pseudoscalar coefficient C_P due to interference with semileptonic axial-vector SM contribution. Data prefers $C_P > 0$

[see for example Babu & Kolda, hep-ph/9900476]

MSSM: Anatomy of $B_s \to \mu^+\mu^-$

- In fact, upper bound on branching ratio of $B_s \to \mu^+\mu^-$ translates into two-sided limit on product μA_t. For example, $R_{\mu^+\mu^-} < 1.3$ gives

$$-\frac{0.6}{\text{TeV}^2} \lesssim \frac{\mu A_t}{m_{\tilde{t}}^2 M_A^2} \left(\frac{t_\beta}{50}\right)^3 \lesssim \frac{5.2}{\text{TeV}^2}$$

Inequality shows that for $\text{sgn}(\mu A_t) = +1$ constraint from $B_s \to \mu^+\mu^-$ more easily evaded. For $\mu A_t > 0$ rate below SM. Taking

$$\frac{\mu A_t}{m_{\tilde{t}}^2 M_A^2} \left(\frac{t_\beta}{50}\right)^3 \approx \frac{2.3}{\text{TeV}^2}$$

for example implies suppression by about 50%

Slice of MSSM Parameter Space

- Above suggests that parameter space with $\mu > 0$ & $A_t > 0$ is least constrained & may lead to interesting effects. Fix relevant MSSM parameters to following weak-scale values

$$t_\beta = 60\,, \quad M_A = 1\,\mathrm{TeV}$$

$$\tilde{m}_{Q_3} = 1.5\,\mathrm{TeV}\,, \quad \tilde{m}_{u_3} = 1.5\,\mathrm{TeV}$$

$$\tilde{m}_{L_3} = 325\,\mathrm{GeV}\,, \quad \tilde{m}_{l_3} = 325\,\mathrm{GeV}\,, \quad A_\tau = 500\,\mathrm{GeV}$$

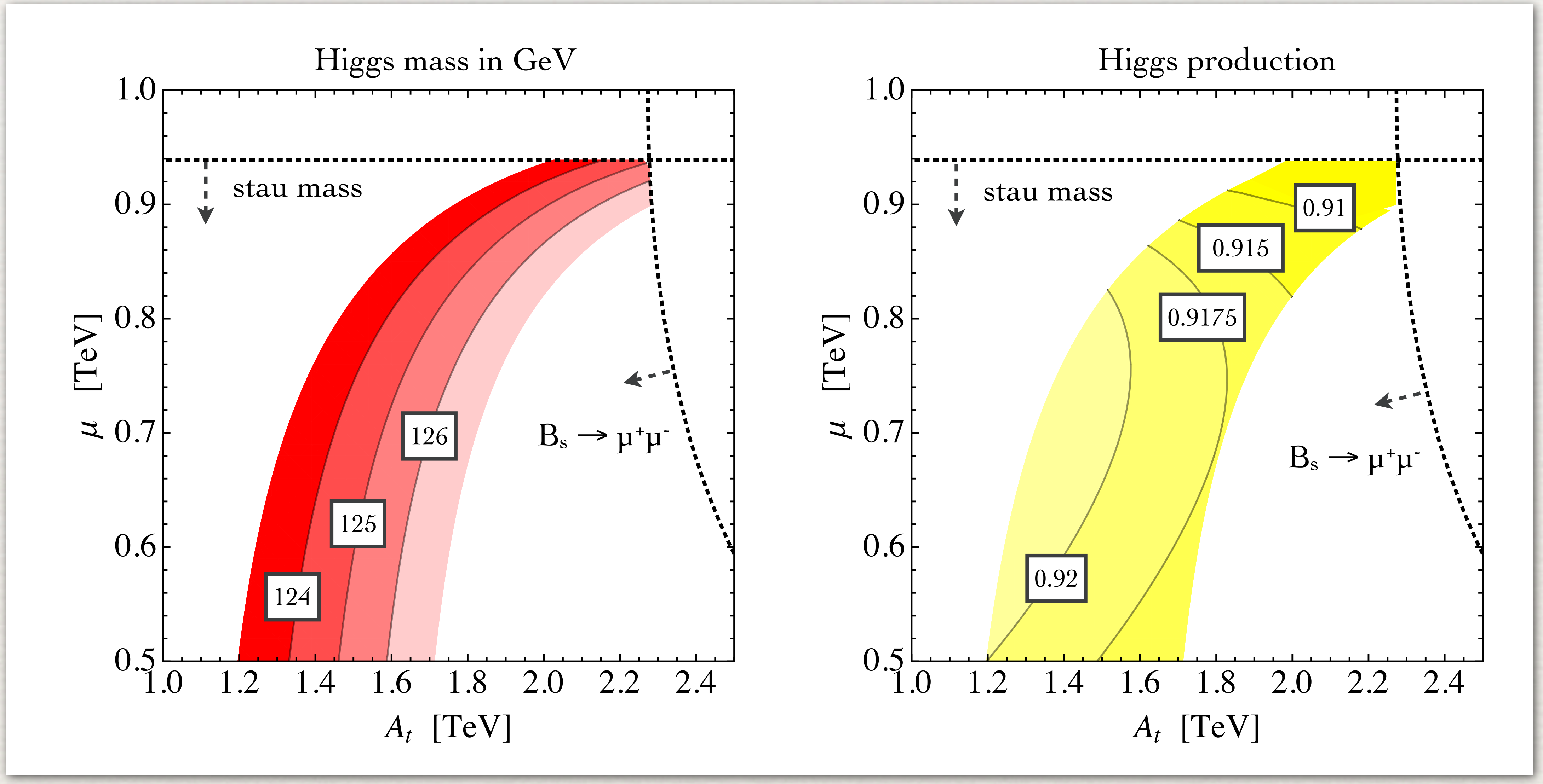
$$M_1 = 100\,\mathrm{GeV}\,, \quad M_2 = 300\,\mathrm{GeV}\,, \quad M_3 = 1.2\,\mathrm{TeV}$$

& vary trilinear term A_t & Higgsino mass parameter μ

[see also Carena et al., 1112.3336; 1205.5842]

A_t-μ Planes: m_h & R_h

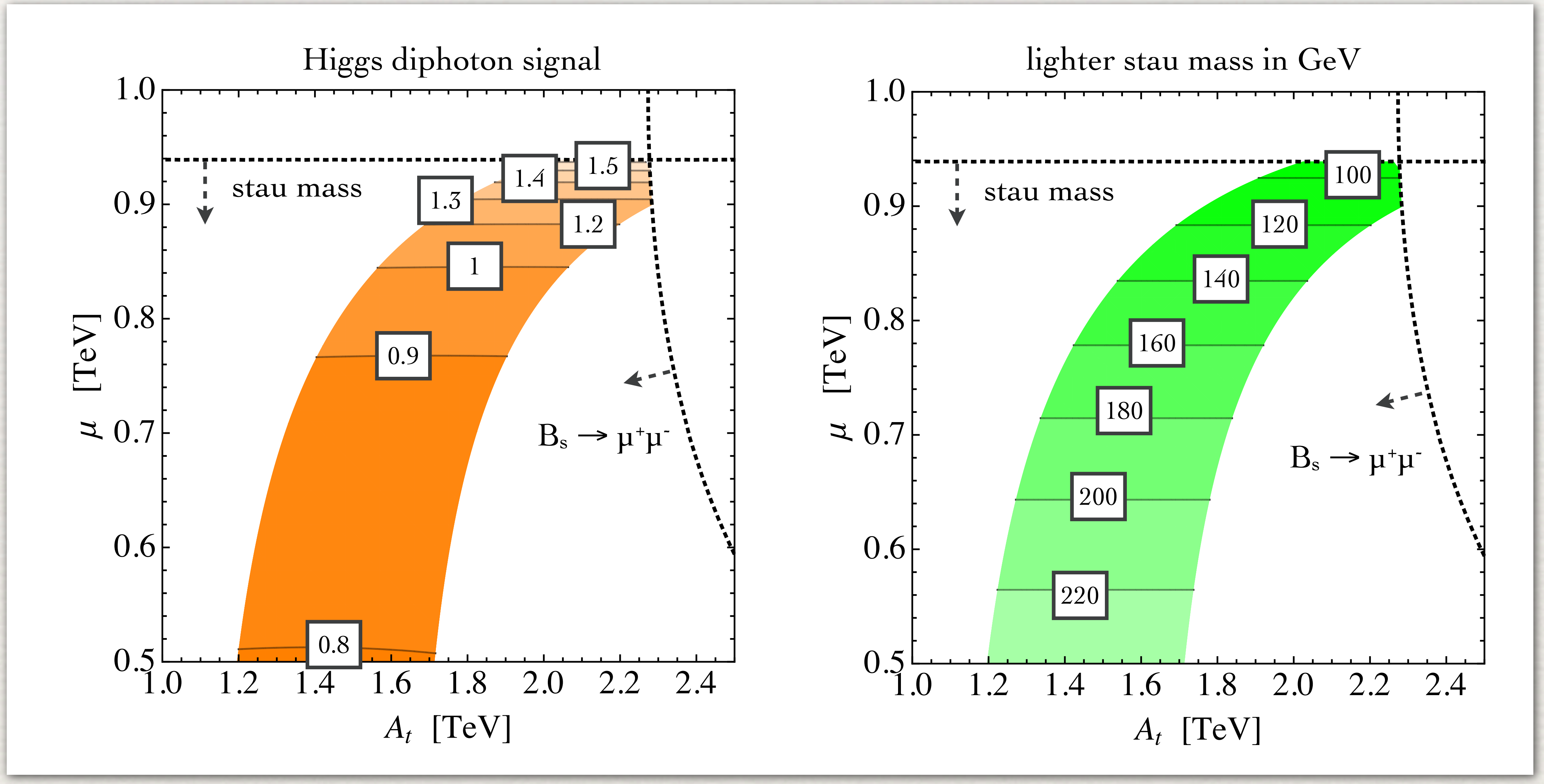
[UH & Mahmoudi, 1208.xxxx]



- Higgs mass determination & lower limit on stau mass of 92 GeV (LHCb bound on $B_s \to \mu^+\mu^-$) bound μ (A_t) from above. In preferred parameter space, Higgs production smaller than SM by about 10%

A_t-μ Planes: $R_{\gamma\gamma}$ & $m_{\tilde{\tau}_1}$

[UH & Mahmoudi, 1208.xxxx]



- Enhancement in diphoton rate strongly correlated with mass of lighter stau mass eigenstate & μ parameter. Can find upper bound on $R_{\gamma\gamma}$ as function of $m_{\tilde{\tau}_1}$ & absolute limit of $R_{\gamma\gamma} \lesssim 1.7$

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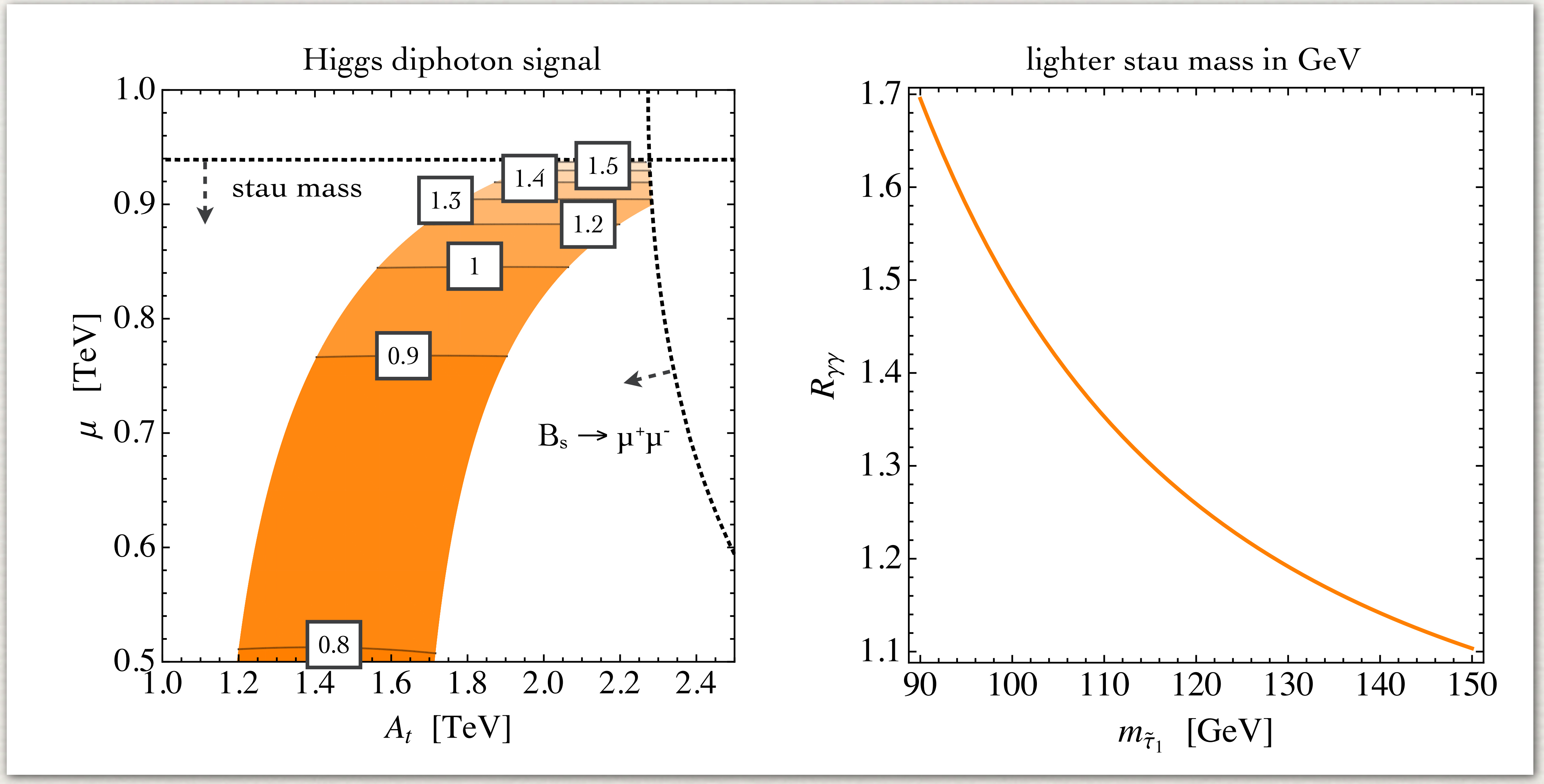
[UH & Mahmoudi, 1208.xxxx]



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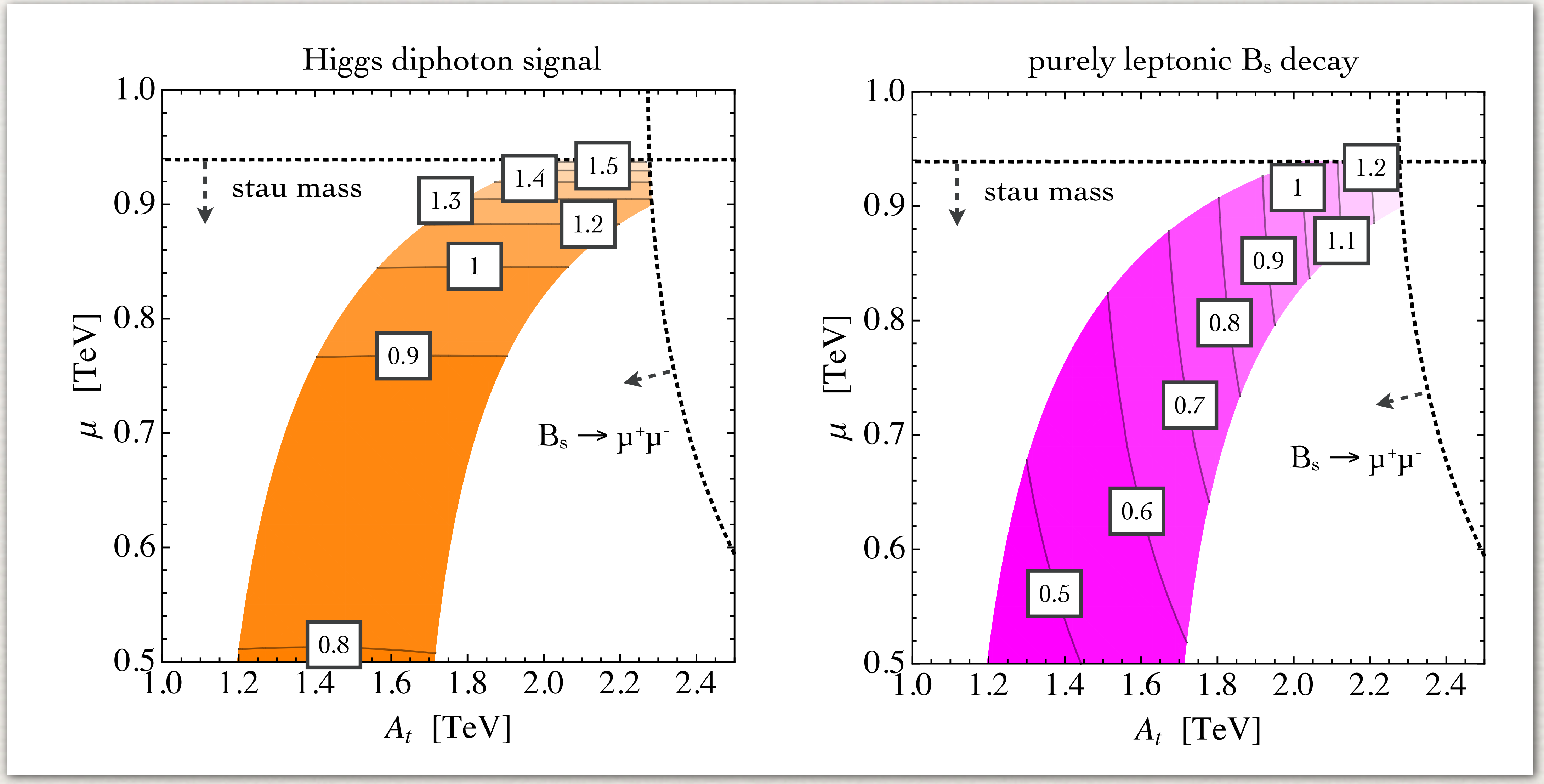
A_t-μ Planes: $R_{\gamma\gamma}$ & $R_{\mu^+\mu^-}$

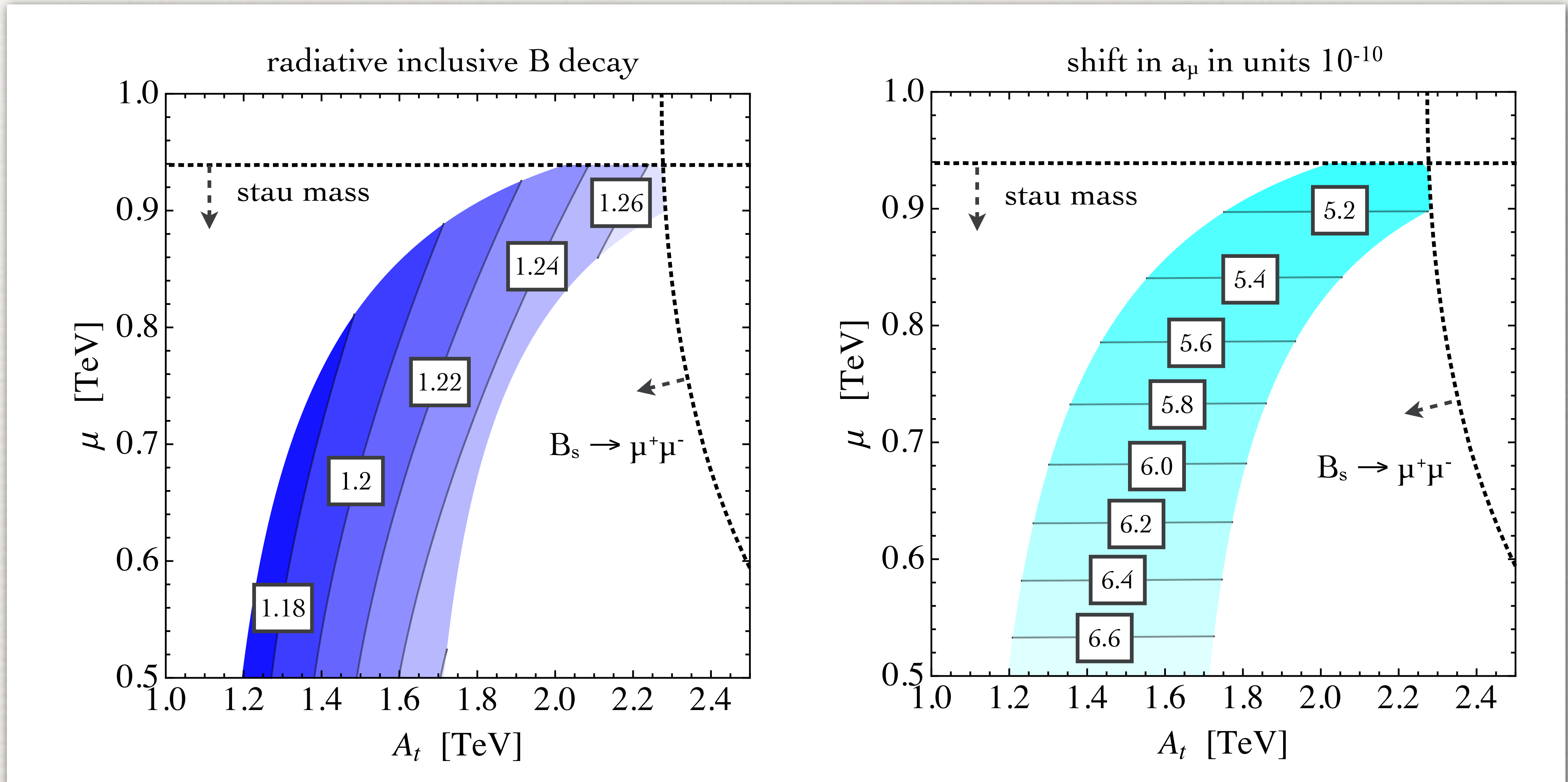
[UH & Mahmoudi, 1208.xxxx]



- Increases in & depletions of $R_{\gamma\gamma}$ & $B_s \to \mu^+\mu^-$ branching ration occur simultaneously. Stringent link can be broken by further decoupling heavy Higgses, $M_A >> 1$ TeV

A_t-μ Planes: R_{X_s} & Δa_μ

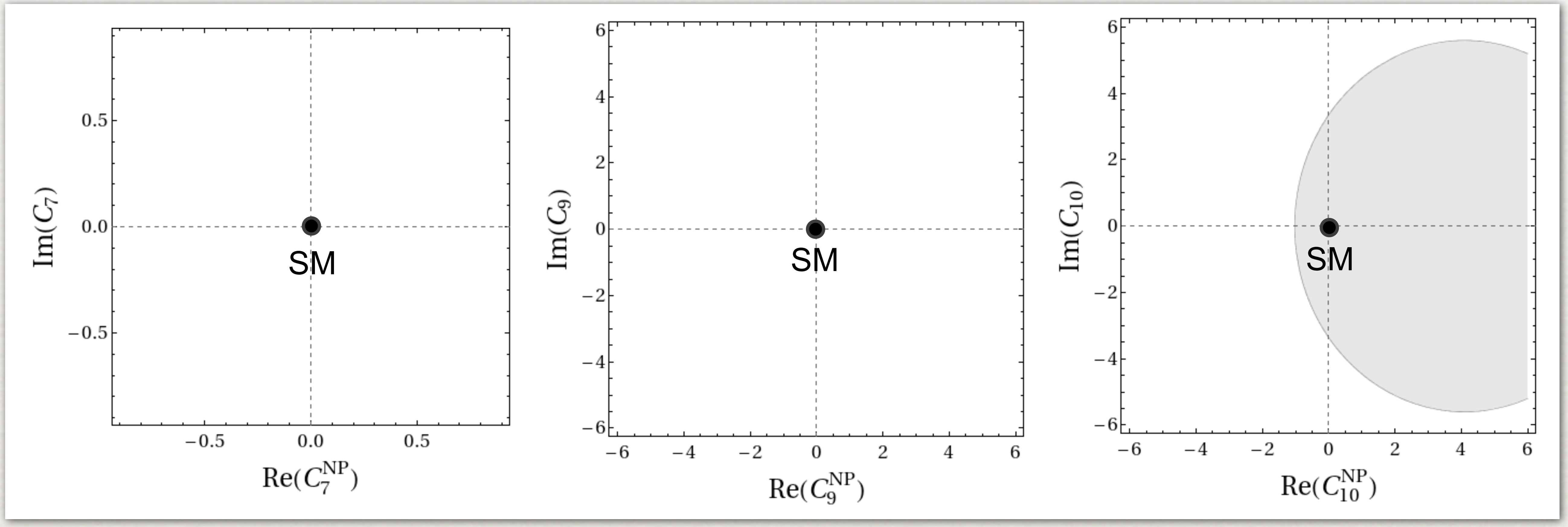
[UH & Mahmoudi, 1208.xxxx]



- Branching ratio of $B \to X_s\gamma$ enhanced by (20-30)%, which can be probed with improved theoretical & experimental accuracy. Tension in anomalous magnetic moment of muon reduced

Constraints On Left-Handed (LH) Currents

[Altmannshofer & Straub, 1206.0273]



- $B_s \to \mu^+\mu^-$

[see also Beaujean et al., 1205.1838;
Hurth & Mahmoudi, 1207.0688;
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as well as other groups & older works for similar studies]

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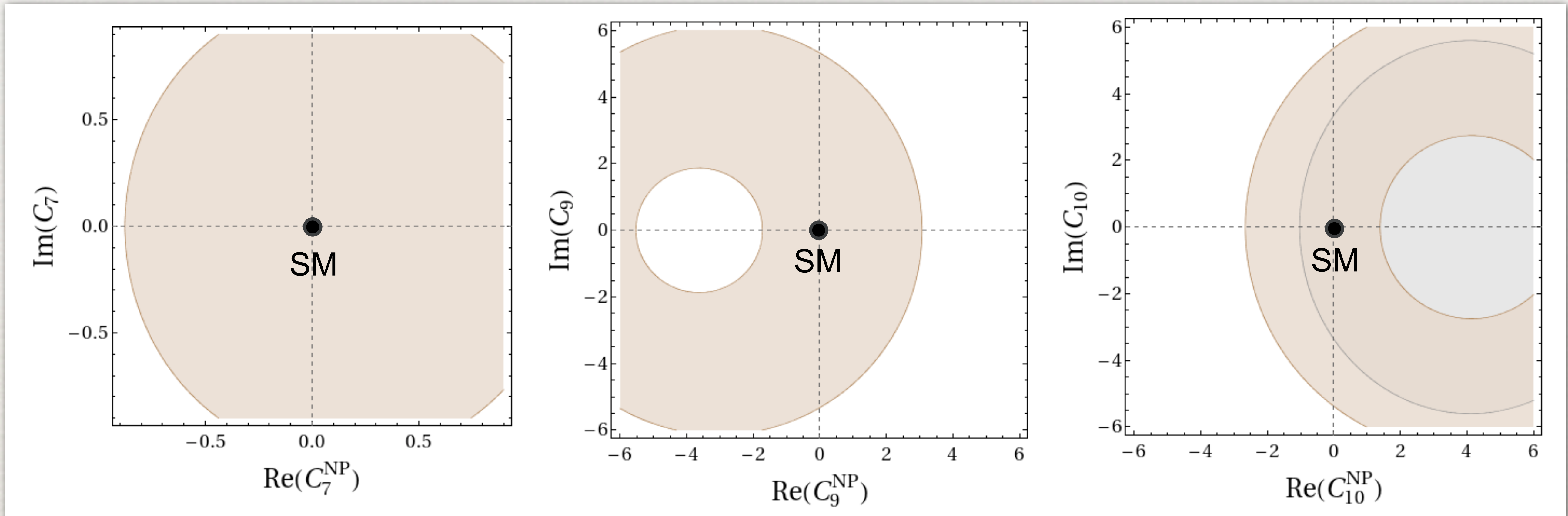

● $B_s \to \mu^+\mu^-$ ● $B \to X_s\mu^+\mu^-$

[see also Beaujean et al., 1205.1838;
Hurth & Mahmoudi, 1207.0688;
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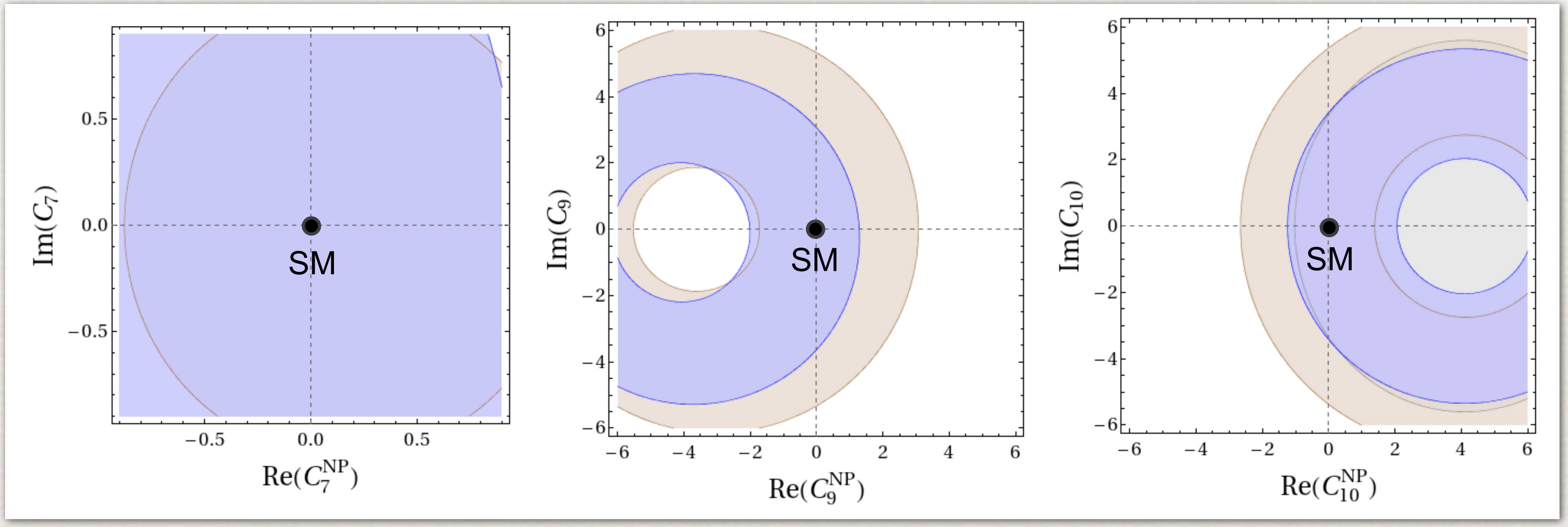

● $B_s \to \mu^+\mu^-$ ● $B \to X_s\mu^+\mu^-$ ● $B \to K\mu^+\mu^-$

[see also Beaujean et al., 1205.1838;
Hurth & Mahmoudi, 1207.0688;
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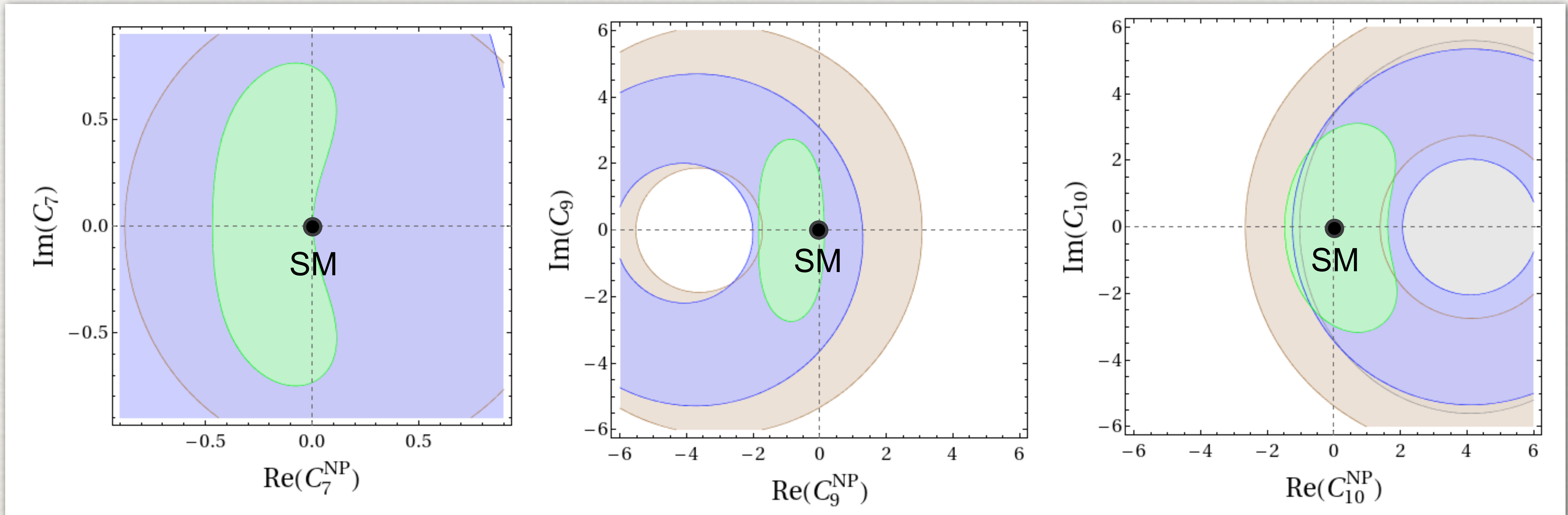

● $B_s \to \mu^+\mu^-$ ● $B \to X_s\mu^+\mu^-$ ● $B \to K\mu^+\mu^-$ ● $B \to K^*\mu^+\mu^-$

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Constraints On Left-Handed (LH) Currents

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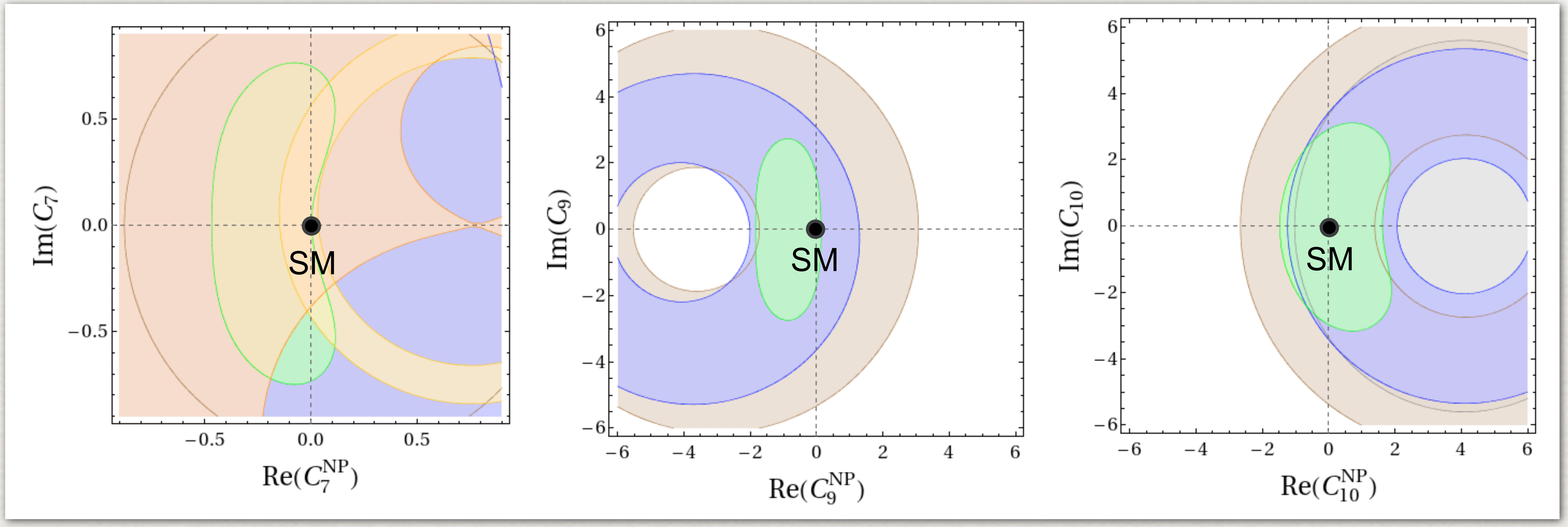

● $B_s \to \mu^+\mu^-$ ● $B \to X_s\mu^+\mu^-$ ● $B \to K\mu^+\mu^-$ ● $B \to K^*\mu^+\mu^-$ ● $B \to X_s\gamma$

[see also Beaujean et al., 1205.1838;
Hurth & Mahmoudi, 1207.0688;
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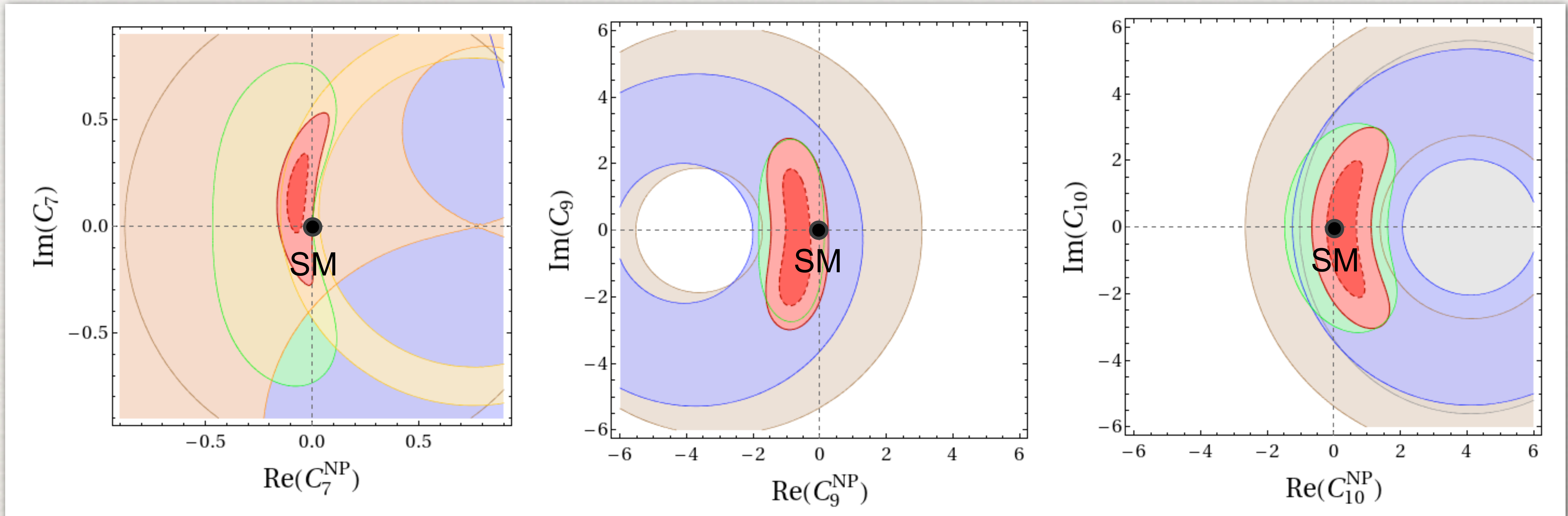
Constraints On Left-Handed (LH) Currents

[Altmannshofer & Straub, 1206.0273]



● $B_s \to \mu^+\mu^-$ ● $B \to X_s\mu^+\mu^-$ ● $B \to K\mu^+\mu^-$ ● $B \to K^*\mu^+\mu^-$ ● $B \to X_s\gamma$

- Data shows reasonable agreement with SM: χ^2/dofs = 21.8/24
- Need to measure CP-violating observables to better determine imaginary parts of Wilson coefficients

Implications for NP Scale

[Altmannshofer & Straub, 1206.0273]

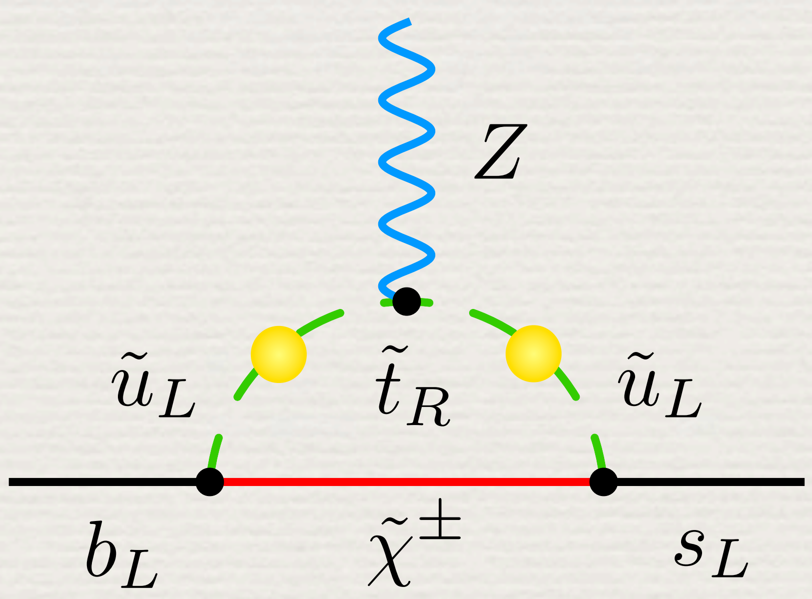
	Operator	Λ_{NP} [TeV] for $\lvert C_i \rvert = 1$			
		$+$	$-$	$+i$	$-i$
$Q_7 =$	$\frac{m_b}{e}(\bar{s}\sigma_{\mu\nu}P_R b)F^{\mu\nu}$	69	270	43	38
$Q_7' =$	$\frac{m_b}{e}(\bar{s}\sigma_{\mu\nu}P_L b)F^{\mu\nu}$	46	70	78	47
$Q_9 =$	$(\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell)$	29	64	21	22
$Q_9' =$	$(\bar{s}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu \ell)$	51	22	21	23
$Q_{10} =$	$(\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$	43	33	23	23
$Q_{10}' =$	$(\bar{s}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$	25	89	24	23
$Q_S^{(\prime)} =$	$\frac{m_b}{m_{B_s}}(\bar{s}P_{R(L)} b)(\bar{\ell}\ell)$	93	93	98	98
$Q_P =$	$\frac{m_b}{m_{B_s}}(\bar{s}P_R b)(\bar{\ell}\gamma_5 \ell)$	173	58	93	93
$Q_P' =$	$\frac{m_b}{m_{B_s}}(\bar{s}P_L b)(\bar{\ell}\gamma_5 \ell)$	58	173	93	93

- Bounds not as strong as those from K–$\overline{\text{K}}$ & B–$\overline{\text{B}}$ mixing, but for generic NP with strong coupling, scales above 20 TeV are probed

Two-Sided Limits on $B_s \to \mu^+\mu^-$

[Altmannshofer & Straub, 1206.0273]

$C_{7,9,10}$	$\mathbb{R}$	$\mathbb{C}$			$\mathbb{R}$	$\mathbb{C}$
$C'_{7,9,10}$			$\mathbb{R}$	$\mathbb{C}$	$\mathbb{R}$	$\mathbb{C}$
$\mathrm{Br}(B_s \to \mu^+\mu^-)\ [10^{-9}]$	$[1.9, 5.2]$	$[1.1, 4.6]$	$[1.1, 4.2]$	$[0.9, 4.6]$	< 4.6	< 4.2



LHC bound on $B_s \to \mu^+\mu^-$ can be saturated without (pseudo)scalar operators. Experiments only now start to probe NP in Z-penguins that enters through semileptonic operators

Conclusions

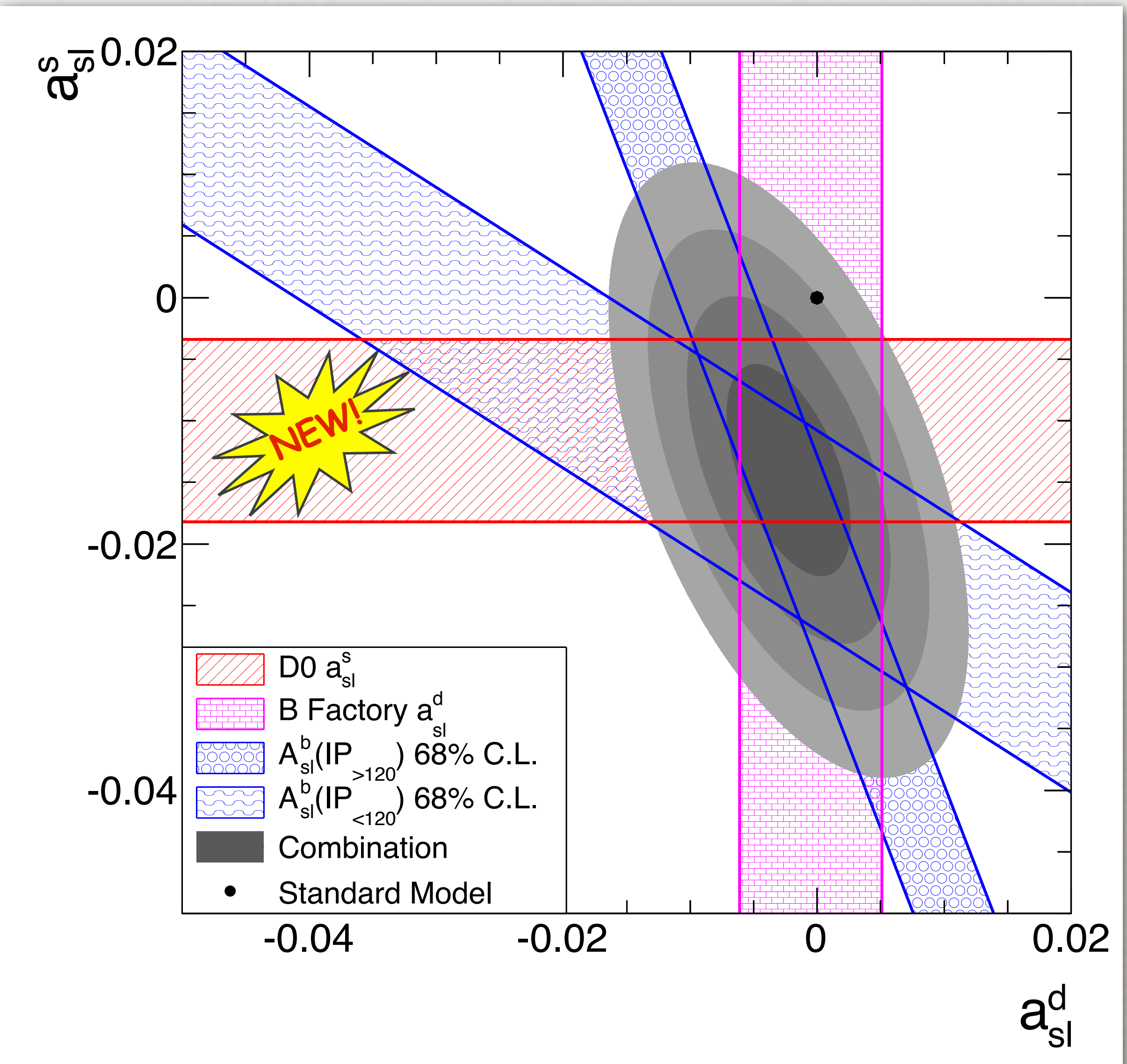
- B-mixing data shows good overall agreement with SM. Large A^b_{SL} requires NP in Γ^s_{12} and/or Γ^d_{12}, which is very difficult to construct. Further refined measurements of CP asymmetries needed to establish origin (statistical fluctuation or NP) of $\Delta B = 2$ anomaly

- First (1–5) fb^{-1} of LHC data took hope for spectacular effects in rare B decays. But at moment data not precise enough to exclude NP contaminations of O(50%). This still leaves room for visible & interesting effects, in particular, if CP violating

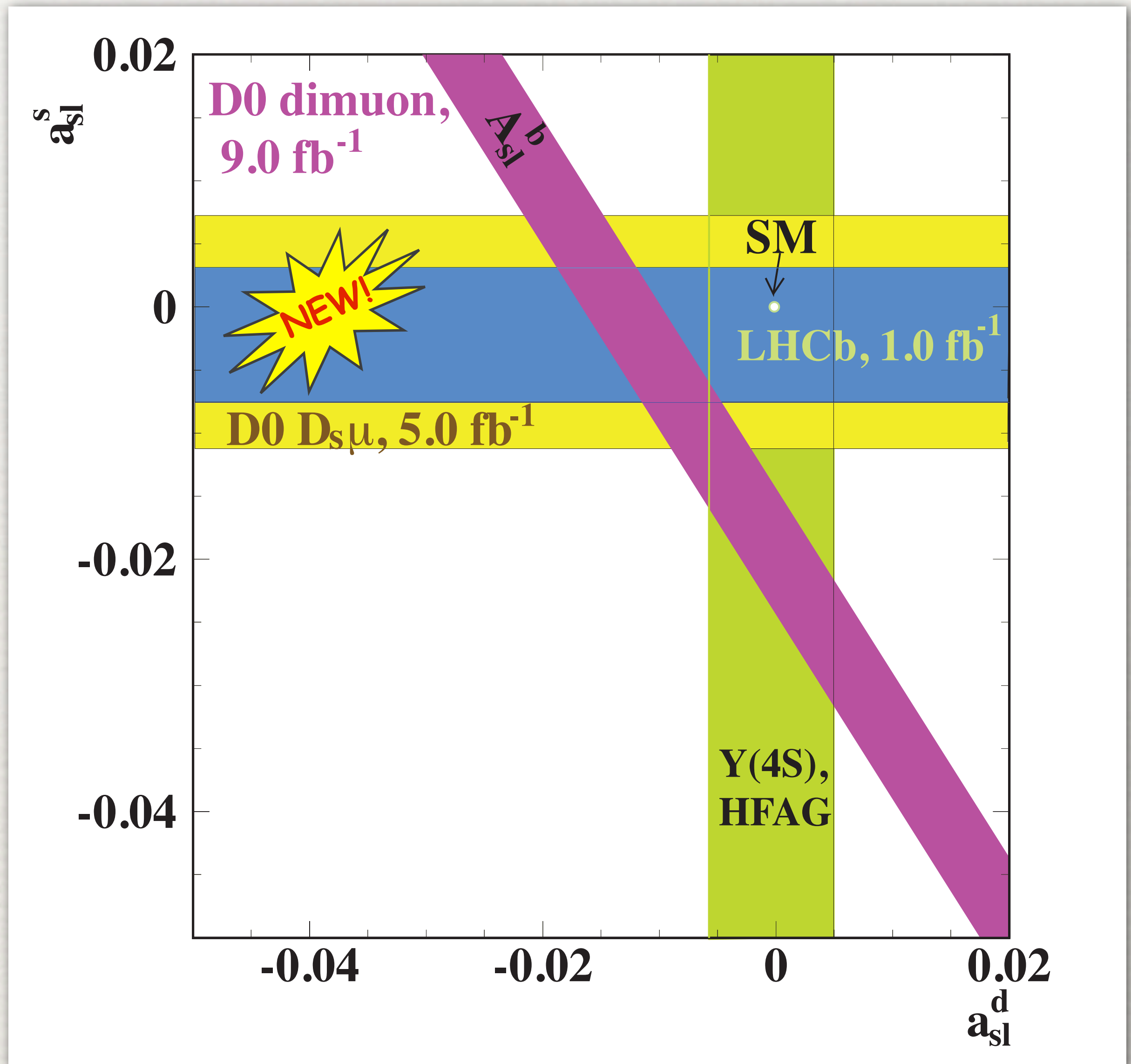
- Only synergy between high- & low-p_T observations may give us key to solving puzzles of fundamental physics. LHCb precision measurements of B-mixing observables, $B_s \to \mu^+\mu^-$, $B \to K^* l^+ l^-$, angle γ, ... crucial in endeavour

New Data on CP asymmetry in B_s Mixing

[DØ, 1207.1769]



[LHCb-CONF-2012-022]



- Recent determinations of a_{fs}^s by DØ & LHCb agree with each other & SM within errors. Further improvements needed to clarify origin of A_{SL}^b anomaly

Best-Fit Solutions to Data

	before 2011	in 2012
R_M	1.05 ± 0.16	1.04 ± 0.16
ϕ_M [°]	-46 ± 19	-0.4 ± 5.0
R_Γ	3.3 ± 1.5	3.4 ± 1.8
ϕ_Γ [°]	7 ± 30	56 ± 22

- Even before measurements of B_s-mixing observables by LHCb, a perfect 4-parameter fit ($\chi^2 = 0$) to data required large corrections in Γ_{12}. New data set favors both enhanced magnitude R_Γ & phase ϕ_Γ

If NP in M_{12}, Which Kind?

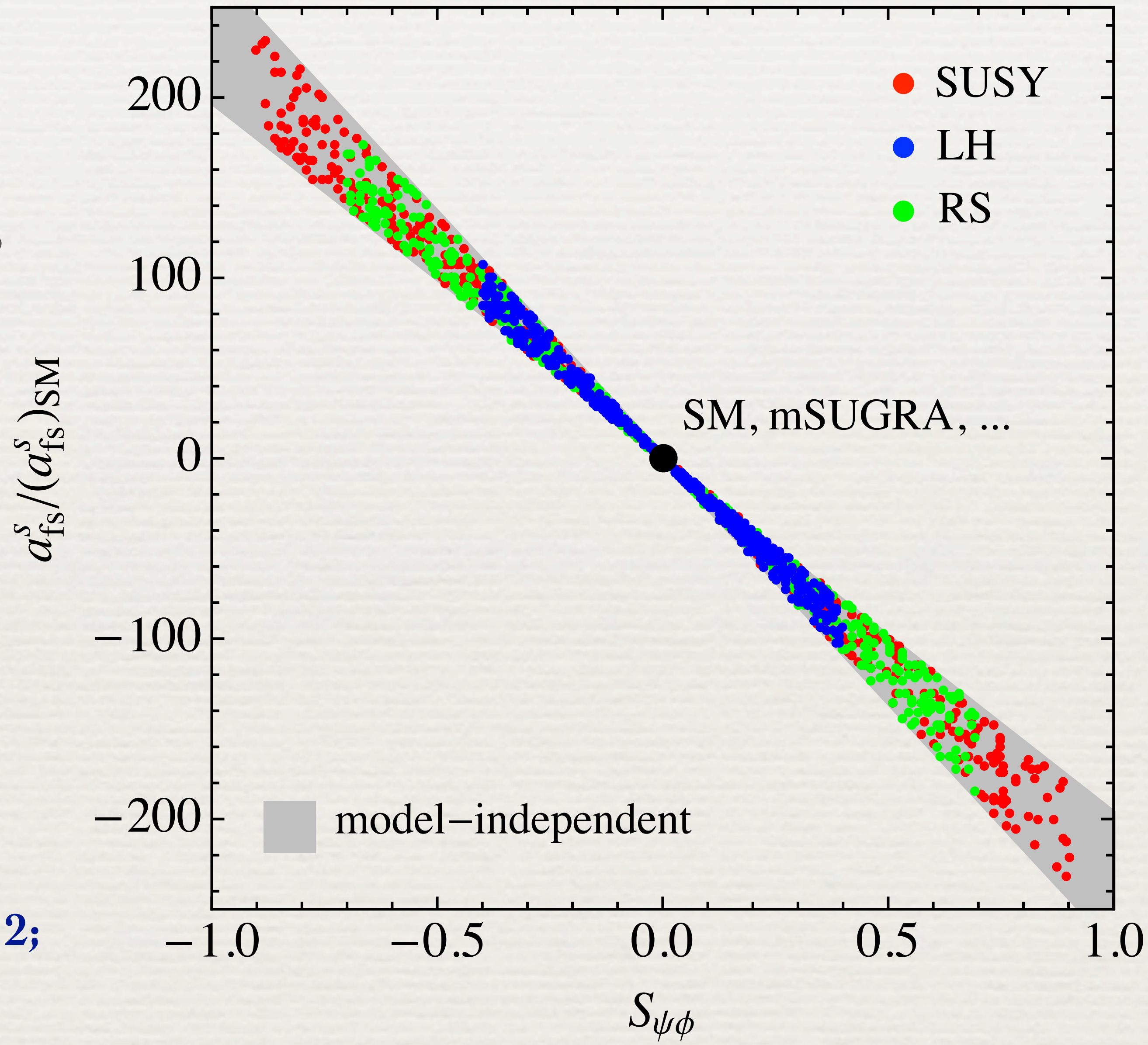
- In all NP models without direct CPV in decay (like SUSY, little Higgs (LH), Randall-Sundrum (RS) scenarios, ...), observables a_{fs}^{s} & $S_{\psi\phi}$ strongly correlated:

$$\frac{a_{fs}^s}{(a_{fs}^s)_{\rm SM}} \approx -240\,\frac{S_{\psi\phi}}{R_M}\,,$$

$$R_M = 1.05 \pm 0.16$$

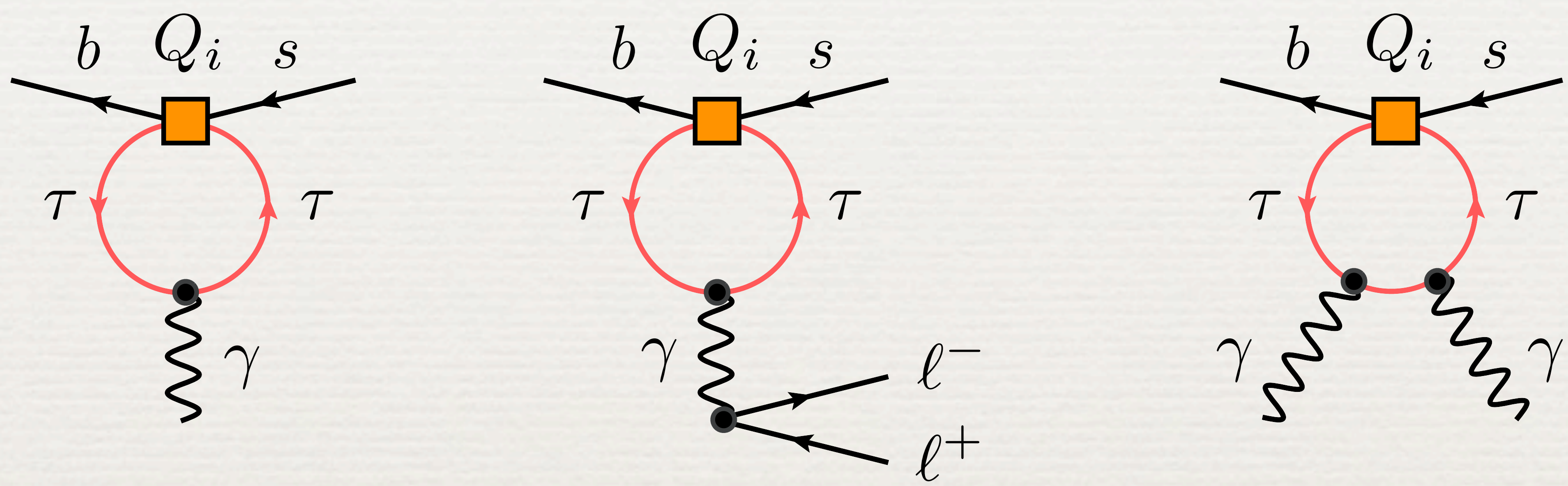
[see e.g. Ligeti, Papucci & Perez, hep-ph/0604112; Blanke et al., 0805.4393, 0809.1073; Altmannshofer et al., 0909.1333; Casagrande et al., 0912.1625; ...]

[schematic plot]



Bounds on (s̄b)(τ̄τ) Operators

- Indirect constraints due to operator mixing & matrix elements:[†]



$Q_{T,R} \to Q_7\,,\quad Q_{T,L} \to Q_7'$

$Q_{V,LA} \to Q_9\,,\quad Q_{V,RA} \to Q_9'$

$Q_{S,AB} \to \vec{\epsilon}_1 \cdot \vec{\epsilon}_2\,,\quad Q_{S,AB}, Q_{V,AB} \to \vec{\epsilon}_1 \times \vec{\epsilon}_2$

Bounds on C_i's derived by taking into account measurements of $B \to X_s\gamma$ (Br), $B \to K^*\gamma$ (Br, S, A_I), $B \to X_s l^+l^-$ (Br), $B \to K l^+l^-$ (Br), $B \to K^* l^+l^-$ (Br, A_{FB}, F_L) & upper limit on $B_s \to \gamma\gamma$ (Br)

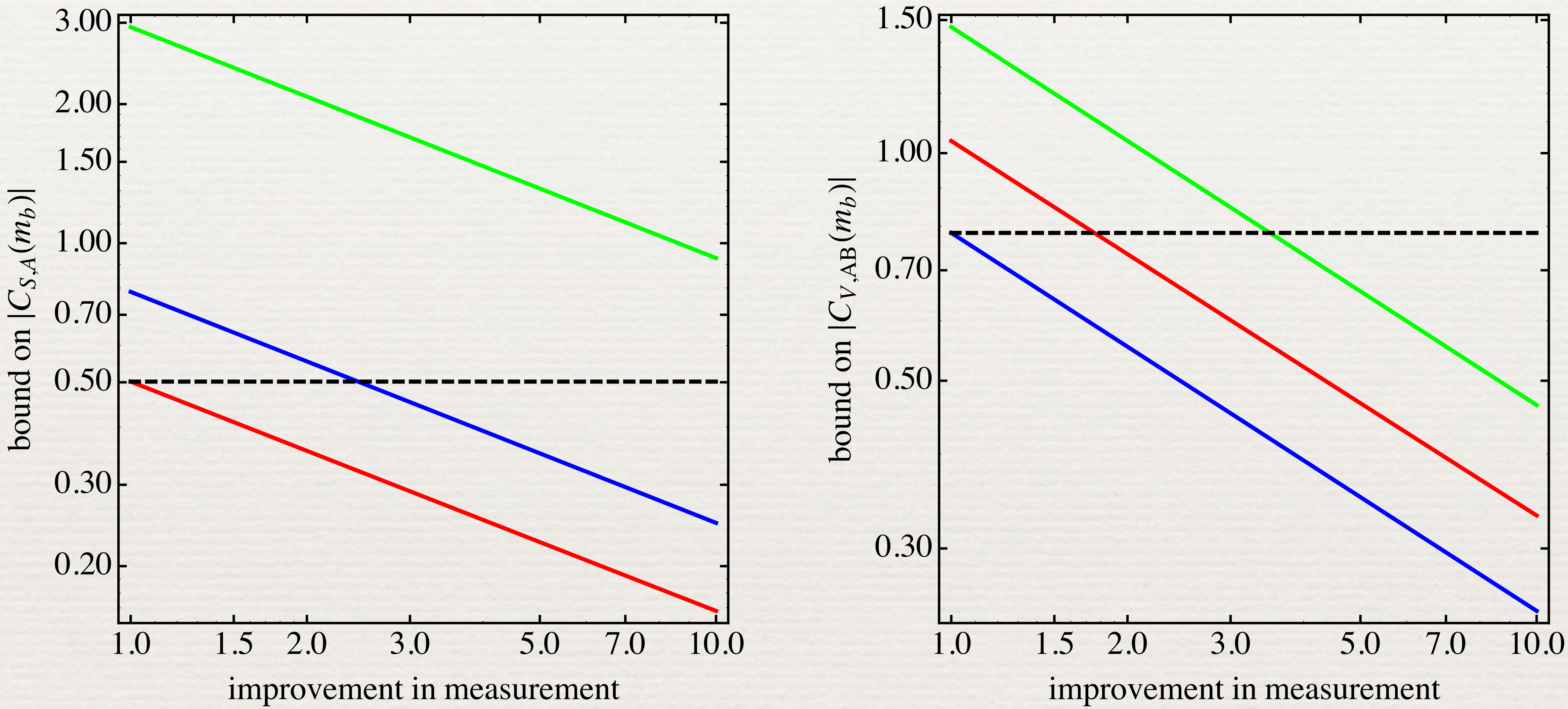
[†]$Q_{S,AB}$ does not mix into $b \to s\gamma$, l^+l^- but has non-zero $b \to s\gamma\gamma$ elements

Details on Bounds on Wilson Coefficients

$C_i(m_b)$	$B^+ \to K^+\tau^+\tau^-$	$B_s \to \tau^+\tau^-$	$B \to X_s\tau^+\tau^-$	$b \to s\gamma,\ l^+l^-$	$B_s \to \gamma\gamma$
S, AB	< 0.8	$\lesssim 0.5$	$\lesssim 2.9$	—	$< 3.4, 2.3$
V, AB	< 0.8	$\lesssim 1.0$	$\lesssim 1.5$	$< 1.1, 1.0$	< 5.9
T, A	< 0.4	—	< 0.4	$< 0.06, 0.09$	—
7	—	—	—	< 0.23	< 2.2
7′	—	—	—	< 0.20	< 1.9
9	—	—	—	< 2.0	—
9′	—	—	—	< 1.7	—

Future (?) Bounds on Wilson Coefficients

[UH, 1206.1230]



Br($B_s \to \tau^+\tau^-$) Br($B^+ \to K^+\tau^+\tau^-$) Br($B \to X_s\tau^+\tau^-$)

at present: $\lesssim 3\%$ $< 3.3 \cdot 10^{-3}$ $\lesssim 2.5\%$

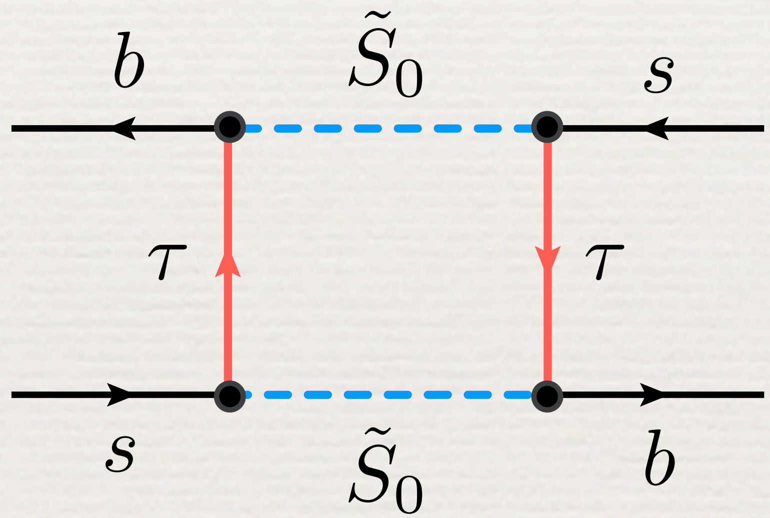
Lepto-Quark Contributions to Γ_{12}

- For SU(2) singlet scalar lepto-quarks (LQs) relevant coupling

$$\mathcal{L}_{\rm LQ} \ni (\lambda_{R\tilde{S}_0})_{ij} \left(\bar{d}_j^c P_R e_i\right) \tilde{S}_0 + \text{h.c.}$$

leads to $\Delta B = 1$ & $\Delta B = 2$ interactions

$$\mathcal{L}_{\rm eff} \ni -\frac{(\lambda_{R\tilde{S}_0})_{32}(\lambda_{R\tilde{S}_0})_{33}}{2M^2_{\tilde{S}_0}} Q_{V,RR}$$

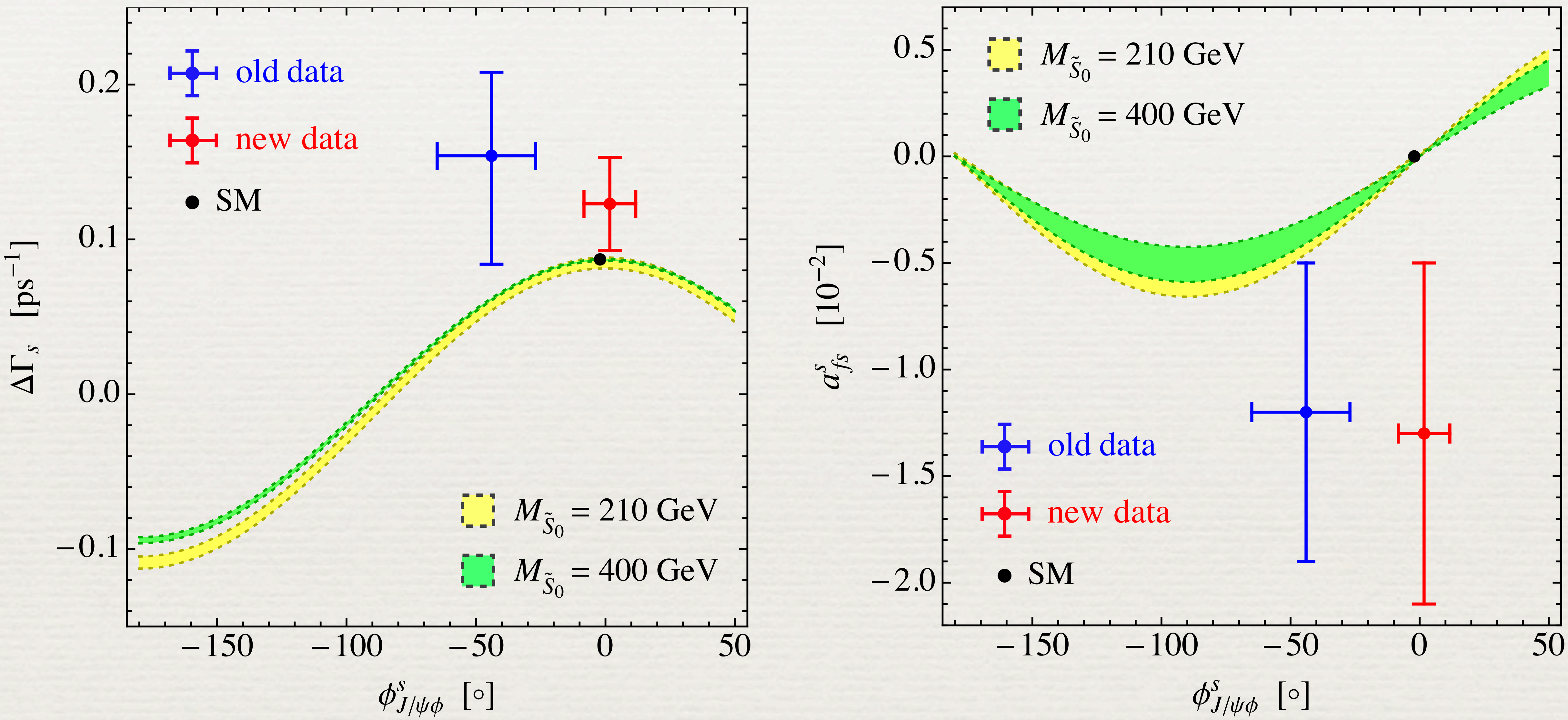


which give a real ratio (btw. $r_{SM} \approx -200$)

$$r_{\rm LQ} = \frac{(M_{12})_{\rm LQ}}{(\Gamma_{12})_{\rm LQ}} = 2084 \left(\frac{M^2_{\tilde{S}_0}}{250\,\text{GeV}}\right)$$

Predictions for SU(2) Singlet Scalar LQs

[Bobeth & UH, 1109.1826]



- Even a light LQ fails to describe data & parameter space shrinks further for heavier LQs. Visible cosine-, sine-like correlations & $\Delta\Gamma < (\Delta\Gamma)_{SM}$ model-independent feature

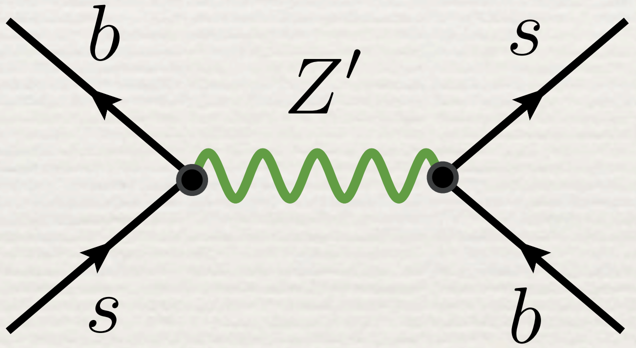
Z' Contributions to Γ_{12}

- For left-handed Z' boson relevant couplings

$$\mathcal{L}_{Z'} \ni \frac{g}{\cos\theta_W} \left[\left(\kappa^L_{sb}\, \bar{s}\gamma^\mu P_L b + \text{h.c.} \right) + \kappa^L_{\tau\tau}\, \bar{\tau}\gamma^\mu P_L \tau \right] Z'_\mu$$

give rise to $\Delta B = 1$ & $\Delta B = 2$ interactions

$$\mathcal{L}_{\text{eff}} \ni -\frac{8G_F}{\sqrt{2}} \frac{M_Z^2}{M_{Z'}^2} \kappa^L_{sb}\, \kappa^L_{\tau\tau}\, Q_{V,LL}$$

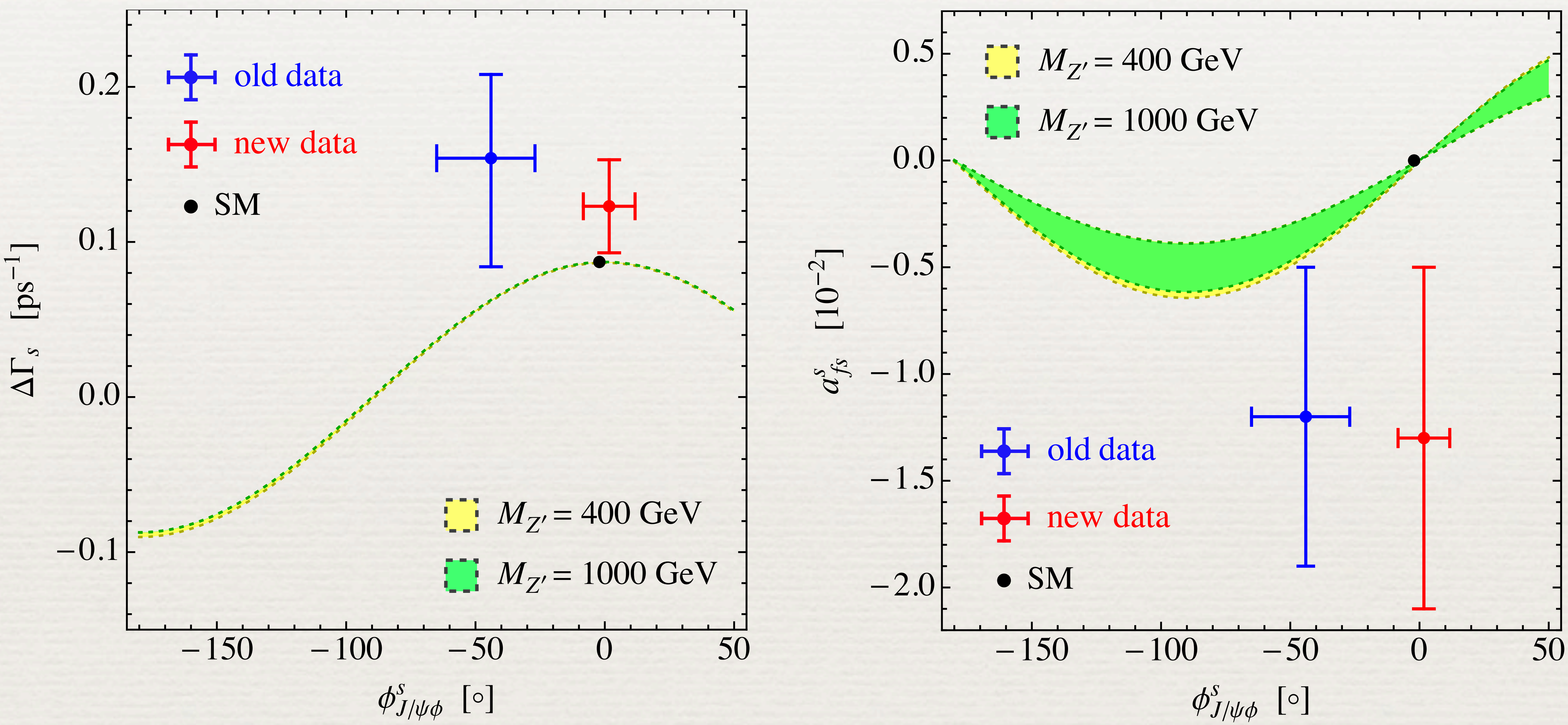


which again produce a real ratio

$$r_{Z'} = \frac{(M_{12})_{Z'}}{(\Gamma_{12})_{Z'}} = 6.0 \cdot 10^5 \left(\frac{M_{Z'}}{250\,\text{GeV}} \frac{1}{\kappa^L_{\tau\tau}} \right)^2$$

Predictions for Left-handed Z'

[Bobeth & UH, 1109.1826]



- Left-handed Z' provides an even worse description of data than LQs. Model-independent correlations & $\Delta\Gamma < (\Delta\Gamma)_{SM}$ also present in case of new neutral vector boson

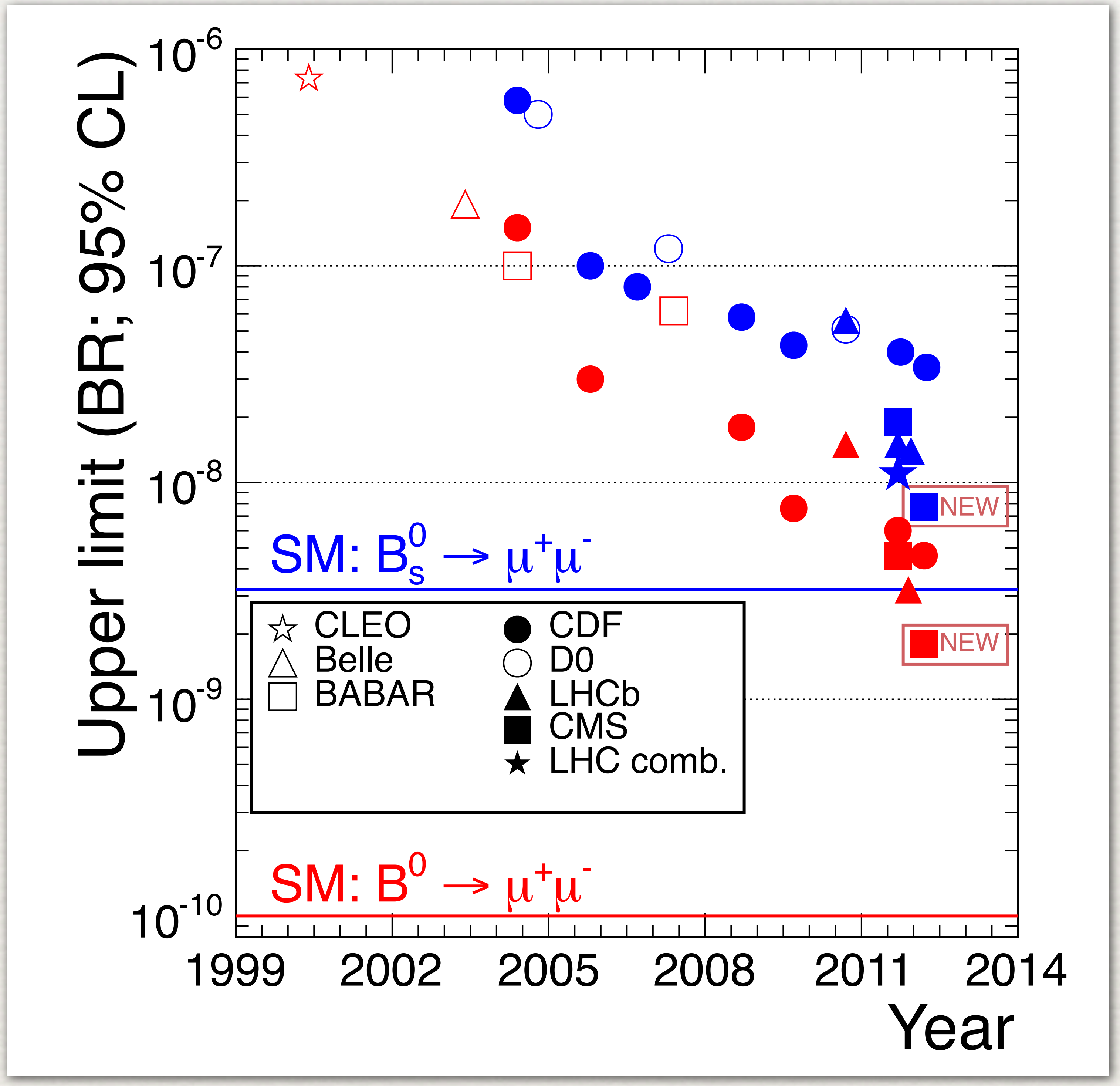
Further Comments on NP in $\Gamma_{12}^{s,d}$

- Bounds on $(\bar{s}b)(\bar{\tau}\mu)$ are stronger by roughly a factor of 7 than those on $(\bar{s}b)(\bar{\tau}\tau)$ operators, since $\mathrm{Br}(B^+ \to K\tau^\pm\mu^\mp) < 7.7 \cdot 10^{-5}$ compared to $\mathrm{Br}(B^+ \to K^+\tau^+\tau^-) < 3.3 \cdot 10^{-3}$. Hence, contributions from $(\bar{s}b)(\bar{\tau}\mu)$ operators cannot improve fit to B_s data notable

- An contribution from $(\bar{d}b)(\bar{\tau}\tau)$ operators to Γ_{12}^{d} large enough to explain data excluded by bound $\mathrm{Br}(B \to \tau^+\tau^-) < 4.1 \cdot 10^{-3}$. Case of $\tau^\pm\mu^\mp$ final state even less favorable

- My naive guess is that $(\bar{d}b)(\bar{c}c)$ operators are heavily constrained (should be numerically smaller than QCD/electroweak penguins in SM) by exclusive B decays & thus also cannot resolve tension in B-mixing sector. A dedicated analysis is however missing

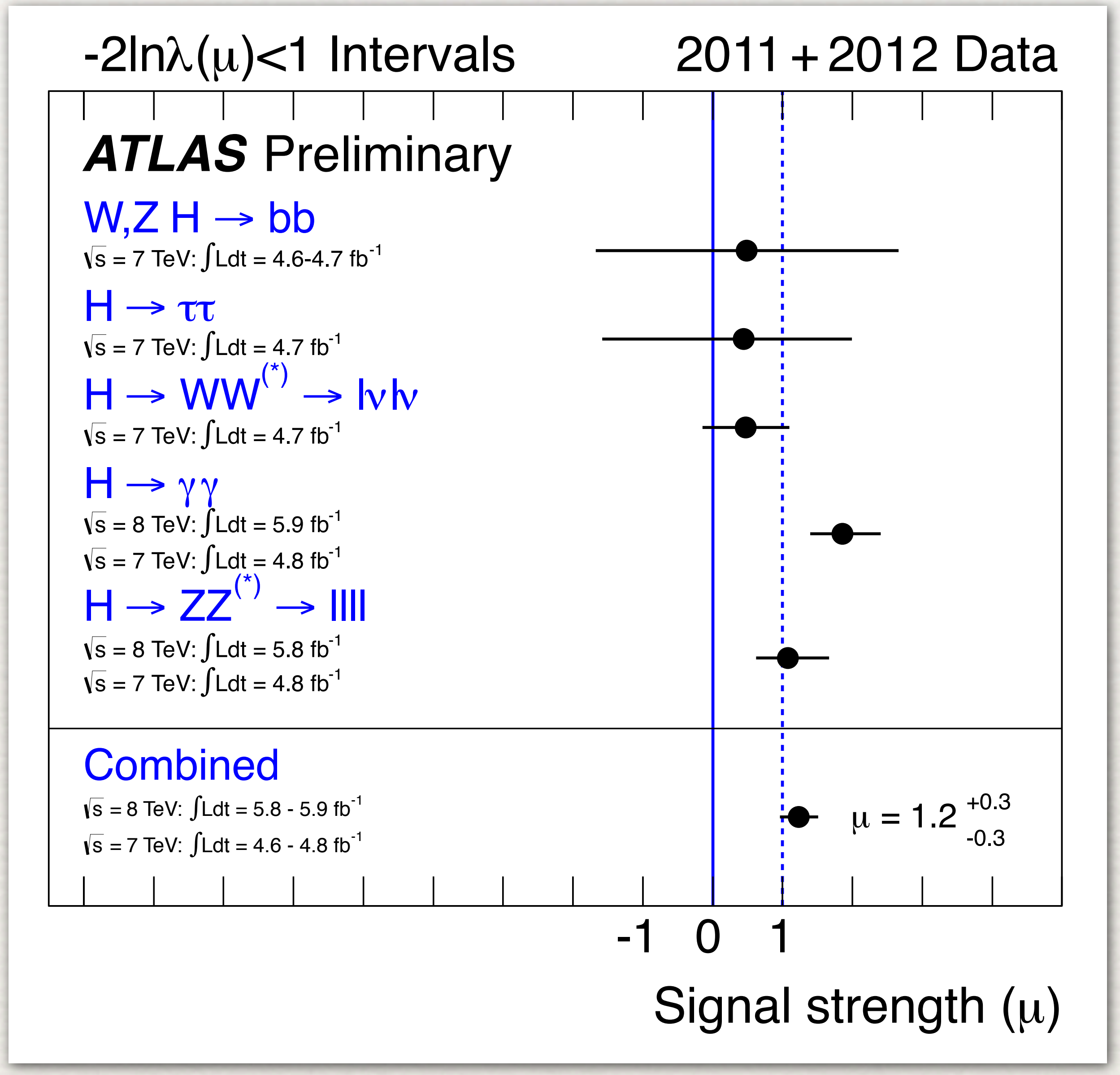
Timeline of $B_{s,d} \to \mu^+\mu^-$



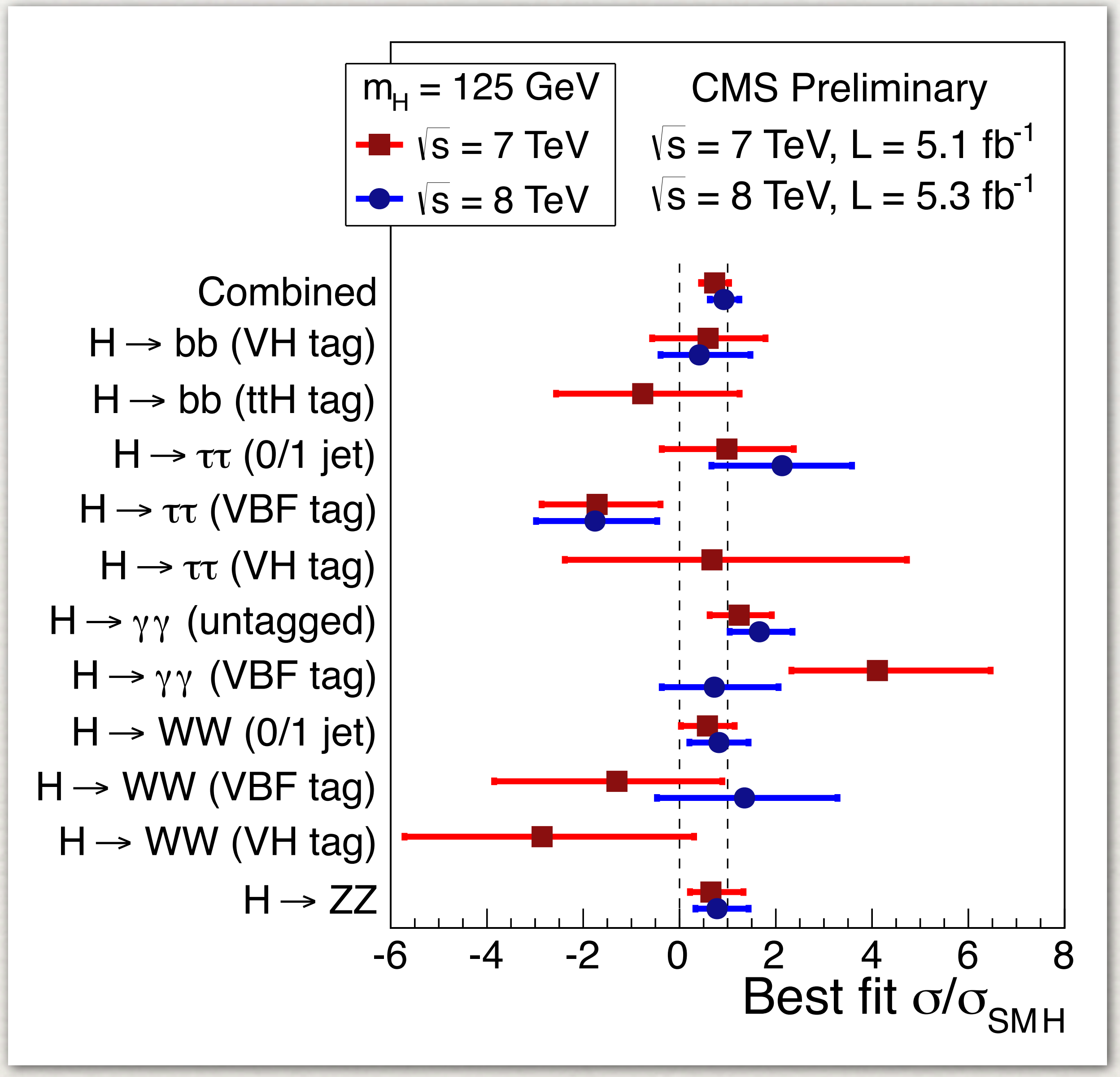
http://cms.web.cern.ch/org/cms-papers-and-results

Higgs: 2011 vs. 2012 Data

[ATLAS-CONF-2012-093]



[CMS-HIG-12-020]



- Both ATLAS & LHC see excess in $h \to \gamma\gamma$, but size of effect smaller in 2012 than 2011 data. Altogether 2012 data looks more SM like

MSSM: Anatomy of Higgs Mass

- For large t_β there are further contributions from sbottom & stau sector that can be relevant ($\tilde{f} = \tilde{b}, \tilde{\tau}$):

$$(\Delta m_h^2)_{\tilde{f}} \approx -\frac{N_c^{\tilde{f}}}{\sqrt{2} G_F} \frac{y_f^4}{48\pi^2} \frac{\mu^4}{m_{\tilde{f}}^4}$$

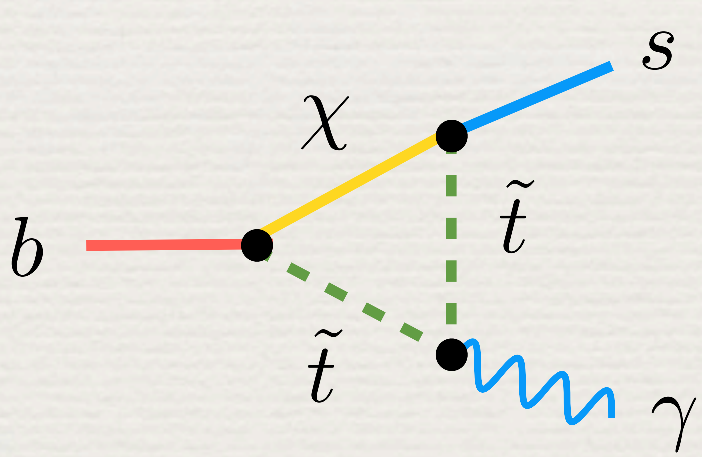
where $N_c^{\tilde{b},\tilde{\tau}} = 3,1$. Corrections are negative & quartic in Higgsino mass μ. Their impact is minimized for $\mathrm{sgn}(\mu M_{3,2}) = +1$

[see for example Carena et al., hep-ph/9504316, hep-ph/9508343; Haber et al., hep-ph/9609331]

MSSM: Anatomy of B → $X_s\gamma$

- In parameter region of interest, dominant MSSM contributions to inclusive radiative B decay stems from loops with stop & higgsino-like chargino:

$$R_{X_s} = \frac{\text{Br}(B \to X_s\gamma)}{\text{Br}(B \to X_s\gamma)_{\text{SM}}} \approx 1 - 2.55\,\Delta C_7 + 1.57\,(\Delta C_7)^2$$

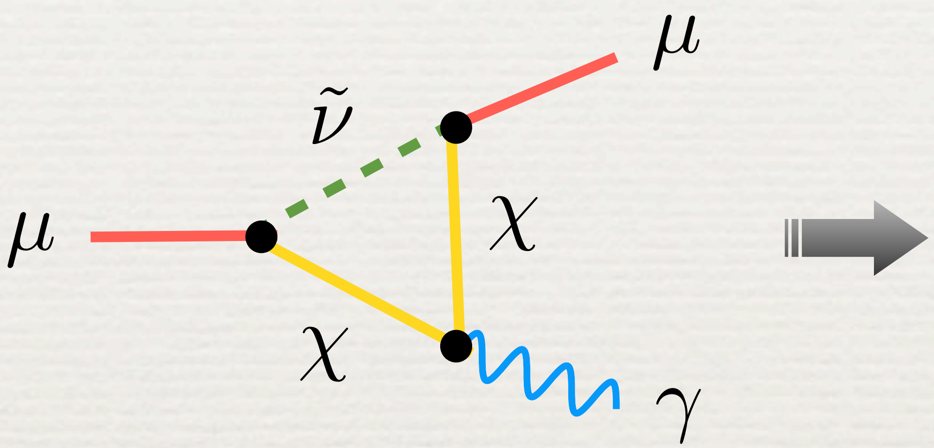


$$\Rightarrow \quad \Delta C_7^{\chi} \propto -\mu A_t\, t_\beta \,\frac{m_t^2}{m_{\tilde{t}}^4}$$

For t_β = 50, $m_{\tilde{t}}$ = |μ| = 1 TeV & $|A_t|$ = 2 TeV, MSSM rate enhanced (suppressed) by around 20% relative to SM for sgn(μA_t) = +1 (-1)

MSSM: Anatomy of a_μ

- Throughout parameter space of interest, dominant contribution to muon anomalous magnetic moment arises from chargino-sneutrino diagrams:



$$\Delta a_\mu^\chi \propto \frac{G_F M_W^2}{\sqrt{2}\pi^2}\, \mu M_2\, t_\beta\, \frac{m_\mu^2}{m_{\tilde{\nu}}^4}$$

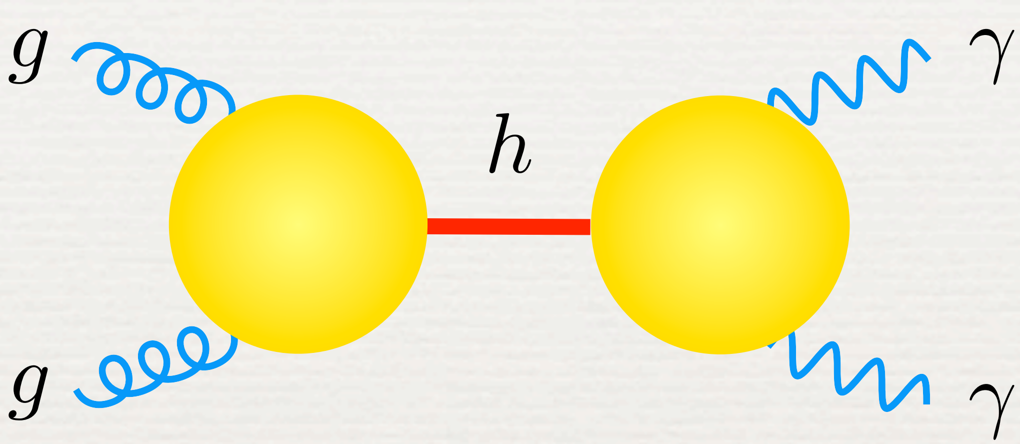
For t_β = 50, $m_{\tilde{\nu}}$ = |μ| = 1 TeV & $|M_2|$ = 0.2 TeV, one has numerically

$$\Delta a_\mu^\chi \approx \text{sgn}\,(\mu M_2)\, 7.5 \cdot 10^{-10}$$

meaning that for $\mu M_2 > 0$ tension between experimental result & SM prediction is reduced

[see for example Moroi, hep-ph/9512396]

Master Formula for pp → γγ

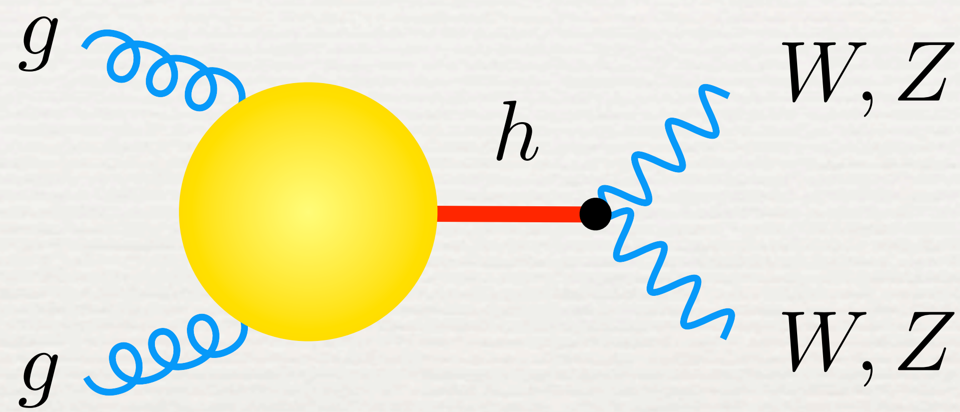


$$R_{\gamma\gamma} \approx 1 + 0.33 \left(\frac{m_t^2}{m_{\tilde{t}_1}^2} + \frac{m_t^2}{m_{\tilde{t}_2}^2} - \frac{m_t^2 X_t^2}{m_{\tilde{t}_1}^2 m_{\tilde{t}_2}^2} \right) - 0.43 \frac{m_b^2 X_b^2}{m_{\tilde{b}_1}^2 m_{\tilde{b}_2}^2}$$

$$+ 0.10 \frac{m_\tau^2 X_\tau^2}{m_{\tilde{\tau}_1}^2 m_{\tilde{\tau}_2}^2} + 1.63 \, \mathrm{sgn}\,(\mu M_2) \, \frac{1}{t_\beta} \frac{M_W^2}{m_{\chi_1} m_{\chi_2}} - 2.46 \frac{M_Z^2}{M_A^2}$$

- Large non-decoupling corrections arise from fact that for Higgs of around 125 GeV branching fraction of Higgs to $b\bar{b}$ is about 60%

Master Formula for pp → WW,ZZ

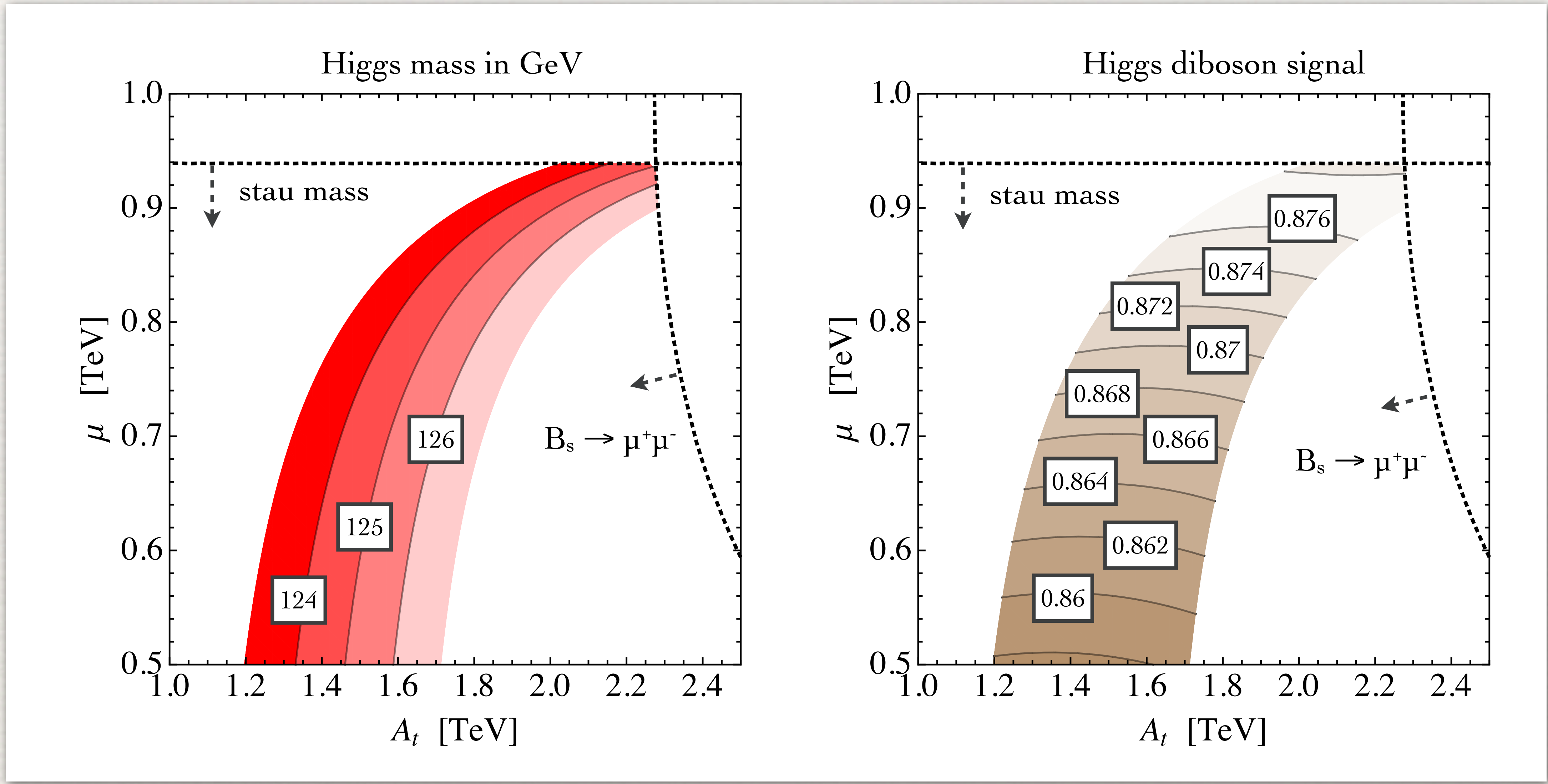


$$R_{VV} \approx 1 + 0.46 \left(\frac{m_t^2}{m_{\tilde{t}_1}^2} + \frac{m_t^2}{m_{\tilde{t}_2}^2} - \frac{m_t^2 X_t^2}{m_{\tilde{t}_1}^2 m_{\tilde{t}_2}^2} - \frac{m_b^2 X_b^2}{m_{\tilde{b}_1}^2 m_{\tilde{b}_2}^2} \right) - 2.46 \frac{M_Z^2}{M_A^2}$$

- Also massive vector-boson channels plagued by non-decoupling corrections associated to Br(h → b$\bar{\text{b}}$) ≈ 60%

A_t-μ Planes: m_h & $R_{WW,ZZ}$

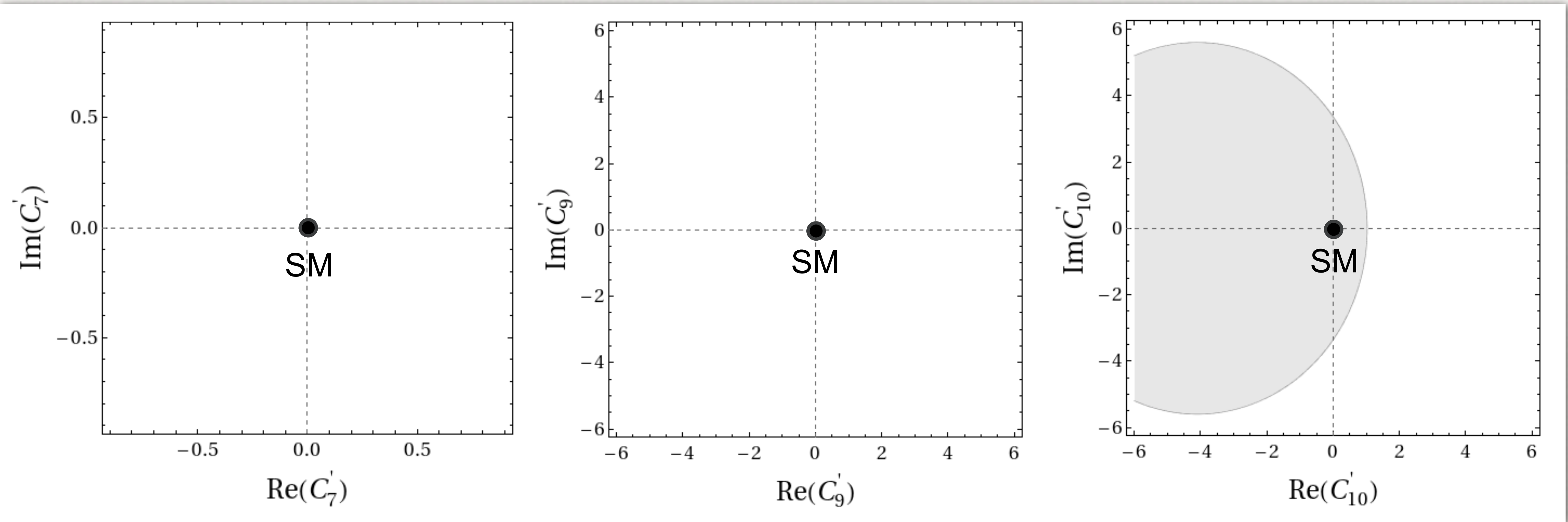
[UH & Mahmoudi, 1208.xxxx]



- Production of Higgs boson times decay to electroweak dibosons reduced with respect to SM by about (10-15)%

Constraints On Right-Handed (RH) Currents

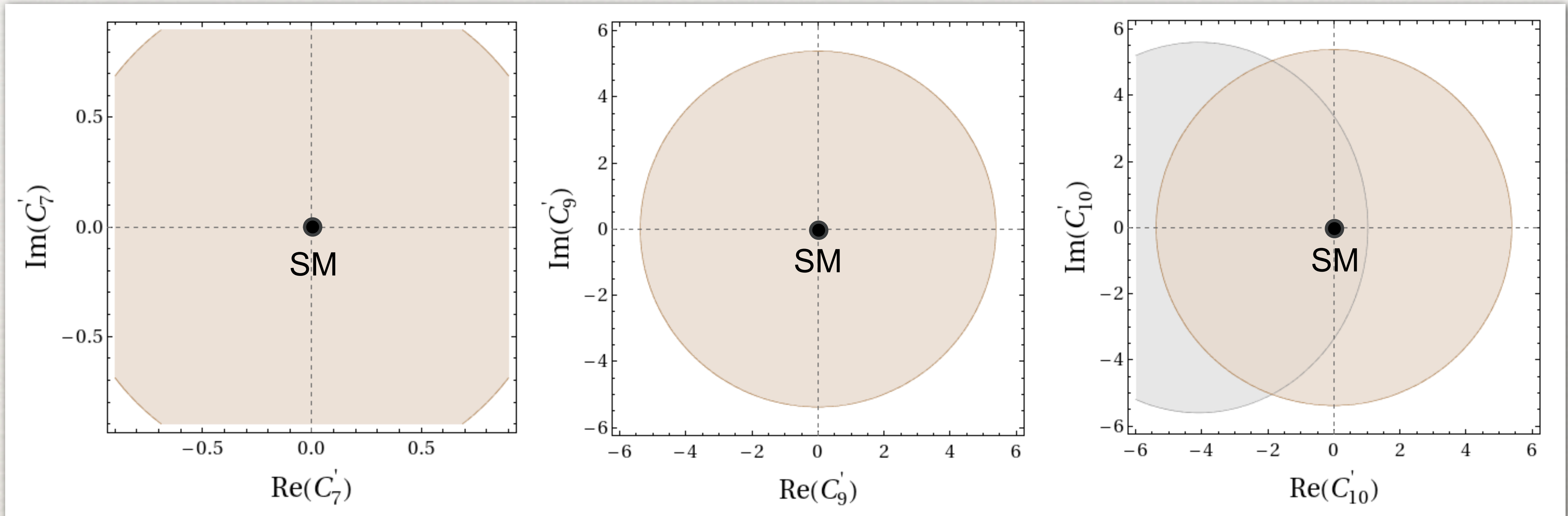
[Altmannshofer & Straub, 1206.0273]



- $B_s \to \mu^+\mu^-$

Constraints On Right-Handed (RH) Currents

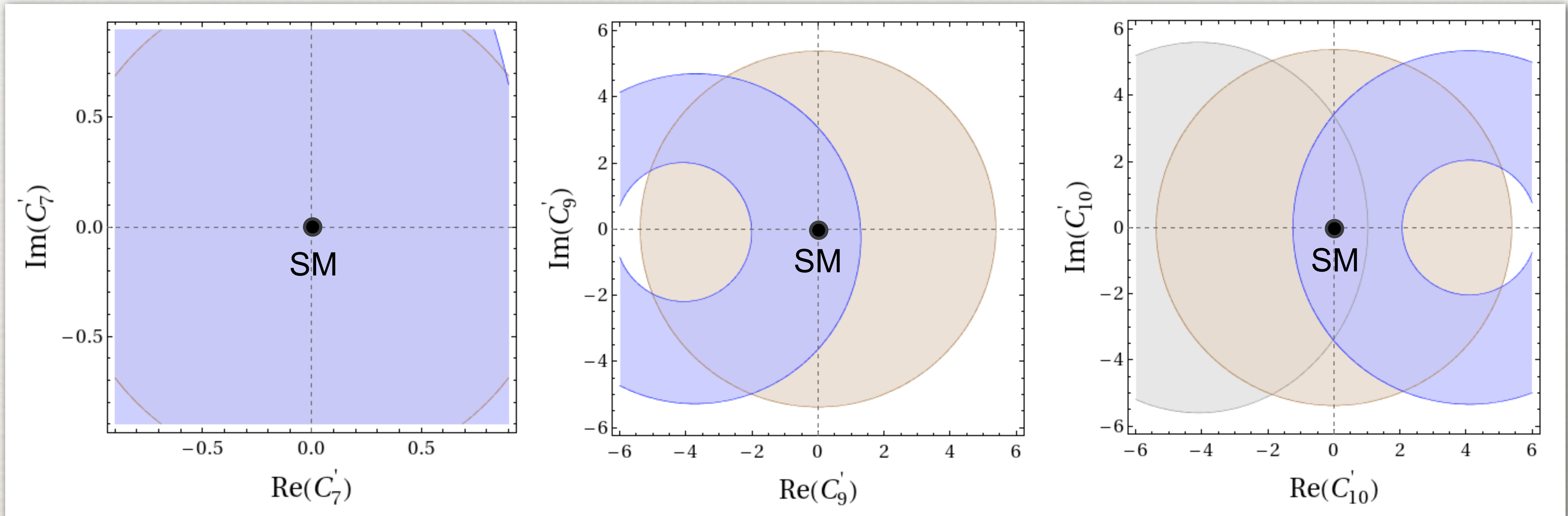
[Altmannshofer & Straub, 1206.0273]



- $B_s \to \mu^+\mu^-$
- $B \to X_s\mu^+\mu^-$

Constraints On Right-Handed (RH) Currents

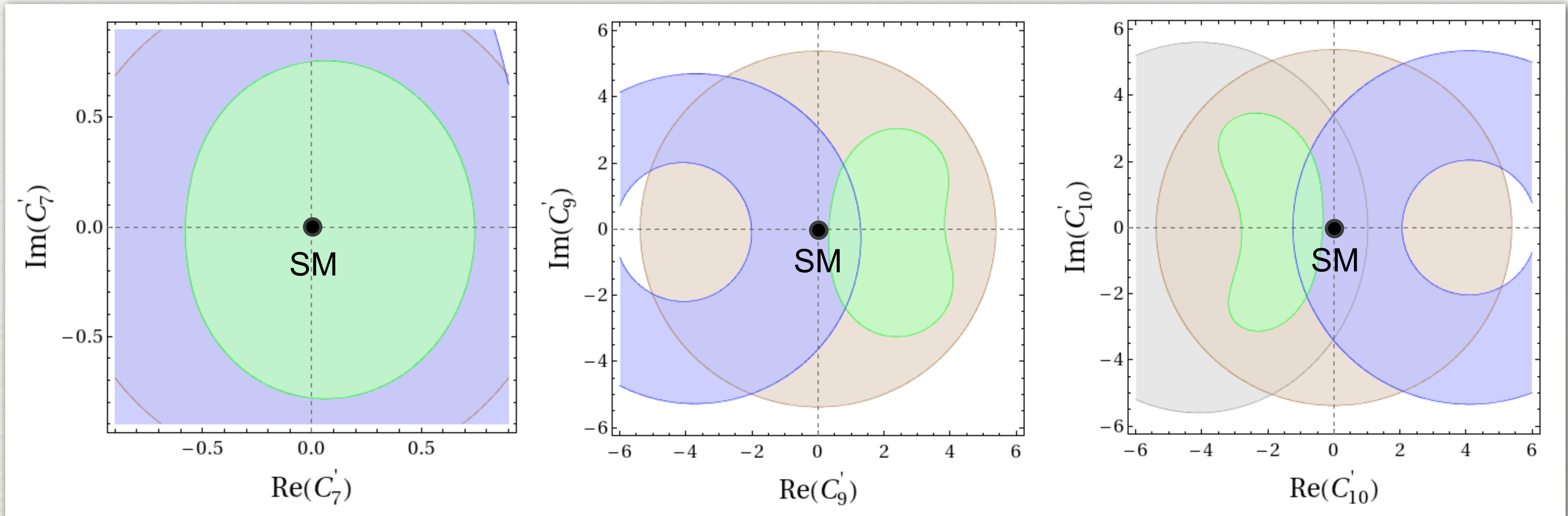
[Altmannshofer & Straub, 1206.0273]



● $B_s \to \mu^+\mu^-$ ● $B \to X_s\mu^+\mu^-$ ● $B \to K\mu^+\mu^-$

Constraints On Right-Handed (RH) Currents

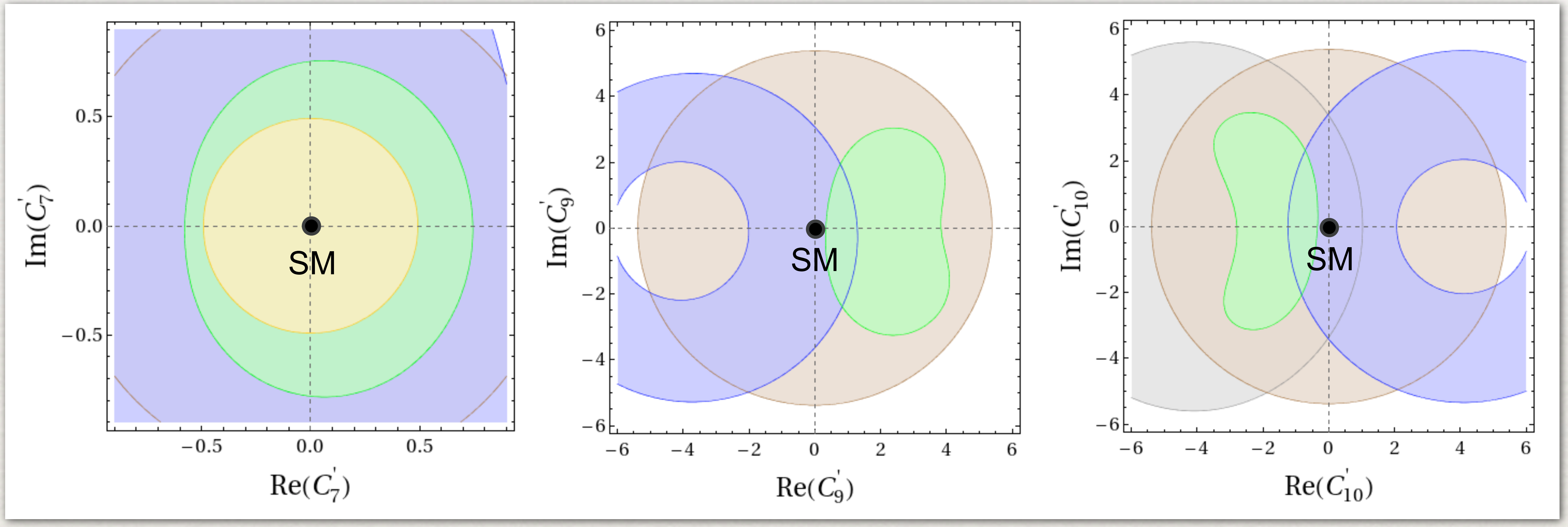
[Altmannshofer & Straub, 1206.0273]



● $B_s \to \mu^+\mu^-$ ● $B \to X_s\mu^+\mu^-$ ● $B \to K\mu^+\mu^-$ ● $B \to K^*\mu^+\mu^-$

Constraints On Right-Handed (RH) Currents

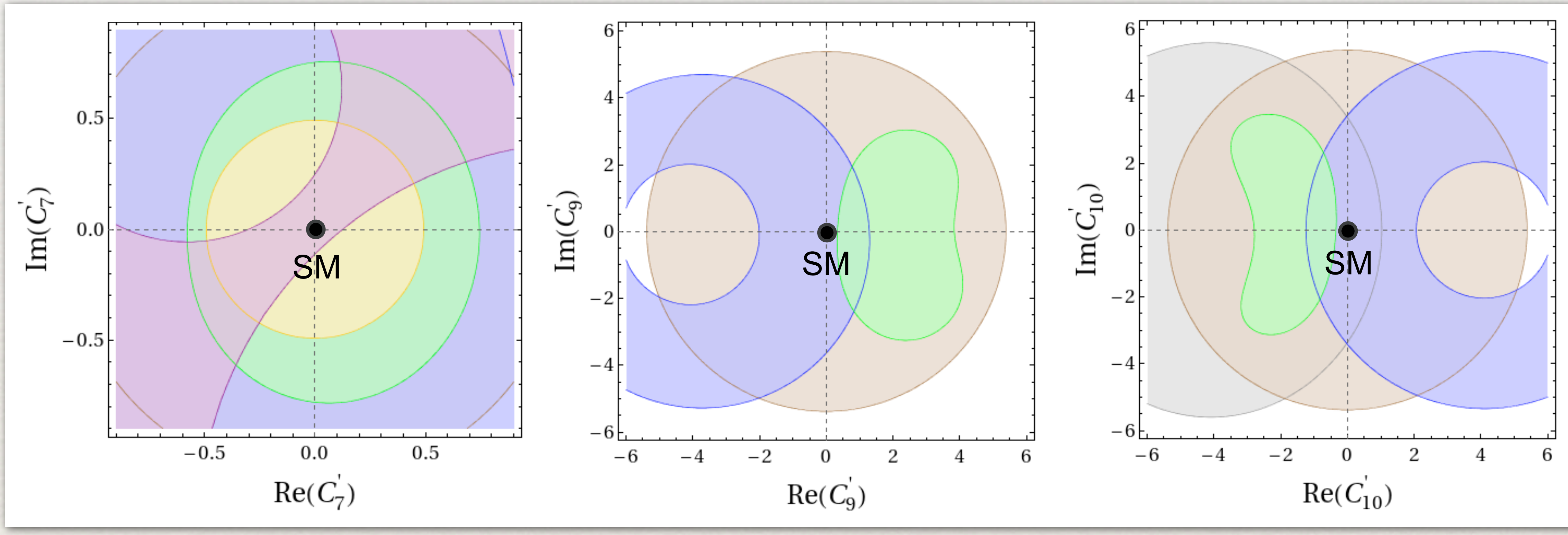
[Altmannshofer & Straub, 1206.0273]



● $B_s \to \mu^+\mu^-$ ● $B \to X_s\mu^+\mu^-$ ● $B \to K\mu^+\mu^-$ ● $B \to K^*\mu^+\mu^-$ ● $B \to X_s\gamma$

Constraints On Right-Handed (RH) Currents

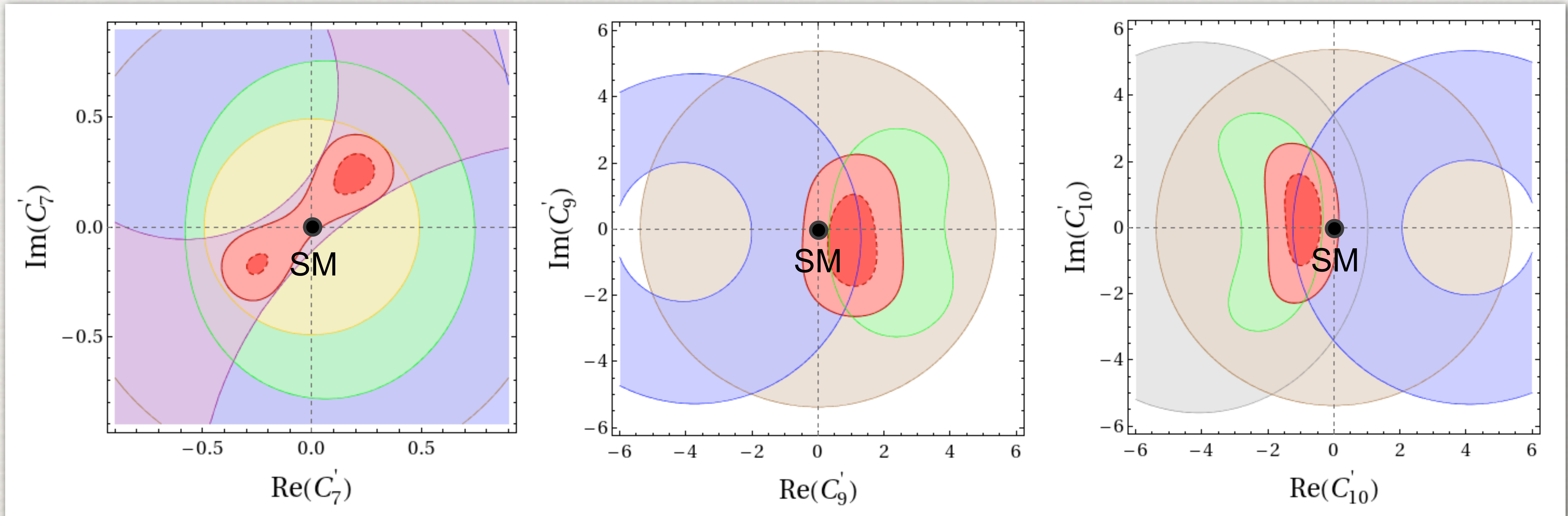
[Altmannshofer & Straub, 1206.0273]



- $B_s \to \mu^+\mu^-$
- $B \to X_s\mu^+\mu^-$
- $B \to K\mu^+\mu^-$
- $B \to K^*\mu^+\mu^-$
- $B \to X_s\gamma$
- $B \to K^*\gamma$

Constraints On Right-Handed (RH) Currents

[Altmannshofer & Straub, 1206.0273]



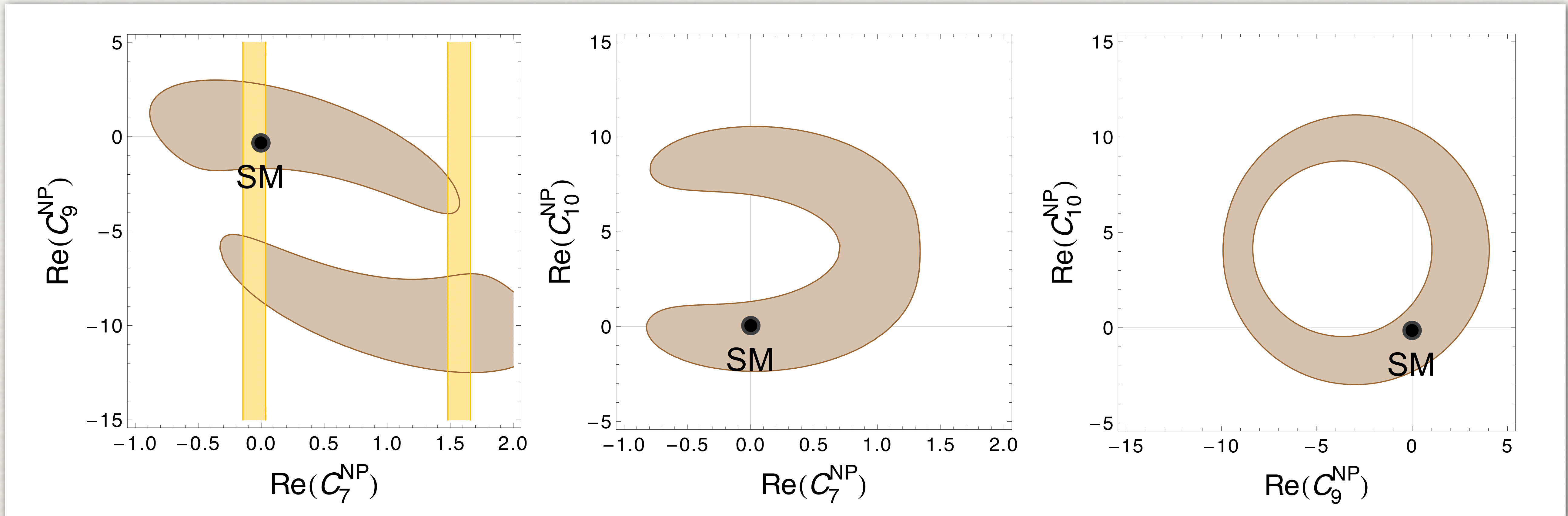
● $B_s \to \mu^+\mu^-$ ● $B \to X_s\mu^+\mu^-$ ● $B \to K\mu^+\mu^-$ ● $B \to K^*\mu^+\mu^-$ ● $B \to X_s\gamma$

● $B \to K^*\gamma$

- Different exclusive decays provide complementary information

Constraints On Pairs of Wilson Coefficients

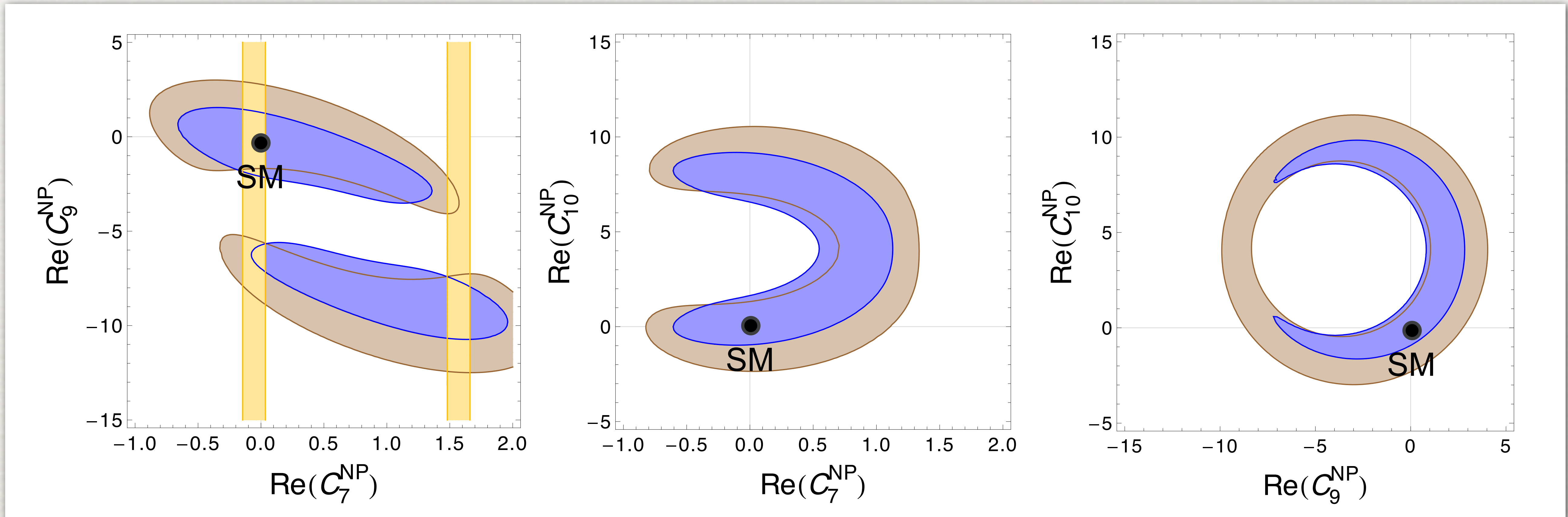
[Altmannshofer, Paradisi & Straub, 1111.1257]



● Br(B → $X_s\mu^+\mu^-$) ● Br(B → $X_s\gamma$)

Constraints On Pairs of Wilson Coefficients

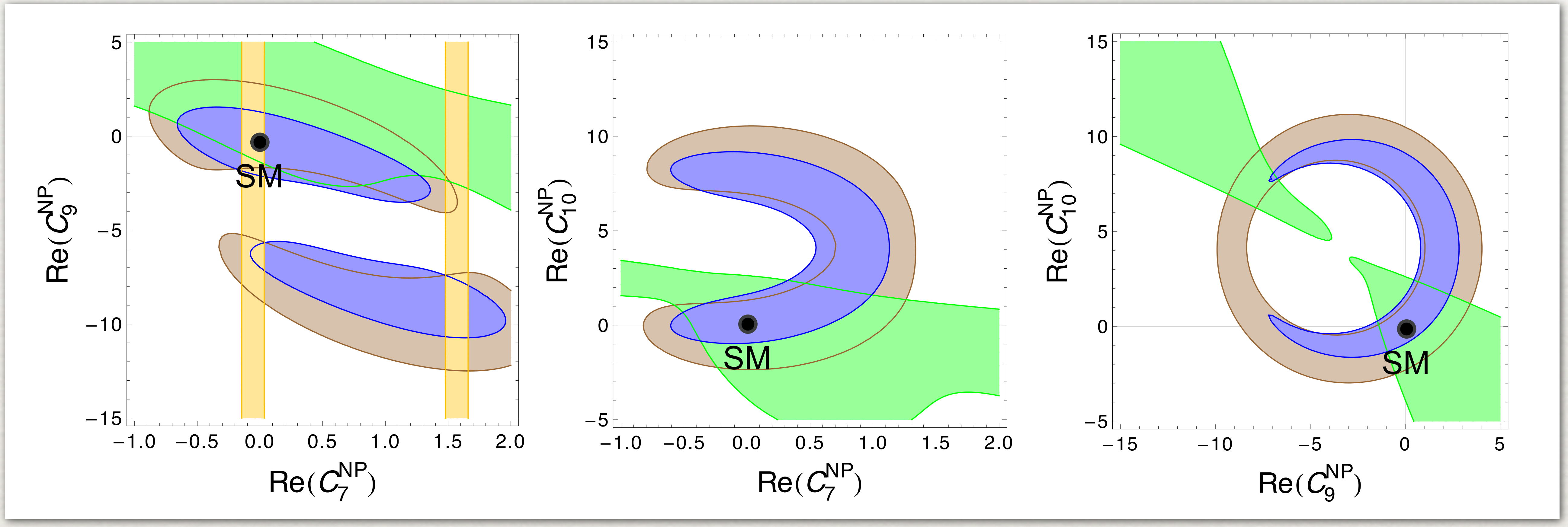
[Altmannshofer, Paradisi & Straub, 1111.1257]



● $Br(B \to X_s \mu^+ \mu^-)$ ● $Br(B \to X_s \gamma)$ ● $Br(B \to K^* \mu^+ \mu^-)$

Constraints On Pairs of Wilson Coefficients

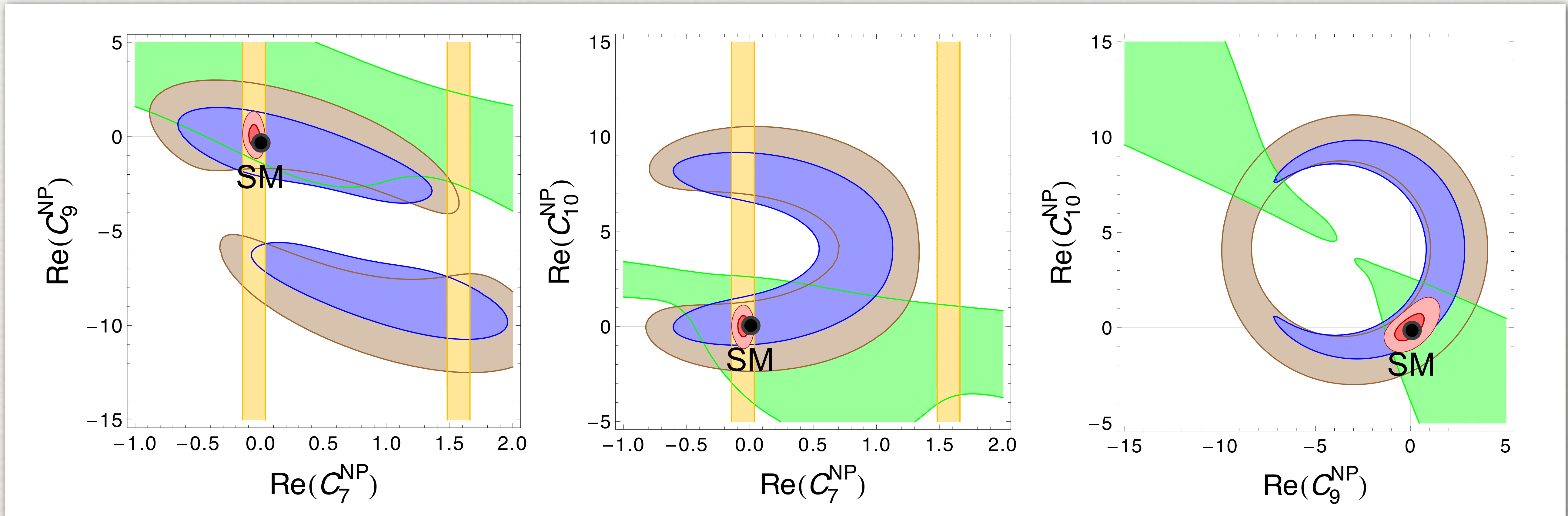
[Altmannshofer, Paradisi & Straub, 1111.1257]



● $Br(B \to X_s \mu^+ \mu^-)$ ● $Br(B \to X_s \gamma)$ ● $Br(B \to K^* \mu^+ \mu^-)$ ● $A_{FB}(B \to K^* \mu^+ \mu^-)$

Constraints On Pairs of Wilson Coefficients

[Altmannshofer, Paradisi & Straub, 1111.1257]

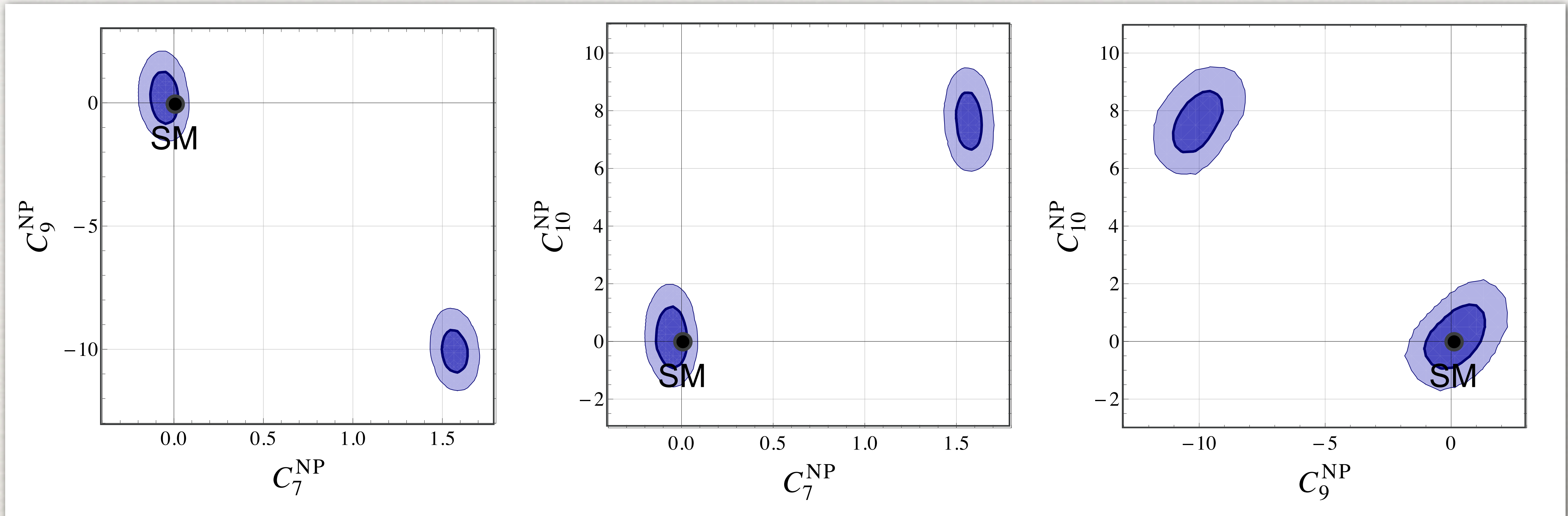


● Br($B \to X_s\mu^+\mu^-$) ● Br($B \to X_s\gamma$) ● Br($B \to K^*\mu^+\mu^-$) ● A_{FB}($B \to K^*\mu^+\mu^-$)

- Exclusive $b \to s\mu^+\mu^-$ data (in particular angular distributions) breaks degeneracies & excludes various mirror solutions

Disfavored Mirror Solutions

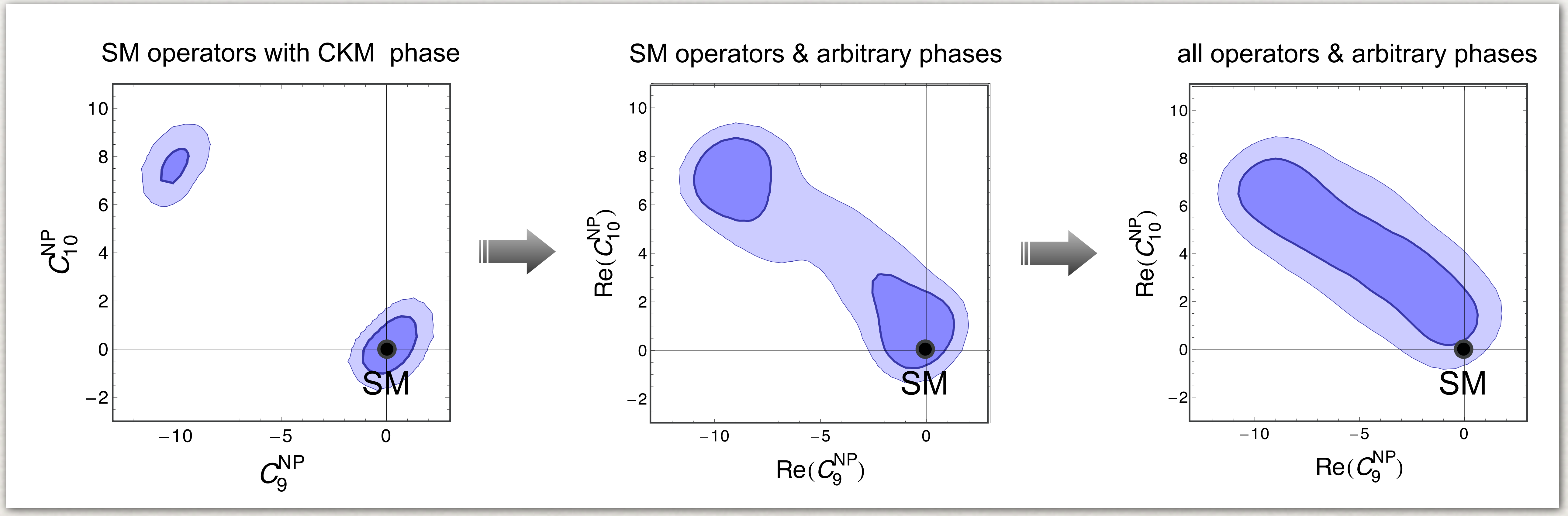
[Altmannshofer, Paradisi & Straub, 1111.1257]



- Flipped-sign solutions:
  - $C_{7,9,10} = -C_{7,9,10}^{SM}$ cannot be excluded, but ...
  - $C_7 = -C_7^{SM}$ disfavored by $Br(B \to X_s \mu^+ \mu^-)$
  - $C_{9,10} = -C_{9,10}^{SM}$ disfavored by $A_{FB}(B \to K^* \mu^+ \mu^-)$

Impact of Assumptions on Constraints

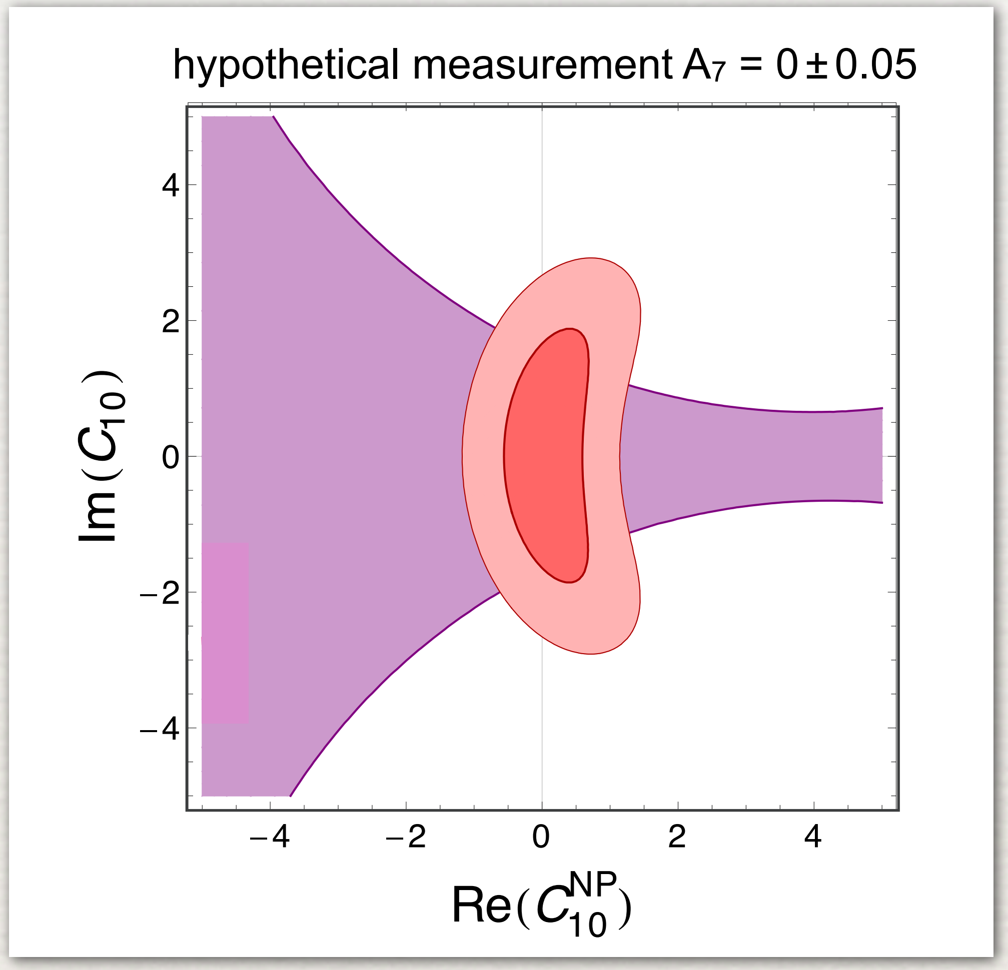
[Altmannshofer, Paradisi & Straub, 1111.1257]



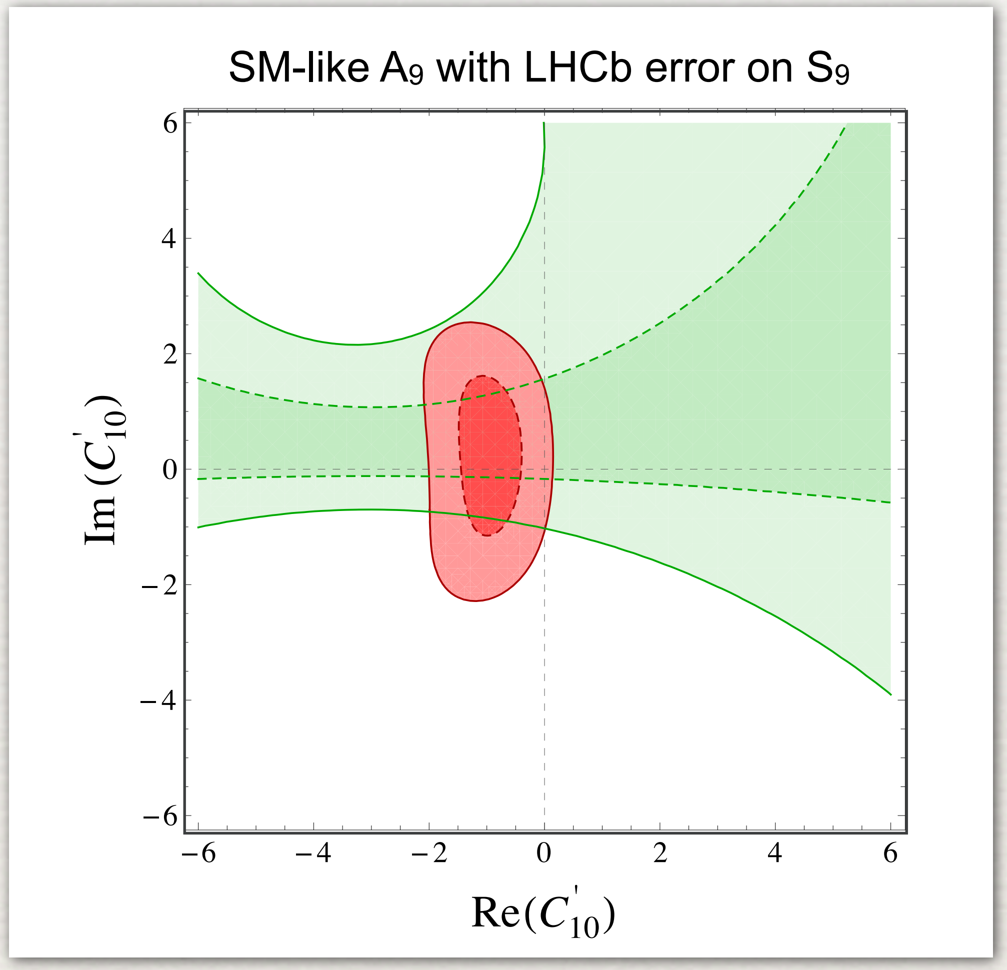
- Constraints significantly weakened by allowing for additional phase and/or chirality-flipped operators. Need more data (in particular on CP-violating observables) to break degeneracies

Future (?) Impact of CP-violating Observables

[Straub, talk at Moriond EW 2012]



[Altmannshofer & Straub, 1206.0273]



- CP-violating observables such as A_7 & A_9 provide constraints that are orthogonal in plane of Wilson coefficients to those of CP-conserving observables like A_{FB}, F_L, S_3, ...