NNV Annual Meeting - 2 November 2018 - Lunteren

Probing New Physics with Rare Leptonic *B*-meson Decays

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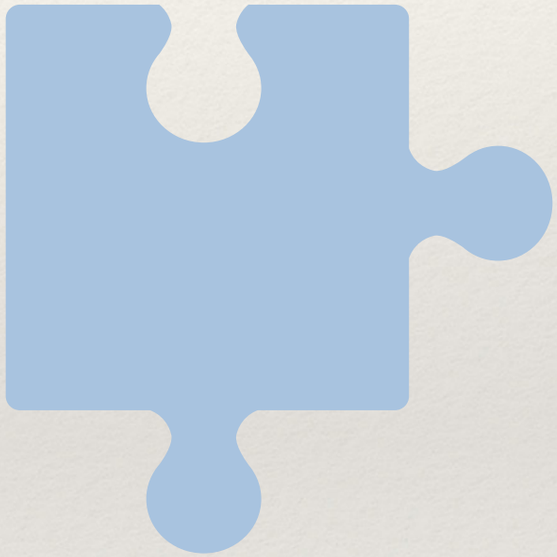
Beyond the Standard Model

- The Standard Model is very successful, but not complete:
  - Dark matter
  - Baryon asymmetry
  - Hierarchy problem
  - …



- Many theories about New Physics
- Experimental searches at High-energy and High-precision

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B-physics experiments

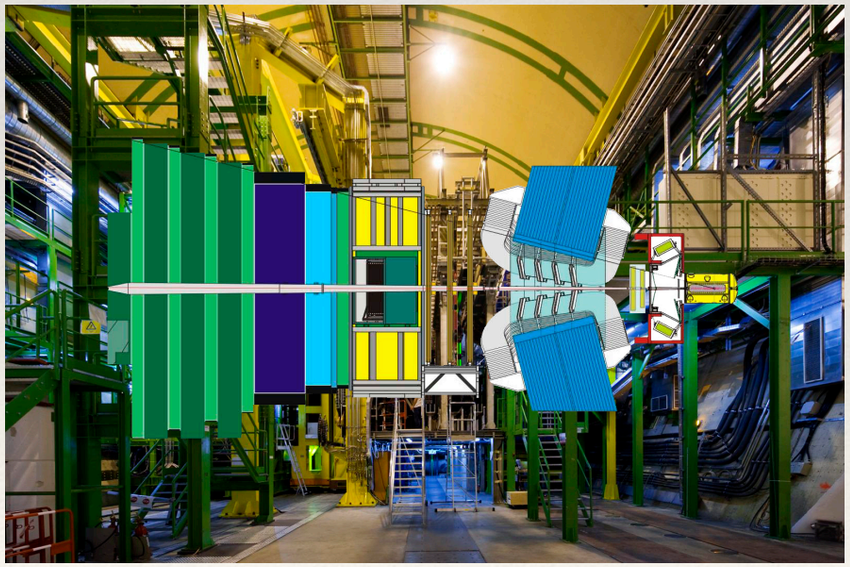
B-meson decays offer a rich field of high-precision SM tests.

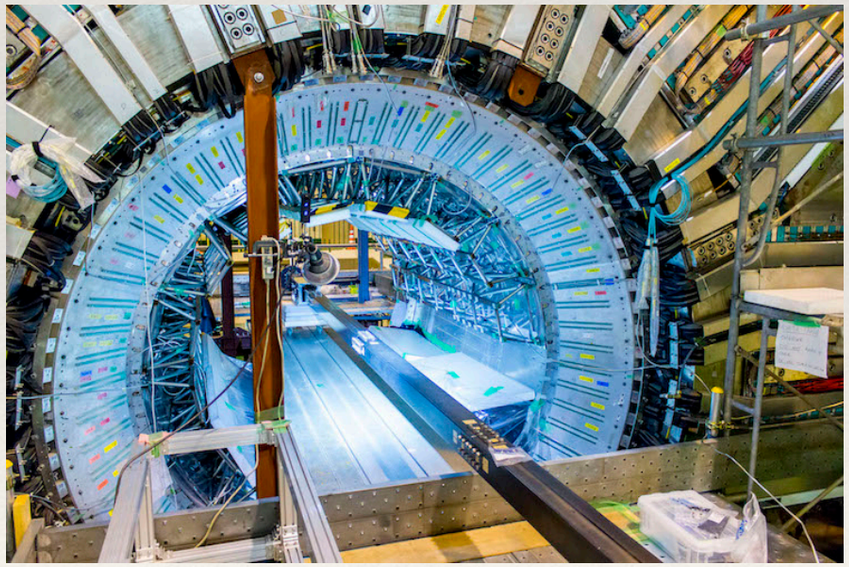
Main experimental players:

LHCb

Current & future

Belle II





Past

BABAR

BELLE

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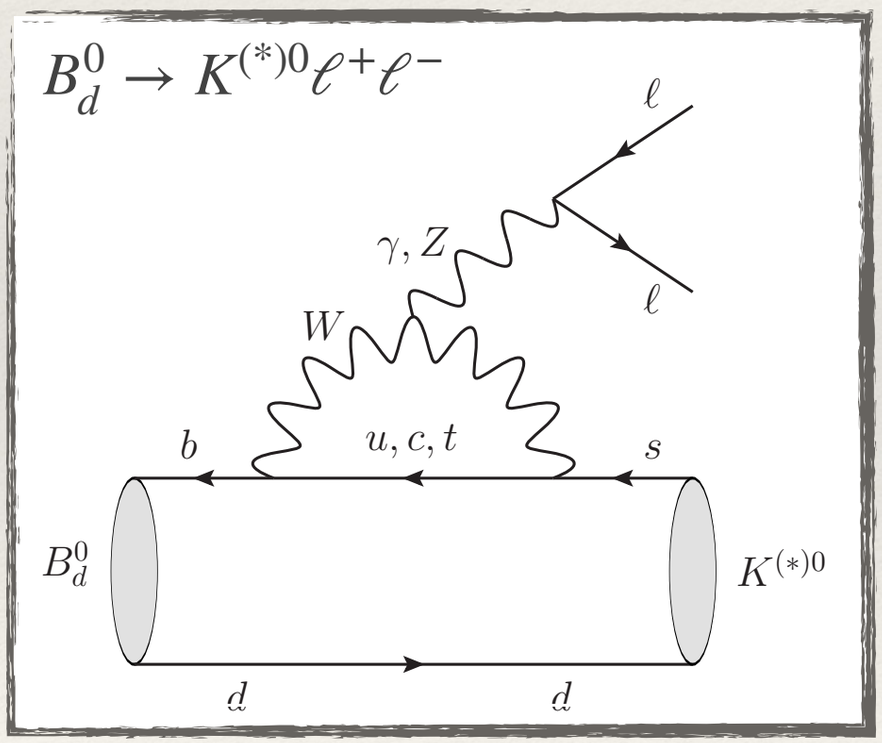
Rare B-meson decays

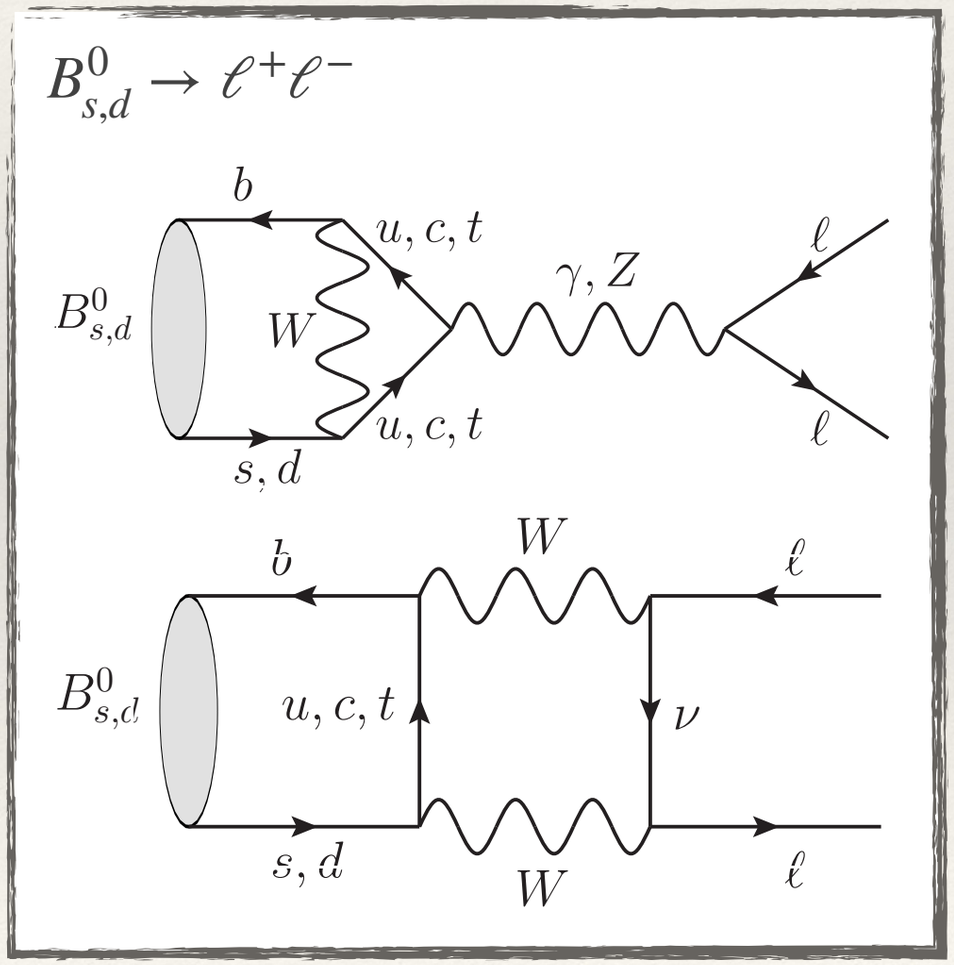
$q \in \{d, s\}$

Decays mediated by $b \to q\ell^+\ell^-$ transition

- Semileptonic transitions, e.g.



- Leptonic transitions:

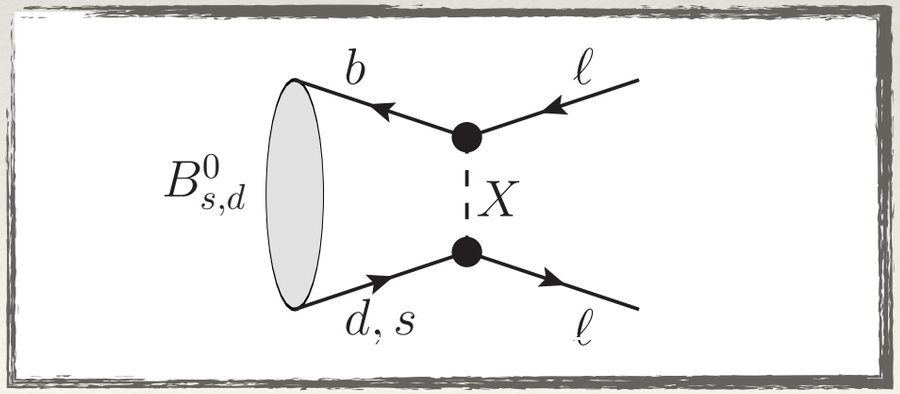


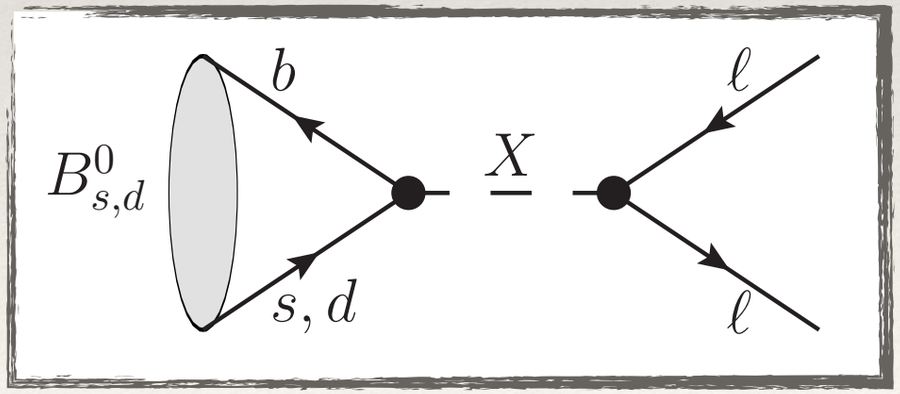
➟ See plenary talk by M. Merk

➟ This talk

Rare Leptonic B-Decays

- Decays of type $B^0_{s,d} \to \ell^+\ell^-$
- In SM helicity suppressed: branching ratio $\mathscr{B} \propto m_\ell^2$
- Theoretically clean, all hadronic physics described by single non-perturbative parameter: $f_{B_{s,d}}$ (decay constant)
- Possible New Physics contributions:





Theoretical description

- Effective Field Theory: integrate out heavy d.o.f. (SM & NP)
- Decays described by low-energy effective Hamiltonian:

$q \in \{d, s\}$

$$\mathscr{H}_{\text{eff}} \propto V_{tq}^* V_{tb} \left[C_{10}^{\ell\ell} O_{10} + C_S^{\ell\ell} O_S + C_P^{\ell\ell} O_P + C_{10}^{\ell\ell'} O'_{10} + C_S^{\ell\ell'} O'_S + C_P^{\ell\ell'} O'_P \right] + \text{h.c.}$$

- Effective 4-point interactions $O_i^{(\prime)}$. In the SM only

$$O_{10} = \frac{1}{2}(\bar{q}\gamma_\mu(1-\gamma_5)b)(\bar{\ell}\gamma^\mu\gamma_5\ell)$$

with real short-distance coefficient C_{10}^{SM}

- NP operators

$$O'_{10} = \frac{1}{2}(\bar{q}\gamma_\mu(1+\gamma_5)b)(\bar{\ell}\gamma^\mu\gamma_5\ell)$$

$$O_S^{(\prime)} = \frac{1}{2} m_b (\bar{q}(1 \pm \gamma_5)b)(\bar{\ell}\ell) \qquad O_P^{(\prime)} = \frac{1}{2} m_b (\bar{q}(1 \pm \gamma_5)b)(\bar{\ell}\gamma_5\ell)$$

- Wilson coefficients $C_i^{\ell\ell(\prime)}$ couplings

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Amplitude

- From effective Hamiltonian to amplitude:

$\lambda = L, R;\ \eta_{L,R} = \pm 1$

$$A(\overline{B}^0_q \to \ell^+_\lambda \ell^-_\lambda) = \left\langle \ell^-_\lambda \ell^+_\lambda \left| \mathscr{H}_{\text{eff}} \right| \overline{B}^0_q \right\rangle \propto V^*_{tq} V_{tb}\, f_{B_q}\, M_{B_q}\, m_\ell\, C_{10}^{\text{SM}} \left[\eta_\lambda P^q_{\ell\ell} + S^q_{\ell\ell} \right]$$

decay constant

helicity suppression

with

$$P^q_{\ell\ell} \equiv \frac{C_{10}^{\ell\ell} - C_{10}^{\ell\ell'}}{C_{10}^{\text{SM}}} + \frac{M^2_{B_q}}{2m_\ell} \left(\frac{m_b}{m_b + m_q} \right) \left[\frac{C_P^{\ell\ell} - C_P^{\ell\ell'}}{C_{10}^{\text{SM}}} \right] \overset{\text{SM}}{\to} 1$$

$$S^q_{\ell\ell} \equiv \sqrt{1 - 4\frac{m^2_\ell}{M^2_{B_q}}}\, \frac{M^2_{B_q}}{2m_\ell} \left(\frac{m_b}{m_b + m_q} \right) \left[\frac{C_S^{\ell\ell} - C_S^{\ell\ell'}}{C_{10}^{\text{SM}}} \right] \overset{\text{SM}}{\to} 0$$

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Branching ratio

- Experimental measurements refer to time-integrated, untagged, helicity-summed rate: $\overline{\mathscr{B}}(B_q \to \ell^+\ell^-) \equiv \frac{1}{2}\int_0^\infty \left\langle \Gamma(B_q(t) \to \ell^+\ell^-) \right\rangle dt$
- Theorists usually consider untagged rate at t=0:

$$\mathscr{B}(B_q \to \ell^+\ell^-)_{\text{theo}} \equiv \left\langle \Gamma(B_q(t) \to \ell^+\ell^-) \right\rangle |_{t=0}$$

- Convert using $\overline{\mathscr{B}}(B_q \to \ell^+\ell^-) = \left[\frac{1 + \mathscr{A}^{\ell\ell}_{\Delta\Gamma_q} y_q}{1 - y_q^2}\right] \mathscr{B}(B_q \to \ell^+\ell^-)_{\text{theo}}$

  [Phys. Rev. D **86** (2012) 014027;
  Phys. Rev. Lett. **109** (2012) 041801]

$y_d = 10^{-3}$, $y_s \equiv \frac{\Delta\Gamma_s}{2\Gamma_s} = 0.0645 \pm 0.0045$
Matters for B_s decays

- We then obtain

$$\overline{\mathscr{B}}(B_q \to \ell^+\ell^-) \propto \left[\frac{1 + \mathscr{A}^{\ell\ell}_{\Delta\Gamma_q} y_q}{1 - y_q^2}\right] |C_{10}^{\text{SM}} V_{tq} V_{tb}^*|^2 f_{B_q}^2 M_{B_q} m_\ell^2 (|P^q_{\ell\ell}|^2 + |S^q_{\ell\ell}|^2)$$

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Experimental status of B_s decays

- $\overline{\mathscr{B}}(B_s \to \mu^+\mu^-)$ is well-established:

  $$\overline{\mathscr{B}}(B_s \to \mu^+\mu^-) = (3.0 \pm 0.5) \times 10^{-9}$$

- Pioneering measurement of effective lifetime:

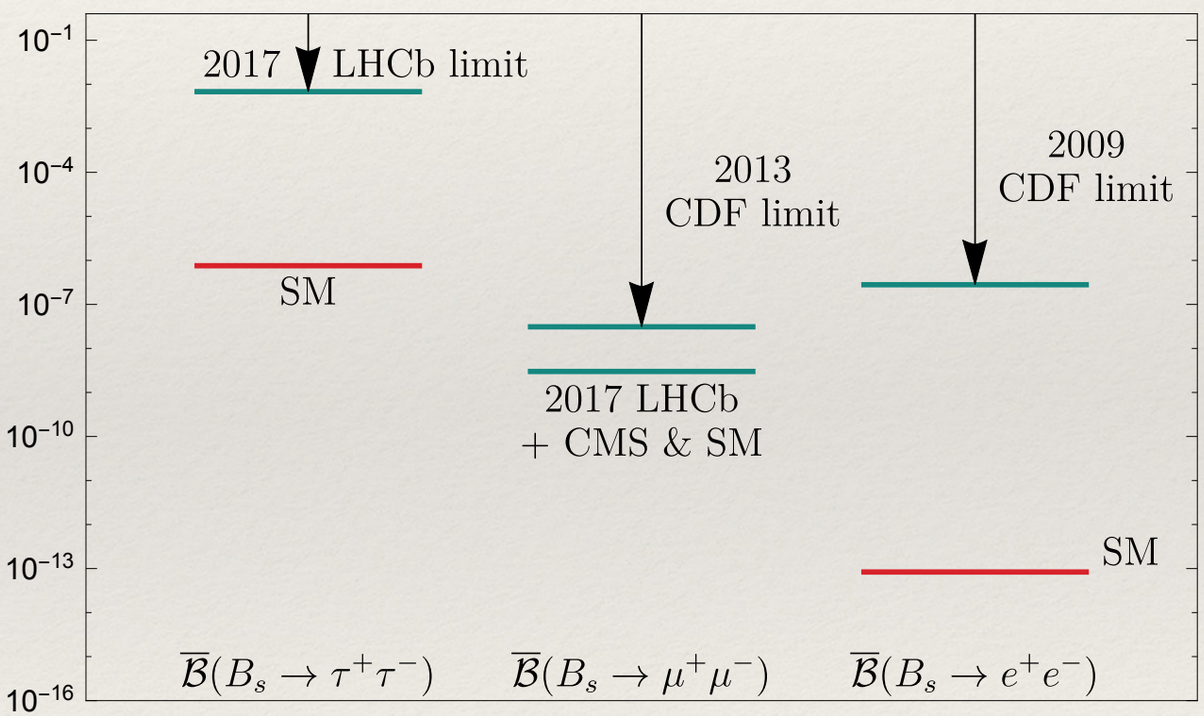
  $$\to \mathscr{A}^{\mu\mu}_{\Delta\Gamma_s} = 8.24 \pm 10.72$$

- LHCb limit on $\overline{\mathscr{B}}(B_s \to \tau^+\tau^-)$
  4 orders of magnitude from SM

- Limit on $\overline{\mathscr{B}}(B_s \to e^+e^-)$ from 2009
  6 order of magnitude from SM
  ➥ **has since been forgotten**

Theoretical prediction in the SM:

$$\overline{\mathscr{B}}(B_s \to \mu^+\mu^-)_{\rm SM} = (3.57 \pm 0.16) \times 10^{-9}$$



How much room for New Physics is left in the branching ratios of $B_s \to \tau^+\tau^-$ and $B_s \to e^+e^-$?

Constraints on short-distance coefficients

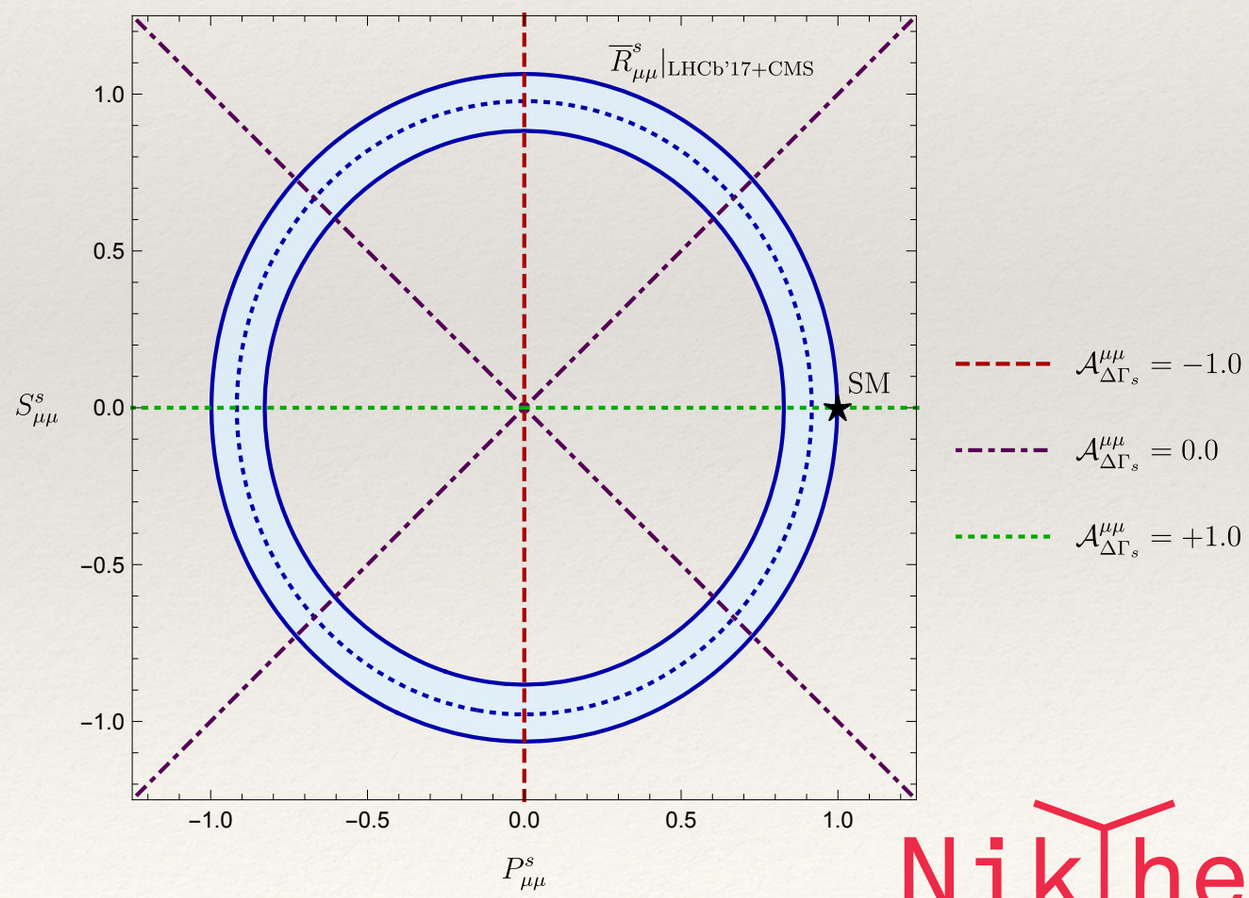
- Useful to introduce:

$$\overline{R}^s_{\ell\ell} \equiv \frac{\overline{\mathscr{B}}(B_s \to \ell^+\ell^-)}{\overline{\mathscr{B}}(B_s \to \ell^+\ell^-)_{\rm SM}} = \left[\frac{1 + \mathscr{A}^{\ell\ell}_{\Delta\Gamma_s} y_s}{1 + y_s}\right](|P^s_{\ell\ell}|^2 + |S^s_{\ell\ell}|^2)$$

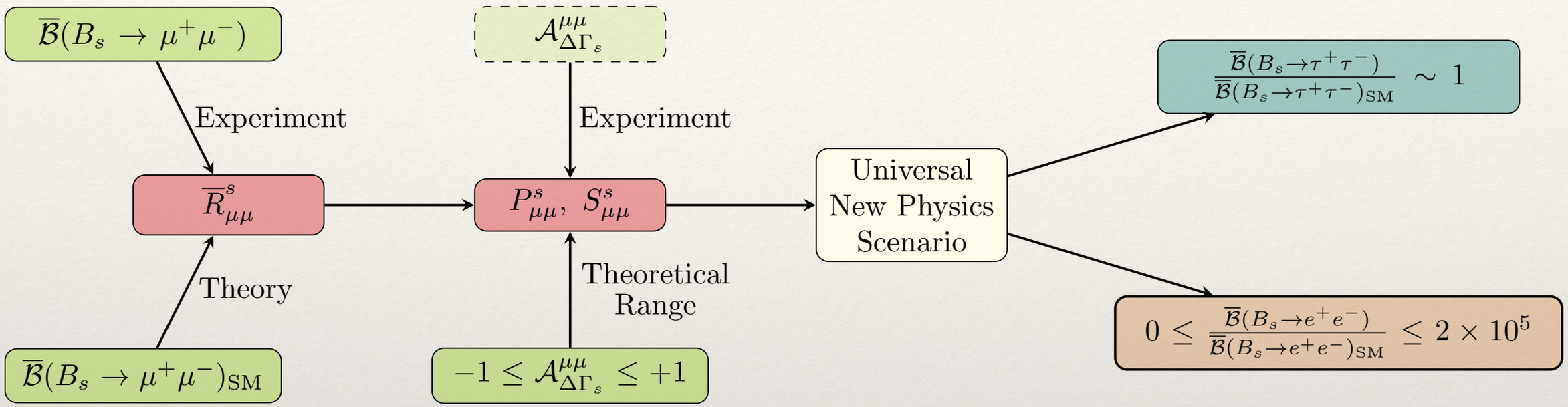
- Experimental value

$$\overline{R}^s_{\mu\mu}\Big|_{\rm LHCb'17+CMS} = 0.84 \pm 0.16$$

yields circular constraint in $P^s_{\mu\mu} - S^s_{\mu\mu}$ plane



Universal New Physics Scenario



- Assume short-distance coefficients are lepton-flavour universal
- Consider $-1 \leq \mathscr{A}^{\mu\mu}_{\Delta\Gamma_s} \leq +1$
- Evaluate effect on $B_s \to \tau^+\tau^-$ and $B_s \to e^+e^-$

Implications for $B_s \to \tau^+\tau^-$

- In the Universal New Physics Scenario:

$$P^s_{\tau\tau} = \left(1 - \frac{m_\mu}{m_\tau}\right)\mathscr{C}_{10} + \frac{m_\mu}{m_\tau} P^s_{\mu\mu} \qquad S^s_{\tau\tau} = \frac{m_\mu}{m_\tau}\sqrt{\frac{1 - 4\frac{m_\tau^2}{M_{B_s}^2}}{1 - 4\frac{m_\mu^2}{M_{B_s}^2}}}\, S^s_{\mu\mu}$$

- NP suppressed through

$$\frac{m_\mu}{m_\tau} = 0.059$$

which yields:

$$0.8 \leq \overline{R}^s_{\tau\tau} \leq 1.0$$

Enhancement of $B_s \to e^+e^-$

- We now obtain the coefficients:

$$P^s_{ee} = \left(1 - \frac{m_\mu}{m_e}\right)\mathscr{C}_{10} + \frac{m_\mu}{m_e} P^s_{\mu\mu} \qquad S^s_{ee} = \frac{m_\mu}{m_e}\sqrt{\frac{1 - 4\frac{m_\tau^2}{M^2_{B_s}}}{1 - 4\frac{m_\mu^2}{M^2_{B_s}}}}\, S^s_{\mu\mu}$$

- NP *enhanced* through

$$\frac{m_\mu}{m_e} = 206.77$$

which yields:

$$0 \leq \overline{R}^s_{ee} \leq 1.7 \times 10^5$$

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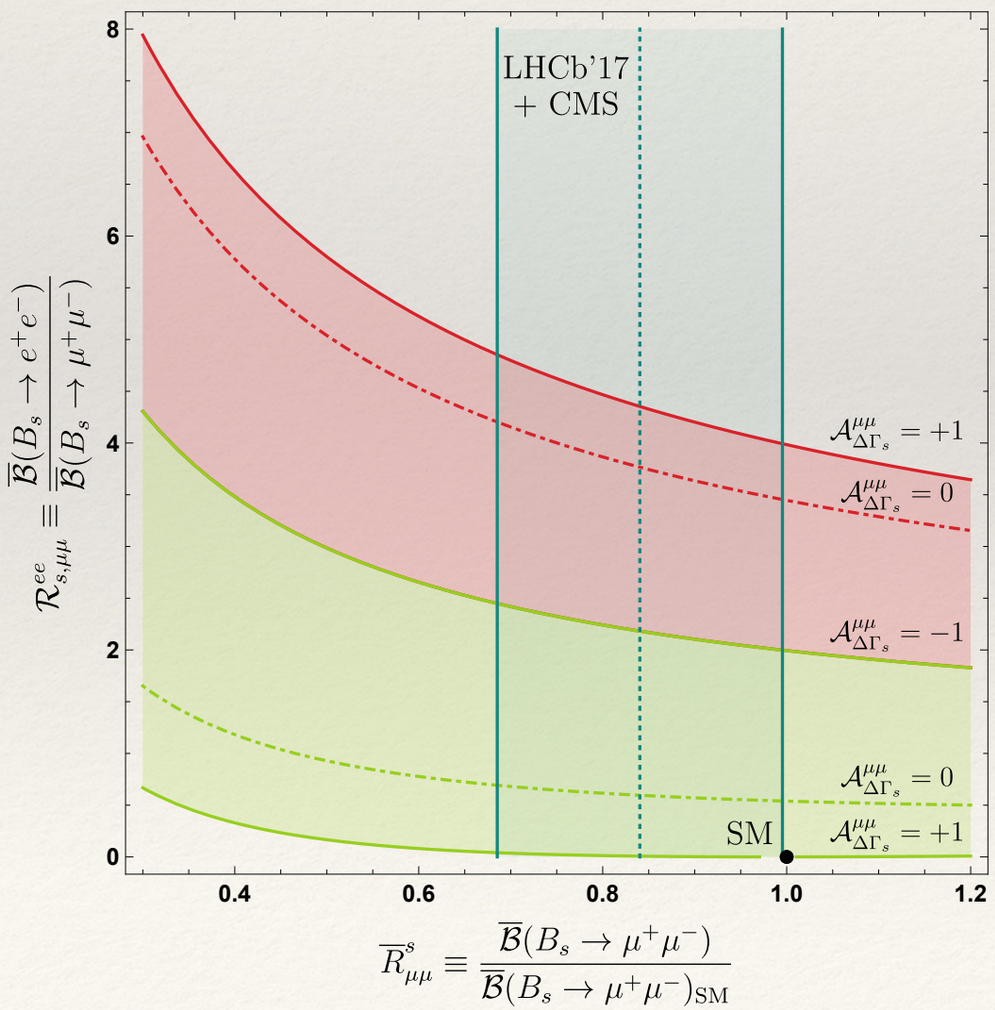
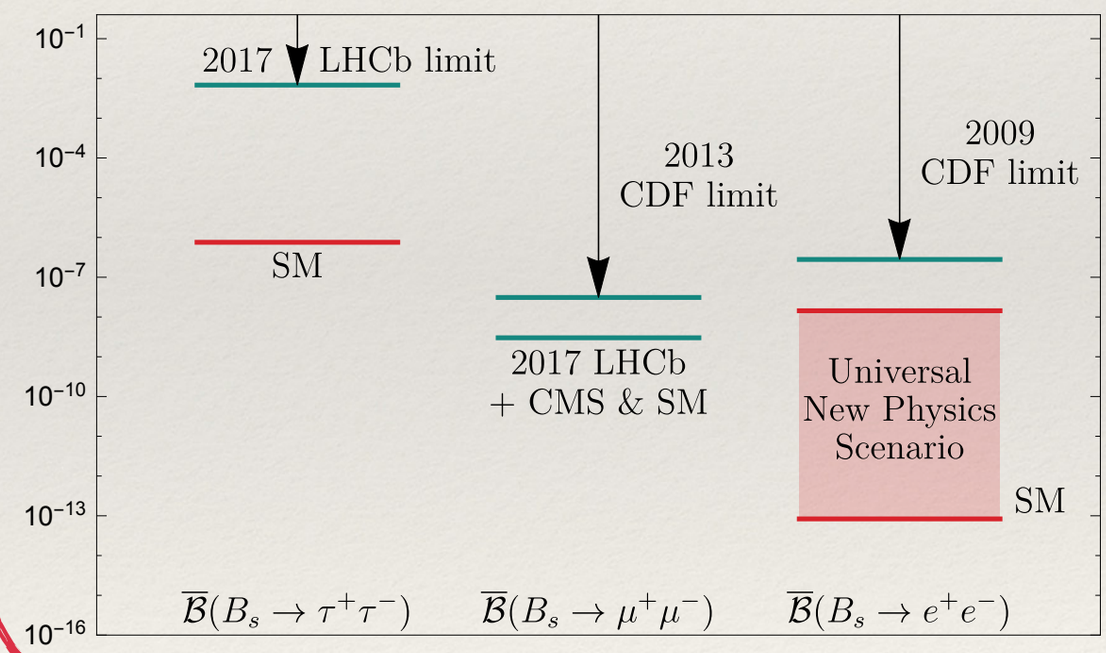
Enhancement of $B_s \to e^+e^-$

- Compare to $B_s \to \mu^+\mu^-$: $\mathcal{R}^{ee}_{s,\mu\mu} \equiv \dfrac{\overline{\mathcal{B}}(B_s \to e^+e^-)}{\overline{\mathcal{B}}(B_s \to \mu^+\mu^-)}$

- We find $0.0 \leq \mathcal{R}^{ee}_{s,\mu\mu} \leq 4.8$

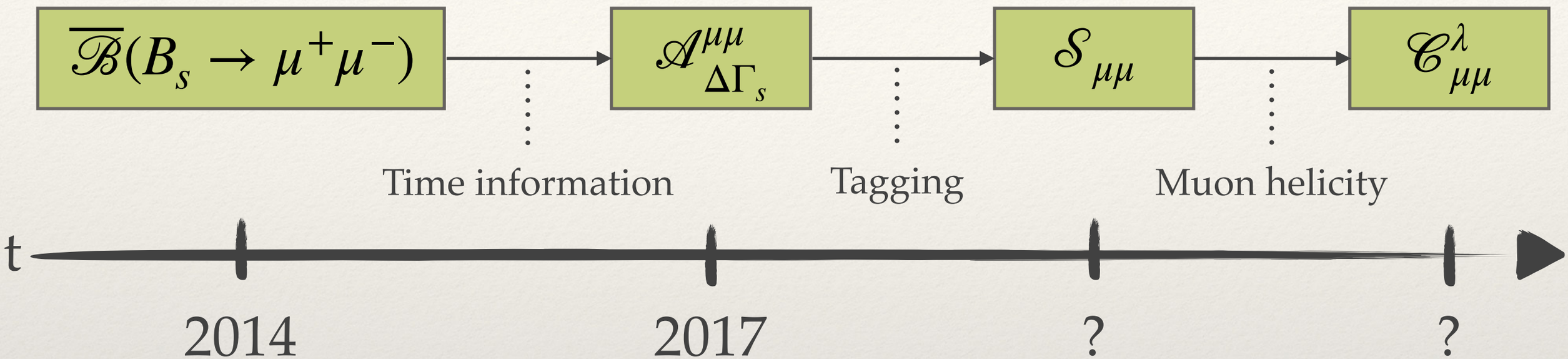


Upper bound only a factor 20 below the CDF limit:



What other observables may reveal New Physics effects?

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



- CP violation → allow for a complex P and S:

$$P \equiv |P|\, e^{i\varphi_P}, \quad S \equiv |S|\, e^{i\varphi_S}$$

- B_s^0—$\bar{B}_s^0$ mixing → time-dependent rate asymmetry:

$$\frac{\Gamma(B_s^0(t) \to \mu_\lambda^+\mu_\lambda^-) - \Gamma(\bar{B}_s^0(t) \to \mu_\lambda^+\mu_\lambda^-)}{\Gamma(B_s^0(t) \to \mu_\lambda^+\mu_\lambda^-) + \Gamma(\bar{B}_s^0(t) \to \mu_\lambda^+\mu_\lambda^-)} = \frac{\mathscr{C}^{\lambda}_{\mu\mu}\cos(\Delta M_s t) + \mathscr{S}_{\mu\mu}\sin(\Delta M_s t)}{\cosh(y_s t/\tau_{B_s}) + \mathscr{A}_{\Delta\Gamma_s}\sinh(y_s t/\tau_{B_s})}$$

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

- Observables are given by:

$$\mathscr{A}^{\mu\mu}_{\Delta\Gamma_s} = \frac{|P|^2 \cos 2\varphi_P - |S|^2 \cos 2\varphi_S}{|P|^2 + |S|^2} \overset{\text{SM}}{\to} 1$$

$$\mathscr{S}_{\mu\mu} = \frac{|P|^2 \sin \varphi_P - |S|^2 \sin \varphi_S}{|P|^2 + |S|^2} \overset{\text{SM}}{\to} 0$$

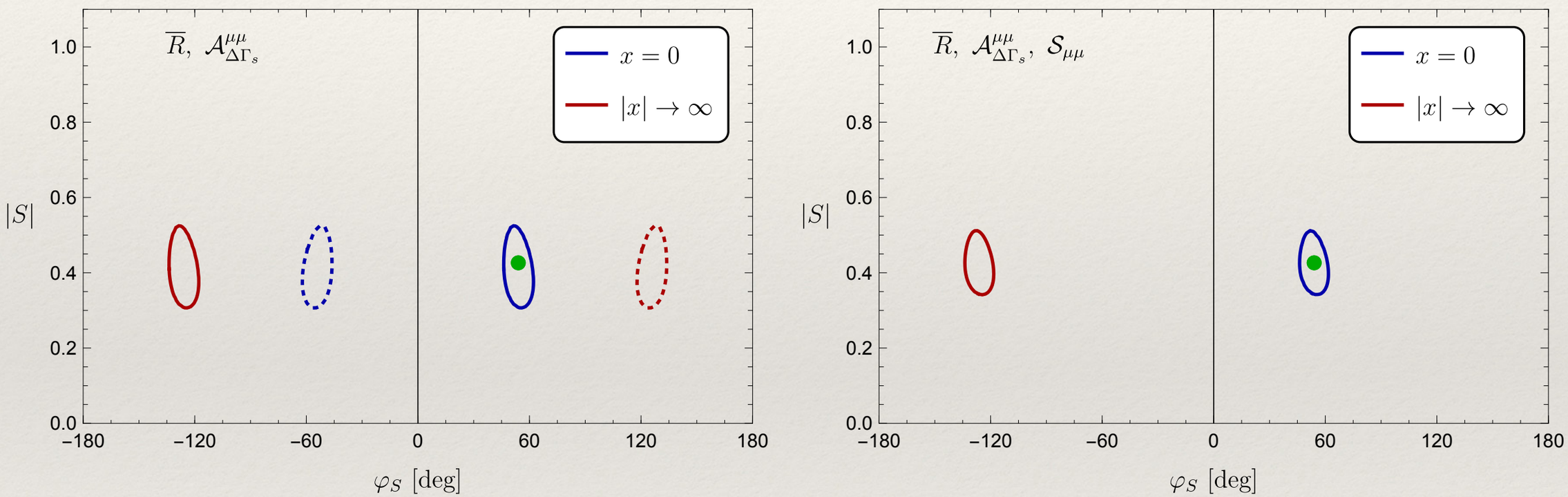
$$\mathscr{C}^{\lambda}_{\mu\mu} = -\eta_\lambda \left[\frac{2|PS|\cos(\varphi_P - \varphi_S)}{|P|^2 + |S|^2} \right] \equiv -\eta_\lambda \mathscr{C}_{\mu\mu} \overset{\text{SM}}{\to} 0$$

- Non-zero value of $\mathscr{S}_{\mu\mu}$ or $\mathscr{C}_{\mu\mu}$ unambiguous signal for New Physics!

- Equivalent for B_d decays, but $\mathscr{A}^{\ell\ell}_{\Delta\Gamma_d}$ not accessible.

Experimental aspects

- The coefficients can be determined in certain scenarios, e.g.



- Example with ± 0.2 uncertainty for asymmetries
- Pin down $|S|$ at 5 σ level!

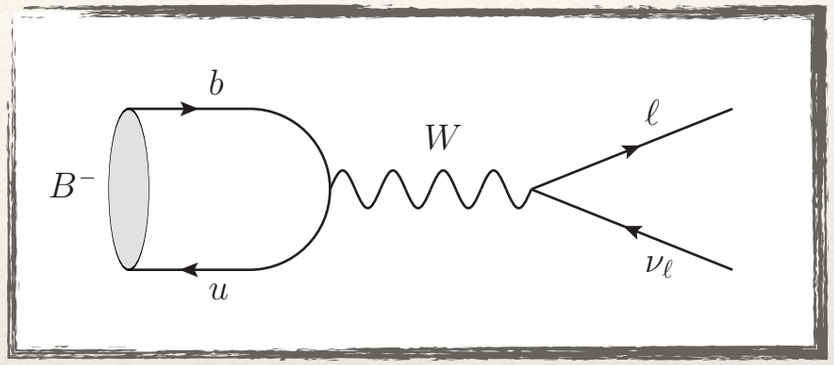
SMEFT: $C_P = -C_S, \quad C'_P = C'_S$

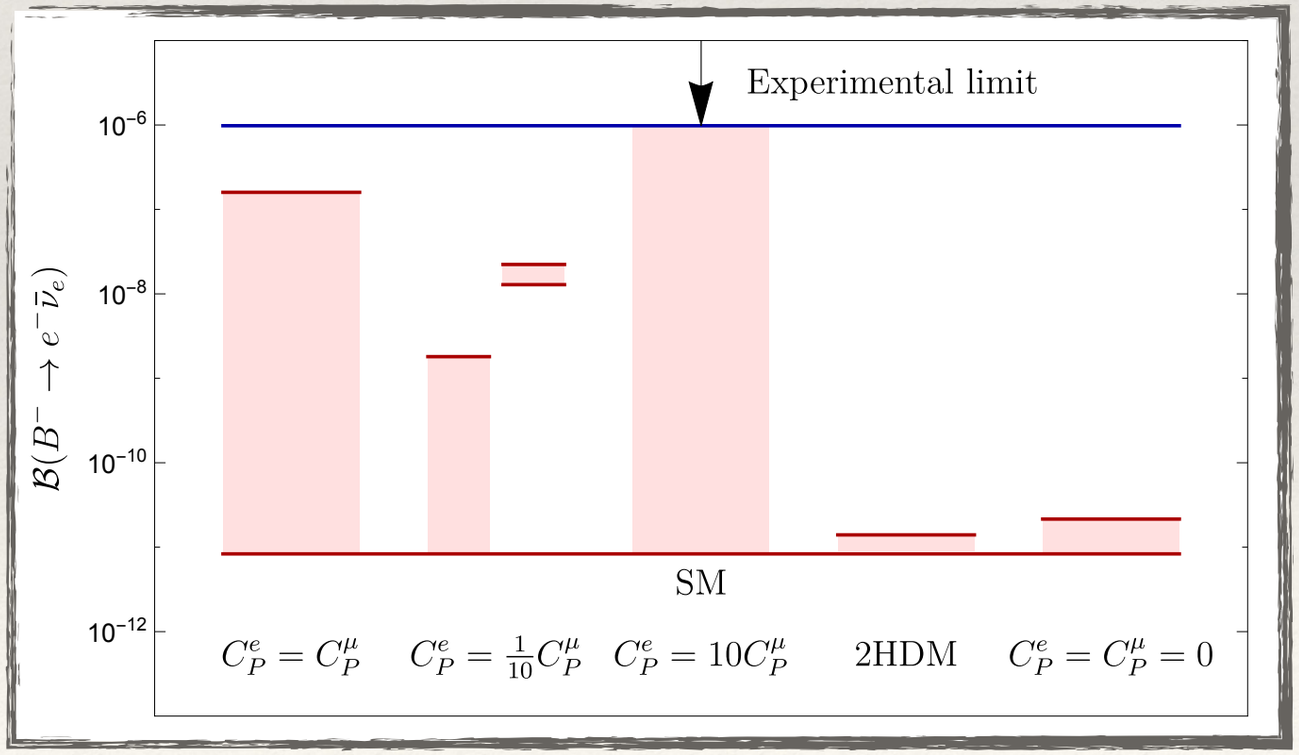
$$|P|e^{i\varphi_P} = \mathscr{C}_{10} - \left[\frac{1+|x|e^{i\Delta}}{1-|x|e^{i\Delta}}\right]|S|e^{i\varphi_S}$$

$$x \equiv |x|e^{i\Delta} \equiv \left|\frac{C'_S}{C_S}\right| e^{i(\tilde{\varphi}'_S - \tilde{\varphi}_S)}$$

$B^- \to \ell^- \bar{\nu}_\ell$ decays

- Arise at the tree level
- As for $B^0_{s,d} \to \ell^+\ell^-$ decays:
  - Hadronic physics described by f_{B^-}
  - Helicity suppressed in SM
- New pseudoscalar contributions can lift the helicity suppression
- $\mathscr{B}(B^- \to e^- \bar{\nu}_e)$ can be enhanced by up to 4 orders of magnitude with respect to the SM!





Conclusions

- Search for new physics in B-meson decays:

  High-precision frontier
- Leptonic B-decays have many interesting aspects.
- $B_s \to e^+e^-$ received little attention,
  now it has moved back in the spotlight.
- Studies of CP violation interesting for LHCb upgrade(s).
- **Exciting times ahead!**

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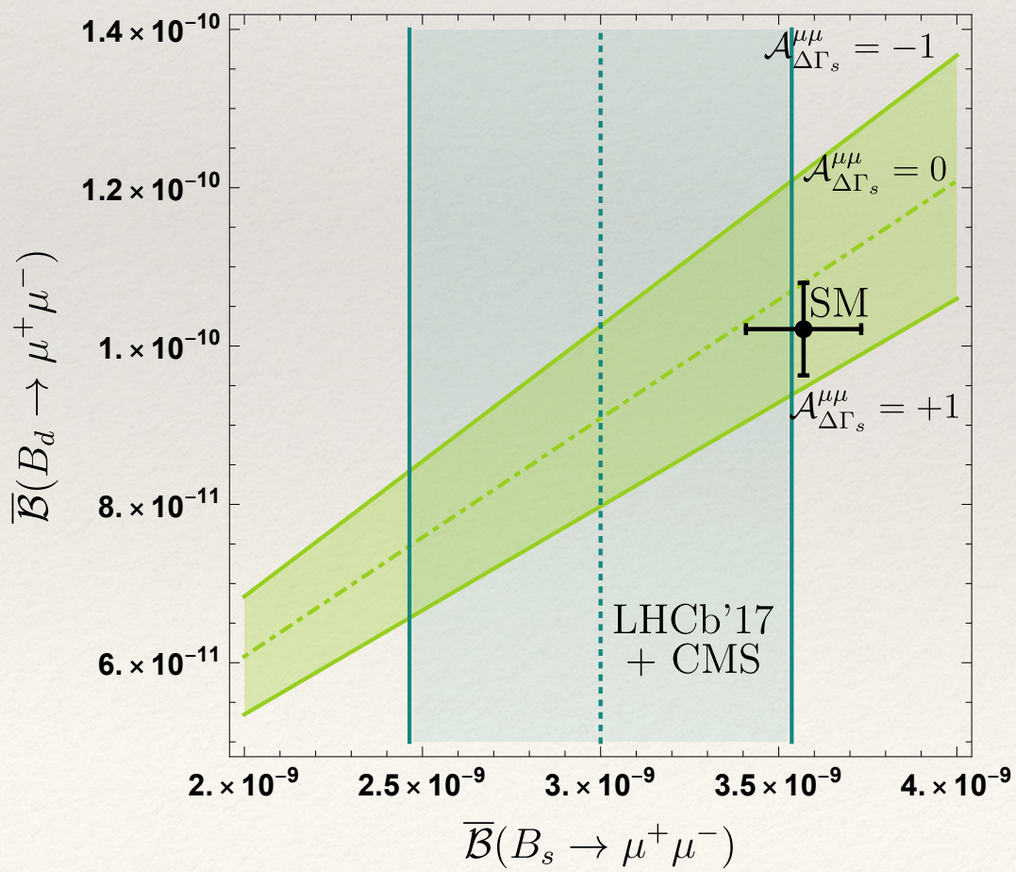
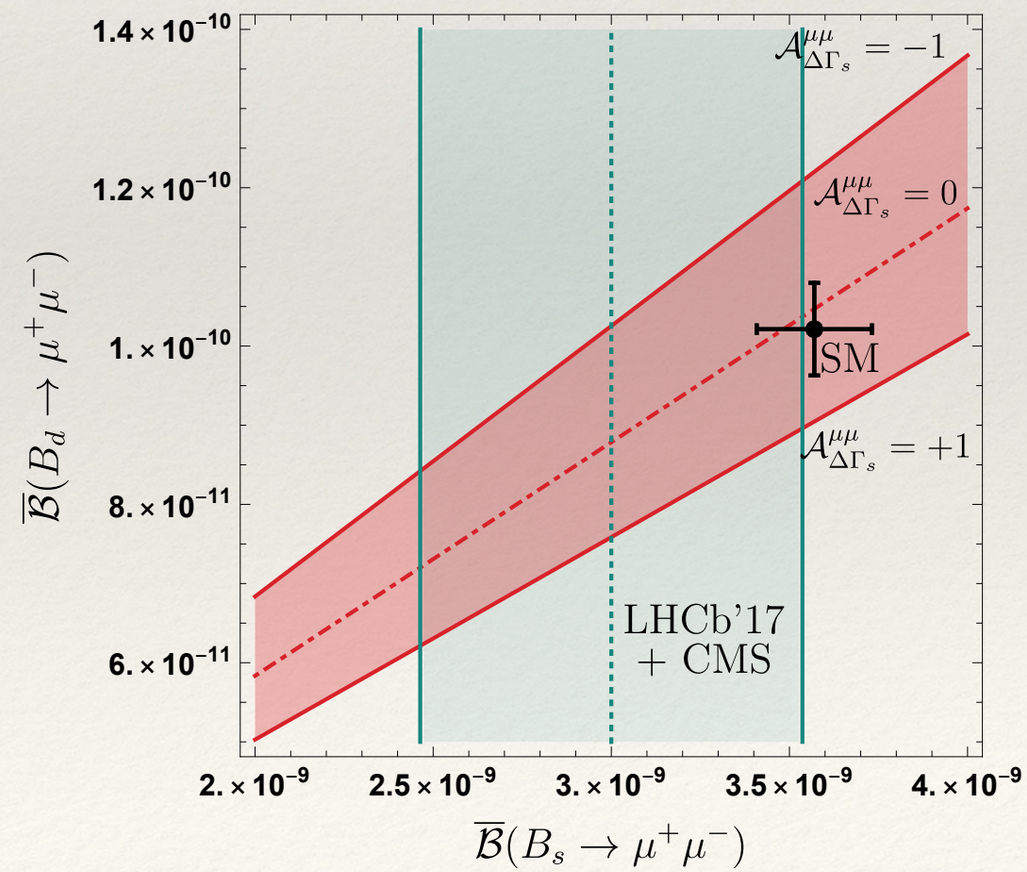
Backup slides

Implications for $B_d \to \mu^+\mu^-$

For $B_d \to \mu^+\mu^-$ we obtain: $0.65 \leq \overline{R}^d_{\mu\mu} \leq 1.11$

as well as $U^{ds}_{\mu\mu} \equiv \sqrt{\dfrac{|P^d_{\mu\mu}|^2 + |S^d_{\mu\mu}|^2}{|P^s_{\mu\mu}|^2 + |S^s_{\mu\mu}|^2}} \overset{\text{SM}}{=} 1 \;\rightarrow\; 0.97 \leq U^{ds}_{\mu\mu} \leq 1.00$





The challenge:

- We have 4 observables…

$$\overline{\mathscr{B}}(B_s \to \mu^+\mu^-), \quad \mathscr{A}^{\mu\mu}_{\Delta\Gamma_s}, \quad \mathscr{S}_{\mu\mu}, \quad \mathscr{C}_{\mu\mu}$$

…but only 3 independent:

$$\left(\mathscr{A}^{\mu\mu}_{\Delta\Gamma_s}\right)^2 + \left(\mathscr{S}_{\mu\mu}\right)^2 + \left(\mathscr{C}_{\mu\mu}\right)^2 = 1$$

- Each can indicate New Physics, but what is its nature?
- We have 4 unknowns: $|P|, \quad |S|, \quad \varphi_P, \quad \varphi_S$
- How can we establish New Physics?

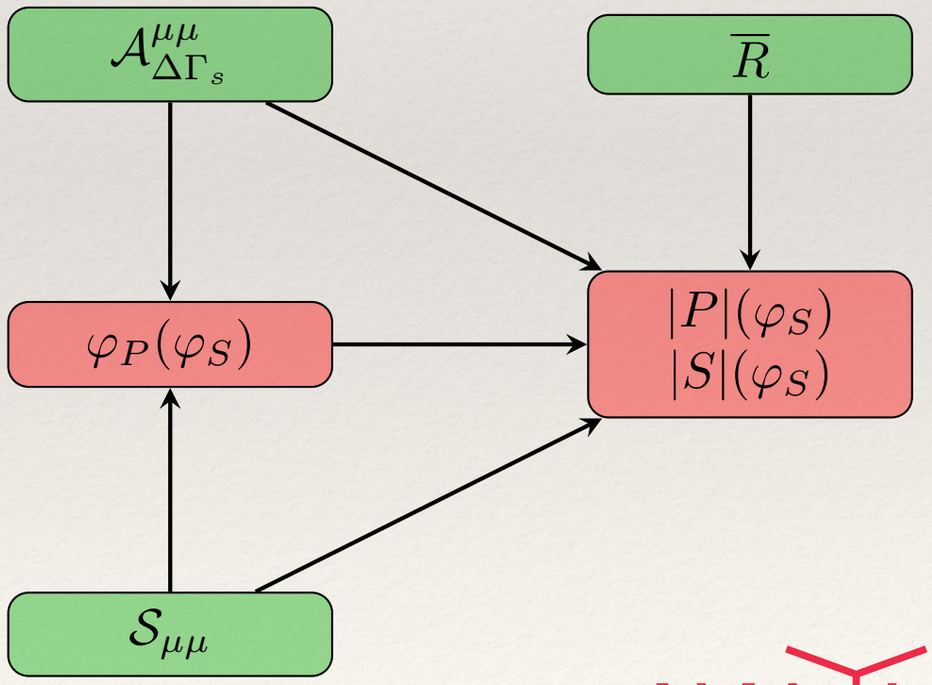
General CP-violating New Physics

- Determine φ_P, $|P|$ and $|S|$ as functions of φ_S
- Assume that we have:

$$\left\{ |S| = 0.30, \quad \varphi_S = 20^\circ, \quad \varphi_P = 30^\circ \right\} \xrightarrow{\overline{R}} |P| = 0.89$$

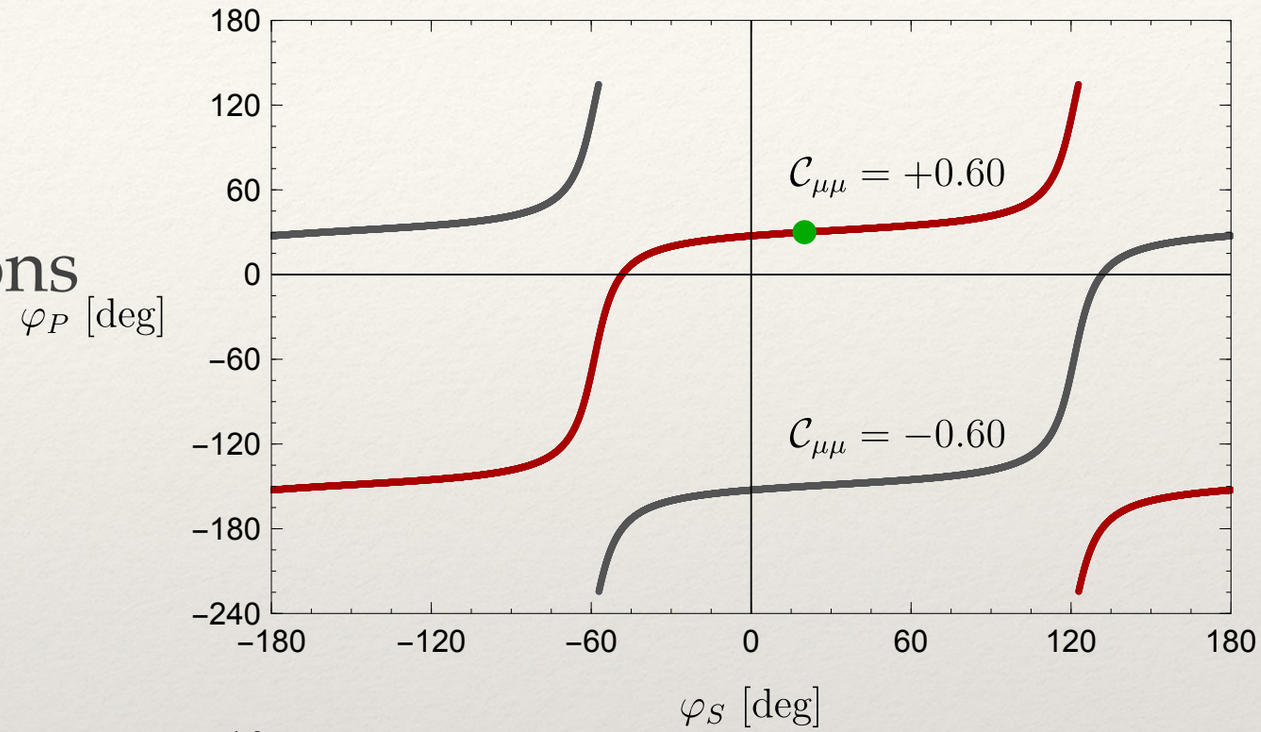
- Then the observables are:

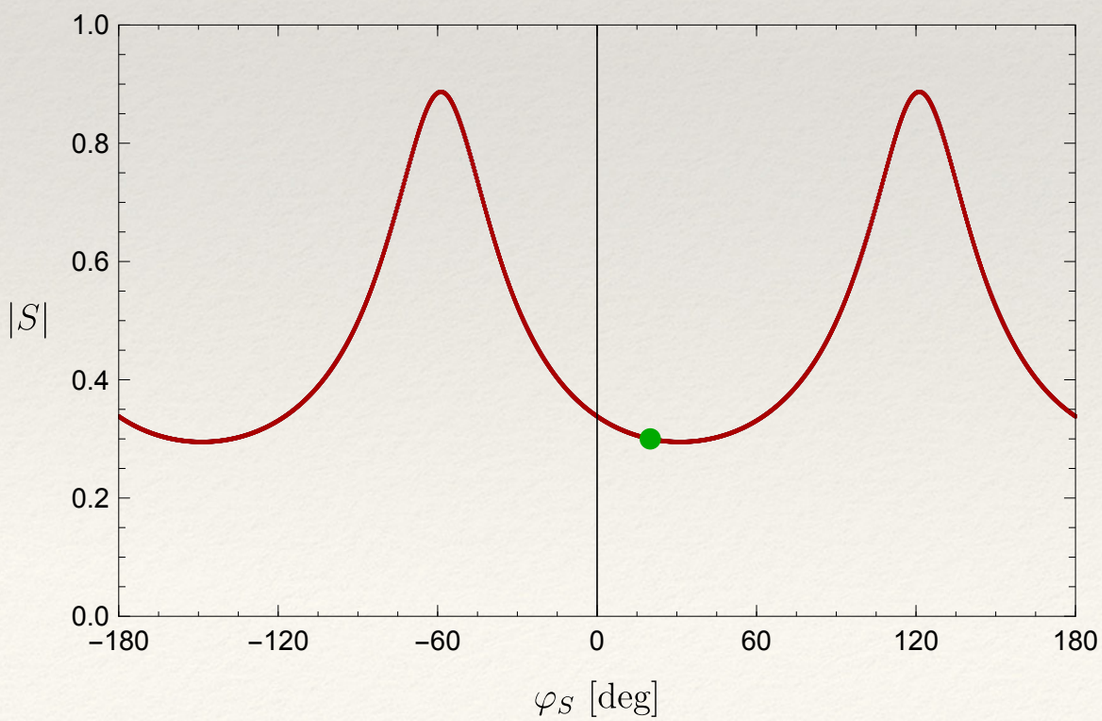
$$\overline{R} = 0.84, \quad \mathscr{A}^{\mu\mu}_{\Delta\Gamma_s} = 0.37$$
$$\mathscr{S}_{\mu\mu} = 0.71, \quad \mathscr{C}_{\mu\mu} = 0.60$$



General CP-violating New Physics

- Profound new insights:
  - New $|P|$ and $|S|$ contributions (non-trivial bounds)
  - CP-violating phases
  - $\mathscr{C}_{\mu\mu}$ solves ambiguity





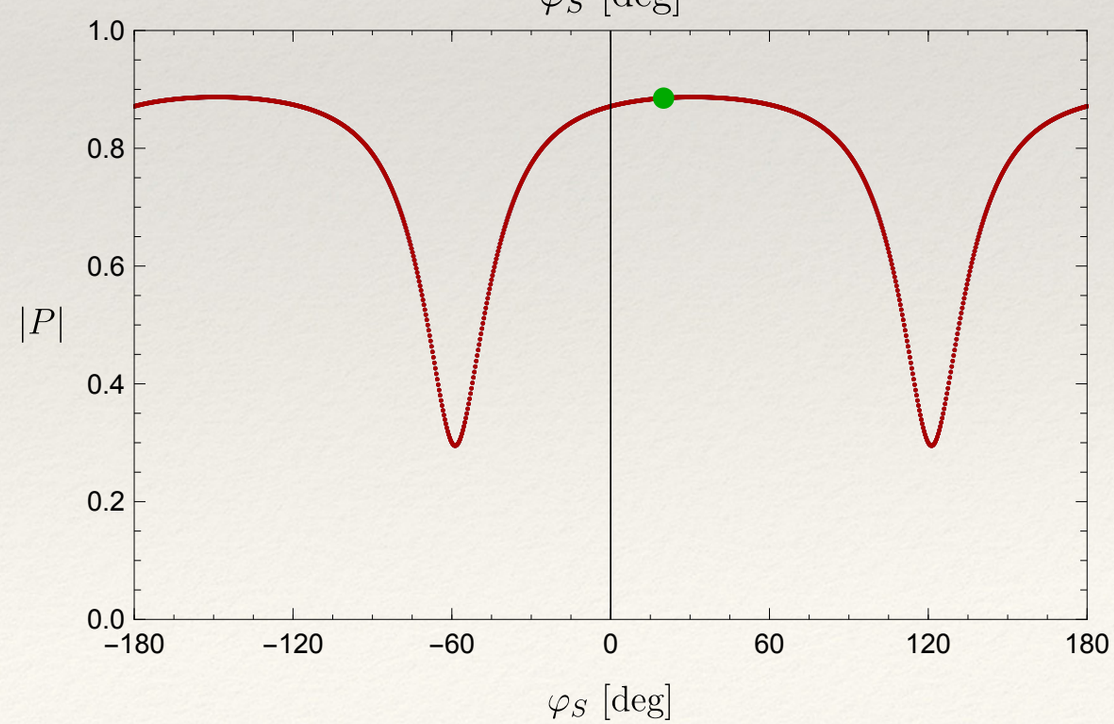


Illustration for $x = 0$, $|x| \to \infty$

$$\mathscr{A}^{\mu\mu}_{\Delta\Gamma_s} = 0.58, \quad \mathscr{S}_{\mu\mu} = -0.80, \quad \mathscr{C}_{\mu\mu} = 0.16$$

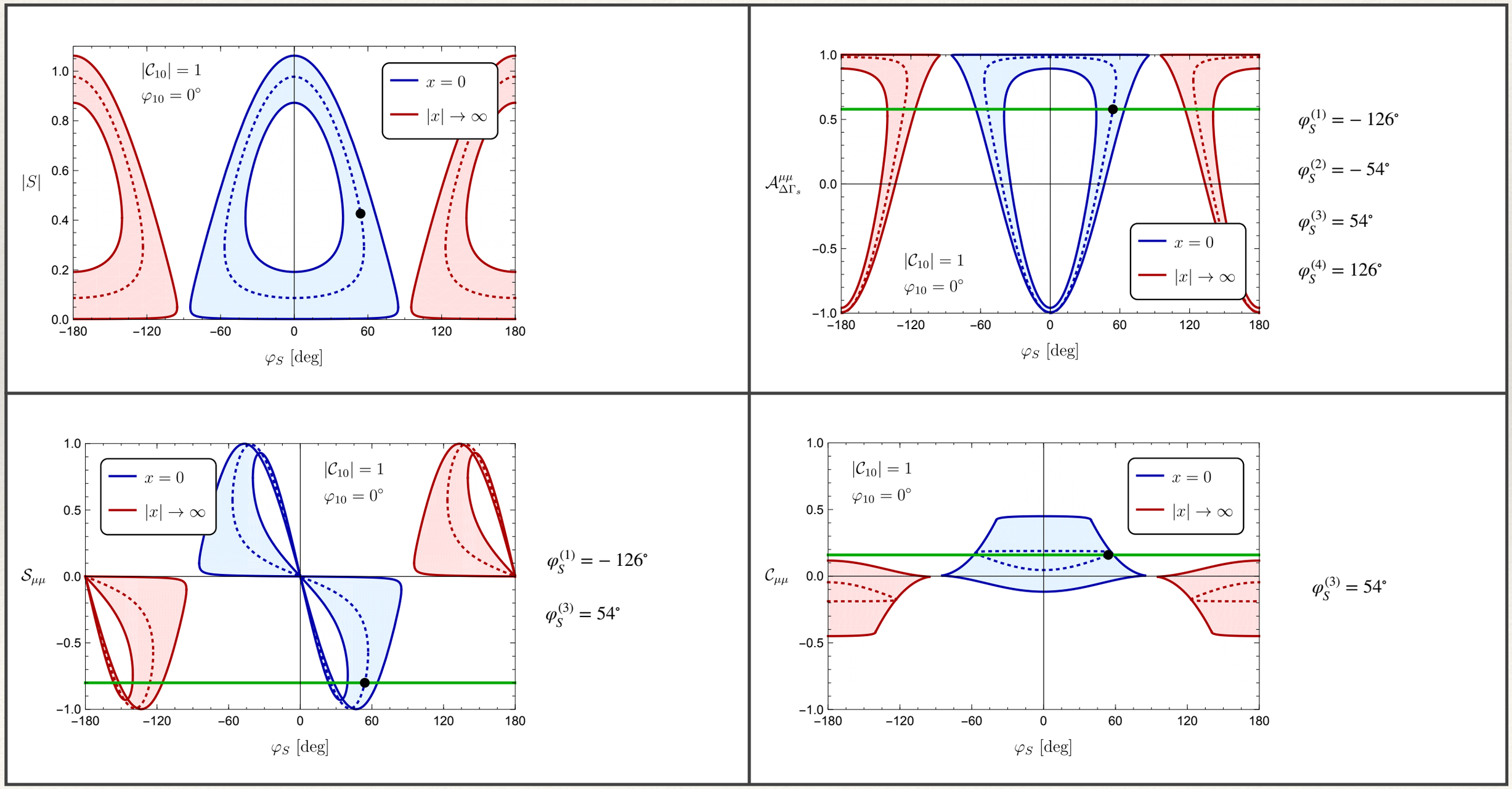


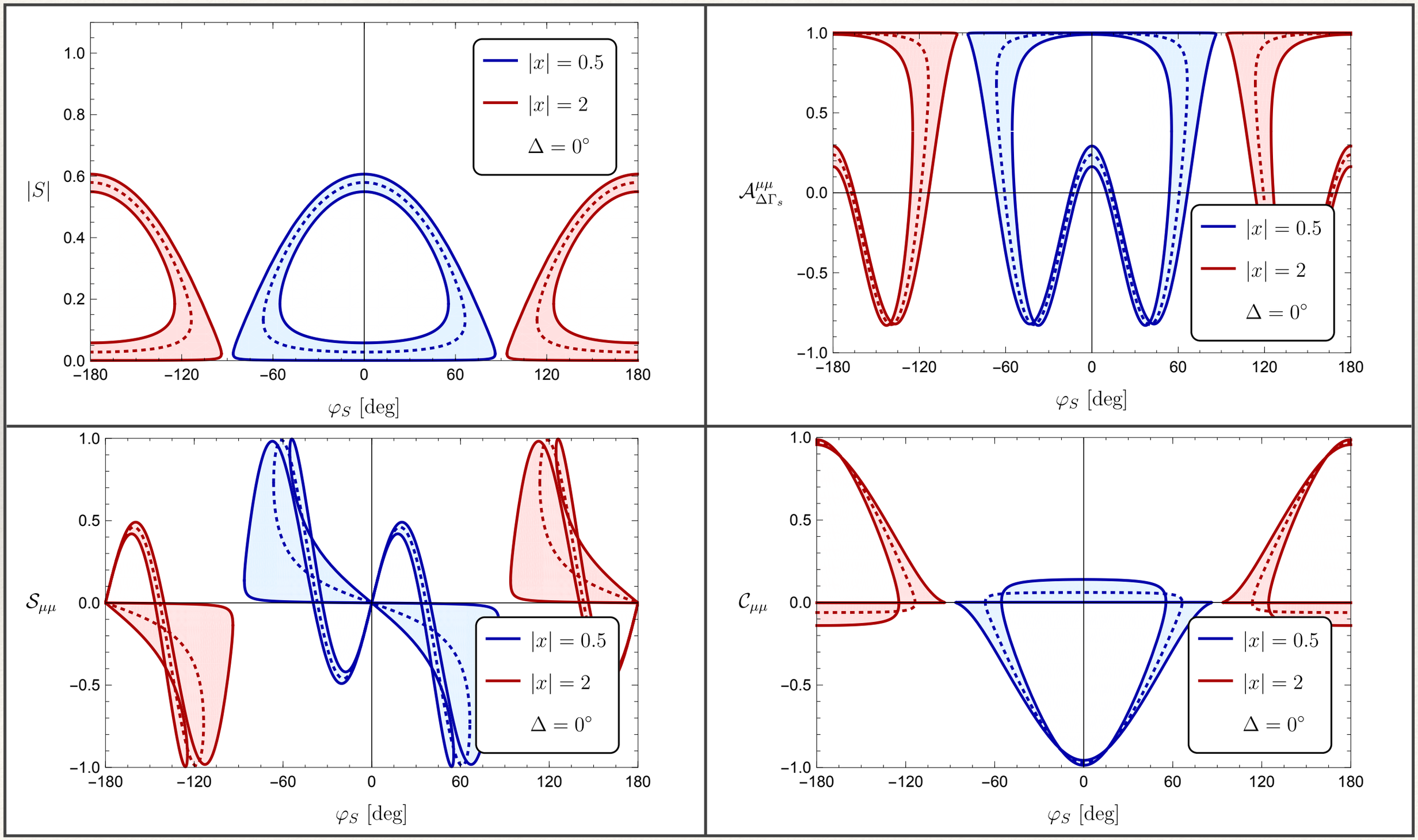
Illustration for $\Delta = 0^\circ$

- Another interesting case: $\Delta = 0^\circ$
  ➥ same CP-violating phase for C_S and C_S'
- $\overline{R}$, $\mathscr{A}^{\mu\mu}_{\Delta\Gamma_s}$ and $\mathscr{S}_{\mu\mu}$ are invariant under

$$|x| \to 1/|x|, \quad \varphi_S \to \varphi_S + \pi$$

- Again $\mathscr{C}_{\mu\mu}$ breaks symmetry by overall minus sign

Illustration for $\Delta = 0^\circ$



R. Fleischer, D. Galárraga Espinosa, RJ, G. Tetlalmatzi-Xolocotzi; Eur. Phys. J. C 78 (2018) 1 [arXiv:1709.04735 [hep-ph]]

Illustration for $\Delta = 0^\circ$

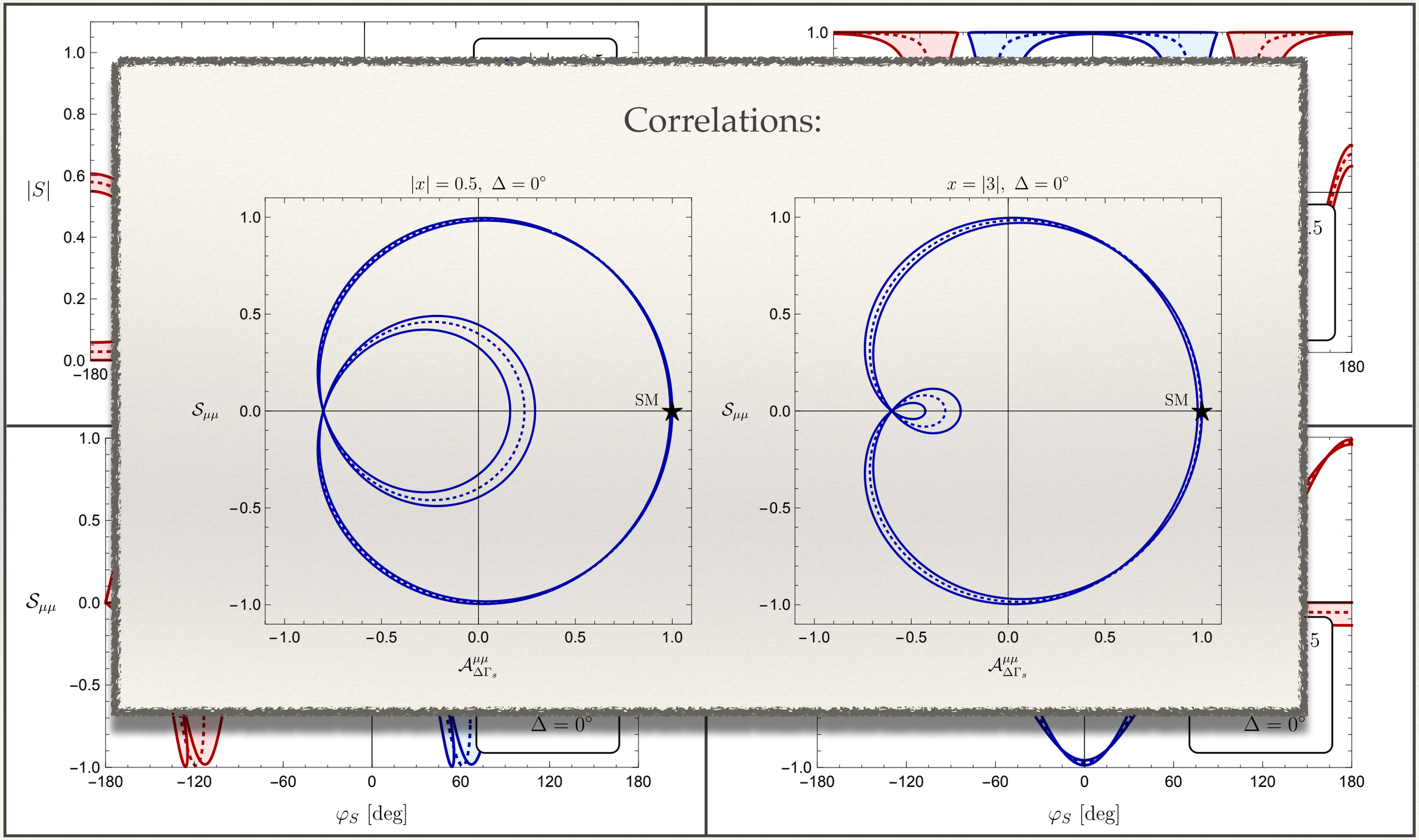
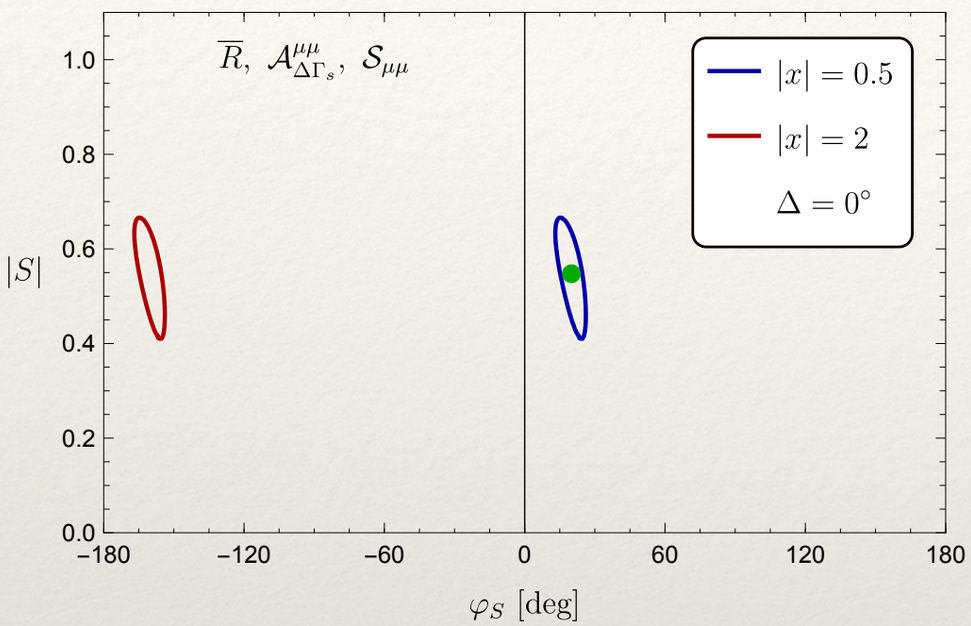
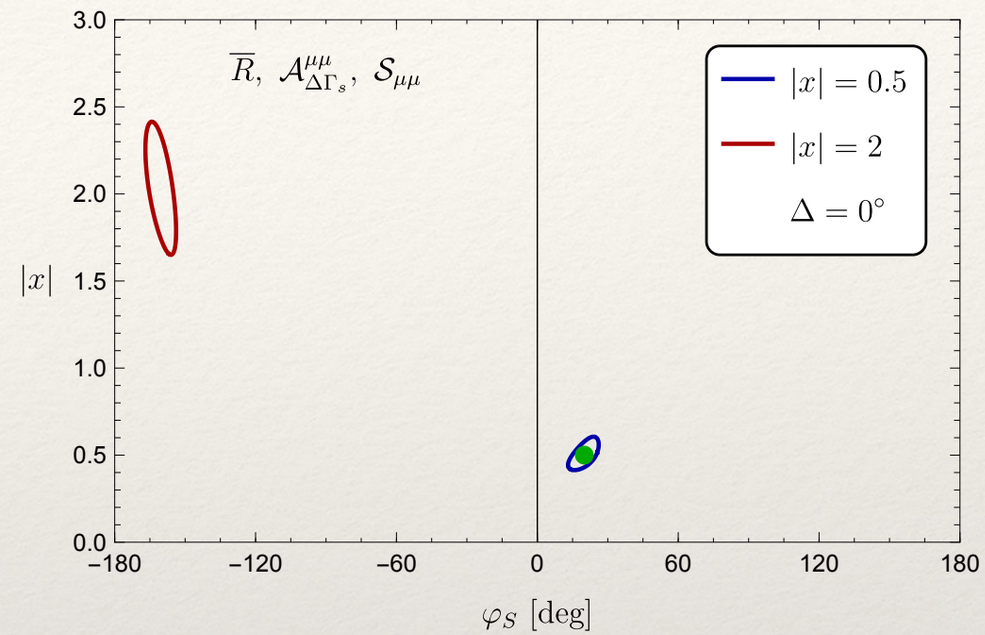
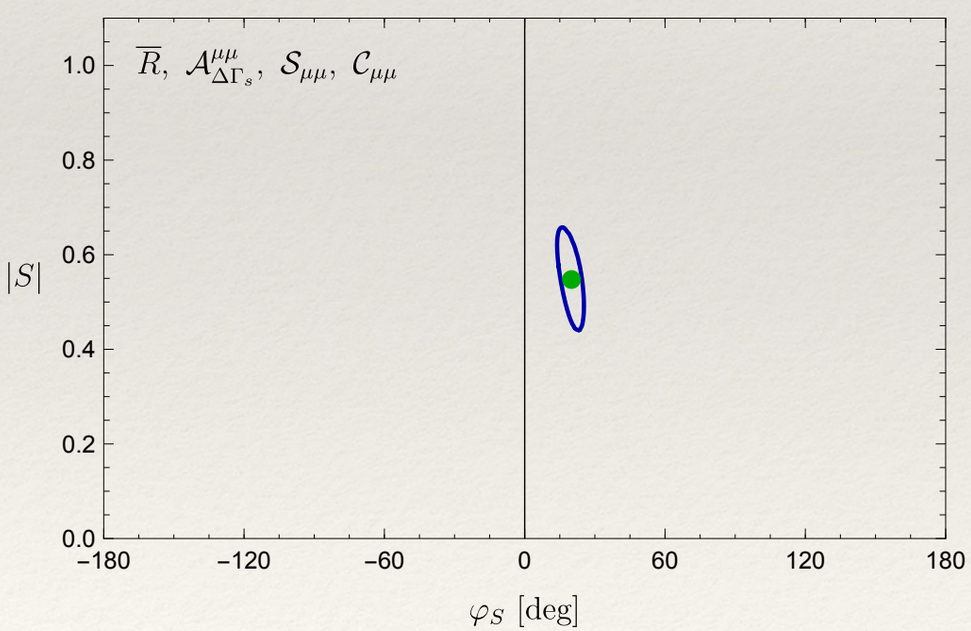
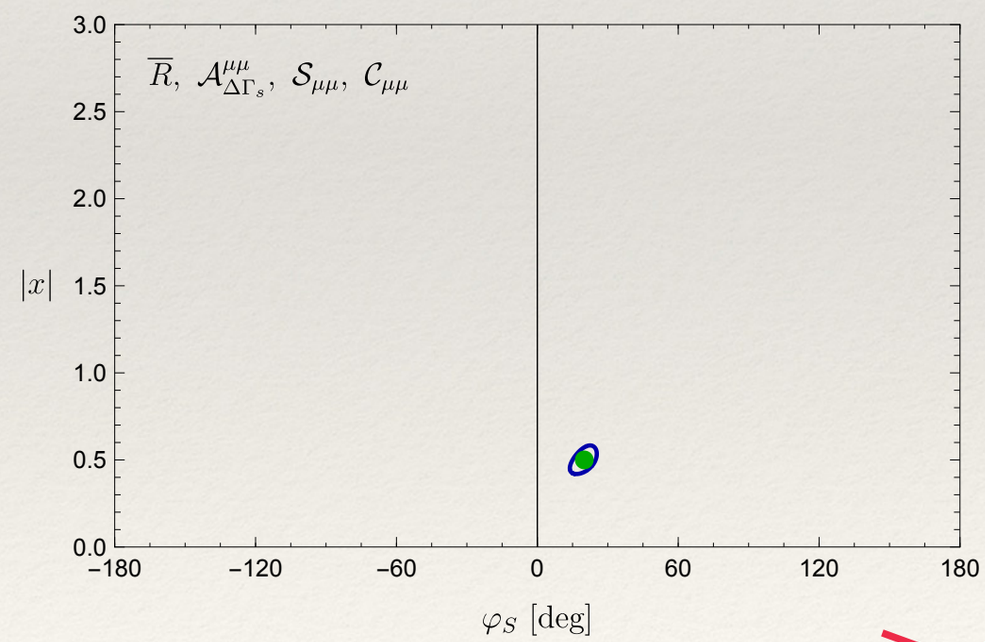


Illustration for $\Delta = 0^\circ$









5 σ

7 σ