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Utilising $B \to \pi K$ decays at the High-Precision Frontier

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Based on:

R. Fleischer, R. Jaarsma, and K. K. Vos; arXiv:1712.02323 [hep-ph]

R. Fleischer, R. Jaarsma, E. Malami, and K. K. Vos; to appear

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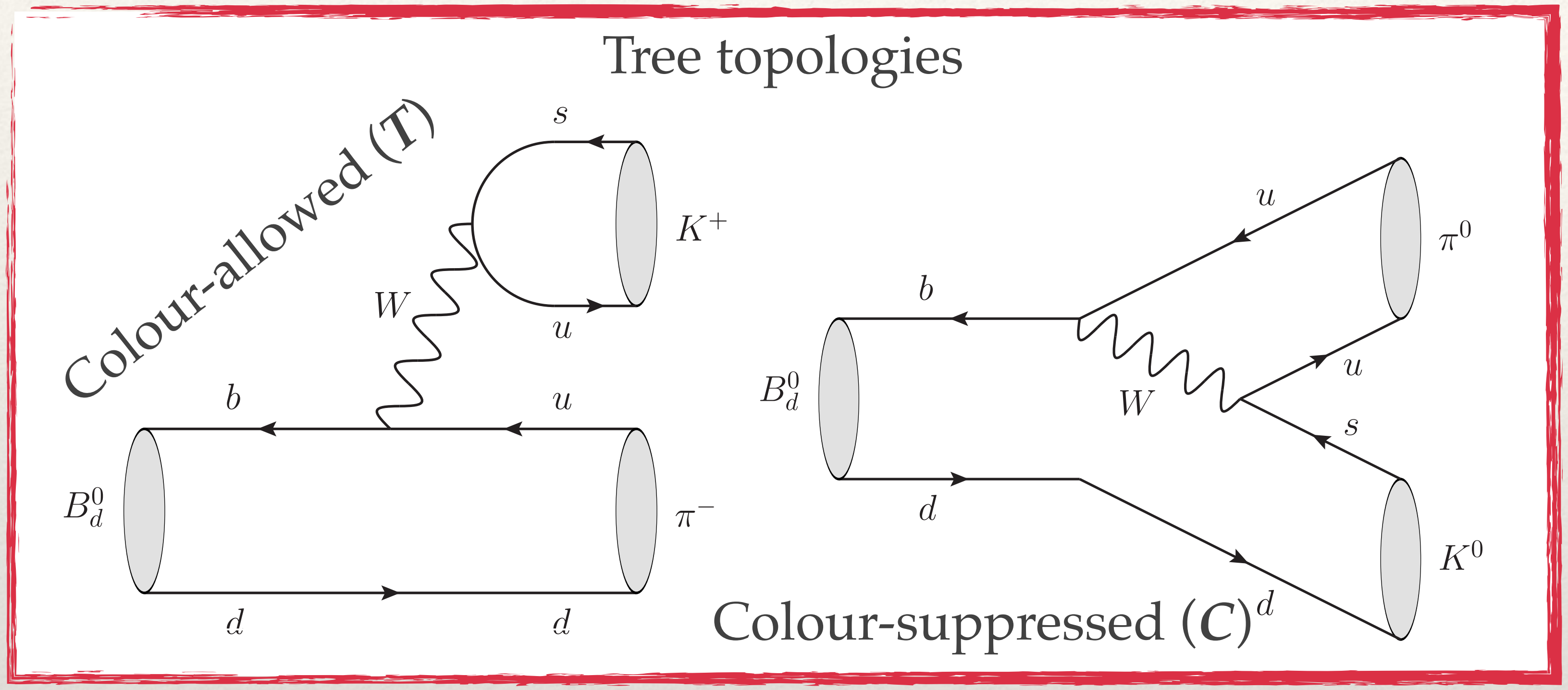
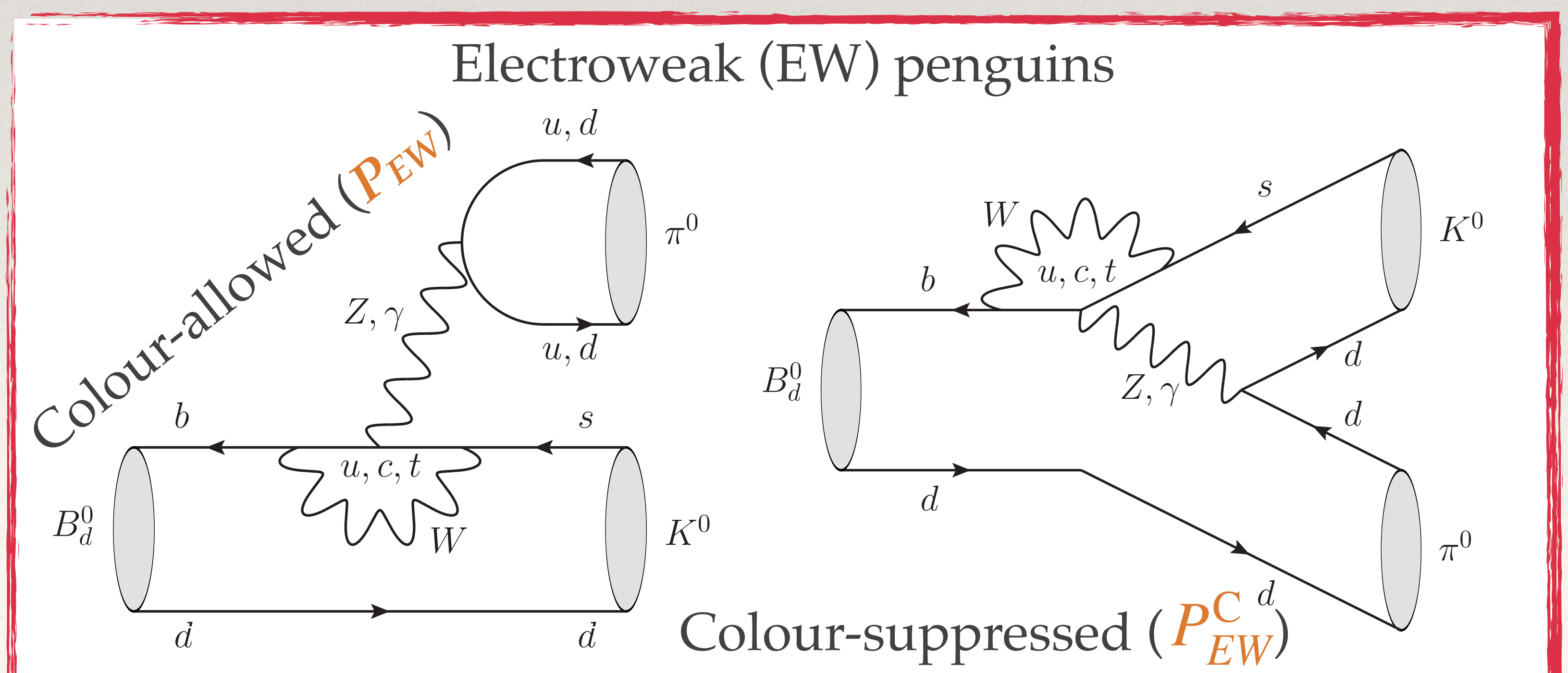
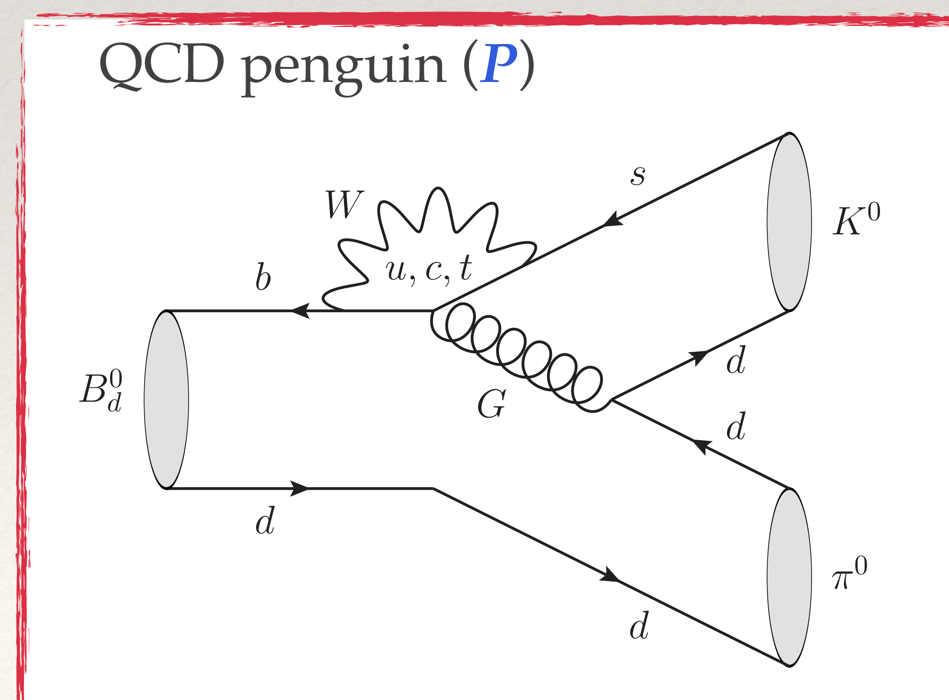
Introduction to $B \to \pi K$ decays

Phenomenology

- Tree topologies suppressed by CKM element V_{ub}
- **Leading contribution from QCD penguins**
- **CA EW penguins at same level as tree topologies**
- QCD flavour symmetry to link topologies

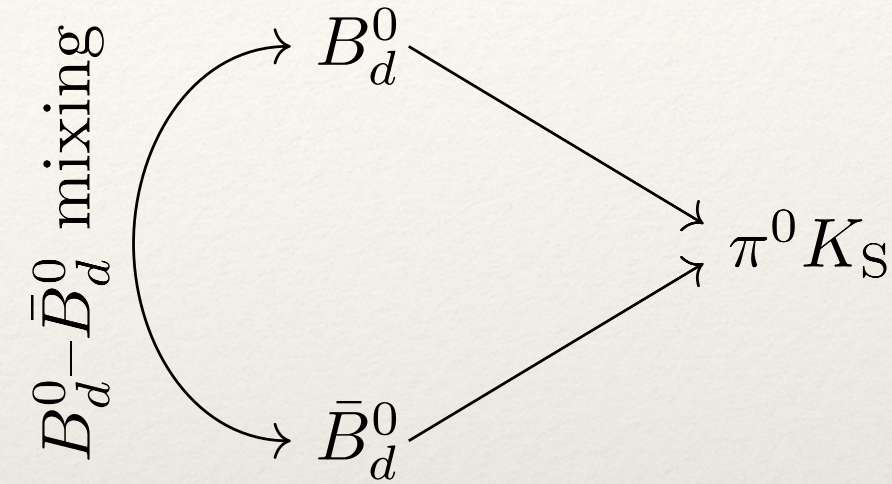


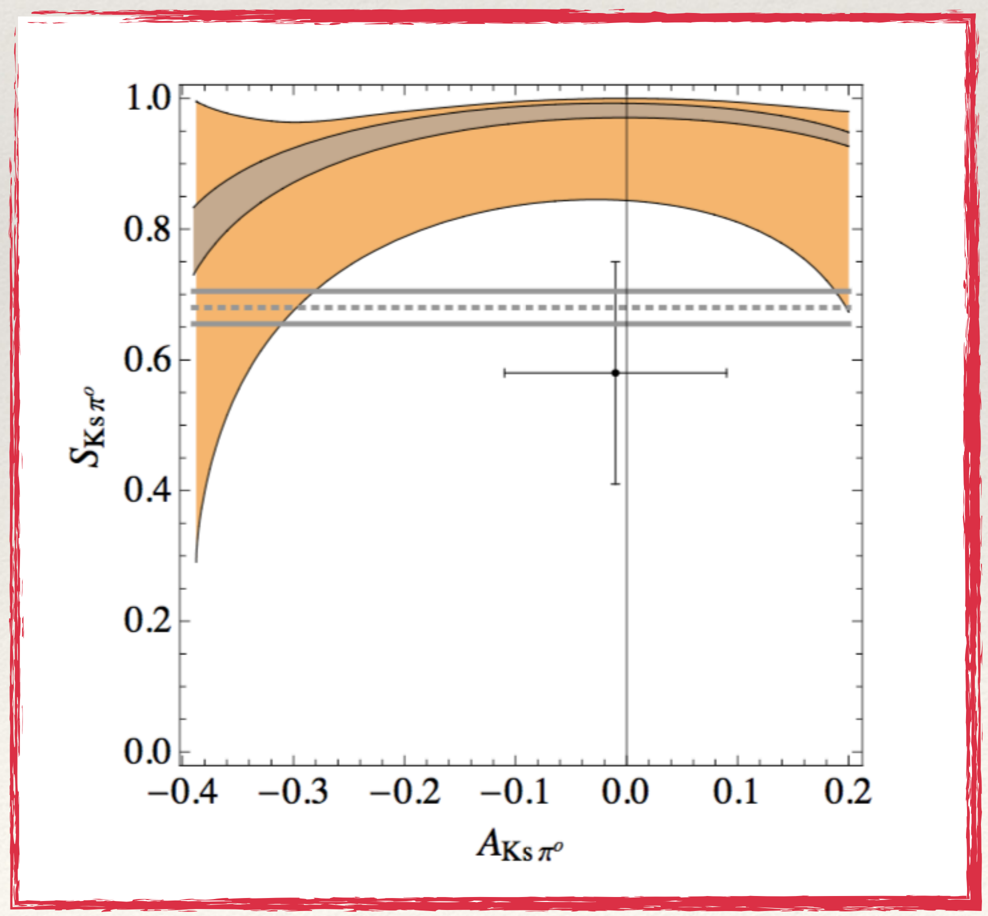




$B \to \pi K$ decays

- Decays in the spotlight for over 2 decades
- Particular $B_d^0 \to \pi^0 K_S$ interesting:
  only channel with
  mixing-induced CP asymmetry
- Puzzling data in correlation between CP asymmetries
  [R. Fleischer, S. Jäger, D. Pirjol, J. Zupan (2008)]
- Modified EWP sector?





$B \to \pi K$ decays

- What is the status of these decays?
- Little attention in recent years:
  - Neutral final state challenging for LHCb, good potential for upcoming Belle II experiment
- Difficult from theory side (QCD), but we can learn a lot!

We shall provide the state-of-the-art picture

$B \to \pi K$ decays in detail

Amplitudes

- General parametrization: [A. J. Buras, R. Fleischer, S. Recksiegel, F. Schwab (2004)]

Neglect small colour-suppressed EWP and annihilation

$$A(B^+ \to \pi^+ K^0) = -P' \left[1 + \rho_c e^{i\theta_c} e^{i\gamma}\right]$$

$$\sqrt{2} A(B^+ \to \pi^0 K^+) = P' \left[1 + \rho_c e^{i\theta_c} e^{i\gamma} - (e^{i\gamma} - q e^{i\phi} e^{i\omega}) r_c e^{i\delta_c}\right]$$

$$A(B_d^0 \to \pi^- K^+) = P' \left[1 - r e^{i\delta} e^{i\gamma}\right]$$

$$\sqrt{2} A(B_d^0 \to \pi^0 K^0) = -P' \left[1 + \rho_n e^{i\theta_n} e^{i\gamma} - q e^{i\phi} e^{i\omega} r_c e^{i\delta_c}\right]$$

Parameters discussed on next slides

- CP-conserving strong amplitude $P' = (1 - \lambda^2/2) A \lambda^2 (P_t - P_c)$

CKM parameters (Wolfenstein parametrization)

- Amplitudes satisfy isospin relation

$$\boxed{\begin{gathered}\sqrt{2} A(B_d^0 \to \pi^0 K^0) + A(B_d^0 \to \pi^- K^+) = \\ \sqrt{2} A(B^+ \to \pi^0 K^+) + A(B^+ \to \pi^+ K^0) = 3 A_{3/2} \\ 3 A_{3/2} \equiv 3 |A_{3/2}| e^{i\phi_{3/2}} = -(\hat{T} + \hat{C})\left(e^{i\gamma} - q e^{i\phi} e^{i\omega}\right)\end{gathered}}$$

[Y. Nir, H. R. Quinn (1991); M. Gronau, O. F. Hernández, D. London, J. L. Rosner (1995)]

Amplitudes

Reminder:
T: colour-allowed (CA) tree
C: colour-suppressed (CS) tree
P: QCD penguin

- Hadronic parameters:

$$re^{i\delta} \equiv \left(\frac{\lambda^2 R_b}{1-\lambda^2}\right)\left[\frac{T-(P_t-P_u)}{P_t-P_c}\right], \quad \rho_c e^{i\theta_c} \equiv \left(\frac{\lambda^2 R_b}{1-\lambda^2}\right)\left[\frac{P_t-P_u}{P_t-P_c}\right] \approx 0,$$

$$r_c e^{i\delta_c} \equiv \left(\frac{\lambda^2 R_b}{1-\lambda^2}\right)\left[\frac{T+C}{P_t-P_c}\right], \qquad \rho_n e^{i\theta_n} \equiv \left(\frac{\lambda^2 R_b}{1-\lambda^2}\right)\left[\frac{C+(P_t-P_u)}{P_t-P_c}\right] = r_c e^{i\delta_c} - re^{i\delta}$$

- $r_c e^{i\delta_c}$, $re^{i\delta}$ are non-perturbative, challenging to calculate from first principles

- Use $B \to \pi\pi$ and $SU(3)$ flavour symmetry [A. J. Buras, R. Fleischer, S. Recksiegel, F. Schwab (2004)]

$$r_c e^{i\delta_c} = (0.17 \pm 0.06)e^{i(1.9\pm 23.9)^\circ},$$
$$re^{i\delta} = (0.09 \pm 0.03)e^{i(28.6\pm 21.4)^\circ},$$

- Assumes 20% non-factorizable $SU(3)$-breaking corrections (guided by data)

Electroweak penguins

- The parameter $qe^{i\phi}e^{i\omega}$ describes EW penguin effects:

$$\boxed{\begin{gathered} qe^{i\phi}e^{i\omega} \equiv -\left(\frac{\hat{P}_{EW} + \hat{P}^{\mathrm{C}}_{EW}}{\hat{T} + \hat{C}}\right) \\[2ex] qe^{i\phi}e^{i\omega} \stackrel{\mathrm{SM}}{=} \frac{-3}{2\lambda^2 R_b}\left(\frac{C_9 + C_{10}}{C_1 + C_2}\right) R_q = (0.68 \pm 0.05) R_q \end{gathered}}$$

CP-violating phase

CP-conserving phase,
vanishes in $SU(3)$ limit

Short-distance coefficients

$SU(3)$-breaking corrections
$R_q = 1.0 \pm 0.3$

[See e.g. R. Fleischer (1995); A. J. Buras, R. Fleischer (1998); M. Neubert, J. L. Rosner (1998)]

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$B \to \pi K$ observables

Branching ratios

Experiment:
$R_c = 1.09 \pm 0.06,$
$R_n = 0.99 \pm 0.06,$
$R = 0.89 \pm 0.04$
[PDG (2016)]

- First observables:
  (Ratios of) CP-averaged branching ratios [A. J. Buras, R. Fleischer, S. Recksiegel, F. Schwab (2004)]

$$R_c \equiv 2\left[\frac{\mathcal{B}r(B^\pm \to \pi^0 K^\pm)}{\mathcal{B}r(B^\pm \to \pi^\pm K)}\right] = 1 - 2r_c \cos\delta_c(\cos\gamma - q\cos\phi) + \mathcal{O}(r_c^2),$$

Expansion in small $r_{(c)}$

$$R_n \equiv \frac{1}{2}\left[\frac{\mathcal{B}r(B_d \to \pi^\mp K^\pm)}{\mathcal{B}r(B_d \to \pi^0 K)}\right] = 1 - 2r_c \cos\delta_c(\cos\gamma - q\cos\phi) + \mathcal{O}(r_c^2),$$

$$R \equiv \left[\frac{\mathcal{B}r(B_d \to \pi^\mp K^\pm)}{\mathcal{B}r(B^\pm \to \pi^\pm K)}\right]\frac{\tau_{B^\pm}}{\tau_{B_d}} = 1 - 2r\cos\delta\cos\gamma + 2r_c\tilde{a}_C q\cos\phi + \mathcal{O}(r_{(c)}^2)$$

Colour-suppressed (CS) EWP parameter $\tilde{a}_C \equiv a_C \cos(\Delta_C + \delta_c)$

- We obtain the relation: $R_c - R_n = 0 + \mathcal{O}(r_c^2)$
- Is satisfied experimentally at the 1σ level

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Direct CP asymmetries

Experiment: [PDG (2016)]

$A_{\rm CP}^{\pi^0 K^0} = 0.00 \pm 0.13$

$A_{\rm CP}^{\pi^+ K^0} = -0.017 \pm 0.016$

$A_{\rm CP}^{K^+ \pi^0} = 0.037 \pm 0.021$

$A_{\rm CP}^{\pi^- K^+} = -0.082 \pm 0.006$

- Interference of penguin and tree
  ➥ *direct CP asymmetry* $A_{\rm CP}^{f}$
- Proportional to $r_{\rm (c)} \sin \delta_{\rm (c)}$ ➜ **values at $\mathcal{O}(10\%)$ level**
- Direct CP asymmetries and branching ratios satisfy sum rule:
  [M. Gronau (2005); M. Gronau, J. L. Rosner (2006)]

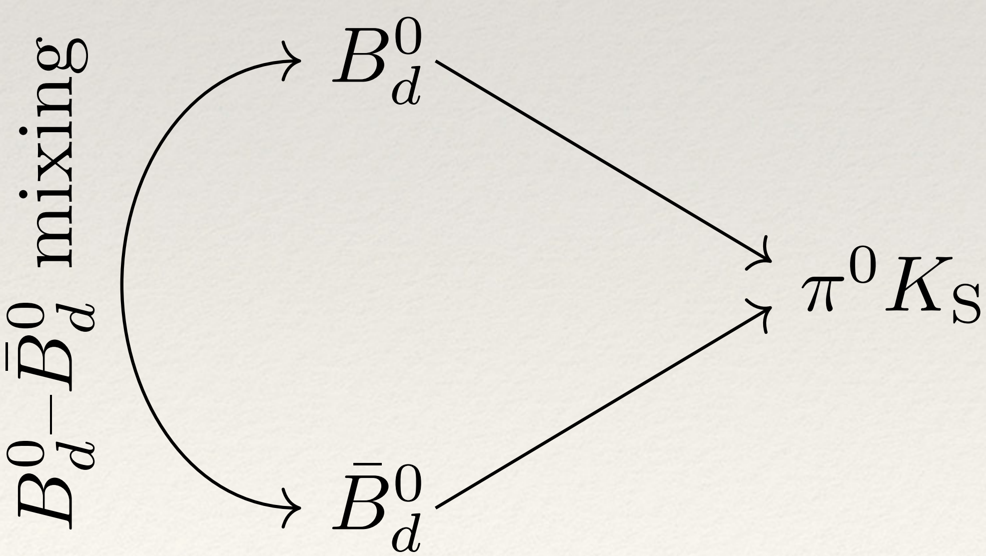
$$\Delta_{\rm SR} \equiv \left[A_{\rm CP}^{\pi^+K^0} \frac{\mathscr{B}r(\pi^+K^0)}{\mathscr{B}r(\pi^-K^+)} - A_{\rm CP}^{\pi^0K^+} \frac{2\mathscr{B}r(\pi^0K^+)}{\mathscr{B}r(\pi^-K^+)} \right] \frac{\tau_{B_d}}{\tau_{B^\pm}}$$
$$+ A_{\rm CP}^{\pi^-K^+} - A_{\rm CP}^{\pi^0K^0} \frac{2\mathscr{B}r(\pi^0K^0)}{\mathscr{B}r(\pi^-K^+)} = 0 + \mathcal{O}(r_{(c)}^2)$$

Difficult for LHCb

- Satisfied experimentally at 1σ level but uncertainty large due to $A_{\rm CP}^{\pi^0K^0}$
- **Experimental uncertainty at Belle II ➜ $\pm$0.04** [Belle-II Collaboration, arXiv:1011.0352]
- Prediction from sum rule: $A_{\rm CP}^{\pi^0K^0} = -0.14 \pm 0.03$

Mixing-induced CP asymmetry

- $B_d^0 \to \pi^0 K^0$ is special ➜ **only channel with mixing-induced CP asymmetry**
- Arises from interference between B_d^0—$\overline{B}_d^0$ mixing and decay
- Just like $A_{\rm CP}^{\pi^0 K^0}$, also difficult for LHCb ➜ large uncertainty
- Also great prospects for Belle II



$$S_{\rm CP}^{\pi^0 K_{\rm S}} = 0.58 \pm 0.17$$ [PDG (2016)]

Mixing-induced CP asymmetry

- Follows from time-dependent rate asymmetry:

$$\frac{\Gamma(\bar{B}^0_d(t) \to \pi^0 K_S) - \Gamma(B^0_d(t) \to \pi^0 K_S)}{\Gamma(\bar{B}^0_d(t) \to \pi^0 K_S) + \Gamma(B^0_d(t) \to \pi^0 K_S)} = A_{CP}^{\pi^0 K_S} \cos(\Delta M_d t) + S_{CP}^{\pi^0 K_S} \sin(\Delta M_d t)$$

with ΔM_d mass difference B_d mass eigenstates

[A. J. Buras, R. Fleischer (1999); R. Fleischer, S. Jäger, D. Pirjol, J. Zupan (2008)]

$$\boxed{S_{CP}^{\pi^0 K_S} = \sin(\phi_d - \phi_{00})\sqrt{1 - (A_{CP}^{\pi^0 K_S})^2}}$$

Measured in $B^0_d \to J/\psi K_S$ $\qquad$ $\phi_{00} \equiv \arg(\bar{A}_{00} A^*_{00})$

- Angle given by

CS EWP parameter

$$\tan\phi_{00} = 2\,(r\cos\delta - r_c\cos\delta_c)\sin\gamma + 2\,r_c\left(\cos\delta_c - 2\,\tilde{a}_C/3\right) q\sin\phi + \mathcal{O}(r_{(c)}^2)$$

What is the best way to calculate ϕ_{00}?

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Isospin relation

- We may use the isospin relation:

$$\boxed{\begin{gathered}\sqrt{2}A(B_d^0 \to \pi^0 K^0) + A(B_d^0 \to \pi^- K^+) \equiv 3A_{3/2} \\ 3A_{3/2} \equiv 3\,|A_{3/2}|\,e^{i\phi_{3/2}} = -\,(\hat{T}+\hat{C})\left(e^{i\gamma} - qe^{i\phi}e^{i\omega}\right)\end{gathered}}$$

Unitarity triangle angle γ as input

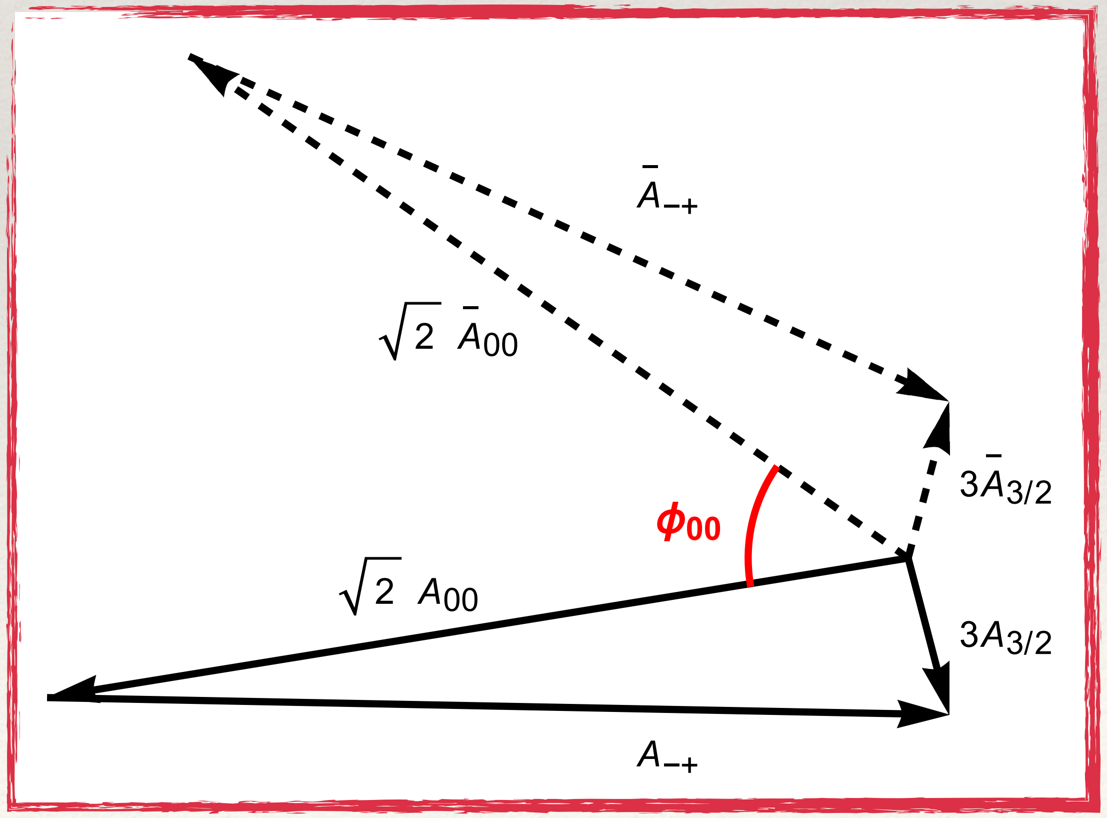
- ϕ_{00} follows from amplitude triangles

- If q and ϕ are known, only $SU(3)$ input for:

$$|\hat{T}+\hat{C}| = R_{T+C}\left|\frac{V_{us}}{V_{ud}}\right|\sqrt{2}\,|A(B^+ \to \pi^+\pi^0)|$$

$$R_{T+C} \approx f_K/f_\pi = 1.2 \pm 0.2$$

- *Minimal hadronic input*



Correlation between CP asymmetries

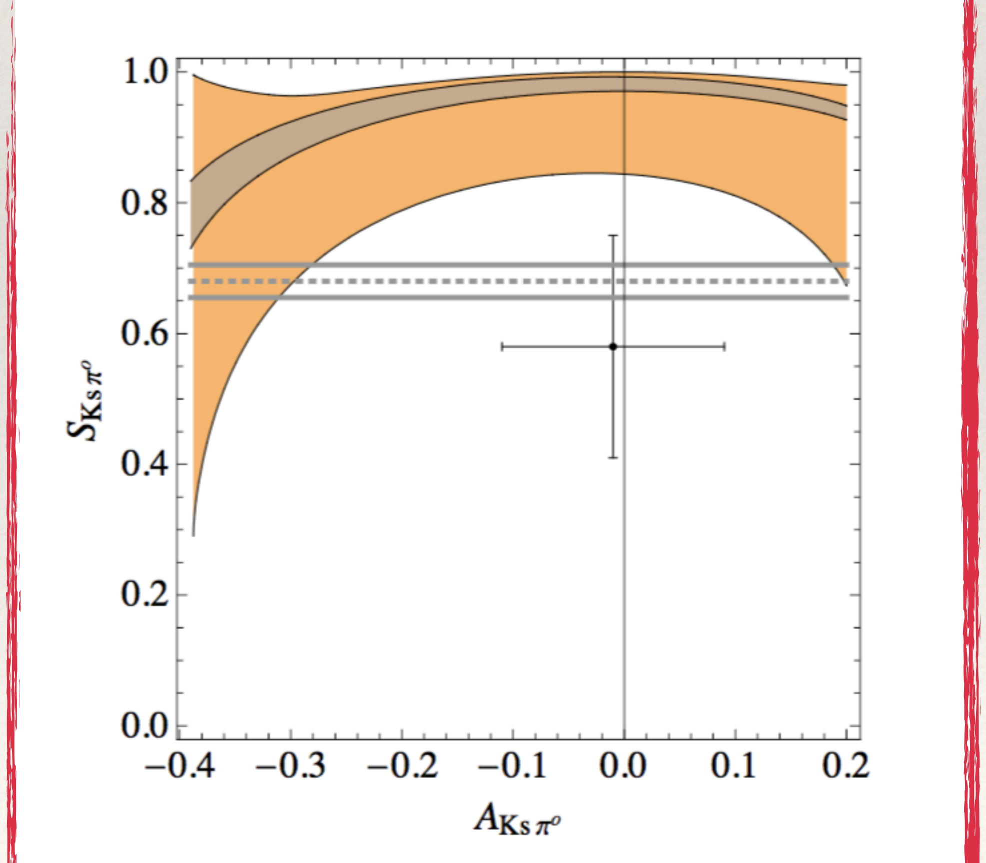
- We may now use

$$\boxed{S_{\rm CP}^{\pi^0 K_{\rm S}} = \sin(\phi_d - \phi_{00})\sqrt{1 - (A_{\rm CP}^{\pi^0 K_{\rm S}})^2}}$$

to obtain a correlation between $S_{\rm CP}^{\pi^0 K_{\rm S}}$ and $A_{\rm CP}^{\pi^0 K_{\rm S}}$

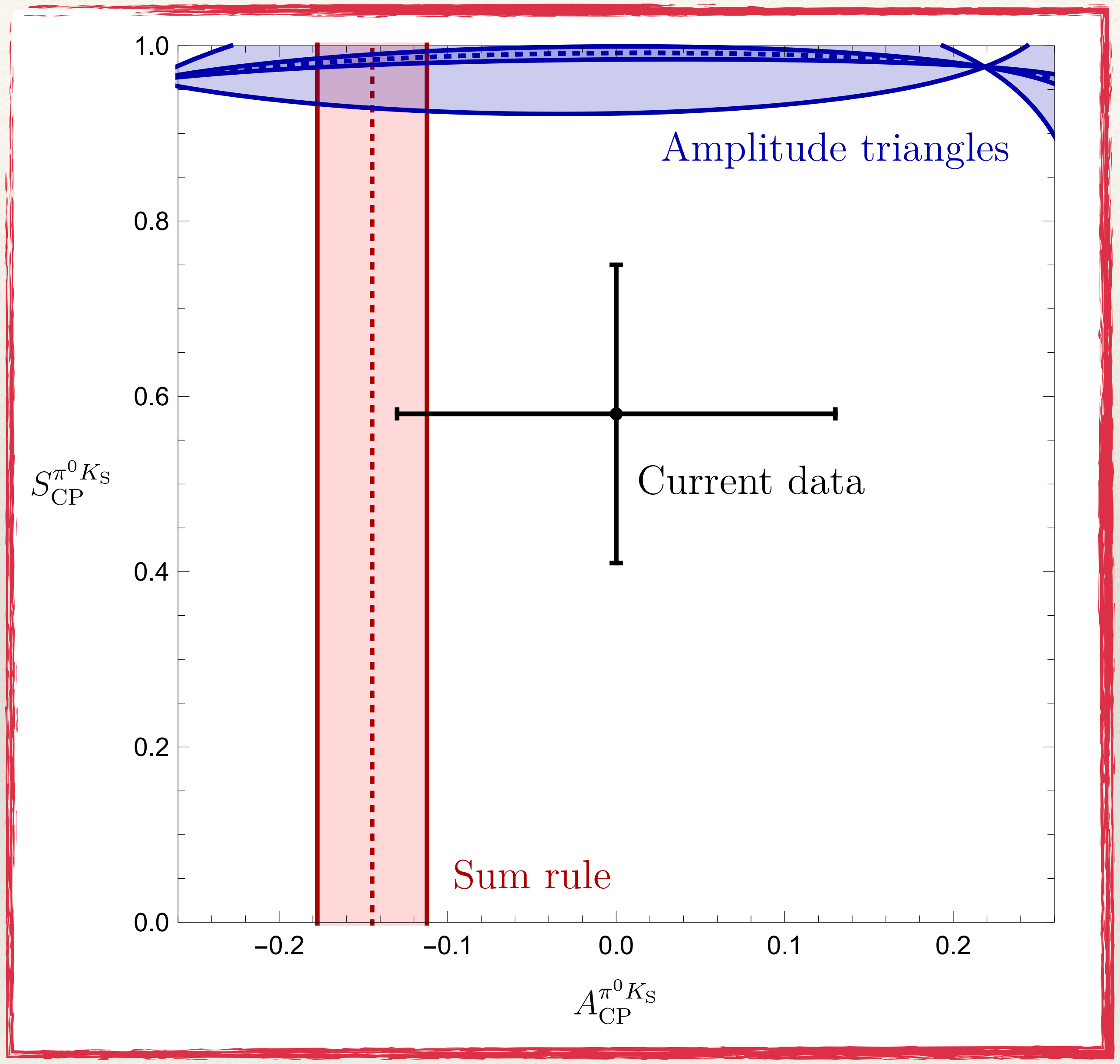
- Discrepancy with SM in 2008

[R. Fleischer, S. Jäger, D. Pirjol, J. Zupan (2008)]



What is the current status?

Correlation between CP asymmetries



Sharper inputs (γ) ➜ **discrepancy stronger!**

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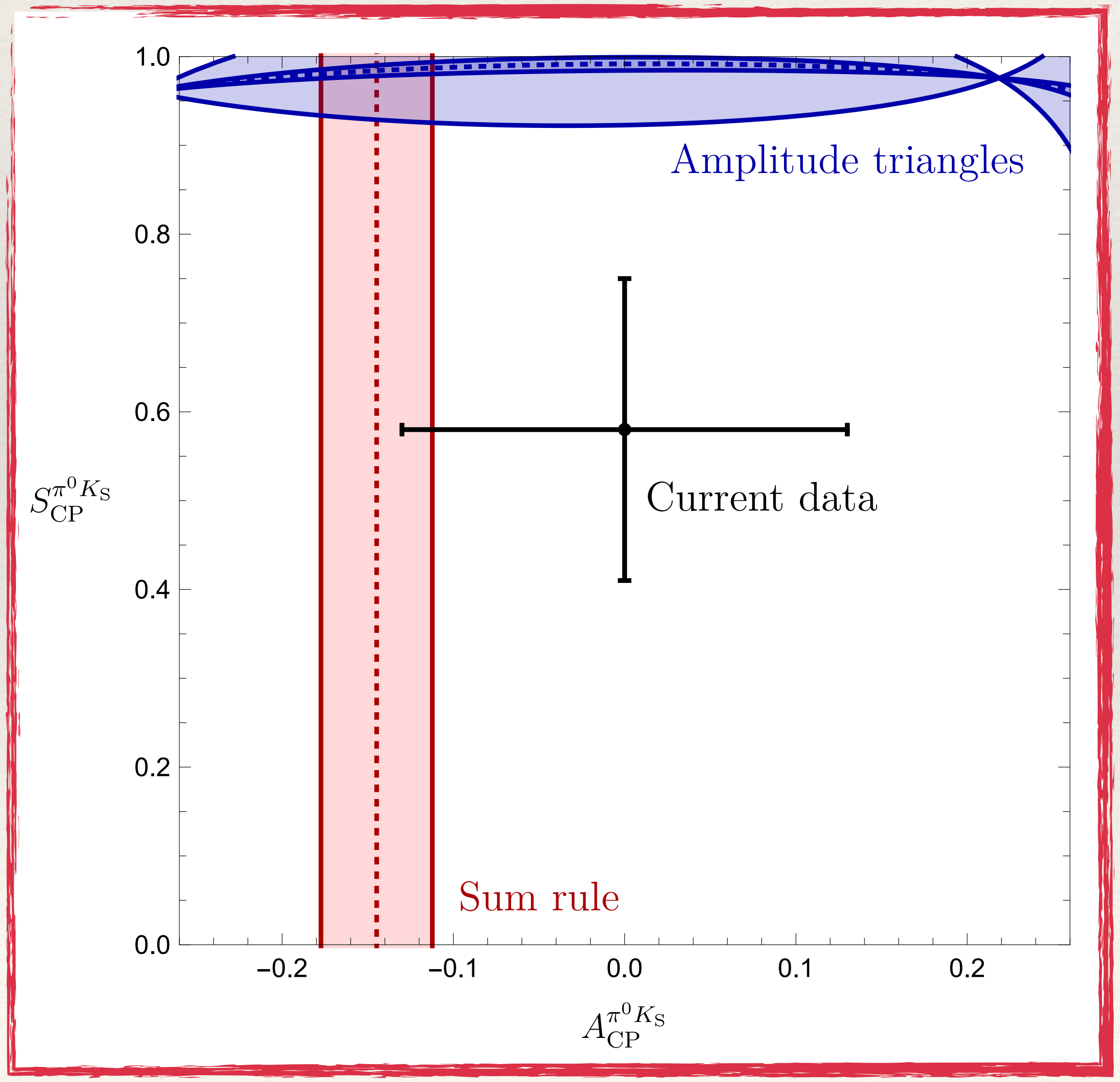
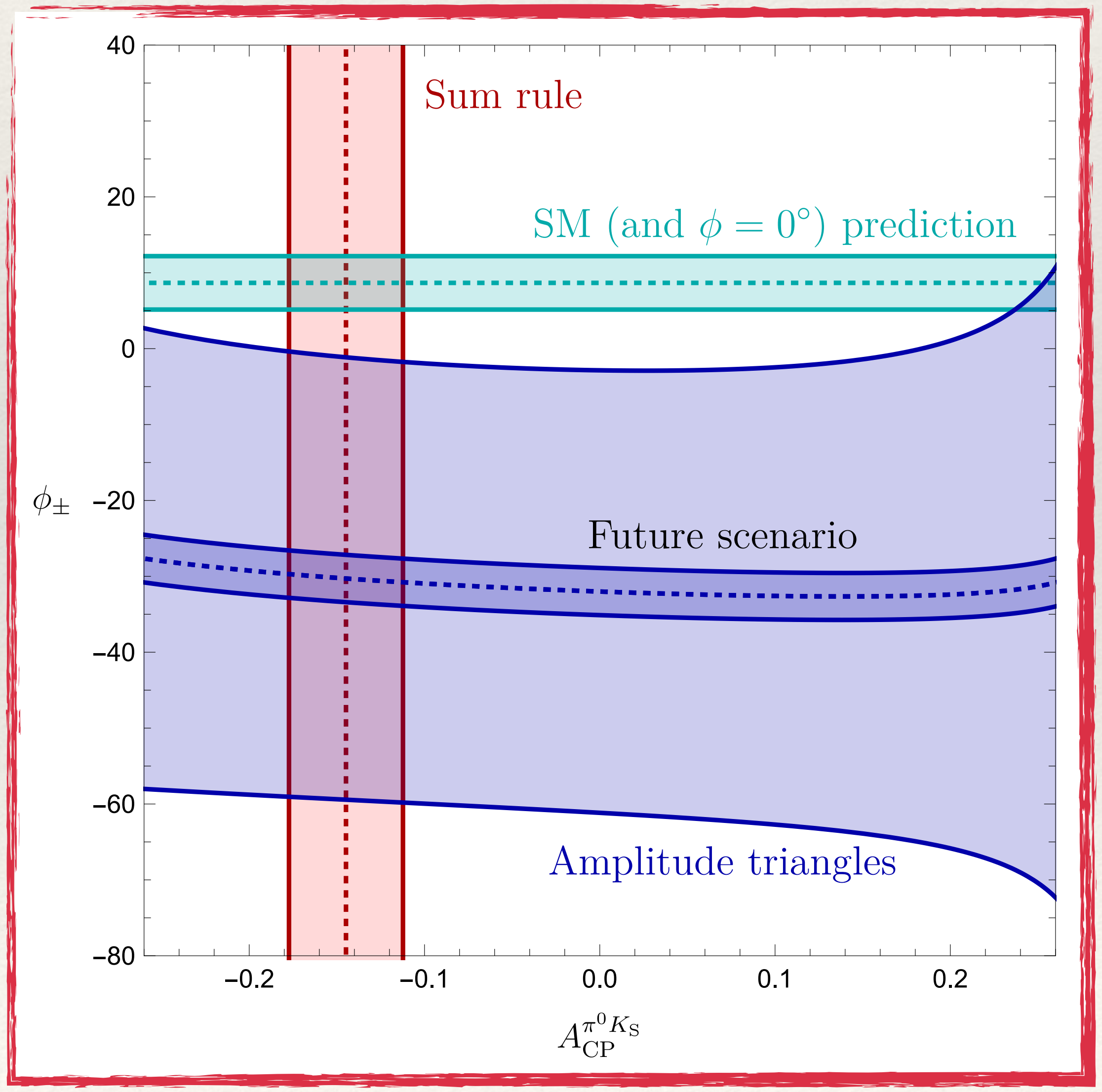
Puzzling patterns

New aspect: $\phi_\pm = \arg(\bar{A}_\pm A_\pm^*)$,

$$\phi_\pm\Big|_{\phi=0} = 2\,r\cos\delta\sin\gamma + \mathcal{O}(r^2) = (8.7 \pm 3.5)^\circ$$

Also the correlation is inconsistent!





Current status

State-of-the-art analysis of $S_{\mathrm{CP}}^{\pi^0 K_S}$:

- Problem with measurements? Discrepancy could be solved if
  - CP asymmetries $B_d^0 \to \pi^0 K_S$ move by ~1σ
  - $\mathscr{B}r(B_d \to \pi^0 K^0)$ moves by ~2.5σ
- Or is it New Physics? ➜ Study possibility of a **modified EWP sector**

With future data from LHCb (upgrade) and Belle II the situation should be resolved

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Determination of q and ϕ

- Use the amplitude triangles in a different way: convert $S_{\mathrm{CP}}^{\pi^0 K_S}$ into q and ϕ
- The isospin relation holds also for neutral as well as charged decays:

$$\sqrt{2}A(B_d^0 \to \pi^0 K^0) + A(B_d^0 \to \pi^- K^+) =$$

$$\boxed{\begin{array}{c}\sqrt{2}A(B^+ \to \pi^0 K^+) + A(B^+ \to \pi^+ K^0) = 3A_{3/2} \\ 3A_{3/2} \equiv 3|A_{3/2}|e^{i\phi_{3/2}} = -(\hat{T}+\hat{C})\left(e^{i\gamma} - q e^{i\phi} e^{i\omega}\right)\end{array}}$$

- Current data is better for charged decays, but the method works for both.
- Derive a set of equations for contours in q, ϕ-plane

$$q = \sqrt{N^2 - 2c\cos\gamma - 2s\sin\gamma + 1},$$

$$\tan\phi = \frac{\sin\gamma - s}{\cos\gamma - c}, \qquad q\sin\phi = \sin\gamma - s,$$

- where

$$c \equiv \pm N\cos(\Delta\phi_{3/2}/2), \quad s \equiv \pm N\sin(\Delta\phi_{3/2}/2),$$

$$N \equiv 3|A_{3/2}|/|\hat{T}+\hat{C}|, \quad \Delta\phi_{3/2} \equiv \phi_{3/2} - \bar{\phi}_{3/2}$$

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Determination of q and ϕ

assume $\omega = 0°$
(robust assumption)

- This method requires minimal $SU(3)$ input, only from

$$|\hat{T} + \hat{C}| = R_{T+C} \left| \frac{V_{us}}{V_{ud}} \right| \sqrt{2}\, |A(B^+ \to \pi^+ \pi^0)|$$

$$R_{T+C} \approx f_K / f_\pi = 1.2 \pm 0.2$$

No topologies have to be neglected

- Need to fix relative orientation triangles:

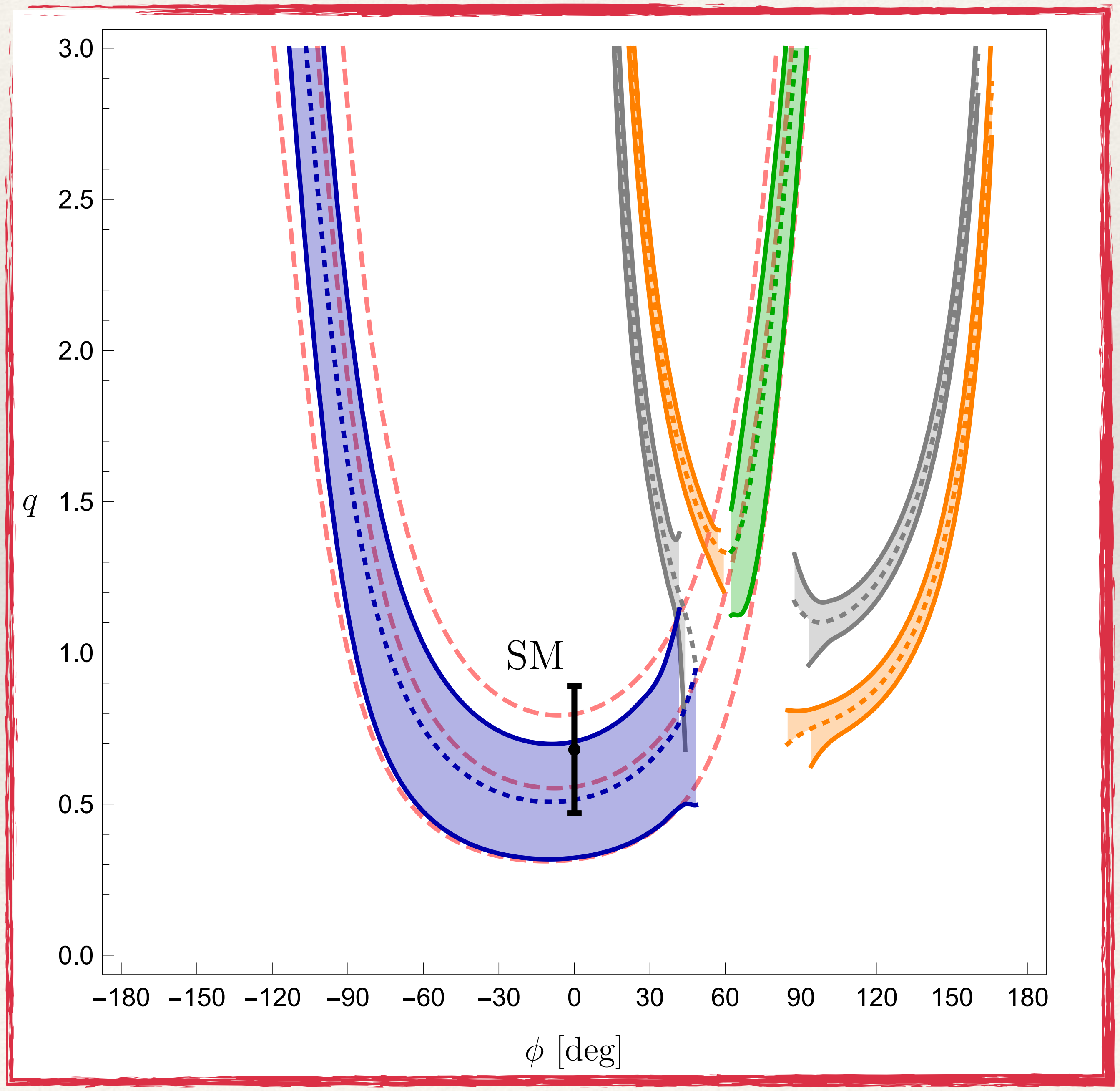
$$\phi_{+0} \equiv \arg(\bar{A}_{+0} A^*_{+0}) \approx 0 \text{ (charged) or } S_{\mathrm{CP}}^{\pi^0 K_S} \text{ (neutral)}$$

Results of the new strategy

Results for current data

Apply method to charged data as current uncertainty $S_{\mathrm{CP}}^{\pi^0 K_S}$ still large

➥ Potential to implement also for neutral data in the future!



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Results for current data

Complement analysis with:

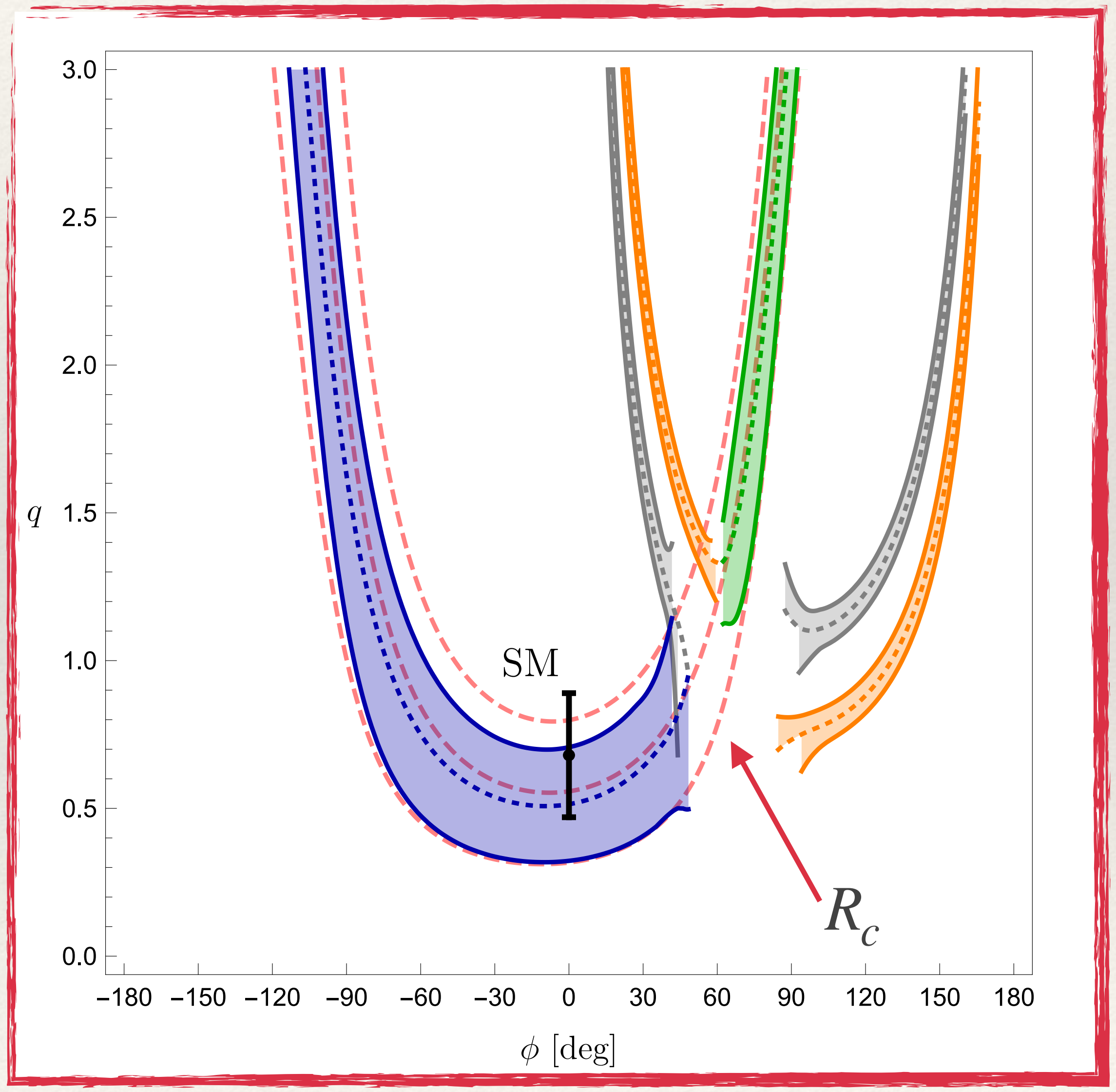
$$R_c = 1 - 2\, r_c \cos\delta_c(\cos\gamma - q\cos\phi) + \mathcal{O}(r_c^2)$$

CS EWPs only at $\mathcal{O}(r_c^2)$

➜ contour in q, ϕ-plane

Excellent agreement

Further input needed to determine the value of q and ϕ



Additional contour from $S_{\mathrm{CP}}^{\pi^0 K_\mathrm{S}}$

- Convert measurement of $S_{\mathrm{CP}}^{\pi^0 K_\mathrm{S}}$ in value of ϕ_{00}
- Obtain contour from

cosines of small phases ➜ low sensitivity to variations

$$\tan\phi_{00} = 2\,(r\cos\delta - r_\mathrm{c}\cos\delta_\mathrm{c})\sin\gamma + 2\,r_\mathrm{c}\left(\cos\delta_\mathrm{c} - 2\,\tilde{a}_\mathrm{C}/3\right)q\sin\phi + \mathcal{O}(r_{(\mathrm{c})}^2)$$

- CS EWP parameter $\tilde{a}_\mathrm{C} \equiv a_\mathrm{C}\cos(\Delta_\mathrm{C} + \delta_\mathrm{c})$ is determined from

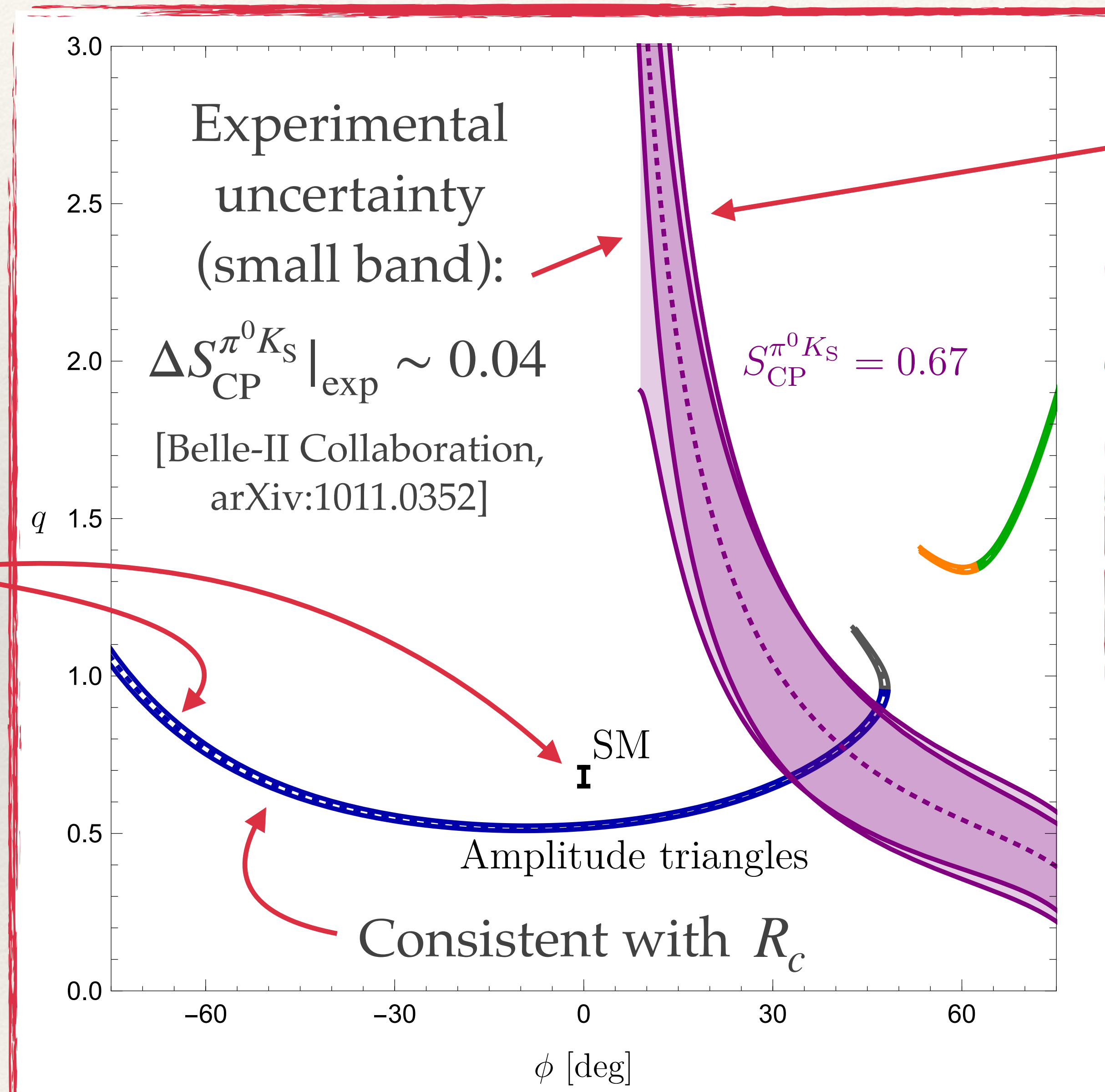
$$R = 1 - 2\,r\cos\delta\cos\gamma + 2\,r_\mathrm{c}\,\tilde{a}_\mathrm{C}\,q\cos\phi + \mathcal{O}(r_{(\mathrm{c})}^2)$$

- **Consider 3 different scenarios for measurements of $S_{\mathrm{CP}}^{\pi^0 K_\mathrm{S}}$ at Belle II**

Future scenarios

Future theory errors

[R. Fleischer, S. Jäger, D. Pirjol, J. Zupan (2008)]



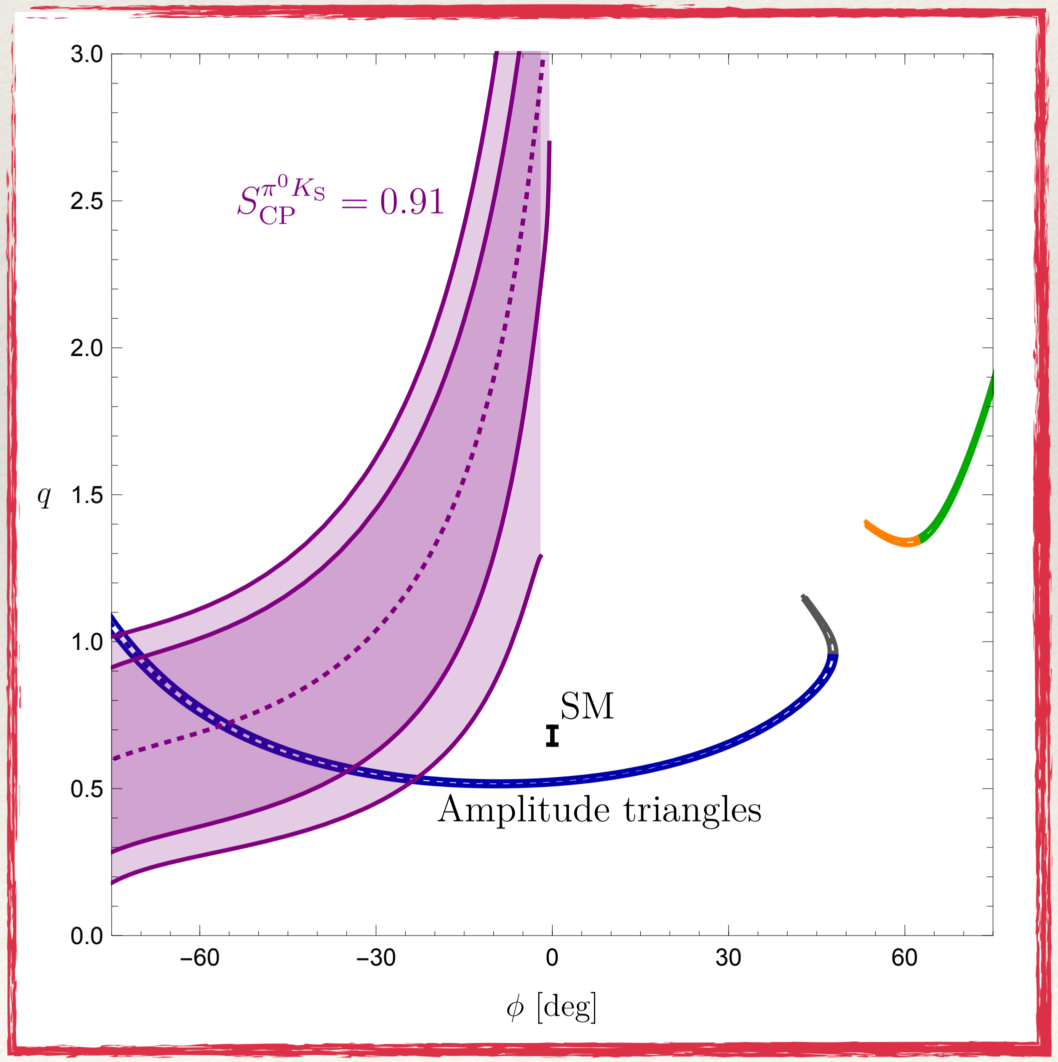
Theoretical uncertainty (wide band):

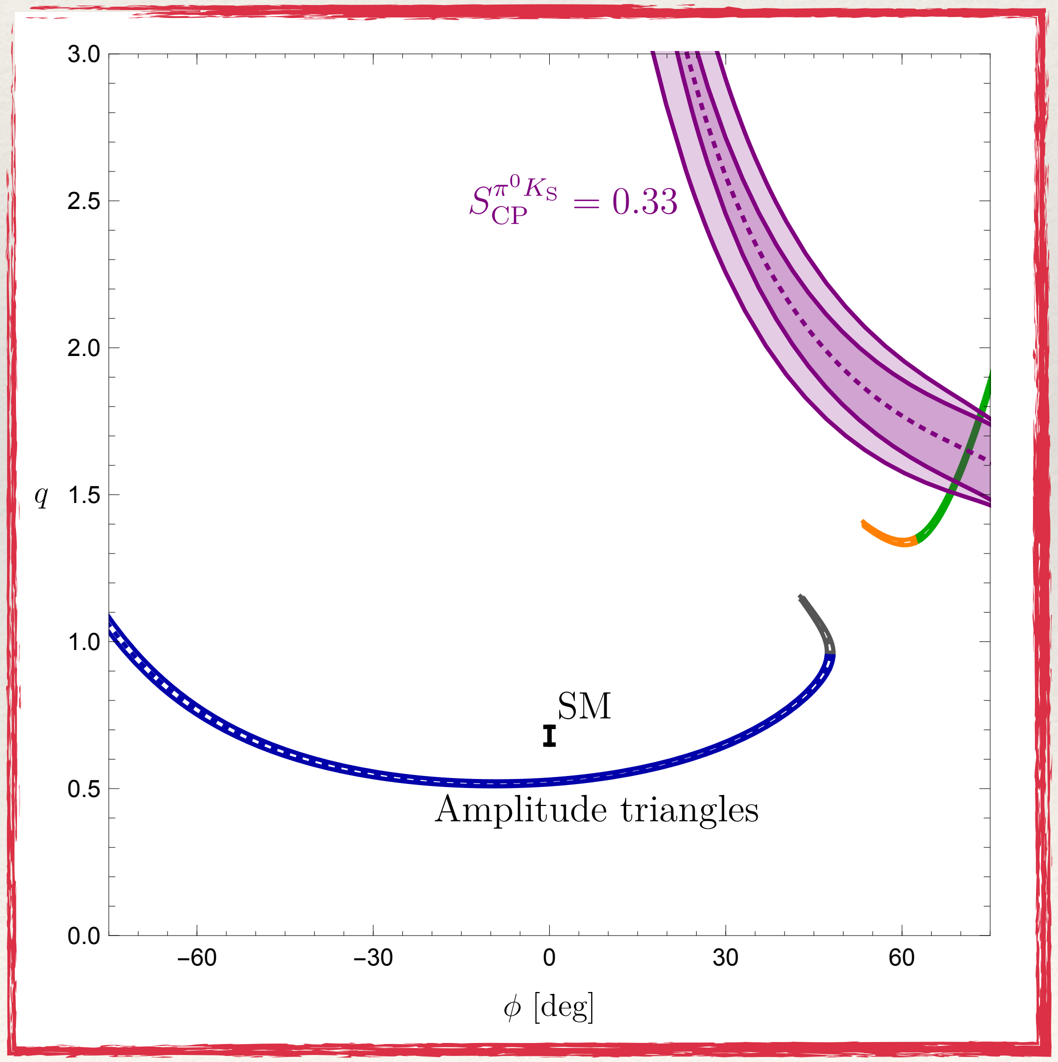
20% non-factorizable $SU(3)$-breaking corrections on the hadronic parameters

We can match the experimental precision with theory!

Future scenarios

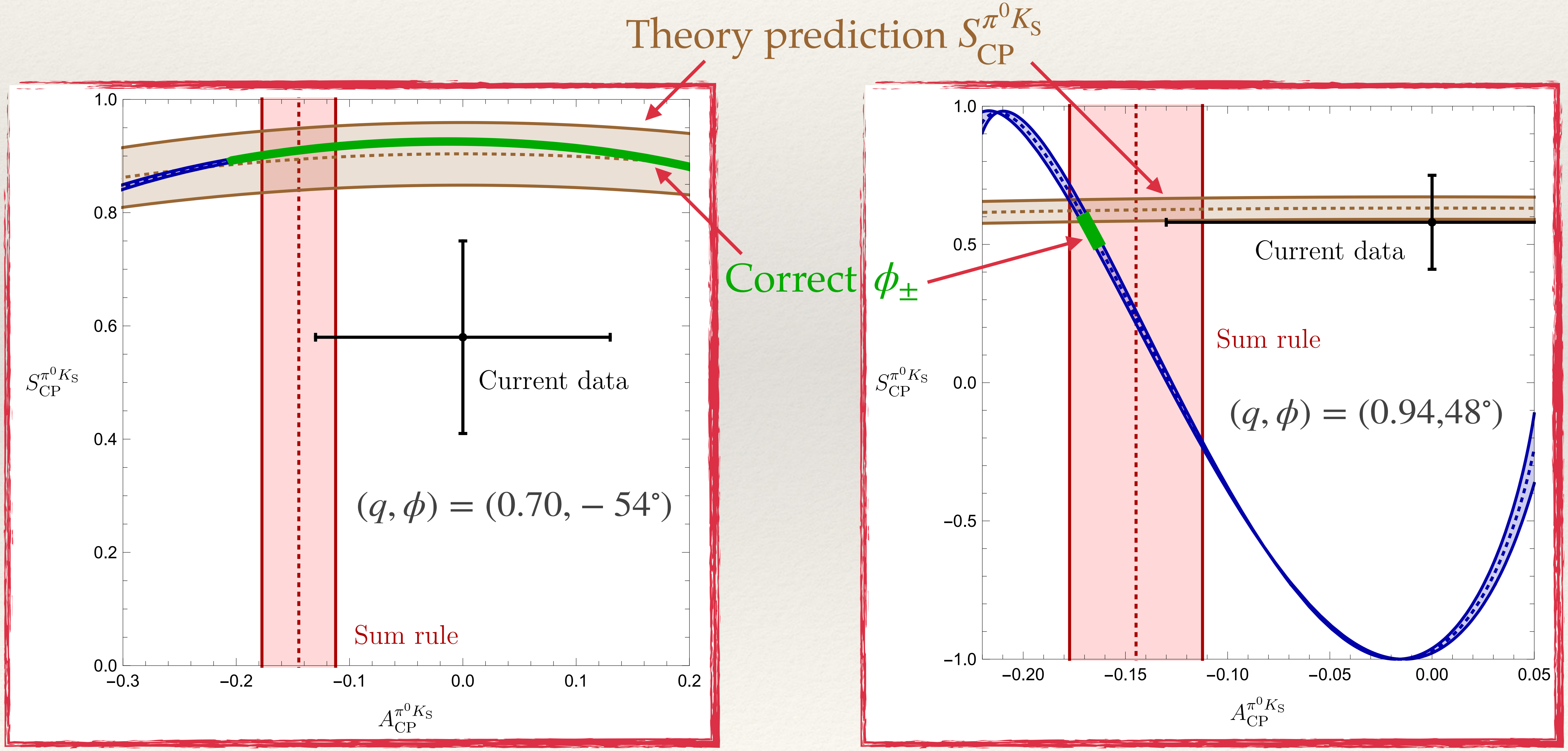
- Precision depends on region in parameter space
- **Potential for discovery of NP with future data!**





Resolution of $B \to \pi K$ puzzle

- **Can we now resolve the $B \to \pi K$ puzzle?**
- Consider 2 scenarios:



Conclusions

- Data from $B \to \pi K$ decays have shown puzzling patterns in the past
- We have performed a state-of-the-art analysis:

Discrepancy became stronger ➜ something has to happen

- Data move to eventually confirm the Standard Model?
- Is it New Physics?

- We have presented a new strategy to pin down the EWP parameters
- We look forward to data from Belle II and LHCb!

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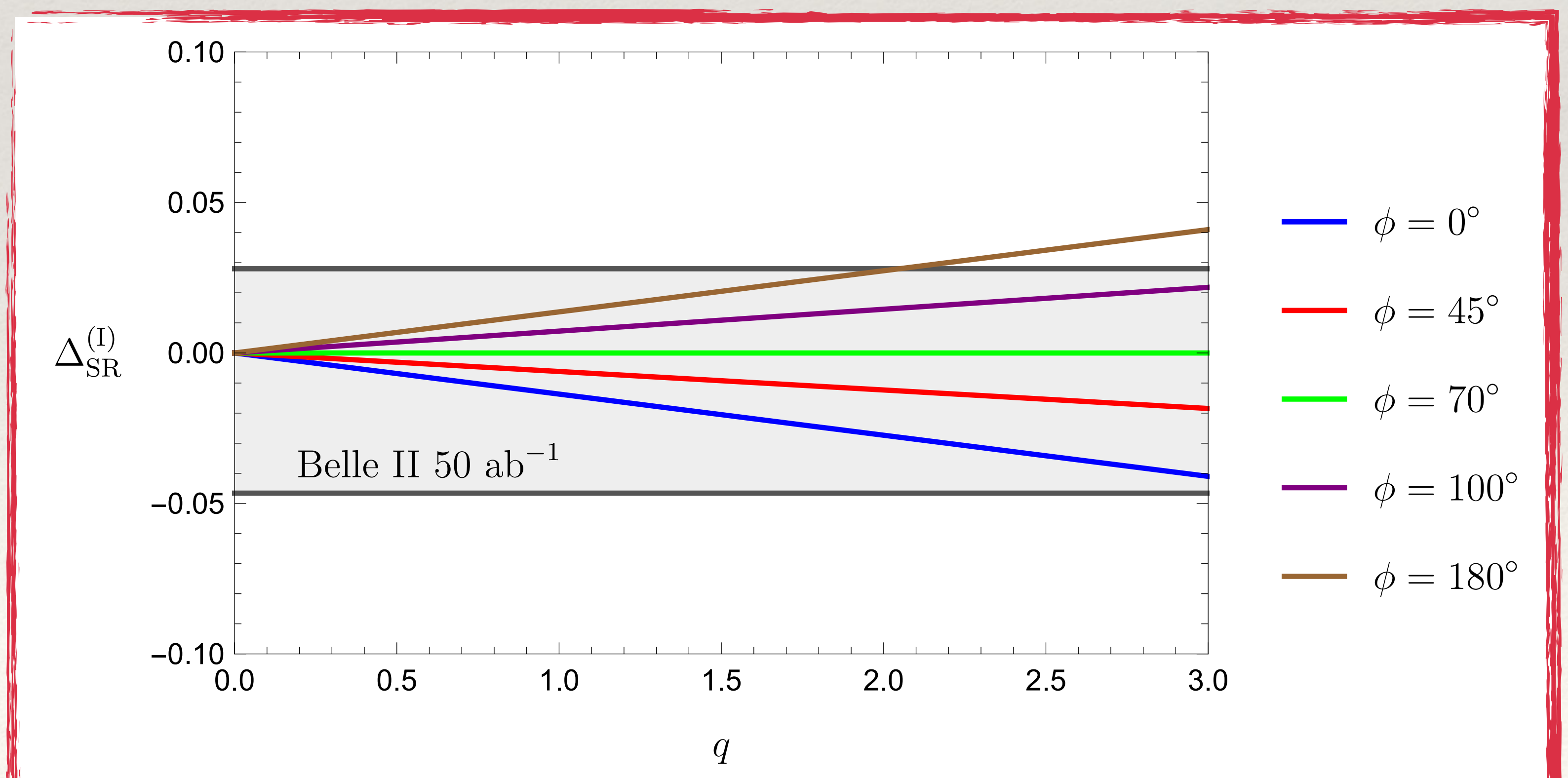
Backup slides

What about the sum rule?

- Belle II performed feasibility study of the sum rule [Belle-II Collaboration, arXiv:1011.0352]

$$\Delta_{\mathrm{SR}} \equiv \left[A_{\mathrm{CP}}^{\pi^+K^0} \frac{\mathcal{B}r(\pi^+K^0)}{\mathcal{B}r(\pi^-K^+)} - A_{\mathrm{CP}}^{\pi^0K^+} \frac{2\mathcal{B}r(\pi^0K^+)}{\mathcal{B}r(\pi^-K^+)} \right] \frac{\tau_{B_d}}{\tau_{B^\pm}} + A_{\mathrm{CP}}^{\pi^-K^+} - A_{\mathrm{CP}}^{\pi^0K^0} \frac{2\mathcal{B}r(\pi^0K^0)}{\mathcal{B}r(\pi^-K^+)} = 0 + \mathcal{O}(r_{(c)}^2)$$

- Could it reveal q and ϕ?



The resolution is not sufficient for $q < 3$

[R. Fleischer, RJ, E. Malami, K. K. Vos; to appear]

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Prediction for $\phi = 0$

- We can define

$$(\sin 2\beta)_{\pi^0 K_S} \equiv \frac{S_{CP}^{\pi^0 K_S}}{\sqrt{1-(A_{CP}^{\pi^0 K_S})^2}} = \sin(\phi_d - \phi_{00})$$

- In the SM we have $\phi = 0$, yielding

Only CS EWPs in
higher-order corrections

$$\tan\phi_{00} = 2\,(r\cos\delta - r_c\cos\delta_c)\sin\gamma + \mathcal{O}(r_{(c)}^2)$$

- From the $B \to \pi\pi$ data we then find

$$(\sin 2\beta)_{\pi^0 K_S} = 0.80 \pm 0.06$$

Includes 20% $SU(3)$-breaking
and higher-order corrections

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