RH Currents, CP Violation, and LR Symmetry in Rare B Decays

Alex Kagan

University of Cincinnati

Outline

- New Physics with Opposite-Chirality Operators: Implications for CP Violation
  - Parity Symmetric: $SU(2)_L \times SU(2)_R \times U(1)_{B-L} \times P$
  - $P \times C$ Symmetric
  - Non-Parity Symmetric

- Sensitivity to RH Currents from $B \to VV$ Polarization

I. New Physics with ‘Opposite Chirality’ Operators

Extensions of Standard Model (SM) often include opposite chirality operators related by Parity ($V - A \leftrightarrow V + A$), e.g.,

- QCD Penguin operators

$$\begin{array}{ll} \underline{\text{SM Chirality}} & \underline{\text{Opposite Chirality}} \\ Q_{3,5} = (\bar{s}b)_{V-A}\,(\bar{q}q)_{V\mp A} & \to \tilde{Q}_{3,5} = (\bar{s}b)_{V+A}\,(\bar{q}q)_{V\pm A} \\ Q_{4,6} = (\bar{s}_i b_j)_{V-A}\,(\bar{q}_j q_i)_{V\mp A} & \to \tilde{Q}_{4,6} = (\bar{s}_i b_j)_{V+A}\,(\bar{q}_j q_i)_{V\pm A} \\ Q_{4,6} = (\bar{s}_i b_j)_{V-A}\,(\bar{q}_j q_i)_{V\mp A} & \to \tilde{Q}_{4,6} = (\bar{s}_i b_j)_{V+A}\,(\bar{q}_j q_i)_{V\pm A} \end{array}$$

- Chromo/Electromagnetic Dipole Operators

$$\begin{array}{ll} Q_{7\gamma} = \frac{e}{8\pi^2} m_b \bar{s}_i \sigma^{\mu\nu}(1+\gamma_5) b_i F_{\mu\nu} & \to \tilde{Q}_{7\gamma} = \frac{e}{8\pi^2} m_b \bar{s}_i \sigma^{\mu\nu}(1-\gamma_5) b_i F_{\mu\nu} \\ Q_{8g} = \frac{g_s}{8\pi^2} m_b \bar{s} \sigma^{\mu\nu}(1+\gamma_5) t^a b G^a_{\mu\nu} & \to \tilde{Q}_{8g} = \bar{s} \sigma^{\mu\nu}(1-\gamma_5) t^a b G^a_{\mu\nu} \end{array}$$

SM vs. Opposite Chiralities and CP Violation

AK, SSI '02

- Under Parity, $Qi \leftrightarrow \tilde{Q}_i$. Therefore, for final state, f, with parity P_f

$$\langle f|Q_i|B\rangle = -(-)^{P_f}\langle f|\tilde{Q}_i|B\rangle$$

$$\Rightarrow A_i^{NP}(B \to f) \propto C_i^{\rm NP}(\mu_b) - (-)^{P_f}\tilde{C}_i^{\rm NP}(\mu_b)$$

Therefore,

$$\begin{aligned} A_i^{NP}(B \to PP) &\propto C_i^{\rm NP}(\mu_b) - \tilde{C}_i^{\rm NP}(\mu_b) \\ A_i^{NP}(B \to VP) &\propto C_i^{\rm NP}(\mu_b) + \tilde{C}_i^{\rm NP}(\mu_b) \end{aligned}$$

- For $B \to VV$, $\perp$ transversity is P-odd; $0, \parallel$ are P-even:

$$A_i^{NP}(B \to VV)_{0,\parallel} \propto C_i^{\rm NP}(\mu_b) - \tilde{C}_i^{\rm NP}(\mu_b)$$
$$A_i^{NP}(B \to VV)_{\perp} \propto C_i^{\rm NP}(\mu_b) + \tilde{C}_i^{\rm NP}(\mu_b)$$

- For $B \to VA$, where $A \equiv$ Axial Vector:

$$A_i^{NP}(B \to VA)_{0,\parallel} \propto C_i^{\rm NP}(\mu_b) + \tilde{C}_i^{\rm NP}(\mu_b)$$
$$A_i^{NP}(B \to VA)_{\perp} \propto C_i^{\rm NP}(\mu_b) - \tilde{C}_i^{\rm NP}(\mu_b)$$

Null CP Asymmetry Predictions in the SM

- Exploit large set of penguin-dominated modes with null rate or time-dependent CP asymmetry predictions in SM:

$$A_{CP}(f) \sim 1\%, \quad \text{or} \quad |\sin 2\beta + (-)^{CP} S_f| \sim 1\%, \quad \text{e.g.,}$$

  - P-even: $A_{CP}(K^0\pi^\pm)$, $A_{CP}(\eta' K^\pm)$, $A_{CP}(\phi K^{*\pm})_{0,\|}$, $S_{\eta' K_s}$, $(S_{\phi K^{*0}})_{0,\|}$, $A_{CP}(K^{*0}\rho^\pm)_{0,\|}$, $A_{CP}(K_1\pi^\pm)$, $A_{CP}(K^0 a_1^\pm)$, $(S_{\phi K_1})_\perp$,...
  - P-odd: $A_{CP}(\phi K^\pm)$, $S_{\phi K_s}$, $A_{CP}(K^{*0}\pi^\pm)$, $A_{CP}(\phi K^{*\pm})_\perp$, $(S_{\phi K^{*0}})_\perp$, $(S_{\phi K_1})_{0,\|}$,...

- Modes with small SM asymmetries
  - $S_{K^+K^-K^0}$ (ϕ subtracted): approximately P-even, penguin-dominated BELLE hep-ex/0208030; Grossman, et al. hep-ph/0303171; Gronau, Rosner hep-ph/0304178
  - $S_{K_s\pi^0}$, $S_{f^0 K_s}$: P-even, penguin-dominated, color-suppressed tree. $SU(3)$ analysis $\Rightarrow |S_{K_s\pi^0} - \sin 2\beta| < 0.2$ Gronau, Grossman, Rosner hep-ph/0310020

A. Parity Symmetric New Physics

- If new physics (NP) is parity symmetric at the weak scale

$$C_i^{\rm NP}(\mu_W) = \tilde{C}_i^{\rm NP}(\mu_W) \quad \Rightarrow$$

  - Negligible impact for P-even final states $\Rightarrow$ null CP asymmetry predictions maintained
  - Substantial impact possible for P-odd final states $\Rightarrow$ large departures from null predictions

- For example, could have
  - significant deviations in $S_{\phi K_s}$, $A_{CP}(\phi K^\pm)$, $(S_{\phi K^{*0}})_\perp$, and
  - no deviations in $(S_{\phi K^{*0}})_{0,\parallel}$, $A_{CP}(\phi K^{*\pm})$, $A_{CP}(K^0\pi^\pm)$

Model-Building Considerations

- Parity symmetric new physics requires underlying symmetry $G \supset SU(2)_L \times SU(2)_R \times U(1)_{B-L} \times P$

- CP violation should be explicit: Spontaneous CP violation $\Rightarrow$ complex P violating VEVs which could feed into new loop contributions to Q_i, $\tilde{Q}_i$

  - e.g., for the dipole operators P invariance above the weak scale $\Rightarrow$

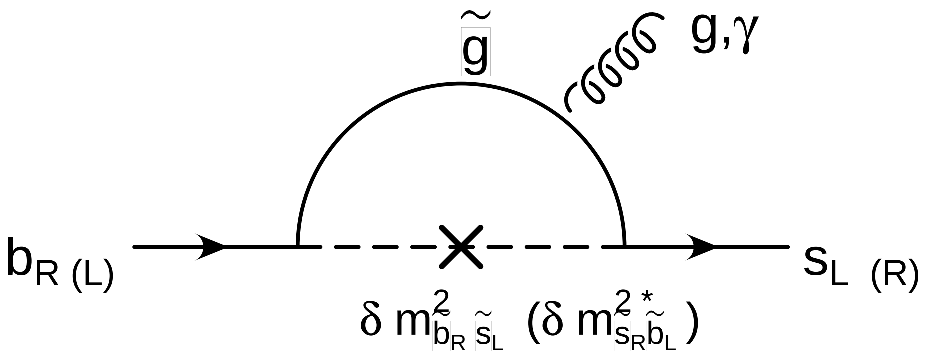
$$C_{8g}^{\rm NP} = k < \phi >, \quad \tilde{C}_{8g}^{\rm NP} = k < \phi^\dagger >,$$

    where $< \phi >$ breaks $SU(2)_L$, and $k \sim 1/M_{NP}^2$ is in general complex due to explicit CP violating phases.

  - Therefore, $C_{8g}^{\rm NP} = \tilde{C}_{8g}^{\rm NP} \Rightarrow < \phi > = < \phi^\dagger >$

Examples of New Physics

- squark-gluino loops in susy L-R symmetric models:



A parity-symmetric squark mass matrix near the weak scale would imply, e.g.,

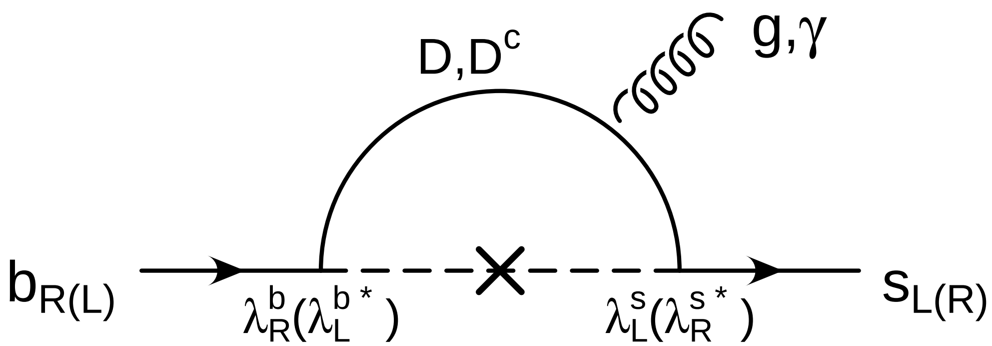
$$\delta m^2_{\tilde{b}_R \tilde{s}_L} = \delta m^{2*}_{\tilde{s}_R \tilde{b}_L}$$

and equal dipole operators, $C_{8g}^{NP} = \tilde{C}_{8g}^{NP}$,

$$\delta m^2_{\tilde{b}_L \tilde{s}_L} = \delta m^2_{\tilde{b}_R \tilde{s}_R}$$

and equal QCD penguin operators $C_{3,..,6}^{NP} = \tilde{C}_{3,..,6}^{NP}$.

- vectorlike quark - neutral scalar loops in susy L-R models:



  - $O(TeV)$ vectorlike isosinglet quarks D, D^c, and scalar $SU(2)_L$, $SU(2)_R$ doublets in loops.
  - parity-symmetric Yukawa couplings near the weak scale would imply

$$\lambda_L^b = \lambda_R^{b*}, \qquad \lambda_L^s = \lambda_R^{s*}$$

and equal dipole operators, $C_{8g}^{NP} = \tilde{C}_{8g}^{NP}$,
equal QCD penguin operators, $C_{3,..,6}^{NP} = \tilde{C}_{3,..,6}^{NP}$.

Survival of Parity-Symmetric effects at the Weak Scale

- $SU(2)_R \times U(1)_{B-L} \times P \to U(1)_Y$ symmetry breaking at M_R $\Rightarrow$ parity violating effects feed into low energy Lagrangian via renormalization group effects
- Sources of parity violation below M_R:
  - $\lambda^t \neq \lambda^b \Rightarrow$ charged Higgs couplings break parity
  - $SU(2)_L$, $U(1)_Y$ gauge loops
  - Small shifts in LH vs. RH squark masses due to D^2 terms

    Drees; Murayama et al.
- Two scenarios for Yukawa couplings:
  - moderate $\tan\beta$, or $\lambda^t >> \lambda^b$
  - Maximal-parity: $\lambda^b = \lambda^t + \mathcal{O}(V_{cb}), \quad \tan\beta \cong m_t/m_b$

    Equal up and down Yukawa matrices, up to small corrections to generate V_{CKM}, lighter quark masses

RGE Analysis

- Impose parity-symmetric boundary conditions at M_R.
- Parameters chosen to obtain

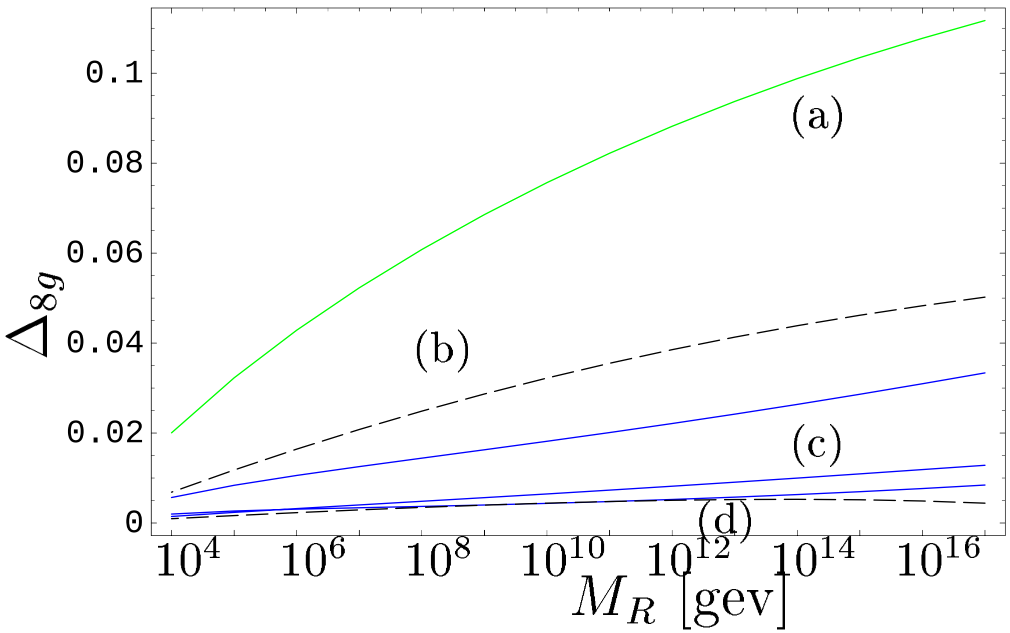
$$C_{8g}^{NP}(m_W) \approx .5e^{i60^\circ} \Rightarrow$$

  - $\mathcal{O}(1)$ $B \to \phi K_s$ amplitude with large weak phase
  - $S_{\phi K_s} < 0$ easily explained
- Evolve parameters entering loop graphs from M_R to weak scale using 2-loop SUSY RGEs

Results for RGE Analysis

To quantify parity violation, evaluate

$$\Delta_{8g} \equiv \frac{|C_{8g}^{\rm NP}(m_W) - \tilde{C}_{8g}^{\rm NP}(m_W)|}{|C_{8g}^{\rm NP}(m_W) + \tilde{C}_{8g}^{\rm NP}(m_W)|}$$



(a) gluino-squark loop, $\tan\beta = 5$, (b) vectorlike quark loop, $\tan\beta = 5$

(c) gluino-squark, $\tan\beta \cong m_t/m_b$ (blue curves span D^2-term shifts)

(d) vectorlike quark, $tan\beta \cong m_t/m_b$

Implications

- Even if $M_R \leq M_{\mathrm{GUT}}$, new contributions to the low energy Lagrangian could respect parity to O(1%)

- Precision CP violation measurements which respect (violate) null SM predictions in P-even (P-odd) final states would be evidence for $SU(2)_L \times SU(2)_R \times U(1)_{B-L} \times P$ symmetry

- Sensitive to $M_R \leq M_{GUT}$

- Parity-symmetry $\Rightarrow$ neutron edm constraints trivially satisfied since new flavor-diagonal weak phases are highly-suppressed Mohapatra and collaborators

- ϵ'/ϵ constraints trivially satisfied since $K \to \pi\pi$ is a parity violating decay

B. L-R Models with $P \times C$ Symmetry

- CP symmetry implies phases must be spontaneous in origin, i.e., complex VEVs. For Q_{8g}, $\tilde{Q}_{8g}$ obtain

$$|C_{8g}^{\rm NP}| = |\tilde{C}_{8g}^{\rm NP}|, \quad {\rm Arg}[C_{8g}^{\rm NP}] = -{\rm Arg}[\tilde{C}_{8g}^{\rm NP}]$$

$\Rightarrow$ CP violation opposite to P-symmetric case

  - P-even final states: ${\rm Arg}[C_{8g}^{\rm NP} - \tilde{C}_{8g}^{\rm NP}] \sim O(1)$, CP violating amplitudes $\Rightarrow$ deviations from null predictions
  - P-odd final states: ${\rm Arg}[C_{8g}^{\rm NP} + \tilde{C}_{8g}^{\rm NP}] \approx 0$, CP conserving amplitudes $\Rightarrow$ no deviations from null predictions

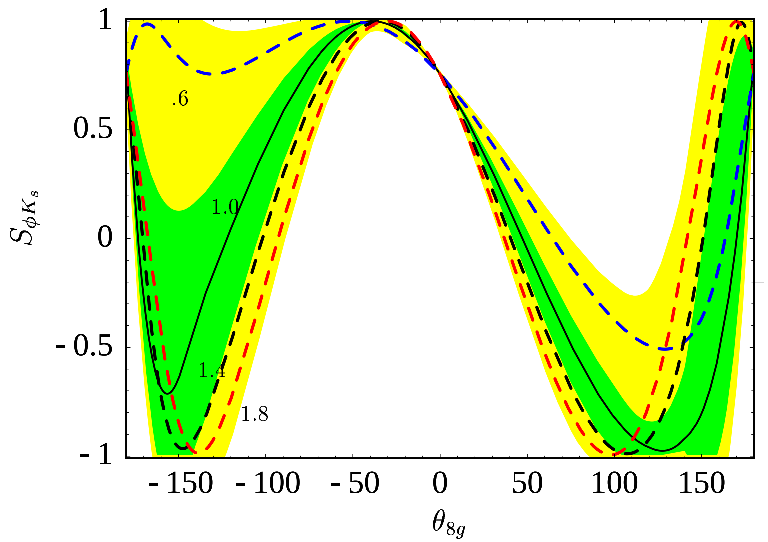
- Thus, even if $M_R \leq M_{\rm GUT}$, precision CP measurements could imply existence of

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

C. Opposite-Chirality Operators without Parity

- In previous two scenarios, unambigous theoretical interpretation of CP violation pattern possible, since P-odd, or P-even null predictions maintained
- If new contributions to Q_i, $\tilde{Q}_i$ unrelated, P-odd and P-even CP asymmetries could differ significantly from each other, and from null predictions, e.g.,
  - $S_{\phi K_s}$ and $S_{\eta' K_s}$ could be affected differently in the MSSM Khalil and Kou hep-ph/0303214; Chua, Hou, Nagashima hep-ph/0308298
- Example: Models with $O(1)$ contributions to $\tilde{Q}_i$, negligible contributions to Q_i. e.g., large $\tilde{s}_R - \tilde{b}_R$ mixing in MSSM Nir and Seiberg; Moroi; Chang, Masiero, Murayama; Harnek et al.; Chua et al., Everett et al., Kane et al.,
  R-parity violation Dutta, Kim, Oh; Datta

- Impact of NP on CP asymmetries has large theoretical uncertainties due to $1/m$ power corrections
  - QCD factorization example: $S_{\phi K_s}$ vs. θ_{8g} for $C_{8g}^{\rm NP} + \tilde{C}_{8g}^{\rm NP} = e^{i\theta_{8g}}$



Solid line: central values of inputs for $|C_{8g}^{\rm NP} + \tilde{C}_{8g}^{\rm NP}| = 1$.

Green band: uncertainty from their variation.

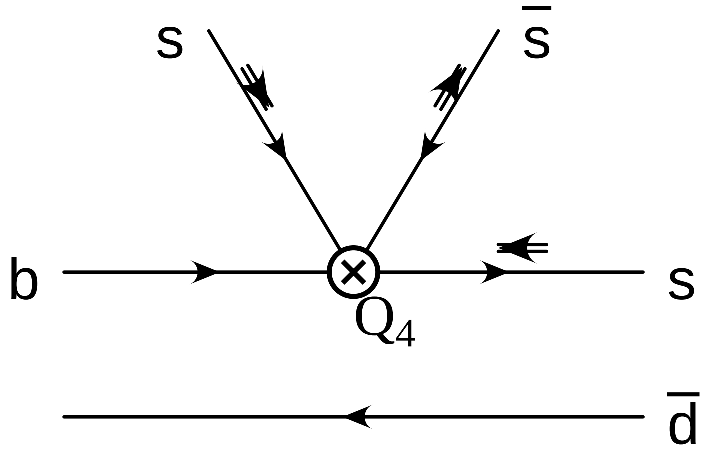
Yellow band: includes estimate of $1/m$ power correction uncertainties

Dashed curves: central values for $C_{8g}^{\rm NP} + \tilde{C}_{8g}^{\rm NP} = (.6, 1.4, 1.8)e^{i\theta_{8g}}$

- $1/m$ corrections depend on final state. Large uncertainties $\Rightarrow$ unlikely opposite-chirality operators can be inferred from CP violation measurements in general case of no parity

III. Polarization in $B \to VV$ Decays (light vectors)

- Consider SM ‘factorizable’ $\bar{B}^{0,-} \to \phi K^{*0,-}$ helicity amplitudes. ($A^{0,-,+} \equiv \phi,\ K^*$ have longitudinal, negative, positive helicities)



  - $A^-/A^0 = \mathcal{O}(m_\phi/m_B)$, helicity of $\bar{s}$ in ϕ flipped
  - $A^+/A^- = \mathcal{O}(m_K^*/m_B)$, helicity of s in K^* flipped
  - Helicity suppression follows formally from Large Energy Form Factor relations Charles et al.; Bauer et al.; Burdman, Hiller; Beneke, Feldman

Hierarchy of Transversity Rates in SM

- Transverse amplitudes in transversity basis:
  $A_{\perp,\|} = (A^- \pm A^+)/\sqrt{2}$
- Allowing for $\mathcal{O}(\Lambda_{QCD}/m_b)$ corrections to the (A_1/V) form factor relation, 'factorizable' SM amplitudes satisy

$$(\Gamma_\perp/\Gamma_\| - 1)/4 = \mathcal{O}(\Lambda_{QCD}/m_b)$$

- A^+/A^- power-counting preserved by 'non-factorizable' contributions in QCD factorization: annihilation graphs, hard spectator interactions, higher fock states
  - again due to required number of helicity-flips
  - helicity-suppression corresponds to twist expansion of meson distribution amplitudes

$\Rightarrow \Gamma_\perp/\Gamma_\| \gg 1$ would be a signal for new physics

- Formally, ($\Gamma_{\rm T}$ is total transverse rate, $\Gamma_\perp + \Gamma_\parallel$)

$$\Gamma_{\rm T}/\Gamma_0 = O(1/m^2)$$

  - Unfortunately, certain 'non-factorizable' graphs contribute to A^-, A^+ at same order in 1/m as 'factorizable contributions' with large uncertainties, although hierarchy between A^-, A^+ maintained
  - Γ_0 also suffers from large uncertainties, e.g., dependence on cancelations between form factors to $O(1/m)$

$\Rightarrow$ Above relation less reliable. Conservatively, need

$$\Gamma_T/\Gamma_0 = O(1)$$

to conclude there is new physics

Direct Signals for RH Currents

- $\Gamma_\perp/\Gamma_\parallel \gg 1$ and $\Gamma_T \sim \Gamma_0$ would be signals for $O(1)$ opposite-chirality operators
  - since $\tilde{Q}_i$ have inverted hierarchy, $A^+/A^- = \mathcal{O}(1/m)$
  - also seen from dependence on SM, NP Wilson coefficients:

$$A_{0,\parallel} \propto C_i^{\rm SM} + C_i^{\rm NP} - \tilde{C}_i^{\rm NP}, \qquad A_\perp \propto C_i^{\rm SM} + C_i^{\rm NP} + \tilde{C}_i^{\rm NP}$$

- The current experimental situation ($R_{0,\perp,\parallel} \equiv \Gamma_{0,\perp,\parallel}/\Gamma_{\rm total}$)

$$\begin{aligned} R_0(B^0 \to \phi K^{*0}) &= 0.58 \pm 0.10, \qquad R_0(B^+ \to \phi K^{*+}) = 0.46 \pm 0.12, \\ R_0(B^+ \to \rho^0 K^{*+}) &= 0.96 \pm 0.16, \\ R_0(B^+ \to \rho^+ \rho^0) &= 0.96 \pm 0.07, \qquad R_0(B^0 \to \rho^+ \rho^-) = 0.99 \pm 0.08. \end{aligned}$$

and

$$R_\perp(B^0 \to \phi K^{*0}) = 0.41 \pm 0.11, \qquad R_\parallel(B^0 \to \phi K^{*0}) = 0.01 \pm 0.15$$