CKM2010 6th International Workshop on the CKM Unitarity Triangle

# Theory of $b \to s/d\ \nu\nu$ decays

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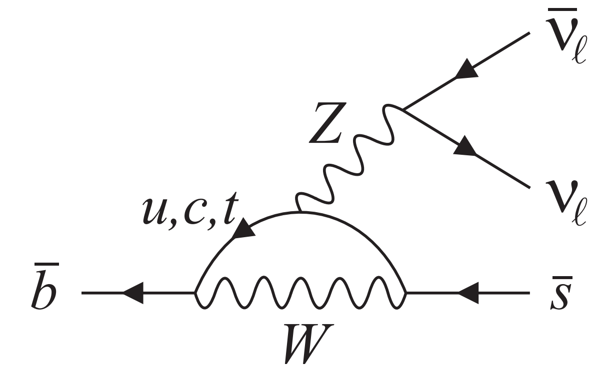
7/9/2010, Warwick

# Outline



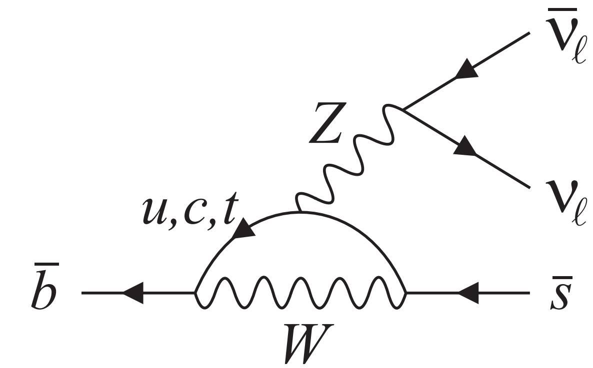

- b → s/d νν in the SM
  - Observables
  - Theory predictions
  - Prospects (given SuperB precision reach)

See later talk by Marco Ciuchini

- b → s/d νν beyond the SM
  - Sensitivity to NP
  - Interplay with other observables

See later talk by David Straub

# Motivation




- Why b → s/d νν ?

$$\mathcal{H}_{\rm eff} = -\frac{4\,G_F}{\sqrt{2}} V_{tb}V_{ts}^* \left(C_L^\nu \mathcal{O}_L^\nu + C_R^\nu \mathcal{O}_R^\nu\right) \ + \ \text{h.c.}$$

$$O_L^\nu = \frac{e^2}{16\pi^2}(\bar{s}\gamma_\mu P_L b)(\bar{\nu}\gamma^\mu(1-\gamma_5)\nu)\,, \quad O_R^\nu = \frac{e^2}{16\pi^2}(\bar{s}\gamma_\mu P_R b)(\bar{\nu}\gamma^\mu(1-\gamma_5)\nu)$$

- **In SM:** Z-penguin observable
  - Leading short distance contribution known to ~1%: $(C_L^\nu)^{\rm SM} = -6.33 \pm 0.06$

    Brod et al., 1009.0947
  - Absence of photonic penguin operator which dominates B → $X_s \ell^+\ell^-$ at low $q^2$
- **Beyond SM:** b → s/d $E_{miss}$ experimental signature allows to probe new light SM singlet particles

# Observables: Inclusive B → $X_{s,d}$ νν

- Theoretically cleanest (HQE & OPE)

$$\frac{d\Gamma(B \to X_s \nu\bar{\nu})^{SM}}{d\hat{s}} = m_b^5 \frac{\alpha^2 G_F^2}{128\pi^5} |V_{ts}^* V_{tb}|^2 \kappa(0) |C_L^{SM}|^2 \mathcal{S}(\hat{m}_s, \hat{s})$$

  - QCD corrections to partonic rate known at NLO (17% reduction of Br)

    Y. Grossman et al., hep-ph/9510378.
    G. Buchalla al., hep-ph/9512380.
    C. Bobeth et al., hep-ph/0112305.

  - NLO ($1/m_b^2$) OPE contributions known at LO in QCD (3% reduction of Br)

    C. W. Bauer, et al., hep-ph/0408002.
    A. F. Falk,et al., hep-ph/9507284.

  - Residual perturbative & non-perturbative uncertainties estimated at 5%

    W. Altmannshofer et al., 0902.0160

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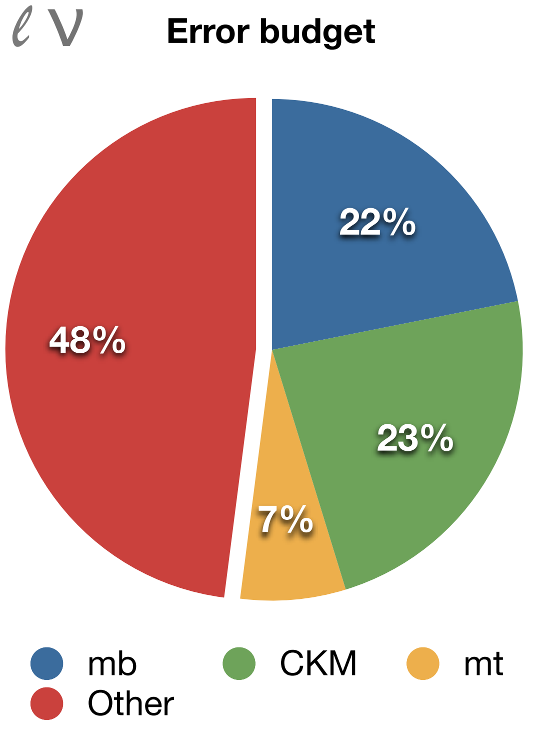
- $m_b^5$ parametric uncertainty traditionally reduced via B → $X_c$ ℓ ν - introduces phase-space dependence on $m_c$

  - recently suggested to use 1S $m_b$ mass (and OPE parameters) directly - introduces ~3% uncertainty in Br

Altmannshofer et al., 0902.0160




- Additional parametric uncertainty due to CKM(~3% in Br)

using UTFit global fit output from 0908.3470

  - Leads to precise SM prediction: $\mathcal{B}(B^0 \to X_s \nu\bar{\nu})^{SM} = (2.8 \pm 0.2) \times 10^{-5}$*

*additional contributions in charged B modes

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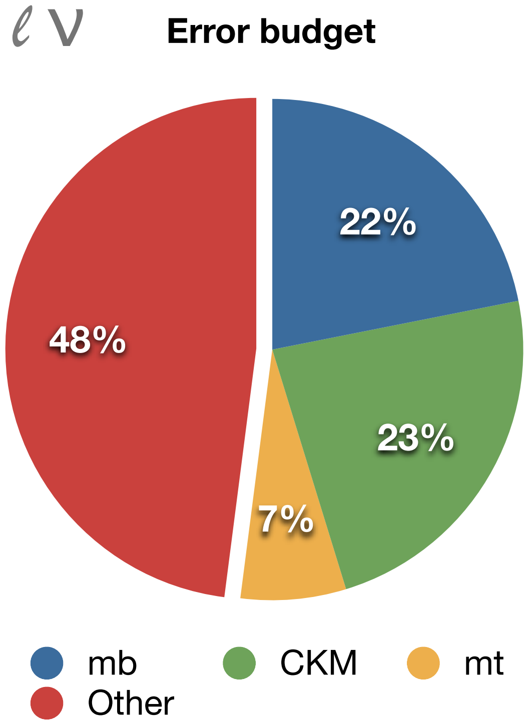


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Experimentally challenging

# Observables: Exclusive B → $K^{(*)}$ νν

- $B^+ \to K^+ \nu\nu$ presently provides most stringent bound on NP (x3 SM)
  - SuperB could reach 3σ with $10ab^{-1}$, while $50ab^{-1}$ needed for B → K* mode

SuperB progress reports: Physics 1008.1541

- K* final state offers additional observable
  - longitudinal/transverse polarization fractions $F_{L,T} = \frac{d\Gamma_{L,T}/ds_B}{d\Gamma/ds_B}$ , $F_L = 1 - F_T$
  - experimentally accessible through angular distribution of K* decay products

$$\frac{d^2\Gamma}{ds_B d\cos\theta} = \frac{3}{4}\frac{d\Gamma_T}{ds_B}\sin^2\theta + \frac{3}{2}\frac{d\Gamma_L}{ds_B}\cos^2\theta \ .$$

  - $F_L$ theoretically cleaner than total Br

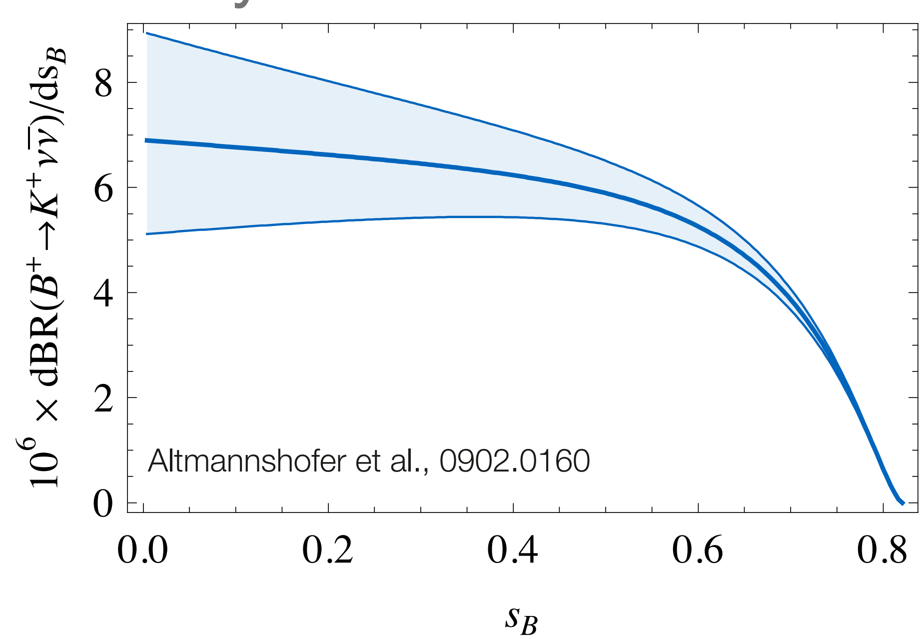
# Observables: Exclusive B → K$^{(*)}$ νν

$$\frac{d\Gamma(B\to K\nu\bar\nu)}{ds_B} = \frac{G_F^2\alpha^2}{256\pi^5}\left|V_{ts}^*V_{tb}\right|^2 m_B^5 \lambda^{3/2}(s_B,\widetilde m_K^2,1)\left[f_+^K(s_B)\right]^2\left|C_L^\nu + C_R^\nu\right|^2 \ .$$

- Main theoretical uncertainty due to normalization & shape of the relevant form factors
  - Most precise calculations based on QCD sum rule techniques

Ball & Zwicky, hep-ph/0406232, hep-ph/0412079

    - Normalization uncertainty estimated at ~14% in the Br.



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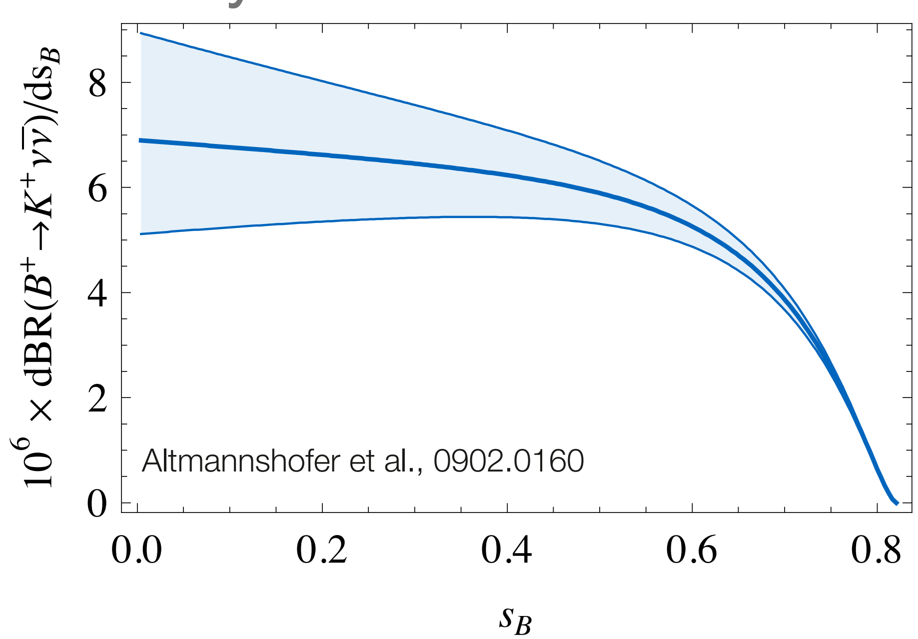
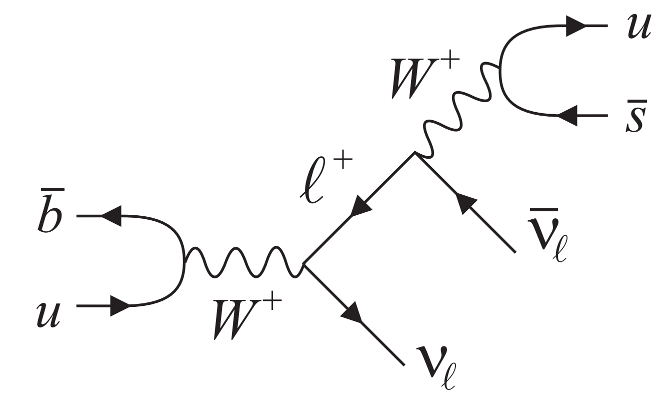
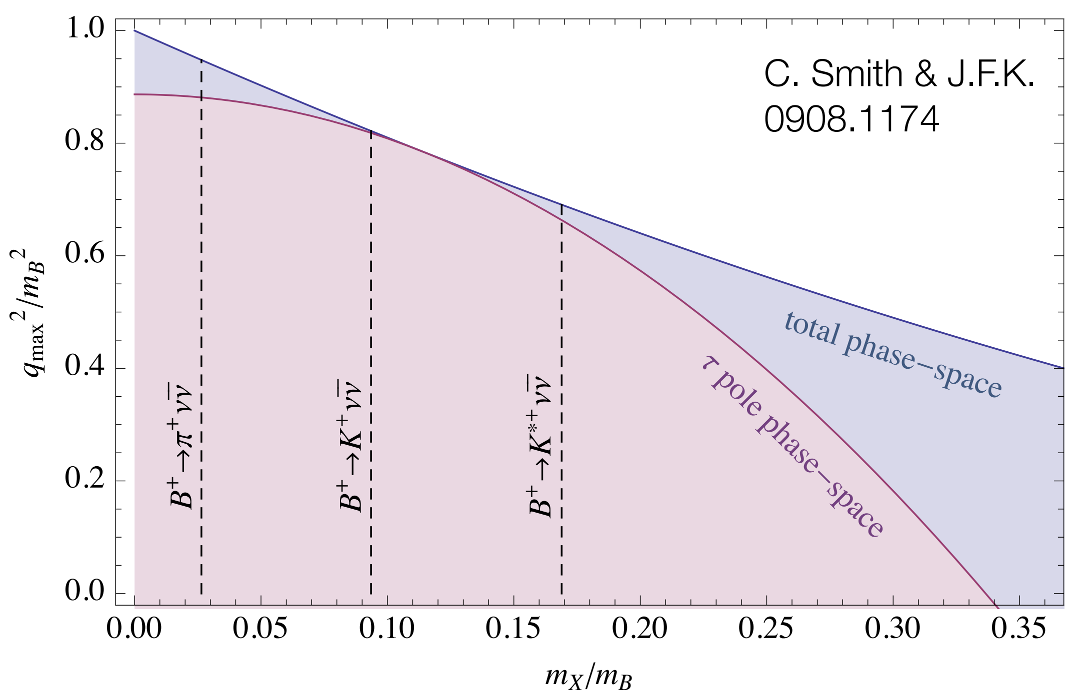



Completely dominates error budget

# LD contributions to $B^+ \to K^{(*)+} \nu\nu$




- Important background from $B^+ \to \tau^+ \nu$ with tau decaying into $K^{(*)+} \nu$




Formally of order $G_F^4$ - compensated by narrow width of intermediate tau lepton

Account for 98% in $B^+ \to \pi^+ \nu\nu$
12% in $B^+ \to K^+ \nu\nu$
14% in $B^+ \to K^{*+} \nu\nu$

(Also affects inclusive $B \to X_{s,d} \nu\nu$)

- can be measured and subtracted

$$\mathcal{B}(B^+ \to K^+ \nu\bar{\nu})^{LD} \propto \mathcal{B}(B^+ \to \tau^+ \nu) \times \mathcal{B}(\tau^+ \to K^+ \bar{\nu})$$

- or can be computed and added ($V_{ub}$, $f_{B,K}$)

- Presently, the associated uncertainty is ~3(4)% in $B^+ \to K^{(*)+} \nu\nu$

Using decay constant estimates from:
V. Lubicz and C. Tarantino, 0807.4605
P. Ball, et al., hep-ph/0612081.

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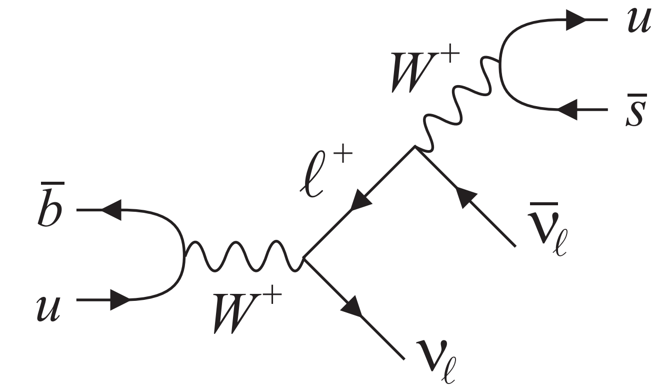


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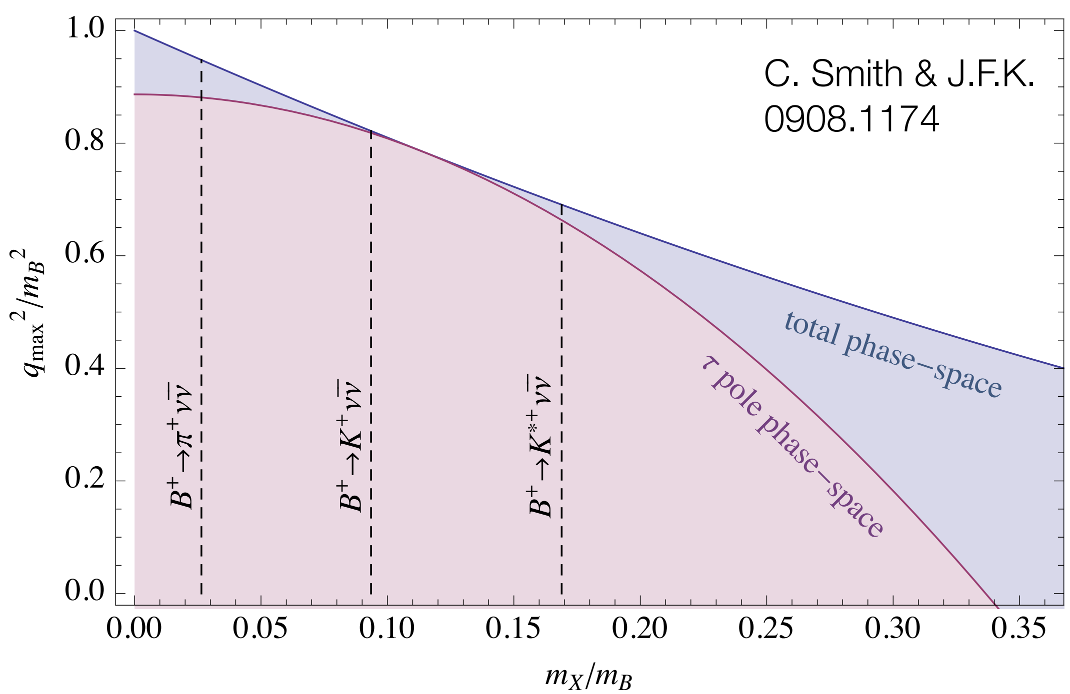


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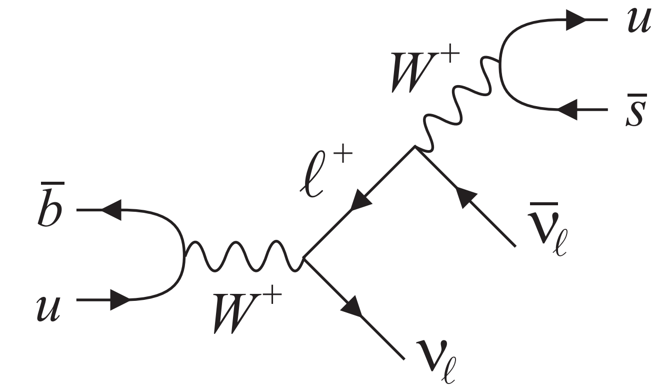
(Implications for leptonic B,D decays)

- $B^+ \to \pi^+ \nu\nu$ much worse - completely dominated by $B \to \tau^+ \nu$
    - need to measure $B^+ \to \tau^+ \nu$ and $\tau^+ \to \pi^+ \nu$ to better than 2% accuracy to have any sensitivity (or impose severe cut on $E_\pi$)!
- Possible to reduce form factor uncertainty via normalization to $B^+ \to \pi^+ l \nu$

# LD contributions to $B^+ \to K^{(*)+} \nu\nu$

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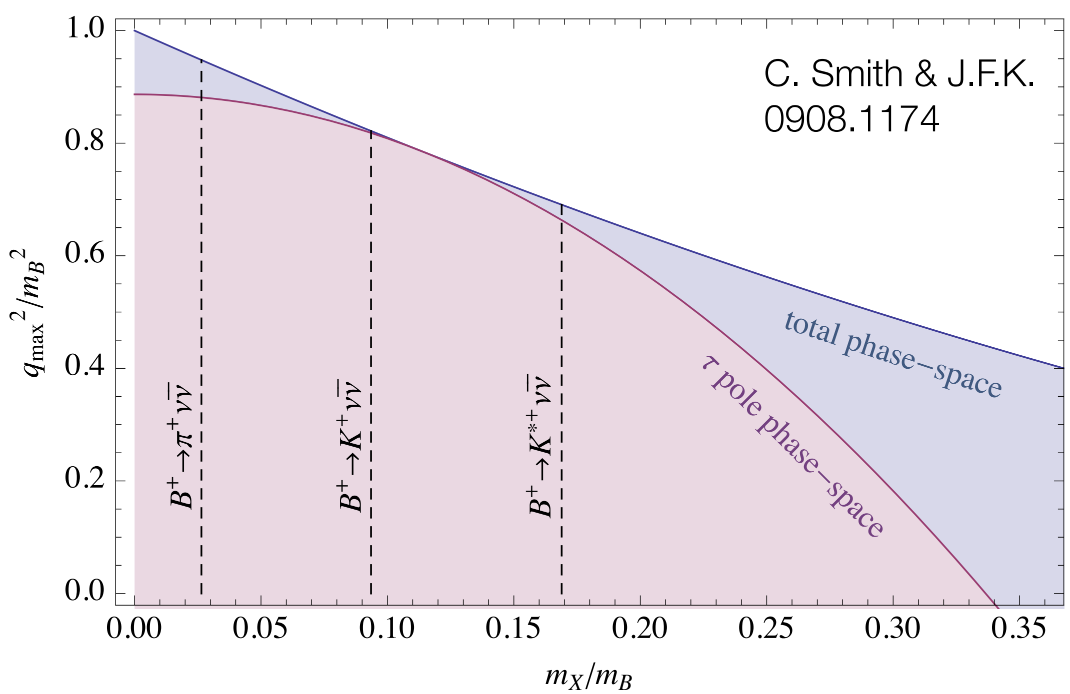


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(Implications for leptonic B,D decays)

- Resulting SM predictions (with τ contribution included in charged modes):

$$\mathcal{B}(B^+ \to K^+ \nu\bar{\nu})^{SM} = 5.1(0.8) \times 10^{-6}$$
$$\mathcal{B}(B^+ \to K^{*+} \nu\bar{\nu})^{SM} = 8.4(1.4) \times 10^{-6}$$
$$\mathcal{B}(B^0 \to K^{*0} \nu\bar{\nu})^{SM} = 6.8(1.1) \times 10^{-6}$$

C. Smith & J.F.K.
0908.1174

Altmannshofer et al.,
0902.0160

# Combining information on B→K $\ell^+\ell^-$ and B→K ν ν

M. Bartsch et al., 0909.1512

- In SM B→K $\ell^+\ell^-$ receives additional (photonic penguin) contributions

$$\frac{dB(\bar{B} \to \bar{K} l^+ l^-)}{ds} = \tau_B \frac{G_F^2 \alpha^2 m_B^5}{1536 \pi^5} |V_{ts} V_{tb}|^2 \, \lambda_K^{3/2}(s) f_+^2(s) \left( |a_9(Kll)|^2 + |a_{10}(Kll)|^2 \right)$$

  - new form factor ($f_T$) associated with $O_7$ operator matrix element
  - long distance ($u\bar{u}$, $c\bar{c}$ loop) resonance contributions to $a_9$
  - larger non-perturbative effects ($\Lambda/m_b$, $\Lambda^2/m_c^2$) M. Beneke, et al., hep- ph/0106067
    - WA contributions appear at LO in HQ expansion
- NP would affect both modes differently

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  - use HQ form factor relations (hold both in soft and hard kaon limits) to reduce $O_7$ operator contributions

also JFK, 0909.2755

$$\frac{f_T(s)}{f_+(s)} = \frac{m_B + m_K}{m_B} + \mathcal{O}(\alpha_s, \Lambda/m_b)$$

  - estimate power corrections, WA using QCD factorization at small s
  - cut away narrow Ψ(1S,2S) resonances, extrapolate non-resonant part
  - estimate higher (broad) resonance contributions using sum over few states

- Leads to SM prediction (‘non-resonant’): $\mathcal{B}(B^-\to K^-\ell^+\ell^-)^{SM} = 0.6(2)\times 10^{-6}$

# Combining information on B→K $\ell^+\ell^-$ and B→K ν ν

M. Bartsch et al., 0909.1512

- Next, define ratio of rates $R = \frac{B(B^- \to K^- \nu \bar{\nu})}{B(B^- \to K^- l^+ l^-)}$
  - form factor uncertainties largely cancel in the ratio
  - (6%) uncertainty dominated by estimate of higher-order perturbative corrections
  - using experimental value for B(B→K $\ell^+\ell^-$) leads to precise SM prediction:

$$B(B^- \to K^- \nu \bar{\nu}) = R \cdot B(B^- \to K^- l^+ l^-)_{exp} = (3.64 \pm 0.47) \cdot 10^{-6} *$$

*assumes subtraction of LD tau contributions

# NP in b → s/d νν

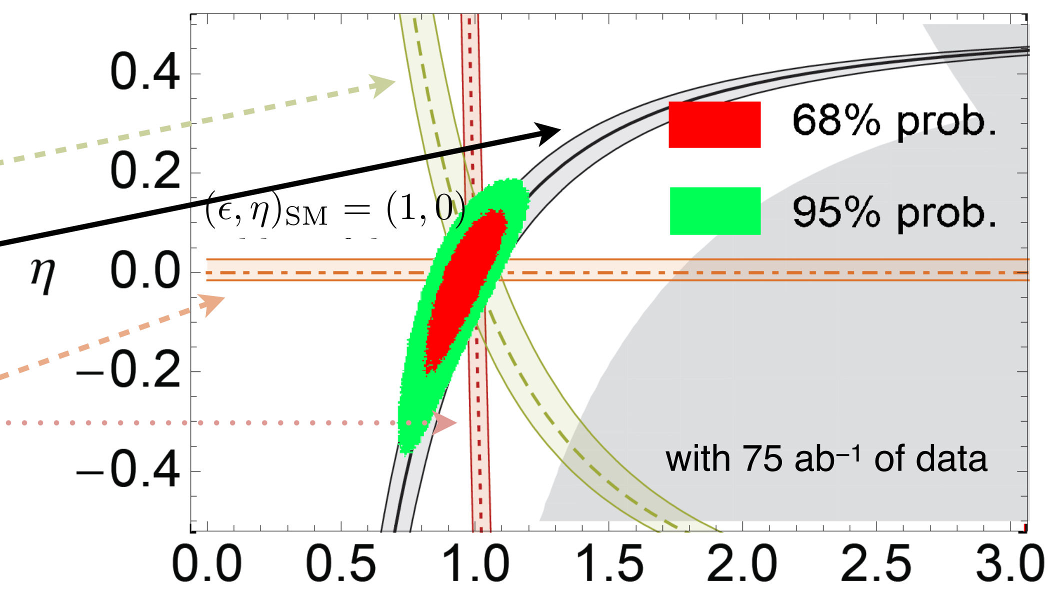
- Parametrize SM+NP in OPE: $\mathcal{H}_{\text{eff}} = -\frac{4\,G_F}{\sqrt{2}} V_{tb} V_{ts}^{*} \left( C_L^\nu \mathcal{O}_L^\nu + C_R^\nu \mathcal{O}_R^\nu \right) \;+\; \text{h.c.}$

- Only two independent combinations measurable with present observables

$$\epsilon = \frac{\sqrt{|C_L^\nu|^2 + |C_R^\nu|^2}}{|(C_L^\nu)^{\text{SM}}|}\,, \qquad \eta = \frac{-\text{Re}\,(C_L^\nu C_R^{\nu *})}{|C_L^\nu|^2 + |C_R^\nu|^2}$$

$$\begin{aligned} R(B \to K^* \nu\bar{\nu}) &= (1 + 1.31\,\eta)\epsilon^2, \\ R(B \to K \nu\bar{\nu}) &= (1 - 2\,\eta)\epsilon^2, \\ R(\bar{B} \to X_s \nu\bar{\nu}) &= (1 + 0.09\,\eta)\epsilon^2, \\ \langle F_L \rangle / \langle F_L \rangle_{\text{SM}} &= \frac{(1 + 2\,\eta)}{(1 + 1.31\,\eta)}, \end{aligned}$$

$$R(X) = \mathcal{B}(X)/\mathcal{B}(X)_{\text{SM}}$$




M. Wick, 0911.0297

- important feature of $F_L$: only depends on η

  - Any deviation from SM would imply presence of right-handed currents

Altmannshofer et al., 0902.0160

# NP in b → s/d νν

G. D'Ambrosio et al., hep-ph/0207036

Chivukula & Georgi, Phys. Lett. B 188, 99

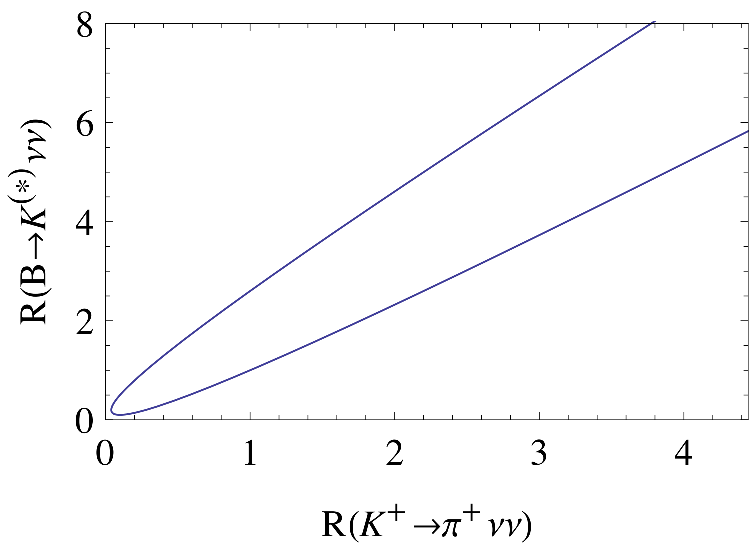
- Most conservative NP scenario: Minimal Flavor Violation

A. J. Buras, et al., hep-ph/0007085

- Only significant modifications of $C_L$, universal in b → s/d νν modes

Buras & Fleischer, hep-ph/0104238

- Correlations with s → d νν*:




  - existing measurement of $K^+ \to \pi^+ \nu\nu$ constrains $B \to K^{(*)} \nu\nu$ modes to be smaller than ~ SM x 8

Hurth, Isidori, JFK & Mescia, 0807.5039

Belle, 0707.0138
BaBar, 0808.1338

  - conversely direct $B^+ \to K^+ \nu\nu$ bound already more constraining!

*In models where bottom yukawa effects can be neglected

# NP in b → s/d νν

Y. Grossman et al., Nucl. Phys. B465, 369.

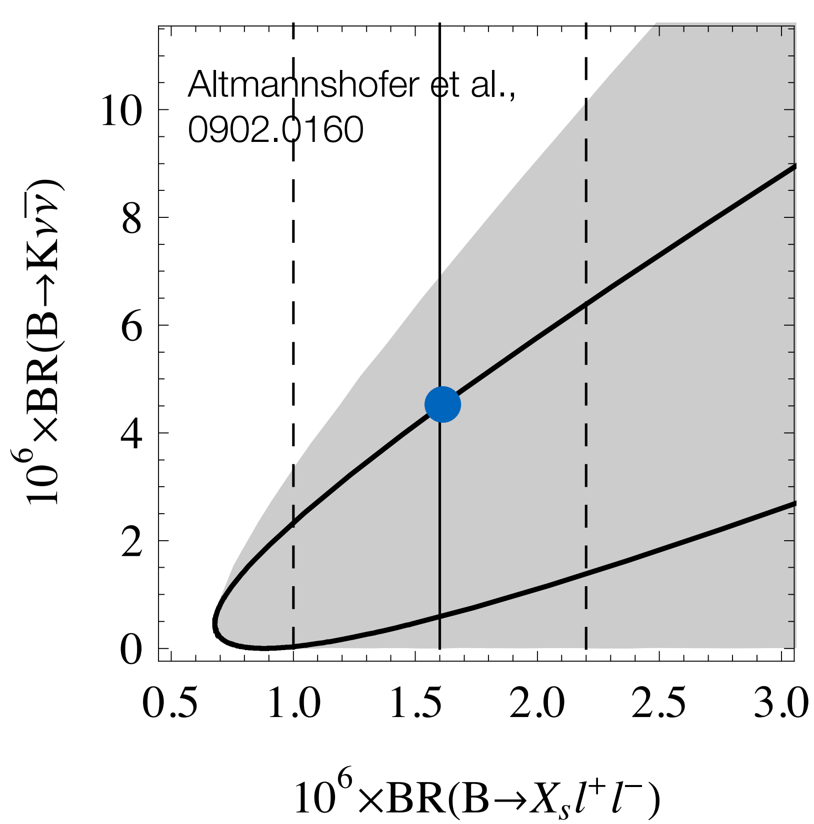
- Parameterize dominance of Z penguin via modified bsZ coupling

C. Bird, et al., Phys. Rev. Lett. 93, 201803.

- Correlations (constraints) from other b observables ($B_s \to \ell^+\ell^-$, $B \to X_s\, \ell^+\ell^-$)

G. Buchalla, et al., hep-ph/0006136

- b → s/d νν cannot be enhanced more than ~ SM x 2*




*or other NP contributions need to compensate $B \to X_s\, \ell^+\ell^-$

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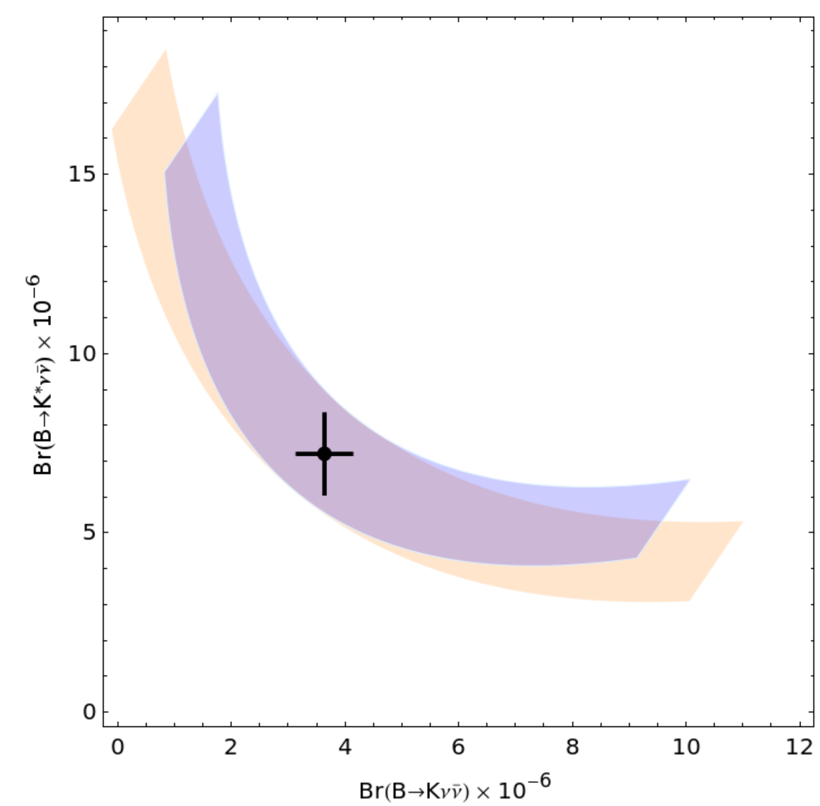
A. Buras et al., 1007.1993

- EFT Example: New right handed sources of flavor violation
  - particular modification of Z couplings

    (motivated by the resolution of the $S_{\psi\phi}$ puzzle)

  - correlations among b → s/d νν modes



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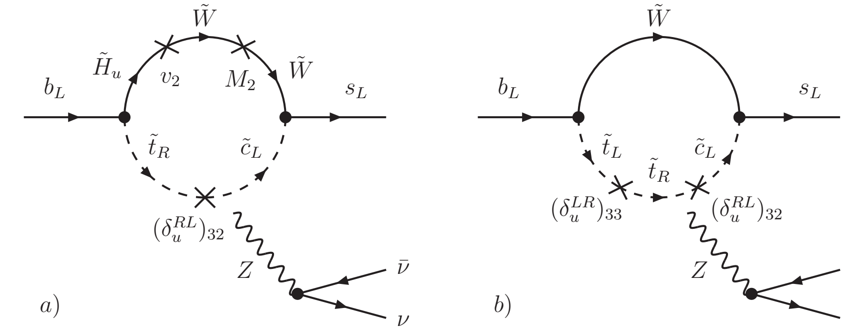



- In MSSM very constrained
    - gluino contributions constrained by B → $X_s$ γ
    - tanβ-enhanced Higgs contributions to $C_R$ constrained by $B_s \to \mu^+\mu^-$
    - up-squark - chargino loops ($\delta_{RL}^{32}$) can enhance/suppress Br ~ 35% (no effect in $F_L$)
- In RPV MSSM still room for large enhancements?

S. Bertolini, et al., Nucl. Phys. B353 (1991) 591–649.

T. Goto, et al., hep-ph/9609512

A. J. Buras, et al., hep-ph/0408142

Y. Yamada, 0709.1022

Isidori & Paradisi, hep-ph/0601094

Altmannshofer et al., 0902.0160

Kim, & Wang, 0904.0318

# NP in $b \to s/d\ E_{miss}$

- Neutrinos not detected in experiments probing $b \to s/d\ \nu\nu$
- Various NP contributions can mimic experimental signature

  very light scalar dark matter
  light neutralinos
  light NMSSM pseudoscalar Higgs
  light radions
  unparticles
  ...

C. Bird, et al., hep-ph/0401195.

R. Adhikari & B. Mukhopadhyaya, hep-ph/9411347.

H. K. Dreiner et al., 0905.2051.

G. Hiller, hep-ph/0404220.

H. Davoudiasl and E. Ponton, 0903.3410.

T. M. Aliev, et al., 0705.4542

- Failure of the individual constraints on the ε-η plane meeting at a single point
- Kinematical distributions modified - need to be taken into account when interpreting experimental searches
  - kinematical cuts to suppress backgrounds
  - reconstruction efficiencies depend on final state kaon/pion momenta

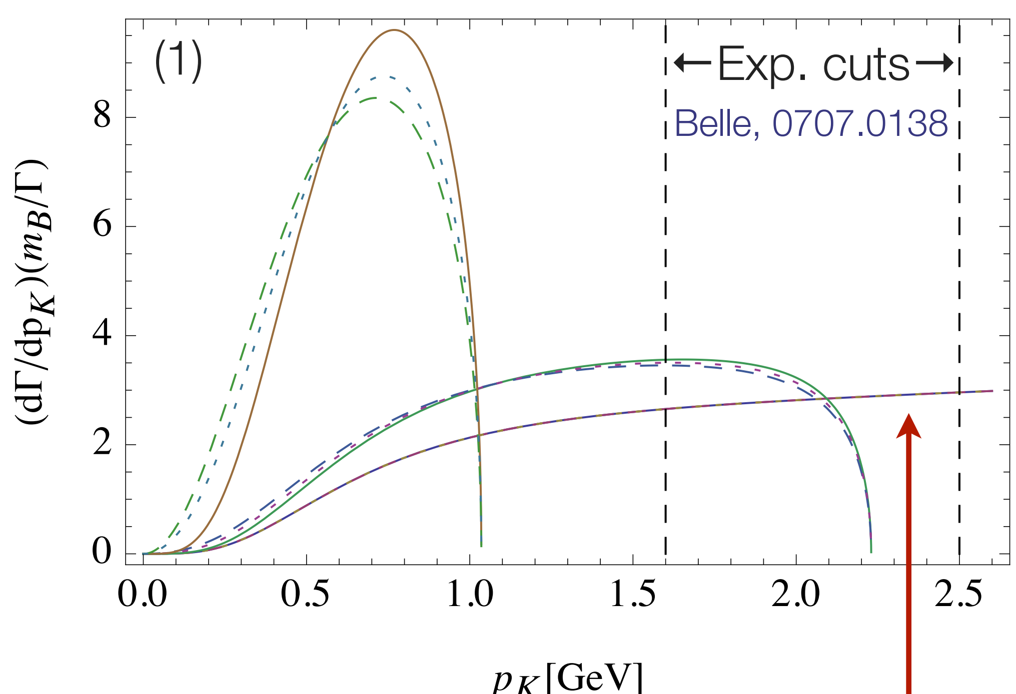
# NP in b → s/d $E_{miss}$

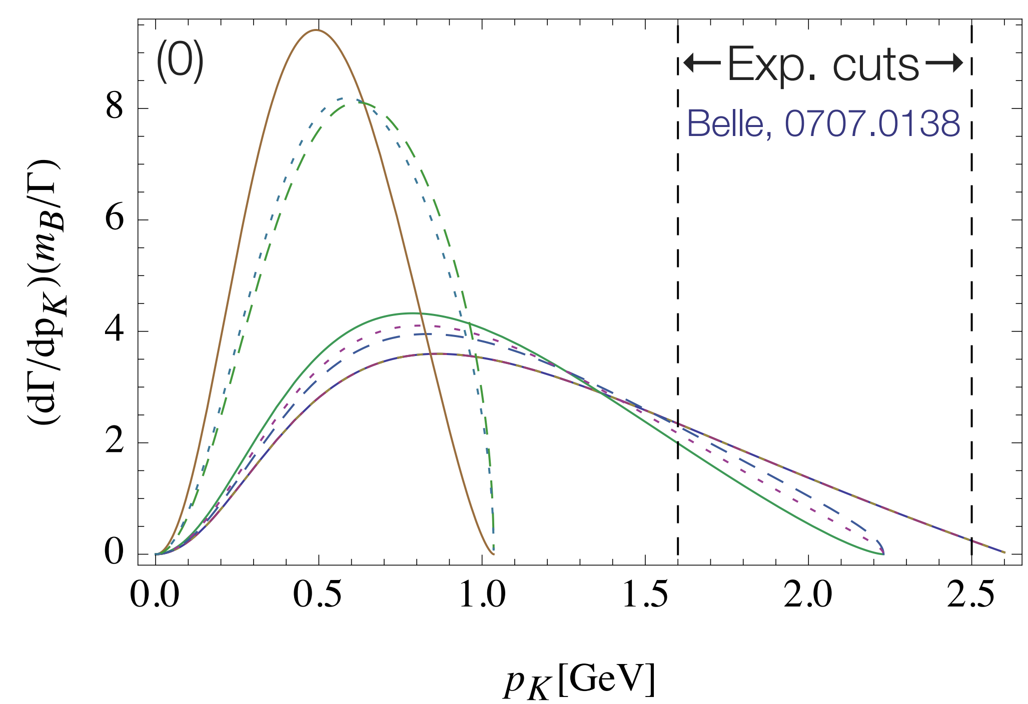
- Example: pair of invisible massive fermions in B→K $E_{miss}$

(1) $$\frac{c_{11}^{1/2}}{\Lambda^2}(\bar{Q}\gamma_\mu Q)(\bar{\psi}\gamma^\mu\psi) + \frac{\tilde{c}_{11}^{1/2}}{\Lambda^2}(\bar{Q}\gamma_\mu Q)(\bar{\psi}\gamma^\mu\gamma_5\psi) + \frac{c_{12}^{1/2}}{\Lambda^2}(\bar{D}\gamma_\mu D)(\bar{\psi}\gamma^\mu\psi) + \frac{\tilde{c}_{12}^{1/2}}{\Lambda^2}(\bar{D}\gamma_\mu D)(\bar{\psi}\gamma^\mu\gamma_5\psi)$$

(0) $$\frac{c_{01}^{1/2}}{\Lambda^3}H(\bar{D}Q)(\bar{\psi}\psi) + \frac{\tilde{c}_{01}^{1/2}}{\Lambda^3}H(\bar{D}Q)(\bar{\psi}\gamma_5\psi) + \frac{c_{02}^{1/2}}{\Lambda^3}H^\dagger(\bar{Q}D)(\bar{\psi}\psi) + \frac{\tilde{c}_{02}^{1/2}}{\Lambda^3}H^\dagger(\bar{Q}D)(\bar{\psi}\gamma_5\psi)$$

  - the resulting final state kaon momentum distributions will differ




axial, vector, chiral couplings
$m_\psi$=0, 1, 2 GeV

SM-like

similar conclusions for two scalars in
Altmannshofer et al., 0902.0160

# Summary

- $b \to s\, \nu\nu$ transitions interesting probes of NP

  (b → d νν with charged B's dominated by LD tau contributions)

  - theoretically clean study of non-standard Z penguin effects

- 4 experimentally accessible observables

  - Inclusive rate of $B \to X_{s,d}\, \nu\nu$ most theoretically clean

    (experimentally challenging)

  - Theory errors in exclusive rates dominated by form factor normalization

    - reduced in rate ratios: $F_L$, $R = \dfrac{B(B^- \to K^- \nu\bar{\nu})}{B(B^- \to K^- l^+ l^-)}$

# Summary

- $b \to s\,\nu\nu$ transitions interesting probes of NP
  - measurable NP effects in $b \to s/d\,\nu\nu$ can be parameterized in terms of two real parameters, $\varepsilon$ and $\eta$,
  - generally correlated with other observables

even in MFV, NP can still saturate present direct bounds

in more concrete scenarios much more constrained

- $b \to s/d\,E_{miss}$ can receive contributions from particles other than neutrinos in final state
  - strong modifications of the invariant mass spectra possible

nontrivial interpretation due to experimental cuts and
momentum-dependent kaon reconstruction efficiencies