Inclusive $\bar{B} \to X_s \nu\bar{\nu}$ Standard Model update

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In collaboration with

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TP1 Theoretical Particle Physics

CPPS Center for Particle Physics Siegen

Collaborative Research Center TRR 257

P³H

Particle Physics Phenomenology after the Higgs Discovery

Introduction

Scope of semileptonic FCNC decays:

- $\bar{B} \to X_s \nu\bar{\nu}$ — top loop dominated, very clean theoretically
- $\bar{B} \to X_s \ell^+\ell^-$ — complementary channel with LD effects and angular observables

Phenomenology of $b \to s\nu\bar{\nu}$ will be limited by experimental precision (Belle/II) for the forseeable future
The inclusive rate has x10 higher statistics of $B \to K$, may be possible to leverage against systematic effects

Outline: Refine SM prediction from 10+ years ago

$$\mathrm{Br}(\bar{B} \to X_s \nu\bar{\nu}) = (3.48 \pm 0.12) \times 10^{-5}$$ (this work, preliminary)

$$= (2.9 \pm 0.3) \times 10^{-5}$$ Buras, Noe, Niehoff, Straub [1409.4557]
Altmannshofer, Buras, Straub, Wick [0902.0160]

Various theoretical developments:

- Updated Wilson coefficients and QCD corrections in the heavy quark limit
- Heavy quark expansion including corrections up to $1/m_b^3$
- Analysis of the neutrino pair invariant mass spectrum
- Comparison with experimental prospects / thoughts on leveraging the M_X distribution

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Electroweak scale matching

Standard model matches to the $V - A$ operator only

$$\mathcal{L}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{ts}^* V_{tb} \left[C_\nu Q_\nu + \text{h.c.} \right] ,$$

$$C_\nu = \frac{\alpha(M_Z)}{2\sin^2\theta_W(M_Z)} X_t \,, \quad Q_\nu = \bar{b}_L \gamma_\mu s_L \sum_\nu \bar{\nu}_L \gamma^\mu \nu_L$$

At NLO QCD: Misiak, Urban [9901278] Buchalla, Buras [9901288] and NLO EW: Brod, Gorbahn, Stamou [1009.0947]

$$X_t = 1.462(9)_{\text{QCD}}(2)_{\text{EW}}(5)_{\text{par}} = 1.462(10) \quad \text{(this work)}$$

$$= 1.462(17) \quad \text{Brod, Gorbahn, Stamou [2105.02868]}$$

- We include higher order running of the top mass $\overline{m}_t(\mu)$
- Perturbative uncertainty will be be clarified when complete NNLO is available
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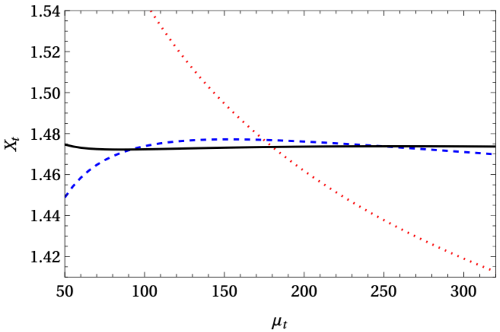
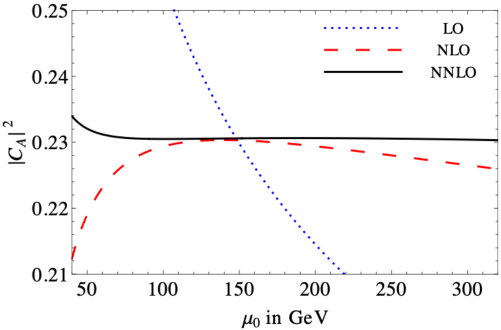
Matching details

$b \to s\nu\bar{\nu}$ **(V-A)** Preliminary, from E. Stamou's talk at Kaon25



$b \to s\mu^+\mu^-$ **(A)** Hermann, Misiak, Steinhauser [1311.1347]



The heavy quark masses are critical parametric inputs

$$\mathrm{Br}(\bar{B} \to X_s \nu\bar{\nu}) \sim (m_t^2)^2 (m_b^5)$$

Top quark mass

Top mass from direct determinations at the LHC

$$m_t^{\text{OS}} = 172.56(31)\ \text{GeV}$$
$$\implies \overline{m}_t(\overline{m}_t) = 162.98(30)_{\text{par}}(25)_{\text{had*}}\ \text{GeV}$$

Hadronic uncertainty from analysis of asymptotic series for m_t^{OS} in the $\overline{\mathrm{MS}}$ scheme at N4LO

Hoang, Lepenik, Preisser [1706.08526]
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*Errors should be combined linearly since the hadronic uncertainty has no statistical interpretation

Bottom quark mass

In principle one can take $\overline{m}_b(\overline{m}_b)$ from lattice QCD / spectroscopy and convert to kinetic scheme at N3LO

Fael, Schönwald, Steinhauser [2005.06487]

$$\overline{m}_b(\overline{m}_b) = 4.200(14)\ \text{GeV},\ N_f = 2+1+1$$
$$\implies m_b^{\text{kin}}(1\ \text{GeV}) = 4.562(18)\ \text{GeV}$$

In practice the kinetic mass determined in this way is treated as a prior entering in a fit to $\bar{B} \to X_c \ell\nu$ decay rate and distributions

$$\implies m_b^{\text{kin}}(1\ \text{GeV}) = 4.573(12)\ \text{GeV}$$

Finauri, Gambino [2310.20324]

Heavy quark masses

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Operator Product / Heavy Quark Expansion

Factorization of leptonic current and optical theorem:

$$\Gamma(\bar{B} \to X_s \nu \bar{\nu}) = \frac{1}{2M_B} \mathrm{Im}\left[i \int d^4x \, \langle \bar{B} | T\{\mathcal{L}^\dagger_{\text{eff}}(x) \mathcal{L}_{\text{eff}}(0)\} | \bar{B} \rangle \right]$$

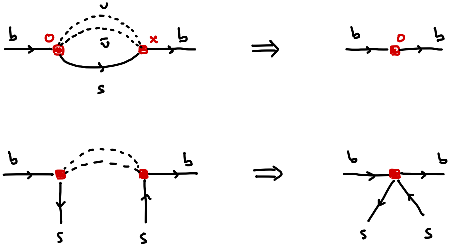
$$\frac{d\Gamma(\bar{B} \to X_s \nu \bar{\nu})}{dq^2} = \frac{1}{2M_B} \mathrm{Im}\left[i \int d^4x \, e^{iqx} \, \langle \bar{B} | T J^\dagger_\mu(x) J_\nu(0) | \bar{B} \rangle \right] L^{\mu\nu}$$

Operator product expansion of *QCD currents*

$J_\mu = \bar{b}_L \gamma_\mu s_L$

$$T J^\dagger_\mu(x) J^\mu(0) = \sum_k C_k(x) Q_k(0) \,,$$

$$Q_k = \{\bar{b}b, \bar{b}(iD)^2 b, \bar{b}\sigma^{\mu\nu}[iD_\mu, iD_\nu] b \ldots\}$$



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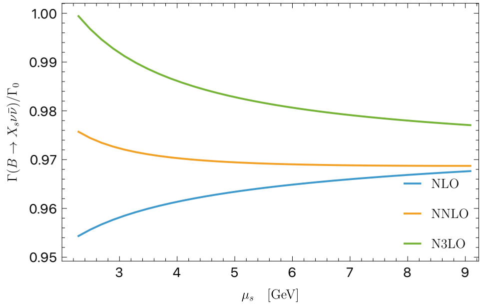

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$$\frac{\Gamma}{\Gamma_0} \simeq 1 - 0.0360_{\alpha_s} + (0.0216 - 0.00020_{n_c})_{\alpha_s^2} + 0.0237_{\alpha_s^3} - 0.0097_{\mu_i, \rho_i}$$

pQCD: Kinetic scheme optimized for $b \to c$ decays, some indication of a divergent series for $b \to u(s)$ at the percent level

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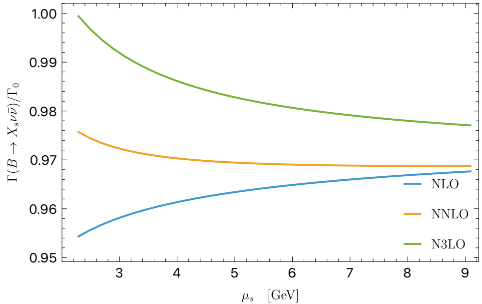

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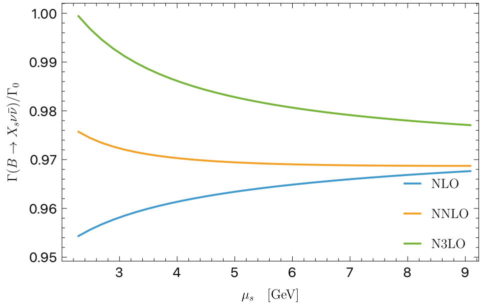

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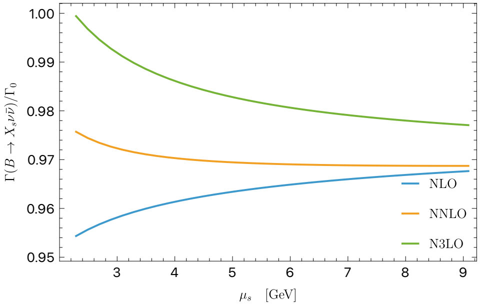

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Nonvalence weak annihilation

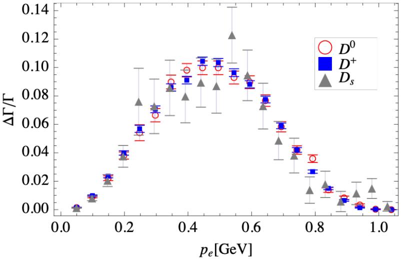
Weak annihilation is suppressed since the valence quark ($q = u, d$) is not involved in the weak transition

$$O_1 = 4(\bar{b}_v \gamma_\mu s_L)(\bar{s}_L \gamma^\mu b_v)\,, \quad O_2 = 4(\bar{b}_v s_L)(\bar{s}_L b_v)$$
$$\langle \bar{B}_q | O_2 - O_1 | \bar{B}_q \rangle = F_B^2 M_B (\tilde{\delta}_2 - \tilde{\delta}_1)$$

Four-quark operators mix with ρ_D at $O(\alpha_s^0)$. We identify the scale independent quantity at this order with input from HQET sum rules King, Lenz, Rauh [2112.03691]

$$\tau_0 = 8\rho_D \ln \frac{\mu^2}{m_b^2} + 16\pi^2 F_B^2 (\tilde{\delta}_2 - \tilde{\delta}_1)$$
$$= -3^{+1.4}_{-0.6}\,\mathrm{GeV}^3\,, \quad (\mu = 1.5\,\mathrm{GeV})$$

WA can be constrained by $\Delta\mathrm{Br}(D_{(s)} \to X_d \ell\nu)$ (exploiting HQ and $SU(3)$ flavor-symmetry)



Using $|V_{cb}|_{\text{inc}} = 41.97(48) \times 10^{-3}$ and including correlation with m_b (-0.428)

$$\text{Br}(B^+ \to X_s \nu\bar{\nu}) = 3.342(40)_{\mu_0}(40)_{\mu_b}(35)_{\mu_k}(27)_{\text{par}}(68)_{\text{HQE}}(58)_{\text{CKM}} \times 10^{-5}$$

$\hookrightarrow (76)_{\text{CKM}}$ *without accounting for correlations with HQE*

$$= 3.342(112) \times 10^{-5} \quad (3.4\%)$$

$$\text{Br}(\bar{B}^0 \to X_s \nu\bar{\nu}) = 3.609(121) \times 10^{-5}$$

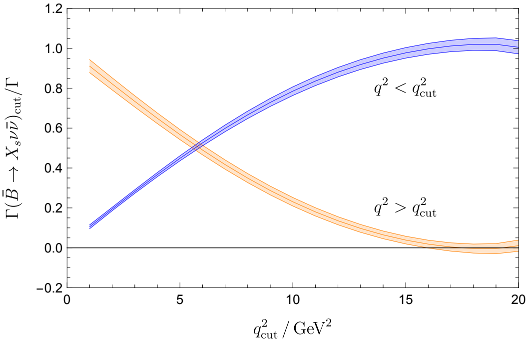
$$\text{Br}(\bar{B} \to X_s \nu\bar{\nu})_{\text{inc V}_{\text{cb}}} = (3.48 \pm 0.12) \times 10^{-5} \quad (3.4\%)$$

Using $|V_{cb}|_{\text{excl}} = 39.46(53) \times 10^{-3}$ (uncorrelated with m_b^5)

$$\text{Br}(\bar{B} \to X_s \nu\bar{\nu})_{\text{excl V}_{\text{cb}}} = (3.07 \pm 0.12) \times 10^{-5} \quad (4.0\%)$$

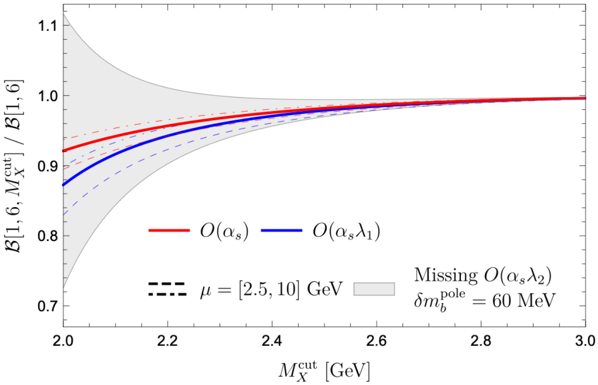
Missing mass distribution

- Similar precision is achieved for the decay rate with a cut $q^2 < q^2_{\text{max}}$
- The complementary cut $q^2 > q^2_{\text{min}}$ is divergent as q^2_{min} approaches the kinematical endpoint $\sim M_B^2$



- There is no photon pole at $q^2 = 0$, but the rate is still large at low q^2 due to phase space
- Point of discussion: what is the q^2-dependent sensitivity for $B \to X_s \nu\bar{\nu}$?

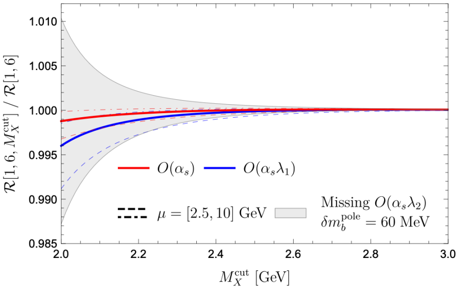
Perturbative tail

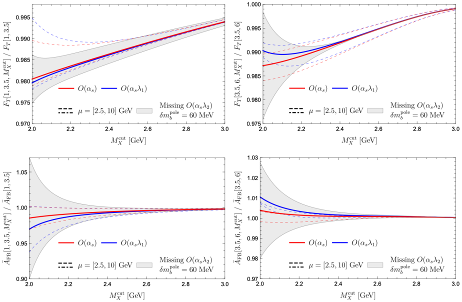


- Hadronic mass distribution can be studied in the OPE for $M_X \gtrsim \sqrt{\Lambda m_b}$
- The spectrum is known at partial α_s/m_b^2 including all penguin interference effects in $\bar{B} \to X_s\ell^+\ell^-$

  Huber, Hurth, JJ, Lunghi [2306.03134]
- $\bar{B} \to X_s\nu\bar{\nu}$ a small subset of the more general result
- Also possible to leverage measured $\bar{B} \to X_s\gamma$ spectrum and QCD factorization to study the shape function region $M_X \simeq \sqrt{\Lambda m_b}$

Hadronic mass distributions





Hadronic mass cut effects at low-q^2 should be suppressed by forming the ratio (also for the neutrino mode)

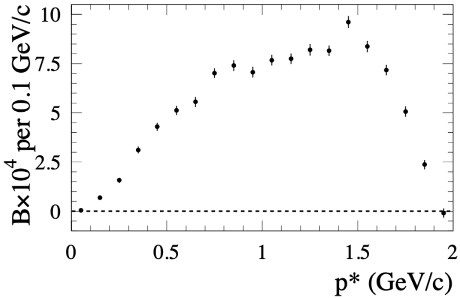
$$R = \mathrm{Br}(\bar{B} \to X_s \ell^+ \ell^-)/\mathrm{Br}(\bar{B} \to X_u \ell \nu)$$

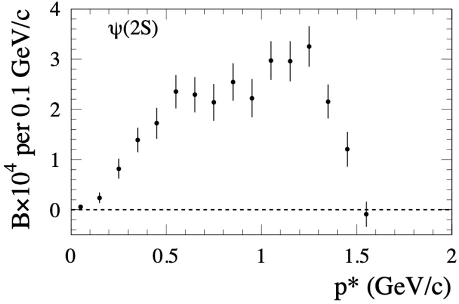
Similar suppression of M_X cut dependence for normalized angular observables A_{FB}, F_T

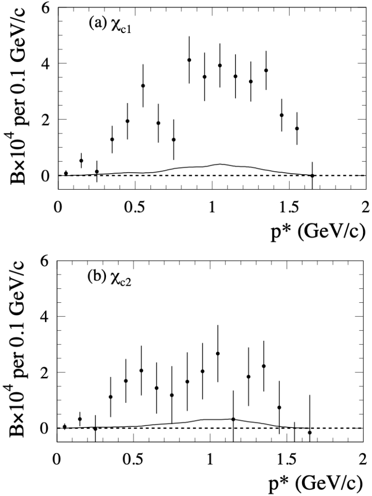
- BaBar measured the differential branching fractions of $B \to \{J/\psi, \psi', \chi_{c1}, \chi_{c2}\} X_s$ with feed-down to $\psi \to \ell^+\ell^-$ and hadronic tagging of the X_s system

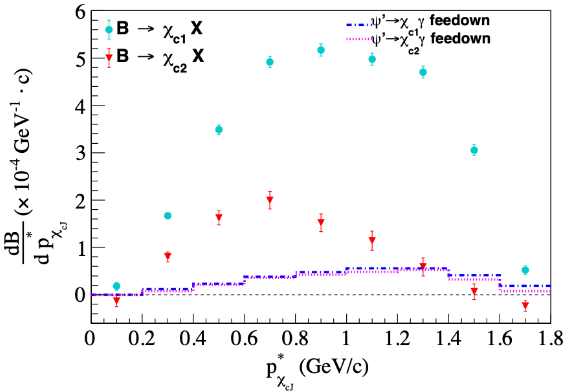
BaBar [0207097]

- The charmonium energy in the B frame is directly related to M_X since q^2 is fixed to a resonance, but results were presented in the laboratory frame (Could Belle/II improve on this?)









Belle [1512.02672]

Summary

- An update of $\mathrm{Br}(B \to X_s \nu\bar{\nu})$ in the Standard Model is timely on the theory side:
  - Leading power upgraded from NLO$\to$N3LO QCD ($\to$NNLO for spectrum)
  - Power corrections are much better known including now $1/m_b^3$
- Result for the total rate is larger and more precise than previous estimates
  Several sources of scale and parametric uncertainty at the 2-3% level remain
- $\sim 30\%$ of the spectrum survives a cut $q^2 < 4$ GeV^2, so it may be useful (with enough statistics) to measure the cut rate
- Predictions with cuts on M_X in principle do-able with larger uncertainties
- Measurements of inclusive charmonium production $B \to (c\bar{c})X_s$ may be useful to test/train hadronization models (important also for $\bar{B} \to X_s \ell^+ \ell^-$)