Electroweak Penguin B Decays with Missing Energy in the Standard Model

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$b \to s$ penguins

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no hadrons in the final state

(see e.g. Badin et al. 1005.1277; Bhattacharya et al. 1809.04606)

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add a spectator quark

- $B \to K\nu\bar{\nu}$, $B \to K^*\nu\bar{\nu}$, $B_s \to \phi\nu\bar{\nu}$, $\Lambda_b \to \Lambda\nu\bar{\nu}$
  $B \to X_s\nu\bar{\nu}$ (see talk by Jack Jenkins on Wednesday)
  SM branching ratios at the level of 10^{-6} to 10^{-5}.

Electroweak Penguin B Decays with Missing Energy

$b \to d$ penguins

pretty much the same story, but branching ratios are smaller by an order of magnitude $\sim |V_{td}|^2/|V_{ts}|^2$

no hadrons in the final state

(see e.g. Badin et al. 1005.1277; Bhattacharya et al. 1809.04606)

- $B^0 \to \nu\bar{\nu}$: helicity suppressed by the neutrino masses; negligible SM branching ratio $\sim 10^{-26}$.
- $B^0 \to \nu\bar{\nu}\nu\bar{\nu}$: not helicity suppressed, but higher order in G_F; much larger, but still negligible SM branching ratio $\sim 10^{-16}$.
- $B^0 \to \nu\bar{\nu}\gamma$: SM branching ratio is not crazy small $\sim 10^{-9}$

add a spectator quark

- $B \to \pi\nu\bar{\nu}$, $B \to \rho\nu\bar{\nu}$, $B_s \to K^{(*)}\nu\bar{\nu}$, $\Lambda_b \to n\nu\bar{\nu}$
  $B \to X_d\nu\bar{\nu}$
  SM branching ratios around 10^{-7}. (see talk by Hector Gisbert on Tuesday)

Introduction

“Fishing Expeditions”

Flavor in the Standard Model and Beyond

CC problem

Hierarchy problem

Vacuum stability?

Strong CP problem

$$\mathcal{L}_{\text{SM}} \sim \Lambda^4 + \Lambda^2 H^2 + \lambda H^4$$

$$+ \bar{\Psi} \not{D} \Psi + (D_\mu H)^2 + (F_{\mu\nu})^2 + F_{\mu\nu}\tilde{F}^{\mu\nu}$$

$$+ Y H \bar{\Psi} \Psi$$

SM flavor puzzle

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$$+ Y H \bar{\Psi}\Psi + \frac{1}{\Lambda}(LH)^2 + \frac{1}{\Lambda^2}\sum_i \mathcal{O}_i^{\rm dim6} + \ldots$$

SM flavor puzzle

Neutrino masses

Flavorful new physics?

Flavor in the Standard Model and Beyond

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SM flavor puzzle

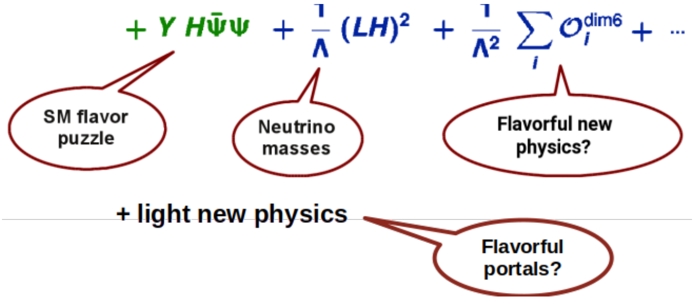
Neutrino masses

Flavorful new physics?

+ light new physics

Flavorful portals?

Two Basic Flavor Questions

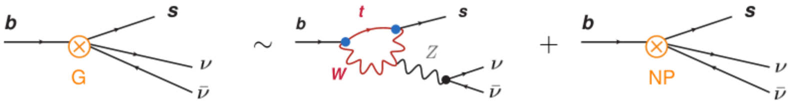


Q1: What is the origin of the hierarchical flavor structure of the SM?

(WA, Greljo 2412.04549, Annual Review of Nuclear and Particle Science Volume 75, 2025)

Q2: Are there new sources of flavor violation beyond the SM?

Example: heavy new physics in rare $b \to s\nu\bar{\nu}$ decays



$$G \sim \frac{1}{16\pi^2} \frac{g^4}{m_W^2} \frac{m_t^2}{m_W^2} V_{tb} V_{ts}^* + \frac{C_{\rm NP}}{\Lambda_{\rm NP}^2}$$

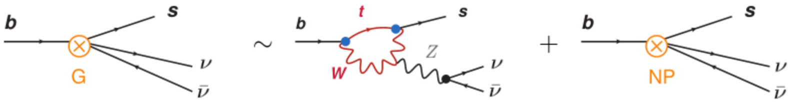
measure precisely

calculate precisely the SM contribution

get information on NP coupling and scale

Searching for New Physics with Flavor

Example: heavy new physics in rare $b \to s\nu\bar{\nu}$ decays



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measure precisely	calculate precisely the SM contribution	get information on NP coupling and scale

Mismatch between experiment and SM prediction
indicates new physics and provides a scale!

The Need for Precision

To maximize the sensitivity to new physics one needs

- precision measurements of flavor observables
- precision SM prediction of the observables

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precision SM predictions require

- high precision parametric input (in particular CKM)
- higher order perturbative calculations
- control over non-perturbative QCD uncertainties

The Weak Effective Hamiltonian

see e.g. Buras hep-ph/9806471 for a review

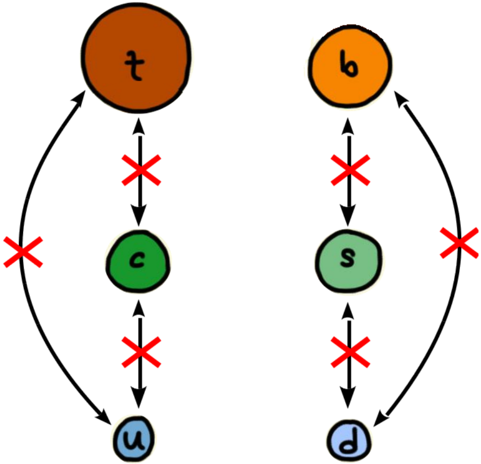
Starting point for many theory predictions is the
"weak effective Hamiltonian"

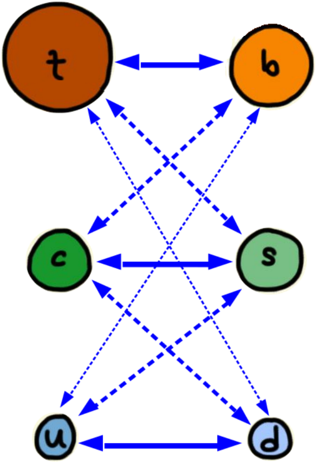
$$\langle f|\mathcal{H}_{\text{eff}}|i\rangle = \frac{4G_F}{\sqrt{2}} \sum_k \lambda_{\text{CKM}}^{(k)}\; C_k(\mu)\; \langle f|O_k(\mu)|i\rangle$$

- $\lambda_{\text{CKM}}^{(k)}$ = combination of CKM matrix elements relevant for a given flavor changing process
- $C_k(\mu)$ = Wilson coefficients that encode the short distance physics (the weak interactions in the SM)
- $\langle f|O_k(\mu)|i\rangle$ = matrix elements of operators made from light SM fields (light quarks, leptons, gluons, photon)
- Wilson coefficients and operator matrix elements depend on the renormalization scale μ

The CKM Matrix

no FCNCs at tree level





no FCNCs at tree level

transitions among the generations are mediated by the $W^\pm$ bosons and their relative strength is parametrized by the CKM matrix

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

CKM matrix is unitary and determined by 4 independent parameters

Parametrization of the CKM Matrix

Standard Parametrization: product of 3 rotation matrices

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

$$= \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$s_{ij} = \sin(\theta_{ij}),\ c_{ij} = \cos(\theta_{ij})$$

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$$= \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -s_{23}c_{12} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

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Parametrization of the CKM Matrix

Wolfenstein Parametrization: introduce the parameters λ, A, ρ, η

$$s_{12} = \lambda \quad , \quad s_{23} = A\lambda^2 \quad , \quad s_{13} e^{i\delta} = A\lambda^3(\rho + i\eta)$$

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measurements show that $\lambda \simeq 0.2 \ll 1$ is a good expansion parameter

$$V = \begin{pmatrix} 1 - \frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

Experimental Status of the CKM Matrix

global fits
of all data give
overall consistent
picture within
few % uncertainties

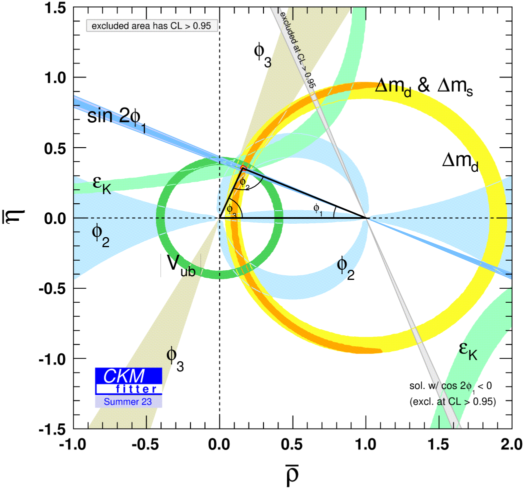
$$\lambda = 0.22498^{+0.00023}_{-0.00021}$$

$$A = 0.8215^{+0.0047}_{-0.0082}$$

$$\bar{\rho} = 0.1562^{+0.0112}_{-0.0040}$$

$$\bar{\eta} = 0.3551^{+0.0051}_{-0.0057}$$

http://ckmfitter.in2p3.fr/
http://www.utfit.org/



Alternative Approach

global CKM fits include many loop observables which
might be affected by new physics

to avoid potential new physics contamination as much as possible,
use 4 measurements based on tree level decays that are
unlikely affected by new physics

$$V_{us} = 0.22431 \pm 0.00085 \, , \quad V_{cb} = (41.1 \pm 1.2) \times 10^{-3}$$

$$V_{ub} = (3.82 \pm 0.20) \times 10^{-3} \, , \quad \gamma = (65.7 \pm 3.0)^\circ$$

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$$\begin{aligned} V_{ud} &\simeq 1 - \frac{\lambda^2}{2} \,, & V_{us} &\simeq \lambda \,, & V_{ub} &\simeq |V_{ub}| e^{-i\gamma} \,, \\ V_{cd} &\simeq -\lambda \,, & V_{cs} &\simeq 1 - \frac{\lambda^2}{2} \,, & V_{cb} &= |V_{cb}| \,, \\ V_{td} &\simeq |V_{cb}|\lambda - |V_{ub}| e^{i\gamma} \left(1 - \frac{\lambda^2}{2}\right) \,, & V_{ts} &\simeq -|V_{cb}| \left(1 - \frac{\lambda^2}{2}\right) - |V_{ub}|\lambda e^{i\gamma} \,, & V_{tb} &\simeq 1 \,, \end{aligned} \tag{9}$$

(see e.g. WA, Lewis 2112.03437; values above from PDG 2024)

[I prefer this approach; I think it is more transparent]

Problem: Which V_{cb} ?

- Longstanding $\sim 3\sigma$ discrepancy between exclusive and inclusive determinations of $|V_{cb}|$

$$|V_{cb}| = (42.2 \pm 0.5) \times 10^{-3} \quad \text{(inclusive)}$$
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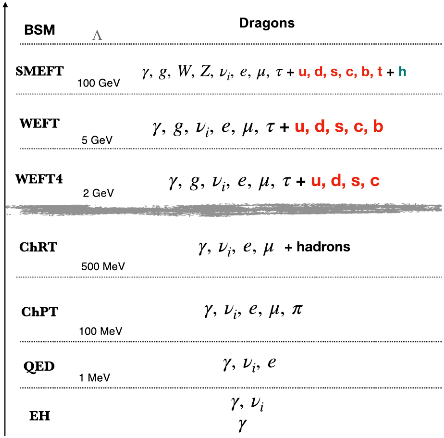
- The uncertainty on $|V_{cb}|$ is a limiting factor in the precision for several SM predictions of rare decays. (e.g. $B_s \to \mu^+\mu^-$, $B \to K\nu\bar{\nu}$, ...)

Effective Field Theories

- Flavor change comes from the weak scale $\mu_{\text{weak}} \sim 100$ GeV where we can perform perturbative calculations.
- But we observe flavor changing processes of hadrons at a low scale $\mu_{\text{had}} \sim 1$ GeV where QCD becomes non-perturbative.



Falkowski Eur.Phys.J.C 83 (2023) 7, 656

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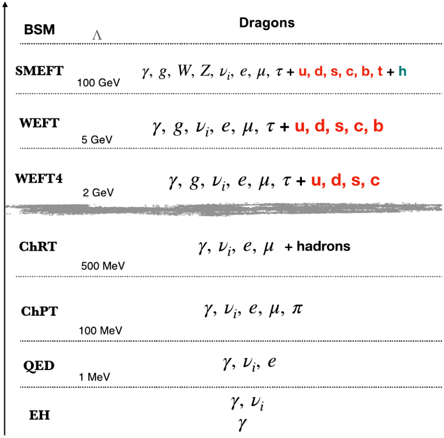
- It is very convenient to cleanly separate the relevant physics at these scales $\rightarrow$ EFTs



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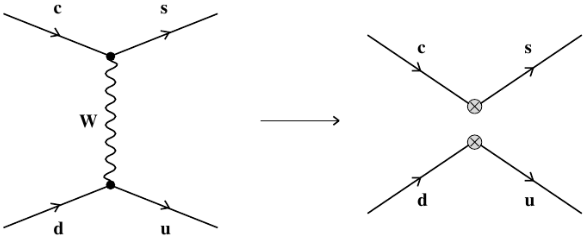
Matching at Tree-Level

Buras hep-ph/9806471

Let's consider the effective Hamiltonian relevant for the decay $c \to su\bar{d}$
(a simple example to illustrates basic features)

"Integrating out the W boson" at tree level gives one dim-6 operator and the corresponding Wilson coefficient



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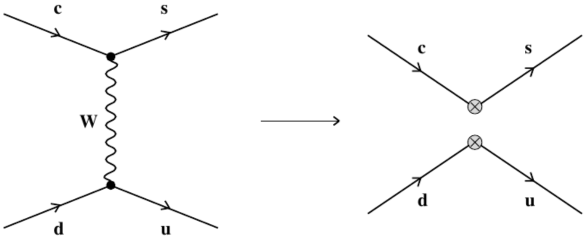
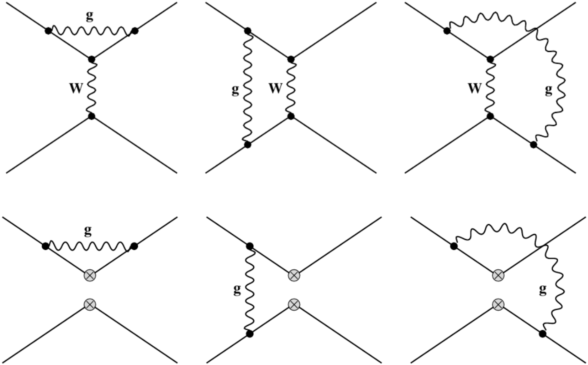


$$\mathcal{H}_{\rm eff} = \frac{4G_F}{\sqrt{2}} V_{cs}^* V_{ud} C_2 (\bar{s}\gamma_\mu P_L c)(\bar{u}\gamma^\mu P_L d)\ , \quad \text{with} \quad C_2 = 1$$

Including 1-Loop QCD corrections

Buras hep-ph/9806471

What happens if we include 1-loop QCD corrections?
(less relevant for $b \to s\nu\bar{\nu}$ because neutrinos don't talk to QCD)



Connecting the High and Low Scales

- Upshot: at higher order, the Wilson coefficients become explicitly renormalization scale dependent

$$\vec{C}(\mu) \cdot \langle f | \vec{O}(\mu) | i \rangle = \vec{C}(\mu_{\rm weak}) \cdot U(\mu_{\rm weak}, \mu_{\rm had}) \cdot \langle f | \vec{O}(\mu_{\rm had}) | i \rangle$$

- Determine Wilson coefficients by matching at the weak scale.
- Run to the low scale using Renormalization Group Equations. This resumms large logarithms $\log(\mu^2_{\rm weak}/\mu^2_{\rm had})$.
- Combine the Wilson coefficients with hadronic matrix elements evaluated at the hadronic scale.

Dealing with Non-Perturbative QCD

1) "Cheat": Focus on observables that are vanishingly small in the Standard Model (null tests)

   examples: $B_s \to \nu\bar{\nu}$, lepton flavor violation $B \to K\tau\mu$, ...

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2) "Ratios": Design observables where hadronic physics (approximately) drops out

   example: lepton flavor universality ratios

$$\frac{\text{BR}(B \to K\mu\mu)}{\text{BR}(B \to Kee)} , \quad \frac{\text{BR}(B \to D\tau\nu)}{\text{BR}(B \to D\ell\nu)} , \quad \frac{\text{BR}(\pi \to e\nu)}{\text{BR}(\pi \to \mu\nu)}$$

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3) Parameterize the hadronic matrix elements and determine them e.g. with lattice QCD or data driven methods

Parameterization of Hadronic Matrix Elements

examples of local matrix elements $\langle f|O(x)|i\rangle$

- decay constants

$$\langle 0|\bar{u}\gamma^\mu\gamma_5 b|B^+\rangle = if_B p_B^\mu$$

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- decay constants

$$\langle 0|\bar{u}\gamma^\mu\gamma_5 b|B^+\rangle = i f_B p_B^\mu$$

- transition form factors

$$\left\langle D\right| \bar{c}\gamma^\mu b \left|\bar{B}\right\rangle \equiv f_+(q^2)(p_B+p_D)^\mu + [f_0(q^2) - f_+(q^2)]\,\frac{m_B^2 - m_D^2}{q^2}\,q^\mu$$

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- “Bag parameters” for meson mixing

$$\langle \bar{B}^0|(\bar{d}\gamma^\mu P_L b)(\bar{d}\gamma_\mu P_L b)|B^0\rangle = \frac{4}{3}B_B m_B f_B^2$$

Summary of the Introduction

Generic structure of a flavor changing amplitude:

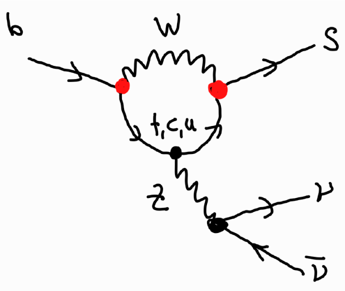
$$\langle f|\mathcal{H}_{\rm eff}|i\rangle = \frac{4G_F}{\sqrt{2}} \sum_k \lambda_{\rm CKM}^{(k)}\ C_k(\mu)\ \langle f|O_k(\mu)|i\rangle$$

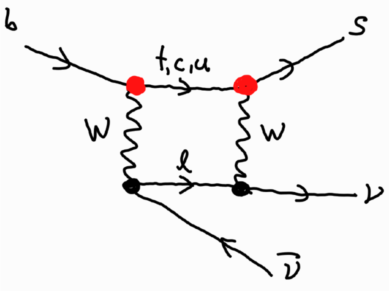
- CKM matrix elements (can be a limiting factor for precision)
- Wilson coefficients / short distance physics (in almost all cases under good perturbative control)
- hadronic matrix elements (can be a limiting factor for precision)

$b \to s\nu\bar{\nu}$

SM Diagrams for $b \to s\nu\bar{\nu}$

- Flavor changing neutral current process
- induced by Boxes and Z penguins





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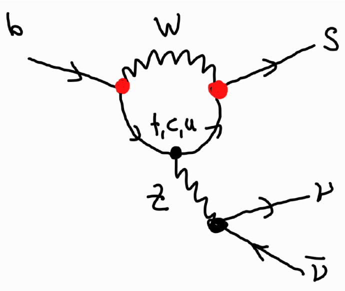

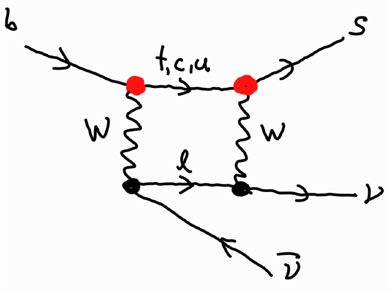

$$A = V_{tb}V_{ts}^* A_t + V_{cb}V_{cs}^* A_c + V_{ub}V_{us}^* A_u$$

$$= V_{tb}V_{ts}^*(A_t - A_c) + V_{ub}V_{us}^*(A_u - A_c) \approx V_{tb}V_{ts}^*(A_t - A_c)$$

Effective Hamiltonian for $b \to s\nu\bar{\nu}$ in the SM

- Integrate out the top, W, Z, ... to arrive at an effective Hamiltonian that describes the $b \to s\nu\bar{\nu}$ decay

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} \frac{\alpha}{4\pi} V_{ts}^* V_{tb} \, C_L \, (\bar{s}\gamma^\mu P_L b)(\bar{\nu}\gamma_\mu(1-\gamma_5)\nu)$$

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- In the SM there is a single Wilson coefficient that is relevant

$$C_L = -\frac{1}{s_W^2} X_t(x_t) = -\frac{1}{s_W^2}\left(X_t^{(0)}(x_t) + \frac{\alpha_s}{4\pi} X_t^{(1)}(x_t) + \ldots \right)$$

Effective Hamiltonian for $b \to s\nu\bar{\nu}$ in the SM

- Integrate out the top, W, Z, ... to arrive at an effective Hamiltonian that describes the $b \to s\nu\bar{\nu}$ decay

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}}\frac{\alpha}{4\pi}V_{ts}^* V_{tb}\, C_L\, (\bar{s}\gamma^\mu P_L b)(\bar{\nu}\gamma_\mu(1-\gamma_5)\nu)$$

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- s_W is the sine of the weak mixing angle
- $X_t^{(0)}$ and $X_t^{(1)}$ are loop functions that depend on $x_t = m_t^2/m_W^2$
- Wilson coefficient is known at NLO in QCD and NLO electro-weak

(Brod, Gorbahn, Stamou, 1009.0947, 2105.02868)

$$C_L^{\text{SM}} = -6.322 \pm 0.031\Big|_{m_t} \pm 0.074\Big|_{\text{QCD}} \pm 0.009\Big|_{\text{EW}}$$

The $b \to s\nu\bar{\nu}$ Decays

- $B \to K\nu\bar{\nu}$ (pseudoscalar to pseudoscalar)
- $B \to K^*\nu\bar{\nu}$ and $B_s \to \phi\nu\bar{\nu}$ (pseudoscalar to vector)
- $\Lambda_b \to \Lambda\nu\bar{\nu}$ (fermion to fermion)

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  (see talk by Martin Novoa-Brunet on Wednesday)

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  (see talk by Martin Novoa-Brunet on Wednesday)
- For $\Lambda_b \to \Lambda\nu\bar{\nu}$ also the initial state Λ_b can in principle be polarized; even more angular information is available.

$B \to K\nu\bar{\nu}$

Definition of $B \to K$ Form Factors

- Parameterize the $B \to K$ hadronic matrix elements in the most generic way.
- In the Standard Model we need the matrix element of vector current

  (Gubernari, Reboud, van Dyk, Virto 2305.06301)

$$\langle \bar{P}(k)| J_V^\mu | \bar{B}(p)\rangle = \left[(p+k)^\mu - \frac{M_B^2 - M_P^2}{q^2} q^\mu \right] f_+^{B\to P} + \frac{M_B^2 - M_P^2}{q^2} q^\mu f_0^{B\to P},$$

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- The matrix element of the axial-vector current vanishes (parity!)
- Beyond the SM one might also encounter scalar and tensor currents
- In total one finds 3 independent form factors f_+, f_0, f_T.
  (In the SM only f_+ is needed.)

$B \to K$ Form Factor Parameterization

Boyd, Grinstein, Lebed hep-ph/9412324; Caprini, Lellouch, Neubert hep-ph/9712417; ...
... Flynn, Juttner, Tsang 2303.11285; Gubernari, Reboud, van Dyk, Virto 2305.06301

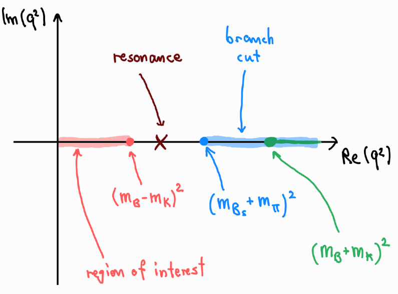
- One would like to work with a robust parameterization of the q^2 dependence of the form factors.
- Use a conformal mapping to the variable z, and use analytic properties of the form factors to express them in a power series in z with coefficients bounded by unitarity

$$z = \frac{\sqrt{s_\Gamma - q^2} - \sqrt{s_\Gamma - s_0}}{\sqrt{s_\Gamma - q^2} + \sqrt{s_\Gamma - s_0}} ,$$

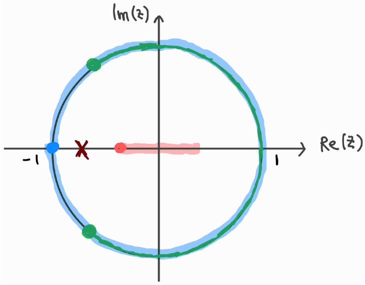
- $s_\Gamma =$ start of the branch cut in q^2.
- $s_0 =$ free parameter $< s_\Gamma$;
  can be chosen to minimize the relevant range of z.

(see talk by Danny van Dyk in the afternoon)

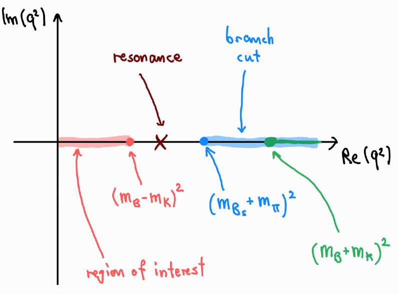
$B \to K$ Form Factor Parameterization



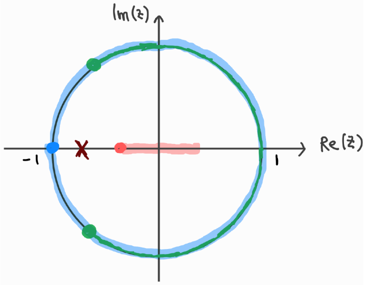
$\Rightarrow$



$B \to K$ Form Factor Parameterization



$\Rightarrow$

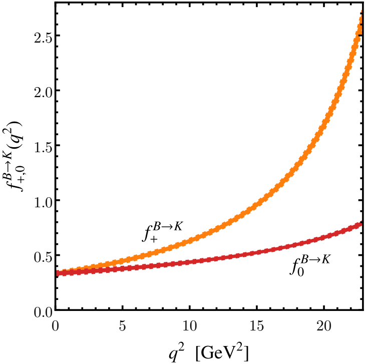


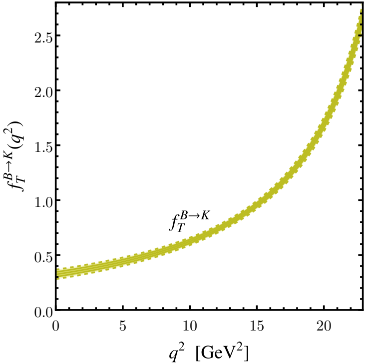
$$\mathcal{F}(q^2) = \frac{1}{\mathcal{B}_\mathcal{F}(z)\phi_\mathcal{F}(z)} \sum_k \alpha_k^\mathcal{F} p_k^\mathcal{F}(z) \quad , \quad \sum_{\mathcal{F},k} |\alpha_k^\mathcal{F}|^2 < 1$$

- $\mathcal{B}_\mathcal{F}(z)$ = Blaschke factor that takes into account poles.
- $\phi_\mathcal{F}(z)$ = outer function ensures unitarity bounds take a simple form.
- $p_k^\mathcal{F}$ = orthonormal polynomials of order k.

$B \to K$ Form Factors: Numerics

- Astonishing precision is achieved on the lattice
  (see talk by Chris Bouchard in the afternoon)
- Plots show 2σ error bands!





[plots based on HPQCD 2207.12468, Fermilab/MILC 1509.06235, Gubernari, Reboud, van Dyk, Virto 2305.06301]

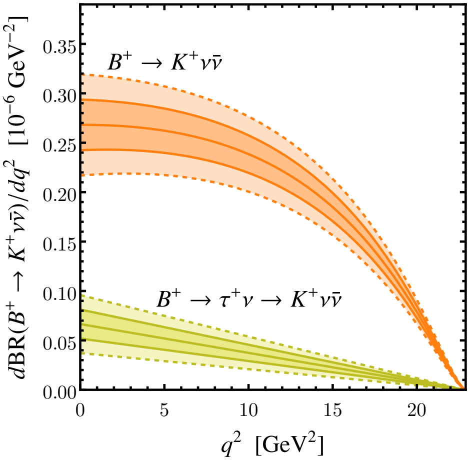
Standard Model Prediction for $B \to K\nu\bar{\nu}$

- SM branching ratio predicted with $\sim 8\%$ precision

$$\text{BR}(B^+ \to K^+\nu\bar{\nu}) = = (4.46 \pm 0.36) \times 10^{-6}$$

$$\text{BR}(B^0 \to K_S\nu\bar{\nu}) = = (2.06 \pm 0.17) \times 10^{-6}$$

- For the charged B decays need also to take into account a “long-distance” contribution from $B^+ \to \tau^+\nu \to K^+\nu\bar{\nu}$



(my evaluation based on $|V_{cb}| = (41.1 \pm 1.2) \times 10^{-3}$)

Error Budget

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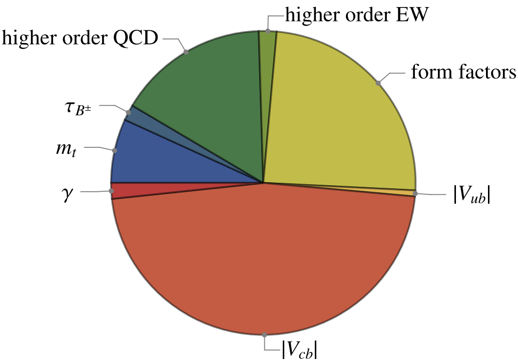
- Uncertainty is dominated by CKM input

(my evaluation based on
$|V_{cb}| = (41.1 \pm 1.2) \times 10^{-3}$)



(the pie chart shows $B^+ \to K^+ \nu\bar{\nu}$,
the one for $B^0 \to K_S \nu\bar{\nu}$ looks pretty much identical)

$B \to K^* \nu\bar{\nu}$

Definition of $B \to K^*$ Form Factors

- $B \to K^*$ matrix elements are more involved. In addition to the momenta, also the K^* polarization vector is available to for the parameterization.

(Gubernari, Reboud, van Dyk, Virto 2305.06301)

$$\langle \bar{V}(k,\eta)|J_V^\mu|\bar{B}(p)\rangle = \epsilon^{\mu\nu\rho\sigma}\eta_\nu^* p_\rho k_\sigma \frac{2V^{B\to V}}{M_B + M_V},$$

$$\langle \bar{V}(k,\eta)|J_A^\mu|\bar{B}(p)\rangle = i\eta_\nu^*\Big[g^{\mu\nu}(M_B+M_V)A_1^{B\to V} - (p+k)^\mu q^\nu \frac{A_2^{B\to V}}{M_B+M_V} - 2M_V\frac{q^\mu q^\nu}{q^2}(A_3^{B\to V} - A_0^{B\to V})\Big],$$

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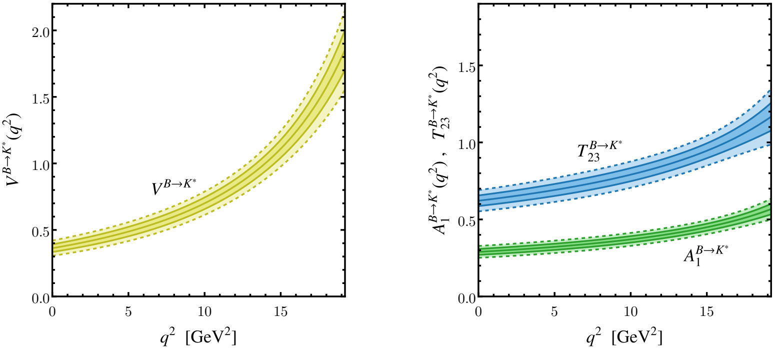
- Beyond the SM one might also encounter scalar, pseudo-scalar, and tensor currents

- In total one finds 7 independent form factors V, A_0, A_1, A_2, T_1, T_2, T_3. (In the SM only V, A_1, A_2 are needed.)

$B \to K^*$ Form Factors: Numerics

- Form factor uncertainties are around 5% - 10%.
- Results from lattice and light cone sum rules.
- Complications due to the sizeable width of the K^*.



[plots based on Horgan et al. 1310.3722, 1501.00367; Gubernari, Kokulu, van Dyk 1811.00983, Gubernari, Reboud, van Dyk, Virto 2305.06301]

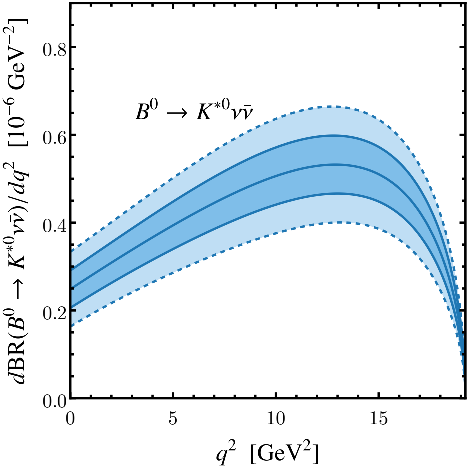
Standard Model Prediction for $B \to K^* \nu\bar{\nu}$

- SM branching ratio predicted with $\sim$ 12% precision

  $\text{BR}(B^+ \to K^{*\,+}\nu\bar{\nu}) =$
  $= (8.8 \pm 1.1) \times 10^{-6}$

  $\text{BR}(B^0 \to K^{*\,0}\nu\bar{\nu}) =$
  $= (8.1 \pm 1.0) \times 10^{-6}$

- For the charged B decays need also to take into account a "long-distance" contribution from $B^+ \to \tau^+\nu \to K^{*\,+}\nu\bar{\nu}$



(my evaluation based on $|V_{cb}| = (41.1 \pm 1.2) \times 10^{-3}$)

Error Budget

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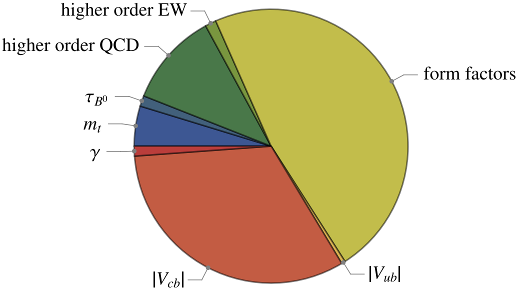
$\text{BR}(B^0 \to K^{*\,0}\nu\bar{\nu}) =$
$= (8.1 \pm 1.0) \times 10^{-6}$

- Main uncertainties shared by form factors and CKM input

(my evaluation based on $|V_{cb}| = (41.1 \pm 1.2) \times 10^{-3}$)



(the pie chart shows $B^0 \to K^{*\,0}\nu\bar{\nu}$,
the one for $B^+ \to K^{*\,+}\nu\bar{\nu}$ looks pretty much identical)

The Longitudinal Polarization Fraction

The angular distribution of the $K^* \to K\pi$ decay product gives access to an additional observable. The K^* logitudinal polarization fraction F_L

(θ is the angle between the K and B in the K^* restframe)

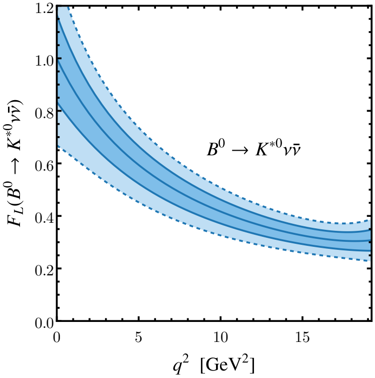
$$\frac{d\text{BR}}{dq^2\; d\cos\theta} = \frac{3}{4}\frac{d\text{BR}_T}{dq^2}\sin^2\theta + \frac{3}{2}\frac{d\text{BR}_L}{dq^2}\cos^2\theta$$

$$F_L = \frac{d\text{BR}_L/dq^2}{d\text{BR}/dq^2}$$

$$\langle F_L \rangle = \frac{\text{BR}_L}{\text{BR}}$$

$$\langle F_L \rangle_{\text{SM}} = 0.47 \pm 0.03$$

(uncertainty entirely due to form factors)



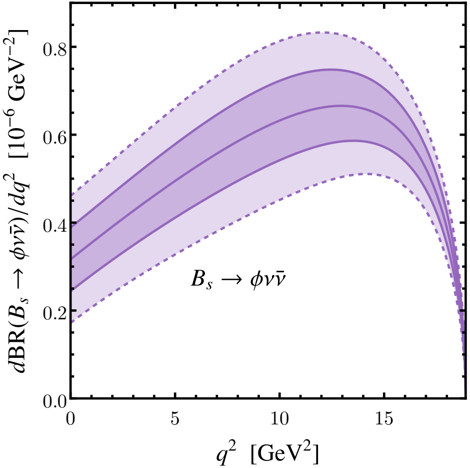
$$B_s \to \phi \nu \bar{\nu}$$

Standard Model Predictions for $B_s \to \phi\nu\bar{\nu}$

- Same story as for $B \to K^*\nu\bar{\nu}$; simply switch out form factors and masses

$$\mathrm{BR}(B_s \to \phi\nu\bar{\nu}) = $$
$$= (10.0 \pm 1.3) \times 10^{-6}$$

$$\langle F_L \rangle_{\mathrm{SM}} = 0.52 \pm 0.03$$



(values based on $|V_{cb}| = (41.1 \pm 1.2) \times 10^{-3}$)

$$\Lambda_b \to \Lambda \nu \bar{\nu}$$

Definition of $\Lambda_b \to \Lambda$ Form Factors

- Shown here is the parameterization of the vector and axial-vector matrix elements

$$\langle \Lambda | \bar{s} \gamma^\mu b | \Lambda_b \rangle = \bar{u}_\Lambda \Bigg[f_t^V(q^2)(m_{\Lambda_b} - m_\Lambda) \frac{q^\mu}{q^2} + f_\perp^V(q^2) \left(\gamma^\mu - \frac{2(m_\Lambda P^\mu + m_{\Lambda_b} p^\mu)}{(m_{\Lambda_b} + m_\Lambda)^2 - q^2} \right) + f_0^V(q^2) \frac{m_{\Lambda_b} + m_\Lambda}{(m_{\Lambda_b} + m_\Lambda)^2 - q^2} \left(P^\mu + p^\mu - (m_{\Lambda_b}^2 - m_\Lambda^2) \frac{q^\mu}{q^2} \right) \Bigg] u_{\Lambda_b}$$

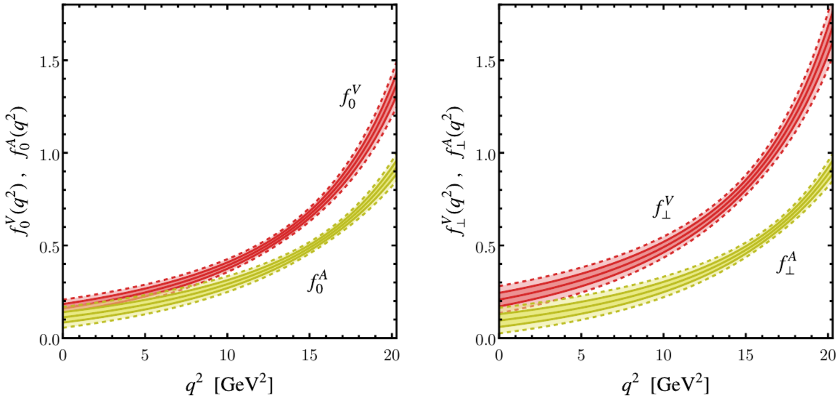
$$\langle \Lambda | \bar{s} \gamma^\mu \gamma_5 b | \Lambda_b \rangle = -\bar{u}_\Lambda \gamma_5 \Bigg[f_t^A(q^2)(m_{\Lambda_b} + m_\Lambda) \frac{q^\mu}{q^2} + f_\perp^A(q^2) \left(\gamma^\mu + \frac{2(m_\Lambda P^\mu - m_{\Lambda_b} p^\mu)}{(m_{\Lambda_b} - m_\Lambda)^2 - q^2} \right) + f_0^A(q^2) \frac{m_{\Lambda_b} - m_\Lambda}{(m_{\Lambda_b} - m_\Lambda)^2 - q^2} \left(P^\mu + p^\mu - (m_{\Lambda_b}^2 - m_\Lambda^2) \frac{q^\mu}{q^2} \right) \Bigg] u_{\Lambda_b}$$

- In total there are 10 $\Lambda_b \to \Lambda$ form factors

  Detmold, Meinel 1602.01399; Blake, Meinel, Rahimi, van Dyk 2205.06041

- In the SM, 4 of them are needed.

- Form factor uncertainties are around 10%.

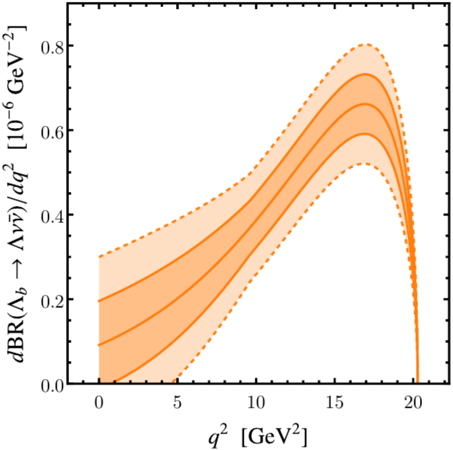


[plots from WA, Gadam, Toner 2501.10652, based on Detmold, Meinel 1602.01399]

SM Prediction for the $\Lambda_b \to \Lambda \nu \bar{\nu}$ Rate

- SM branching ratio predicted with $\sim 14\%$ precision

$$\text{BR}(\Lambda_b \to \Lambda \nu \bar{\nu}) = \\ = (7.71 \pm 1.06) \times 10^{-6}$$



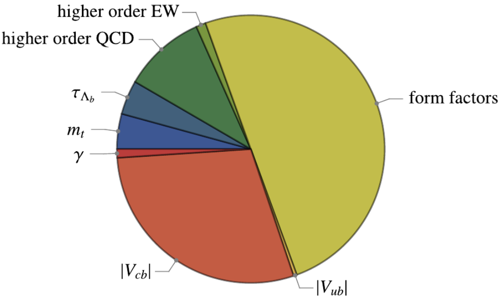
WA, Gadam, Toner 2501.10652

(based on $|V_{cb}| = (41.1 \pm 1.2) \times 10^{-3}$)

Error Budget

$$\mathrm{BR}(\Lambda_b \to \Lambda \nu \bar{\nu}) =$$
$$= (7.71 \pm 1.06) \times 10^{-6}$$

- main theory uncertainty from form factors
- also uncertainty from V_{cb} is still relevant



WA, Gadam, Toner 2501.10652

(based on $|V_{cb}| = (41.1 \pm 1.2) \times 10^{-3}$)

Λ_b Polarization

One can get longitudinally polarized Λ_b baryons from Z decays
($\rightarrow$ FCC-ee)

$$\mathcal{P}_{\Lambda_b} = \frac{N^{\uparrow}_{\Lambda_b} - N^{\downarrow}_{\Lambda_b}}{N^{\uparrow}_{\Lambda_b} + N^{\downarrow}_{\Lambda_b}} = \begin{cases} -0.23^{+0.24\,+0.08}_{-0.20\,-0.07}\,, & \text{ALEPH}\,, \\ -0.49^{+0.32}_{-0.30} \pm 0.17\,, & \text{DELPHI}\,, \\ -0.56^{+0.20}_{-0.13} \pm 0.09\,, & \text{OPAL}\,, \end{cases}$$

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Can define a angular distribution in the angle between the Λ_b spin and the Λ momentum

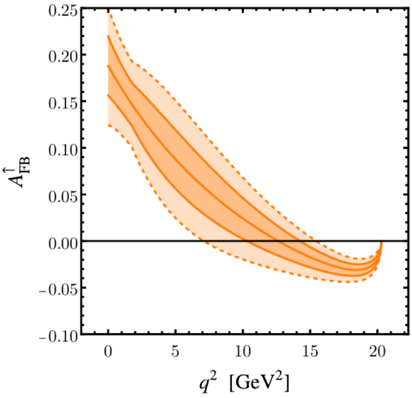
WA, Gadam, Toner 2501.10652

$$\frac{d\text{BR}(\Lambda_b \to \Lambda \nu \bar{\nu})}{dE_\Lambda\, d\cos\theta_\Lambda} = \frac{d\text{BR}(\Lambda_b \to \Lambda \nu \bar{\nu})}{dE_\Lambda} \left(\frac{1}{2} + A^{\uparrow}_{\text{FB}} \cos\theta_\Lambda \right)$$

The Forward Backward Asymmetry

- $A_{\rm FB}^{\uparrow}$ has a zero crossing in q^2
- Large cancellation in the integrated asymmetry

$$\langle A_{\rm FB}^{\uparrow}\rangle_{\rm SM} = -\mathcal{P}_{\Lambda_b} \times (2.7 \pm 3.4) \times 10^{-2}$$



WA, Gadam, Toner 2501.10652

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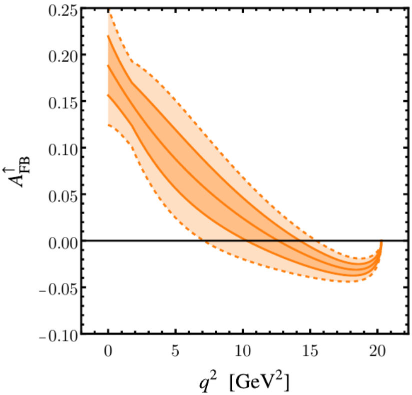
- Large cancellation in the integrated asymmetry

$$\langle A_{\rm FB}^{\uparrow}\rangle_{\rm SM} = -\mathcal{P}_{\Lambda_b} \times (2.7 \pm 3.4) \times 10^{-2}$$

- Zero crossing point is given by (independent of new physics!)

$$q^2 = \frac{m_{\Lambda_b}^2}{2}\left(1 - \frac{m_{\Lambda}^2}{m_{\Lambda_b}^2}\right)\frac{f_0^V(q^2) f_0^A(q^2)}{f_\perp^V(q^2) f_\perp^A(q^2)}$$

$$(q^2)_0^{\rm SM} = (12.6 \pm 1.2)\text{GeV}^2$$



WA, Gadam, Toner 2501.10652

Summary

- The SM predicts branching ratios around 10^{-6} to 10^{-5} for several rare $b \to s\nu\bar{\nu}$ decays

  $B \to K\nu\bar{\nu}$, $B \to K^*\nu\bar{\nu}$, $B_s \to \phi\nu\bar{\nu}$, $\Lambda_b \to \Lambda\nu\bar{\nu}$

- Available observables: total branching ratios, q^2 spectra, and agular observables.

- Theory precision of the branching ratios is around $\sim 10\%$. It is limited by hadronic form factors and CKM input (V_{cb})

  Angular observables avoid the uncertainty from CKM.

大漁を祈ります

Back Up

Promising Indirect Probes of New Physics

- **Test bedrock assumptions of particle physics**

  Lorentz invariance; CPT invariance; ...
  ($\Lambda \gtrsim M_{\text{Planck}} \sim 10^{19}$ GeV)

Probe more generic new physics

Reach to higher new physics scales

Promising Indirect Probes of New Physics

Probe more generic new physics

- Test bedrock assumptions of particle physics

  Lorentz invariance; CPT invariance; ...
  ($\Lambda \gtrsim M_{\text{Planck}} \sim 10^{19}$ GeV)

- Test (approximate) accidental symmetries of the SM

  Baryon Number: e.g. proton decay
  ($\Lambda \sim \Lambda_{\text{GUT}} \sim 10^{16}$ GeV)

  Lepton Number: e.g. neutrinoless double beta decay
  ($\Lambda \sim \Lambda_{\text{see-saw}} \sim 10^{12}$ GeV)

  Flavor: e.g. flavor changing neutral currents
  ($\Lambda \sim 10^3 - 10^8$ GeV)

  CP: e.g. electric dipole moments
  ($\Lambda \sim 10^3 - 10^8$ GeV)

Reach to higher new physics scales

Promising Indirect Probes of New Physics

Probe more generic new physics

- Test bedrock assumptions of particle physics

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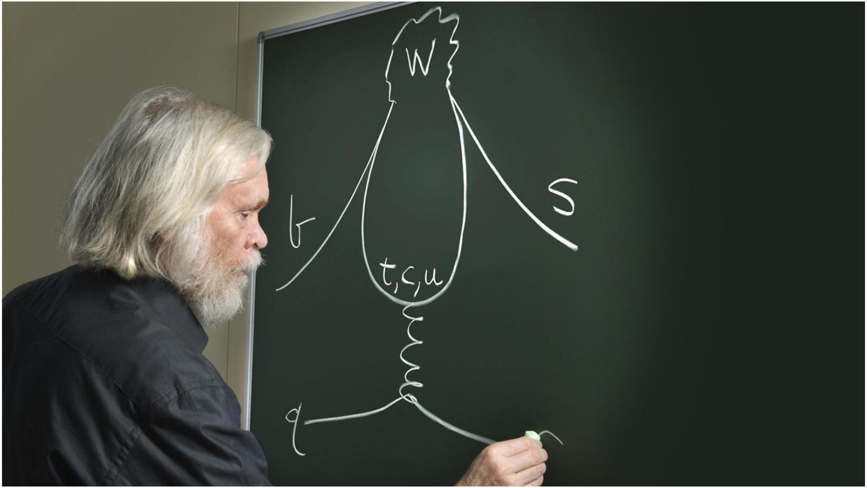
- Test "ordinary" Standard Model processes

  Higgs precision program; Electroweak precision observables; muon anomalous magnetic moment; ...
  ($\Lambda \sim 10^3$ GeV)

Reach to higher new physics scales

Penguin Diagrams



https://www.symmetrymagazine.org/article/june-2013/the-march-of-the-penguin-diagrams

Far Future: Flavor at FCC-ee

Running on the Z pole allows one to probe the flavor structure of Z couplings with extreme precision.

In addition one gets very large samples of all b hadrons, c hadrons, τ's with large boost in a clean environment.

Running at higher $\sqrt{s}$ can probe e.g. FCNC single top production or lepton flavor violating 4-fermion contact interactions

Can measure V_{cb} from W decays

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$\Rightarrow$ sensitivity to various flavor processes that are not accessible at LHC(b) or Belle II

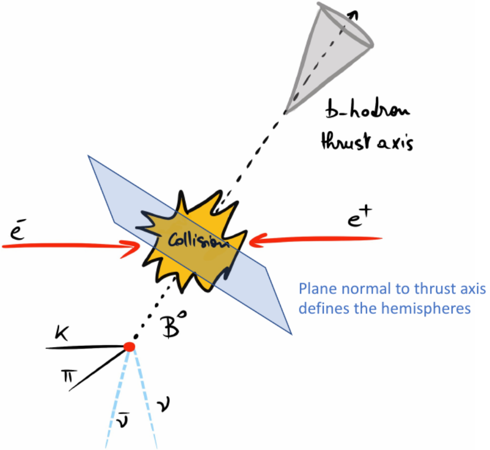
Far Future: $b \to s\nu\bar{\nu}$ on the Z pole

- Tera-Z machines get access to the entire family of decays:

  $B \to K\nu\bar{\nu}$
  $B \to K^*\nu\bar{\nu}$
  $B_s \to \phi\nu\bar{\nu}$
  $\Lambda_b \to \Lambda\nu\bar{\nu}$

- Tera-Z machines can measure $B \to K^{(*)}\nu\bar{\nu}$ and $B_s \to \phi\nu\bar{\nu}$ with percent level precision

- $\Lambda_b \to \Lambda\nu\bar{\nu}$ can be measured with precision of $\sim 10\%$



Amhis, Kenzie, Reboud, Wiederhold 2309.11353