Physics Week Summary: Theory

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UC SANTA CRUZ

2025 Belle II Physics Week
KEK, October 6 - 10, 2025

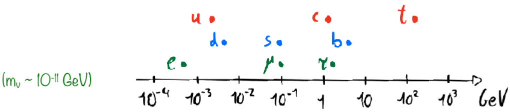
Theory at the 2025 Belle II Physics Week

- Wolfgang Altmannshofer: EWP B decays with missing energy in the SM
- David Marzocca: New Physics in EWP B decays with missing E
- Claudia Cornella: Interplays with $B \to K\tau\tau$, $B \to \tau\tau$, and $K \to \pi\nu\bar{\nu}$
- Chris Bouchard: LQCD results for rare B-decays with missing energy
- Danny van Dyk: Unitarity Bounds for Hadronic Form Factors
- Hector Gisbert: Charm decays with missing energy (NP and SM)
- Hector Gisbert: Introduction to $c \to u\nu\bar{\nu}$ decays
- Hector Gisbert: Introduction to $b \to d\nu\bar{\nu}$ decays
- Olcyr Sumensari: $B \to K^{(*)}\nu\bar{\nu}$ in SM and observables beyond rate
- Jack Jenkins: $B \to X_s\nu\bar{\nu}$ in SM
- Martin Novoa-Brunet: Probing CP Violation in $b \to s\nu\bar{\nu}$ decays
- Michael Schmidt: BSM for $B \to K\nu\bar{\nu}$ & related anomalies
- Patrick Bolton: Impact of new particles on missing energy B decays

13 presentations by theorists

Motivation: Flavor is Puzzling

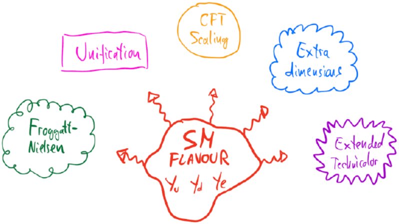
- **hierarchical fermion masses**



- **hierarchical quark mixing matrix**

$V_{\text{CKM}} \sim$ 

This puzzle in general **doesn't point to a specific New Physics scale for its solutions**.
They could be anywhere from **near the TeV** till up to **GUT/Planck**.



Necessarily Flavourful New Physics:
- **non universal**
- **flavour changing**

[David Marzocca]

Heavy and Light New Physics

- new physics could be heavy

  $m_{\text{NP}} \gg m_B$

- new physics only shows up as virtual particles

- can capture the effect of all possible new physics models using EFTs

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- can capture the effect of all possible new physics models using EFTs

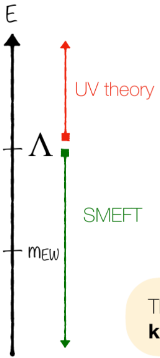
- new physics could be light

  $m_{\text{NP}} < m_B$

- new physics particles are produced on-shell in the B decays

- axions, sterile neutrinos, dark photons, ... (could have entire dark sectors containig many light particles)

Heavy New Physics and SMEFT



$$\mathcal{L}^{(d=6)}_{SMEFT} = \sum_i \frac{C_i^{(6)}}{\Lambda^2} \mathcal{O}_i^{(6)}[\varphi_{SM}]$$

in general violate all the accidental symmetries and properties of the SM

We can expect large effects in rare or forbidden processes!

Precision tests of forbidden or suppressed processes in the SM **are powerful probes of physics Beyond the Standard Model.**

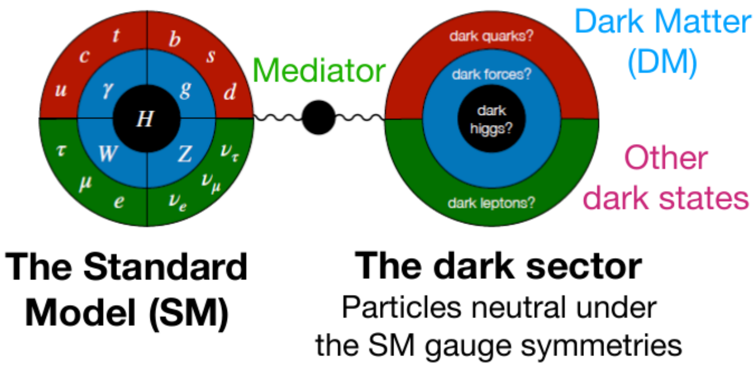
>> Flavour Physics ! <<

The **SMEFT** is a consistent **framework to systematically parametrise our knowledge of fundamental interactions** between the known particles.

Every little improvement in any direction in the (big) EFT parameter space means that we learn something more of how particles behave at microscopic scales.

[David Marzocca]

Light New Physics and Dark Sectors



- Dark matter could consist of light fermions
- Dark photons could be a mediator between dark matter and the SM
- light axions motivated by the strong CP problem and can show up in flavour models ("axiflavons")
- ...

Complementarity of Rare Decays

$b \to s$ decays

$$\propto G_F \frac{\alpha}{4\pi} V_{ts}^* V_{tb} \frac{m_t^2}{m_W^2}$$

$b \to d$ decays

$$\propto G_F \frac{\alpha}{4\pi} V_{td}^* V_{tb} \frac{m_t^2}{m_W^2}$$

New Physics

$s \to d$ decays

$$\propto G_F \frac{\alpha}{4\pi} V_{td}^* V_{ts} \frac{m_t^2}{m_W^2}$$

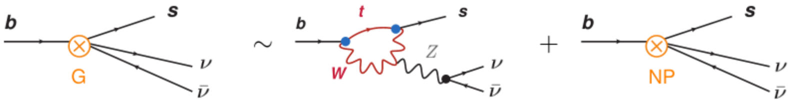
$c \to u$ decays

$$\propto G_F \frac{\alpha}{4\pi} V_{cb}^* V_{ub} \frac{m_b^2}{m_W^2}$$

Are there BSM sources of flavor violation?
What structure do they have?
What is their origin?

Searching for New Physics with Rare Decays

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



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

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 Issue with V_{cb}

Global Fits

UTfit

V_{cb} and V_{ub}

average of arXiv:2105.08674, 2204.05925, 2310.03680

$|V_{cb}|$ *(excl)* = $(40.12 \pm 0.55)\ 10^{-3}$

$|V_{cb}|$ *(incl)* = $(41.97 \pm 0.48)\ 10^{-3}$

from arXiv:2310.20324

update of arXiv:2202.10285

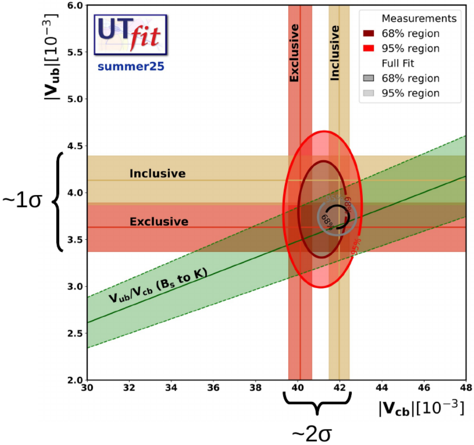
$|V_{ub}|$ *(excl)* = $(3.63 \pm 0.26)\ 10^{-3}$

$|V_{ub}|$ *(incl)* = $(4.13 \pm 0.26)\ 10^{-3}$

PDG 2025

from arXiv:2310.03680

$|V_{ub} / V_{cb}| = (8.7 \pm 0.9)\ 10^{-2}$



Marcella Bona

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[Marcella Bona]

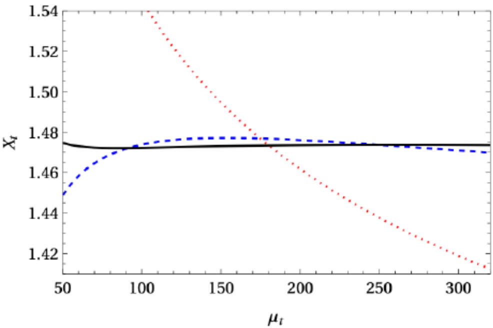
The SM Wilson Coefficient for $b \to s\nu\bar{\nu}$

- In the SM there is a single Wilson coefficient relevant for the $b \to s\nu\nu$ decays

$$C_L = -\frac{1}{s_W^2} X_t$$

- known at NLO in QCD and NLO in EW interactions;
  NNLO QCD corrections will be available very soon.

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



[Jack Jenkins]

Inclusive vs Exclusive

inclusive:

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

- at leading order the decay rate is given by the quark level decay rate.
- corrections are calculated using heavy quark expansion

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exclusive:

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

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

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

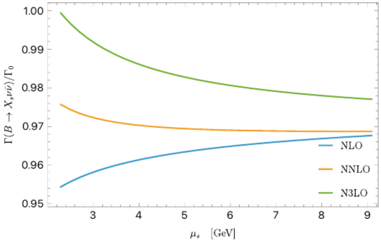
...

- hadronic physics is captured by local transition form factors.

The Inclusive Decay $B \to X_s \nu \bar{\nu}$

We take $m_s/m_b \sim 0$, then the structure of the QCD corrections is equivalent to $B \to X_u \ell \nu$

$$\Gamma(\bar{B} \to X_s \nu\bar{\nu}) = N_\nu \frac{G_F^2 m_b^5}{192\pi^3} |V_{ts}V_{tb}|^2 |C_\nu|^2 \left\{ 1 + C_F \sum_{n=1} X_n \left(\frac{\alpha_s}{\pi}\right)^n - \frac{\mu_\pi^2}{2m_b^2} - \frac{3\mu_G^2}{2m_b^2} + \frac{3\rho_{LS}^3}{2m_b^3} + \frac{77\rho_D^3}{6m_b^3} + \frac{\tau_0}{m_b^3} \right\}$$



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

Matrix elements: $\langle .. \rangle = \langle \bar{B}|...|\bar{B}\rangle / (2M_B)$

$$\begin{aligned}
\mu_\pi^2 &= -\langle \bar{b}_v (iD)^2 b_v \rangle \ , \\
\mu_G^2 &= \frac{1}{2} \langle \bar{b}_v (-i\sigma^{\mu\nu}) [iD_\mu, iD_\nu] b_v \rangle \ , \\
\rho_{LS}^3 &= \frac{1}{2} \langle \bar{b}_v (-i\sigma^{\mu\nu}) \{iD_\mu, [iv \cdot D, iD_\nu]\} b_v \rangle \ , \\
\rho_D^3 &= \frac{1}{2} \langle \bar{b}_v [iD_\mu, [iv \cdot D, iD^\mu] \bar{b}_v \rangle
\end{aligned}$$

Stability of HQE

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

[Jack Jenkins]

The Inclusive Decay $B \to X_s \nu\bar{\nu}$

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

$$\begin{aligned}
\mathrm{Br}(B^+ \to X_s \nu\bar{\nu}) &= 3.342(40)_{\mu_0}(40)_{\mu_b}(35)_{\mu_k}(27)_{\text{par}}(68)_{\text{HQE}}(58)_{\text{CKM}} \times 10^{-5} \\
&= 3.342(112) \times 10^{-5} \quad (3.4\%) \\
\mathrm{Br}(\bar{B}^0 \to X_s \nu\bar{\nu}) &= 3.609(121) \times 10^{-5}
\end{aligned}$$

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

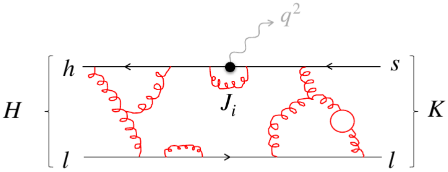
$$\mathrm{Br}(\bar{B} \to X_s \nu\bar{\nu})_{\text{inc}\,\mathrm{V_{cb}}} = (3.48 \pm 0.12) \times 10^{-5} \quad (3.4\%)$$

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

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

[Jack Jenkins]

Calculating form factors: hadronic matrix elements



$\langle K | J_i | H \rangle$

hadronic matrix elements have:

- momentum transfer dependence, $0 \leq q^2 \leq q^2_{\max} = (M_H - M_K)^2$
- effects from short distance weak interactions: $M_W \sim \mathcal{O}(100\,\mathrm{GeV})$
- long distance QCD interactions: $\Lambda_{\mathrm{QCD}} \sim 0.5\,\mathrm{GeV}$

[Chris Bouchart]

Form Factor Parameterizations Including Unitarity

Boyd-Grinstein-Lebed Parametrization

- absorb χ, weight factor ω, and kernel $1/(t - Q^2)$ into "outer function" ϕ

$$1 \geq \frac{1}{\chi(0)} \int_{-\pi}^{+\pi} \frac{d\vartheta}{2\pi} z\, J_{z\to t}(z) \left[\frac{d^n}{d(Q^2)^n} \frac{\omega(t)|F(t(z))|^2}{t - Q^2} \right]_{z=e^{i\vartheta}, Q^2=0} \equiv \int_{-\pi}^{+\pi} \frac{d\vartheta}{2\pi} \left|\phi(z) F(t(z))\right|^2 \Big|_{z=e^{i\vartheta}}$$

- use an orthonormal basis of analytic functions on the unit circle

$$\int_{-\pi}^{+\pi} \frac{d\vartheta}{2\pi} z^k z^{*,l} = \delta_{mn} \qquad \text{for } k, l \geq 0$$

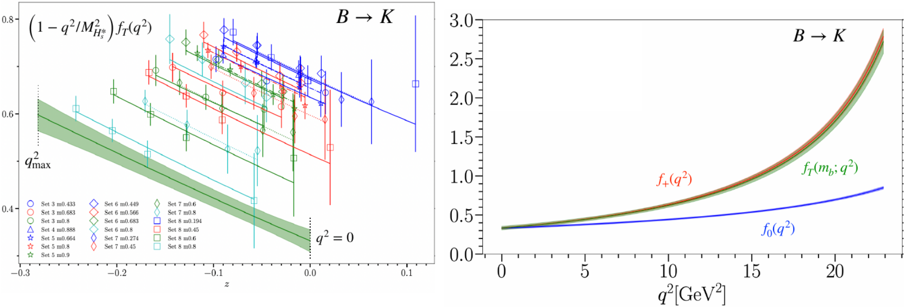
- expand $\phi(z)F(t(z))$ into a series around $z = 0$

$$F(t) = \frac{1}{\phi(z(t))} \sum_{k=0}^{\infty} a_k [z(t)]^k \qquad \Rightarrow \qquad \sum_{k=0}^{\infty} |a_k|^2 \leq 1$$

- each expansion coefficient is absolutely bounded to the interval $[-1, +1]$

[Danny van Dyk]

Lattice Calculations of Form Factors



- improved precision, especially at low q^2, where it is needed
- errors statistics dominated, so improvement straightforward

[Chris Bouchart]

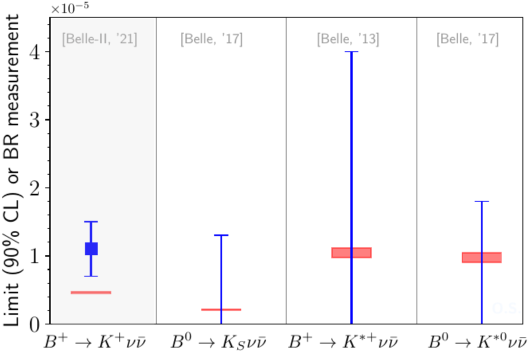
SM Predictions for the Branching Ratios

Decay	Branching ratio
$B^+ \to K^+ \nu\bar{\nu}$	$(4.44 \pm 0.14 \pm 0.27) \times 10^{-6}$
$B^0 \to K_S \nu\bar{\nu}$	$(2.05 \pm 0.07 \pm 0.12) \times 10^{-6}$
$B^+ \to K^{*+} \nu\bar{\nu}$	$(9.79 \pm 1.30 \pm 0.60) \times 10^{-6}$
$B^0 \to K^{*0} \nu\bar{\nu}$	$(9.05 \pm 1.25 \pm 0.55) \times 10^{-6}$

FF CKM

*Using V_{cb} $[B \to D\ell\bar{\nu}]$ for illustration — *the central value changes by* $-7\,\%$ *or* $+10\,\%$ *if we use* $B \to D^*\ell\bar{\nu}$ *or* $B \to X_c\ell\bar{\nu}$*, respectively.*

[Becirevic, Piazza, **OS**. 2301.06990]



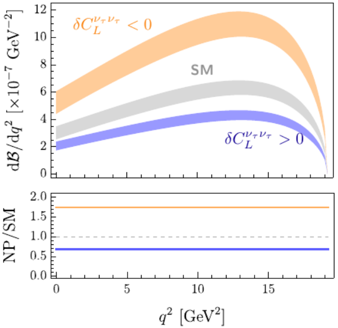
[Olcyr Sumensary]

Predictions for Differential Rates

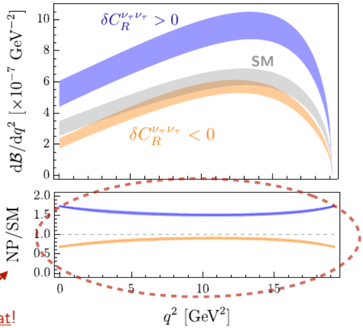
- The q^2-**shapes** of $B \to K^* \nu\nu$ can be **mildly modified** by the **EFT** (with **LH neutrinos**):

LH:

Rescaling of the SM:



RH:



Almost flat!

$\Rightarrow$ The **differential** q^2-**distribution** is **mostly sensitive** to the $B \to K^*$ **form-factors.**

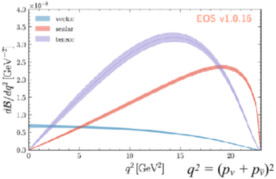
NB. They could be modified by operators with light NP — *cf. back-up.*

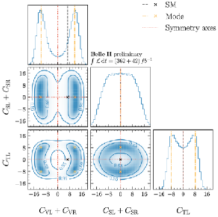
[Olcyr Sumensary]

Scalar and Tensor Operators

Reinterpretation framework of $B \to K^+ \nu\nu$, **generalising the EFT beyond the d=6 SMEFT**:

Gartner at al. 2402.08417, Belle-II 2507.12393





$$\mathcal{L}^{\mathrm{WET}} = -\frac{4G_F}{\sqrt{2}}\frac{\alpha}{2\pi}V_{ts}^* V_{tb}\sum_i C_i(\mu_b)O_i + \mathrm{h.c.}$$

$$\mathcal{O}_{\mathrm{VL}} = (\overline{\nu_L}\gamma_\mu \nu_L)(\overline{s_L}\gamma^\mu b_L)$$
$$\mathcal{O}_{\mathrm{VR}} = (\overline{\nu_L}\gamma_\mu \nu_L)(\overline{s_R}\gamma^\mu b_R)$$

d=6: $O_{lq}^{(1,3)}$, O_{ld}

$$\mathcal{O}_{\mathrm{SL}} = \left(\overline{\nu_L^c}\nu_L\right)(\overline{s_R} b_L)$$
$$\mathcal{O}_{\mathrm{SR}} = \left(\overline{\nu_L^c}\nu_L\right)(\overline{s_L} b_R)$$
$$\mathcal{O}_{\mathrm{TL}} = \left(\overline{\nu_L^c}\sigma_{\mu\nu}\nu_L\right)(\overline{s_R}\sigma^{\mu\nu} b_L)$$

ΔL = 2

Lepton number-violating operators
Generated at d=7 in SMEFT

Fridell et al. 2306.08709

$$\frac{C^{(7)}}{\Lambda^3}(\bar{d}_R L_L)(\bar{Q}^c_L L_L)H$$

If at d=6 the EFT scale required was $\Lambda^{(6)} \sim 7$ TeV,
at d=7 it becomes $\mathbf{\Lambda^{(7)} \sim 2}$ **TeV**.

Bounds from $0\nu\beta\beta$ decay ~ **100 TeV** (for down quarks). 2306.08709
Why should flavour-conserving couplings be more suppressed than violating ones?

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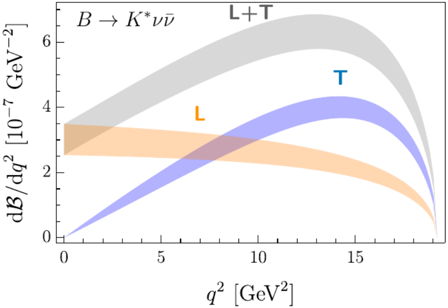
[David Marzocca]

Longitudinal Polarization Fraction in $B \to K^* \nu \bar{\nu}$

$$F_L \equiv \frac{d\Gamma_L}{dq^2} \Big/ \frac{d\Gamma}{dq^2}$$



$$\frac{d\Gamma_L}{dq^2} \propto \underline{|C_L - C_R|^2} A_{12}(q^2)^2$$

$$\frac{d\Gamma_T}{dq^2} \propto \underline{|C_L - C_R|^2} A_1(q^2)^2 + \# \underline{|C_L + C_R|^2} V(q^2)^2$$

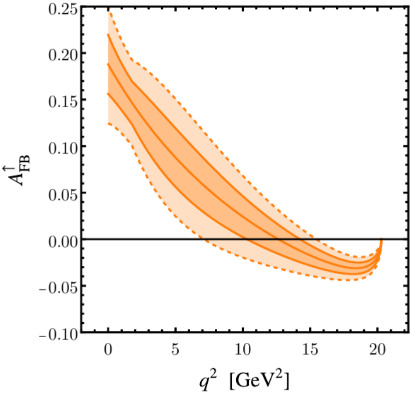
Contributions from **LH operators** ($\delta C_L \neq 0$) **cancel out** in F_L.

This observable is **sensitive** to **right-handed currents** ($\delta C_R \neq 0$)!

[Olcyr Sumensary]

Forward Backward Asymmetry in $\Lambda_b \to \Lambda\nu\bar{\nu}$

- All observables in the meson decays depend on two combinations of Wilson coefficients $|C_L + C_R|$ and $|C_L - C_R|$
- $A_{\rm FB}^{\uparrow}$ in $\Lambda_b \to \Lambda\nu\bar{\nu}$ depends on an independent combination $|C_L|^2 - |C_R|^2$ $\to$ complementary information
- To measure this, need polarized Λ_b from Z decays at FCC-ee ...



WA, Gadam, Toner 2501.10652

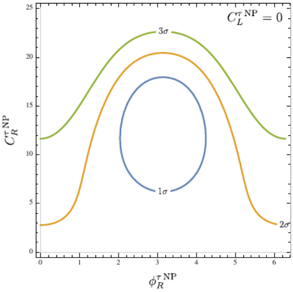
$$\frac{d\mathrm{BR}(\Lambda_b \to \Lambda\nu\bar{\nu})}{dE_\Lambda d\cos\theta_\Lambda} = \frac{d\mathrm{BR}(\Lambda_b \to \Lambda\nu\bar{\nu})}{dE_\Lambda}\left(\frac{1}{2} + A_{\rm FB}^{\uparrow}\cos\theta_\Lambda\right)$$

(θ_Λ is the angle between the Λ_b spin and the Λ momentum)

What about CP phases?

Limits of Current observables

- Br and FL cannot fully disentangle RHC from relative CL/CR phase
- Only partial control over the relative phase
- Thanks to the maximal value for eta relative phase is partially constrained



What about $\Lambda_b \to \Lambda\nu\bar{\nu}$?

Polarized $Br(\Lambda_b \to \Lambda\nu\bar{\nu})$ @ FCCee help disentangle

$$A_{FB} \propto P_{\Lambda_b}|\mathscr{C}_R|^2 - |\mathscr{C}_L|^2$$

Breakes the degeneracy of Meson decays (ε_ν, η_ν)

(See Wolfgang Altmannshofer Talk)

Direct CP-Asymmetries

Due to lack of strong phases $\mathscr{A}^{\mathrm{dir}}_{\mathrm{CP}} = 0$

(Neutrinos couple to Z, only short distance)

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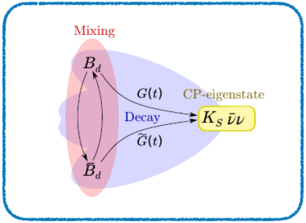
[Martin Novoa-Brunet]

CP Violation in $b \to s\nu\bar{\nu}$

Indirect



CP-Average

Time-evolution of CP-average

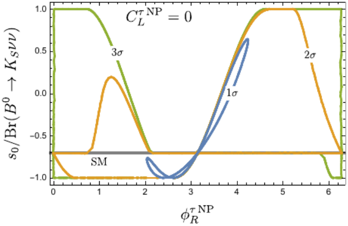
Encodes the same information as si Re vs Im part

$$G_i(t) + \tilde{G}_i(t) = e^{-\Gamma t}\left[(G_i + \tilde{G}_i)\cosh\left(\frac{\Delta\Gamma t}{2}\right) - h_i \sinh\left(\frac{\Delta\Gamma t}{2}\right)\right]$$

$$G_i(t) - \tilde{G}_i(t) = e^{-\Gamma t}\left[(G_i - \tilde{G}_i)\cos(\Delta m t) - s_i \sin(\Delta m t)\right]$$

Indirect CP-Asymmetry

Direct CP-Asymmetry



Complex NP

$$s_0 \simeq -2\sin(\phi^{\mathrm{mix}} - \phi^{\mathrm{decay}})G_0$$

Interference between weak (CP-odd) phase and mixing phases

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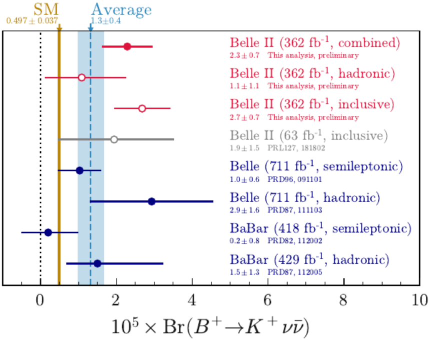
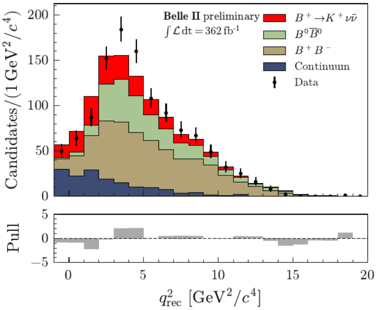
[Martin Novoa-Brunet]

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

Belle II 2311.14647

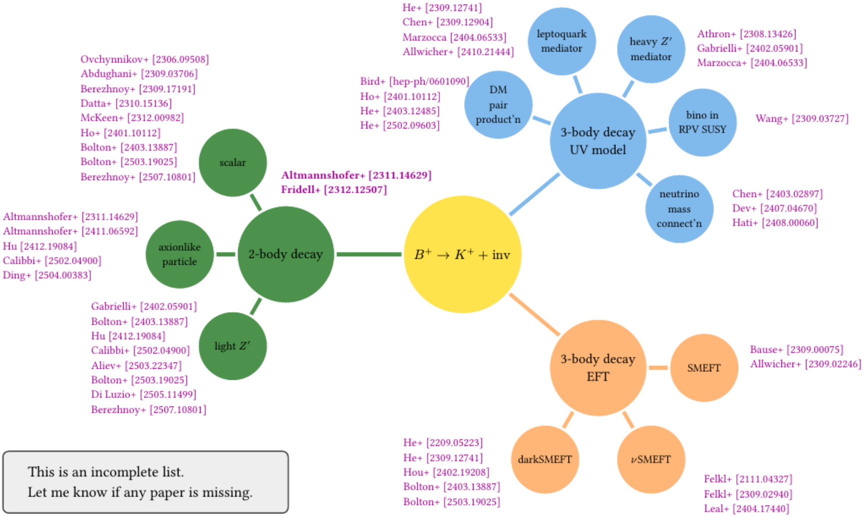




- Evidence for $B \to K\nu\bar{\nu}$ at 3.5σ above background and 2.7σ above the SM prediction.
- Excess of events is particularly pronounced around $q^2 \simeq 4\ \mathrm{GeV}^2$.

Theorists Having Fun

Proposed new physics explanations



This is an incomplete list.
Let me know if any paper is missing.

[Michael Schmidt]

Heavy New Physics Interpretation

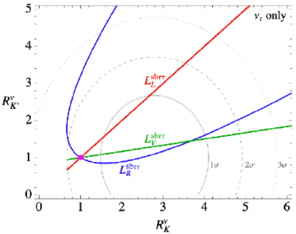
Assuming **only NP in tau**

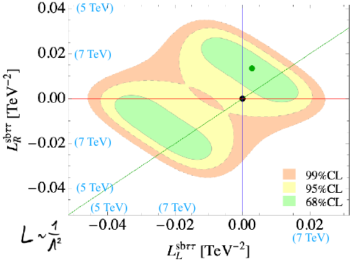
$$\mathcal{L}_{EFT} \supset L_{L,R}^{ij\tau\tau} \left(\bar{d}_{iL,R}\gamma_\mu d_{jL,R}\right)\left(\bar{\nu}_\tau \gamma^\mu \nu_\tau\right)$$

DM, M. Nardecchia, A. Stanzione, C. Toni [2404.06533]

The limits from R(K) and $B_s \to \mu\mu$ disfavour interpretations with electron or muon neutrinos

$L^{sb\alpha\beta}_{V,A} = L^{sb\alpha\beta}_R \pm L^{sb\alpha\beta}_L$



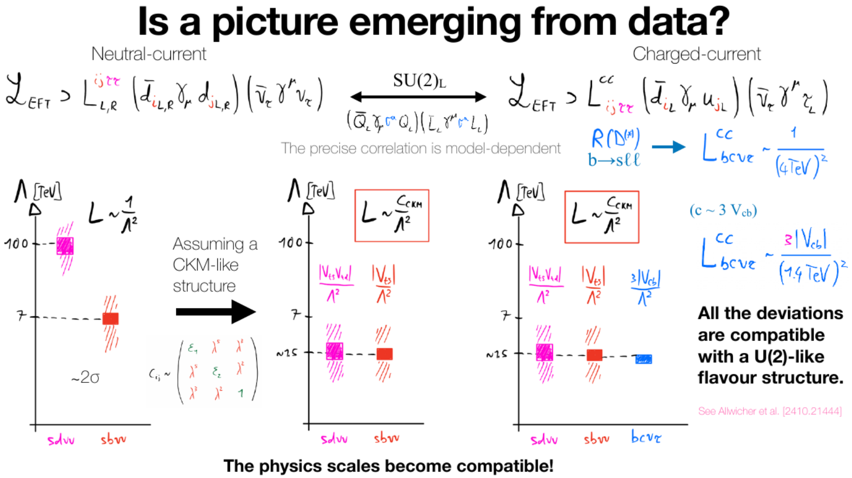


$L \sim \frac{1}{\Lambda^2}$

$\Lambda_{bs\nu\nu} \sim$ **7 TeV**

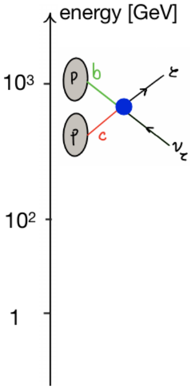
Future Belle II results (in particular from the K* mode) will help to clarify the preferred chiral structure.

[David Marzocca]



[David Marzocca]

Complementarity with Collider Searches



LHC searches [CMS & ATLAS] [See talks by T.Vazquez & M. Martinez]

- largest effects in 3rd-family processes:
  - lepton sector: $pp \to t\bar{t}$, $pp \to b\bar{b}\ldots$
  - quark sector: $pp \to \tau\tau$, $pp \to \tau\nu$
  - also LFU, e.g. comparing $pp \to \tau\tau$ to $pp \to \mu\mu$

- energy enhancement in tails helps overcome pdf suppression of heavy flavours in the proton

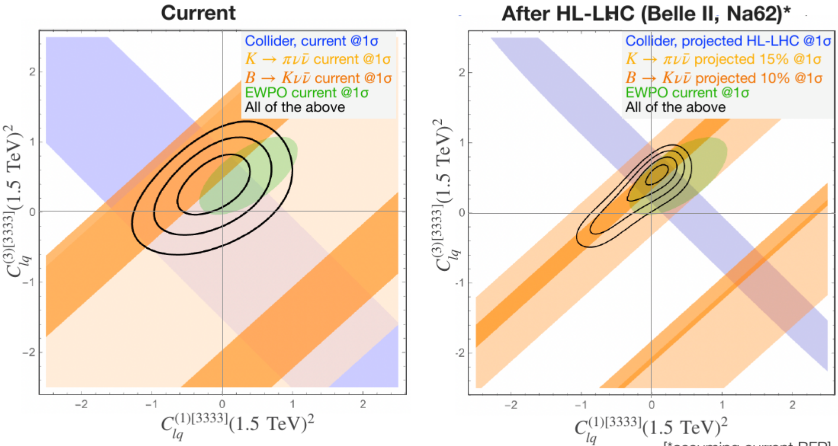
Status and prospects

- currently, LHC probes scales $\sim$ 1 TeV
- HL-LHC: improvement in WCs bounds range from 20% to 4 x for semileptonic operators (factor 2x in the scale)

[Claudia Cornella]

Complementarity with Electroweak Precision

Combining $\nu\bar{\nu}$ data with EW precision and collider:



[*assuming current BFP]

Setup: analysis with $C_{\ell q}^{(3)[3333]}$, $C_{\ell q}^{(1)[3333]}$, ϵ_F

[Plots from Allwicher, CC, Isidori, Stefanek, 2311.00020 updated with more recent data]

[Claudia Cornella]

Light New Physics

Favoured Scenarios

Jožef Stefan Institute

Viable scenarios (better fit w.r.t to the re-scaled SM):

Two-body:

$$B \to K\phi \text{ or } B \to KV \text{ with } m_{\phi/V} = (2.1 \pm 0.1)\ \mathrm{GeV}$$

Three-body:

$B \to K\psi\bar{\psi}$ for vector couplings with $m_\psi = 0.60^{+0.11}_{-0.14}$ GeV

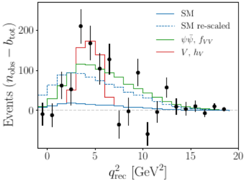
$B \to K\phi\bar{\phi}$ for vector couplings with $m_\phi = 0.38^{+0.13}_{-0.15}$ GeV

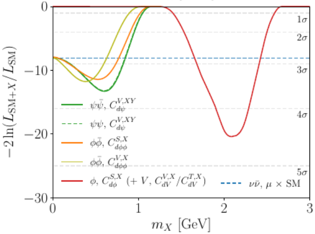
scalar couplings with $m_\phi = 0.52^{+0.11}_{-0.14}$ GeV

Non-viable scenarios (worse fit w.r.t to the re-scaled SM:

- $B \to K\psi\bar{\psi}$ for scalar and tensor couplings
- $B \to KVV/\Psi\bar{\Psi}$ for all couplings

$\Rightarrow$ Kinetics cannot accommodate excess at $q^2_{\mathrm{rec}} \sim 4\ \mathrm{GeV}^2$





Patrick Bolton, Jožef Stefan Institute (IJS), 08.10.25

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[Patrick Bolton]

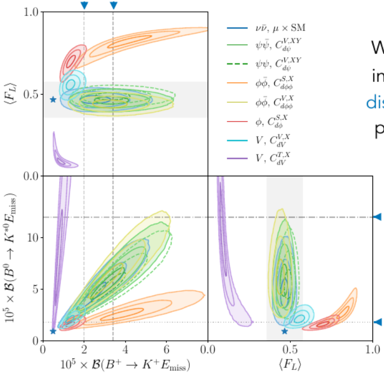
Light New Physics

Implications for Future Measurements

Jožef Stefan Institute

Belle II @ 68% CL (assuming SM) [Adachi et al. 2023]

Combined fit to Belle II, *BABAR* and ALEPH data



With $\mathcal{O}(10\%)$ sensitivities to integrated BRs and F_L clear distinction of some scenarios possible (mostly two-body)

◀ BaBar @ 90% CL [Lees et al. 2013]

◀ Belle @ 90% CL [Grygier, 2017]

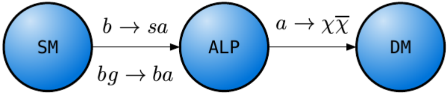
Patrick Bolton, Jožef Stefan Institute (IJS), 08.10.25 19 [PDB, Fajfer, Kamenik, Novoa-Brunet 2025]

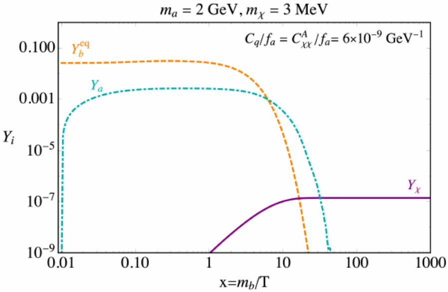
[Patrick Bolton]

Dark Matter and Axion Mediator

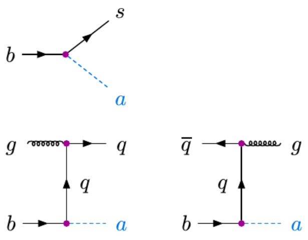
DM freeze-in production - ALP mediator

Calibbi, Li, Mukherjee, MS [2502.04900] 2-body decay





ALP production Aghaie+ [2404.12199]



- ALP reaches thermal equilibrium through decay and scattering processes
- χ DM frozen in through ALP decays

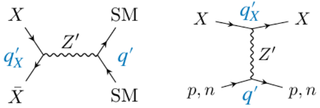
[Michael Schmidt]

GeV Scale DM

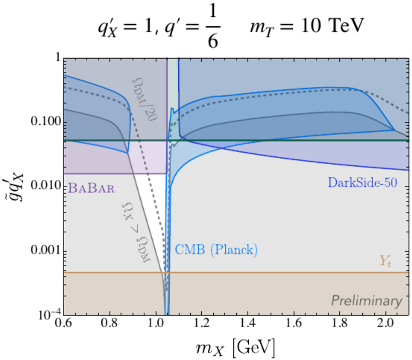
Jožef Stefan Institute

For the allowed window, is correct DM relic abundance (Ω_X) possible? Yes!

Resonant enhancement of $\langle \sigma v \rangle$ for $2m_X \sim M_{Z'}$



Mass range $0.9\ \text{GeV} \lesssim m_X \lesssim 1\ \text{GeV}$ gives correct Ω_X and evades bounds from direct (DarkSide-50) and indirect (CMB) detection



Patrick Bolton, Jožef Stefan Institute (IJS), 08.10.25   30   [PDB, Kamenik, Novoa-Brunet, 2025]

[Patrick Bolton]

Don't Forget $c \to u\nu\bar{\nu}$!

$$\mathcal{B}(c \to u\nu\bar{\nu}) \sim 10^{-19} \approx 0$$

This is almost zero!

Thanks to the GIM mechanism!

Experimentally, this means that any signal is NP!

[Hector Gisbert]

Many Opportunities with Rare Charm Decays

Rare charm decays

This talk

$SU(2)_L$

$c \to u\,\ell^+\ell^-$

- $D \to \ell^+\ell^-$
- $D \to P\,\ell^+\ell^-$
- $D \to P_1P_2\,\ell^+\ell^-$
- $B_c \to B\,\ell^+\ell^-$

Observables:

Branching ratios
Angular observables
LU ratios & LFV
CP asymmetries

$\Uparrow$

Theory:
2011.12856, 2004.01206, 1909.11108, 1510.00311, 1606.05521, 1703.08799, 1705.02251, 1705.05891, 1707.00988, 1510.00311, 0810.4858 , 1409.0181, 1208.0759 , 2004.01206, 1805.08516, 2202.02331, 2107.13010, 1712.05783, 1805.02516, 2101.02421, ... ,

Experiment:
1305.5059 , 1512.00322, 1107.4465 , 2011.00217, 1802.09752, 1510.08367, 1310.2535 , 1707.08377, 2111.03327, 1712.07938, 1806.10793, ...

$c \to u\,\nu\bar{\nu}$

- $D \to \nu\bar{\nu}$
- $D \to P\,\nu\bar{\nu}$
- $D \to P_1P_2\,\nu\bar{\nu}$
- $B_c \to B\,\nu\bar{\nu}$

Observables:

Branching ratios

$\Uparrow$

Theory:
2007.05001, 2010.02225, 2012.15847, 2101.10712, 2107.07291, ...

Experiment:
2112.14236, 1611.09455.

Ideally:
Theory + Experiment
$\Downarrow$
Optimized observables!

$c \to u\,\gamma$

- $D \to V\,\gamma$
- $D \to P_1P_2\,\gamma$
- $B_c \to B\,\gamma$

Observables:

Branching ratios
Angular observables
CP asymmetries

$\Uparrow$

Theory:
2104.08287, 2009.14212, 1812.04679, 1905.00907, 1802.02769, 1702.05059, 1701.06392, 2203.14982, ...

Experiment:
1603.03257, 0808.1838, 0808.1838,

For a review:
Mod. Phys. Lett. A 36 (2021) 04, 2130002

[Hector Gisbert]

Final Remark

One of my first papers as a graduate student, 16 years ago:

New strategies for New Physics search in $B \to K^* \nu \bar{\nu}$, $B \to K \nu \bar{\nu}$ and $B \to X_s \nu \bar{\nu}$ decays

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It is happening!

I look very much forward to more $b \to s \nu \bar{\nu}$ results from Belle II!

Thank You!