CIPANP-HFCKM-Summary

Racha Cheaib
Carla Marín
Alejandro Vaquero

September 4th, 2022

HFCKM: Topics covered and attendance

- 3 HFCKM + 2 combined PPHI/HFCKM sessions

- Exclusive determination of CKM matrix elements
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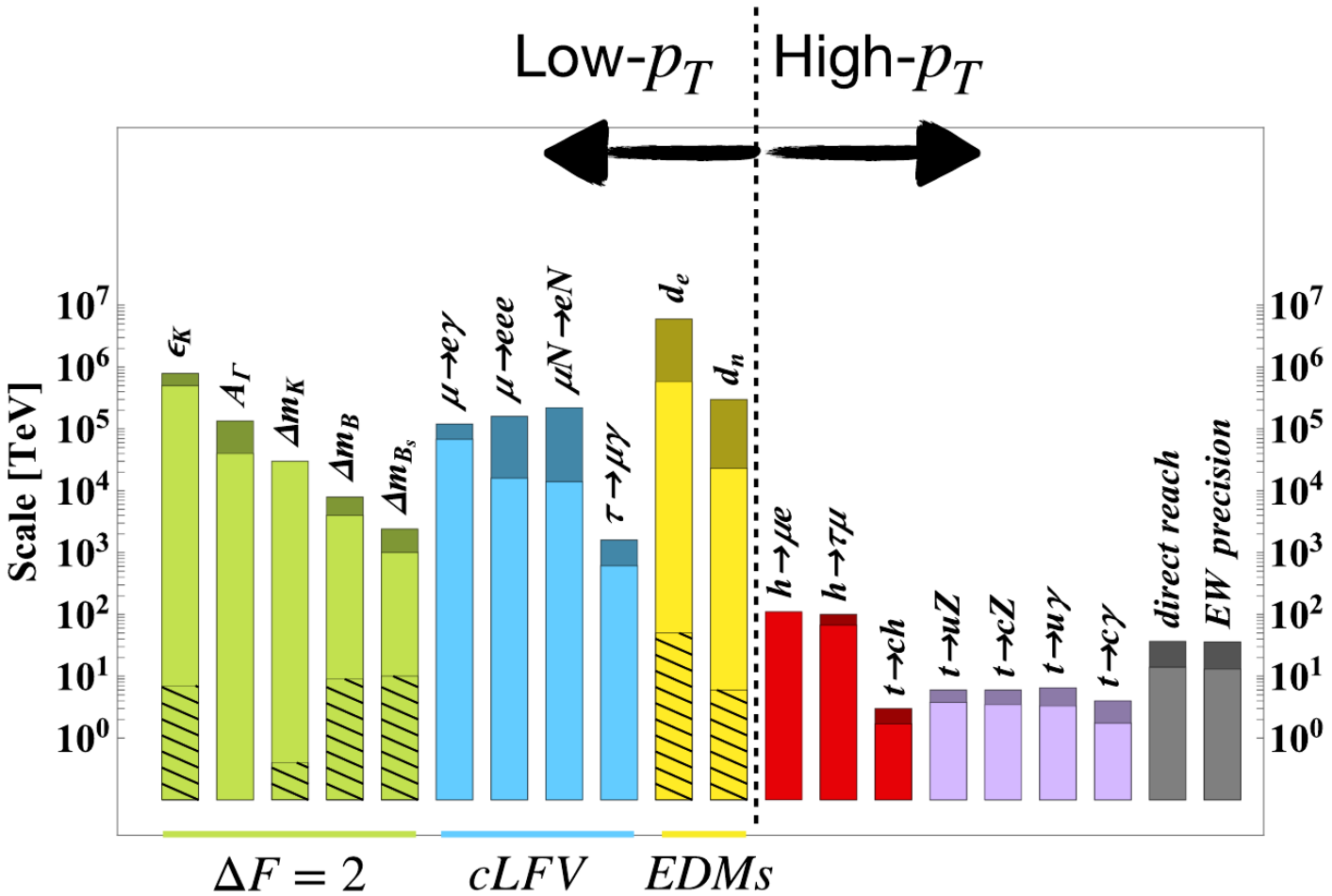
- Rare decays and Lepton Flavor (Universality) violations
- CP symmetry violation
- Interpretation of results and BSM physics

- Attendance approached $\approx$ 20-25 consistently in all our sessions (last one 15)

HFCKM: BSM interpretations

- Why indirect searches? (The intensity frontier)
  - Higher sensitivity for high-energy probes in indirect searches
  - But **no info on physics**

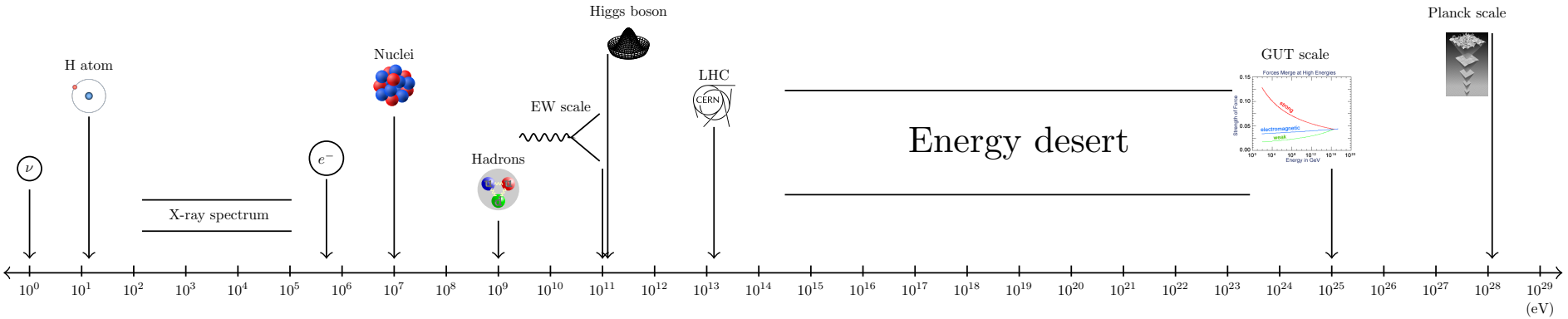
Stangl



HFCKM: BSM interpretations

- Why indirect searches? (intensity frontier)
  - Energy scale for new physics may be too large
    - Effective approach SMEFT including new operators
    - Expected scale depends on the model
    - The tighter a model is constrained, the smaller the NP scale is
    - Unfeasible to explore the whole energy desert with direct searches
    - High-energy tails can give us valuable information (di-electron)

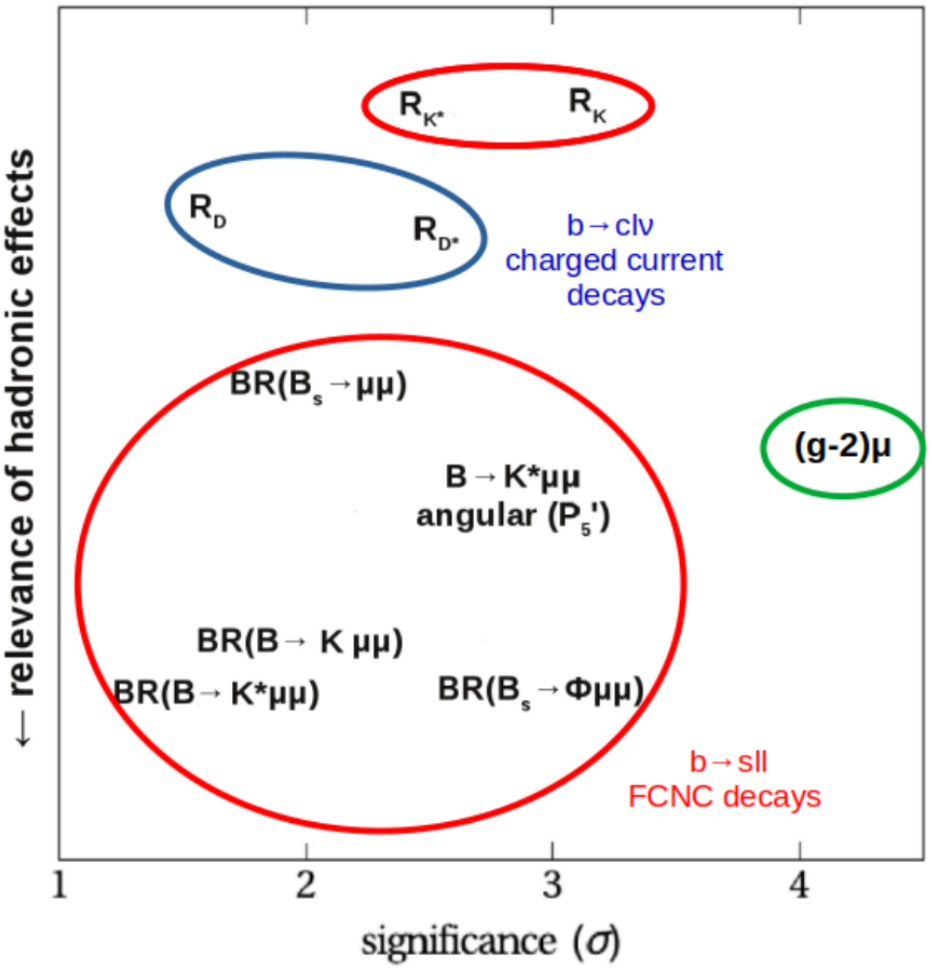
Altmannshofer, Stangl, Fedele



HFCKM: BSM interpretations

- Why indirect searches? (intensity frontier)

Altmannshofer, Ligeti



HFCKM: BSM interpretations

- A myriad of models have been proposed to address current open questions in flavor physics

- Highlights: Altmannshofer
  - Z' with gauged $L_\mu - L_\tau$
    - Works well with $b \to s\ell\ell$ anomalies
    - Might explain the m_W problem as well
  - Leptoquarks
    - Most versions ruled out
    - U_1 leptoquarks fits current bounds for $R(D^{(*)})$ and $R(K^{(*)})$

HFCKM: BSM interpretations

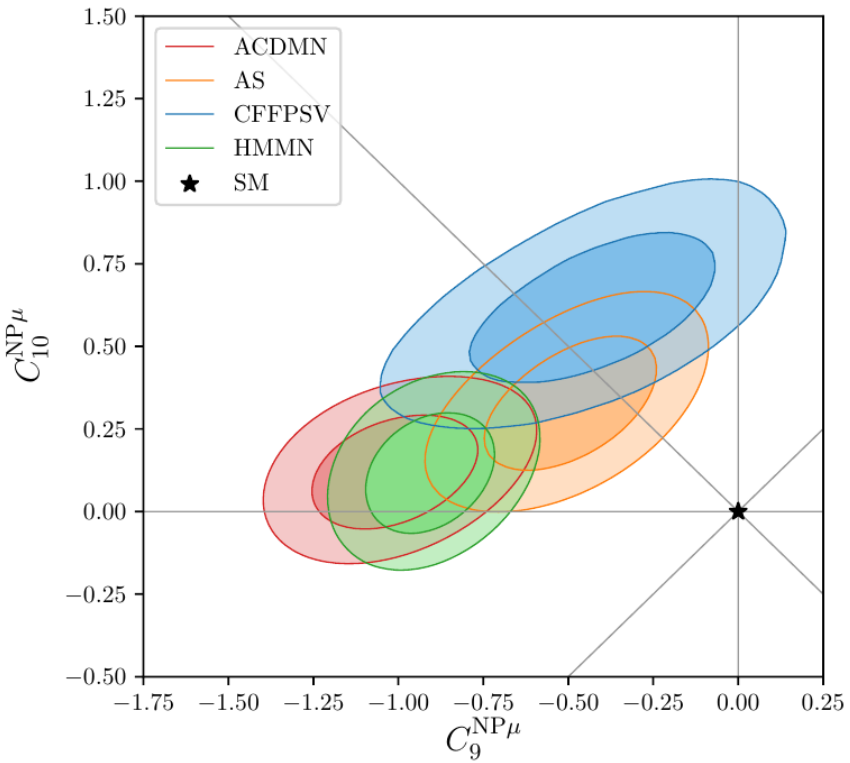
- Global fits constrain models in a consistent way
  - Different models constrain different processes $\rightarrow$ provide a likelihood function
  - Likelihoods cannot be considered separately Stangl, Fedele
    - All observables and likelihoods must be computed for every model and compared to experiment
    - RG loop effects mixes different sectors

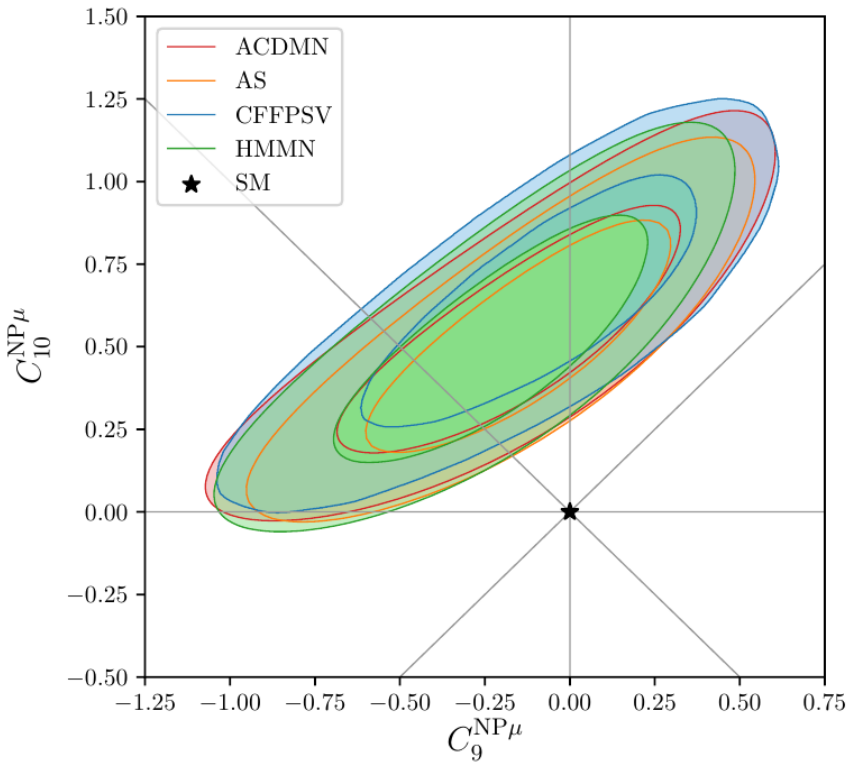
Software packages to streamline the whole procedure within the SMEFT framework

- **Flav-io** package, computes hundreds of flavor observables with theoretical uncertainties
- **WCxf** format, to store/exchange Wilson coefficients for different models
- **Wilson** package, runs the RGE above and below the EW scale, matching the SMEFT to the Weak Effective Theory
- **Smelli** package, encompassing all the previous tools Stangl

HFCKM: BSM interpretations

- Other groups have developed different tools — Fedele
  - Allows for a comprehensive comparison
  - Very good agreement between different approaches — Fedele
- Global analysis $b \to s\ell\ell$ including up to 250 observables — Fedele
  - LFU observables are cleaner — Altmannshofer, Fedele

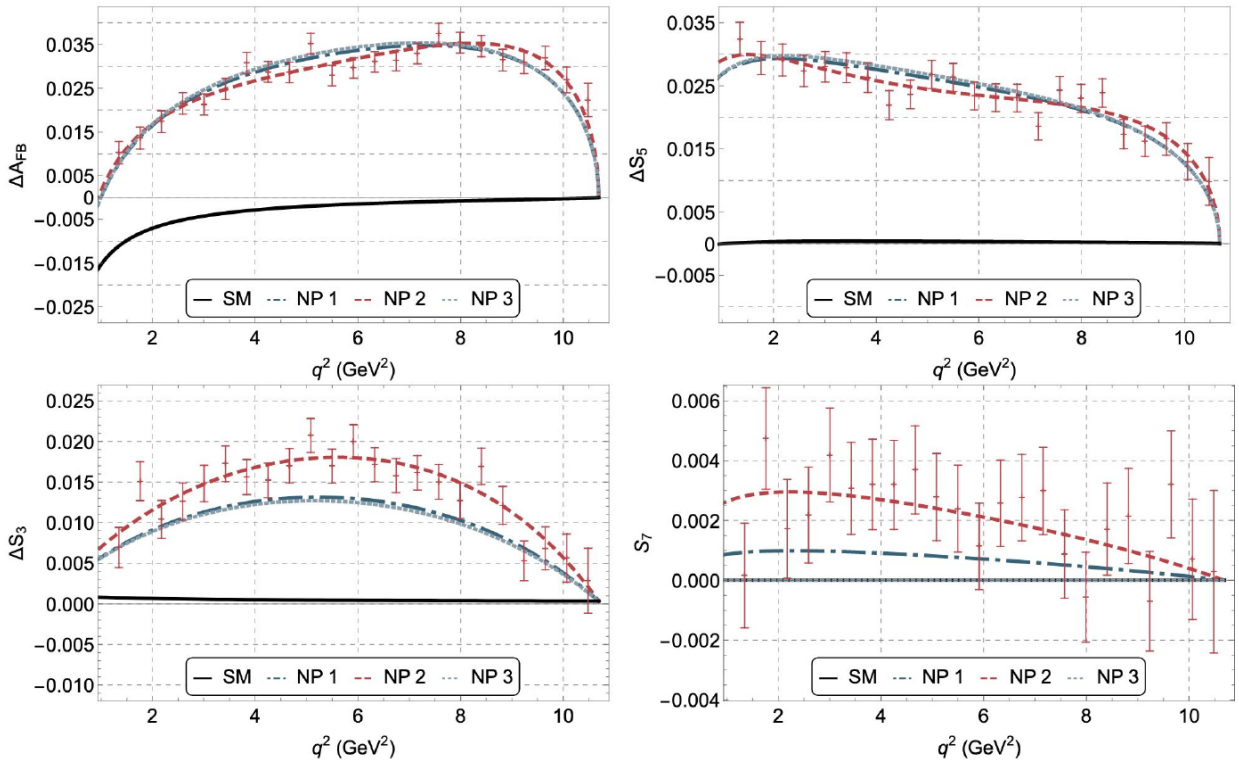




HFCKM: BSM interpretations

- Some groups focus on LFU ratios → EVTGEN Campagna
- Specific tool for NP in $R(D^{(*)})$

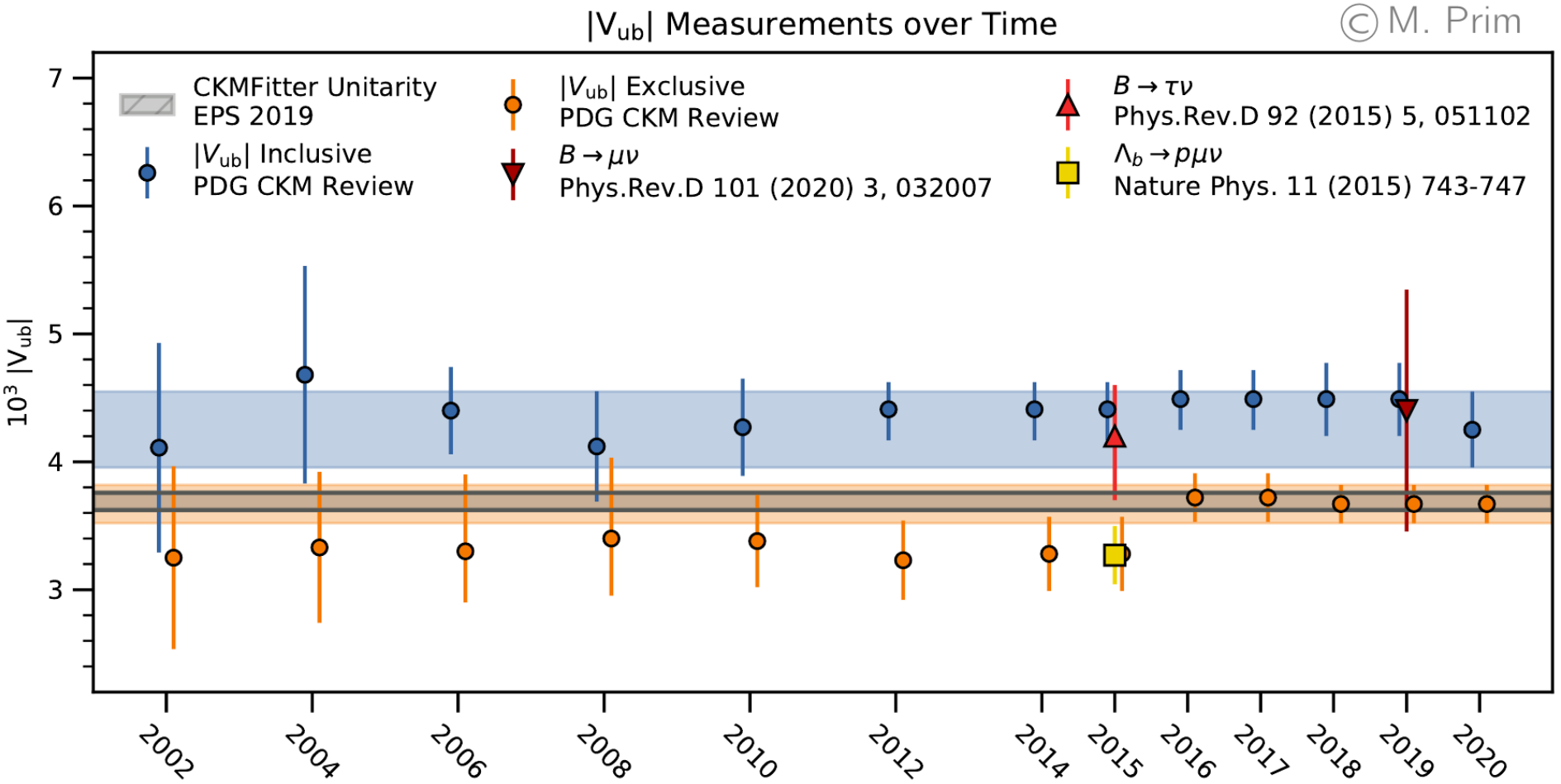
- A^{μ}_{FB} anomaly in Belle data Bobeth
- Work with $\Delta A_{FB} = A^{\mu}_{FB} - A^{e}_{FB}$, almost independent of the parametrization



CKM tensions

HFCKM: CKM tensions

- Long-standing tension between inclusive and exclusive determinations in $|V_{xb}|$



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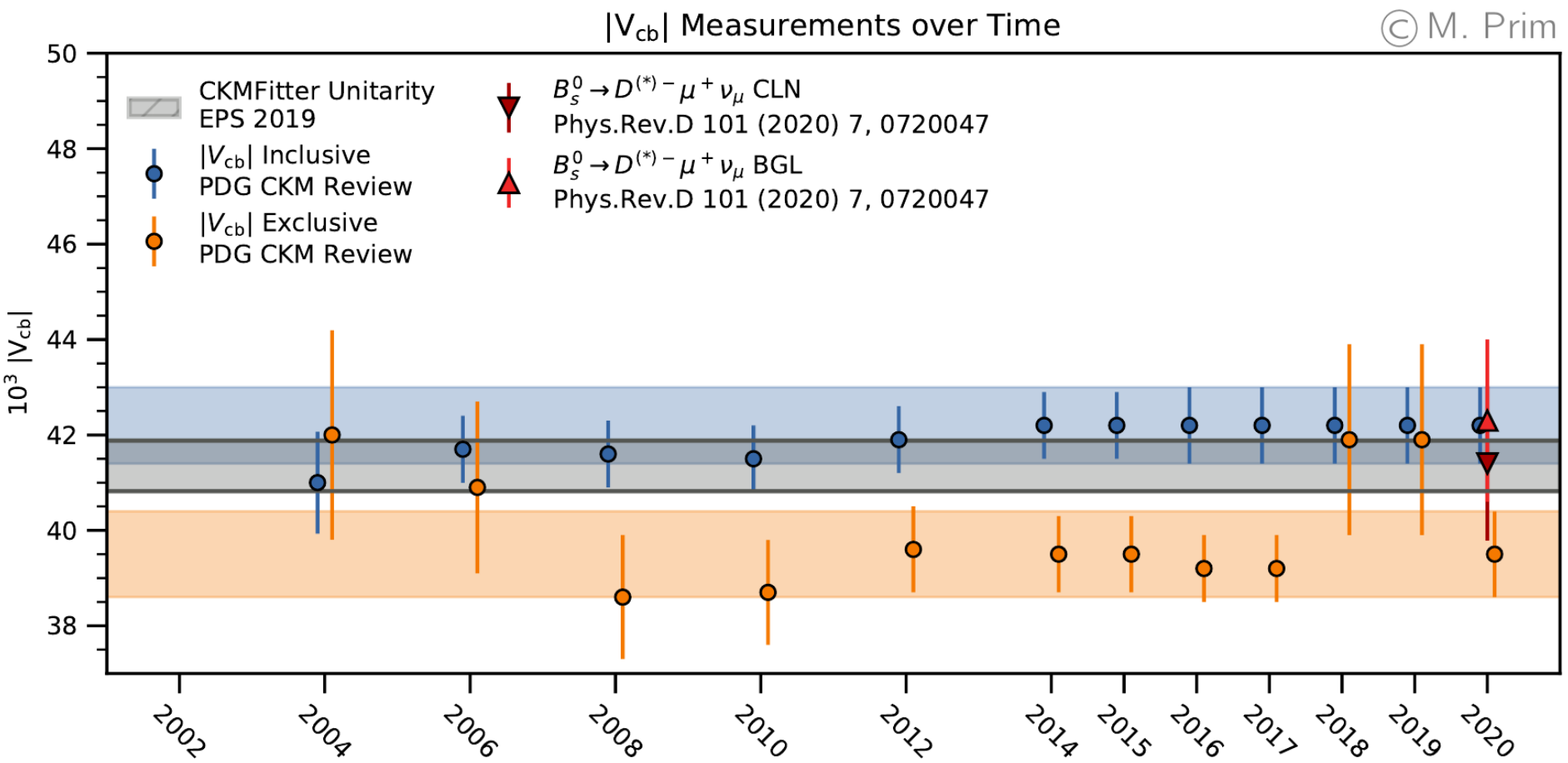
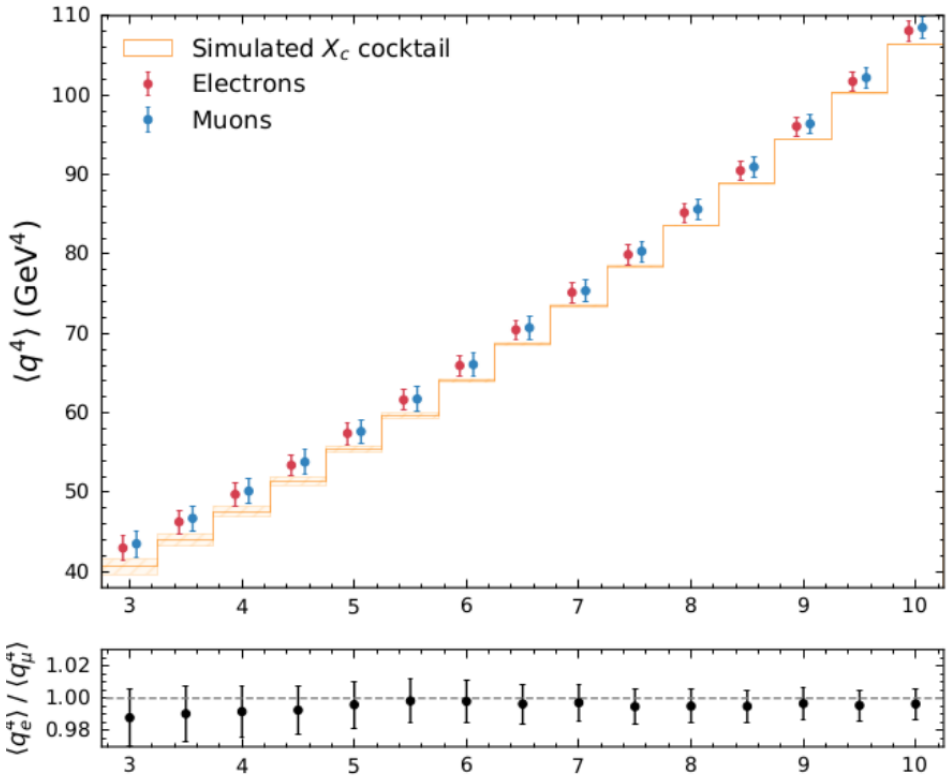


Inclusive CKM

HFCKM: Inclusive CKM

- Improved results from Belle II for $B \to X_u \ell \nu$ and $B \to X_c \ell \nu$ Meier

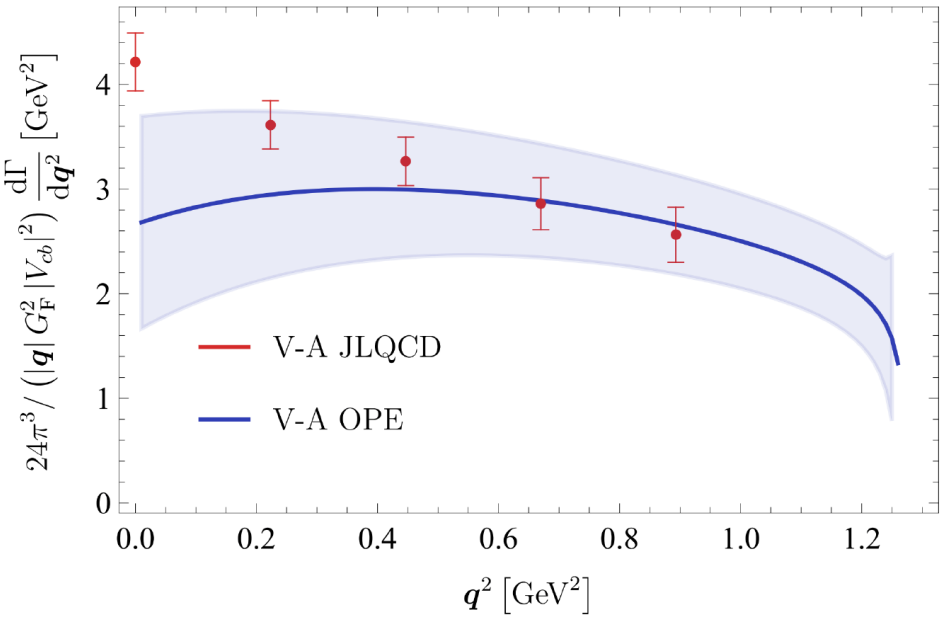
- $B \to X_u \ell \nu$ uses Full Event Interpretation (tagged)
  - Reduces $B \to X_c \ell \nu$ background
  - $|V_{ub}| = 4.10(28) \times 10^{-3}$
- $B \to X_c \ell \nu$ calculation of $\langle q^2 \rangle$ moments with hadronic tagging
  - Moments $\langle q^{2n} \rangle$ up to $n = 4$
  - No deviation between μ and e, but differences at low q^2 accounted in systematic errors
  - $|V_{cb}| = 41.69(63) \times 10^{-3}$



HFCKM: Inclusive CKM

- Recent efforts in LQCD to calculate inclusive observables Mächler
- Uses similarities between a 4pt function, the hadronic tensor and the integral defining the total inclusive decay rate

- Exploratory study with two different ensembles/regularizations comparing to OPE
  - OPE can match the unphysical m_b of the LQCD calculations
  - Expect low q^2 deviations due to OPE
  - First results quite encouraging

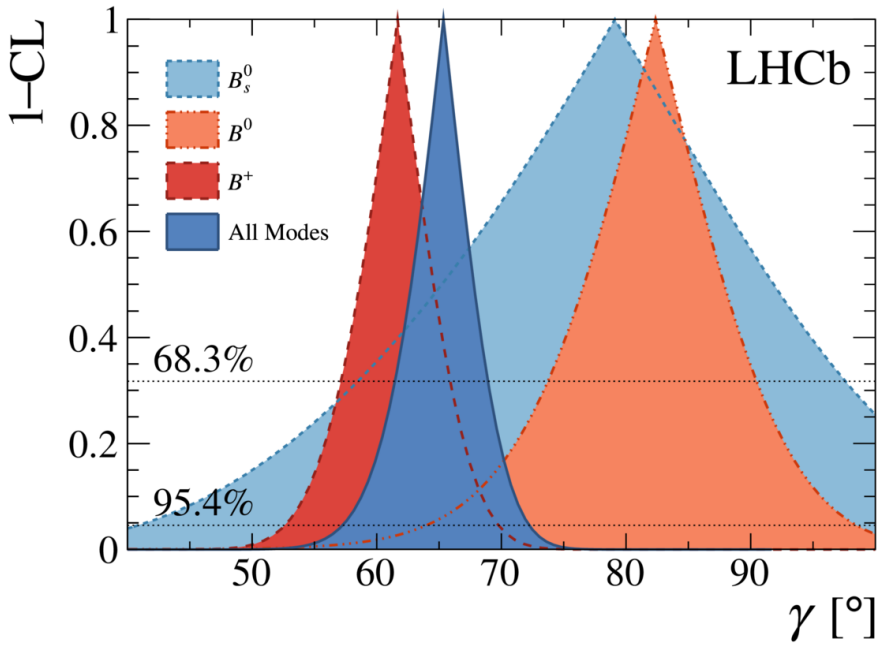


Exclusive CKM

HFCKM: Exclusive CKM

- New results on γ and γ combination by LHCb Sazak
  - $B^{\pm} \to DK^{\pm}$, $D \to K\pi\pi\pi$, up to 85% A_{CP} in phase-space bins, $\delta_\gamma \sim 7^\circ$
  - $B^{\pm} \to Dh^{\pm}$, $D \to hh\pi^0$, $h = \pi, K$, best precision in 11 CP observables, $\delta_\gamma \sim 20^\circ$
  - γ combination: input from B and D decays, 2 new measurements and 5 updated (ones above not included)
    - New LHCb average: $\gamma = 65.4^{\circ}{}^{+3.8}_{-4.2}$, consistent with CKM and UT fits

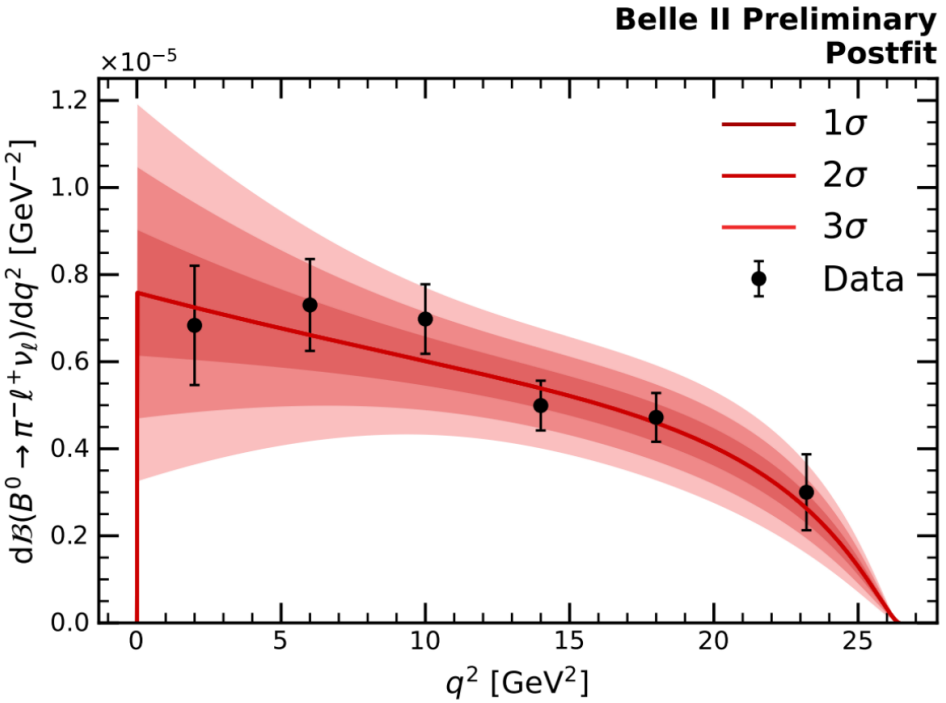
- $|V_{ub}|$ from $B^{\pm} \to K^{\pm}\mu\nu$, slight tension in low and high q^2 regions, using FF from LCSR and LQCD, respectively
- Δm_s in $B_s \to D_s^- \pi^+$: most precise measurement $\delta = 0.051 ps^{-1}$, ok with SM



HFCKM: Exclusive CKM

- Several new results by Belle II in 2022 — Horak
  - Trade-off purity and signal yields in tagged vs untagged analyses
  - $|V_{cb}|$ from tagged and untagged $B \to D^{(*)}\ell\nu$
    - BGL (CLN) fit in q^2 bins, using constraints from Fermilab/MILC LQCD
    - Untagged at 3% precision, comparable to previous results, goal is $< 1\%$
    - Main systematics in the tagged analysis will scale down with more data
  - $\mathcal{B}(B \to \rho\ell\nu)$ ok with SM, motivated by previous tensions in ρ decays
    - Must improve large background systematic to extract $|V_{ub}|$

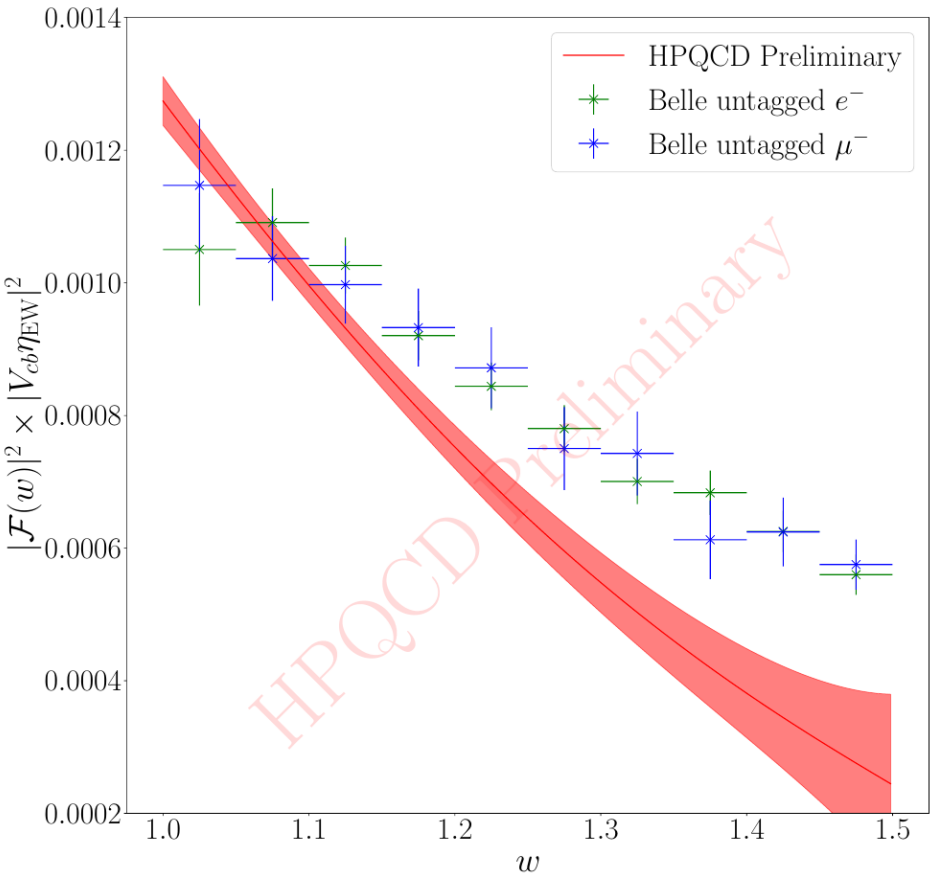
- $|V_{ub}|$ from tagged and untagged $B \to \pi\ell\nu$, $\ell = \mu, e$:
  - Extend BaBar's diamond frame method to reconstruct p_B
  - Fit BCL parametrization, using LQCD Fermilab/MILC constraints
  - BR compatible with SM, competitive $|V_{ub}|$ precision



HFCKM: Exclusive CKM

- State-of-the-art LQCD calculation of $B \to D^* \ell \nu$, preliminary results Harrison

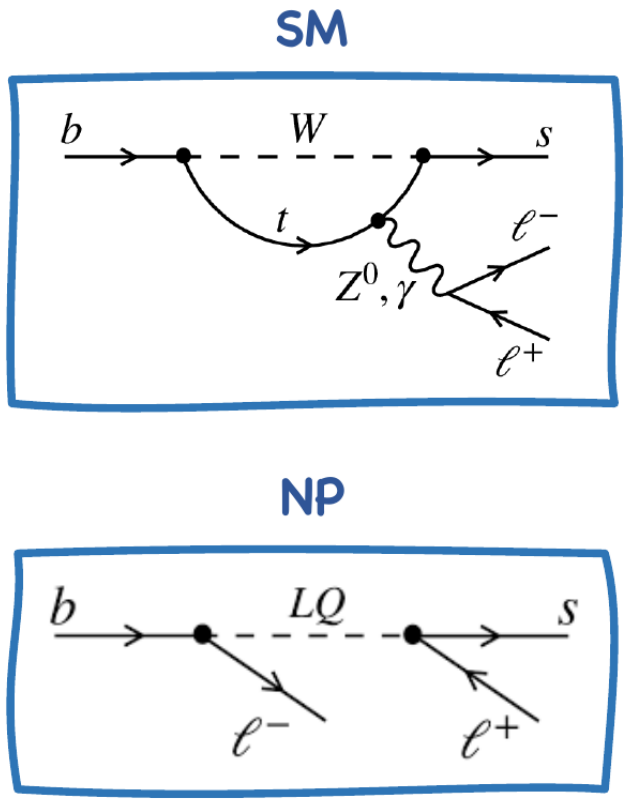
  - Includes tensor ff for BSM
  - Covers the whole q^2 range
  - Full relativistic b quark
    - Simplifies the renormalization
    - Extrapolation to physical m_b
  - Combined extrapolation
  - Decay amplitude in tension with experiment, good agreement with Fermilab/MILC
  - $R_{\mathrm{LQCD}}(D^*) = 0.280(13)$, $|V_{cb}| = 39.2(0.8) \times 10^{-3}$, $\chi^2_{\mathrm{aug}}/\mathrm{dof} = 1.3$



Rare decays and lepton flavor universality

HFCKM: Rare decays and LFU

- Rare decays very suppressed in SM Frau, Martel
  - FCNC processed not possible at tree level
  - Decays allowed only via penguin diagrams
- **Highly sensitive to BSM mediators**
- For $b \to s\ell\ell$ Bouchard
  - Loop suppressed $\propto G_F \sim 10^{-5}$
  - CKM suppressed $\propto |V_{tb}V_{ts}| \sim 0.04$
- **Excellent candidates for indirect searches**



HFCKM: Rare decays and LFU

- Extensive program at LHCb Frau, Hara, Marín
- Achieves most stringent limits up to date in many decays, no clear departures from SM
  - $\mathcal{B}(B \to \mu\mu) < 2.6 \times 10^{-10}$
  - $\mathcal{B}(B_s \to \mu\mu\gamma)_{m_{\mu\mu} > 4.9\mathrm{GeV/c^2}} < 2.0 \times 10^{-9}$
  - $B_{(s)} \to \mu\mu\mu\mu$ most stringent in most channels
- Experimental measurements of $B_s \to \phi\mu\mu$ consistently below the SM predictions
- No signal on $B \to K^*\mu e$, $B_s \to \phi\mu e$ or $B \to \phi\mu\mu$
- LFU searches in a variety of rare decays
  - R_K shows 3.1σ deviation from the SM
    - Isospin partner study of $B^0 \to K^0_s \ell\ell$ and $B^+ \to K^{*+}\ell\ell$ consistent with SM
- Further results in $D \to \mu\mu$, $D \to PP\mu\mu$ and $\Lambda_b \to \Lambda\gamma$ compatible with SM

HFCKM: Rare decays and LFU

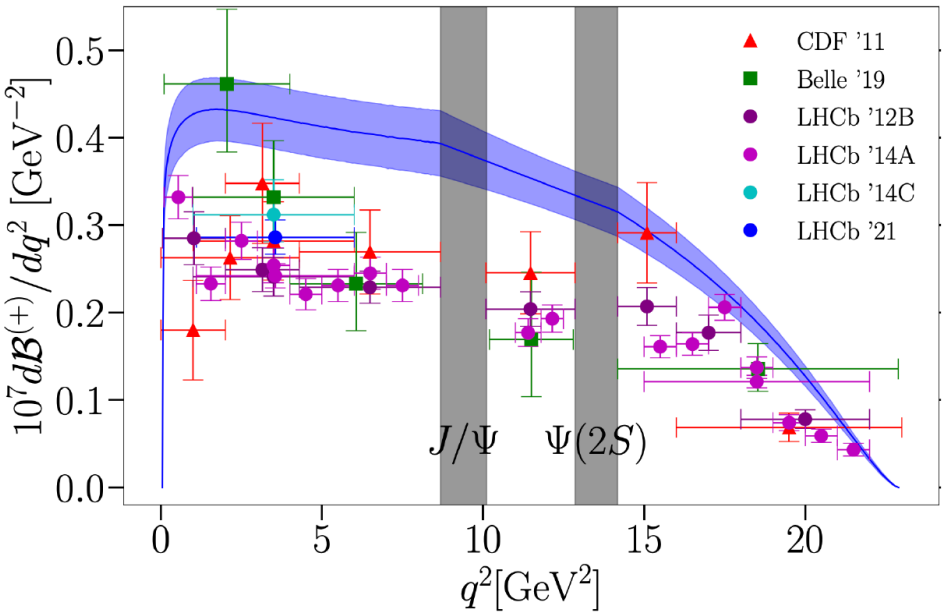
- More focused program in Belle II — Martel, Hara, Prell
- Exploring $B \to K^{(*)}\ell\ell$ decays
  - $B \to K^*\mu\mu$ @ 189 fb^{-1} similar performance $\mu - e$
  - $B \to K\nu\nu$ @ 63 fb^{-1} new inclusive approach, no signal
  - Control channel $B \to J/\psi K$ well understood, approaches Belle precision
- $B \to X_s\gamma$ inclusive with hadronic tagging @ 189 fb^{-1}
  - Results competitive with BaBar and keep improving

- New measurement of LFU ratios — Hara
  - FEI increases efficiency by 50% wrt Belle
  - $R(X_{e/\mu})$ inclusive semileptonic ratio most precise, compatible with SM
  - Aim for $R(X_{\ell/\tau})$

HFCKM: Rare decays and LFU

- State-of-the-art LQCD calculation of $B \to K\ell\ell$ Bouchard

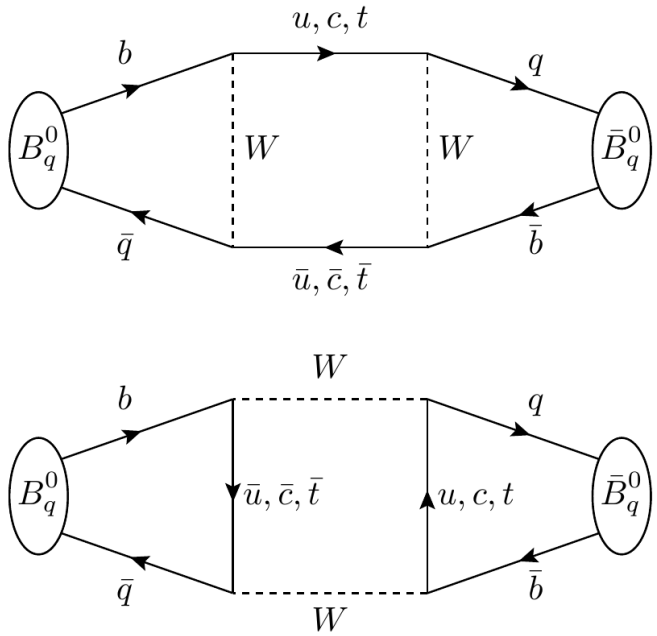
- Covers the whole q^2 range
- Full relativistic b quark
  - Simplifies the renormalization
  - Extrapolation to physical m_b
- Combined extrapolation
- Matches expected Belle II precision @ 50 ab^{-1} for $B \to K\nu\nu$
- Confirms tensions with experiment



CPV

HFCKM: CPV

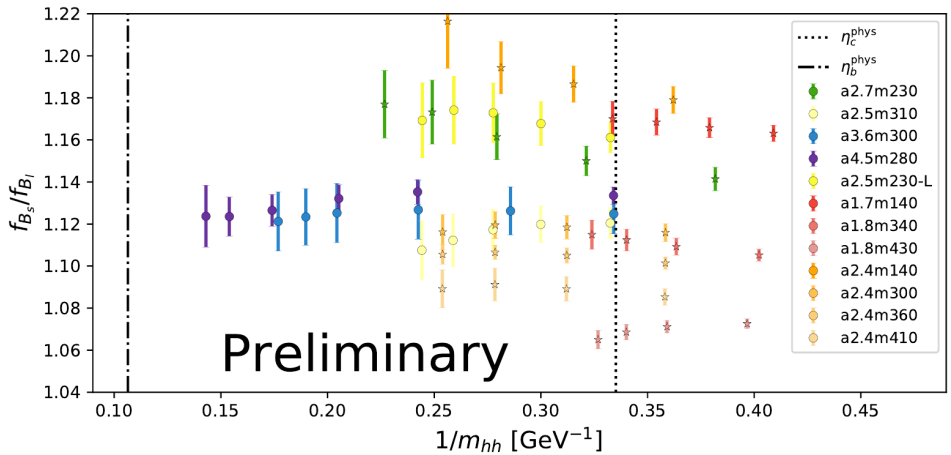
- CP violating processes in the SM Erben, Zlebcik, Villa
  - B- and D-mixing, enhanced by t quark
  - Interference between mixing and decay
  - Related to angles of the unitarity triangle
  - BSM physics introduces inconsistencies that can be detected
- **Good place to look for NP**

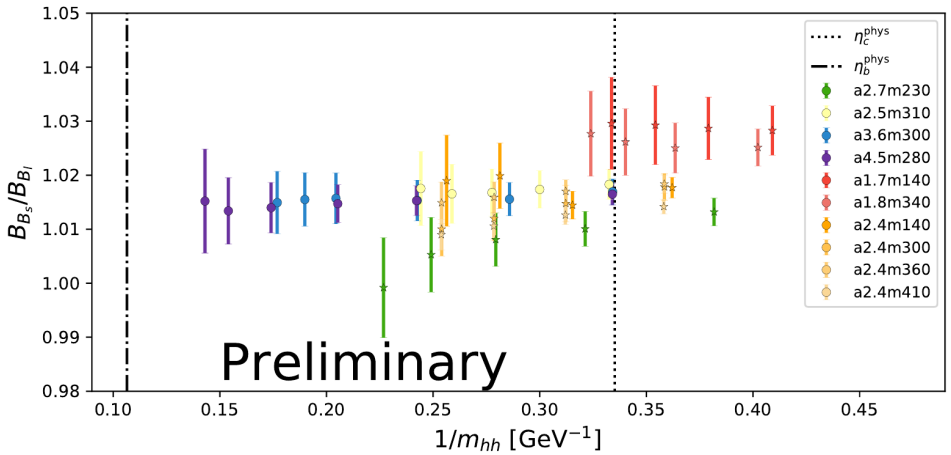


HFCKM: CPV

- Ongoing state-of-the-art B-mixing LQCD calculation, advanced state — Erben

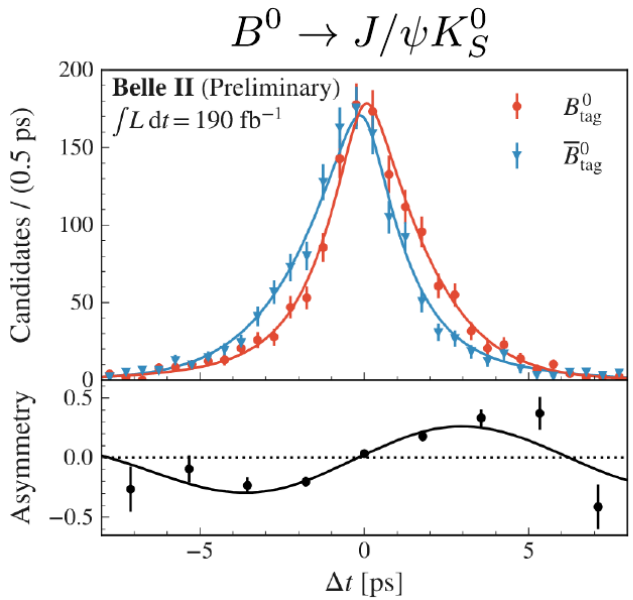
- DW action for light and heavy quarks
  - Simplifies the renormalization
    $$\rightarrow \begin{pmatrix} O_1 & 0 & 0 \\ 0 & O_{2,3} & 0 \\ 0 & 0 & O_{4,5} \end{pmatrix}$$
  - Extrapolation to physical m_b
- Simultaneous fit 2pt and ratios (better than 3pt) to reduce correlations
- Direct calculation of volume effects with available ensembles
- Mild dependence with m_b

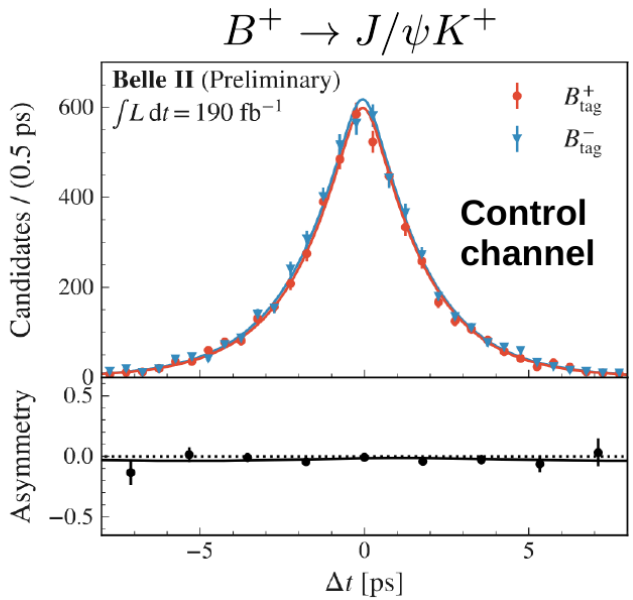




HFCKM: CPV

- Belle II CPV program focused to highlight B-factories strengths Zlebcik, Prell
  - Can measure time resolution with tagging
  - Time dependent measurements $\Upsilon(4S) \to BB$, with very competitive results for lifetime and mixing frequency, bound to improve
    - $B \to D^{(*)}\pi$ @ 190 fb^{-1} competitive with previous B factories
    - $B \to J/\psi K^0_S$ golden channel, controlled systematics $\sim$ Belle
    - $B^0 \to K^0_S K^0_S K^0_S$ extremely interesting but challenging
    - $A(K^0\pi^0)$ from $B \to K^0_S\pi^0$ exclusive to B factories @ 190 fb^{-1}





HFCKM: CPV

- Extensive CPV program in LHCb — Villa
- Includes charm and bottom physics
- Charm decays
  - Benefits from the bin-flip method of Dalitz plots
  - In $D^0 \to K^0_s \pi\pi$ ruling out CP violation due to mixing (just direct)
  - Precise results for the ys, improving WA
  - $A_{cp}(D^0 \to \pi\pi)$ new results with improved techniques show evidence of direct CP violation
- Bottom decays
  - Solid evidence for direct CPV in $B \to hhh$ in several channels
  - Clear evidence for $h = \pi, K$
  - First results for $V(hh)h \to$ new systematics due to $\omega - \rho$ mixing
  - Small tensions in $B \to \rho K$ with BaBar/Belle
  - Evidence of P breaking from $B \to ppK\pi$ analyzing triple-product asymmetries

HFCKM: Conclusions

- Great progress in both experiment and theory
  - Systematization of global fits
  - Large amount of new LQCD calculations at unprecedented precision
  - LHCb keeps producing high precision results (CMS)
  - Belle II is reaching the point it becomes more precise than Belle
- Many anomalies to explore

Hopefully we will find NP soon