Recent results in B-physics

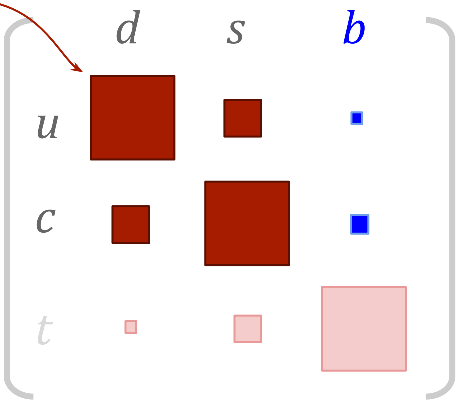
Peter Mandeville Lewis | *The University of Hawaii at Manoa*

DPF-Pheno 2024 | *Pittsburgh*

Why *b*-physics?

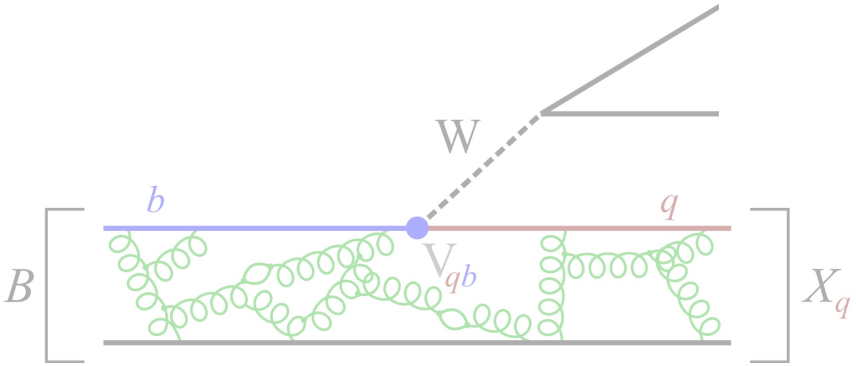
Rich flavor dynamics

- **CKM** close to *unit matrix*: loops, boxes, large CP asymmetries, flavor oscillations are visible
- Straightforward NP enhancements to heavy ***b*** vertex could be competitive to small SM contributions



Theoretically tractable

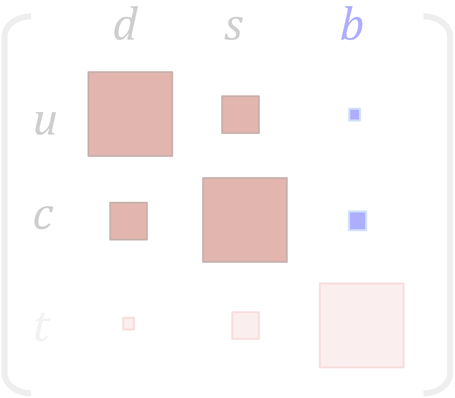
- **Hadronic component** is (usually) **factorizable** from weak component
- Heavy quark methods useful, with $\Lambda_{\mathrm{QCD}}/m_b \sim 0.1$



$$\frac{d\Gamma}{dq^2} \propto |V_{qb}|^2 |f(q^2)|^2$$

A powerful and clean window to NP…

Why *b*-physics?



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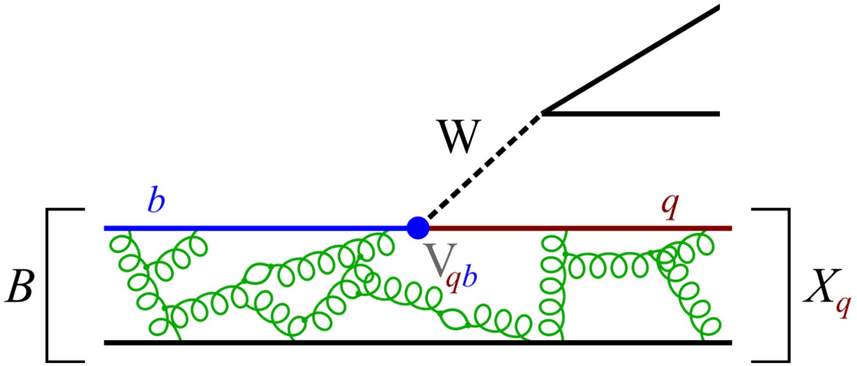


$$\frac{\mathrm{d}\Gamma}{\mathrm{d}q^2} \propto |V_{qb}|^2 |f(q^2)|^2$$

A powerful and clean window to NP…

Hot topic: Lepton Universality

LU: no lepton flavor preference in nature

Evidence of *violation* (LUV) in semileptonic decays:

$$R(H_{\tau/\ell}) = \frac{\mathcal{B}(B \to H\tau\nu)}{\mathcal{B}(B \to H\ell\nu)}$$

$$H = D, D^*, X, \pi, \ldots$$
$$\ell = e, \mu$$

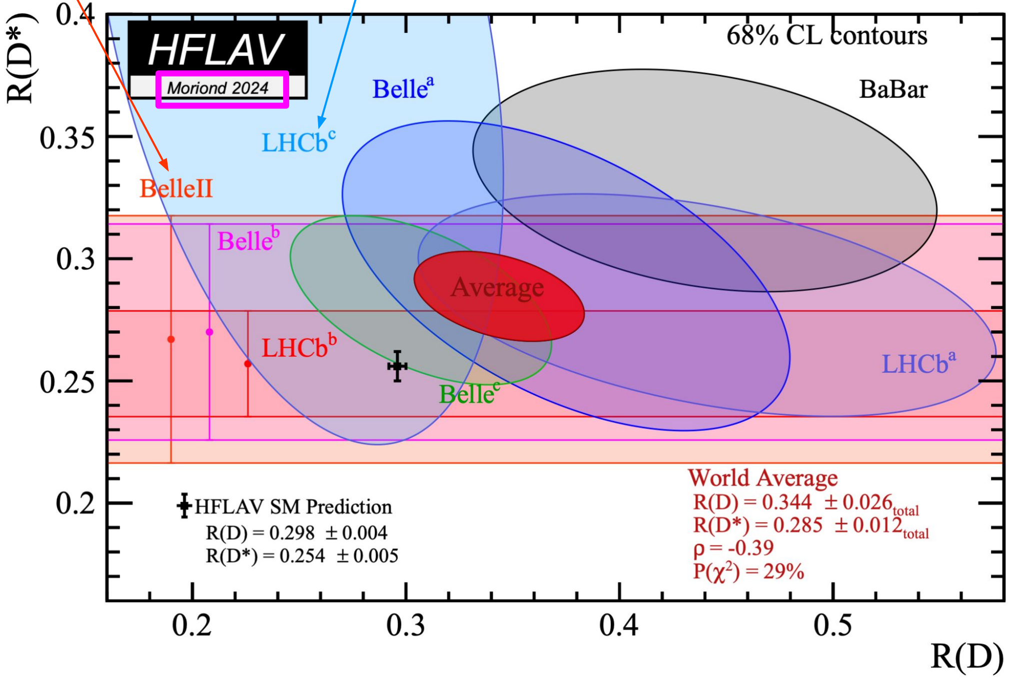
"Traditional" modes

Novel, featured today

(next decade?)

arXiv:2401.02840 (Jan 2024)

Moriond 2024, **featured today**



(interesting hints in **angular observables** too!)

Longstanding **~3σ tension** with SM from BaBar, Belle, LHCb, Belle II… *a sign of NP?*

Hot topic: flavor-changing neutral currents

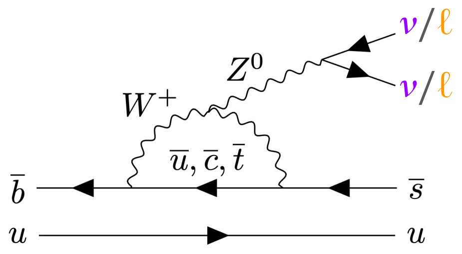
No tree-level SM process

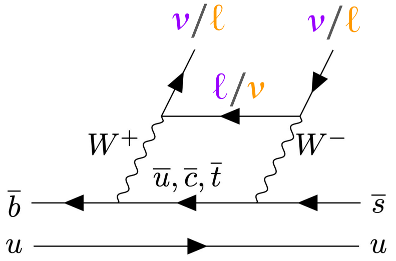
- $b \to s\ell^+\ell^-$: experimentally clean, theoretically more challenging (factorization breaks down due to photon exchange)
- $b \to s\nu\nu$: theoretically clean (no photon exchange), experimentally challenging (two missing neutrinos)

Signs of tension with SM:

- Branching fractions and **angular observables**
- R_K and R_{K^*} ratios *(gone now? Thanks LHCb!)*

$$R_{K^{(*)}} = \frac{\mathcal{B}\left(B \to K^{(*)}\mu^+\mu^-\right)}{\mathcal{B}\left(B \to K^{(*)}e^+e^-\right)}$$

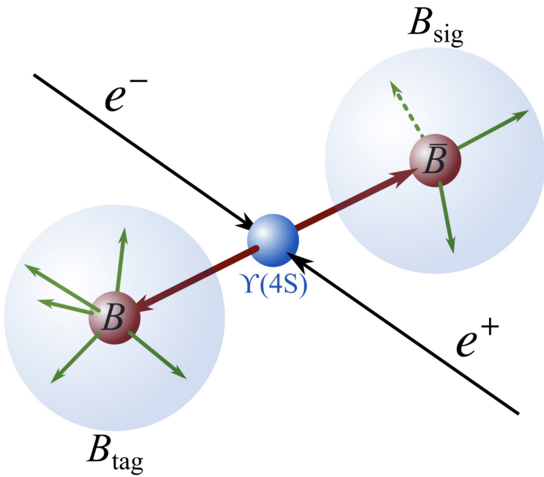




Lingering (and consistent) signs of NP here too!

How?

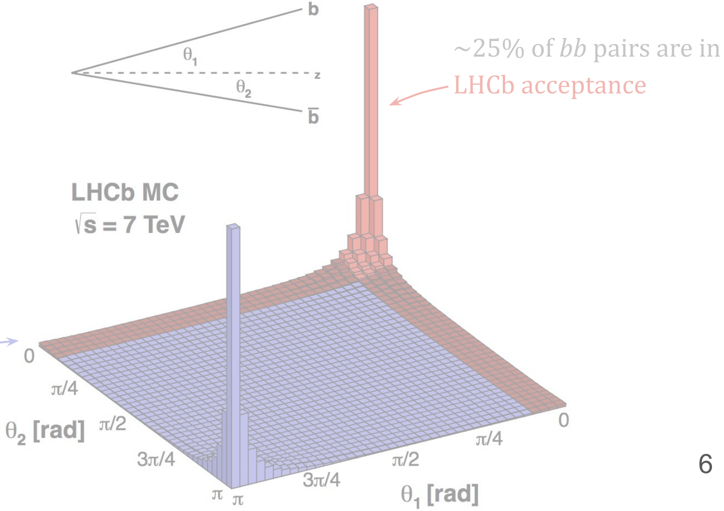
B-factories (BaBar, Belle, Belle II)



- e^+e^- colliders on $\Upsilon(4S)$ resonance ($\to B\bar{B}$)
- Low cross-section $\to$ high luminosity
- Full kinematics known
- **Spherical** events
- Exactly one collision per trigger

Hadron colliders (LHCb, ATLAS, CMS…)

- Parton collisions produce $b\bar{b}$ pairs
- Hadronize into all sorts of b mesons *and* baryons
- High cross-section
- Full kinematics not known
- Production preferentially **along beam**



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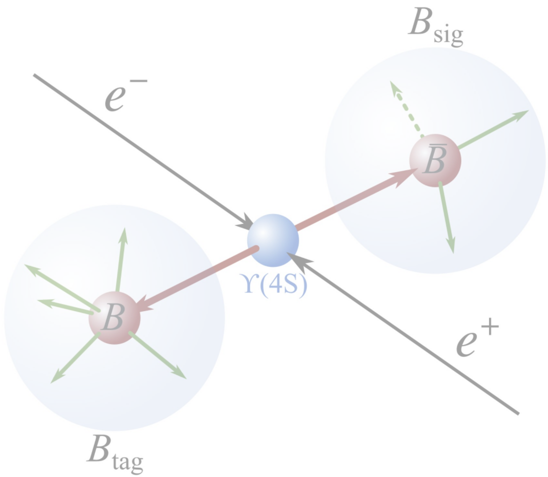

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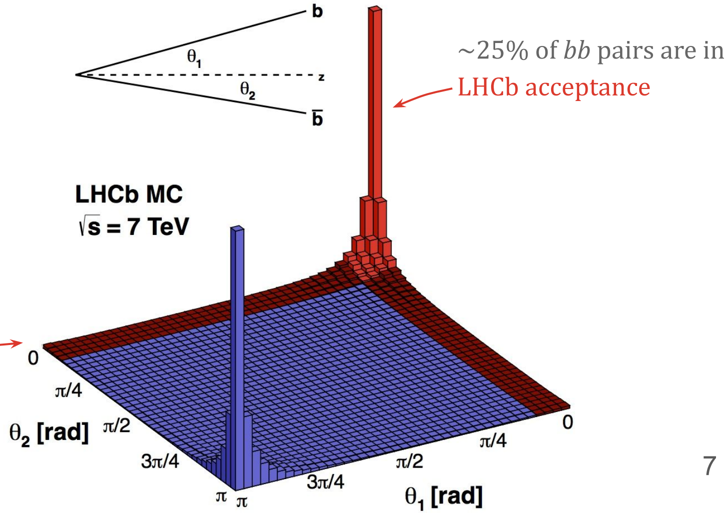
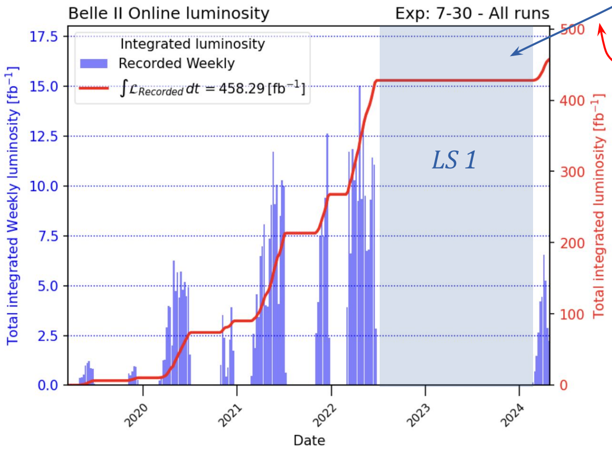
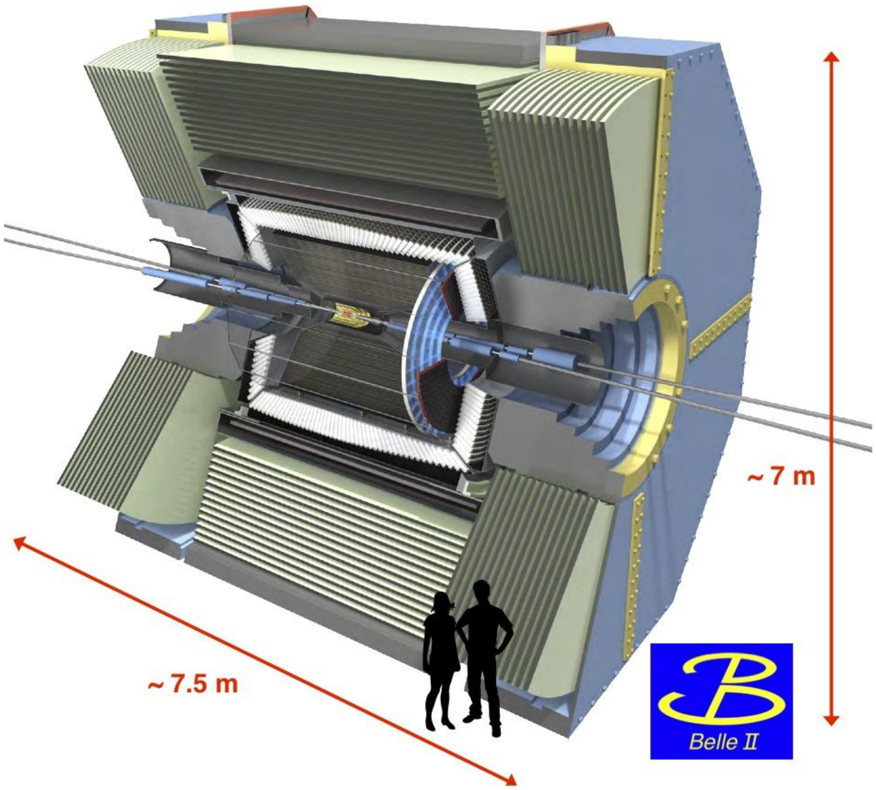


Belle II

- Nearly hermetic detector
- Modest boost; B mesons fly $\sim$100 μm
- Ideal for **neutral** or **invisible** final states
- World-record luminosity before *Long Shutdown 1,* which has just ended
- Current results use $\leq$362 fb^{-1} at $\Upsilon(4S)$: similar to BaBar and Belle already, but **<1% of target**



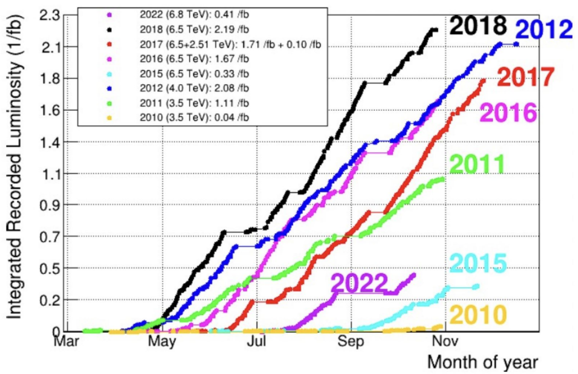
Target 50,000!

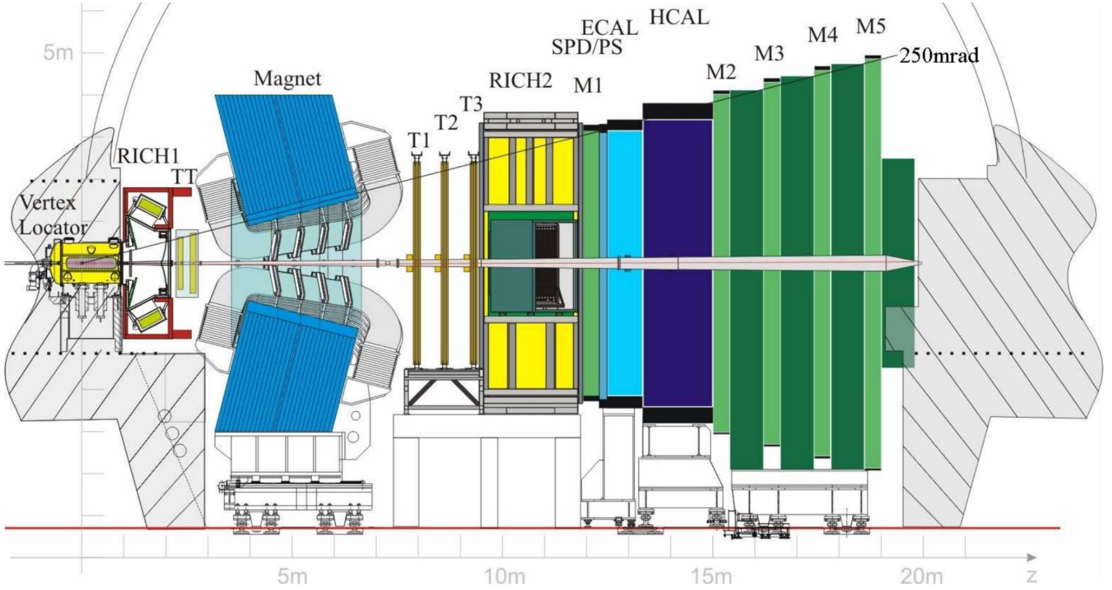


Belle II

LHCb

- Single-arm forward spectrometer
- Large boost; *B* mesons fly ~1 cm (easily resolvable)
- Excels at **charged particle** final states, notably **muons**





Recent results: Lepton Universality

Belle II: R($X_{\tau/\ell}$)

First measurement of $R(X_{\tau/\ell})$ as an inclusive test of the $b \to c\tau\nu$ anomaly

(Accepted by PRL, April 2024)

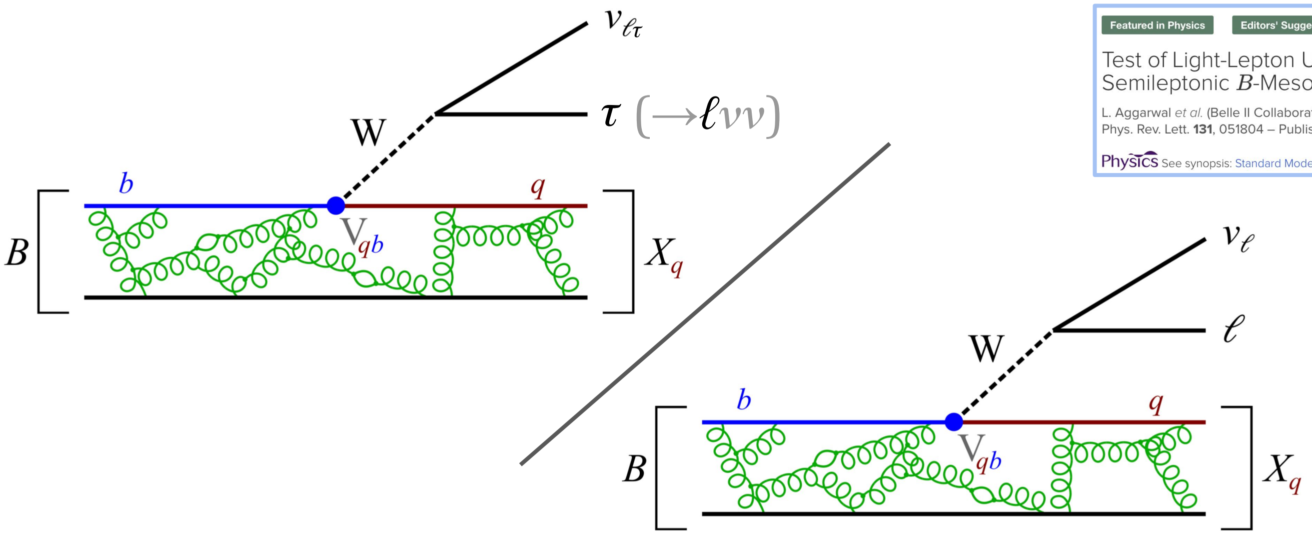
A followup to last-year's *light* lepton ratio $R(X_{\mu/e})$, a first

Featured in Physics | Editors' Suggestion | Open Access

Test of Light-Lepton Universality in the Rates of Inclusive Semileptonic B-Meson Decays at Belle II

L. Aggarwal *et al.* (Belle II Collaboration)
Phys. Rev. Lett. **131**, 051804 – Published 2 August 2023

Physics See synopsis: Standard Model Stays Strong for Leptons



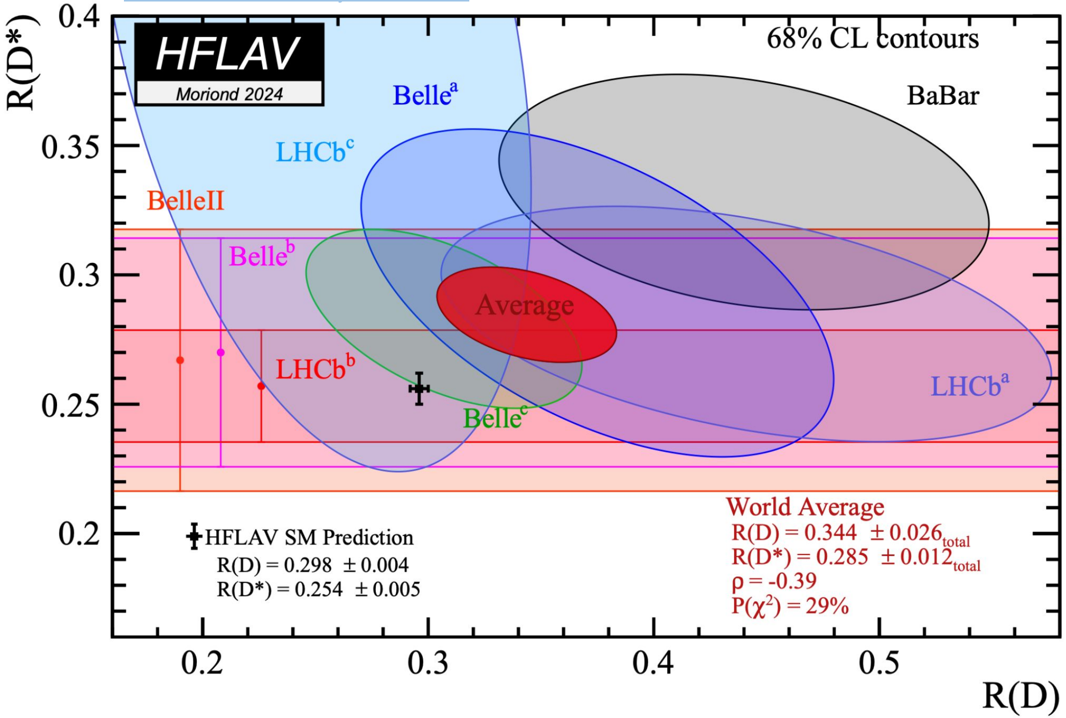
The $b\to c\tau\nu$ excess

Q: *What if the "anomaly" is just a shared systematic?*

Or a problem with the (shared) theory description?

Is there anything we can do except ***measure R(D) and R(D*) over and over again****?*

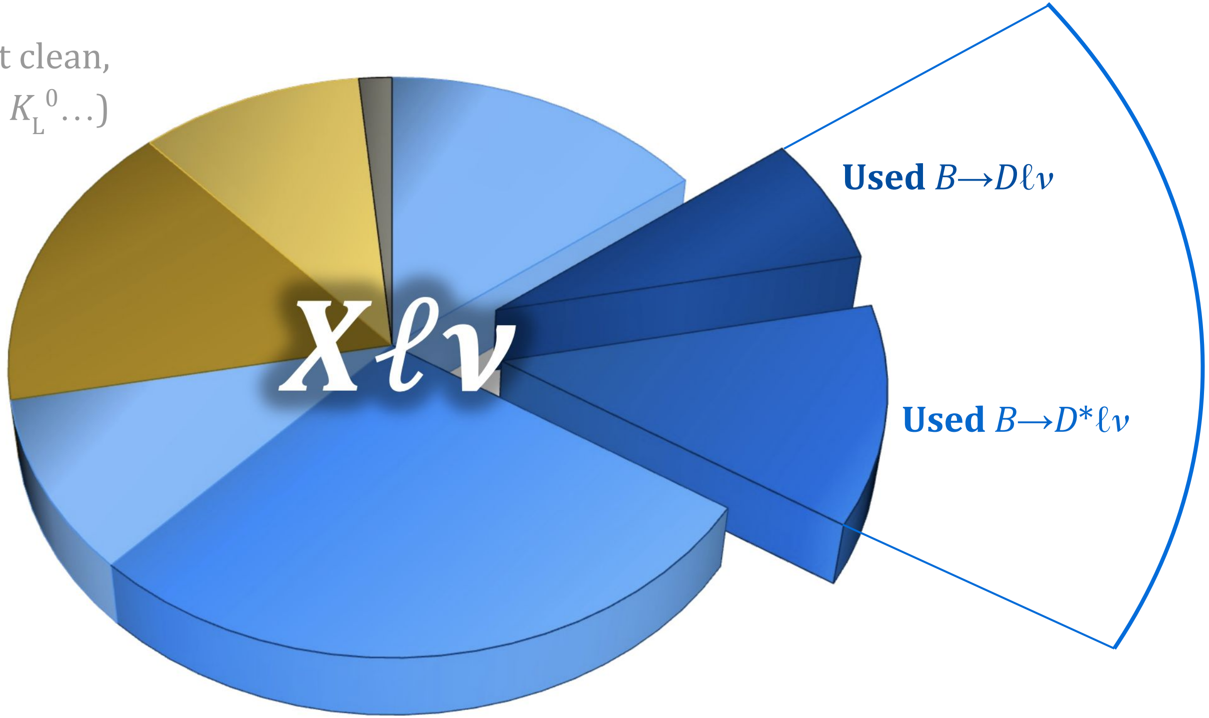
Moriond 2024 summary from HFLAV



Consider…

Composition of $B \to X\ell\nu$ events

(**not well-known**, not clean, missing ν, K_L^0…)



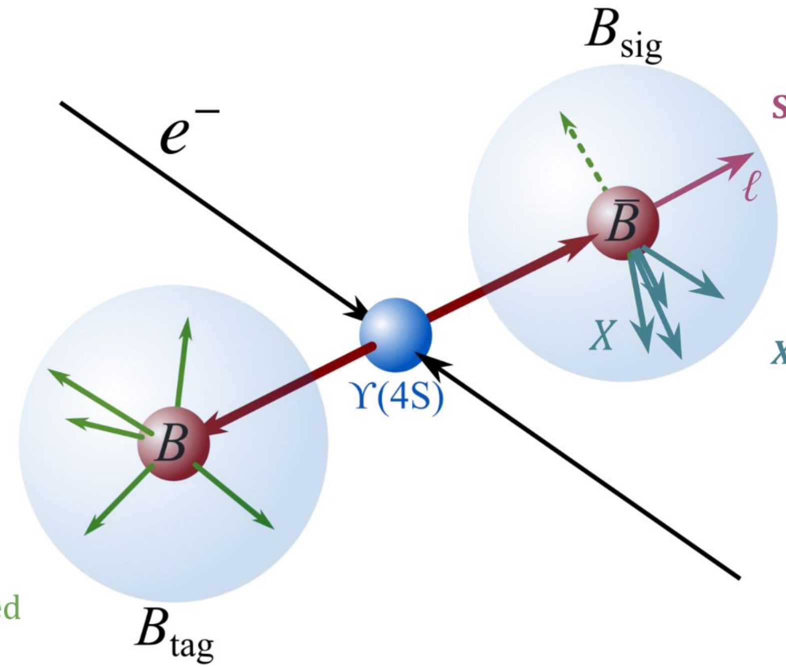
Used: <20%

Well-known, clean decays (mostly $K^{\pm}$,$\pi^{\pm}$)

No missing particles

*So then: how can we use "**not well-known**" as the signal?*

General strategy



Signal lepton:
- High electron or muon likelihood

***X* system:**
- **Everything else in the event…**
- (passing quality criteria)

Tag-side *B* meson
- Fully reconstructed
- Tight tag quality selections

*Use a **data-driven corrections** for the "**not well-known**" stuff…*

Data-driven corrections

The ***invariant mass of the X system*** controls the **physics** we know the least about

Control variable

$$M_X^2 = \begin{pmatrix} E_X \\ \overrightarrow{p_X} \end{pmatrix}^2$$

Extraction variable

$$M_{\text{miss}}^2 = \left[\begin{pmatrix} E_{\text{CMS}} \\ \overrightarrow{p_{\text{CMS}}} \end{pmatrix} - \begin{pmatrix} E_{\text{CMS}}/2 \\ -\overrightarrow{p_{B_{\text{tag}}}} \end{pmatrix} - \begin{pmatrix} E_\ell \\ \overrightarrow{p_\ell} \end{pmatrix} - \begin{pmatrix} E_X \\ \overrightarrow{p_X} \end{pmatrix}\right]^2$$

Independent test variable

$$q^2 = \left[\begin{pmatrix} E_{\text{CMS}}/2 \\ -\overrightarrow{p_{B_{\text{tag}}}} \end{pmatrix} - \begin{pmatrix} E_X \\ \overrightarrow{p_X} \end{pmatrix}\right]^2$$

*Using M_X to reweight the signal **fixes*** the observed mismodeling*

$R(X_{\tau/\ell})$ results

$$R(X_{\tau/\ell}) = 0.228 \pm 0.016\ (\mathrm{stat}) \pm 0.036\ (\mathrm{syst})$$

SM: 0.223 ± 0.005

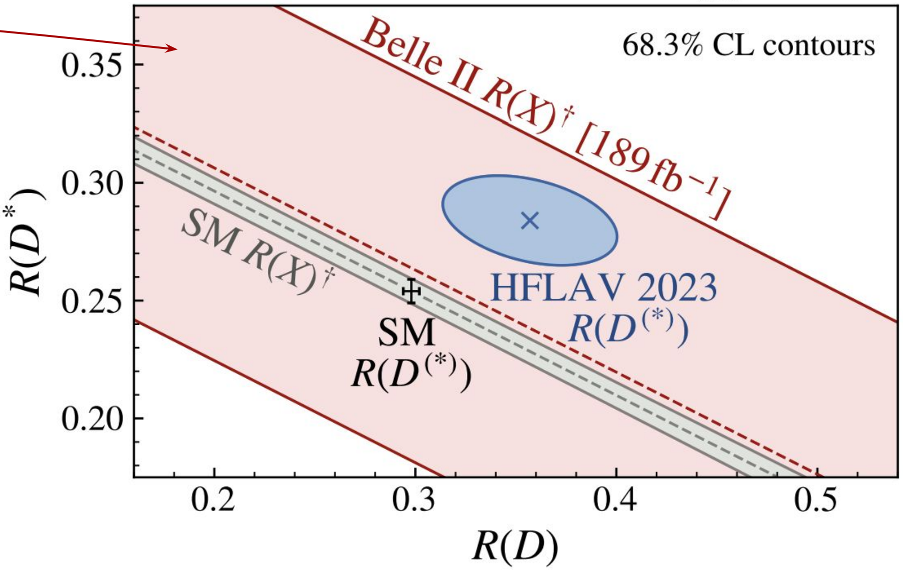
From 2D fit to lepton momentum and $M_{\mathrm{miss}}{}^2$

Constraints **inferred** on $R(D(*))$ are weak, *but*:

- **Statistics dominant**, with **<0.4% of the target Belle II dataset**
    - (even the systematics are statistics-dominant*)
- **Independent** of $R(D^*)$ measurement: ~0.4% statistical overlap, different theory descriptions, different observable

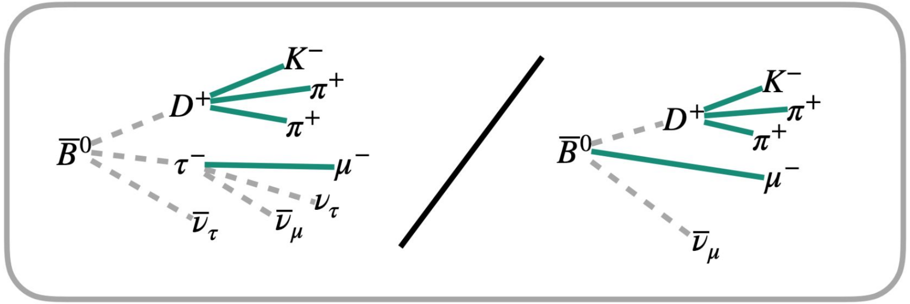
Take-home: Belle II has developed a powerful and independent new test of the $b \to c\tau\nu$ anomalies driven by **new inclusive techniques**

† = with expected SM contributions of $D^{**}_{(\mathrm{gap})}, X_u$ removed

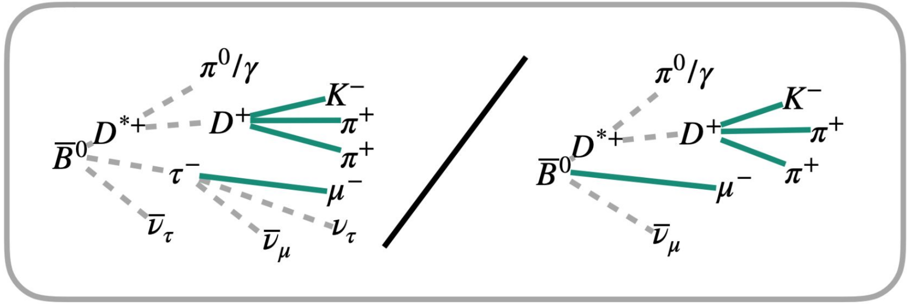


LHCb: New $R(D^{+})$ and $R(D^{*+})$

$R(D^{+})$ =



$R(D^{*+})$ =



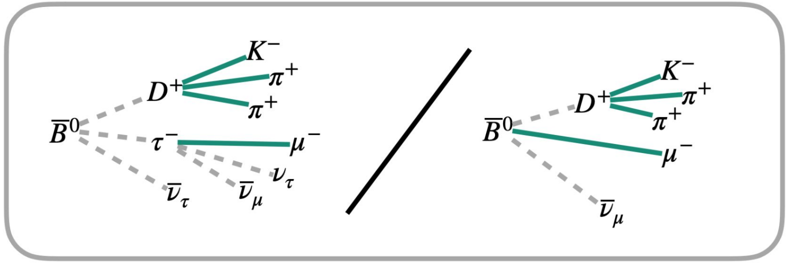
[Moriond EW 2024]

LHCb: New $R(D^+)$ and $R(D^{*+})$

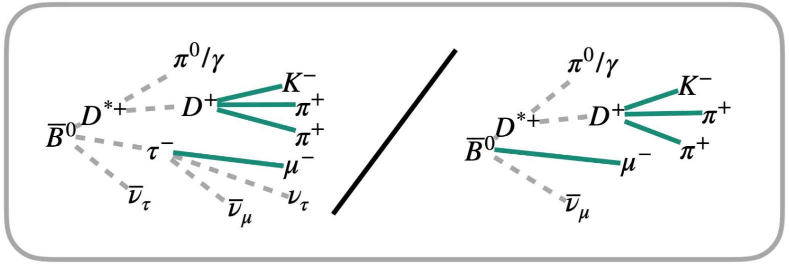
Main goal: measure isospin-related $R(D^+)$ to complement $R(D^0)$ [LHCb 2023*]

Simultaneous measurement shares visible final state: $[D^+ \to \boldsymbol{K^- \pi^+ \pi^+}] + \boldsymbol{\mu^-}$

R(D⁺) =



R(D*⁺) =



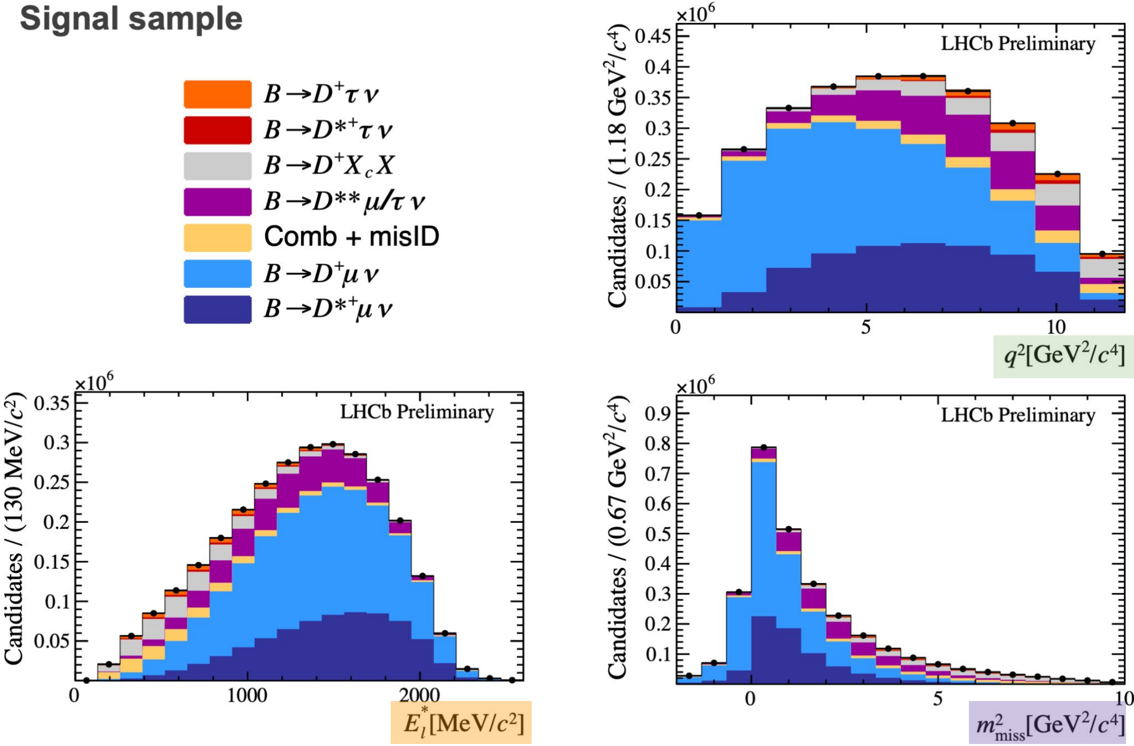
Control of many classes of backgrounds essential…

Signal extraction

3D binned fit:

- *Variables*: m^2_{miss}, E_l^*, q^2
- *Components*:
  - Signal (*D* and *D**)
  - Normalization (*D* and *D**)
  - Feed-down from **1P** D^{**} states
  - Muon **mis-ID**
  - (other charm, neutronic, combinatorial background)
- Simultaneous fit to *four data samples:*
  - **Signal sample** ($D^+\mu^-$)
  - 1p sample ($D^+\mu^-\pi^-$)
  - 2p sample ($D^+\mu^-\pi^+\pi^-$)
  - 1K sample($D^+\mu^-K^{\pm}$)

Signal sample



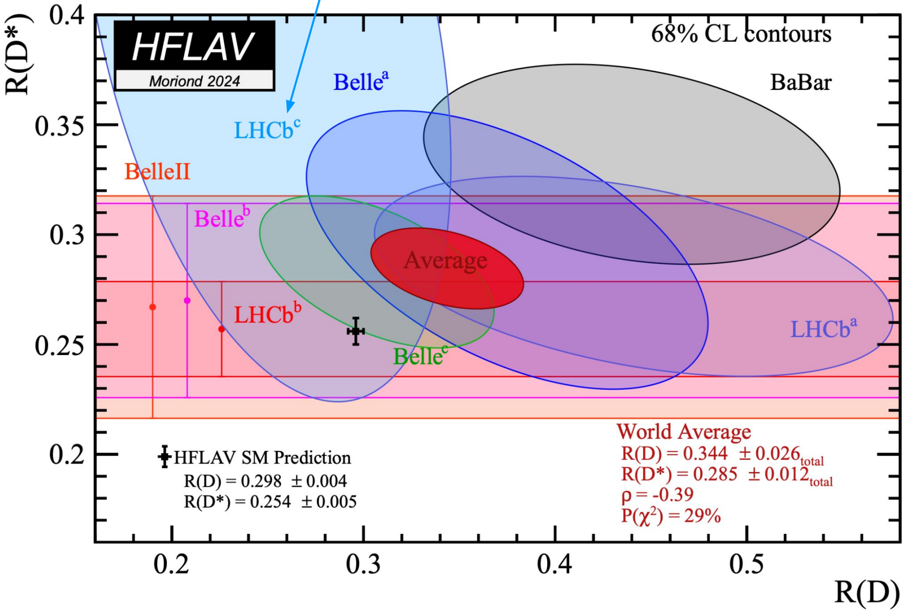
(preliminary) Results

Two new and promising methods* for simulation and reweighting used

Summary

- Compatible with SM at **0.78σ**
- Compatible with previous world average at **1.09σ**
- Uncertainties from stats and systematics approximately equal
  - (Dominant systematics remain FFs and BFs)

$R(D^+) = 0.249 \pm 0.043(stat) \pm 0.047(syst)$
$R(D^{*+}) = 0.402 \pm 0.081(stat) \pm 0.085(syst)$
$\rho = -0.39$



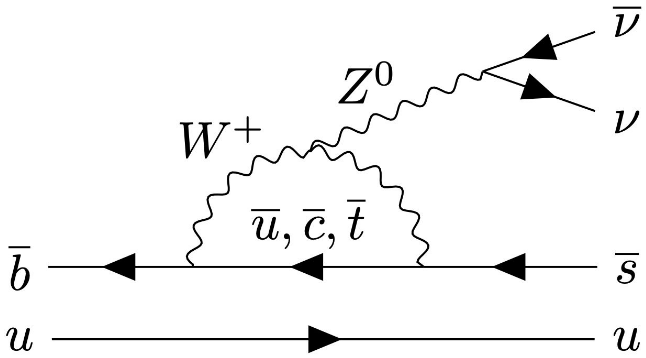
Take-home: new $R(D)$ channel, with new methods, unlocked at LHCb

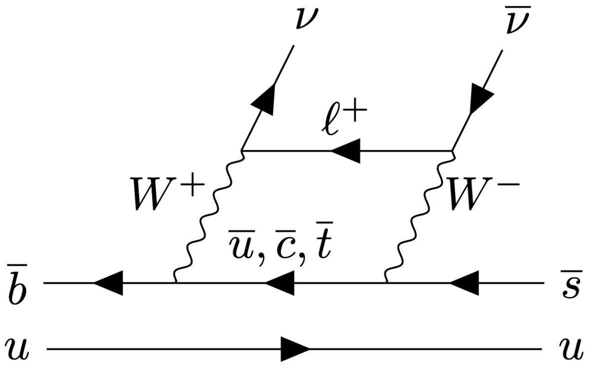
Recent results: FCNCs

Belle II: $B^+ \to K^+\nu\nu$

Evidence for $B^+ \to K^+\nu\bar{\nu}$ decays

(Accepted by PRD, Feb 2024)

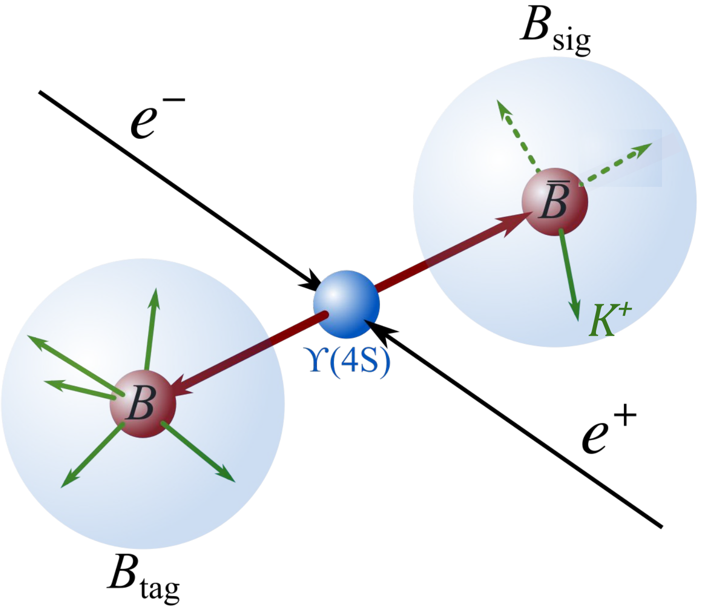




Belle II: $B^+ \to K^+\nu\nu$

Two approaches run in parallel:

- *Inclusive tag (**ITA**)*: **no** reconstruction of second *B*. High efficiency, high backgrounds.
- *Hadronic tag (**HTA**)*: **strict** reconstruction of second *B*. Low efficiency, low backgrounds.



This is something only Belle II can do…

$B^+ \to K^+\nu\nu$ signal extraction

Variables

- η: a signal classifier* remapped so that signal is **flat**
- q^2_{rec}: inferred neutrino mass squared

ITA:

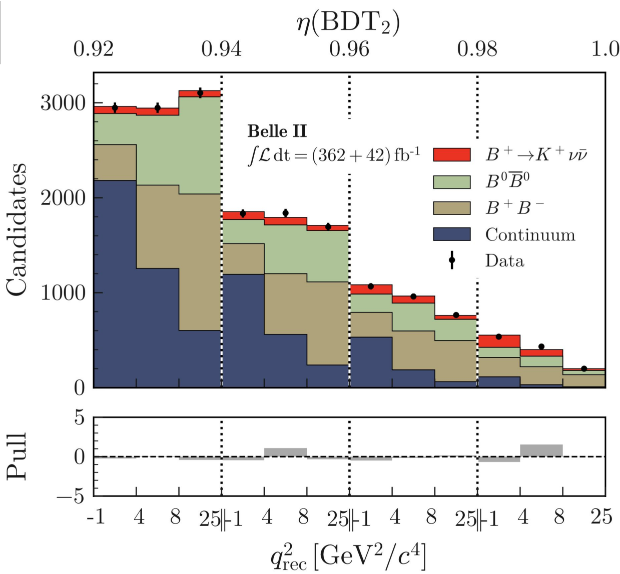
- Simultaneous on-/off-resonance fit
- (4 bins in η)×(3 bins in q^2_{rec})

HTA:

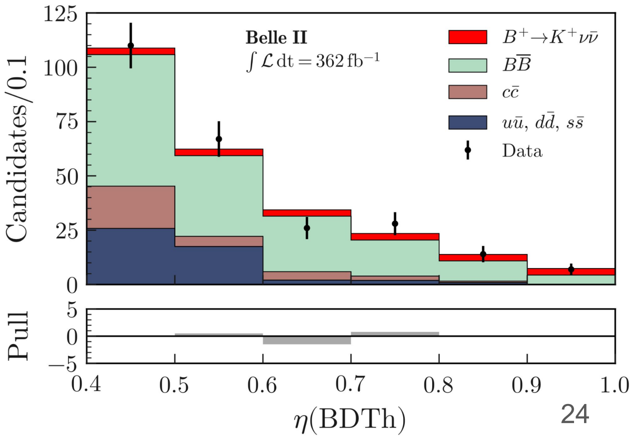
- Fit to six bins of signal classifier η(BDTh)

(the key is extensive controls/validations)

ITA



HTA



$B^+ \to K^+\nu\nu$: results

Combined ITA and HTA:

- Signal strength ($\mu_{\text{SM, short-range}} \equiv 1$):

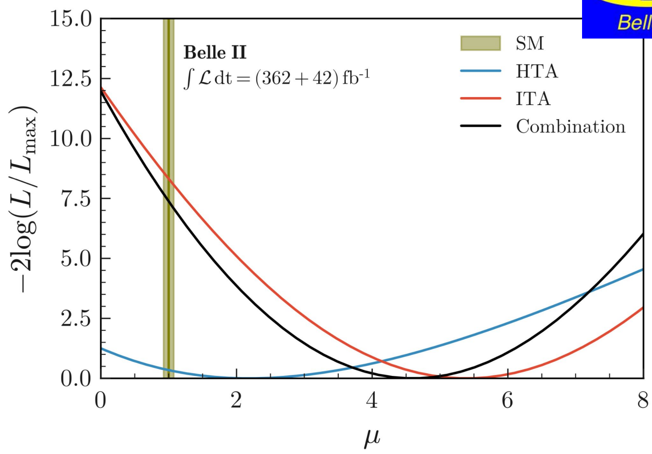
$$\boxed{\mu = 4.6 \pm 1.0(\text{stat}) \pm 0.9(\text{syst}) = 4.6 \pm 1.3}$$

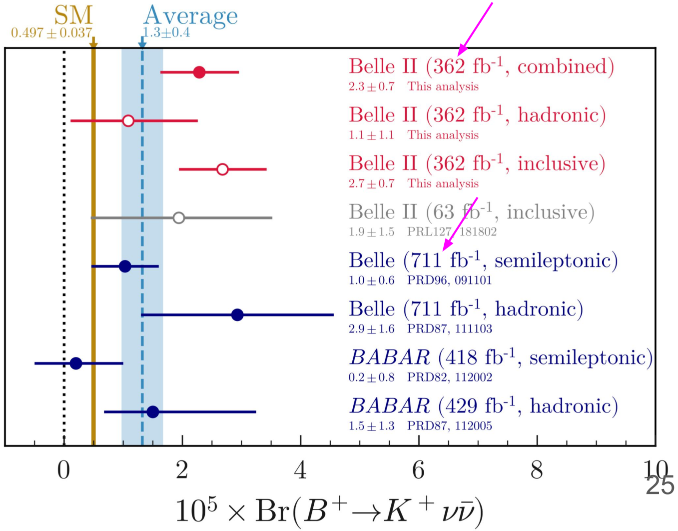
- Branching fraction:

$$\boxed{\left[2.3 \pm 0.5(\text{stat})^{+0.5}_{-0.4}(\text{syst})\right] \times 10^{-5} = (2.3 \pm 0.7) \times 10^{-5}}$$

ITA and HTA results are **compatible**, **independent**, and both approximately equally limited by stats and systematics

Take-home: first evidence for $K^+\nu\nu$ (3.5σ), BF in excess of SM by 2.7 σ; enabled by **new inclusive techniques**





LHCb: $B^0 \to K^{*0}\mu^+\mu^-$

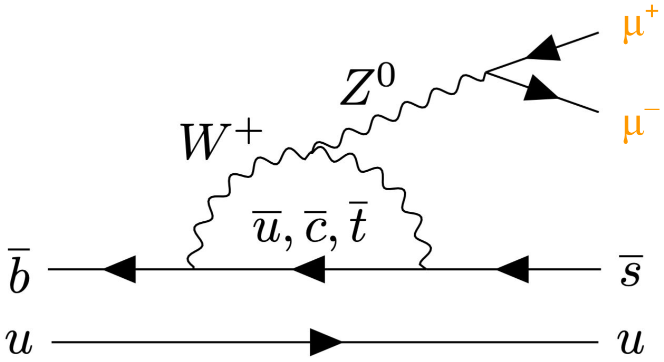
LHCb-PAPER-2024-011 ([LHC EFT slides]())

Complementary followup to

PHYSICAL REVIEW D **109,** 052009 (2024)

Determination of short- and long-distance contributions in $B^0 \to K^{*0}\mu^+\mu^-$ decays

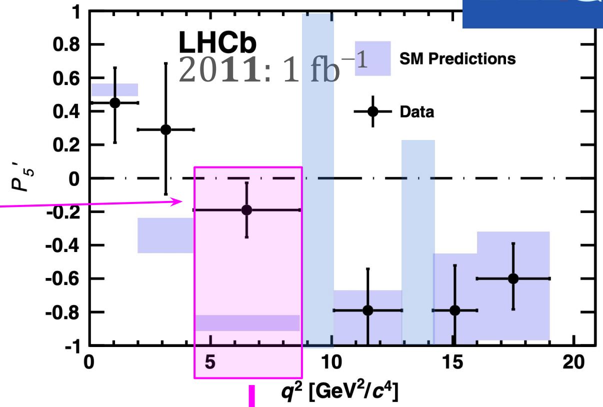
R. Aaij *et al.**
(LHCb Collaboration)



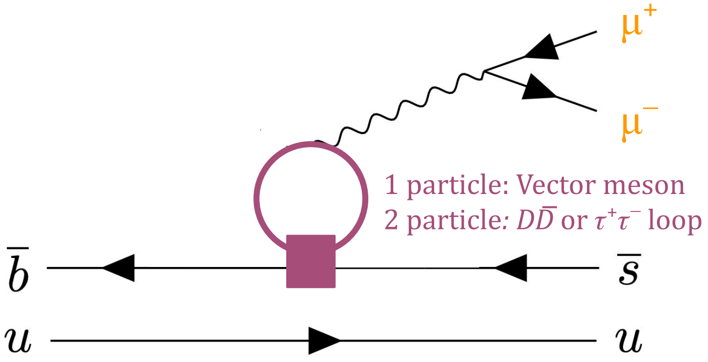
LHCb: $B^0 \to K^{*0}\mu^+\mu^-$

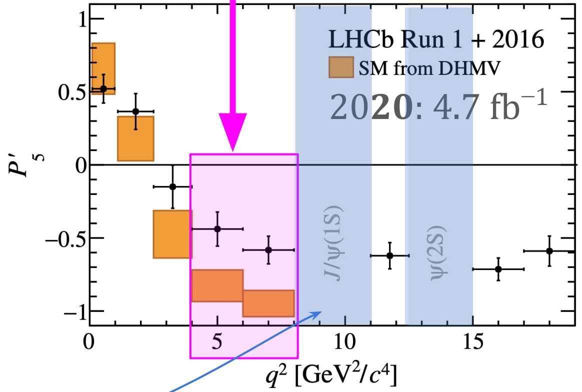
Context:

- Longstanding **tensions** in angular analyses of $b \to s\mu^+\mu^-$
- Tensions in P_5' (coefficient in angular decay rate*) can be related to tensions in the C_9 Wilson Coefficient in EFT



But is this NP or **non-local QCD**?





Can't **ignore the resonances**; interference could be far from poles

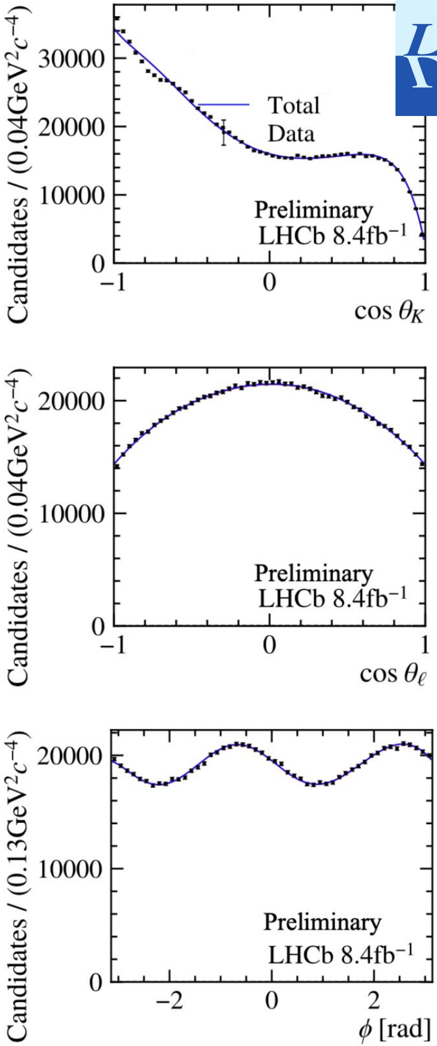
Analysis concept

Signal description:

- Signal amplitudes parameterized with *local* and *non-local* contributions using a dispersion relation (*effective* C_9)

Fit:

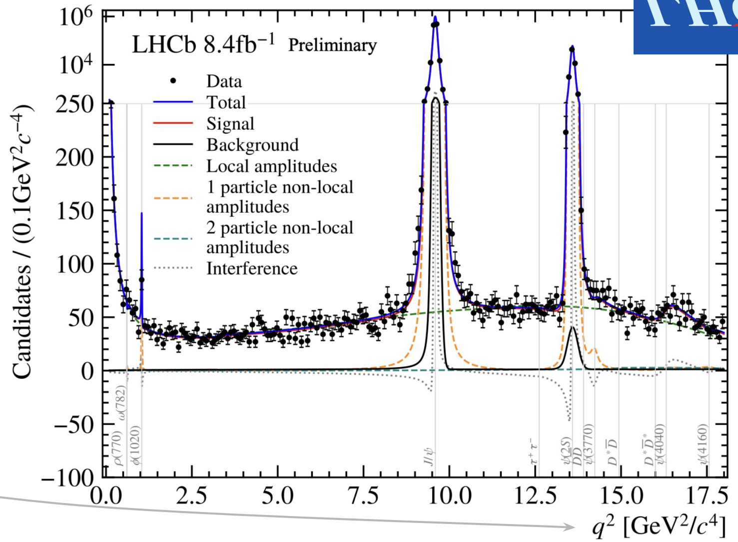
- 4D unbinned fit (**three helicity angles*** + **full** q^2)
- Determines **150 parameters**:
  - Wilson coefficients
  - Magnitude and phase on 1-particle contributions
  - 2-particle contribution
  - Form factors
  - *Everything…*

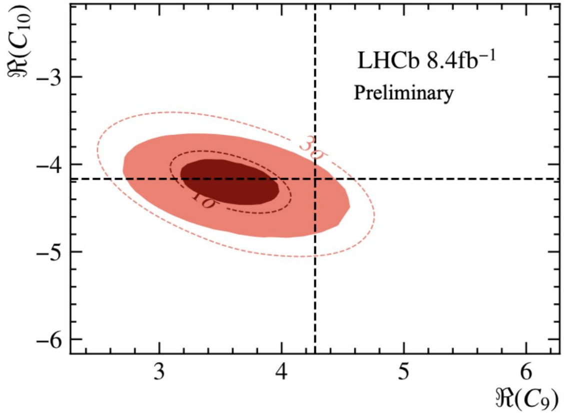


Results

Wilson coefficients from fit:

- Global tension with SM at **1.5σ**
- Mostly driven by **2.1σ** tension in C_9 (again)
- First result **including the whole q^2 range**
  - (equivalent to $\ell\ell$ invariant mass)
- The data prefer **more non-local** contributions than in SM
  - (but not enough to explain the tension)
  - Consistent with PRD 109, 052009





Take-home: A tension in C_9 persists, and it **isn't** due to long-range QCD effects

Conclusions

Progress in LUV and $b \to c\tau\nu$ anomalies:

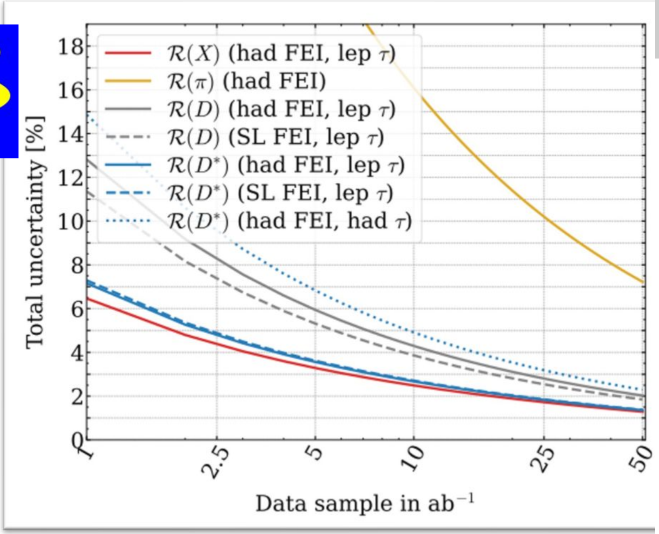
- First inclusive $R(X)$, at Belle II
- First $R(D^{+})$ at LHCb
- Plus more, not featured today!
- Tension remains at **~3σ**

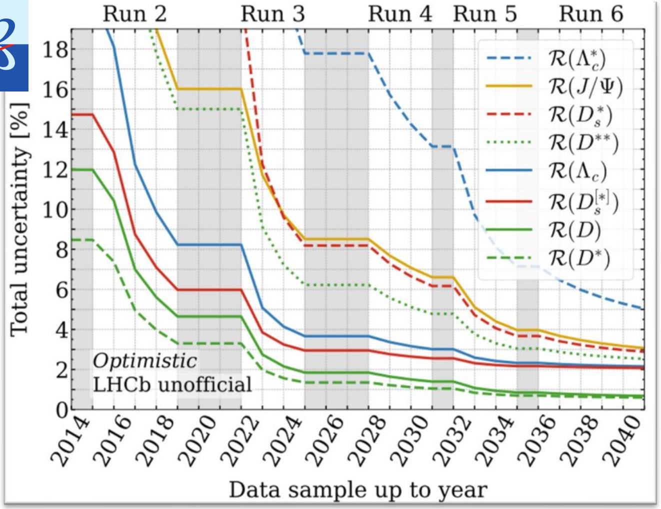
Progress in FCNCs:

- Intriguing hints of NP in Belle II-only $B \to K\nu\nu$
- Tension in angular analysis of $b \to s\ell\ell$ persists and isn't explainable by long-range QCD

*This is a **tiny** fraction of what Belle II and LHCb are up to, not to mention ATLAS and CMS B-physics programs*

*Look for an **explosion** of new results in the **next several years**!*





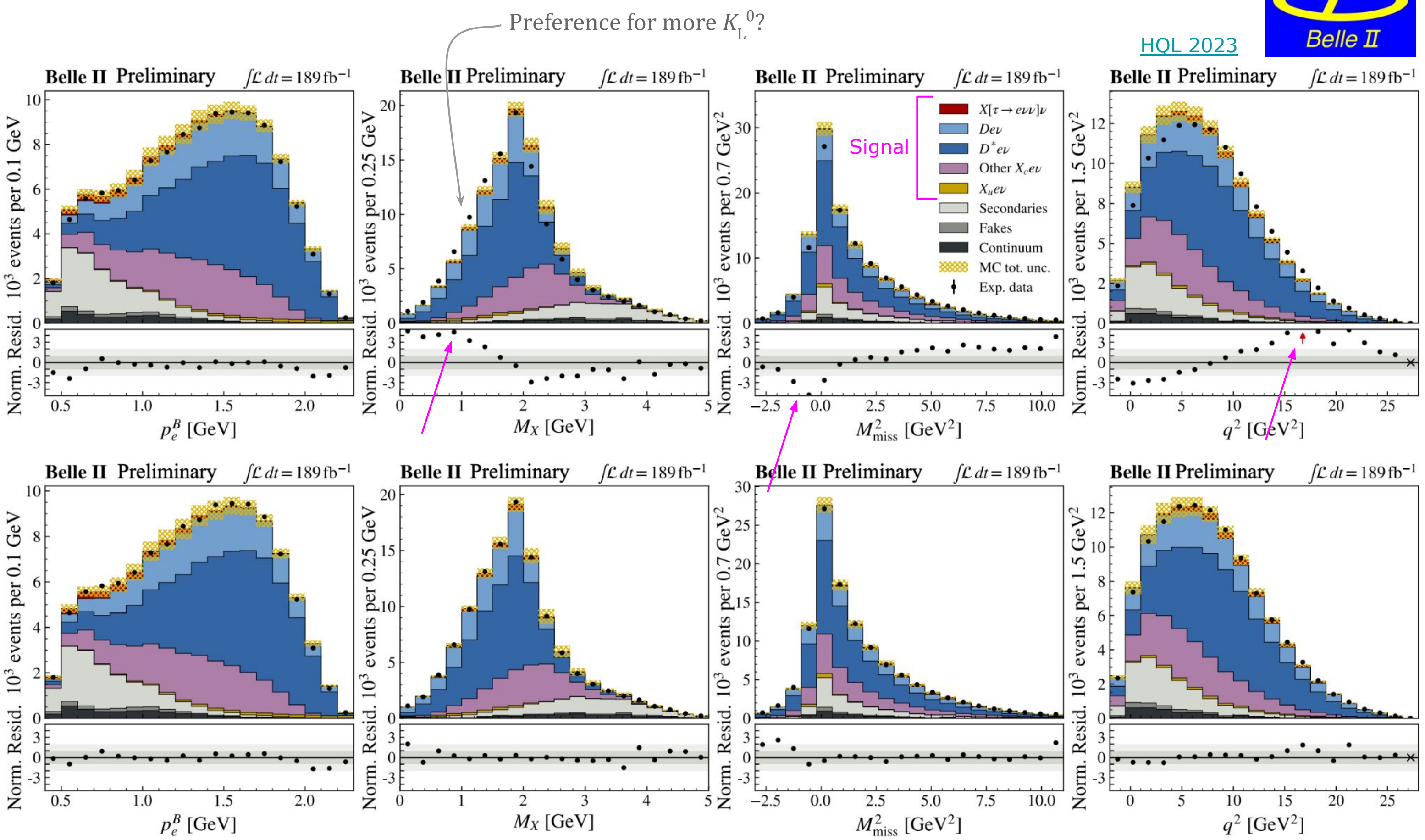
Thank you!

(additional slides)

R(X) reweighting

HQL 2023

Reweight $X\ell\nu$ based on M_X, backgrounds based on (p_ℓ, M_X)



Mismodeling is fixed in **all other variables!**

$R(X_{\tau/\ell})$ uncertainties

Preliminary

Source	Uncertainty [%] e	μ	ℓ
Experimental sample size	8.8	12.0	7.1
Simulation sample size	6.7	10.6	5.7
Tracking efficiency	2.9	3.3	3.0
Lepton identification	2.8	5.2	2.4
$X_c \ell \nu$ M_X shape	7.3	6.8	7.1
Background (p_ℓ, M_X) shape	5.8	11.5	5.7
$X \ell \nu$ branching fractions	7.0	10.0	7.7
$X \tau \nu$ branching fractions	1.0	1.0	1.0
$X_c \tau(\ell) \nu$ form factors	7.4	8.9	7.8
Total	18.1	25.6	17.3

Uncertainties that will likely scale as statistical uncertainties with luminosity

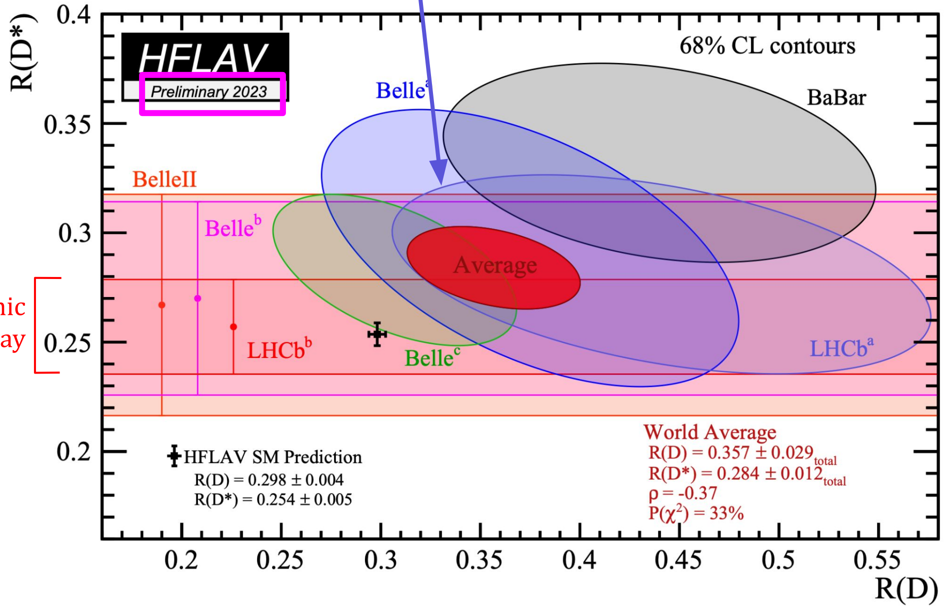
LHCb: New $R(D^+)$ and $R(D^{*+})$

PRL 131, 111802

Context: **2023 result** from LHCb for $R(D^0)$ and $R(D^{*0,+})$

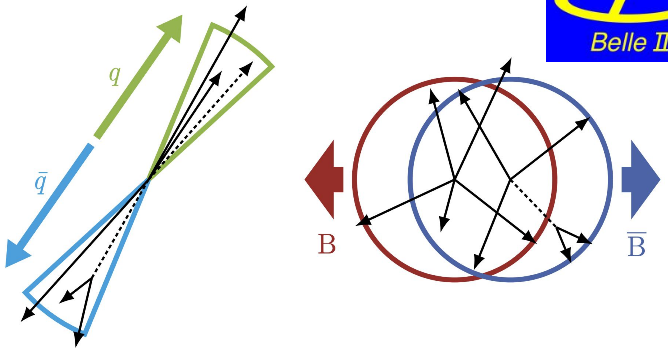
- Run 1 ($3.0\ fb^{-1}$)
- First simultaneous measurement of $R(D^*)$ and $R(D^0)$ at a hadron collider
- Muonic tau decay (high BF, high backgrounds)

With hadronic τ decay



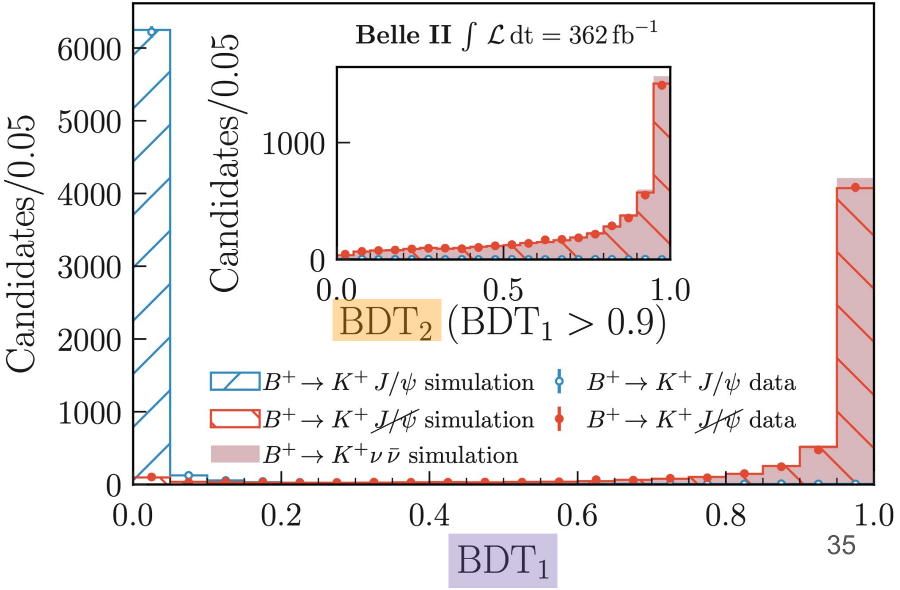
Complementary measurement with charged D^+ now needed…

$B^+ \to K^+\nu\nu$ analysis



Background suppression

- ITA: Two consecutive Boosted Decision Trees (BDTs)
  - **BDT_1**: basic filter; kinematics, **event shapes**
  - **BDT_2**: trained on events with BDT_1>0.9
  - Validated with **embedding procedure** using $B^+ \to K^+ J/\psi$:
    - "Delete" muons from J/ψ decay
    - Replace K^+ with simulated signal K^+
- HTA: Single BDT (BDTh)



Two new methods

Das ist der HAMMER: Consistent new physics interpretations of semileptonic decays

Florian U. Bernlochner[a,1], Stephan Duell[b,1], Zoltan Ligeti[c,2], Michele Papucci[d,2,3], Dean J. Robinson[e,2]

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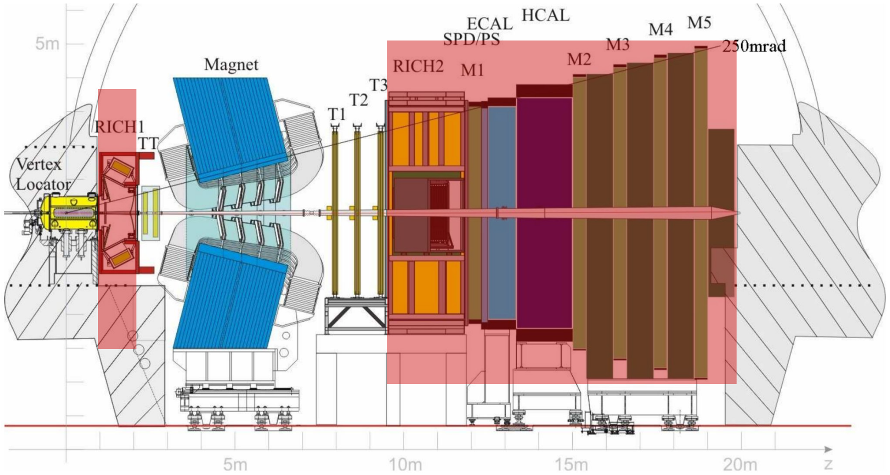
[3]Burke Institute for Theoretical Physics, California Institute of Technology, Pasadena, CA 91125, USA

Form Factor variations: ***HAMMER***

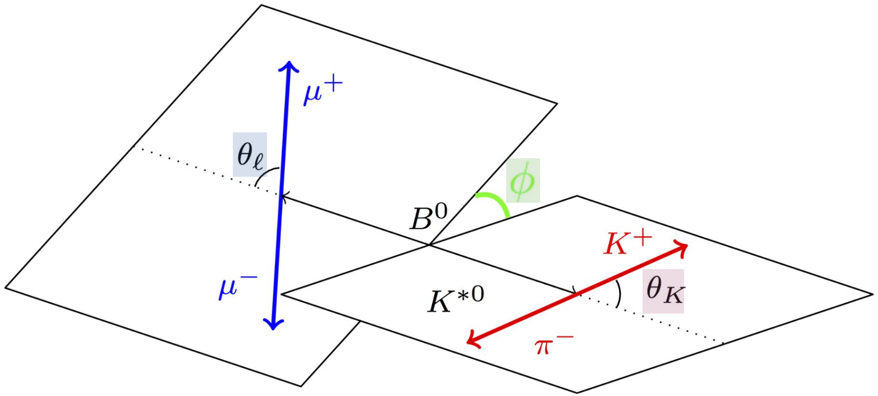
- Efficient reweighting of MC for FF variations and NP scenarios
- Developed by Belle II collaborators with theorists; **first use** in this analysis

Tracker-only **ultra-fast simulation**

- "Turn off" all but tracker in simulation → faster simulations → reduced uncertainty from MC stats
- Effects of missing detectors emulated in analysis
- Multi-dimensional reweightings and QED corrections
- Excellent agreement achieved



$b \to s\ell\ell$ angular distributions



$$\frac{1}{\mathrm{d}\Gamma/\mathrm{d}q^2}\frac{\mathrm{d}^4\Gamma}{\mathrm{d}q^2\,\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_K\,\mathrm{d}\varphi} = \frac{9}{8\pi}\left\{\frac{2}{3}\left[(F_S + A_S\cos\theta_K)\,(1-\cos^2\theta_\ell)\right.\right.$$
$$\left. + A_S^5\sqrt{1-\cos^2\theta_K}\sqrt{1-\cos^2\theta_\ell}\cos\varphi\right]$$
$$+ (1-F_S)\Big[\,2F_L\cos^2\theta_K\,(1-\cos^2\theta_\ell)$$
$$+ \frac{1}{2}(1-F_L)\,(1-\cos^2\theta_K)\,(1+\cos^2\theta_\ell)$$
$$+ \frac{1}{2}P_1\,(1-F_L)(1-\cos^2\theta_K)(1-\cos^2\theta_\ell)\cos 2\varphi$$
$$\left.\left. + 2P_5'\cos\theta_K\sqrt{F_L\,(1-F_L)}\sqrt{1-\cos^2\theta_K}\sqrt{1-\cos^2\theta_\ell}\cos\varphi\right]\right\}$$