Recent results in B-physics

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DPF-Pheno 2024 | Pittsburgh

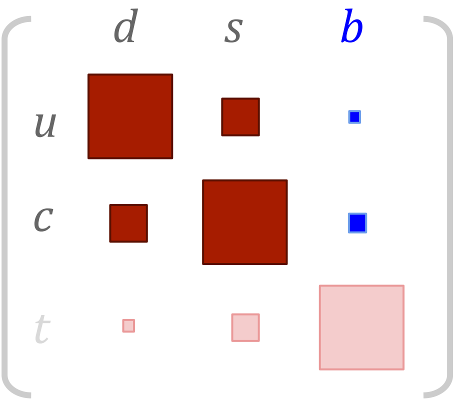
Why *b*-physics?

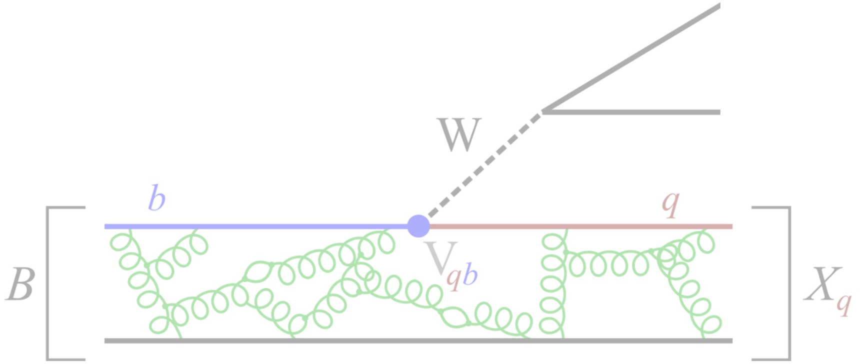
Rich flavor dynamics

- **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 $\Lambda_{\mathrm{QCD}}/m_b \sim 0.1$

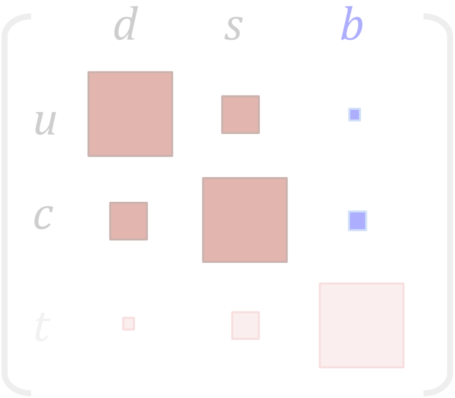




$$\frac{\mathrm{d}\Gamma}{\mathrm{d}q^2} \propto |V_{qb}|^2 |f(q^2)|^2$$

A powerful and clean window to NP…

Why *b*-physics?



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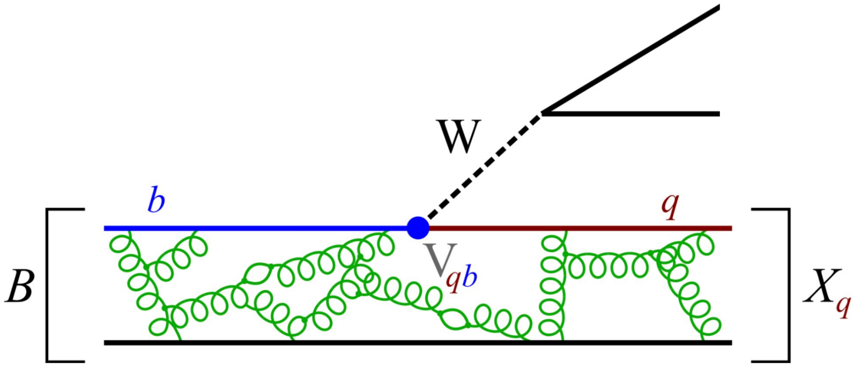


$$\frac{d\Gamma}{dq^2} \propto |V_{qb}|^2 |f(q^2)|^2$$

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:

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

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

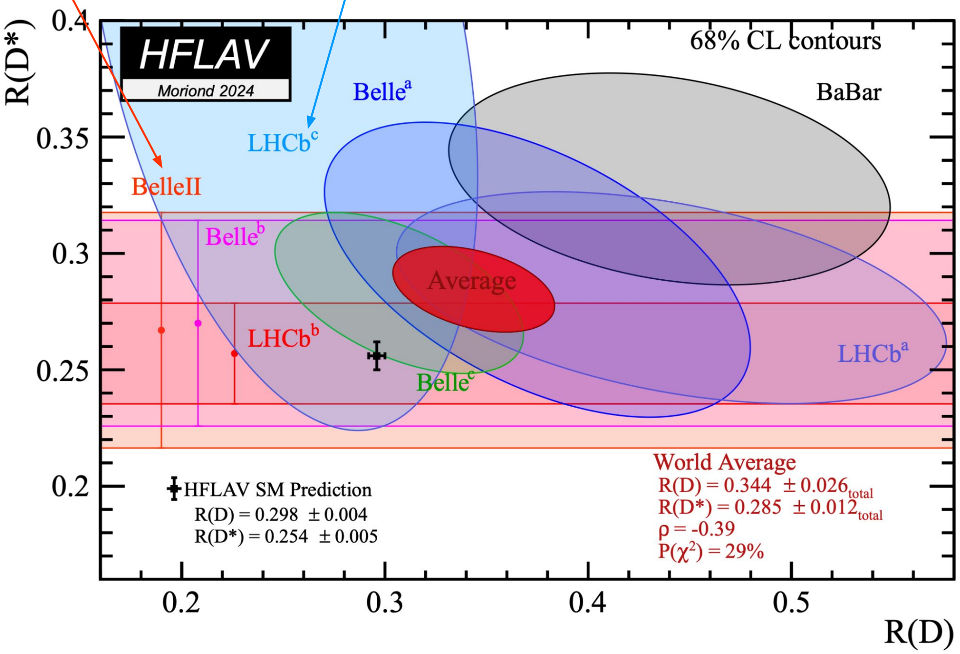
(next decade?)

New! Featured today

"Traditional" modes

arXiv:2401.02840 (Jan 2024)

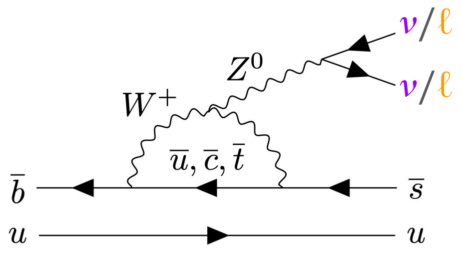
Moriond 2024, **featured today**



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

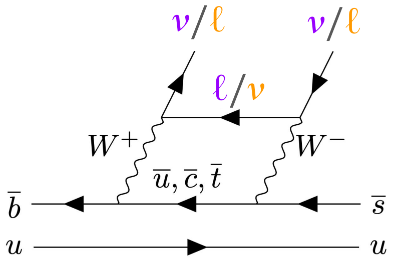
Longstanding **~3σ tension** with SM from BaBar, Belle, LHCb, Belle II… *a sign of NP?*

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 $R(K^*)$ [μ/e ratios]... gone now? (thanks LHCb!)

Lingering (and consistent) signs of NP here too!

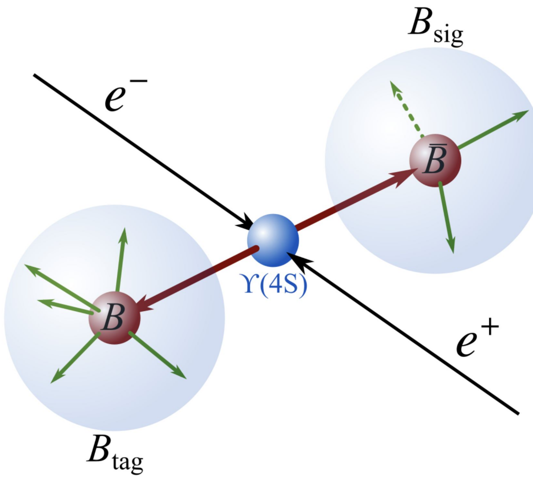
How?

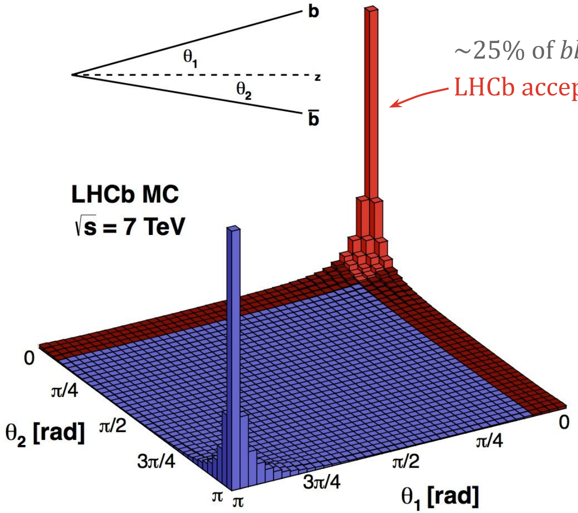
B-factories (BaBar, Belle, Belle II)

- e^+e^- colliders on $\Upsilon(4S)$ resonance ($\rightarrow B\bar{B}$)
- Low cross-section $\rightarrow$ high luminosity
- Full kinematics known
- **Spherical** events
- No pileup

Hadron colliders (LHCb, ATLAS, CMS…)

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

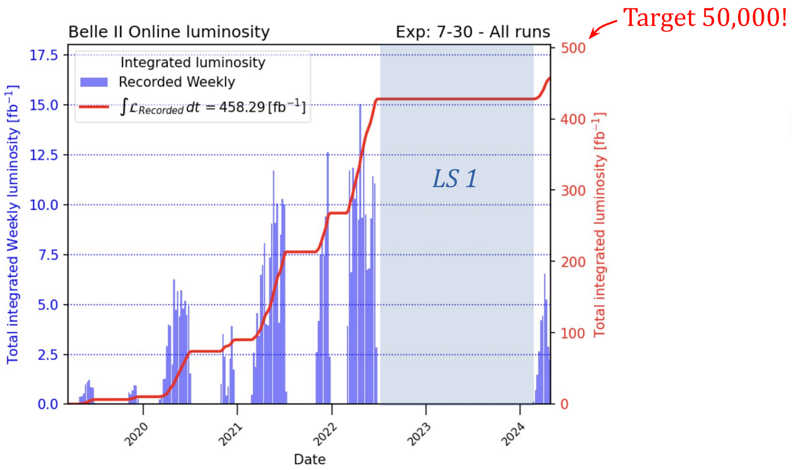


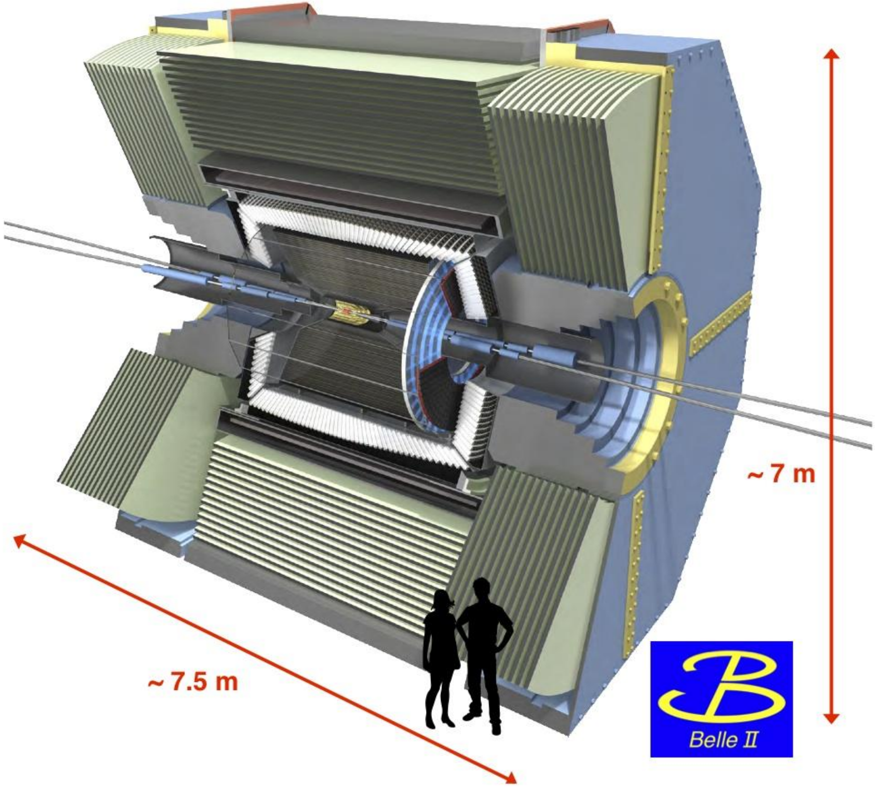


∼25% of bb pairs are in LHCb acceptance

Belle II

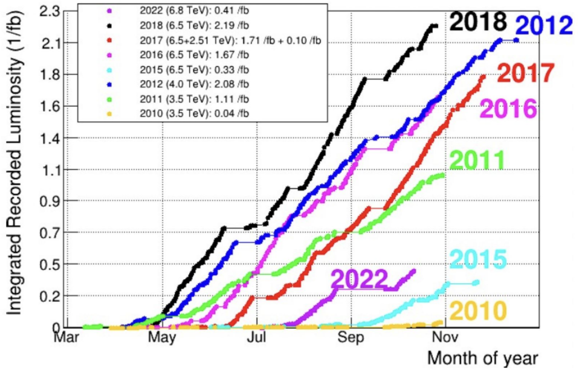
- Hermetic detector
- Modest boost; B mesons fly $\sim$100 μm
- Ideal for **neutral** or **invisible** final states
- World-record luminosity before *Long Shutdown 1,* which has just ended
- Current results use $\leq$362 fb^{-1}: competitive with BaBar and Belle already, but **<1% of target**

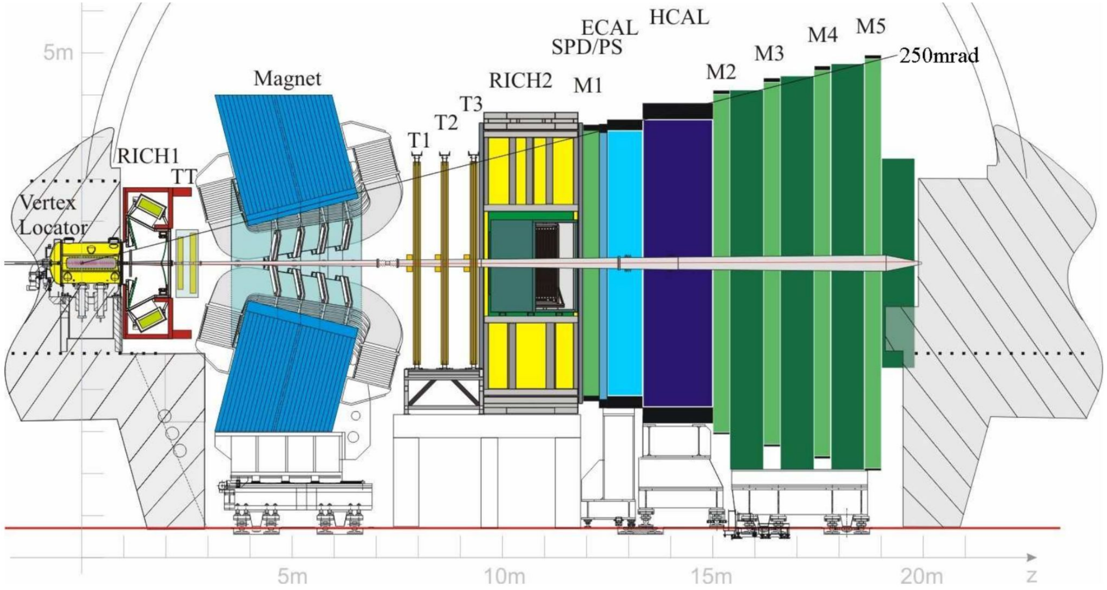




LHCb

- Single-arm forward spectrometer
- Large boost; B mesons fly $\sim$1 cm (easily resolvable)
- Access to all b-hadron species
- Excels at **charged particle** final states, notably **muons**

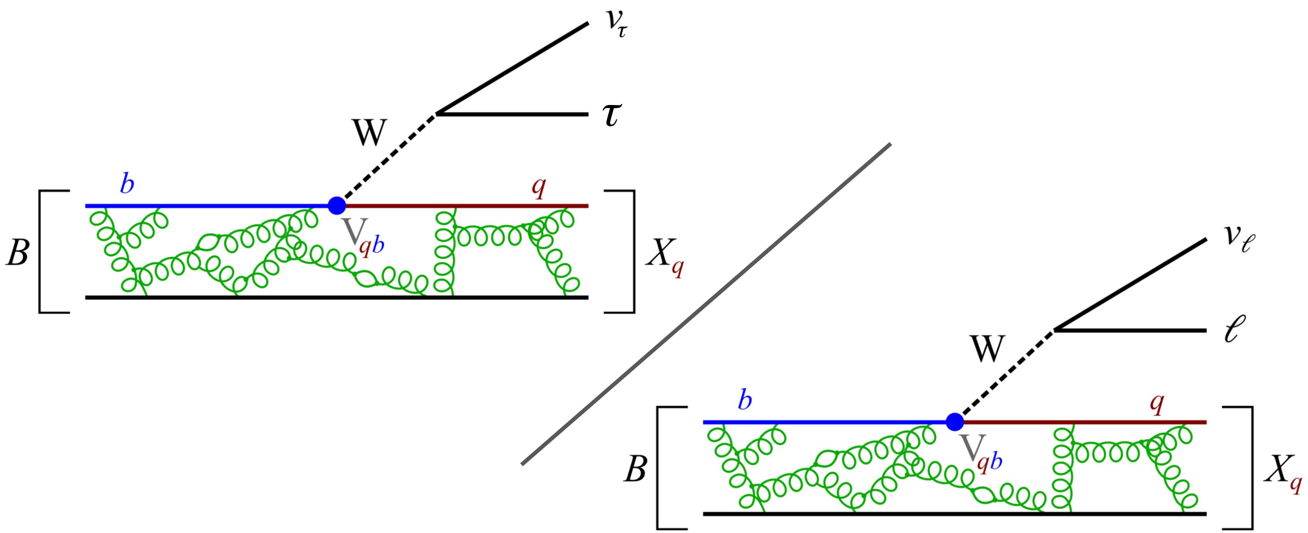




Recent results: Lepton Universality

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



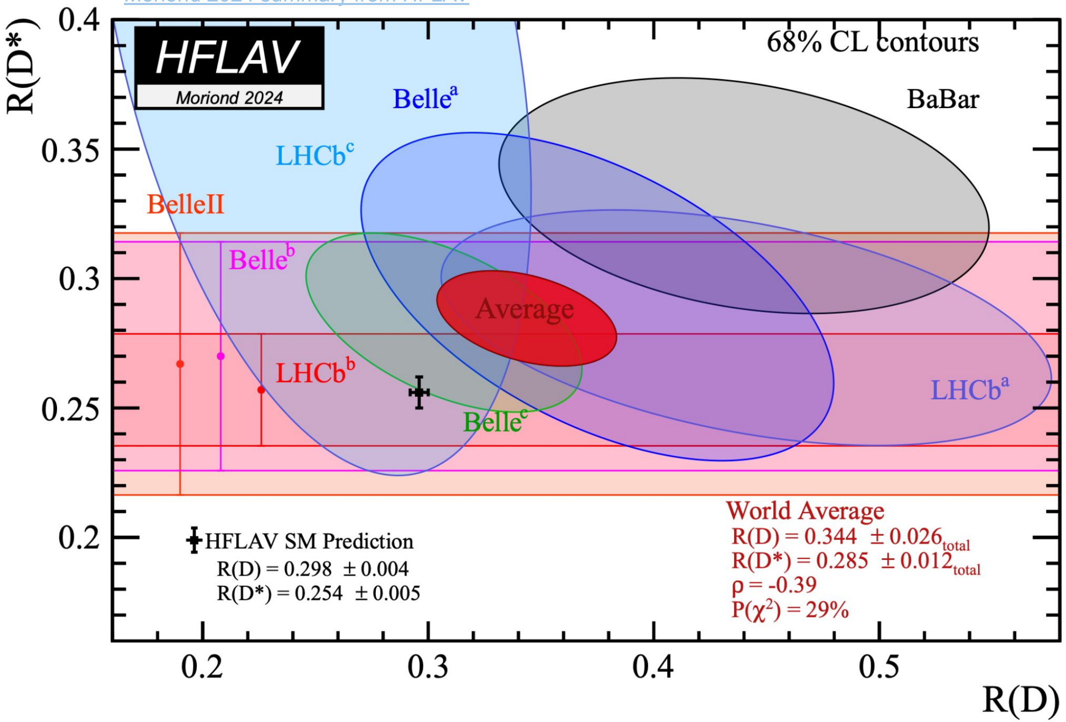
The $b \to c\tau\nu$ excess

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

Or a problem with the (shared) theory description?

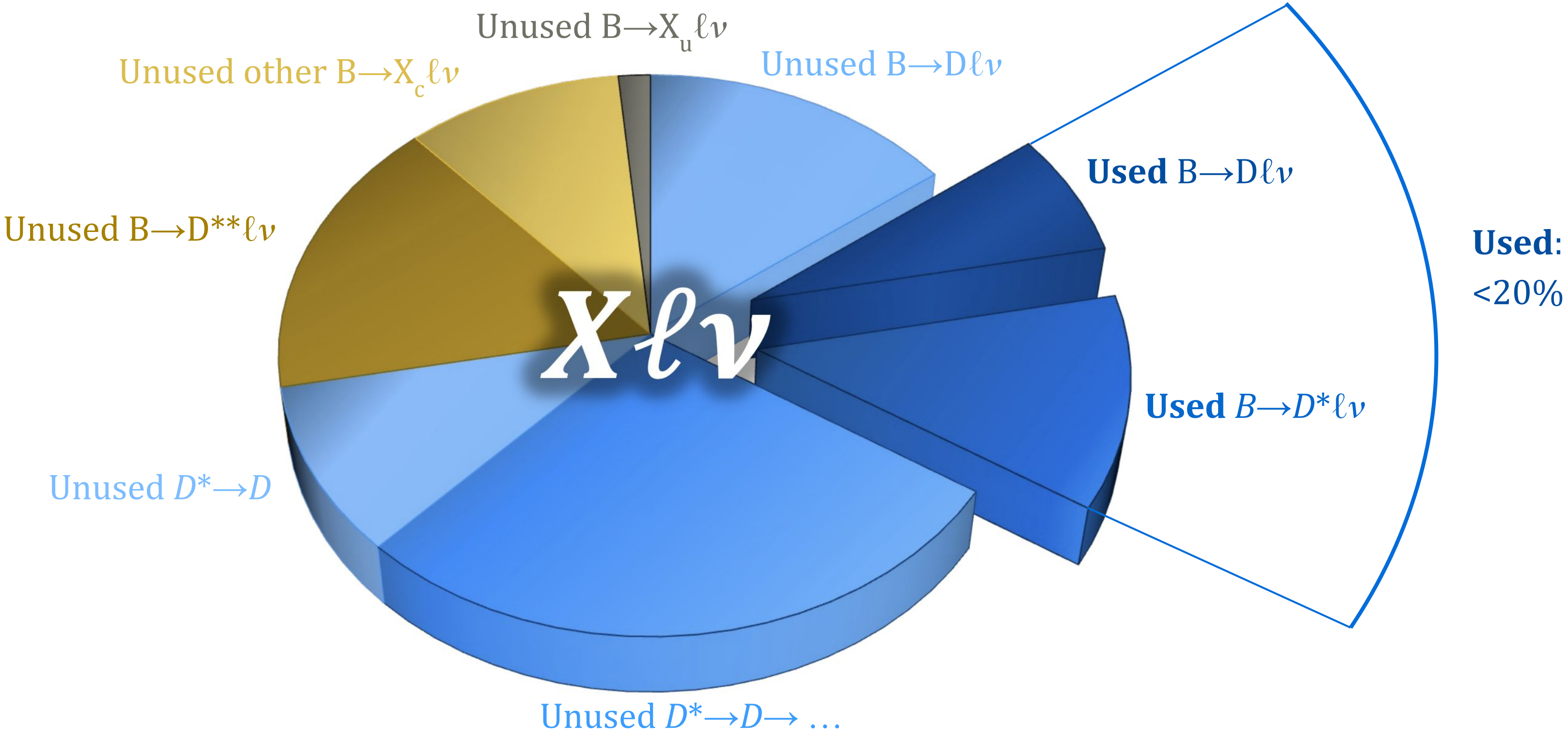
Is there anything we can do except ***measure R(D) and R(D*) over and over again****?*

Moriond 2024 summary from HFLAV



Consider…

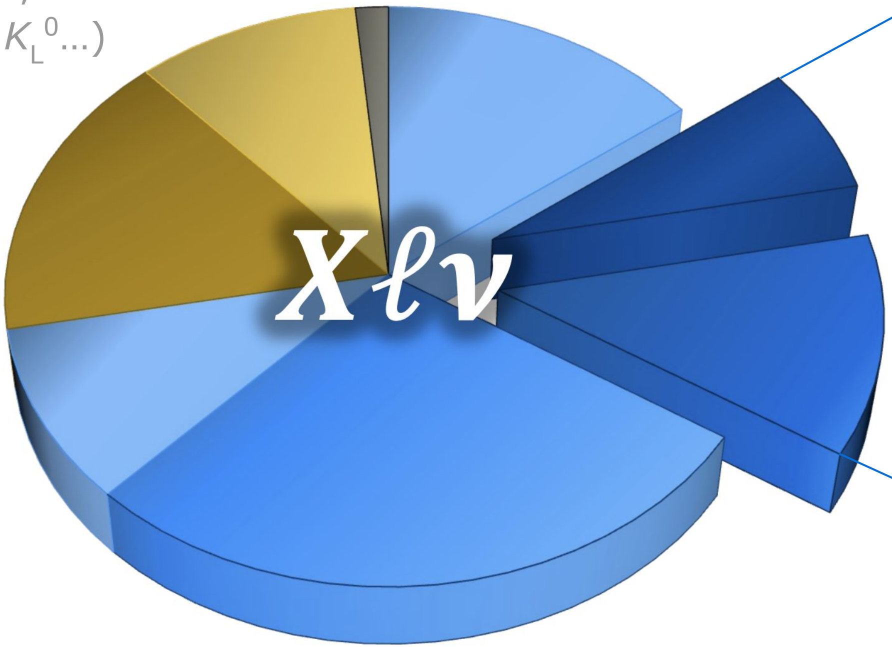
Composition of $B \to X\ell\nu$ events



*So why don't we use **everything**?*

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

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

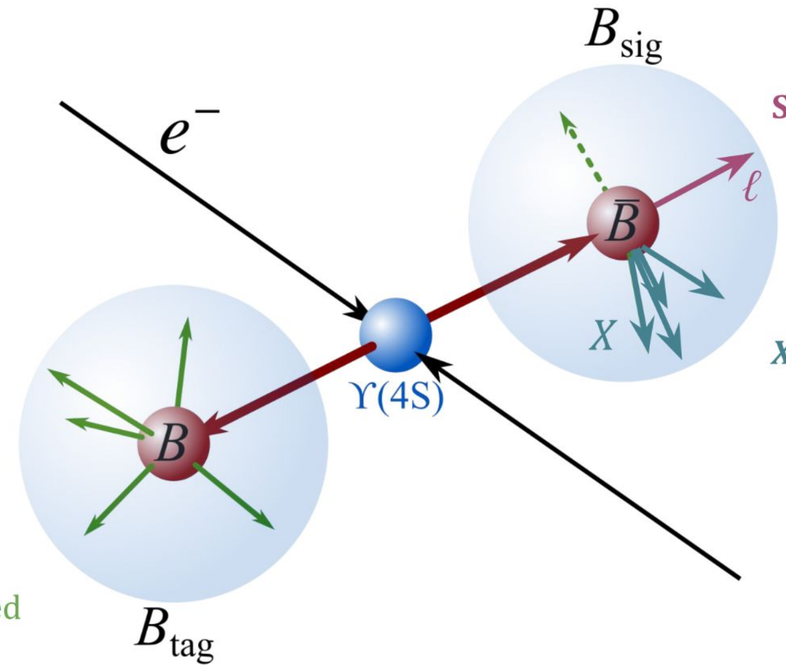


Well-known, clean decays
(mostly $K^{\pm}$,$\pi^{\pm}$)

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 (hadronic FEI)
- Tight tag quality selections

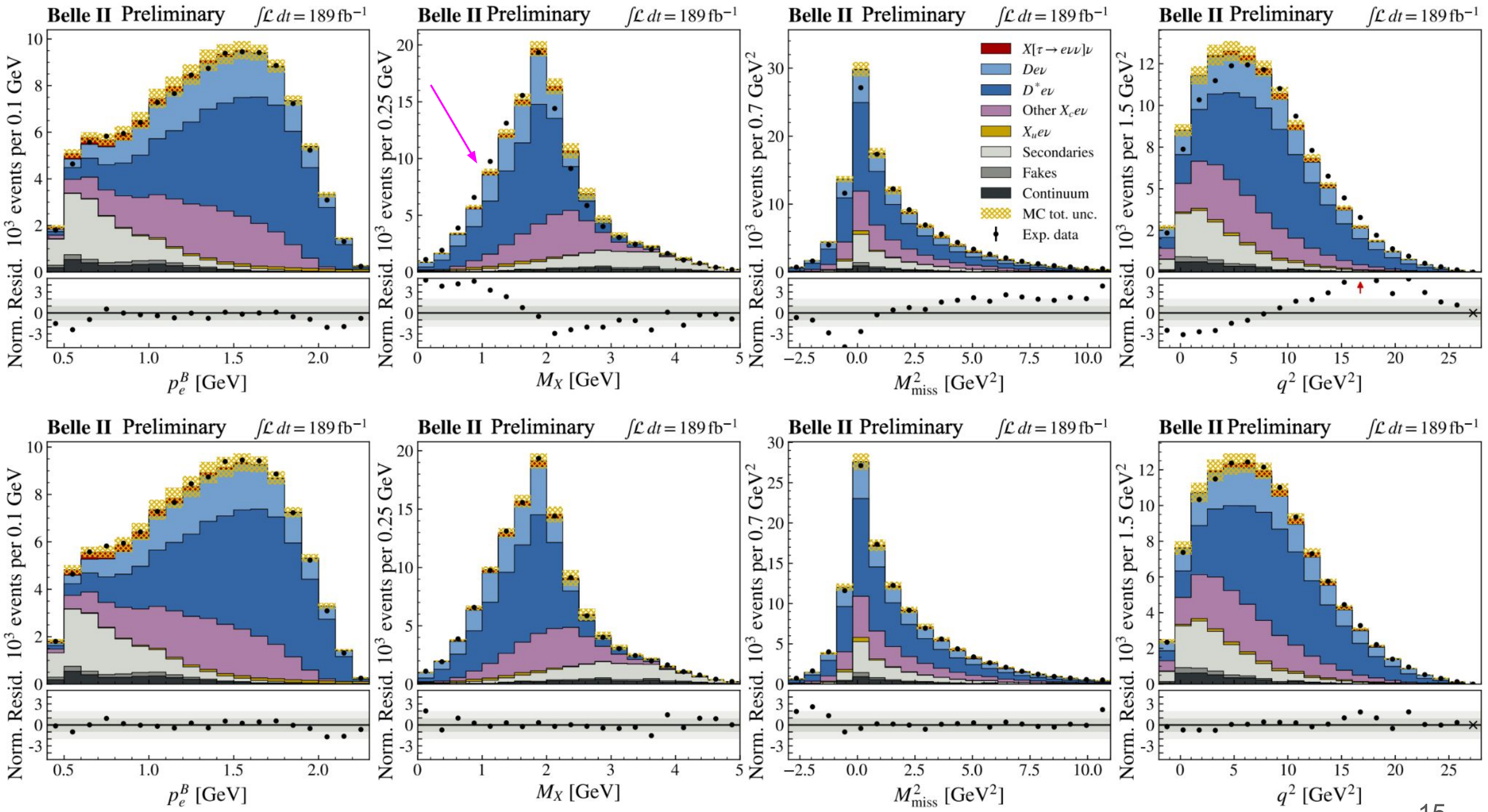
Use a ***data-driven corrections*** *for the "***not well-known***" stuff…*

Data-driven corrections

Henrik Junkerkalefeld

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

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



Lepton momentum Invariant mass of X Missing mass squared

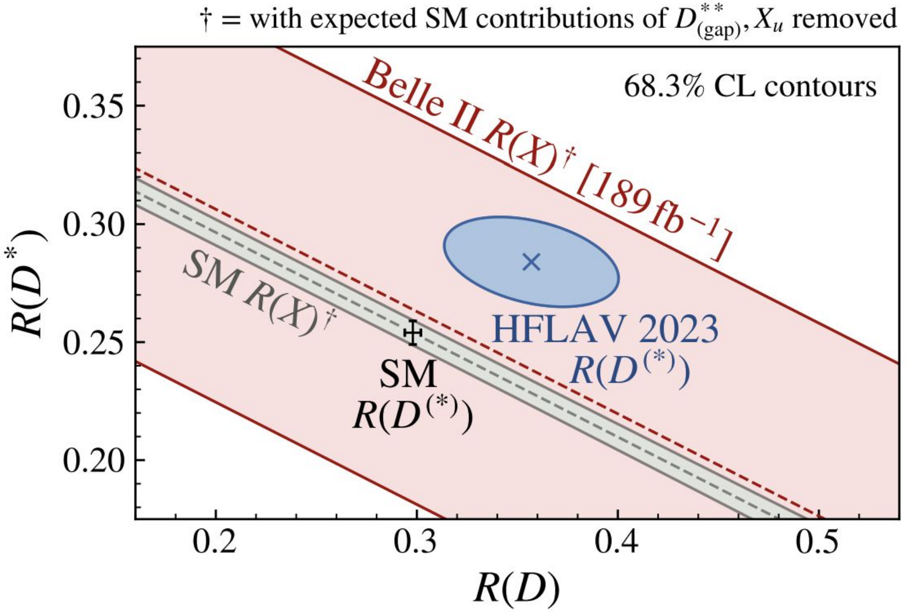
$R(X_{\tau/\ell})$ results

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

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

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

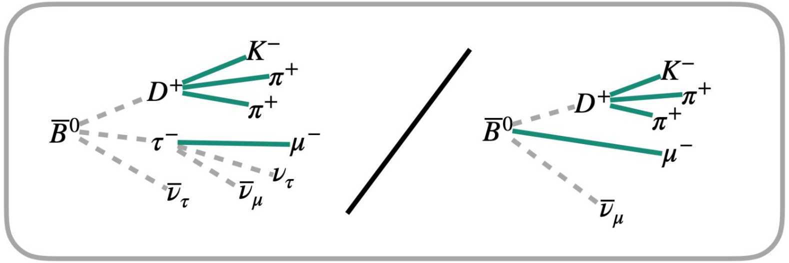
$$R(X_{\tau/\ell}) = 0.228 \pm 0.016\ (\text{stat}) \pm 0.036\ (\text{syst})$$



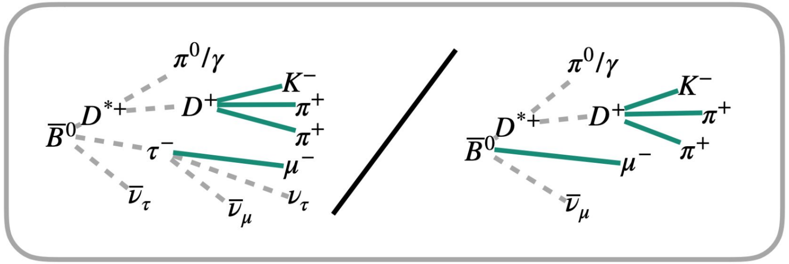
Take-home: Belle II has developed a powerful and independent new test of the $b \to c\tau\nu$ anomalies driven by **new inclusive techniques**

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

R(D⁺) =



R(D*⁺) =



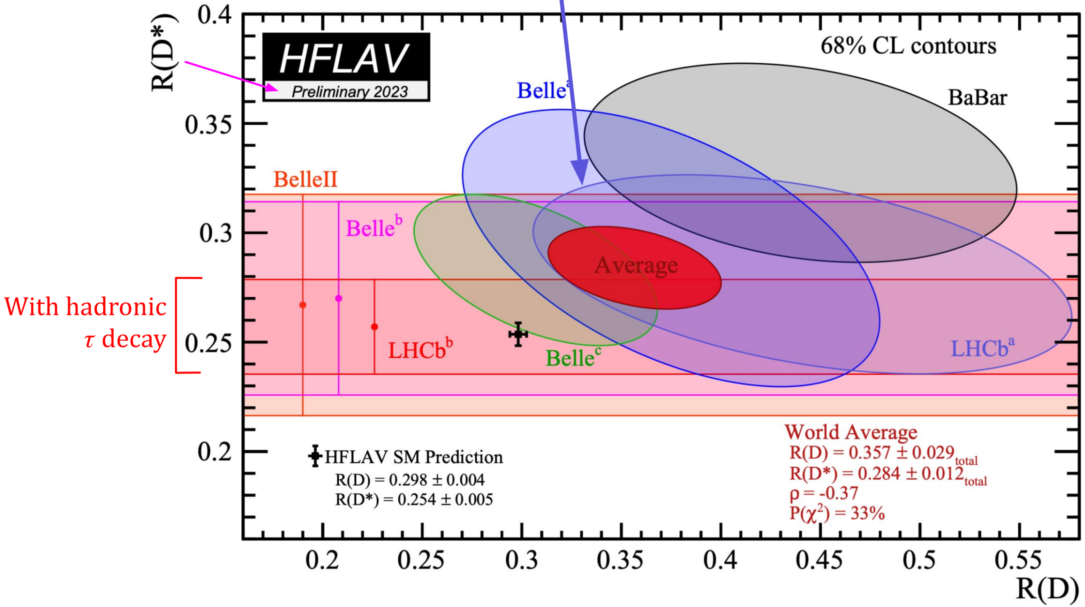
Julián García Pardiñas

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

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

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

PRL 131, 111802



Complementary measurement with charged D^+ now needed…

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

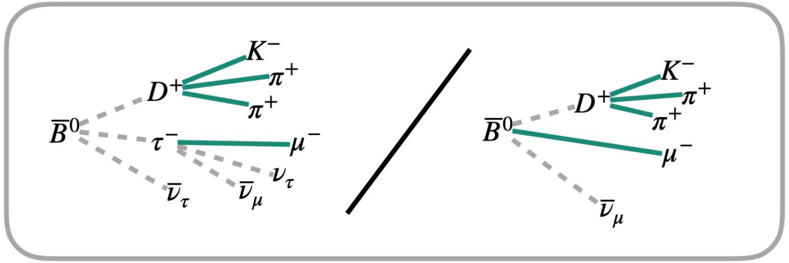
Main goal: measure isospin-related $R(D^+)$ to complement $R(D^0)$

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

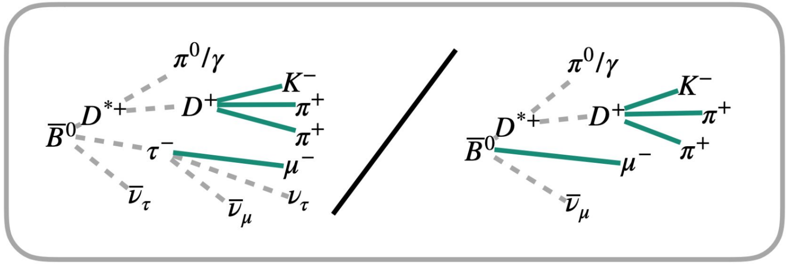
Signal identification:

- Subtract fake D backgrounds in $M(\boldsymbol{K^- \pi^+ \pi^+})$ using sPlot technique
- Track isolation criteria to define signal and control regions

R(D⁺) =



R(D*⁺) =

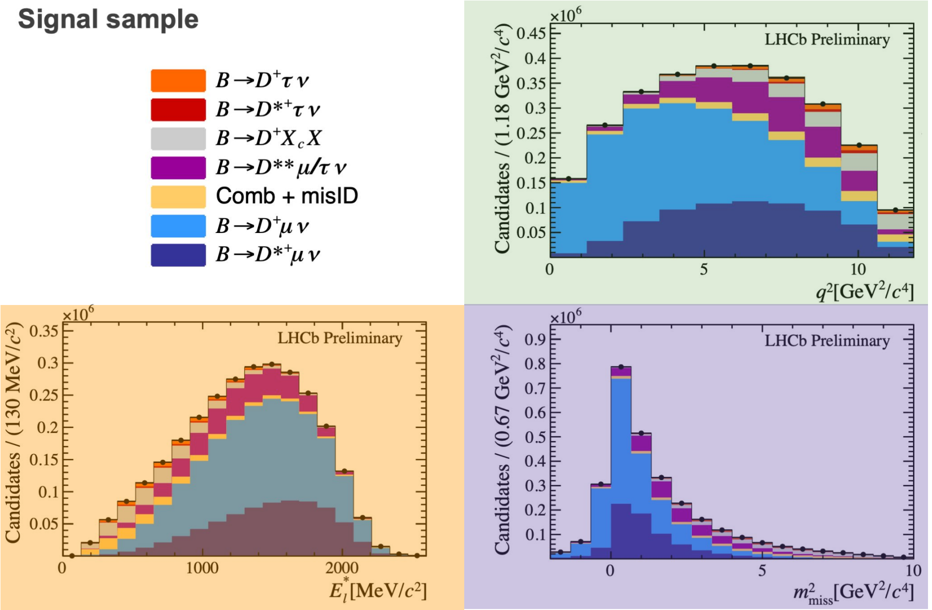


Signal extraction

3D binned fit:

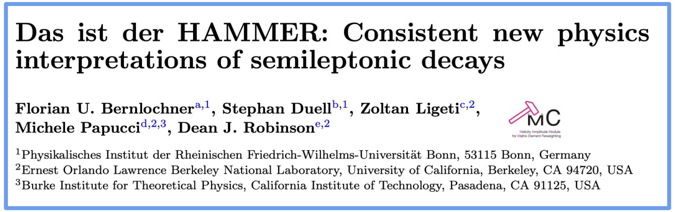
- *Variables*: m^2_{miss}, E_l^*, q^2
- *Components*:
  - Signal (***D*** and ***D****)
  - Normalization (***D*** and ***D****)
  - Feed-down from **1P *D******* states
  - Muon **mis-ID**
  - (other charm, neutronic, combinatorial background)
- Simultaneous fit to *four data samples:*
  - **Signal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

Signal sample



Two new methods

Form Factor variations: ***HAMMER***



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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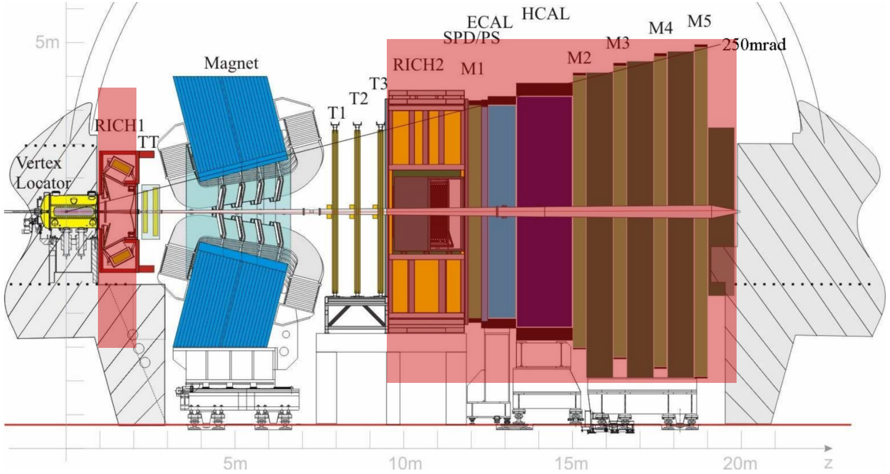
[2]Ernest Orlando Lawrence Berkeley National Laboratory, University of California, Berkeley, CA 94720, USA
[3]Burke Institute for Theoretical Physics, California Institute of Technology, Pasadena, CA 91125, USA

- 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**

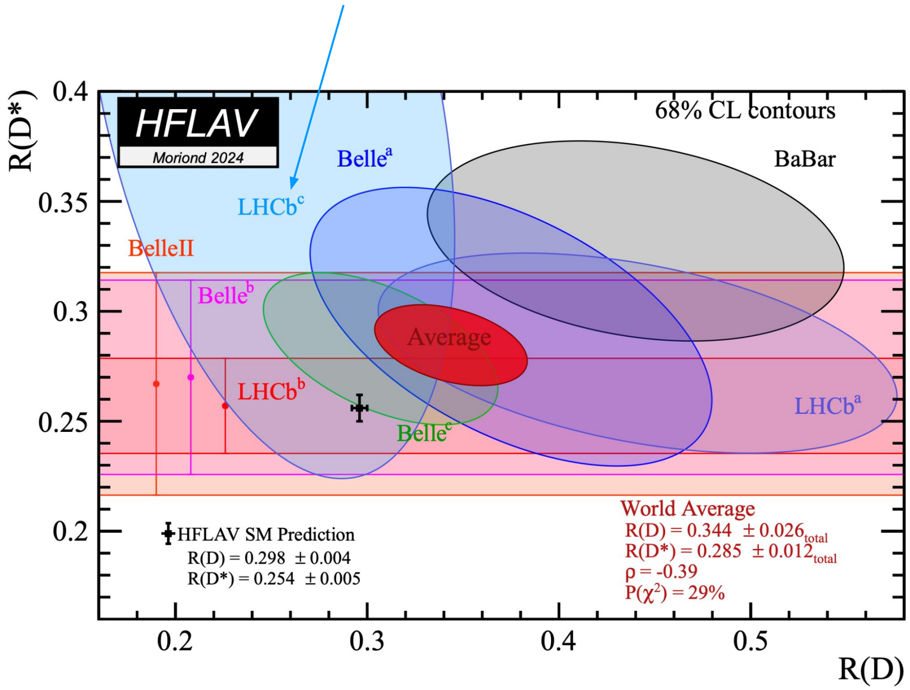
- "Turn off" all but tracker in simulation → faster simulations → reduced uncertainty from MC stats
- Effects of missing detectors emulated in analysis
- Multi-dimensional reweightings and QED corrections
- Excellent agreement achieved



Results

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

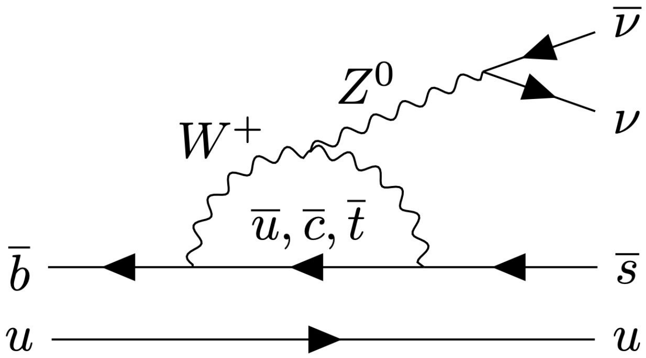


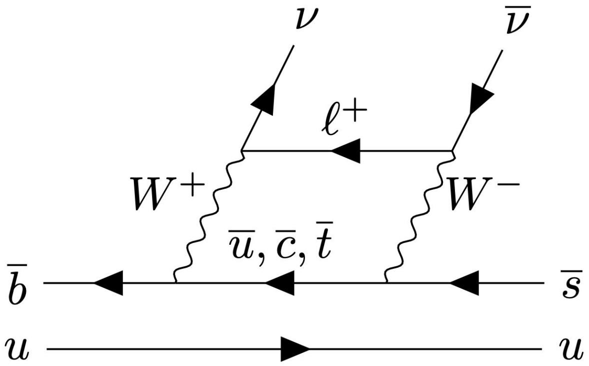
Recent results: FCNCs

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

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

(Accepted by PRD, Feb 2024)





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

Suppressed in SM (10^{-6}), only accessible via **box** or **penguin**

Could be enhanced by same NP as $R(D^{(*)})$, $b\to s\ell^+\ell^-$, $(g\text{-}2)_\mu$…

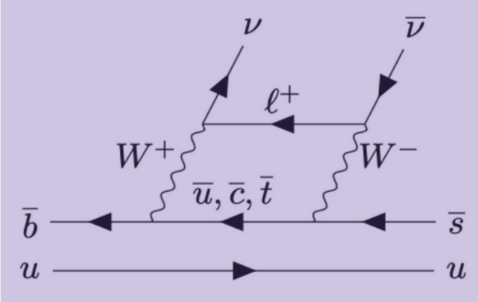
Very challenging:

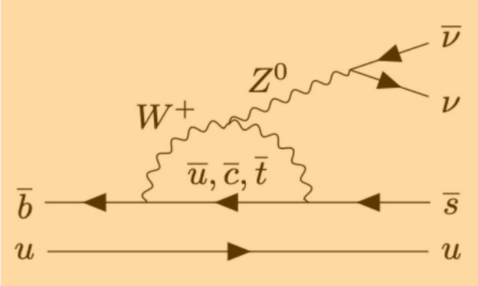
- Two missing neutrinos, only one final state particle
- $K_L^{\ 0}$ backgrounds key but poorly constrained

Two approaches run in parallel:

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

This is something only Belle II can do…





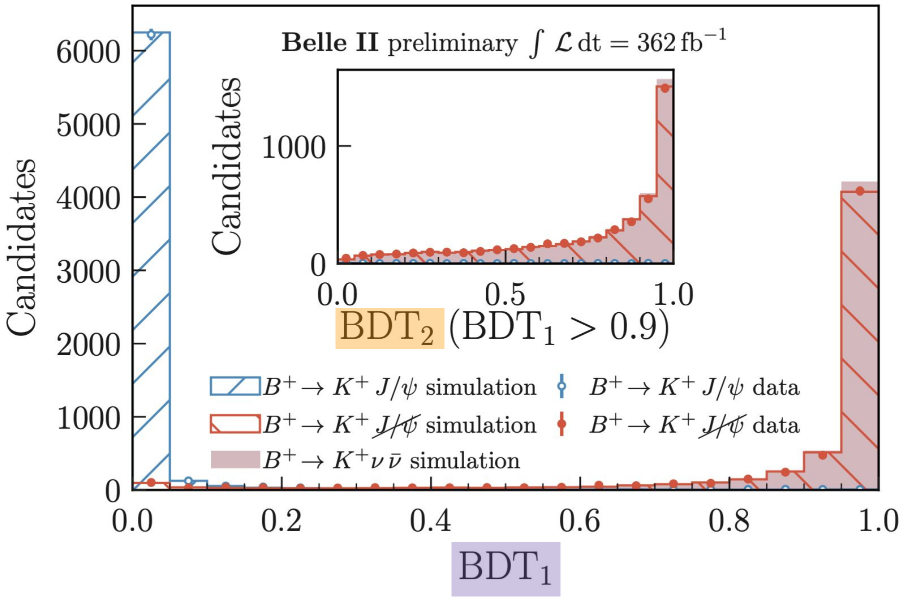
$B^+ \to K^+\nu\nu$ analysis

Basic selections

- Energy and number of tracks consistent with $B\bar{B}$
- Missing momentum in detector acceptance

Background suppression

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



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

Strategy and variables

- η: a signal classifier remapped so that signal is **flat**
- q^2_{rec}: inferred neutrino mass squared
- Systematic uncertainties included as nuisance parameters

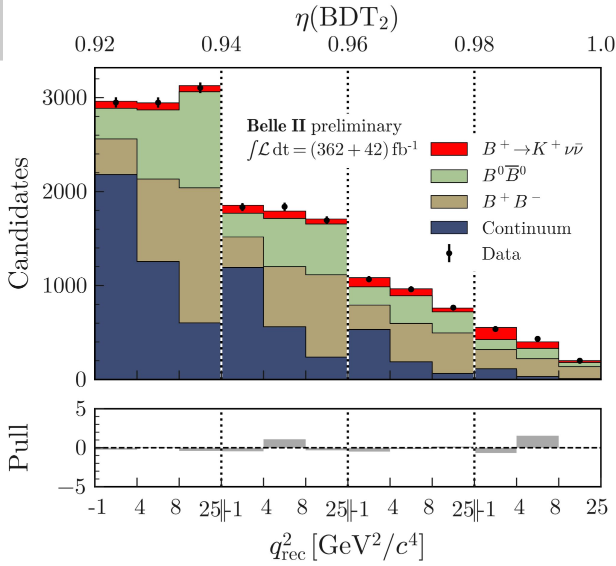
ITA:

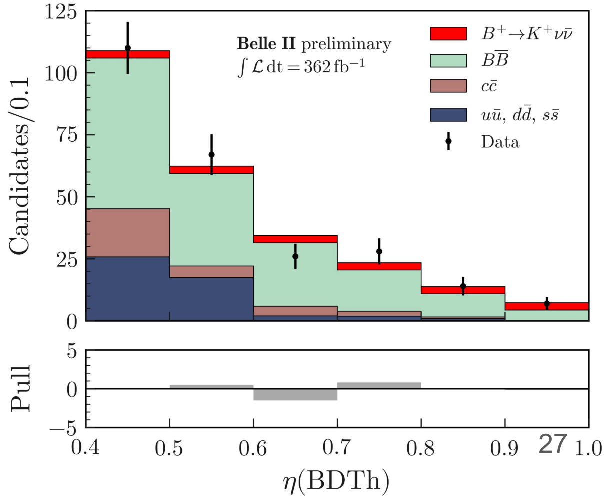
- Simultaneous on-/off-resonance fit
- (4 bins in η)×(3 bins in q^2_{rec})

HTA:

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

A large number of controls/validations I have to skip…





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

Combined ITA and HTA:

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

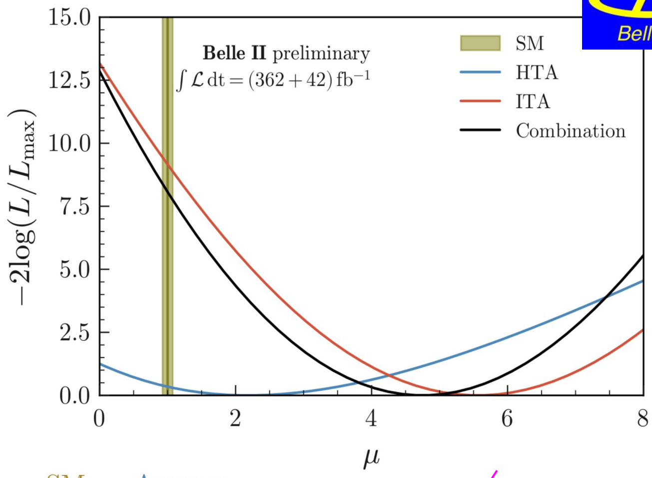
$$\mu = 4.6 \pm 1.0(\text{stat}) \pm 0.9(\text{syst}) = 4.6 \pm 1.3$$

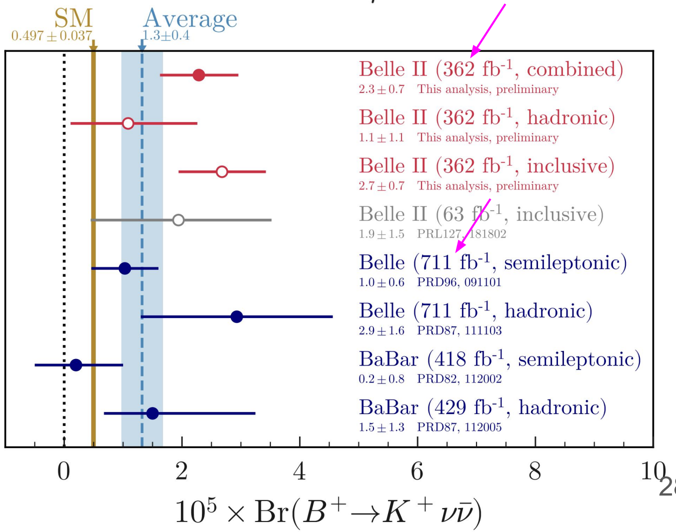
- Branching fraction:

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

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

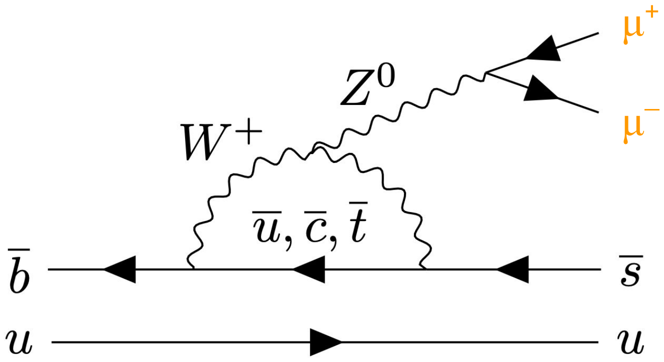
Take-home: first evidence for $K^+\nu\nu$ (3.5σ), BF in excess of SM by 2.7 σ; enabled by **new inclusive techniques**





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

LHCb-PAPER-2024-011

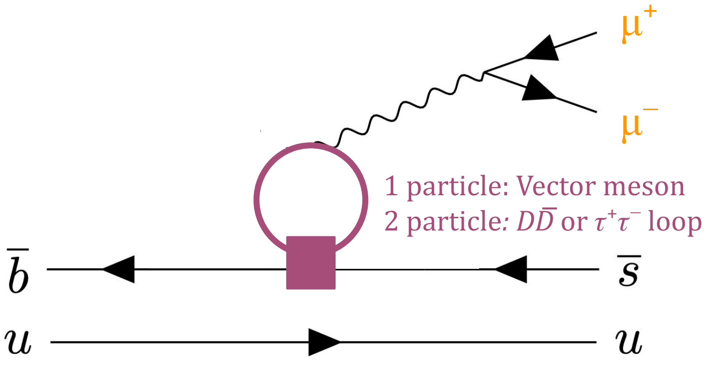


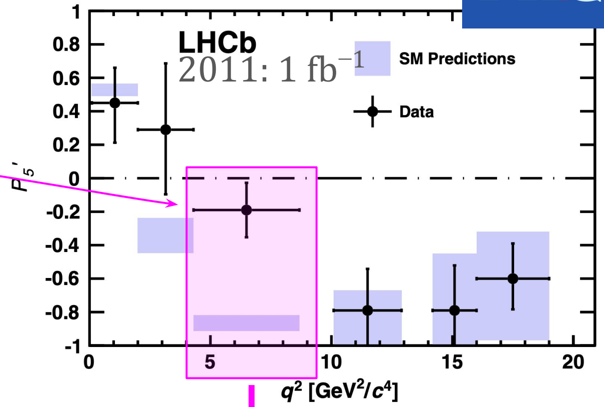
LHCb: $B^0 \to K^{*0}\mu^+\mu^-$

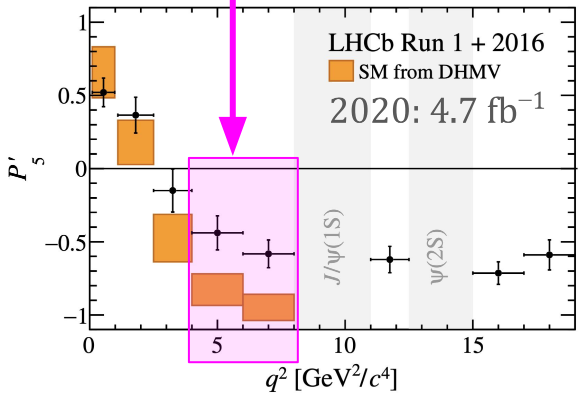
Context:

- Longstanding **tensions** in angular analyses of $b \to s\mu^+\mu^-$
- Tensions in p_5' can be related to tensions in the C_9 Wilson Coefficient in EFT

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







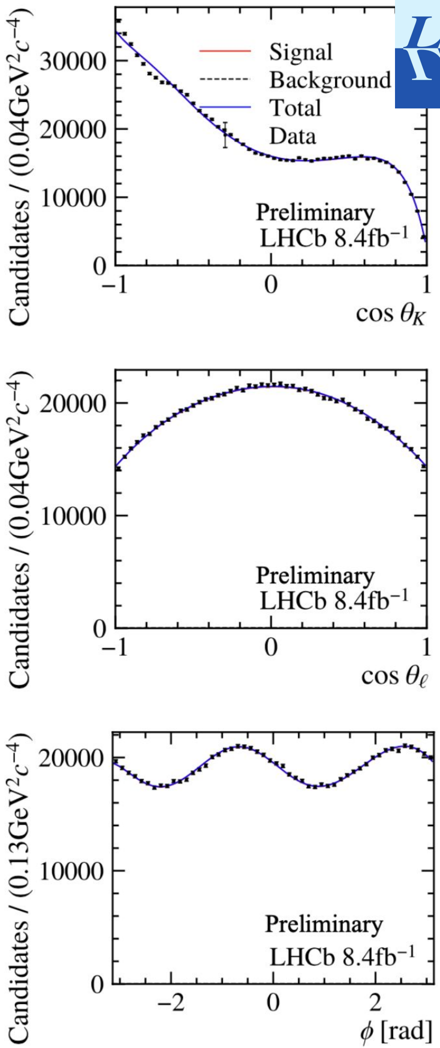
Analysis concept

Signal description:

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

Fit:

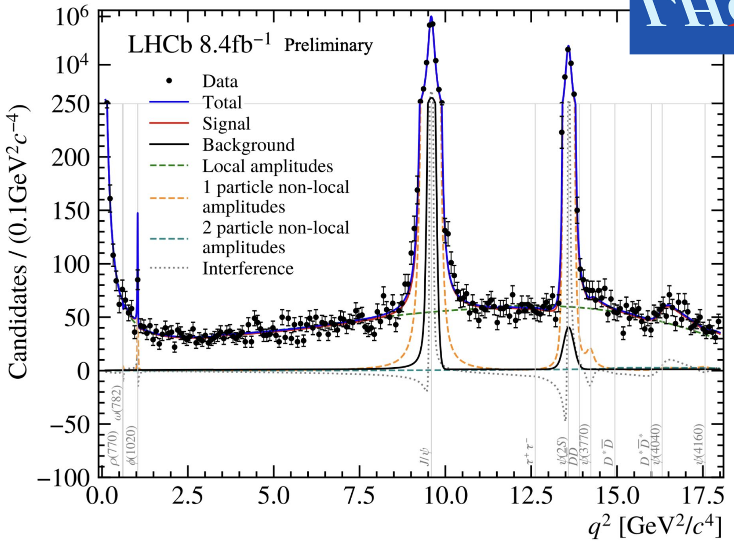
- 4D unbinned fit (**three helicity angles** + q^2)
- Determines **150 parameters**:
  - Wilson coefficients
  - Magnitude and phase on 1-particle contributions
  - 2-particle contribution
  - Form factors
  - …

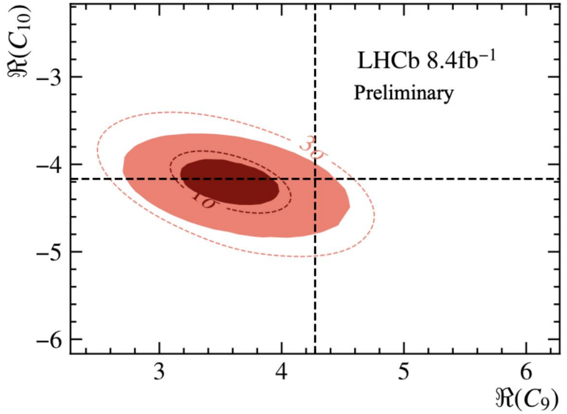


Results

Wilson coefficients from fit:

- Global tension with SM at **1.5s**
- Mostly driven by **2.1σ** tension in C_9 (again)
- The data prefer **more non-local** contributions than in formal SM calculations
  - (but not enough to explain the tension)





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

Conclusions

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

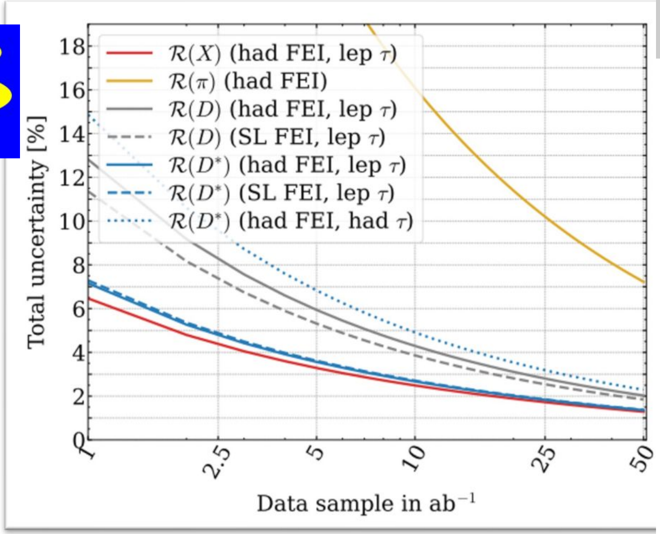
- All-new inclusive $R(X)$ at Belle II
- First $R(D^+)$ at LHCb
- Plus more, not featured today!
- Tension remains at **~3σ**

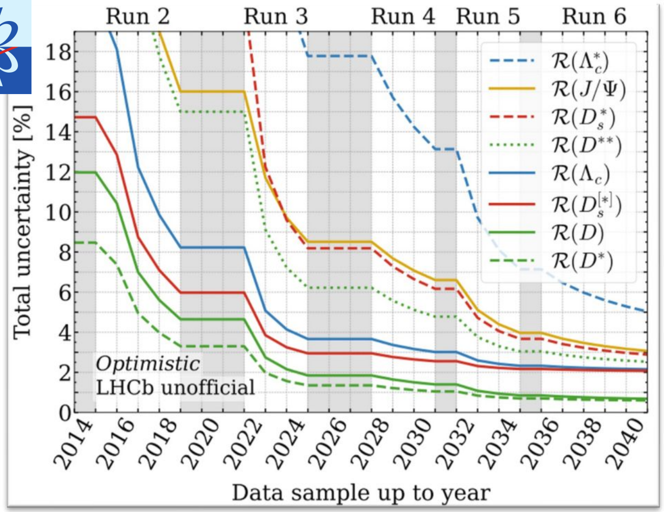
Progress in FCNCs:

- 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**!*

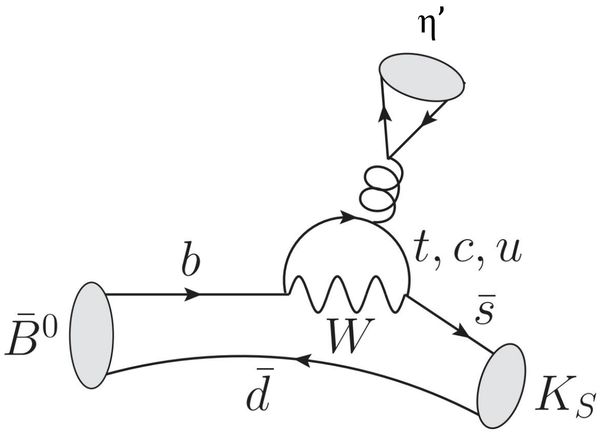




Thank you!

Belle II: Time-dependent *CP* violation

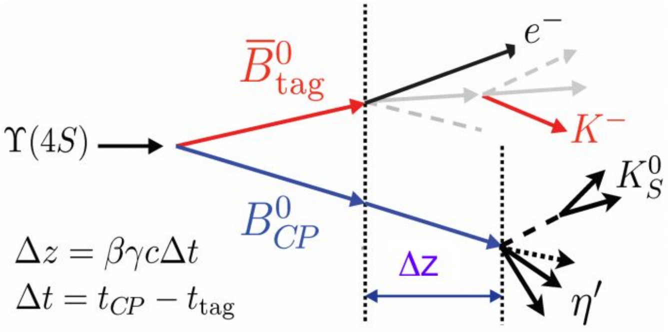
Measurement of CP asymmetries in $B^0 \to \eta' K_s^0$ decays at Belle II



Belle II: $B^0 \to \eta' K_s^0$

Time-Dependent CP Violation in a **gluonic penguin** $b \to s\bar{q}q$ (where q is u, d, or s):

- Dominated by loop amplitudes; sensitive to NP sources of CPV
- $B^0 \to \eta' K_s^0$: large BF, limited tree amplitudes



$$\mathcal{A}_{CP}(\Delta t) = \frac{\Gamma(\bar{B}^0 \to f_{CP}) - \Gamma(B^0 \to f_{CP})}{\Gamma(\bar{B}^0 \to f_{CP}) + \Gamma(B^0 \to f_{CP})}(\Delta t) = S \sin(\Delta m \Delta t) - C \cos(\Delta m \Delta t)$$

Mixing-induced (S); Direct (C)

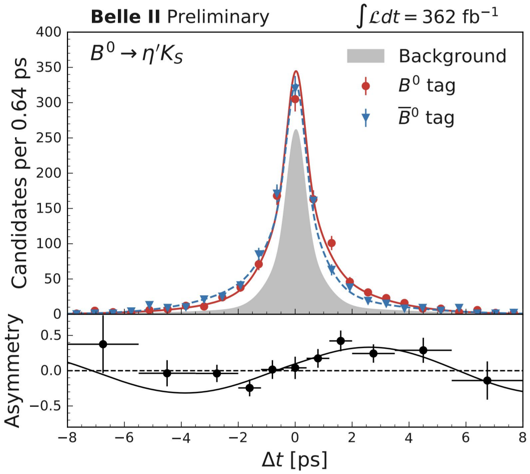
Measurements:

$$C_{\eta' K_S^0} = -0.19 \pm 0.08 \pm 0.03,$$

Consistent with **SM** (0) and **world average** (−0.05 ± 0.04)

$$S_{\eta' K_S^0} = +0.67 \pm 0.10 \pm 0.04,$$

Consistent with **world average** (0.63 ± 0.06)



Take-home: "best" gluonic penguin competitive with Belle/BaBar despite smaller sample; **statistically limited**