NOVEL APPROACHES TO DETERMINE $B^{\pm}$ AND B^0 MESON PRODUCTION FRACTIONS

Based on PRD **110** (2024) 014007 w/ Florian Bernlochner, Martin Jung, Munira Khan, and Zoltan Ligeti

Greg Landsberg - Challenges in Semileptonic B Decays Workshop

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Why Do We Care?

- A number of the B meson branching fractions are claimed to be precisely determined (≈2% precision):

Semileptonic and leptonic modes					
Γ_1	$\ell^+\nu_\ell X$	[1]	$(10.99 \pm 0.28)\%$		
D, D^*, or D_s modes					
Γ_{54}	$\overline{D}^0\pi^+$		$(4.61 \pm 0.10) \times 10^{-3}$	2308	
Γ_{295}	$J/\psi(1S)K^+$		$(1.020 \pm 0.019) \times 10^{-3}$	1684	
K or K^* modes					
Γ_{288}	$K^+\pi^-$		$(2.00 \pm 0.04) \times 10^{-5}$	2615	

- However, this is not quite true:
  - A number of measurements made at B factories assumed isospin universality in ϒ(4S) decays, namely that

$$R^{\pm,0} \equiv f_{+-}/f_{00} \equiv \frac{\Gamma[\Upsilon(4S) \to B^+B^-]}{\Gamma[\Upsilon(4S) \to B^0\overline{B}^0]} = 1$$

  - Other take into account a few existing measurements of $R^{\pm,0}$, which may be statistically different from unity:
    - HFLAV 2023: $R^{\pm,0} = 1.059^{+0.024}_{-0.025}$ dominated by the 2005 BaBar measurement using single vs. double tags: PRL **94** (2005) 141801

Why Do We Still Care?

- The problem is not new [pointed out by Martin and others nearly a decade ago, e.g., Jung, PLB **753** (2016) 187] but often ignored or swept under the rug [as often is the case for the PDG branching fraction values]
- There are two immediate implications of $R^{\pm,0}$ not equal to unity:
  - Many of the B^+, B^0 branching fractions (measured under the assumption of $R^{\pm,0}$ = 1) may be off by as much as 6%
  - For those that explicitly use the HFLAV $R^{\pm,0}$ number, there is an additional 3% uncertainty related to the current uncertainty in $R^{\pm,0}$
- In fact, with the experimental community paying more and more attention to this issue, many of the new results coming from Belle II and LHCb often have the $R^{\pm,0}$ uncertainty as the leading one
- Consequently, one would like to have a significantly more precise determination of $R^{\pm,0}$ with the uncertainty of about 1%

Can One Calculate $R^{\pm,0}$

- Naively it's not hard to do, as ϒ(4S) → BB decay is non-relativistic
  - The main effect is expected from Coulomb interaction in the B^+B^- system, which is absent in the neutral meson case
    - It significantly enhances the B^+B^- fraction
  - However, if one does it, the $R^{\pm,0}$ value obtained is about 1.2, clearly inconsistent with the experimental determination
    - Atwood, Marciano, PRD **41** (1990) 1736
    - Lepage, PRD **42** (1990) 3251
  - A decade later, there have been several attempts to lower this value by considering various additional effects, such as the ϒ(4S) lineshape, but all of them can't really go below 1.1, and have large uncertainties
    - Kaiser, Manohar, Mehen, PRL **90** (2003) 142001
    - Voloshin, Phys. Atom. Nucl. **63** (2005) 771
    - Dolinsky et al, PRD **75** (2007) 113001
    - Milstein, Salnikov, PRD **104** (2021) 014007

Our Approach

- We decided to systematically review available information on $R^{\pm,0}$ and derive a new average
- We further discuss the dependence of the results on the assumption of the non-BB fraction of the $\Upsilon(4S)$ decays
- With these in mind, we propose an experimental program that could be carried out by Belle II and the (HL-)LHC experiments to determine $R^{\pm,0}$ with the precision of about 1%

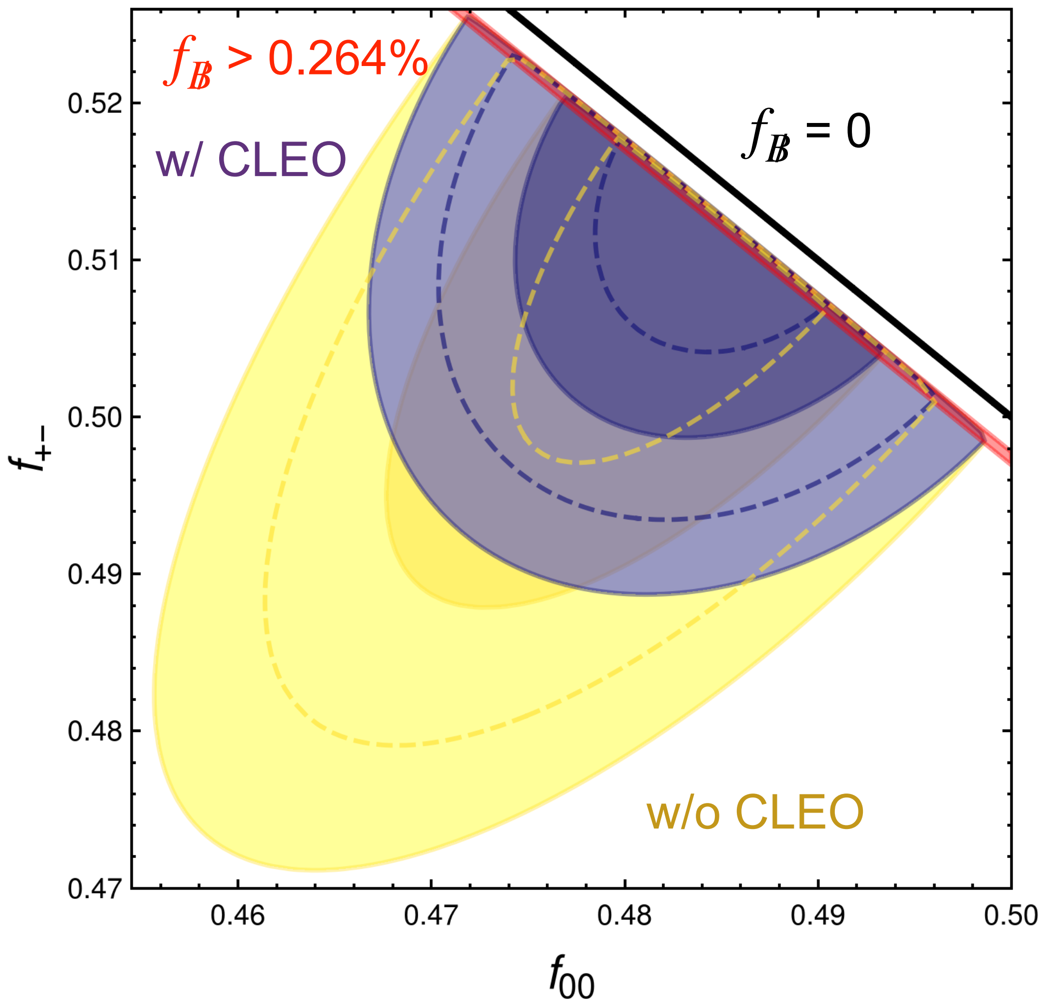
BROWN

Present $R^{\pm,0}$ Average

- The HFLAV average [Amhis et al, PRD 107 (2023) 052008] is $R^{\pm,0} = 1.059^{+0.024}_{-0.025}$
- This number assumes that all Υ(4S) decays are into BB
- We note that $f_{\not B} = 1 - f_{00} - f_{+-}$ and given $R^{\pm,0} = f_{+-}/f_{00}$, it's clear that in order to relate $R^{\pm,0}$ to absolute branching fractions, the knowledge of $f_{\not B}$ is required
  - The best available measurement to date comes from CLEO $f_{\not B} = (-0.11 \pm 1.43 \pm 1.07)\ \%$ [PRL **76** (1996) 1570]
    - The precision is hardly satisfactory; a better measurement is definitely needed!
  - It is ***not*** included in the HFLAV determination of $R^{\pm,0}$
  - Instead, HFLAV uses a lower bound $f_{\not B} > (0.264 \pm 0.021)\ \%$ that comes from the measurements of the Υ(4S) decay modes with additional pions

The $f_{\not B}$ Treatment

- ✦ Accounting for $f_{\not B}$ makes significant difference



N.B. HFLAV does not provide the correlation between the two fractions

Our $R^{\pm,0}$ Analysis

- We considered three classes of measurements w/ different theoretical assumptions and assign uncertainties for these assumptions when deriving the new average

$R^{\pm 0}$	Method	Comment
1.047(44)(36)	Single vs. double-tag	Uses $f_{\not B}$, see text
1.039(31)(50)	$B \to X_c \ell \nu$	Assumes negligible isospin violation
1.068(32)(20)(21)	$B \to X_s \gamma$	Third uncertainty due to resolved photon contributions
1.055(30)		Average categories I and II
1.065(12)(19)(32)	$B \to J/\psi K$	Third uncertainty due to isospin violation in $B \to J/\psi K$
1.013(36)(27)(30)	$B \to J/\psi K$	Third uncertainty due to isospin violation in $B \to J/\psi K$
1.100(35)(35)(33)	$B \to J/\psi(ee)K$	Third uncertainty due to isospin violation in $B \to J/\psi K$
1.066(32)(34)(32)	$B \to J/\psi(\mu\mu)K$	Systematic uncertainties $\sim 100\%$ correlated with ee mode
1.060(18)(32)		Average for $B \to J/\psi K$
1.057(23)		**Average of all categories I–III**

$$R^{\pm,0} = 1.057 \pm 0.023$$

$$R^{\pm,0}_{\mathrm{HFLAV}} = 1.059^{+0.024}_{-0.025}$$

Little more precise than HFLAV, consistent in central value, but significantly more robust

Back to $R^{\pm,0}$ from Theory

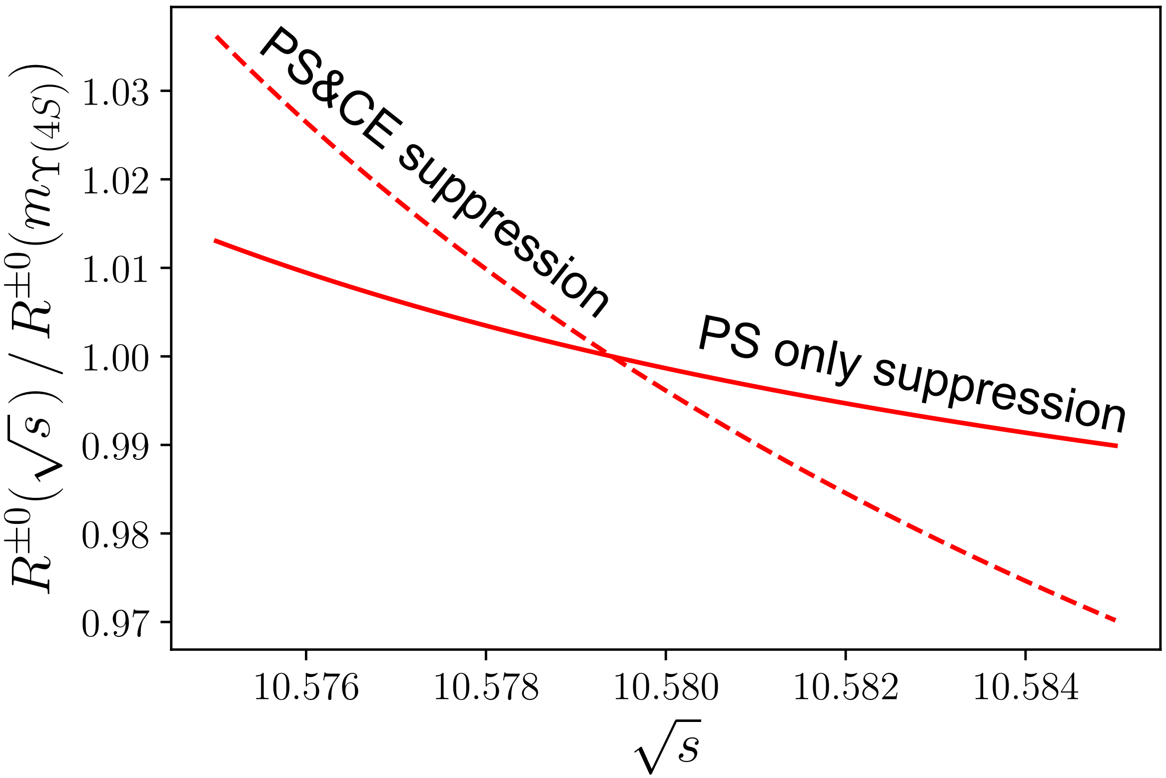
- Let's examine more closely the original "naive" $R^{\pm,0}$ calculations
- There are two factors that enter $R^{\pm,0}$:
  - Phase space difference between charged and neutral BB system
  - Coulomb interactions

Decay Mode	$R^{\pm0}_{\rm PS}$	$R^{\pm0}_{\rm CE}$	$R^{\pm0}_{\rm PS}\, R^{\pm0}_{\rm CE}$
$\Upsilon(4S) \to B\overline{B}$	1.048	1.20	1.26

- Interestingly enough, our average $R^{\pm,0} = 1.057 \pm 0.023$ is consistent with phase space only suppression

Boring but Important

- All the averages assume the beam energy stability and exactly the same beam energy for various measurements
  - This may not be exactly the case, as the typical beam energy resolution at B factories is 4-6 MeV (compared to the 20.5 MeV width of ϒ(4S))
  - A 5 MeV shift in the beam energy affects the $R^{\pm,0}$ by 1-3%
  - Important that the energy is kept under control in future measurements!



A Way Out (Barolo Lunch)

- Should use a different system with smaller PS/CE effects to ensure that $R^{\pm,0}$ is closer to one!
- Why not use ϒ(5S)? 💡
- Indeed:

Decay Mode	$R_{\mathrm{PS}}^{\pm 0}$	$R_{\mathrm{CE}}^{\pm 0}$	$R_{\mathrm{PS}}^{\pm 0}\, R_{\mathrm{CE}}^{\pm 0}$
$\Upsilon(4S) \to B\overline{B}$	1.048	1.20	1.26
$\Upsilon(5S) \to B\overline{B}$	1.003	1.05	1.05
$\Upsilon(5S) \to B^*\overline{B}^*$	1.004	1.06	1.06

- Expect that $R^{\pm,0}$ should be very close to 1 on ϒ(5S)

$$R_{5S}^{\pm,0} = \frac{\Gamma[\Upsilon(5S) \to B^{(*)+}B^{(*)-}]}{\Gamma[\Upsilon(5S) \to B^{(*)0}\overline{B}^{(*)0}]} \approx 1$$

A Way Out (Barolo Dinner)

- Consider the double ratio of the ϒ(4S) to ϒ(5S) for specific decays:

$$r(f, f') = \left[\frac{N(B^+ \to f)}{N(B^0 \to f')}\right]_{\Upsilon(4S)} \Bigg/ \left[\frac{N(B^+ \to f)}{N(B^0 \to f')}\right]_{\Upsilon(5S)}$$

- All systematic uncertainties related to specific final states (e.g., possible isospin violation) cancels in this double-ratio, giving a direct access to $R^{\pm,0}$ on ϒ(4S), assuming it's ≈1 for ϒ(5S)!
- Requires dedicated running on ϒ(5S) for Belle II and/or reanalysis of the existing BaBar/Belle ϒ(5S) data
- Can one reach the desired O(1%) precision?

A Way Out (Aftermath)

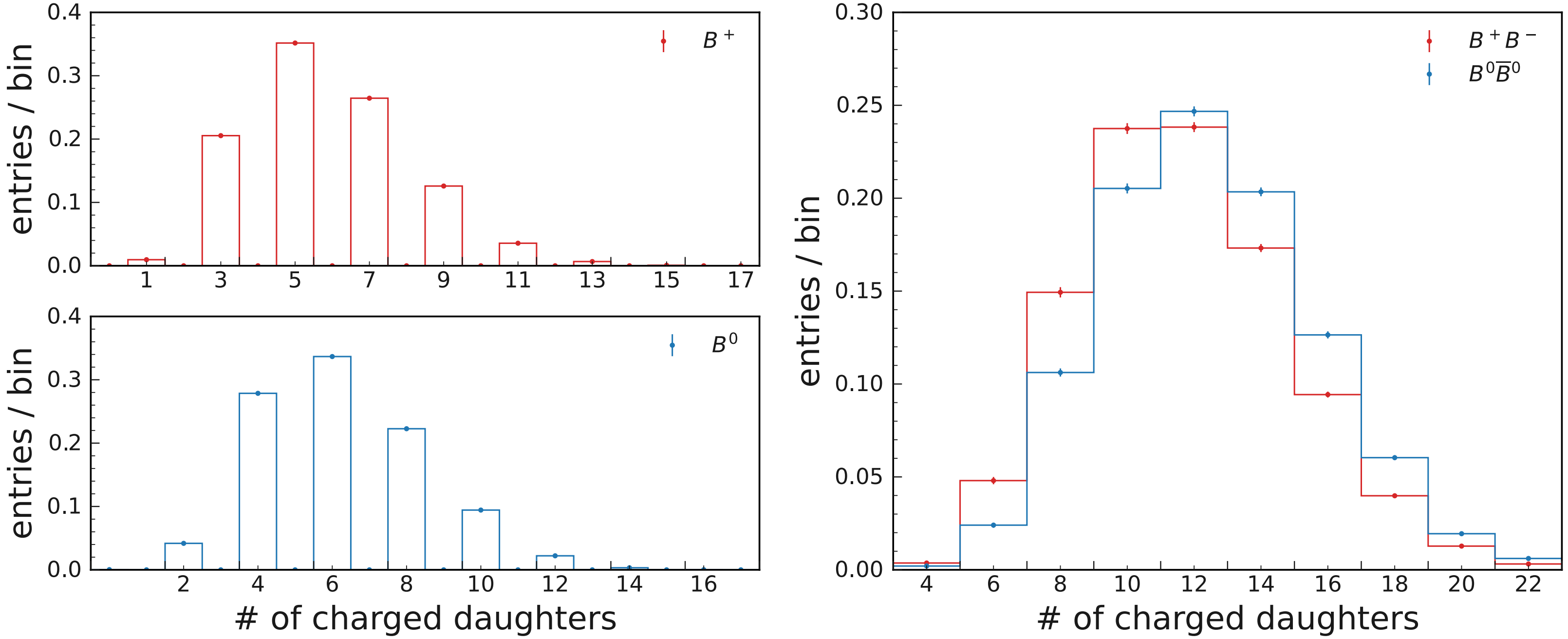
- Here are our projections for the few most promising channels we identified

	Belle	Belle II partial	Belle II full
$\mathcal{L}_{\Upsilon(5S)}$ / $\mathcal{L}_{\Upsilon(4S)}$ [ab^{-1}/ab^{-1}]	0.12 / 0.71	0.5 / 5	5 / 50
$N^{\Upsilon(5S)}_{B^{(*)}B^{(*)}}$ / $N^{\Upsilon(4S)}_{BB}$	2.74×10^7 / 7.72×10^8	1.13×10^8 / 5.55×10^9	1.13×10^9 / 5.55×10^{10}
$f,\ f'$		$\Delta r(f, f')/r(f, f')$	
$J/\psi K^+,\ J/\psi K^0$	7.1%	3.5%	1.1%
$\bar{D}^0\,\pi^+,\ D^-\pi^+$	2.4%	1.2%	0.4%
$\bar{D}^{*0}\ell^+\nu,\ D^{*-}\ell^+\nu$	4.5%	2.2%	0.7%
$\bar{D}^0\pi^+,\ D^{*-}\ell^+\nu$	1.8%	0.9%	0.3%

- Already could reach the present precision by reanalyzing Belle data
- Even with partial Belle II data (0.5/5 ab^{-1} on Y(5/4S)), a percent precision can be reached, reaching a fraction of a percent with full Belle II data
- Very encouraging and resonated with Belle II management about potential advancement of the Y(5S) program

Another Way Out

- Using global event variables to measure $R^{\pm,0}$
- Efficiencies of detection of charged and neutral B pairs at B factories are very similar and close to 100%
  - Also common triggers are typically used for both types
- Simplest global variable one could imagine is the total number of tracks above a certain threshold



Track Counting: Sensitivity

- Projected sensitivity is similar to that of the ϒ(4S)/ϒ(5S) double ratio
- Can be done before ϒ(5S) running and with the existing data
- Calibrate the track reconstruction efficiency with known decays, e.g. $B^\pm \to D^0\pi^\pm$ and $B^0 \to D^-\pi^+$

	Belle	Belle II partial	Belle II full
$\mathcal{L}_{\Upsilon(4S)}$ [ab^{-1}]	0.71	5	50
$\Delta(R^{\pm 0})/R^{\pm 0}$	2.2%	0.9%	0.3%

What About (HL-)LHC?

- At hadron colliders, measurements of the production fractions f_s, f_u, f_d of B_s^0, B^+, B^0 mesons play similar role to $R^{\pm,0}$ at the B factories
  - The f_s/f_u is now the leading uncertainty in the $\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ measurement
  - Implicitly relies on an assumption of $f_u = f_d$

Summary of the systematic uncertainties for the $B_s^0 \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ branching fraction measurements.

Effect	$B_s^0 \to \mu^+\mu^-$	$B^0 \to \mu^+\mu^-$
f_s/f_u ratio of the B meson production fractions	3.5%	–
d_{MVA} correction	2–3%	
Tracking efficiency (per kaon)	2.3%	
Trigger efficiency	2.4–3.7%	
Fit bias	2.2%	4.5%
Pileup	1%	
Vertex quality requirement	1%	
$B^+ \to J/\psi K^+$ shape uncertainty	1%	
$B^+ \to J/\psi K^+$ branching fraction	1.9%	

CMS, PLB **842** (2023) 137955

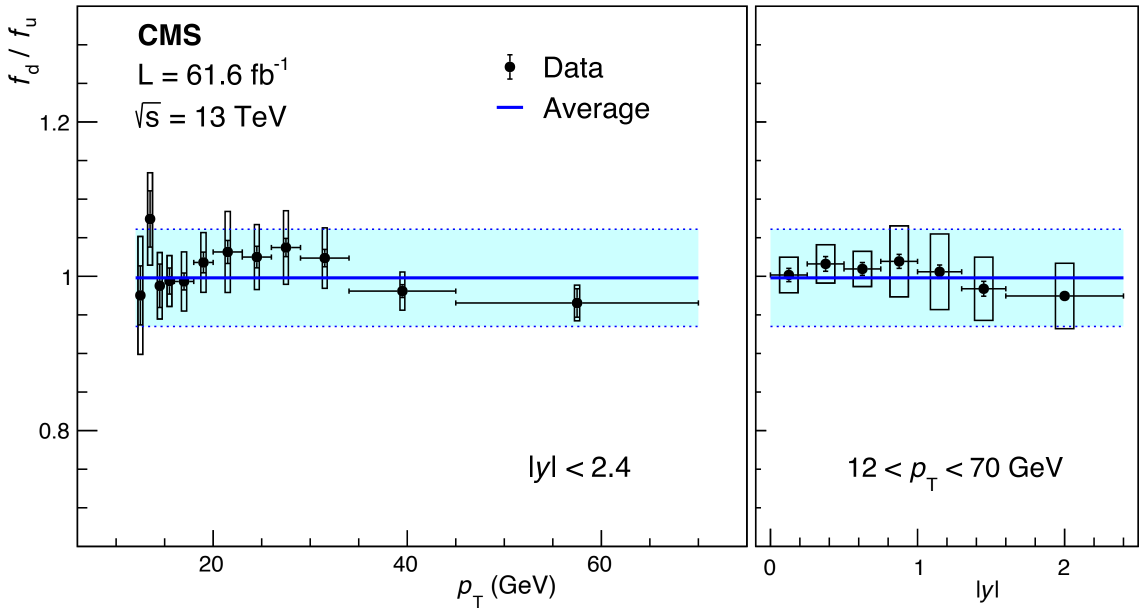
Is f_u Equal to f_d

- This is essentially an isospin invariance assumption
- However, unlike e^+e^-, pp initial state is not an isospin eigenstate, so the isospin conservation in the final state is questionable
  - Furthermore, there are additional particles always present, so the produced system is not a pure BB final state
- Since b and $\overline{b}$ quarks fragment independently, measurements of Type I (single vs. double tag) are not possible
- Hence, there is always a mixture of potential isospin violation in the initial and final state, with the latter needed to be disentangled

First Measurement of f_d/f_u

- The first Type-II measurement of the f_d/f_u ratio has been recently performed by CMS
  - Based on the ratio of $B^0 \to K^{*0} J/\psi$ and $B^+ \to K^+ J/\psi$ decay
  - Explicitly uses HFLAV $R^{\pm,0}$ as an external input, thus bringing in an 3% extra uncertainty
  - $f_d/f_u = 0.998 \pm 0.063$

CMS, PRL **131** (2023) 121901



Can We Do Better?

- Potentially yes!
- At HL-LHC, one could use the fact that the branching fractions of semileptonic decays are expected to show small isospin violation
  - e.g., $\Gamma(B^0 \to \bar{D}^{(*)} X \mu\nu) \approx \Gamma(B^+ \to \bar{D}^{(*)} X \mu\nu)$
    - Similar technique has been already used for fs/fd determination in LHCb
  - Charged and neutral B mesons can potentially be separated through the oscillations in B^0 system
    - Again, this approach has been used by LHCb in time-dependent Δm_d variable to remove $B^\pm$ background
- Whether a 1% precision can be achieved in these types of measurements is an experimental question worth pursuing
- Finally at hadron colliders we could use an isosinglet $t\bar{t}$ system in a similar way ϒ(ns) or Z are used at e^+e^- machines
  - B mesons produced in top quark decays are expected to preserve the isospin invariance
  - It would be interesting to test this experimentally!

Conclusions

- Precision determination of $R^{\pm,0}$ is important for a variety of measurements and theoretical calculations in many areas of B physics
  - Current precision makes it inconclusive whether the central value is consistent with unity or not
  - Affects precision of several important branching fractions determination
- A precision measurement of non-BB fraction in ϒ(4S) decays is an important input to the extraction of $R^{\pm,0}$
  - The only existing measurement by CLEO, which is nearly 30 years old and has ~2% precision is not sufficient to reach a percent precision in $R^{\pm,0}$
- We developed several novel methods of significantly shrinking the $R^{\pm,0}$ uncertainties (along with the fragmentation fraction ratios), using combination of B factories and (HL-)LHC measurements
- The results look promising and we hope that they will serve as a guide for experimental resolution of the $R^{\pm,0}$ puzzle