LHCP, May 2023

CURRENT ISSUES IN FLAVOR PHYSICS

Flavor highlights as of May 2023

Avital Dery

Overview

Highlights* in flavor physics

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d u

B physics

The B anomalies

$|V_{cb}|, |V_{ub}|$

Puzzles in $B_s \to KK$

Kaon physics

$K \to \pi\nu\nu$

$K \to \mu\mu$

Charm physics

Charm CPV

* my personal favorites!

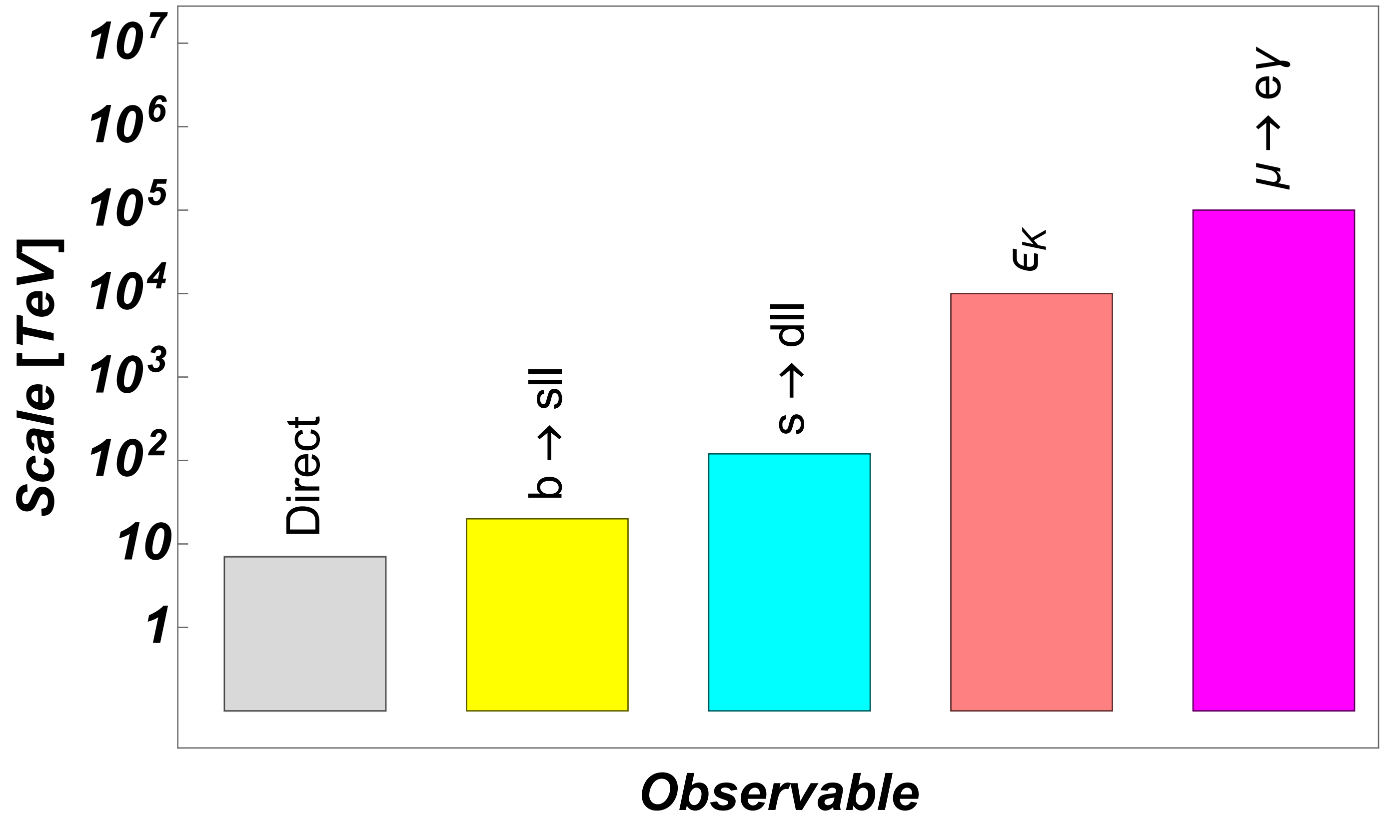
The INTENSITY Frontier

The vast, unprecedented production statistics of hadrons in the current era allow us to peer into the **extremely rare** and achieve **extreme precision**.

THE NEW YORKER

"Make sure you can see how insignificant I am."

Flavor physics sensitivity



Sensitive to **high scales of generic NP -** SM rates often suppressed by GIM, CKM, etc.

Flavor physics **pushes the limits of the SM -** subjecting it to meticulous scrutiny.

Naturally related to **BIG questions** - flavor puzzles, neutrino masses and the baryon asymmetry of the universe.

B physics: The B anomalies

Several hints of Lepton Flavor Universality (LFU) violation appeared since 2012 in semileptonic B decays

Charged current, $b \to c\ell\nu$

$$R(D^{(*)}) = \frac{\mathscr{B}(B \to D^{(*)}\tau\nu)}{\mathscr{B}(B \to D^{(*)}\ell\nu)}$$

Neutral current, $b \to s\ell\ell$

$$R(K^{(*)}) = \frac{\mathscr{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathscr{B}(B \to K^{(*)}e^+e^-)}$$

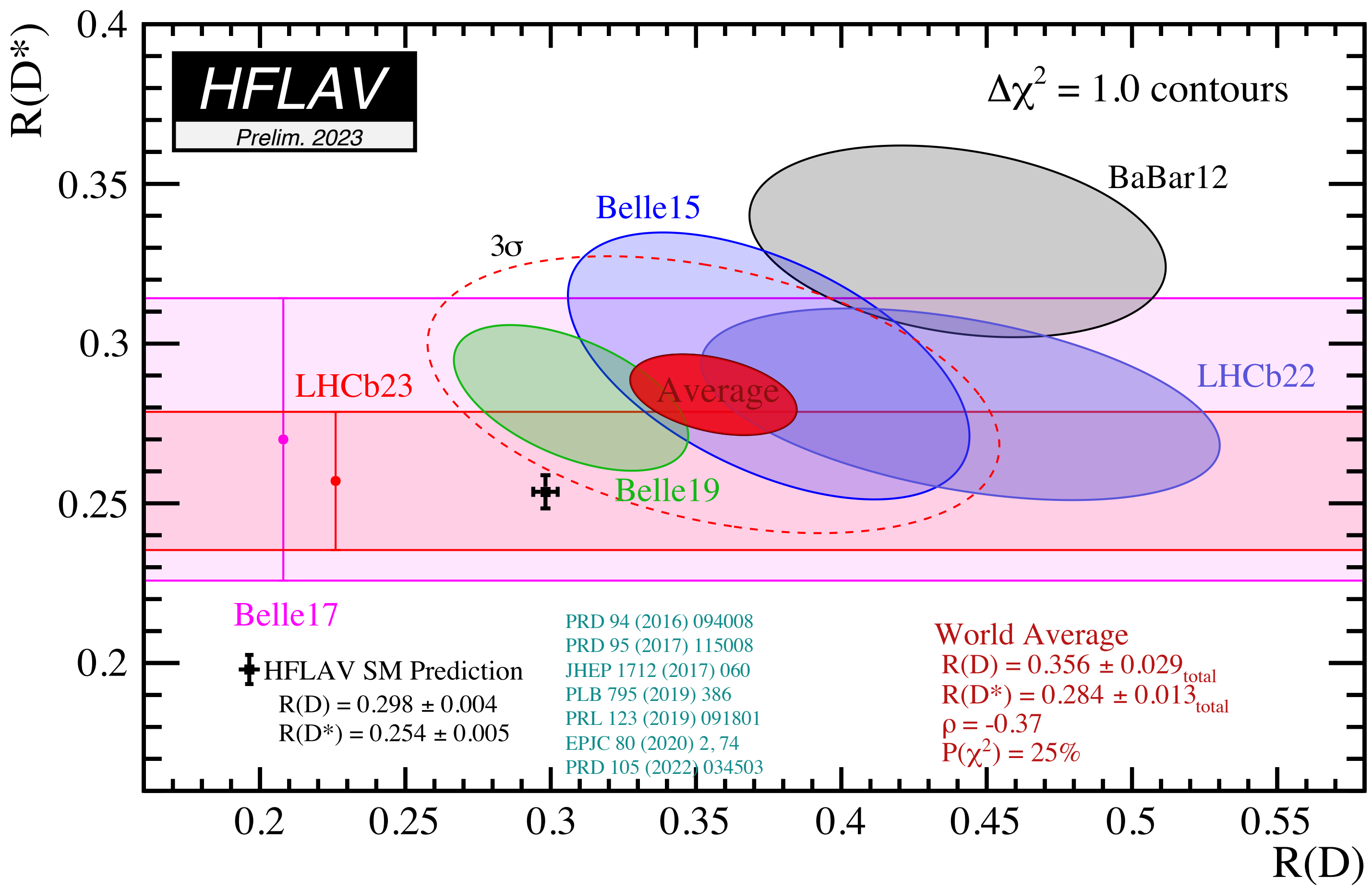
What is the current status?

B physics: The B anomalies

Charged current, $b \to c\ell\nu$

$$R(D^{(*)}) = \frac{\mathscr{B}(B \to D^{(*)}\tau\nu)}{\mathscr{B}(B \to D^{(*)}\ell\nu)}$$

First results in 2012 from the B factories - BaBar, then Belle (exp. clean, low stats)
Today LHCb is strong in the game (high bkg, high stats)



Average has gotten closer to SM, but uncertainty has shrunk accordingly -
Still $\sim 3\sigma$ tension with SM for world average.

Individual measurements taken alone do not exhibit severe tension.

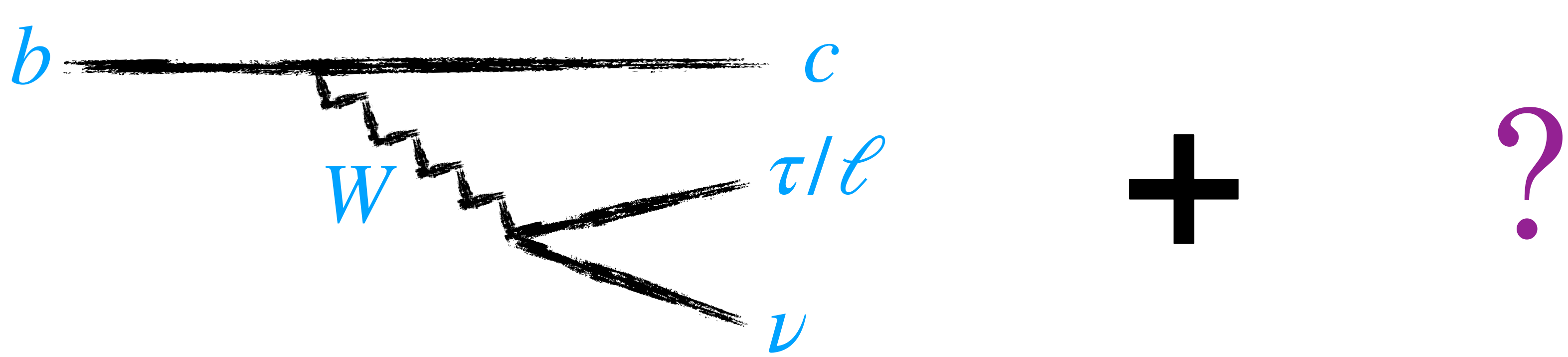
SOON:
Belle II enters the picture.
Uncertainties expected under 10%

B physics: The B anomalies

Charged current, $b \to c\ell\nu$

$$R(D^{(*)}) = \frac{\mathscr{B}(B \to D^{(*)}\tau\nu)}{\mathscr{B}(B \to D^{(*)}\ell\nu)}$$

If the tension persists, this will strengthen the case for New Physics, naively pointing to TeV scales contributing at tree-level.



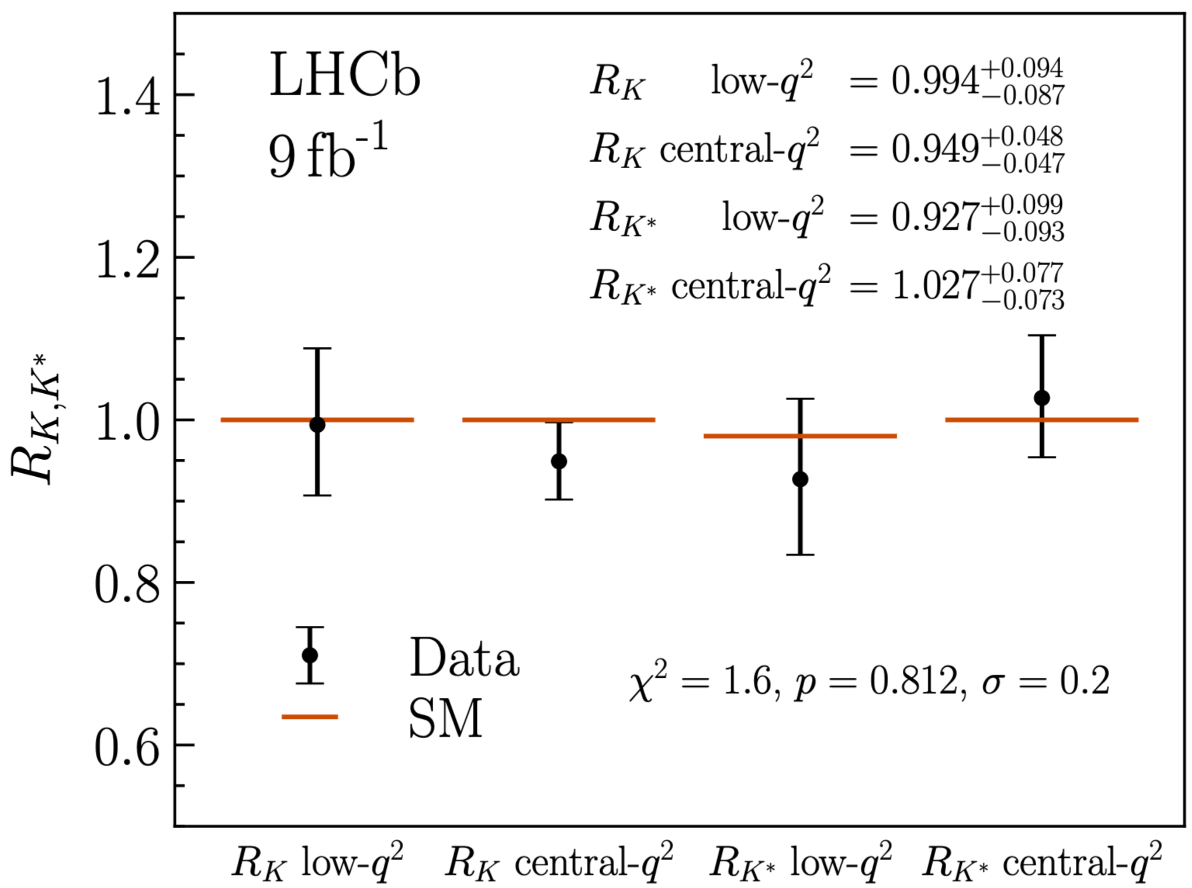
Many relevant direct searches are being carried out by ATLAS & CMS.

B physics: The B anomalies

Neutral current, $b \to s\ell\ell$

$$R(K^{(*)}) = \frac{\mathscr{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathscr{B}(B \to K^{(*)}e^+e^-)}$$

LHCb results from December 2022 improve Bkg estimation previously underestimated (misidentification of π & K as e).



Latest results are consistent with SM for both $R(K), R(K^*)$.

B physics: The B anomalies FUTURE PROSPECTS

- LFU ratios with other final state hadrons (partial list):

Charged current

measured:
$R(J/\psi)$
$R(\Lambda_c)$

Future:
$R(D_s)$
$R(D^{**})$
Inclusive $R(X)$ (Belle II)
$R(\pi)$

Neutral current

measured:
$R(pK)$
$R(K_s)$
$R(K^{*+})$

Future:
$R(\phi)$
$R(K\pi\pi)$
$R(\Lambda)$

- Belle II - potential to better understand feed down from D^{**} (e.g., $D^{**}\mu\nu$ can mimic $D^*(\tau \to \mu\nu\nu)\nu$)
- Important Lattice QCD progress
- ATLAS & CMS also working towards semileptonic B decay measurements

B physics: The B anomalies - Looking forward:

Clearly precision observables such as LFU ratios are interesting.

Still room for $\mathcal{O}(10\%)$ deviations even in the neutral current.

Difficult Bkg estimations are being better understood.

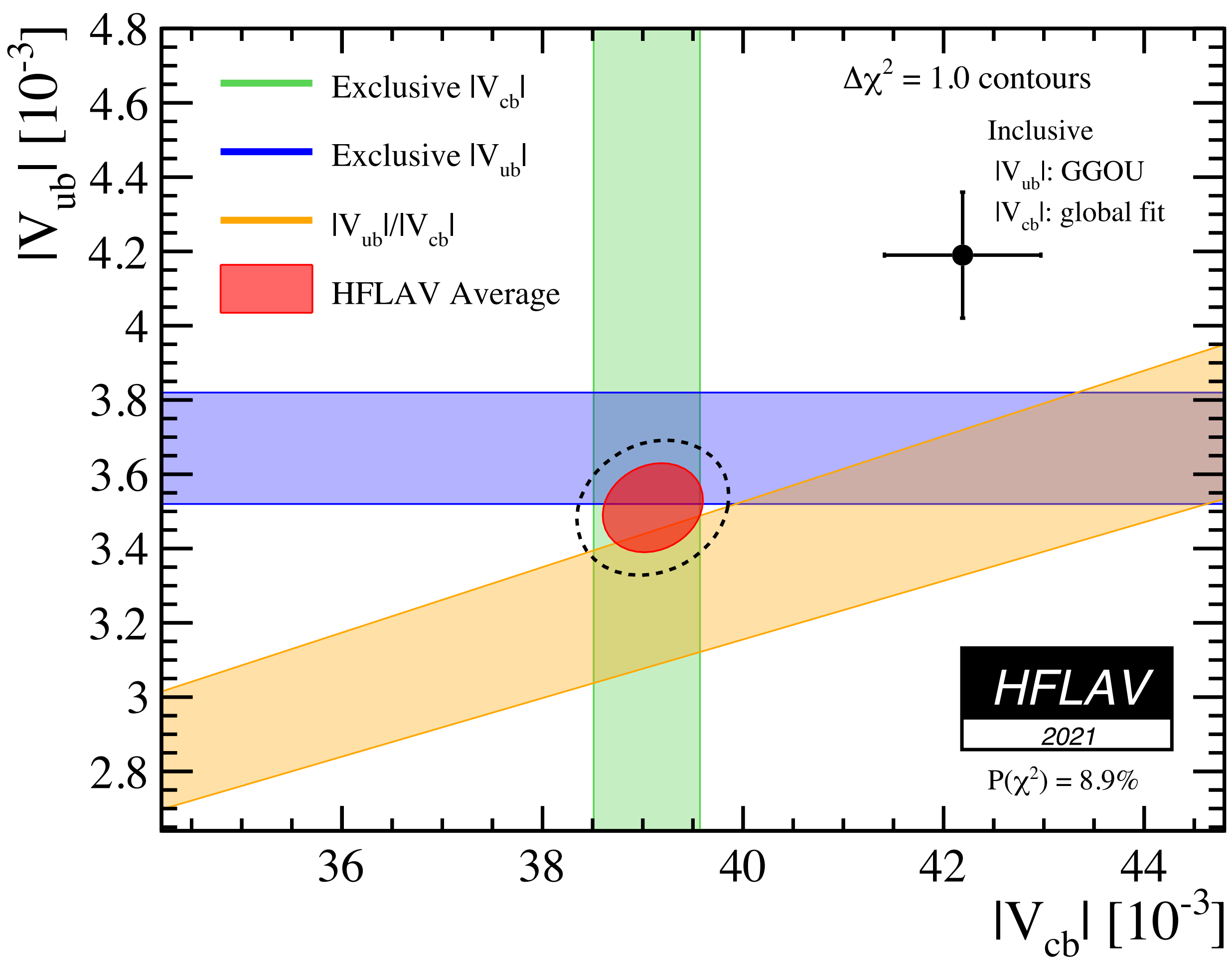
Many more measurements in various channels to appear.

B physics: $|V_{cb}|, |V_{ub}|$

$|V_{ub}|$, $|V_{cb}|$ also determined from semileptonic B decays.

Large tension between inclusive and exclusive measurements.

Enters into many SM predictions as large parametric uncertainties (e.g., $\varepsilon_K \propto |V_{cb}|^4$).



Can also extract from loop observables (meson mixing and rare decays)

〔Altmannshofer Lewis 2112.03437〕

Belle II expected to improve on both inclusive and exclusive measurements of $|V_{cb}|$ and $|V_{ub}|$

B physics: Puzzles in $B_s \to KK$

[Amhis Grossman Nir 2212.03874]
[Biswas et al. 2301.10542]

Three puzzles identified related to $b \to d\bar{d}s$ transitions measured by LHCb and Belle

#1	$R^{sd}_{KK} \equiv \left\| \frac{V_{td}}{V_{ts}} \right\|^2 \frac{\Gamma(B_s \to K^0\overline{K}^0)}{\Gamma(B^0 \to K^0\overline{K}^0)} = 0.61 \pm 0.13$	$\neq 1$	U-spin limit prediction
#2	$R^{ss}_{KK} \equiv \frac{\Gamma(B_s \to K^0\overline{K}^0)}{\Gamma(B_s \to K^+K^-)} = 0.66 \pm 0.13$	$\neq 1$	Approximate Isospin limit prediction
#3	$R^{ss}_{KK}/R^{ud}_{\pi K} \equiv \left(\frac{\Gamma(B_s \to K^0\overline{K}^0)}{\Gamma(B_s \to K^+K^-)}\right) / \left(\frac{\Gamma(B^+ \to \pi^+K^0)}{\Gamma(B^0 \to \pi^-K^+)}\right) = 0.59 \pm 0.12$	$\neq 1$	SU(3)-flavor prediction

Each of these exhibits a $\sim 3\sigma$ deviation from the SM prediction.

B physics: Puzzles in $B_s \to KK$

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[Biswas et al. 2301.10542]

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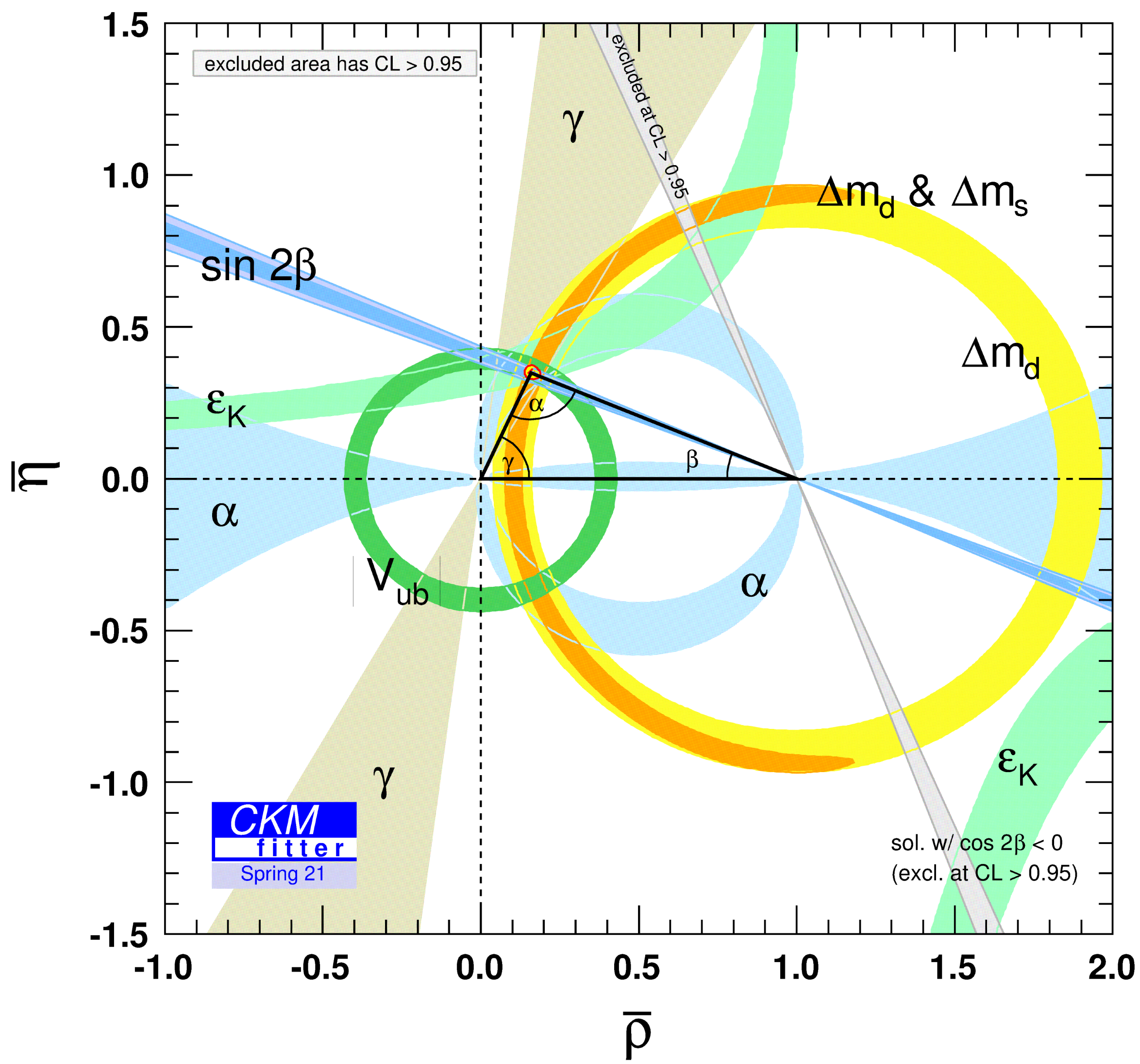
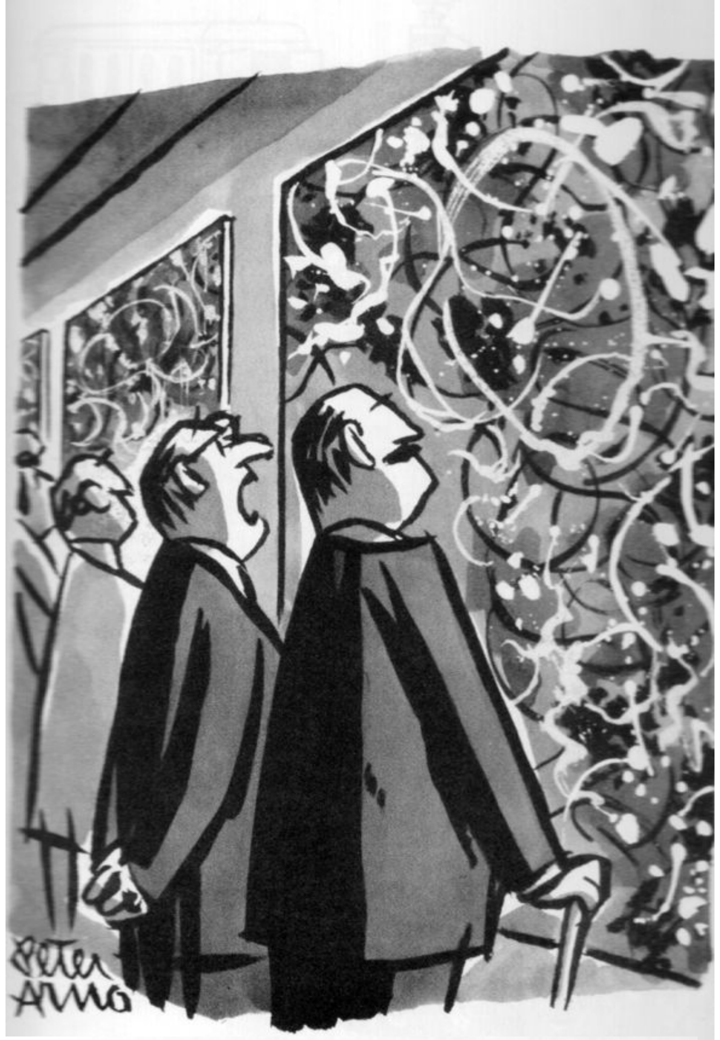
Possible SM effects such as rescattering, SU(3) breaking etc. cannot account for all three combined.

If the real value of $\mathscr{B}(B_s \to K^0\overline{K}^0)$ turns out to be 3σ above the current average measured value, that would solve all three puzzles. Stay tuned!

Moving on to a second arena: Kaon physics

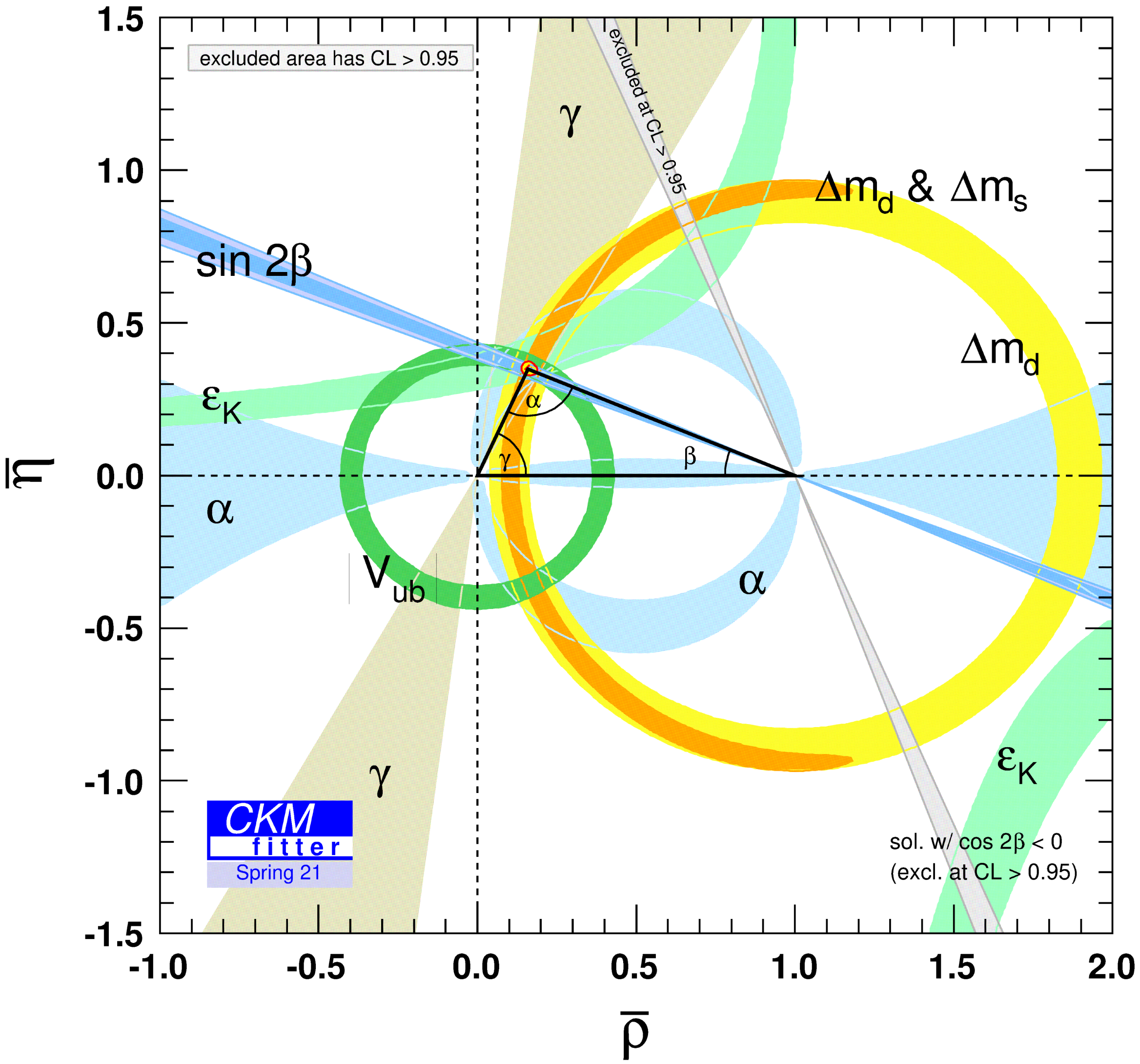


THE NEW YORKER



"His spatter is masterful, but his dribbles lack conviction."

Kaon physics: A crucial and unique test of the SM



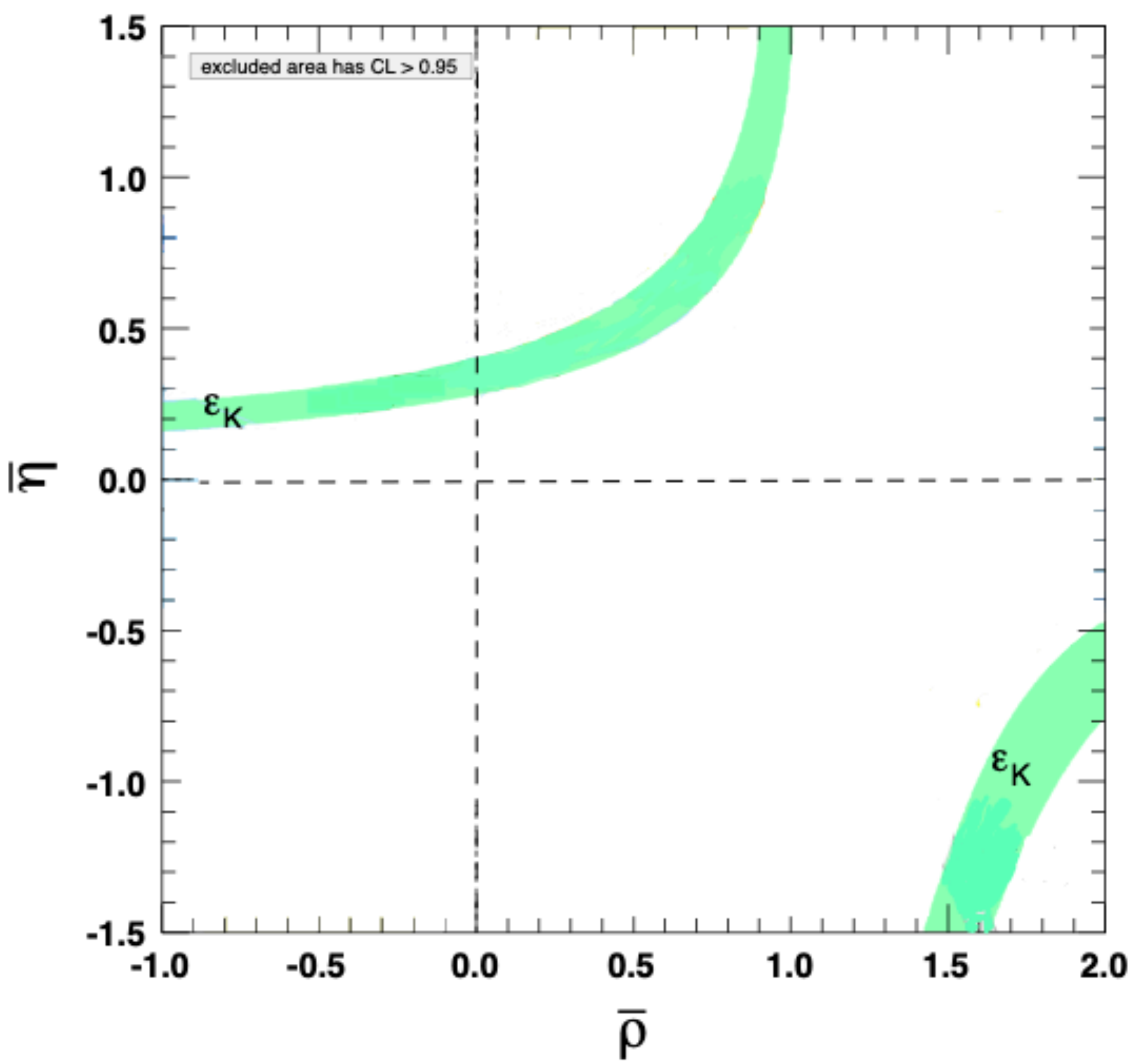
The flavor program has managed to measure the parameters of the CKM matrix in many independent ways, creating a remarkably consistent picture.

However, almost all of these cross-checks arise from B physics.

What is the corresponding picture from K physics?

Kaon physics: A crucial and unique test of the SM

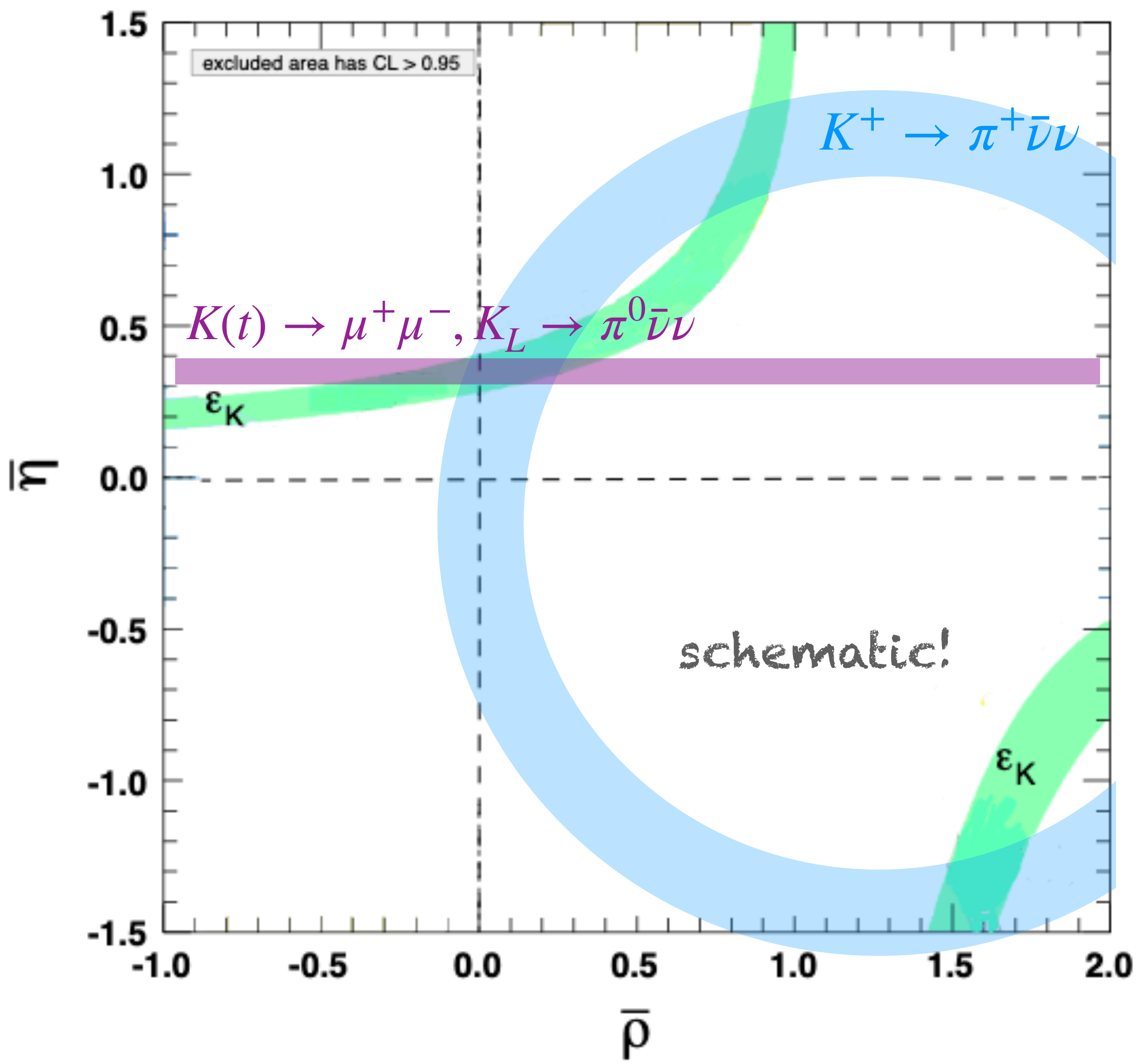
Kaon physics picture:



still many values of both $\bar{\eta}$ and $\bar{\rho}$ consistent with measurement

Kaon physics: A crucial and unique test of the SM

Kaon physics picture:



$K^+ \to \pi^+ \nu\bar{\nu}$ Evidence by NA62

$K_L \to \pi^0 \nu\bar{\nu}$ KOTO

Recent progress - a ***third kaon golden mode***

$$K(t) \to \mu^+\mu^-$$

[AD Ghosh Grossman Schacht 2104.06427]

- Same SM CKM dependence as $K_L \to \pi^0 \nu\bar{\nu}$
- Different dependence on effective NP operators

[AD Ghosh 2112.05801]

* see backup slide for details!

Kaon physics FUTURE PROSPECTS

- NA62 to reach $\sim 5\,\%$ precision on $\mathscr{B}(K^+ \to \pi^+ \nu \bar{\nu})$
- KOTO collaboration continued efforts to observe the elusive $K_L \to \pi^0 \nu \bar{\nu}$
- Next generation kaon program at CERN currently being developed.
- Recent theory and lattice QCD progress

Charm physics: CPV in charm

Discovery of CPV in Kaons — 1964

Discovery of CPV in B mesons — 2001

Discovery of CPV in Charm mesons — 2019 ★ **new arena**

Charm physics is challenging.

- Strong GIM suppression = > rare decays are much rarer compared to B physics

- No small parameter to expand in = > calculations are harder, difficult to interpret measurements

Charm physics: CPV in charm

Discovery of CPV in Kaons	Discovery of CPV in B mesons	Discovery of CPV in Charm mesons ★ **new arena**
1964	2001	2019

$$\Delta A_{CP} \equiv A_{CP}(D^0 \to K^+K^-) - A_{CP}(D^0 \to \pi^+\pi^-)$$
$$= (-1.54 \pm 0.29) \times 10^{-3}$$

LHCb 2019

$$A_{CP}(D^0 \to K^+K^-) = (6.8 \pm 5.4 \pm 1.6) \times 10^{-4}$$

LHCb Sep 2022

$$\boxed{\begin{aligned} a^d_{K^+K^-} &= (7.7 \pm 5.7) \times 10^{-4} \\ a^d_{\pi^+\pi^-} &= (23.2 \pm 6.1) \times 10^{-4} \end{aligned}}$$

→ First evidence for CPV in a single mode, 3.8σ

Charm physics: CPV in charm

Both results are somewhat surprising -

1) $\Delta A_{\mathrm{CP}} = (-1.54 \pm 0.29) \times 10^{-3}$ LHCb 2019

=> requires large rescattering or NP

[Khodjamirian Petrov 1706.07780]
[Grossman Schacht 1903.10952]
[AD Nir 1909.11242]

2) $$\boxed{\begin{aligned} a^d_{K^+K^-} &= (7.7 \pm 5.7) \times 10^{-4} \\ a^d_{\pi^+\pi^-} &= (23.2 \pm 6.1) \times 10^{-4} \end{aligned}}$$

LHCb 2019 +. LHCb 2022

Implies U-spin breaking of $\left(173^{+85}_{-74}\right)\,\%$ compared to the expectation of $\mathcal{O}(30\%)$.

[Schacht 2207.08539]

More statistics are needed to see if this behavior persists.

- More charm CPV measurements are coming in

e.g., local CPV in $D_{(s)}^+ \to K^- K^+ K^+$ LHCb March 2023

- In the future, can expect more to appear (partial list)

LHCb		Belle II
$A_{\rm CP}(D^0 \to K_S^0 K_S^0)$	$D^+ \to K^- K^+ \pi^+$	$A_{\rm CP}(D^+ \to \pi^+ \pi^0)$ SM null test
$A_{\rm CP}(D^0 \to K_S^0 K^{*0})$	$D^+ \to \pi^- \pi^+ \pi^+$	$A_{\rm CP}(D^0 \to \pi^0 \pi^0)$
$A_{\rm CP}(D_s^+ \to K_S^0 \pi^+)$	$D^+ \to \pi^- K^+ \pi^+$	$A_{\rm CP}(D^0 \to K^+ \pi^- \pi^0)$
$A_{\rm CP}(D^+ \to K_S^0 K^+)$	$D^0 \to \pi^- \pi^+ \pi^- \pi^+$	$A_{\rm CP}(D^0 \to K_S^0 \pi^+ \pi^- \pi^0)$
$A_{\rm CP}(D^+ \to \phi \pi^+)$	$D^0 \to K^- K^+ \pi^- \pi^+$	
$A_{\rm CP}(D_{(s)}^+ \to \eta' \pi^+)$		

These can then be used together to test sum rules

[Grossman Robinson 1211.3361]

[Müller Nierste Schacht 1506.04121]

Summary

B physics - Many measurements expected to provide a more comprehensive picture. In particular, Belle II, ATLAS, CMS, will supply additional independent takes.

Kaon physics - A unique and crucial SM test. Recent progress on $K \to \mu\mu$ introduces promising directions.

Charm physics - Intriguing first charm CPV measurements at LHCb. Many relevant future results.

Interplay of th. and exp. efforts on all fronts -

=> Tests of the SM   => Look for New Physics leads

=> A playground to test understanding of non-perturbative physics

=> STAY TUNED!

Thank you for your attention!

write a poem about flavor physics

In the realm of particles, small and unseen,
Lies a captivating dance, a cosmic machine.
Flavor physics, the science so grand,
Unveiling the secrets of particles and their brand.

Oh, flavors of quarks, diverse and distinct,
Up, down, charm, strange, beauty, and truth linked.
Intricate symphony, a subatomic ballet,
Where flavors entwine in a mysterious array.

ChatGPT poetry

(Full version in backup)

In the tapestry of particles, flavor's embrace,
Lies the gateway to knowledge, a cosmic chase.
Flavor physics, a voyage with no end,
Unveiling the universe, its mysteries to comprehend.

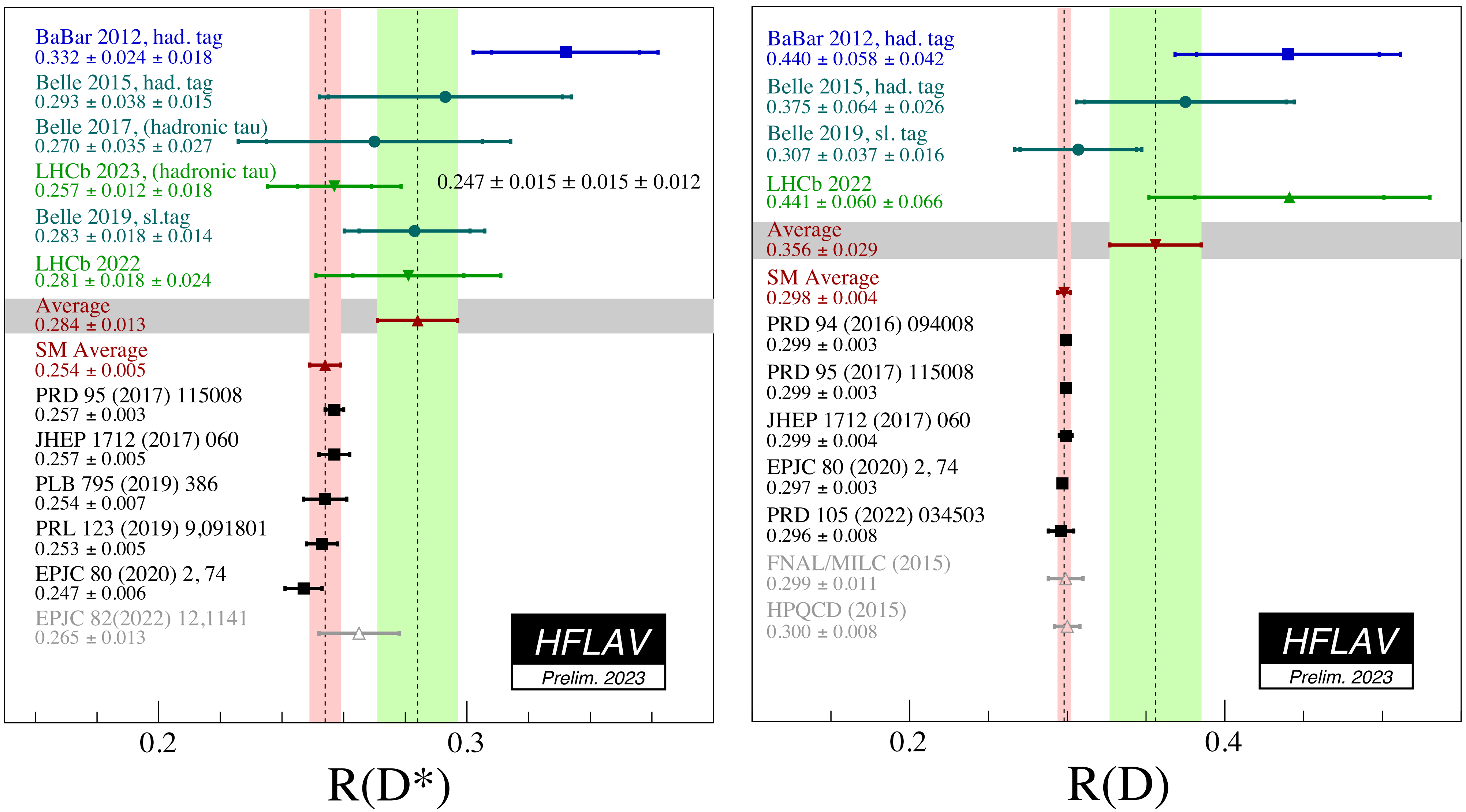
So let us delve deeper into this enigmatic terrain,
Where particles twirl, their secrets to attain.
With each discovery, a step closer we stride,
Flavor physics, our intellectual guide.

BACKUP

B physics: The B anomalies

Charged current, $b \to c\ell\nu$

$$R(D^{(*)}) = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu)}{\mathcal{B}(B \to D^{(*)}\ell\nu)}$$



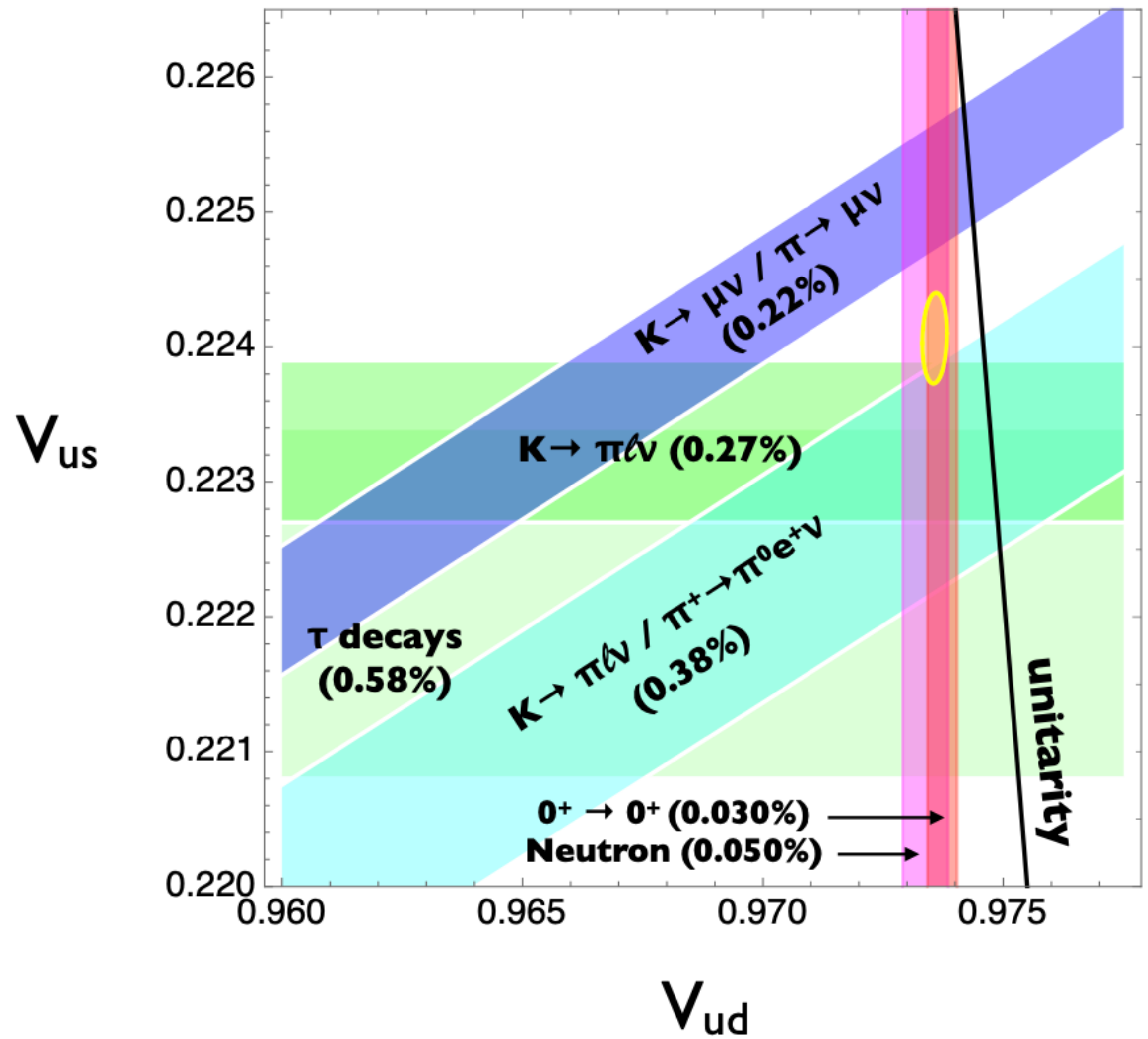
The Cabibbo anomaly   1st row unitarity

Measurements of the Cabibbo angle from pion, kaon and tau decays are inconsistent with the most precise determination, from super-allowed beta decays.

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9985(5)$$

$$|V_{ud}|^2 + |V_{cd}|^2 + |V_{td}|^2 = 0.9970(18)$$

G_F at low energies is an important input for beta decay => NP explanations related to muon decay and EWPT



[Crivellin 2207.02507]

Kaon physics: $K(t) \to \mu^+\mu^-$

Third golden mode

[D'Ambrosio Kitahara 1707.06999]
[AD Ghosh Grossman Schacht 2104.06427]
[AD Ghosh 2112.05801]
[AD Ghosh Grossman Kitahara Schacht 2211.03804]

$\mathscr{B}(K_L \to \mu^+\mu^-)_{exp.} = (6.84 \pm 0.11) \cdot 10^{-9}$

$\mathscr{B}(K_S \to \mu^+\mu^-)_{\mathrm{LHCb\,2020}} < 2.1 \cdot 10^{-10}$

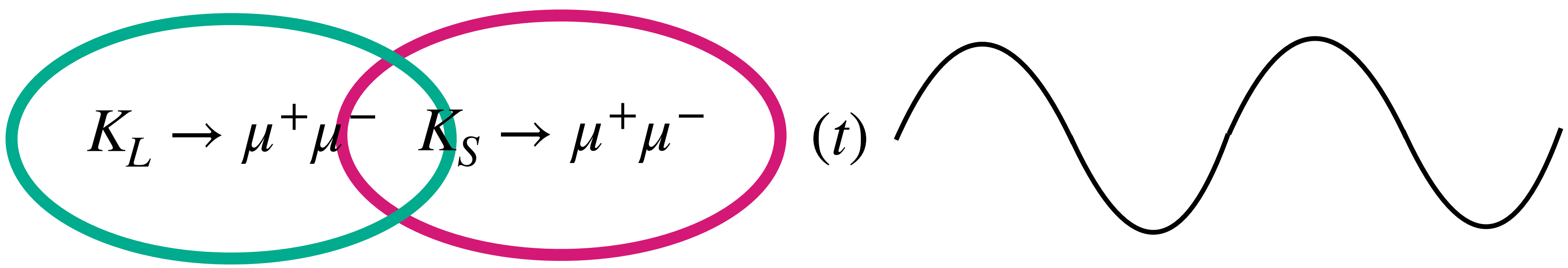
Each of the integrated rates exhibits **large hadronic uncertainties** -

Hadronic uncertainty

$$\boxed{\mathscr{B}(K_L \to \mu^+\mu^-)_{\mathrm{SM}} = \begin{cases} (6.85 \pm 0.80 \pm 0.06) \times 10^{-9}\,(+) \\ (8.11 \pm 1.49 \pm 0.13) \times 10^{-9}\,(-) \end{cases}}$$

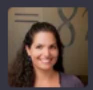
Hadronic uncertainty

$$\boxed{\mathscr{B}(K_S \to \mu^+\mu^-)_{\mathrm{SM}} = (5.18 \pm 1.50 \pm 0.02) \times 10^{-12}}$$



$K_L - K_S$ interference in a measurement of the **time dependent rate** is cleanly sensitive to the CKM parameter $\bar{\eta}$ with theory uncertainty of $\mathcal{O}(1\%)$.

*ChatGPT poetry



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Oh, flavors of quarks, diverse and distinct,
Up, down, charm, strange, beauty, and truth linked.
Intricate symphony, a subatomic ballet,
Where flavors entwine in a mysterious array.

Lepton flavors, electrons, muons, and more,
Leptons that oscillate, changing their chore.
Universality challenged, anomalies arise,
In the quest for new physics, our curious eyes.

Neutrinos, elusive messengers, ethereal and light,
Their flavors and masses, veiled from sight.
Hierarchy unknown, a puzzle profound,
Through oscillations, we seek answers unfound.

CP violation, a mystery profound and deep,
Matter and antimatter, an imbalance to peep.
In B meson decays, a subtle hint,
New physics whispers, waiting to imprint.

Anomalies arise, both alluring and bold,
Deviant paths, the standard model's threshold.
Do they herald new particles, realms yet unseen,
Or mere statistical quirks within the machine?

Flavor-changing neutral currents, a realm sublime,
Exquisite transitions, a tantalizing rhyme.
Rare decays whisper of physics anew,
Beyond the standard model, where insights accrue.

In the tapestry of particles, flavor's embrace,
Lies the gateway to knowledge, a cosmic chase.
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