Vector-like leptons

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Precision EW physics from Beta Decays to the Z-pole
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(based on 2008.03261 plus 2002.07184/2008.01113 by other authors)

Vector-like leptons

- Heavy counterpart to SM leptons, but with L & R having same quantum numbers
  - Non-chiral or vector-like

VLL - motivations

- Can be arbitrarily heavy (not EW scale)
- Unlike new chiral fermions, no strong bounds from Higgs data
  - See discussion in 10.1155/2013/910275

VLL – BSM motivations

- Can arise from composite Higgs, GUTs, neutrino mass models
- E.g. current "hot" topic:
  - B anomalies – 4321 model predicts LQ + Z′ + colouron + VLQs and VLLs

Vector-like leptons

- Six possible states (if you want them to couple to the SM)

	$SU(3)$	$SU(2)_L$	$U(1)_Y$
N	1	1	0
E	1	1	-1
Δ_1	1	2	$-1/2$
Δ_3	1	2	$-3/2$
Σ_0	1	3	0
Σ_1	1	3	-1

LHC bounds

- Direct searches with first generation couplings:
  - Singlets: M > 150 GeV
  - Doublets: M > 700 GeV
  - Triplets: M > 450 GeV

	$SU(3)$	$SU(2)_L$	$U(1)_Y$
N	1	1	0
E	1	1	-1
Δ_1	1	2	$-1/2$
Δ_3	1	2	$-3/2$
Σ_0	1	3	0
Σ_1	1	3	-1

Electroweak precision bounds

- For first generation couplings (2σ):
  - N: M/g > 4 TeV
  - E: M/g > 5.5 TeV
  - Δ_1: M/g > 5.5 TeV
  - Δ_3: M/g > 8 TeV
  - Σ_0: M/g > 6 TeV
  - Σ_1: M/g > 4 TeV

	$SU(3)$	$SU(2)_L$	$U(1)_Y$
N	1	1	0
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Δ_1	1	2	$-1/2$
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Electroweak precision bounds

- For second generation couplings (2σ):
  - N: M/g > 4 TeV
  - E: M/g > 4 TeV
  - Δ_1: M/g > 3 TeV
  - Δ_3: M/g > 5.5 TeV
  - Σ_0: M/g > 5 TeV
  - Σ_1: M/g > 2.5 TeV

	$SU(3)$	$SU(2)_L$	$U(1)_Y$
N	1	1	0
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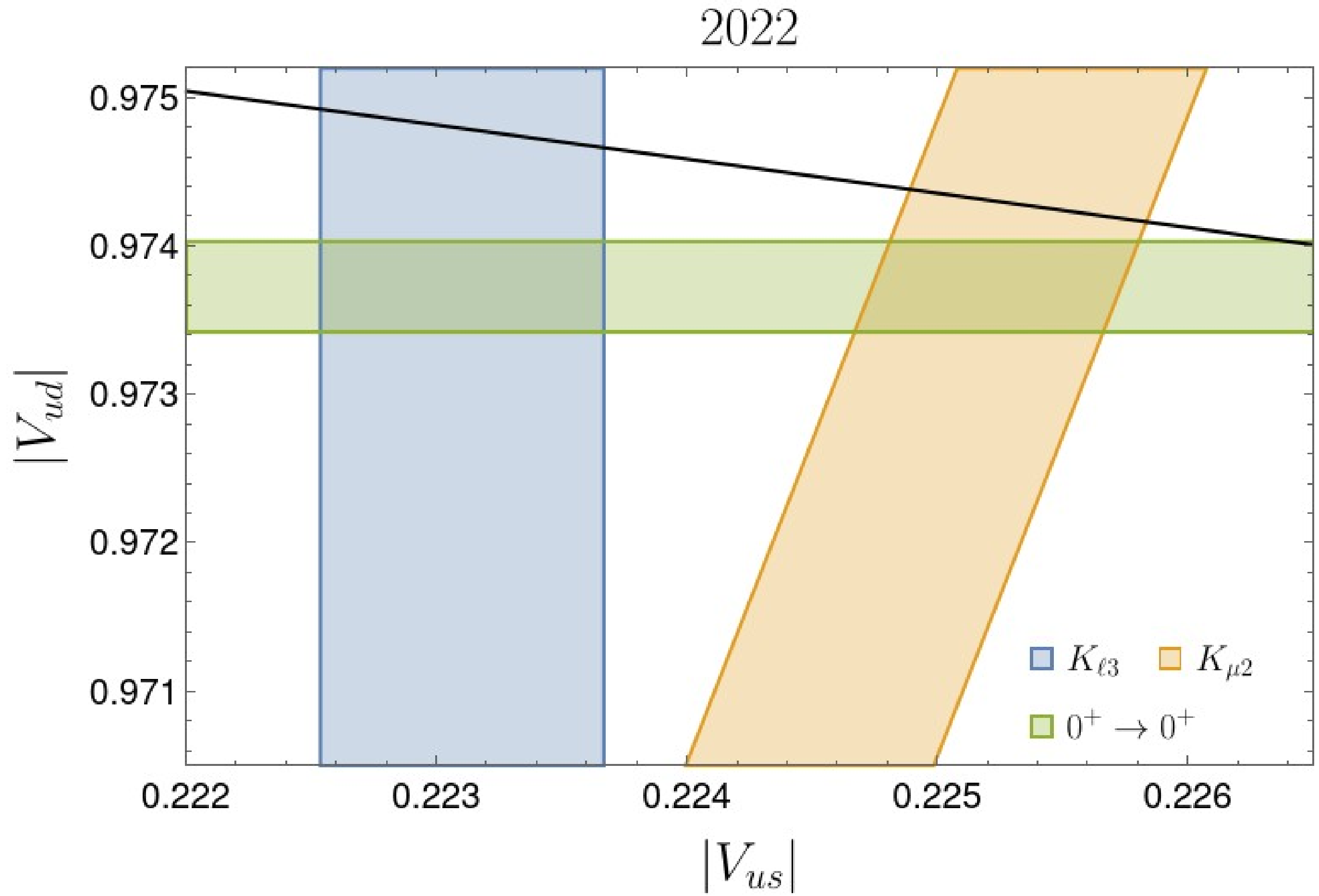
How do they alter precision physics?

- In general:
  - Tree level: modify $Z\ell\ell$ & $Z\nu\nu$ (Z pole), and $W\ell\nu$ (CKM determination, G_F determination)
  - 1-loop: modify $(\bar{\ell}\ell)(\bar{\ell}\ell)$ contact operator (G_F determination)

G_F

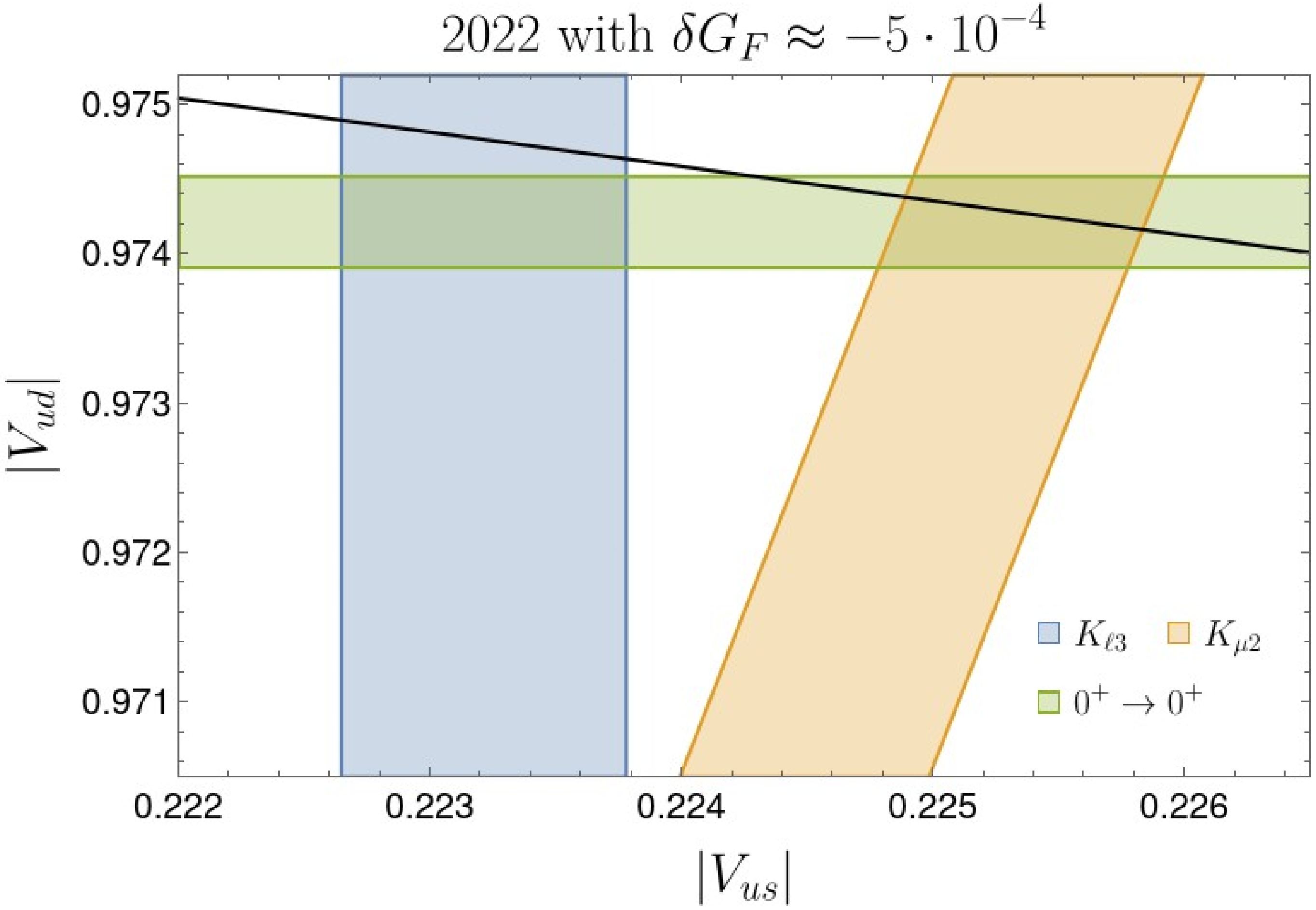
- From $\mu \to e\nu\nu$
  - With $(\bar{\ell}\ell)(\bar{\ell}\ell)$ need 1st and 2nd gen coupling
  - With $W\ell\nu$ only need one
- In principle all V_{uq} determinations depend on G_F like $V_{uq} \propto 1/G_F$
- But $K_{\mu 2}$ is really $K_{\mu 2}/\pi_{\mu 2}$ => G_F cancels

G_F



2022
0.975
0.974
0.973
0.972
0.971
$|V_{ud}|$
0.222
0.223
0.224
0.225
0.226
$|V_{us}|$
$K_{\ell 3}$
$K_{\mu 2}$
$0^+ \to 0^+$

G_F



2022 with $\delta G_F \approx -5 \cdot 10^{-4}$
0.975
0.974
0.973
0.972
0.971
$|V_{ud}|$
0.222
0.223
0.224
0.225
0.226
$|V_{us}|$
$K_{\ell 3}$
$K_{\mu 2}$
$0^+ \to 0^+$

G_F

- Cannot reconcile V_{us} and V_{ud} data with G_F alone
  - $\delta G_F \approx -5 \cdot 10^{-4}$ brings V_{ud} to $V_{us}^{K_{\mu 2}}$
  - $\delta G_F \approx -10^{-2}$ needed to bring $V_{us}^{K_{\ell 3}}$ to $V_{us}^{K_{\mu 2}}$
  - Factor of 20 difference

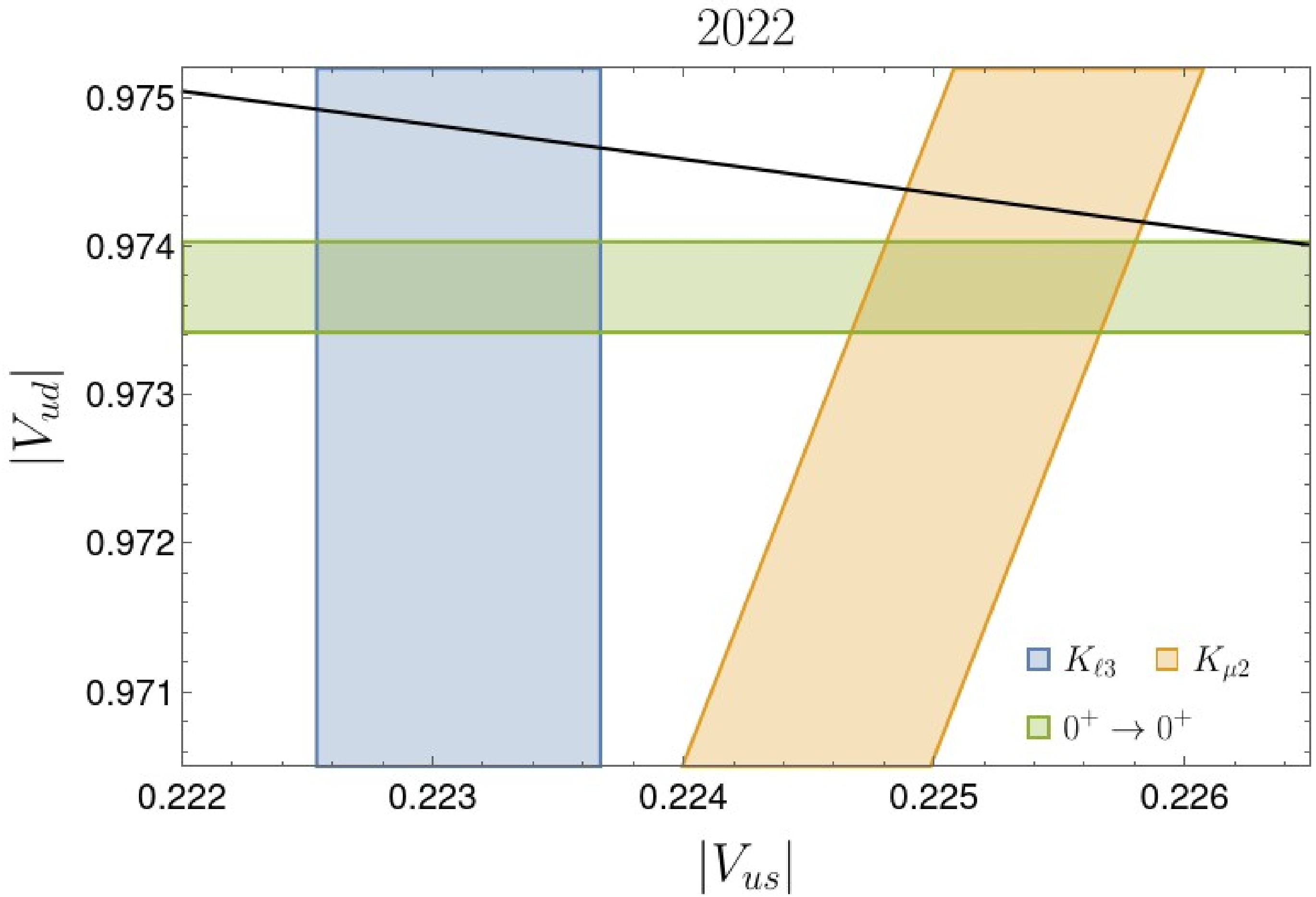
$W\ell\nu$

- Slightly more complex, as $W\ell\nu$ changes directly affect semileptonic decays which determine V_{uq}, but also G_F
  - $G_F \to G_F(1+\delta_{ee}+\delta_{\mu\mu})$
- E.g. NP in $We\nu$ cancels in beta decay, only sensitive to $W\mu\nu$

$W\ell\nu$

- V_{us}/V_{ud} from $K_{\mu 2}/\pi_{\mu 2}$ is independent of both G_F and $W\ell\nu$ changes
- $V_{us}^{K_{\ell 3}}$ sensitive to both G_F and $W\ell\nu$, but either only $We\nu$ or $W\mu\nu$ for $K_{\mu 3}$ or K_{e3} respectively
  - Important to have separate data

$W\ell\nu$



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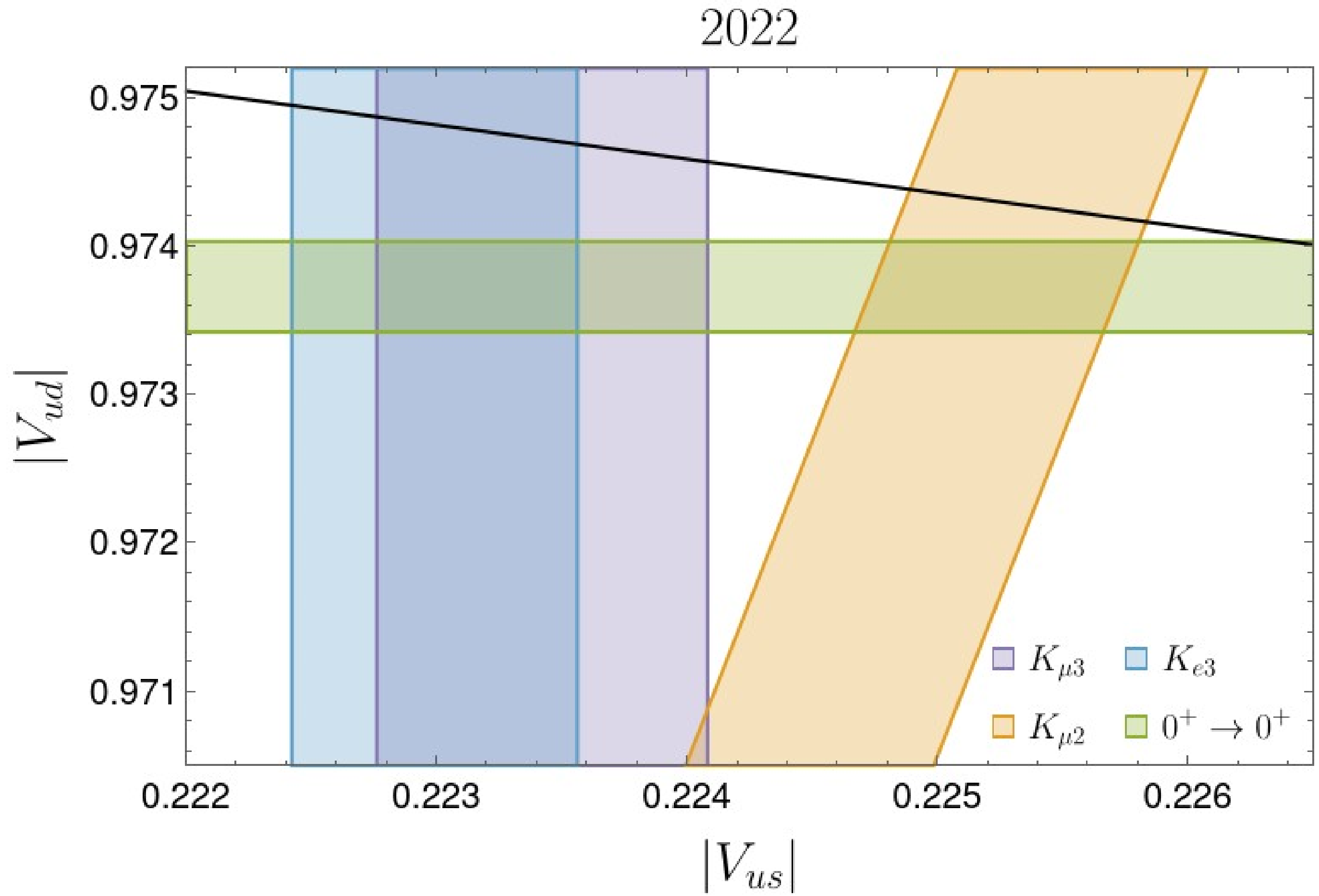
$W\ell\nu$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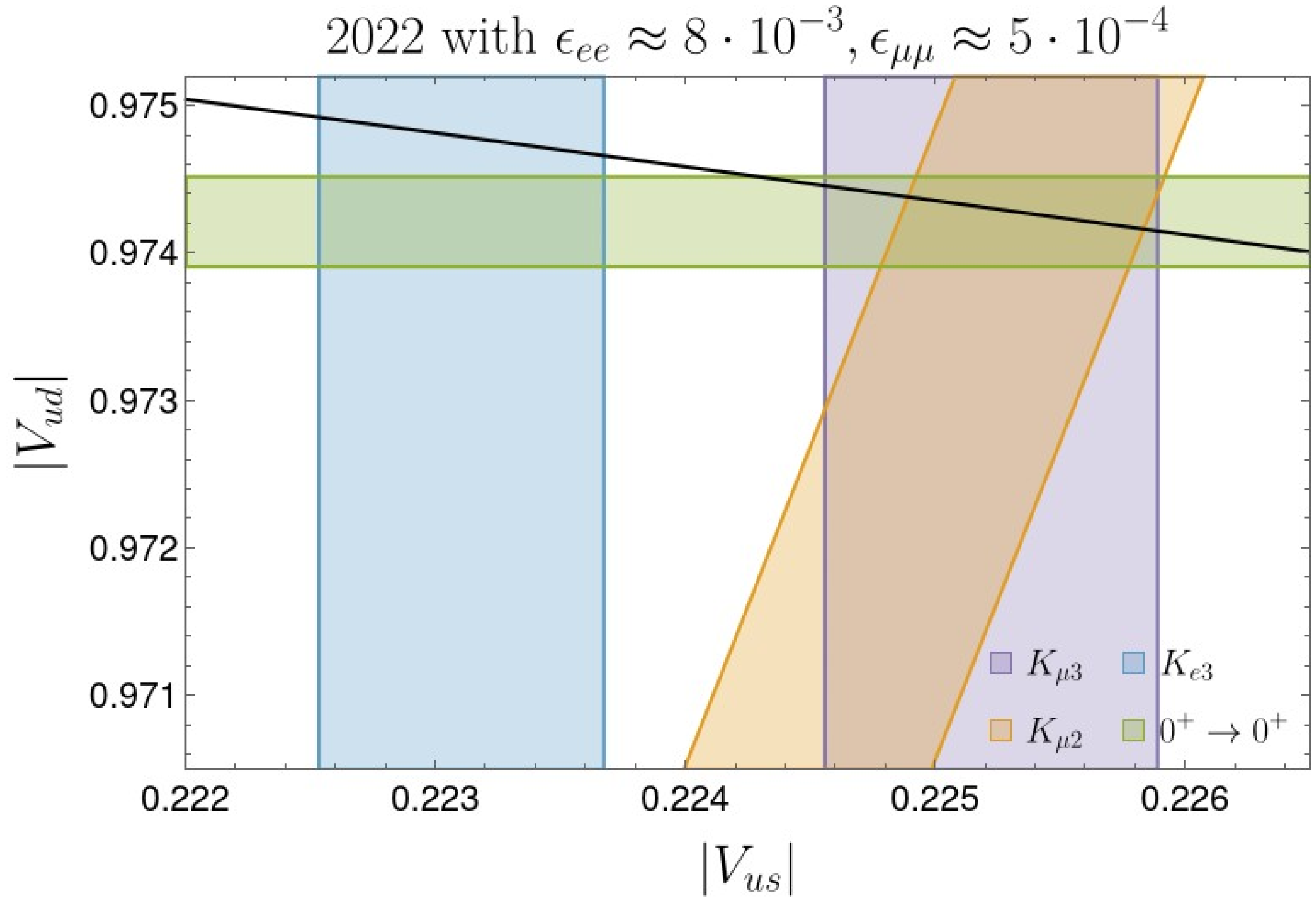
0.226
|V_us|
K_μ3
K_e3
K_μ2
0+ → 0+

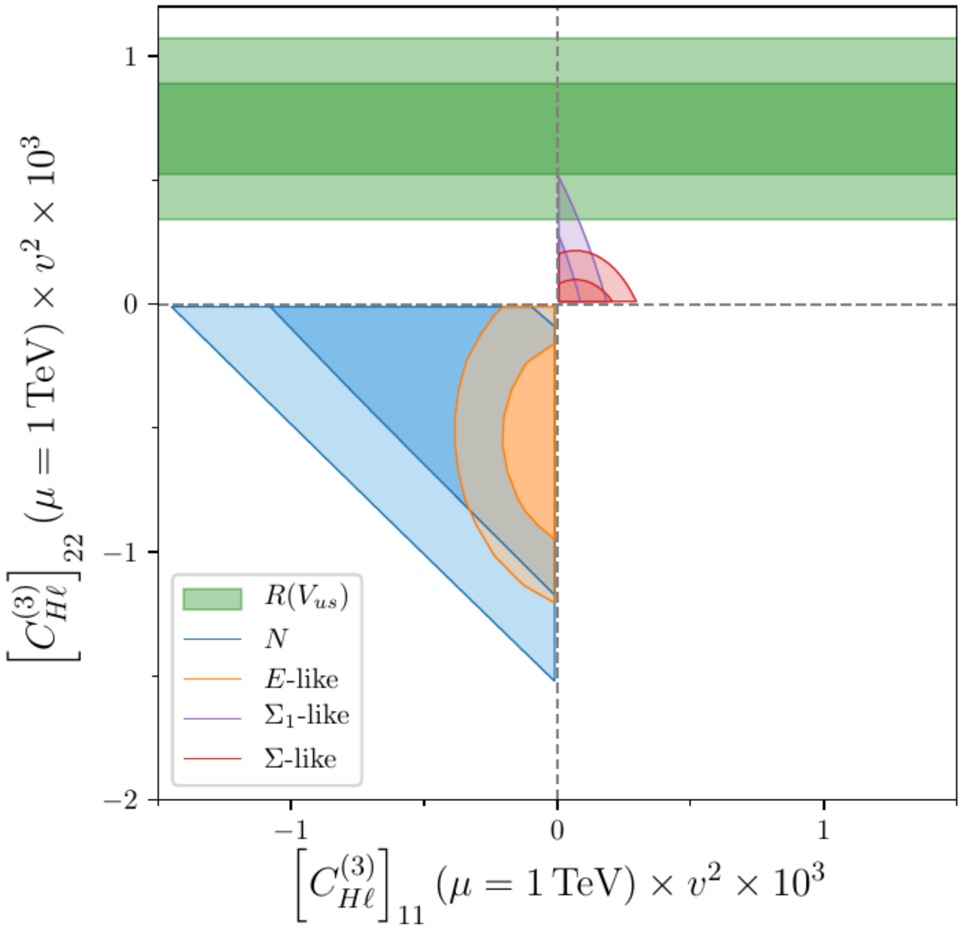
Explaining CAA with VLLs



CKM vs EWPO

- As mentioned, SU2 invariance means changes to $W\ell\nu$ also give changes to $Z\ell\ell$
- So we must test our CKM solutions against EWPO

CKM vs EWPO



$$R(V_{us}) \equiv \frac{V_{us}^{K\mu 2}}{V_{us}^{\beta}} \equiv \frac{V_{us}^{K\mu 2}}{\sqrt{1 - |V_{ud}^{\beta}|^2 - |V_{ub}|^2}}$$

$$\approx 1 - \left(\frac{V_{ud}}{V_{us}}\right)^2 \varepsilon_{\mu\mu} \approx 1 - 20\varepsilon_{\mu\mu}$$

LFV strikes back

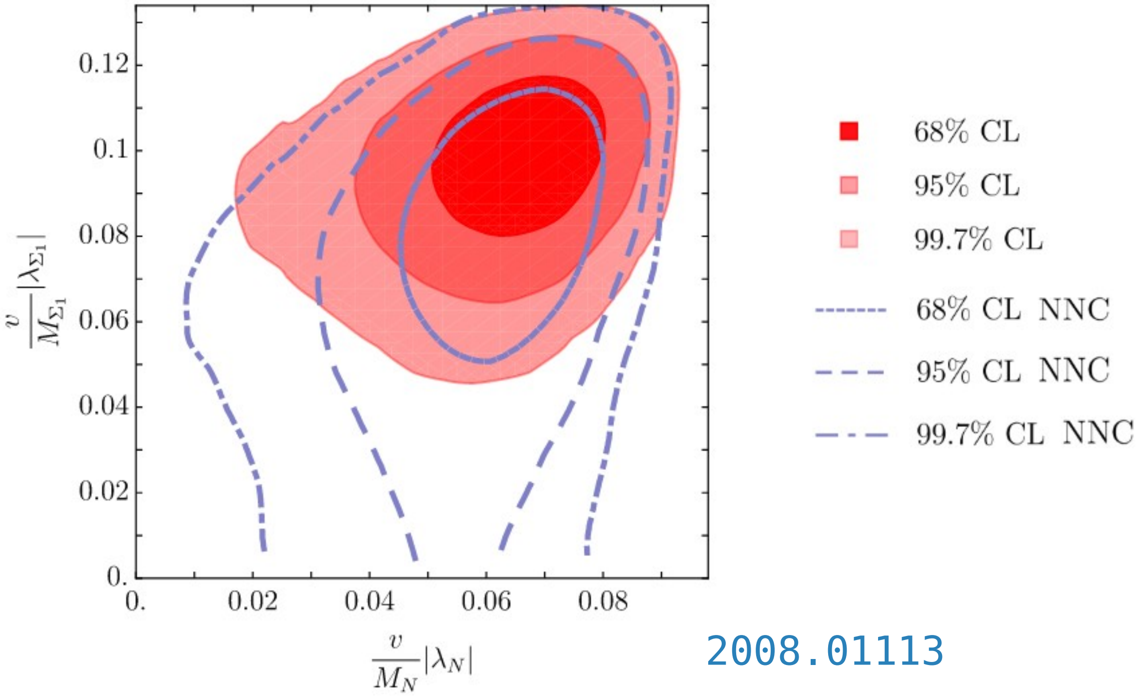
- With a single VLL, giving NP in μ and e, you get LFV
  - Because $Z\ell_i\ell_j \sim \sqrt{(W\ell_i\nu_i)(W\ell_j\nu_j)}$
- And LFV bounds are at least an order of magnitude stronger than other EWPO

Beyond simplest model

- With two independent VLLs can avoid LFV bounds

Beyond simplest model

- Consider RH neutrino coupled to electrons, and Σ_1 ($SU(2)$ triplet equivalent of RH e) coupled to muons
- Improves fit by 3σ



2008.01113

Conclusions

- VLLs well motivated extensions of the SM
  - And can still exist below the TeV scale
- VLLs coupled to muons and electrons can (partially) resolve the CAA
  - But EWPO and LFV are important constraints

Backup

4321 VLLs at CMS?

Search for pair-produced vector-like leptons in final states with third-generation leptons and at least three b quark jets in proton-proton collisions at $\sqrt{s} = 13\,\text{TeV}$

The CMS Collaboration

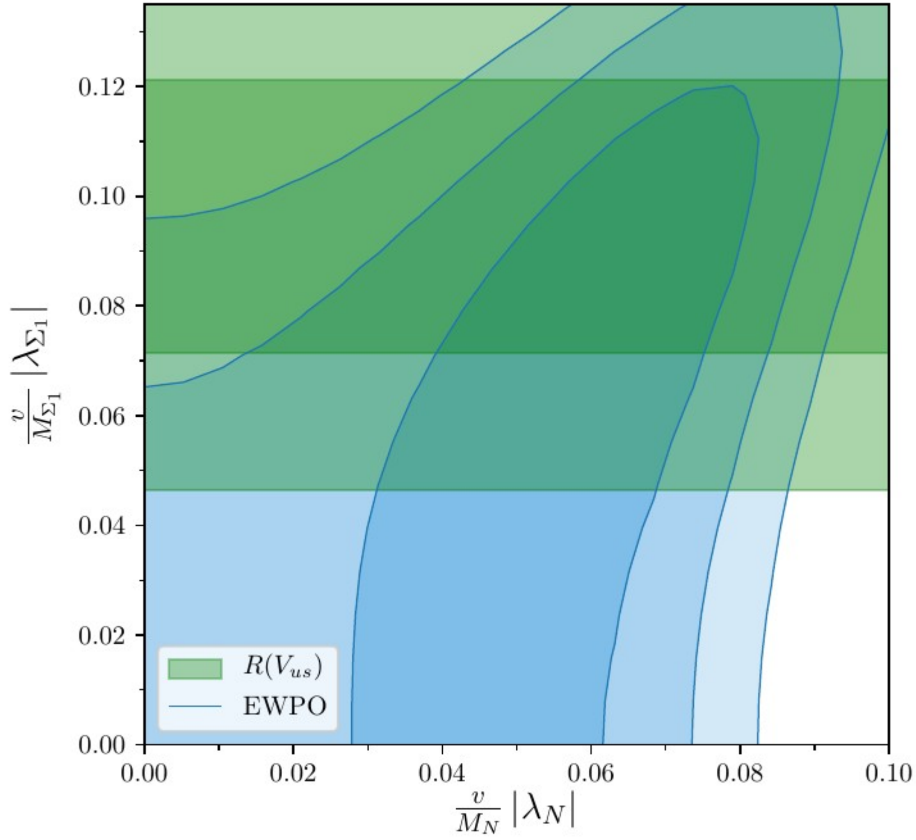
Abstract

The first search is presented for vector-like leptons (VLLs) in the context of the "4321 model", an ultraviolet-complete model with the potential to explain existing B physics measurements that are in tension with standard model predictions. The analyzed data, corresponding to an integrated luminosity of $96.5\,\text{fb}^{-1}$, were recorded in 2017 and 2018 with the CMS detector at the LHC in proton-proton collisions at $\sqrt{s} = 13\,\text{TeV}$. Final states with ≥ 3 b-tagged jets and two third-generation leptons ($\tau\tau$, $\tau\nu_\tau$, or $\nu_\tau\nu_\tau$) are considered. Upper limits are derived on the VLL production cross section in the VLL mass range 500–1050 GeV. The maximum likelihood fit prefers the presence of signal at the level of 2.8 standard deviations, for a representative VLL mass point of 600 GeV. As a consequence, the observed upper limits are approximately double the expected limits.

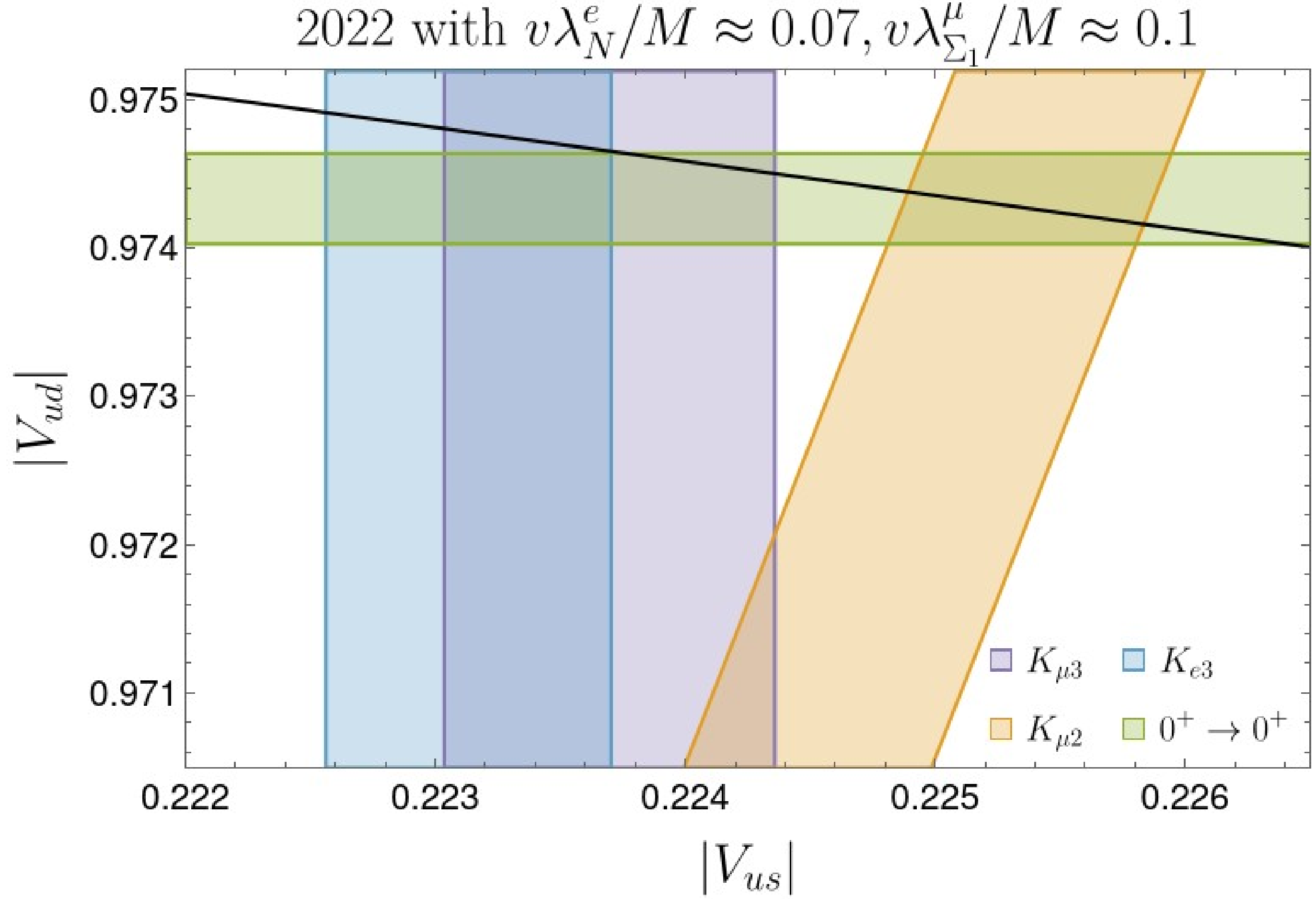
Submitted to Physics Letters B

Beyond simplest model

- My version of Andi's plot



Beyond simplest model



LHC bounds

- Direct searches with third generation couplings:
  - Singlets: M > ? GeV
  - Doublets: M > 790 GeV
  - Triplets: M > ? GeV

	$SU(3)$	$SU(2)_L$	$U(1)_Y$
N	1	1	0
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