# Leptophilic New Physics

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# Outline

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# Vectorlike Leptons

Left- & right-handed parts couple in same way to electroweak gauge bosons: "L=R"

$\Rightarrow$ Vectorlike leptons can have "bare" masses (before EWSB):

$$\mathcal{L}_{VLL} = i\overline{\psi}\gamma_\mu D^\mu \psi - M_\psi \overline{\psi}\psi$$

$\Rightarrow$ Anomaly-free

Neutral under $SU(3)_c$

$\Rightarrow$ Only modify the electroweak sector

$\Rightarrow$ Couple to SM-leptons & -Higgs

$\Rightarrow$ Mix with SM-leptons

$\Rightarrow$ modify $W\ell\nu$, $Z\nu\nu$ & $Z\ell\ell$

# Vectorlike leptons respecting the SM gauge group

|      |                                                   | $SU(3)$ | $SU(2)_L$ | $U(1)_Y$ |
|------|---------------------------------------------------|---------|-----------|----------|
| SM   | $\ell$                                            | 1       | 2         | -1/2     |
|      | e                                                 | 1       | 1         | -1       |
|      | $\phi$                                            | 1       | 2         | 1/2      |
| VLLs | N                                                 | 1       | 1         | 0        |
|      | E                                                 | 1       | 1         | -1       |
|      | $\Delta_1 = (\Delta_1^0, \Delta_1^-)$             | 1       | 2         | -1/2     |
|      | $\Delta_3 = (\Delta_3^-, \Delta_3^{--})$          | 1       | 2         | -3/2     |
|      | $\Sigma_0 = (\Sigma_0^+, \Sigma_0^0, \Sigma_0^-)$ | 1       | 3         | 0        |
|      | $\Sigma_1 = (\Sigma_1^0, \Sigma_1^-, \Sigma_1^{--})$ | 1    | 3         | -1       |

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# The Singly Charged Scalar Singlet $\phi^+$

|          | $SU(3)_c$ | $SU(2)_L$ | $U(1)_Y$ |                           |
|----------|-----------|-----------|----------|---------------------------|
| $\phi^+$ | 1         | 1         | 1        | new singly charged scalar |

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$\Rightarrow$ no couplings to quarks, right-handed leptons

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} - \left( \frac{\lambda_{ij}}{2} \, \bar{L}^c_{a,i} \, \varepsilon_{ab} \, L_{b,j} \, \phi^+ + \mathrm{h.c.} \right)$$

Here

    a,b: $SU(2)_L$ indices      $\varepsilon_{ab} = i\sigma_2 = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}$

    i,j: flavour indices

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i,j: flavour indices

$\Rightarrow$ $\lambda_{ij}$ antisymmetric in flavour
$\Rightarrow$ automatically lepton flavour (universality) violating

Only 4 new parameters: $\boldsymbol{\lambda_{12}}$, $\boldsymbol{\lambda_{13}}$, $\boldsymbol{\lambda_{23}}$ and $\boldsymbol{m_\phi}$

# Outline

# "Standard" $Z'$ Bosons vs. Leptophilic $Z'$ Bosons

- Simple Extension of the SM

- Predicted by many models

- Strongly constrained by di-jet, di-lepton searches
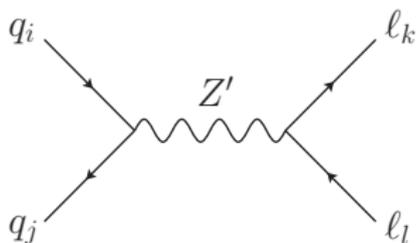
- $Z'$ bosons that couple to leptons
  - $\Rightarrow$ less constrained by LHC data ($\Rightarrow$ LEP)
  - $\Rightarrow$ can be lighter ($<$ TeV-scale)

- Gluons like quarks, $Z'$ likes leptons?

# Outline

# The Cabibbo Angle Anomaly: Determination of $V_{us}$
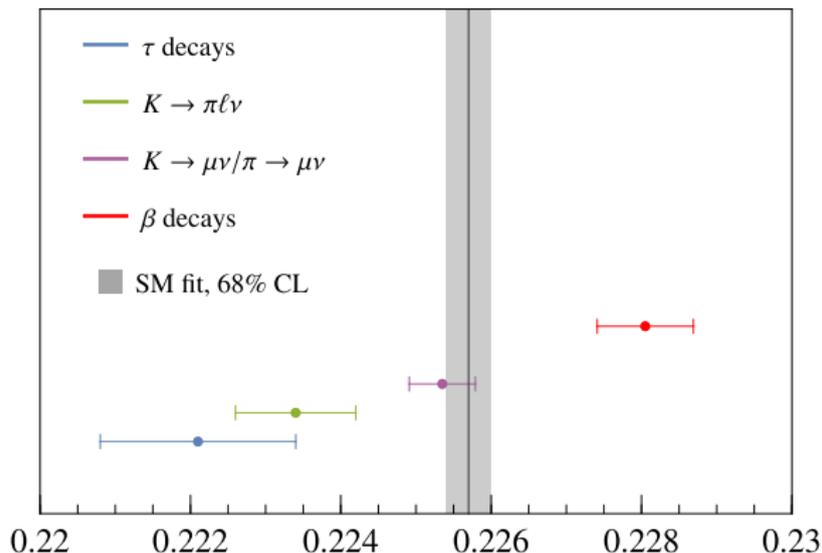


**"$V_{us}$ from $\beta$ decays":**

$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1 \Rightarrow V_{us} \sim \sqrt{1 - V_{ud}^2}$    ($V_{ub} \approx 0.0037 \sim 0$)

$\Rightarrow 3\,\sigma$ tension (PDG)

# Leptophilic Resolutions of the Cabibbo Angle Anomaly
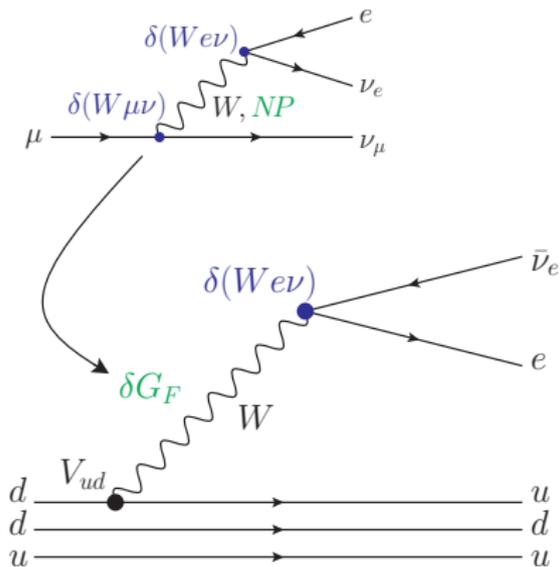


- Singly charged scalar singlet

  $\Rightarrow$ Modified Fermi constant, $G_F$

- Leptophilic $Z'$ bosons

  $\Rightarrow$ Modified Fermi constant, $G_F$

- Vectorlike Leptons

  $\Rightarrow$ Modified $W\ell\nu$, $Z\ell\ell$, $Z\nu\nu$

# Outline

# Lepton Flavour Universality Violation in $\tau$ decays
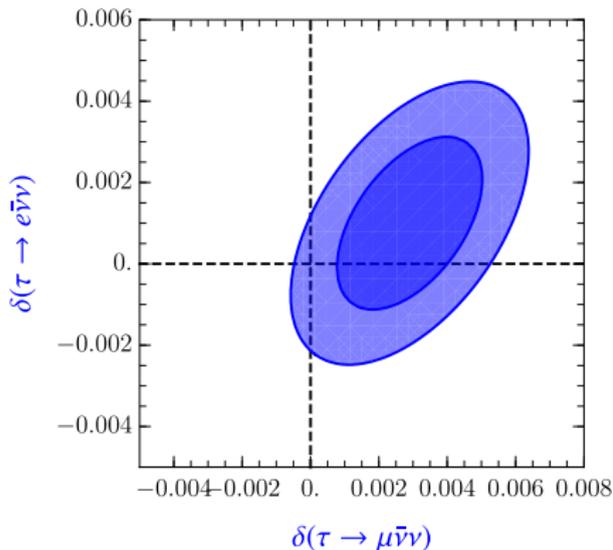


Plot for $\delta(\mu \to e\bar{\nu}\nu) = 0$

$$\left.\frac{\mathcal{A}(\tau \to \mu\bar{\nu}\nu)}{\mathcal{A}(\mu \to e\bar{\nu}\nu)}\right|_{\text{EXP}} = 1.0029(14)$$

$$\left.\frac{\mathcal{A}(\tau \to \mu\bar{\nu}\nu)}{\mathcal{A}(\tau \to e\bar{\nu}\nu)}\right|_{\text{EXP}} = 1.0018(14)$$

$$\left.\frac{\mathcal{A}(\tau \to e\bar{\nu}\nu)}{\mathcal{A}(\mu \to e\bar{\nu}\nu)}\right|_{\text{EXP}} = 1.0010(14)$$

$$\delta(\tau \to \mu\bar{\nu}\nu) = \frac{\mathcal{A}_{NP}(\tau \to \mu\bar{\nu}\nu)}{\mathcal{A}_{SM}(\tau \to \mu\bar{\nu}\nu)}$$

$$\delta(\tau \to e\bar{\nu}\nu) = \frac{\mathcal{A}_{NP}(\tau \to e\bar{\nu}\nu)}{\mathcal{A}_{SM}(\tau \to e\bar{\nu}\nu)}$$

# Leptophilic New Physics in $\tau \to \mu\bar{\nu}\nu/\tau(\mu) \to e\bar{\nu}\nu$
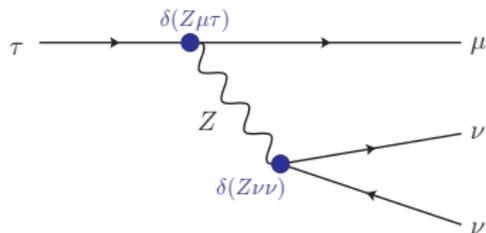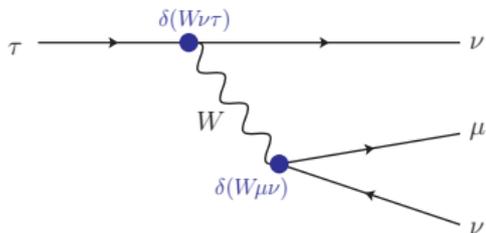


Vectorlike Leptons
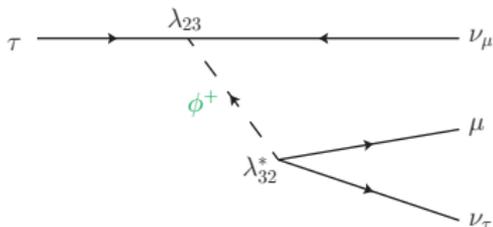


Singly charged scalar singlet, $\phi^+$
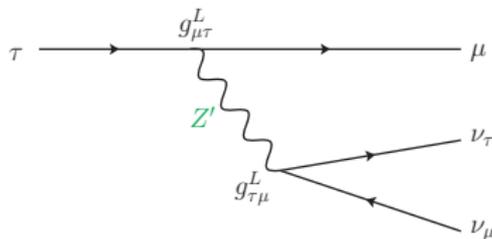
Leptophilic $Z'$ boson

## Outline

## Vectorlike Leptons: Constraints from $\mu \to e$
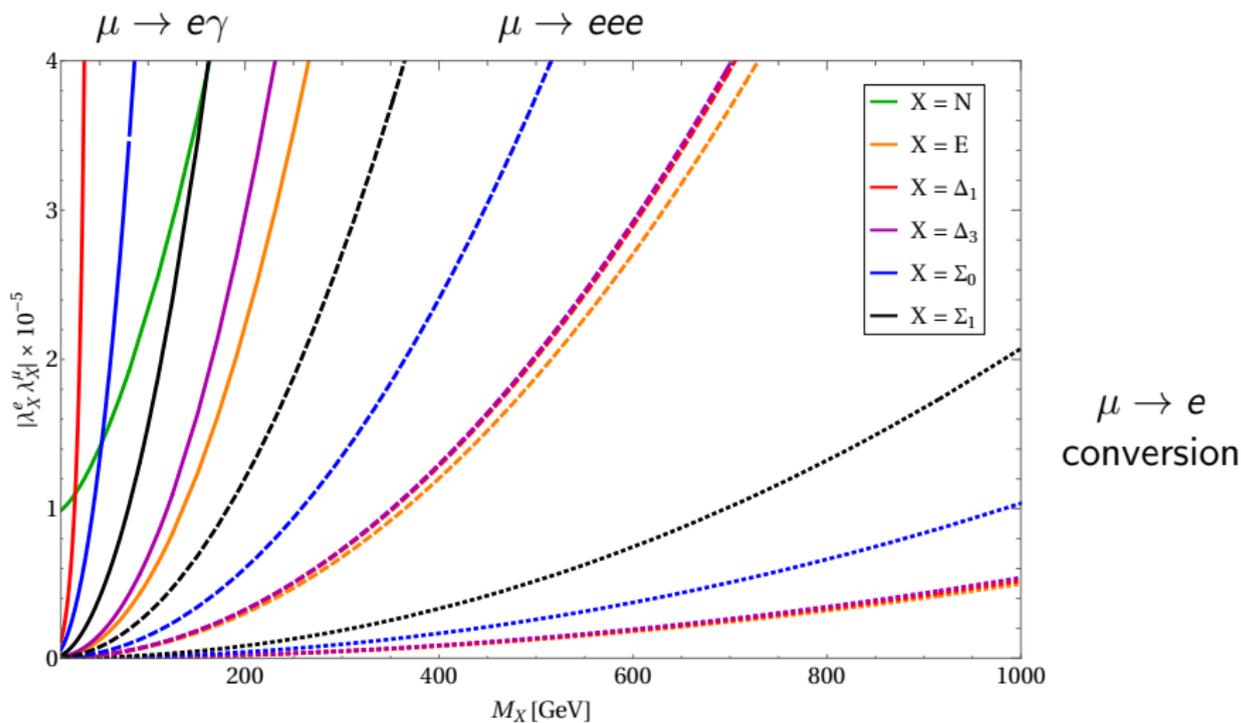
# Vectorlike Leptons: Best Fit

- One generation of singlet $N$ coupling **only** to electrons
- One generation of triplet $\Sigma_1$ coupling **only** to muons
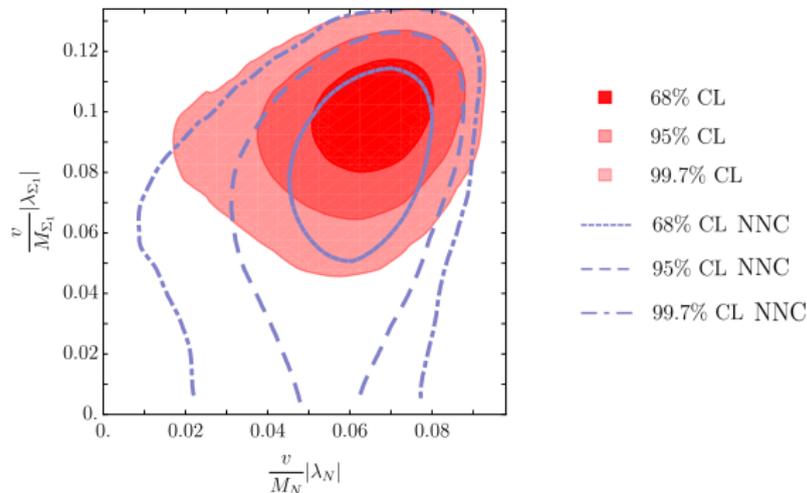


$\lambda_N$: $N\phi e$-coupling,　　$\lambda_{\Sigma_1}$: $\Sigma_1\phi\mu$-coupling;　　$M_{N,\Sigma_1}$: masses of $N$, $\Sigma_1$

# Outline

# Singly Charged Scalar: Flavour bounds & EW data
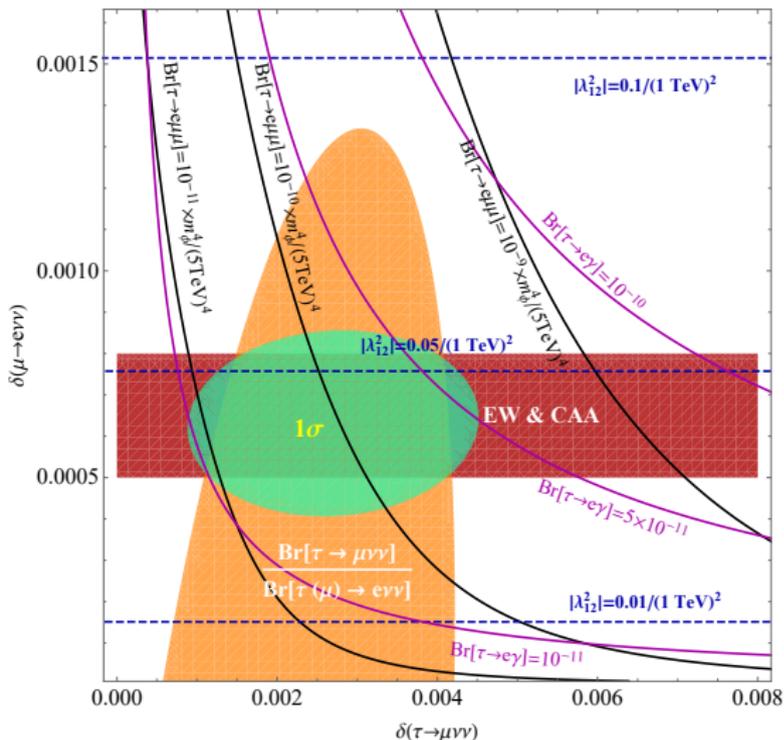


**Scenario with** $\lambda_{13} = 0$
(constraints from $\mu \to e\gamma$, $\mu \to e$ conv.)

### Best fit region for

- EW data & the Cabibbo angle anomaly
- $\tau \to \mu\bar{\nu}\nu / \tau(\mu) \to e\bar{\nu}\nu$

### suggests

- $\mathrm{Br}(\tau \to e\mu\mu) \sim 10^{-10} \frac{m_\phi^4}{(5\,\mathrm{TeV})^4}$
- $10^{-11} \lesssim \mathrm{Br}(\tau \to e\gamma) \lesssim 5 \times 10^{-11}$
- $|\lambda_{12}|^2 \sim \frac{0.05}{(1\,\mathrm{TeV})^2}$ ($\to$ mono photon)

# Outline

# Leptophilic $Z'$ Bosons: $M_{Z'} = 1$ TeV, $g_{\mu\tau}$ only
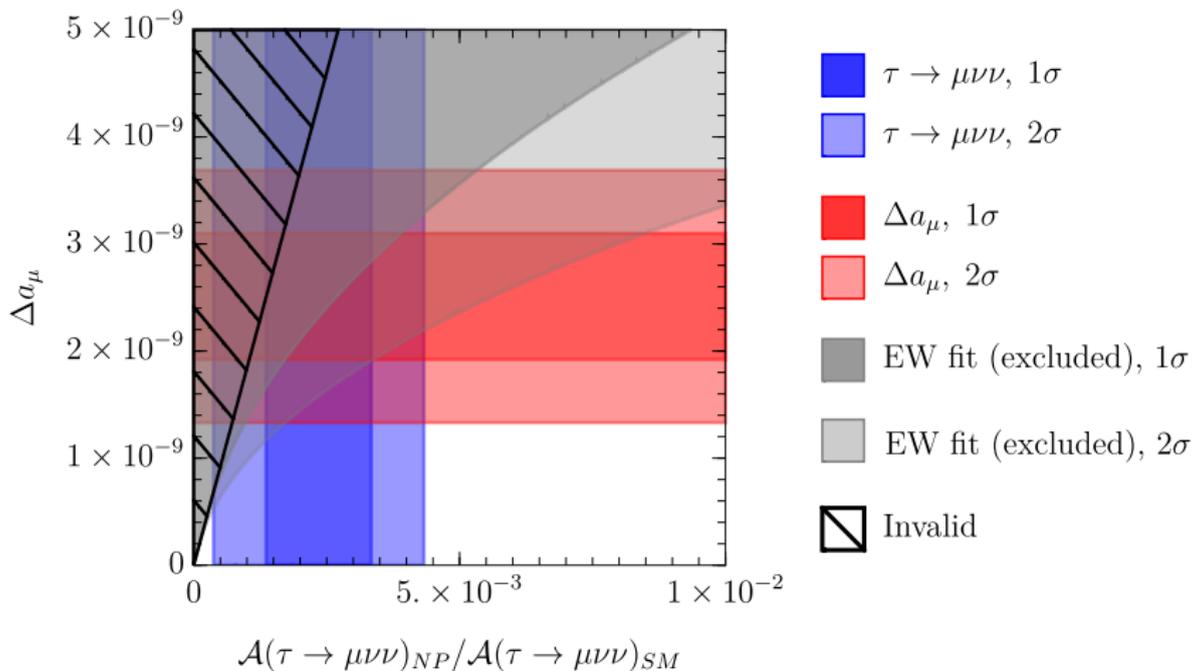
## Conclusions

Recent hints for Lepton Flavour Universality Violation, in particular

- The Cabibbo Angle Anomaly
- Deviations from the SM in $\tau \to \mu\bar{\nu}\nu / \tau(\mu) \to e\bar{\nu}\nu$

can be addressed by leptophilic new physics.

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Examples presented here:

- Vectorlike Leptons
- Singly Charged Scalar Singlet
- Leptophilic $Z'$ Bosons

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Examples presented here:

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Lepton Flavour Violation

- Forbidden in the SM
- Strongly constrained by experiment
- $\Rightarrow$ Clean discovery channels

## For "The Details":

- Vectorlike leptons
  arXiv:2008.01113/ JHEP 12 (2020) 166, with Andreas Crivellin, FK,
  Claudio Andrea Manzari, Marc Montull

- Singly charged scalar singlet, $\phi^+$
  arXiv:2012.09845/ Phys.Rev.D 103 (2021), Andreas Crivellin, FK,
  Claudio Andrea Manzari, Luca Panizzi

- Leptophilic $Z'$ bosons
  arXiv:2104.07680/ JHEP06 (2021) 068, Andrzej J. Buras, Andreas
  Crivellin, FK, Claudio Andrea Manzari and Marc Montull

Questions?

Backup slides

# Possible Signatures of Leptophilic New Physics

- Cabibbo Angle Anomaly

- Anomalous magnetic moments of charged leptons $\Delta a_\ell$

- Electric dipole moments of charged leptons $d_\ell$

- Flavour violating decays of charged leptons $\ell \to 3\ell'$, $\ell \to \ell'\bar{\nu}\nu$

- Radiative leptonic decays $\ell \to \ell'\gamma$

- $\mu \to e$ conversion in nuclei

- Neutrino trident prodcution $\nu N \to \nu\bar{\mu}\mu N$

- Contact interactions $e^+e^- \to \ell^+\ell^-$ (LEP)

- $Z - Z'$ mixing $\Rightarrow$ modified $Z$-pole observables

# The Cabibbo Angle

The Cabibbo angle can be determined from

- $V_{ud}$ from superallowed $\beta$-decays ($0^+ - 0^+$-transitions)
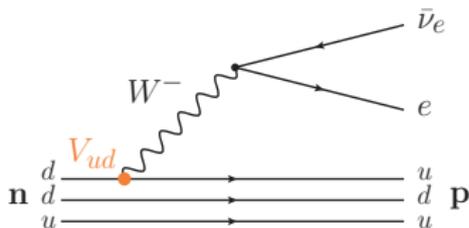


- $V_{us}$ from $\tau$-decays & from $K$-decays
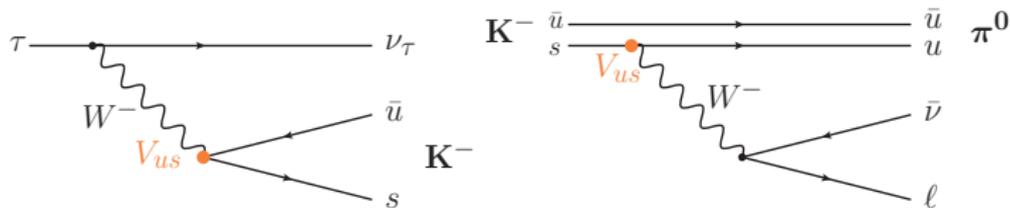


- $V_{cd}$ from $D \to \mu\nu$

- Direct contributions to $\beta$-decays

- Modified $Wud$-coupling

- Modified $W\ell\nu$-coupling

- Direct contributions to $\mu$-decays
  $\Rightarrow$ Modified Fermi constant, $G_F$

$$\delta(\mu \to e\bar{\nu}\nu) = \frac{\mathcal{A}_{NP}(\mu \to e\bar{\nu}\nu)}{\mathcal{A}_{SM}(\mu \to e\bar{\nu}\nu)}$$

$$\Rightarrow \boxed{G_F = G_F^{\mathrm{SM}}\left(1 + \delta(\mu \to e\bar{\nu}\nu)\right)}$$
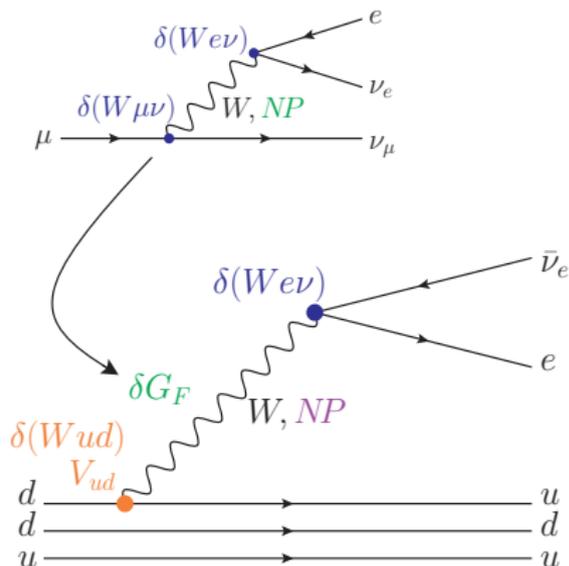
## Resolution of the Cabibbo Angle Anomaly

Assume

$$|V_{ud}|^2(1 - \delta(\mu \to e\nu\nu))^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9985(5)$$

$$\Rightarrow V_{us}^{\beta} \equiv \sqrt{1 - \left(V_{ud}^{\beta}\right)^2 - |V_{ub}|^2}$$

$$\simeq V_{us}^{\mathcal{L}}\left[1 + \left(\frac{V_{ud}^{\mathcal{L}}}{V_{us}^{\mathcal{L}}}\right)^2 \delta(\mu \to e\nu\nu)\right].$$

$V_{us}^{\beta}$: determined via CKM unitarity from $V_{ud}^{\beta}$ ($\beta$ decays)

$V_{us(ud)}^{\mathcal{L}}$: values in the CKM matrix

# Leptophilic $Z'$ Bososns: The Pragmatic Approach

- Agnostic about origin of $Z'$ boson
- Simply assume $M_{Z'} > M_{EW}$
- Leptophilic $Z'$ boson $\Rightarrow$ couplings to SM leptons $\ell$, $\nu$
- Can allow for $Z - Z'$-mixing $\Rightarrow$ correction to $m_Z$ (destructive)

Lagrangian:

$$\mathcal{L} \supset \underbrace{-i g_{Z'}^\varphi Z'^\mu \varphi^\dagger \overleftrightarrow{D}_\mu \varphi}_{\substack{\Rightarrow Z - Z'\text{-mixing} \\ \Rightarrow \text{mod. pole mass}}} + \underbrace{\bar{\ell}_i \left( g_{ij}^L \gamma_\mu P_L + g_{ij}^R \gamma_\mu P_R \right) \ell_j Z'^\mu}_{Z'\ell\ell-\text{couplings}} + \underbrace{\bar{\nu}_i g_{ij}^L \gamma_\mu P_L \nu_j Z'^\mu}_{Z'\nu\nu-\text{couplings}}$$

$\overleftrightarrow{D}_\mu = D_\mu - \overleftarrow{D}_\mu$, $\quad g_{Z'}^\varphi \in \mathbb{R}$, $\quad g_{ij}^{L/R}$ are Hermitian in flavour space

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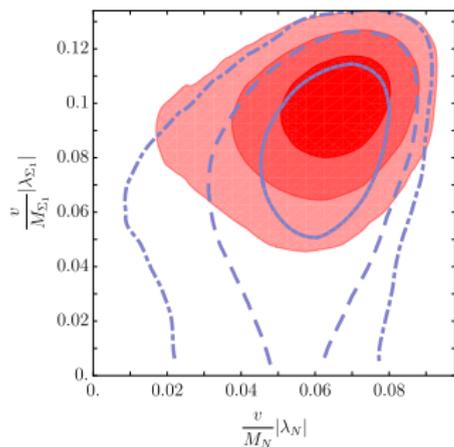


| Observable | Measurement | SM Posterior | NP Posterior | Pull |
|---|---|---|---|---|
| $M_W$ [GeV] | 80.379(12) | 80.363(4) | 80.369(6) | 0.56 |
| $R\left[\frac{K\to\mu\nu}{K\to e\nu}\right]$ | $0.9978 \pm 0.0020$ | 1 | 1.00168(39) | $-0.80$ |
| $R\left[\frac{\pi\to\mu\nu}{\pi\to e\nu}\right]$ | $1.0010 \pm 0.0009$ | 1 | 1.00168(39) | 0.42 |
| $R\left[\frac{\tau\to\mu\nu\bar{\nu}}{\tau\to e\nu\bar{\nu}}\right]$ | $1.0018 \pm 0.0014$ | 1 | 1.00168(39) | 1.2 |
| $|V_{us}^{K_{\mu3}}|$ | 0.22345(67) | 0.22573(35) | 0.22519(39) | 0.77 |
| $|V_{ud}^{\beta}|$ | 0.97365(15) | 0.97419(8) | 0.97378(13) | 2.52 |

IC value: 73 (vs. IC$_{SM}$: 93)

- 68% CL
- 95% CL
- 99.7% CL
- 68% CL NNC
- 95% CL NNC
- 99.7% CL NNC

## IC-value

Information criterion (IC): allows for a comparison between different models within a Bayesian approach

$$IC = -2 \log L + 4\,\sigma^2_{\log L}$$

where
$\log L$: average of the log-likelihood
$\sigma_{\log L}$: variance of the log-likelihood

$\Rightarrow$ *The smaller the IC-value, the better the NP-model.*

## Pull

Pull of an observable $\mathcal{O}_i$:

$$P(\mathcal{O}_i) = \left| \frac{\mathcal{O}_i^{exp} - \mathcal{O}_i^{SM}}{\sqrt{(\sigma_i^{exp})^2 + (\sigma_i^{SM})^2}} \right| - \left| \frac{\mathcal{O}_i^{exp} - \mathcal{O}_i^{NP}}{\sqrt{(\sigma_i^{exp})^2 + (\sigma_i^{NP})^2}} \right|$$

$\Rightarrow$ *The larger the pull, the better the NP-model.*

**DM searches with mono-photon signatures at LEP:**
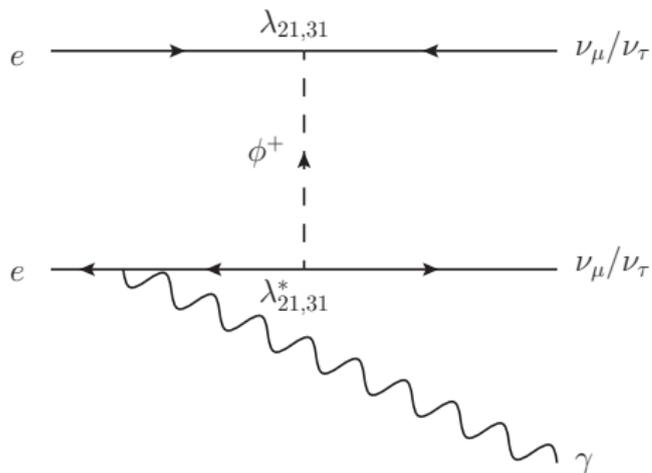


DELPHI analyses
(arXiv:0406019, 0901.4486
[hep-ex])

& 1103.0240 [hep-ph]

$$\Rightarrow \frac{|\lambda_{12,13}|^2}{m_\phi^2} \lesssim \frac{1}{(175 \text{ GeV})^2}$$