Leptophilic New Physics

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Outline

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The Cabibbo Angle Anomaly: Determination of V_{us}

Cabibbo matrix:

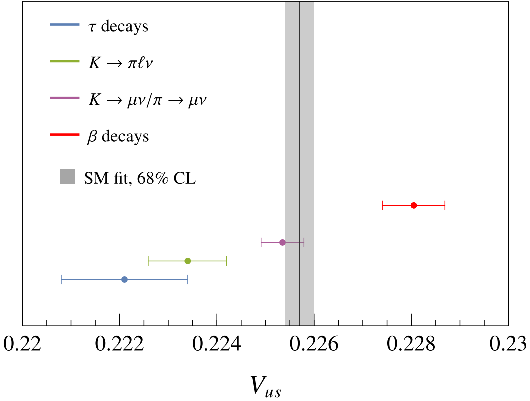
$$\begin{pmatrix} d' \\ s' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} \\ V_{cd} & V_{cs} \end{pmatrix} \begin{pmatrix} d \\ s \end{pmatrix}$$
$$= \begin{pmatrix} \cos\theta_c & \sin\theta_c \\ -\sin\theta_c & \cos\theta_c \end{pmatrix} \begin{pmatrix} d \\ s \end{pmatrix}$$

Cabibbo angle

CKM matrix:

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

The Cabibbo Angle Anomaly: Determination of V_{us}



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Cabibbo angle

CKM matrix:

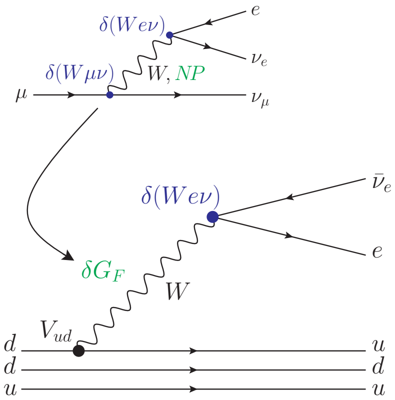
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

"V_{us} from β decays":

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

$\Rightarrow$ **3 σ tension** (PDG)

Leptophilic Resolutions of the Cabibbo Angle Anomaly



- Singly charged scalar singlet

  $\Rightarrow$ Modified Fermi constant, G_F

- Leptophilic Z' bosons

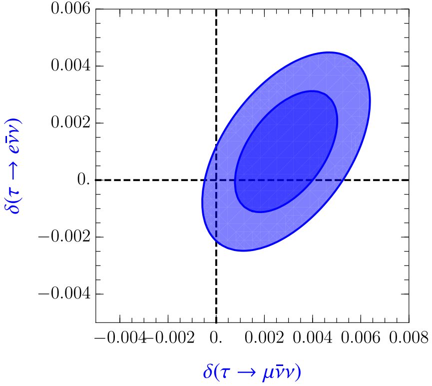
  $\Rightarrow$ Modified Fermi constant, G_F

- Vectorlike Leptons

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

Outline

Lepton Flavour Universality Violation in τ decays



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

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

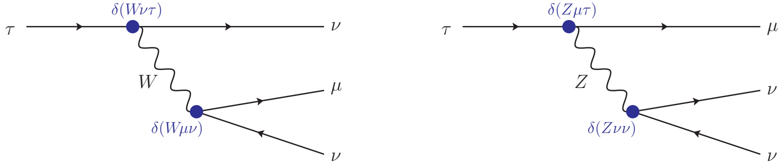
$$\left.\frac{\mathcal{A}(\tau \to \mu\bar{\nu}\nu)}{\mathcal{A}(\tau \to e\bar{\nu}\nu)}\right|_{\mathrm{EXP}} = 1.0018(14)$$

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

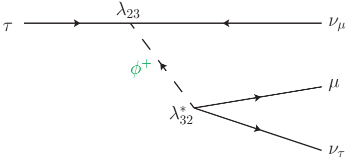
$$\delta(\tau \to \mu\bar{\nu}\nu) = \frac{\mathcal{A}_{NP}(\tau \to \mu\bar{\nu}\nu)}{\mathcal{A}_{SM}(\tau \to \mu\bar{\nu}\nu)}$$

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

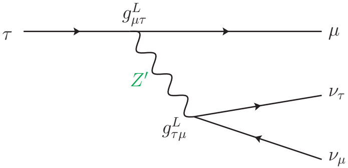
Leptophilic New Physics in $\tau \to \mu\bar{\nu}\nu / \tau(\mu) \to e\bar{\nu}\nu$



Vectorlike Leptons



Singly charged scalar singlet, ϕ^+



Leptophilic Z' boson

Outline

Vectorlike Leptons

Interact in a non-chiral way with 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 after EWSB

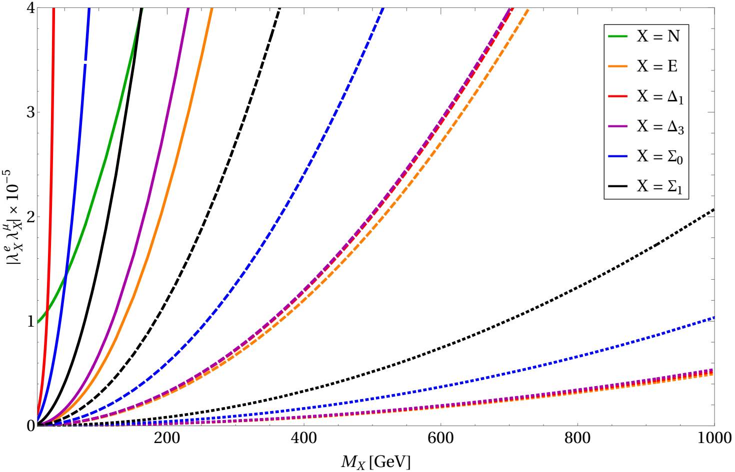
$\Rightarrow$ $\boxed{\text{modify } W\ell\nu,\ Z\nu\nu\ \&\ Z\ell\ell}$

Vectorlike leptons respecting the SM gauge group

		$SU(3)$	$SU(2)_L$	$U(1)_Y$
SM	ℓ	1	2	-1/2
	e	1	1	-1
	ϕ	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

Vectorlike Leptons: Constraints from $\mu \to e$

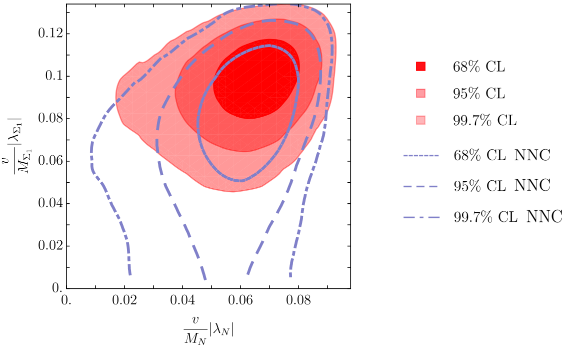
$\mu \to e\gamma$ $\mu \to eee$



$\mu \to e$ conversion

Vectorlike Leptons: Best Fit

- One generation of singlet N coupling **only** to electrons
- One generation of triplet Σ_1 coupling **only** to muons



λ_N: $N\phi e$-coupling, λ_{Σ_1}: $\Sigma_1\phi\mu$-coupling; M_{N,Σ_1}: masses of N, Σ_1

Outline

The Singly Charged Scalar Singlet ϕ^+

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	
ϕ^+	1	1	1	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 $\qquad \varepsilon_{ab} = i\sigma_2 = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}$

i,j: flavour indices

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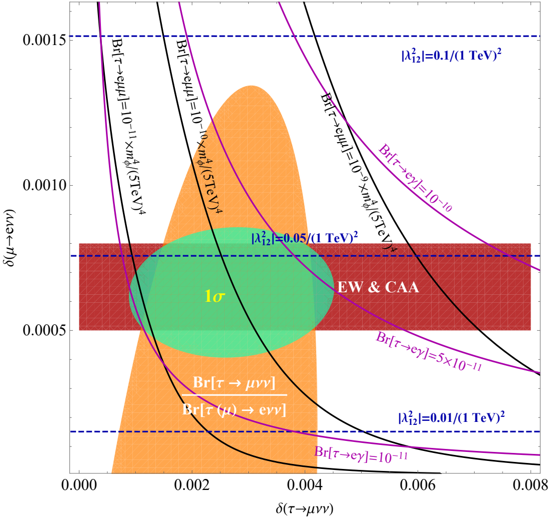
i,j: flavour indices

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

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

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

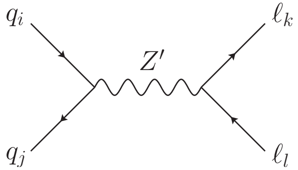
- $\text{Br}(\tau \to e\mu\mu) \sim 10^{-10} \frac{m_\phi^4}{(5\text{ TeV})^4}$
- $10^{-11} \lesssim \text{Br}(\tau \to e\gamma) \lesssim 5 \times 10^{-11}$
- $\frac{|\lambda_{12}|^2}{m_\phi^2} \sim \frac{0.05}{(1\text{ TeV})^2}$ ($\to$ mono photon)

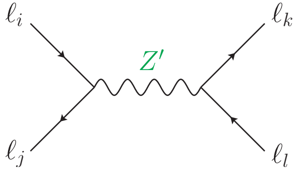
Outline

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

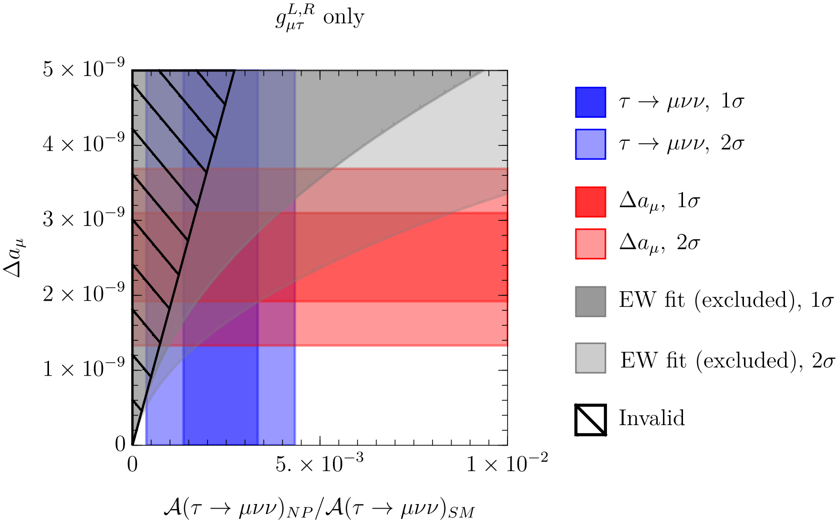
- Simple Extension of the SM
- Predicted by many models
- Strongly constrained by di-jet, di-lepton searches

- Z' bosons that couple to leptons
  - $\Rightarrow$ less constrained by LHC data ($\Rightarrow$ LEP)
  - $\Rightarrow$ can be lighter ($<$ TeV-scale)
- Gluons couple to quarks, Z' couples to leptons?





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: N, E, Δ_1, Δ_3, Σ_0, Σ_1
- Singly Charged Scalar Singlet, ϕ^+
- Leptophilic Z' Bosons

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- Singly Charged Scalar Singlet, ϕ^+
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Lepton Flavour Violation

- Forbidden in the SM
- Strongly constrained by experiment

$\Rightarrow$ Clean discovery channels

For "The Details":

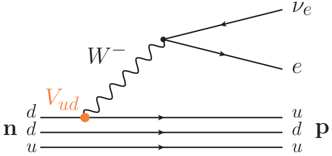
- Vectorlike leptons
  arXiv:2008.01113/ JHEP 12 (2020) 166, with Andreas Crivellin, FK, Claudio Andrea Manzari, Marc Montull
- Singly charged scalar singlet, ϕ^+
  arXiv:2012.09845/ Phys.Rev.D 103 (2021), Andreas Crivellin, FK, Claudio Andrea Manzari, Luca Panizzi
- Leptophilic Z' bosons
  arXiv:2104.07680/ JHEP06 (2021) 068, Andrzej J. Buras, Andreas Crivellin, FK, Claudio Andrea Manzari and Marc Montull

Backup slides

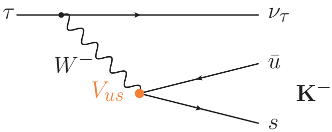
The Cabibbo Angle

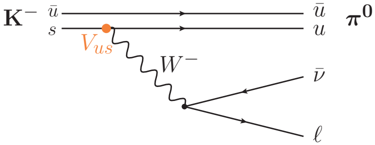
The Cabibbo angle can be determined from

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



- V_{us} from τ-decays & from K-decays





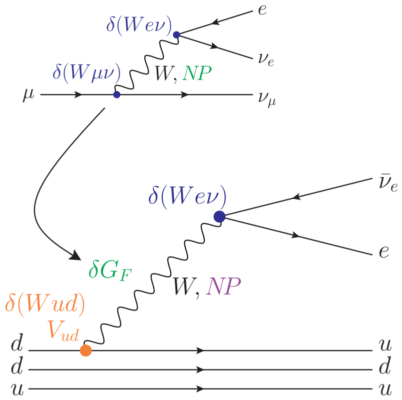
- V_{cd} from $D \to \mu\nu$

New Physics Interpretations of the CAA arXiv: 2008.03261

- Direct contributions to β-decays
- Modified Wud-coupling
- Modified $W\ell\nu$-coupling
- Direct contributions to μ-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

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

$$\begin{aligned}\Rightarrow V_{us}^{\beta} &\equiv \sqrt{1-\left(V_{ud}^{\beta}\right)^2-|V_{ub}|^2}\\ &\simeq V_{us}^{\mathcal{L}}\left[1+\left(\frac{V_{ud}^{\mathcal{L}}}{V_{us}^{\mathcal{L}}}\right)^2\delta(\mu\to e\nu\nu)\right].\end{aligned}$$

V_{us}^{β}: determined via CKM unitarity from V_{ud}^{β} (β 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 ℓ, ν
- Can allow for $Z - Z'$-mixing $\Rightarrow$ correction to m_Z (destructive)

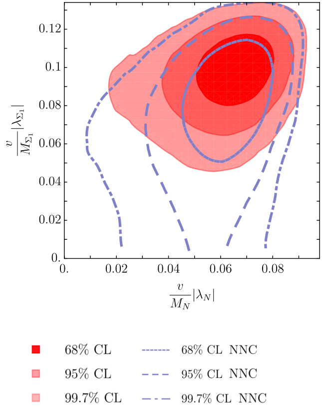
Lagrangian:

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

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

Vectorlike Leptons: Best Fit

- one generation of singlet N coupling **only** to electrons
- one generation of triplet Σ_1 coupling **only** to muons



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 ± 0.0020	1	1.00168(39)	−0.80
$R\left[\frac{\pi\to\mu\nu}{\pi\to e\nu}\right]$	1.0010 ± 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 ± 0.0014	1	1.00168(39)	1.2
$\lvert V_{us}^{K_{\mu 3}}\rvert$	0.22345(67)	0.22573(35)	0.22519(39)	0.77
$\lvert V_{ud}^{\beta}\rvert$	0.97365(15)	0.97419(8)	0.97378(13)	2.52

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

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.*

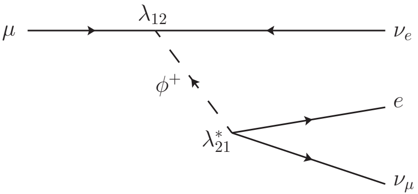
Pull

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.*

LFV via ϕ^+: $\ell \to \ell'\overline{\nu}\nu$



Effect is necessarily constructive:

$$\delta(\mu \to e\bar{\nu}\nu) = \frac{\mathcal{A}_{NP}(\mu \to e\bar{\nu}\nu)}{\mathcal{A}_{SM}(\mu \to e\bar{\nu}\nu)} = + \frac{|\lambda_{12}|^2}{g_2^2} \frac{m_W^2}{m_\phi^2} \stackrel{\text{fit}}{=} 0.00065(15)$$

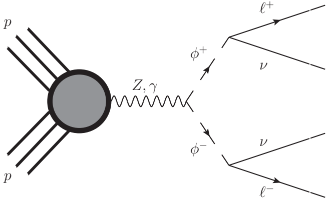
$$\delta(\tau \to \mu\bar{\nu}\nu) = \frac{\mathcal{A}_{NP}(\tau \to \mu\bar{\nu}\nu)}{\mathcal{A}_{SM}(\tau \to \mu\bar{\nu}\nu)} = + \frac{|\lambda_{23}|^2}{g_2^2} \frac{m_W^2}{m_\phi^2} \stackrel{\text{fit}}{\approx} 0.0019$$

LHC Searches

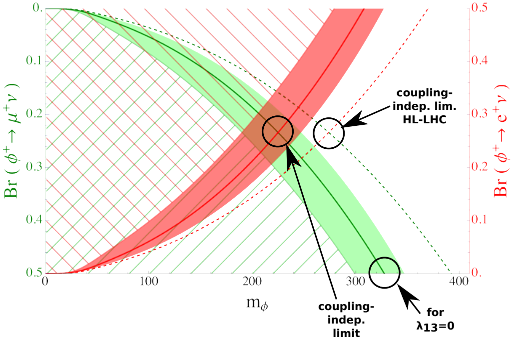
ϕ^+: same quantum numbers as right-handed sleptons

Drell-Yan Pair Production

of ϕ^+, with final state e^+e^- or $\mu^+\mu^-$ & missing transverse energy



$\mathrm{Br}(\phi^+ \to e^+\nu) + \mathrm{Br}(\phi^+ \to \mu^+\nu) \geq \frac{1}{2}$

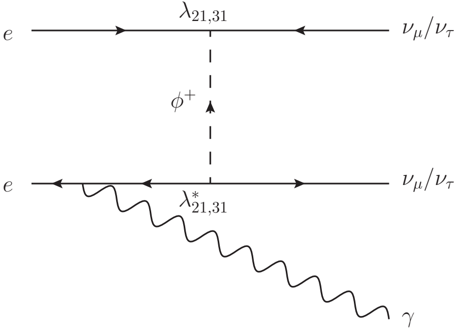


Recast of ATLAS searches for sleptons with 139/fb data, arXiv:1908.08215 [hep-ex]

Dashed lines: projected exclusion reach for an integrated luminosity of 3/ab at HL-LHC

LEP Searches

DM searches with mono-photon signatures at LEP:



DELPHI analyses

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

& 1103.0240 [hep-ph]

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