Neutrino Tridents: Theory

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UC SANTA CRUZ

based on

1406.2332 with Gori, Pospelov, Yavin
1902.06765 with Gori, Martin-Albo, Sousa, Wallbank

Meeting of the FLArE Far Forward Physics working group
October 4, 2022

Neutrino Trident Production

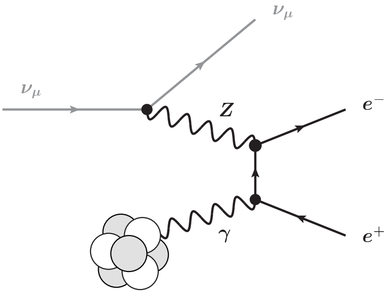
Neutrino induced production of a charged lepton pair in the Coulomb field of a heavy nucleus

Mediated by the electro-weak interactions at tree level
$\rightarrow$ sensitive to EW-scale new physics

A rare process: cross section is many orders of magnitude smaller than the inclusive neutrino-nucleus scattering cross section ($2 \rightarrow 4$ vs $2 \rightarrow 2$)

(Will focus on muon-neutrino induced processes in the following)

e^+e^- Tridents

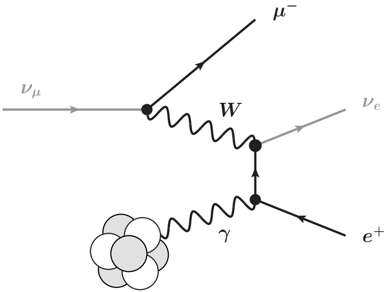


$\nu_\mu \to \nu_\mu e^- e^+$

in the SM mediated by the Z boson

not observed so far

$e^+\mu^-$ Tridents



($\mu^+ e^-$ from muon anti-neutrinos)

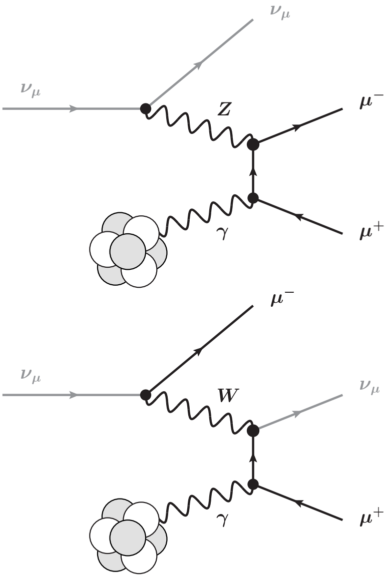
$\nu_\mu \to \nu_e \mu^- e^+$

in the SM mediated by the W boson

not observed so far

visible final state looks flavor violating (but flavor is conserved because of the neutrinos)

$\mu^+\mu^-$ Tridents



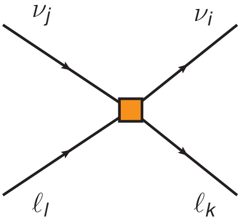
$$\nu_\mu \to \nu_\mu \mu^- \mu^+$$

Z and *W* contributions interefere destructively

observation claimed at CHARM II ('90) CCFR ('91)

Predicting the Cross Section (part 1)

can integrate out W and Z bosons
and describe the interaction through a
4 fermion operator



$$\mathcal{H}_{\text{eff}} = \frac{G_F}{\sqrt{2}} (\bar{\nu}_i \gamma^\alpha P_L \nu_j)(\bar{\ell}_k \left[g^V_{ijkl} \gamma_\alpha + g^A_{ijkl} \gamma_\alpha \gamma_5 \right] \ell_l)$$

Process	g^V_{SM}	g^A_{SM}
$\nu_e \to \nu_e e^+ e^-$	$1 + 4\sin^2\theta_W$	-1
$\nu_e \to \nu_e \mu^+ \mu^-$	$-1 + 4\sin^2\theta_W$	$+1$
$\nu_e \to \nu_\mu \mu^+ e^-$	2	-2
$\nu_\mu \to \nu_\mu e^+ e^-$	$-1 + 4\sin^2\theta_W$	$+1$
$\nu_\mu \to \nu_\mu \mu^+ \mu^-$	$1 + 4\sin^2\theta_W$	-1
$\nu_\mu \to \nu_e e^+ \mu^-$	2	-2

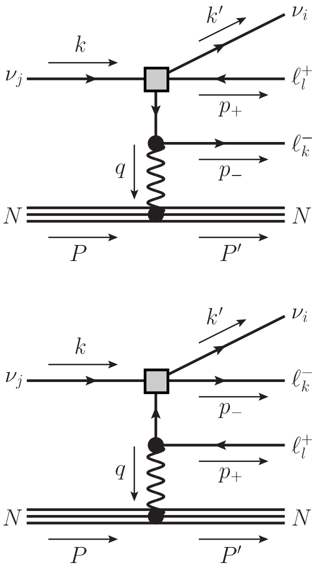
Predicting the Cross Section (part 2)

The leptons connect to the nucleus via a virtual photon

The equivalent photon approximation ($\sim$ calculating $\nu\gamma \to \nu\ell^+\ell^-$ and tacking on the nucleus in a second step) was found to introduce sizable uncertainties

(Magill, Plestid 1612.05642; Ge et al. 1702.02617; Ballet et al. 1807.10973)

Need to calculate the full $2 \to 4$ process.
($\nu N \to \nu\ell^+\ell^- N$)



Coherent Scattering on the Full Nucleus

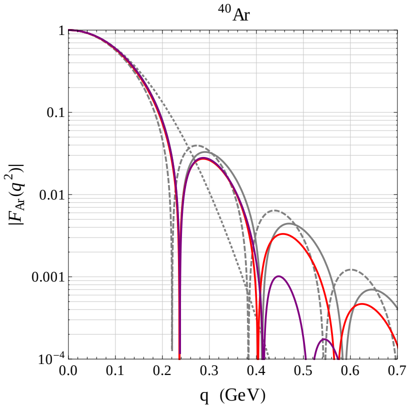
experimental signature of coherent scattering on a nucleus:
two oposite sign leptons without any hadronic activity

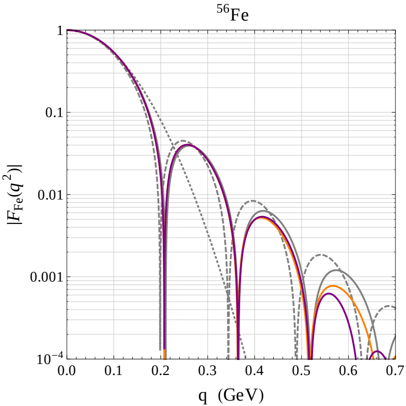
$$d\sigma_{\text{coh.}} \propto Z^2 \alpha_{\text{em}}^2 G_F^2 |F_N(q^2)|$$

- enhanced by Z^2
- for scattering on spin 0 nuclei,
  need the electric form factors of the nuclei

Nuclear Form Factors

Electric form factors of nuclei are very well measured.





We use nuclear charge densities from De Vries, De Jager, De Vries '87.

Different parameterizations lead to $< 1\%$ shifts in the results.

Incoherent Scattering on Individual Nucleons

experimental signature of incoherent scattering on nucleons:
two oposite sign leptons + proton or neutron
that is kicked out from nucleus

$$d\sigma_{\text{incoh.}} \simeq \Theta(|\vec{q}|)(Z d\sigma_p + (A - Z) d\sigma_n)$$

- Θ is a Pauli blocking factor, derived by approximating the nucleus as an ideal Fermi gas (Lovseth, Radomski, PRD 3, 2686 (1971)).
  Approximation should work at the $\sim 20\%$ level
  (Llewellyn Smith, Phys Rept 3, 261 (1972))
- for scattering on protons and neutrons, need the electric and magnetic form factors (very well known, e.g. Alberico et al. 0812.3539, Ye et al. 1707.09063)

Event Generator

- The 4-body phase space integrals needed for the cross section prediction can't be performed fully analytically.
- We developed a Monte Carlo that numerically calculates the cross section and also can generate events.
- Available in the source files of the arXiv submission arXiv:1902.06765 (WA, Gori, Martin-Albo, Sousa, Wallbank)
- Simple interface lets the user pick
  - target material (public version contains Argon and Iron; other materials available on request)
  - energy spectrum of the incoming neutrino beam (fixed energy, or various spectra based on the DUNE CDR/TDR; easy to implement your own neutrino spectrum)
  - calculation can be done in the SM and a few BSM scenarios (SM + 4 fermion operators; Z' gauge boson)

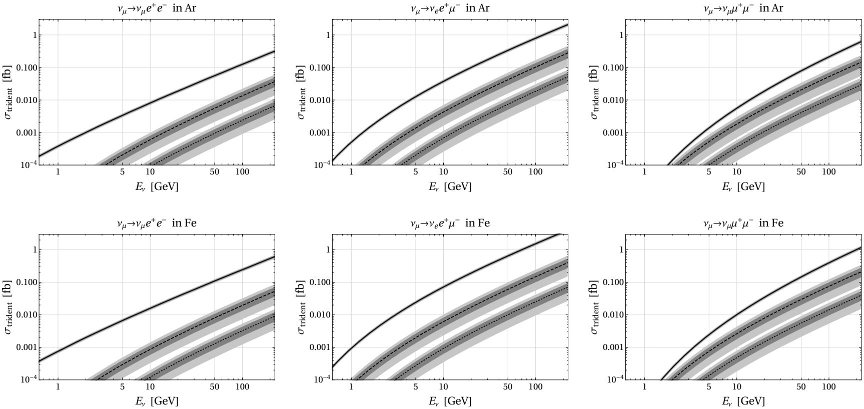
User Interface

```
Select the trident process  [enter 1 - 12]

 [1] nu_e -> nu_e e+ e-                  [7] nu_mu -> nu_mu e+ e-
 [2] nu_e -> nu_e mu+ mu-                [8] nu_mu -> nu_mu mu+ mu-
 [3] nu_e -> nu_mu mu+ e-                [9] nu_mu -> nu_e e+ mu-
 [4] anti-nu_e -> anti-nu_e e+ e-        [10] anti-nu_mu -> anti-nu_mu e+ e-
 [5] anti-nu_e -> anti-nu_e mu+ mu-      [11] anti-nu_mu -> anti-nu_mu mu+ mu-
 [6] anti-nu_e -> anti-nu_mu e+ mu-      [12] anti-nu_mu -> anti-nu_e mu+ e-

8

Select the target material  [enter Ar, Fe, proton, neutron]

 [Ar] Argon      [Fe] Iron

 [proton]  Proton inside an ideal Fermi gas
 [neutron] Neutron inside an ideal Fermi gas

Ar

Are you using a fixed neutrino energy or an energy distribution?

[1] fixed neutrino energy

[2] nu_mu flux at DUNE near detector: 'Reference beam 80 GeV, 204m x 4m DP' from the CDR
[3] nu_mu flux at DUNE near detector: 'Optimized beam 80 GeV, 204m x 4m DP' from the CDR
[4] nu_mu flux at DUNE near detector: 'Optimized beam 120 GeV' for the TDR

[5] anti-nu_mu flux at DUNE near detector: 'Reference beam 80 GeV, 204m x 4m DP' from the CDR
[6] anti-nu_mu flux at DUNE near detector: 'Optimized beam 80 GeV, 204m x 4m DP' from the CDR
[7] anti-nu_mu flux at DUNE near detector: 'Optimized beam 120 GeV' for the TDR

[8] nu_mu flux at the CCFR experiment

2

Select the model

[4F]      Model independent 4 Fermi operators
[SM]      Standard Model
[LmuLtau] Standard Model + Z' gauge boson based on L_mu - L_tau

SM

You can compute the trident [CrossSection] or [GenerateEvents]

CrossSection


computing cross section:  [==================================================]  100 %

The trident cross section is  ( 0.000820527 +- 3.31086e-07 ) fb
(uncertainty is the statistical uncertainty of the numerical phase space integration)
```

the generated event files follow standard conventions


```
<event>
14 -1 0.00000000 0.00000000 9.92620075 9.92620075 0.0
14  1 -0.40583609 -0.60127220 3.30583808 3.38449355 0.0
13  1 0.69396474 0.85524958 4.45224744 4.58766931 0.10565800
-13  1 0.09416738 -0.05179305 1.78386095 1.79021605 0.10565800
</event>
<event>
14 -1 0.00000000 0.00000000 13.25030492 13.25030492 0.0
14  1 0.18037122 -0.19890842 0.64758197 0.70104261 0.0
13  1 0.05969243 -0.23222055 10.37270599 10.37601478 0.10565800
-13  1 -0.45799836 0.16564537 2.03303183 2.09322309 0.10565800
</event>
```

SM Predictions



coherent scattering has largest cross section (upper band), followed by the sum of incoherent scattering on protons (middle band), then sum of incoherent scattering on neutrons (lower band)

main uncertainties from higher order EW (coherent), and nuclear modeling (incoherent)

Existing Measurements

first signal claimed at CHARM II:
neutrinos with average energy
$\sim$ 20 GeV on glass

Phys.Lett. B245, 271 (1990)

$$\sigma_{\text{CHARM II}}/\sigma_{\text{SM}} = 1.58 \pm 0.57$$

similar significance at CCFR:
neutrinos with average energy
$\sim$ 160 GeV on iron

Phys.Rev.Lett. 66, 3117 (1991)

$$\sigma_{\text{CCFR}}/\sigma_{\text{SM}} = 0.82 \pm 0.28$$

no conclusive signal at NuTeV:
neutrinos with average energy
$\sim$ 160 GeV on iron

Phys.Rev.D 61, 092001 (2000)

$$\sigma_{\text{NuTeV}}/\sigma_{\text{SM}} = 0.72^{+1.73}_{-0.72}$$

Issues with Previous Observations?

NuTeV analysis identified an additional background that was not included by CCFR and CHARM II

Furthermore, the neutrino trident process must be considered in combination with the expected signal from

diffractive charm production in experiments that are only sensitive to two-muon final states. This point has not been recognized in previous measurements of neutrino tridents.

and "improved" the signal modeling

This procedure incorporated all possible kinematic correlations between the two muons and represents an improvement over previous methods

NuTeV, Phys.Rev.D 61, 092001 (2000)

How reliable are the CCFR and CHARM II results?

Neutrino Tridents and New Physics

Gauged L_μ - L_τ

- The difference of muon number and tau number is one of the few anomaly free global symmetries of the Standard Model

$\Rightarrow$ can be gauged without introducing any additional matter content

He, Joshi, Lew, Volkas PRD 43, 22-24 (1991)

- After spontaneous symmetry breaking one gets a massive Z' that couples to muons, taus, muon-neutrinos, and tau-neutrinos

$$\mathcal{L} = -\frac{1}{4}(Z'_{\alpha\beta})^2 + \frac{m_{Z'}^2}{2}(Z'_\alpha)^2 + g' Z'_\alpha \left(\bar\mu\gamma^\alpha\mu - \bar\tau\gamma^\alpha\tau + \bar\nu_\mu\gamma^\alpha P_L\nu_\mu - \bar\nu_\tau\gamma^\alpha P_L\nu_\tau\right)$$

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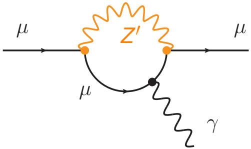
- The minimal model can explain the anomalous magnetic moment of the muon

- Extended versions can explain the hints for lepton flavor universality violation in rare B decays (R_K, R_{K^*})

WA, Gori, Pospelov, Yavin 1403.1269; WA, Yavin 1508.07009

Z' contributes to $(g-2)_\mu$ at the 1-loop level

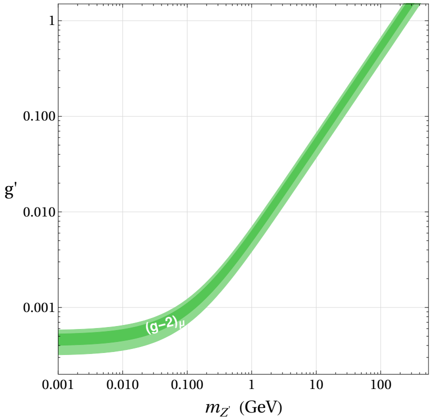


$$\Delta a_\mu \simeq \frac{(g')^2}{12\pi^2}\frac{m_\mu^2}{m_{Z'}^2} + \mathcal{O}\left(\frac{m_\mu^4}{m_{Z'}^4}\right)$$

Can it explain the long standing discrepancy?

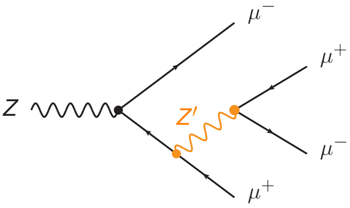
$$\Delta a_\mu = (2.51 \pm 0.59) \times 10^{-9}$$

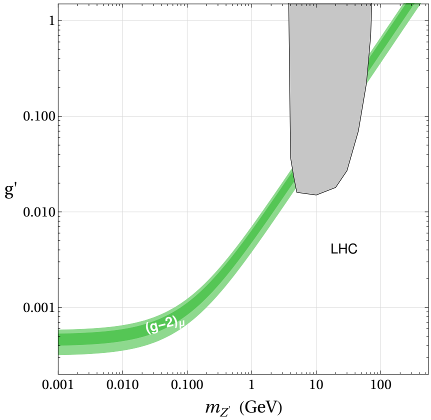
Note: plot was done before the new Fermilab result.
The shown band actually corresponds to
$\Delta a_\mu \simeq (2.9 \pm 0.9) \times 10^{-9}$



Can obtain bounds from measured
$Z \to 4\mu$ branching ratio

(WA, Gori, Pospelov, Yavin, 1406.2332)





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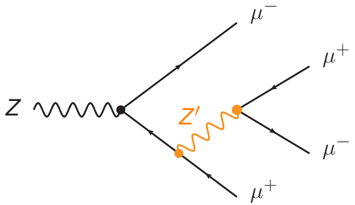
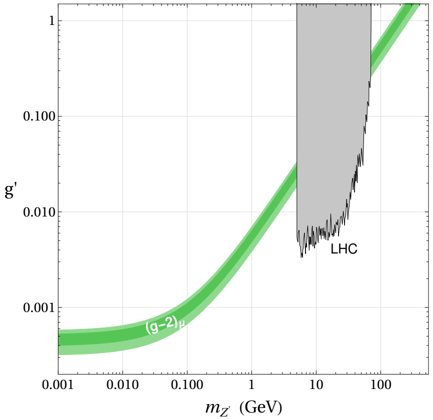
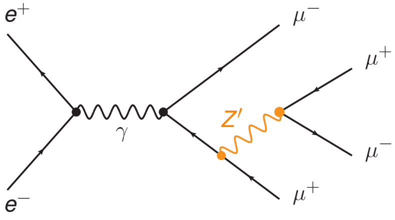




dedicated search for the $L_\mu - L_\tau$ gauge boson (CMS 1808.03684)

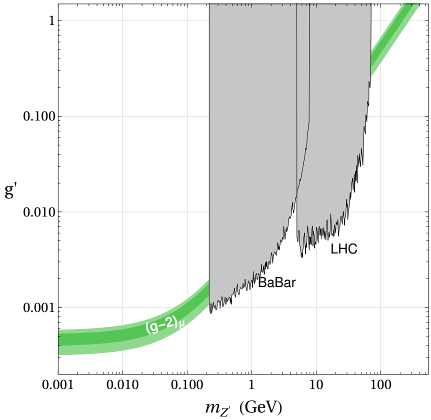
Direct Search at B-factories

$$e^+e^- \to 2\mu Z' \to 4\mu$$

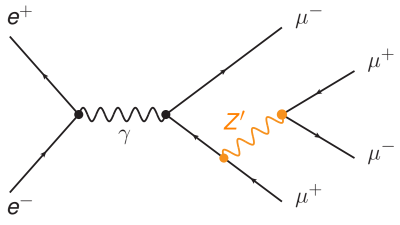


BaBar 1606.03501; Belle 2109.08596

(Can be improved at Belle II)



$$e^+e^- \to 2\mu Z' \to 4\mu$$



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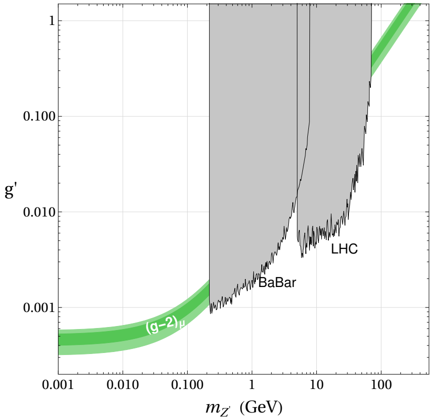
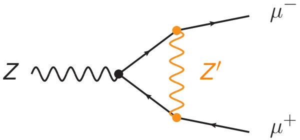


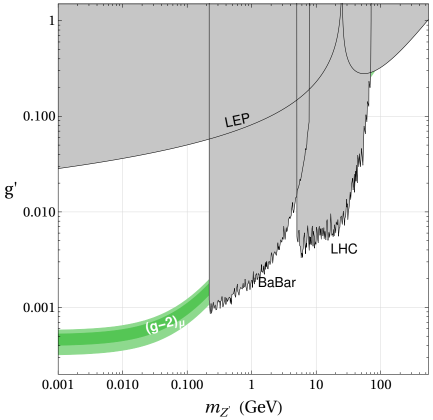
region below the di-muon threshold is difficult $e^+e^- \to \mu^+\mu^- + E_{\text{miss}}$

Belle II 1912.11276

Modified Z Couplings to Leptons

loops involving the Z'
lead to corrections of the
couplings of the SM Z to
muons, taus and neutrinos

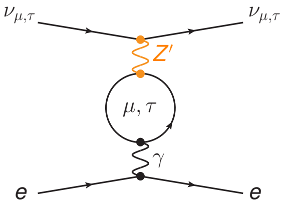




→ constraints from
LEP measurements

WA, Gori, Pospelov, Yavin 1403.1269

Borexino measures the scattering rate of solar neutrinos on electrons

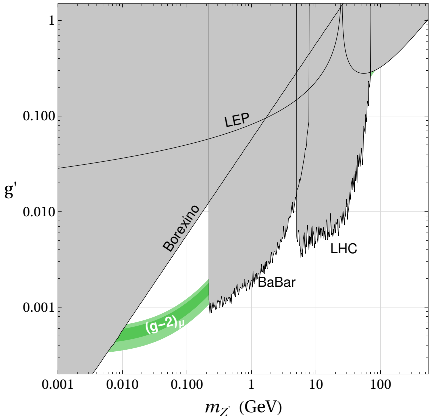


tiny momentum transfer
$\Rightarrow$ Z' kinetically mixes with photon

relevant constraint at low masses

Kamada, Yu 1504.00711

(constraint can be modified by adding kinetic mixing by hand)

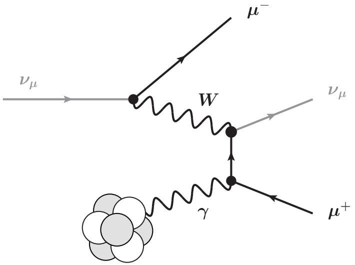


The Z' contributes to trident production

effect has some dependence on the
neutrino beam spectrum

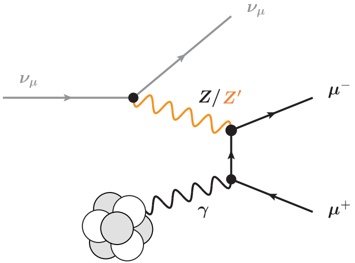
$$\frac{\sigma^{\text{CCFR}}}{\sigma^{\text{CCFR}}_{\text{SM}}} \simeq \frac{1.13 + \left(1 + 4s_W^2 + \frac{2v^2 (g')^2}{M_{Z'}^2}\right)^2}{1.13 + (1 + 4s_W^2)^2}$$

(for Z' masses $\gtrsim$ few GeV)



$$\frac{\sigma^{\text{DUNE}}}{\sigma^{\text{DUNE}}_{\text{SM}}} \simeq \frac{1.54 + \left(1 + 4s_W^2 + \frac{2v^2 (g')^2}{M_{Z'}^2}\right)^2}{1.54 + (1 + 4s_W^2)^2}$$

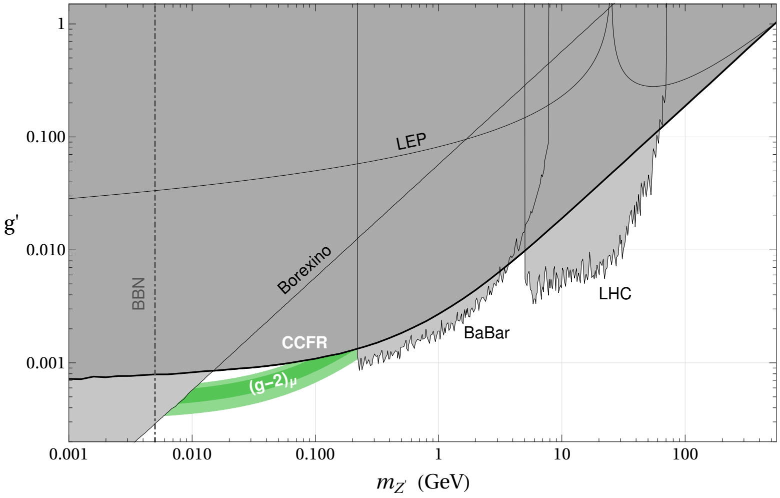
(for Z' masses $\gtrsim$ few hundred MeV)



(WA, Gori, Martin-Albo, Sousa, Wallbank 1902.06765)

Summary of Current Constraints on $L_\mu - L_\tau$

WA, Gori, Pospelov, Yavin, 1406.2332; WA, Gori, Martin-Albo, Sousa, Wallbank 1902.06765



(for the expected DUNE sensitivity see the next talk)

Summary

- Neutrino induced di-lepton production in the Coulomb field of a heavy nucleus is a rare SM process, which has hardly been observed
- Can probe new physics at the electroweak scale and below
- Has unique sensitivity to new muonic forces (e.g. gauged $L_\mu - L_\tau$)