Probing New Physics with Neutrino Tridents

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Neutrino Trident Production

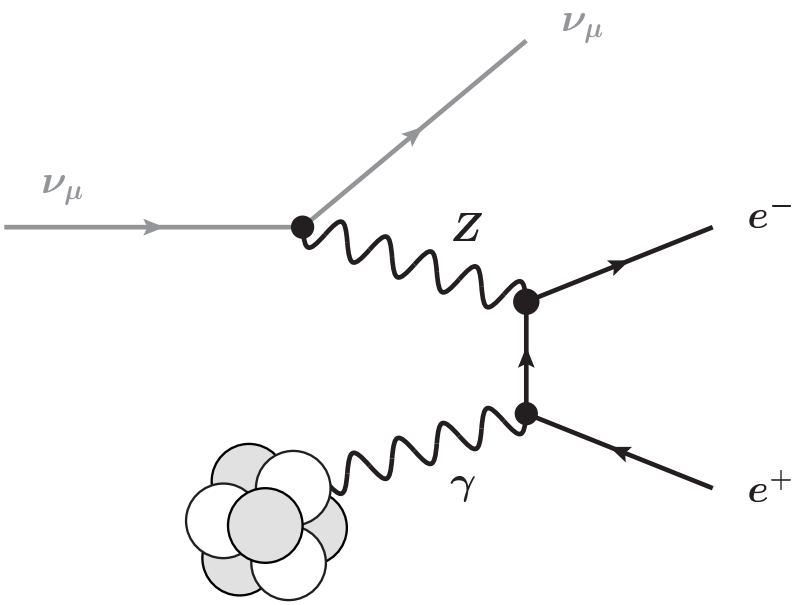
Neutrino induced production of a charged lepton pair in the Coulomb field of a heavy nucleus

Induced by 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)

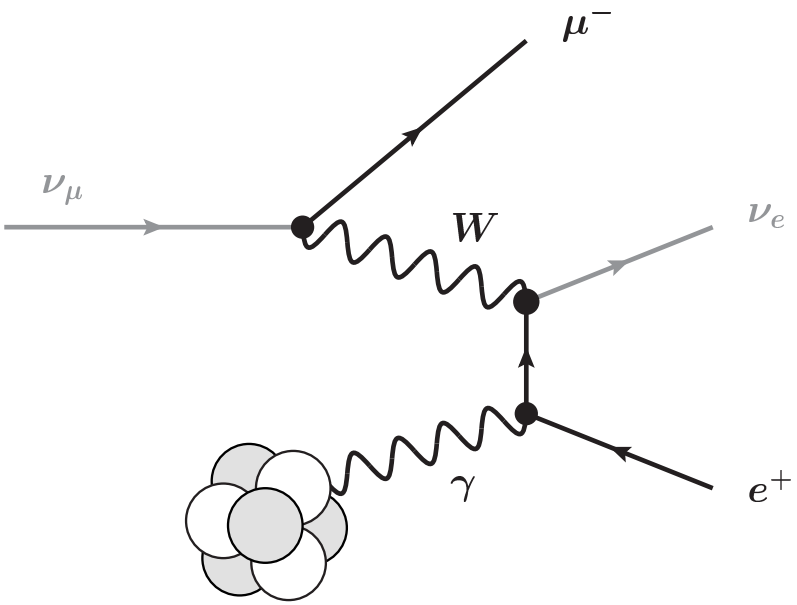
e^+e^- Tridents



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

not observed
so far

$e^+\mu^-$ Tridents

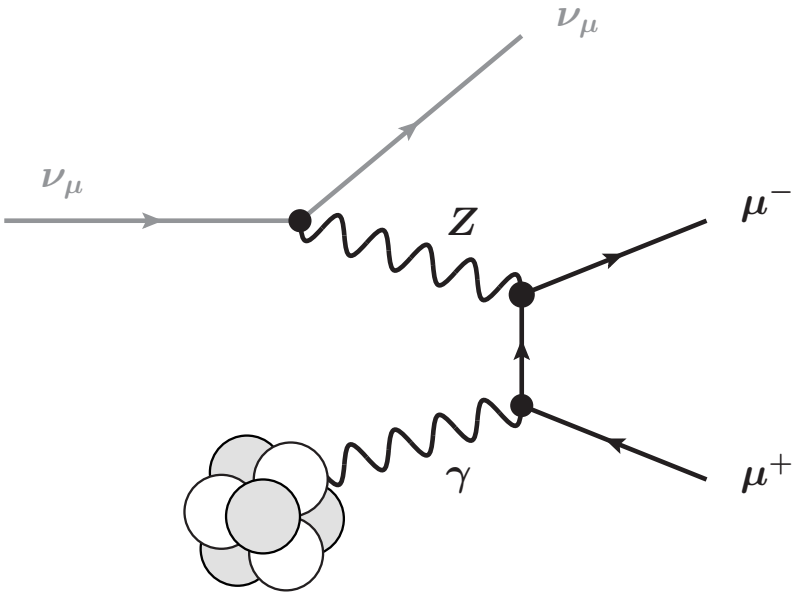


$\nu_\mu \to \nu_e \mu^- e^+$

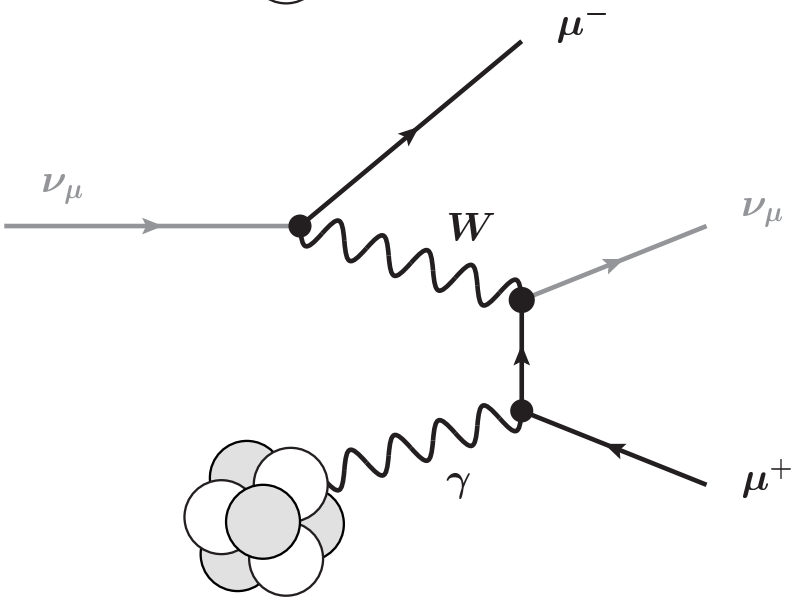
not observed
so far

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

$\mu^+\mu^-$ Tridents



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



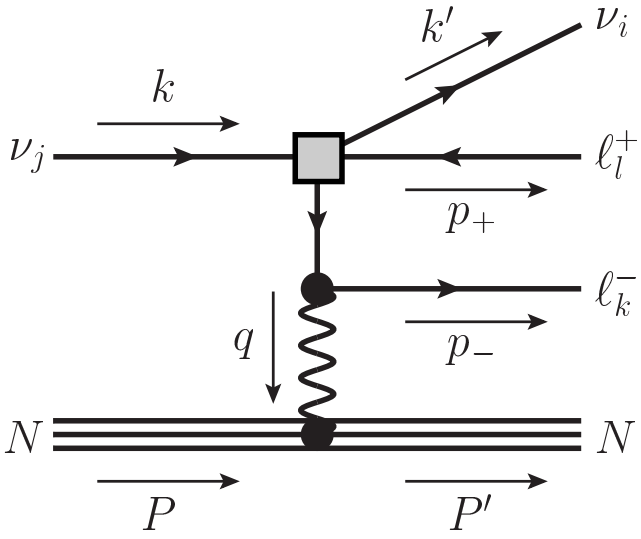
observation claimed at
CHARM II ('90)
CCFR ('91)

Predicting the Cross Section

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

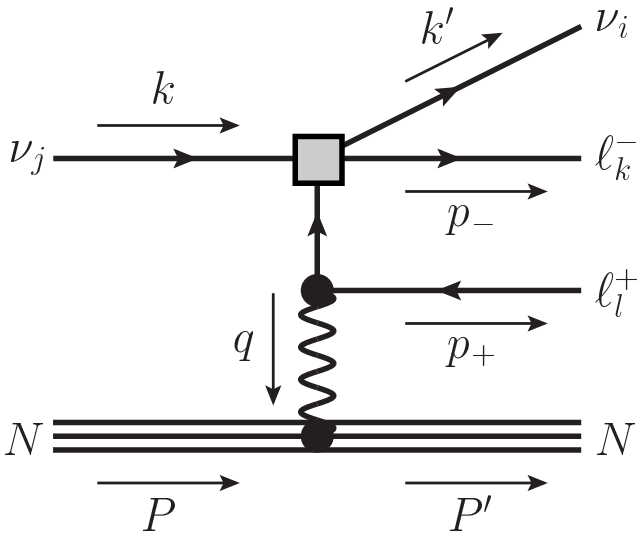
$$\mathcal{H}_{\text{eff}} = \frac{2G_F}{\sqrt{2}}(\bar{\mu}\left[C_V\gamma_\alpha + C_A\gamma_\alpha\gamma_5\right]\mu)(\bar{\nu}_\mu\gamma^\alpha P_L\nu_\mu)$$

connect to nucleus via a virtual photon



need to calculate the full $2 \to 4$ process.
Equivalent photon approximation was found to
introduce sizable uncertainties

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



Coherent Scattering on the Full Nucleus

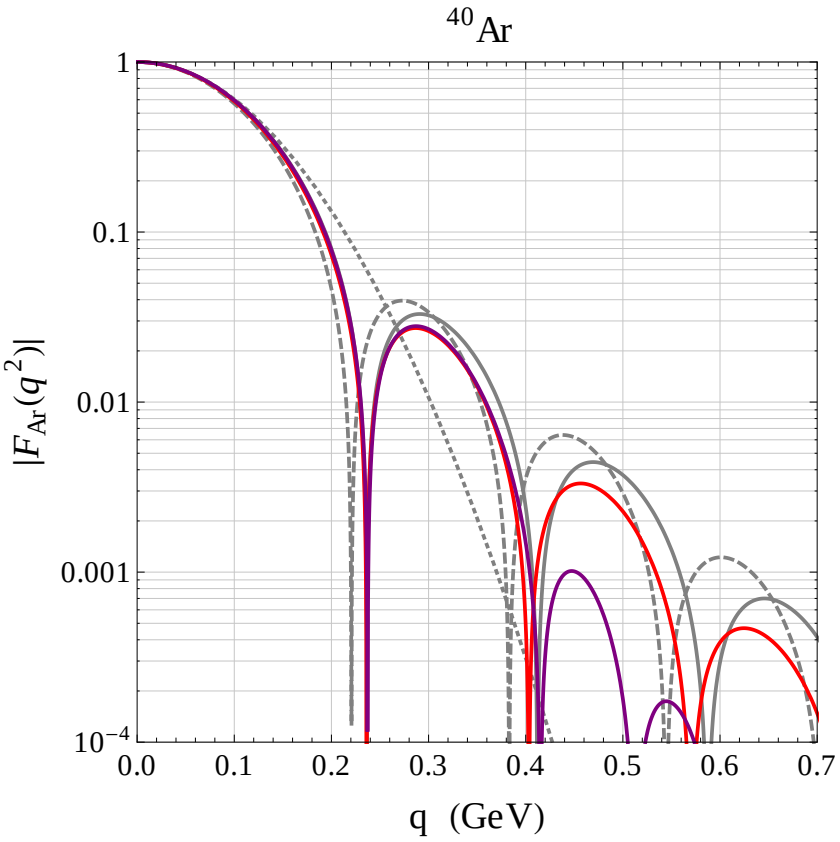
experimental signature of coherent scattering on a nucleus:
two oposite sign leptons without any hadronic activity

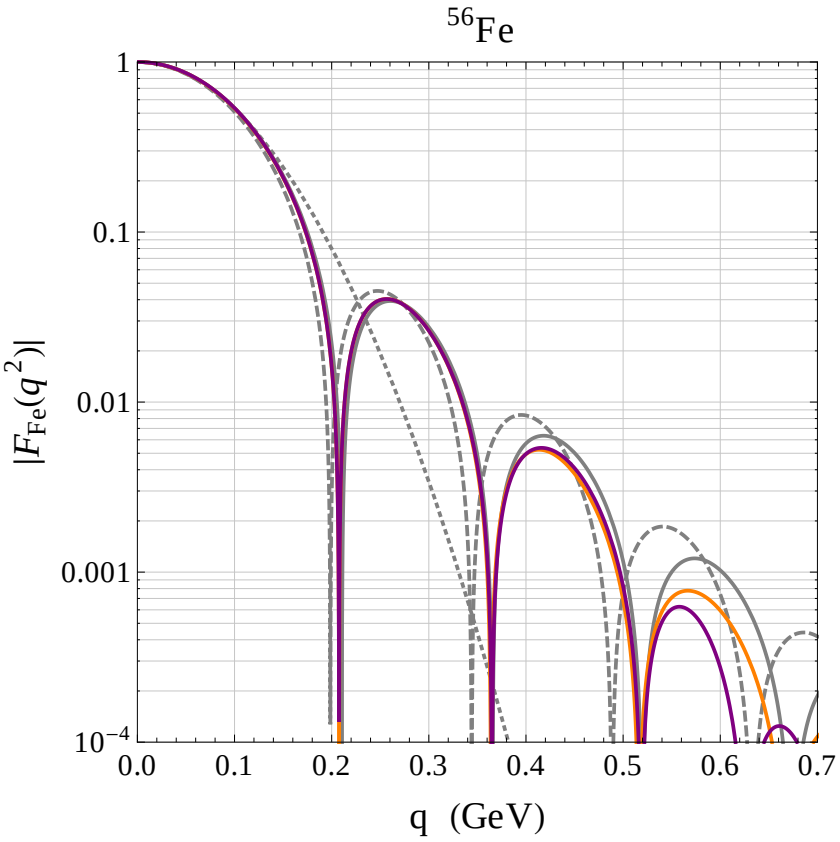
$$d\sigma_{\text{coh.}} \propto Z^2 \alpha_{\text{em}}^2 G_F^2 |F_N(q^2)|$$

- 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.

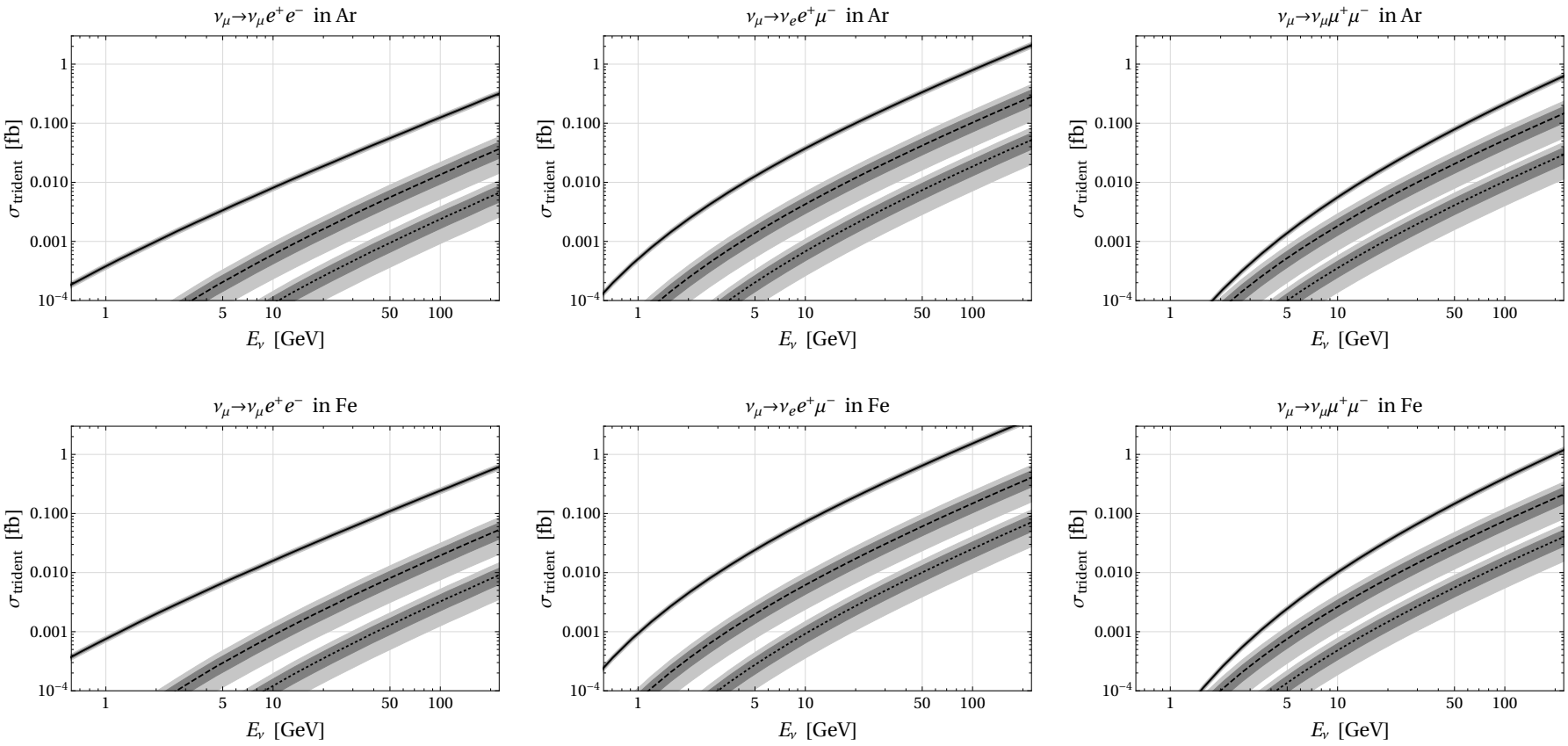
Incoherent Scattering on Individual Nucleons

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

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

- 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)

SM Predictions



coherent scattering has largest cross section, followed by incoherent scattering on protons, then scattering on neutrons

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 the CCFR Result?

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

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 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)

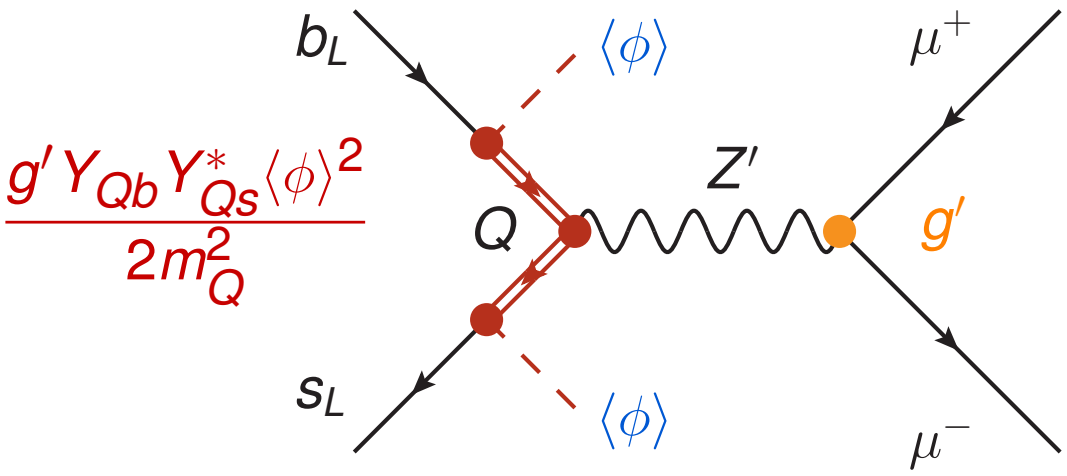
How reliable is the CCFR result?

Neutrino Tridents and New Physics

My Favorite Model for $R_{K^{(*)}}$

Z' based on gauging $L_\mu - L_\tau$
with effective flavor violating couplings to quarks

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



Q: heavy vectorlike fermions with mass $\sim 1 - 10$ TeV
ϕ: scalar that breaks $L_\mu - L_\tau$

(see also recent extented model WA, Davighi, Nardecchia 1909.02021)

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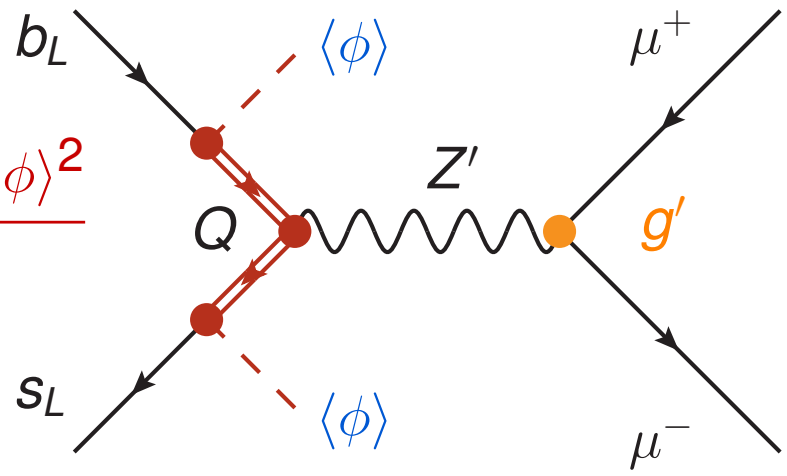
$$\frac{g' Y_{Qb} Y^*_{Qs} \langle\phi\rangle^2}{2 m_Q^2}$$



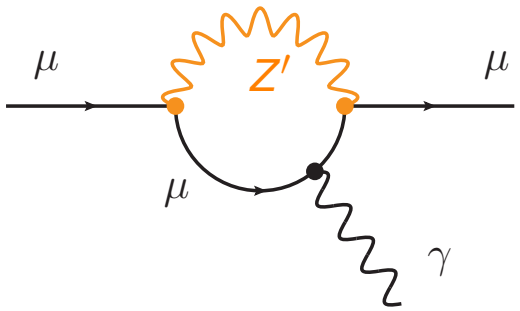
predicted Lepton Universality Violation in rare B decays!

Q: heavy vectorlike fermions with mass $\sim 1 - 10$ TeV
ϕ: scalar that breaks $L_\mu - L_\tau$

(see also recent extented model WA, Davighi, Nardecchia 1909.02021)

Muon Anomalous Magnetic Moment

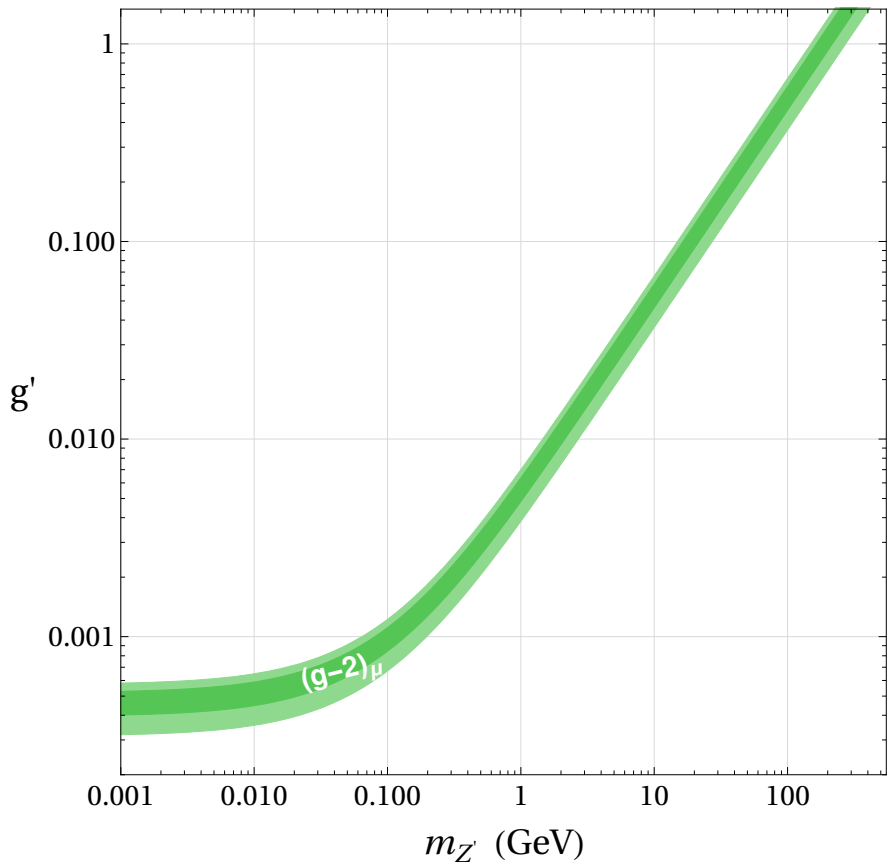
Z' contributes to $(g-2)_\mu$ at the 1-loop level



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

Can it explain the long standing discrepancy?

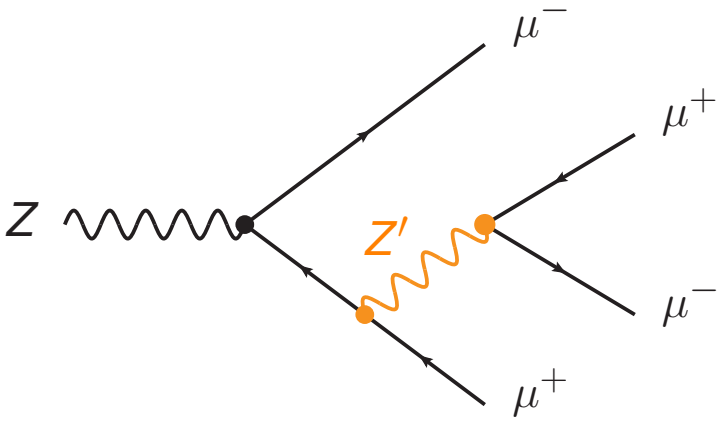
$$\Delta a_\mu \simeq (2.9 \pm 0.9) \times 10^{-9}$$

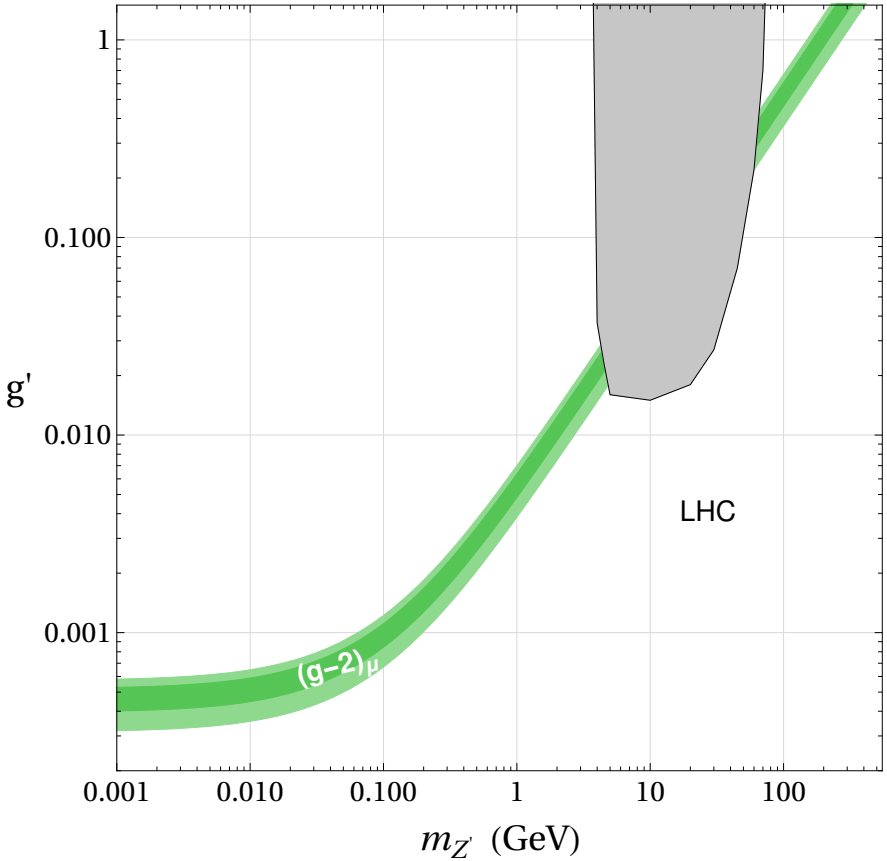


LHC Searches

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

(WA, Gori, Pospelov, Yavin, 1406.2332)





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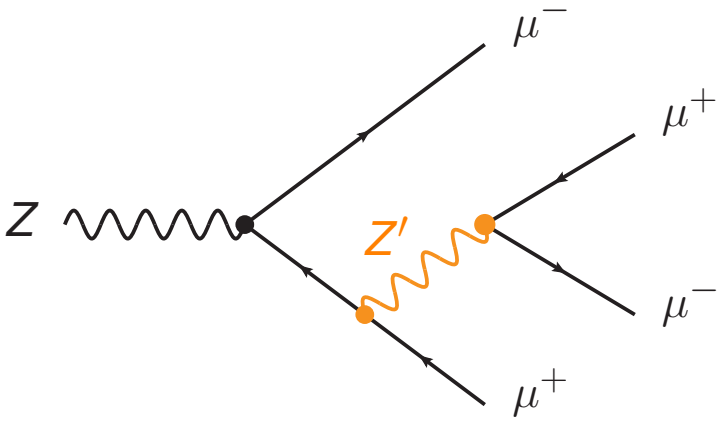
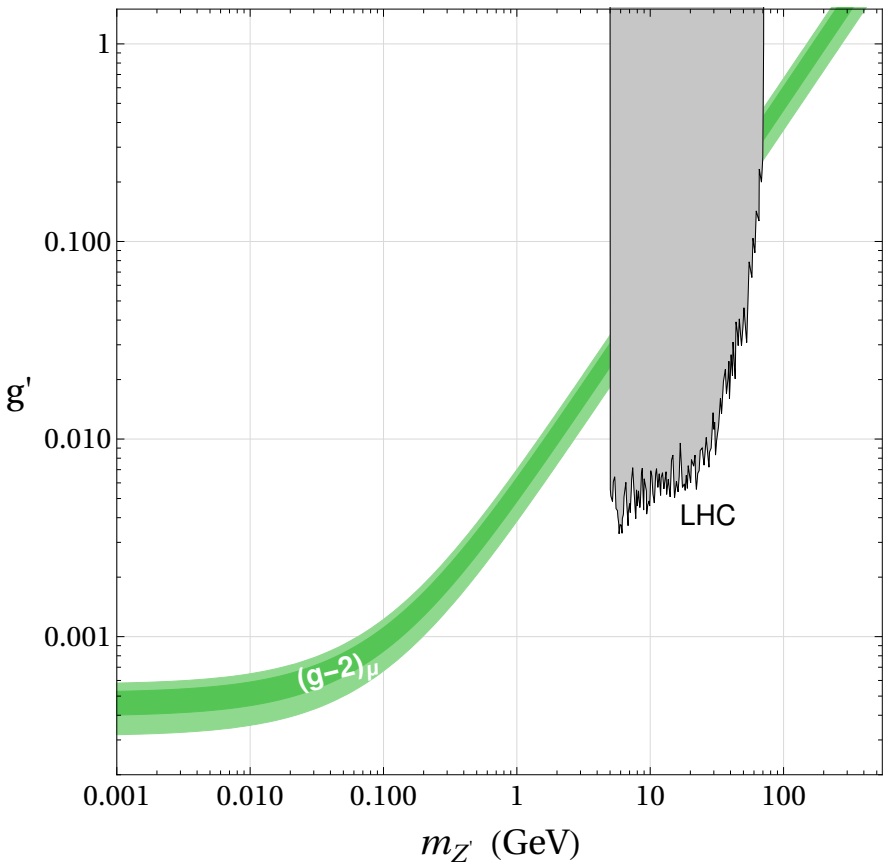




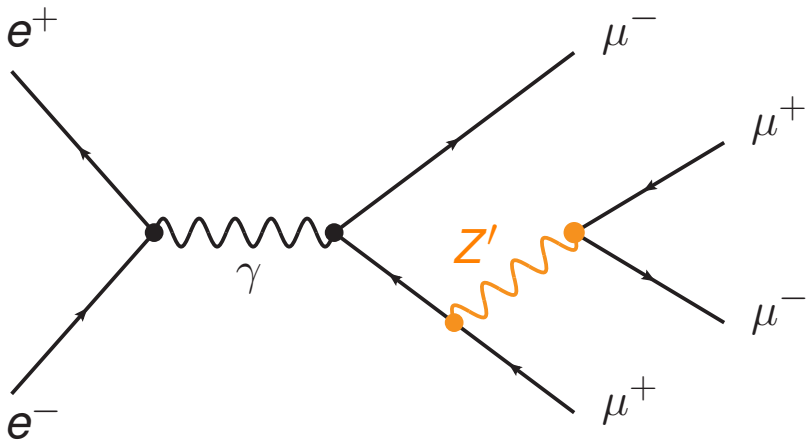
recent dedicated search for the $L_\mu - L_\tau$ gauge boson (CMS 1808.03684)

extension to lower masses possible?

(Elahi, Martin 1511.04107)

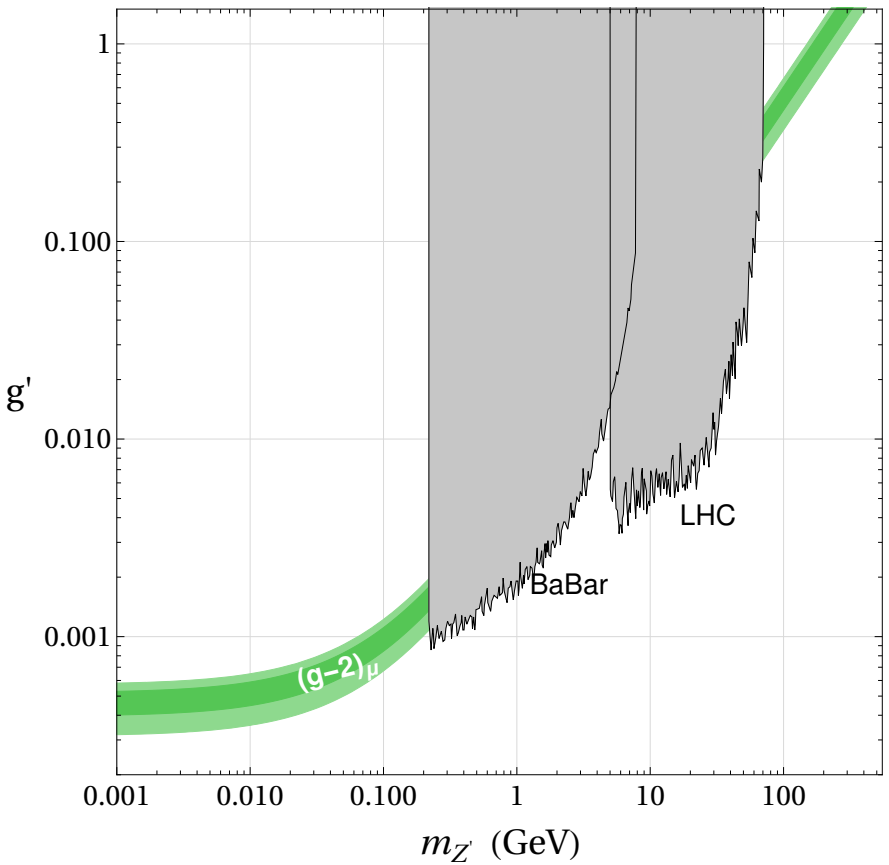
Direct Search at B-factories

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



BaBar 1606.03501

(Can be improved at Belle II)



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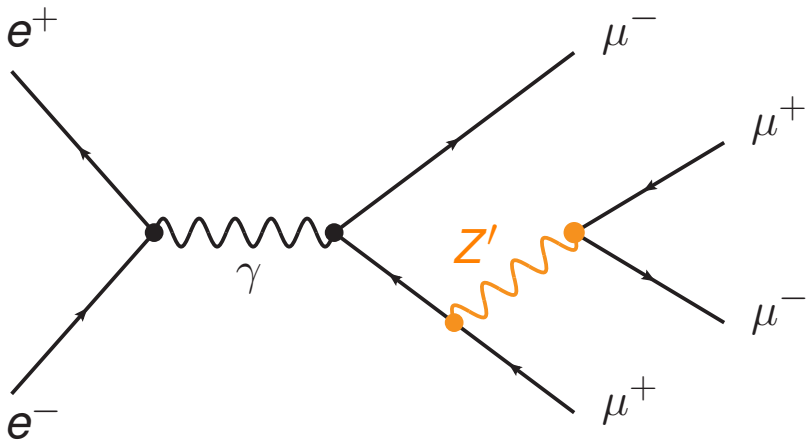

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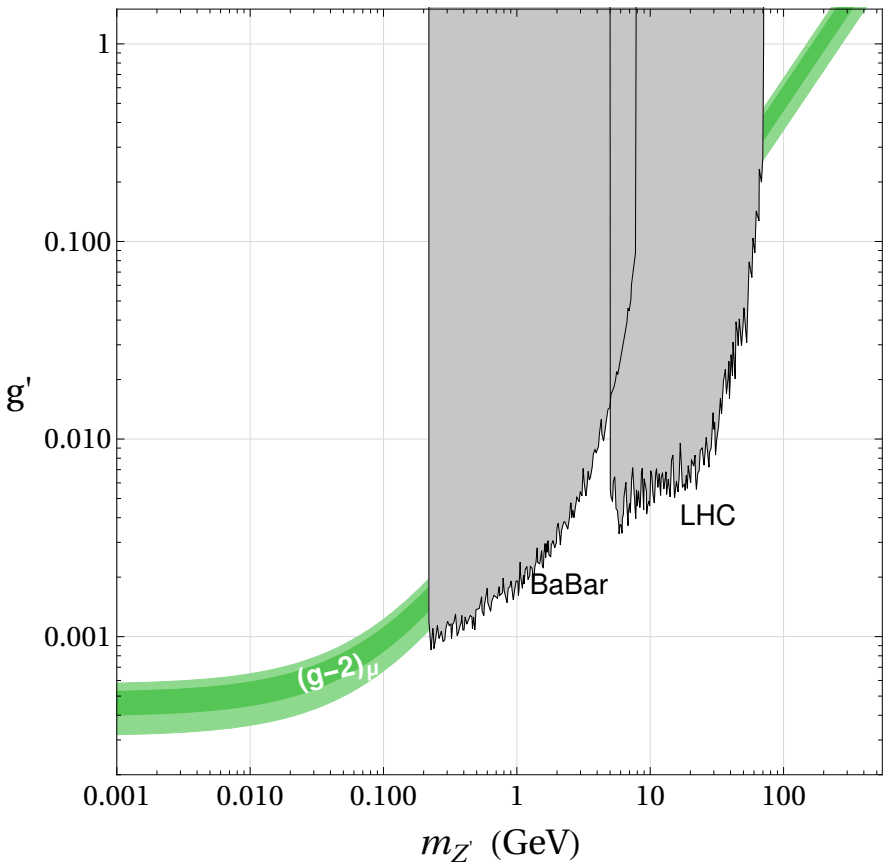
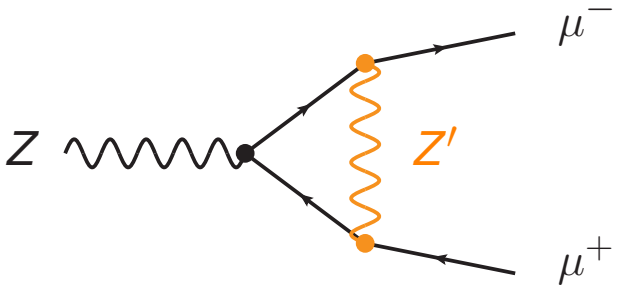


What about the region below the di-muon threshold?

$$e^+e^- \to \mu^+\mu^- + E_{\text{miss}} \ ?$$

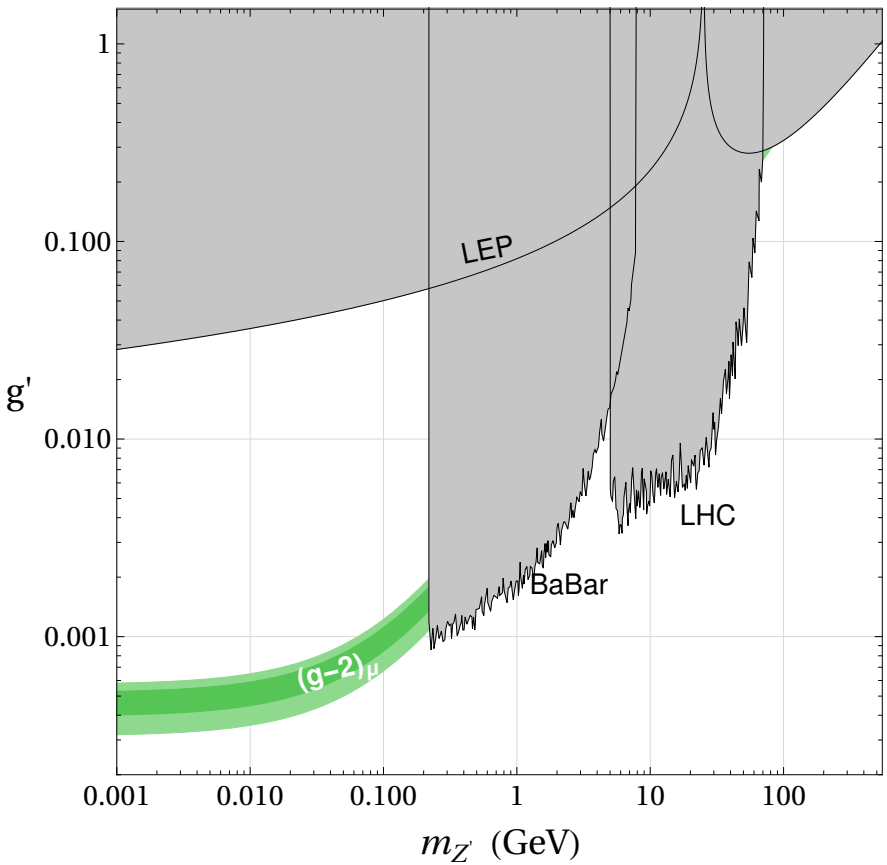
Modified Z Couplings to Leptons

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



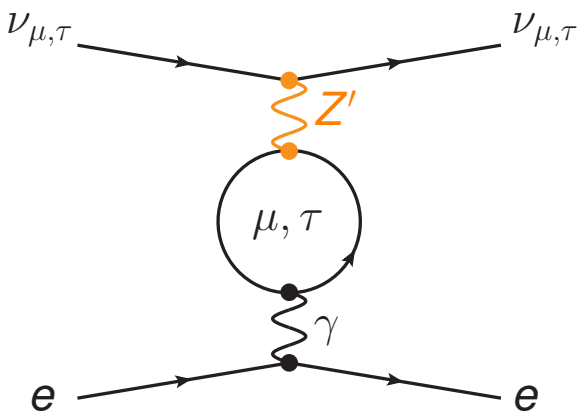
$\rightarrow$ constraints from LEP measurements

WA, Gori, Pospelov, Yavin 1403.1269



Neutrino-Electron Scattering

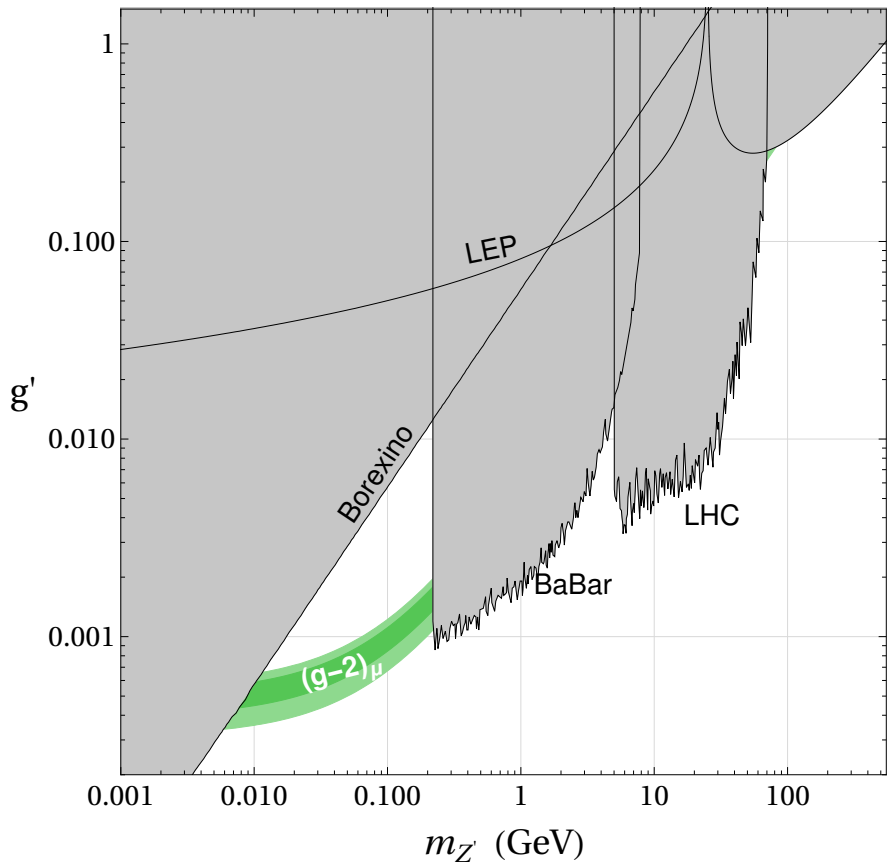
Borexino measures the scattering rate of solar neutrinos on electrons



tiny momentum transfer
$\Rightarrow$ Z' can mix with photon

relevant constraint at low masses

Kamada, Yu 1504.00711



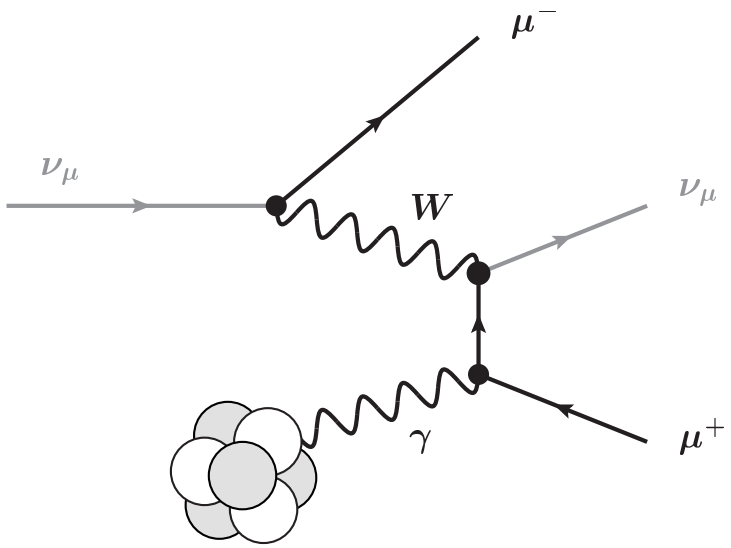
Neutrino Tridents

The Z' contributes to trident production

effect has some dependence on the neutrino beam spectrum

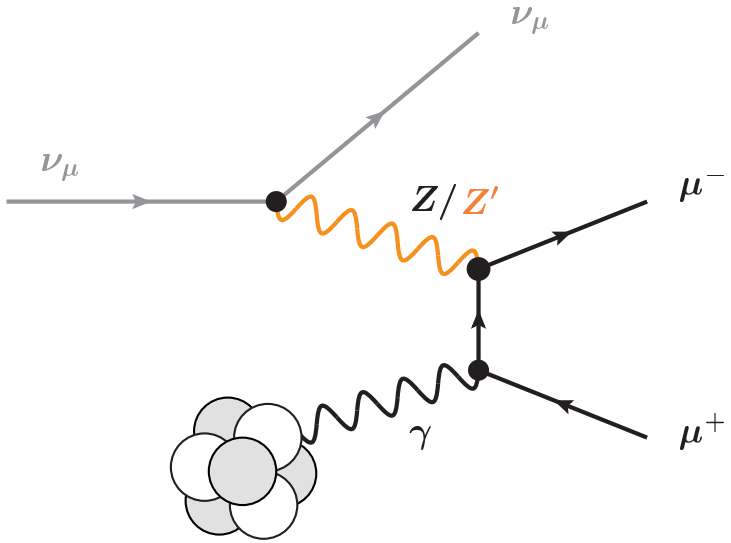
$$\frac{\sigma^{\text{CCFR}}}{\sigma^{\text{CCFR}}_{\text{SM}}} \simeq \frac{1.13 + \left(1 + 4s_W^2 + \frac{2v^2(g')^2}{M_{Z'}^2}\right)^2}{1.13 + (1 + 4s_W^2)^2}$$

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



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

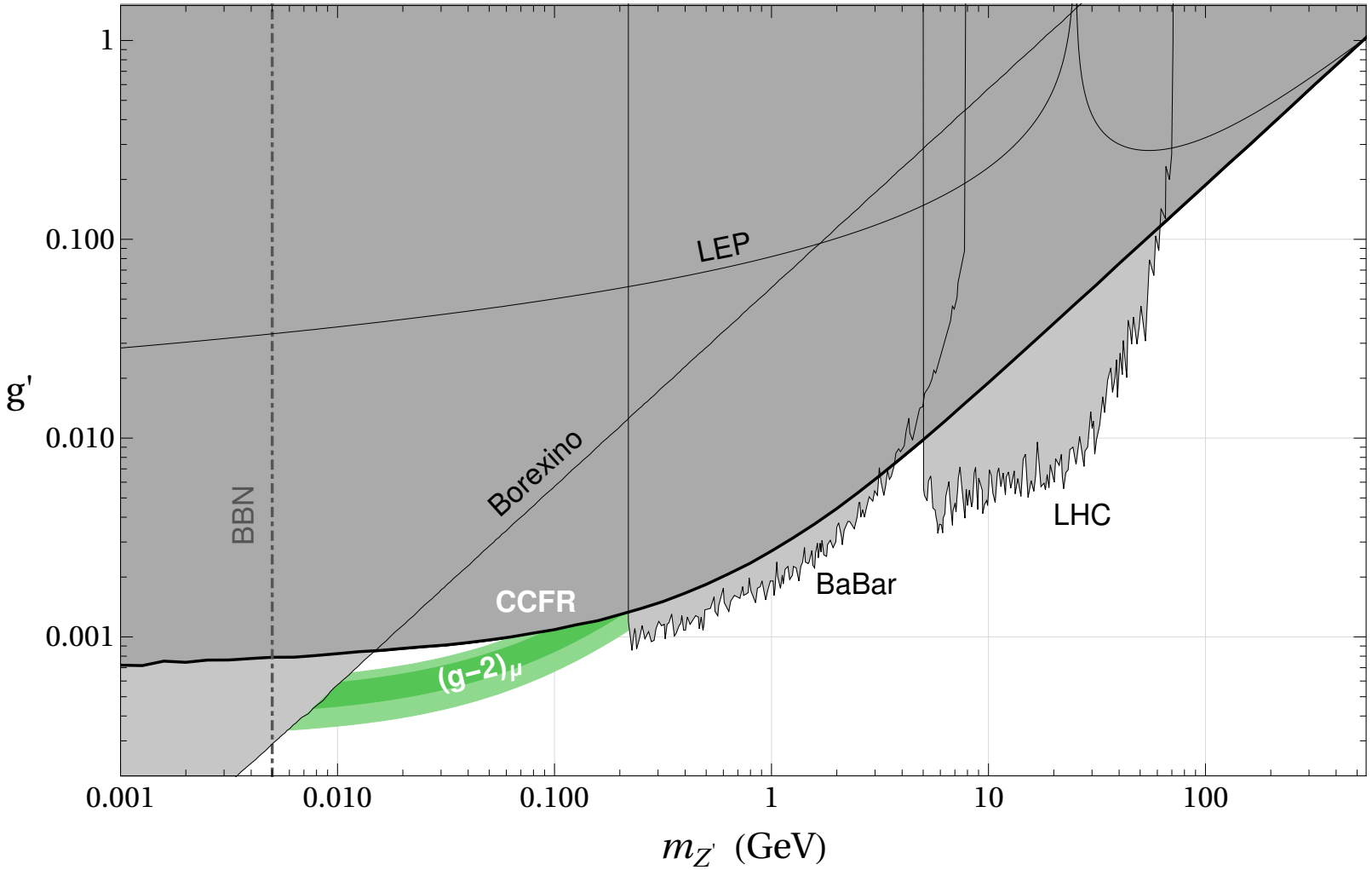
(for Z' masses $\gtrsim$ few hundred MeV)



(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



Neutrino Tridents at DUNE

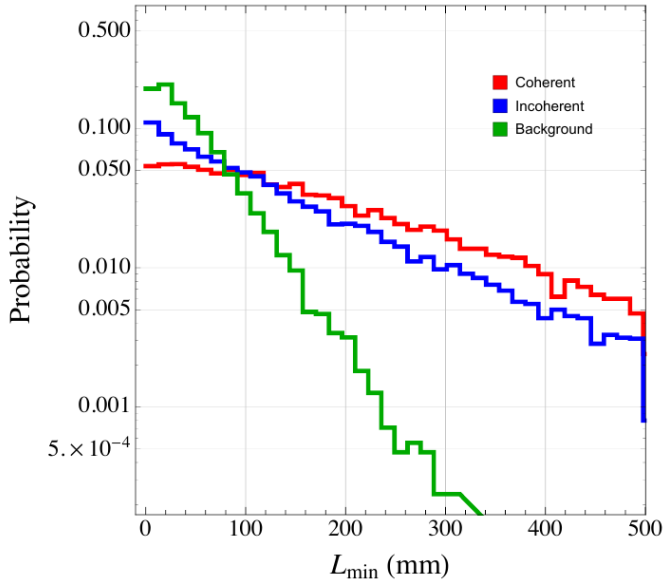
WA, Gori, Martin-Albo, Sousa, Wallbank 1902.06765

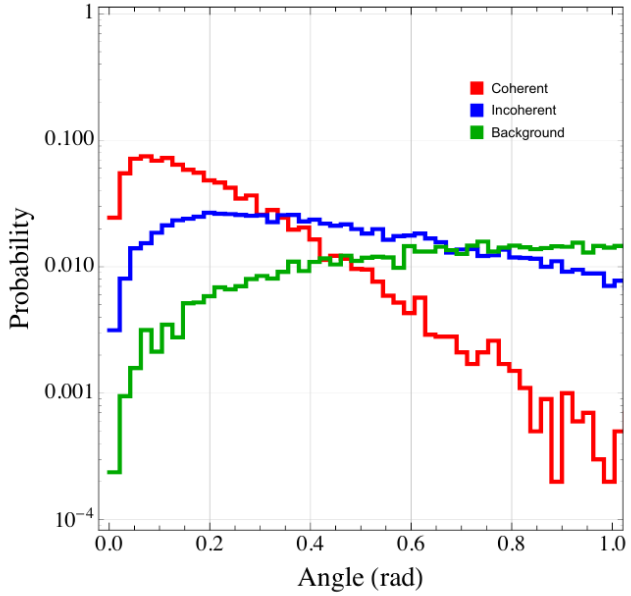
expect $\sim$ 700 $\nu_\mu \to \nu_\mu \mu^+ \mu^-$ trident events after 3 years in the DUNE near detector

main challenge:
huge background from $\nu_\mu N \to \mu^- N' \pi$

developed event selection based on simple kinematical cuts

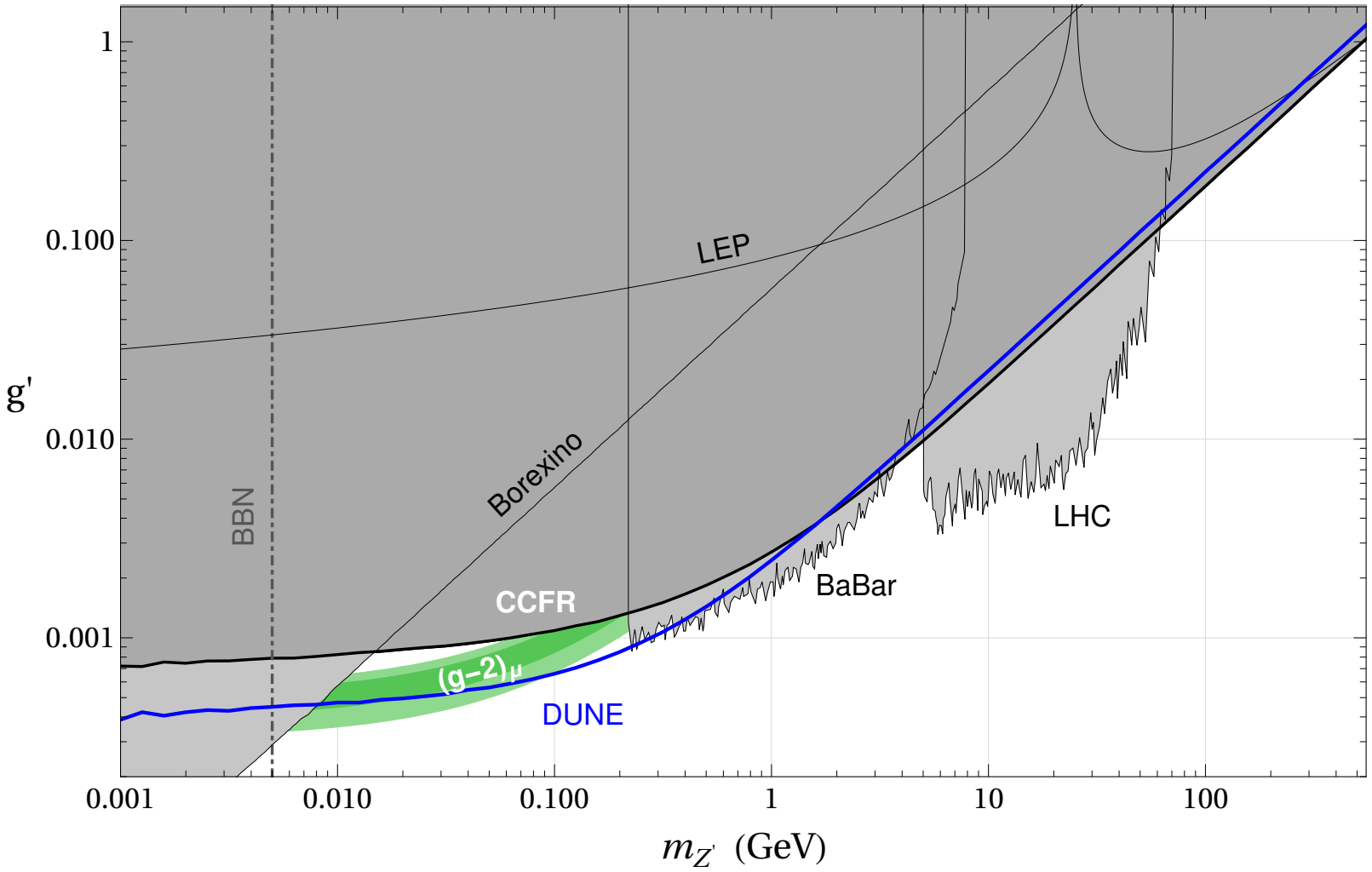
using only information from the LArTPC, we find that DUNE should be able to measure the trident cross section with at least $\sim$ 40% accuracy





Expected DUNE Sensitivity to $L_\mu - L_\tau$

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



Model Independent Sensitivity to New Physics

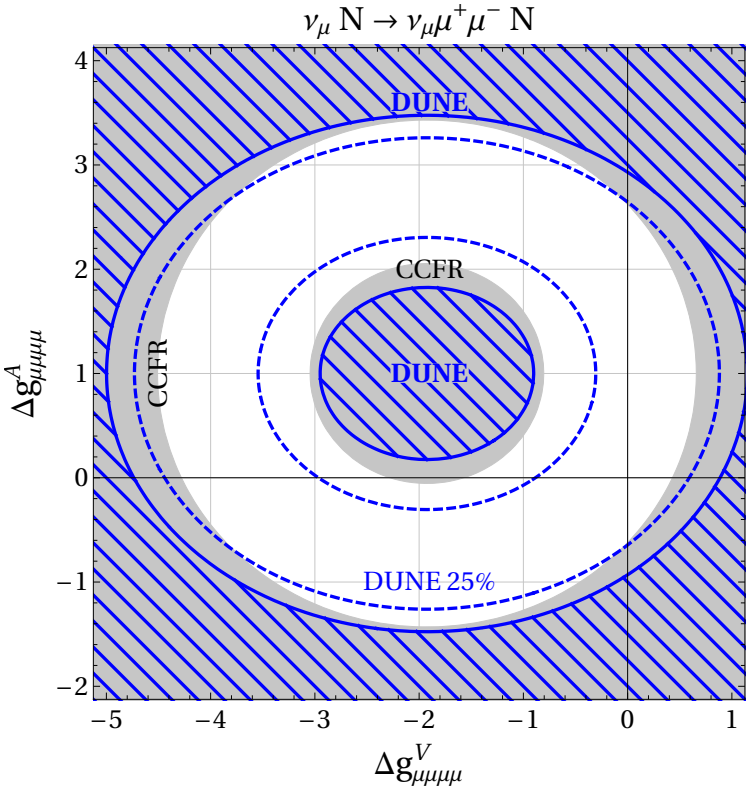
parameterize effects of heavy new physics model independently through four fermion contact interactions
(corresponds to NSI of muon neutrinos with muons)

$$\mathcal{H}_{\text{eff}}^{\text{SM}} = \frac{G_F}{\sqrt{2}}\Big(g^V_{\mu\mu\mu\mu}\,(\bar{\nu}_\mu \gamma_\alpha P_L \nu_\mu)(\bar{\mu}\gamma^\alpha \mu)$$

$$+ g^A_{\mu\mu\mu\mu}\,(\bar{\nu}_\mu \gamma_\alpha P_L \nu_\mu)(\bar{\mu}\gamma^\alpha \gamma_5 \mu)\Big)$$

$$g^V_{\mu\mu\mu\mu} = 1 + 4\sin^2\theta_W + \Delta g^V_{\mu\mu\mu\mu}$$

$$g^A_{\mu\mu\mu\mu} = -1 + \Delta g^A_{\mu\mu\mu\mu}$$



WA, Gori, Martin-Albo, Sousa, Wallbank

1902.06765

Summary

- Neutrino tridents have unique sensitivity to new muonic forces
- Existing measurements constrain Z' solutions of the $(g-2)_\mu$ anomaly, but still leave viable parameter space ($m_{Z'} \lesssim$ few hundred MeV)
- DUNE should be able to probe most of the remaining open parameter space