Probing New Physics with Neutrino Tridents

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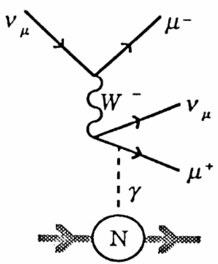
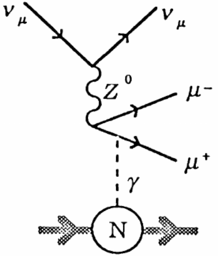
Neutrino Trident Production

production of a muon anti-muon pair
in the scattering of a muon neutrino
in the Coulomb field of a heavy nucleus

probes the electro-weak interactions
of 2nd generation leptons

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



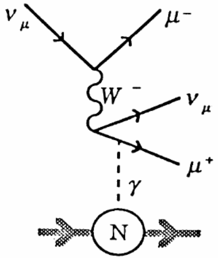


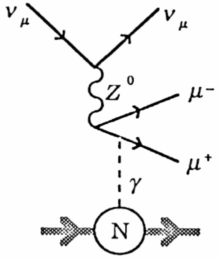
Standard Model Prediction

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

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

$$\sigma_{\text{trident}}^{\text{SM}} \sim \frac{1}{2}\left(|C_V|^2 + |C_A|^2\right) \frac{2G_F^2 \alpha s}{9\pi^2} \log\left(\frac{s}{m_\mu^2}\right)$$





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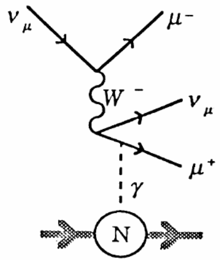
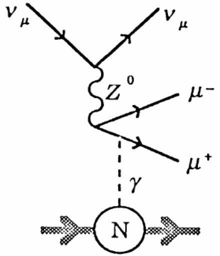
test the presence of SM neutral currents

$$\frac{\sigma_{\text{trident}}^{V-A}}{\sigma_{\text{trident}}^{\text{SM}}} \simeq \frac{8}{1+(1+4s_W^2)^2} \simeq 1.7$$

(Fujikawa, Phys. Rev. D 8, 1623 (1973);
Belusevic, Smith, Phys. Rev. D 37, 2419 (1988))





Existing Measurements

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

Phys.Lett. B245, 271 (1990)

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

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demonstration of the destructive W-Z
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Phys.Rev.Lett. 66, 3117 (1991)

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

Phys.Rev.D 61, 092001 (2000)

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

Neutrino Tridents and New Physics

New Forces for Muons

New forces with vector couplings to muons are motivated by the anomaly in the muon $g-2$

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

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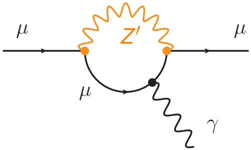
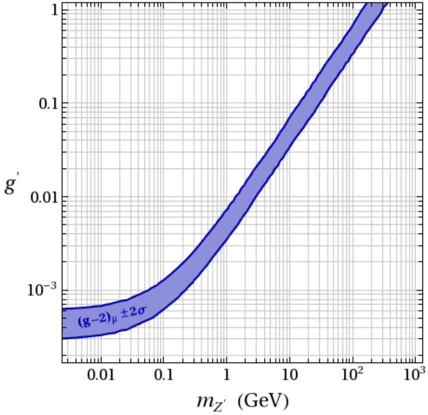
"benchmark" example:
Z' based on gauging $L_\mu - L_\tau$
(He, Joshi, Lew, Volkas '91)

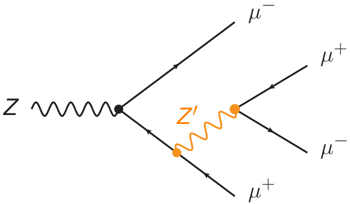


$$\Delta a_\mu \simeq \frac{(g')^2}{12\pi^2}\frac{m_\mu^2}{m_{Z'}^2} + \mathcal{O}\left(\frac{m_\mu^4}{m_{Z'}^4}\right)$$

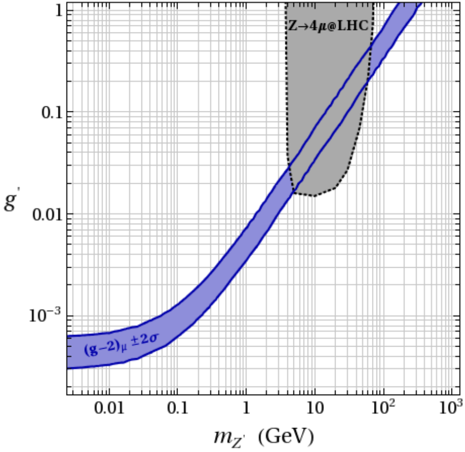


only relevant collider constraint

$Z \to 4\mu$ @LHC



BaBar/Belle/Belle 2 sensitivity for Z' masses around 1 GeV ?



(WA, Gori, Pospelov, Yavin, Phys.Rev.Lett. 113 (2014) 091801)

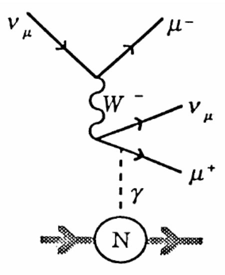
Muonic Forces and Neutrino Tridents

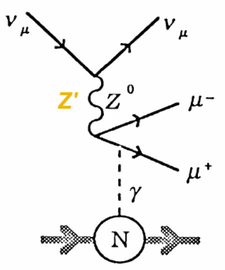
Z' bosons that couple vectorially to muons also couple to muon neutrinos

their contribution to neutrino trident production interferes constructively with the SM

for heavy enough Z':

$$\frac{\sigma}{\sigma_{\text{SM}}} \simeq \frac{1 + (1 + 4s_W^2 + 2(g')^2 v^2/m_{Z'}^2)^2}{1 + (1 + 4s_W^2)^2}$$





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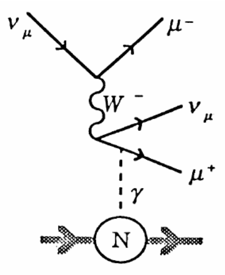
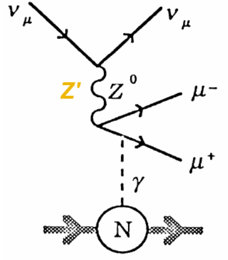
$(g-2)_\mu$ anomaly requires Z' with electro-weak scale coupling

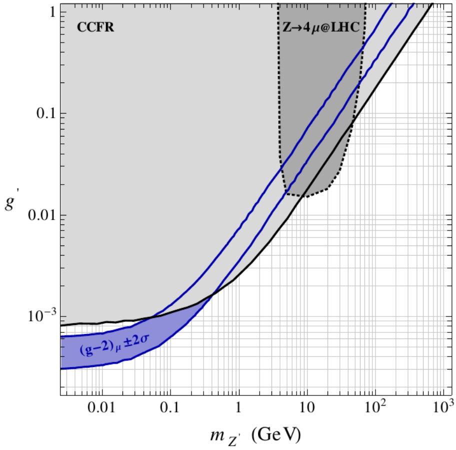
neutrino tridents probe Z' with electro-weak scale coupling





Current Trident Limit

(WA, Gori, Pospelov, Yavin, Phys.Rev.Lett. 113 (2014) 091801)

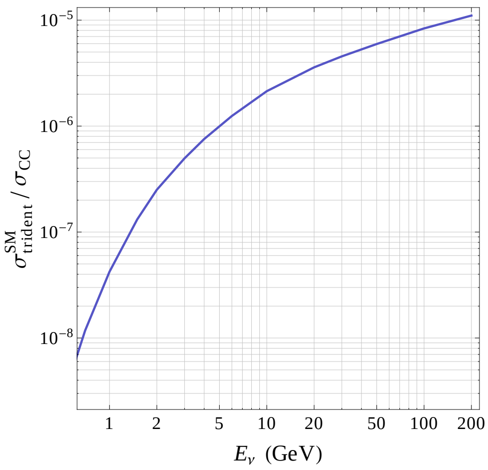


Z' based on $L_\mu - L_\tau$ can explain $(g-2)_\mu$
only if it is very light ($m_{Z'} \lesssim$ 400 MeV)

What is the Sensitivity of
Current and Future Neutrino Facilities
to the Trident Process?

The Challenge

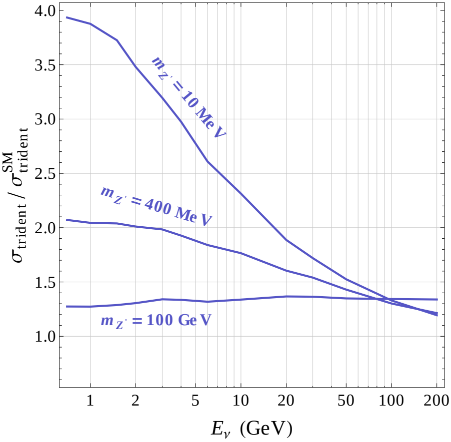
(plot for Argon target; cross-section ratio scales approximately as Z^2/A)



the trident cross section drops fast with the energy of the neutrino beam

for neutrino energy of few GeV need a detector that collects several $\times 10^7$ CC events to get a meaningful number of trident events

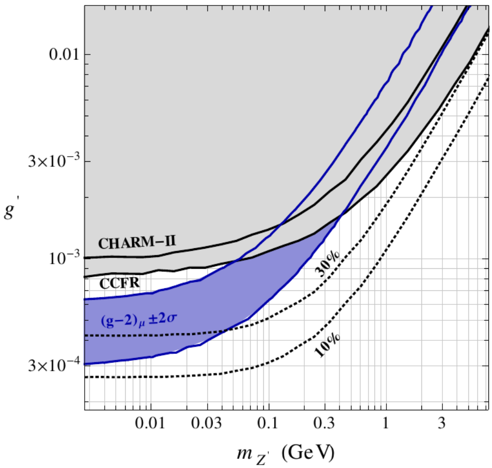
The Opportunity



very light Z' could increase the trident signal by a factor of few
(without being excluded by previous measurements)

The Opportunity

(WA, Gori, Pospelov, Yavin, Phys.Rev.Lett. 113 (2014) 091801)



CCFR

$\sim$ 160 GeV neutrinos on Iron

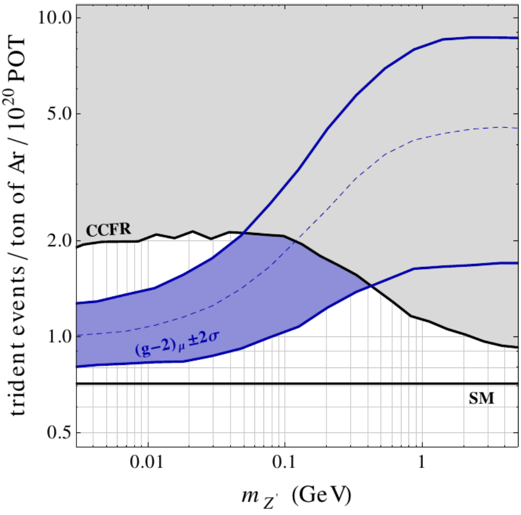
....

5 GeV neutrinos on Argon

a neutrino beam with lower energy allows to extend the reach to lower Z' masses

Expected Number of Events

(WA, Gori, Pospelov, Yavin, Phys.Rev.Lett. 113 (2014) 091801)



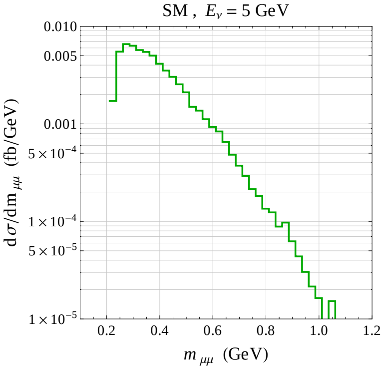
5 GeV neutrinos on Argon

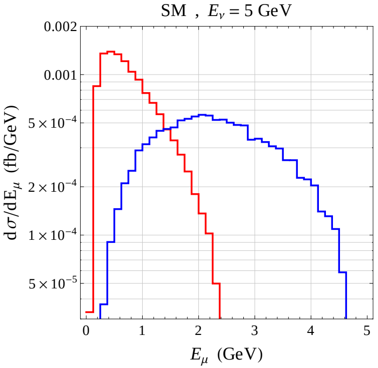
assumed number of neutrino CC events:

$\sim 236K/\mathrm{ton}/10^{20}\,\mathrm{POT}$

(LBNE CDR)

Muon Energy Spectrum





what are the experimental efficiencies?

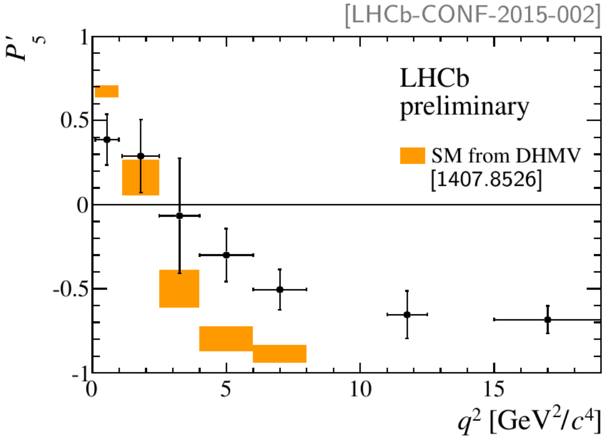
what about backgrounds? $\pi^+\pi^-$ misidentification? diffractive charm?

Summary

- Neutrino trident production has unique sensitivity to new muonic forces
- Existing measurements exclude a Z' coupled vectorially to muons as a solution of the $(g-2)_\mu$ anomaly, unless the Z' is very light ($m_{Z'} \lesssim 400$ GeV)
- Future neutrino experiments might be able to probe remaining open parameter space

Back Up

Anomalies in $B \to K^* \mu^+ \mu^-$



Z' based on gauged $L_\mu - L_\tau$ can also explain certain B physics anomalies

(WA, Gori, Pospelov, Yavin, Phys.Rev. D89 (2014) 095033)