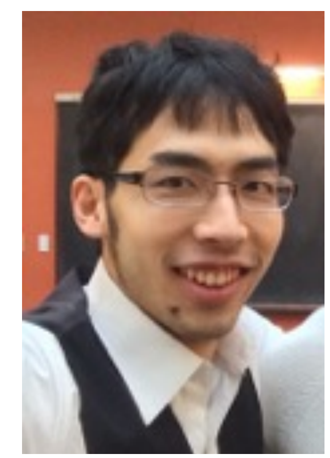
Rare Physics at the Intensity Frontier

4th PIKIO Meeting, University of Kentucky

In collaboration with

Maxim Pospelov Ryan Plestid Yu-Dai Tsai



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2017/09/16

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Rare Physics

Neutrino physics driven by oscillations and search for eV sterile neutrino

A lot of money invested in new generation experiments

With planned technology, what else can neutrino beam dump experiments look for?

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Rare Physics

#1 Neutrino Trident

#2 Neutrino Dipole Moments

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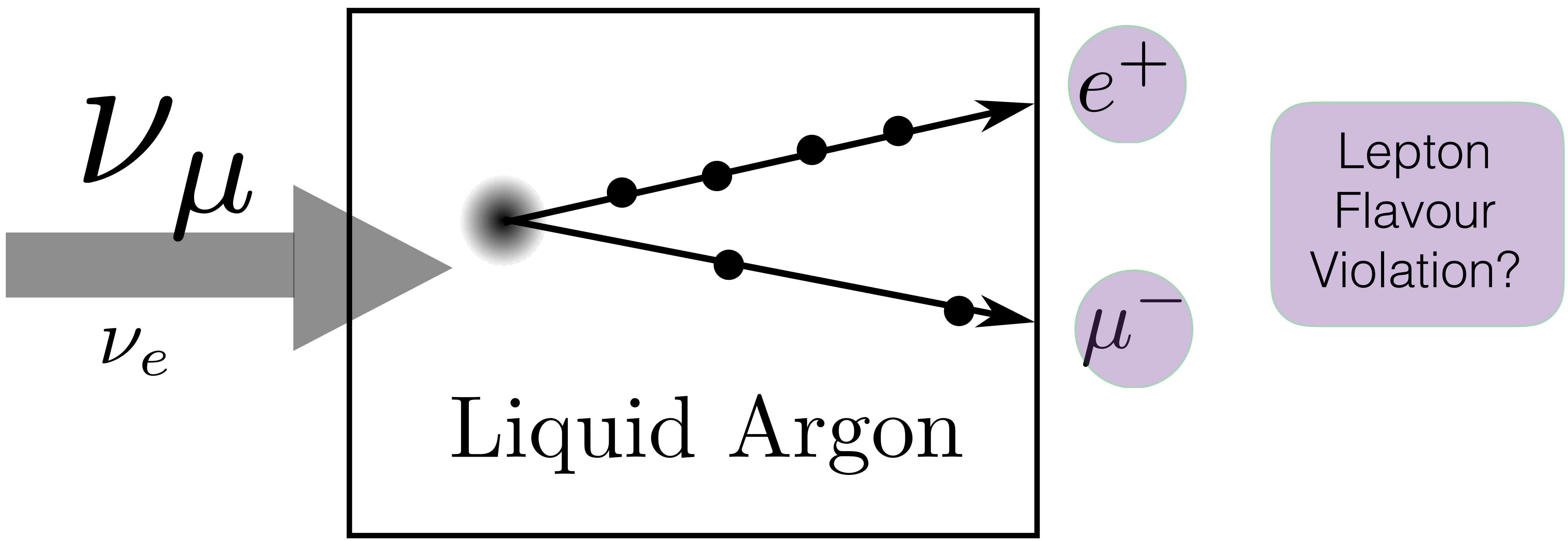
Neutrino Trident



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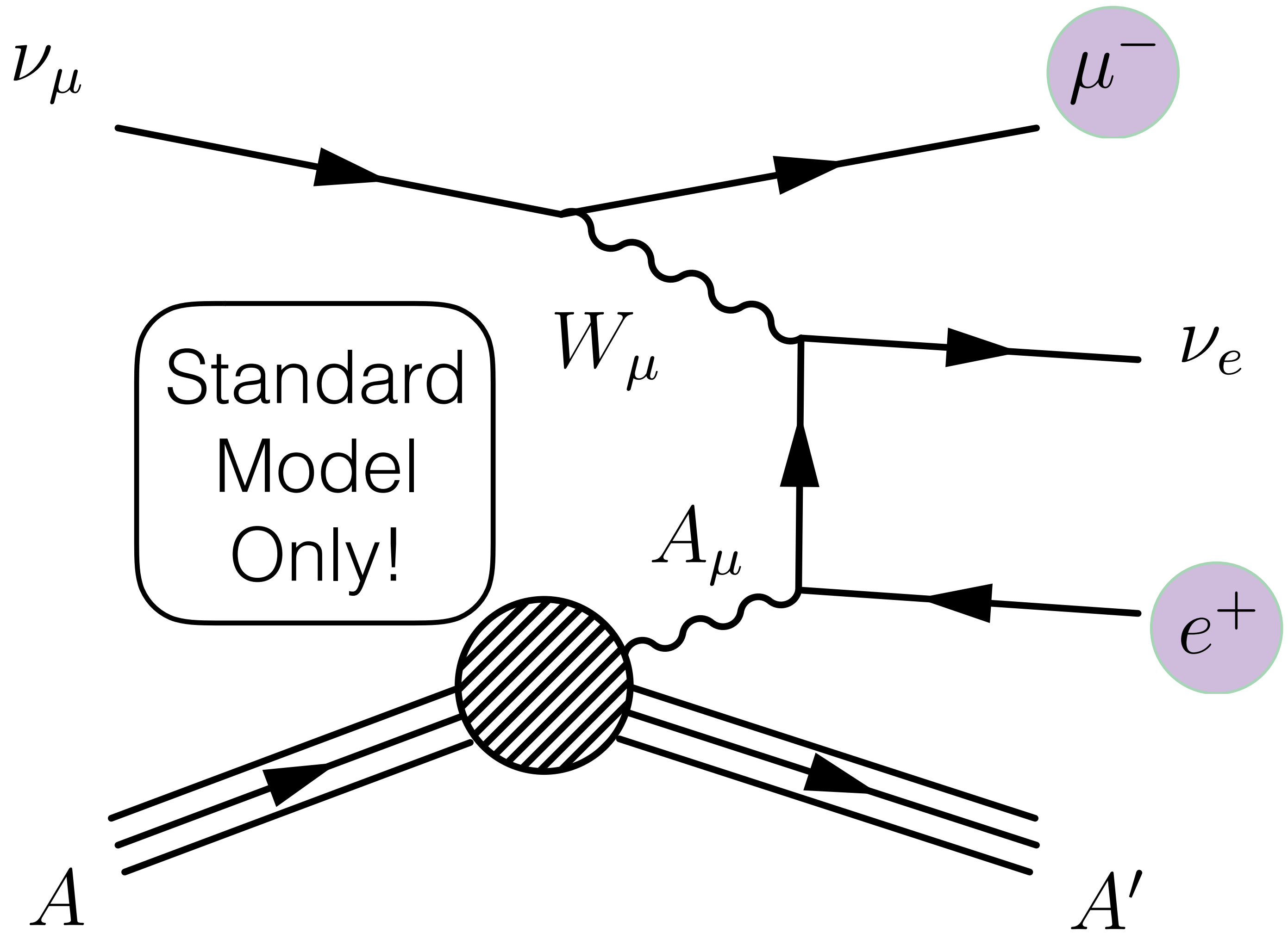
Neutrino Trident Standard Model



Can have any combination of $e^\pm, \mu^\pm, \tau^\pm$
Important BSM background!

Process dependent

Rare Process

$$\sigma_{\nu A} \approx \frac{1}{2}(C_V^2 + C_A^2)\frac{2\ Z^2\alpha^2\ G_F^2}{9\pi^3} s_{\max} \log\left(\frac{s_{\max}}{(m_i+m_j)^2}\right)$$

$$\approx 10^{-45}\text{cm}^2 Z^2 \left(\frac{E_\nu}{\text{GeV}}\right) \approx 10^{-5}\sigma_{\text{CC}}$$

Belusevic and Smith, PRD (1988)

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Neutrino Trident Standard Model

Has trident ever been measured?

Yes! For μ^-, μ^+

CCFR (Fermilab)	CHARM-II (CERN)	NuTeV (Fermilab)
$\frac{\sigma_{\rm CCFR}}{\sigma_{\rm SM}} = 0.82 \pm 0.28$	$\frac{\sigma_{\rm CHARM\text{-}II}}{\sigma_{\rm SM}} = 1.58 \pm 0.57$	$\frac{\sigma_{\rm NuTeV}}{\sigma_{\rm SM}} = 0.67 \pm 0.27$
CCFR Collaboration, PRL (1991)	CHARM-II Collaboration, Phys.Lett.B (1990)	NuTeV Collaboration, PRD (2000)

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Neutrino Trident Standard Model

What about mixed flavours?

Not yet, however . . .

DUNE
(Fermilab)

SHiP
(CERN)

SBND
(Fermilab)

. . . should be capable!

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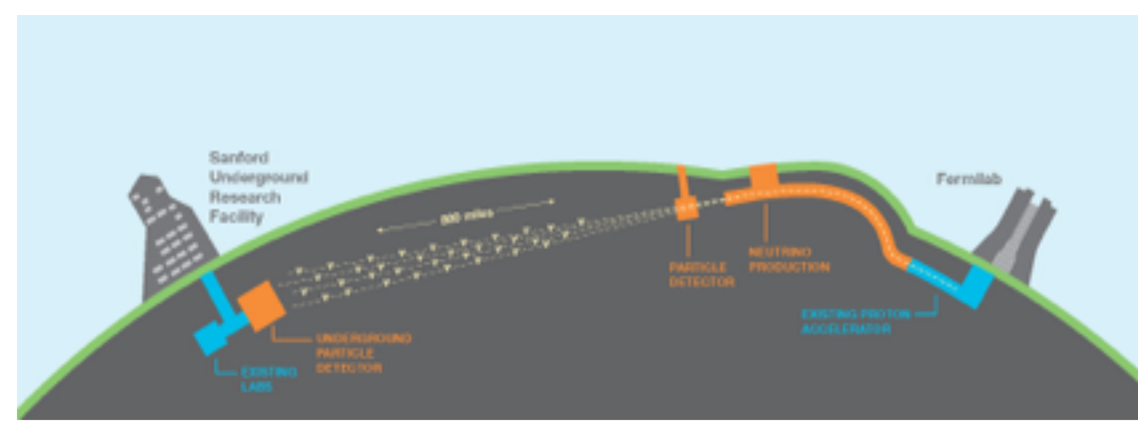
Neutrino Trident **Standard Model**

arXiv:1612.05642, PRD 2017 (GM, Plestid)

Neutrino Beam			Anti-Neutrino Beam		
Process	Coh	Diff	Process	Coh	Diff
$\nu_\mu \to \nu_e e^+ \mu^-$	73.98	53.15	$\bar{\nu}_\mu \to \bar{\nu}_e e^- \mu^+$	25.23	18.7
$\nu_\mu \to \nu_\mu e^+ e^-$	23.03	9.64	$\bar{\nu}_\mu \to \bar{\nu}_\mu e^+ e^-$	16.45	6.79
$\nu_\mu \to \nu_\mu \mu^+ \mu^-$	2.03	5.28	$\bar{\nu}_\mu \to \bar{\nu}_\mu \mu^+ \mu^-$	2.16	4.3
$\nu_e \to \nu_e e^+ e^-$	0.7	0.29	$\bar{\nu}_e \to \bar{\nu}_e e^+ e^-$	0.54	0.22
$\nu_e \to \nu_\mu \mu^+ e^-$	0.21	0.17	$\bar{\nu}_e \to \bar{\nu}_\mu \mu^- e^+$	0.4	0.27
$\nu_e \to \nu_e \mu^+ \mu^-$	0.01	0.01	$\bar{\nu}_e \to \bar{\nu}_e \mu^+ \mu^-$	0.	0.01
Total	99.96	68.54		44.78	30.29

Mixed flavour states can see large enhancements.
As much as 35x bigger!

Rates for DUNE



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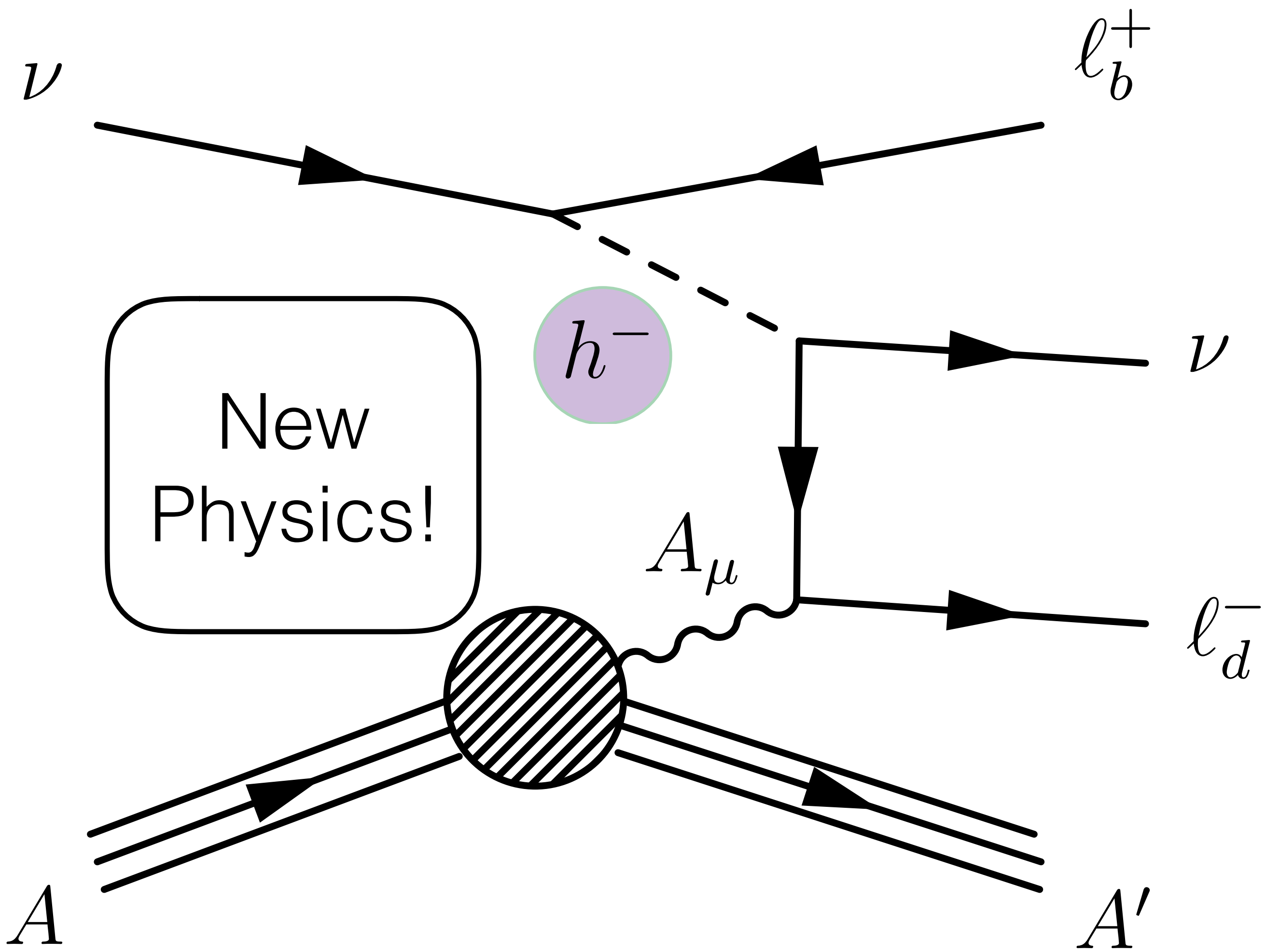
Neutrino Trident

New Physics



New Charged Scalar

Potential UV Realizations

$$\mathcal{L}_{\text{Zee-Babu}} \supset f^{ab} L_a L_b \mathcal{F} + s^{ab} \ell_a \ell_b \mathcal{S}$$

$$\mathcal{L}_{\text{Higgs Triplet}} \supset t^{ab} L_a \mathcal{T} L_b$$

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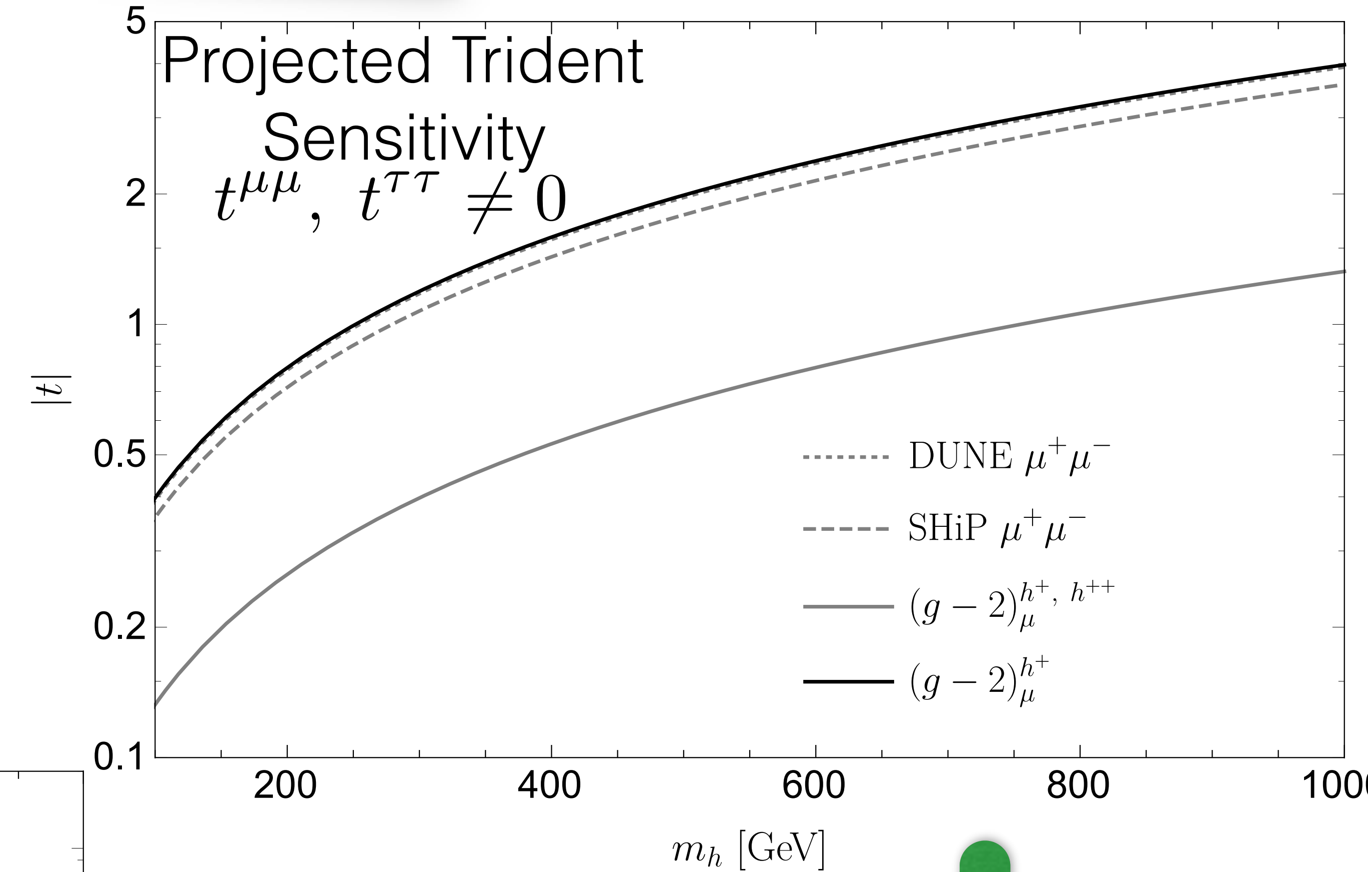
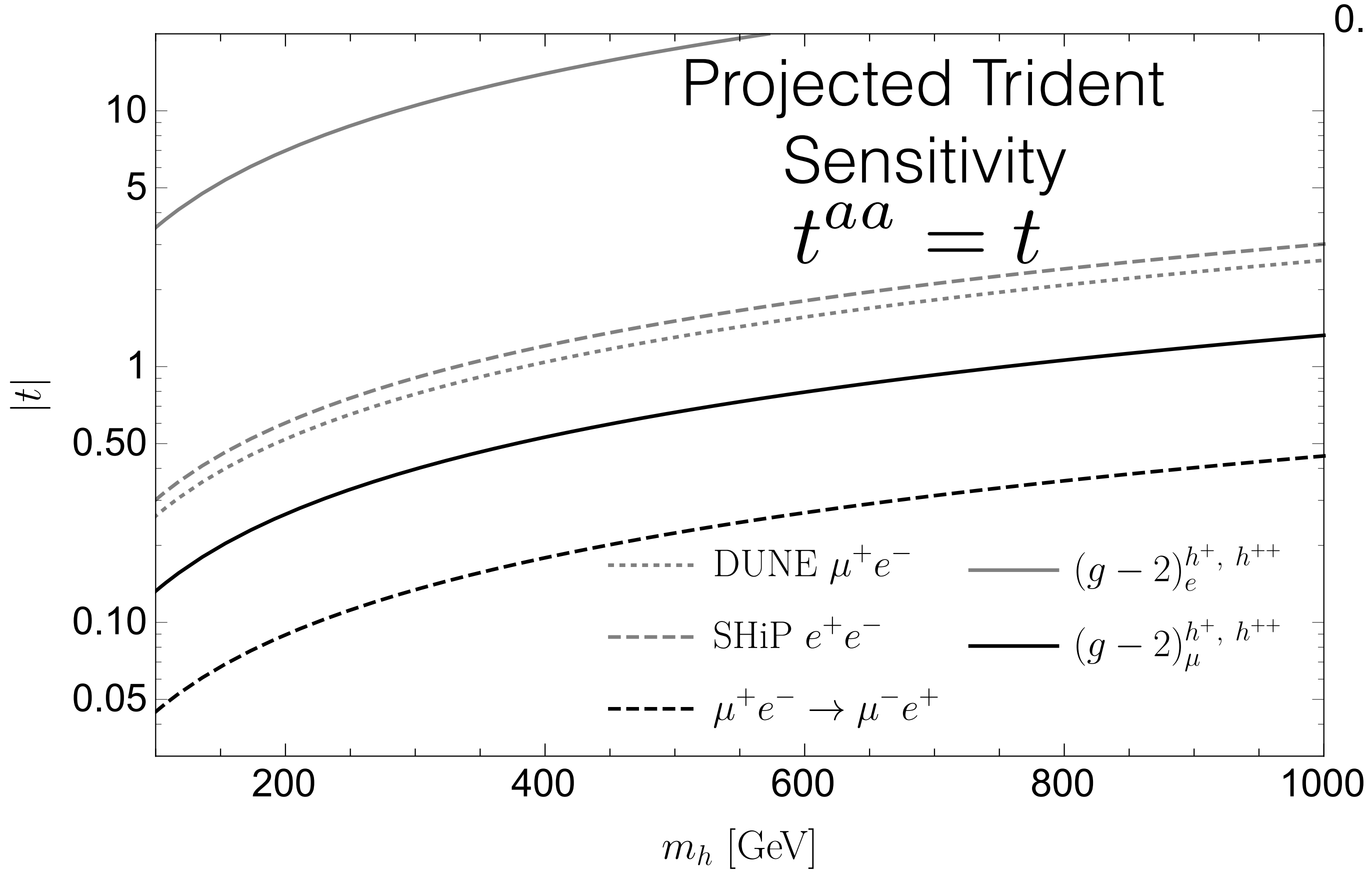
Neutrino Trident

New Physics

Higgs Triplet $\mathcal{L} \supset t^{ab} L_a \mathcal{T} L_b$
$\mathcal{T}$ contains scalars of electric charge 0, 1 and 2

In preparation (GM, Ryan Plestid)





Trident becomes competitive against lepton flavour violation, magnetic moment, charged current universality for $t^{\mu\mu},\ t^{\tau\tau} \neq 0$

Trident targets only h^+

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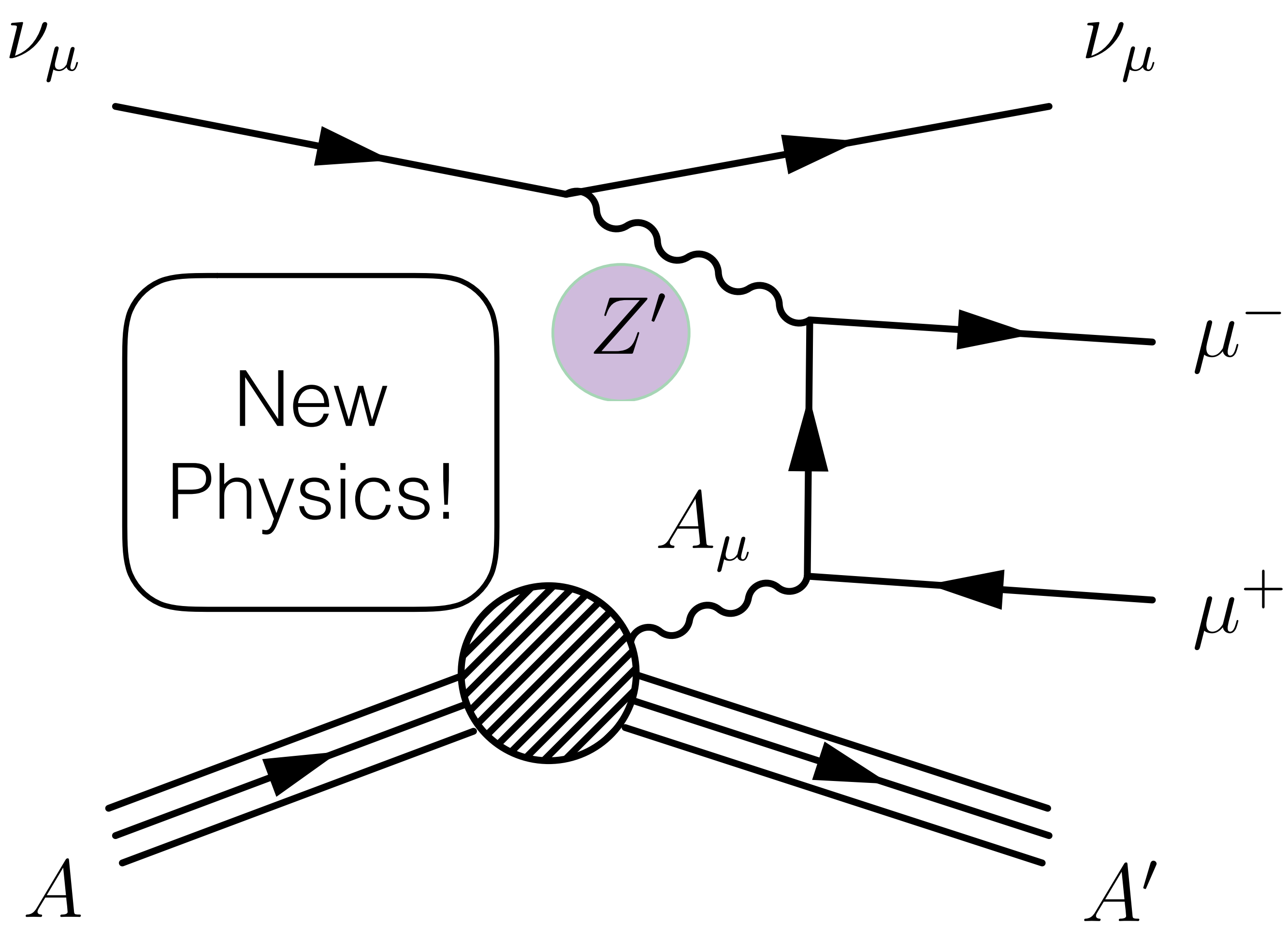
Neutrino Trident

New Physics



New Vector Boson

Potential UV Realization

$$\mathcal{L}_{L_\mu - L_\tau} \supset g' Z'^{\alpha}\left(\bar{\mu}\gamma_\alpha\mu - \bar{\tau}\gamma_\alpha\tau + \bar{\nu}_\mu\gamma_\alpha\nu_\mu - \bar{\nu}_\tau\gamma_\alpha\nu_\tau\right)$$

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Neutrino Trident

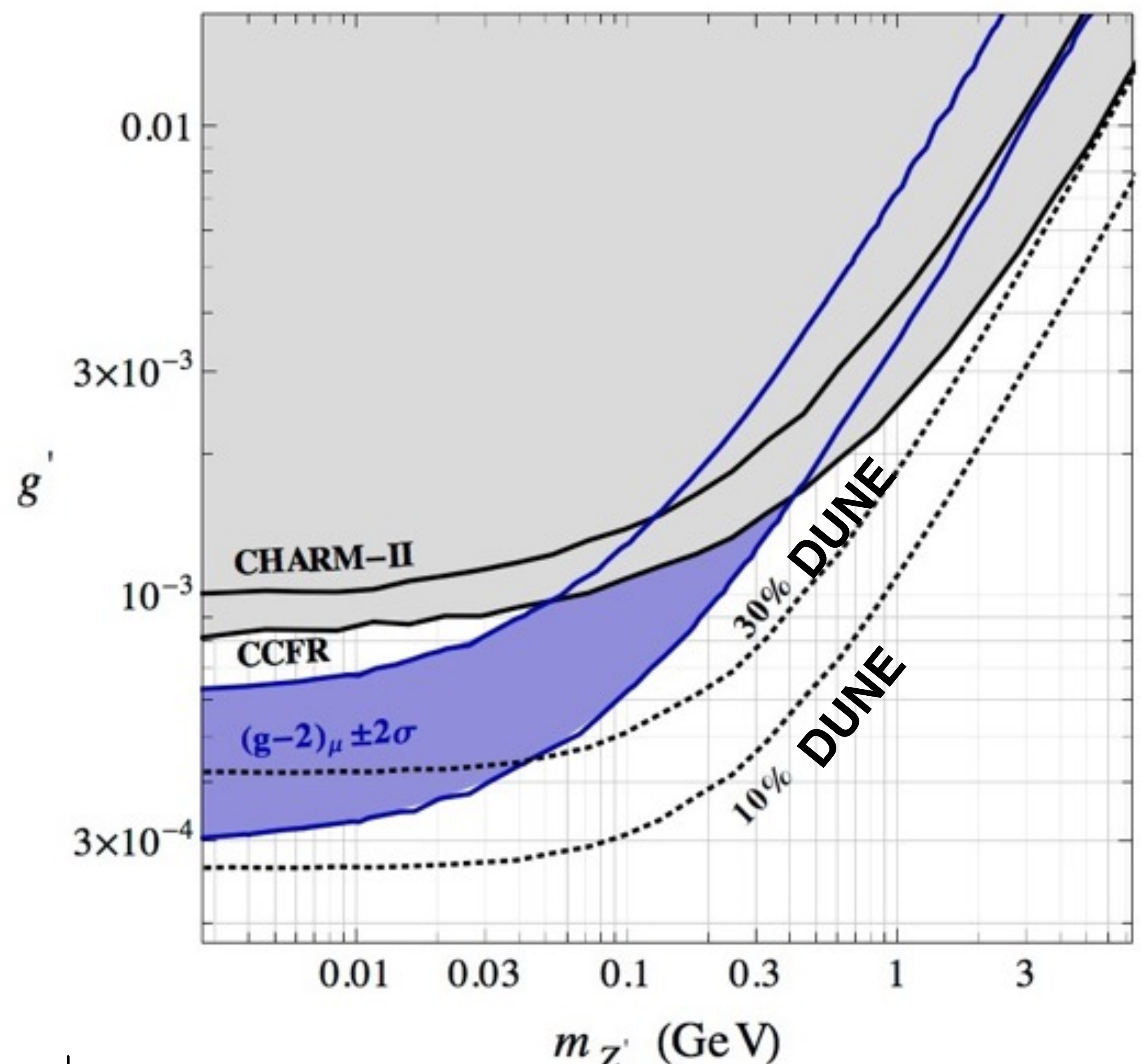
New Physics

$\mu^-\mu^+$ channel provides best constraints on hidden Z' gauged under $L_\mu - L_\tau$

Upcoming experiments to target parameter space favoured by

$$(g-2)_\mu$$

arXiv:1406.2332, PRL 2014
(Altmannshofer, Gori, Pospelov, Yavin)



With a little model building, can couple Z' to light quarks:
Provides explanation to $B \to K^* \mu^+ \mu^-$

arXiv:1403.1269, PRD 2014
(Altmannshofer, Gori, Pospelov, Yavin))

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Rare Physics

#1 Neutrino Trident

#2 Neutrino Dipole Moments

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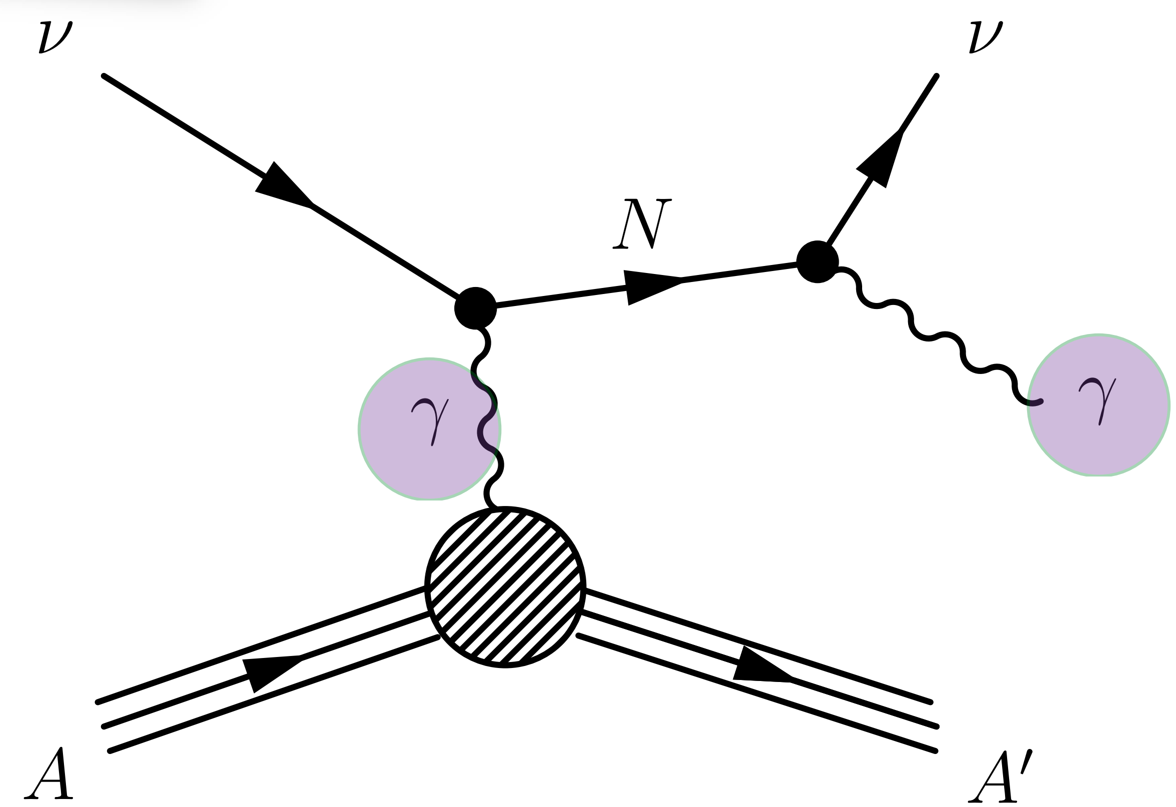
ν Dipole Portal

Follow up:

~ Considered Dirac heavy neutral lepton
~ Mix with SM via magnetic dipole moment

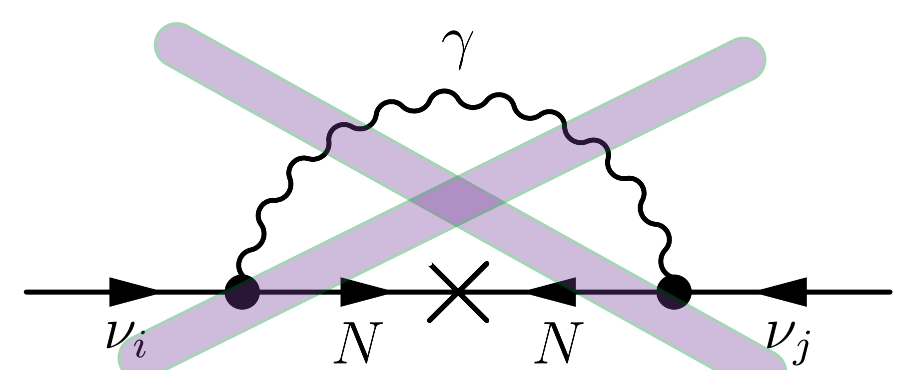
~ *Exotic* resolution to MiniBooNE low energy oscillation anomaly
~ Fairly low dimension operator and quite minimalistic: should be studied
~ Implement analysis via collected data of future neutrino experiments



$$\mathcal{L}_{dim\ 5} \supset d_a \overline{\nu_L}_a \sigma_{\mu\nu} F^{\mu\nu} N - m\bar{N}N$$

$$\mathcal{L}_{dim\ 6} \supset \bar{L}\left(\bar{d}_W W^a_{\mu\nu}\tau^a + \bar{d}_B B_{\mu\nu}\right)\tilde{H}\sigma_{\mu\nu}N_D$$

Won't be detectable in neutrino textures!



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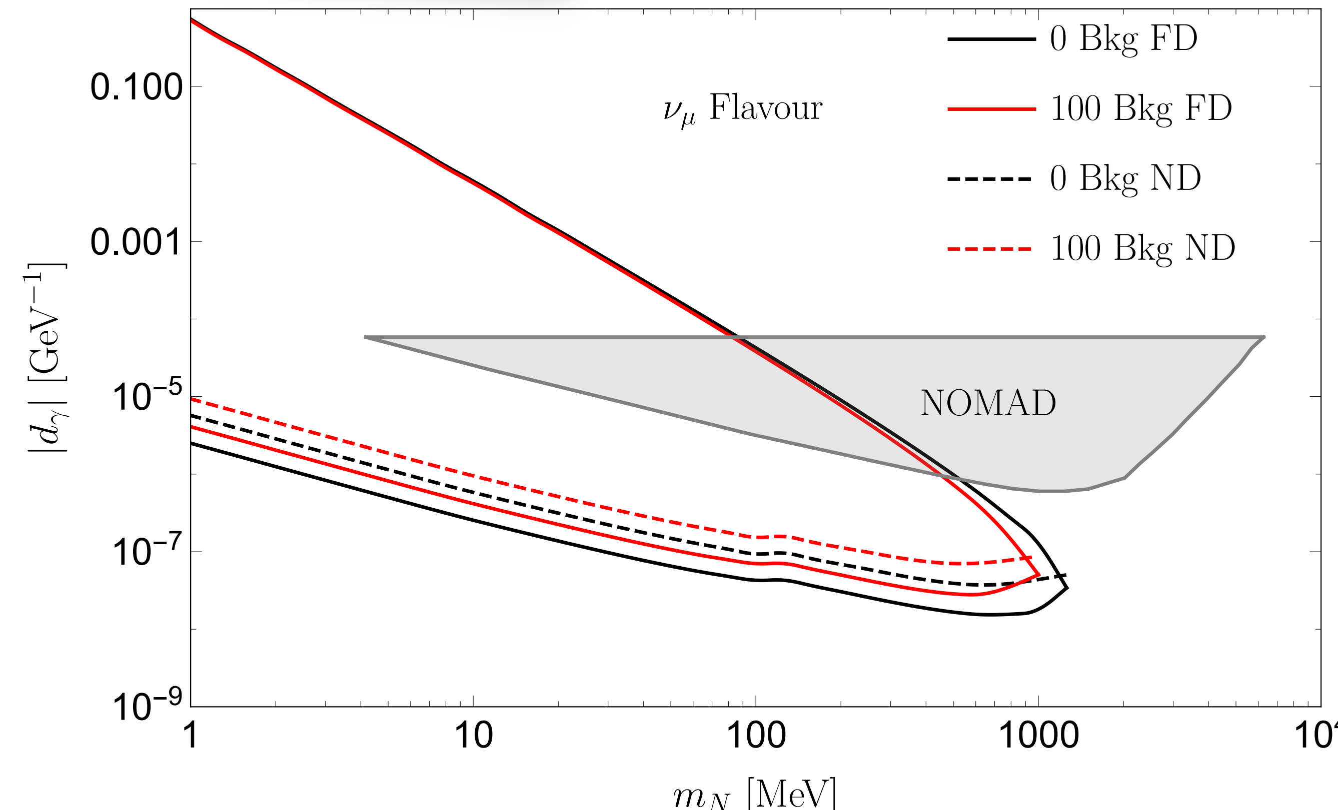
ν Dipole Portal

In preparation (GM, Ryan Plestid, Maxim Pospelov, Yu-Dai Tsai)

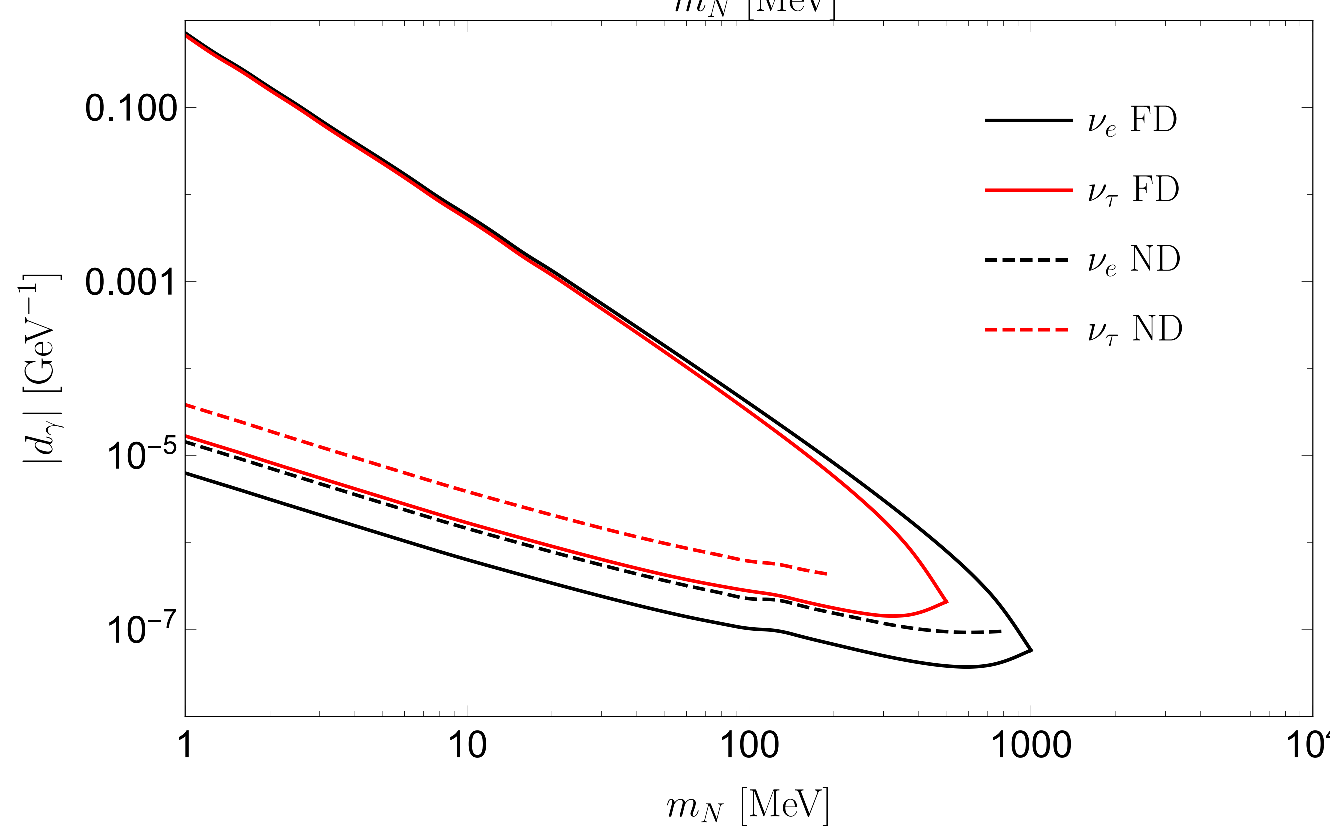
SHiP ν_μ

Limits at SHiP for muon dipole moments at the near and far detector, for various backgrounds. Also show existing NOMAD constraints.



SHiP ν_e, ν_τ

Limits at SHiP for electron and tau neutrino dipole moments, at the near and far detectors. We consider 10 background events.



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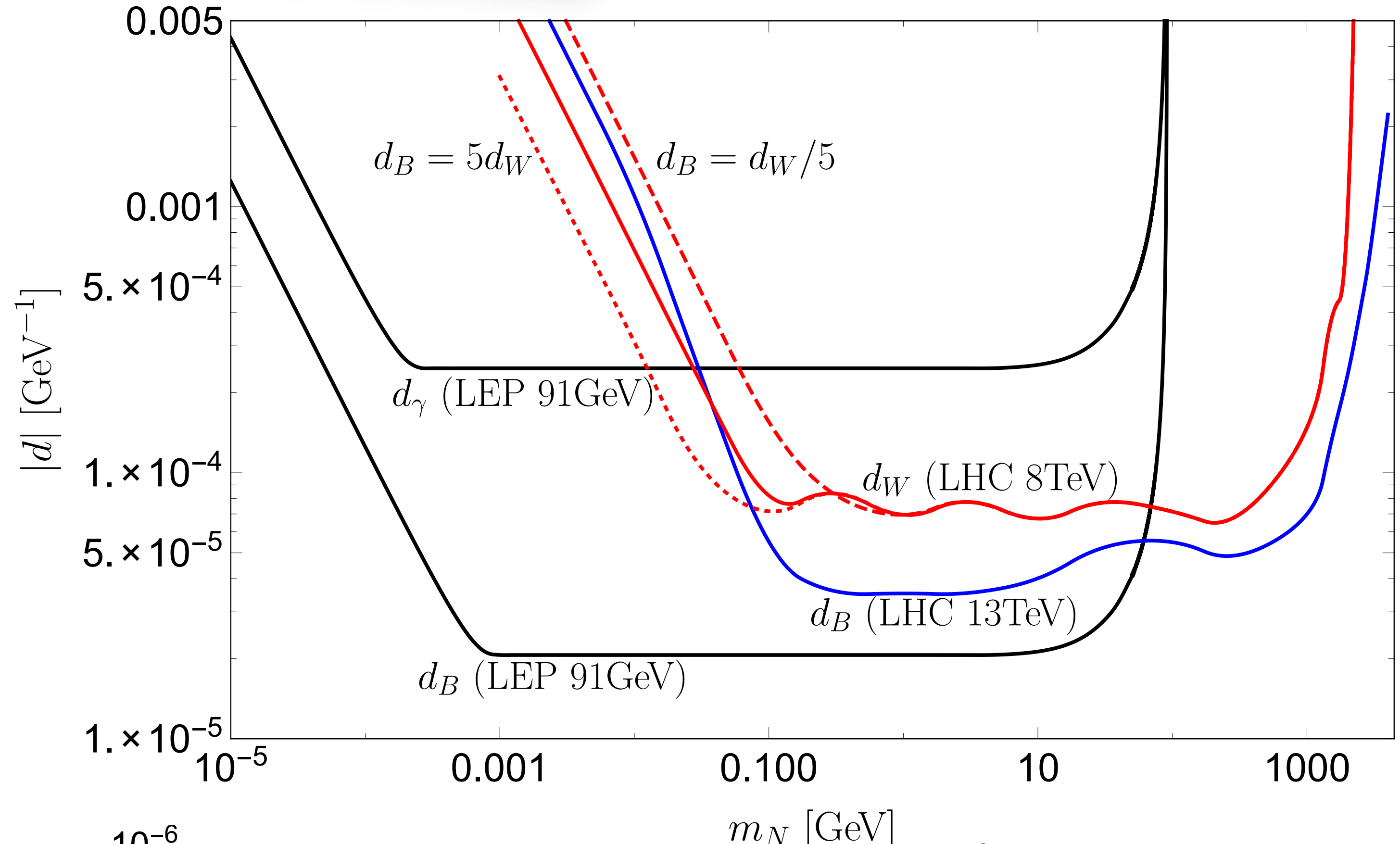
ν Dipole Portal

In preparation (GM, Ryan Plestid, Maxim Pospelov, Yu-Dai Tsai)

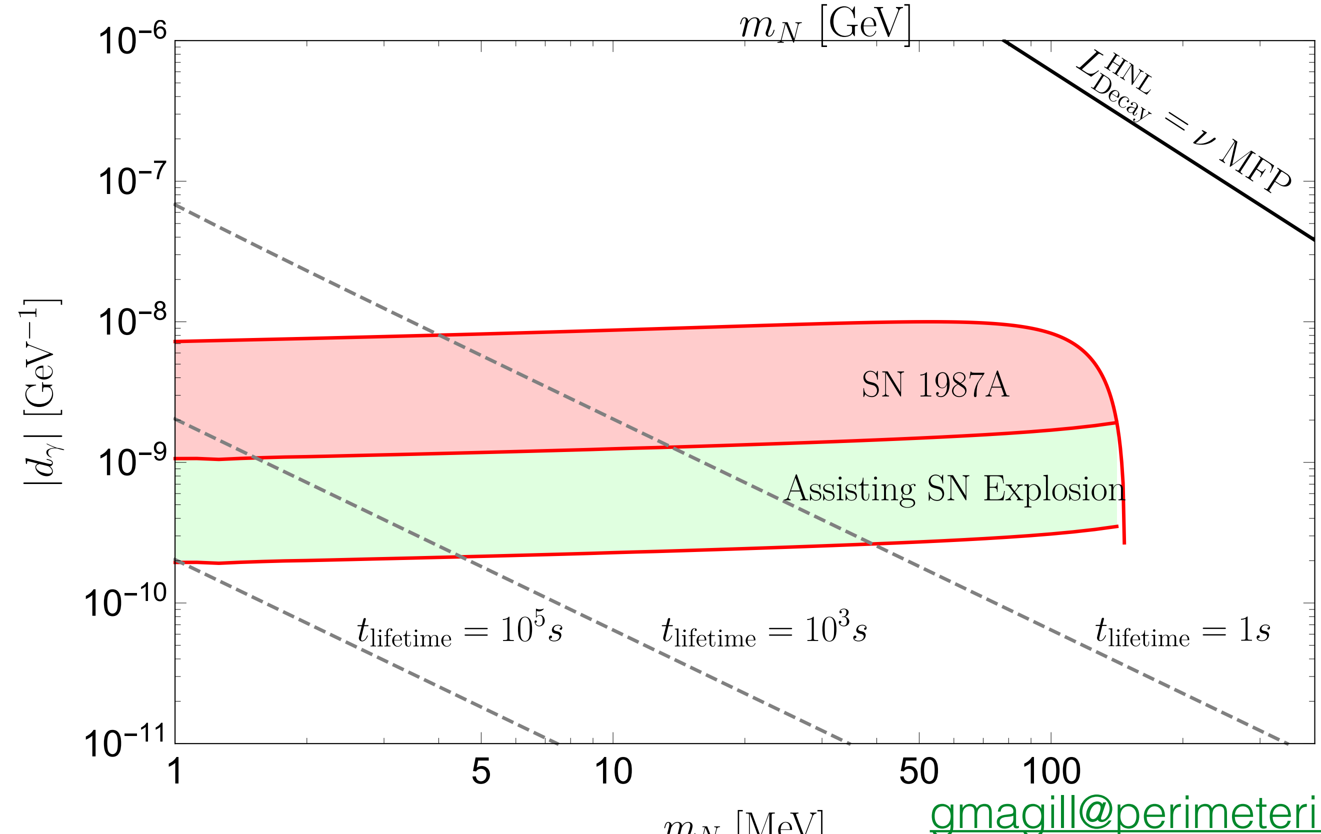
Colliders

95% CL sensitivities at LHC and LEP. Limits are shown for the dimension 5 (photon) and dimension 6 (photon + heavy bosons) extensions.



Astrophysics

Emissivity and optical depth constraints from SN1987A. Parameter space facilitating SN conversion to neutron star. Constant HNL lifetimes (for BBN).



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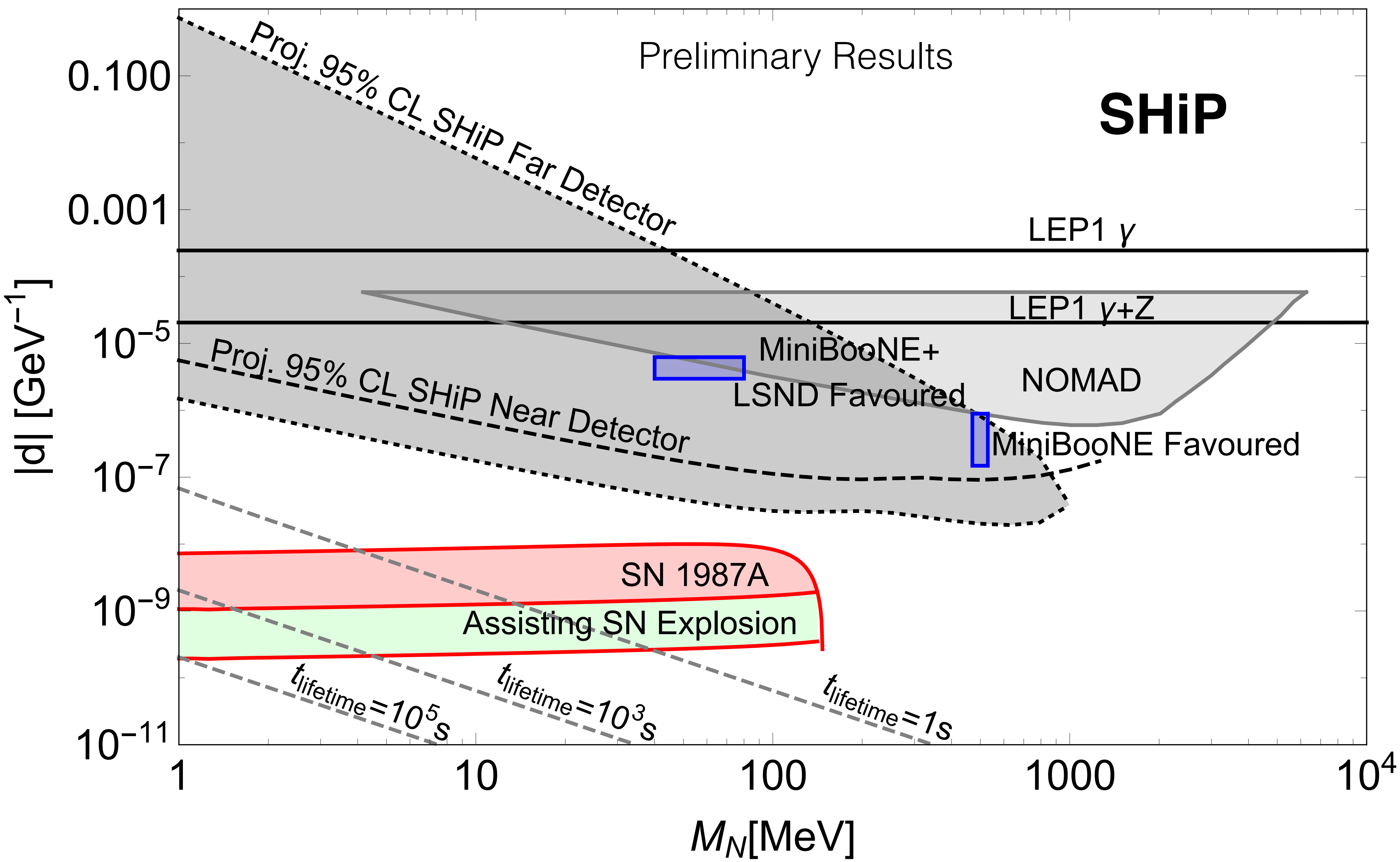
Neutrino Dipole

In preparation (GM, Ryan Plestid, Maxim Pospelov, Yu-Dai Tsai)

~ Produced at SHiP via Coherent, Diffractive, DIS, Meson Decay
~ ν_τ factory implies leading constraints on d_τ (see backup)
~ Requires dedicated study to single photon backgrounds!



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Conclusion

~ Very interesting SM and BSM physics at upcoming neutrino experiments: SBNB, SHiP, DUNE near detector

~ Experiments well suited to search for mixed flavour $\ell^+\ell^-$ and single photon signals

~ Neutrino trident production and neutrino dipole moments important in the search for new physics

This work is supported by NSERC CRSNG

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Backup Slides

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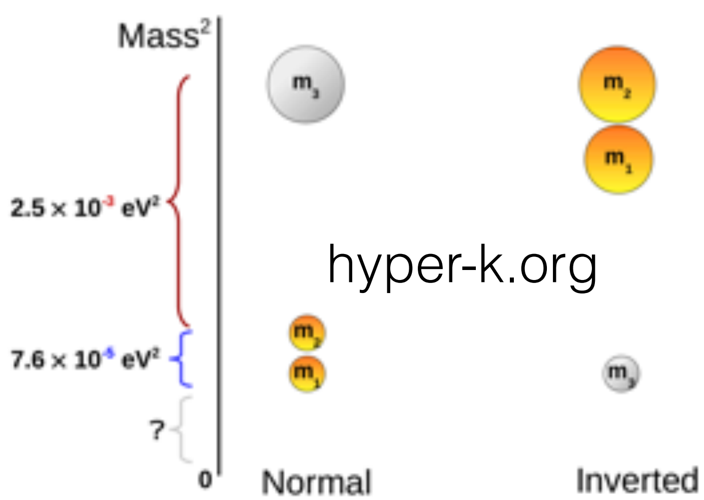
Motivation

Unanswered questions about neutrinos

They have mass
~ How is the mass generated?
~ Majorana or Dirac?
~ Mass hierarchy?



hyper-k.org

ν_τ DONUT: 9 candidates
OPERA: 4 from oscillations

$\overline{\nu}_\tau$ Never observed!

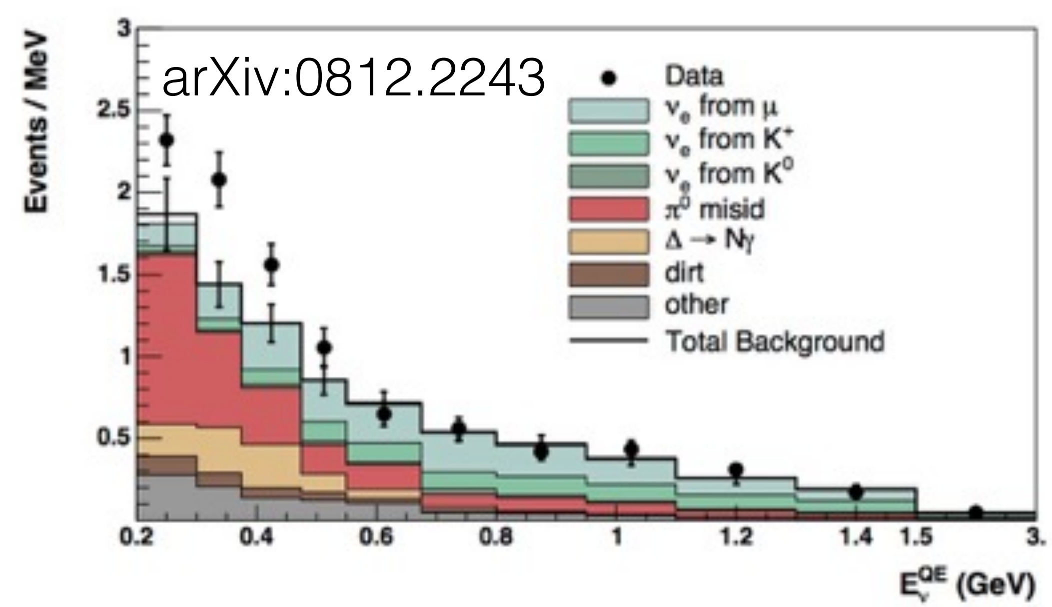
PMNS Matrix
~ CP Violating angle

$$\delta_{CP}^{NH}(\pm 1\sigma) = 202^\circ - 312^\circ$$

$$\delta_{CP}^{NH}(\pm 3\sigma) = 0^\circ - 360^\circ$$

nu-fit.org

Oscillation Anomalies
~ LSND; MiniBooNE:



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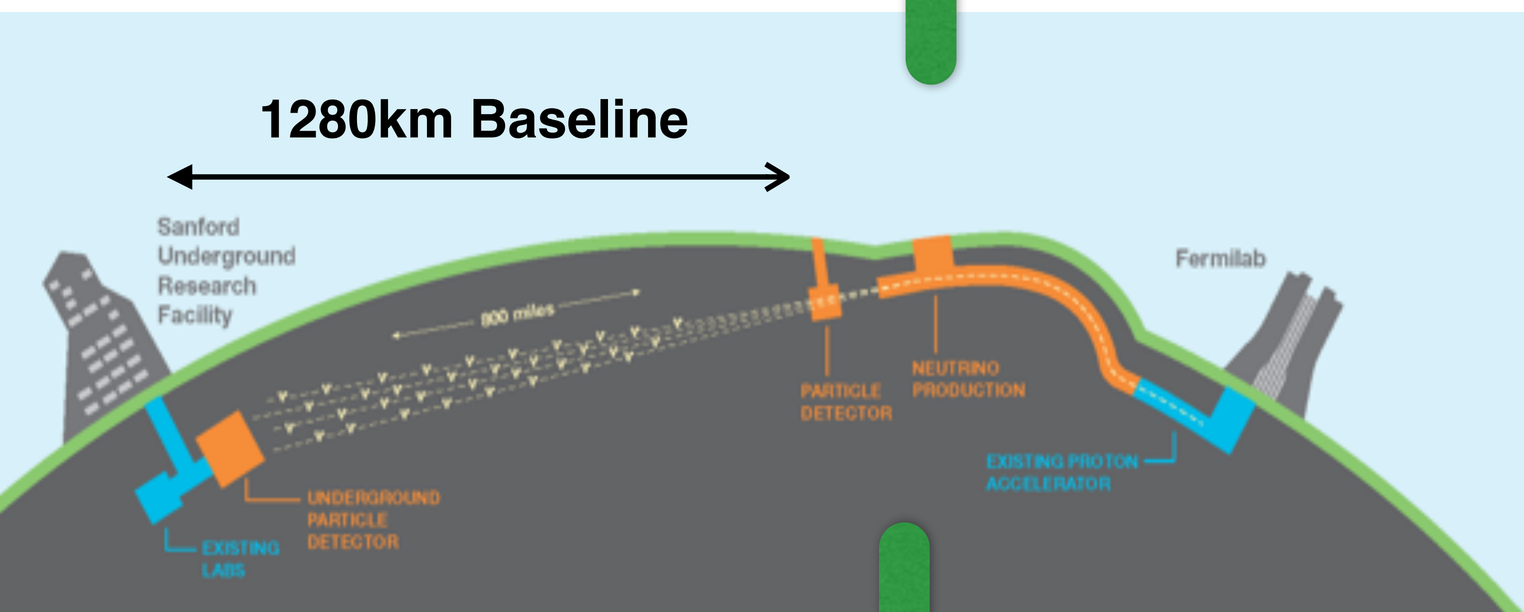
New Experiments

DUNE arXiv:1512.06148

$$\langle E_{\nu_\mu} \rangle = 3 \text{ GeV}$$

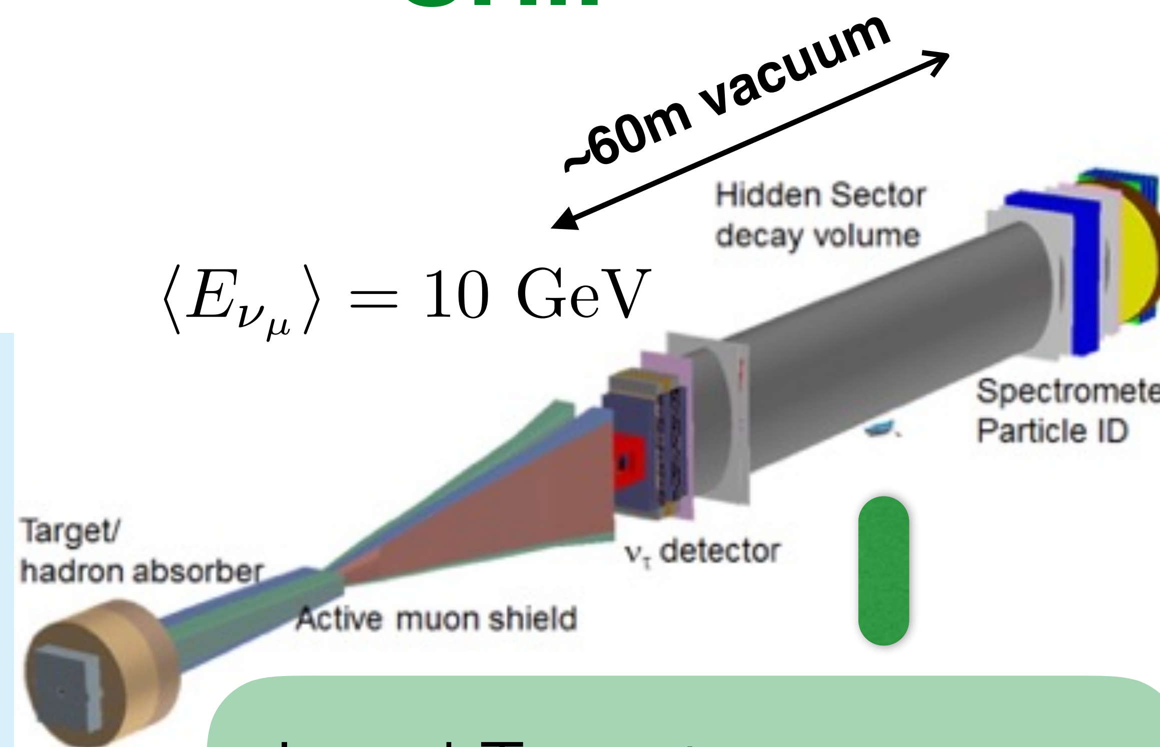
Anti-neutrino & neutrino mode



Liquid Argon TPC

SHiP arXiv: 1504.04956

$$\langle E_{\nu_\mu} \rangle = 10 \text{ GeV}$$



Lead Target
Emulsion Film Detector
Micron Vertex Resolution

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Neutrino Trident

arXiv:1612.05642, PRD 2017 (GM, Plestid)

ν Process	$\overline{\nu}$ Process	V_{ijk}	A_{ijk}	Mediator
$\nu_e \to \nu_e e^+ e^-$	$\overline{\nu}_e \to \overline{\nu}_e e^+ e^-$	$\frac{1}{2} + 2\sin^2\theta_w$	$\frac{1}{2}$	W,Z
$\nu_\mu \to \nu_\mu \mu^+ \mu^-$	$\overline{\nu}_\mu \to \overline{\nu}_\mu \mu^+ \mu^-$	$\frac{1}{2} + 2\sin^2\theta_w$	$\frac{1}{2}$	W,Z
$\nu_e \to \nu_\mu \mu^+ e^-$	$\overline{\nu}_e \to \overline{\nu}_\mu e^+ \mu^-$	1	1	W
$\nu_\mu \to \nu_e e^+ \mu^-$	$\overline{\nu}_\mu \to \overline{\nu}_e \mu^+ e^-$	1	1	W
$\nu_e \to \nu_e \mu^+ \mu^-$	$\overline{\nu}_e \to \overline{\nu}_e \mu^+ \mu^-$	$-\frac{1}{2} + 2\sin^2\theta_w$	$-\frac{1}{2}$	Z
$\nu_\mu \to \nu_\mu e^+ e^-$	$\overline{\nu}_\mu \to \overline{\nu}_\mu e^+ e^-$	$-\frac{1}{2} + 2\sin^2\theta_w$	$-\frac{1}{2}$	Z
$\nu_\mu \to \nu_\mu \tau^+ \tau^-$	$\overline{\nu}_\mu \to \overline{\nu}_\mu \tau^- \tau^+$	$-\frac{1}{2} + 2\sin^2\theta_w$	$-\frac{1}{2}$	Z
$\nu_\mu \to \nu_\tau \mu^- \tau^+$	$\overline{\nu}_\mu \to \overline{\nu}_\tau \mu^+ \tau^-$	1	1	W
$\nu_\tau \to \nu_\mu \tau^- \mu^+$	$\overline{\nu}_\tau \to \overline{\nu}_\mu \tau^+ \mu^-$	1	1	W
$\nu_\tau \to \nu_\tau \mu^+ \mu^-$	$\overline{\nu}_\tau \to \overline{\nu}_\tau \mu^- \mu^+$	$-\frac{1}{2} + 2\sin^2\theta_w$	$-\frac{1}{2}$	Z
$\nu_\tau \to \nu_\tau e^+ e^-$	$\overline{\nu}_\tau \to \overline{\nu}_\tau e^- e^+$	$-\frac{1}{2} + 2\sin^2\theta_w$	$-\frac{1}{2}$	Z

TABLE I: Modified vector and axial coupling constants for different combinations of incident neutrino flavours and final states

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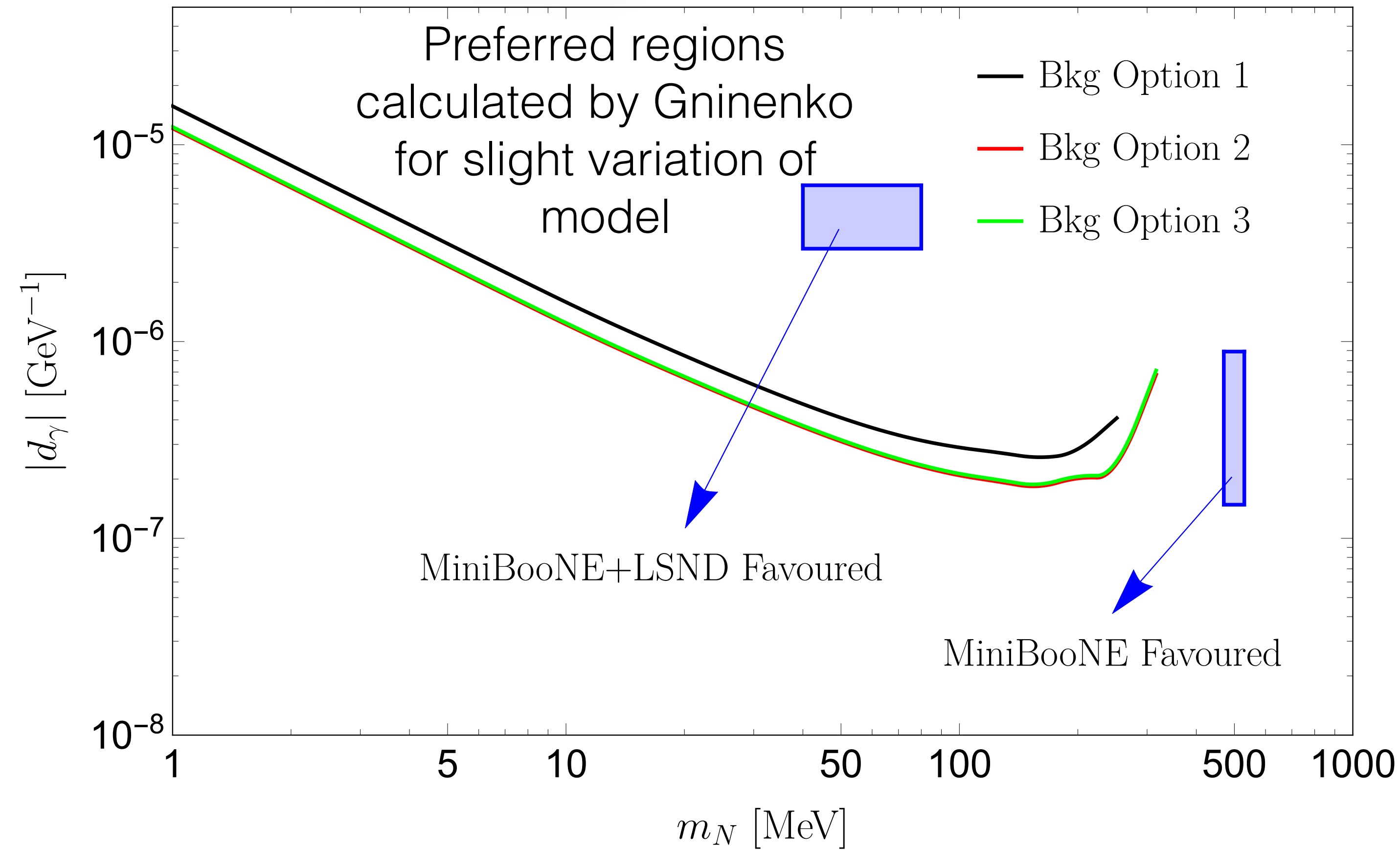
ν Dipole Portal

Preliminary Results:
Background estimates subject to change!

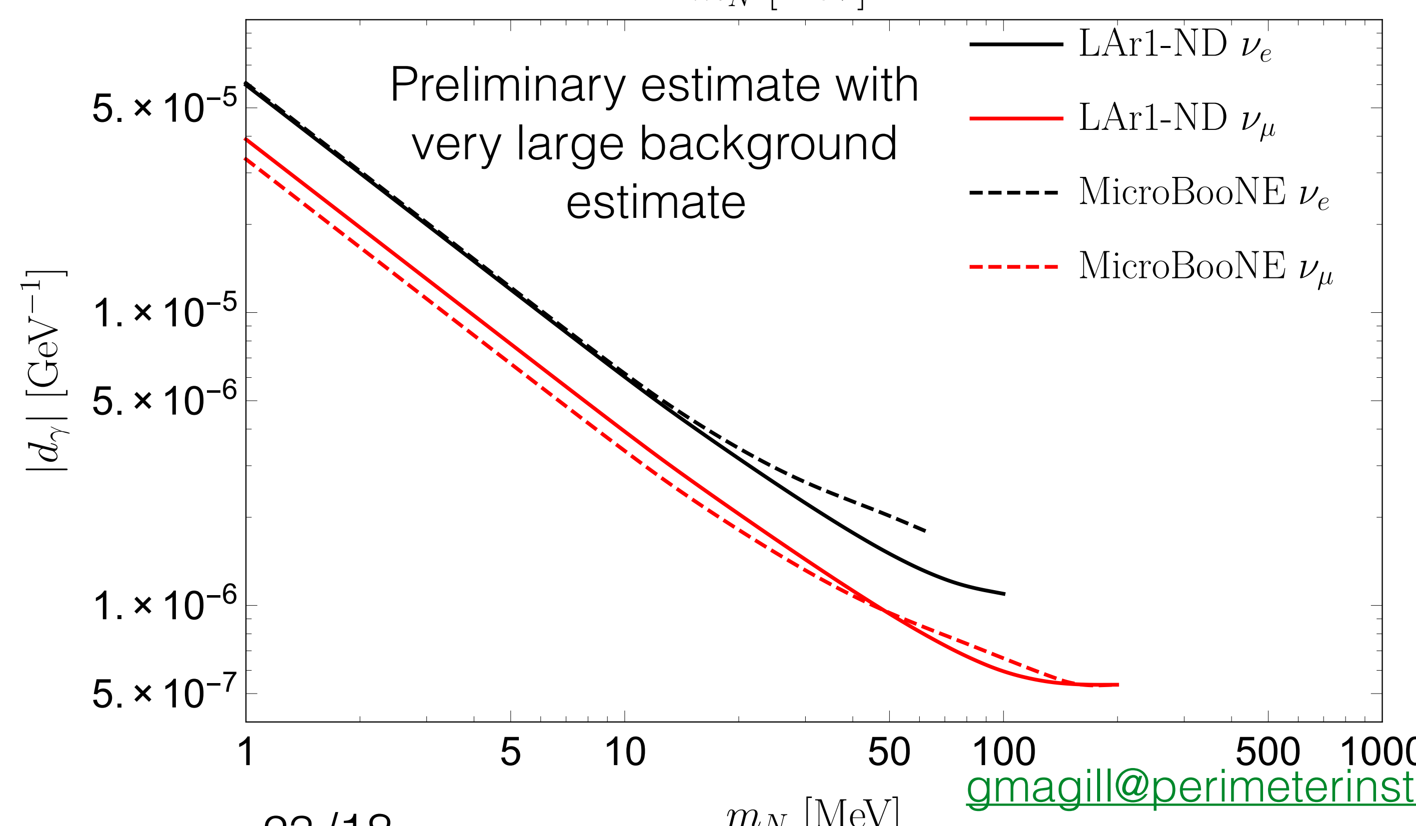
Past Fermilab

HNL limits using MiniBooNE. In light of anomaly, 3 background options.
Preferred regions explaining MiniBooNE and LSND anomalies.



Future Fermilab

Projected sensitivities at Fermilab's upcoming short-baseline program. Backgrounds are calculated based on expected lifetime single photons.



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Neutrino Trident

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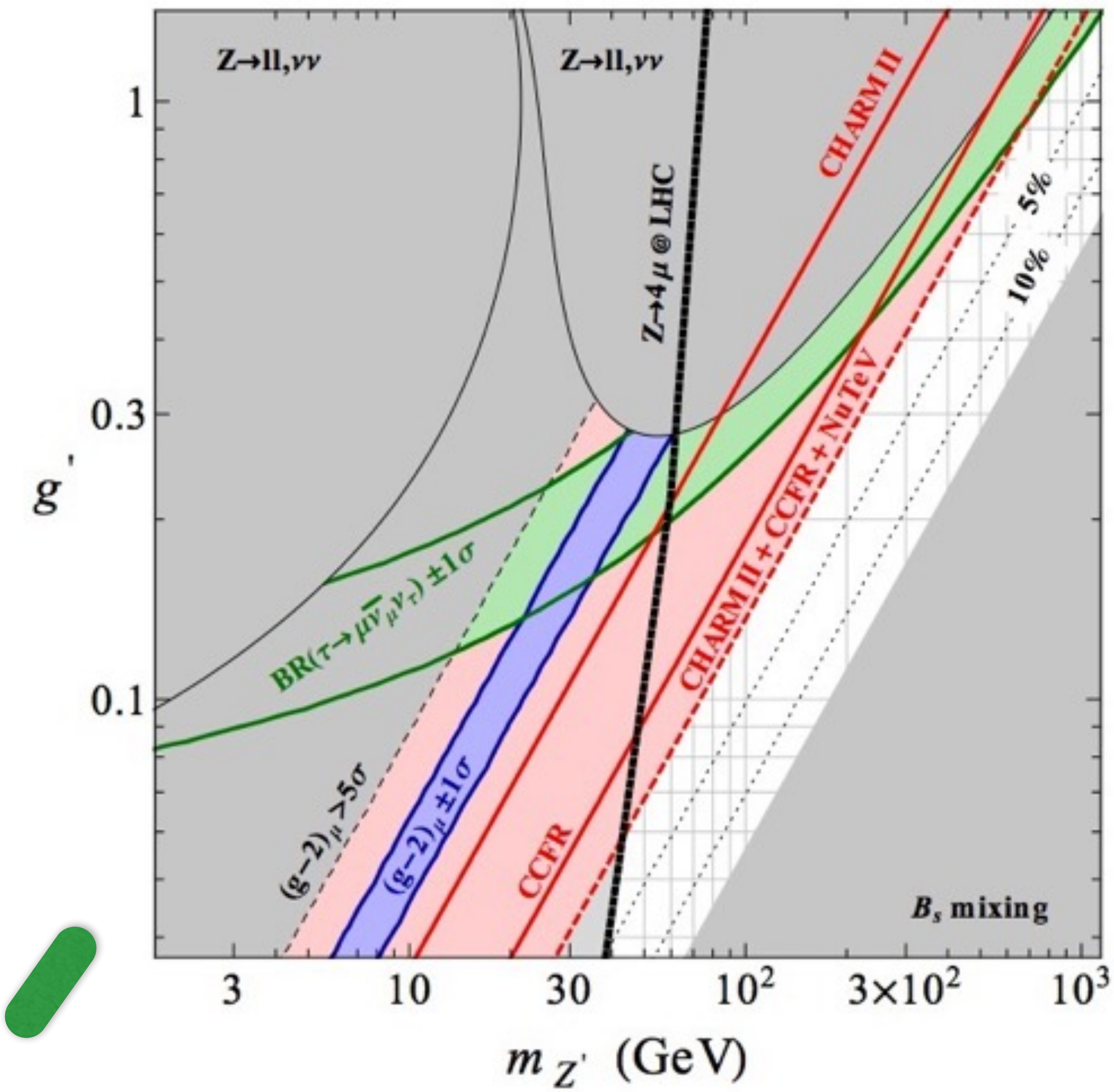

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