New Signals in the Intensity Frontier

2017 CAP Congress, Queen's University

In collaboration with

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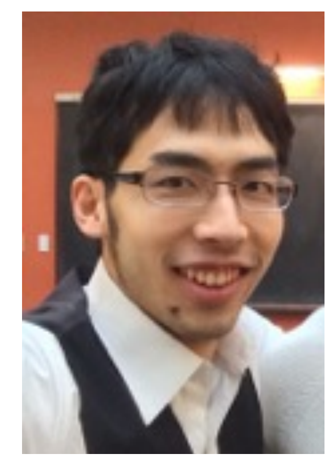

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2017/05/31

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Motivation

~ Neutrinos are interesting

Many SM parameters not measured

Many anomalies

Mass requires physics BSM!

~ New high luminosity state of the art experiments to address this

DUNE & SHiP

~ How to get the most out of these experiments?

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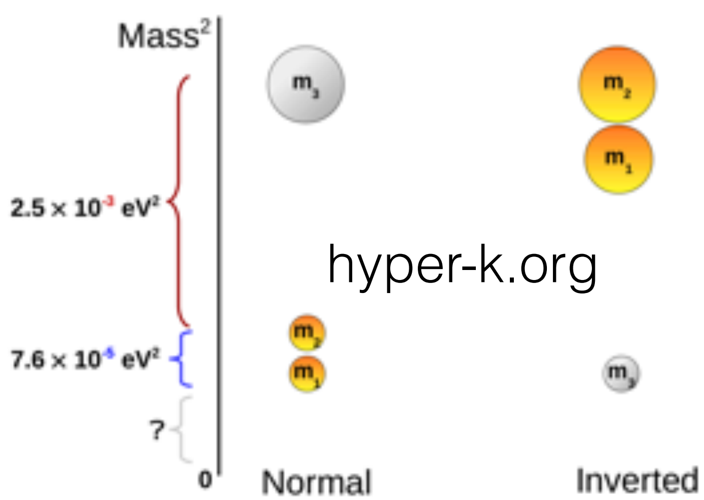
Motivation

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

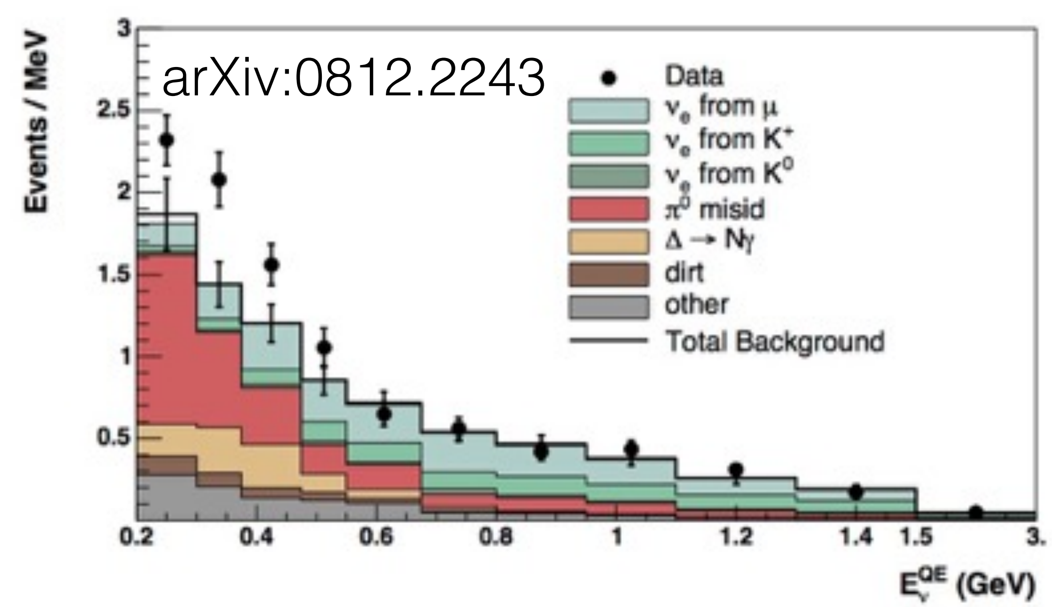
$$\delta_{CP}^{NH}(\pm 1\sigma) = 202^\circ - 312^\circ$$

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

nu-fit.org

Oscillation Anomalies

~ LSND; MiniBooNE:



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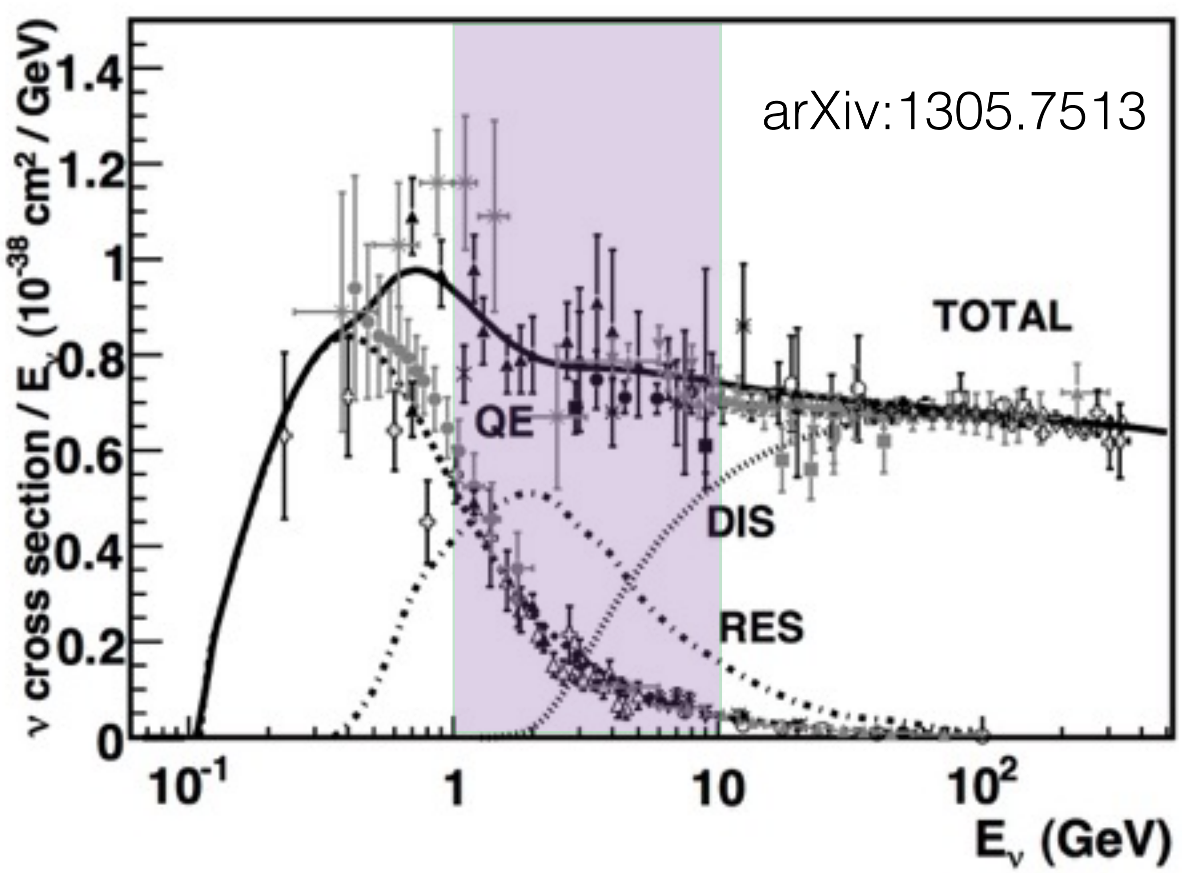
Motivation

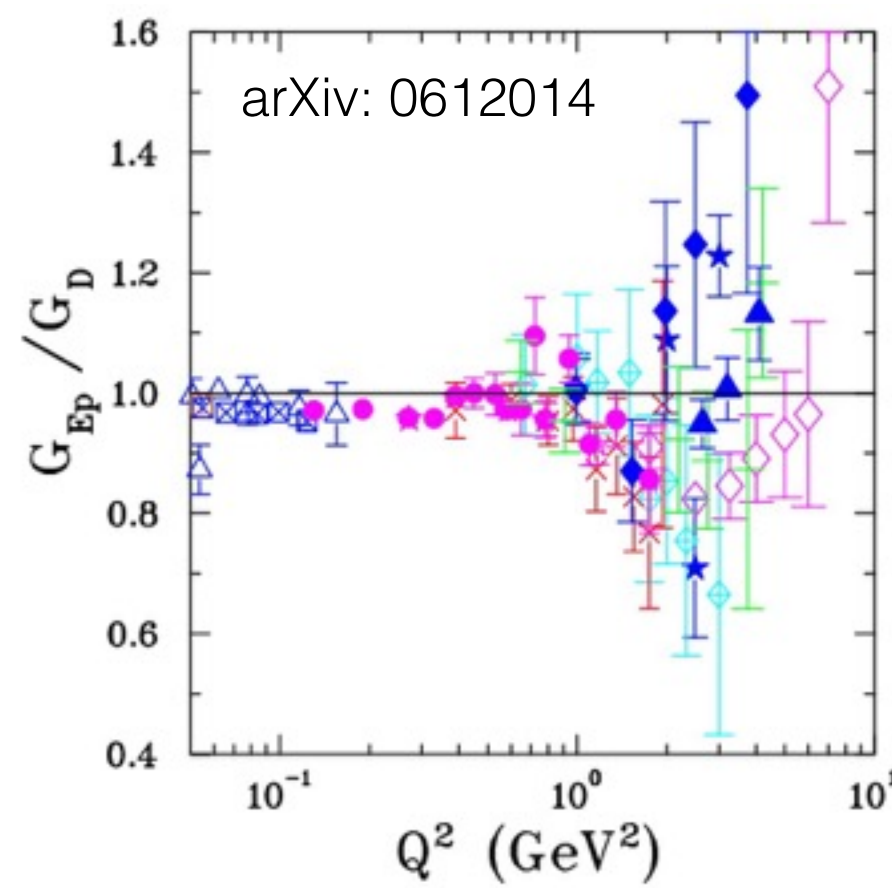
Neutrinos are challenging

~ QE, RES & DIS crossover



$E_\nu = 1 - 10\text{GeV}$ is the Wild Wild West
~ Richard J. Hill

Other challenges
~ Beam energy spectrum
~ Initial state of nucleus
~ Form factors



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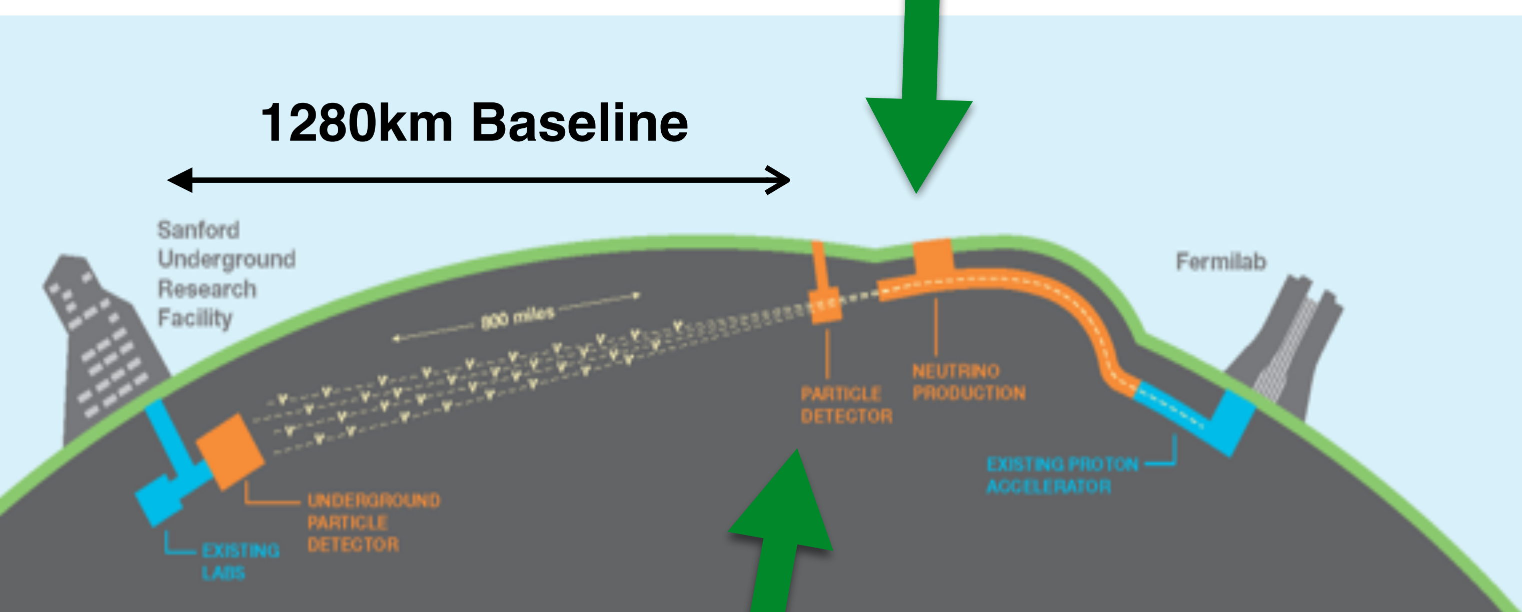
New Experiments

DUNE

arXiv:1512.06148

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

Anti-neutrino & neutrino mode



Liquid Argon TPC

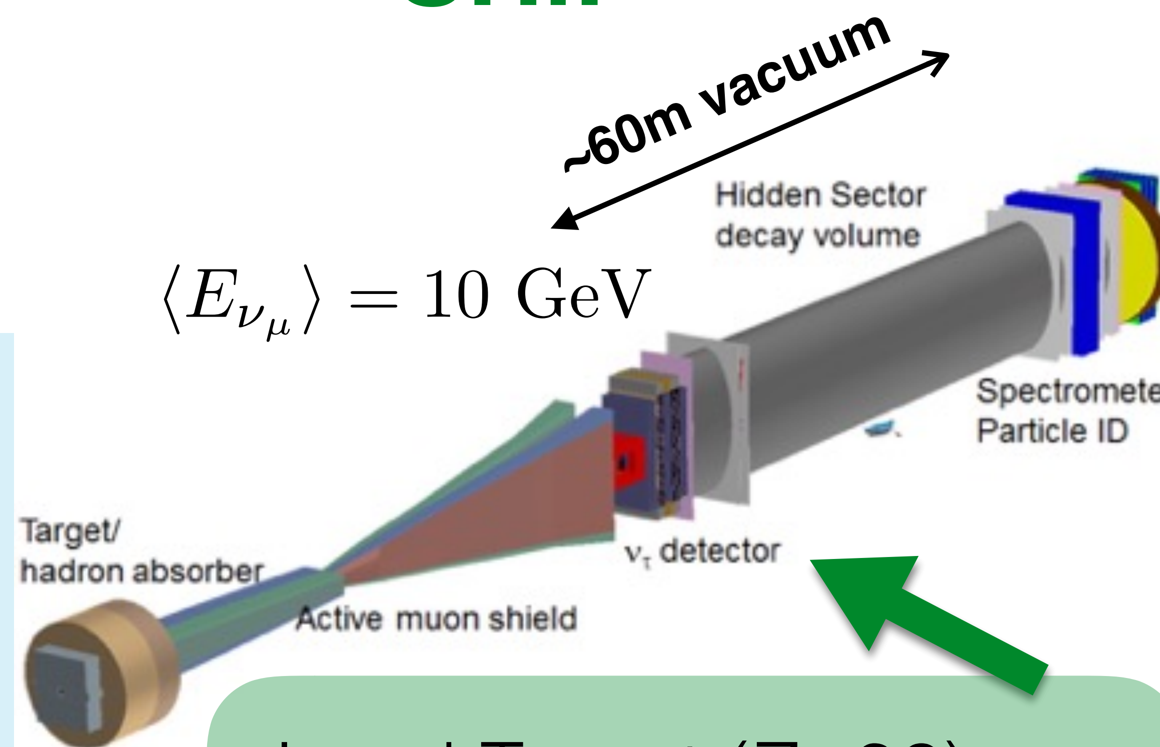
Determine Mass Hierarchy and δ_{CP}

3×10^6 CC Events

SHiP

arXiv: 1504.04956

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



Lead Target (Z=82)
Emulsion Film Detector
Micron Vertex Resolution

Search for long lived resonances and $\overline{\nu}_\tau$

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Rare Signals

With high luminosities and state of the art technology, we can look for new rare signals!

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Rare Signals

Signal #1:
Lepton Flavour Violation
Mixed flavour $\ell^+\ell^-$

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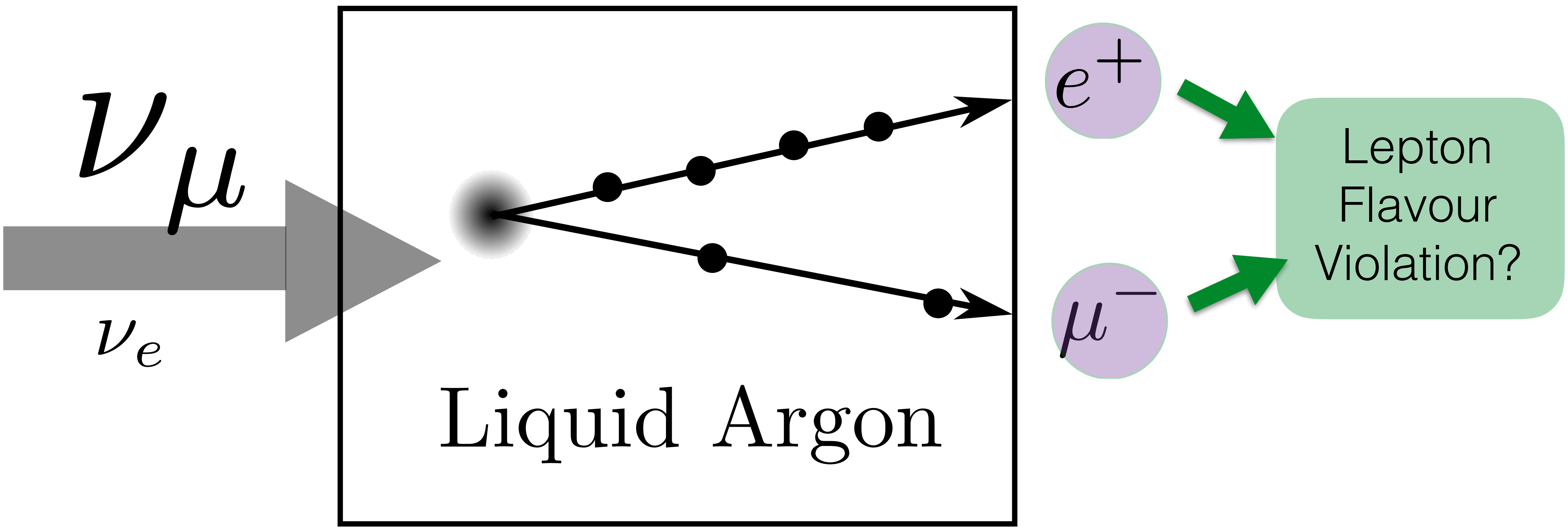
Rare Signals

arXiv:1612.05642, PRD 2017 (GM, Plestid)



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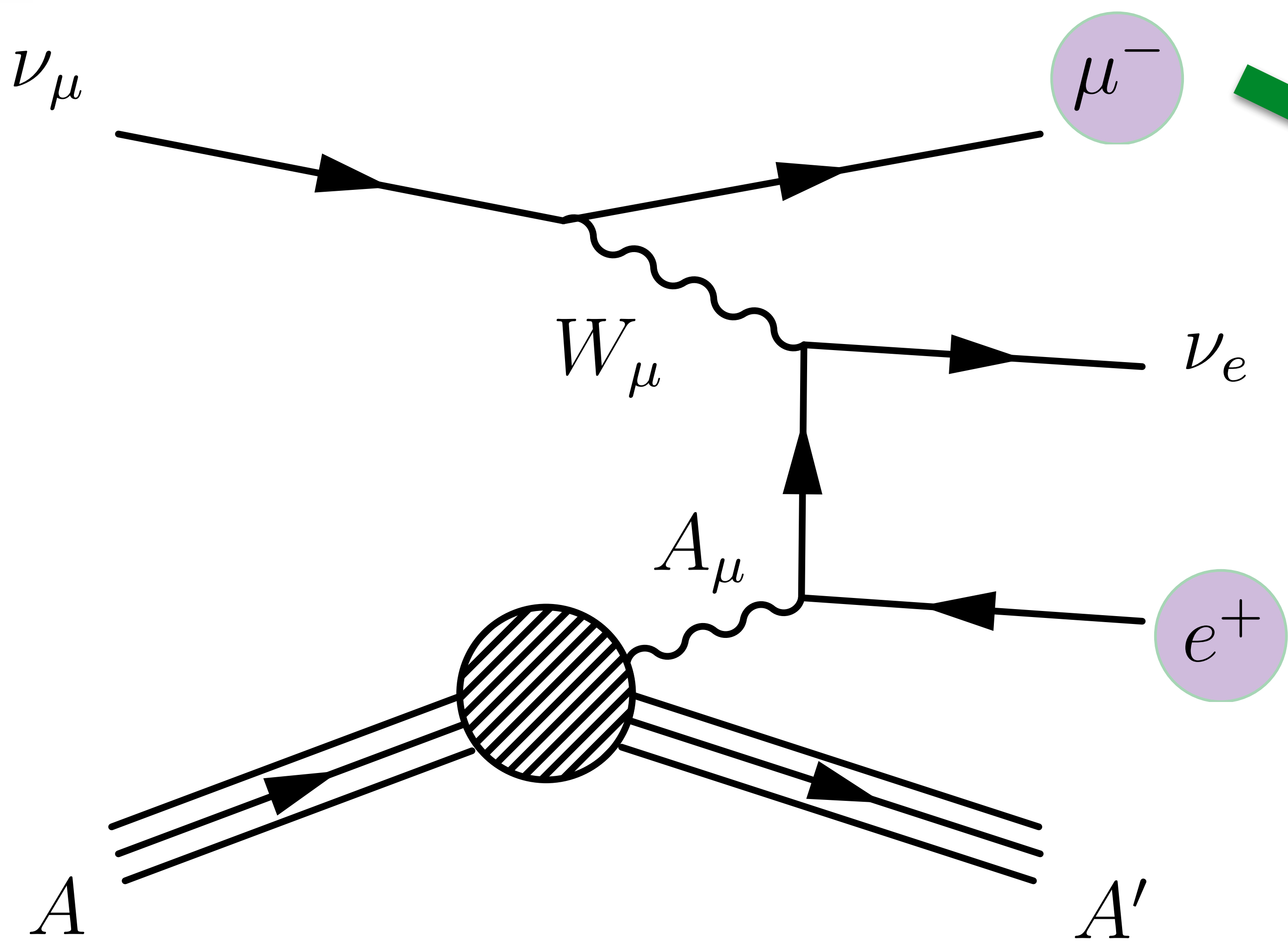
Neutrino Trident

arXiv:1612.05642, PRD 2017 (GM, Plestid)



Standard Model Only!

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

Rare Process

Process dependent

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

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

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Neutrino Trident

arXiv:1612.05642, PRD 2017 (GM, Plestid)

SHiP

Neutrino Beam			Anti-Neutrino Beam		
Process	Coh	Diff	Process	Coh	Diff
$\nu_\mu \to \nu_e e^+ \mu^-$	85.46	24.6	$\bar{\nu}_\mu \to \bar{\nu}_e e^- \mu^+$	29.96	9.61
$\nu_\mu \to \nu_\mu e^+ e^-$	28.28	5.32	$\bar{\nu}_\mu \to \bar{\nu}_\mu e^+ e^-$	22.48	3.58
$\nu_e \to \nu_e e^+ e^-$	21.69	2.95	$\bar{\nu}_e \to \bar{\nu}_e e^+ e^-$	15.65	2.45
$\nu_e \to \nu_\mu \mu^+ e^-$	9.1	2.31	$\bar{\nu}_e \to \bar{\nu}_\mu \mu^- e^+$	14.31	3.16
$\nu_\mu \to \nu_\mu \mu^+ \mu^-$	4.79	3.01	$\bar{\nu}_\mu \to \bar{\nu}_\mu \mu^+ \mu^-$	3.76	2.38
$\nu_e \to \nu_e \mu^+ \mu^-$	0.42	0.16	$\bar{\nu}_e \to \bar{\nu}_e \mu^+ \mu^-$	0.3	0.12
$\nu_\tau \to \nu_\tau e^+ e^-$	0.13	0.03	$\bar{\nu}_\tau \to \bar{\nu}_\tau e^+ e^-$	0.13	0.02
$\nu_\tau \to \nu_\tau \mu^+ \mu^-$	0.01	0.	$\bar{\nu}_\tau \to \bar{\nu}_\tau \mu^+ \mu^-$	0.01	0.
$\nu_\tau \to \tau^- \mu^+ \nu_\mu$	0.	0.01	$\bar{\nu}_\tau \to \tau^+ \mu^- \bar{\nu}_\mu$	0.	0.
$\nu_\mu \to \mu^- \tau^+ \nu_\tau$	0.	0.23	$\bar{\nu}_\mu \to \mu^+ \tau^- \bar{\nu}_\tau$	0.	0.39
Total	149.88	38.62		86.6	21.71

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

Helicity effects:
Cross section changes under
$\mu \Leftrightarrow e$
Gives additional discriminants

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Neutrino Trident

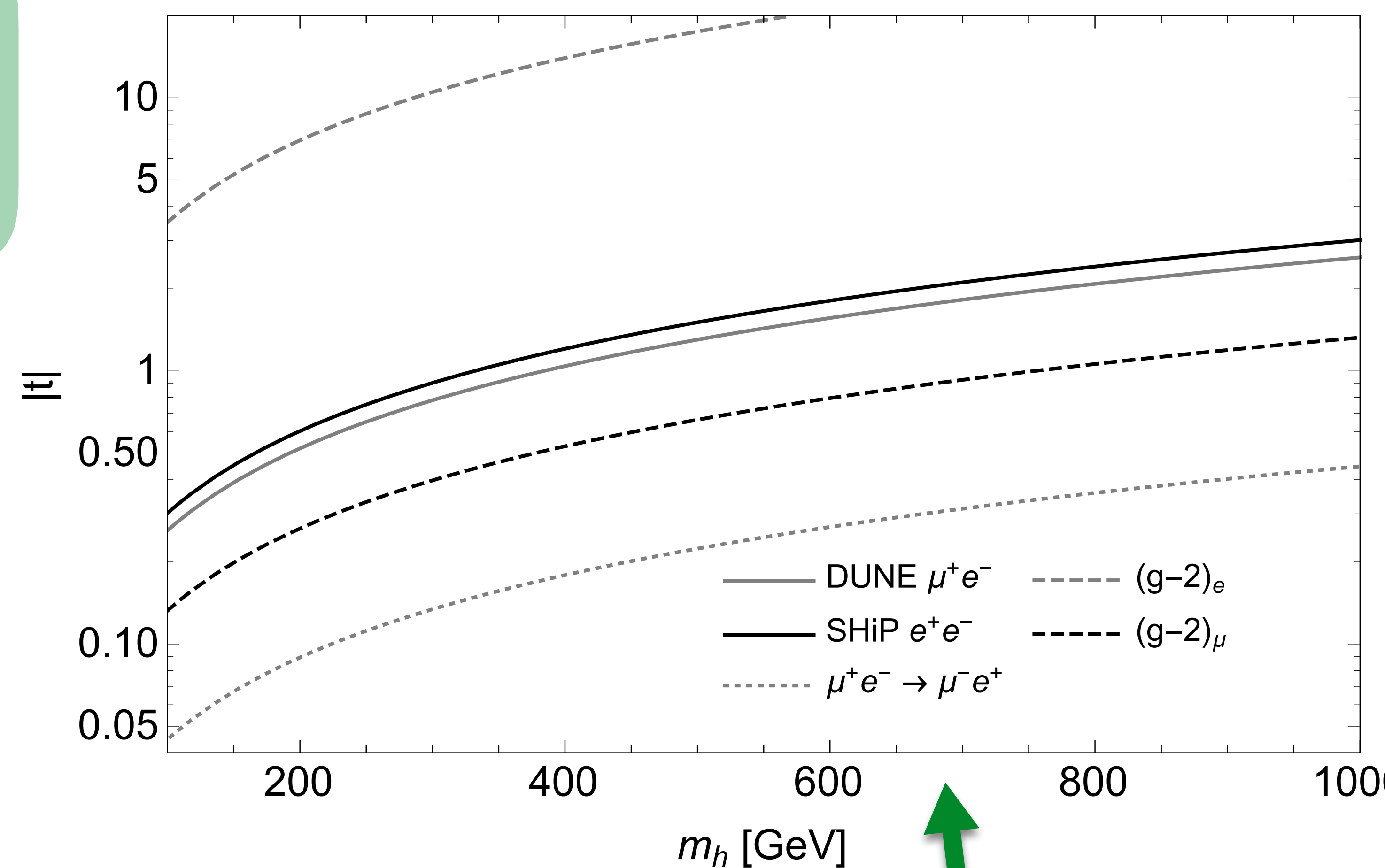
arXiv:1706.xxxx (GM, Plestid)

Measuring SM mixed flavour rates gives competitive constraints of charged scalars

Case Study: Higgs Triplet (Type II Seesaw)

$$\mathcal{L} \supset t^{ab} L_a \mathcal{T} L_b$$

DUNE:
Approximately 0 background when in Neutrino Mode



90% CL Sensitivity assuming universal flavour diagonal couplings

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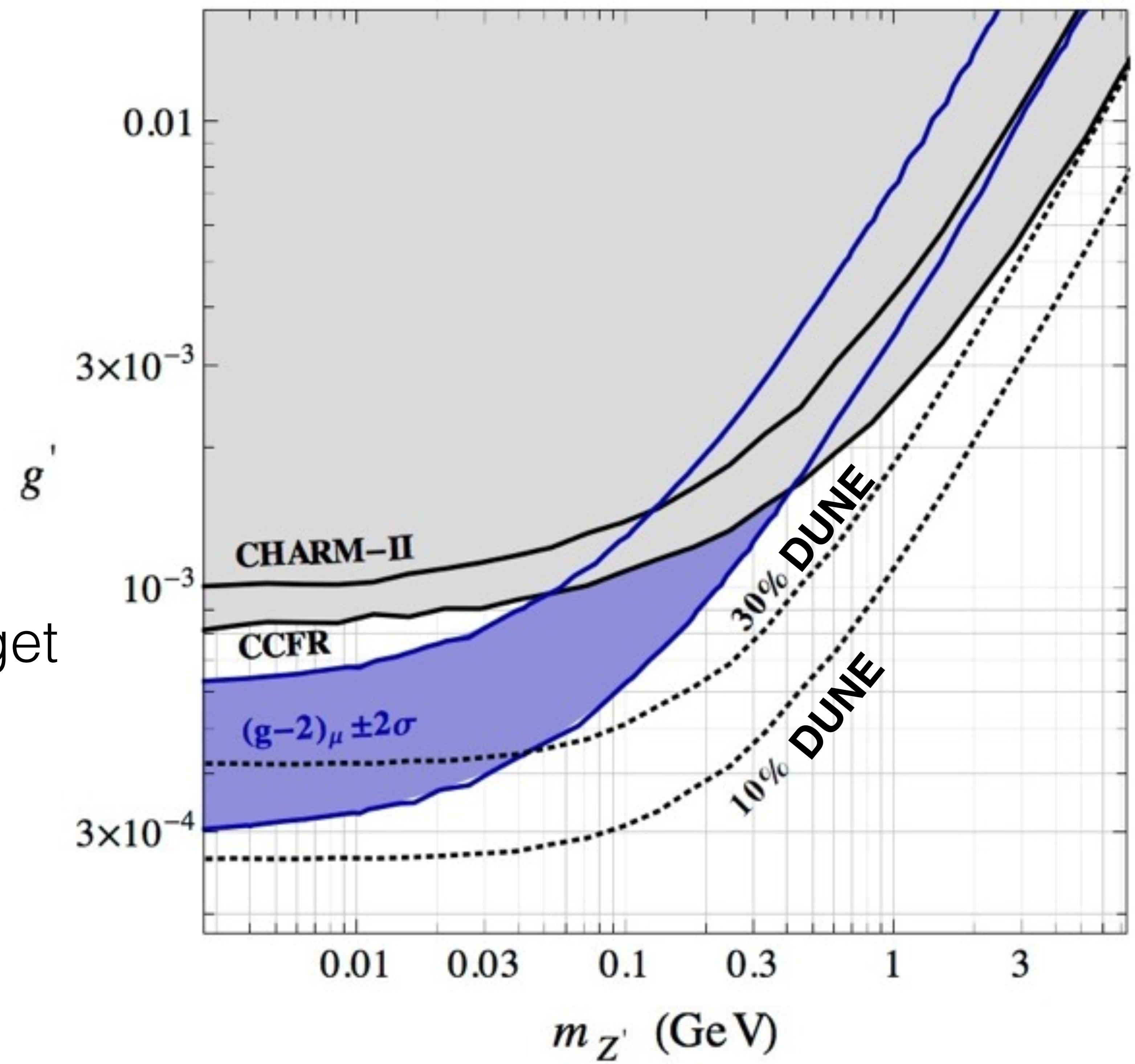
Neutrino Trident

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

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

Upcoming experiments to target parameter space favoured by $(g-2)_\mu$



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New Signals

Signal #2
Displaced Single Photon

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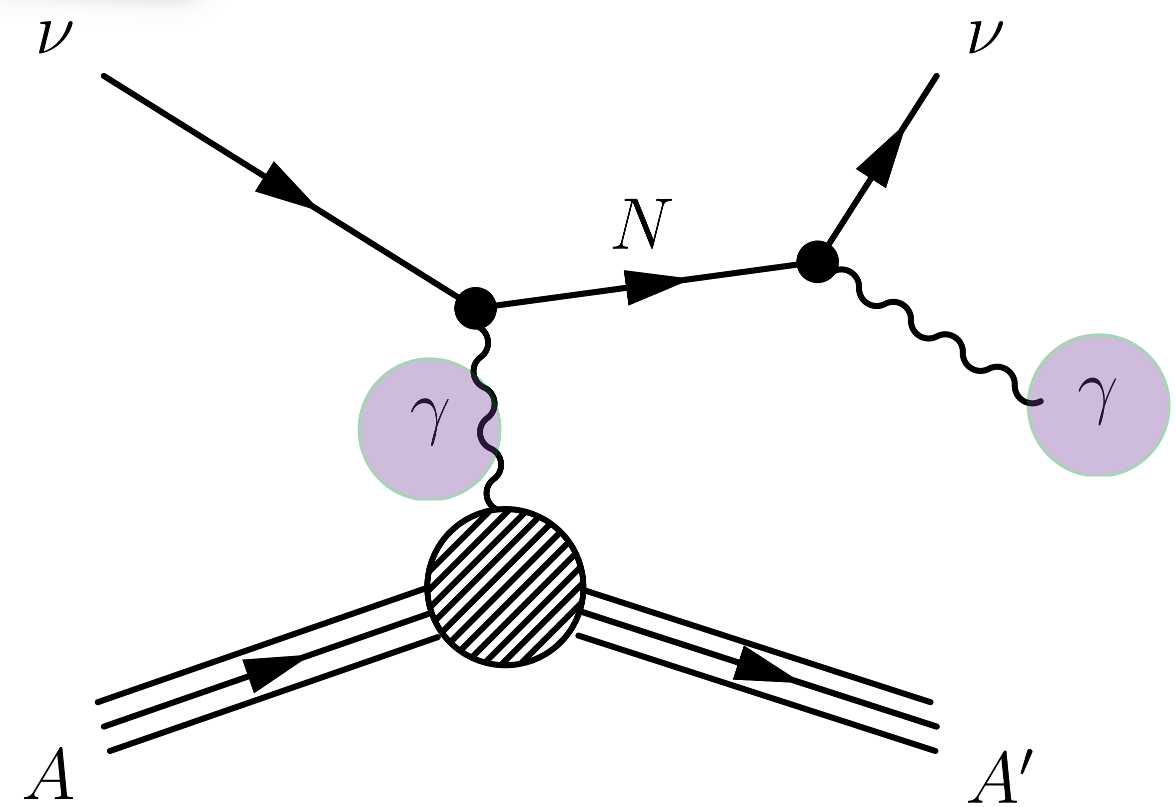
ν Dipole Portal

arXiv:170x.xxxx (GM, Pospelov, Plestid, Tsai)



Sterile Neutrinos

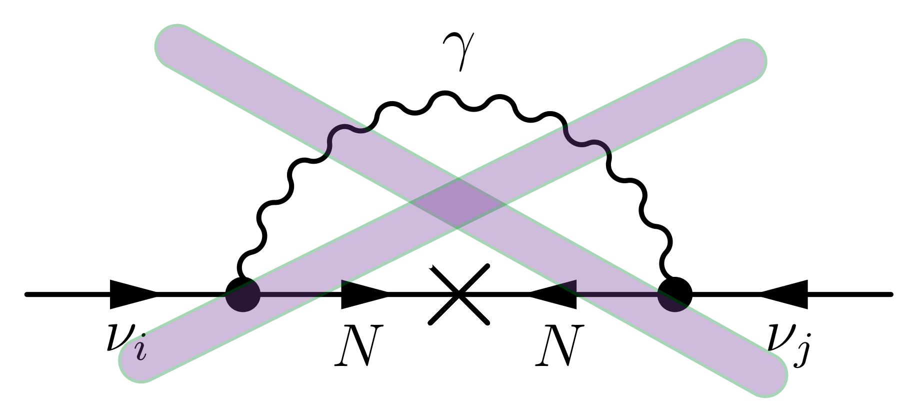
~ Very motivated (chiral completion of SM, solves anomalies, ν masses)
~ Evaded detection so far!

> Lack of sensitivity?
> Or are they hidden?

Alternative Direction

~ Consider Dirac sterile neutrinos
~ Only interact with SM via magnetic dipole portal
~ Potential resolution to MiniBooNE oscillation anomaly

$$\mathcal{L} \supset d_a \overline{\nu_L}_a \sigma_{\mu\nu} F^{\mu\nu} N + m\overline{N}N$$



> Won't be detectable in neutrino textures!

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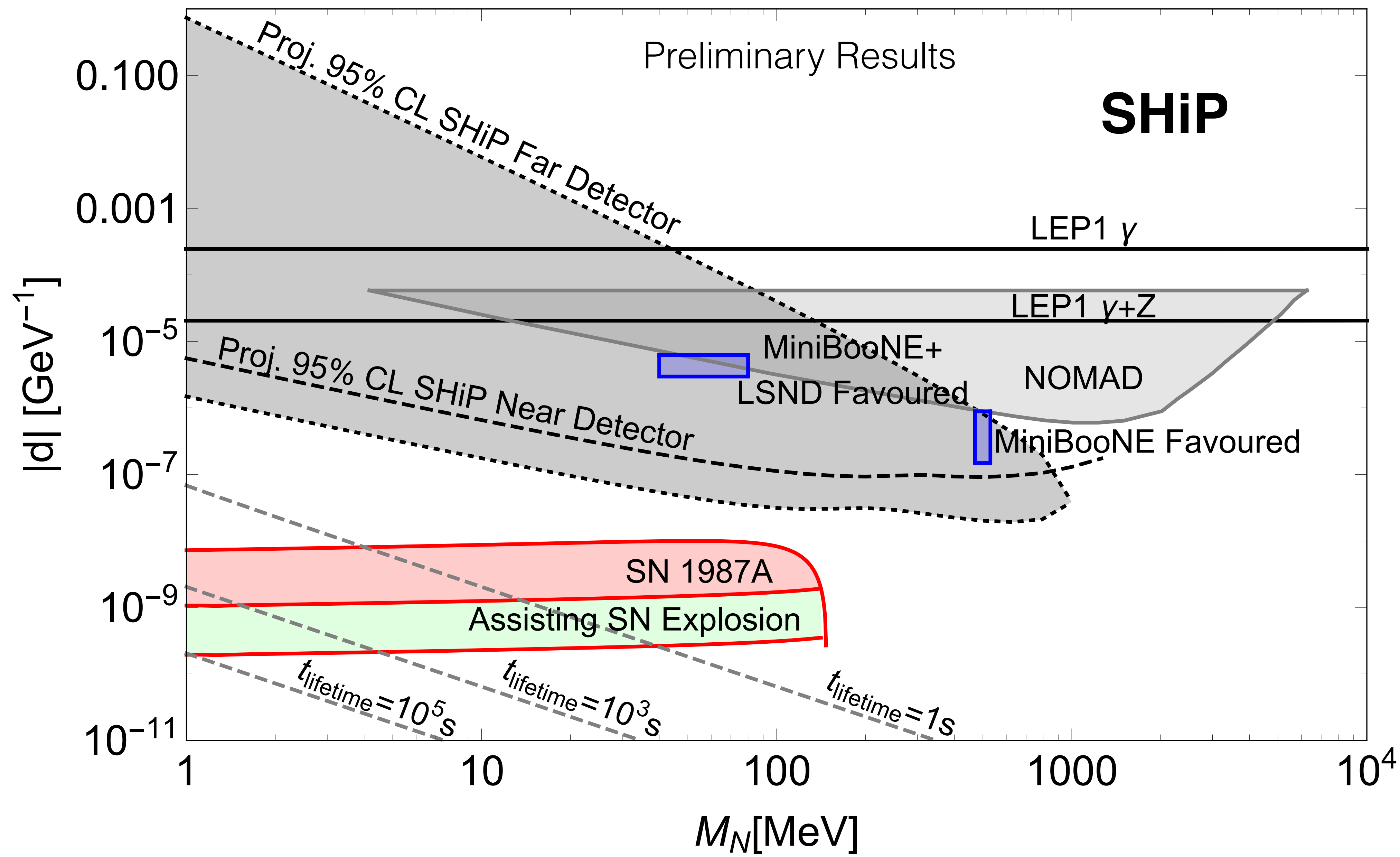
ν Dipole Portal

arXiv:170x.xxxx (GM, Pospelov, Plestid, 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: SHiP, DUNE (also MicroBooNE, …)

~ 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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Luminosities

Beam Dumps = High Luminosity

SHiP (~ 5 years) arXiv: 1504.04956

$$2 \times 10^{20}\ \mathrm{POT}$$

$$2 \times 10^{6}\ \mathrm{CC\ Events}$$

$$15500\ \mathrm{fb}^{-1}$$

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

DUNE (~ 20 years) arXiv:1512.06148

$$1 \times 10^{22}\ \mathrm{POT}$$

$$3 \times 10^{6}\ \mathrm{CC\ Events}$$

$$147000\ \mathrm{fb}^{-1}$$

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

Collider Comparison

LEP (12 years)

$$1\ \mathrm{fb}^{-1}$$

LHC-HL (10 years)

$$3000\ \mathrm{fb}^{-1}$$

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Neutrino Trident

arXiv:1612.05642 (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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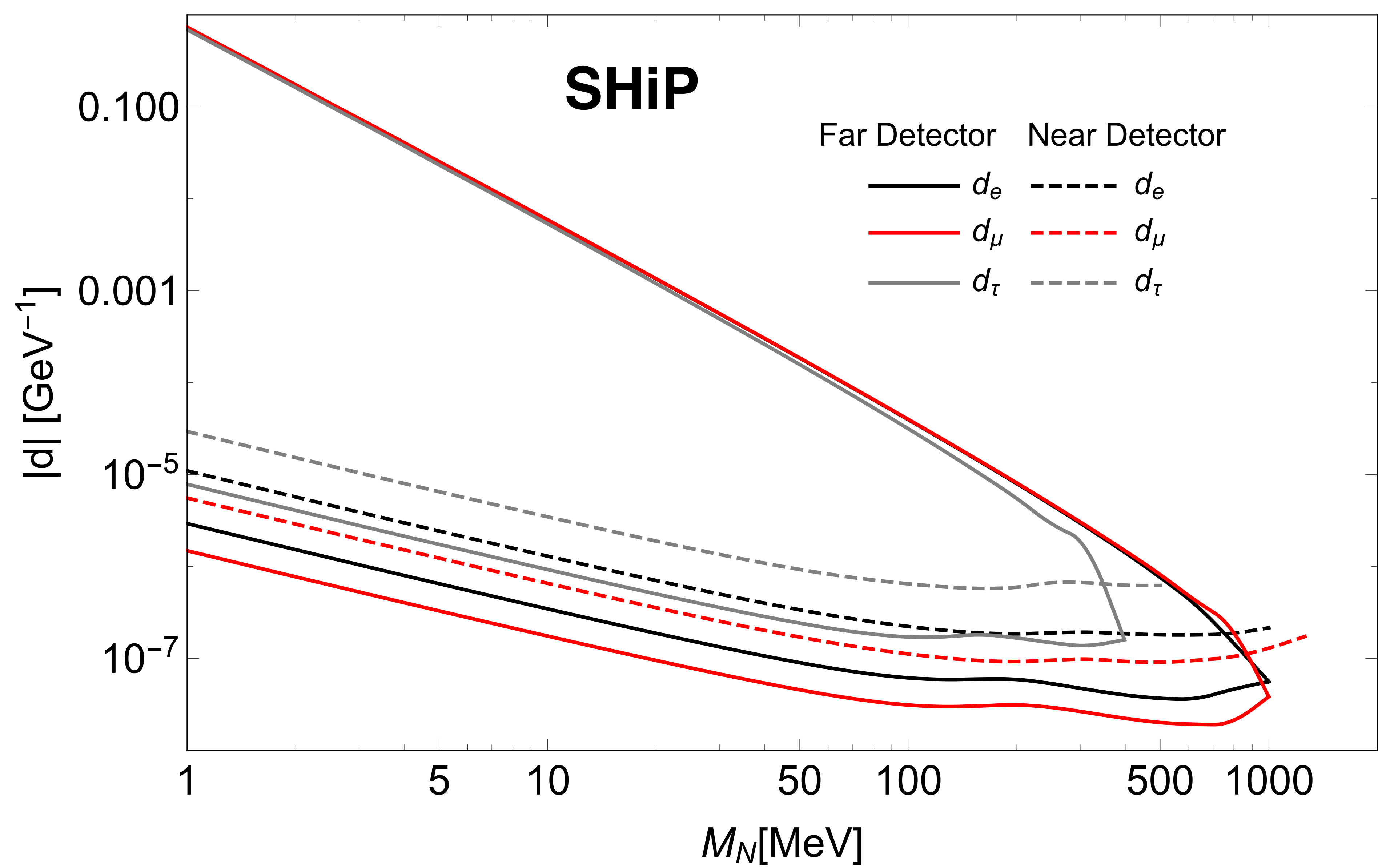
ν Dipole Portal

arXiv:170x.xxxx (GM, Pospelov, Plestid, Tsai)

~ SHiP projected 95% CL sensitivity to d_e, d_μ, d_τ



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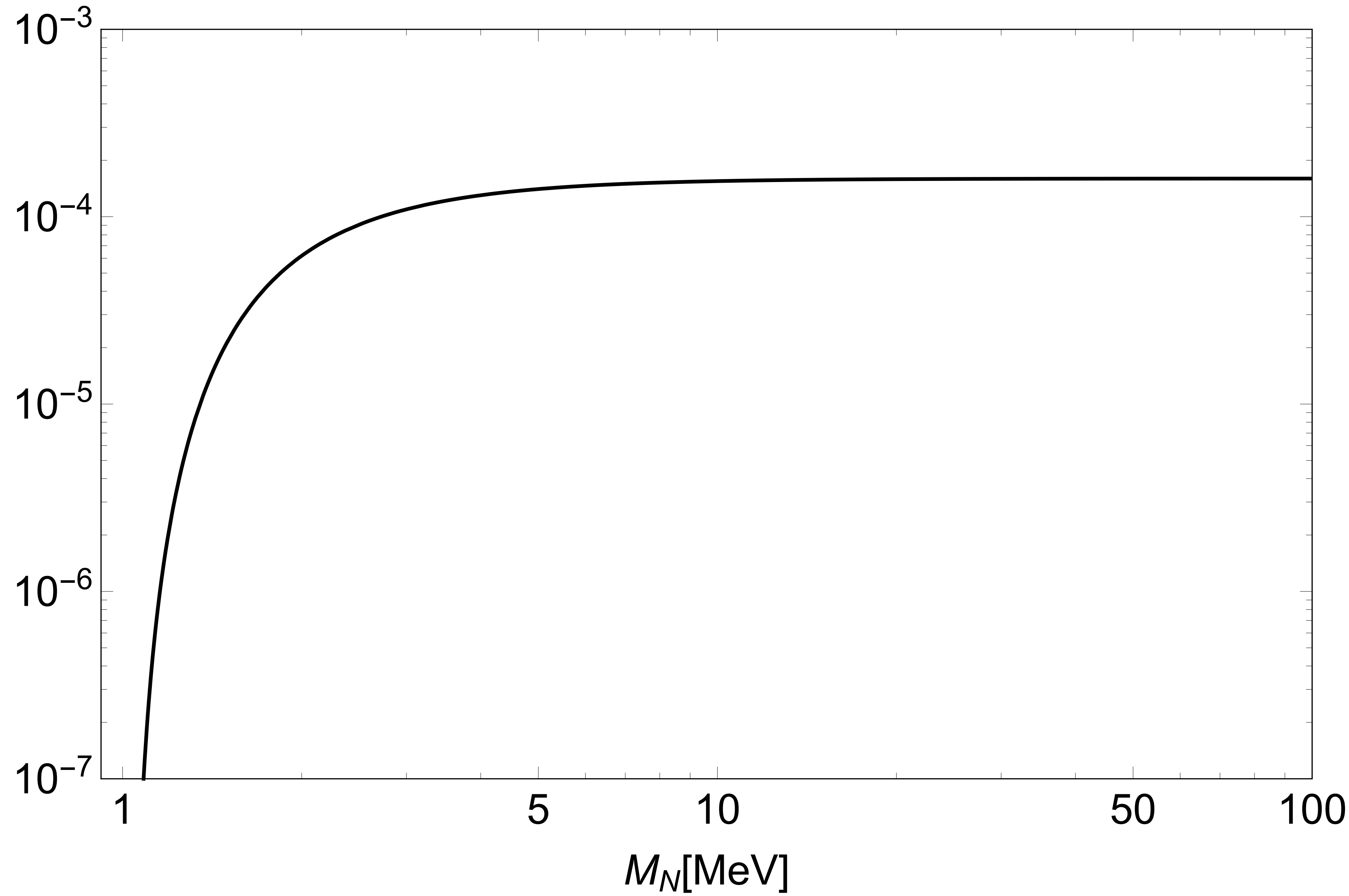
ν Dipole Portal

arXiv:170x.xxxx (GM, Pospelov, Plestid, Tsai)

$$\frac{\Gamma\left(N \to \nu e^- e^+\right)}{\Gamma\left(N \to \nu \gamma\right)}$$



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