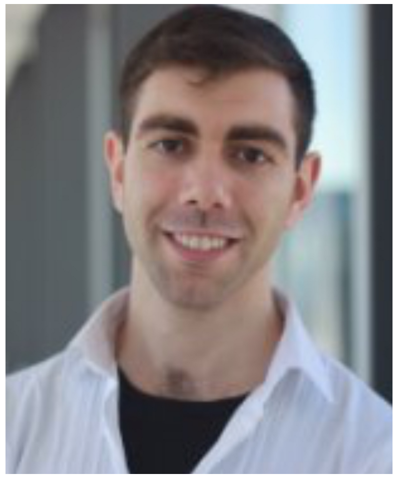
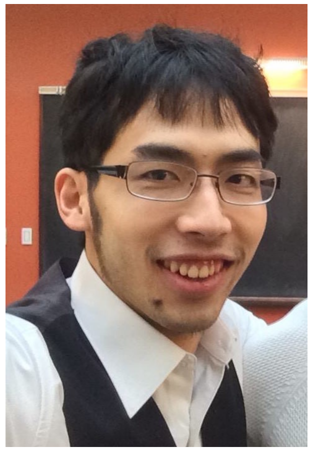
Rare Neutrino Physics at the Intensity Frontier

WNPPC 2018, Mont Tremblant Quebec

In collaboration with


Maxim Pospelov


Gabriel Magill


Yu-Dai Tsai

Ryan Plestid
Perimeter Institute for Theoretical Physics (Waterloo, Ontario)
McMaster University (Hamilton, Ontario)
2018/02/17

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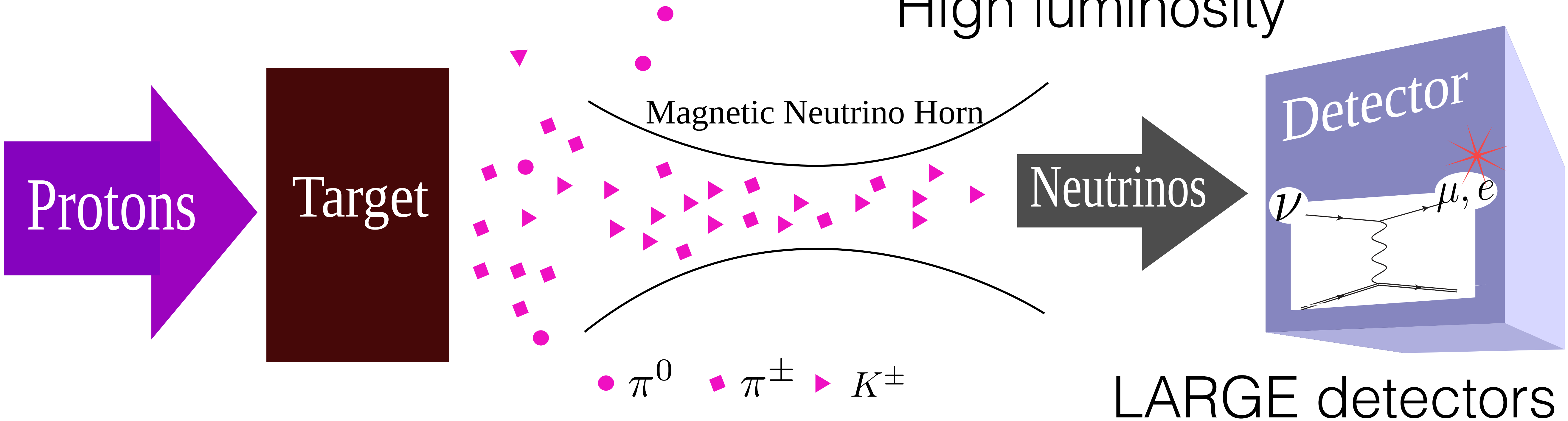
Intensity Frontier

10^{20} protons on target

High luminosity

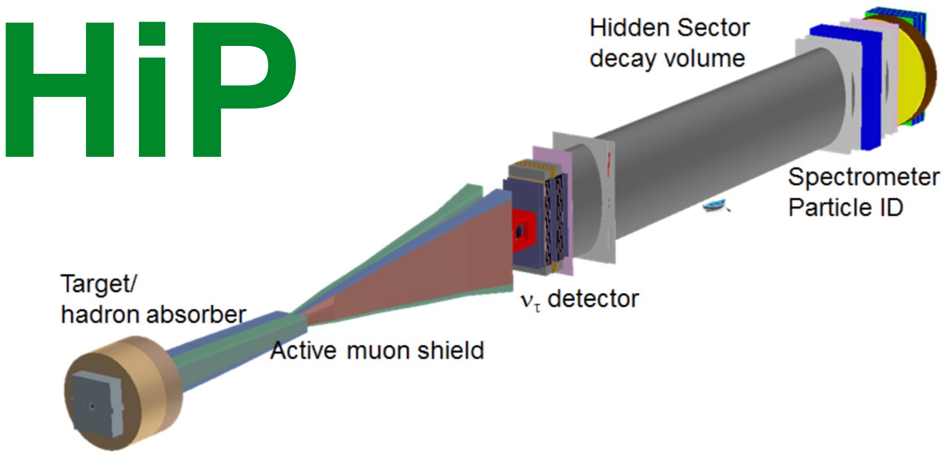


LARGE detectors

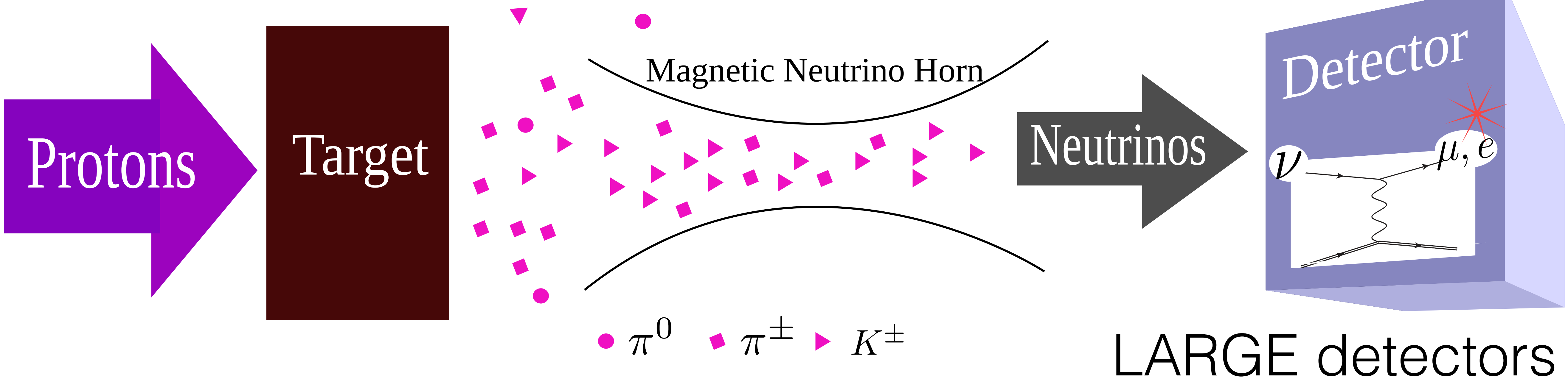
300,000 CC events

Intensity Frontier

SHiP



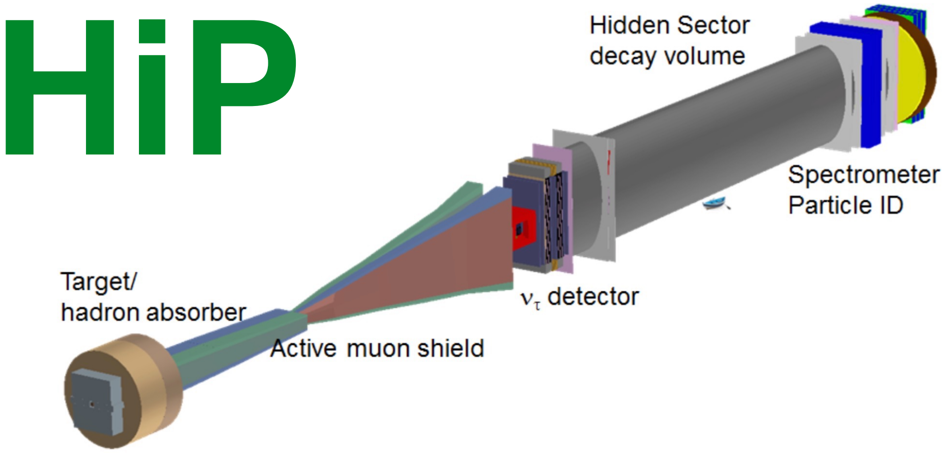
High luminosity



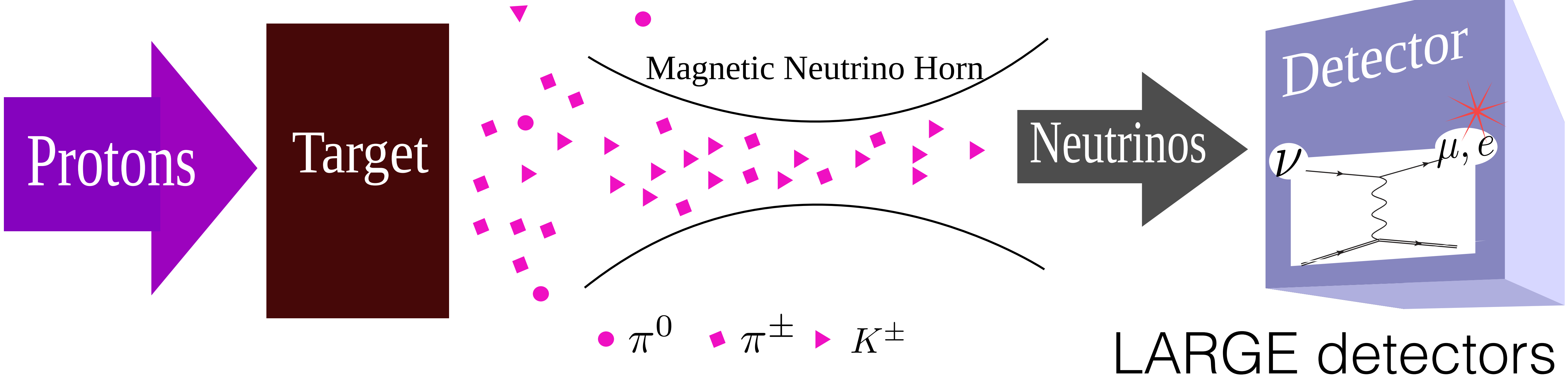
LARGE detectors

Intensity Frontier

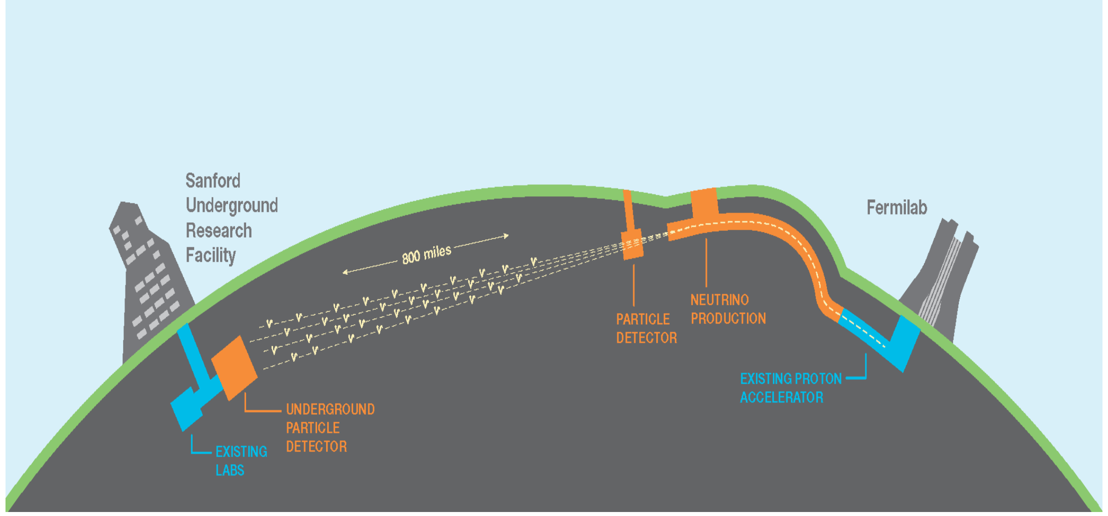
SHiP



High luminosity



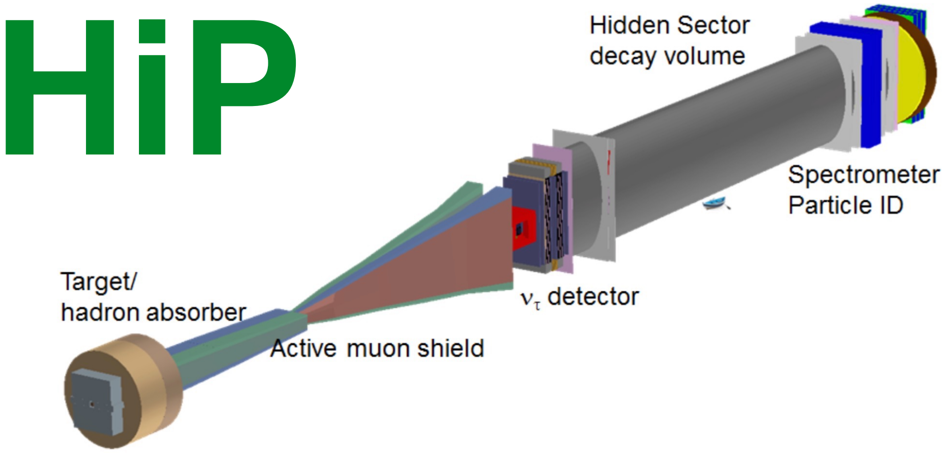
LARGE detectors



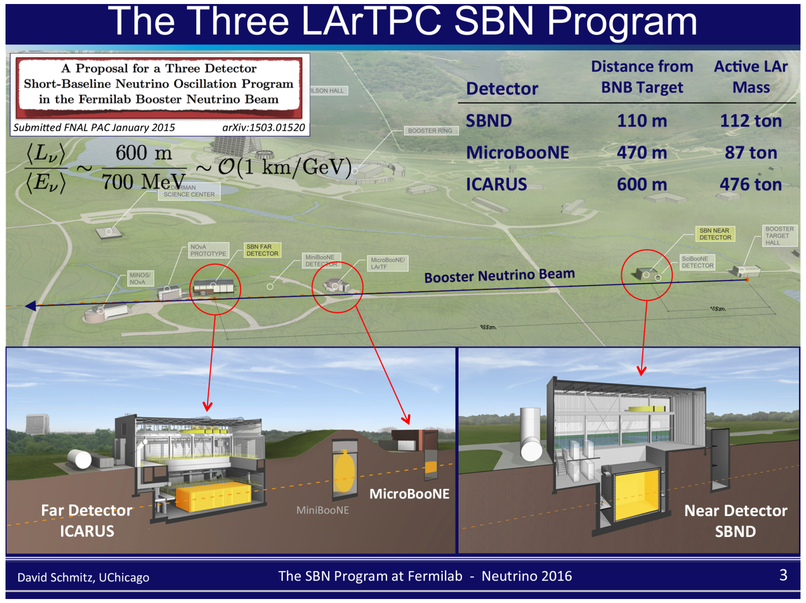
DUNE

Intensity Frontier

SHiP



SBN



The Three LArTPC SBN Program

A Proposal for a Three Detector Short-Baseline Neutrino Oscillation Program in the Fermilab Booster Neutrino Beam

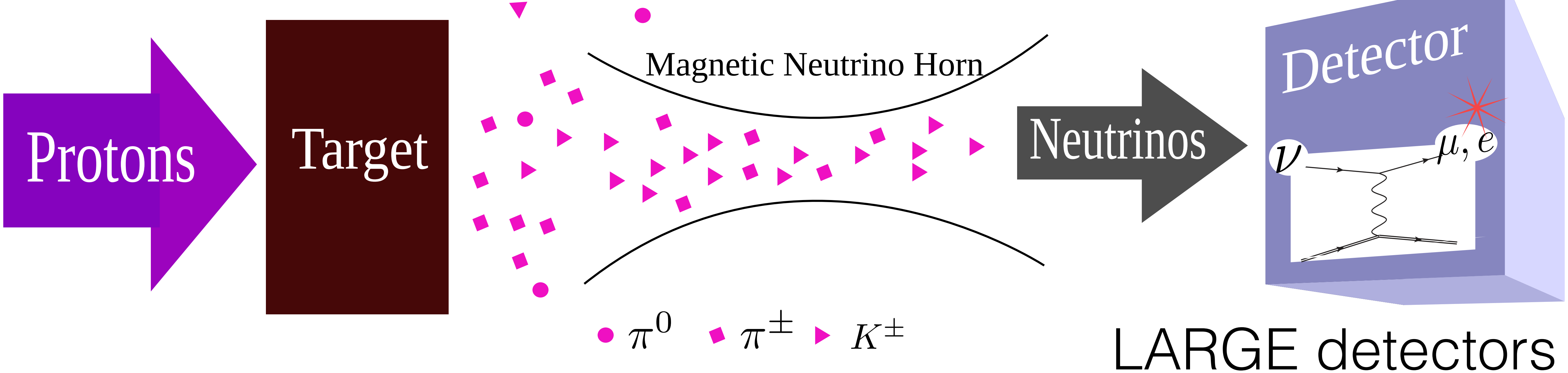
Submitted FNAL PAC January 2015 arXiv:1503.01520

$$\frac{\langle L_\nu \rangle}{\langle E_\nu \rangle} \sim \frac{600\ \mathrm{m}}{700\ \mathrm{MeV}} \sim \mathcal{O}(1\ \mathrm{km/GeV})$$

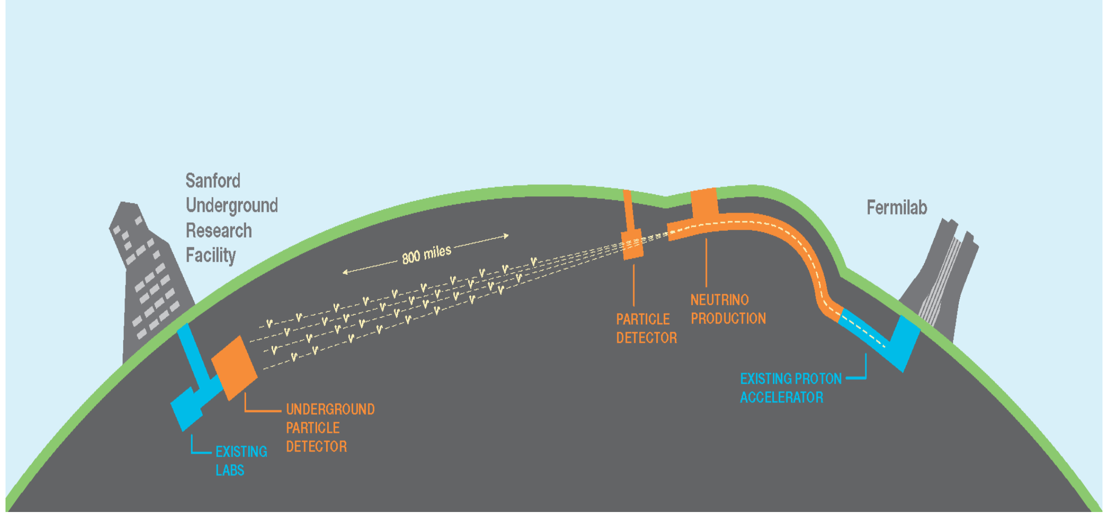
Detector	Distance from BNB Target	Active LAr Mass
SBND	110 m	112 ton
MicroBooNE	470 m	87 ton
ICARUS	600 m	476 ton

David Schmitz, UChicago The SBN Program at Fermilab - Neutrino 2016 3

High luminosity



LARGE detectors



DUNE

Intensity Frontier

Neutrino physics driven by oscillations and search for eV sterile neutrino

A lot of money invested in next generation of experiments

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

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Rare Physics

#1 Neutrino Trident Production

#2 Dipole Portal to HNLs (single photons)

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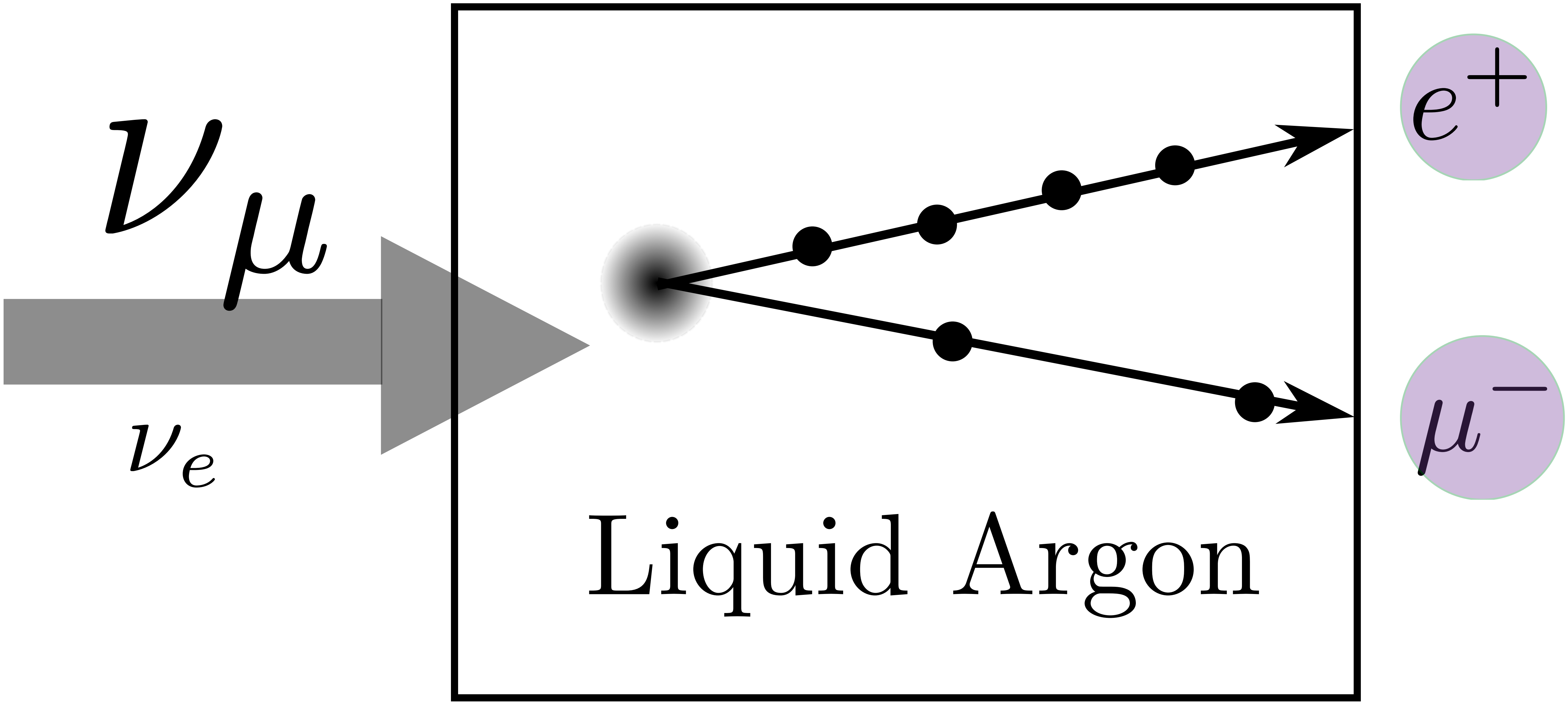
Neutrino Trident Production



ν_μ

ν_e

Liquid Argon

e^+

μ^-

Lepton
Flavour
Violation?

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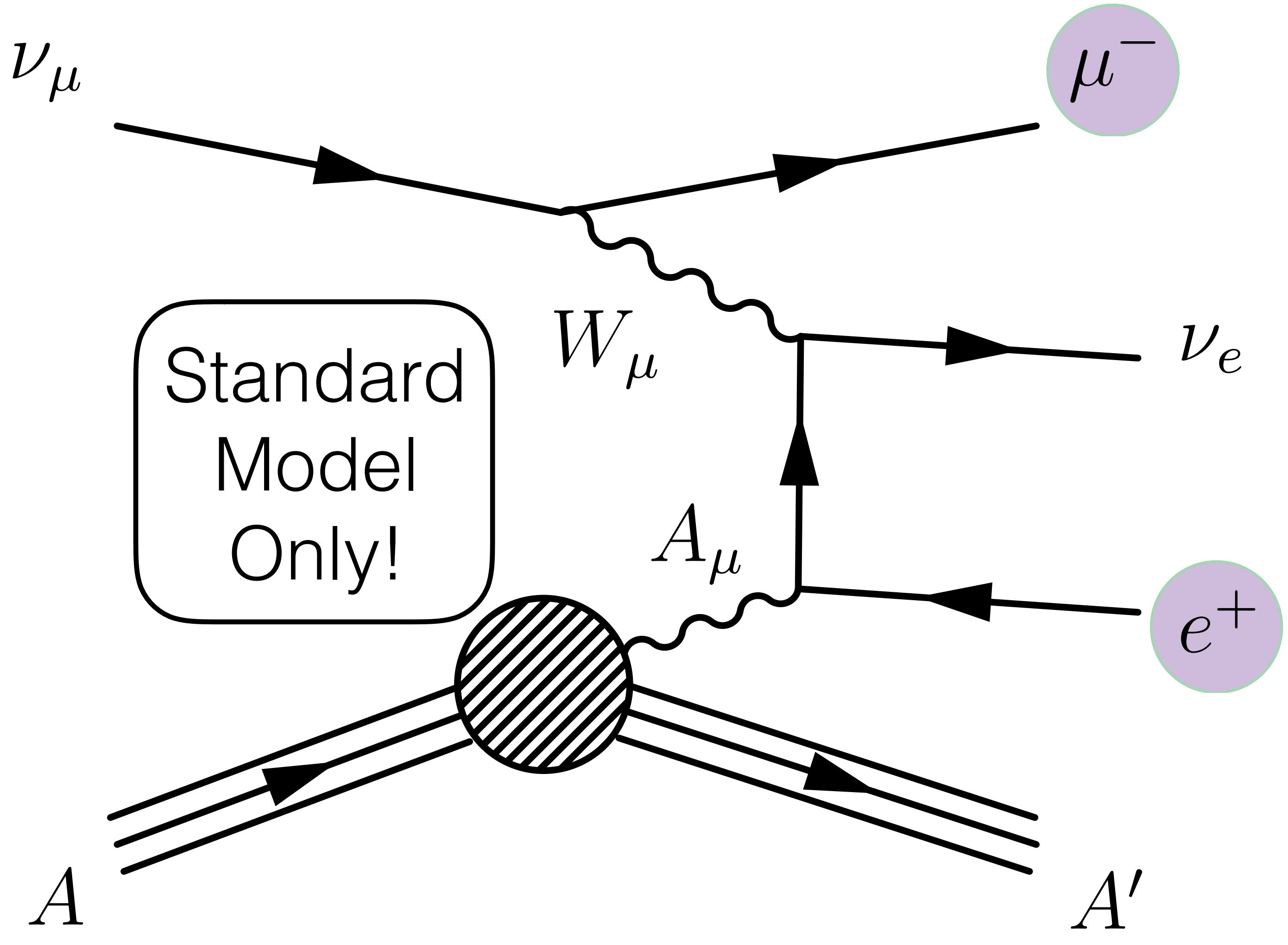
Neutrino Trident Standard Model



Standard Model Only!

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

Process dependent

Rare Process

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

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

Belusevic and Smith, PRD (1988)

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Neutrino Trident Standard Model

Has trident ever been measured?

Yes! For μ^-, μ^+

CCFR
(Fermilab)

$$\frac{\sigma_{\rm CCFR}}{\sigma_{\rm SM}} = 0.82 \pm 0.28$$

CCFR Collaboration,
PRL (1991)

CHARM-II
(CERN)

$$\frac{\sigma_{\rm CHARM\text{-}II}}{\sigma_{\rm SM}} = 1.58 \pm 0.57$$

CHARM-II Collaboration,
Phys.Lett.B (1990)

NuTeV
(Fermilab)

$$\frac{\sigma_{\rm NuTeV}}{\sigma_{\rm SM}} = 0.67 \pm 0.27$$

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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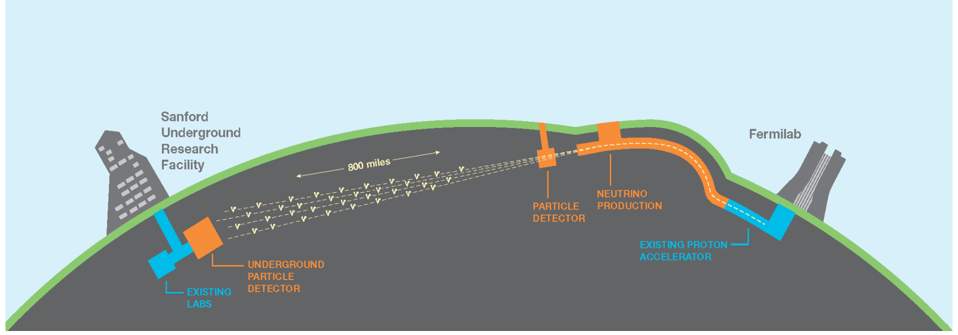
Neutrino Trident **Standard Model**

Rates for DUNE

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!



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

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

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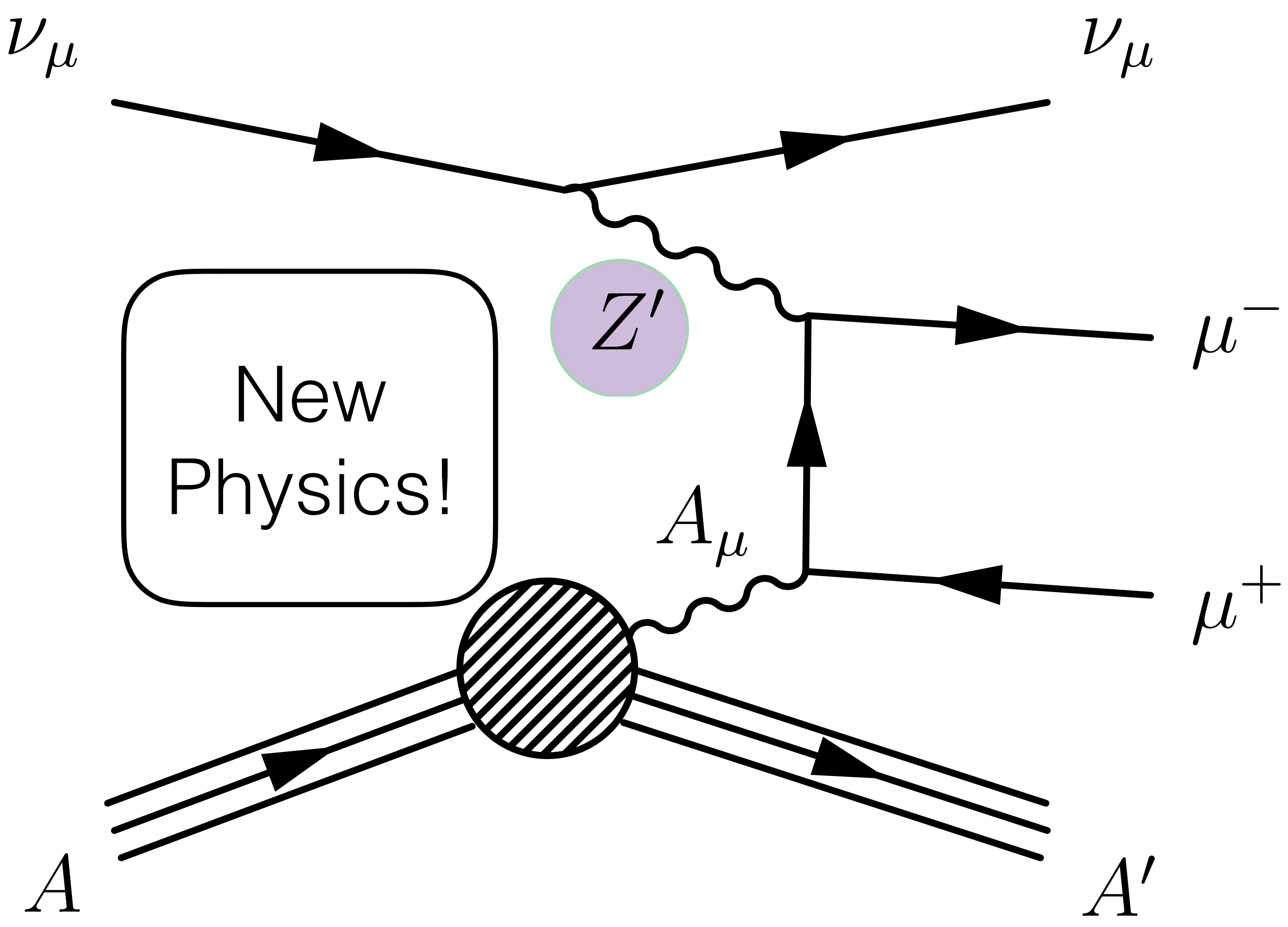
Neutrino Trident

New Physics



New Physics!

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

New Vector Boson

Potential UV Realization

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

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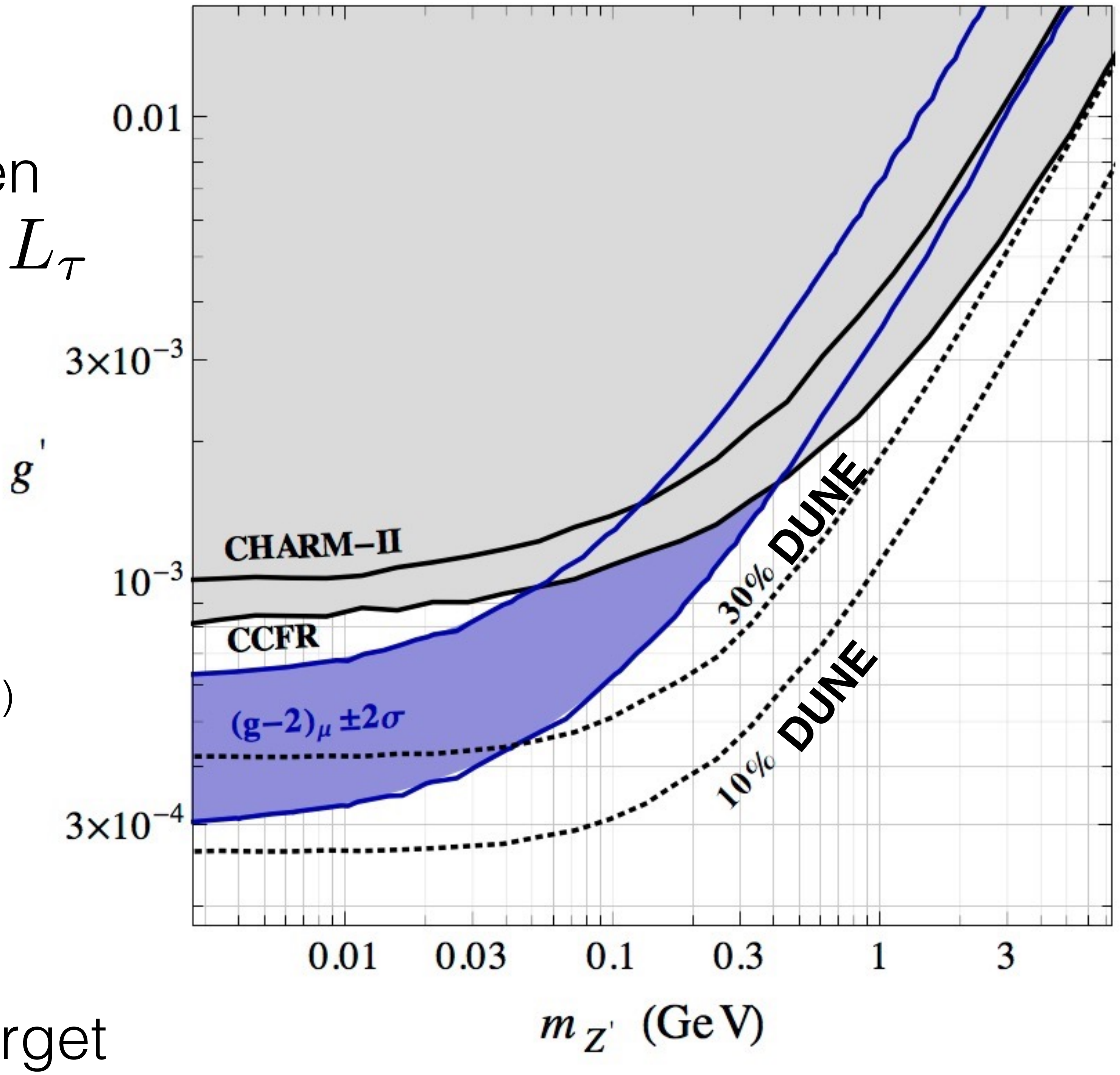
Neutrino Trident

New Physics

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



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

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

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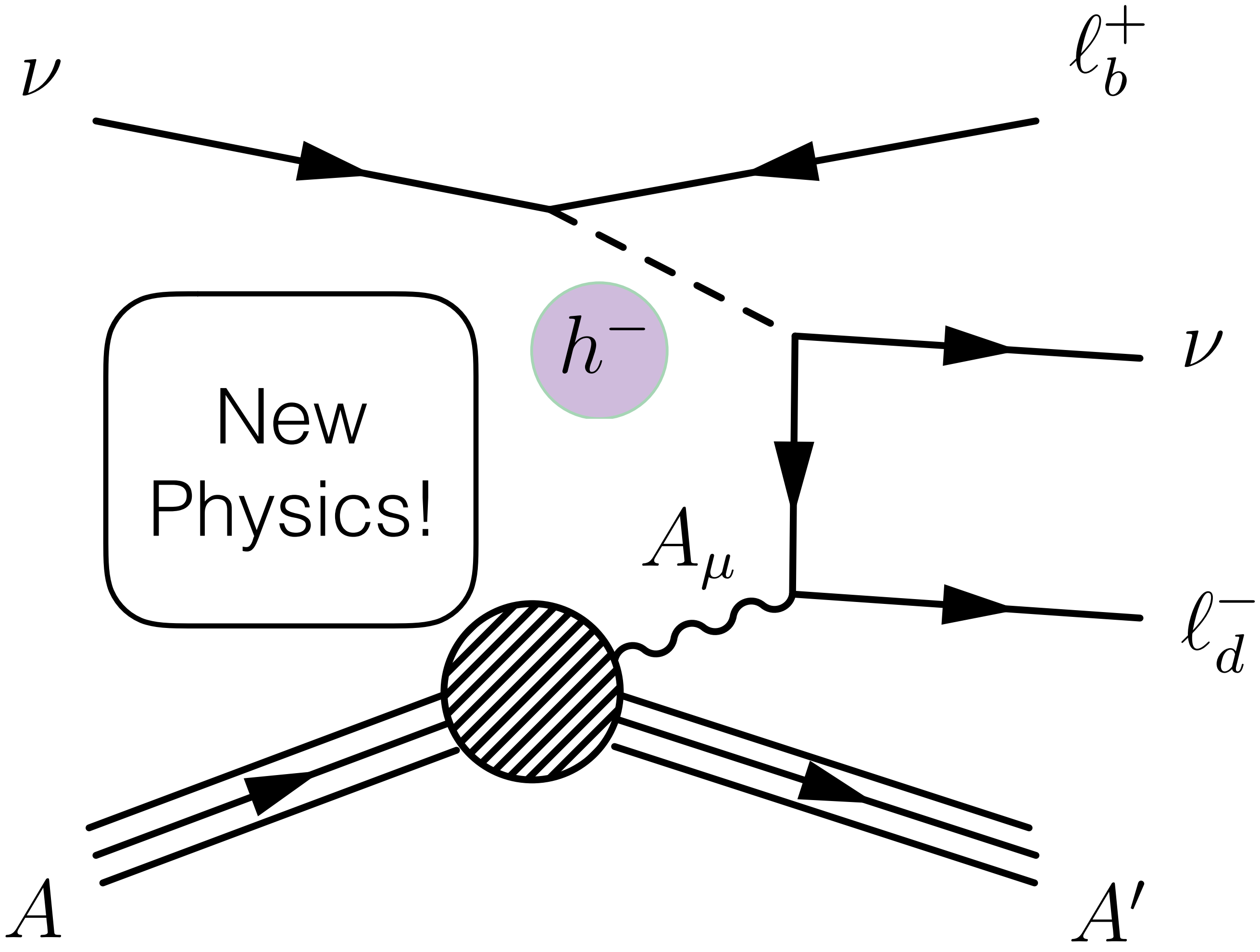
Neutrino Trident

New Physics



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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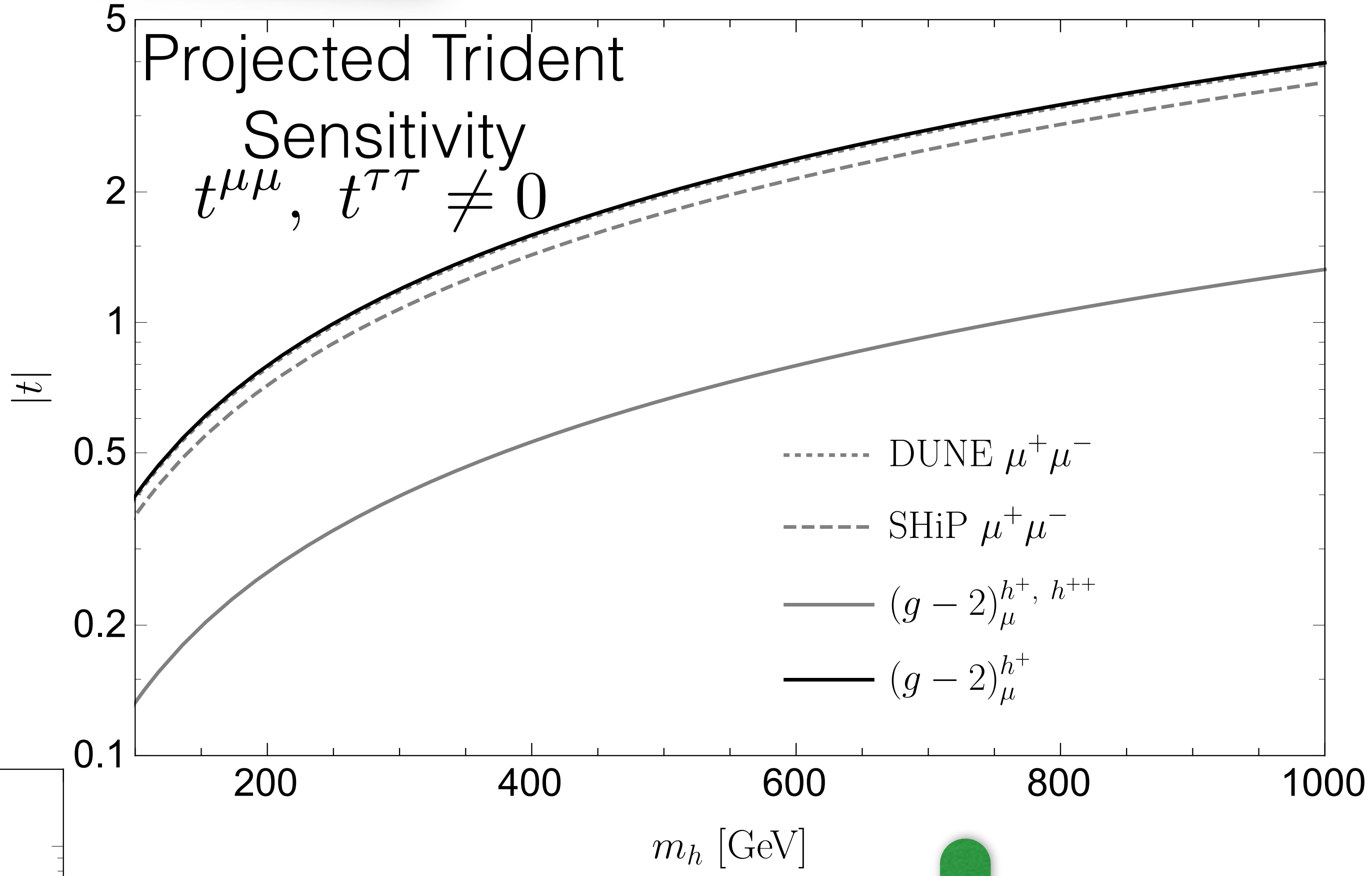
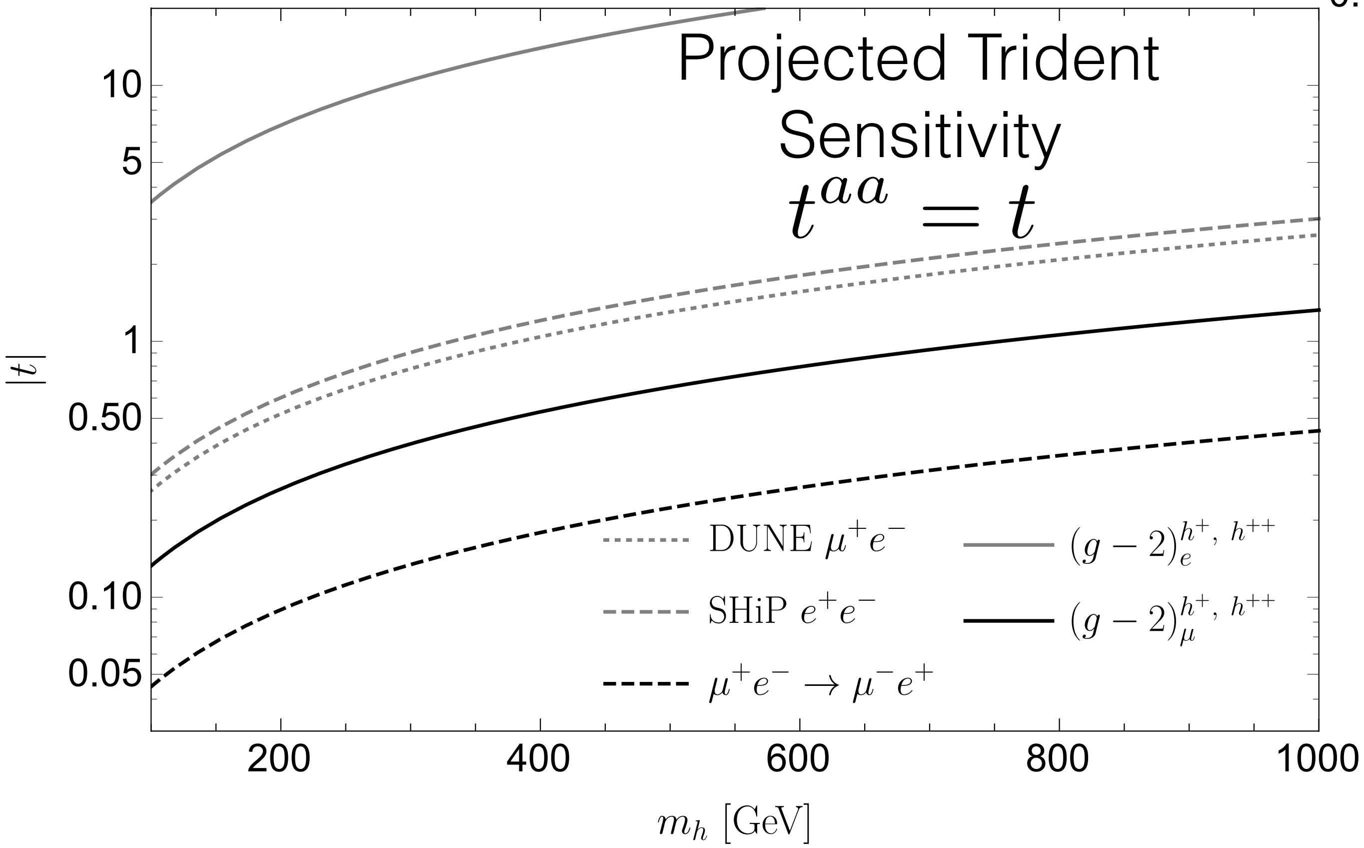
Neutrino Trident

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

arXiv:1710.08431 (RP, Gabriel Magill)





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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Rare Physics

#1 Neutrino Trident

#2 Neutrino Dipole Moments

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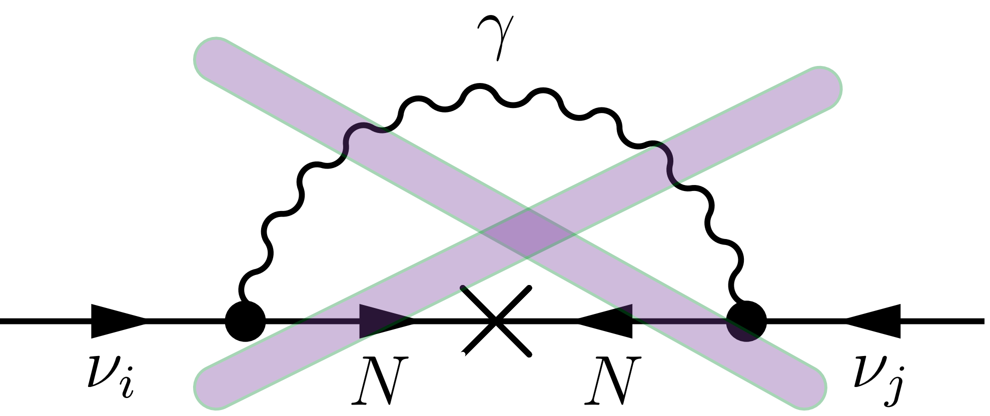
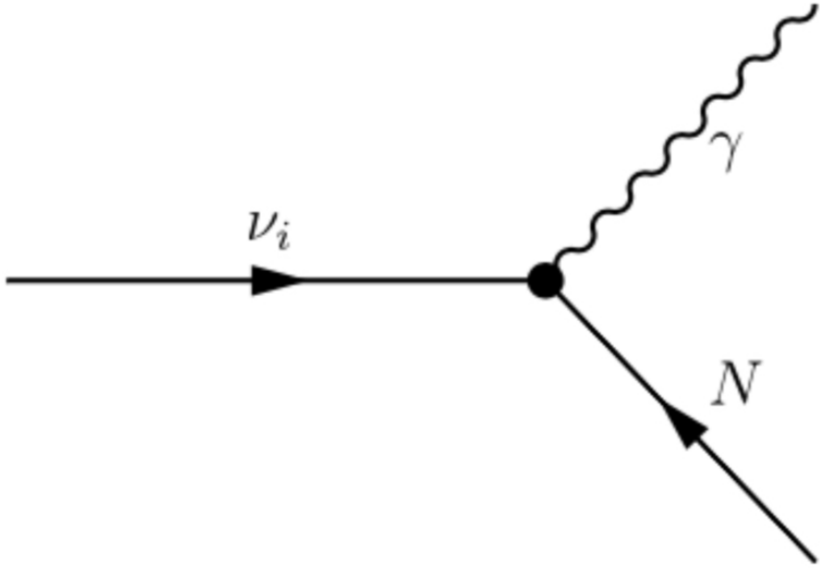
ν Dipole Portal

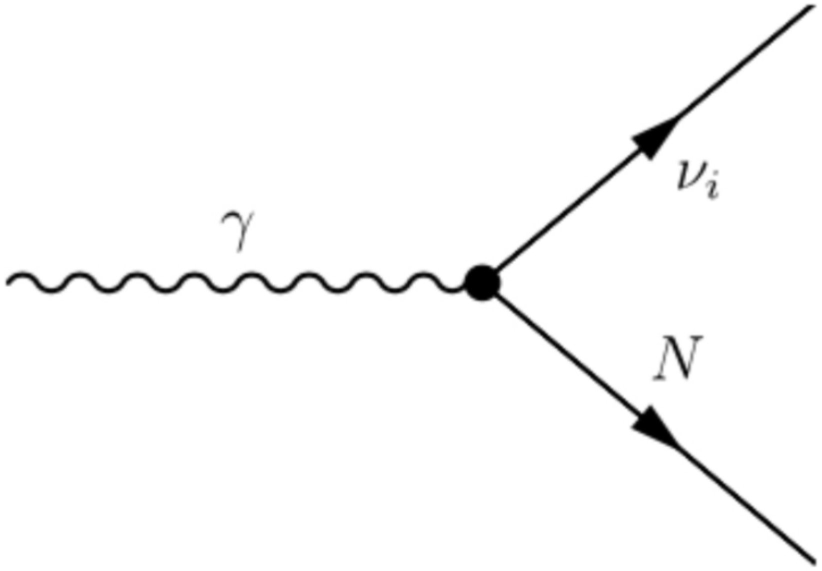
$$\mathcal{L}_{dim\ 5} \supset d_a \overline{\nu_L}_a \sigma_{\mu\nu} F^{\mu\nu} N - m\bar{N}N$$



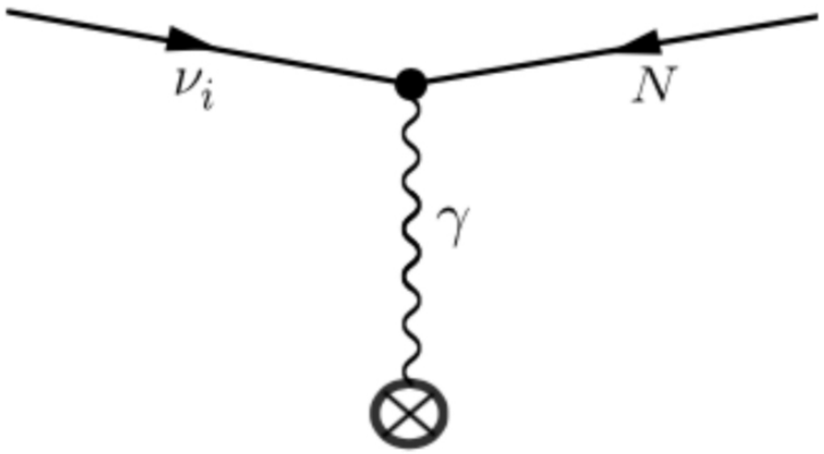
Won’t be detectable in neutrino textures!



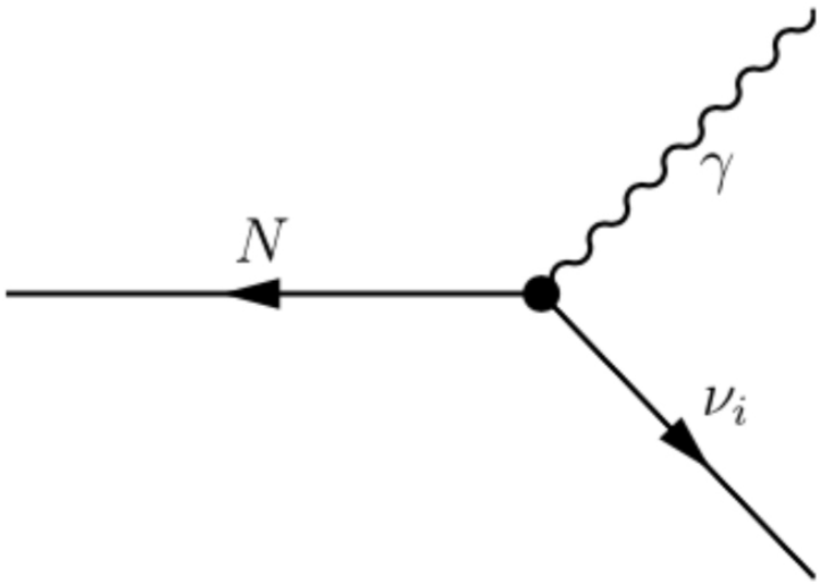
(a) Weak meson decays



(b) Dalitz-like decay

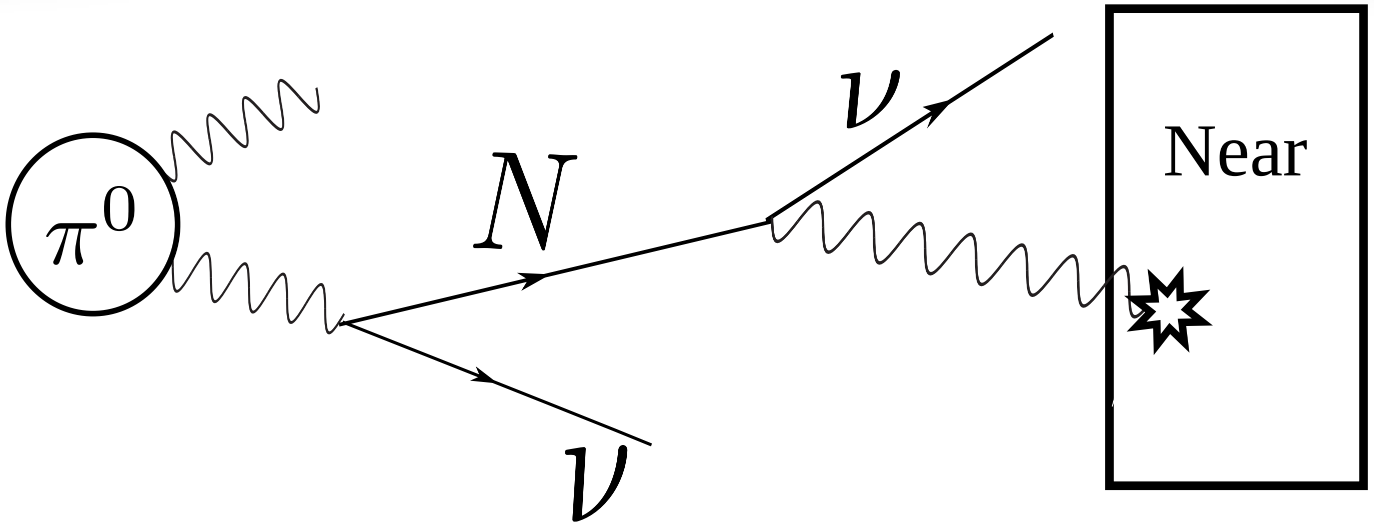


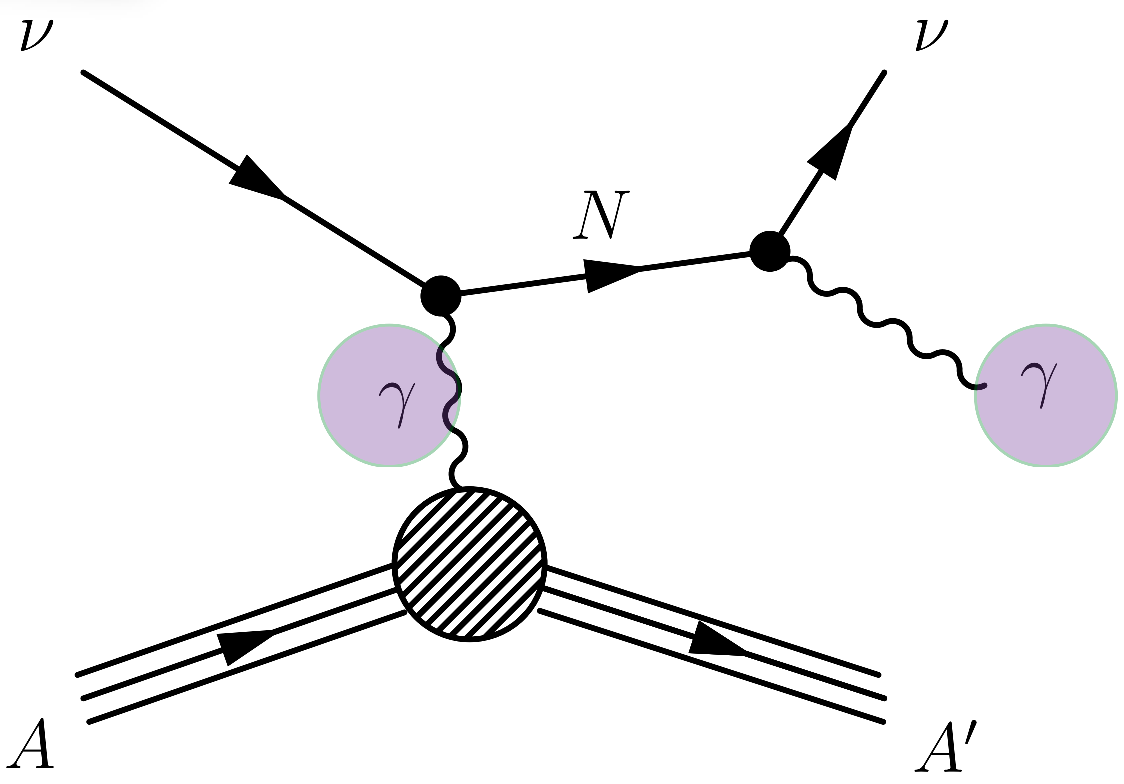
(c) Primakoff upscattering



(d) $N \to \gamma\nu$ (signal)

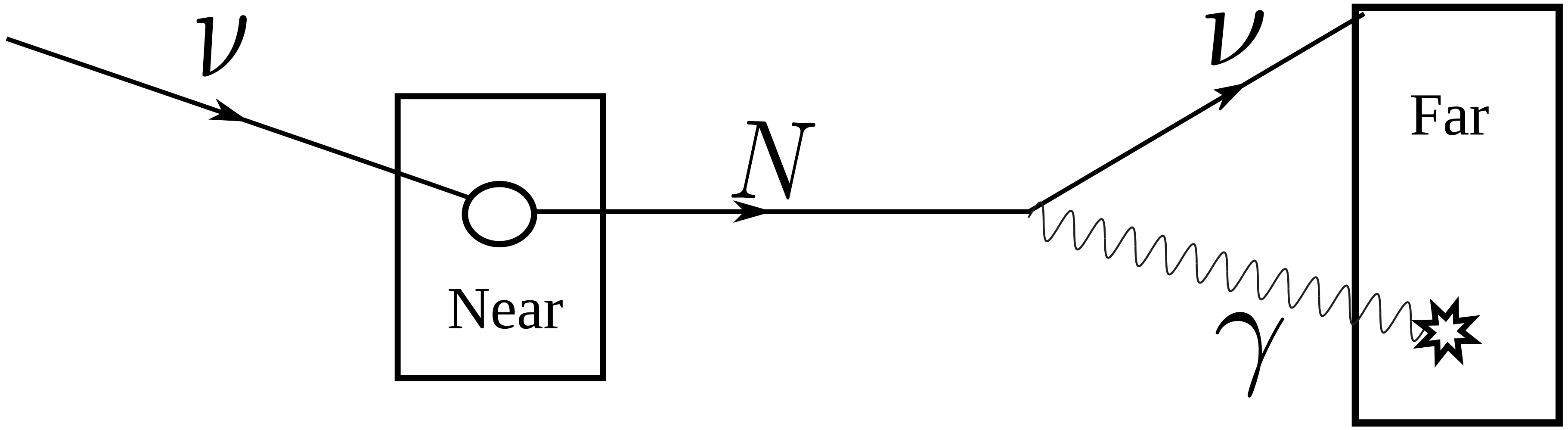
ν Dipole Portal





Upscattering production

$$\Gamma = \frac{d^2 m_N^3}{4\pi}$$



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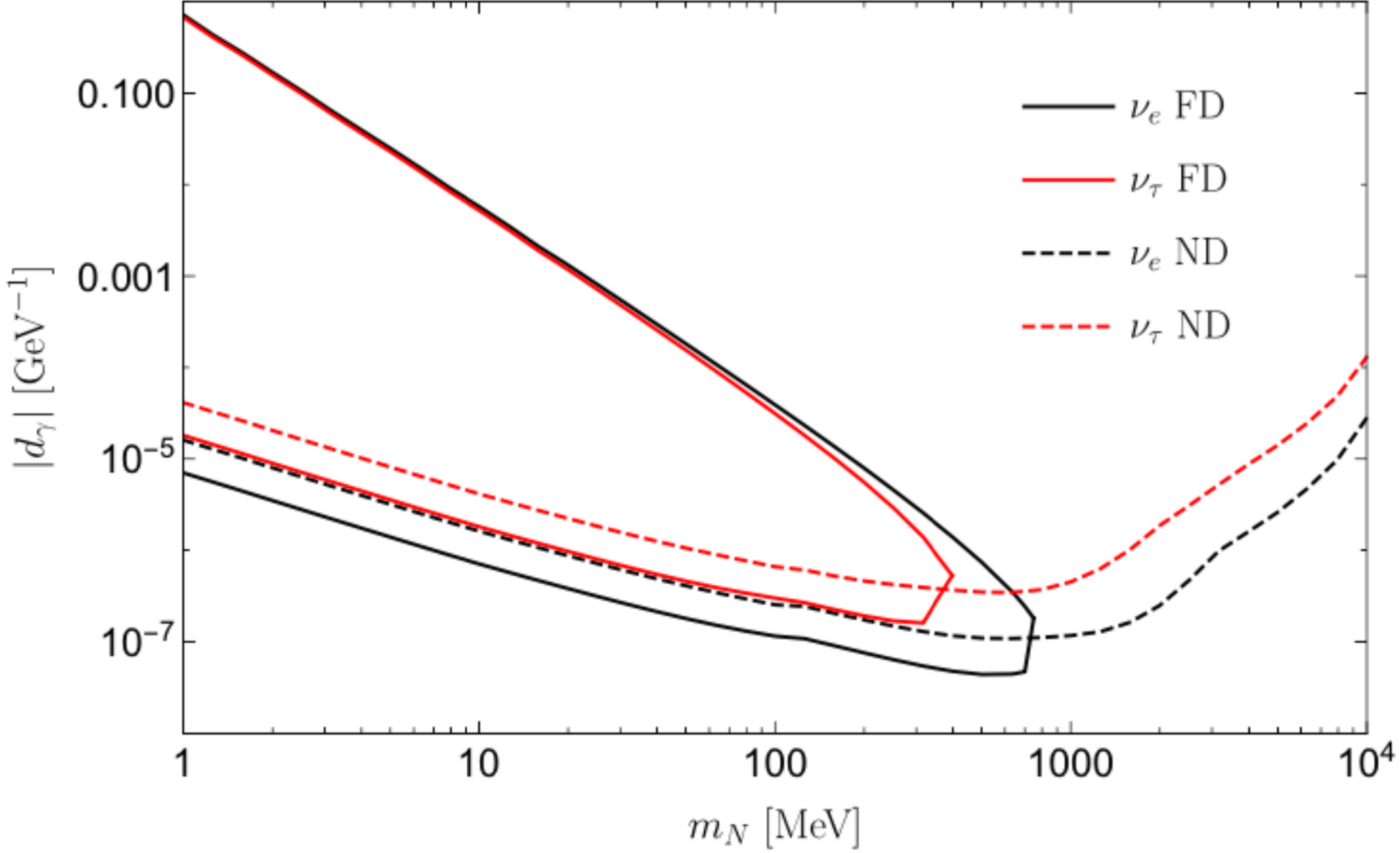
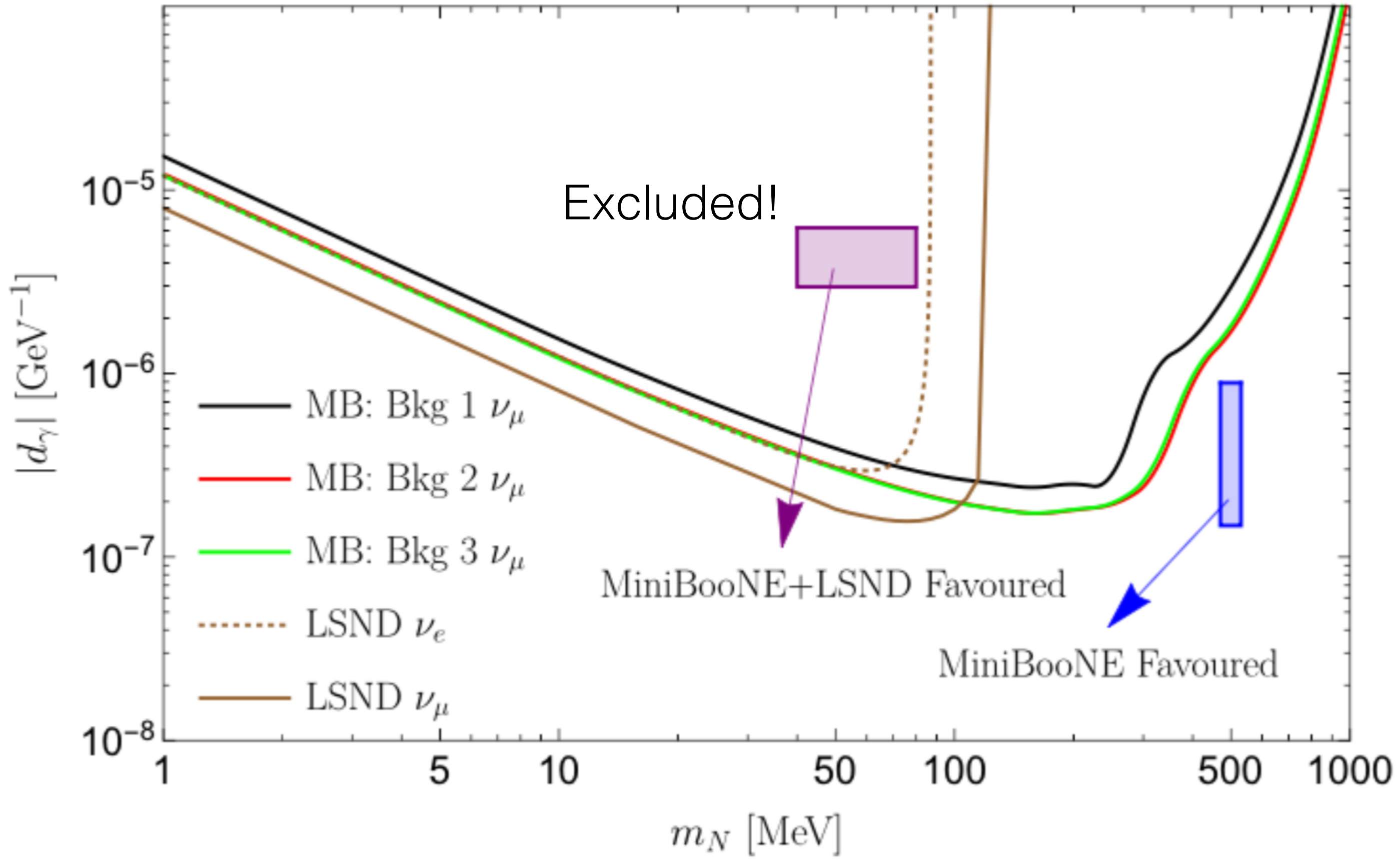
SHiP ν_μ

Limits at SHiP far and near detector. Near detector is sensitive to high masses, while far detector is limited to M~1GeV.

SBN Program

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





$$L_{\rm dec} = 400{\rm m}\left(\frac{m_N}{50\ {\rm MeV}}\right)^4\left(\frac{d}{10^{-6}\ {\rm GeV}^{-1}}\right)^2$$

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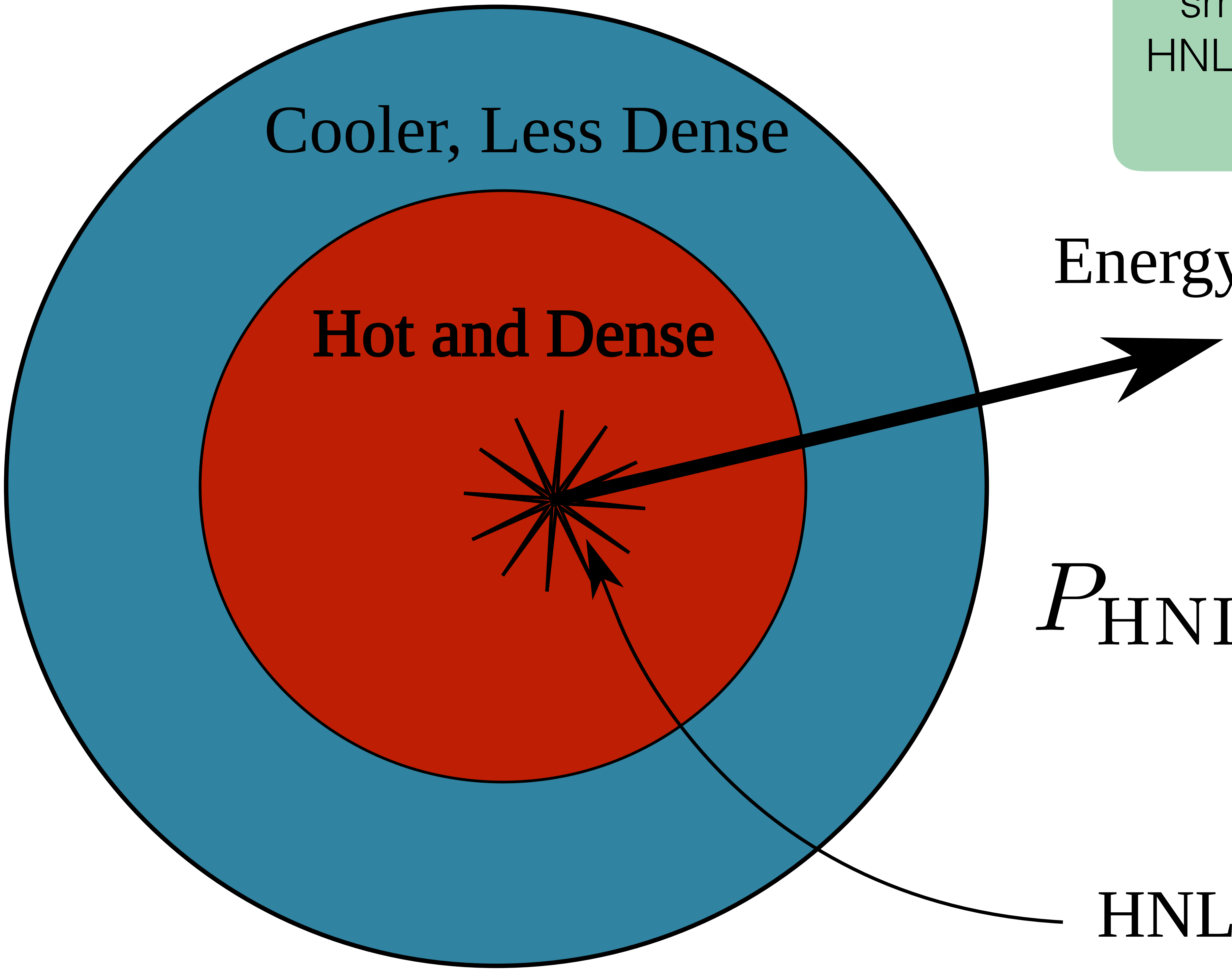
SN1987A

Need to produce HNL to affect cooling

If the dipole coupling is too small then not enough HNLs will be produced to affect cooling.



Energy is lost

$$P_{\mathrm{HNL}} < 10\% P_\nu$$

HNL Produced

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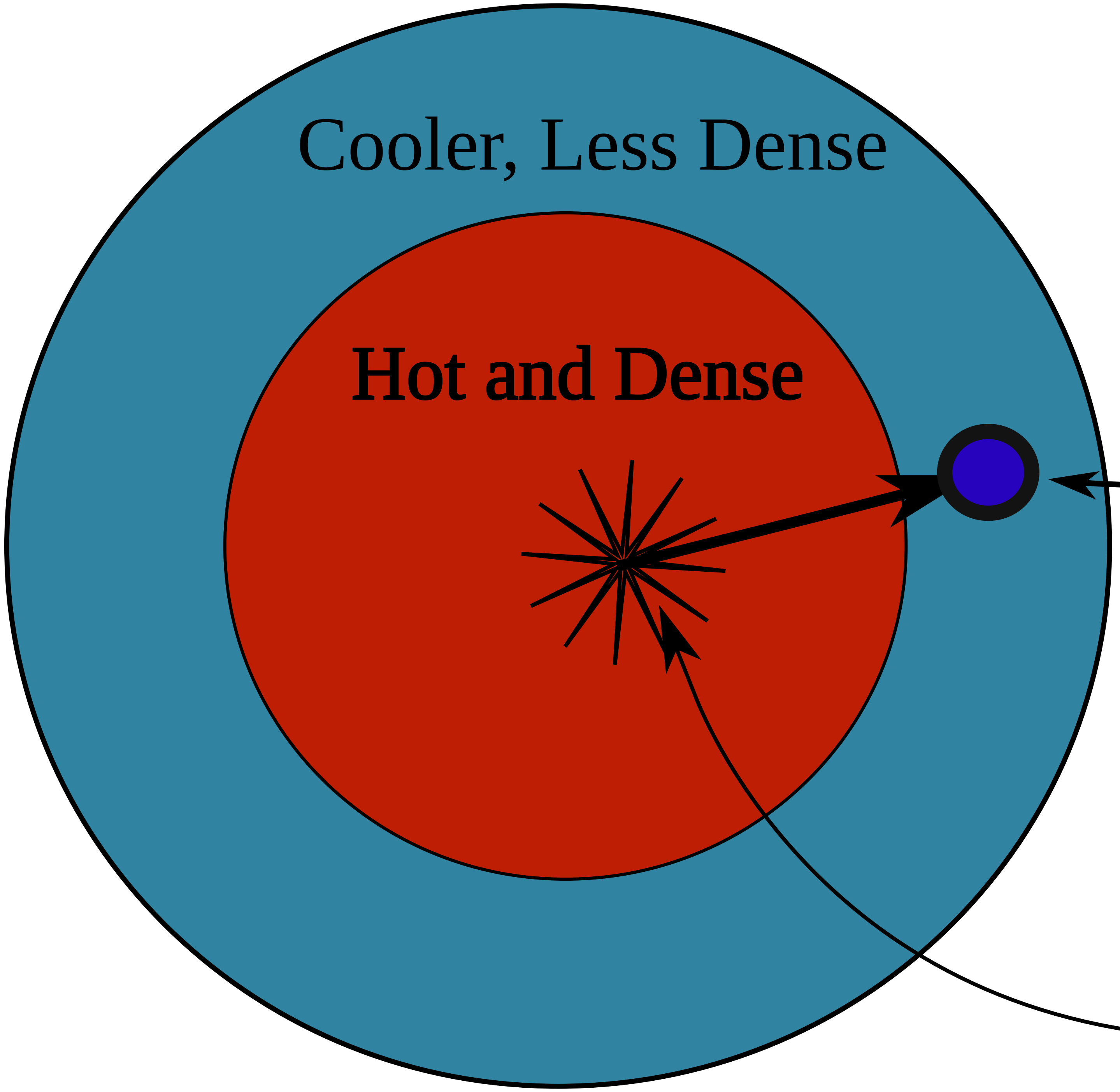
SN1987A

No cooling if HNL cannot escape

If the dipole coupling is too big then all of the HNLs will be reabsorbed without cooling the core



Energy is recaptured

$$P_{\text{escape}} < 50\%$$

HNL Produced

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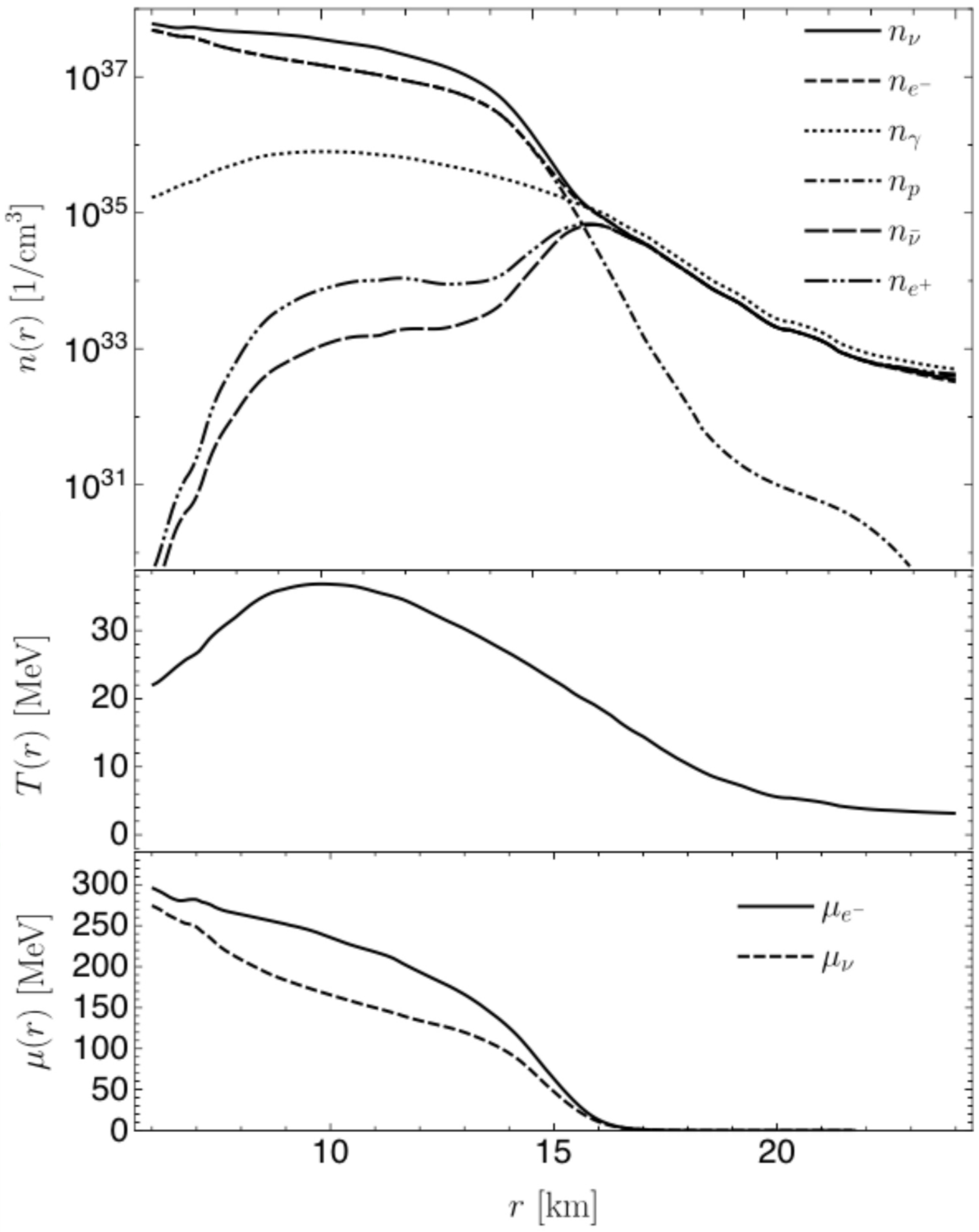
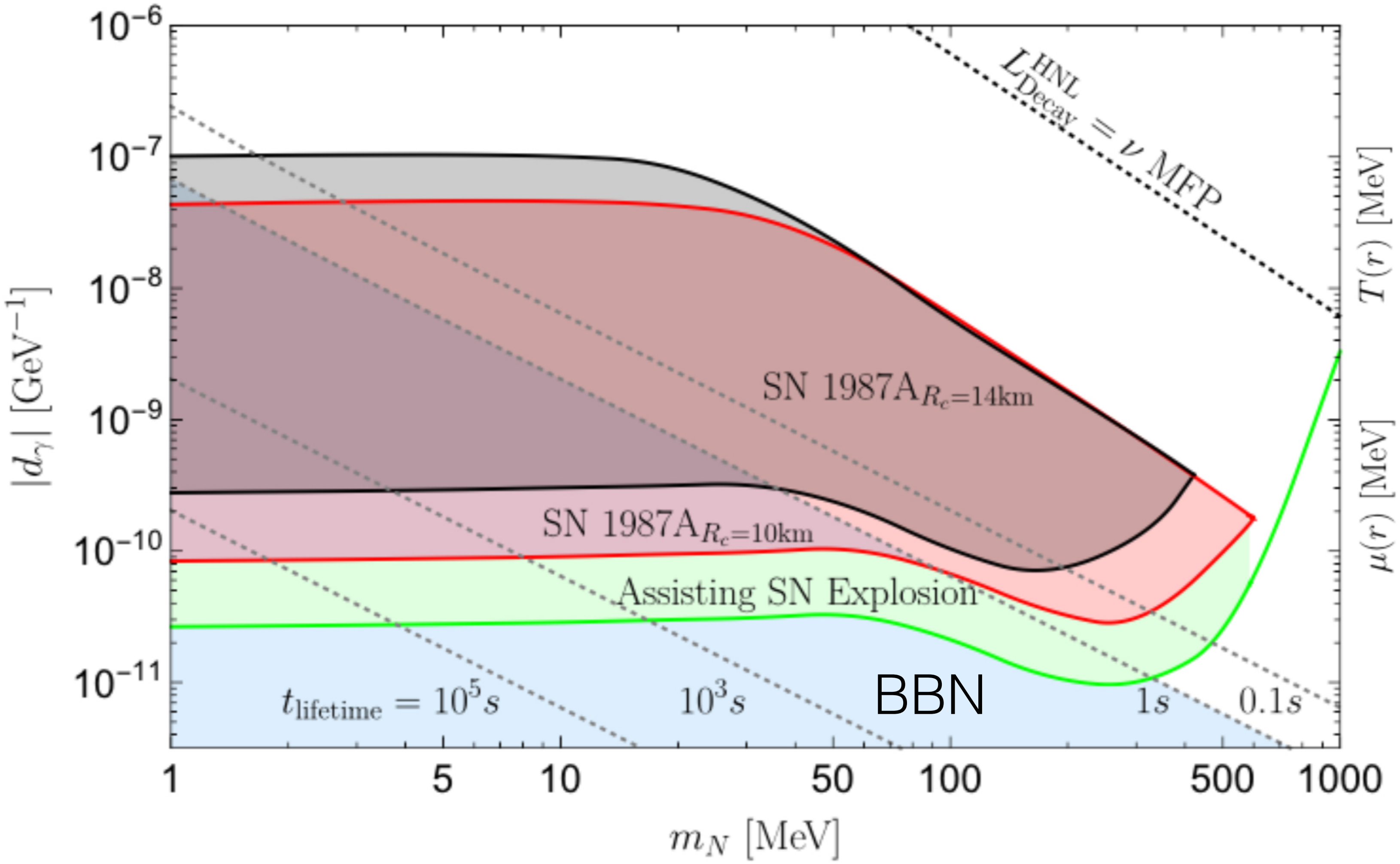
ν Dipole Portal

In preparation (RP, Gabriel Magill
Maxim Pospelov, Yu-Dai Tsai)

SN1987A

- High chemical potentials.
- Pauli blocking is very important.
- High energy (250 MeV) Fermi sea.
- Can probe high masses of HNLs.





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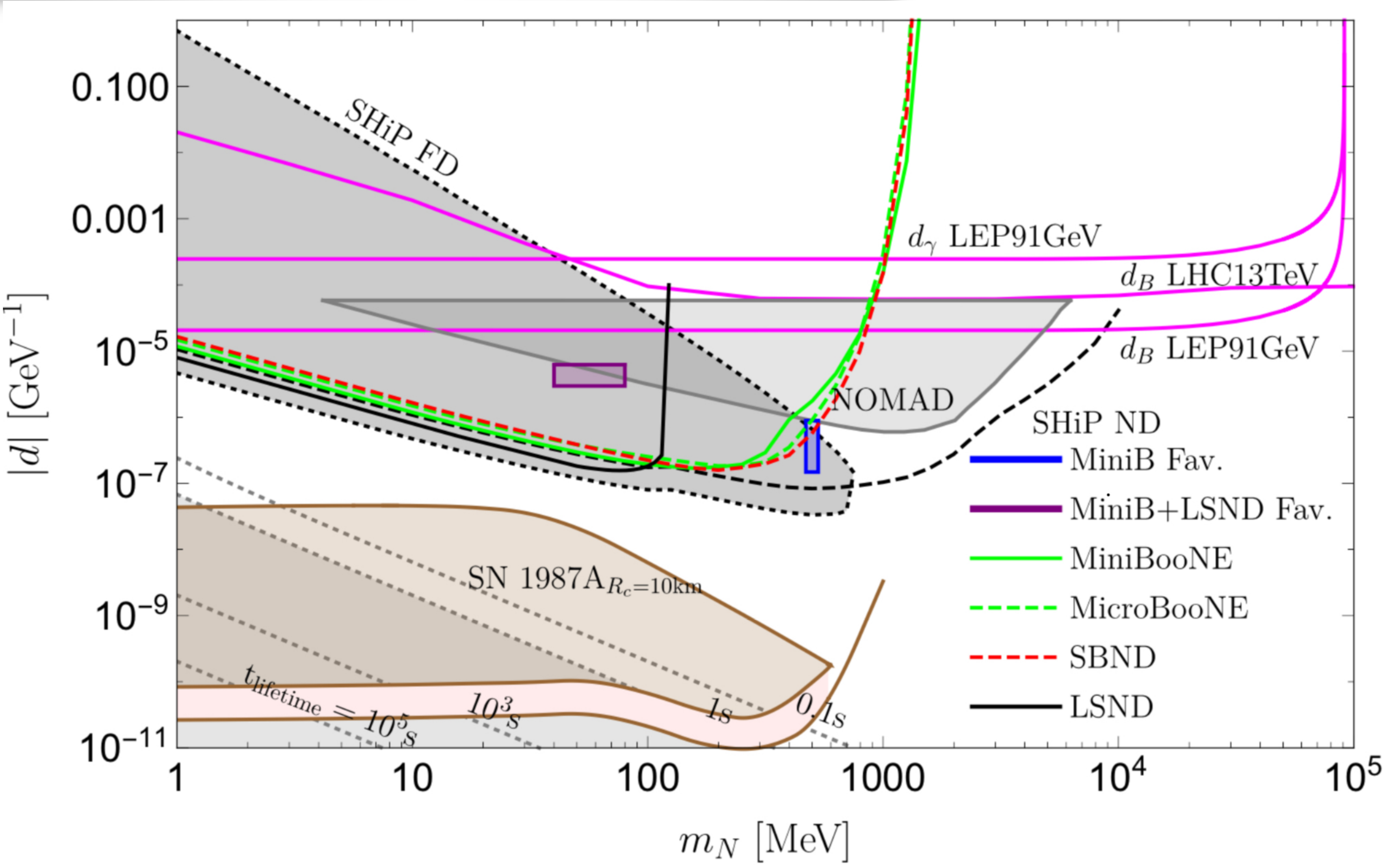
Dipole Portal to HNL

In preparation (RP, Gabriel Magill
Maxim Pospelov, Yu-Dai Tsai)



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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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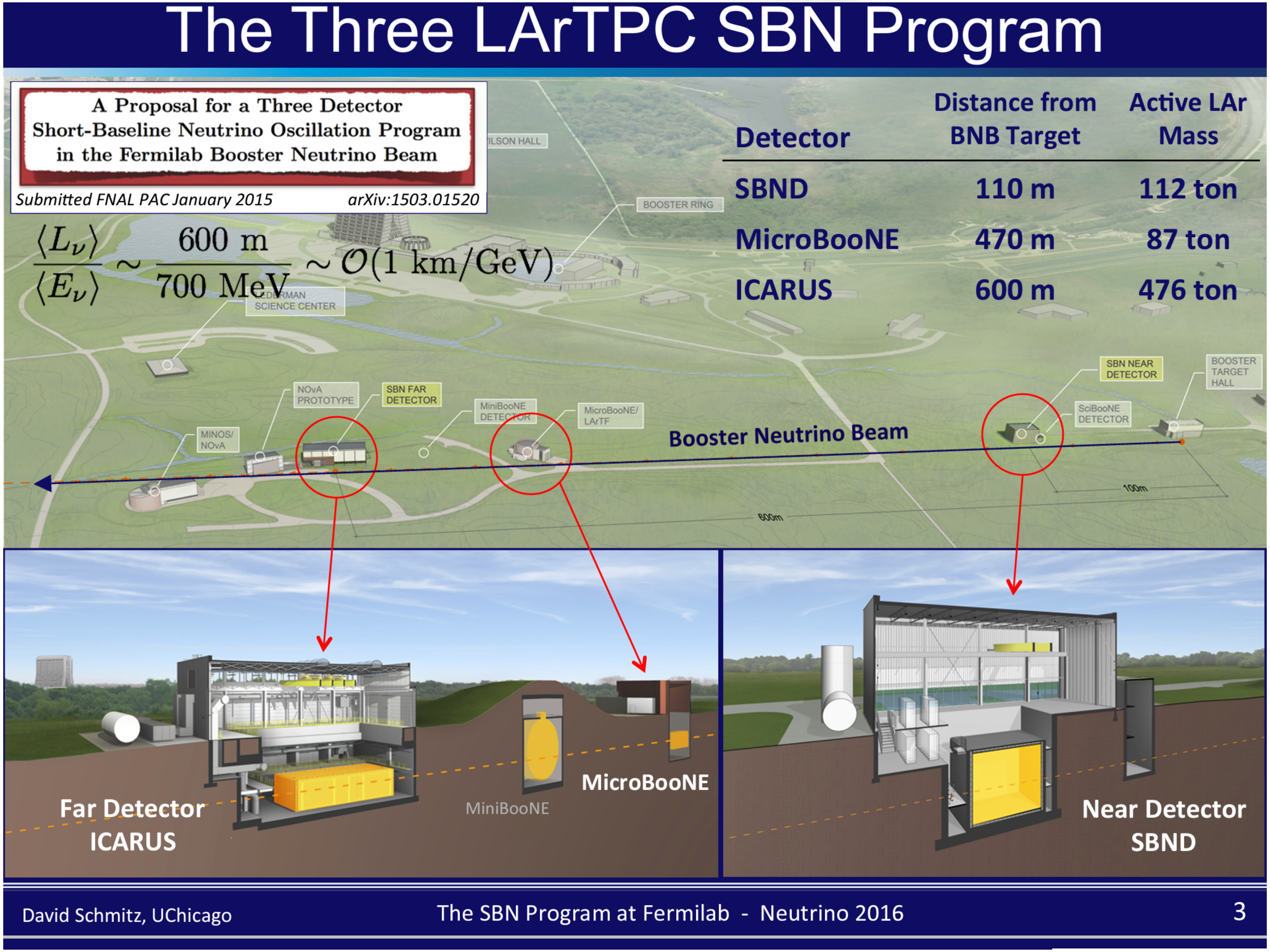
New Experiments

SBN



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Submitted FNAL PAC January 2015 *arXiv:1503.01520*

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David Schmitz, UChicago The SBN Program at Fermilab - Neutrino 2016 3

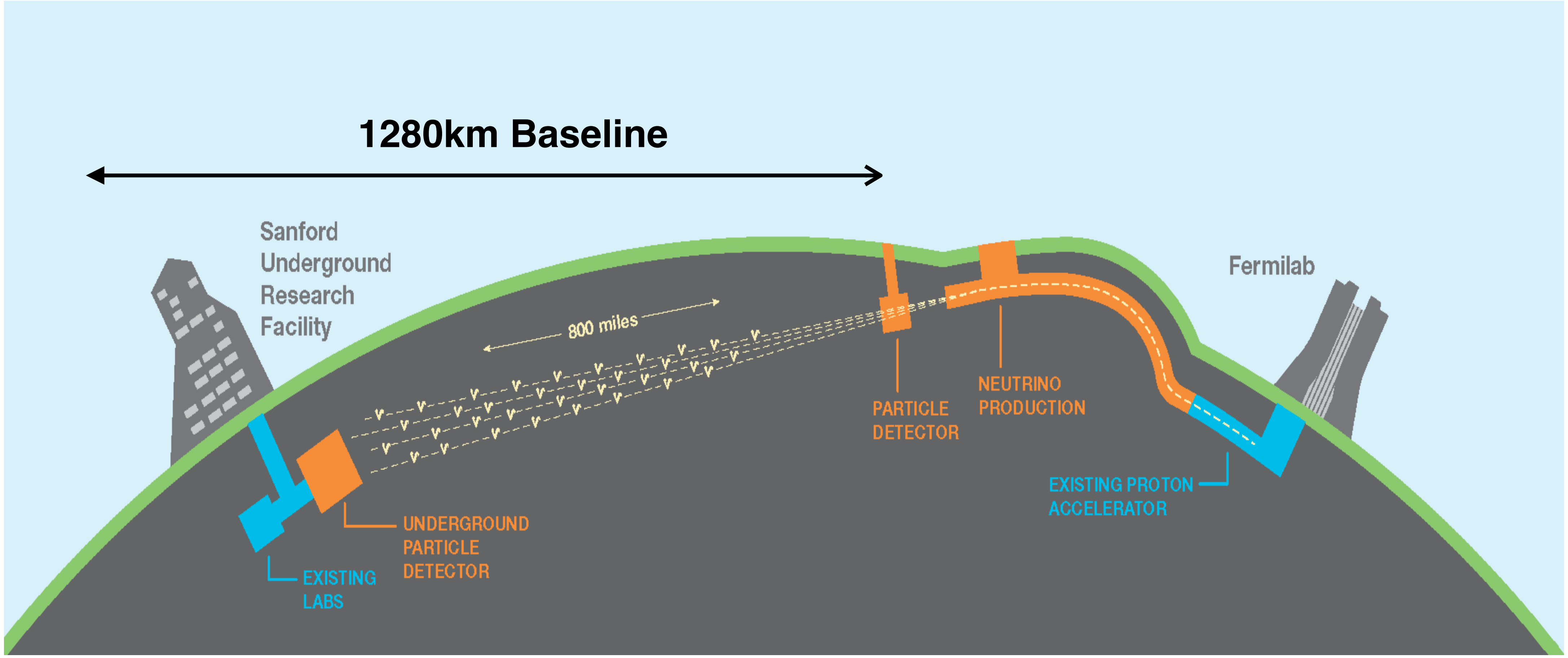
New Experiments

DUNE

arXiv:1512.06148

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

Anti-neutrino & neutrino mode



Liquid Argon TPC

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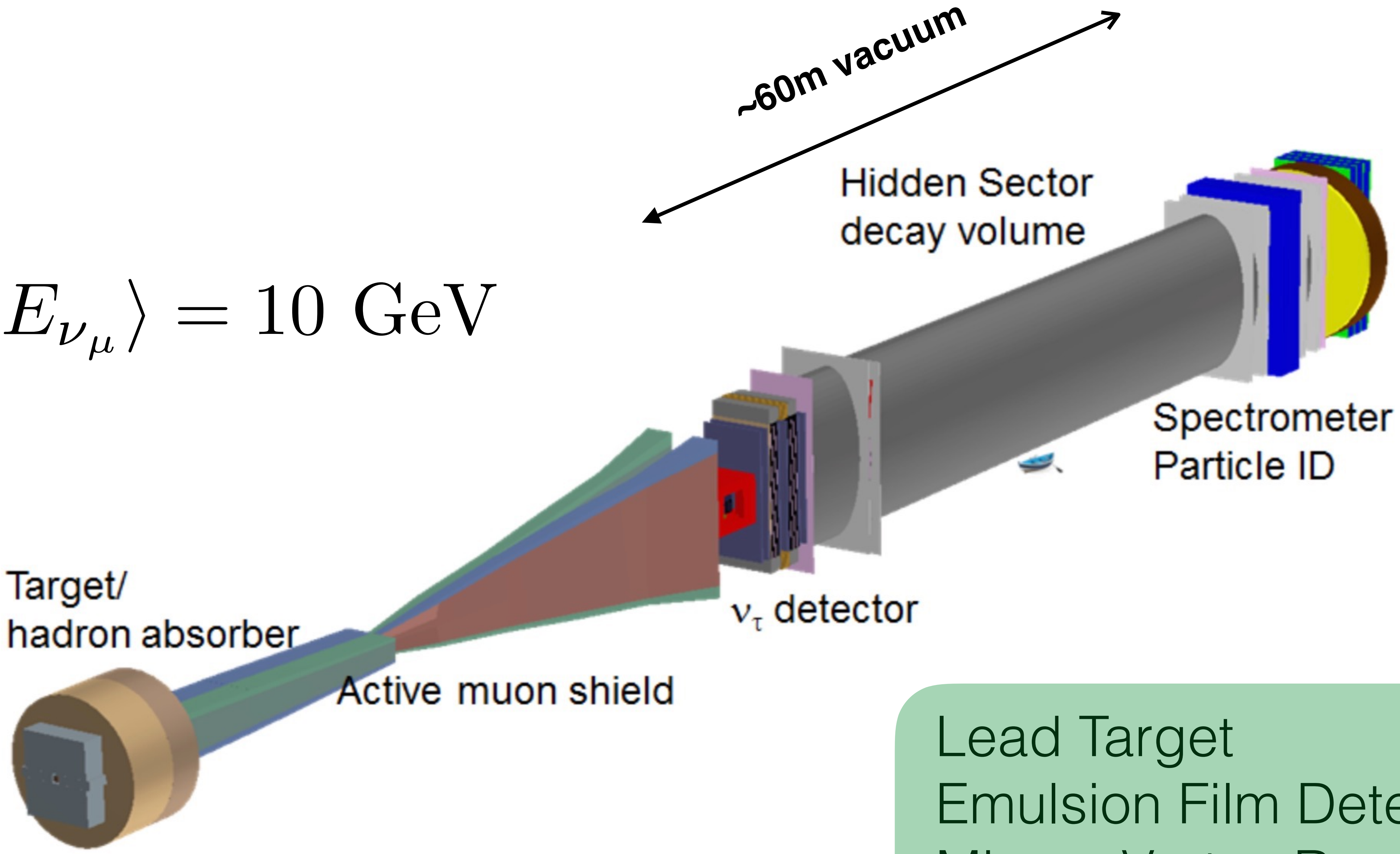
New Experiments

SHiP

arXiv: 1504.04956

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



Lead Target
Emulsion Film Detector
Micron Vertex Resolution

Motivation

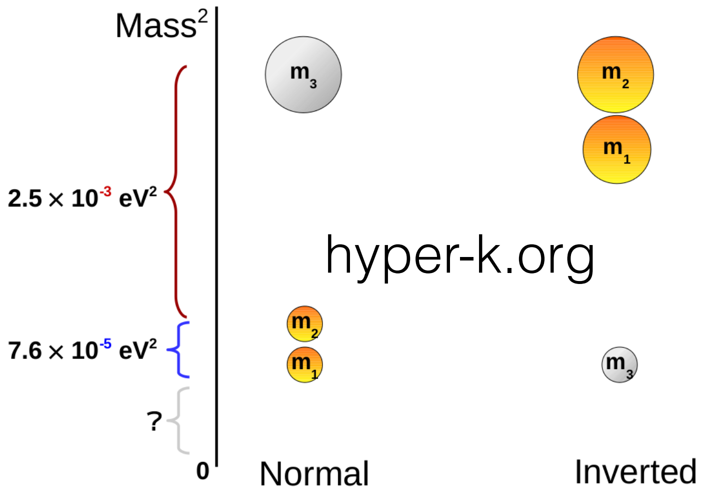
Unanswered questions about neutrinos

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

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

PMNS Matrix

~ CP Violating angle

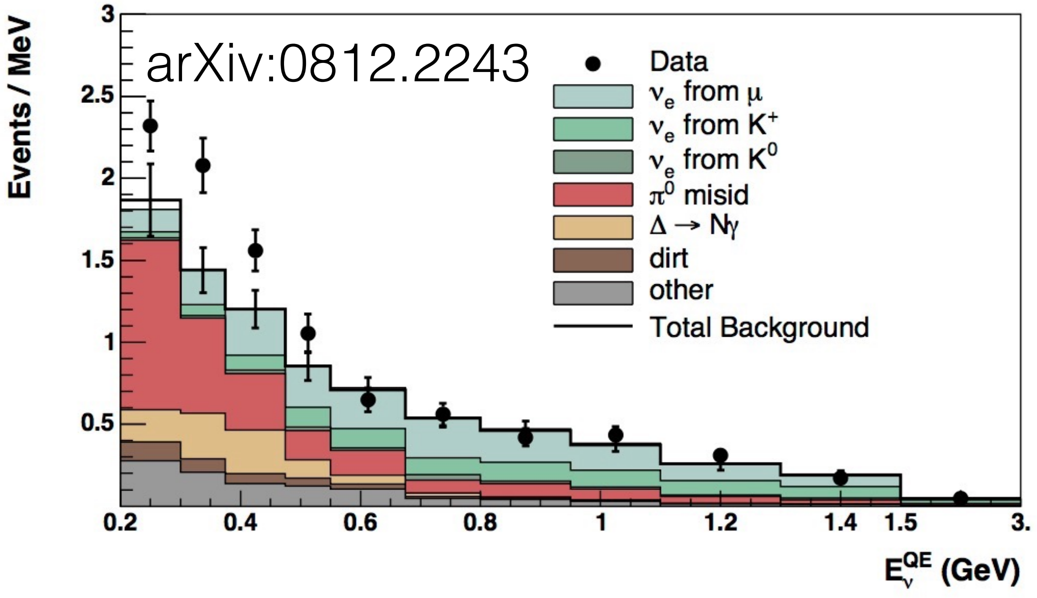
$$\delta_{CP}^{NH}(\pm 1\sigma) = 202^\circ - 312^\circ$$

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

nu-fit.org

Oscillation Anomalies

~ LSND; MiniBooNE:



arXiv:0812.2243

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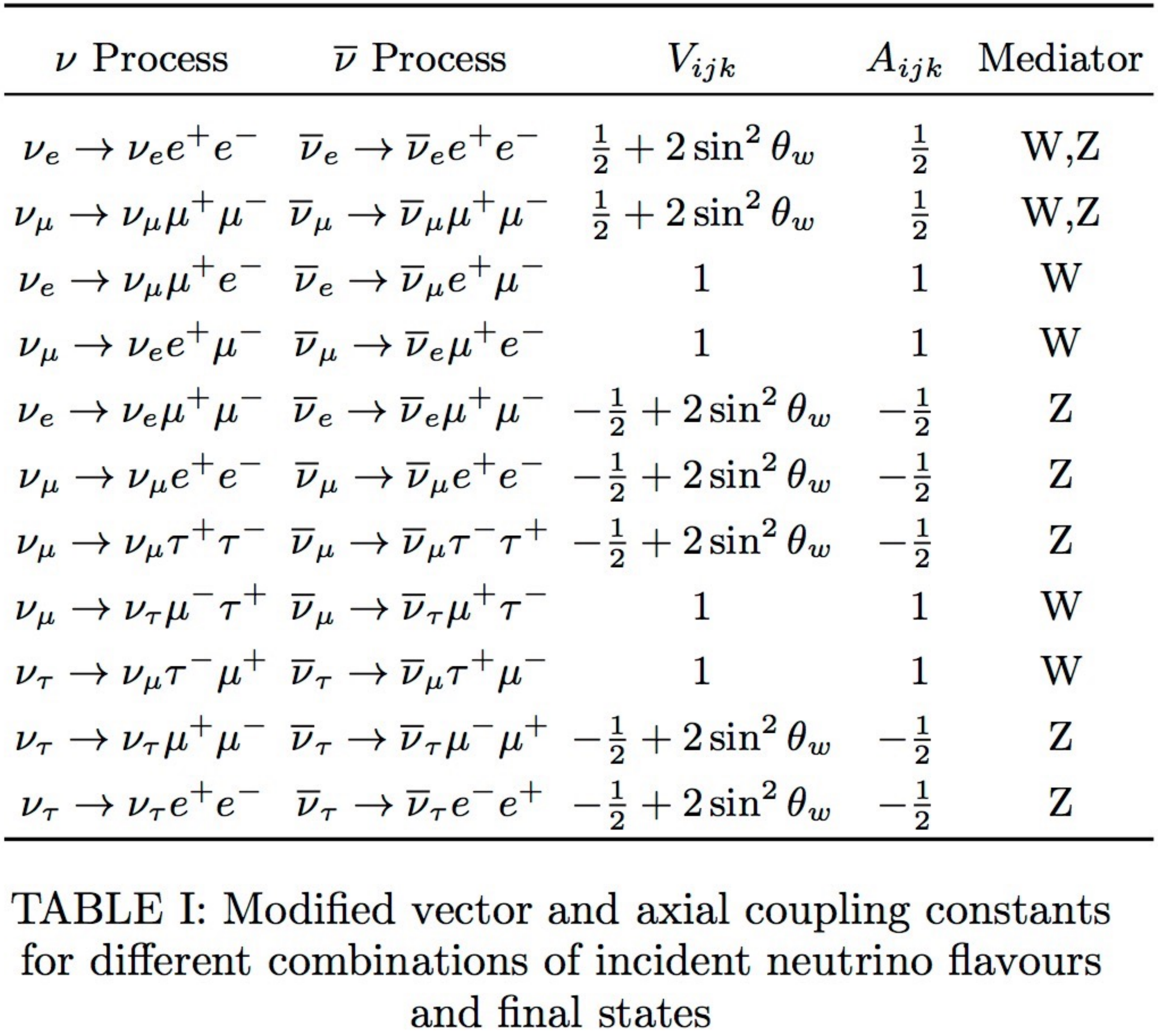
Neutrino Trident

arXiv:1612.05642, PRD 2017 (RP, Gabriel Magill)



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

calculated by
Gninenko for slight
variation of model

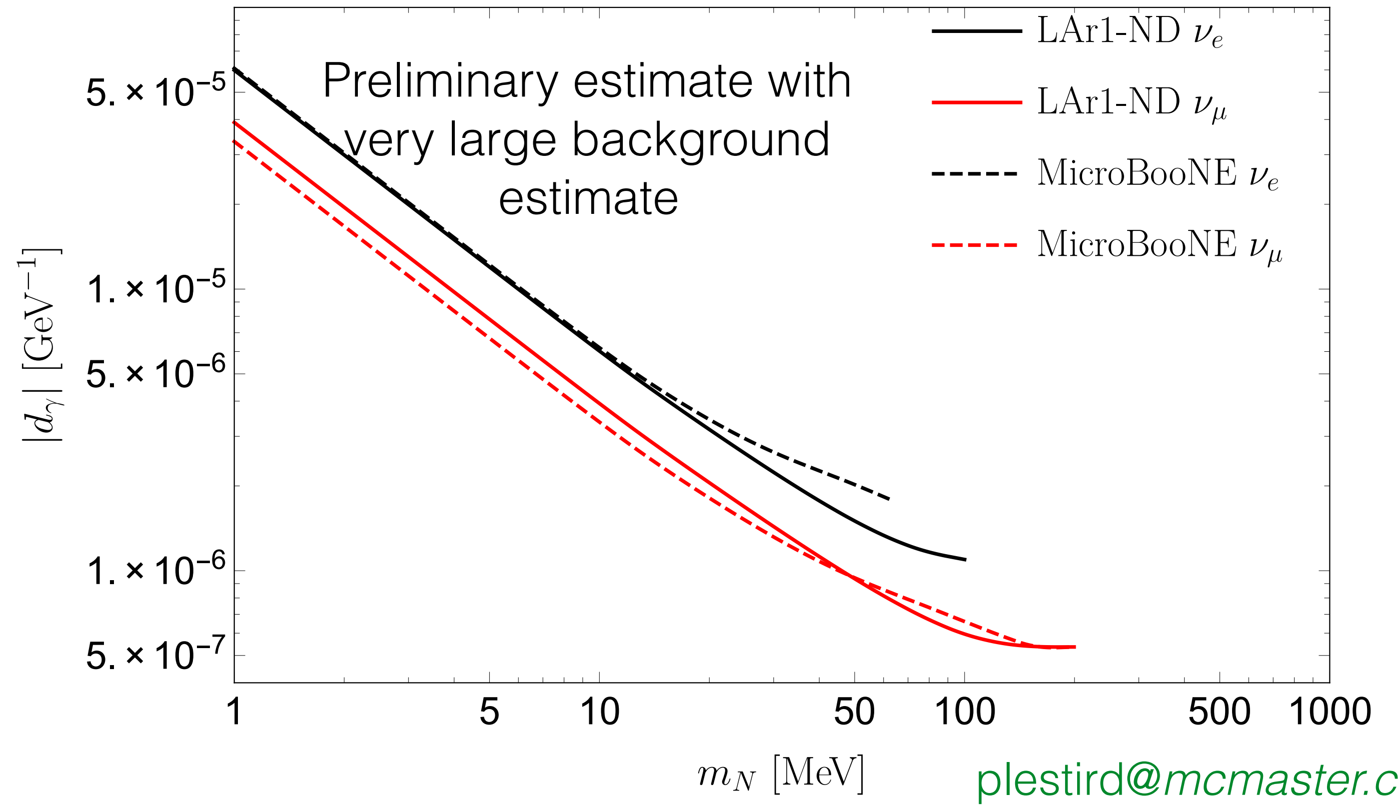
Preliminary Results:
Background estimates subject to change!

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.



Preliminary estimate with very large background estimate

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Neutrino Trident

New Physics

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

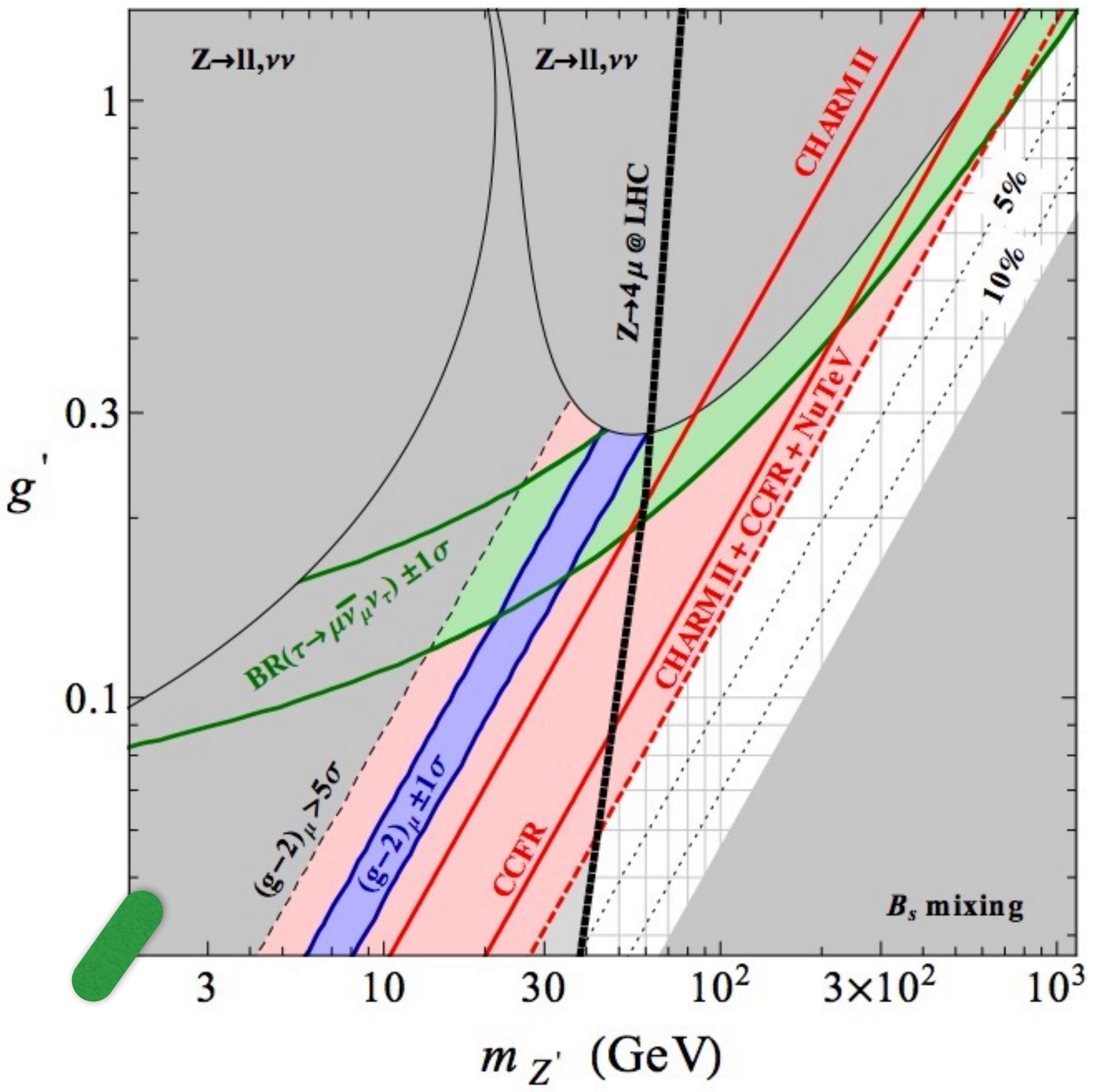
Upcoming experiments to target parameter space favoured by

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

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

With a little model building, can couple Z' to light quarks: Provides explanation to $B \rightarrow K^{*} \mu \;\; \mu$

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



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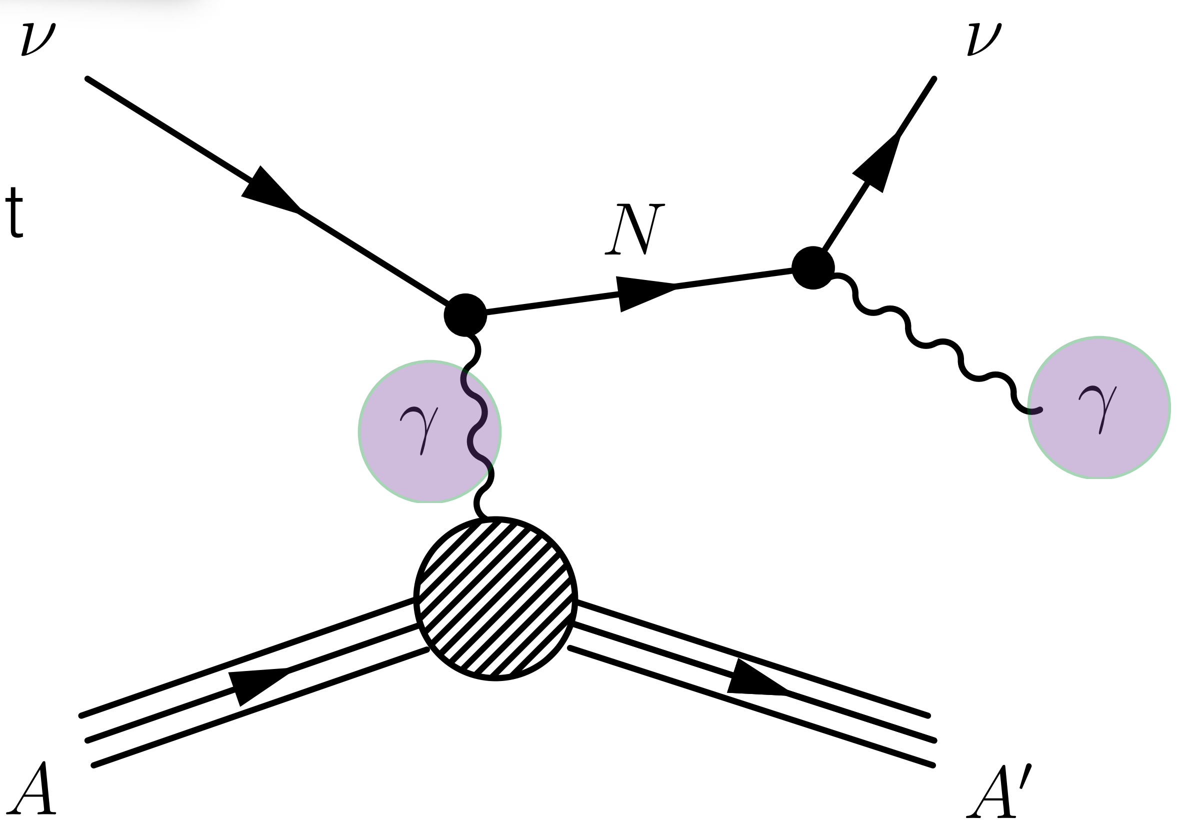
ν Dipole Portal



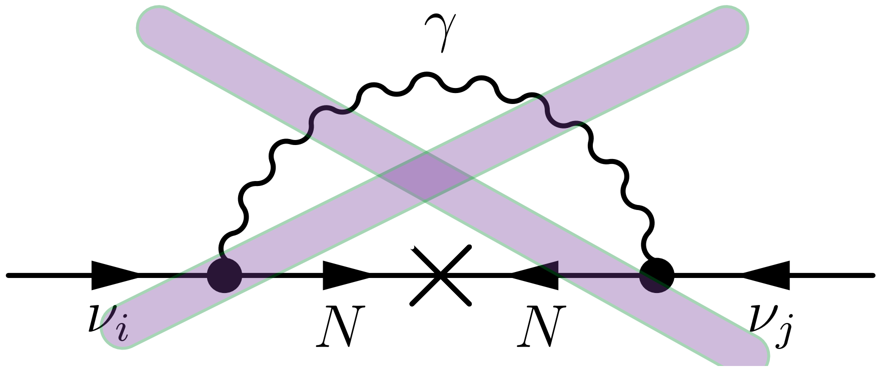
Follow up:

~ 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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