Thoughts on the optimization of the VLENF

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DISCLAIMER:

Most of the following is based on the high energy Neutrino Factory

However: many of the basic conclusions should be transferable …

Contents

- Neutrino factory flux
- Treatment of near detectors
- Treatment of sterile neutrinos
- Systematics/energy resolution issues
- Conclusions

Neutrino factory flux

$$\frac{d^2\Gamma}{dE_{\nu_\mu}d\cos\theta} = \frac{G_F^2 m_\mu}{24\pi^3}\gamma(1-\beta\cos\theta)E_{\nu_\mu}^2\left[3m_\mu - 4\gamma E_{\nu_\mu}(1-\beta\cos\theta)\right],$$

$$\frac{d^2\Gamma}{dE_{\nu_e}d\cos\theta} = \frac{G_F^2 m_\mu}{4\pi^3}\gamma(1-\beta\cos\theta)E_{\nu_e}^2\left[m_\mu - 2\gamma E_{\nu_e}(1-\beta\cos\theta)\right].$$

$$\gamma = E_\mu/m_\mu = 1/\sqrt{1-\beta^2}$$

- Sometimes useful to integrate over energy:

$$\frac{d\Gamma}{d\cos\theta} = \frac{G_F^2 m_\mu^5}{384\pi^3}\frac{1}{[\gamma(1-\beta\cos\theta)]^2}$$

[neglect beam collimation for the moment]

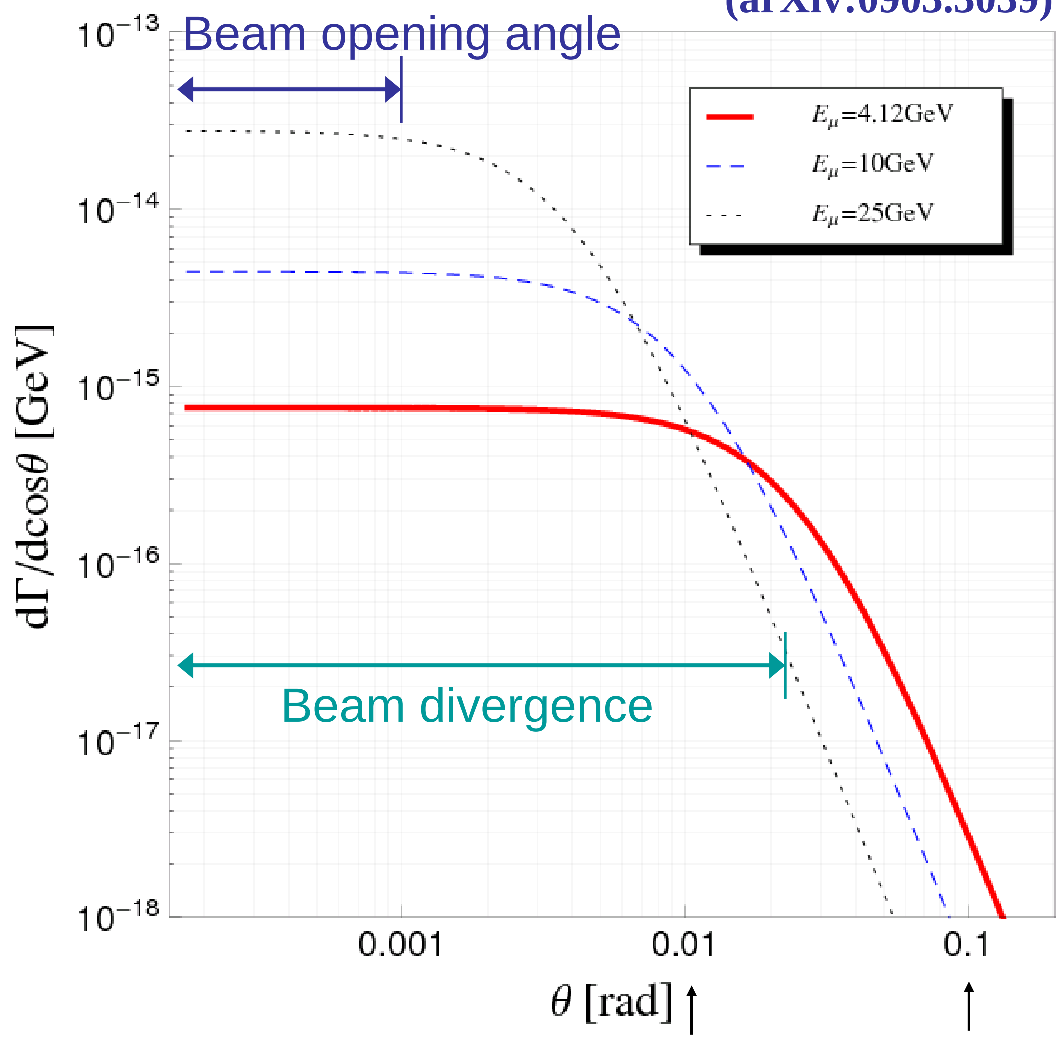
Geometry of the beam

- Beam diameter ~ 2 x L x θ
- We use two beam angles:
  - Beam opening angle:

$$\left.\frac{\Gamma}{d\cos\theta}\right|_{\theta} = 0.9\left.\frac{\Gamma}{d\cos\theta}\right|_{\theta=0}$$

  - Beam divergence: contains 90% of total flux

(arXiv:0903.3039)

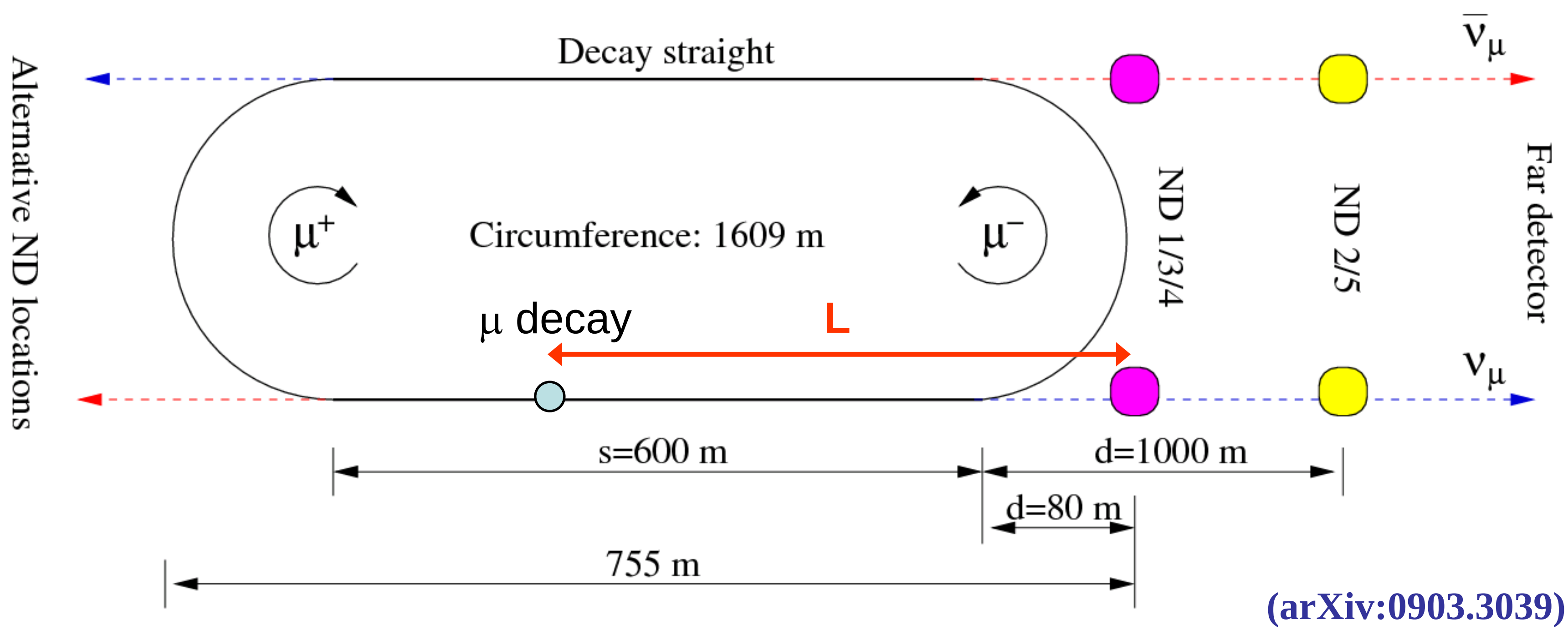


Diameter ~0.4 m in d=20 m

4 m in d=20 m

Geometry of decay ring

- Example: high energy version

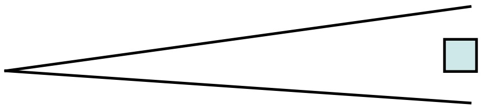


- d = distance from end of straight
- s = length of straight
- L = baseline (from decay point to detector)

Approximations

- **Far distance approximation:**
  Flux in whole detector looks like on-axis flux

$$\frac{d^2\Gamma}{dE_{\nu_\alpha}\, d\cos\theta}(\cos\theta) \simeq \frac{d^2\Gamma}{dE_{\nu_\alpha}\, d\cos\theta}\Big|_{\theta=0}$$



- **Point source approximation:**
  Extension of source can be neglected

d ~ L >> s

(arXiv:0903.3039)

Extreme cases

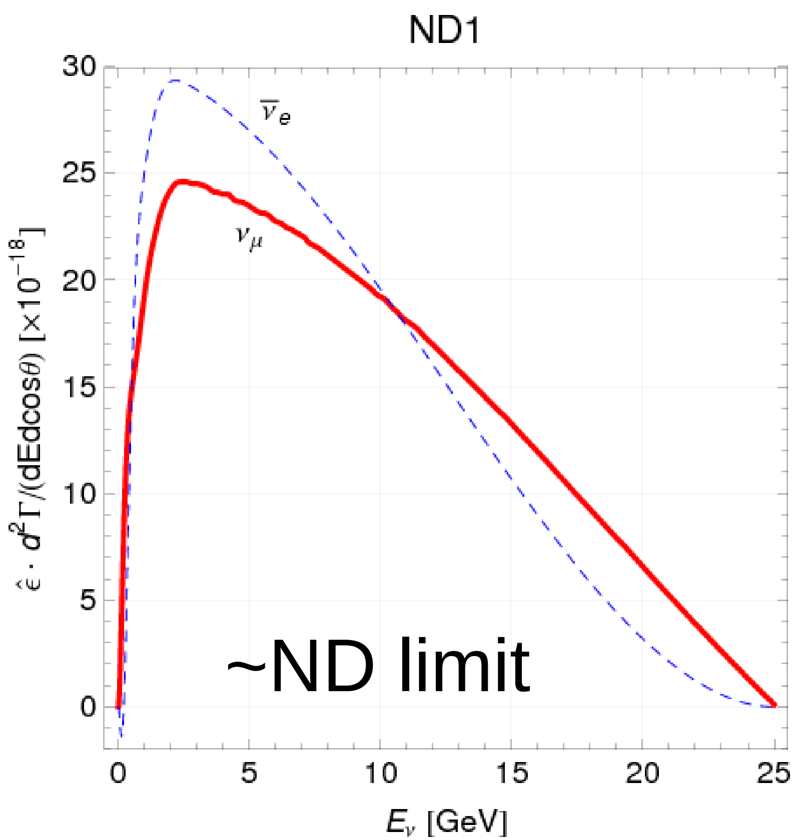
- **Far detector limit:**
  Far distance approximation for *any* point of the decay straight, i.e., the detector diameter D < 2 x L x θ, where θ is the beam opening angle
- **Near detector limit:**
  The detector catches almost the whole flux for *any* point of the decay straight, i.e., the detector diameter D > 2 x L x θ, where θ is the beam divergence

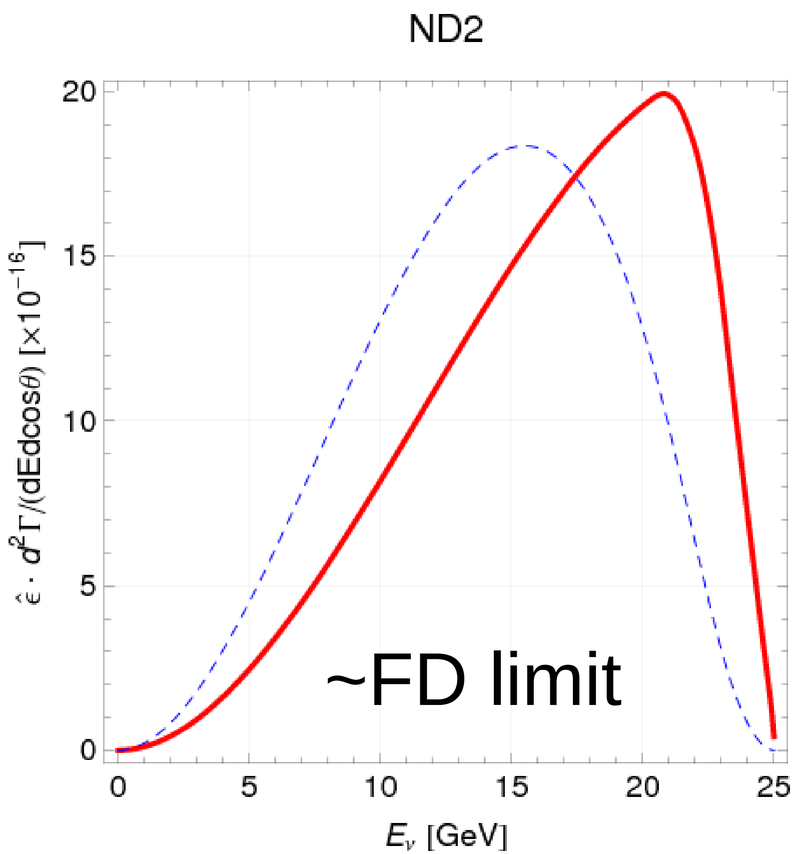
(arXiv:0903.3039)

Extreme cases: Spectra

- Some examples (HENF):

Parameter	ND1	ND2
Diameter D	17 m	4 m
Distance d	80 m	1000 m
Mass	450 t	25 t





(arXiv:0903.3039)

Some technicalities

- How to treat arbitrary detectors in GLoBES?
  (which uses the point source and far distance approximations)

1) Take into account extension of detector

$$A_{\mathrm{eff}} = \frac{2\pi L^2}{\frac{d^2\Gamma}{dE\,d\cos\theta}\big|_{\theta=0}} \int_0^{\frac{D}{2L}} \frac{d^2\Gamma}{dE\,d\cos\theta} \sin\theta\, d\theta \quad \text{and} \quad \varepsilon(E,L) = \frac{A_{\mathrm{eff}}}{A_{\mathrm{Det}}}$$

2) Take into account extension of straight

$$\frac{dN_{\mathrm{avg}}}{dE} = \frac{dN_{\mathrm{PS}}(L_{\mathrm{eff}},E)}{dE} \frac{L_{\mathrm{eff}}^2}{s} \int_d^{d+s} \frac{\varepsilon(L,E)}{L^2} dL = \boxed{\frac{dN_{\mathrm{PS}}(L_{\mathrm{eff}},E)}{dE}} \hat{\varepsilon}(E)$$

$$\hat{\varepsilon}(E) \equiv \frac{L_{\mathrm{eff}}^2}{s} \int_d^{d+s} \frac{\varepsilon(L,E)}{L^2} dL$$

GLoBES built-in with

$$L_{\mathrm{eff}} = \sqrt{d(d+s)}$$

(for details: arXiv:0903.3039)

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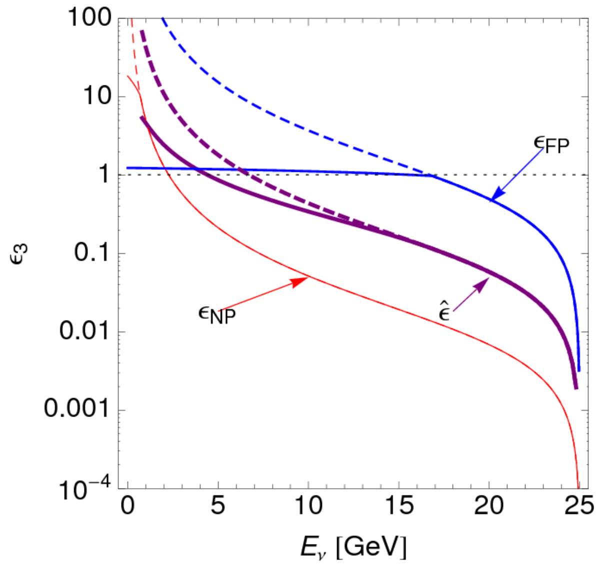
Examples for near detectors

Parameter	ND1	ND2	ND3	ND4	ND5
Diameter D	17 m	4 m	4 m	0.32 m	6.8 m
Distance d	80 m	1000 m	80 m	80 m	1000 m
Mass	450 t	25 t	25 t	0.2 t	2000 t
	Hypothetical	SciBar-size		Silicon-vertex size?	OPERA-size

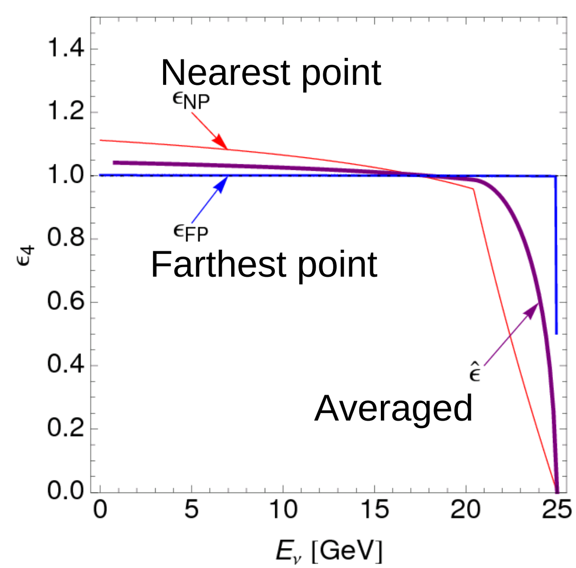
Near detector limit

Far detector limit

ND3



ND4



ε=1: FD limit
Dashed: ND limit

(Tang, Winter, arXiv:0903.3039)

- Leads to excess of low-E events
  - ➢ near detector has to be large enough to have sufficient rates in high energy bins!

- VLENF example: 200t TASD @ 20m, 2-3 m radius: ~ qualitatively similar to ND 3
- VLENF example: 800t @ >> 600m, 6-7 m radius: ~ qualitatively similar to ND 4

Sterile neutrinos: thoughts

- First approximation (use L_{eff}!): $$\frac{\Delta m_{41}^2 L_{\rm eff}}{4E} \sim \frac{\pi}{2}$$
- Examples (VLENF): E ~ 1 GeV
  s=100 m, d=20 m: L_{eff}=49 m ⇨ Δm^2 ~ 60 eV^2
  s=100 m, d=600 m: L_{eff} = 648 m ⇨ Δm^2 ~ 5 eV^2
- The problem: are there effects from averaging over the straight?
- Oscillations depend on x=L/E, where

  dx/x ~ |dL/L| + |dE/E| ~ s/L_{eff} + 0.05 (TASD)

  s/L_{eff} ~ 15% in far detector (d=600m)
  ⇨ Constrained by extension of straight, not energy resolution of detector!? Why need 5%?

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Treatment of steriles

- Requires generalization of ND scheme:

$$\frac{dN_{\mathrm{avg}}}{dE} = \frac{dN_{\mathrm{PS}}(L_{\mathrm{eff}}, E)}{dE} \frac{L_{\mathrm{eff}}^2}{s} \int_d^{d+s} \frac{\varepsilon(L,E)}{L^2} P_{ee}(L,E) dL = \frac{dN_{\mathrm{PS}}(L_{\mathrm{eff}}, E)}{dE} \hat{P}(E)$$

$$\hat{P}(E) \equiv \frac{L_{\mathrm{eff}}^2}{s} \int_d^{d+s} \frac{\varepsilon(L,E)}{L^2} P_{ee}(L,E) dL$$

Effect of beam geometry

Effect of osc. prob.

Assumption: muon decays per dL ~ const

- So far only tested for ε ~ 1 (far detector limit); however, not in principle impossible if ε integrated in osc. engine (GLoBES)

(Giunti, Laveder, Winter, arXiv:0907.5487)

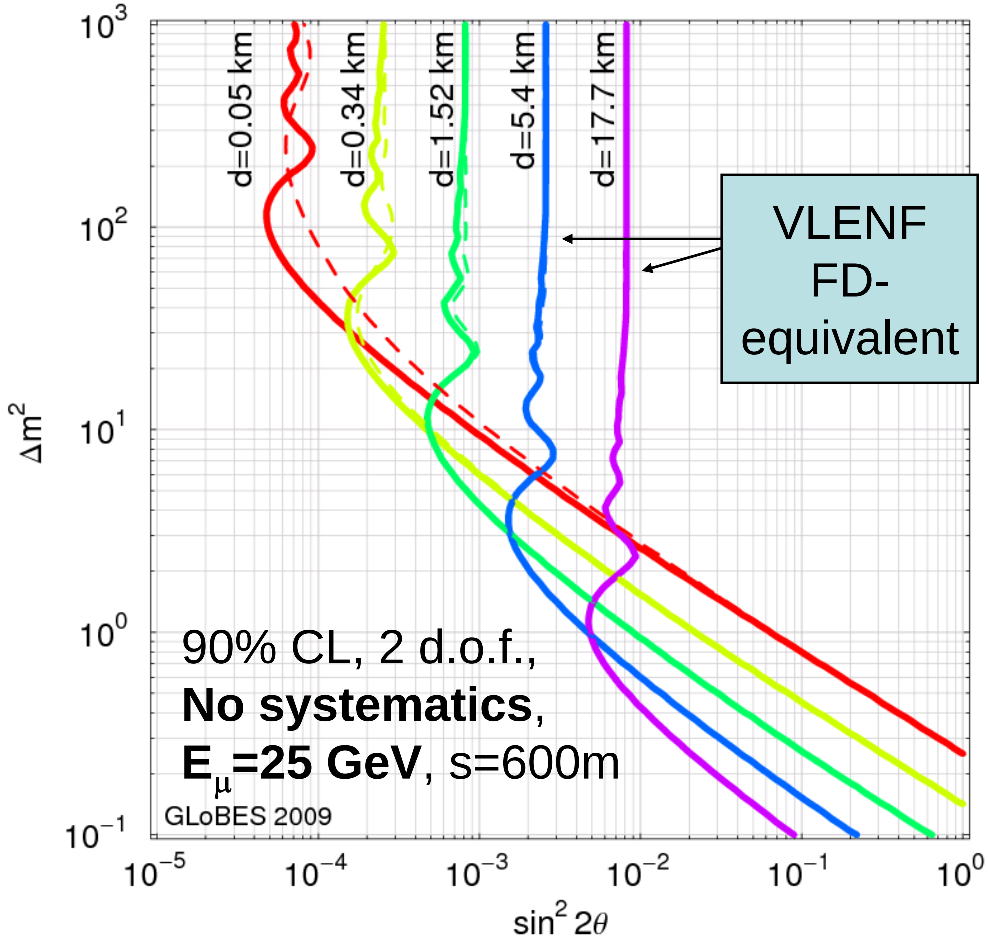
Example: ν_e disappearance

- ν_e disppearance:

$$P_{ee} = 1 - \sin^2(2\theta_\nu)\,\sin^2\left(\frac{\Delta m_\nu^2 L}{4E}\right)$$

- Averaging over straight important (dashed versus solid curves)
- VLENF: Expect significant averaging effects if d <~ s, i.e., in near detector

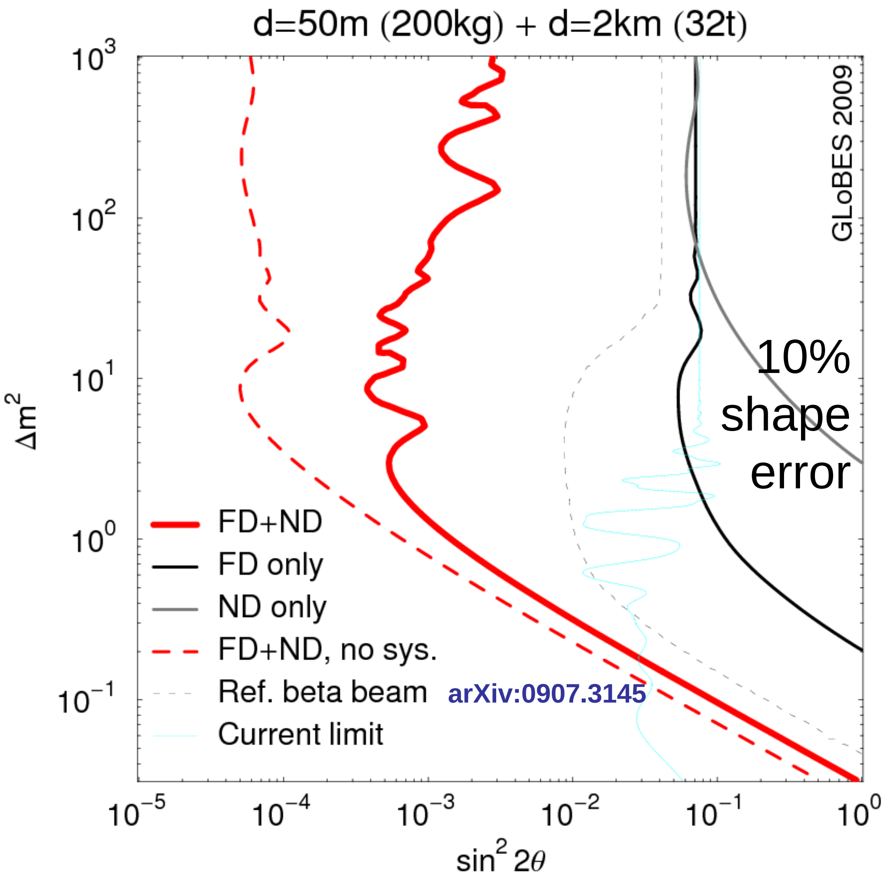
  [and limitation of x=L/E-resolution everywhere (see before)]

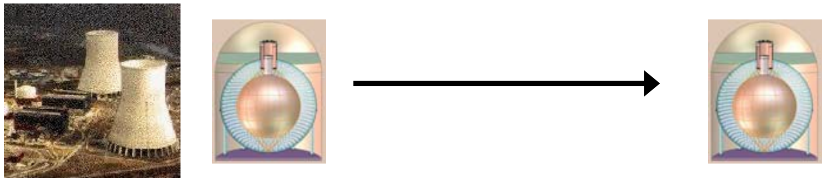


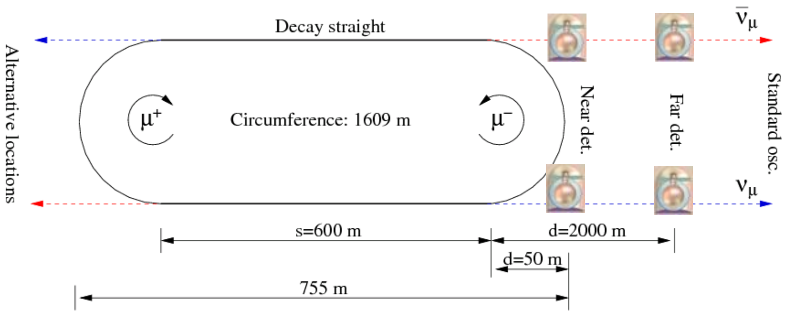
(arXiv:0907.5487)

Disappearance systematics

- Systematics similar to reactor experiments: Use two detectors to cancel X-Sec errors







(arXiv:0907.5487)

On the VLENF optimization
(general conclusions)

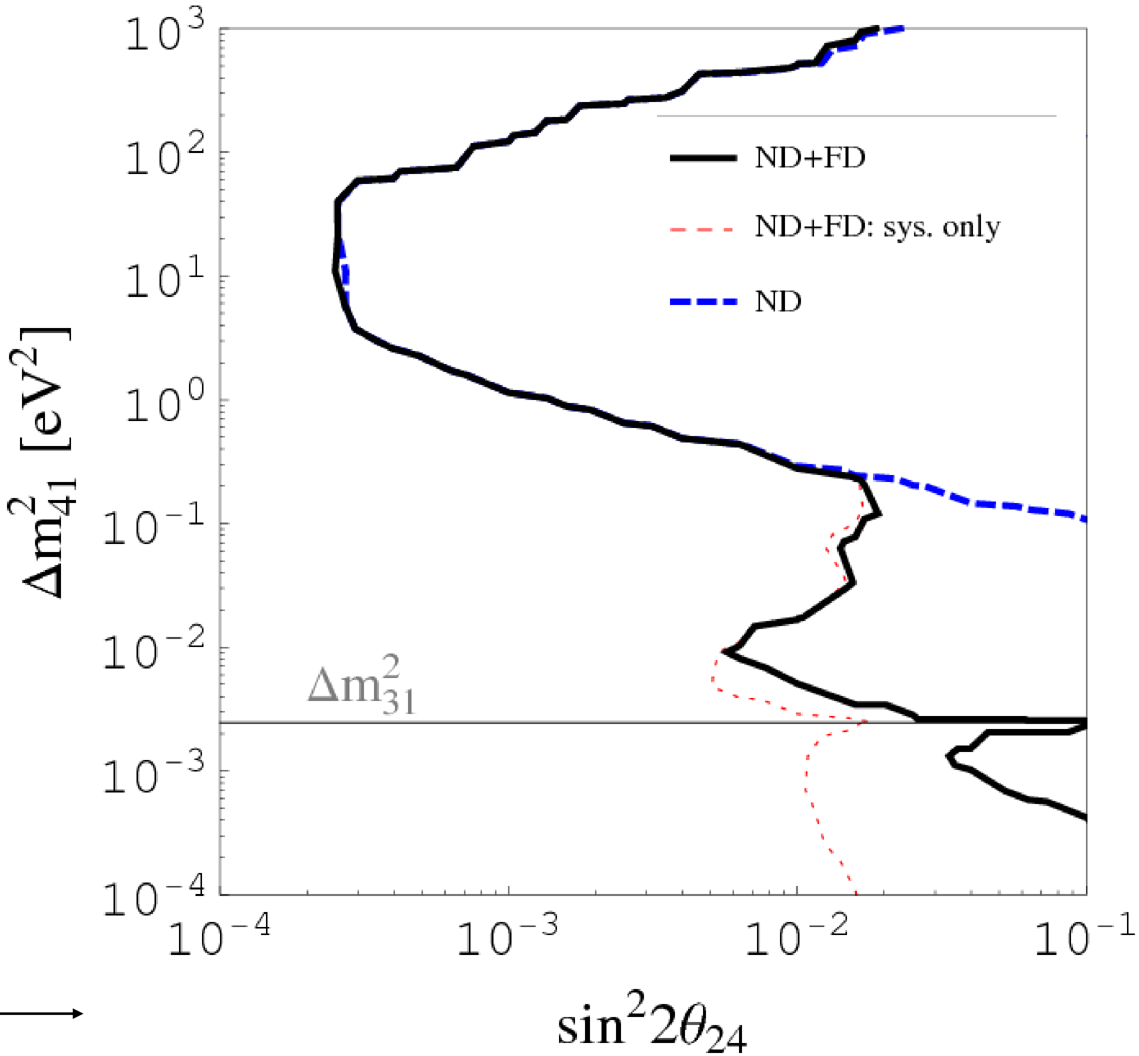
- From the above: E_μ can be rescaled if the baselines are adjusted accordingly (e.g. if required by X-sec measurements)
- Advantage: Higher E_μ ⇨ longer d ⇨ less rel. effect of averaging of the straight
- In principle: d >~ 2000m necessary if 5% energy resolution needs to be useful in FD ⇨ E_μ higher by a factor of three possible
- However: not so clear to me where energy resolution important … [maybe not at first osc. maximum]

On the VLENF optimization
(technical conclusions)

- Numerical studies challenging, since optimization depends on detector geometry and straight averaging (needs some coding), but recipe clear
- But: sensitivity to sterile neutrinos will mostly depend on far detector, which can be typically approximated by far detector limit
- One has to ensure that the near detector has a sufficient event rate at all energies; it may limit the energy resolution of the system because of the decay straight averaging
- Some systematics difference between appearance and disappearance searches!

Outlook

- Dedicated pheno studies should include:
  - Full N flavor framework
  - Near+far+very far detectors
  - Full Δm^2 range
- So far: only effective near detector system →



(Meloni, Tang, Winter, arXiv:1007.2419)