Neutrino Physics: ~~the~~ little theory and phenomenology a bit of new in LArTPCs and beyond

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May 2020

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Neutrino Physics: theory and phenomenology

an Adventure!

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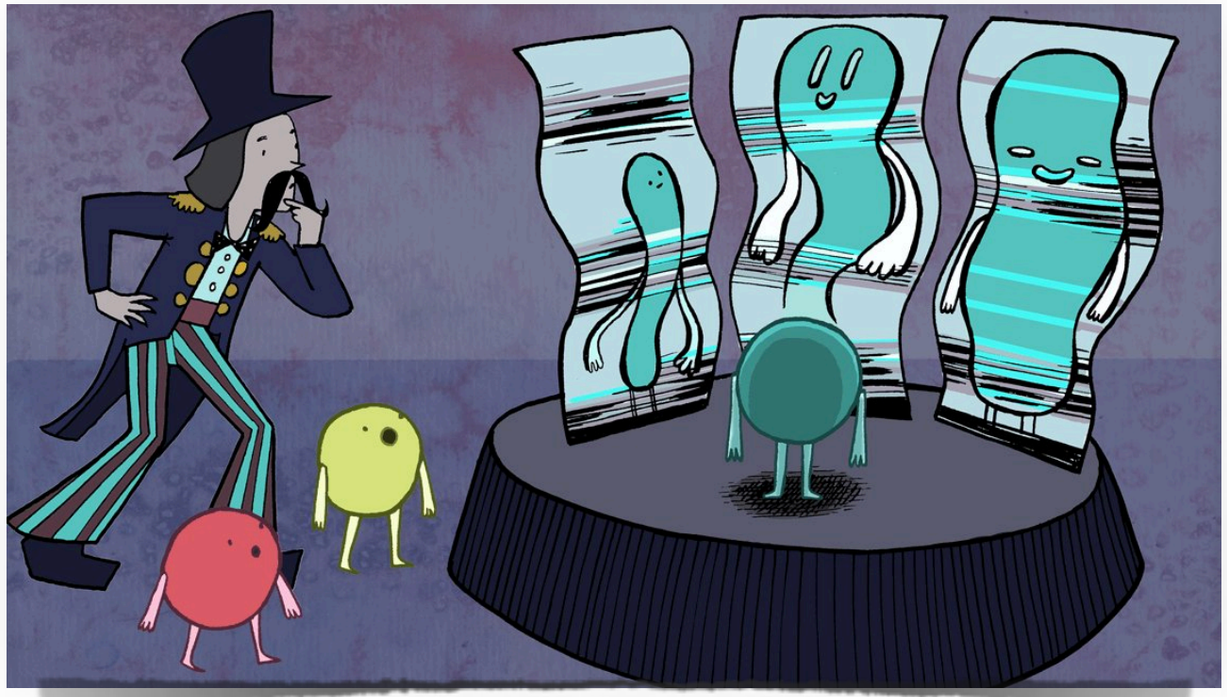
Why neutrinos?

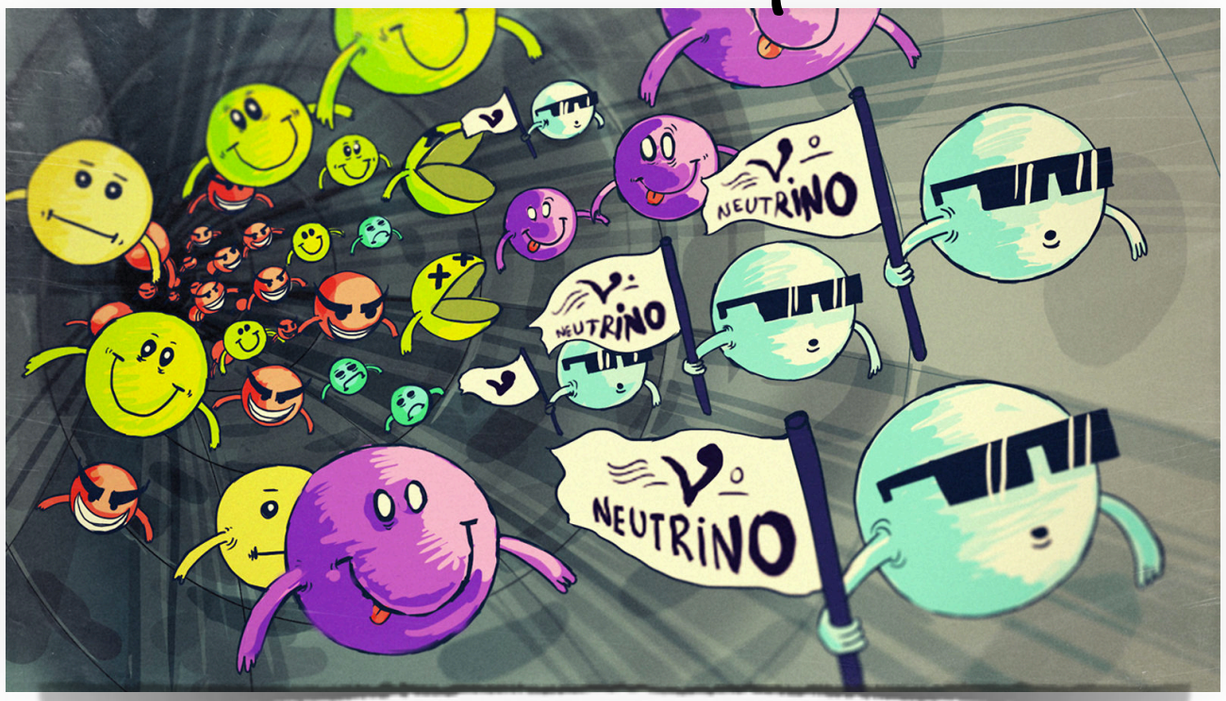
The mystery of neutrino masses

The nature of neutrinos

The least known sector of the SM



The darkest of all particles



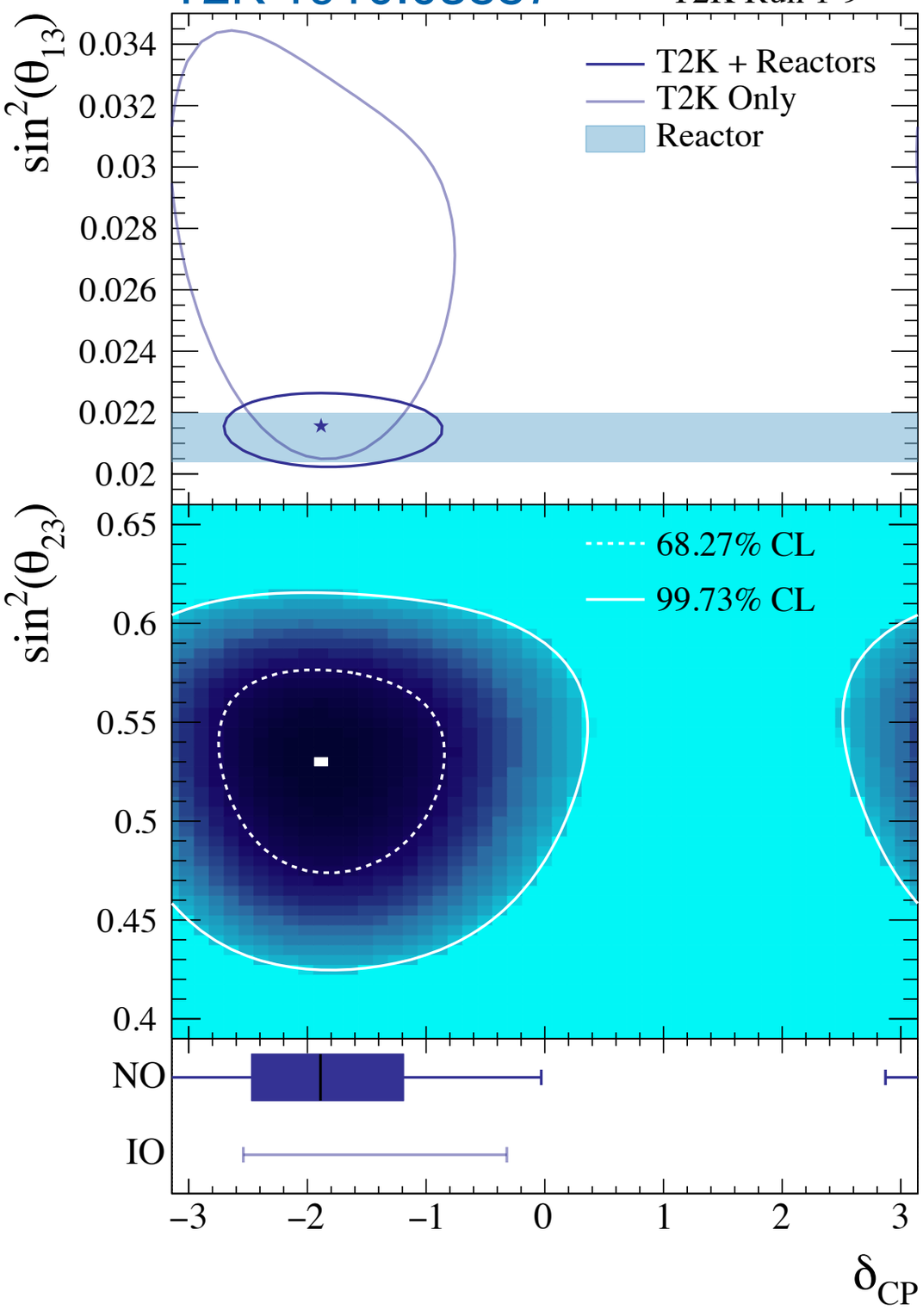
Fortress of Redundancy

cross section

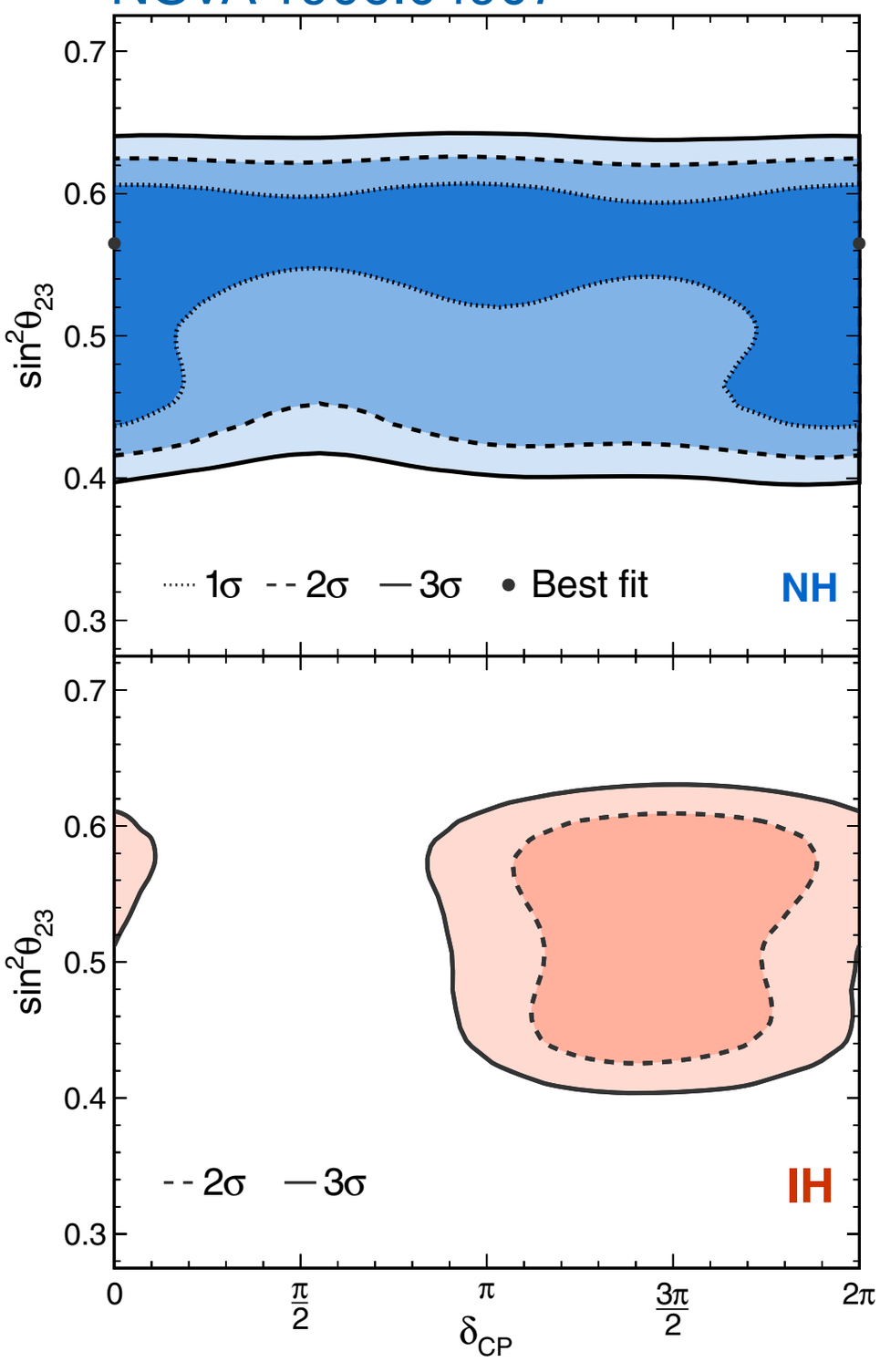
badlands

CP violation, at last???

T2K 1910.03887



NOvA 1906.04907



Fermilab
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CP violation, at last???

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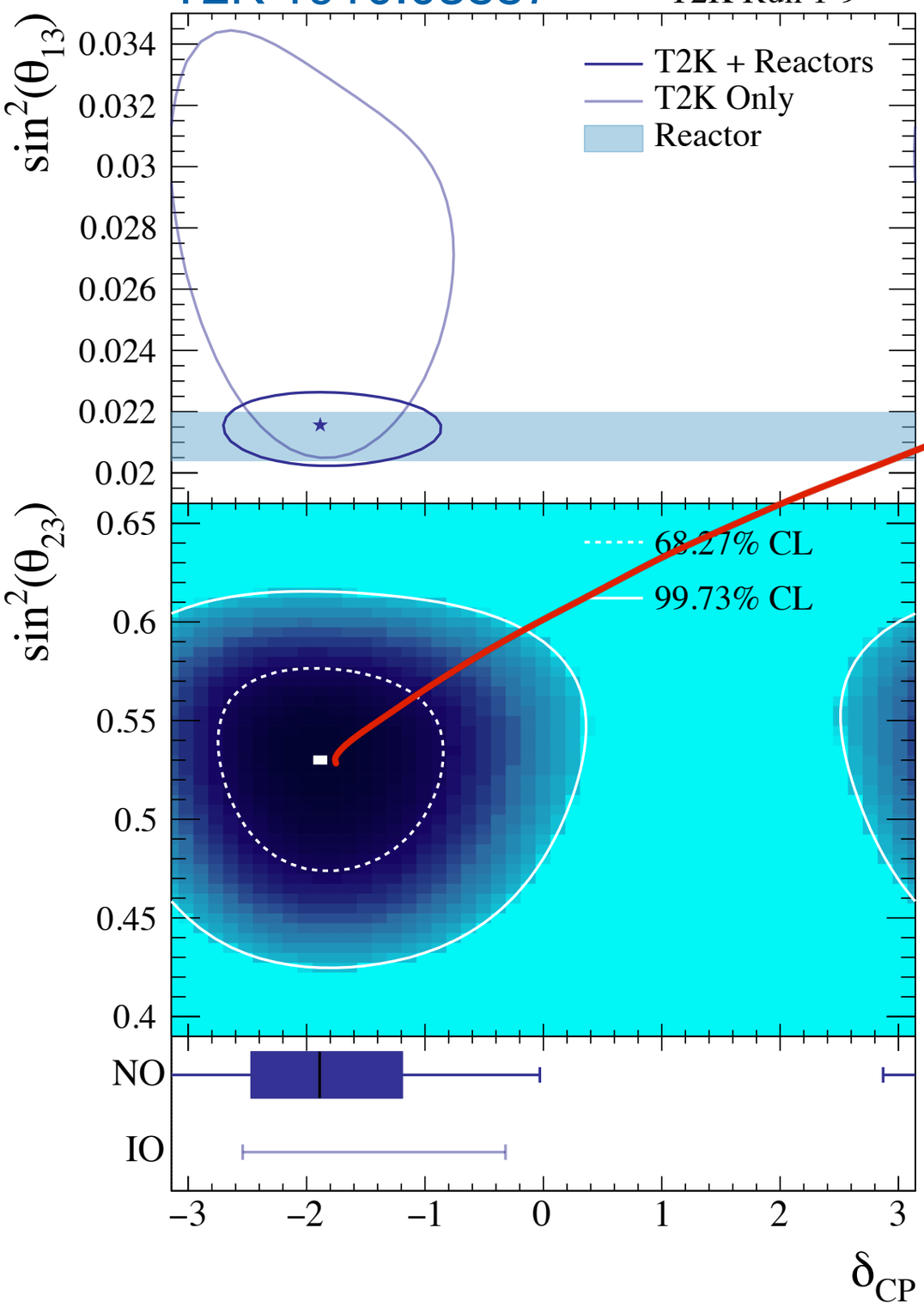
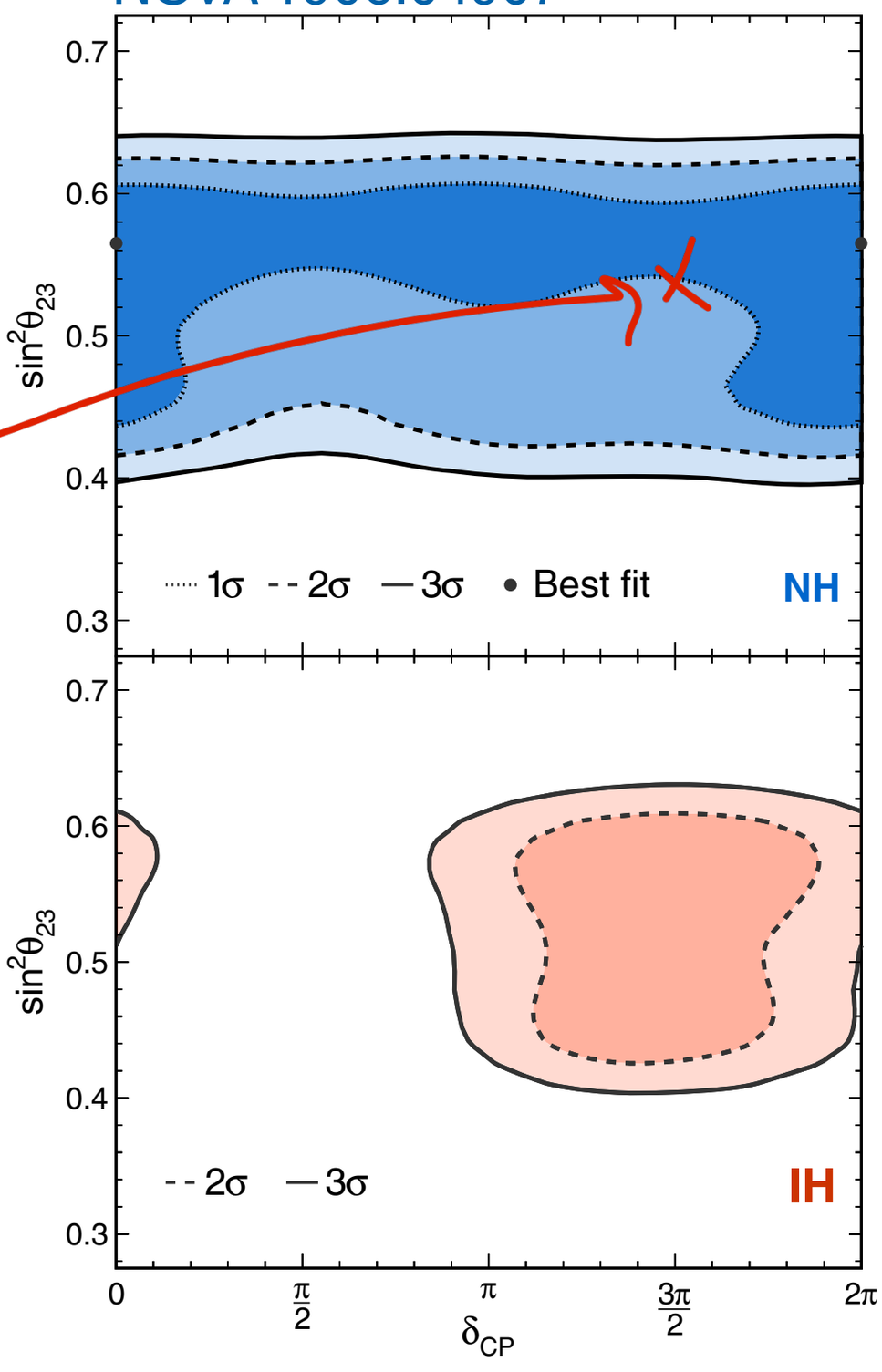


NOvA 1906.04907



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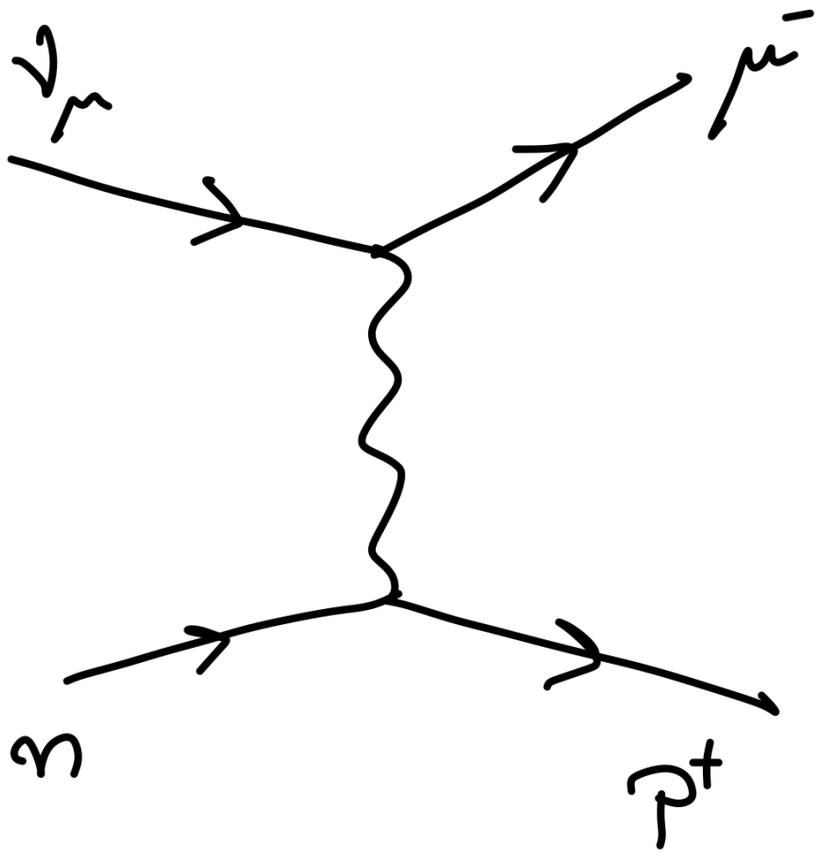
Fermilab

CP violation, at last???

cross section
badlands

How do we measure oscillation parameters?

$$P(\nu_\mu \to \nu_e) \sim \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right)$$

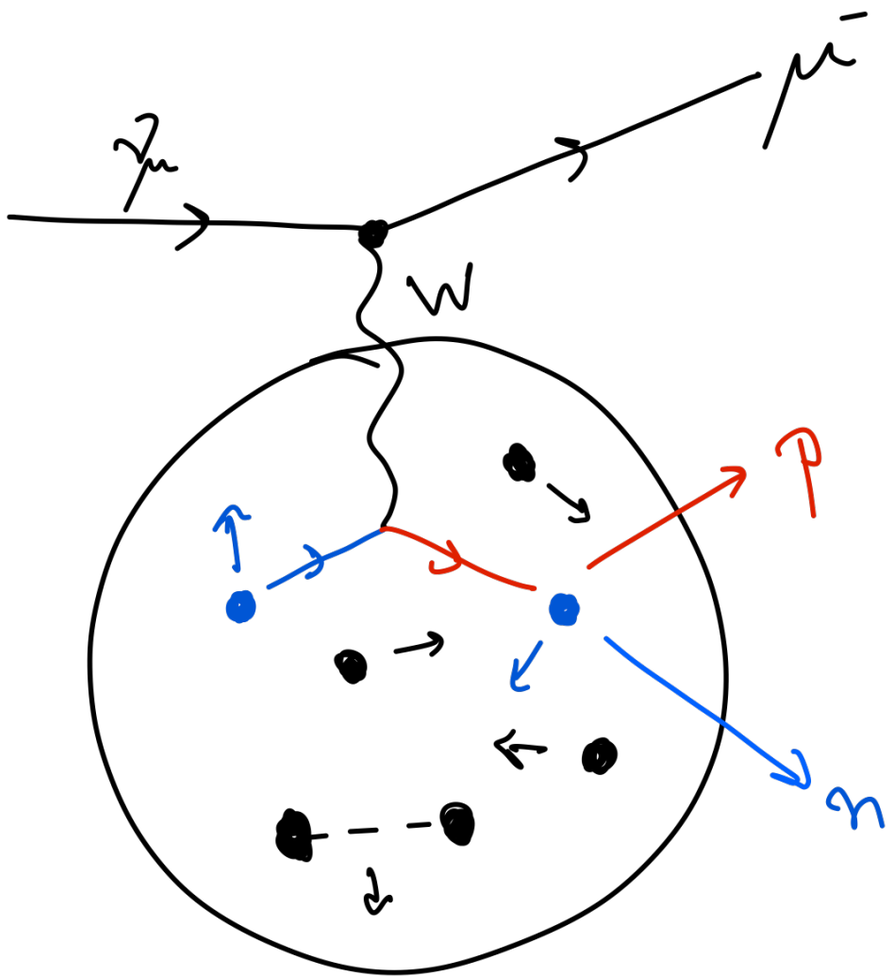


Trivial to get E_ν!

Right?

How do we measure oscillation parameters?

$$P(\nu_\mu \to \nu_e) \sim \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right)$$



Well...

E_ν (E_p, E_n, E_μ, nuclear physics,...)

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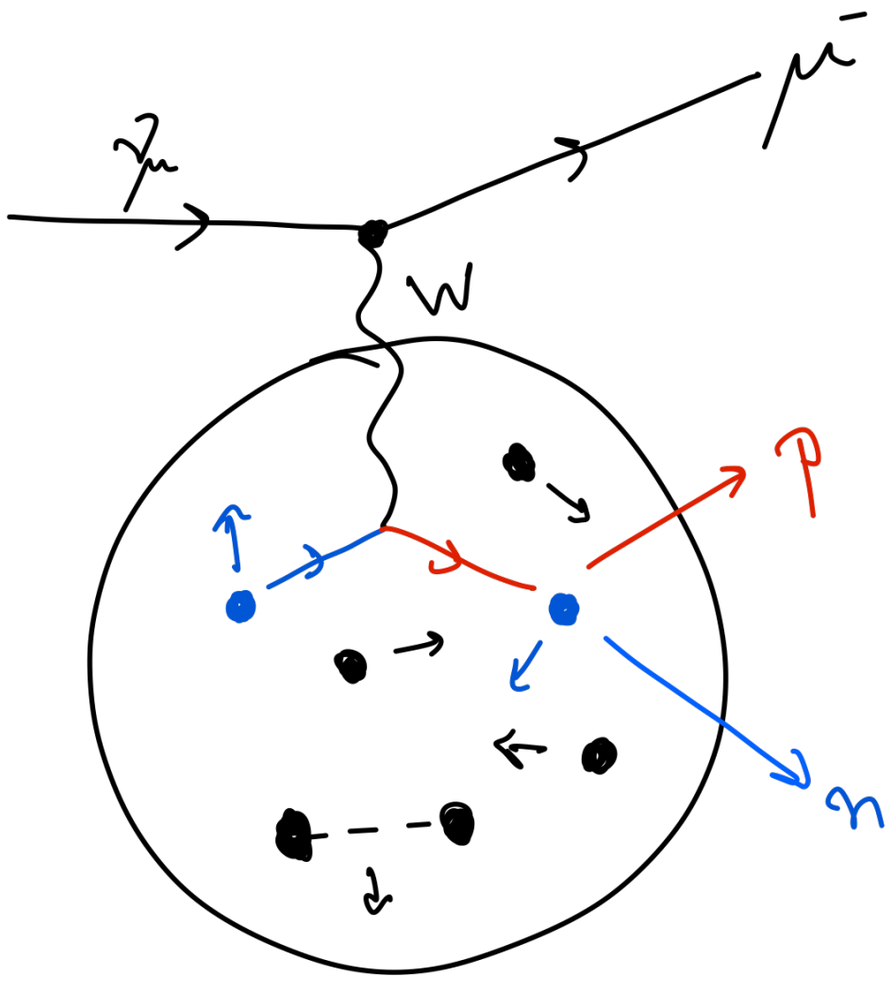
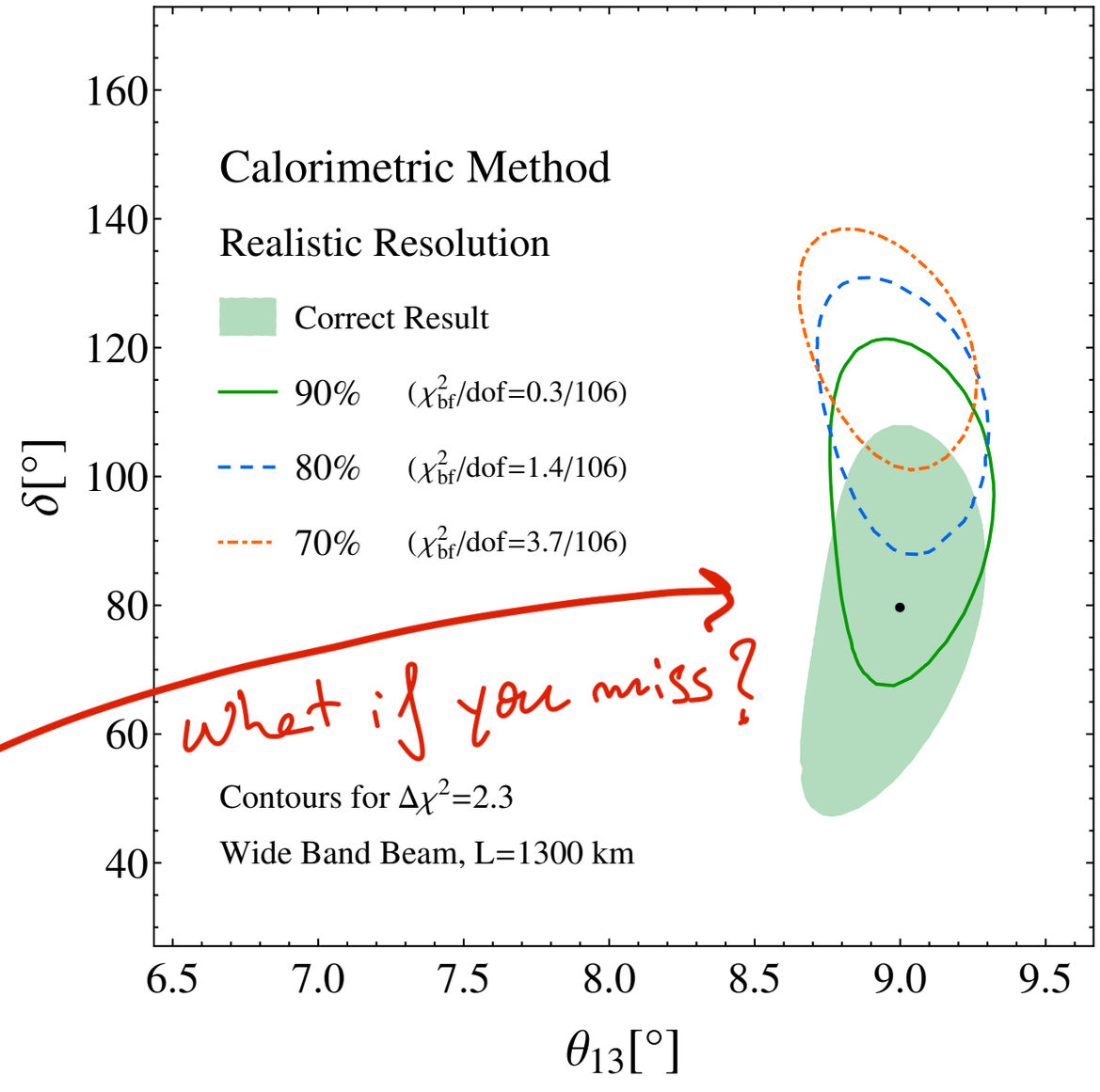
How do we measure oscillation parameters?

$$P(\nu_\mu \to \nu_e) \sim \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right)$$



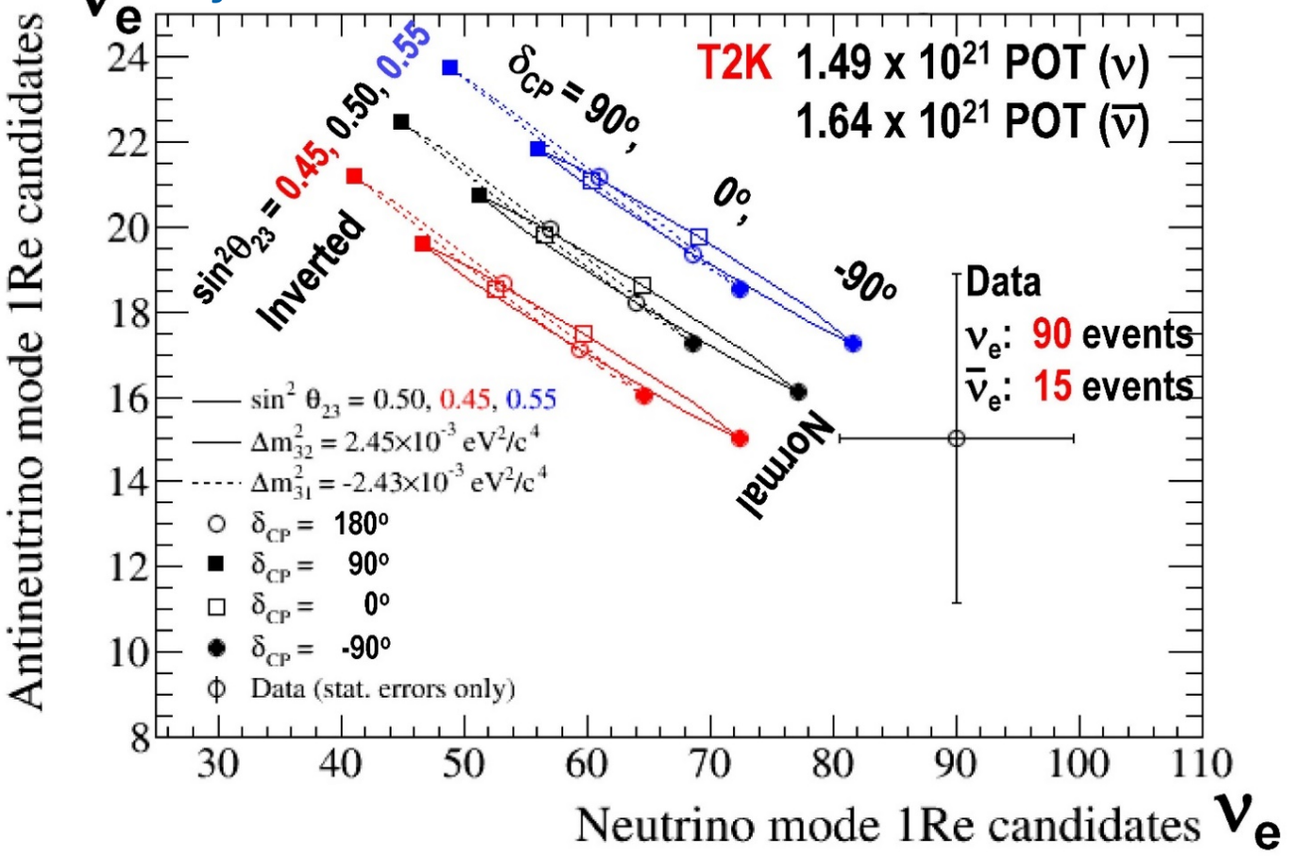
E_ν (E_p, E_n, E_μ, nuclear physics,...)

Ankowski et al 1507.08561



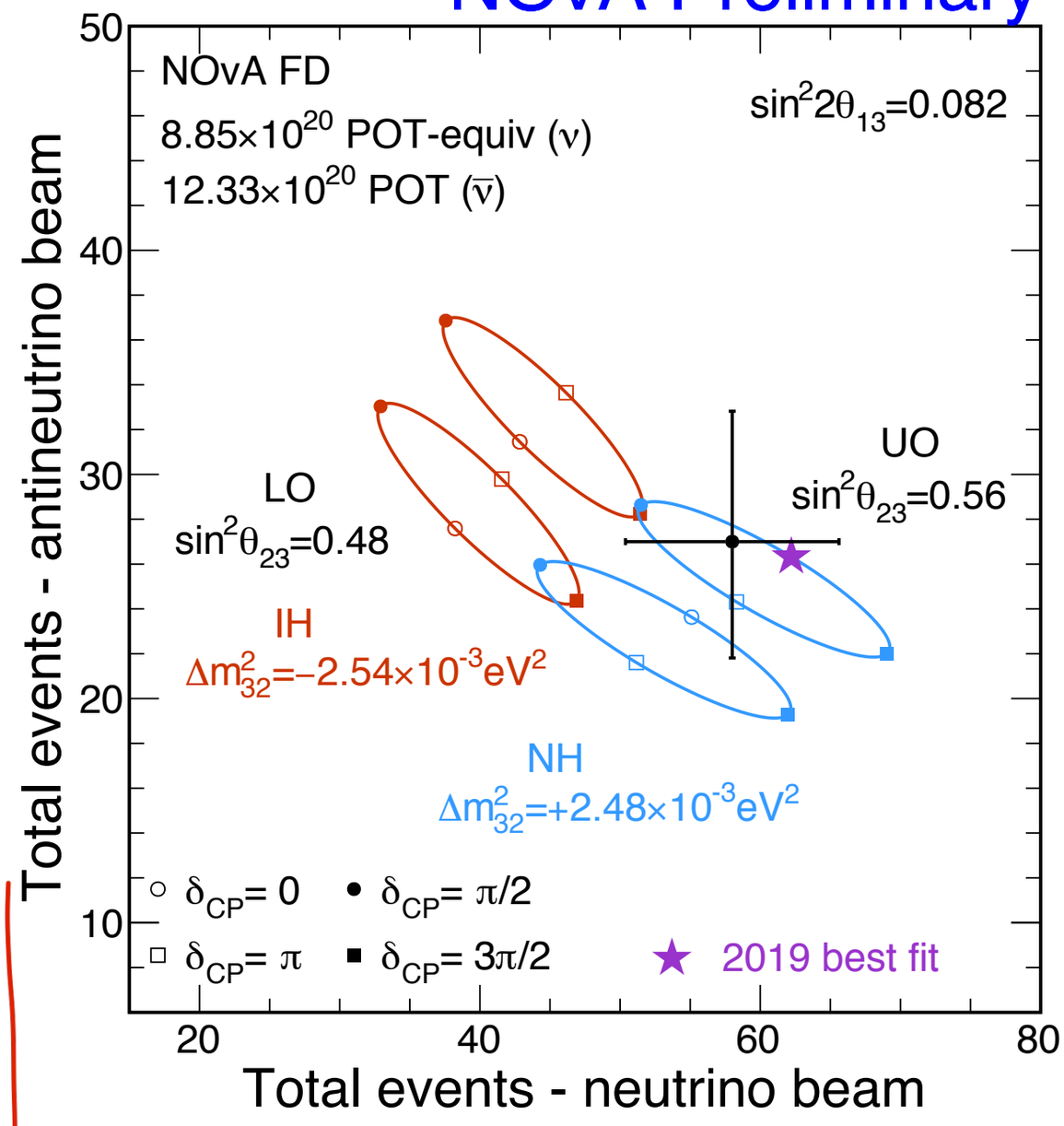
How do we measure oscillation parameters?

Oyama@CNNP2020



Hewes@NuPhys2019

NOvA Preliminary



There is no tension, but good to keep an eye there...

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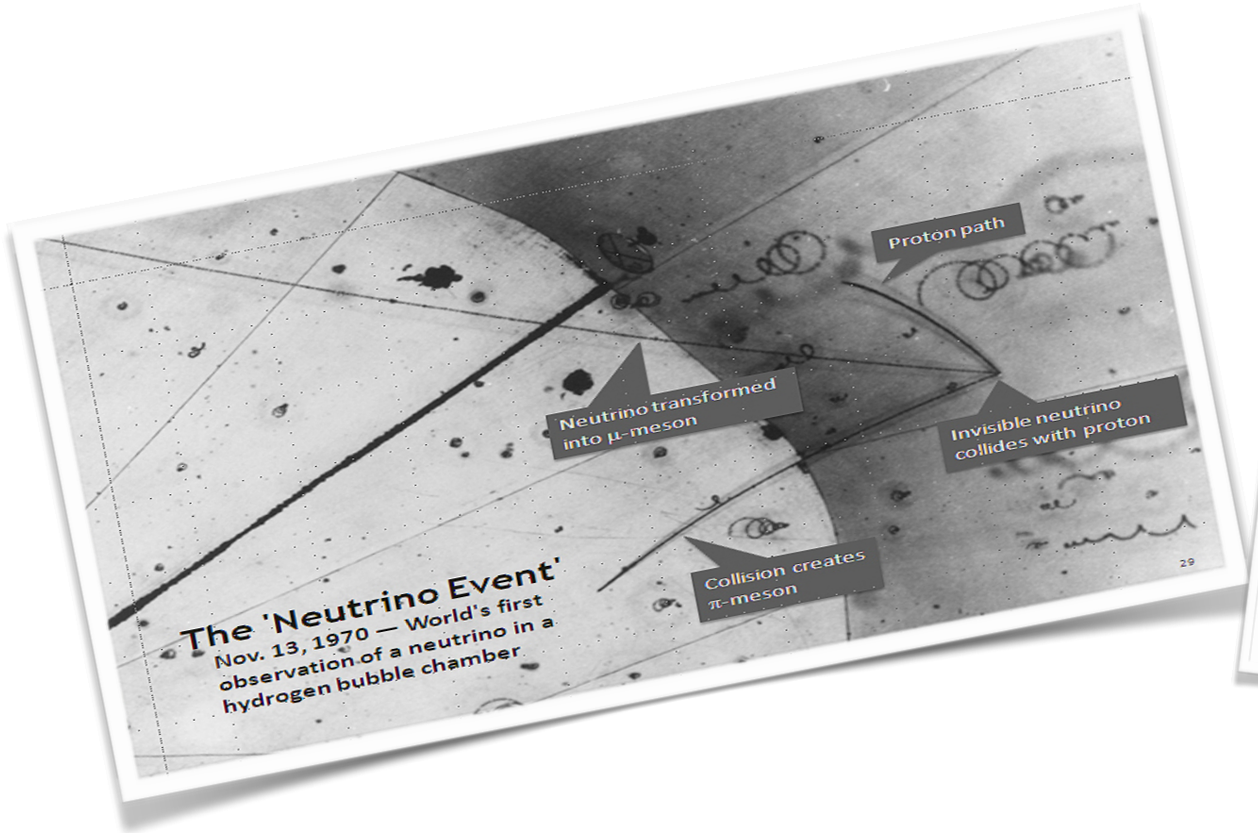
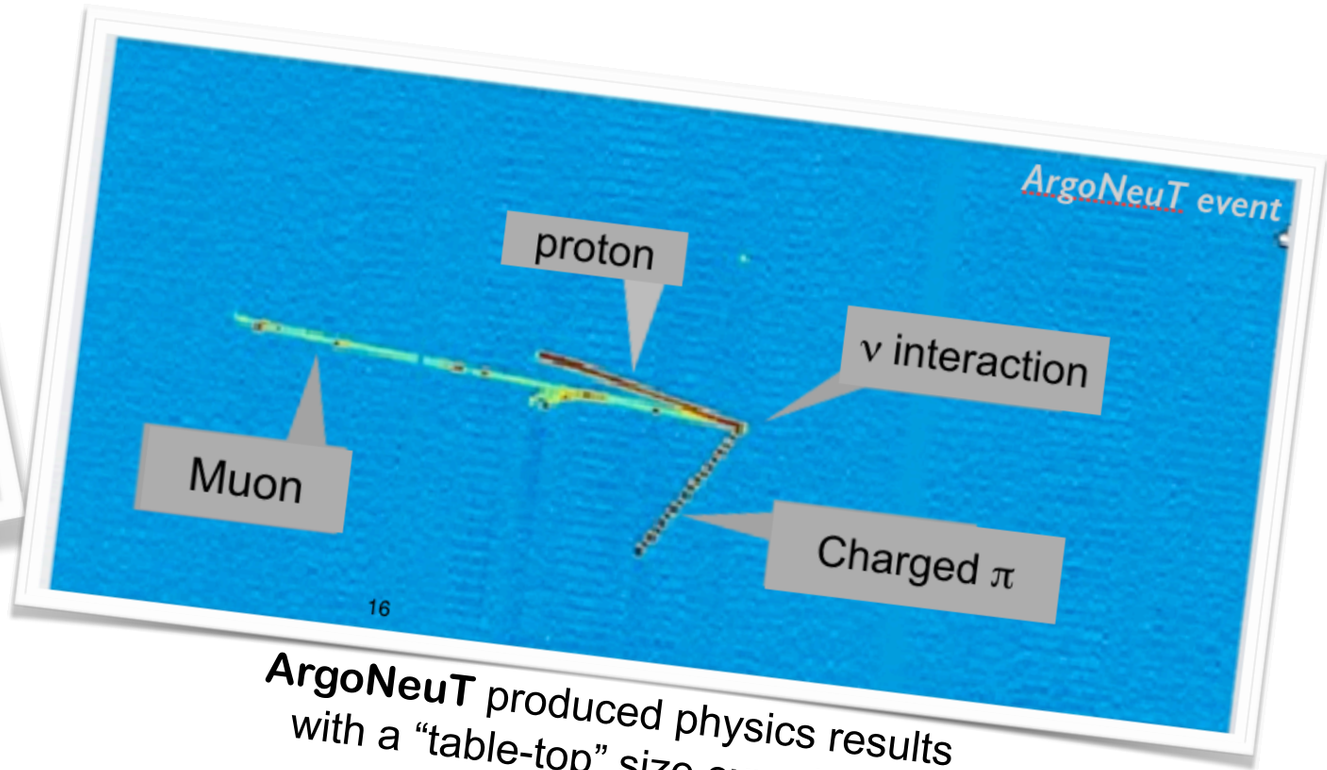
Fermilab

Liquid argon time projection chambers

From O. Palamara





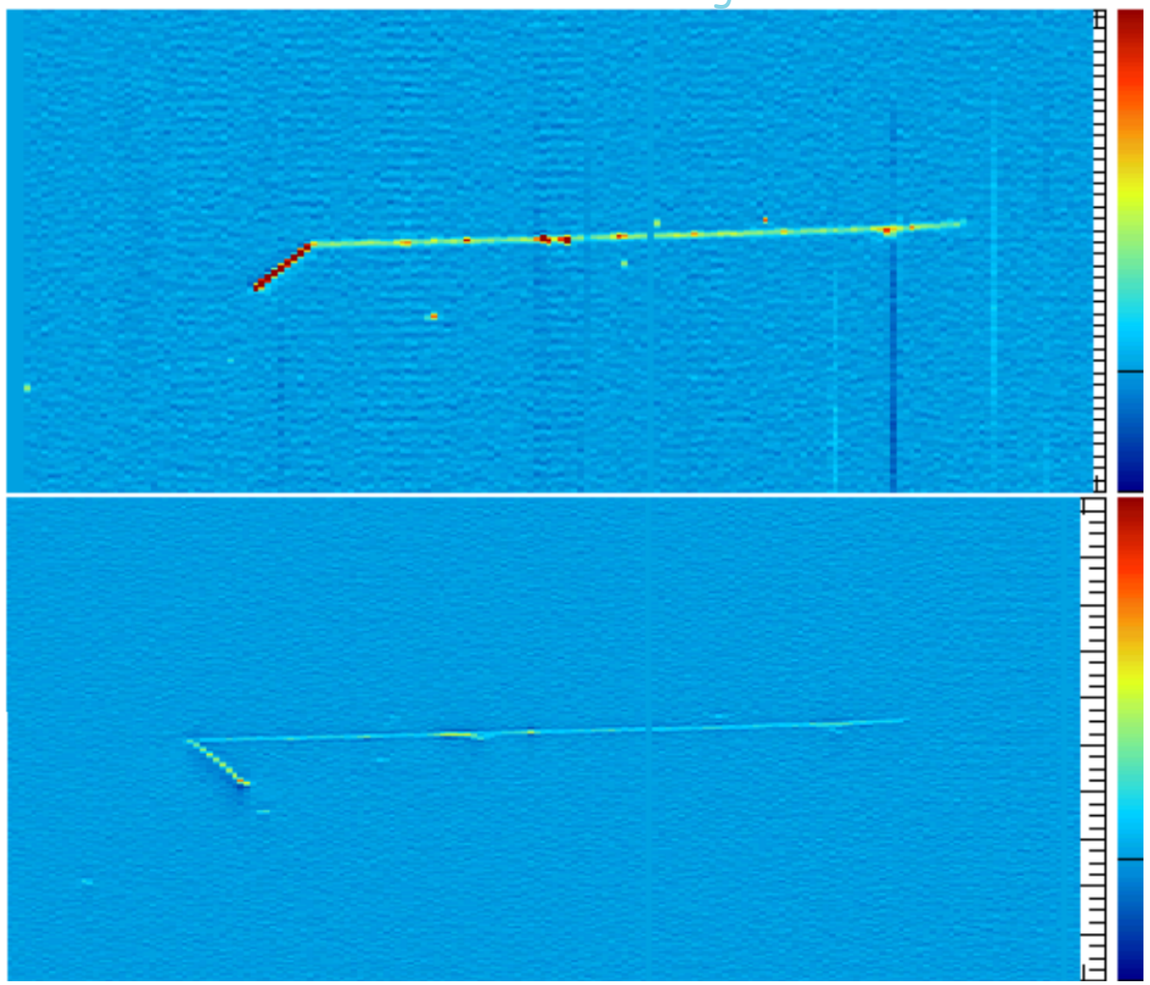
ArgoNeuT produced physics results with a "table-top" size experiment [240 Kg LArTPC]

LAr TPC: Bubble chamber quality of data with added calorimetry

…or LArTPC is "a "colored" bubble chamber"

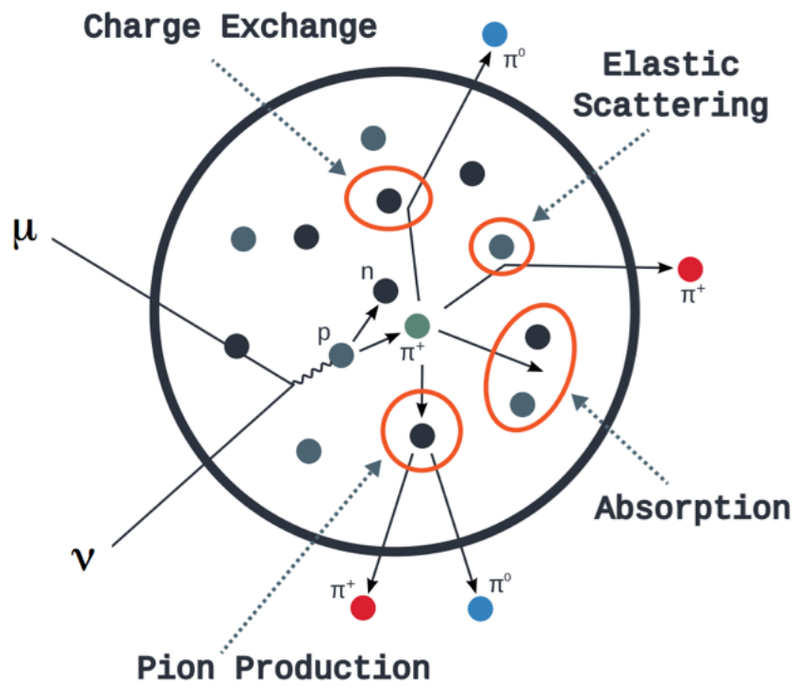
(theorist simplified view!)

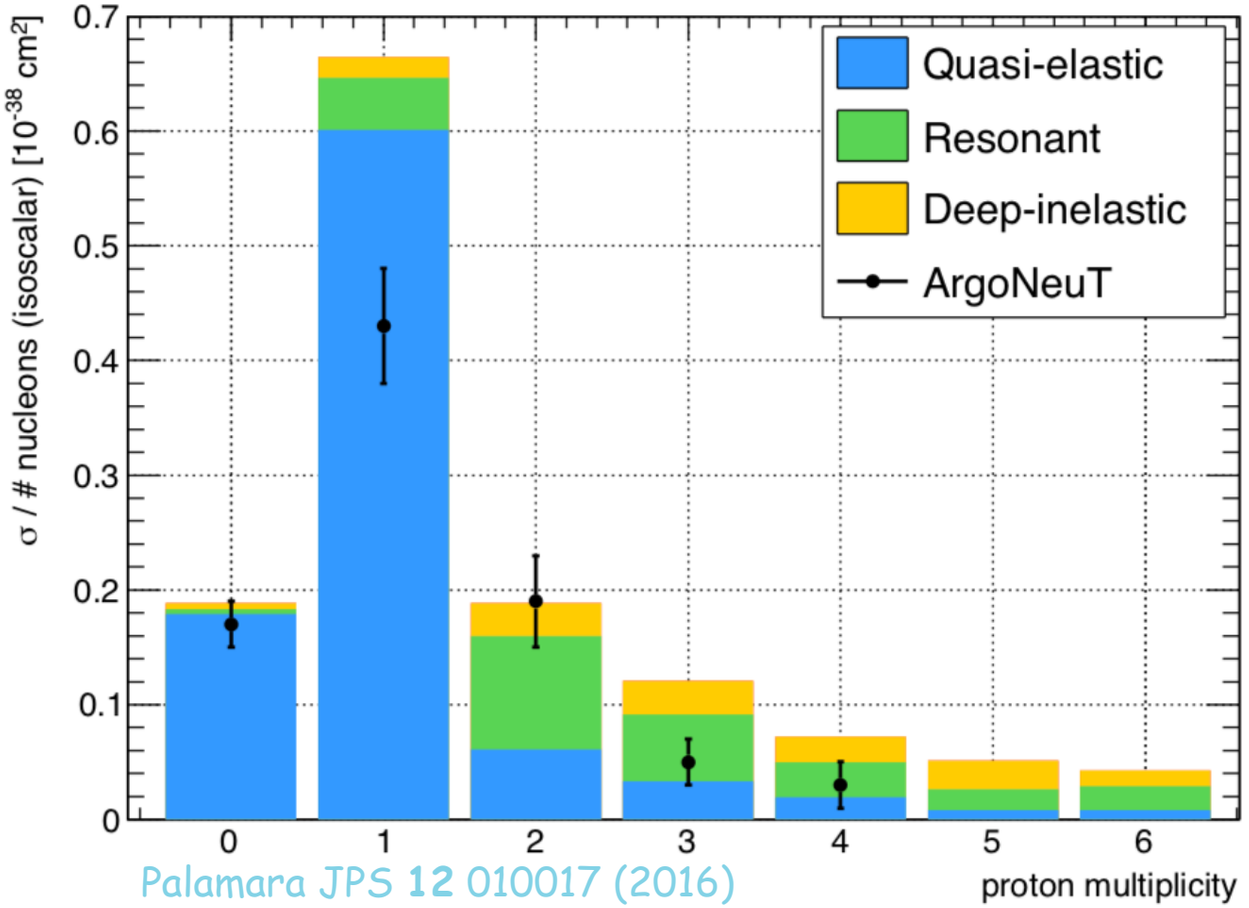
ArgoNeuT 1810.06502



ArgoNeuT demonstrated the LAr capability to detect 21 MeV recoil protons.

Event topology carries extra information





Palamara JPS 12 010017 (2016)

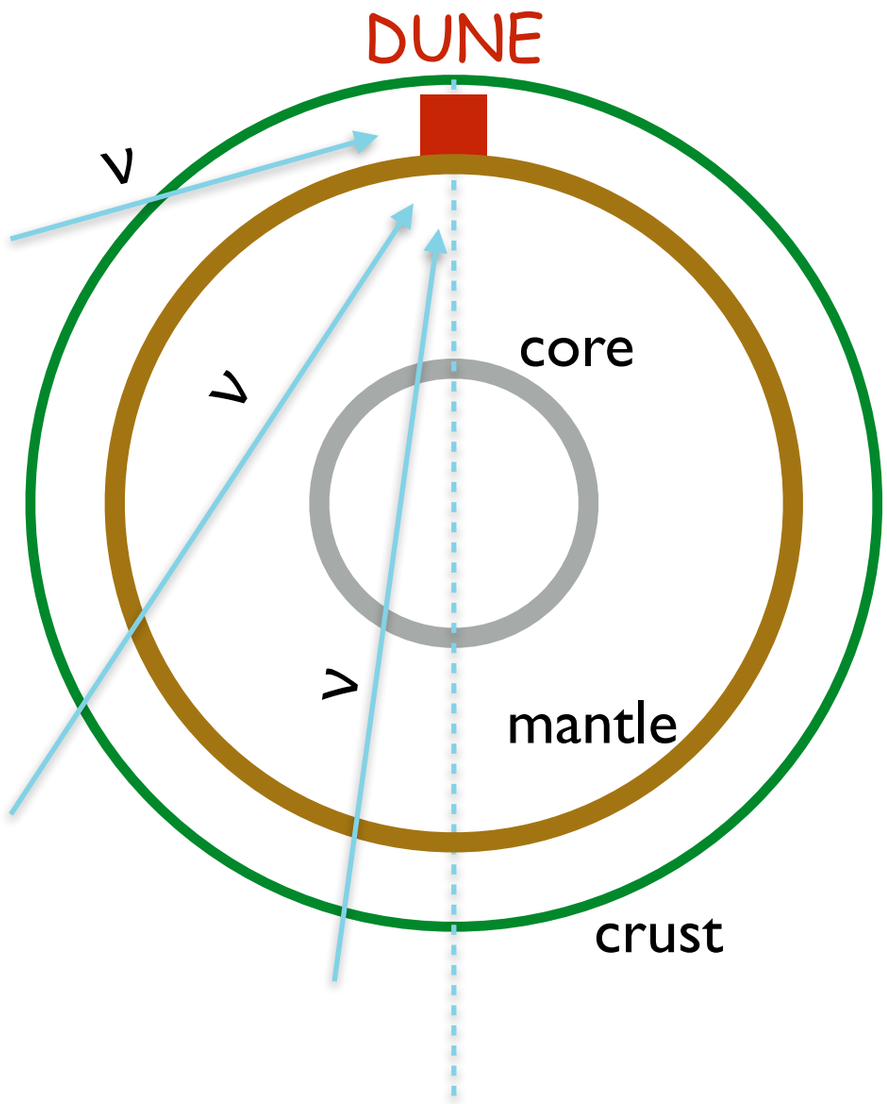
Fortress of Redundancy

cross section

badlands

Redundancy: CP phase with sub-GeV atmospheric neutrinos

Kelly et al 1904.02751



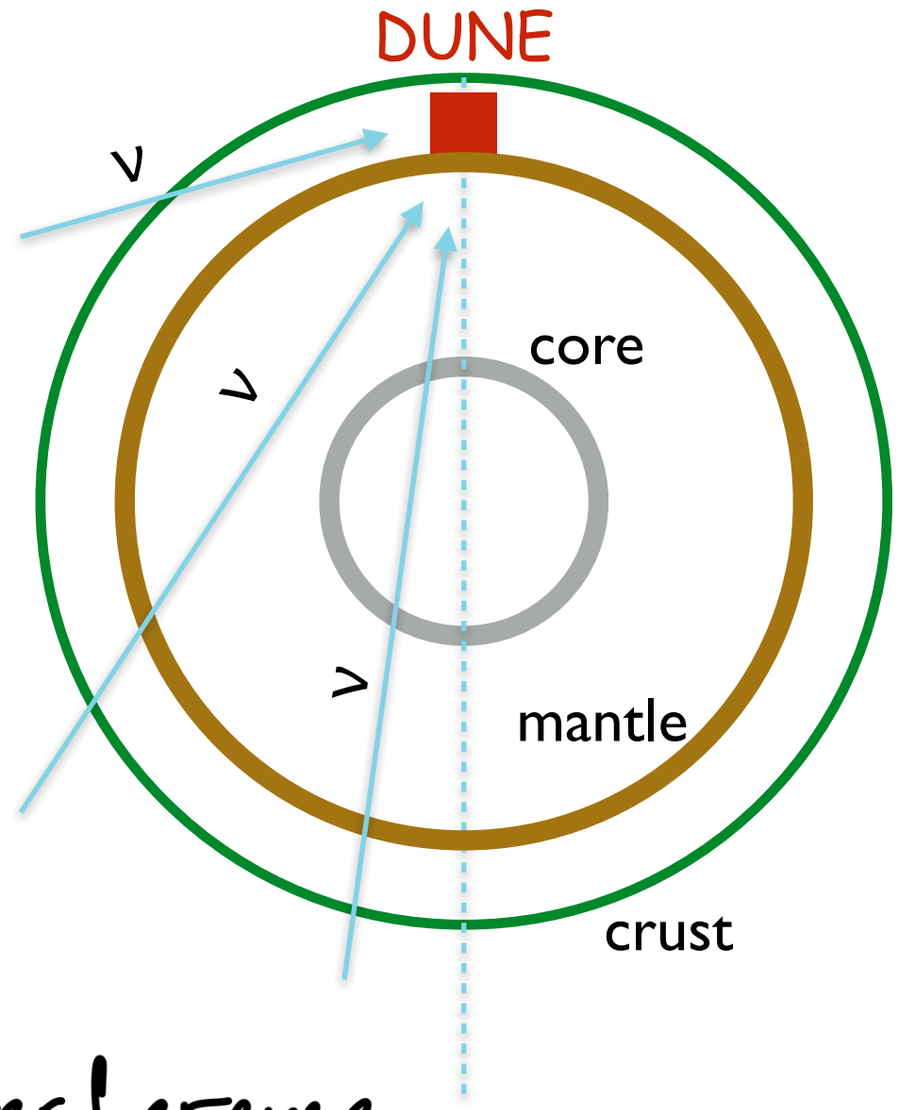
Redundancy: CP phase with sub-GeV atmospheric neutrinos

Kelly et al 1904.02751

$$P(\nu_\mu \to \nu_e) \sim \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

$$\varphi \equiv \frac{\Delta m^2 L}{4E} = 1.27 \frac{\Delta m^2/eV^2 \times L/Km}{E/GeV}$$

$$\Delta m^2 \simeq \begin{cases} 7.5\times10^{-5}\,eV^2 & \text{(solar)} \\ 2.5\times10^{-5}\,eV^2 & \text{(atmospheric)} \end{cases}$$



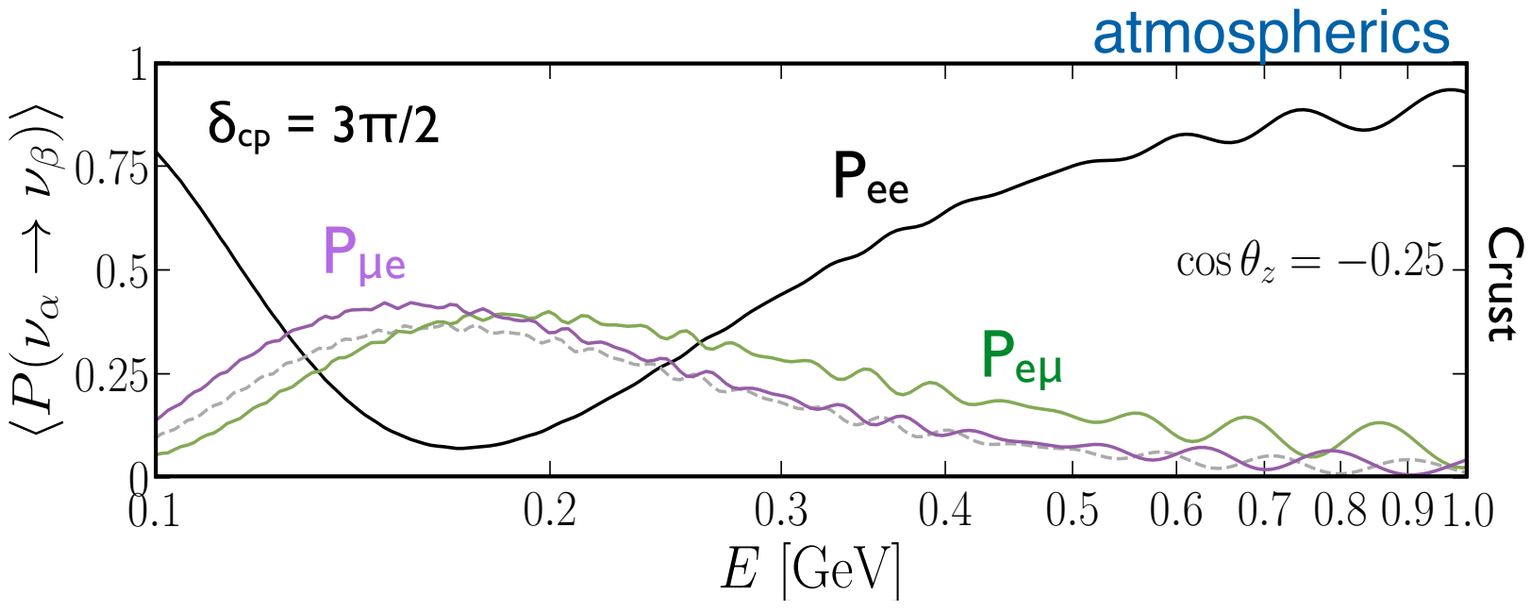
$L = 5{,}000$ Km $\quad E_\nu = 0.5$ GeV

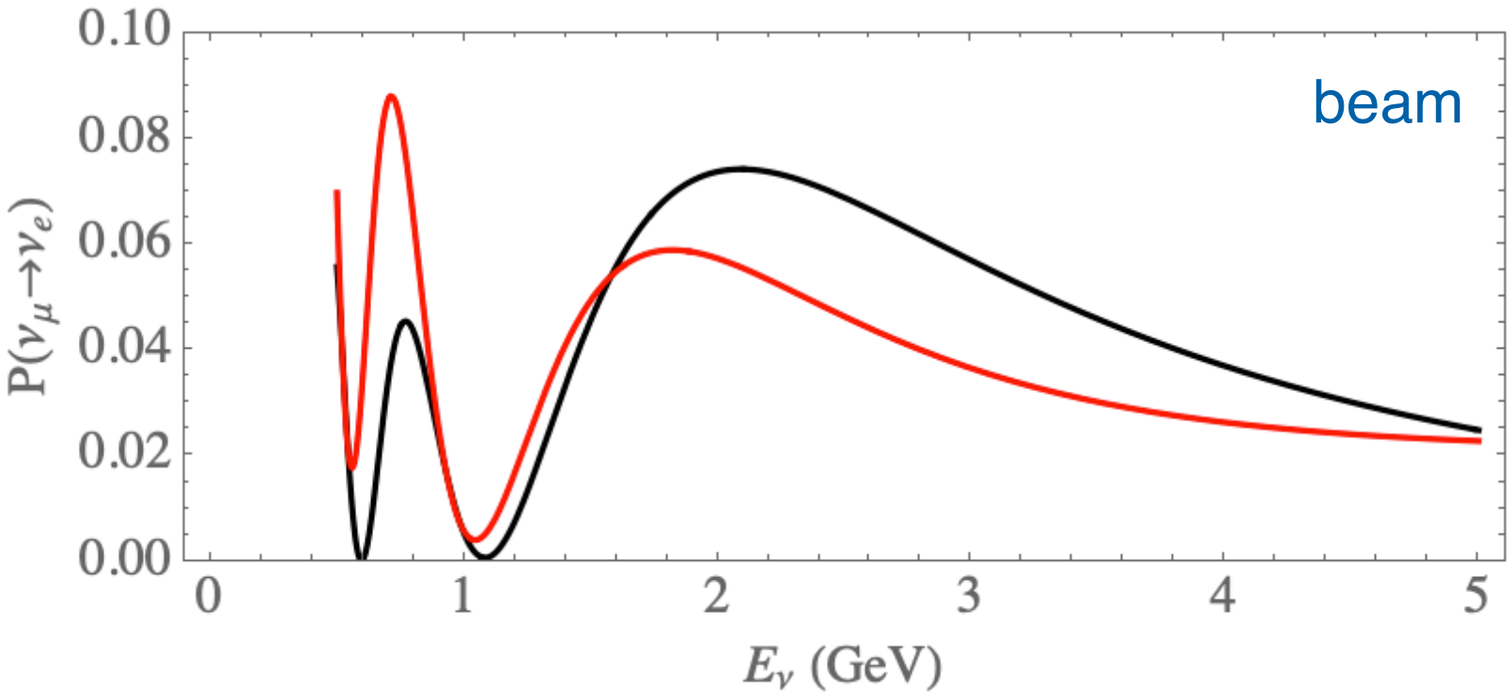
$\Rightarrow \varphi_{atm} \sim 30 \quad \varphi_0 \sim 1 \Rightarrow$ Lots of interference

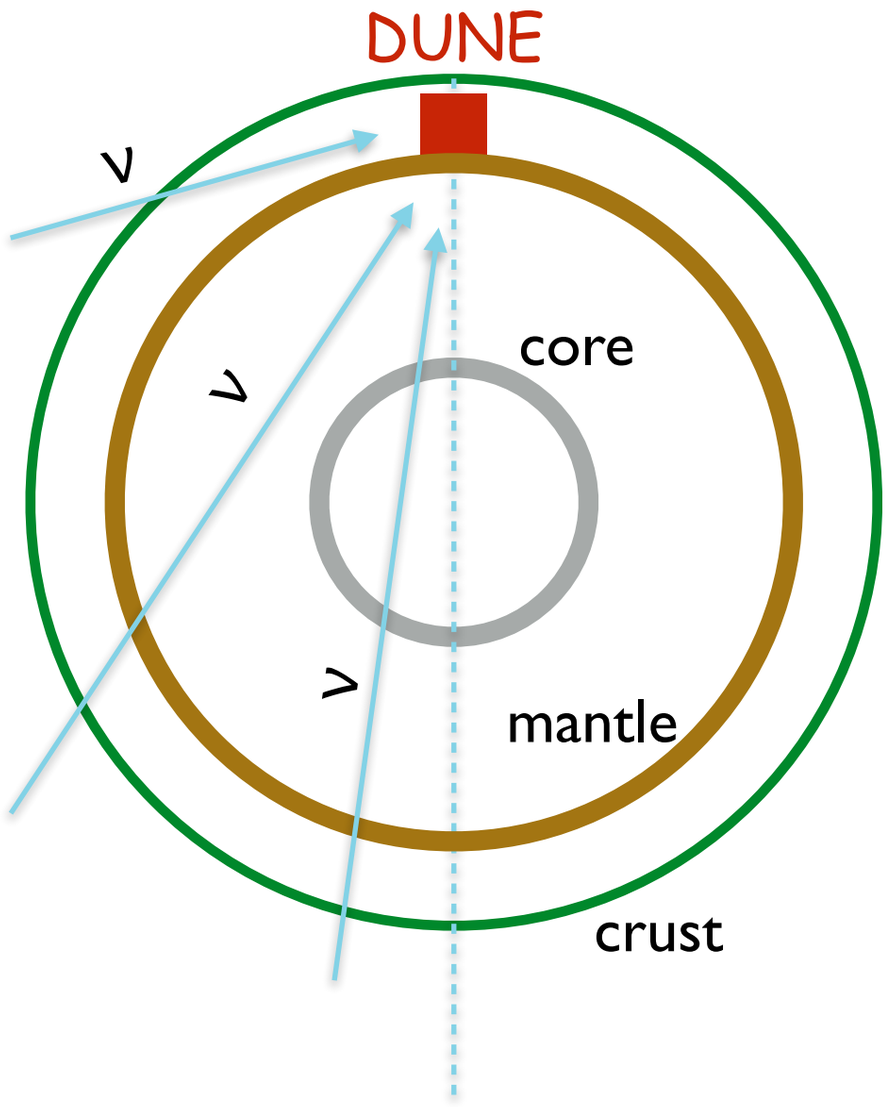
CP violation!

Redundancy: CP phase with sub-GeV atmospheric neutrinos

Kelly et al 1904.02751



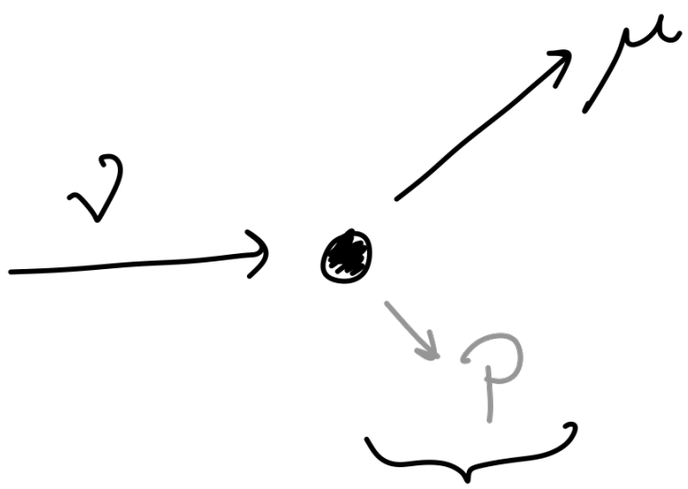




Redundancy: CP phase with sub-GeV atmospheric neutrinos

Kelly et al 1904.02751

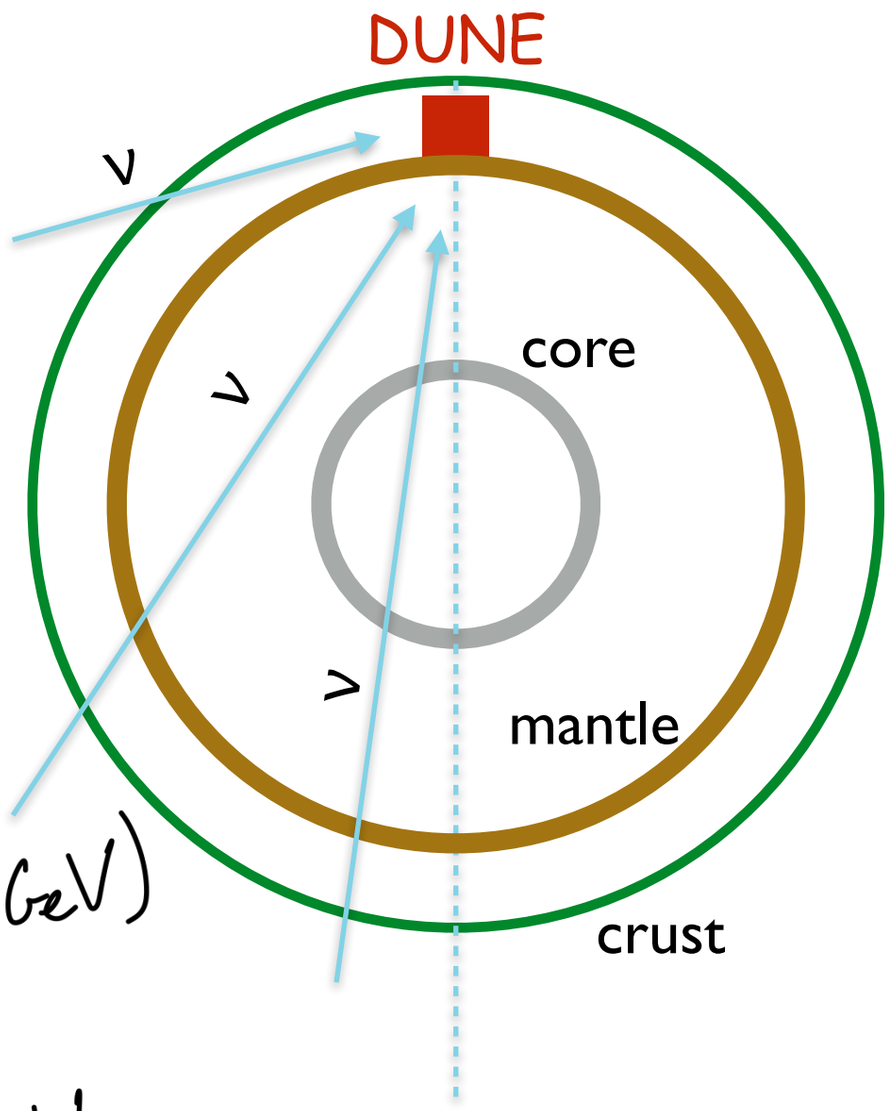
Why didn't we do it already?



Invisible @ Super-Kamiokande

(protons Cherenkov only when $K_p > 1.4$GeV)

$\Rightarrow (E_\nu, \theta_\nu)$ impossible to reconstruct!



Redundancy: CP phase with sub-GeV atmospheric neutrinos

Kelly et al 1904.02751

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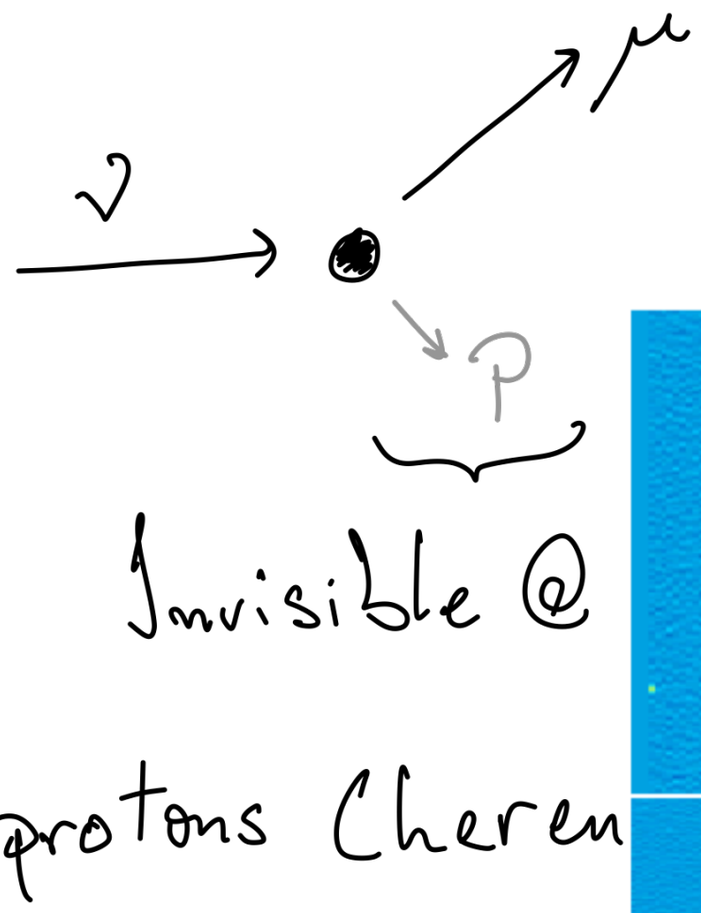

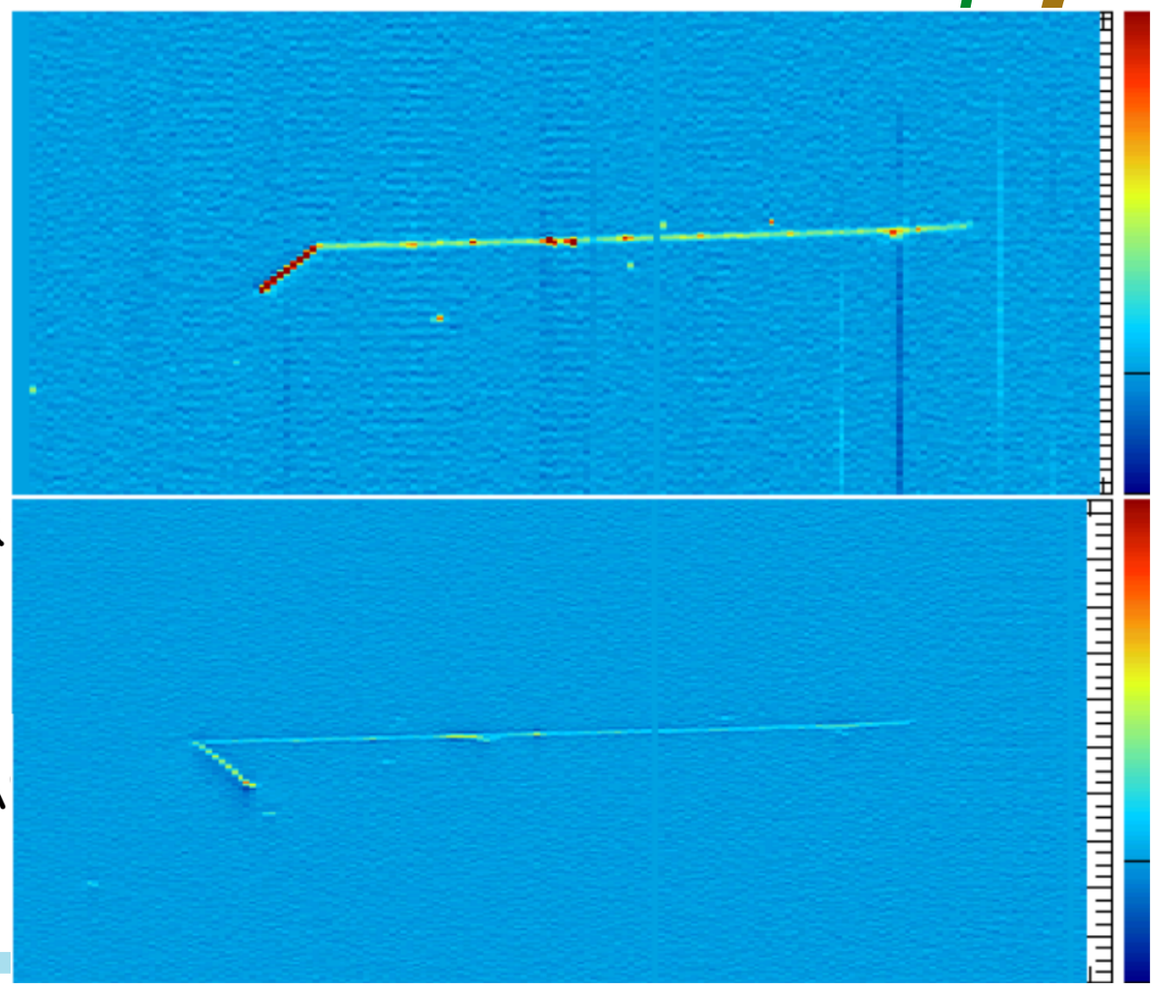

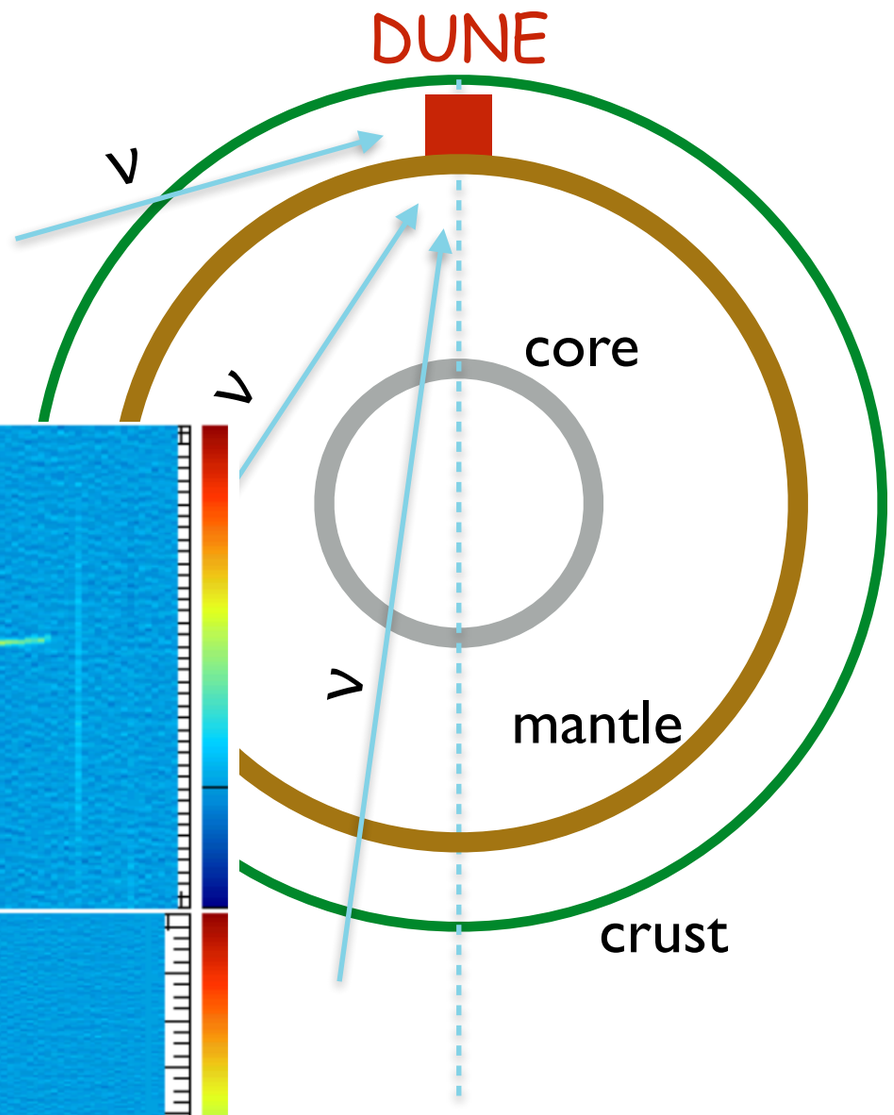

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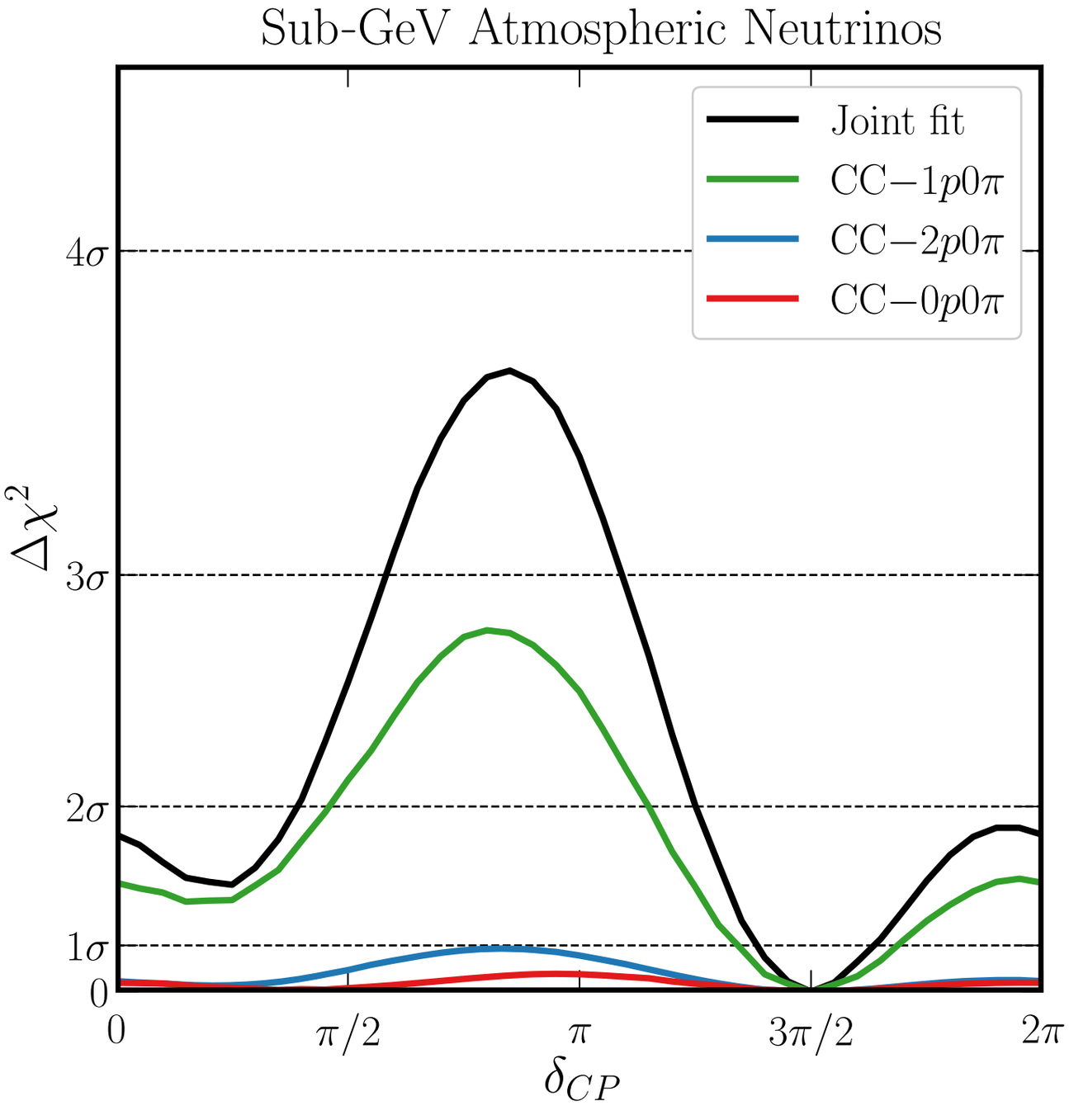
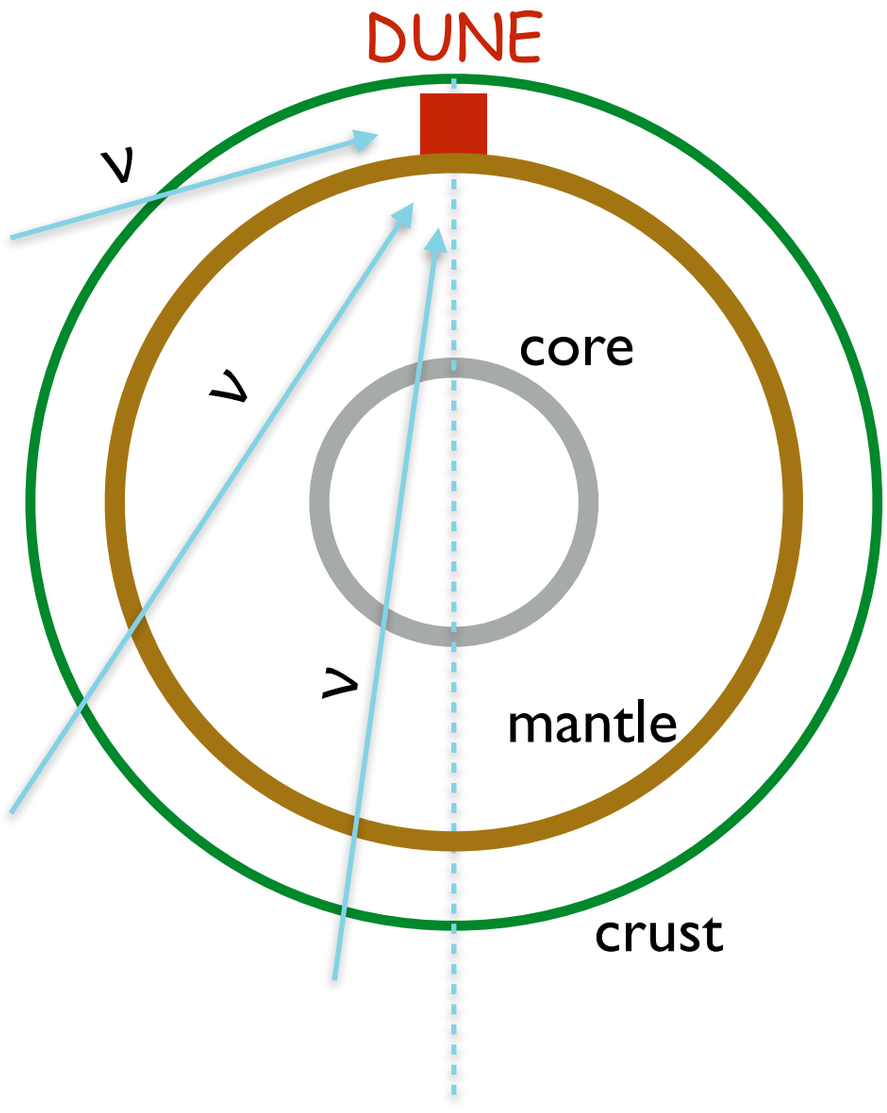
Fermilab

Redundancy: CP phase with sub-GeV atmospheric neutrinos

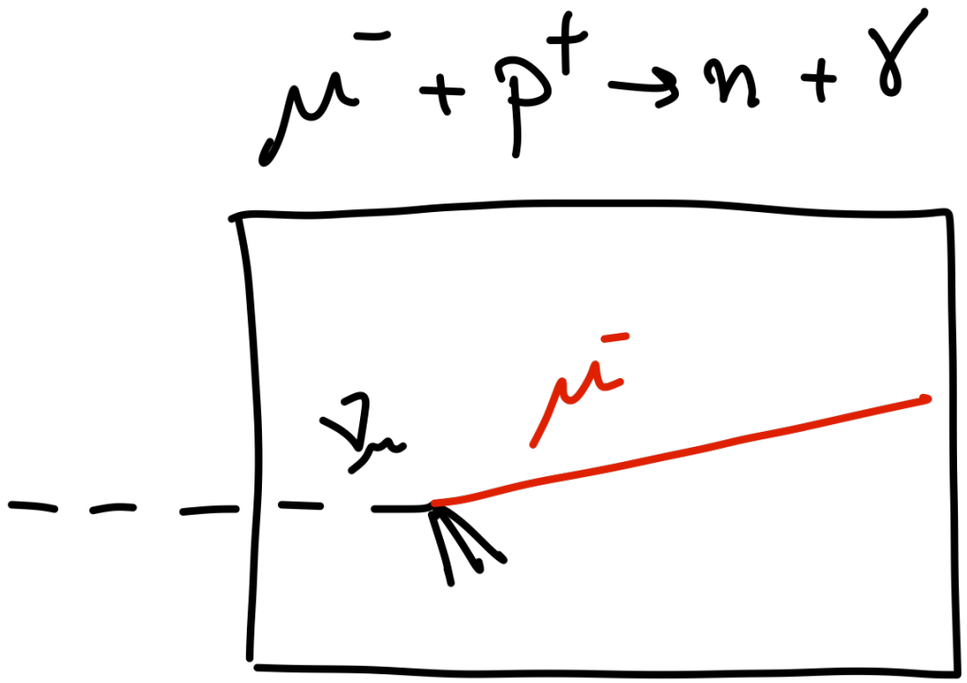
Kelly et al 1904.02751

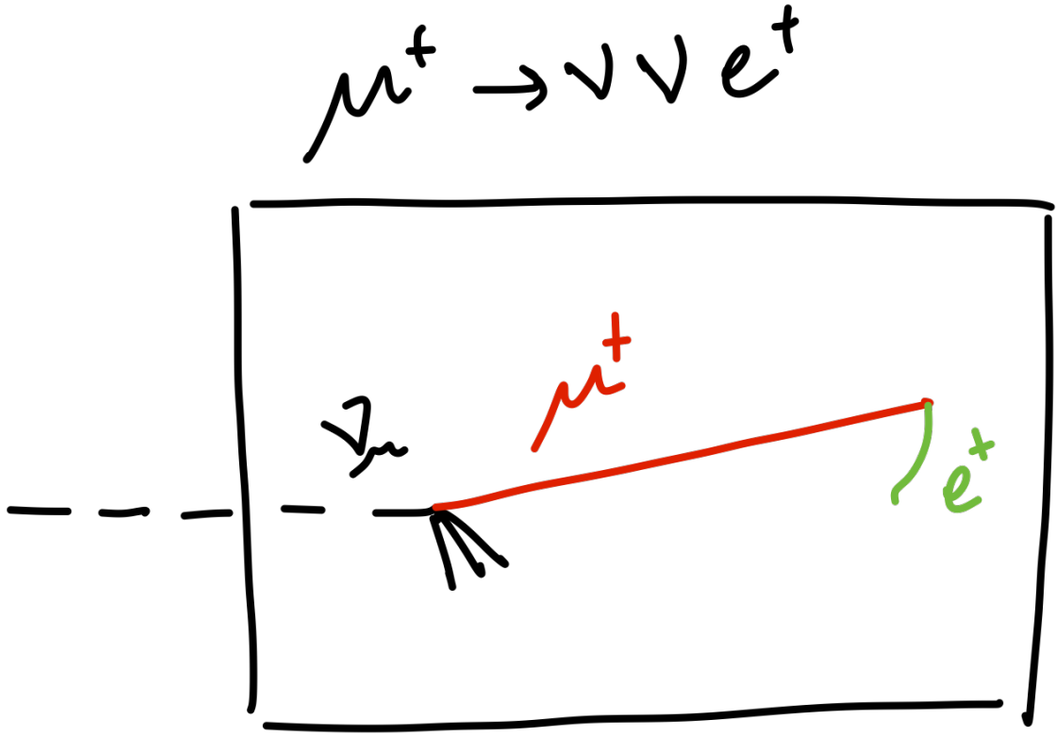


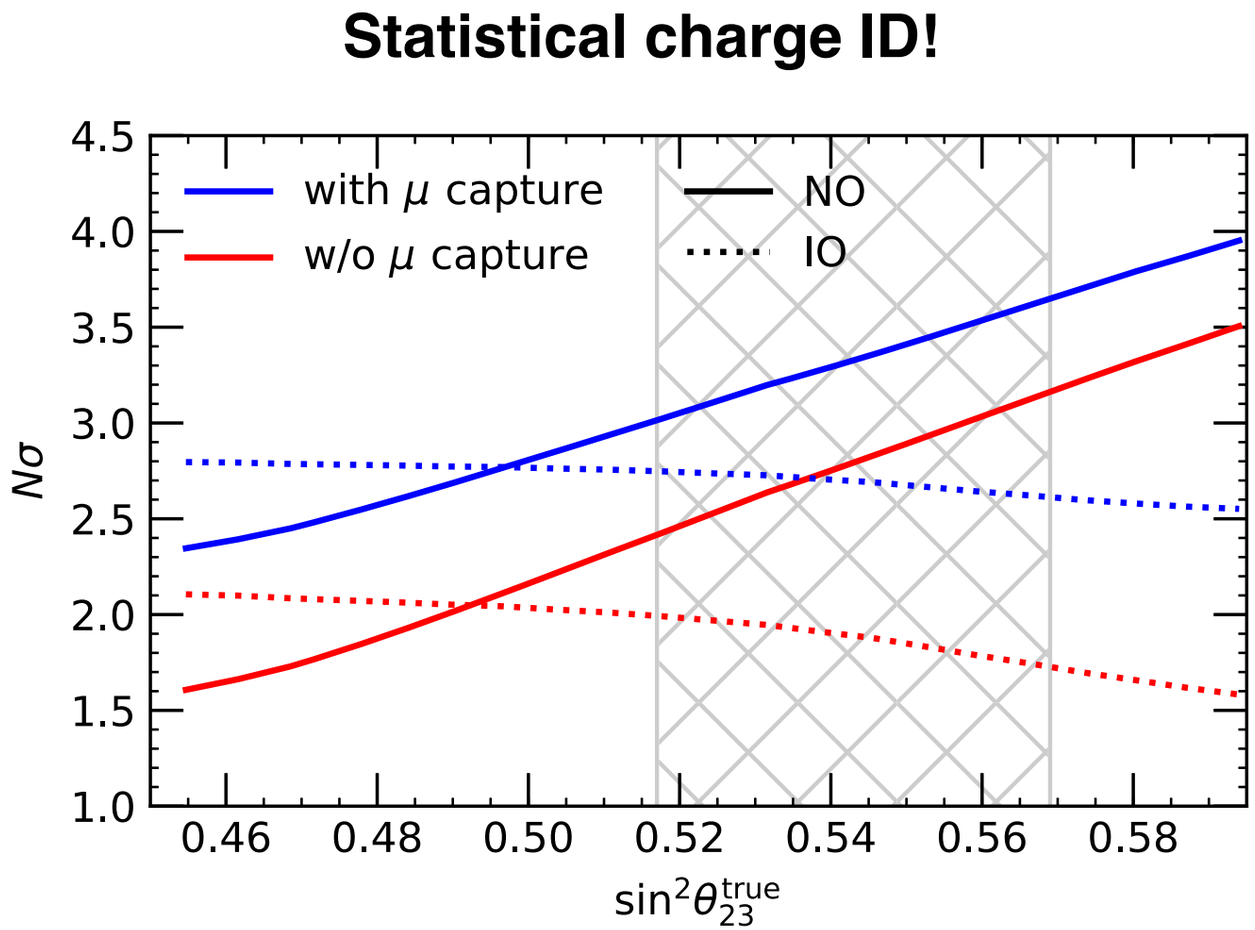


Redundancy: hierarchy with atmospheric neutrinos

Ternes et al 1905.03589







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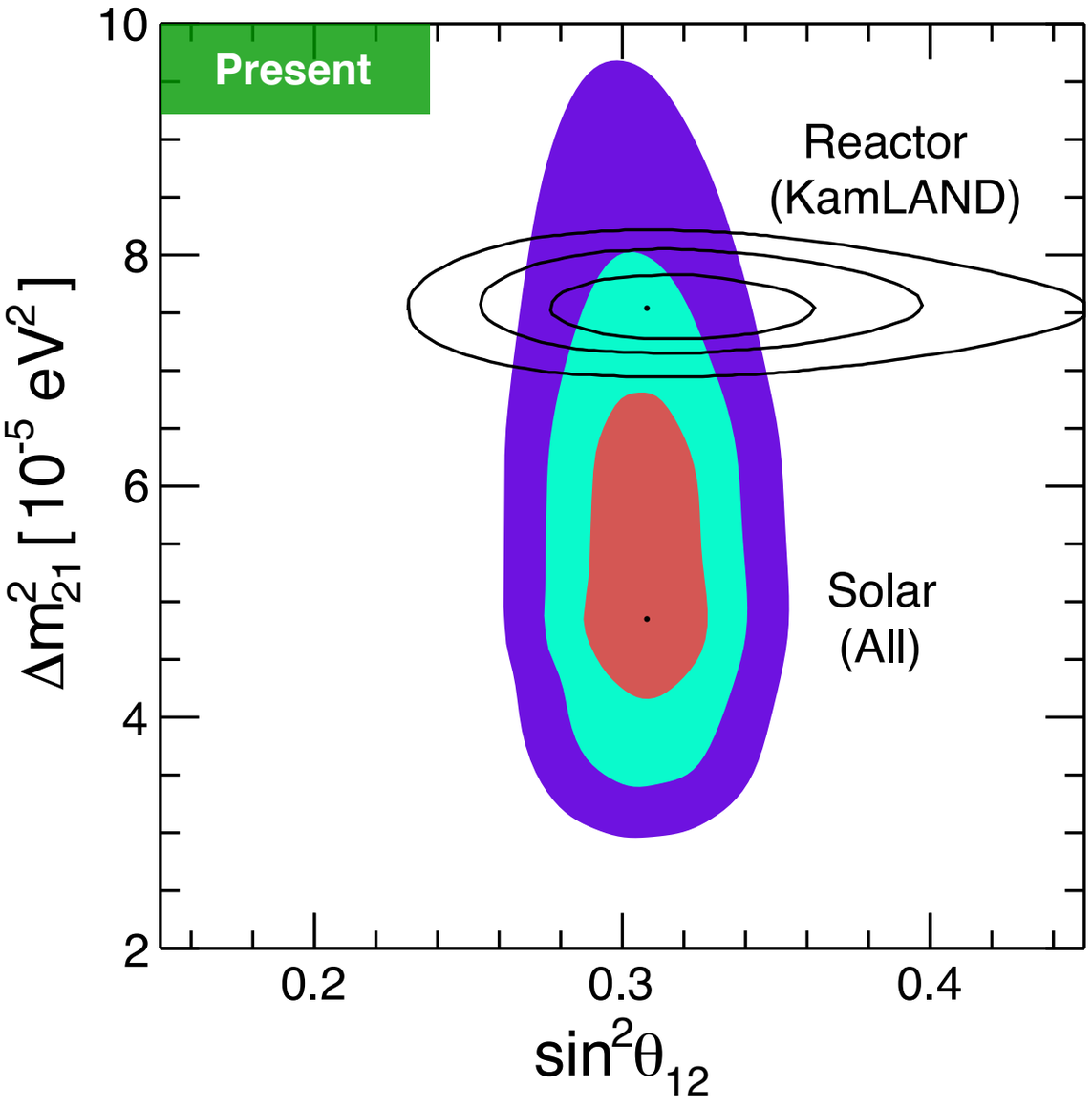
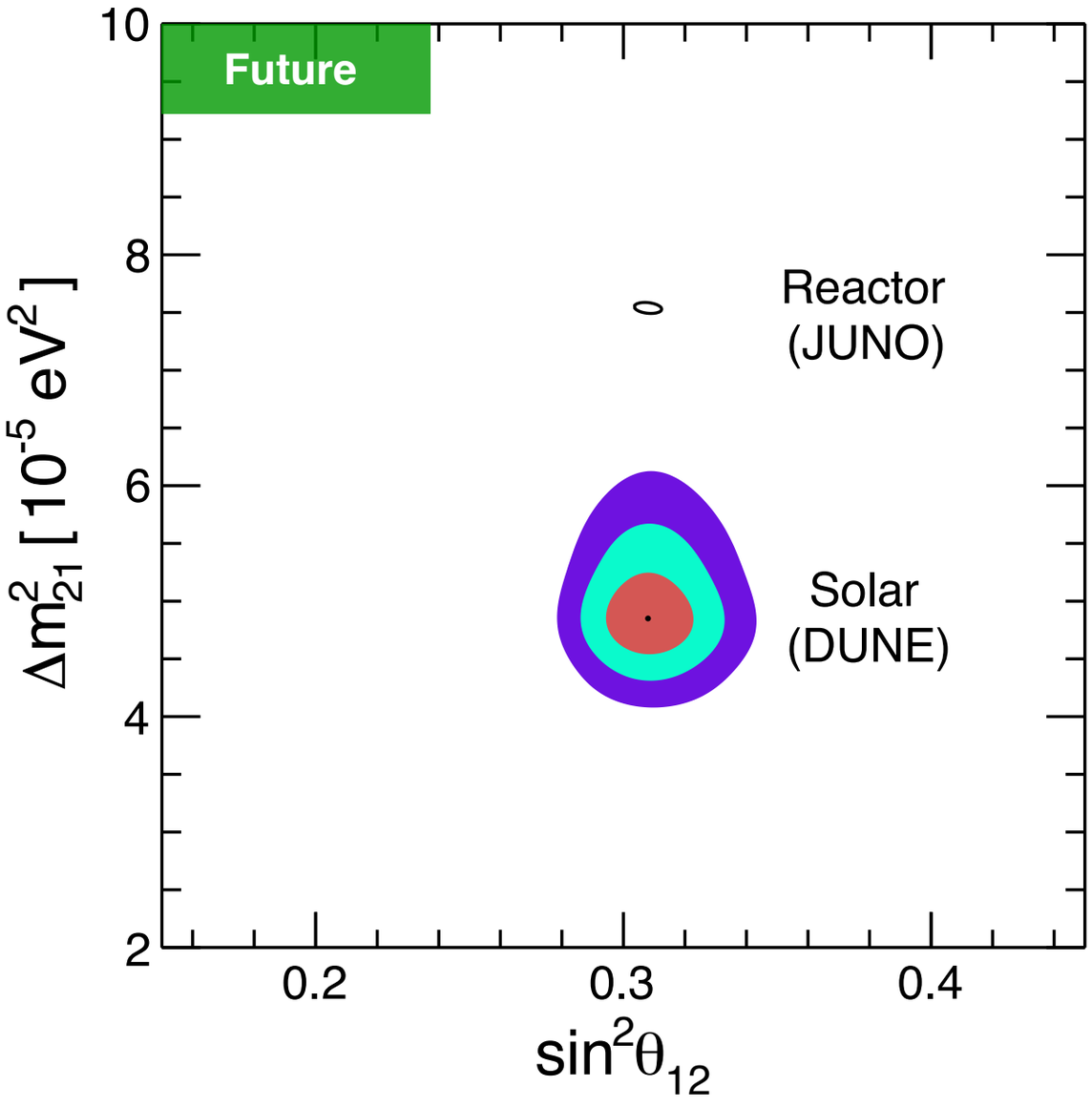
Redundancy: solar mass splitting with DUNE

Capozzi et al 1808.08232

$$\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K^*$$

$$\nu_x + {}^{40}Ar \rightarrow \nu_x + {}^{40}Ar^*$$





Fortress of Redundancy

woods

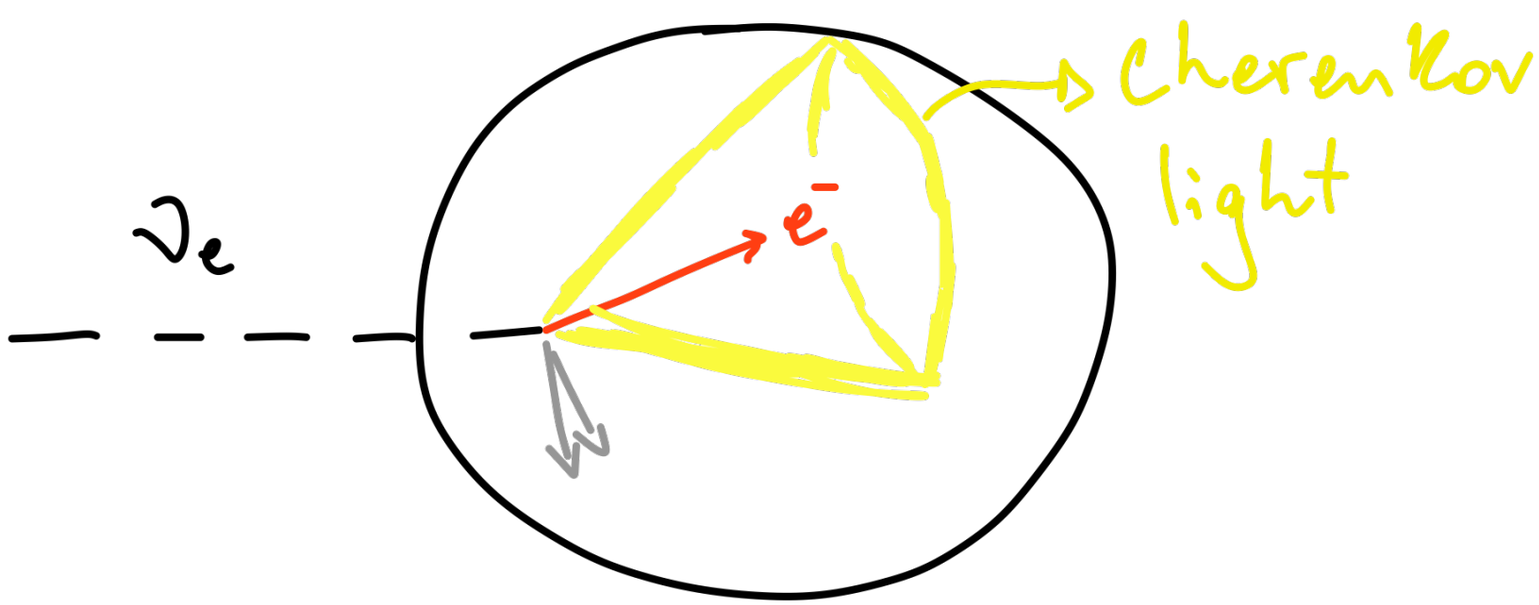
cross section

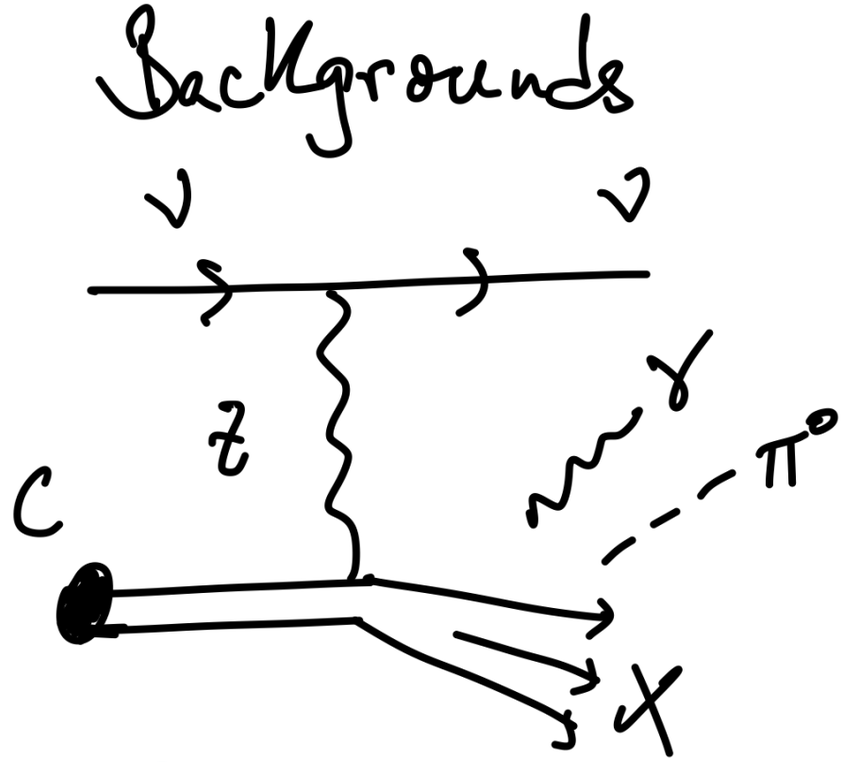
badlands

BSM

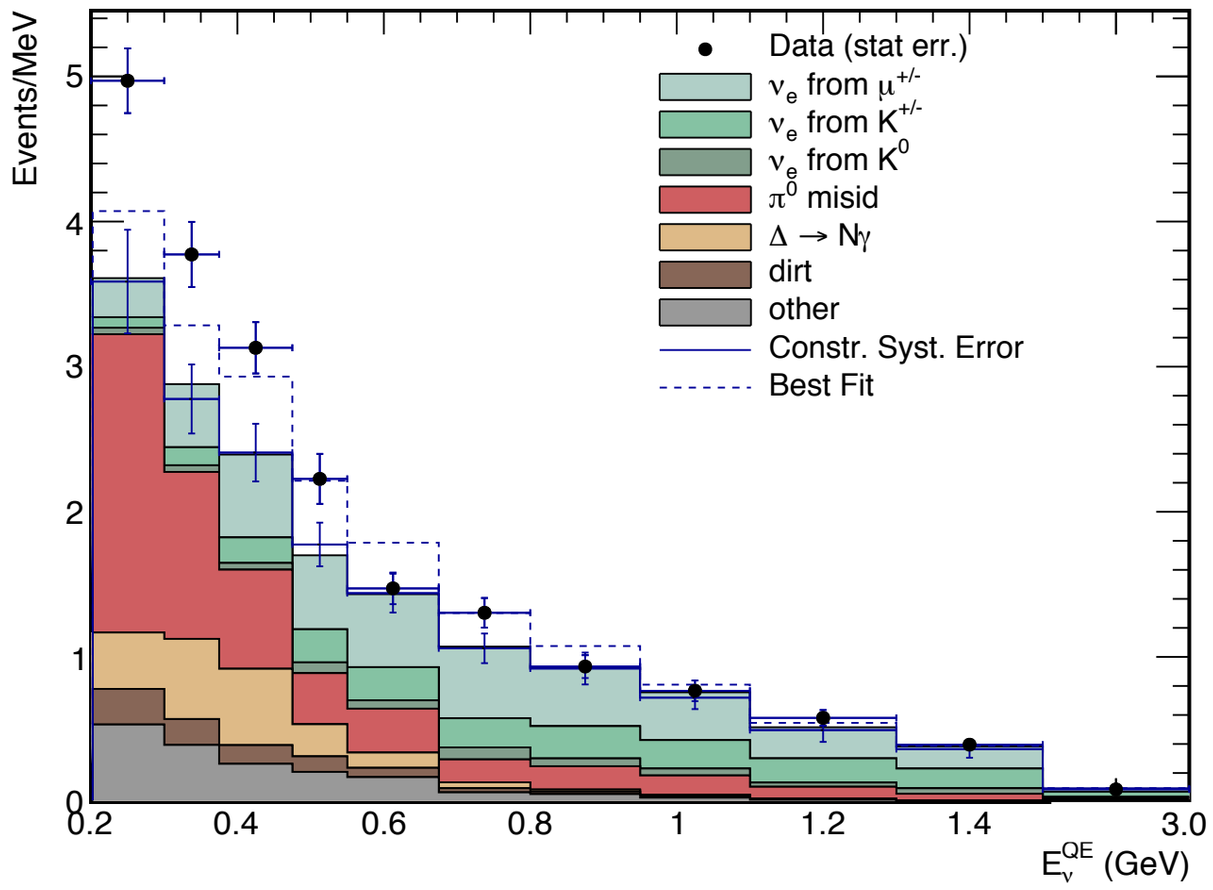
Mountains

Beyond standard physics in neutrino experiments





MiniBooNE 1805.12028



+ LSND

+ Reactor anomaly

+ Gallium anomaly

Lots of work here:
Arguelles, Ballett, Bertuzzo, Cabezudo, Conrad, De Gouvea, Dentler, Esteban, Gariazzo, Giunti, Gninenko, Hostert, Ignarra, Jana, Karagiorgi, Kopp, Laveder, Li, Machado, Maltoni, Martinez-Soler, Palomares-Ruiz, Pascoli, Peres, Schwetz, Shaevitz, Spitz, Stenico, Tsai, Zukanovich Funchal, ……

Fermilab
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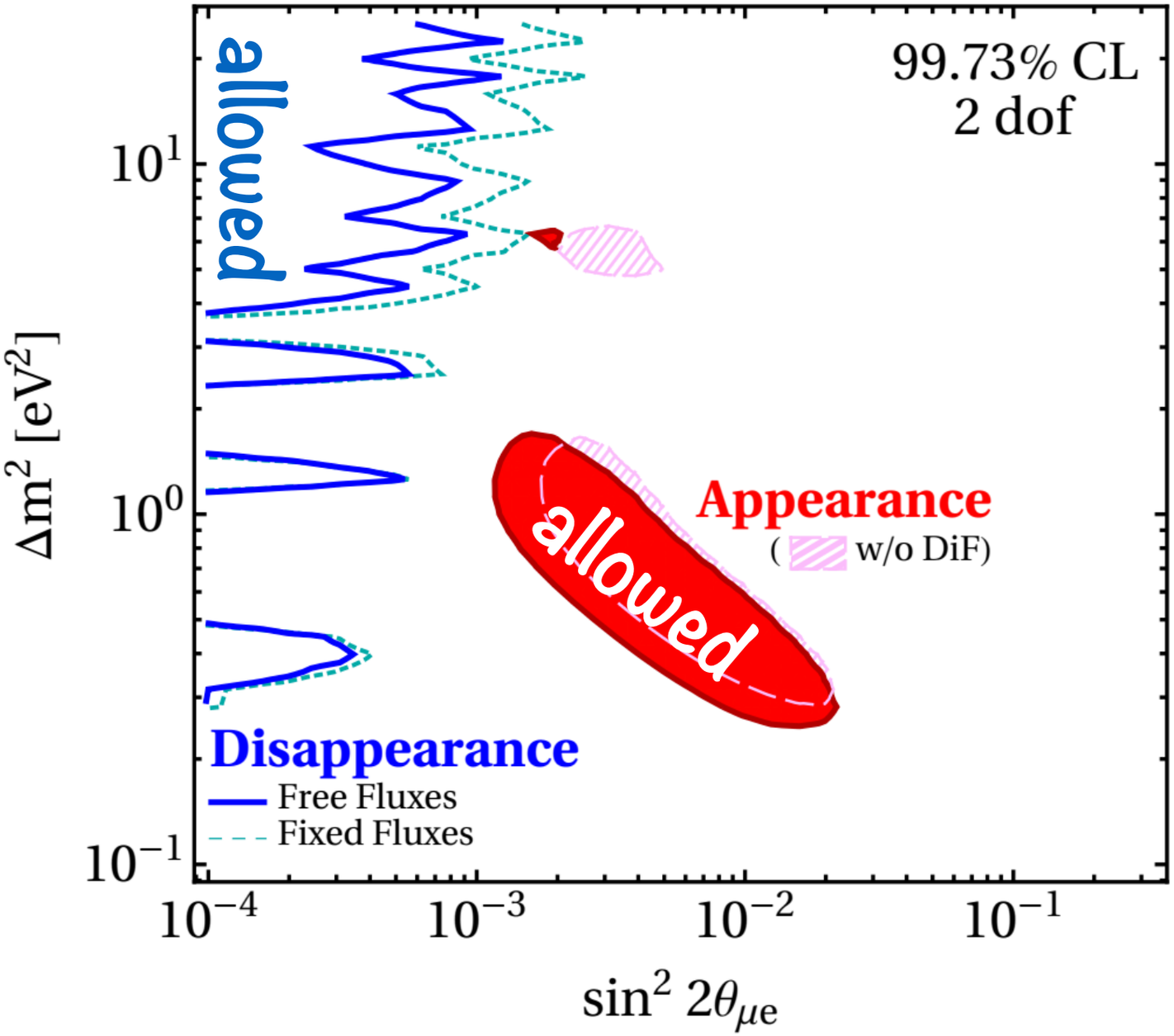
Beyond standard physics in neutrino experiments

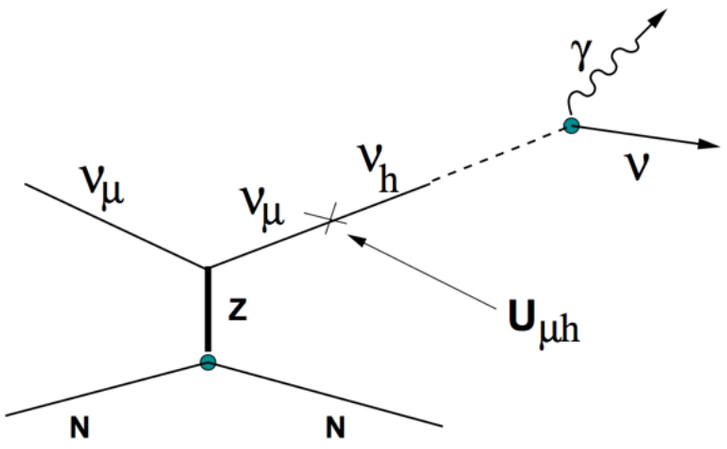
Dentler et al 1803.10661



No overlap in 3σ region = Tension

Beyond standard physics in neutrino experiments

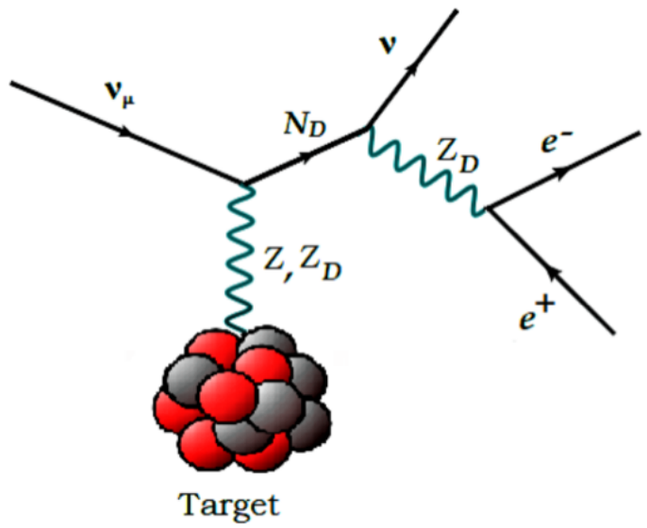
ν magnetic moment



Explains MiniBooNE

Gninenko 0902.3802

Dark neutrinos



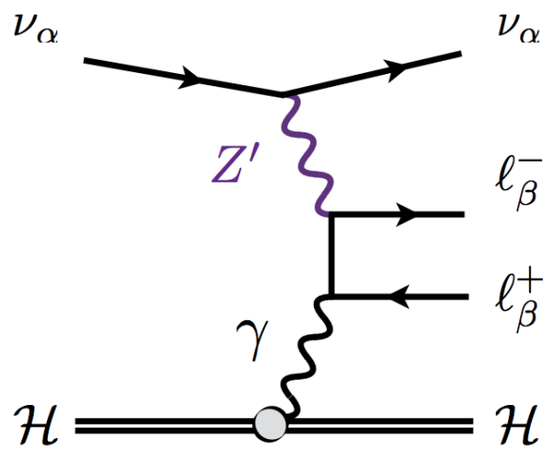
Explains MiniBooNE

Explains m_ν

Bertuzzo et al 1807.09877, 1807.02500

Ballett et al 1808.02915, Arguelles et al 1812.08768

New gauge bosons (e.g. L_μ-L_τ)

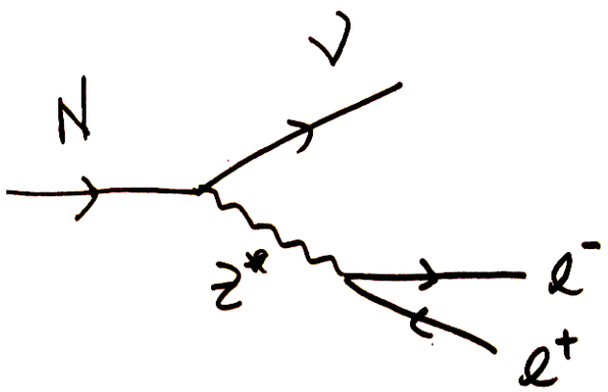


Explains $(g-2)_\mu$

Altmannshofer et al 1406.2332

Ballet et al 1902.08579

Heavy neutrinos

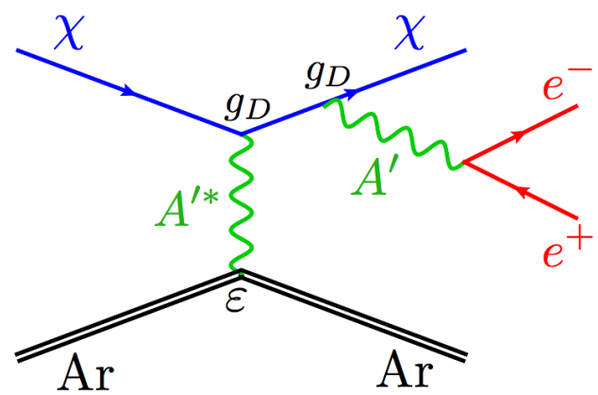


Explains m_ν

so many people...

- Neutrino decay
- Decoherence
- Non-unitarity
- Non-standard interactions
- Ultra-light scalars
- Dark matter
- Extra dimensions
- New forces/mediators
- Millicharged particles
- Neutrino self interactions
- ...

Dark tridents



Explains DM

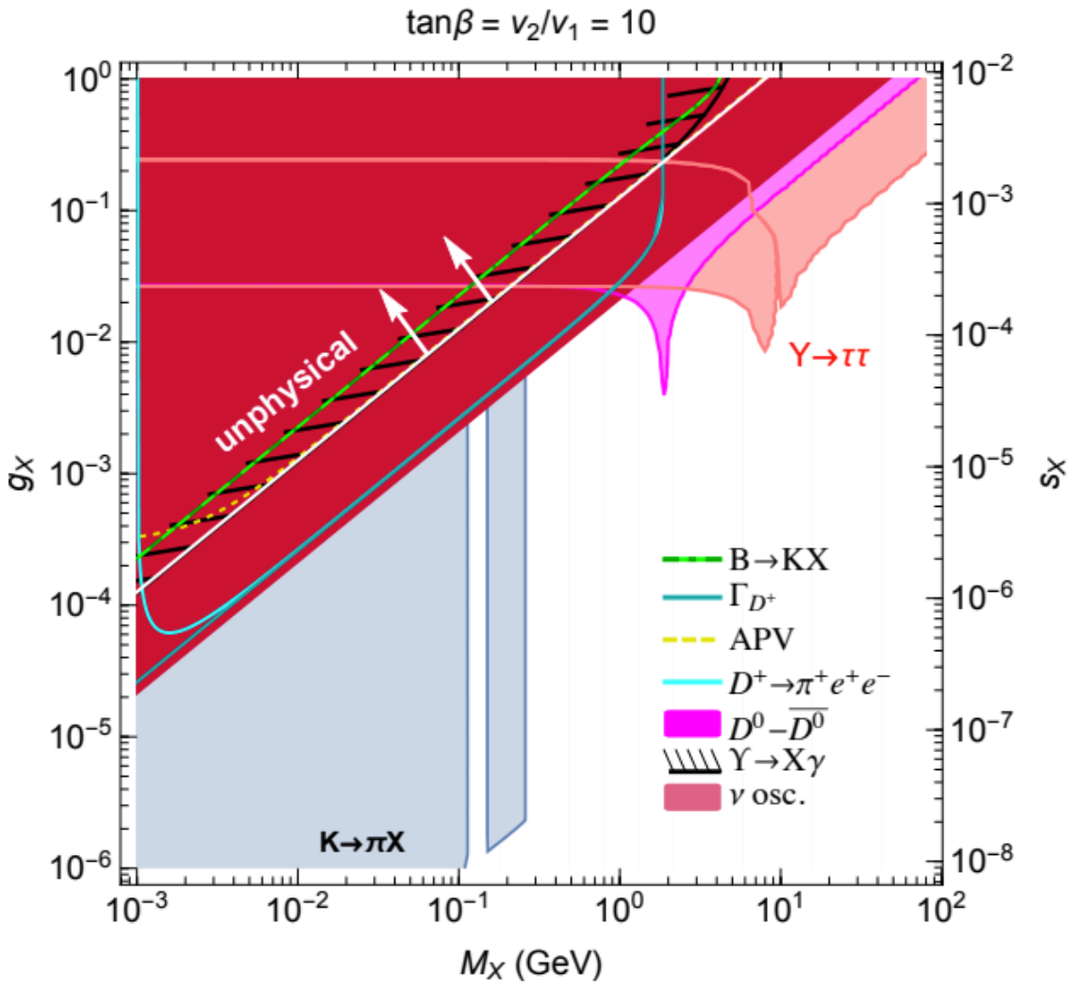
de Gouvêa et al 1809.06388

A BSM case study: low scale models

Flavor model at low scales: gauged B - L of the 3rd family

A BSM case study: low scale models

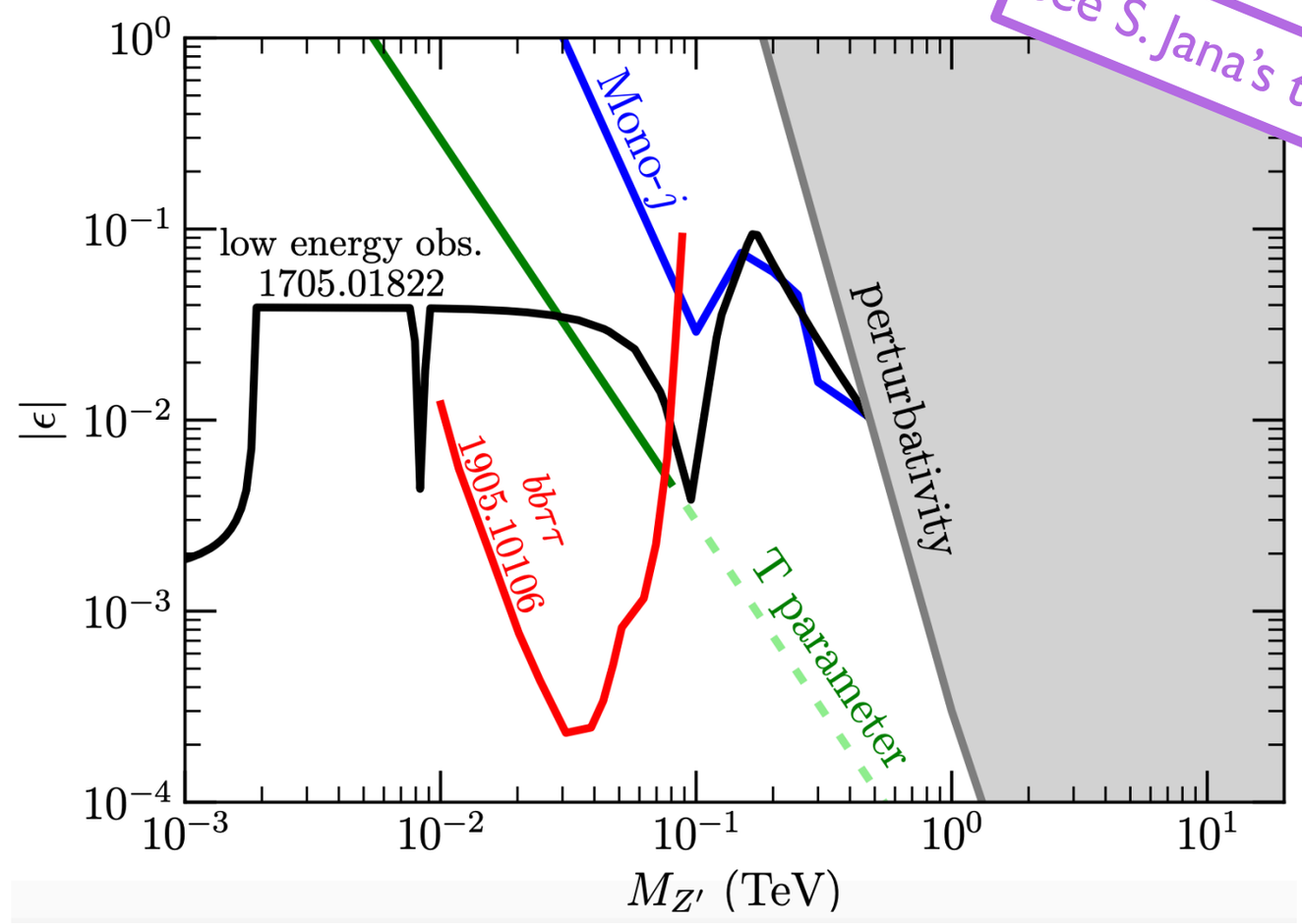
Flavor model at low scales: gauged B - L of the 3rd family



Complementarity: ν oscillations, meson decay and oscillation, parity violation, kaon physics…

Babu Friedland M Mocioiu 1705.01822

see S. Jana's talk

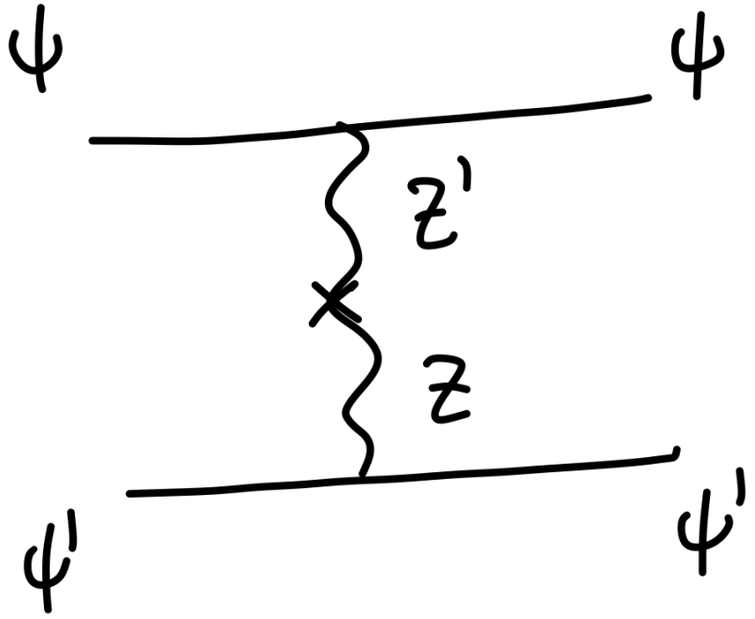


More complementarity: low energy measurements, dedicated collider searches, general searches, …

Elahi Martin 1905.10106
Babu Gonçalves Jana M 2003.03383
see also Farzan Shoemaker 1512.09147,
Han et al 1910.03272,

A BSM case study: low scale models

	$SU(2)_L$	$U(1)_Y$	$U(1)'$	
H	2	$1/2$	0	$(B, W^3) \to (A, Z)$
H'	2	$1/2$	1	$(B, W^3, X) \to (A, Z, Z')$



A BSM case study: low scale models

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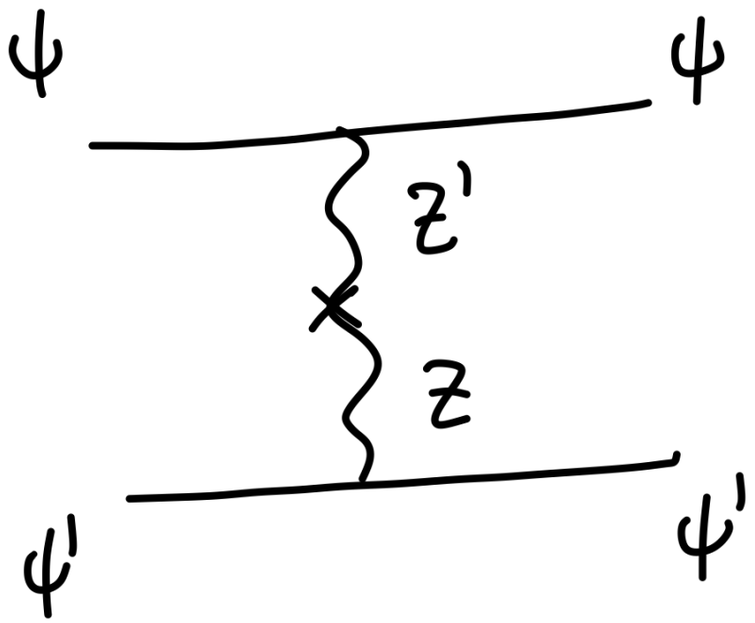
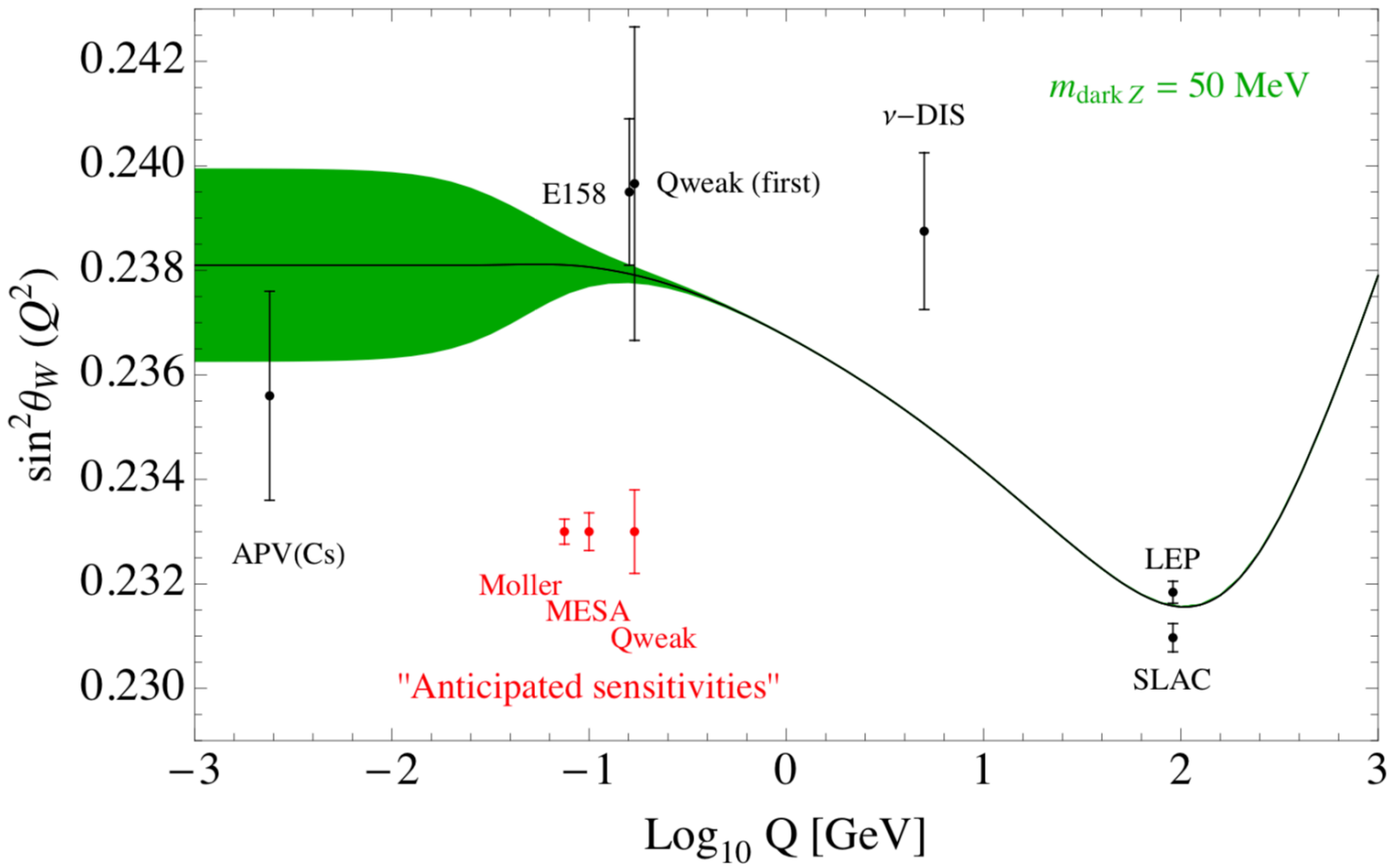
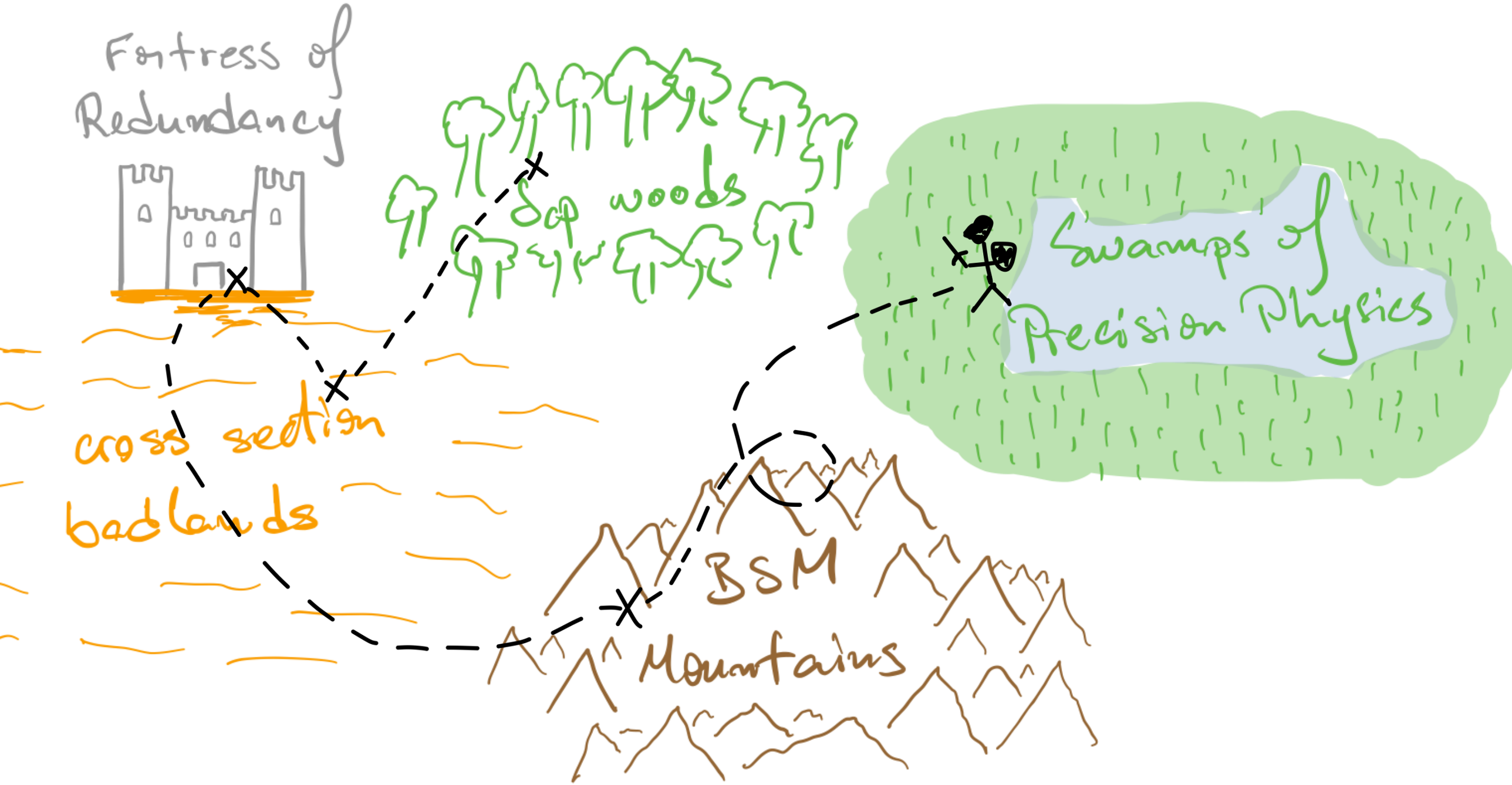


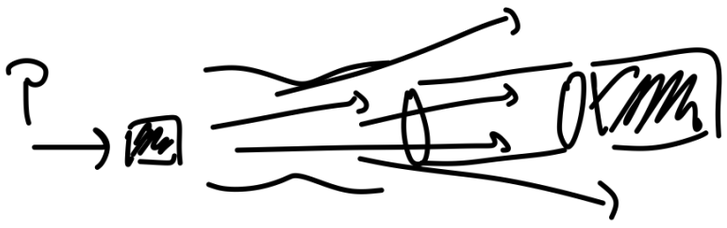
Davoudiasl Lee Marciano 1402.3620

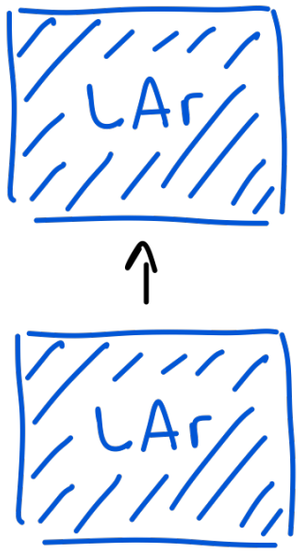


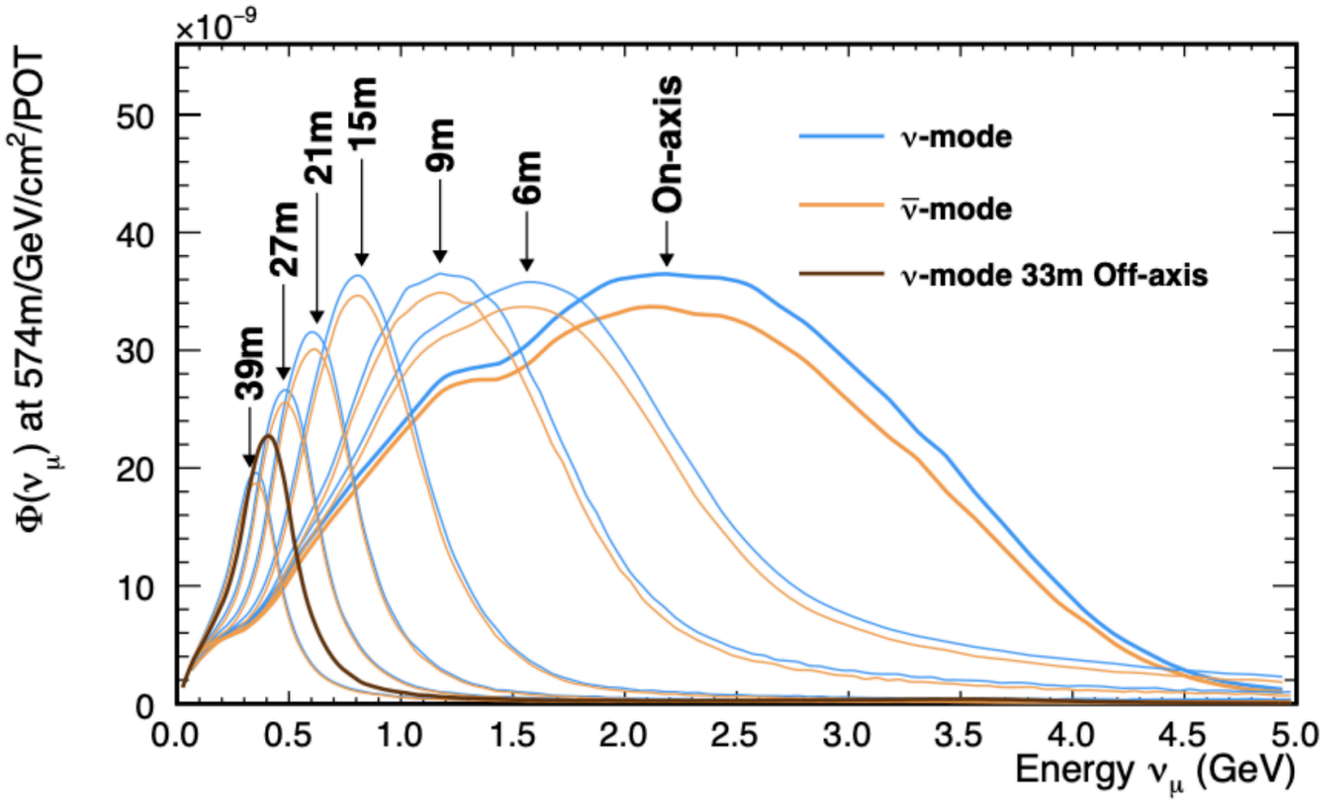

Fortress of Redundancy
cross section
badlands
Sap woods
BSM Mountains
Swamps of Precision Physics

Weak mixing at DUNE

DUNE-PRISM

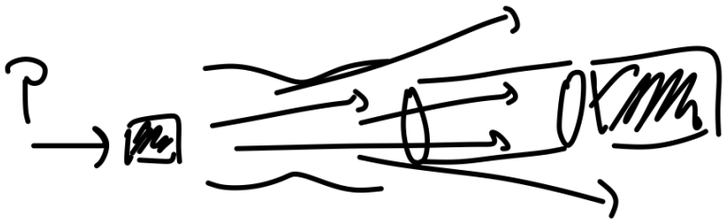




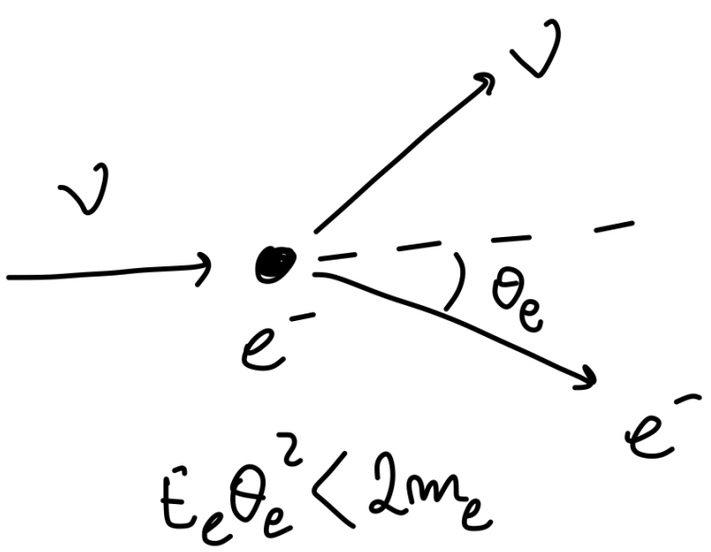


Weak mixing at DUNE

DUNE-PRISM

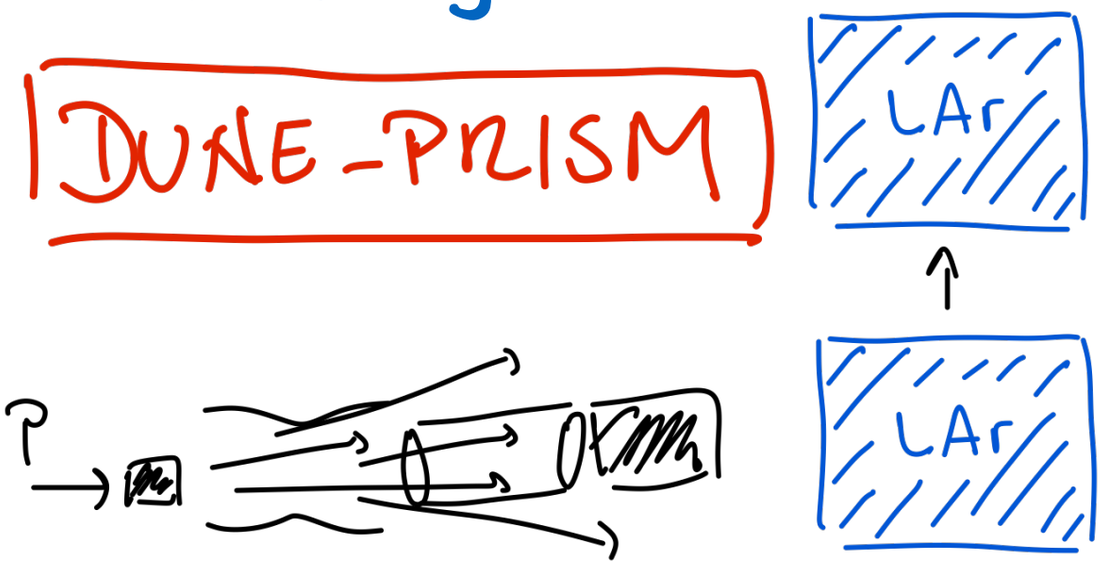


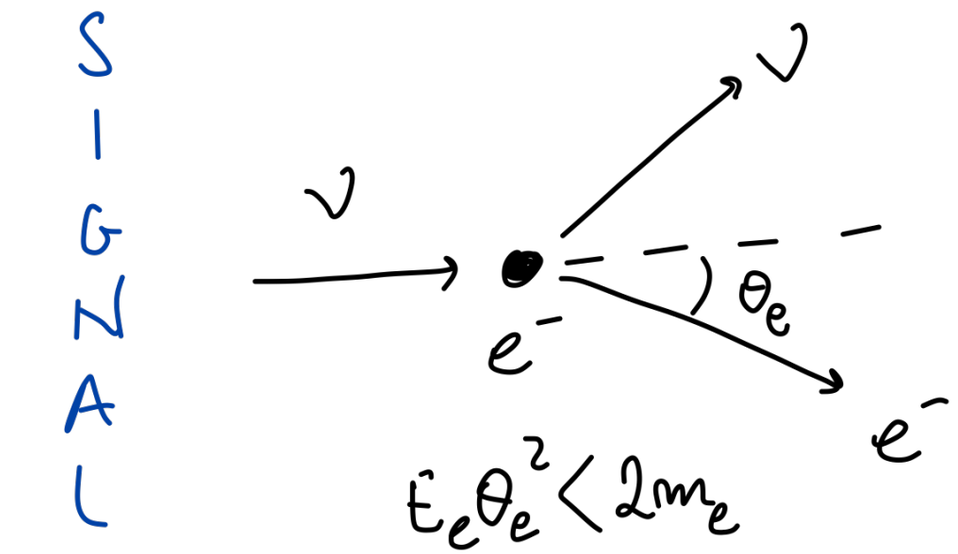
SIGNAL

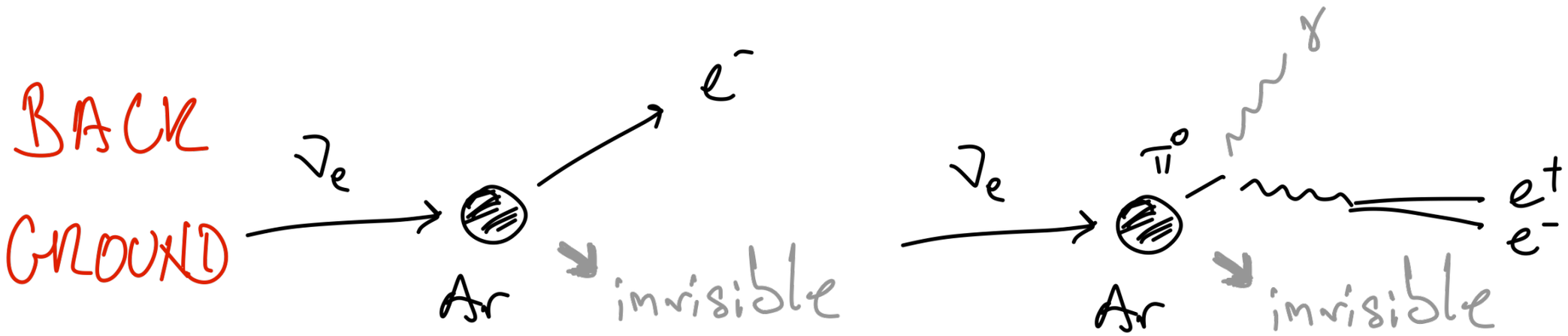


Weak mixing at DUNE

DUNE-PRISM

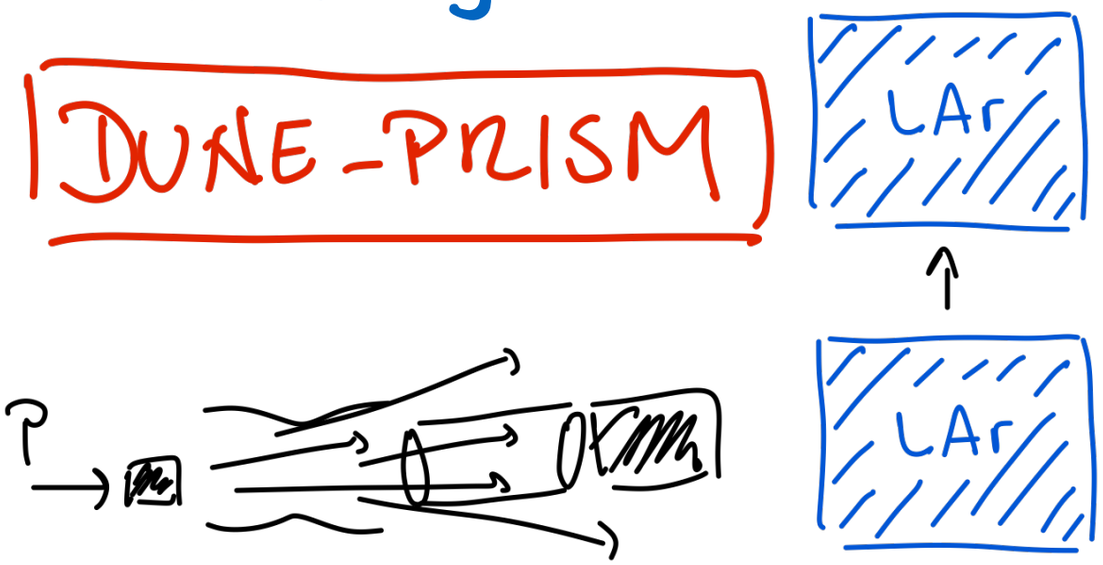


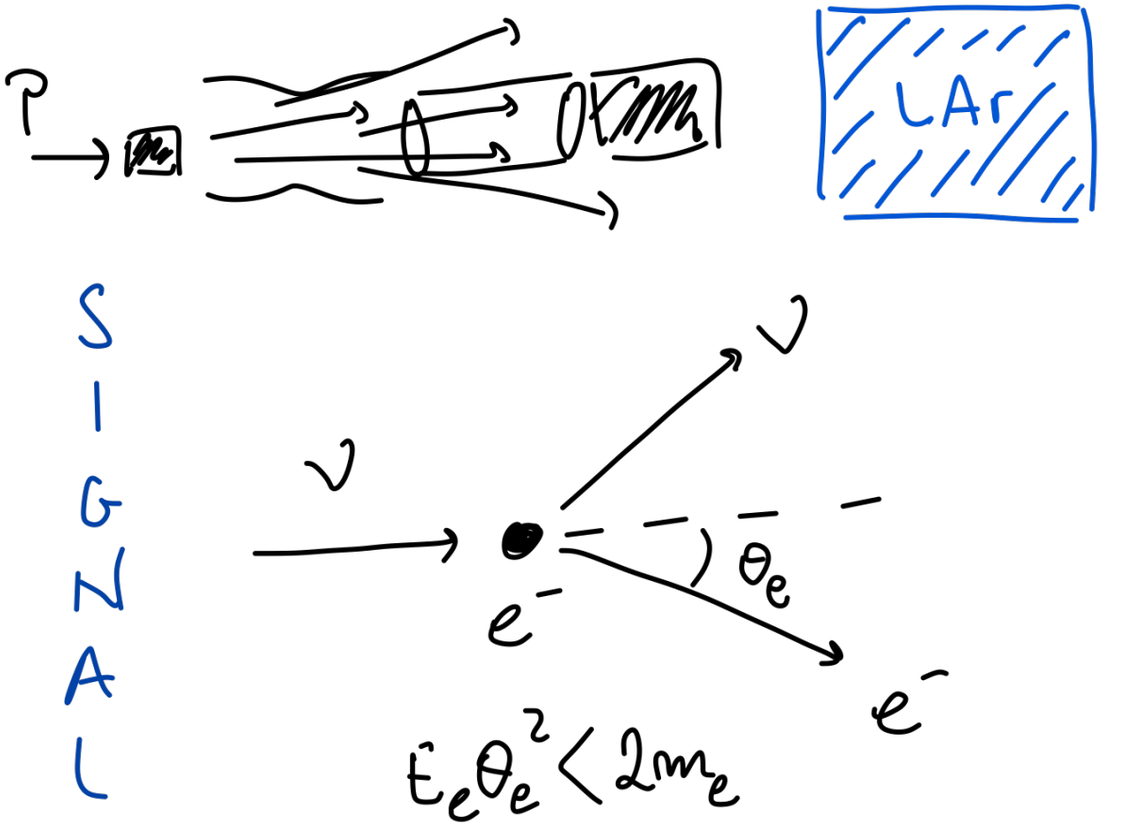


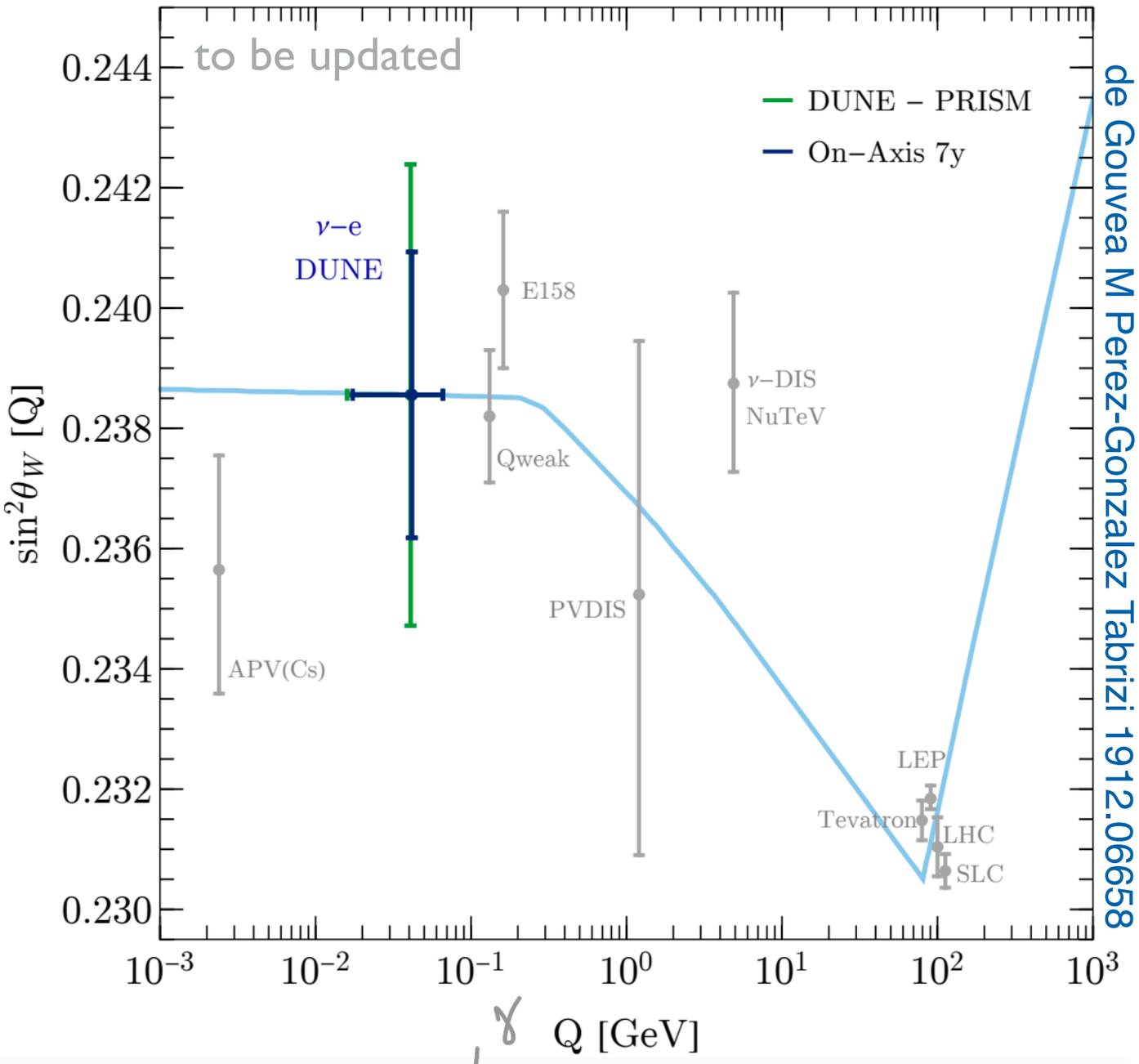


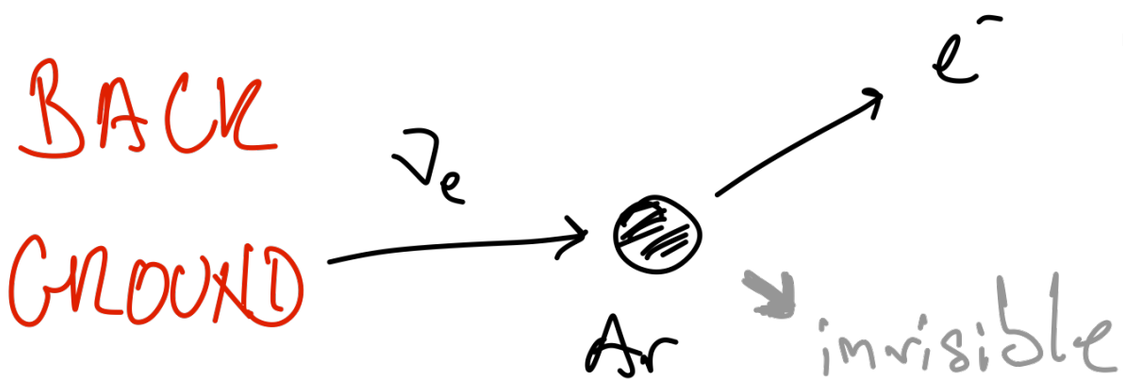
Weak mixing at DUNE

DUNE-PRISM









see also O. Tomalak's talk

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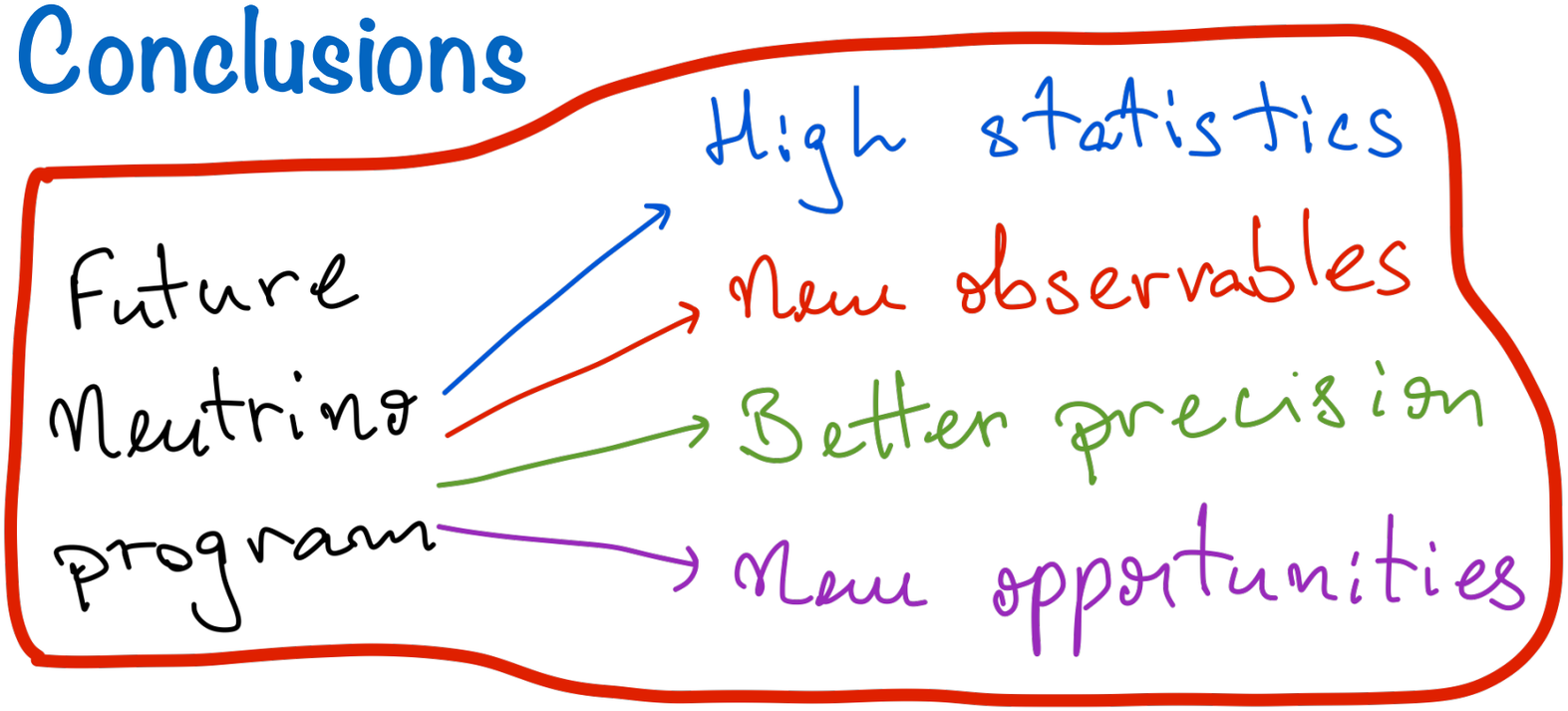
Conclusions



Conclusions

Future Neutrino program

- High statistics
- New observables
- Better precision
- New opportunities

LArTPC capabilities still largely unexplored!

What else can we learn with topology?

TH-EXP collaborations much needed!

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What else can we learn with topology?

TH-EXP collaborations much needed!

Could not cover many interesting topics: astro, cosmo, m_ν, $0\nu\beta\beta$, colliders, CEvNS, ...

I will be around to chat, ping me on email!

Thanks!

pmachado@fnal.gov