Sterile Neutrinos

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CERN | Neutrino PLATFORM | erc | JG|U JOHANNES GUTENBERG UNIVERSITÄT MAINZ

The Neutrino Portal

$$\mathcal{L} \supset y\,\bar{L}\,(i\sigma^2 H^*)\,N$$

- ☑ the only renormalizable coupling of the SM to a singlet fermion (aka “sterile neutrino” or “heavy neutral lepton”)

The Neutrino Portal

SM lepton doublet

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SM lepton doublet

SM Higgs doublet

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The Neutrino Portal

SM lepton doublet

SM Higgs doublet

SM singlet fermion
(sterile neutrino)

$$\mathcal{L} \supset y \bar{L} (i\sigma^2 H^*) N$$

☑ the only renormalizable coupling of the SM to a singlet fermion (aka "sterile neutrino" or "heavy neutral lepton")

Sterile Neutrinos

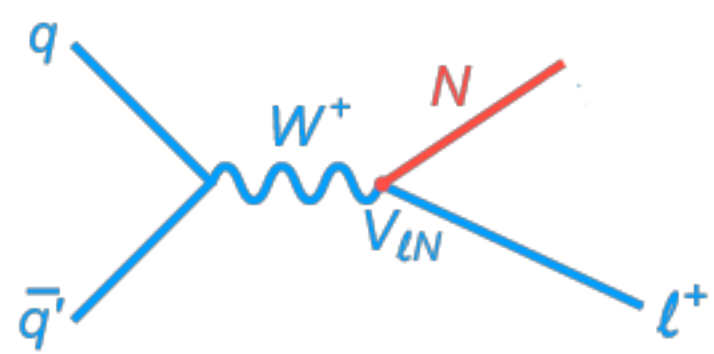
Definition: sterile neutrino = SM singlet fermion

- ☑ Very generic extension of SM
  - can be leftover of extended gauge multiplet
- ☑ Useful phenomenological tool
  - can explain ν masses (seesaw mechanism, $m \sim$ TeV...M_{Pl})
  - can explain cosmic baryon asymmetry
    (thermal leptogenesis at $m \gg 100$ GeV, ARS leptogenesis at $m < 100$ GeV)
  - can explain dark matter ($m \sim$ keV)
  - can act a mediator to a dark sector (any mass)
  - can explain oscillation anomalies ($m \sim$ eV)
    ➠ Georgia Karagiorgi's talk

Neutrino Portal Phenomenology

$$\mathcal{L} \supset y\, \bar{L}\, (i\sigma^2 H^*)\, N$$

- ☑ new contribution to the ν mass matrix
  leads to mass mixing between ν and *N*
  - ➠ active–sterile neutrino oscillations
  - ➠ *N* production in neutrino interactions



Neutrino Oscillations

☑ Initial state

$$|\nu_\alpha\rangle = \sum_j U^*_{\alpha j} |\nu_j\rangle$$

☑ Transition probability

$$P_{\alpha\to\beta} = \left|\langle\nu_\beta|e^{-i\hat{H}T}|\nu_\alpha\rangle\right|^2$$
$$= \sum_{j,k} U^*_{\alpha j} U_{\beta j} U_{\alpha k} U^*_{\beta k} \exp\left[-i(E_j - E_k)T\right]$$

☑ Two flavor approximation

$$U = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \qquad P_{\alpha\to\beta} \simeq \sin^2 2\theta \sin^2 \frac{\Delta m^2 T}{4E}$$

Neutrino Oscillations

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generalizes to
> 3 flavors

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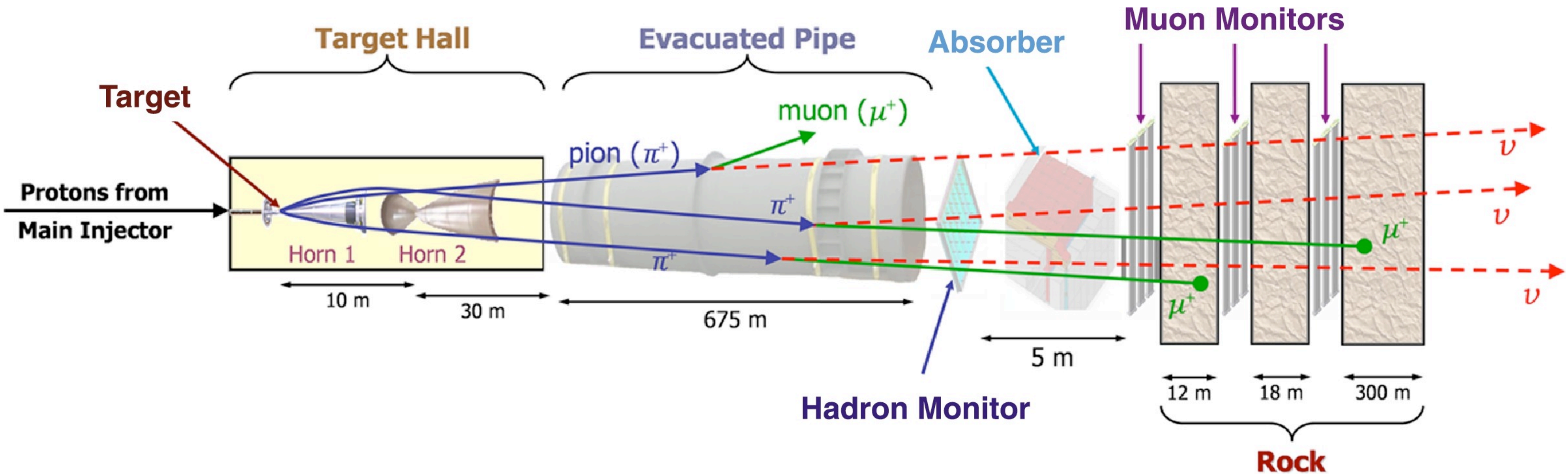
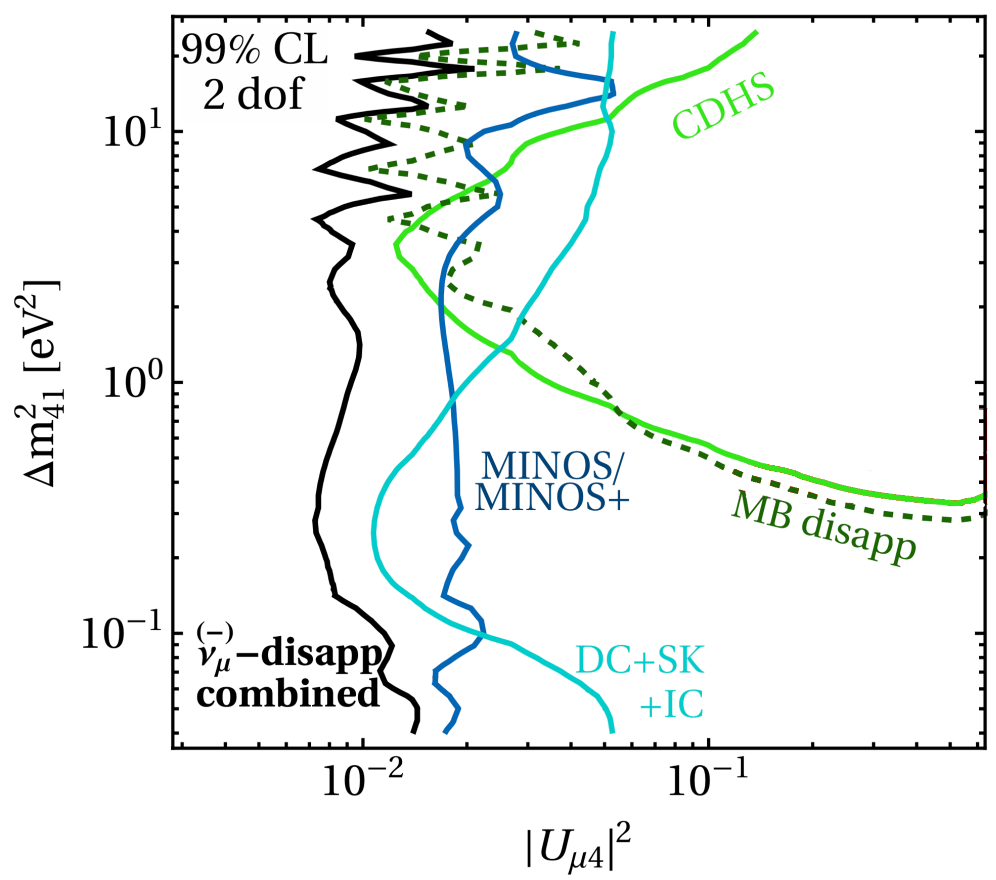


Oscillation Example: ν_μ Disappearance

- Use intense flux of ν_μ from pion decay in accelerator experiment or in the upper atmosphere
- Look for "missing" ν_μ at distances too short to be compatible with standard oscillations

Dentler *et al.* 2018



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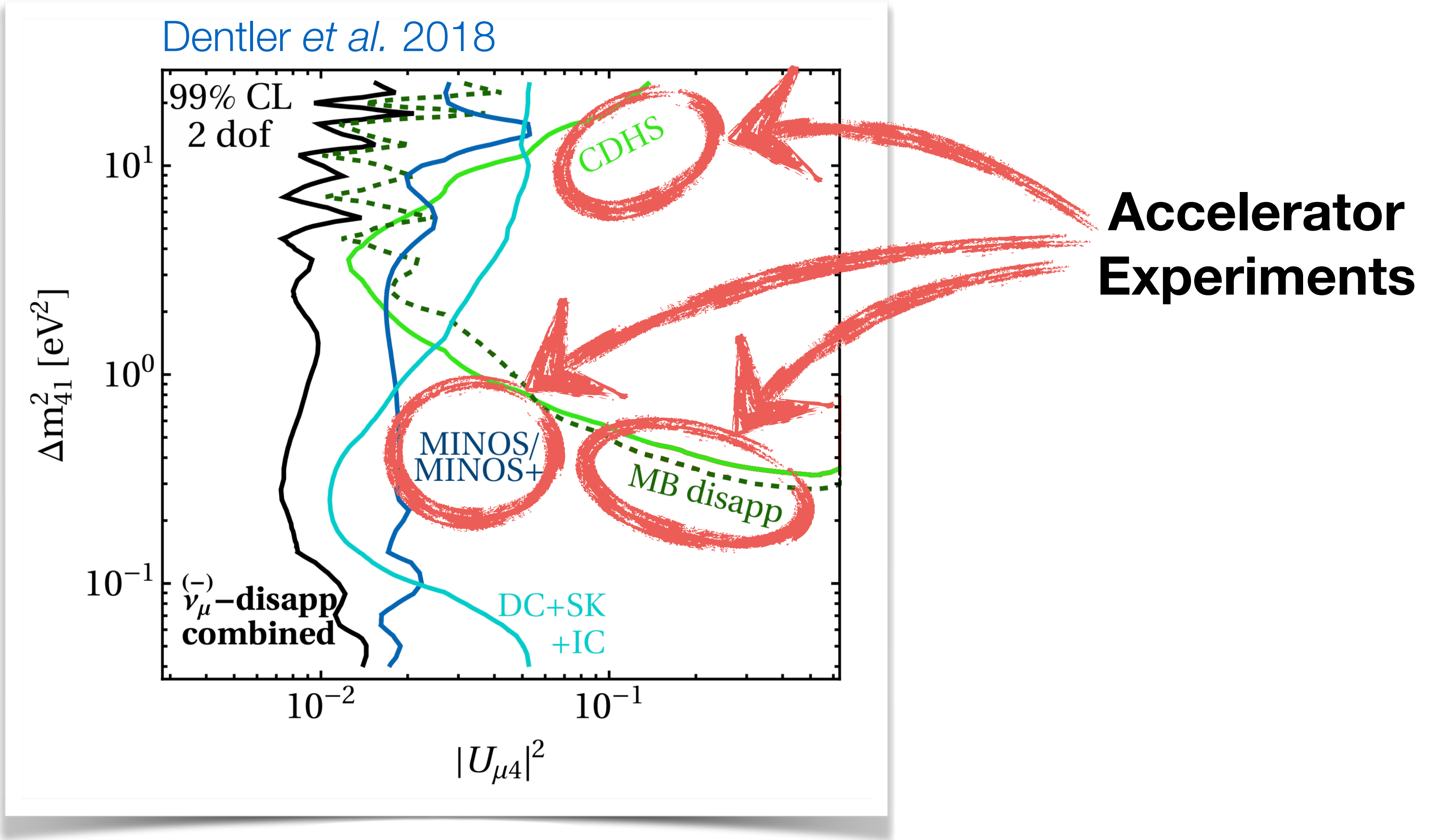

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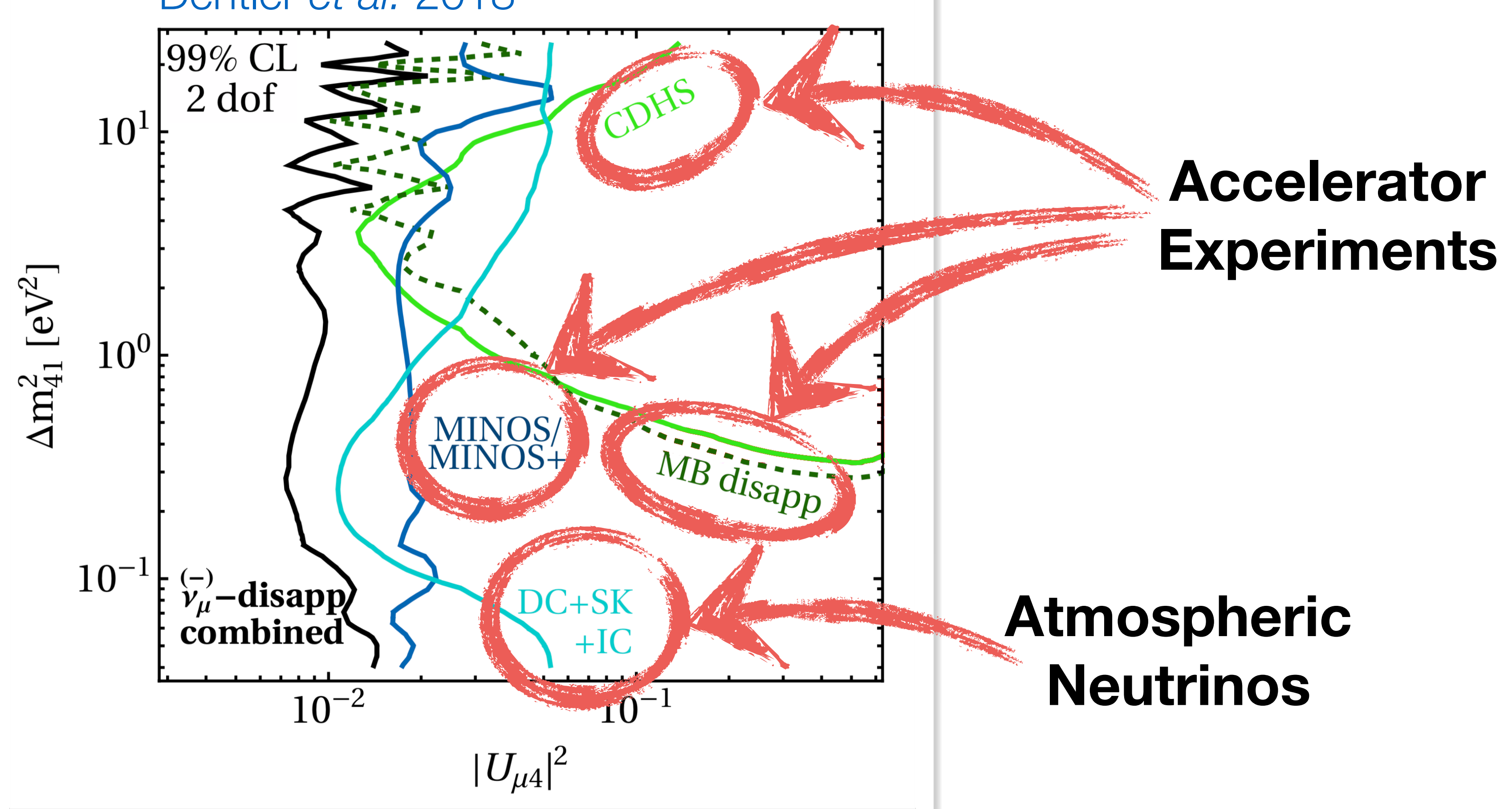

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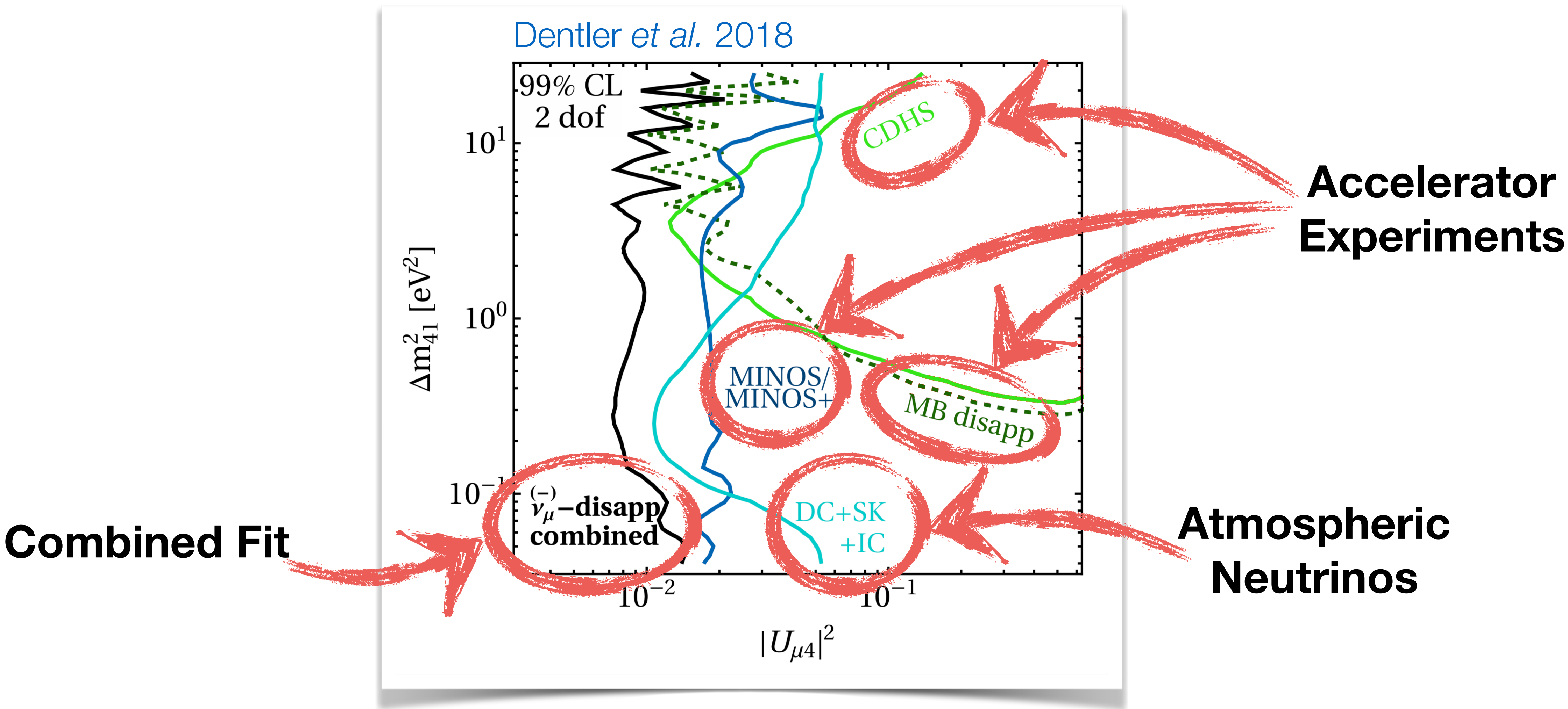


Short-Baseline Anomalies

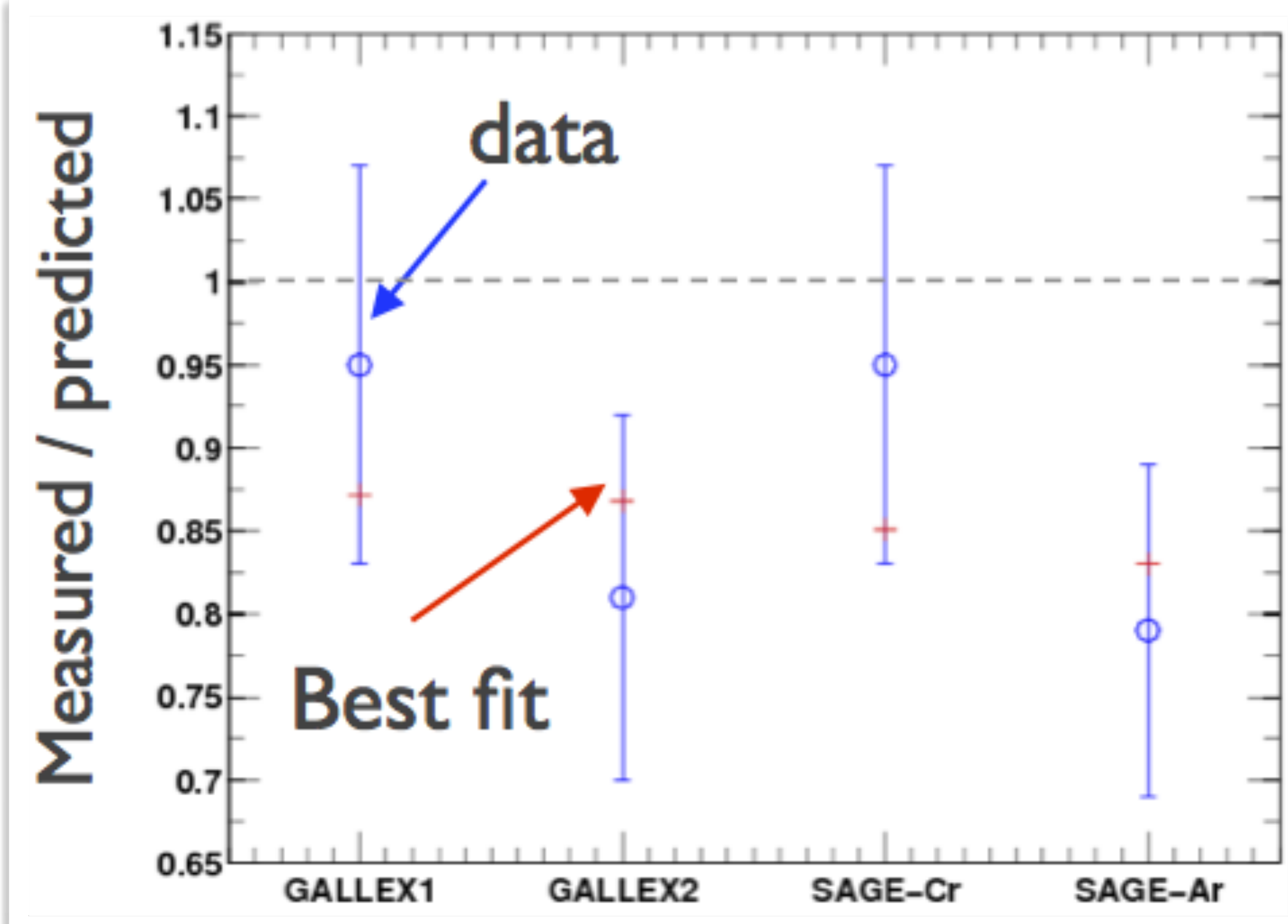
Interestingly, some experiments have presented results consistent with oscillations involving sterile neutrinos

The Gallium Anomaly

- Experiments with intense radioactive sources
- Neutrino detection via

$$^{71}\mathrm{Ga} + \nu_e \to {}^{71}\mathrm{Ge} + e^-$$

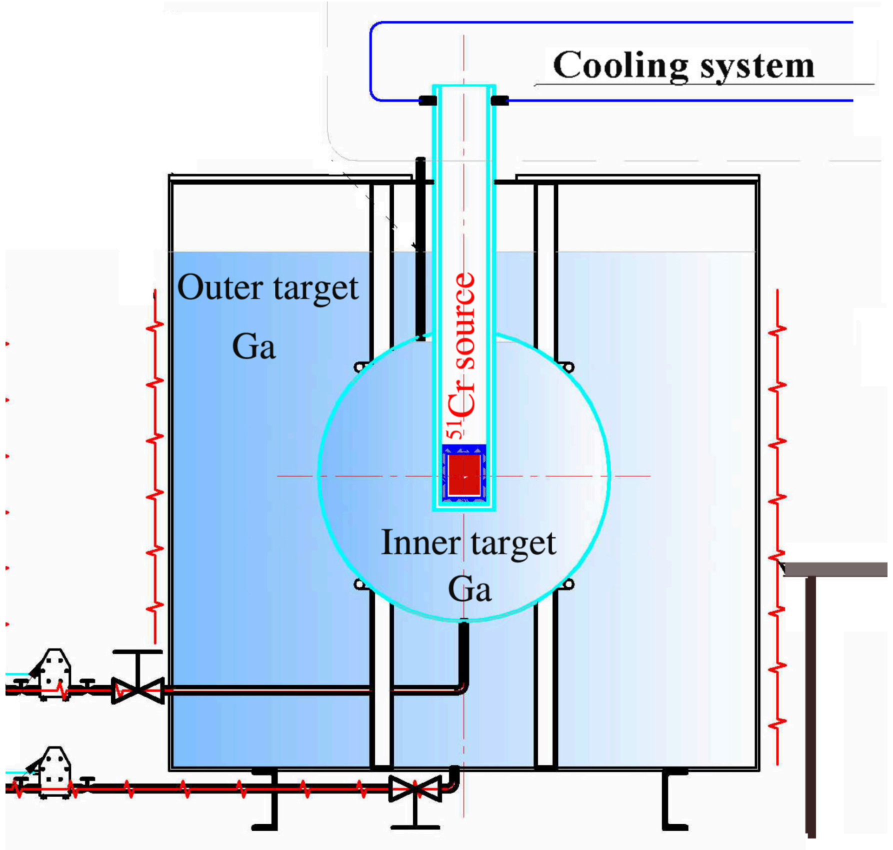
- ~3σ deficit
- ν_e disappearance into sterile state?
- would require very large mixing (conflict with reactor observations)



Giunti Laveder 1006.3244

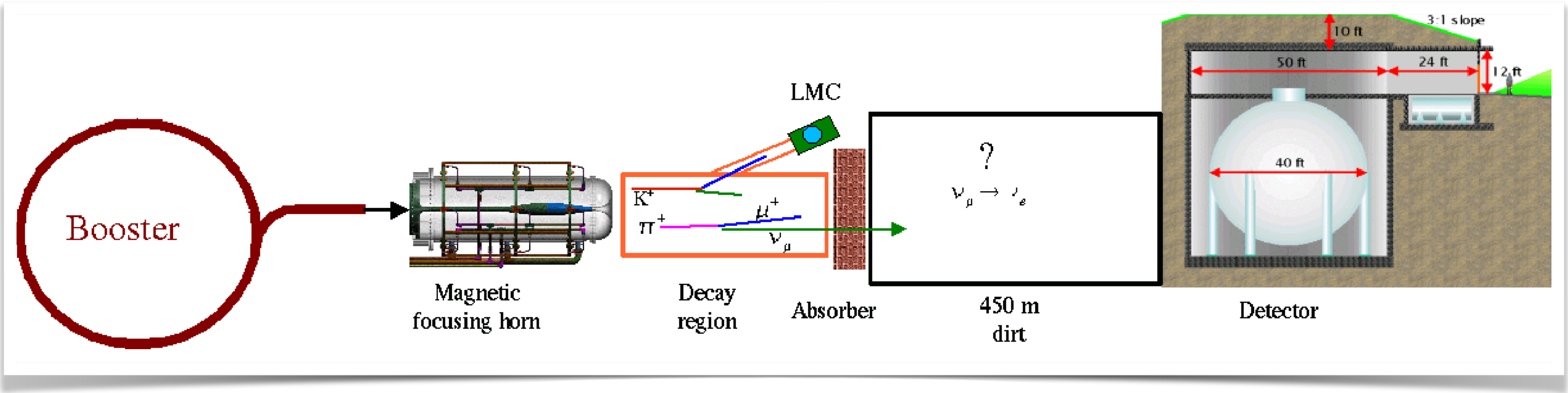
The Gallium Anomaly

- ☑ recently confirmed by BEST
- ☑ two independent target volumes
  (hoping to see oscillation pattern)
- ☑ radiochemistry similar to other gallium experiments
  (correlated systematics?)
- ☑ but: past experiments cross-calibrated with solar neutrinos



BEST arXiv:2109.11482
Barinov Gorbunov arXiv:2109.14654

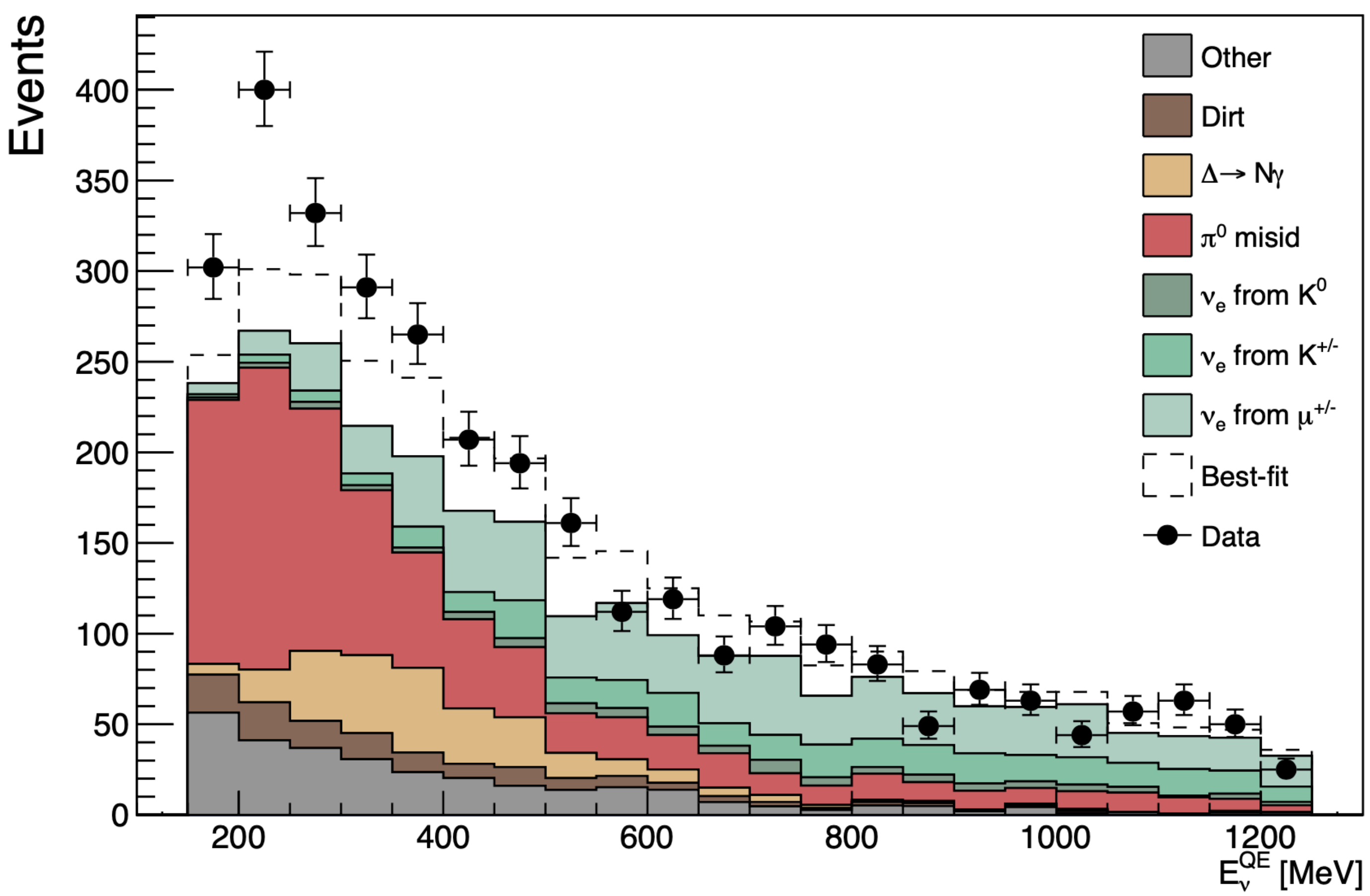
MiniBooNE



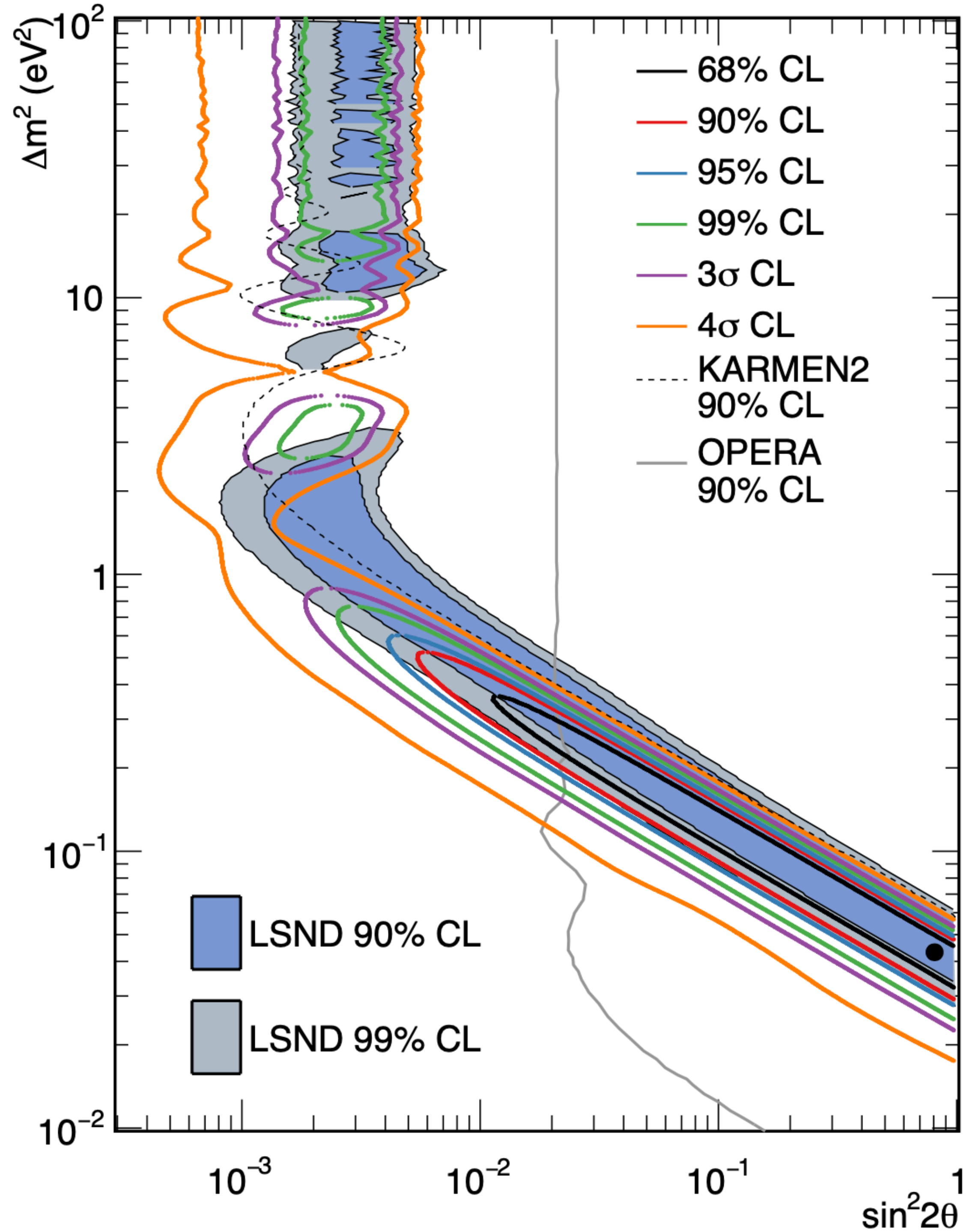
Booster
Magnetic focusing horn
LMC
K+
π^+
μ^+
ν_μ
Decay region
Absorber
?
450 m dirt
10 ft
3:1 slope
50 ft
24 ft
12 ft
40 ft
Detector

MiniBooNE

- ☑ Unexplained low-*E* excess
- ☑ L/E too small for std. oscillations (wrong Δm^2)

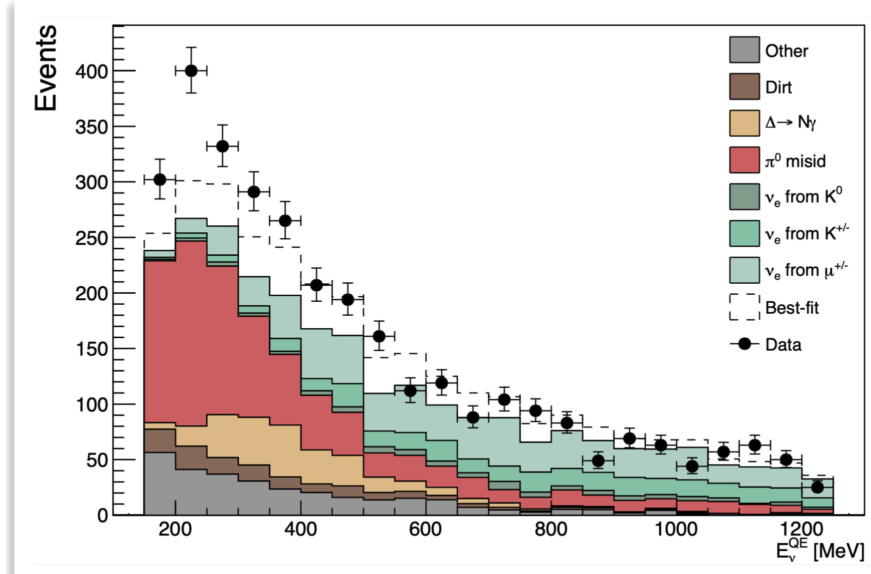


MiniBooNE Collaboration arXiv:2006.16883

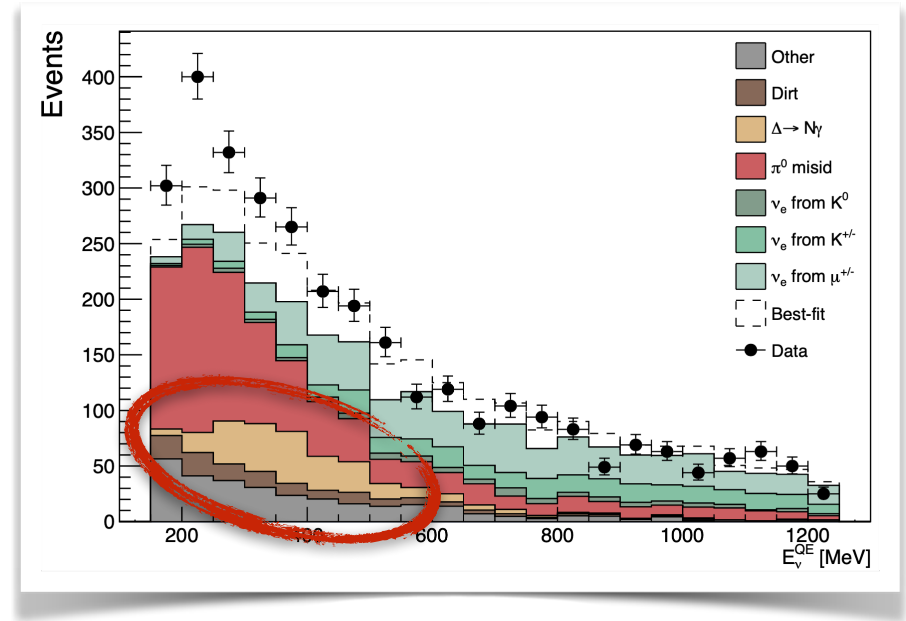


$\Delta \to \gamma$ N

- Neutral current neutrino interaction:
  $\nu + N \to \nu + \Delta(1232)$
- $\Delta(1232)$ mostly decays to $\pi + N$
- But a rare decay exists to $\gamma + N$
- MiniBooNE cannot distinguish γ from e^-



Δ → γ N



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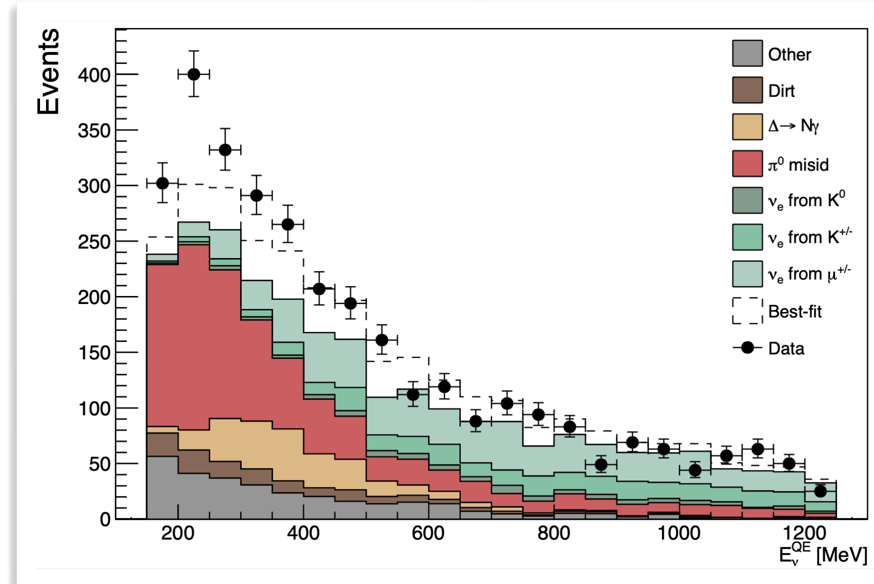
Δ → γ N

- Δ production rate can be estimated from Δ → πN
- Pions may be absorbed on their way out of the nucleus
  - may excite another Δ resonance
    ➠ Δ → γN enhanced by ~factor 2
  - or may be absorbed
    ➠ control region suppressed by ~factor 2



Ioannisian 1909.08571
Giunti Ioannisian Ranucci 1912.01524

- This factor 2 has been taken into account by MiniBooNE

private communication from Bill Louis

Cross Section Uncertainties

- Large systematic uncertainties in
  - Composition of neutrino beam
  - Neutrino interaction cross sections

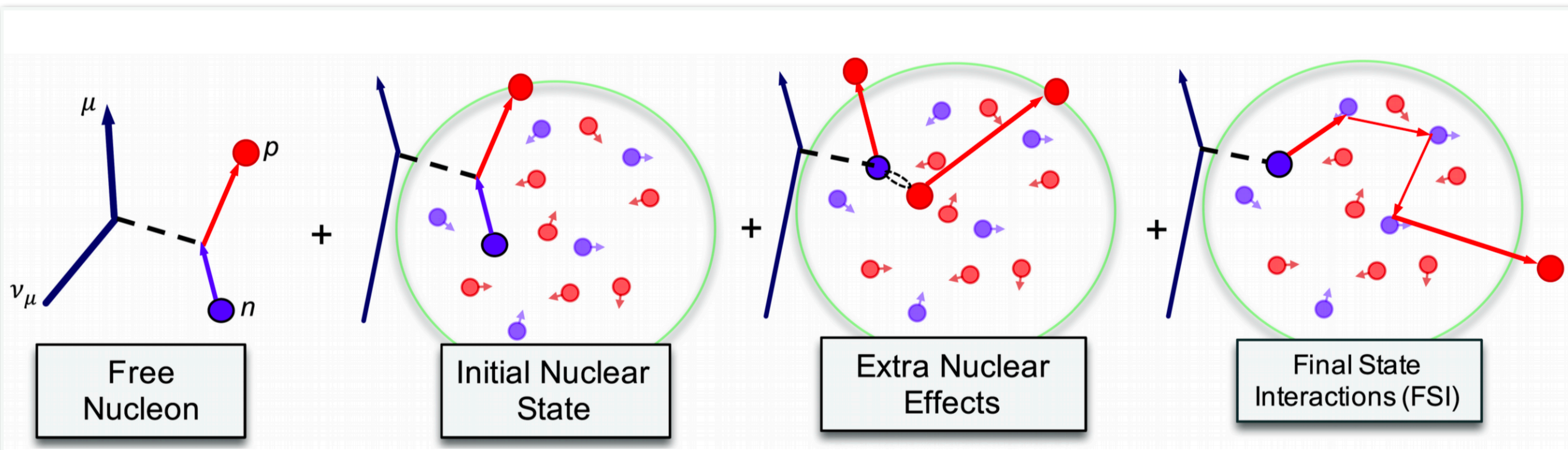
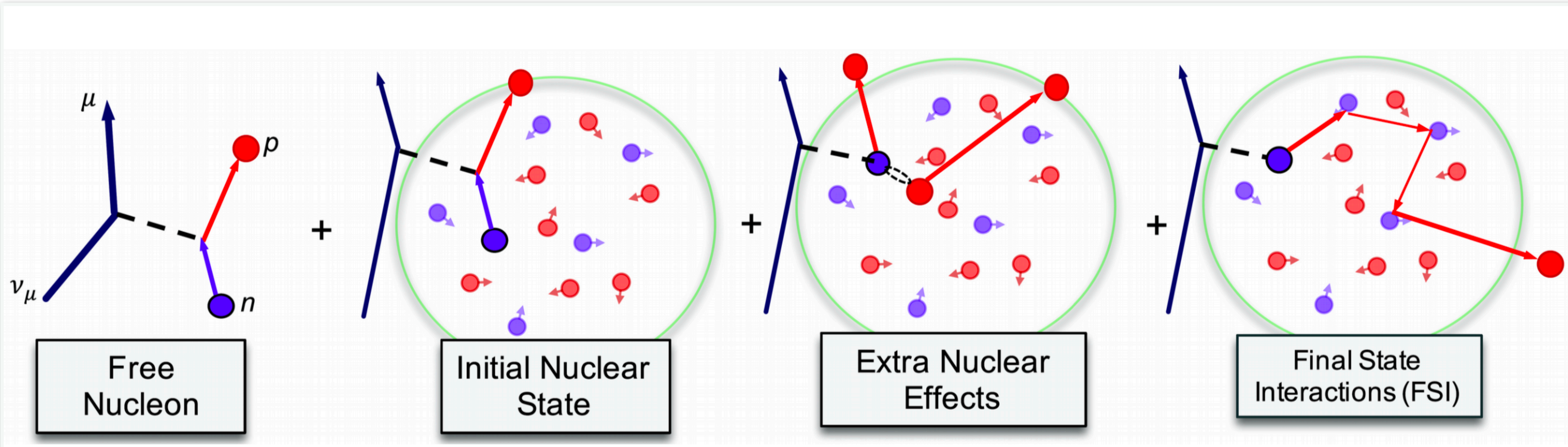


Image Credit: Callum Wilkinson

Understanding Neutrino Interactions



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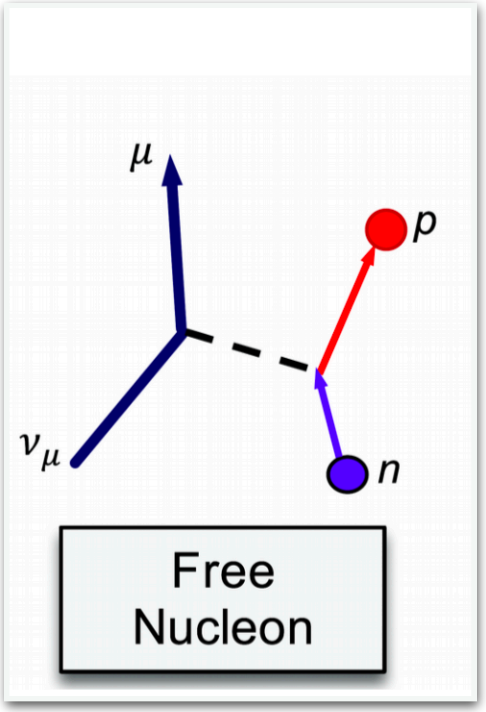

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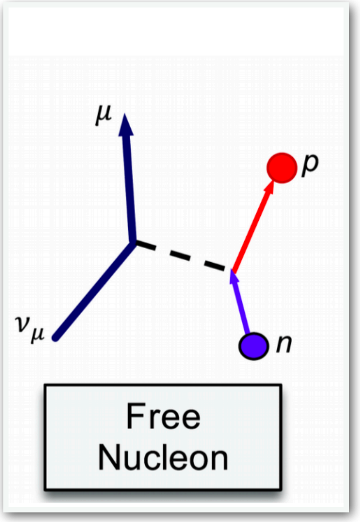

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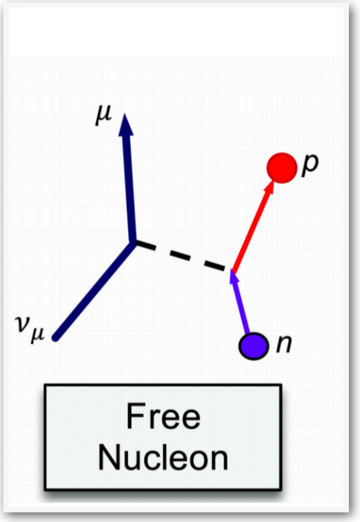

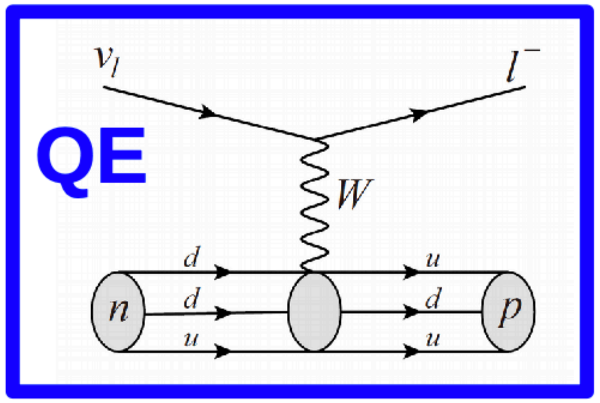

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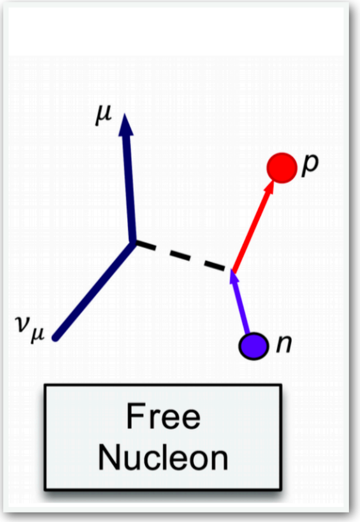

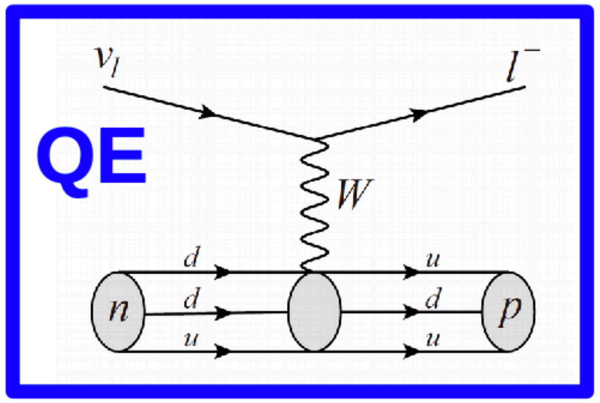

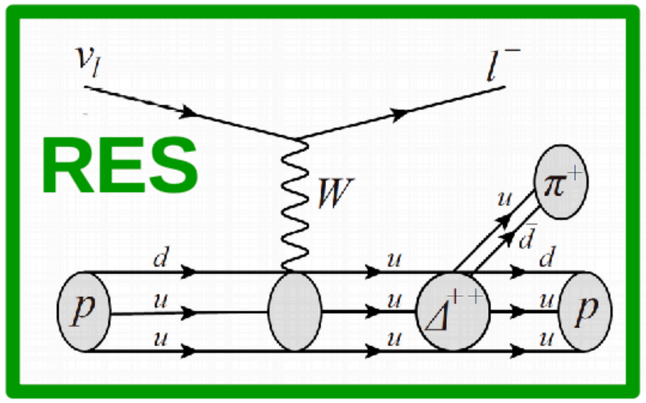

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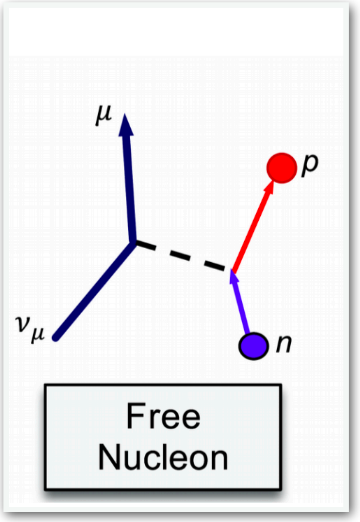

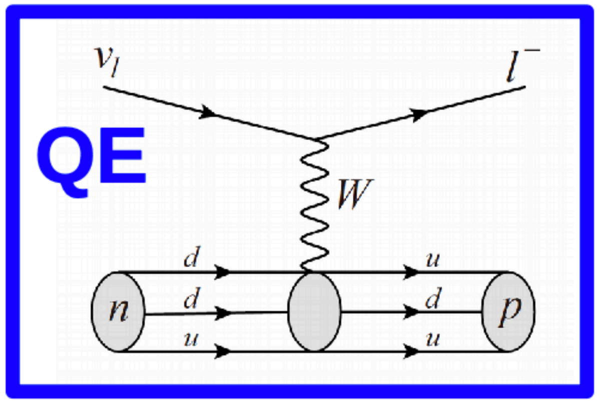

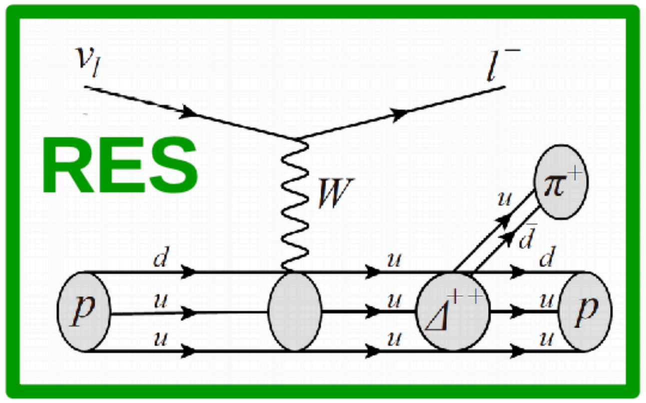

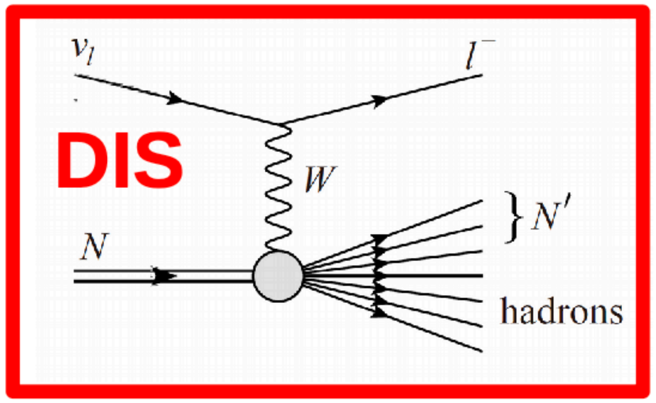

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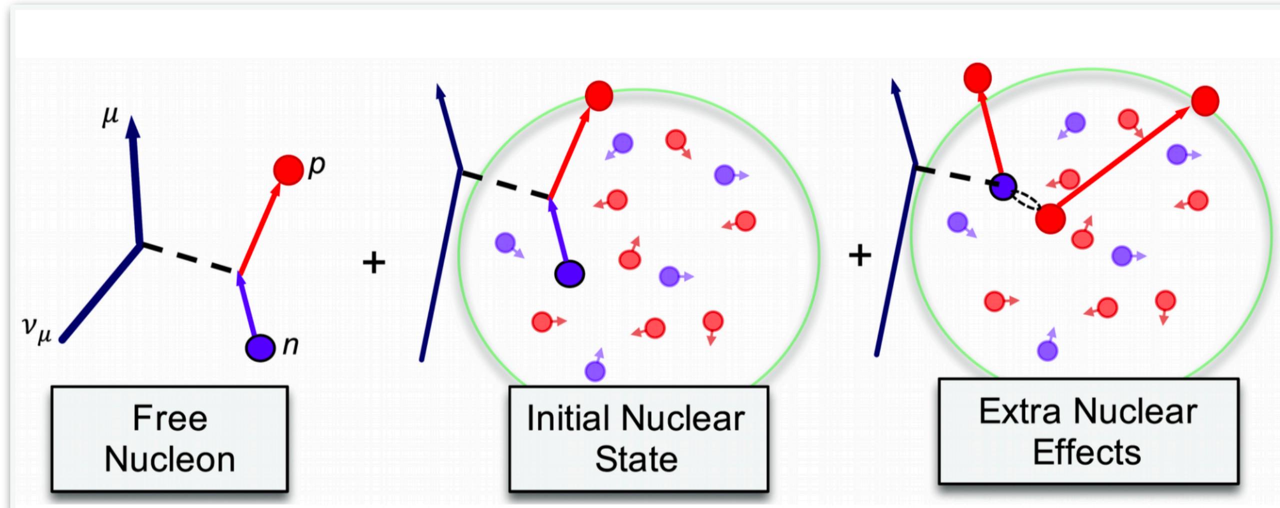

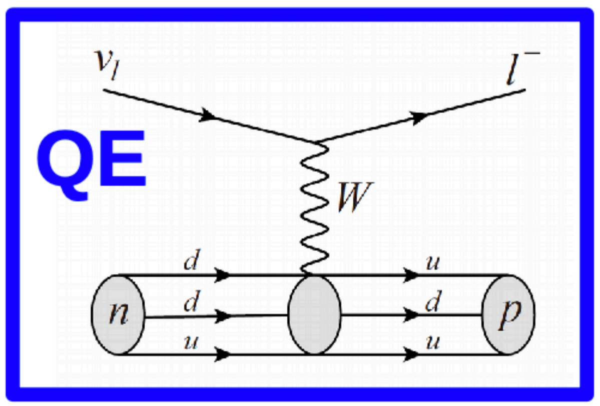

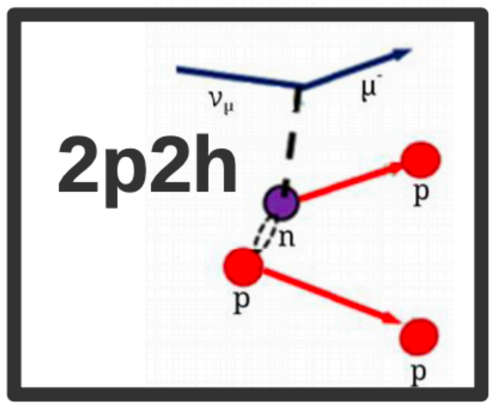

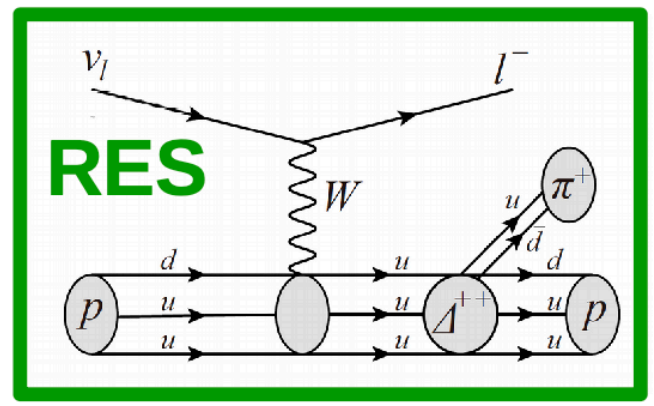

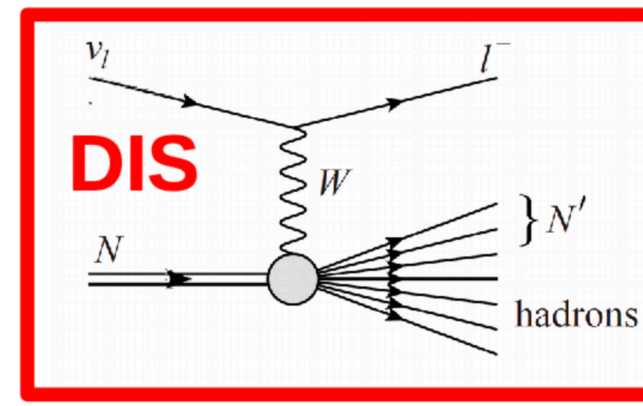

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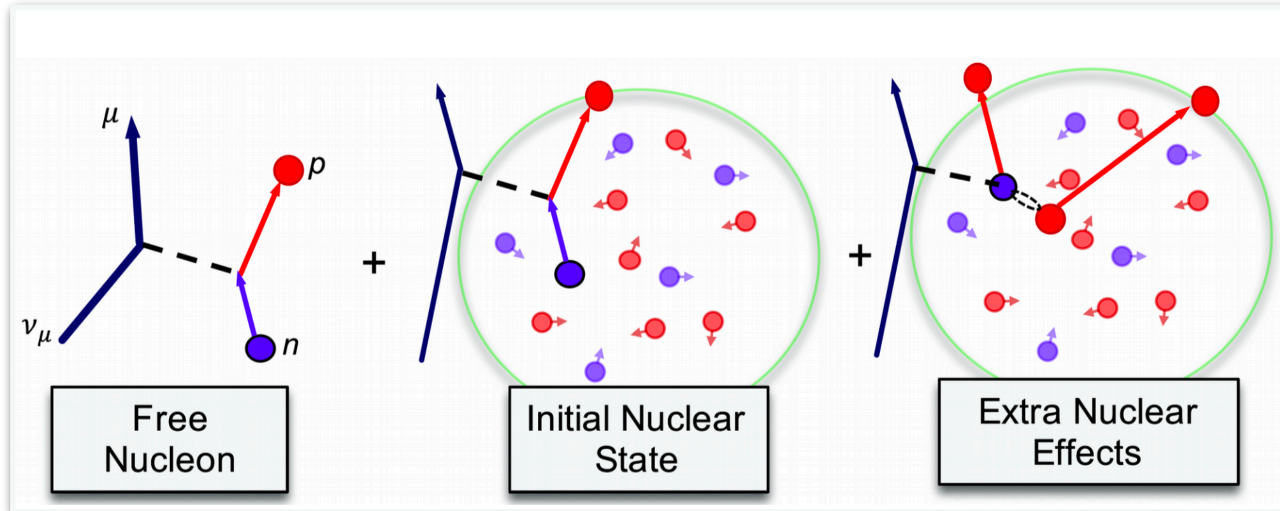

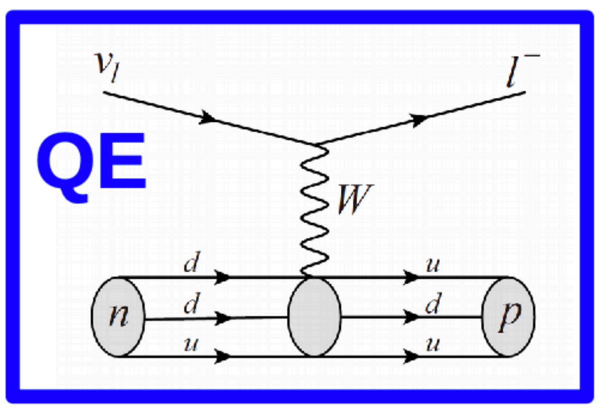

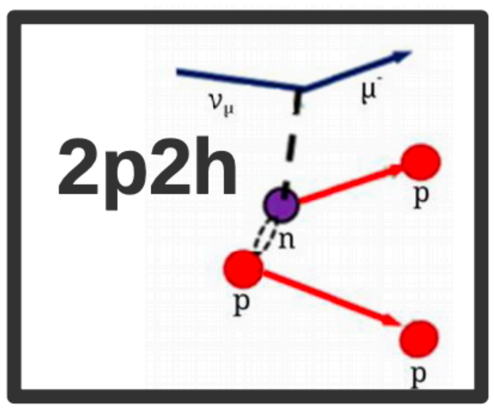

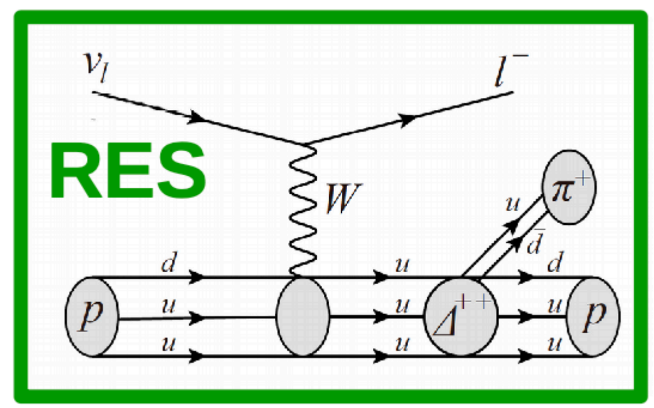

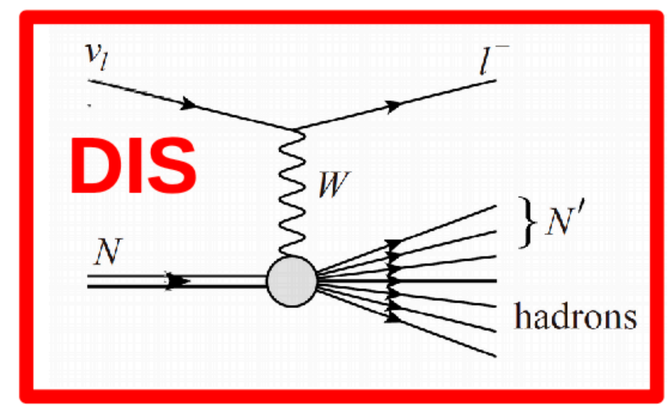

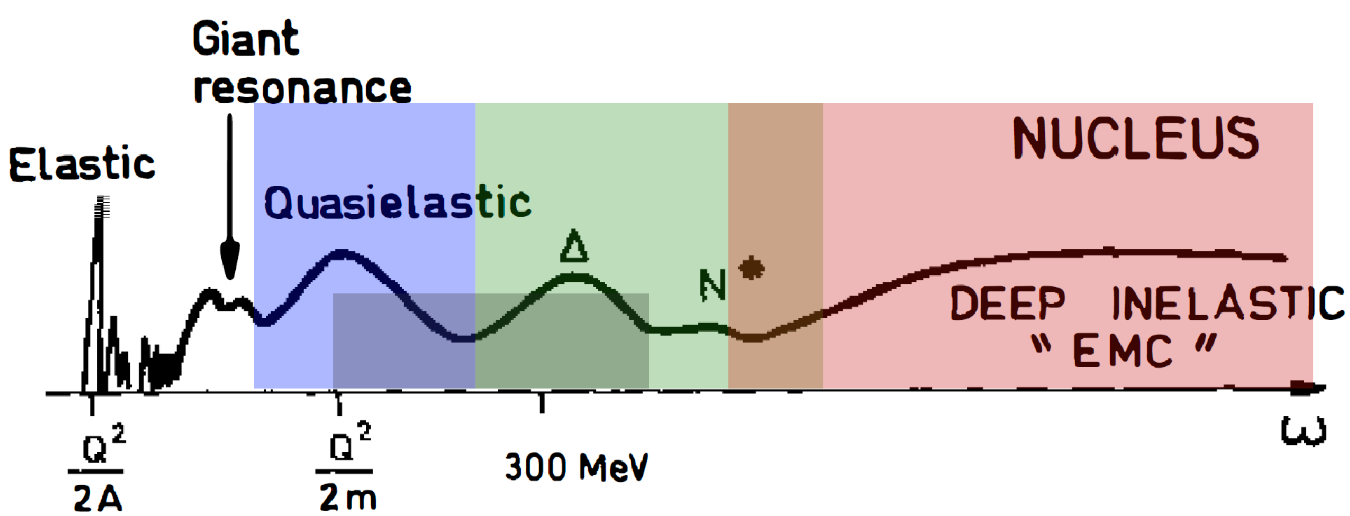

multi-nucleon effects are crucial

Image Credit: Callum Wilkinson