Impact of Neutrino Interaction Uncertainties on BSM Searches

Joachim Kopp (CERN & JGU Mainz)

NuInt 2024 • São Paulo • April 2024

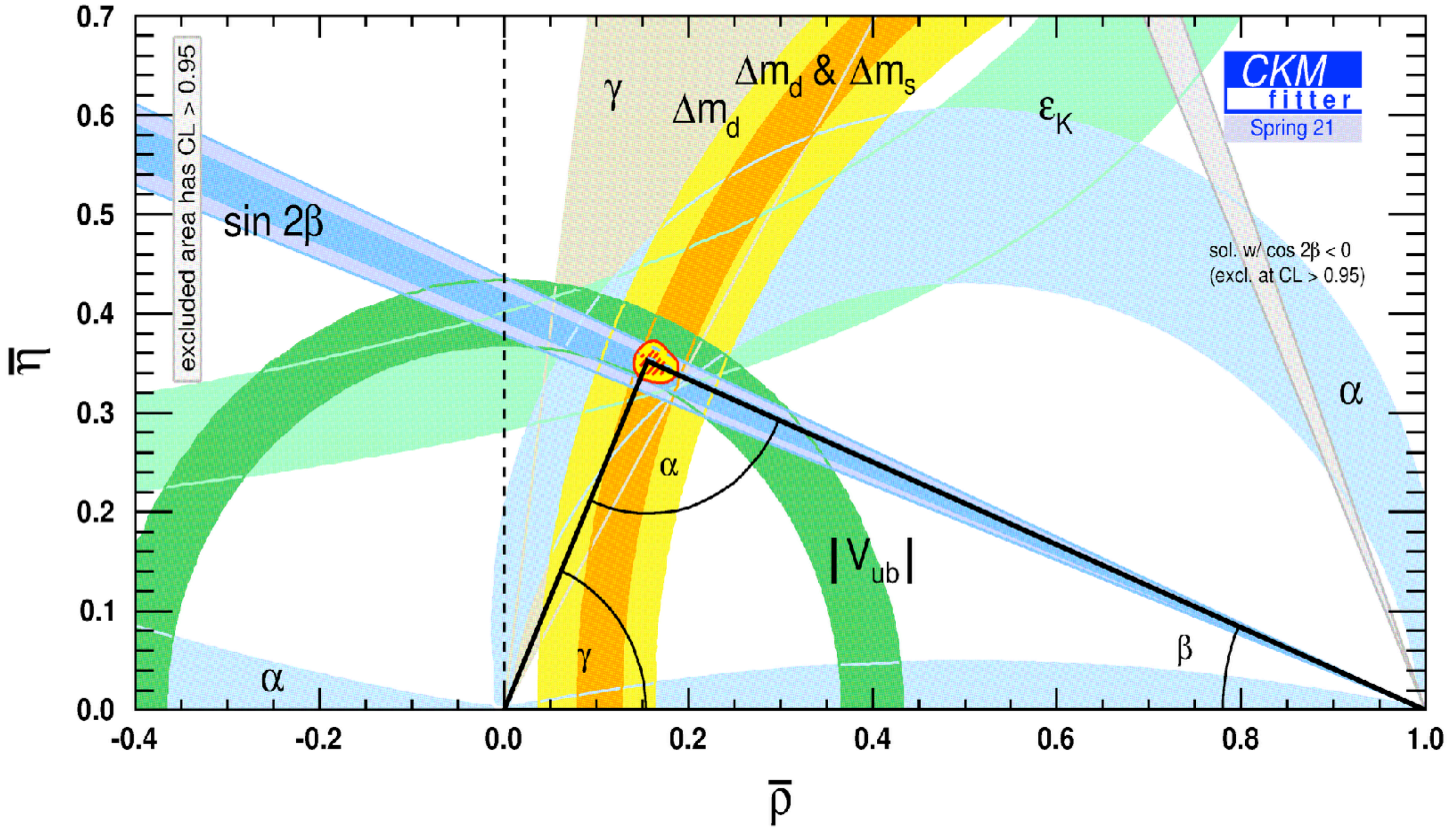
CERN

Neutrino PLATFORM

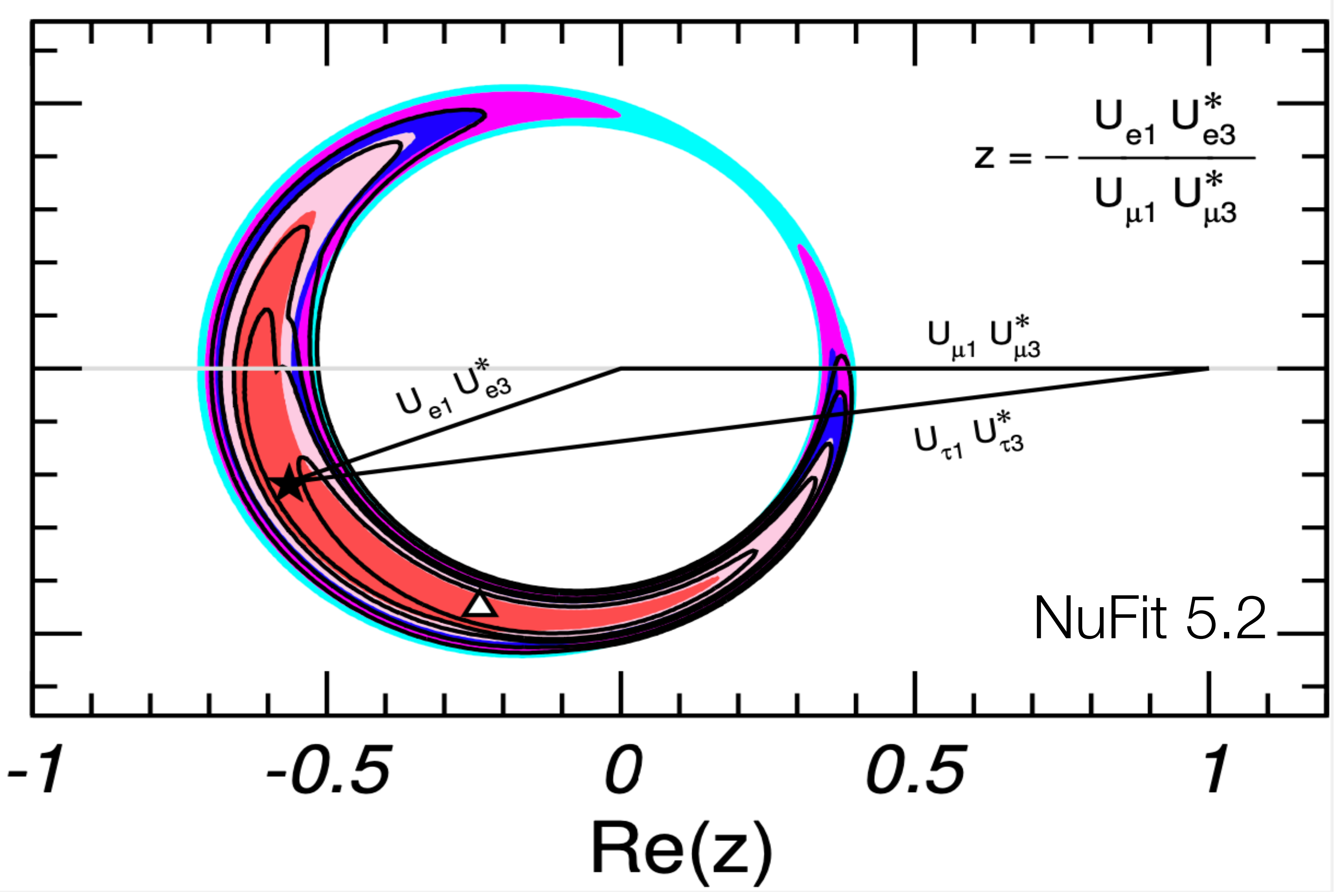
JG|U JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Precision Neutrino Physics

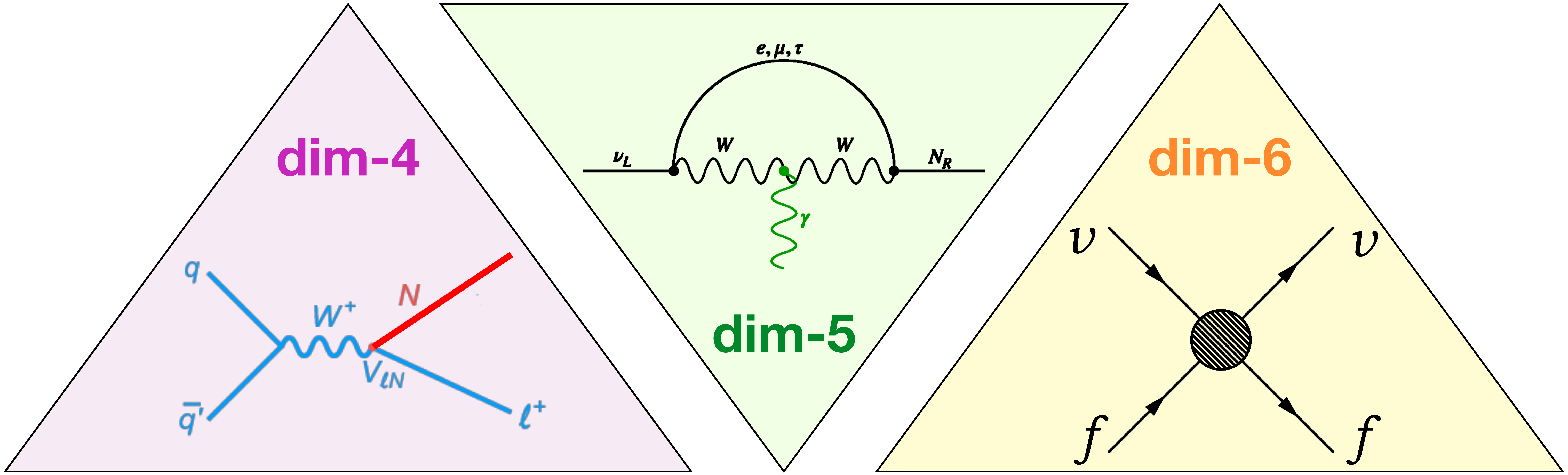
Quarks



Leptons

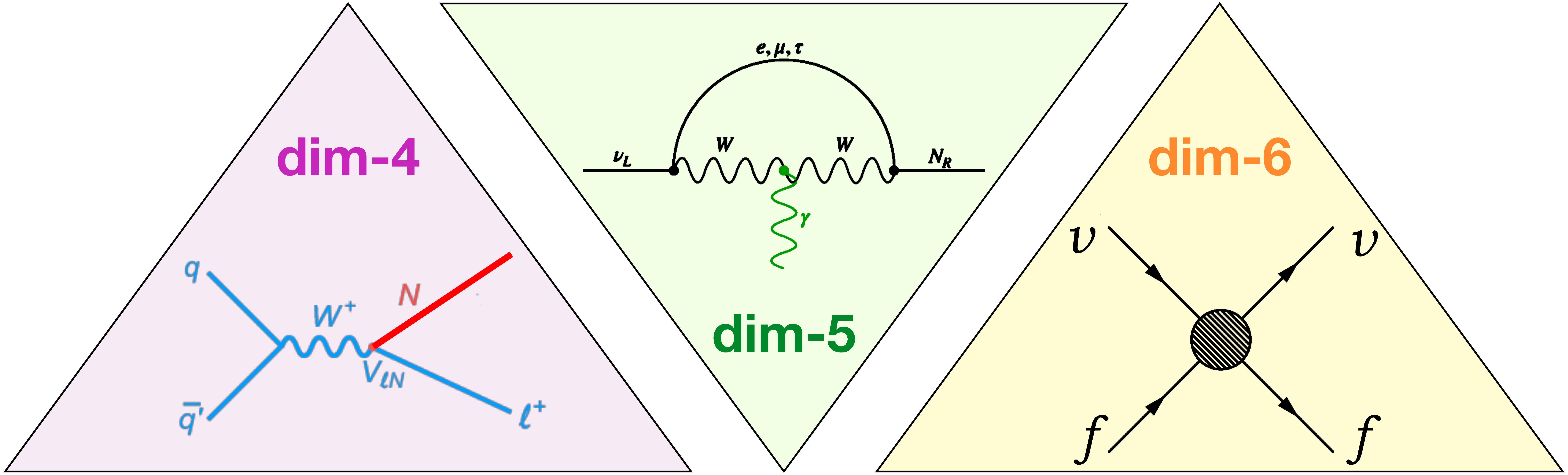


Neutrino Physics Beyond the Standard Model



Neutrino Physics Beyond the Standard Model

e.g. neutrino magnetic moments



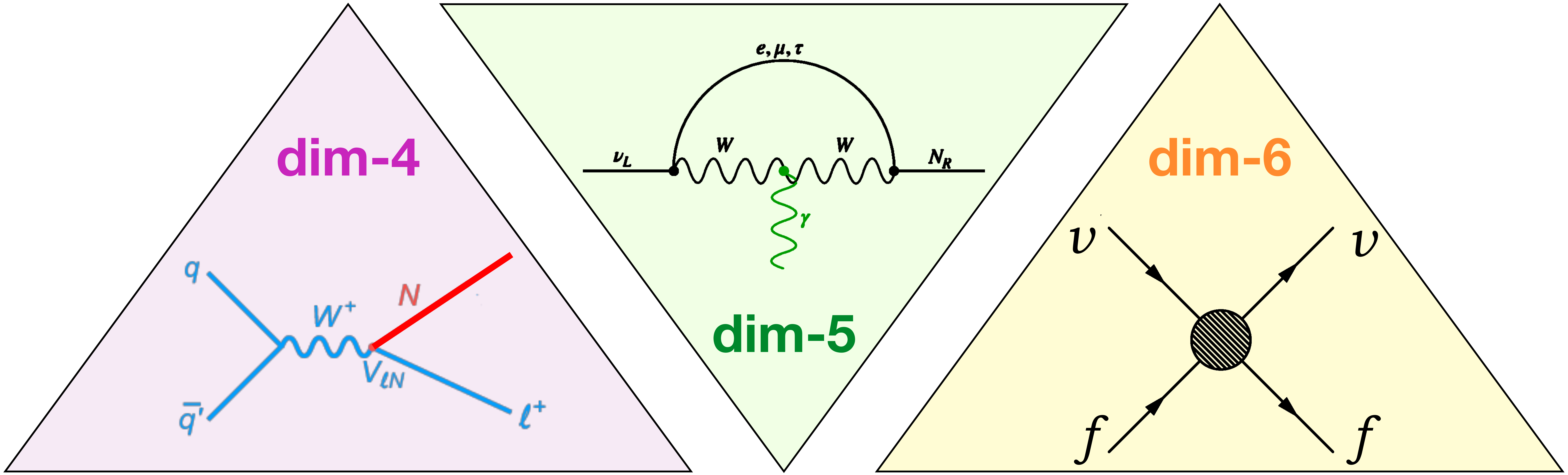
e.g. sterile neutrinos

e.g. non-standard interactions

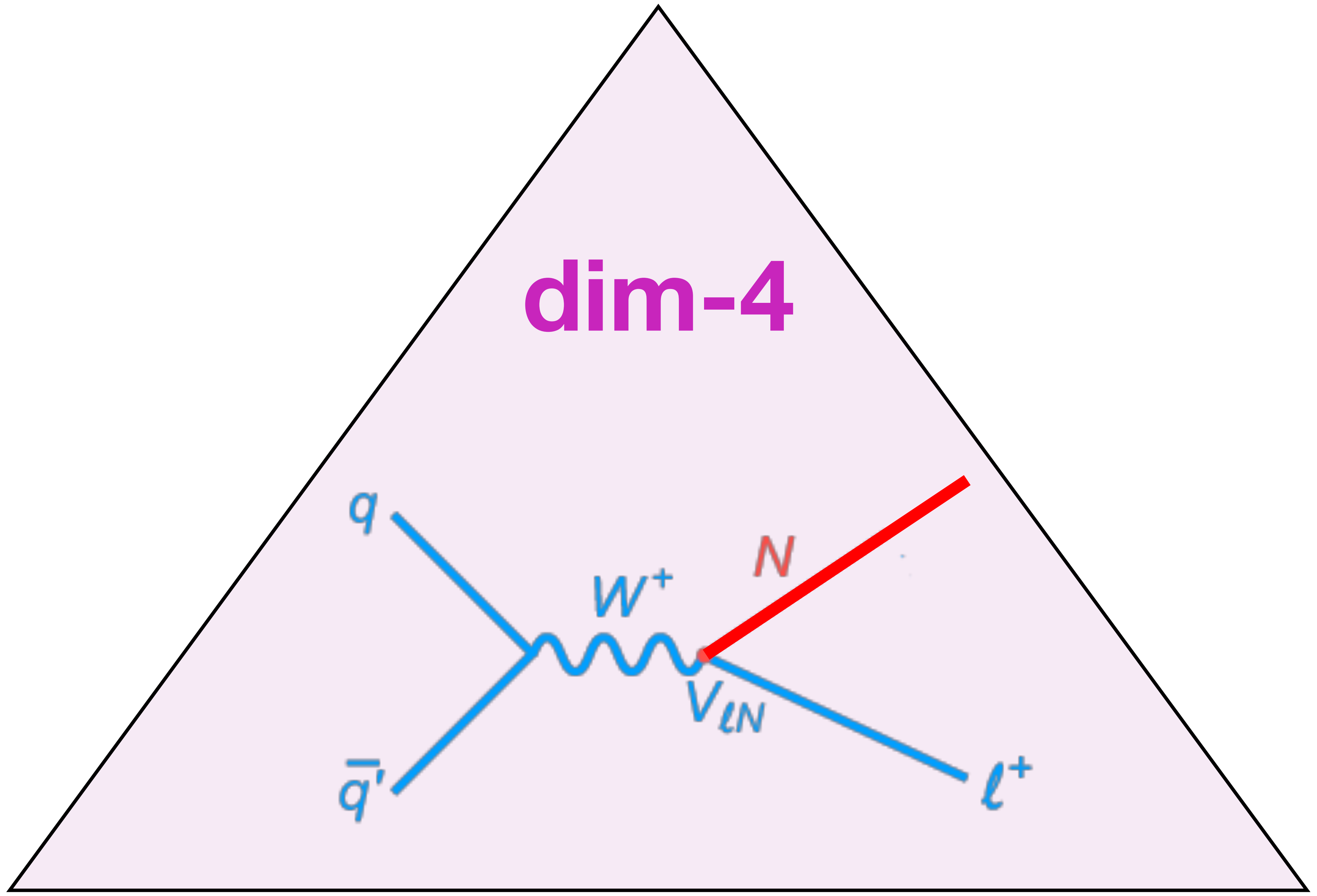
“With great precision comes great responsibility.”

Tim Linden, WIN 2021

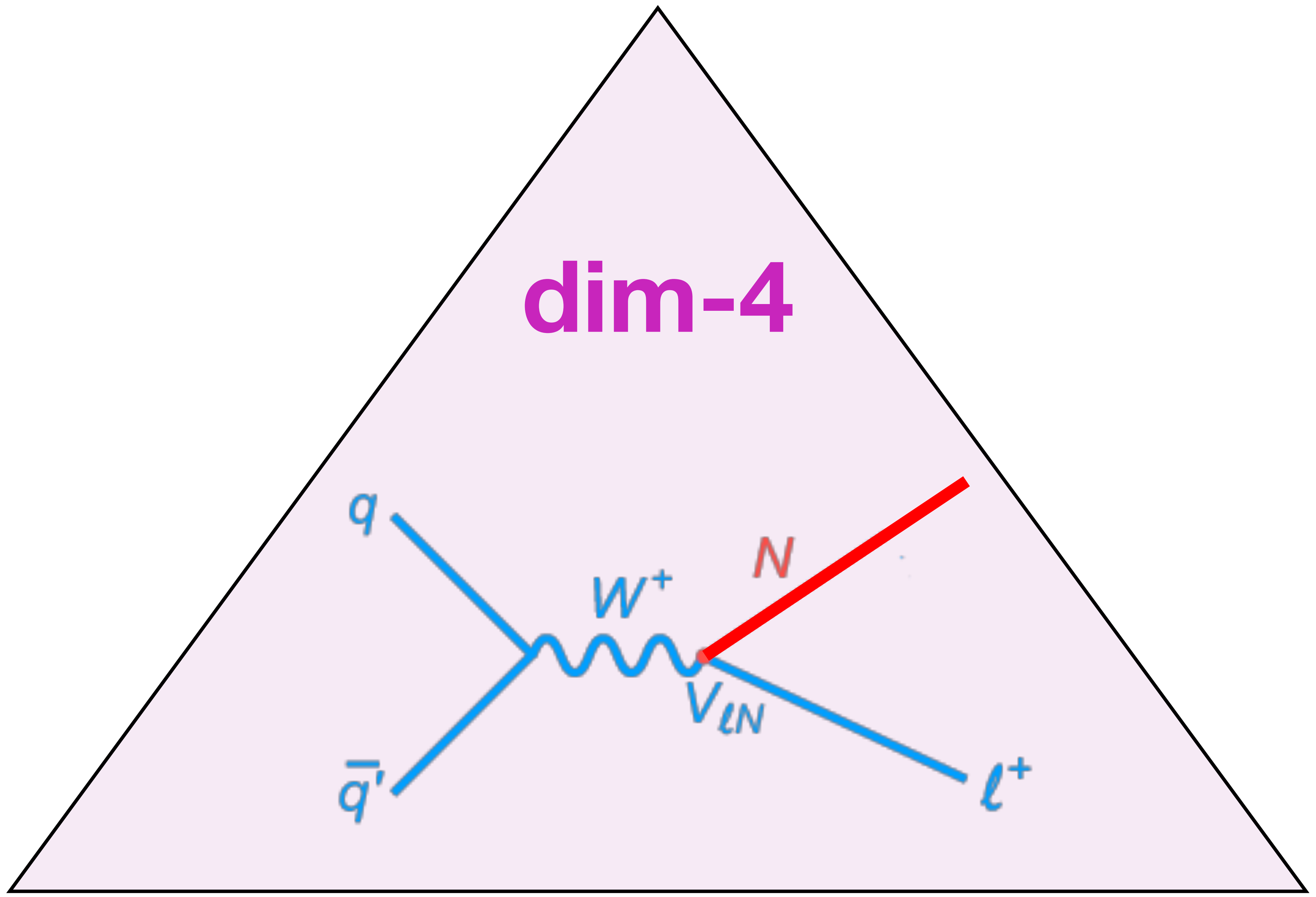
Neutrino Physics Beyond the Standard Model

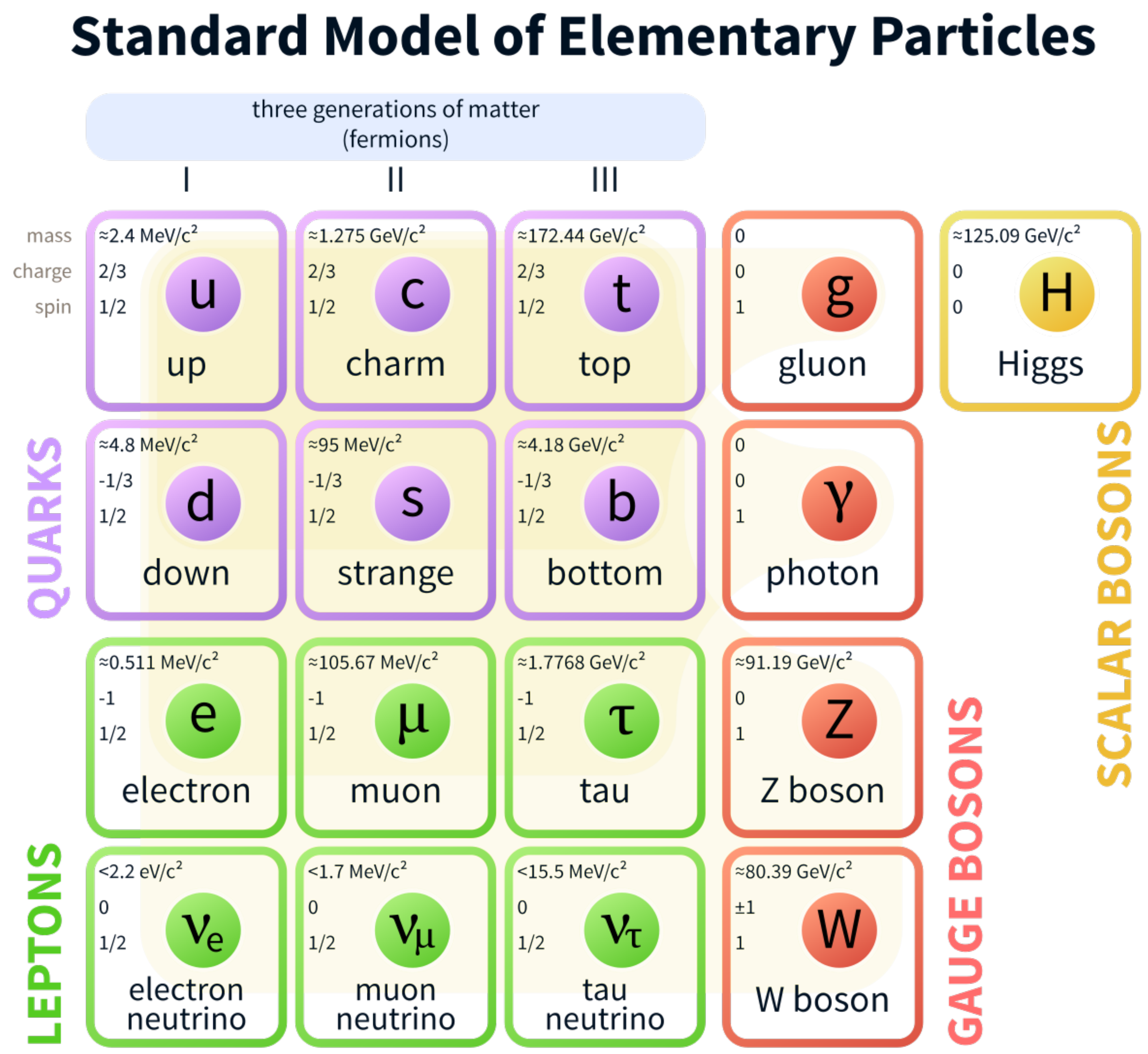


Sterile Neutrinos = new, uncharged fermions

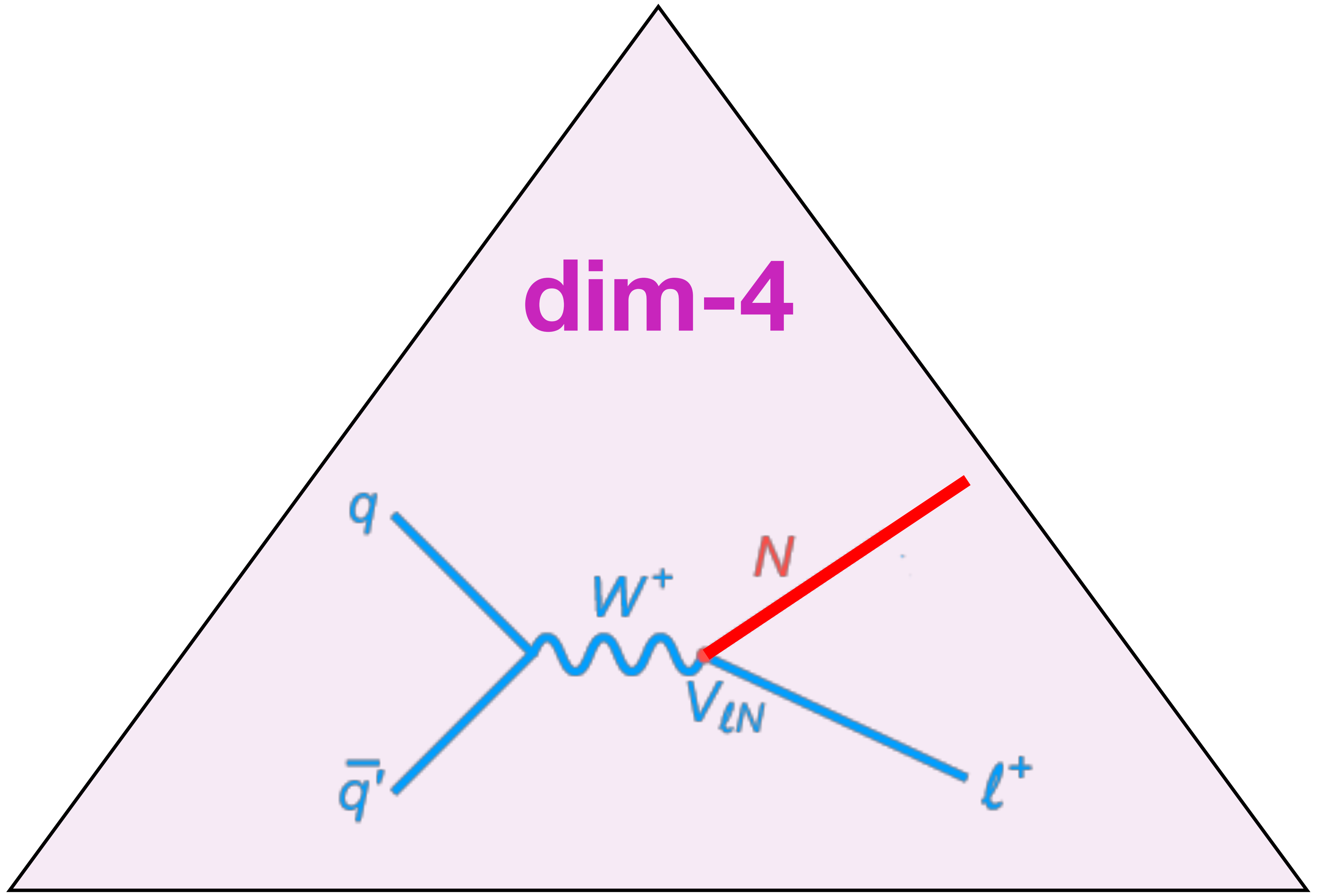


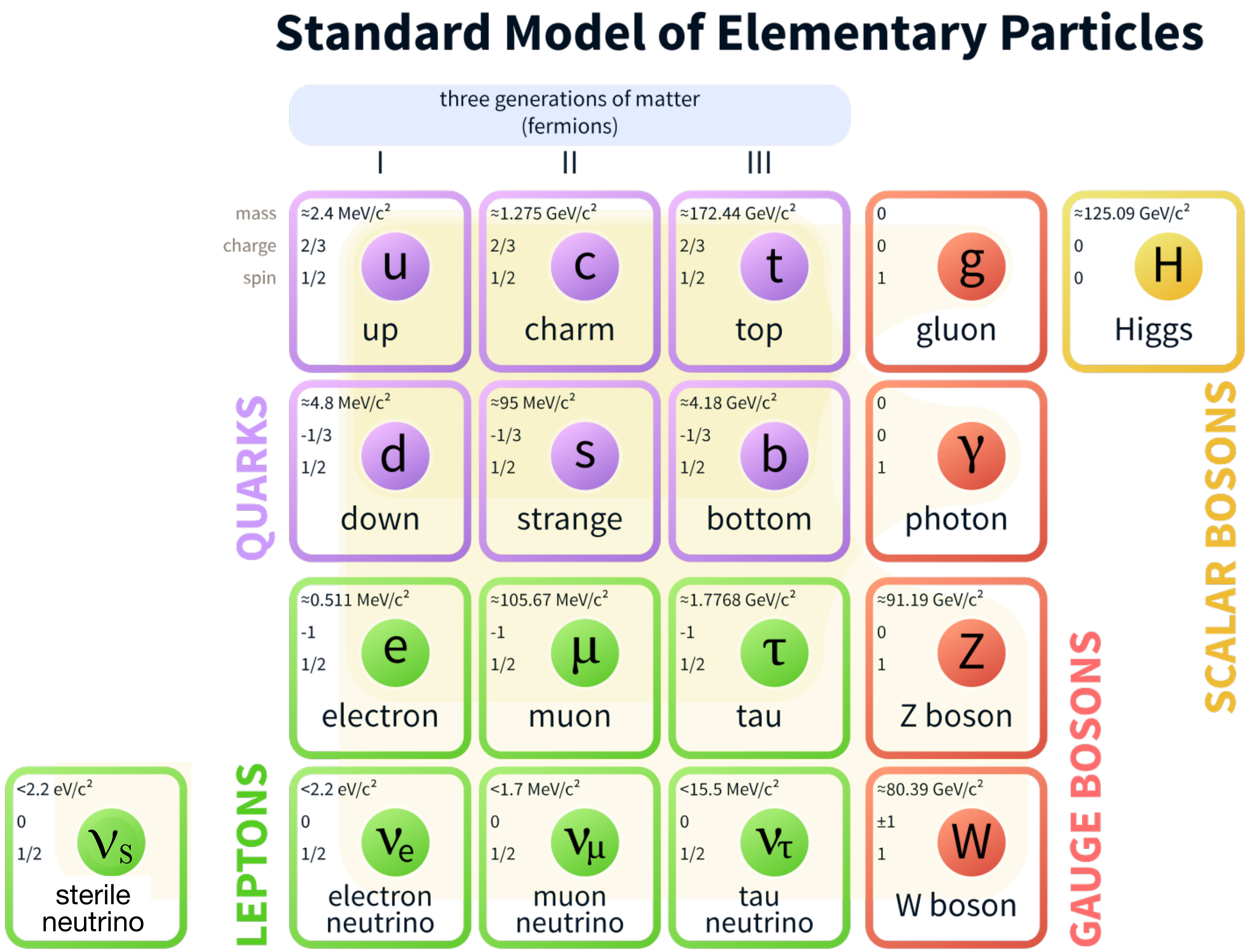
Sterile Neutrinos = new, uncharged fermions





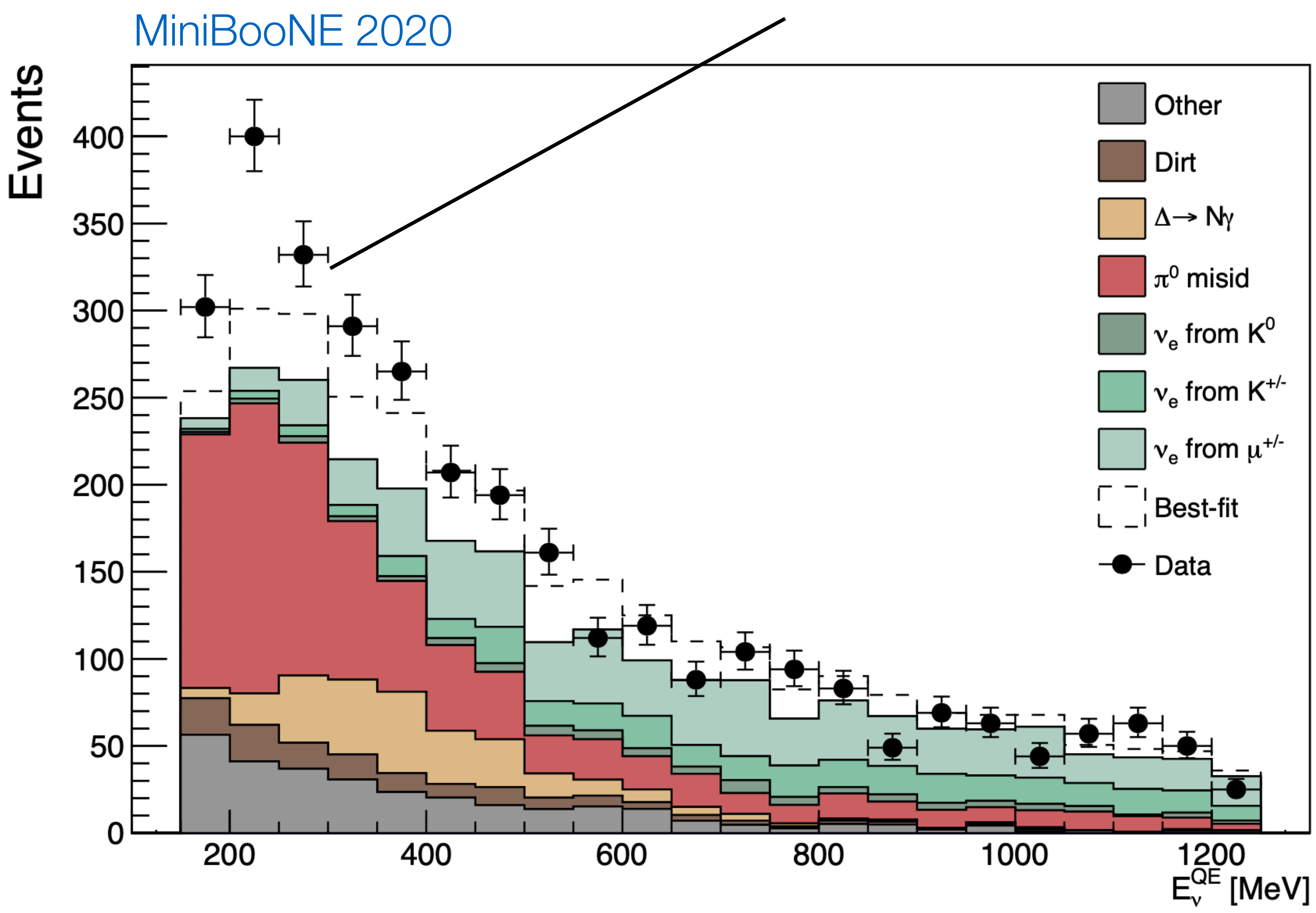
Sterile Neutrinos = new, uncharged fermions



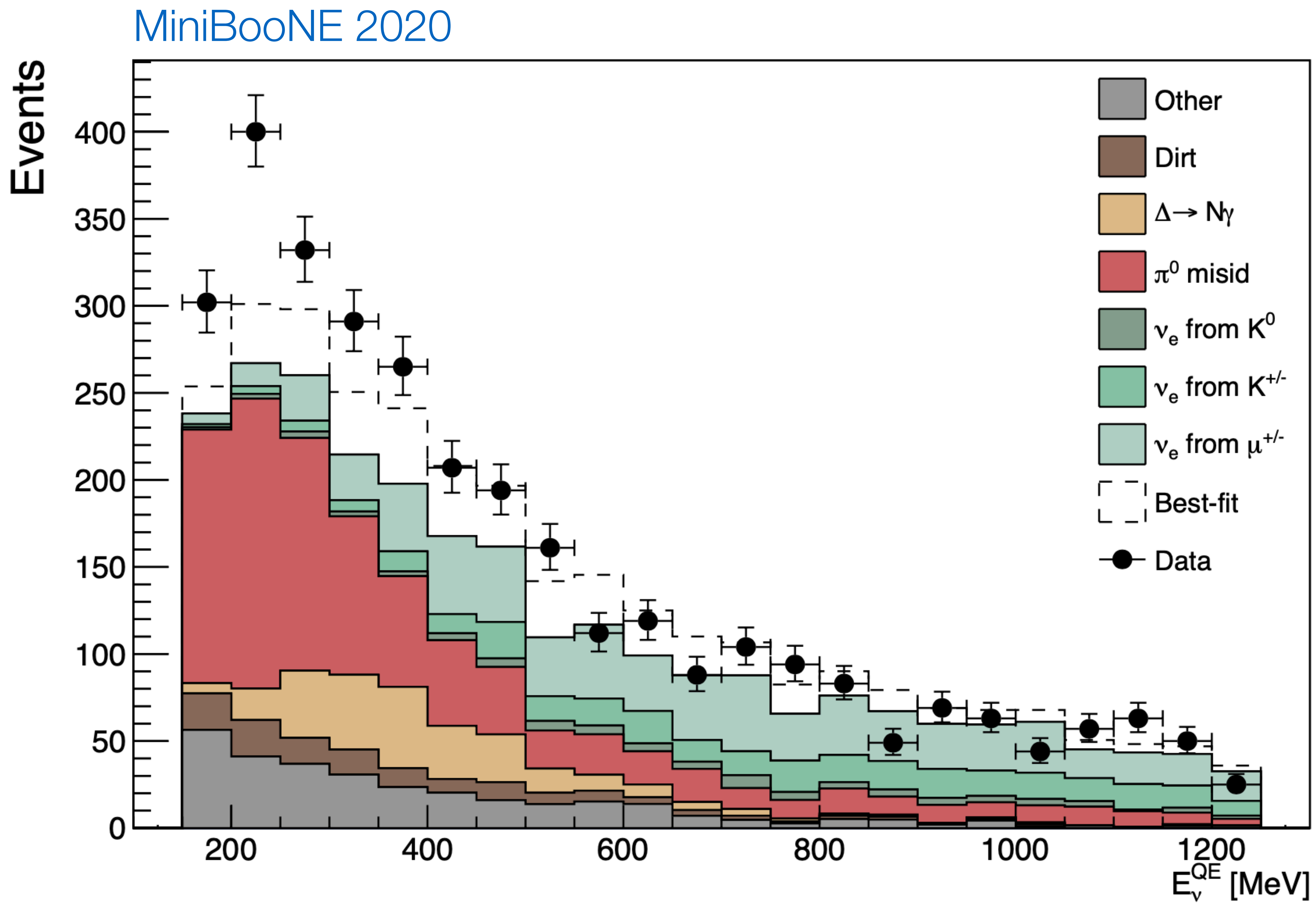


MiniBooNE

$4.8\,\sigma$ excess of ν_e in a ν_μ beam

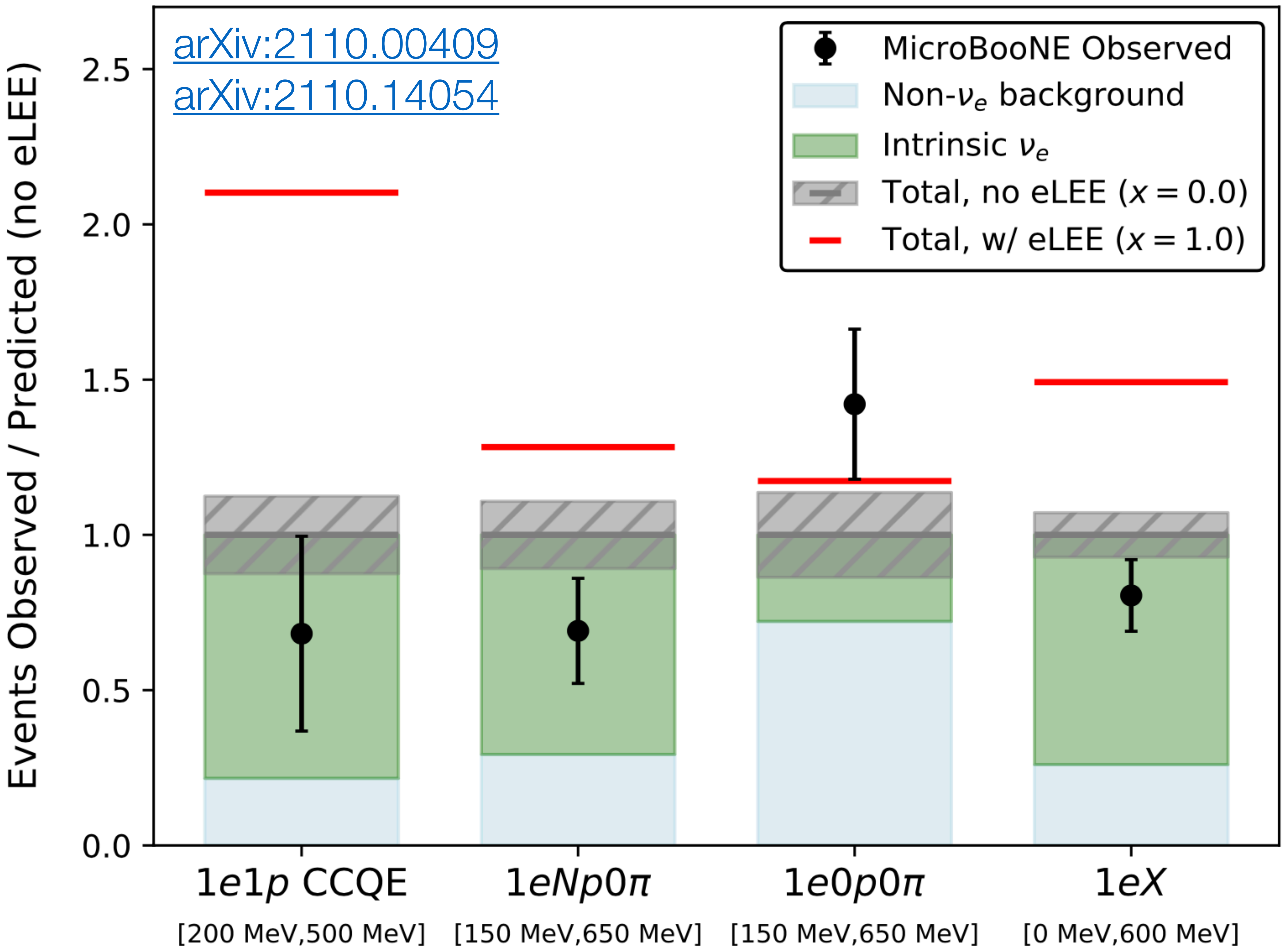


MiniBooNE



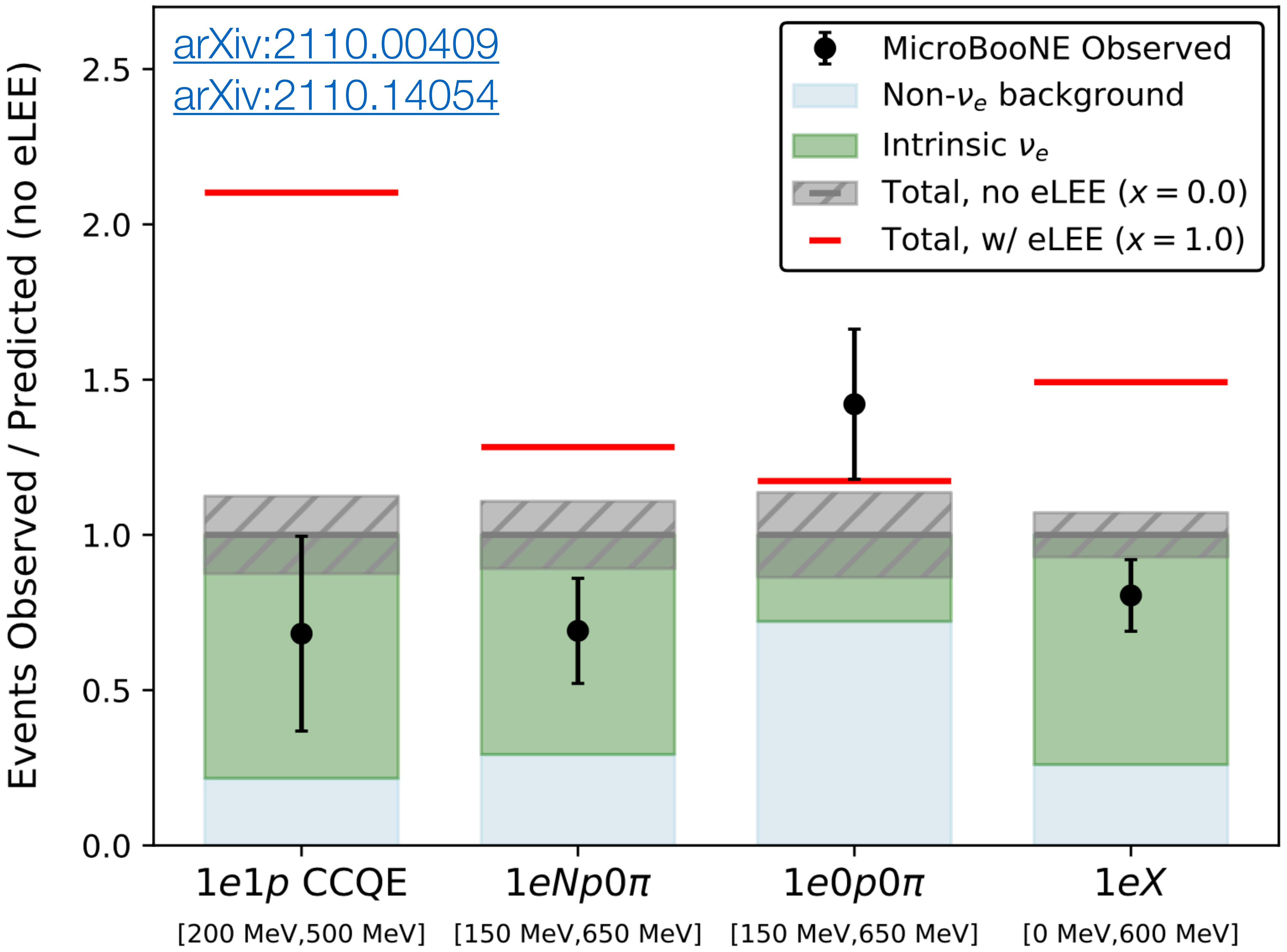
- baseline too short for std. oscillations
- but could be explained by eV-scale sterile neutrino ("ν_μ ➡ ν_s ➡ ν_e")
- ~ consistent with other anomalies
- but inconsistent with null searches

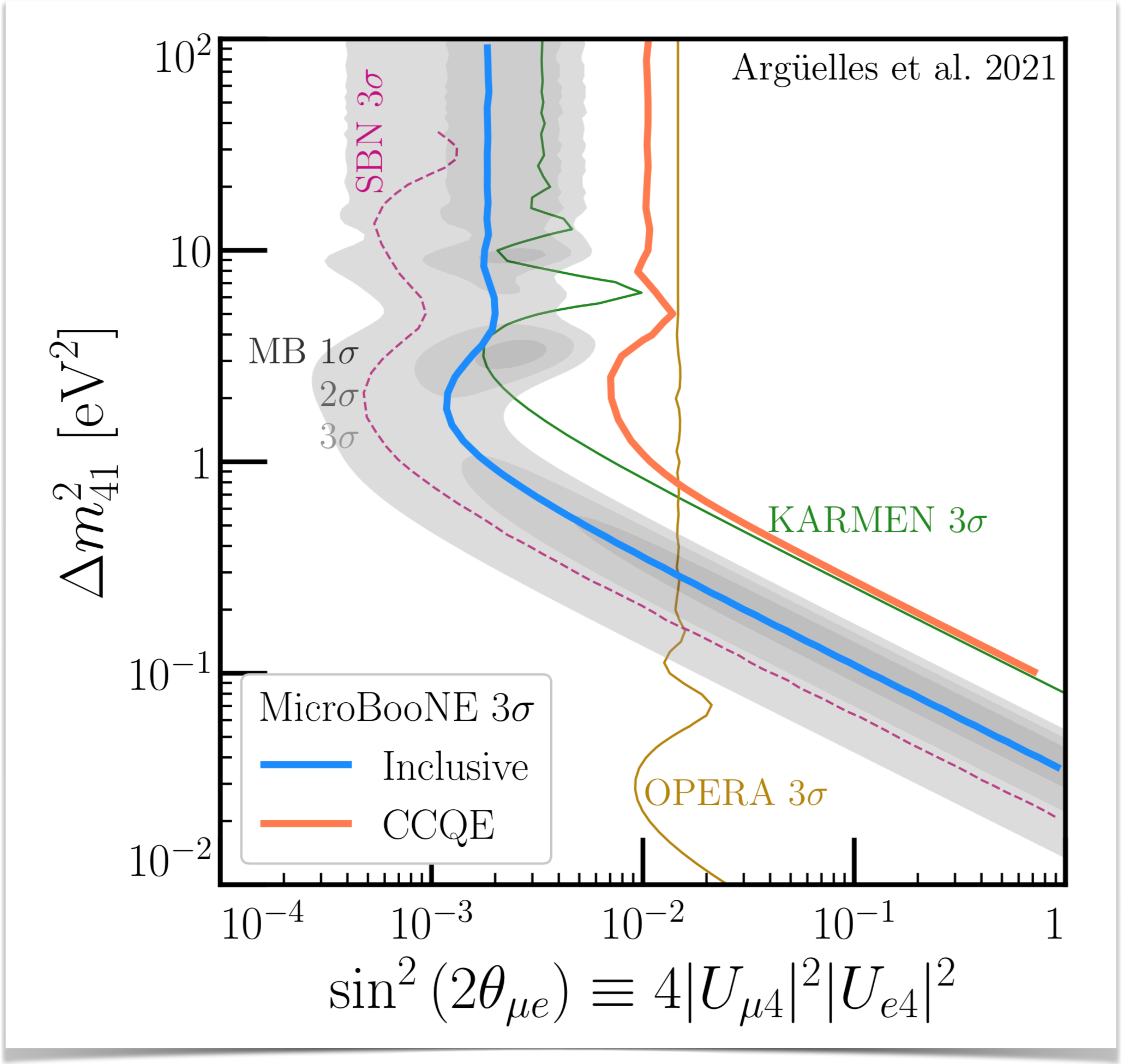
MicroBooNE



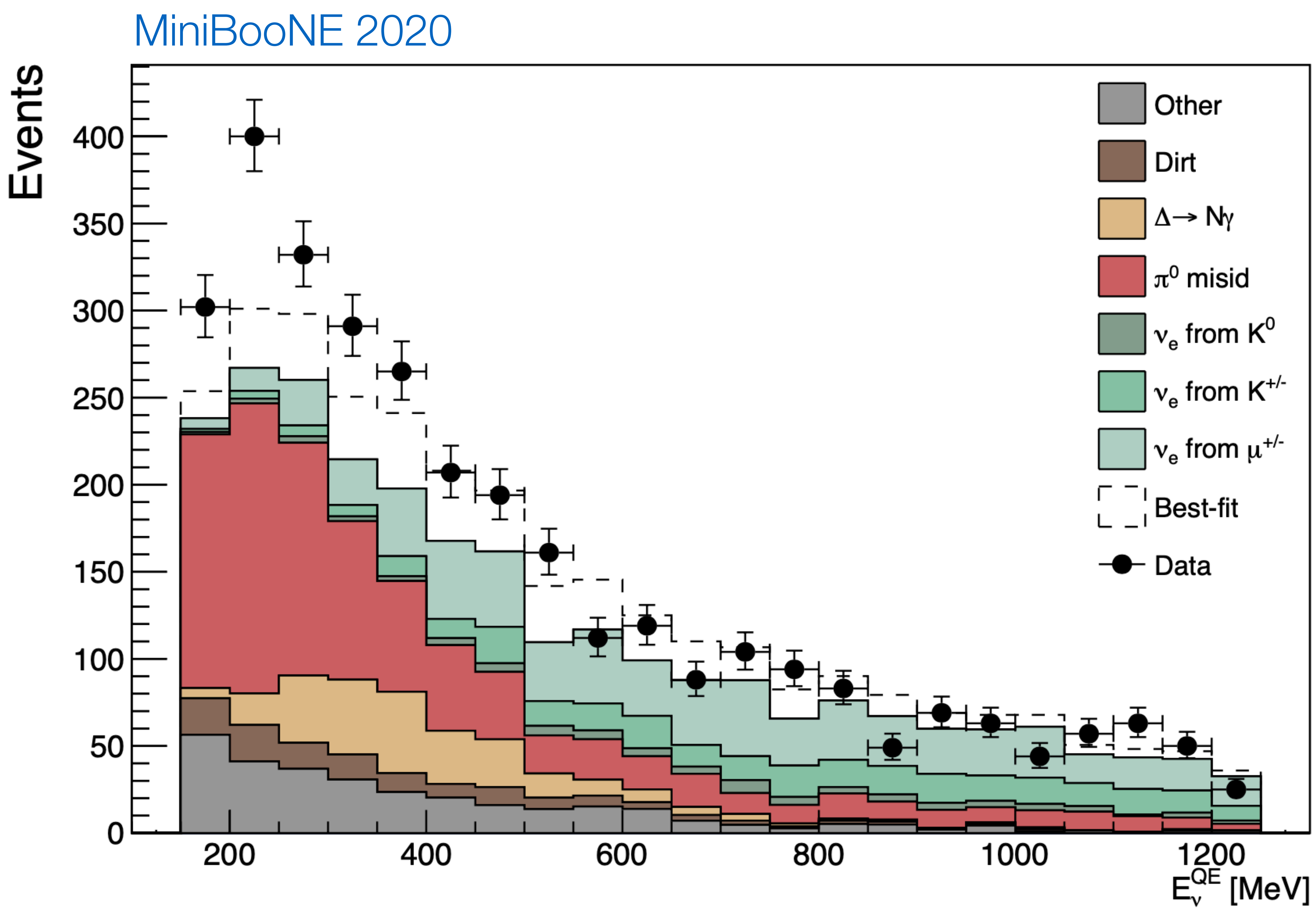
- LAr TPC ➠ superior event reconstruction
- no excess seen so far
  (but still consistent with MiniBooNE)

MicroBooNE

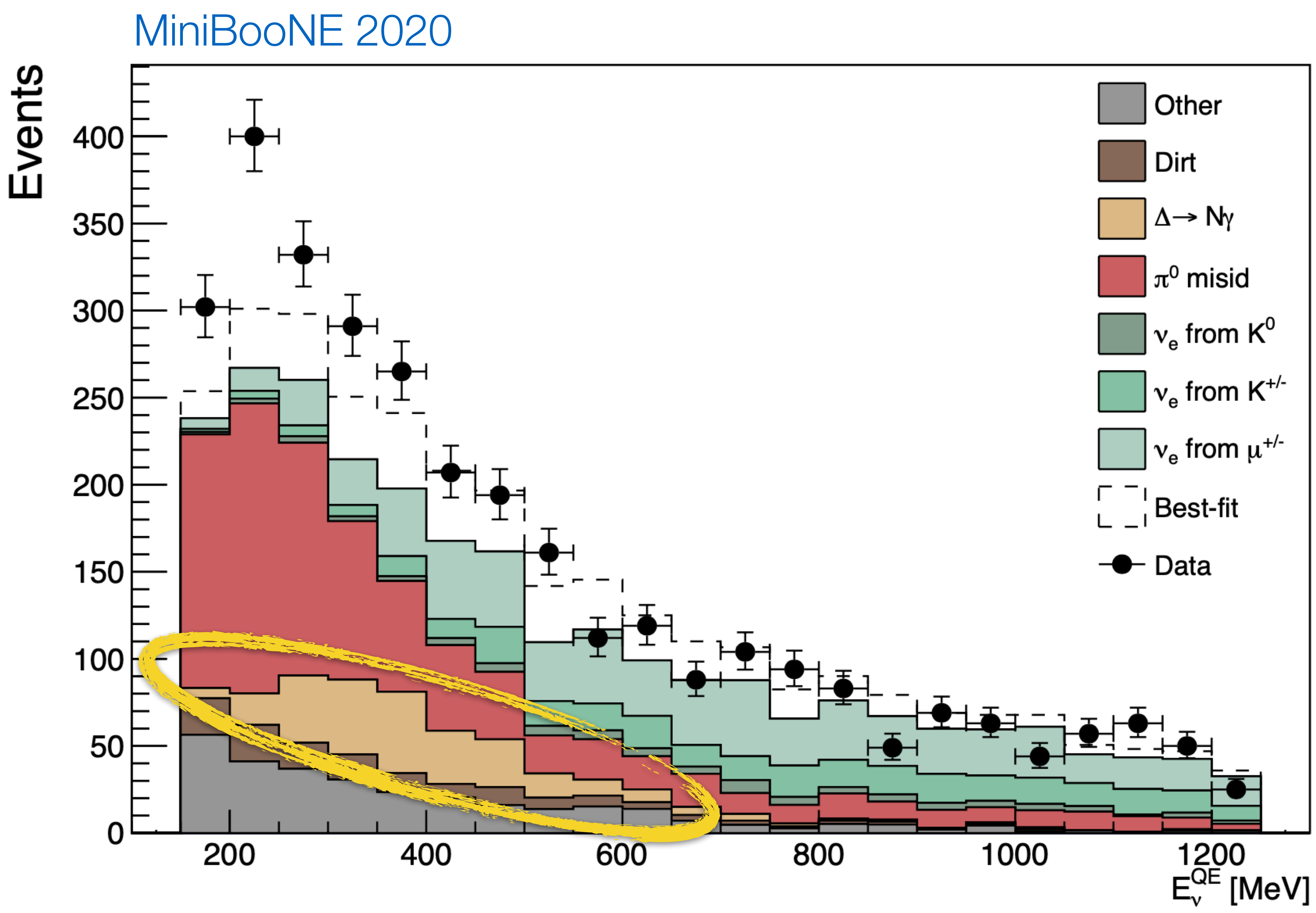

arXiv:2110.00409
arXiv:2110.14054
MicroBooNE Observed
Non-ν_e background
Intrinsic ν_e
Total, no eLEE ($x = 0.0$)
Total, w/ eLEE ($x = 1.0$)
Events Observed / Predicted (no eLEE)
0.0
0.5
1.0
1.5
2.0
2.5
$1e1p$ CCQE
[200 MeV,500 MeV]
$1eNp0\pi$
[150 MeV,650 MeV]
$1e0p0\pi$
[150 MeV,650 MeV]
$1eX$
[0 MeV,600 MeV]


Argüelles et al. 2021
SBN 3σ
MB 1σ
2σ
3σ
KARMEN 3σ
OPERA 3σ
MicroBooNE 3σ
Inclusive
CCQE
Δm^2_{41} [eV^2]
10^2
10
1
10^{-1}
10^{-2}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
$\sin^2(2\theta_{\mu e}) \equiv 4|U_{\mu 4}|^2|U_{e4}|^2$

MiniBooNE


MiniBooNE 2020
Events
400
350
300
250
200
150
100
50
0
200
400
600
800
1000
1200
E_ν^{QE} [MeV]
Other
Dirt
$\Delta \rightarrow N\gamma$
π^0 misid
ν_e from K^0
ν_e from $K^{+/-}$
ν_e from $\mu^{+/-}$
Best-fit
Data

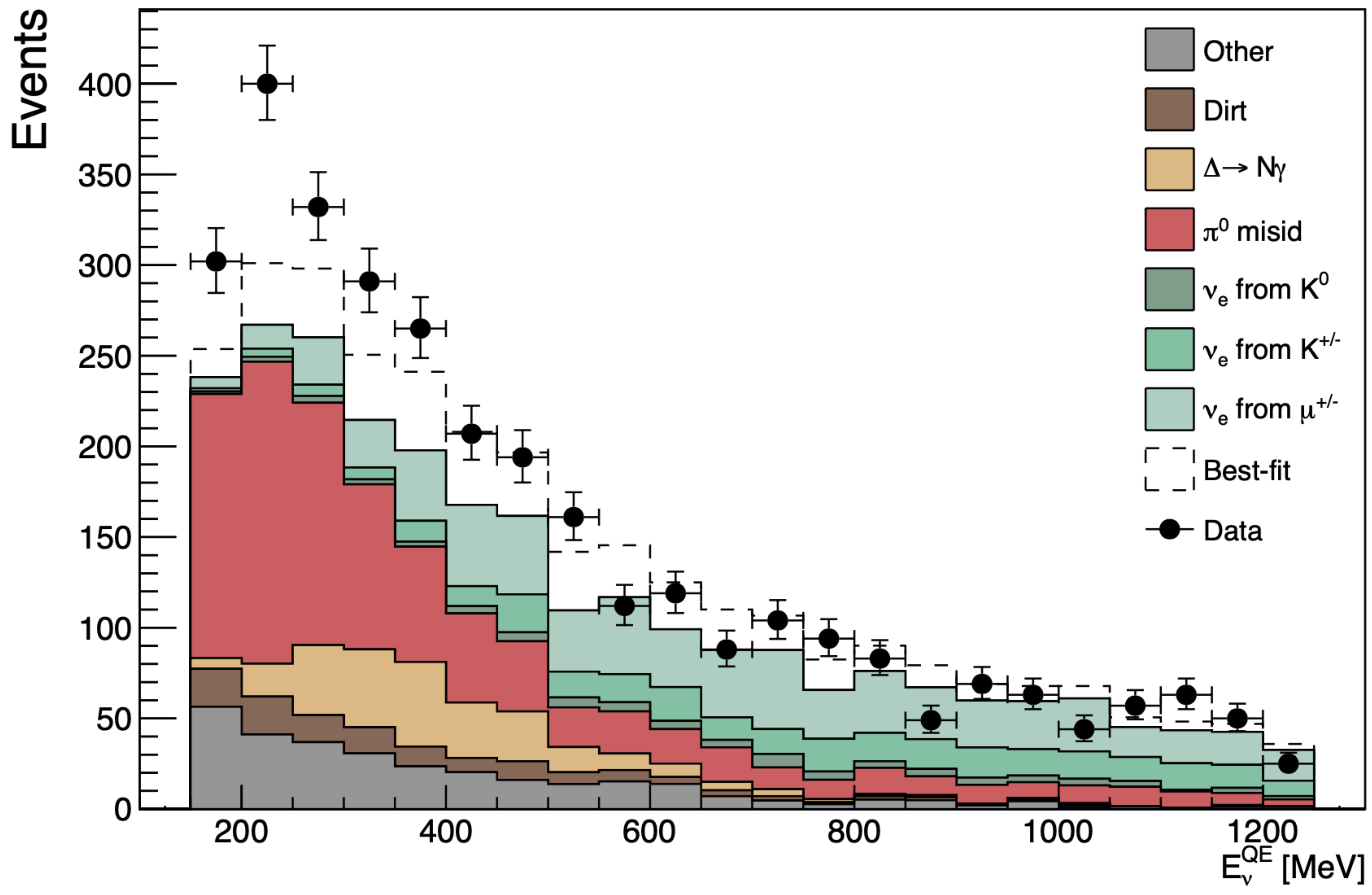
MiniBooNE



MiniBooNE 2020
Events
400
350
300
250
200
150
100
50
0
200
400
600
800
1000
1200
E_ν^{QE} [MeV]
Other
Dirt
$\Delta \to N\gamma$
π^0 misid
ν_e from K^0
ν_e from $K^{+/-}$
ν_e from $\mu^{+/-}$
Best-fit
Data

$\Delta \rightarrow N \gamma$ Background

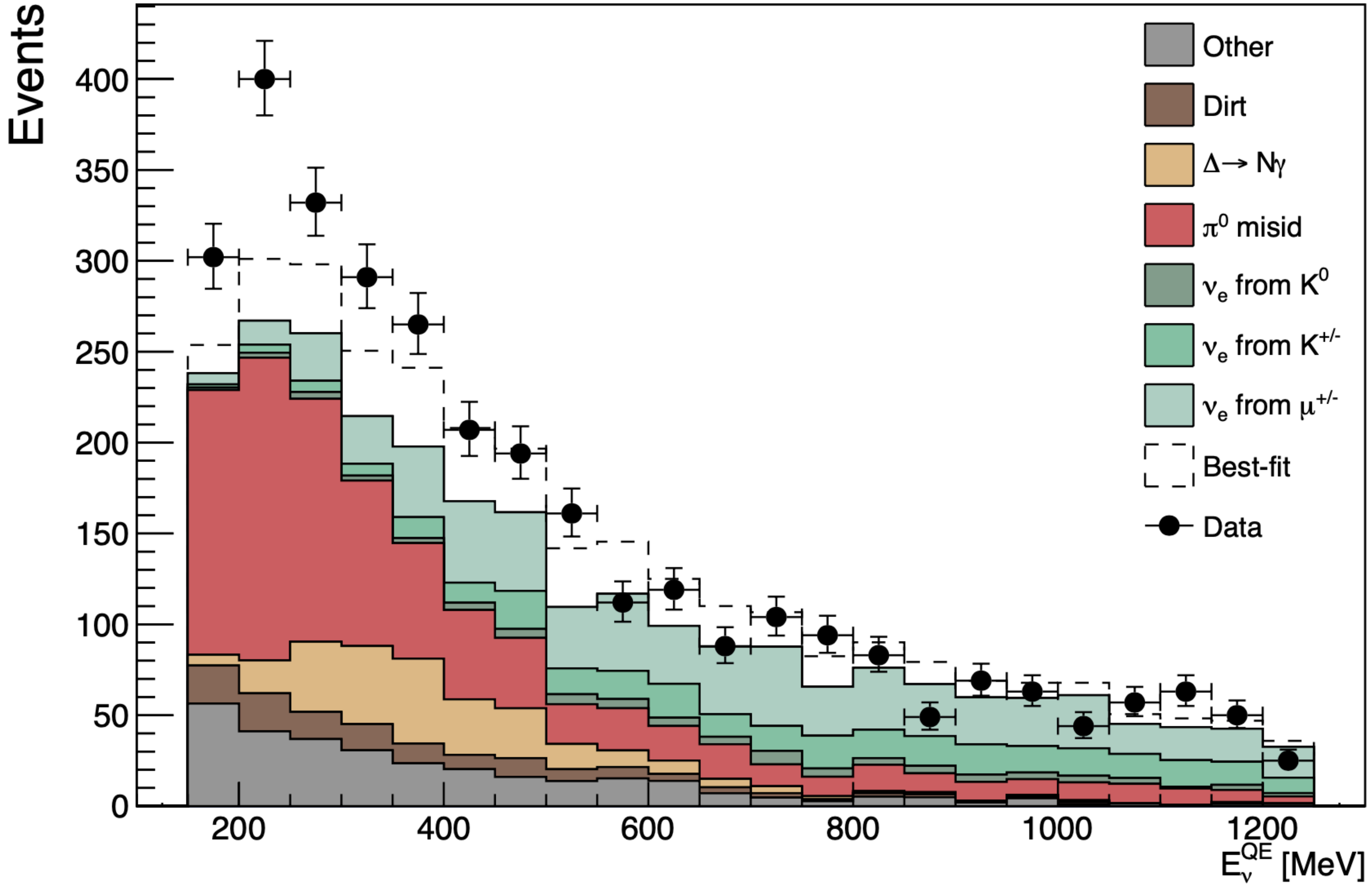
MiniBooNE 2020



- NC interaction:
  $\nu + N \rightarrow \nu + \Delta(1232)$
- Most $\Delta(1232)$ decay to π + N
- But rare decay exists to γ + N
- MiniBooNE cannot distinguish single-γ background from CC ν_e signal

$\Delta \to N\gamma$ Background

MiniBooNE 2020



- Δ production rate can be estimated from Δ → πN
- Pions may be absorbed on their way out of the nucleus
  - may excite another Δ(1232) ➠ Δ → γN enhanced
  - or may be absorbed ➠ control region suppressed

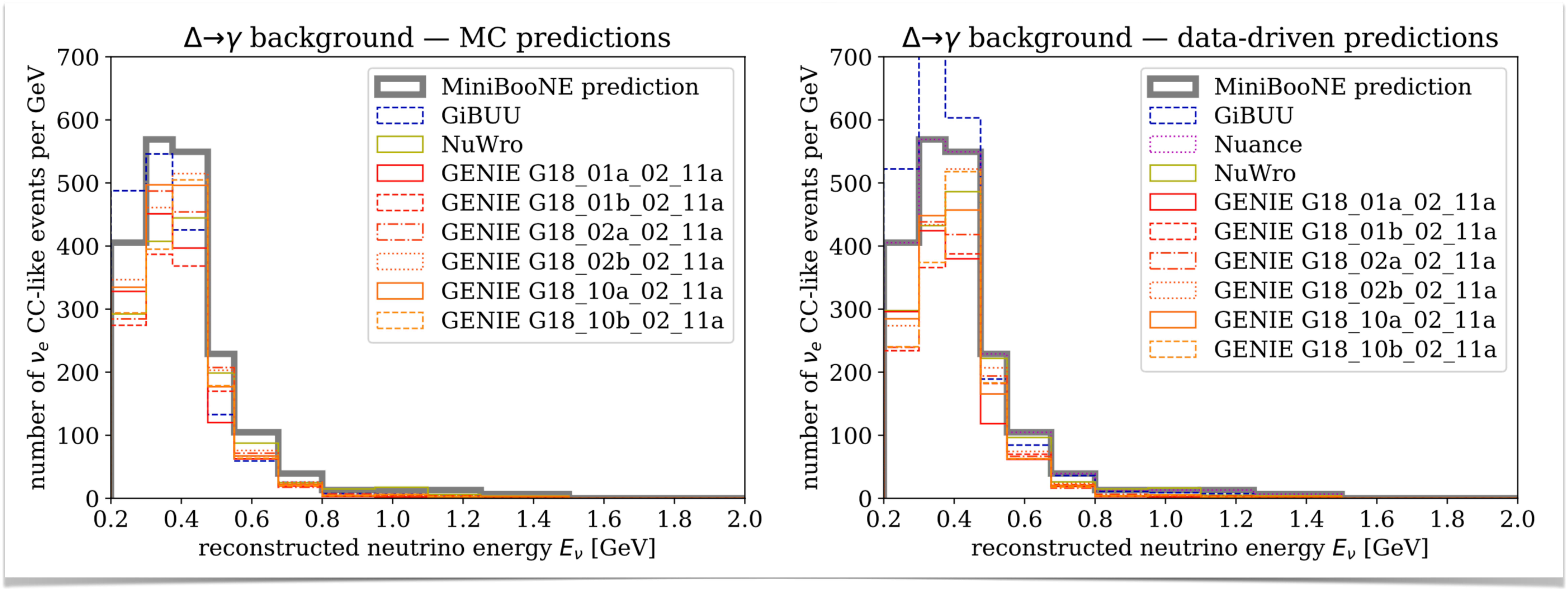
Ioannisian 1909.08571
Giunti Ioannisian Ranucci 1912.01524

(These effects have been taken into account by MiniBooNE)

MiniBooNe, arXiv:2006.16883

$\Delta \to N\gamma$ – Comparison of Generators

Brdar JK, arXiv:2109.08157

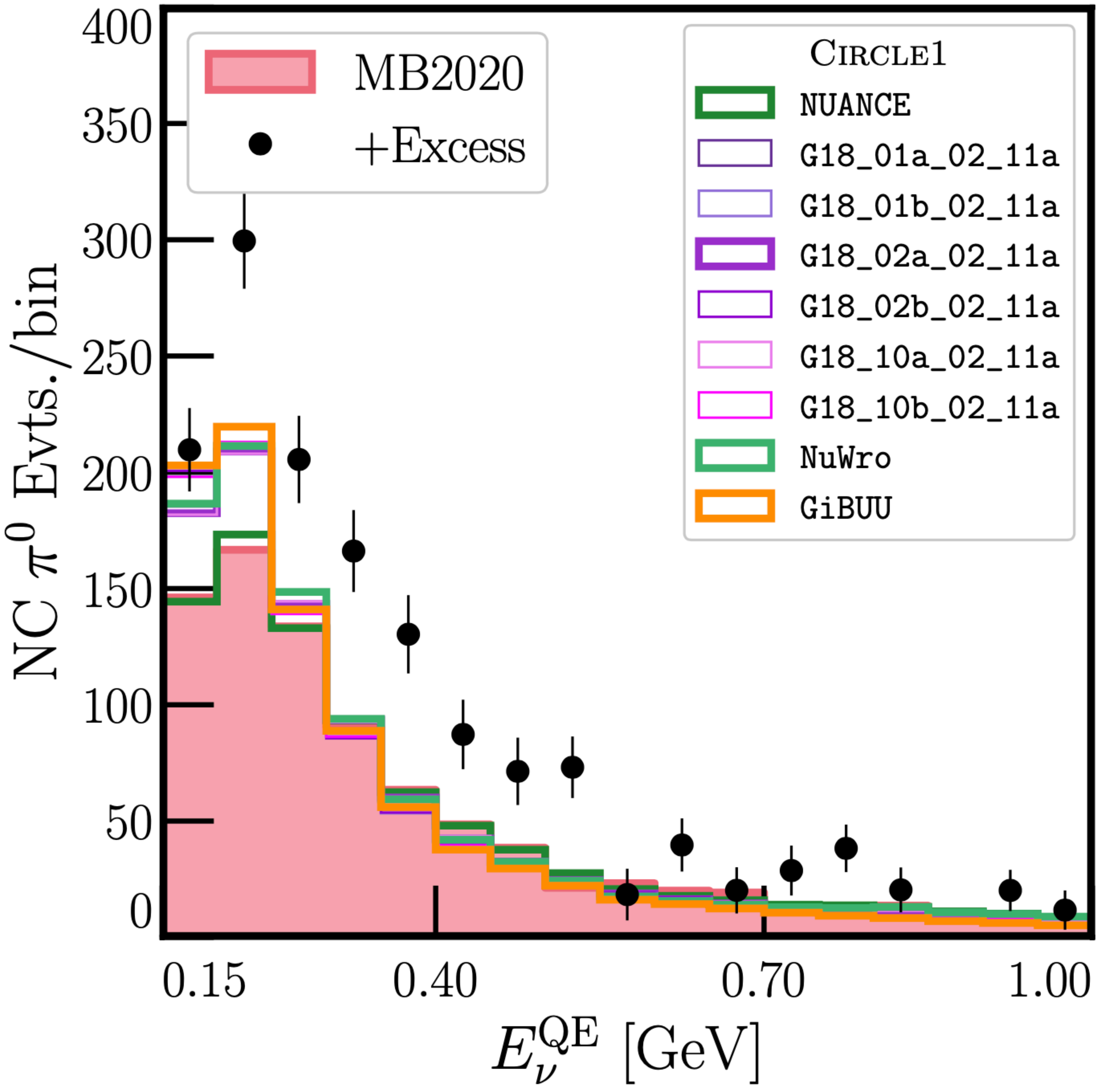


- NUANCE prediction matched to MB prediction, others rescaled in the same way
- using our own implementation of radiative resonance decays in GiBUU, NuWro, NUANCE

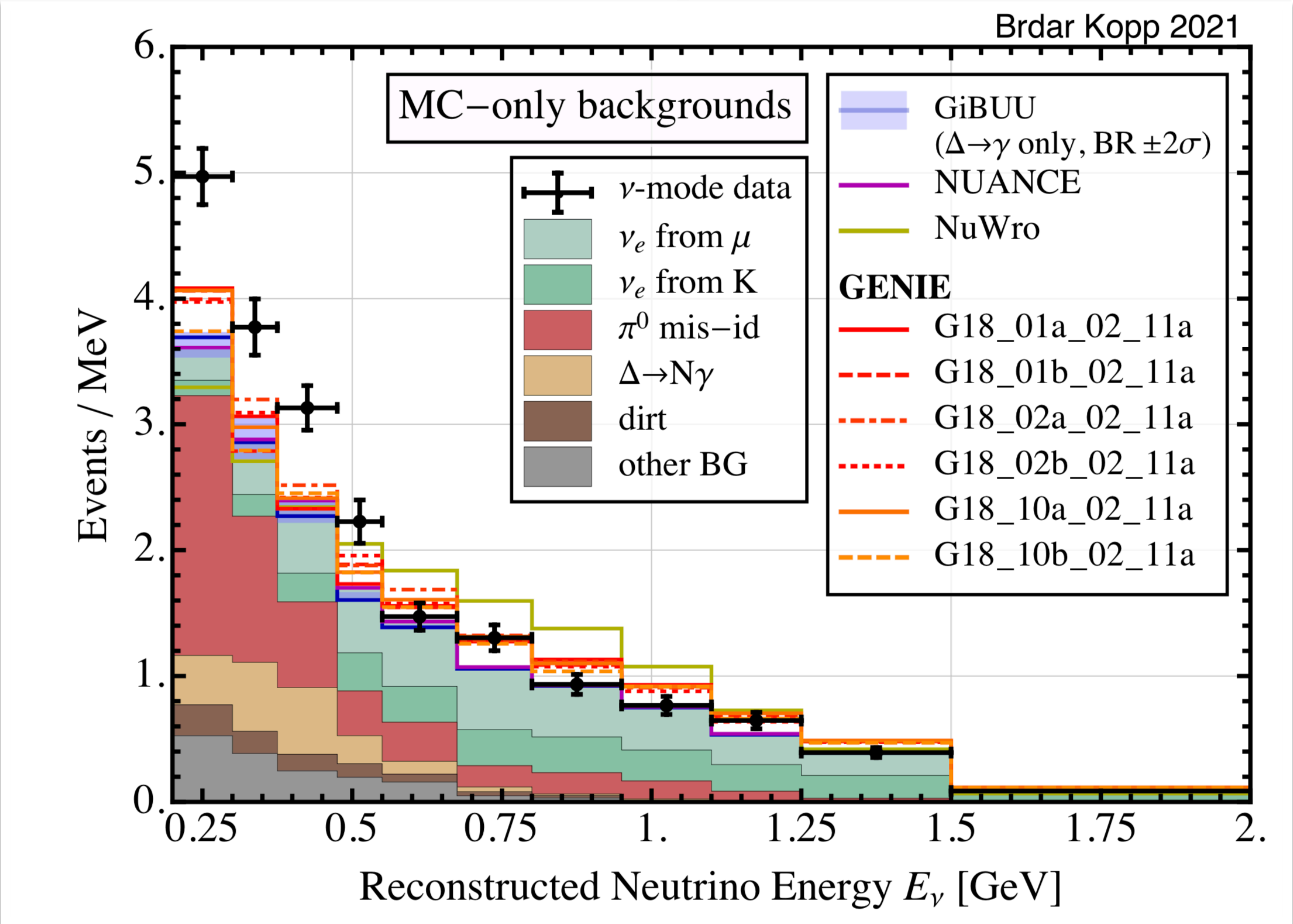
MiniBooNE π^0 Background

- Attempt to reproduce MiniBooNE's π^0 mis-ID probability
- using our own implementation of radiative resonance decays in GiBUU, NuWro, NUANCE

Kelly JK, arXiv:2210.08021

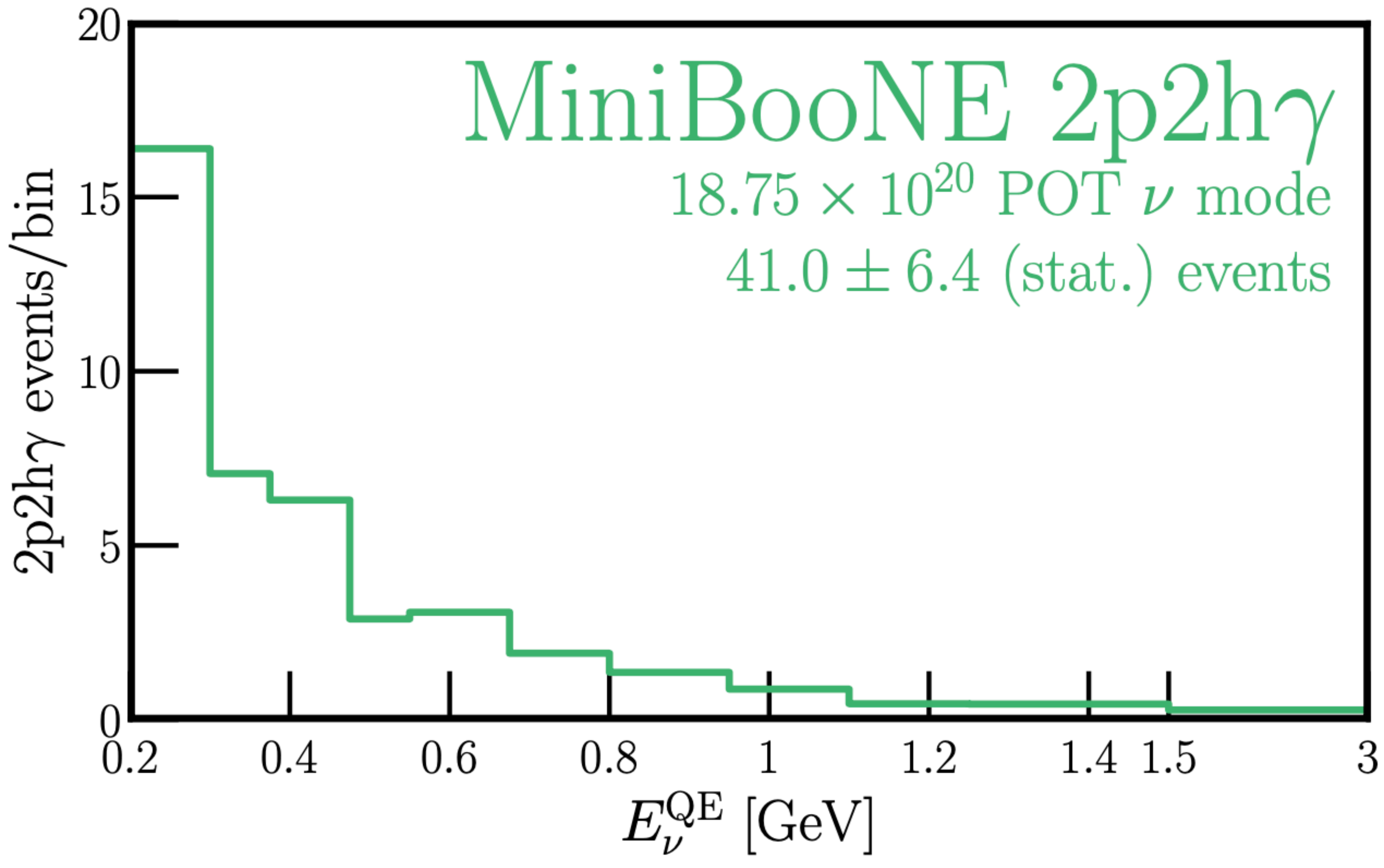


All Backgrounds – Comparison of Generators



New Processes? – 2p2h+γ

- intuition: neutrino scatters on 2-nucleon system
  ➠ radiated γ sees both nucleons coherently
  ➠ enhanced by factor 2
- *very* naïve implementation (elastic scattering on 2-nucleon system)
- event rate falls far short of explaining the anomaly



Kelly JK, arXiv:2210.08021

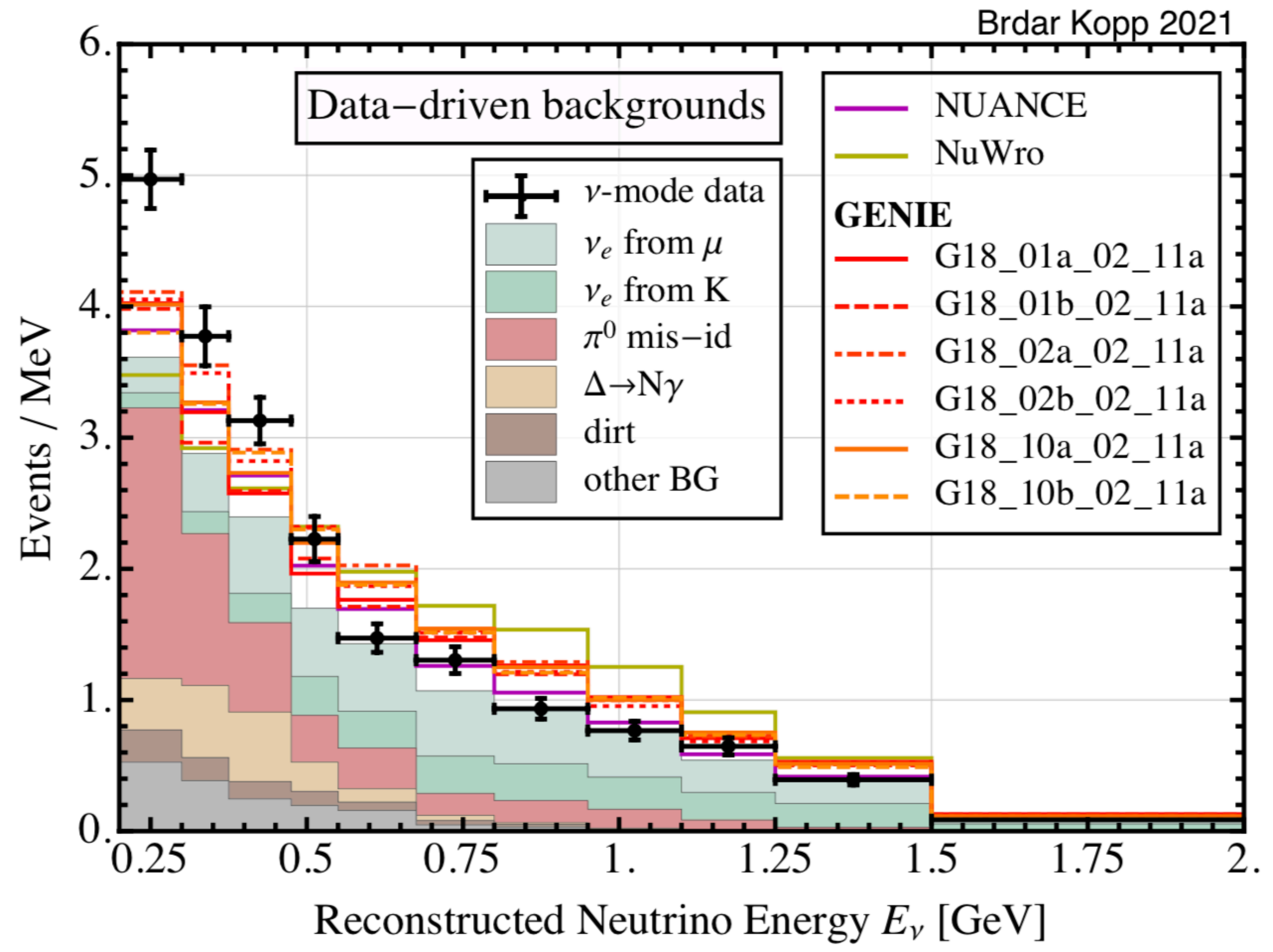
My Bet for MiniBooNE

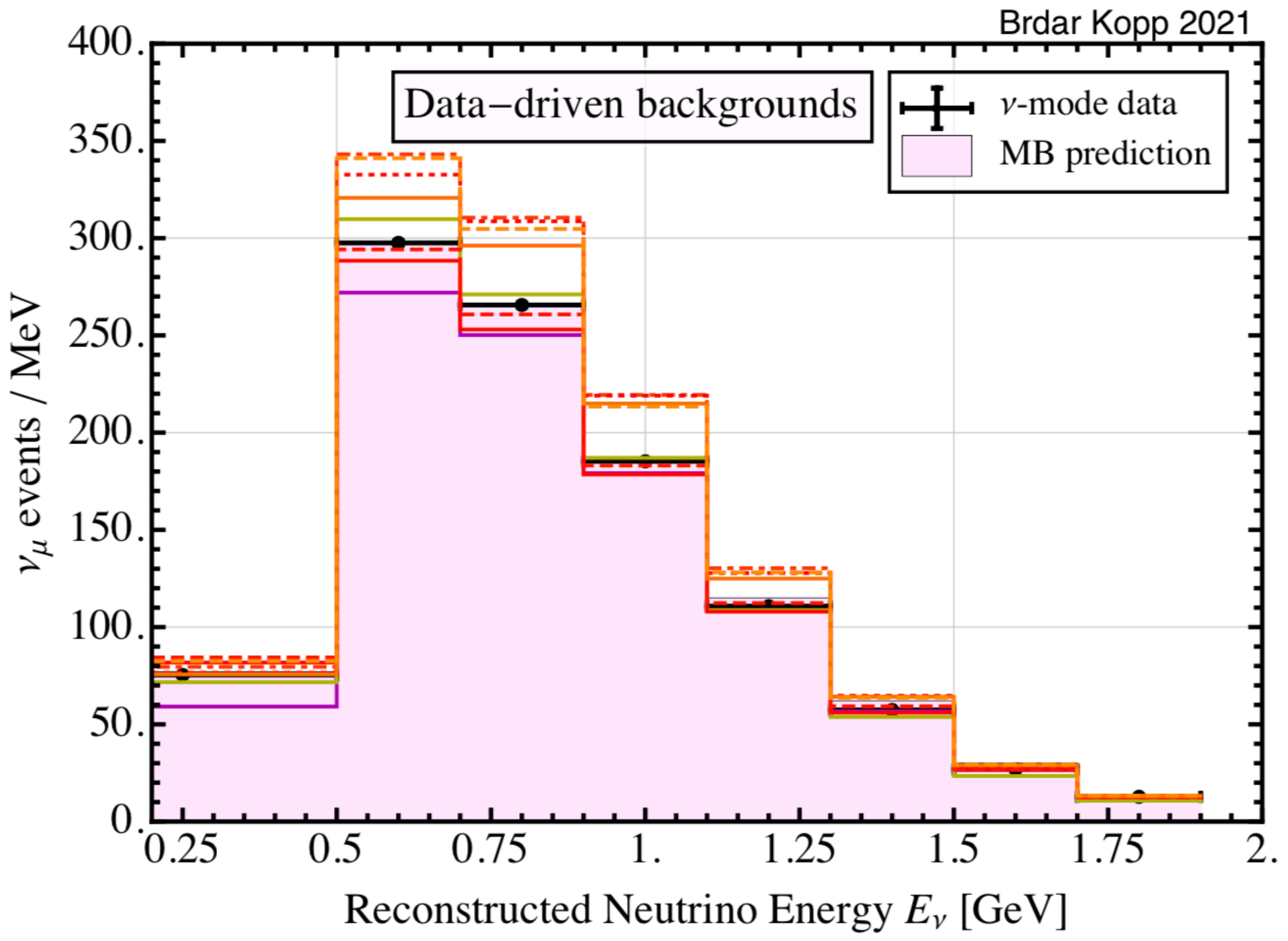
an

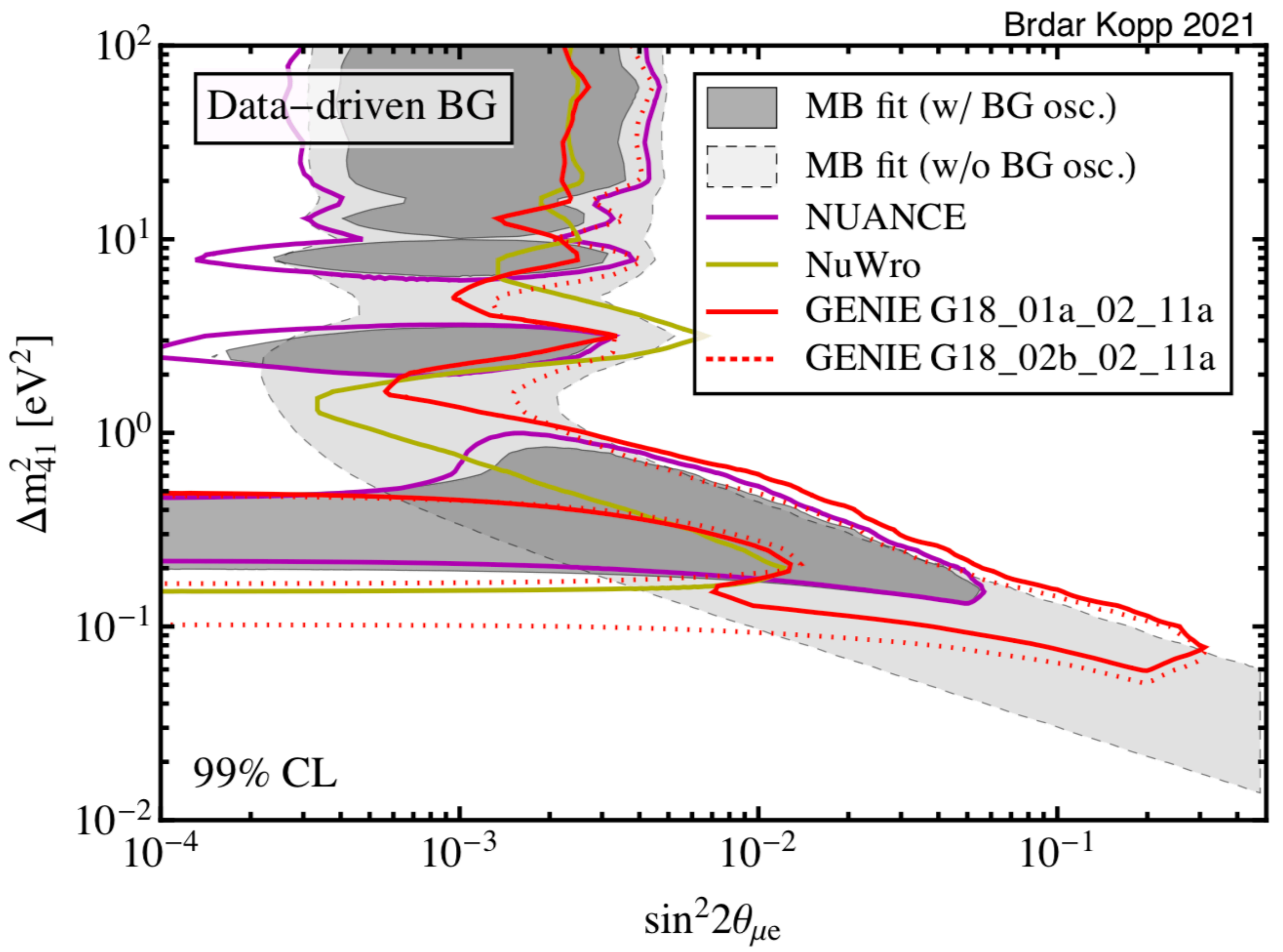
"***Altarelli Cocktail***"

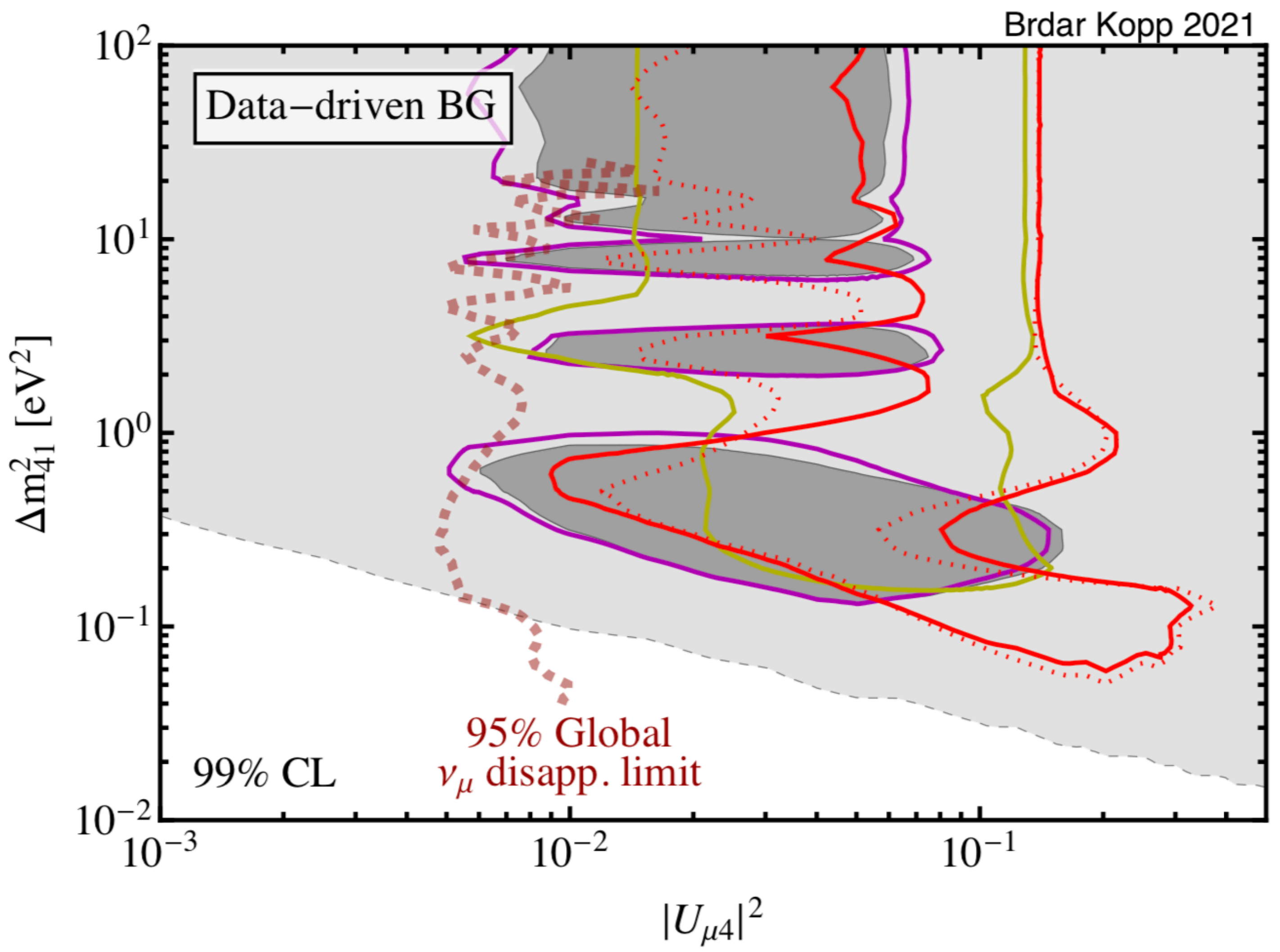
Image: ChatGPT
(who refused to draw an Italian physicist w/o a beard)

3+1 Models in MiniBooNE – Comparison of Generators



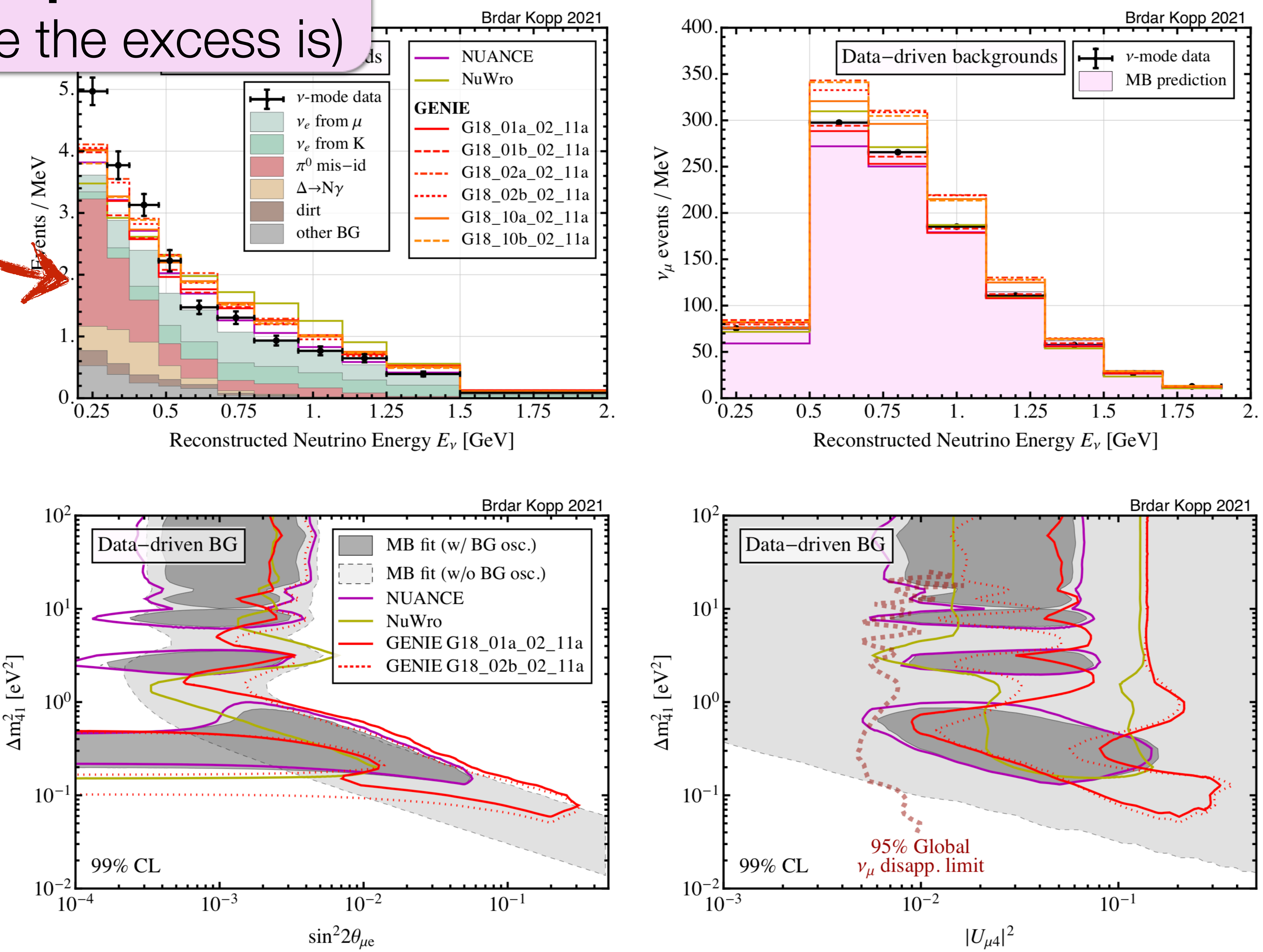






3+1 Models in MiniBooNE – Comparison of Generators

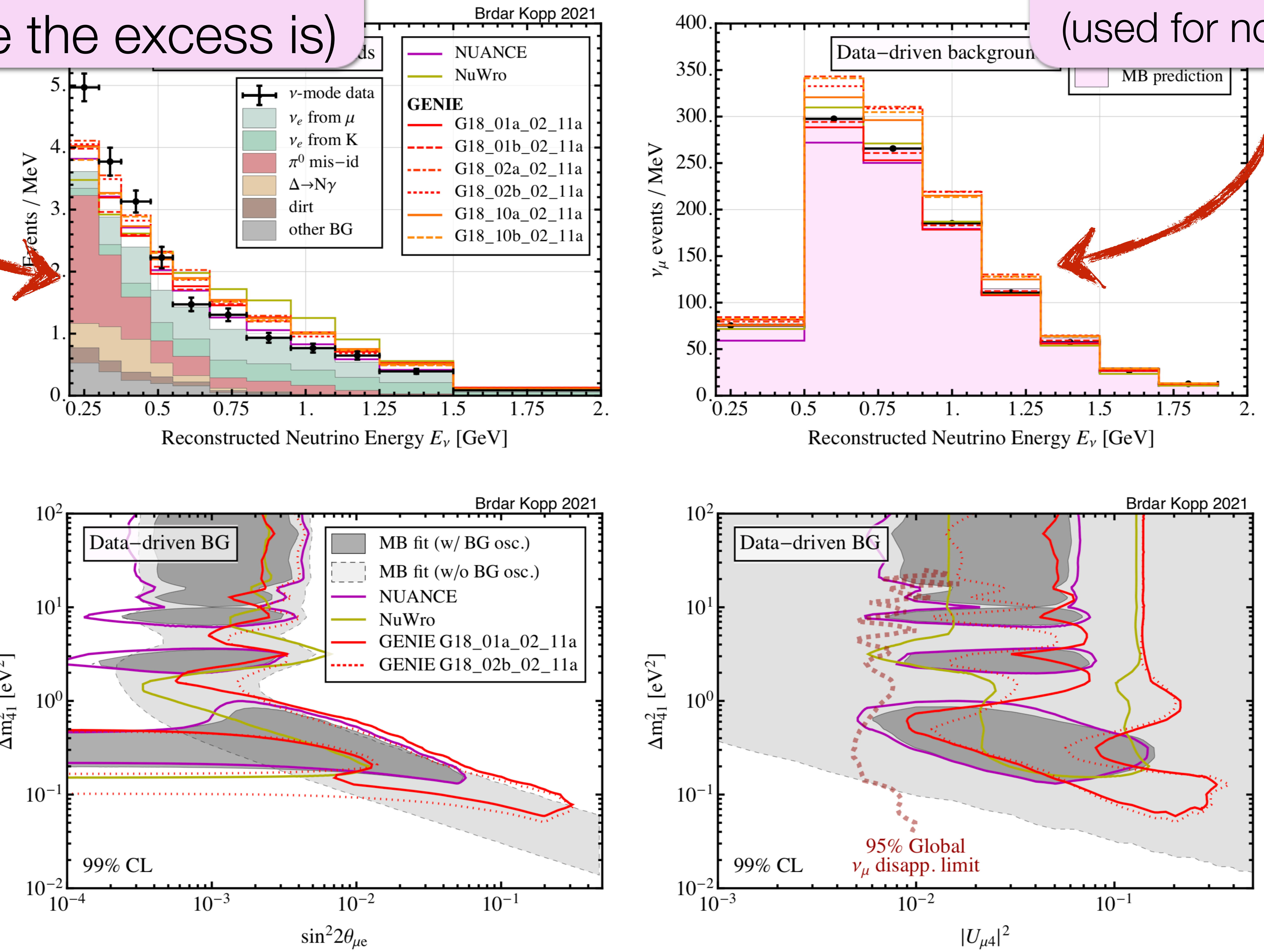
ν_e spectrum
(where the excess is)



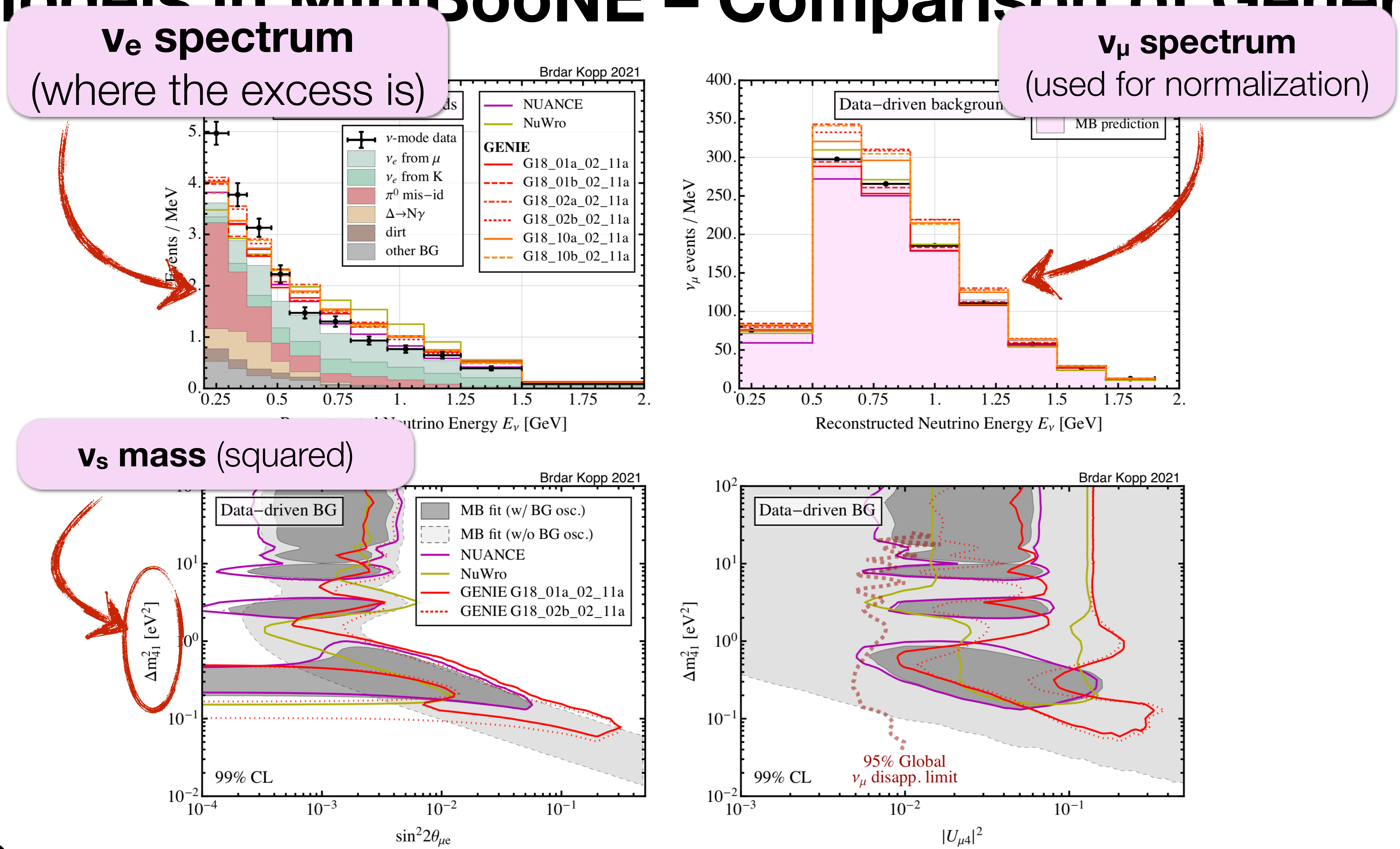
3+1 Models in MiniBooNE – Comparison of Generators

ν_e spectrum
(where the excess is)

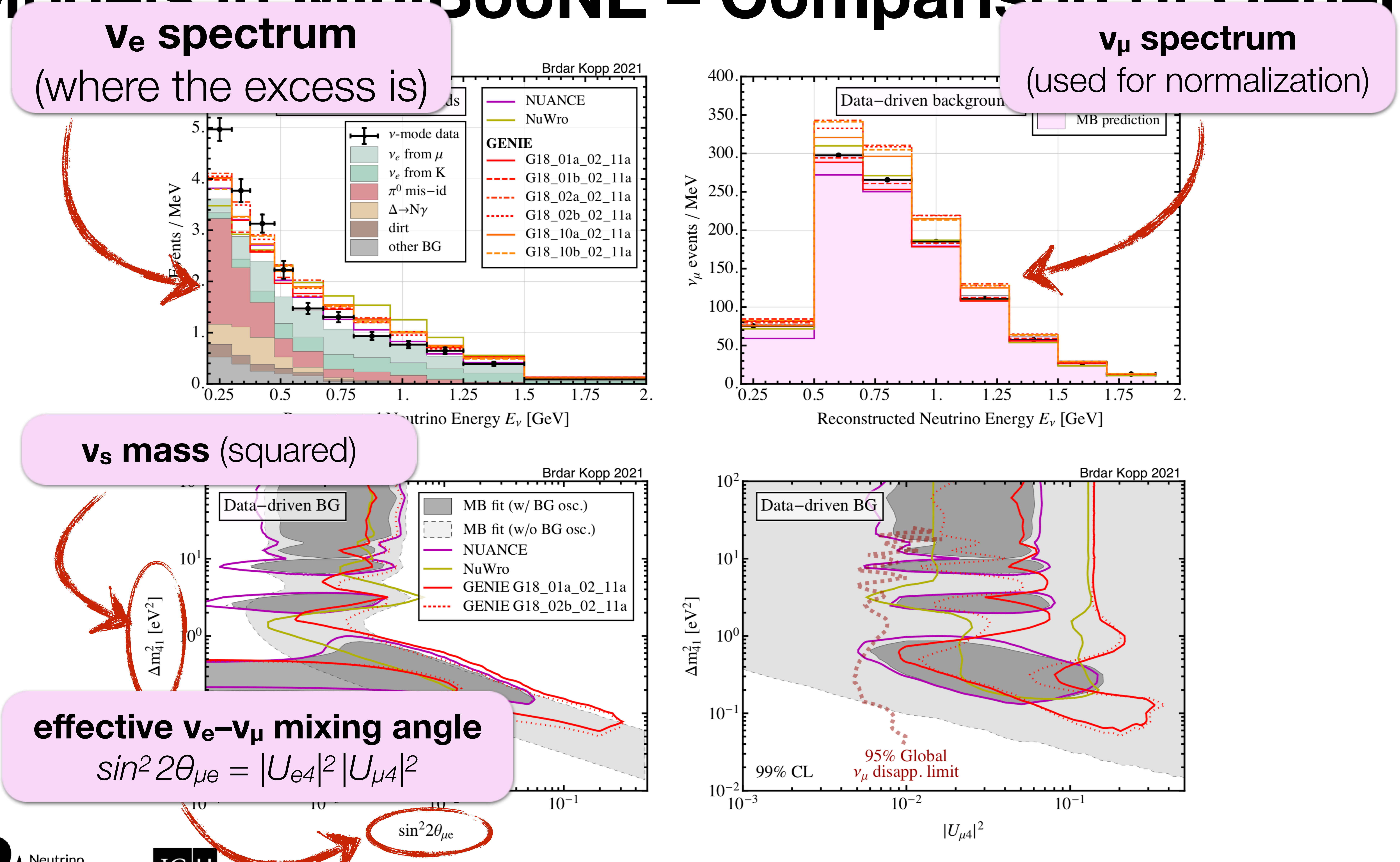
ν_μ spectrum
(used for normalization)



3+1 Models in MiniBooNE – Comparison of Generators

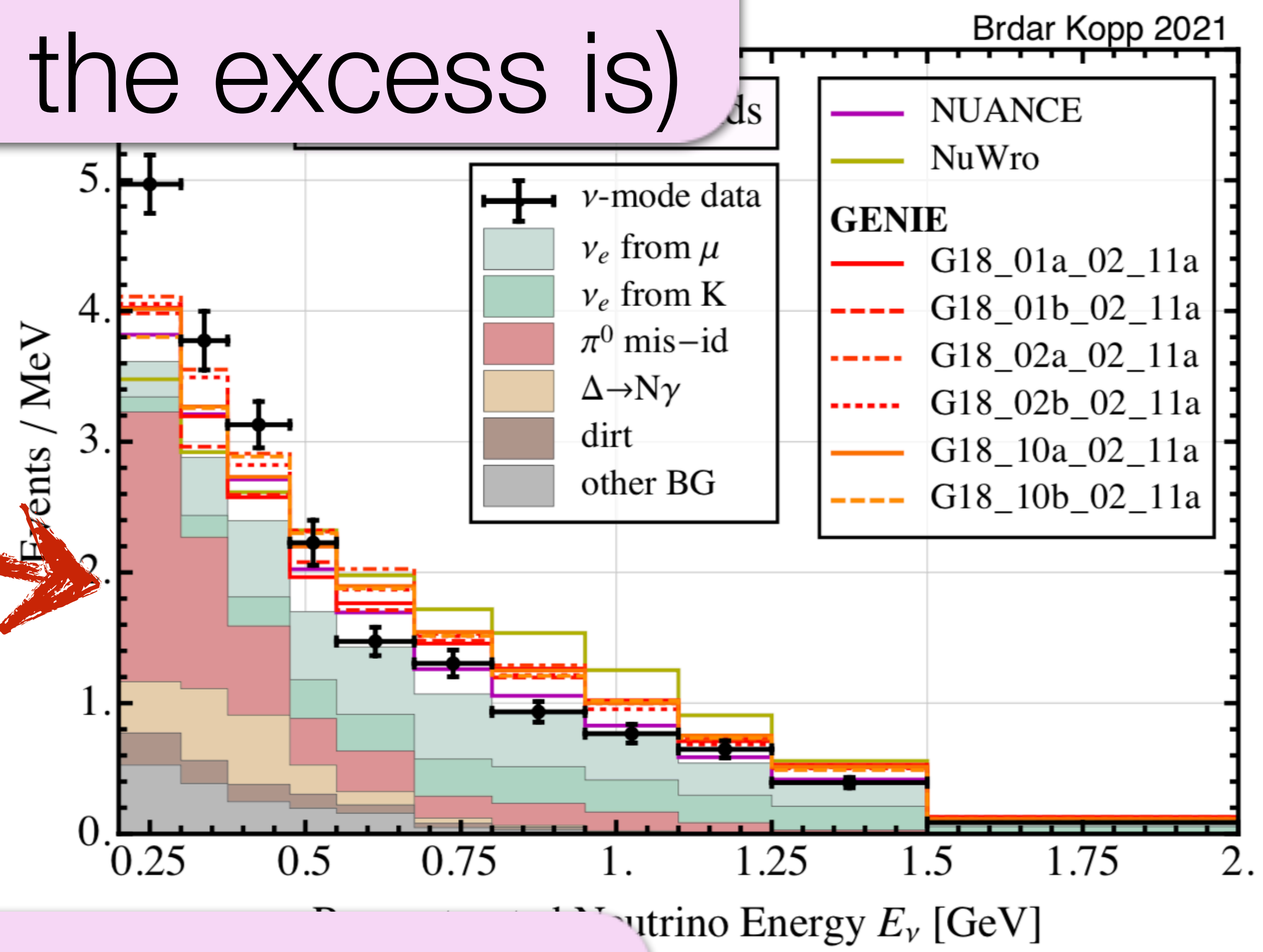


3+1 Models in MiniBooNE – Comparison of Generators

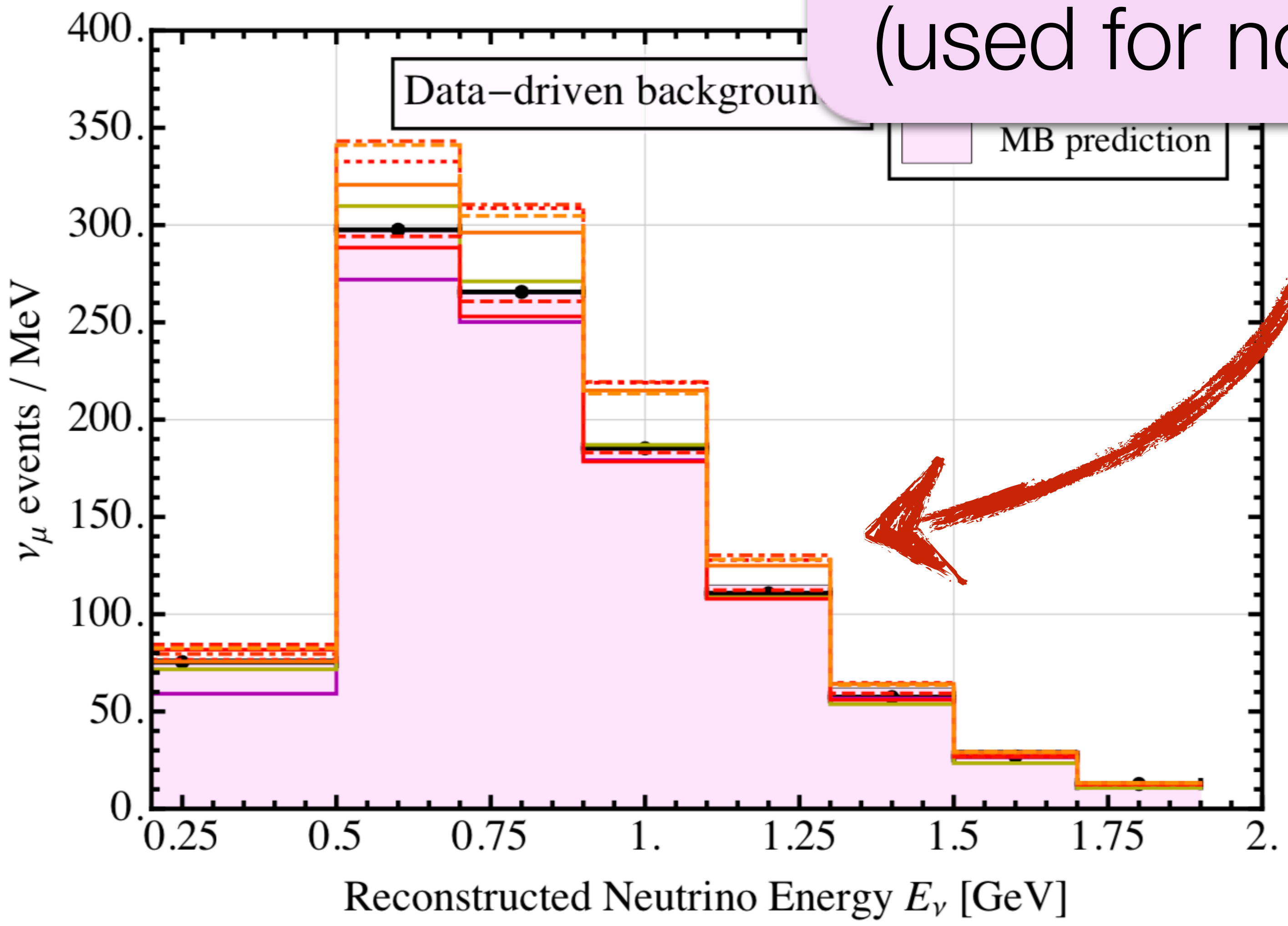


3+1 Models in MiniBooNE – Comparison of Generators

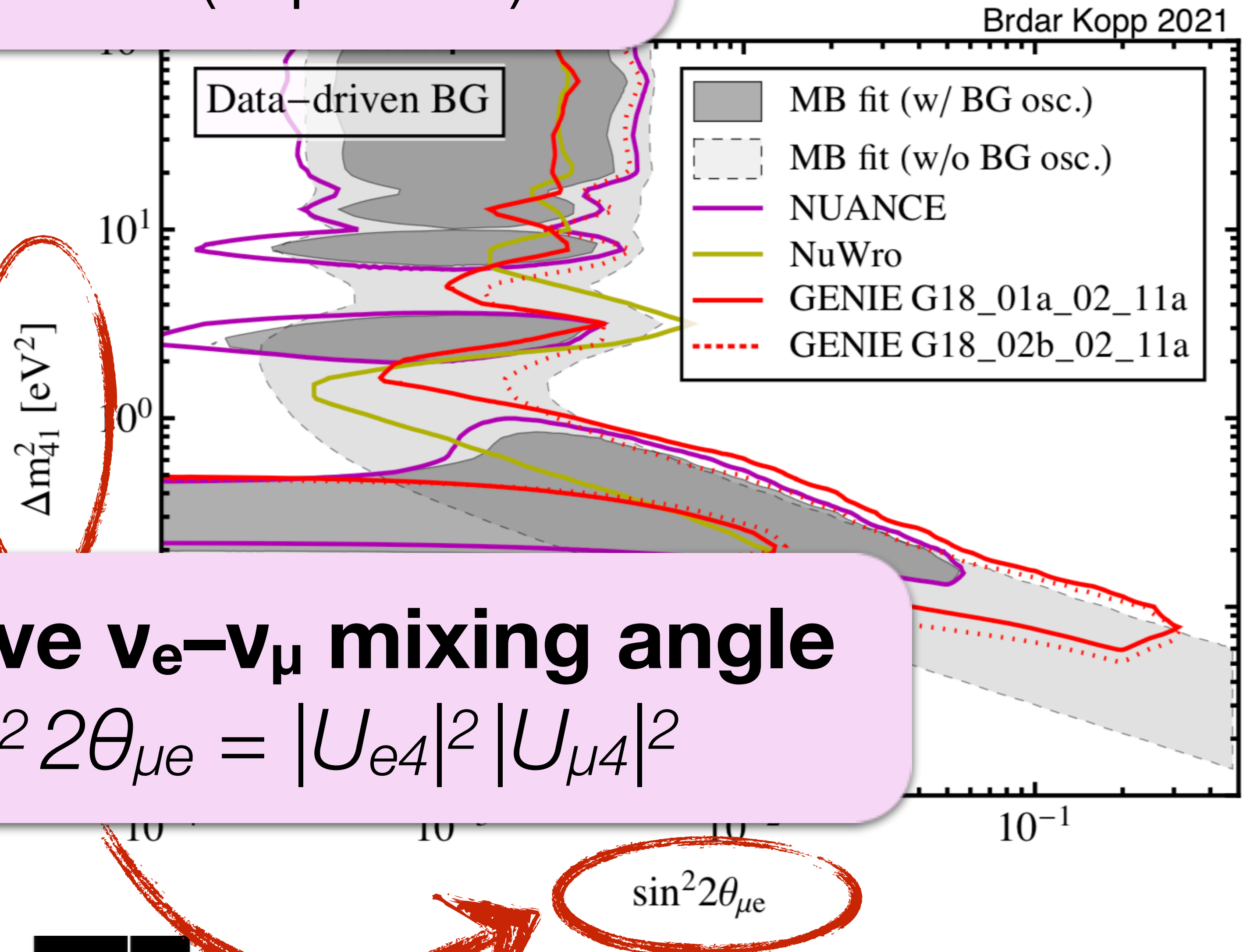
ν_e spectrum
(where the excess is)



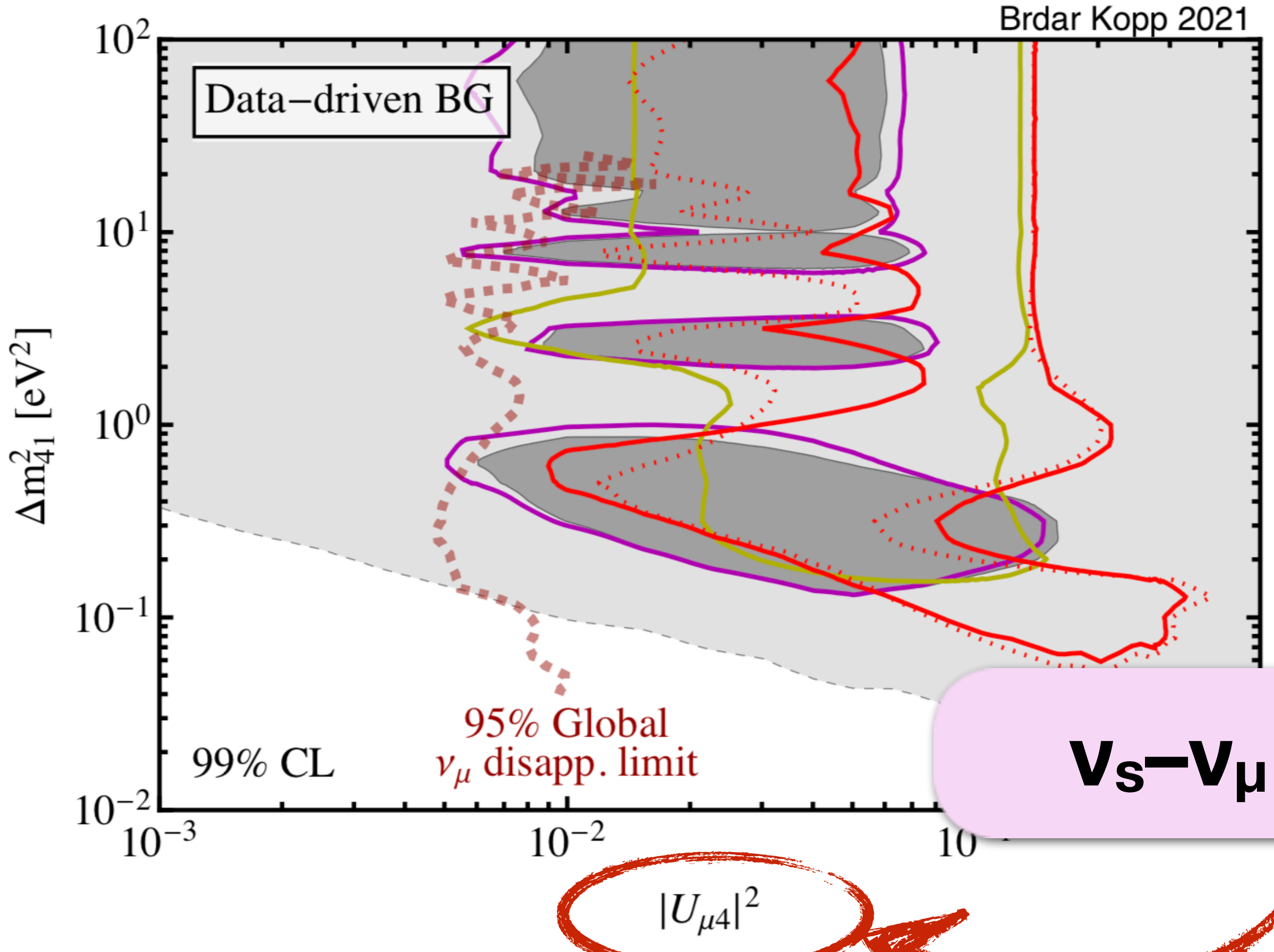
ν_μ spectrum
(used for normalization)



ν_s mass (squared)



effective ν_e–ν_μ mixing angle
$\sin^2 2\theta_{\mu e} = |U_{e4}|^2 \, |U_{\mu 4}|^2$



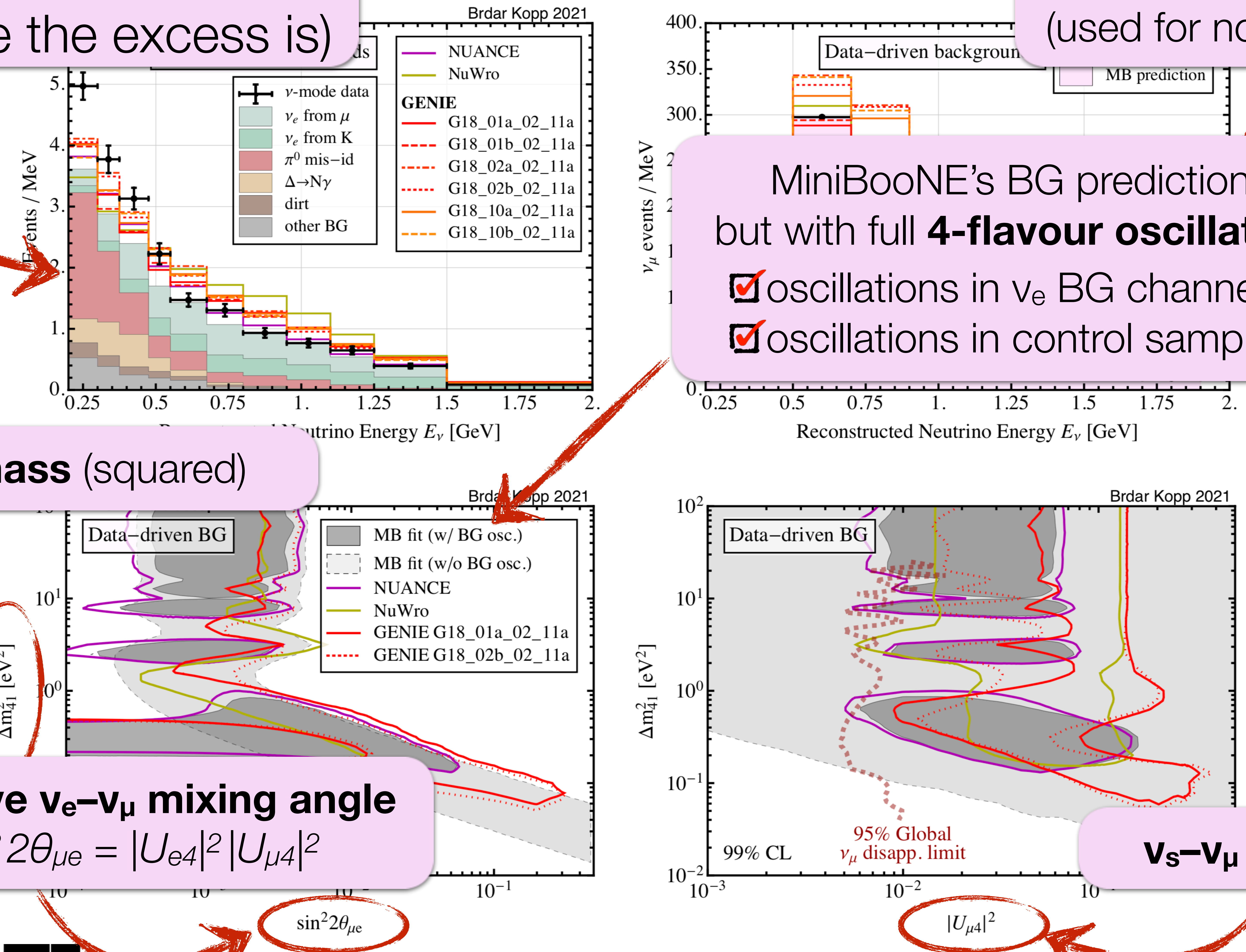
ν_s–ν_μ mixing

CERN Neutrino PLATFORM JG|U

3+1 Models in MiniBooNE – Comparison of Generators

ν_e spectrum
(where the excess is)

ν_μ spectrum
(used for normalization)



MiniBooNE's BG predictions,
but with full **4-flavour oscillations**

☑ oscillations in ν_e BG channels
☑ oscillations in control sample

ν_s mass (squared)

effective ν_e–ν_μ mixing angle
$\sin^2 2\theta_{\mu e} = |U_{e4}|^2 \, |U_{\mu 4}|^2$

ν_s–ν_μ mixing

3+1 Models in MiniBooNE – Comparison of Generators

ν_e spectrum (where the excess is)

ν_μ spectrum (used for normalization)

MiniBooNE's BG predictions, but with full **4-flavour oscillations**

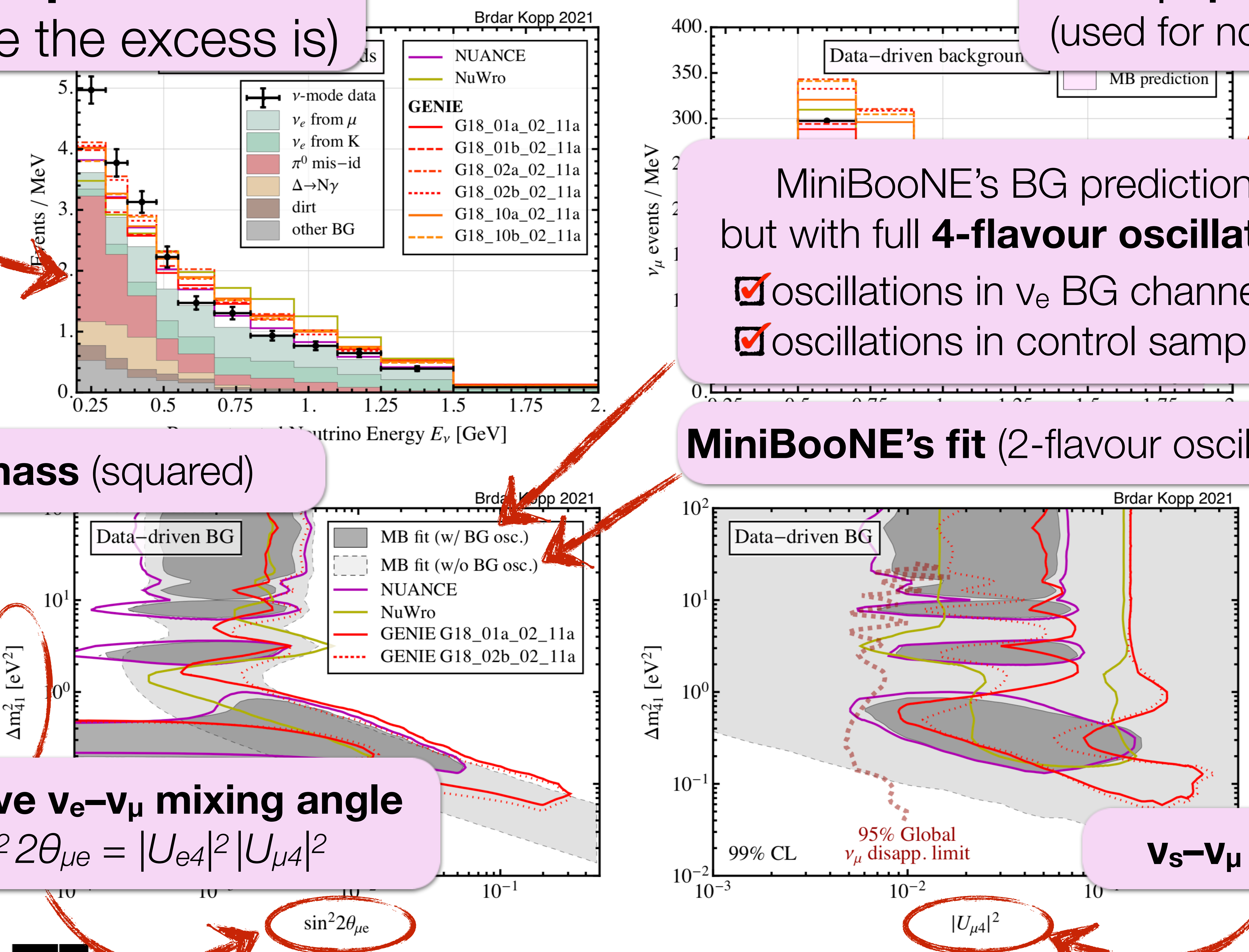
- ☑ oscillations in ν_e BG channels
- ☑ oscillations in control sample

MiniBooNE's fit (2-flavour oscillations)

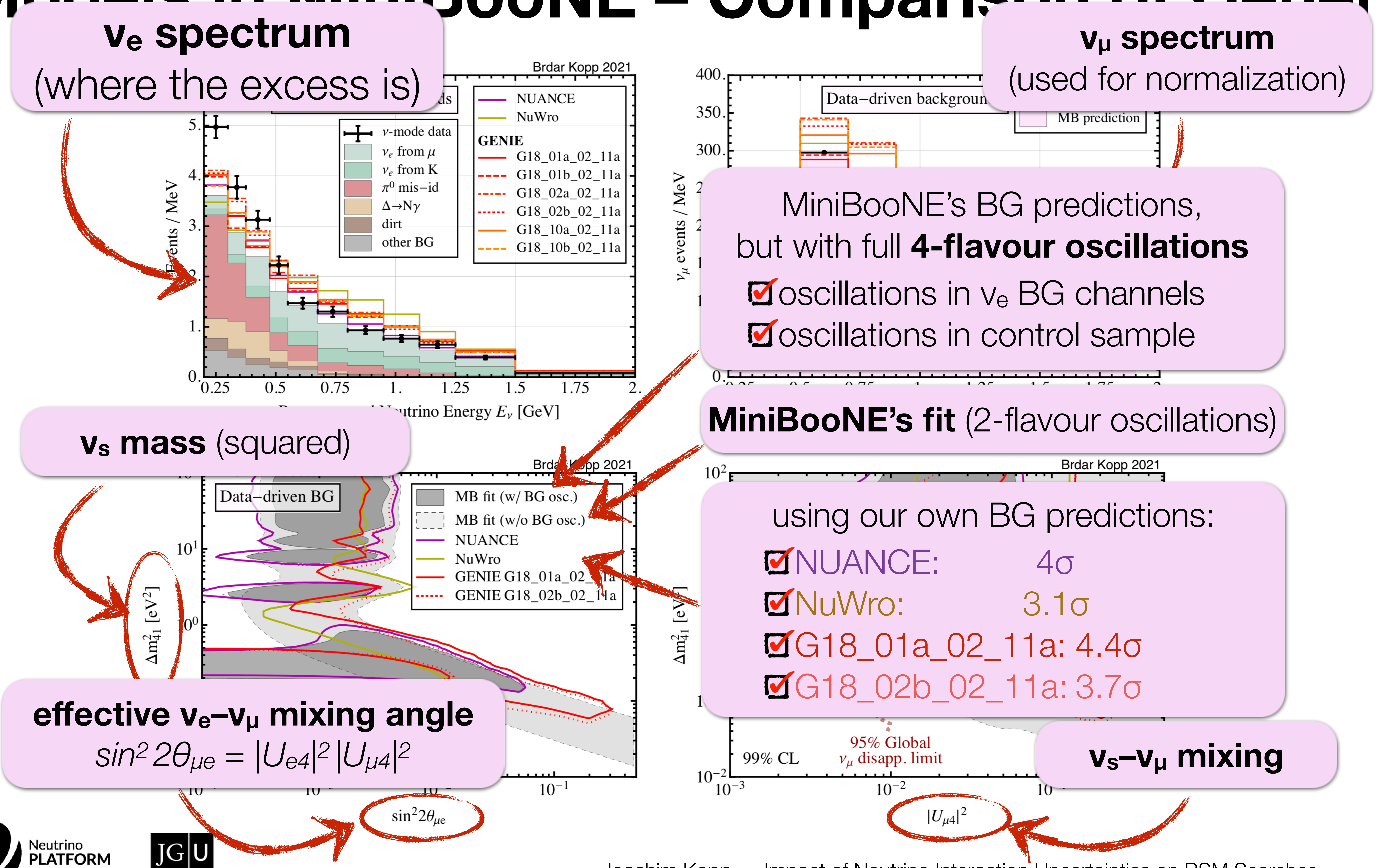
ν_s mass (squared)

effective ν_e–ν_μ mixing angle
$\sin^2 2\theta_{\mu e} = |U_{e4}|^2 \, |U_{\mu4}|^2$

ν_s–ν_μ mixing



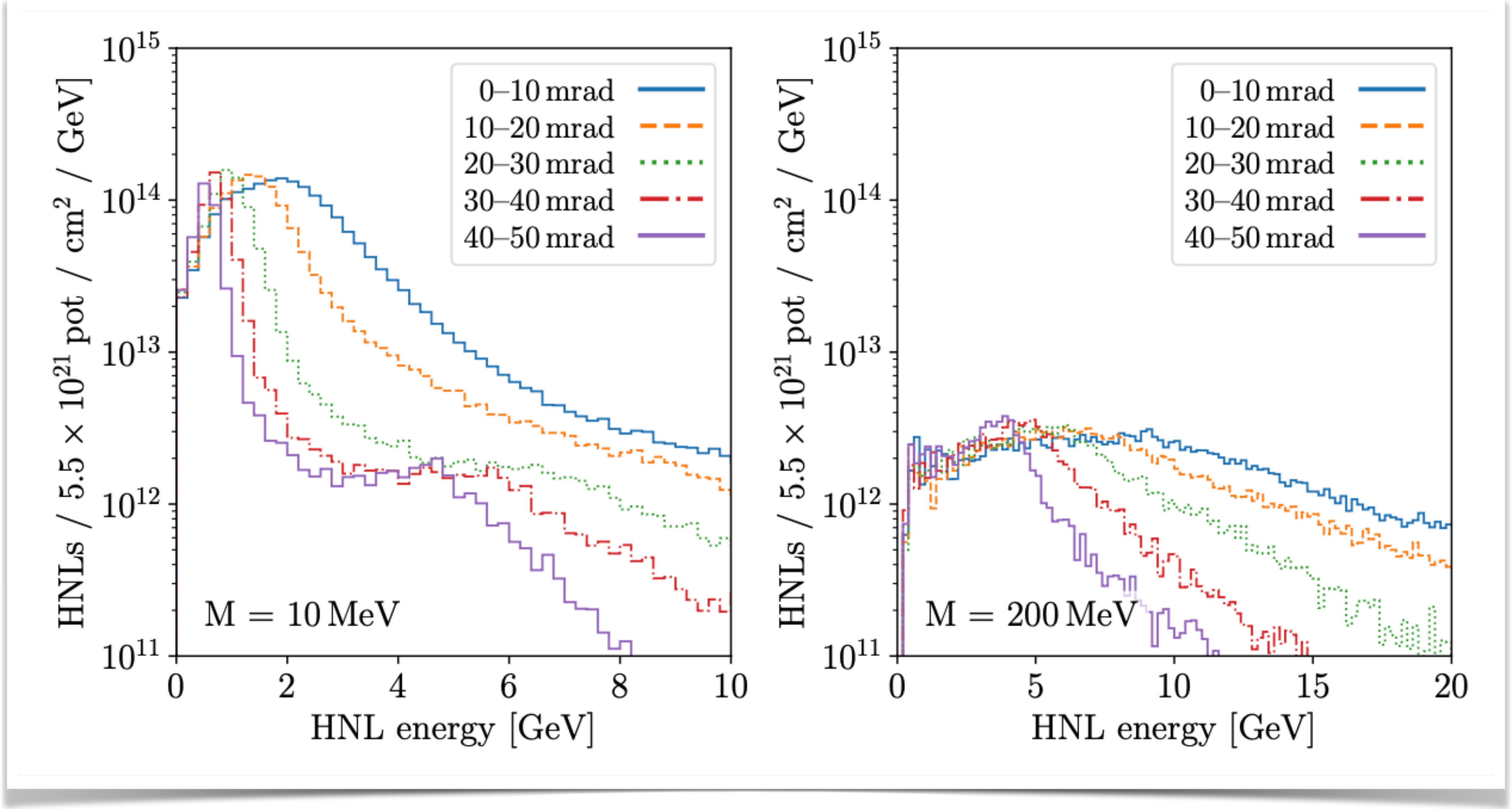
3+1 Models in MiniBooNE – Comparison of Generators



Heavy Neutral Leptons

- Neutrino portal leads to mixing between *ν* and heavy sterile neutrino *N*

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



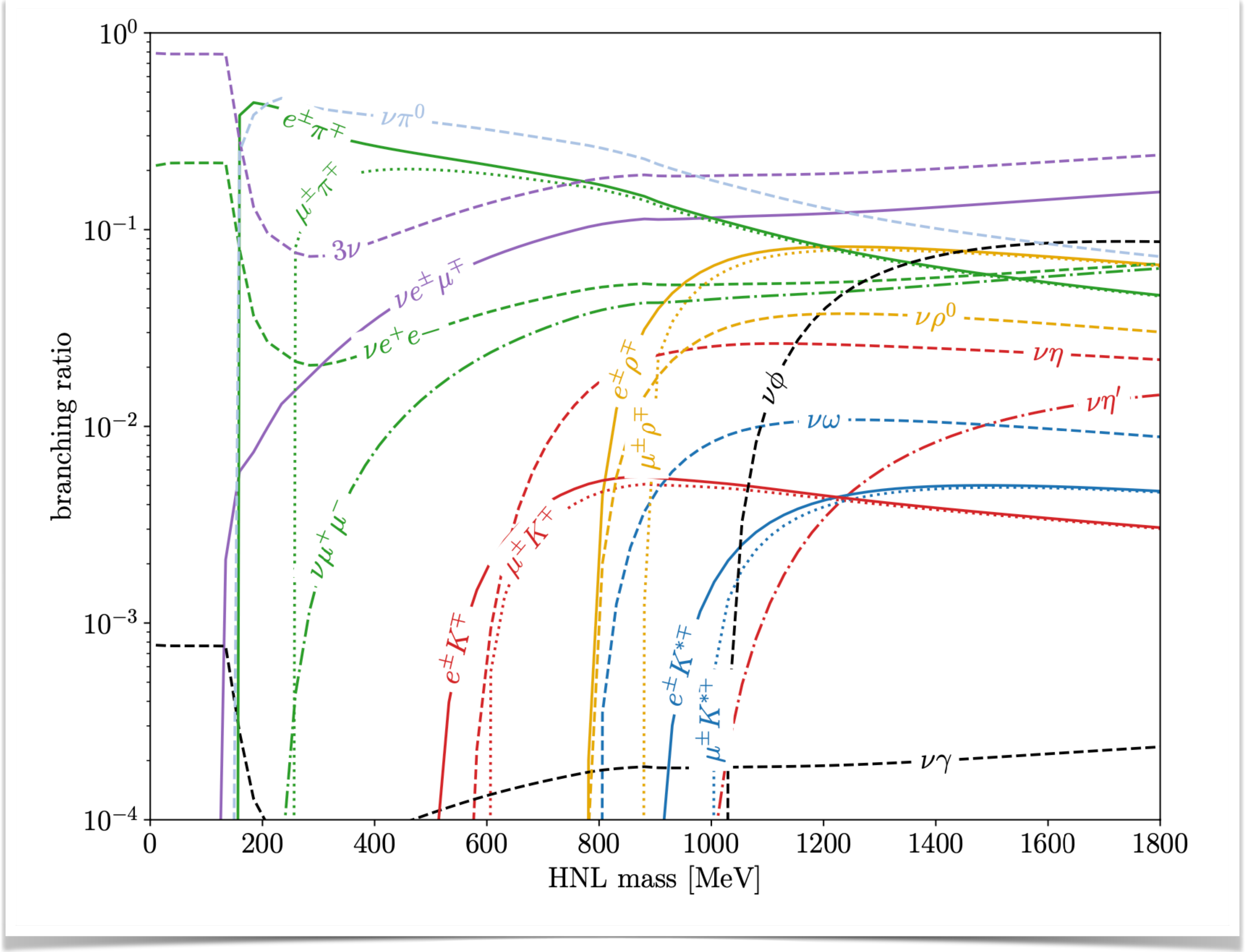
- any process that makes *ν* in the SM can also make *N* (suppressed by a mixing angle)
- production in meson decays

Heavy Neutral Leptons

- Neutrino portal leads to mixing between *ν* and heavy sterile neutrino *N*

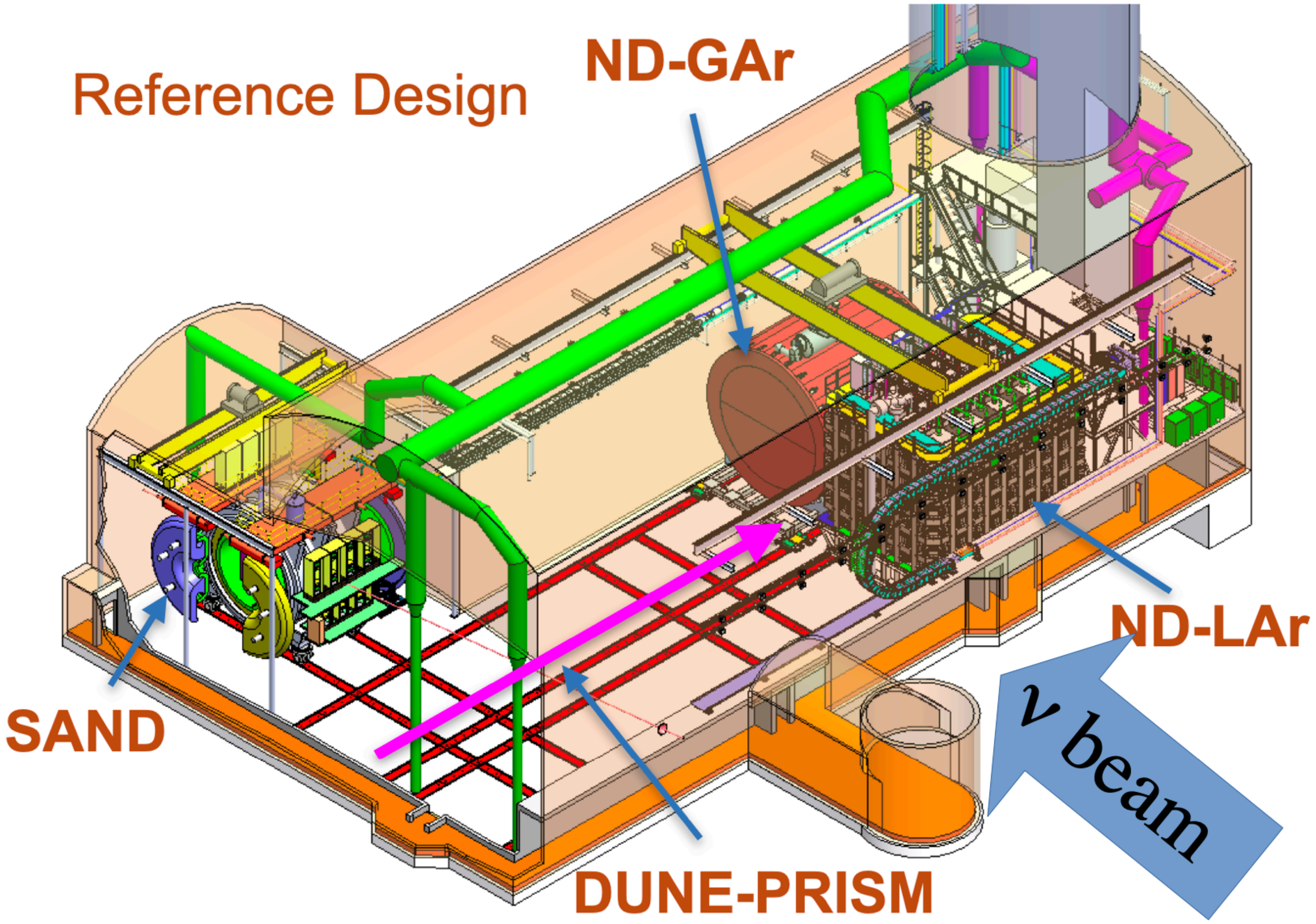
$$\mathcal{L} \supset y\,\bar{L}\,(i\sigma^2 H^*)\,N$$

- any process that makes *ν* in the SM can also make *N* (suppressed by a mixing angle)
- production in meson decays
- many 2-body and 3-body decay channels
- background estimates require detailed understanding of ***exclusive final states***



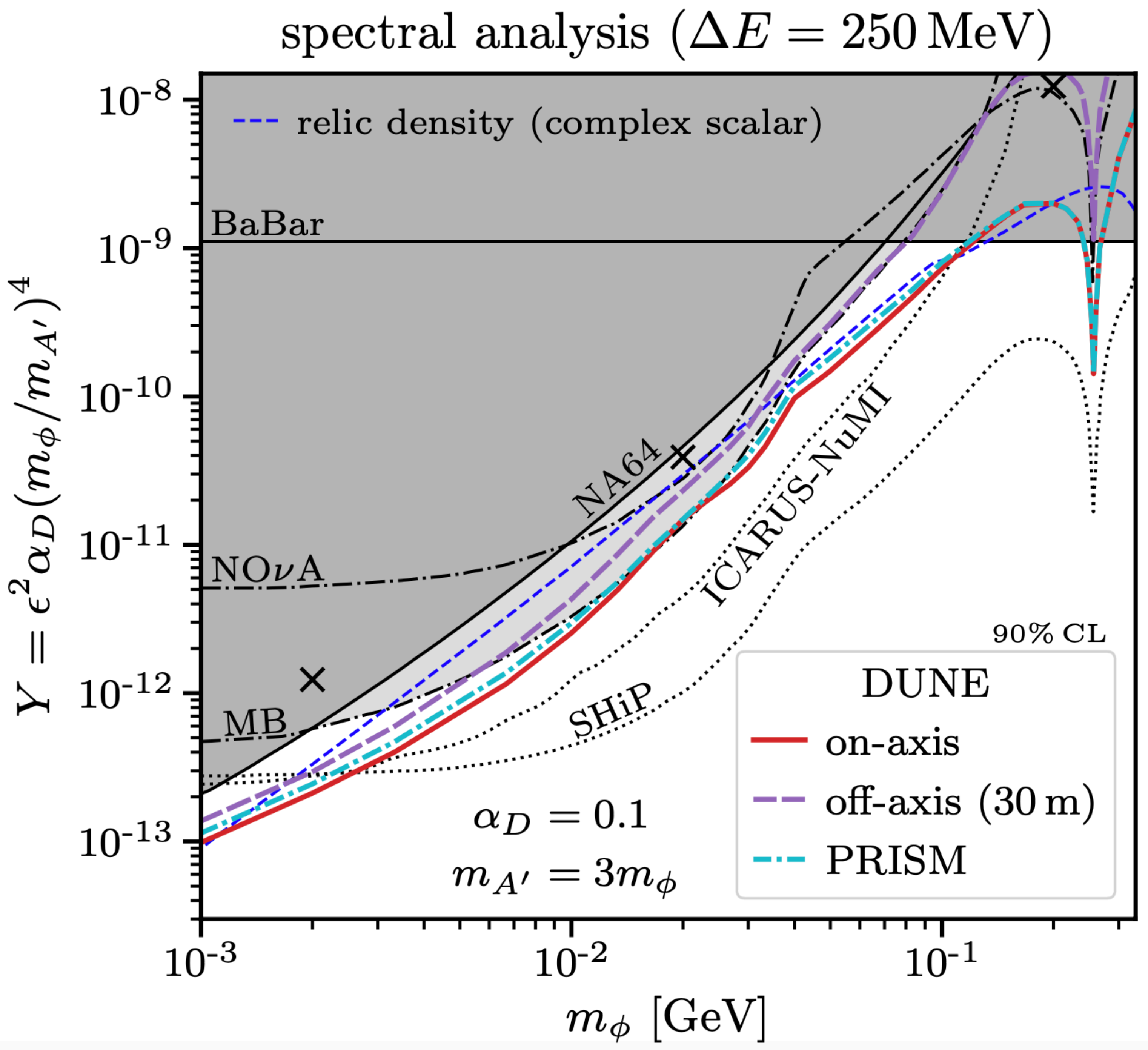
DUNE-PRISM

- Movable near detectors measure event rates at different off-axis angles
  ➠ disentangle flux and x-sec uncertainties
- Interesting opportunities for BSM searches
  - heavy particle less boosted
  - backgrounds lower off-axis

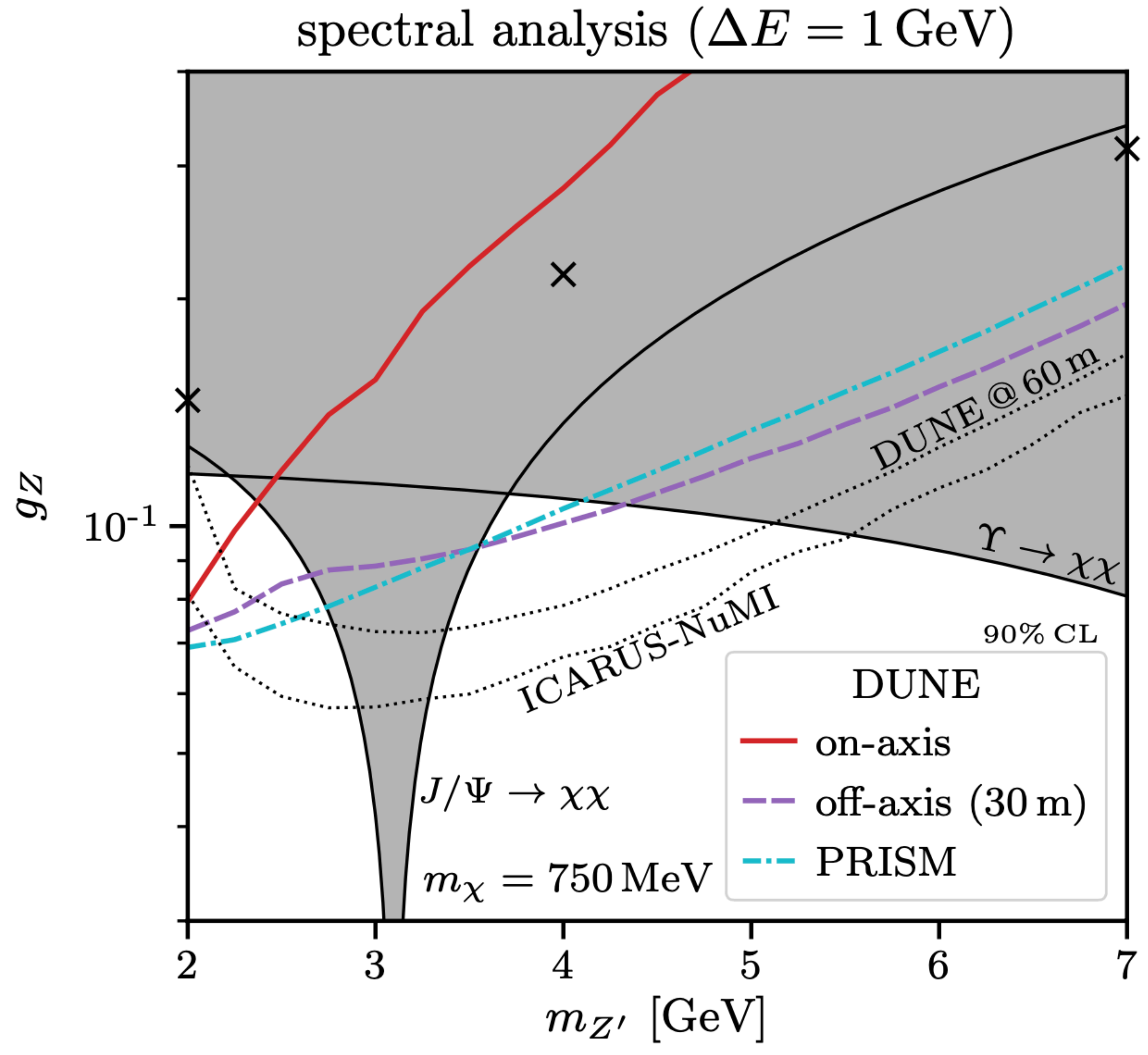


DUNE-PRISM

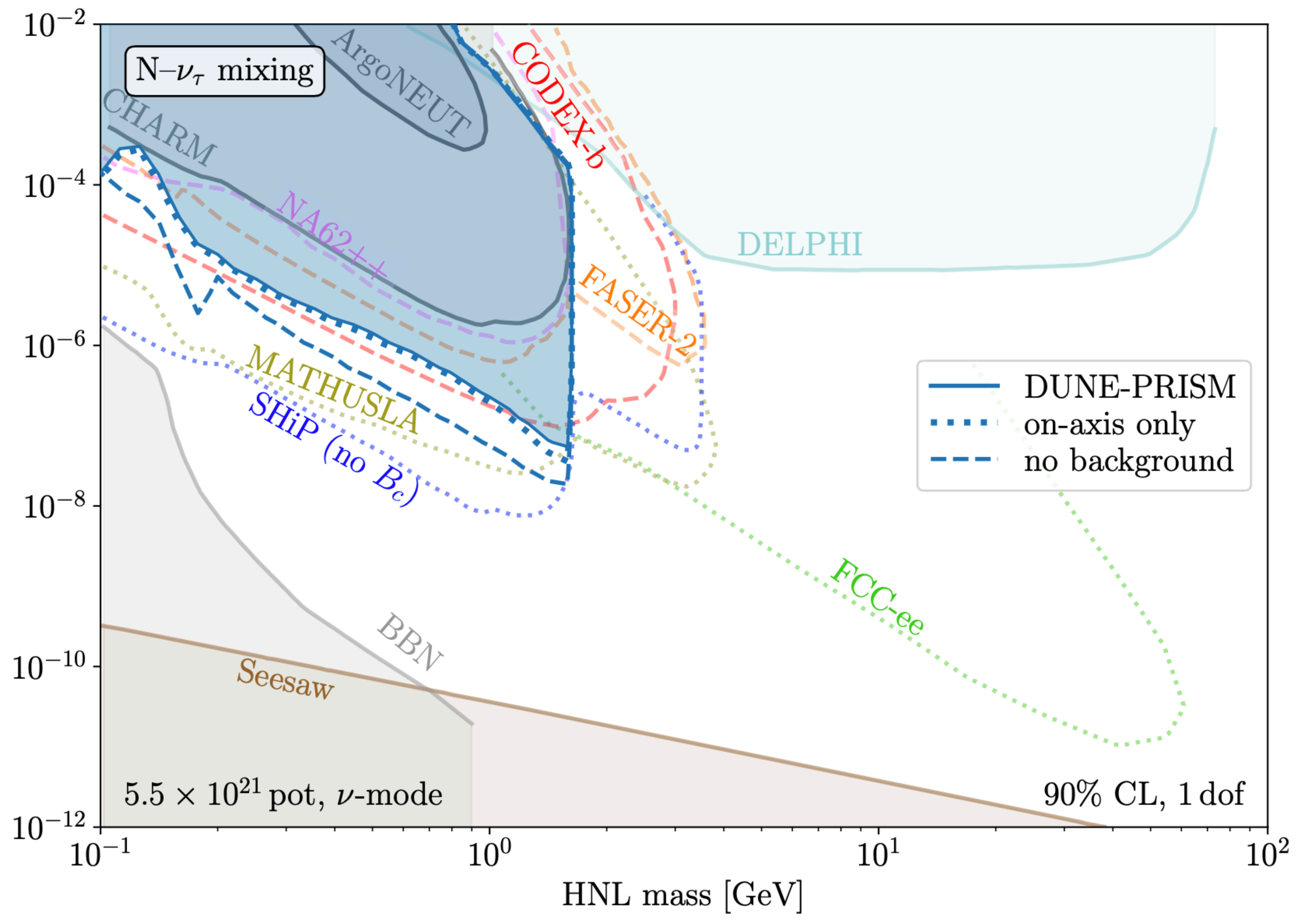
A'-mediated DM



leptophobic DM

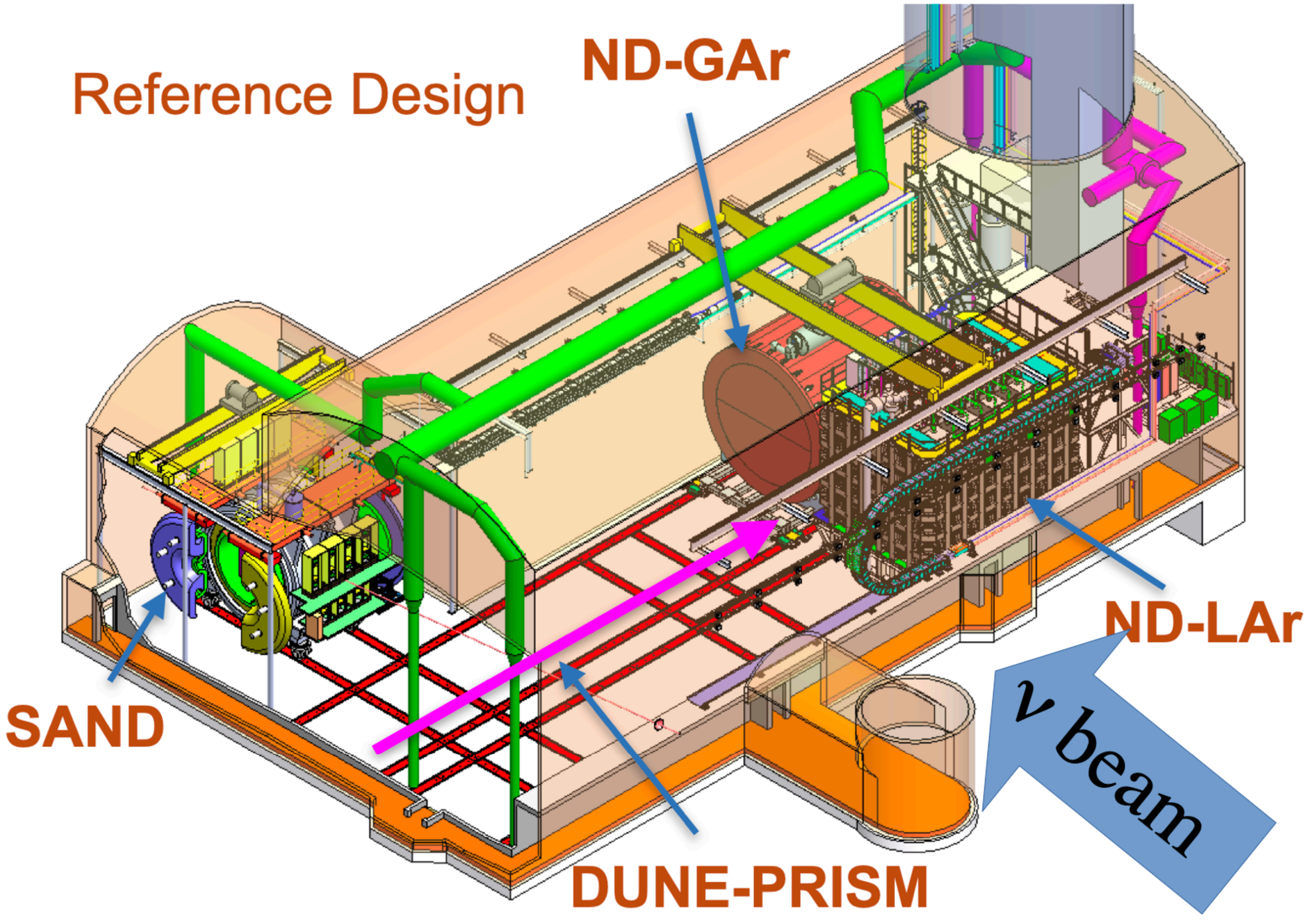


heavy neutral leptons



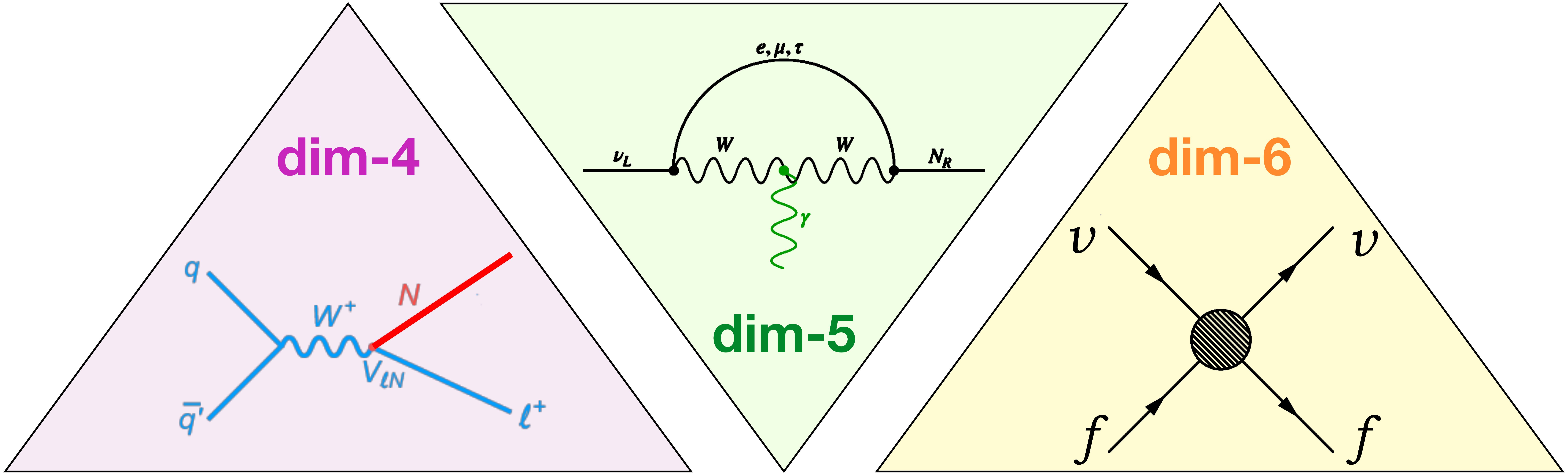
DUNE-PRISM

- Movable near detectors measure event rates at different off-axis angles
  ➠ disentangle flux and x-sec uncertainties
- Interesting opportunities for BSM searches
  - heavy particle less boosted
  - backgrounds lower off-axis
- BSM searches are typically robust w.r.t. running strategy



Neutrino Physics Beyond the Standard Model

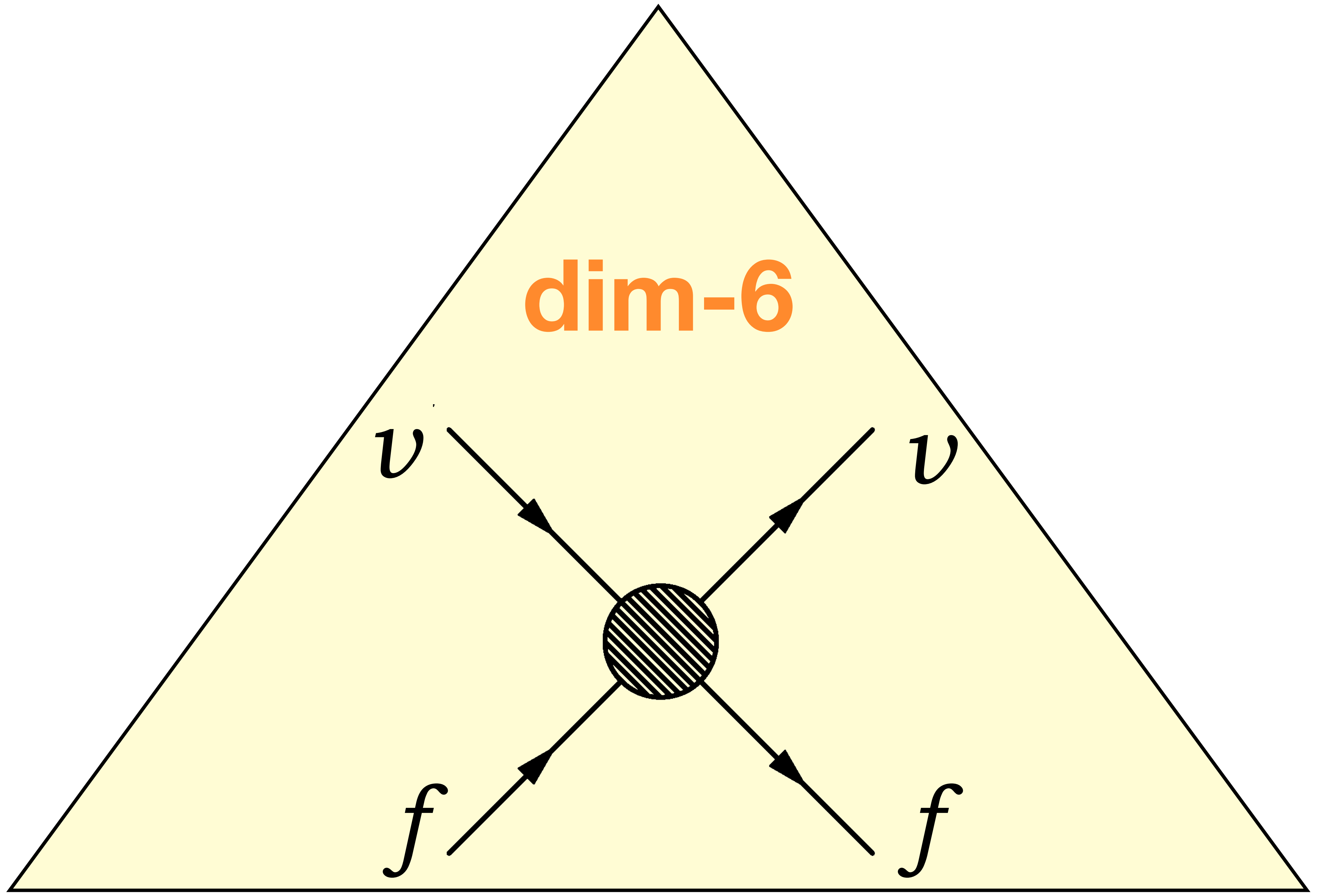
e.g. neutrino magnetic moments



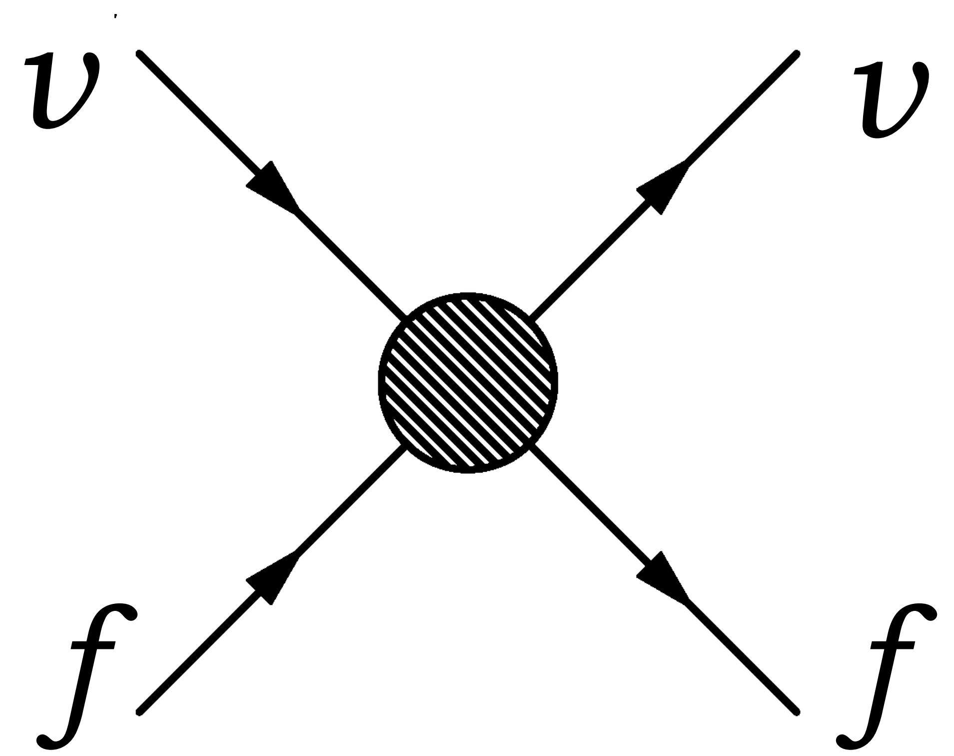
e.g. sterile neutrinos

e.g. non-standard interactions

Effective Field Theories for Neutrinos

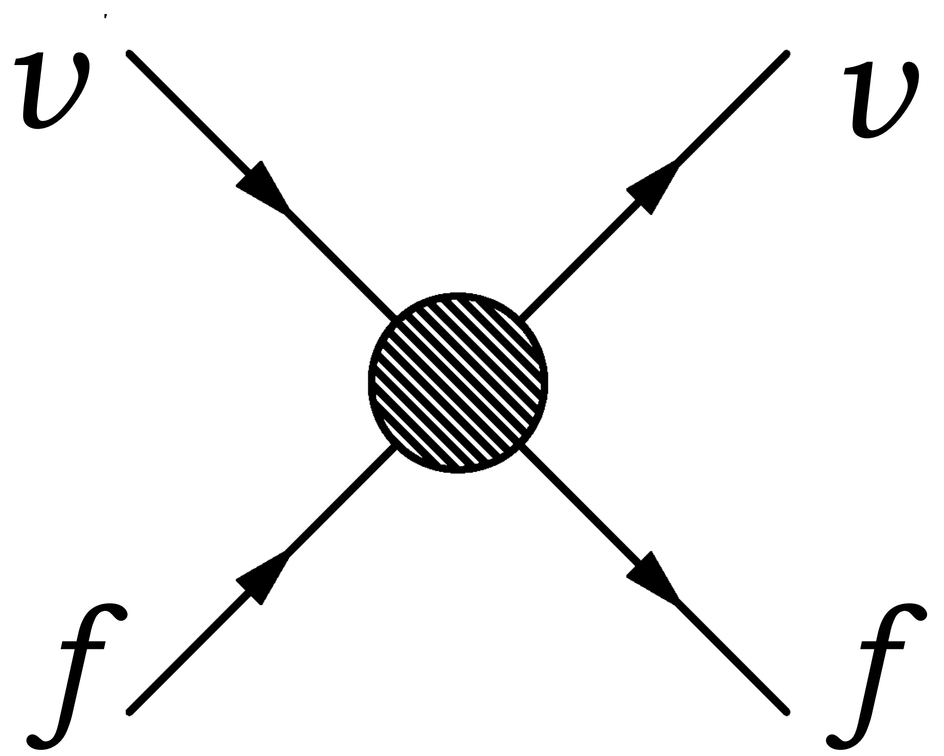


Effective Field Theories for Neutrinos



$$\mathcal{L}_{\text{WEFT}} \supset -\frac{2V_{ud}}{v^2}\Big\{[\mathbf{1}+\epsilon_L]_{\alpha\beta}(\bar{q}_u\gamma^\mu P_L q_d)(\bar{\ell}_\alpha\gamma_\mu P_L\nu_\beta) + [\epsilon_R]_{\alpha\beta}(\bar{q}_u\gamma^\mu P_R q_d)(\bar{\ell}_\alpha\gamma_\mu P_L\nu_\beta)$$
$$+ \frac{1}{2}[\epsilon_S]_{\alpha\beta}(\bar{q}_u q_d)(\bar{\ell}_\alpha P_L\nu_\beta) - \frac{1}{2}[\epsilon_P]_{\alpha\beta}(\bar{q}_u\gamma_5 q_d)(\bar{\ell}_\alpha P_L\nu_\beta)$$
$$+ \frac{1}{4}[\epsilon_T]_{\alpha\beta}(\bar{q}_u\sigma^{\mu\nu}P_L q_d)(\bar{\ell}_\alpha\sigma_{\mu\nu}P_L\nu_\beta) + \text{h.c.}\Big\}\,.$$

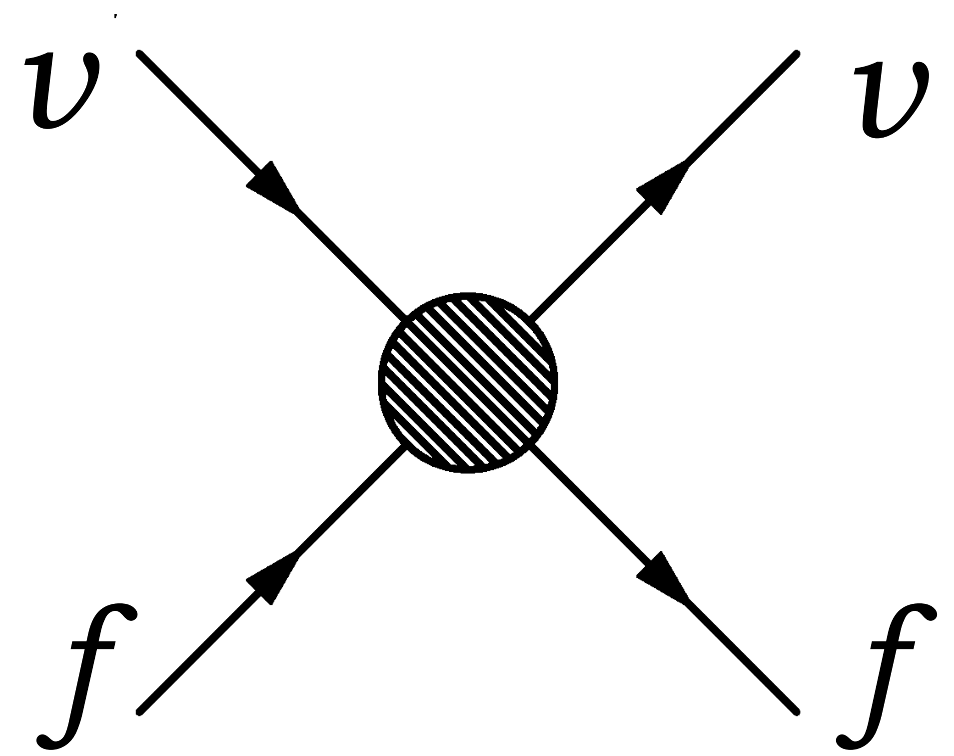
Effective Field Theories for Neutrinos



dimensionless coefficients
(interaction strength
relative to SM weak interactions)

$$\mathcal{L}_{\text{WEFT}} \supset -\frac{2V_{ud}}{v^2}\Big\{[\mathbf{1}+\epsilon_L]_{\alpha\beta}(\bar{q}_u\gamma^\mu P_L q_d)(\bar{\ell}_\alpha\gamma_\mu P_L\nu_\beta) + [\epsilon_R]_{\alpha\beta}(\bar{q}_u\gamma^\mu P_R q_d)(\bar{\ell}_\alpha\gamma_\mu P_L\nu_\beta)$$
$$+\frac{1}{2}[\epsilon_S]_{\alpha\beta}(\bar{q}_u q_d)(\bar{\ell}_\alpha P_L\nu_\beta) - \frac{1}{2}[\epsilon_P]_{\alpha\beta}(\bar{q}_u\gamma_5 q_d)(\bar{\ell}_\alpha P_L\nu_\beta)$$
$$+\frac{1}{4}[\epsilon_T]_{\alpha\beta}(\bar{q}_u\sigma^{\mu\nu}P_L q_d)(\bar{\ell}_\alpha\sigma_{\mu\nu}P_L\nu_\beta) + \text{h.c.}\Big\}.$$

Effective Field Theories for Neutrinos



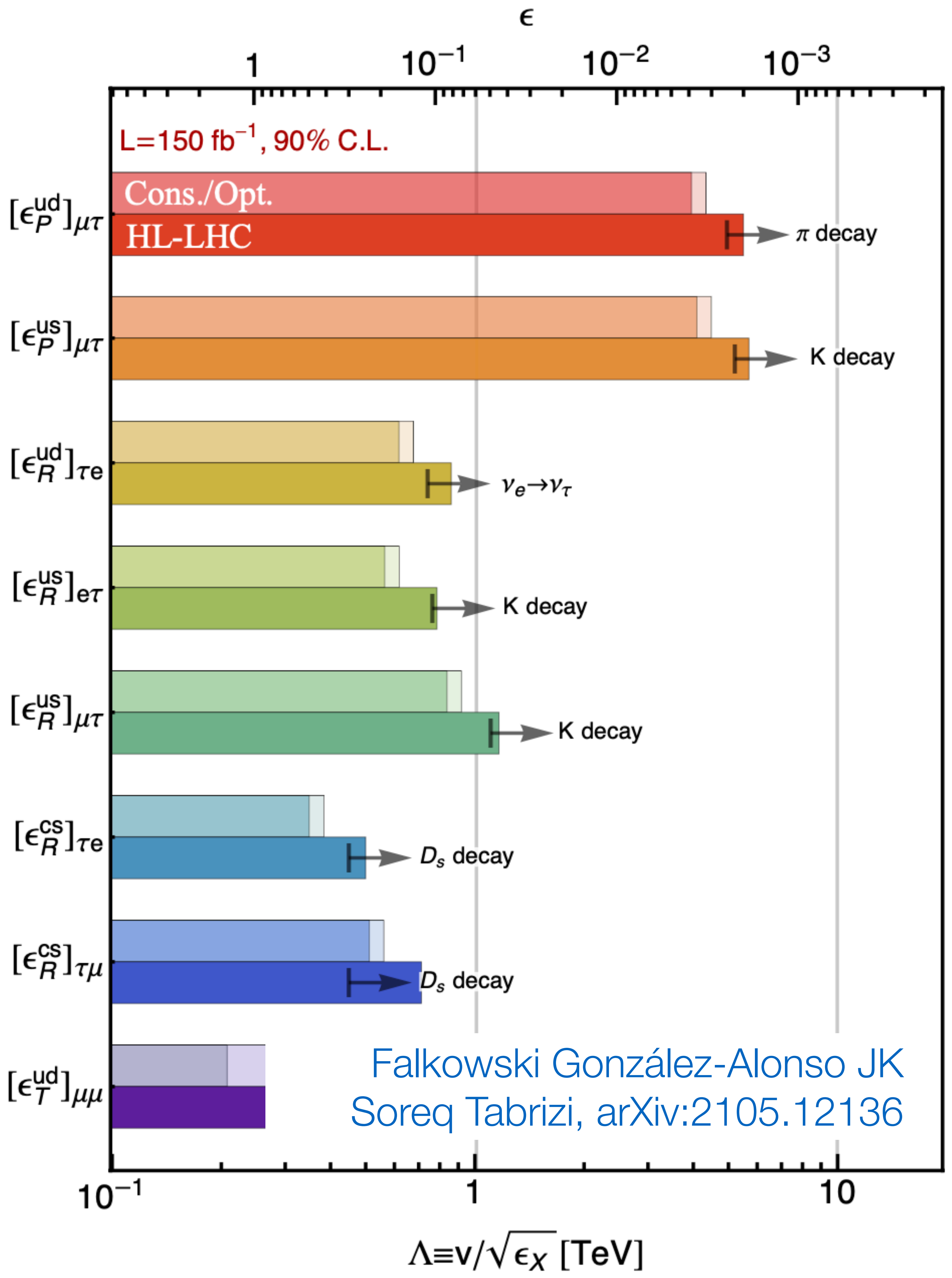
dimensionless coefficients
(interaction strength
relative to SM weak interactions)

$$\mathcal{L}_{\text{WEFT}} \supset -\frac{2V_{ud}}{v^2}\Big\{[\mathbf{1}+\epsilon_L]_{\alpha\beta}(\bar{q}_u\gamma^\mu P_L q_d)(\bar{\ell}_\alpha\gamma_\mu P_L\nu_\beta) + [\epsilon_R]_{\alpha\beta}(\bar{q}_u\gamma^\mu P_R q_d)(\bar{\ell}_\alpha\gamma_\mu P_L\nu_\beta)$$
$$+\frac{1}{2}[\epsilon_S]_{\alpha\beta}(\bar{q}_u q_d)(\bar{\ell}_\alpha P_L\nu_\beta) - \frac{1}{2}[\epsilon_P]_{\alpha\beta}(\bar{q}_u\gamma_5 q_d)(\bar{\ell}_\alpha P_L\nu_\beta)$$
$$+\frac{1}{4}[\epsilon_T]_{\alpha\beta}(\bar{q}_u\sigma^{\mu\nu}P_L q_d)(\bar{\ell}_\alpha\sigma_{\mu\nu}P_L\nu_\beta) + \text{h.c.}\Big\}.$$

dim-6 operators
with different Lorentz structures

New Interactions in DIS

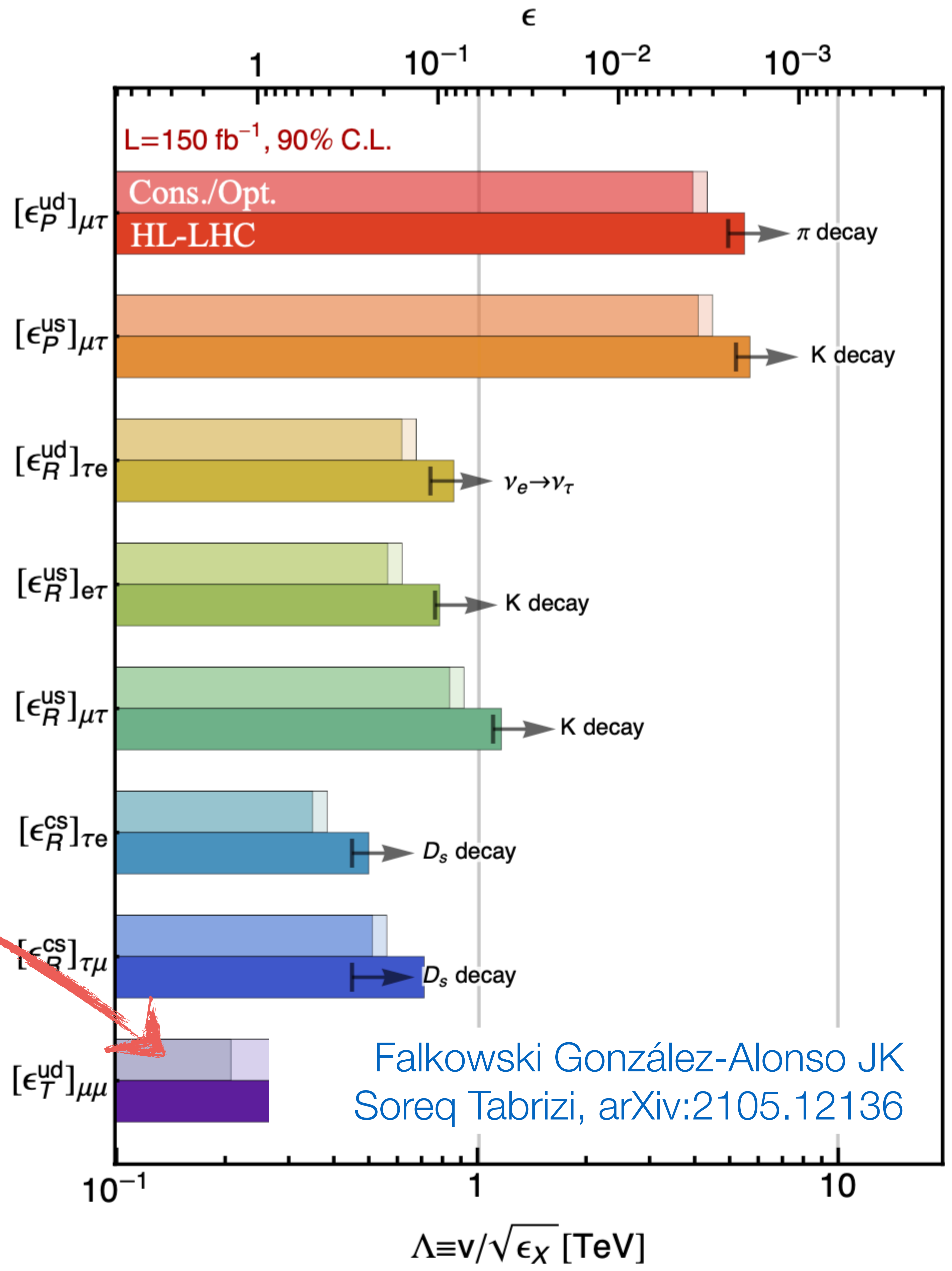
- straightforward – ν scattering described in terms of PDFs
- though flux uncertainties remain a problem



New Interactions in DIS

- straightforward – ν scattering described in terms of PDFs
- though flux uncertainties remain a problem

conservative scenario
flux uncertainties 30% / 40% / 50%
for ν_e / ν_μ / ν_τ

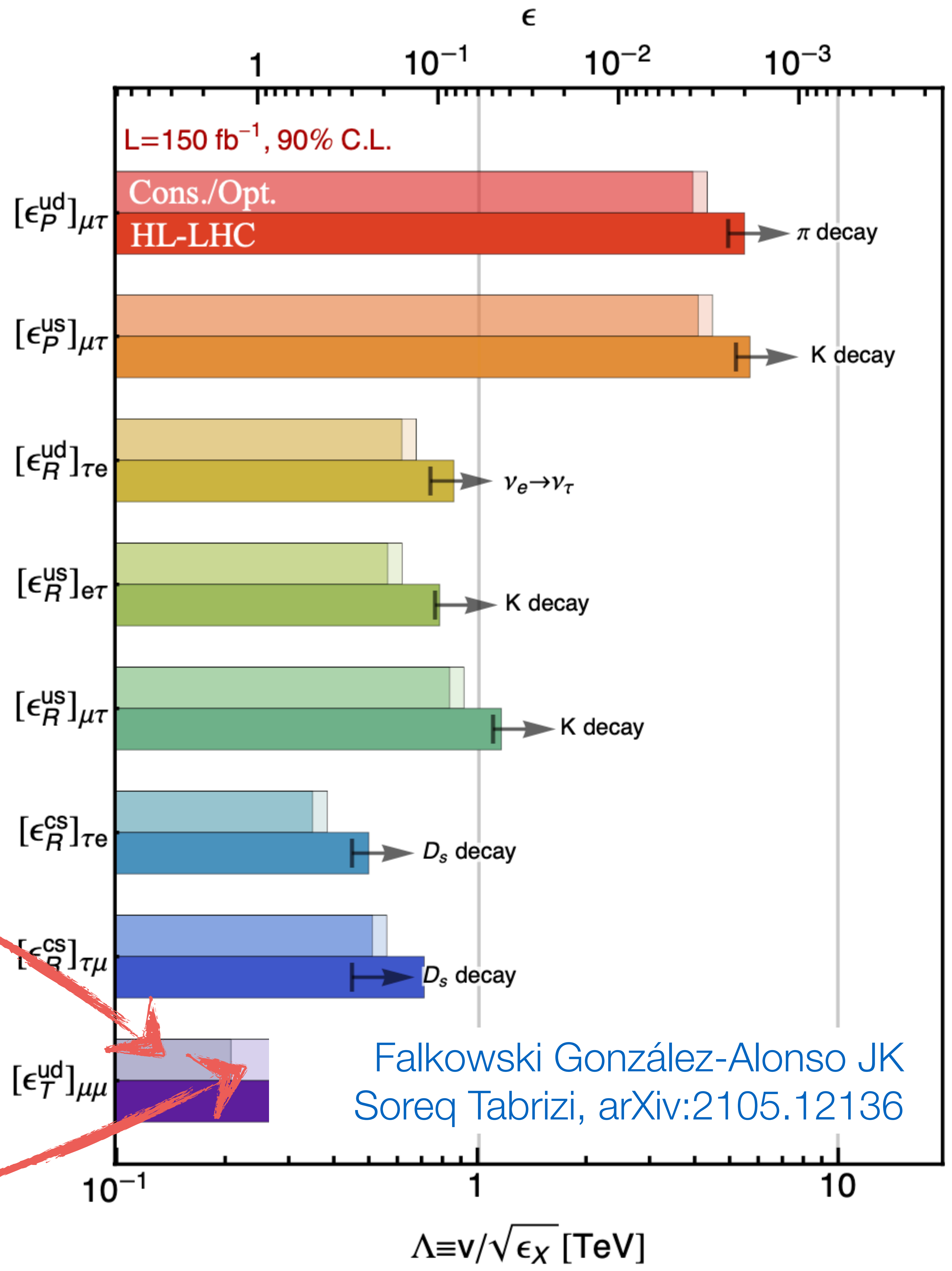


New Interactions in DIS

- straightforward – ν scattering described in terms of PDFs
- though flux uncertainties remain a problem

conservative scenario
flux uncertainties 30% / 40% / 50%
for ν_e / ν_μ / ν_τ

optimistic scenario
flux uncertainties 5% / 10% / 15%
for ν_e / ν_μ / ν_τ



Falkowski González-Alonso JK Soreq Tabrizi, arXiv:2105.12136

New Interactions in QES

- For V–A: same uncertainties as in the SM
- For other Lorentz structures: significant nucleon form factor uncertainties

$$\langle p(p_p)|\bar{q}_u\gamma_\mu q_d|n(p_n)\rangle = \bar{u}_p(p_p)\left[G_V(Q^2)\gamma_\mu + i\frac{\tilde{G}_{T(V)}(Q^2)}{2M_N}\sigma_{\mu\nu}q^\nu - \frac{\tilde{G}_S(Q^2)}{2M_N}q_\mu\right]u_n(p_n)\,,$$

$$\langle p(p_p)|\bar{q}_u\gamma_\mu\gamma_5 q_d|n(p_n)\rangle = \bar{u}_p(p_p)\left[G_A(Q^2)\gamma_\mu\gamma_5 + i\frac{\tilde{G}_{T(A)}(Q^2)}{2M_N}\sigma_{\mu\nu}q^\nu\gamma_5 - \frac{\tilde{G}_P(Q^2)}{2M_N}q_\mu\gamma_5\right]u_n(p_n)\,,$$

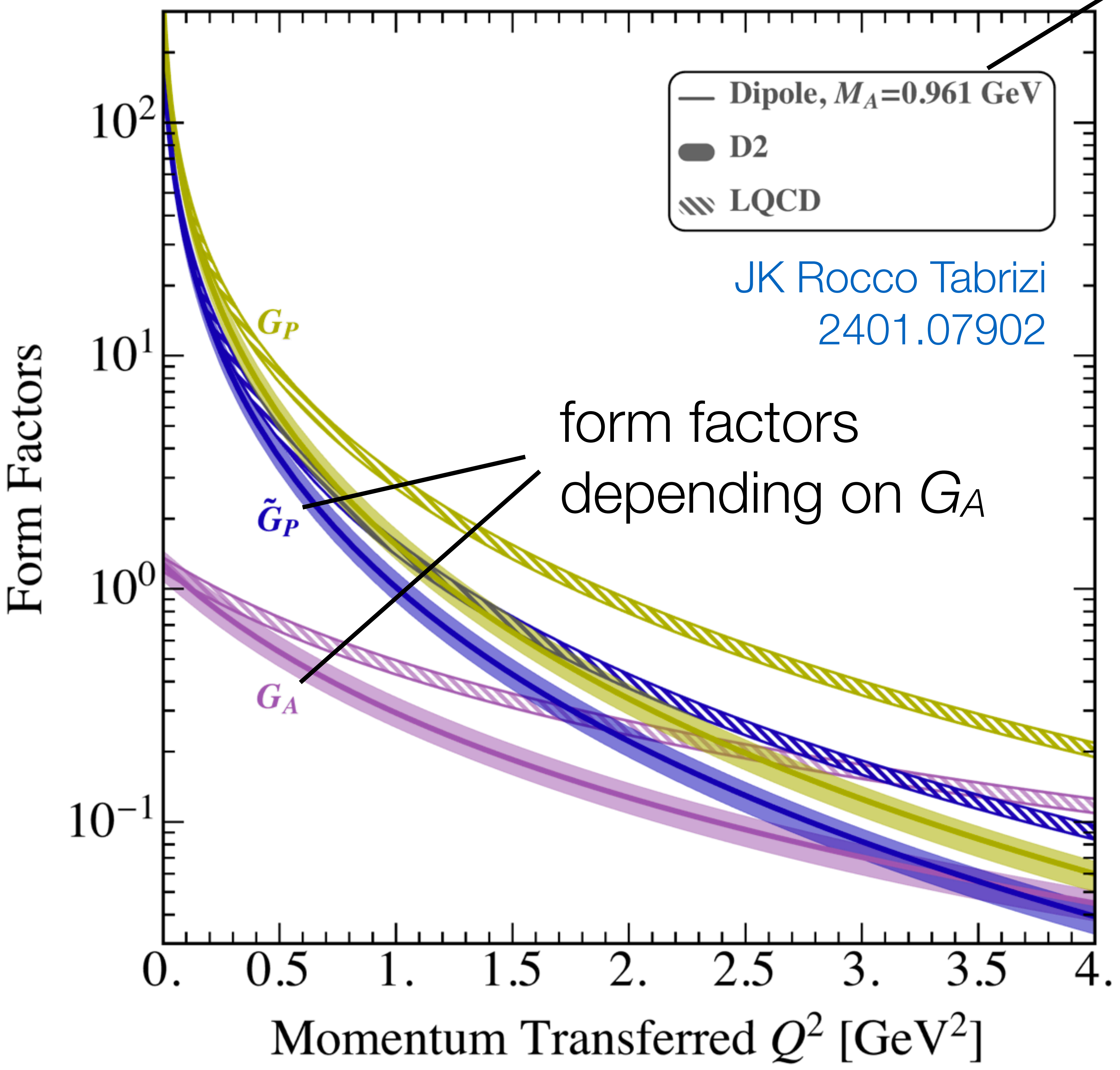
$$\langle p(p_p)|\bar{q}_u q_d|n(p_n)\rangle = G_S(Q^2)\,\bar{u}_p(p_p)u_n(p_n)\,,$$

$$\langle p(p_p)|\bar{q}_u\gamma_5 q_d|n(p_n)\rangle = G_P(Q^2)\,\bar{u}_p(p_p)\gamma_5 u_n(p_n)\,,$$

$$\langle p(p_p)|\bar{q}_u\sigma_{\mu\nu} q_d|n(p_n)\rangle = \bar{u}_p(p_p)\Big[G_T(Q^2)\sigma_{\mu\nu} - \frac{i}{M_N}G_T^{(1)}(Q^2)(q_\mu\gamma_\nu - q_\nu\gamma_\mu)$$
$$- \frac{i}{M_N^2}G_T^{(2)}(Q^2)(q_\mu P_\nu - q_\nu P_\mu) - \frac{i}{M_N}G_T^{(3)}(Q^2)(\gamma_\mu\not{q}\gamma_\nu - \gamma_\nu\not{q}\gamma_\mu)\Big]u_n(p_n)\,,$$

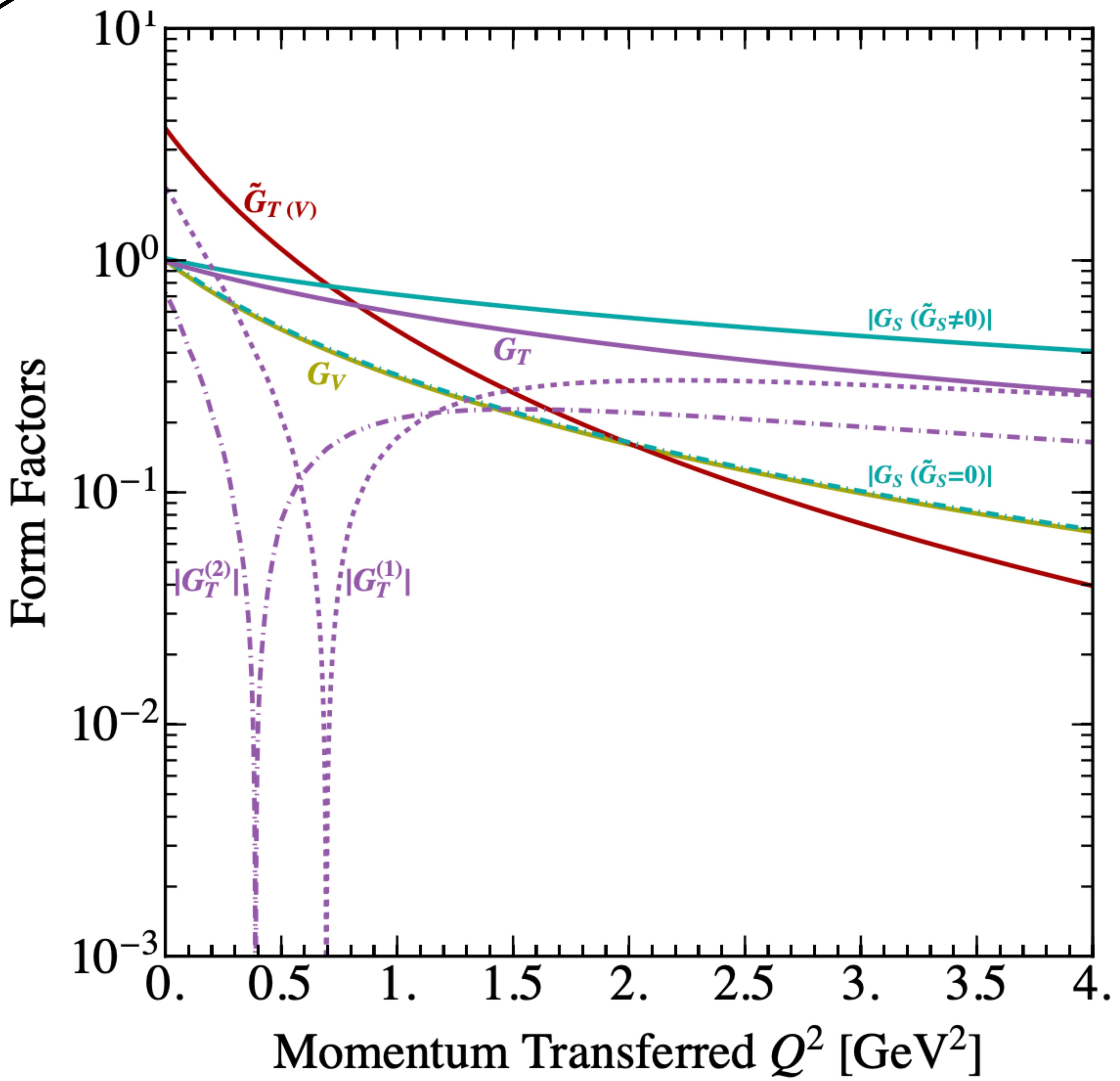
New Interactions in QES

three different estimates
for the axial form factor



JK Rocco Tabrizi
2401.07902

form factors
depending on G_A



New Interactions in QES

- in addition: nuclear effects, parameterized via a spectral function

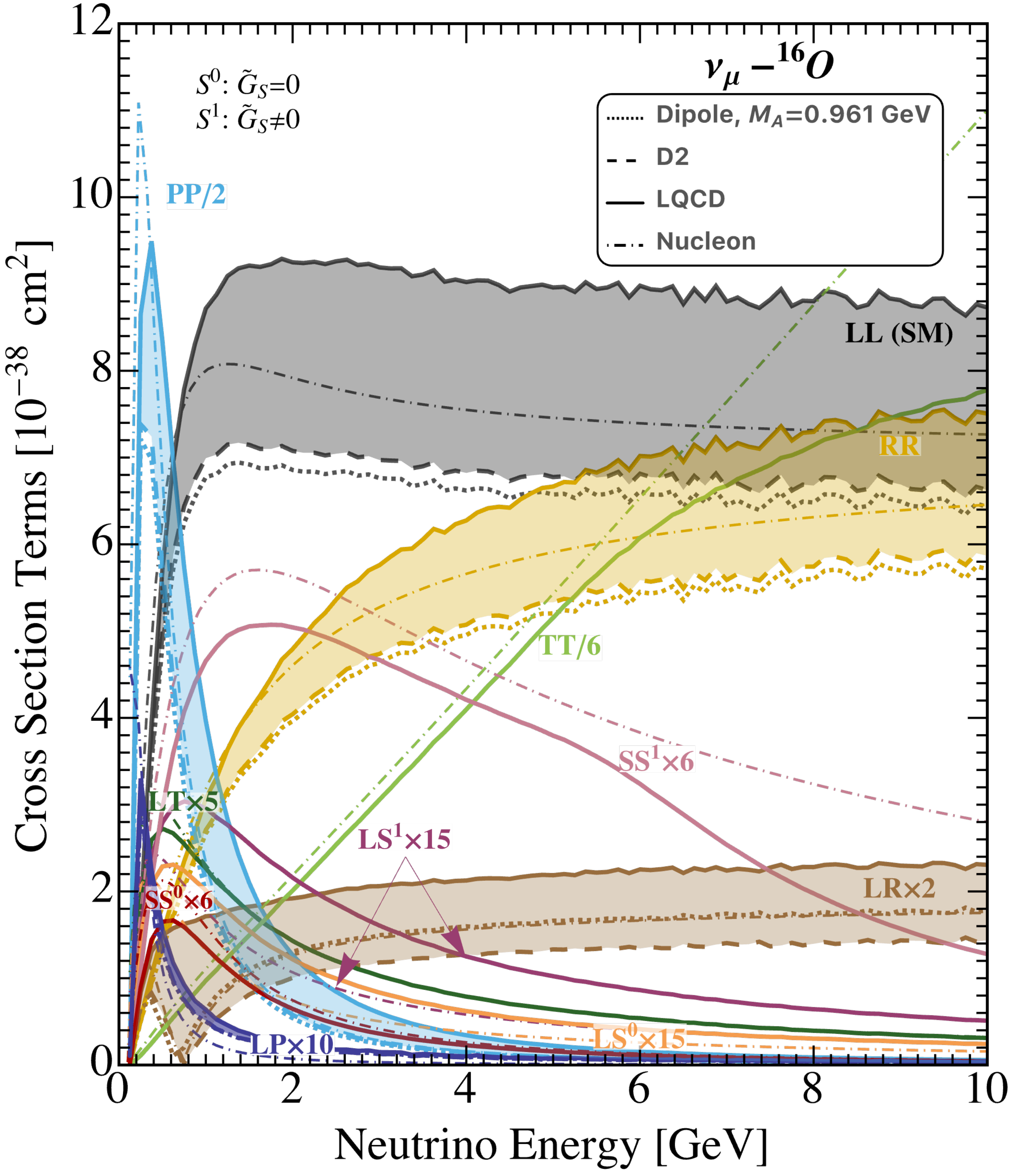
$$\frac{1}{2}\sum_{\text{spin}}\mathcal{A}_{X,\alpha}\mathcal{A}^*_{Y,\alpha} = \frac{1}{2}\int\frac{d^3p_N}{(2\pi)^3}P_h(\mathbf{p}_N,E^*)\frac{m_N}{e(\mathbf{p}_N)}\frac{m_N}{e(\mathbf{q}+\mathbf{p}_N)}$$

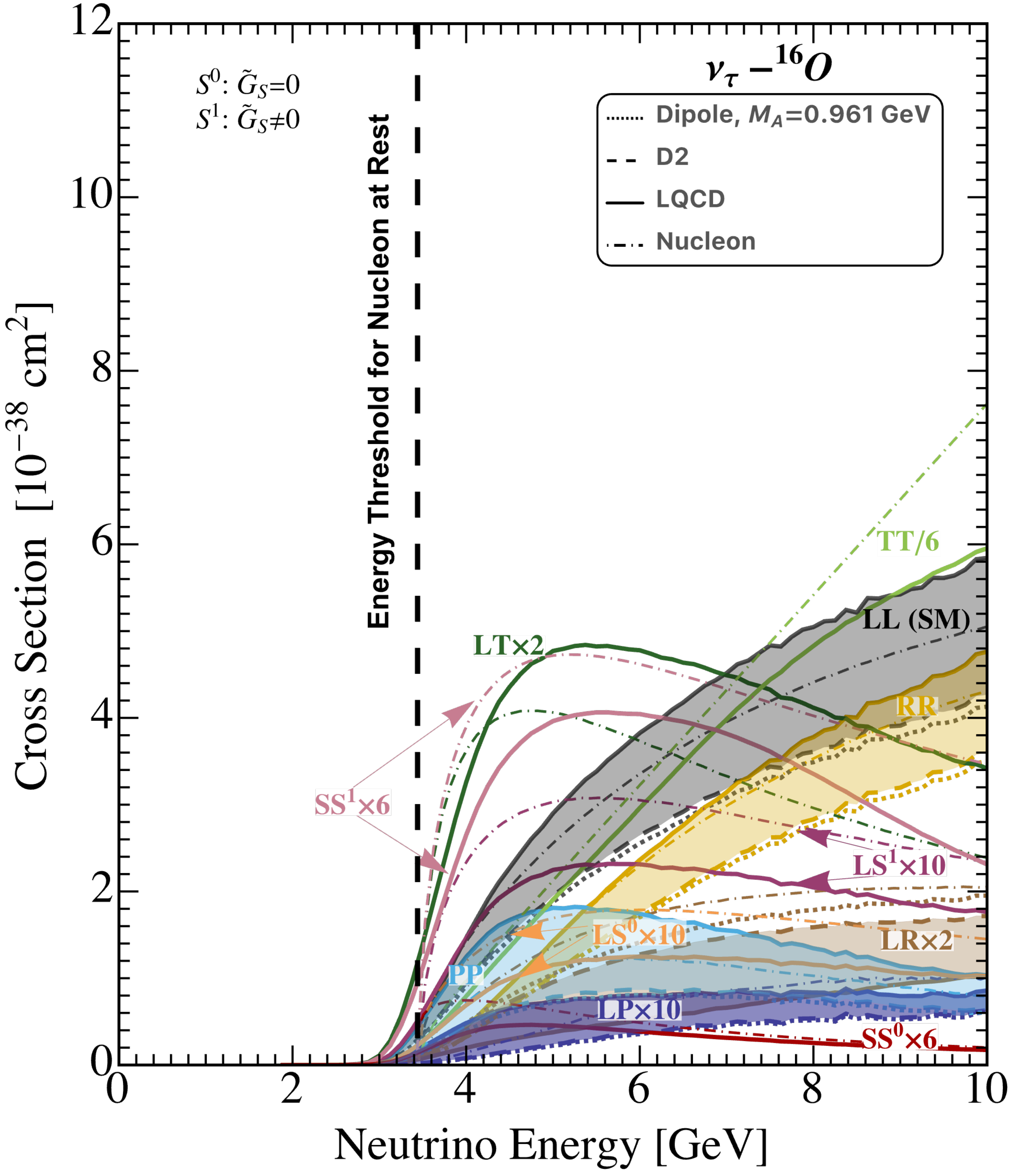
$$\times\sum_{\text{spin}}\sum_N A_{X,\alpha}A^*_{Y,\alpha}\,\delta\big(\tilde{\omega}+e(\mathbf{p}_N)-e(\mathbf{q}+\mathbf{p}_N)\big)\,,$$

- cross-section decomposed into contributions with different Lorentz structures

$$\frac{d\sigma_{\alpha\beta}}{dQ^2} = \frac{d\hat{\sigma}_{LL,\alpha}}{dQ^2}\delta_{\alpha\beta} + \sum_X\left([\epsilon_X]_{\alpha\beta}\frac{d\hat{\sigma}_{LX,\alpha}}{dQ^2}\delta_{\alpha\beta} + h.c.\right) + \sum_{X,Y,\beta}[\epsilon_X]_{\alpha\beta}[\epsilon_Y]^*_{\alpha\beta}\frac{d\hat{\sigma}_{XY,\alpha}}{dQ^2}$$

New Interactions in QES





Thank You!

CERN

Neutrino PLATFORM

JG|U JOHANNES GUTENBERG UNIVERSITÄT MAINZ

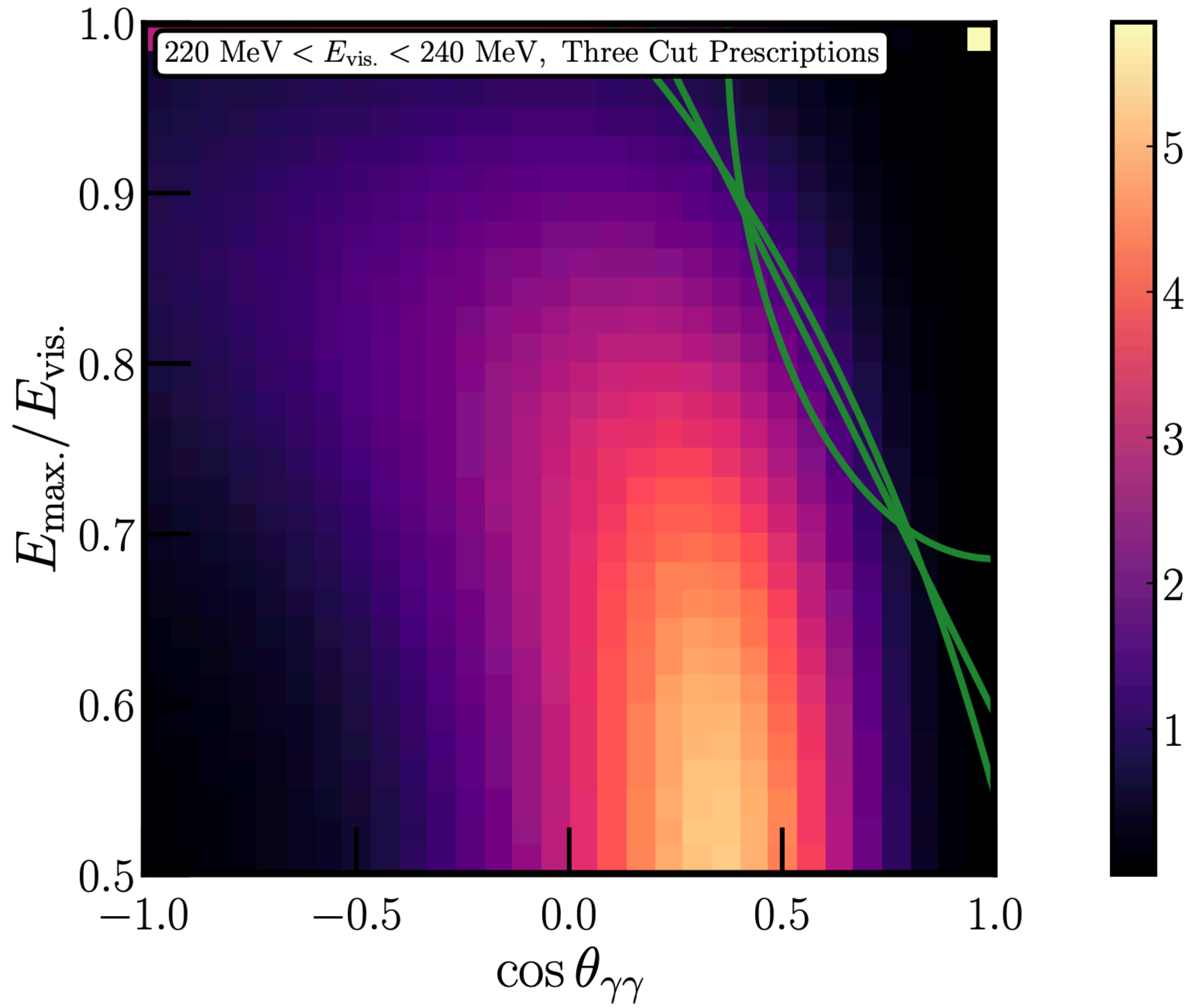
Bonus Slides

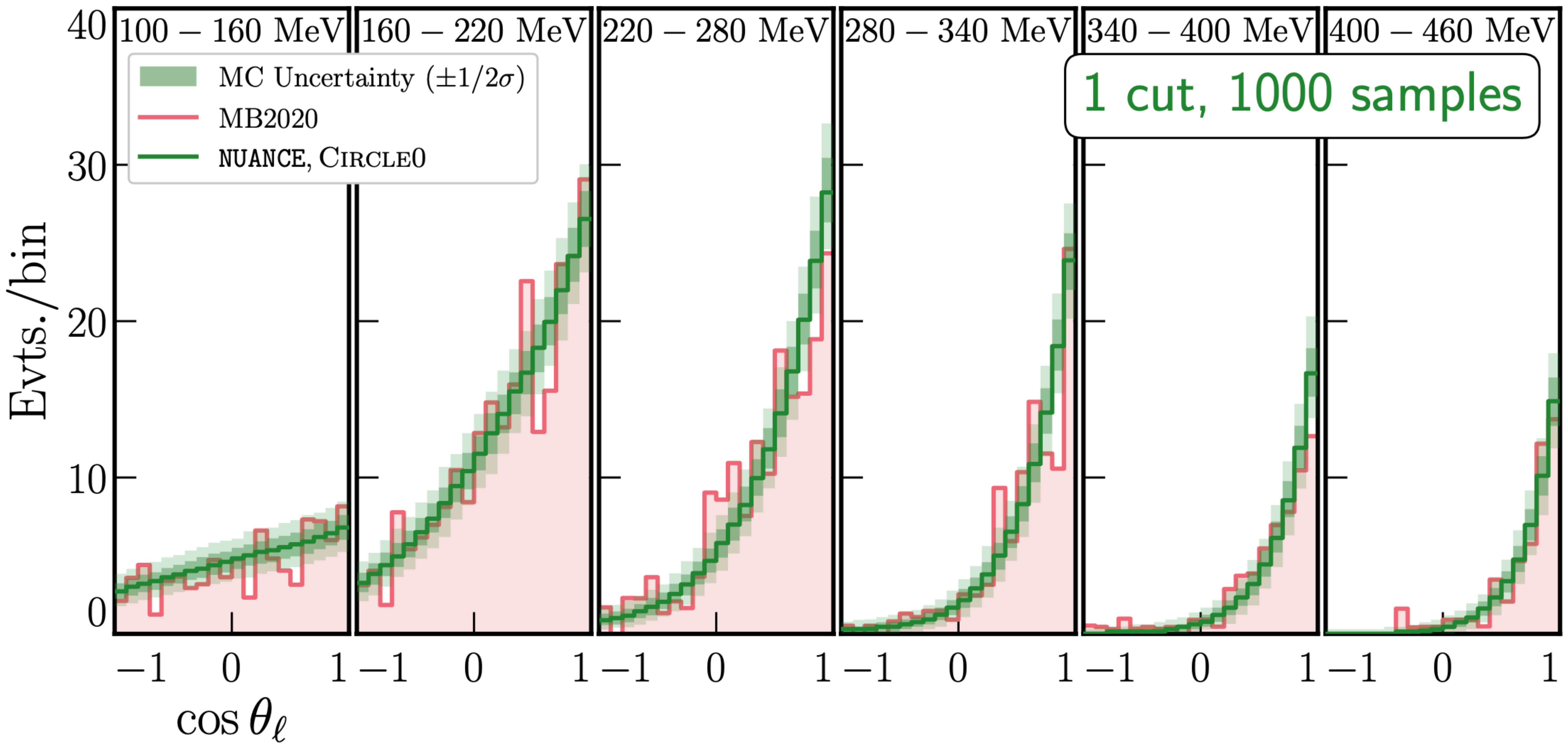
CERN

Neutrino PLATFORM

JG|U JOHANNES GUTENBERG UNIVERSITÄT MAINZ

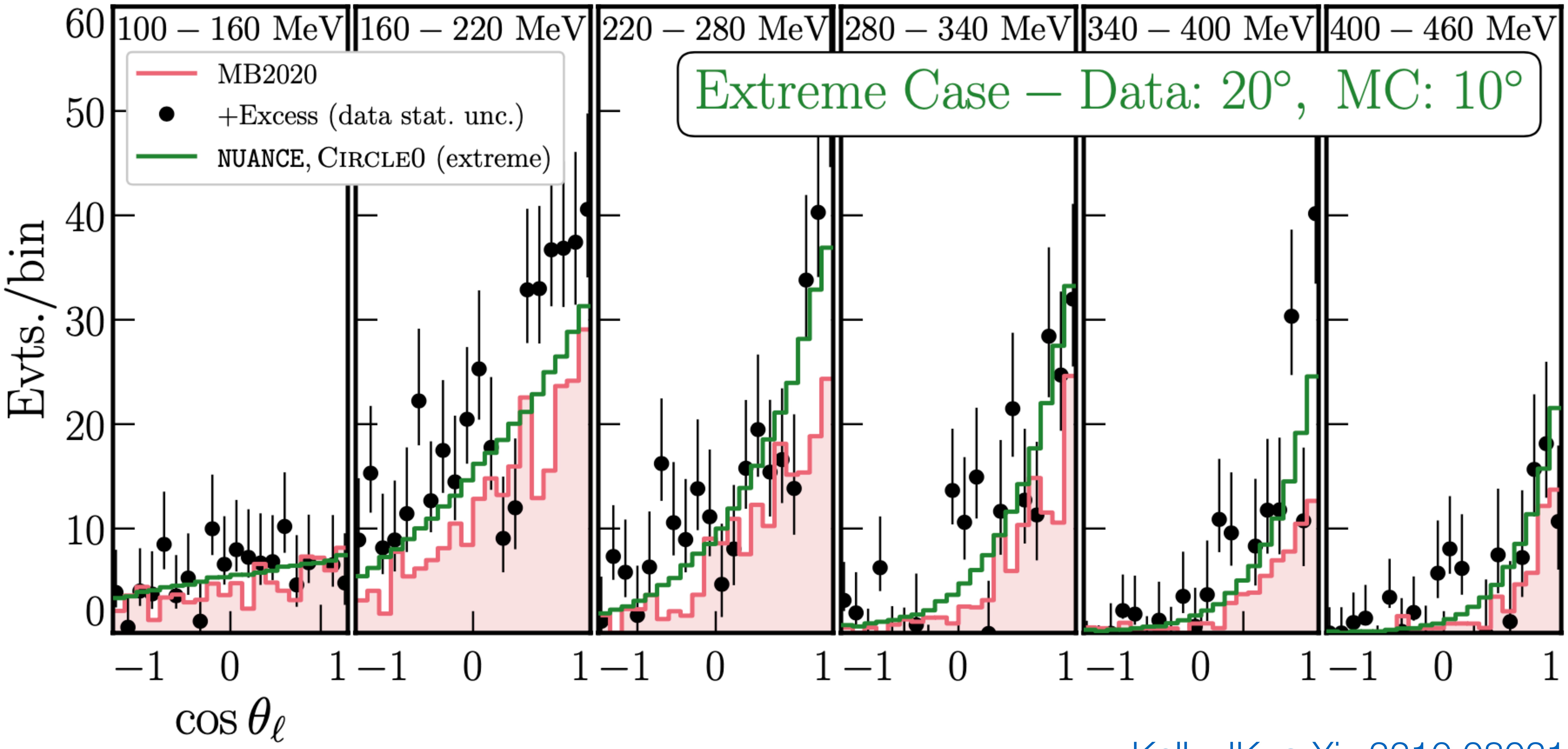
Modeling π^0 Mis-ID in MiniBooNE





Kelly JK, arXiv:2210.08021

Can mis-modeling of π^0 mis-ID explain the anomaly?



Kelly JK, arXiv:2210.08021