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Light vector bosons and the weak mixing angle in the light of new reactor-based CEνNS experiments

Manfred Lindner, Thomas Rink and Manibrata Sen

Max-Planck-Institut für Kernphysik (MPIK), Heidelberg

Light Dark World 2023 Karlsruhe
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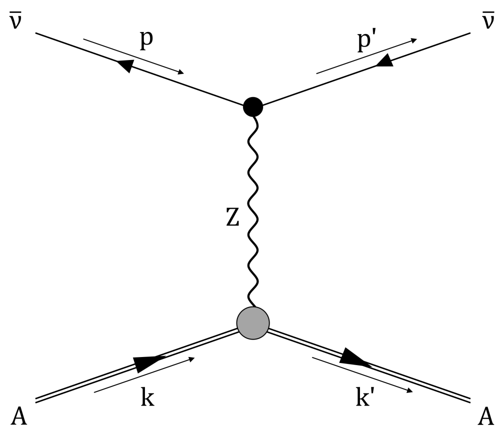
Max-Planck-Institut für Kernphysik Heidelberg

Coherent elastic neutrino-nucleus scattering (CEνNS)

CEνNS chronology:

- Daniel Freedman (1974): weak (SM) NC, flavor-blind, threshold-free!
- First detection with π-DAR ν's: COHERENT CsI (2017) & LAr (2021)
- Reactor experiments (2019 - ...):
  CONNIE (Si), CONUS (Ge), NCC-1701 (Ge), νGEN (Ge)
- Additional running and future experiments:
  CCM (Ar), Miνer (Ge/Si), NEON (NaI[Tl]), ν-cleus ($CaWO_4$, Al_2O_3),
  RED100 (Xe), Ricochet (Ge/Zn), Texono (Ge), CONUS+ (Ge)



The Channel:

- Coherence = enhancement ~ N^2

Upper limit on neutrino energy:

$$E_\nu \leq \frac{1}{2R_A} \approx \frac{197}{2.5\sqrt[3]{A}}[\mathrm{MeV}]$$

Cross section σ
vs.
nuclear recoil T_A

- Observable = nuclear recoil energy T_A

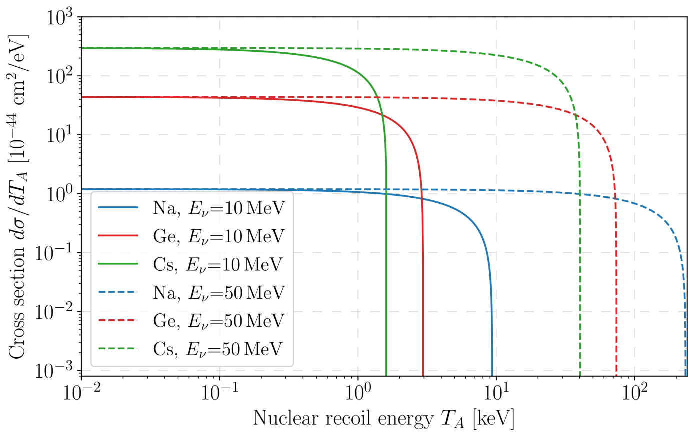
$$\frac{\mathrm{d}\sigma}{\mathrm{d}T_A} = \frac{G_F^2 m_A}{4\pi}\left[(1-4\sin^2\theta_W)Z - N\right]^2\left(1-\frac{m_A T_A}{2E_\nu^2}\right)F^2(T_A)$$

→ detector material

→ neutrino source

→ energy threshold / neutrino source

[TR, 10.11588/heidok.00031274, 2022]



- Very low energy threshold needed:
  - T_A~N^{-1}
  - Quenching: T_A → “detectable“ energy

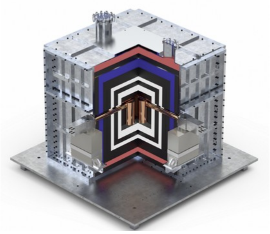
Brand-new results of the CONUS experiment!

Reactor: Brokdorf nuclear power plant

- @17 m to 3.9 GW_{th} : inside reactor building!
- Neutrino flux: $2.3 \cdot 10^{13}/cm^2/s$
- Reactor information (fuel composition, thermal power) + **data-driven reactor spectra**

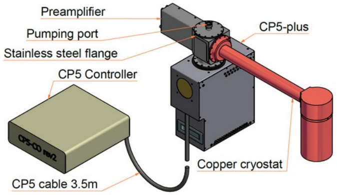
Background & shield
[Bonet et al., 10.1140/epjc/s10052-023-11240-4, 2021]

- Overburden: 10-45 m w.e.
- Active and passive components: bkg reduction x10^3-10^4
- Critical reactor-correlated bkg under control!
- Background level O(10)/keV/d/kg

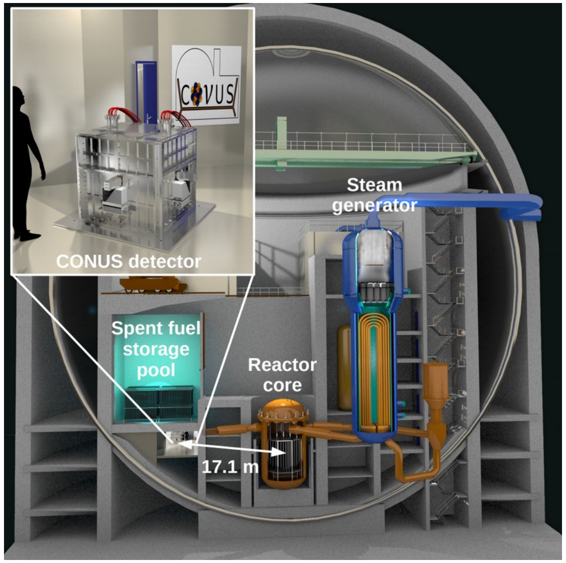


Detectors:
[Bonet et al., 10.1140/epjc/s10052-021-09038-3, 2021]

- HPGe PPC: 4*1kg
- E^{thr}~300eV → **210 eV**
- Low Bkg design
- Electric cryocooling
- **New DAQ: Pulse shape discrimination**



[Bonet et al., 10.1007/JHEP05(2022)085, 2022]



New (and last) RUN-5 data sets:

Brand-new results of the CONUS experiment!

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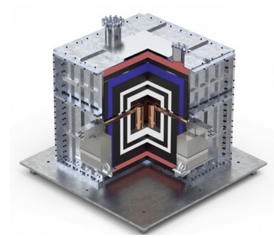

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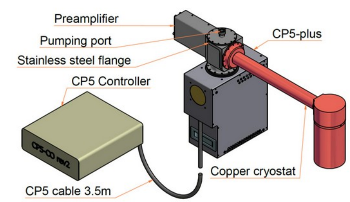
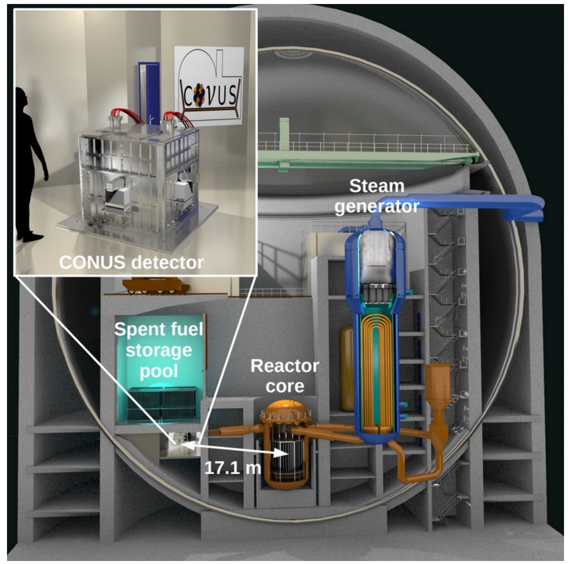


[Bonet et al., 10.1007/JHEP05(2022)085, 2022]

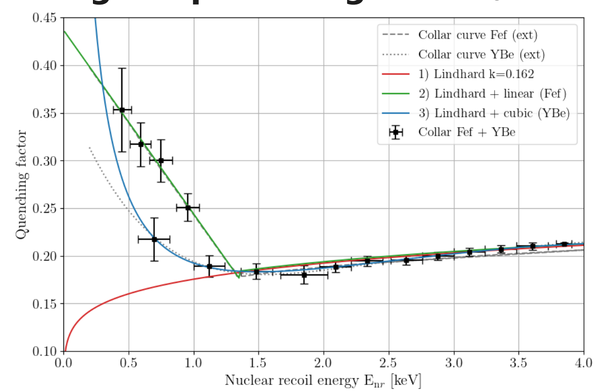


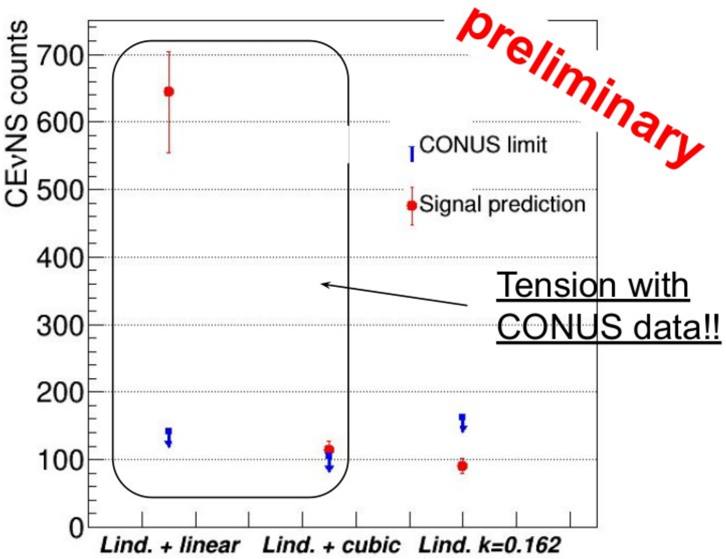
New (and last) RUN-5 data sets: ON~458 kg·d, OFF~293 kg·d

- CEνNS events < 163 events (90% C.L.)
- Factor <2 above SM prediction
- **More than one order of magnitude improvement** compared to previous analysis (2020)!
- Strongest limit on CEνNS from reactors!

Upcoming publication!

Signal quenching: T → E_{Ion}

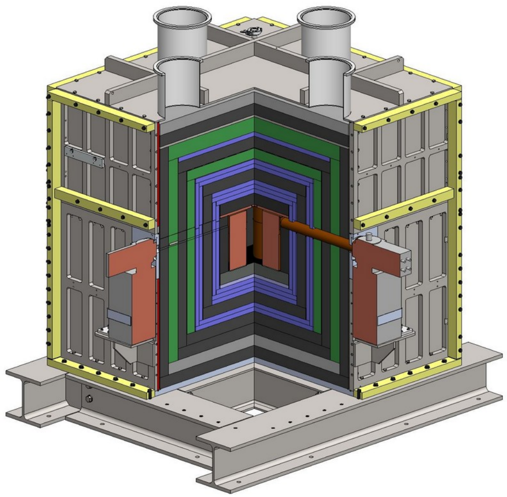




New experiment at new site: CONUS+

Aim: First CEνNS detection @ reactor-site!

- Installation in Leibstadt (Switzerland) this summer
  → **@ 20 m** distance to the 3.5 GW_{th} reactor core
- Refurbishment of existing COνUS Ge detectors
  → energy threshold **< 200 eV**!
- Increased muon rejection efficiency via additional plastic scintillator layer
- **Full background characterization** at experimental site already performed
  → array of Bonner spheres + liquid scintillator cell



Future: Results from / upgrades of NCC-1701 (Ge), νGEN (Ge) and Texono (Ge)?

The weak mixing angle at low energy

- **SM:** $SU(2)_L x U(1)_Y$ + Higgs + renormalizability:

$$\sin^2\theta_W^0 = e_0^2/g_0^2 = 1 - m_W^{0^2}/m_Z^{0^2}$$

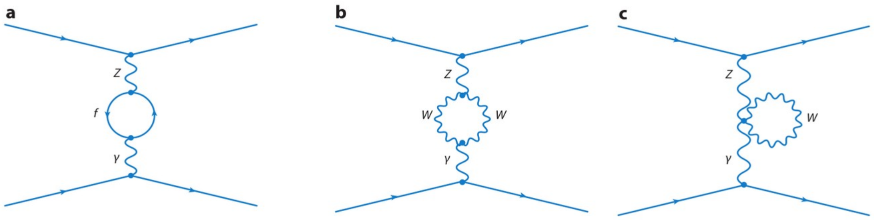
→ respected by renorm. parameters (finite corrections)

- test SM @ quantum level / probe BSM physics
  → precision of O(±0.1%) desired!

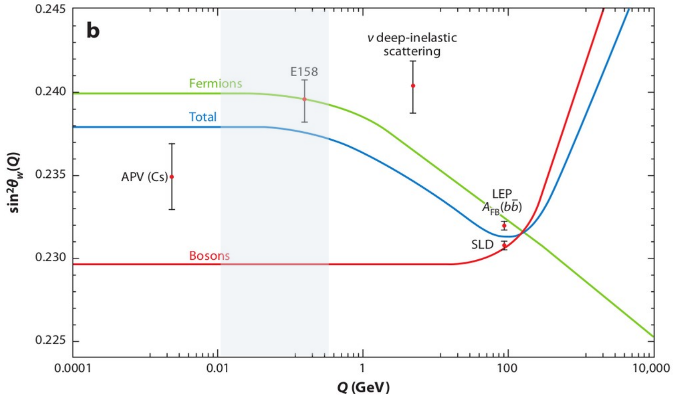
- At low energy γ-Z interference introduces small degree of parity violation
  → current experimental precision O(±1%)

- Best precision achieved at Z pole: O(±0.1%)

- **BUT** low-Q^2 measurements probe kinematic regions where Z pole measurements are insensitive to NP
  → weakly-coupled light vector boson:
  dark parity violation / dark Z'



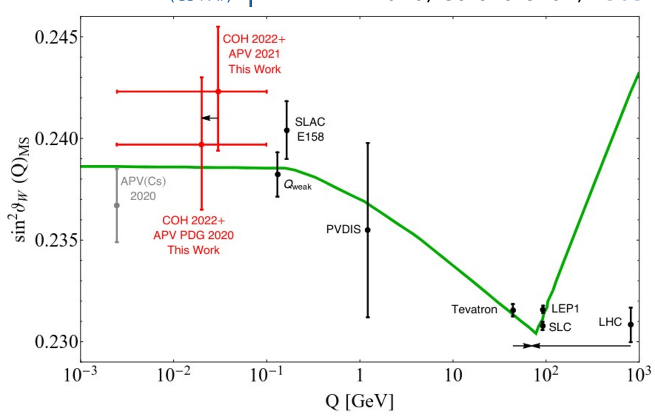
[Kumar et al., 10.1146/annurev-nucl-102212-170556, 2013]



$$\Delta \sin^2\theta_W(Q^2) \simeq -0.42\,\varepsilon\delta\,\frac{m_Z}{m_{Z_d}}\left(\frac{m_{Z_d}^2}{Q^2 + m_{Z_d}^2}\right)$$

COHERENT (Cs+Ar)

[Cadeddu et al., 10.1103/PhysRevD.102.015030, 2020; Corona et al., 2303.09360, 2023]



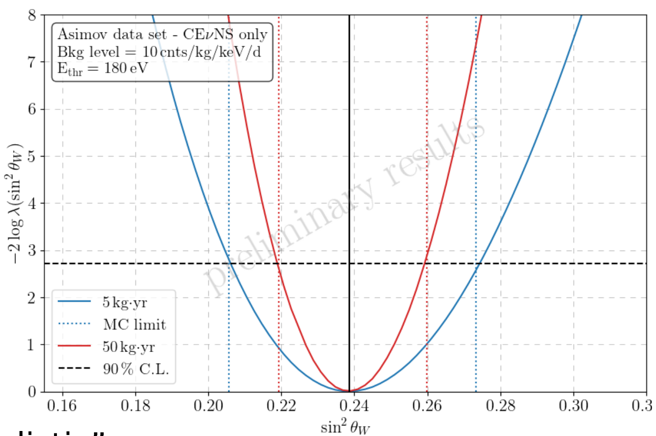
Future Weinberg angle sensitivity

$\Delta\chi^2$ contours for different mass and threshold configurations:

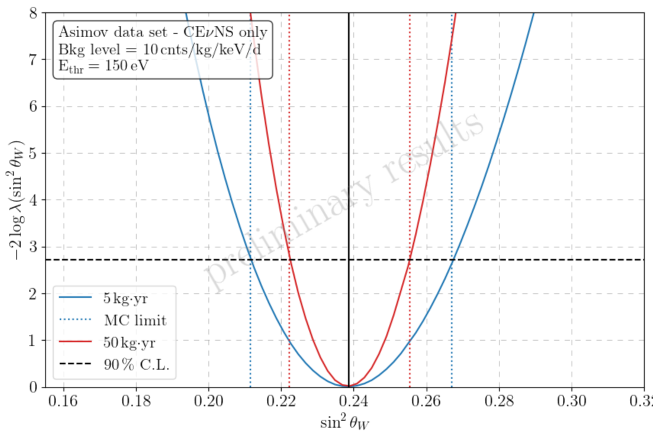
- EνeS alone is generally not competitive
- Combined analysis dominated by contributions below 1keV → CEνNS only
- Sensitivity limited by systematics: ~5% relative uncertainty

"Realistic" improvement: ~3-8% relative

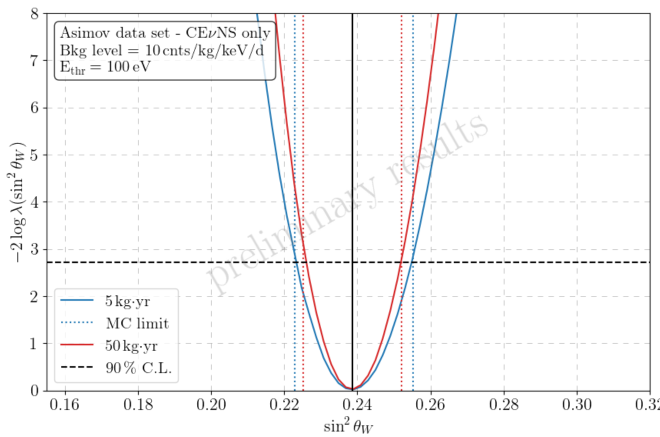
"Realistic" improvement: ~1-6% relative



Exposure	Rel. uncertainty
5 kg*yr	(-14; +15) %
50 kg*yr	(-8; +9) %



Exposure	Rel. uncertainty
5 kg*yr	(-11; +12) %
50 kg*yr	± 7 %



Exposure	Rel. uncertainty
5 kg*yr	(-6; +7) %
50 kg*yr	(-5; +6) %

Future light vector sensitivity

Simplified mediator model → contribution to CEνNS / EνeS

[Cerdeño et al., 10.1007/JHEP05(2016)118, 2016]

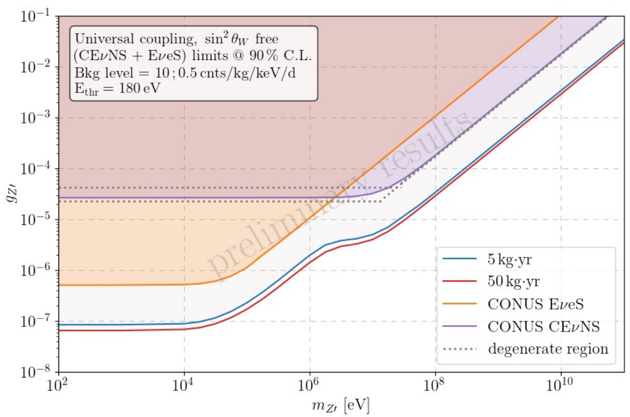
$$\mathcal{L}_{Z'} = Z'_\mu \left(g_{Z'}^{\nu V} \bar{\nu}_L \gamma^\mu \nu_L + g_{Z'}^{eV} \bar{e} \gamma^\mu e + g_{Z'}^{qV} \bar{q} \gamma^\mu q \right) + \frac{1}{2} m_{Z'}^2 Z'_\mu Z'^\mu$$

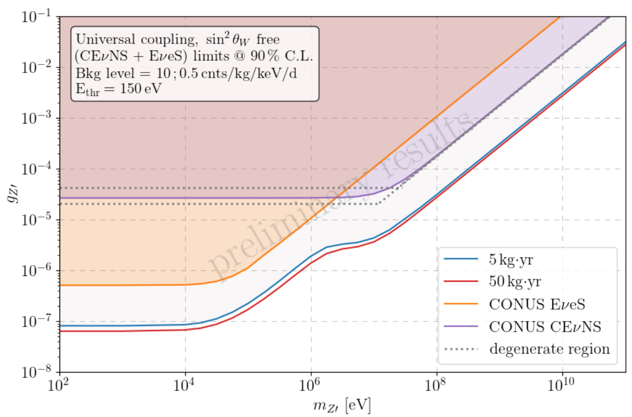
$$\frac{d\sigma}{dT} \propto \left[Q_{SM} + \frac{3 g_{Z'}^2}{\sqrt{2} G_F} \frac{Z+N}{|q|^2 + m_{Z'}^2} \right]^2$$

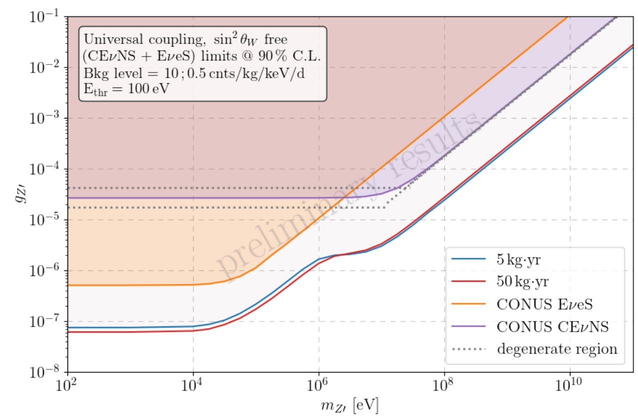
[Cadeddu et al., 10.1007/JHEP01(2021)116, 2021]

- Assume universal coupling to quarks / electron / neutrinos: $(m_{Z'}, g_{Z'})$
- EνeS more sensitive to lower mediator masses: m_e vs. m_{Ge} [Bonet et al., 10.1007/JHEP05(2022)085, 2022]
- CONUS benchmark points (keV, GeV): EνeS - (5.2·10⁻⁷, 1.1·10⁻²); CEνNS – (2.7·10⁻⁵, 1.8·10⁻³)

"Realistic" improvements: CEνNS~7-29%, EνeS~3-12%







"Real." improv.:
EνeS~18-23%
CEνNS~15%

Exposure	Limit @ keV	Limit @ GeV
5 kg*yr	8.6·10⁻⁸	3.4·10⁻⁴
50 kg*yr	6.6·10⁻⁸	2.9·10⁻⁴

Exposure	Limit @ keV	Limit @ GeV
5 kg*yr	8.2·10⁻⁸	3.1·10⁻⁴
50 kg*yr	6.4·10⁻⁸	2.7·10⁻⁴

Exposure	Limit @ keV	Limit @ GeV
5 kg*yr	7.6·10⁻⁸	2.4·10⁻⁴
50 kg*yr	6.2·10⁻⁸	2.7·10⁻⁴

Reactor neutrinos for low masses ↔ π-DAR neutrinos for higher masses

Future light vector sensitivity

THE benchmark (mediator) model → U(1)$_{B-L}$

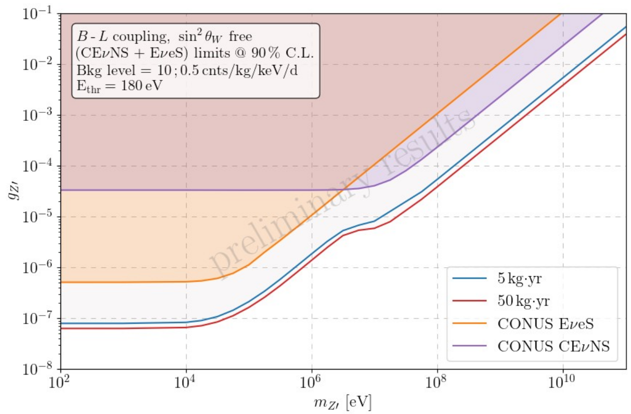
$$\mathcal{L}_{Z'} = Z'_\mu \left(g_{Z'}^{\nu V} \bar{\nu}_L \gamma^\mu \nu_L + g_{Z'}^{eV} \bar{e} \gamma^\mu e + g_{Z'}^{qV} \bar{q} \gamma^\mu q \right) + \frac{1}{2} m_{Z'}^2 Z'_\mu Z'^\mu$$

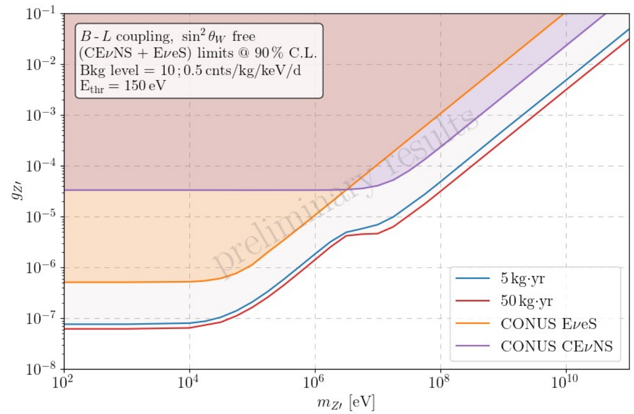
$$\frac{d\sigma}{dT} \propto \left[Q_{SM} - \frac{g_{Z'}^2}{\sqrt{2} G_F} \frac{Z+N}{|q|^2 + m_{Z'}^2} \right]^2$$

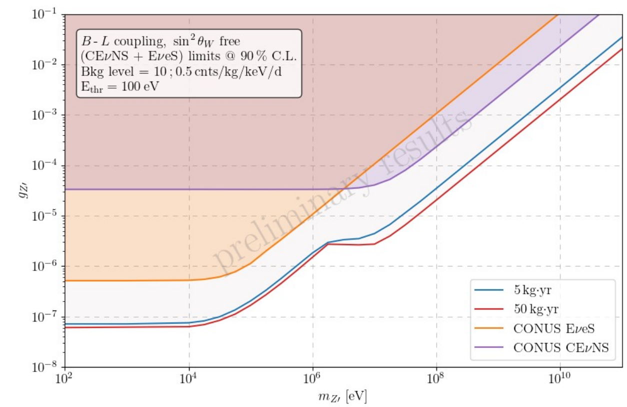
[Cadeddu et al., 10.1007/JHEP01(2021)116, 2021]

- Assume gauged B-L charge: $(m_{Z'}, g_{Z'})$
- EνeS more sensitive to lower mediator masses: m_e vs. m_{Ge}
- CONUS benchmark points (keV, GeV): EνeS - ($5.2 \cdot 10^{-7}$, $1.1 \cdot 10^{-2}$); CEνNS – ($3.3 \cdot 10^{-5}$, $2.3 \cdot 10^{-3}$)

“Realistic” improvements: CEνNS~12-35%, EνeS~2-10%







“Real.” improv.:
EνeS~15-21%
CEνNS~27-43%

Exposure	Limit @ keV	Limit @ GeV
5 kg*yr	$8.0 \cdot 10^{-8}$	$5.4 \cdot 10^{-4}$
50 kg*yr	$6.3 \cdot 10^{-8}$	$3.9 \cdot 10^{-4}$

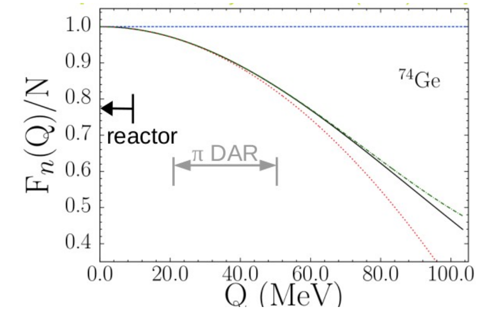
Exposure	Limit @ keV	Limit @ GeV
5 kg*yr	$7.7 \cdot 10^{-8}$	$4.8 \cdot 10^{-4}$
50 kg*yr	$6.2 \cdot 10^{-8}$	$3.1 \cdot 10^{-4}$

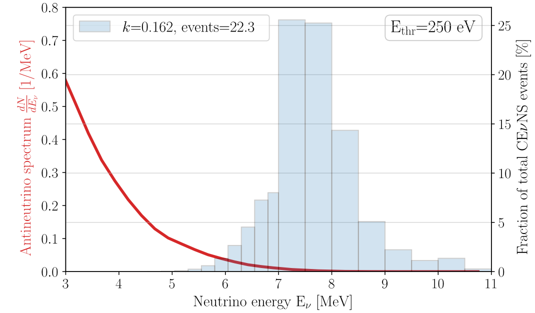
Exposure	Limit @ keV	Limit @ GeV
5 kg*yr	$7.2 \cdot 10^{-8}$	$3.5 \cdot 10^{-4}$
50 kg*yr	$6.1 \cdot 10^{-8}$	$2.0 \cdot 10^{-4}$

Reactor neutrinos for low masses ↔ π-DAR neutrinos for higher masses

Opportunities for CEνNS experiments

[Patton et al., 10.1103/PhysRevC.86.024612, 2012]





SM investigations with enhanced precision:

- **Nuclear form factors:**
  Model-independent extraction of neutron density distributions
  → Beam-reactor complementarity

- **Measuring reactor antineutrino spectrum:**
  CEνNS sensitive to all flavors of high-E part where uncertainty is largest

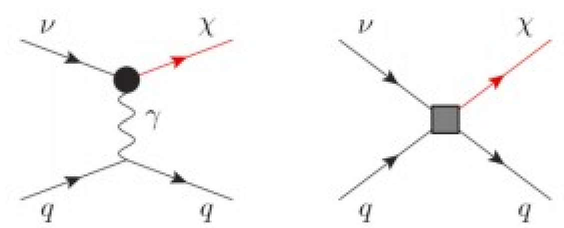
BSM investigations:

- **Light sterile neutrinos:**
  Use CEνNS for ν flux measurements

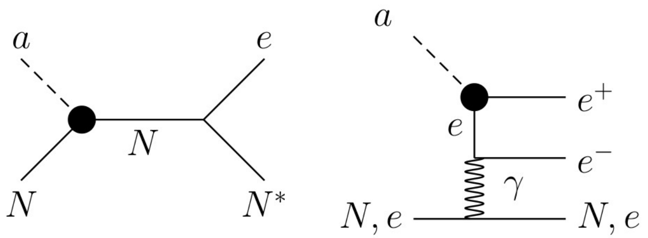
- **New fermion searches:**
  Test further ν interactions
  → ν mass, DM, ...

- **Probing portals:**
  ALPs, dark photons, etc.

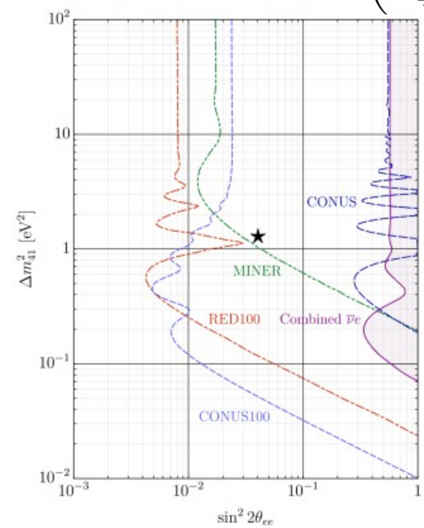
[Chang & Liao, 10.1103/PhysRevD.102.075004, 2022]



[Aristizabal Sierra et al., 10.1007/JHEP03(2021)294, 2021]

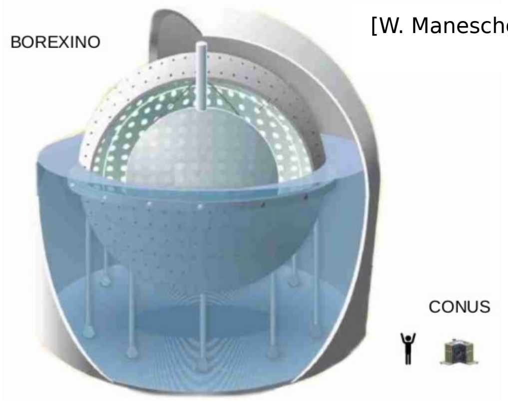


$$P_{\nu_\alpha \to \nu_\alpha} = 1 - \sin^2 2\theta_{\alpha\alpha} \sin^2\left(\frac{\Delta m^2_{41} L}{4E_\nu}\right)$$



[Berryman, 10.1103/PhysRevD.100.023540, 2019]

Conclusion



[W. Maneschg, 2019]

- **CEνNS opens new path to high-statistics neutrino physics**
  → beams and reactors go hand in hand!
  → full spectrum of modern detection technologies
  → "car-size" neutrino detectors!

- **Sensitivity for the next-gen. of Ge-based reactor experiments**
  → Weinberg angle:
    - relative uncertainty ≲10%
    - systematics become crucial!

  → Light vector bosons (universal coupling & B-L):
    - probing the next order of magnitude
    - improved threshold critical for CEνNS-dominated limit regions

Paper to appear soon!

- **CONUS RUN-5 SM results to be published soon**
  → BSM analyses are coming!

Next-generation experiments (π-DAR, reactors & DM DD!) = huge playground for phenomenology

(Neutrino magnetic moment, neutrino charge radius, vector NSI, tensor NSI, light scalars, light vectors, sterile neutrinos, dark matter, weak mixing angle, nuclear form factors, neutrino-electron-scattering, supernova neutrinos, antineutrino reactor spectra, neutrino floor, etc.)

Thank You!

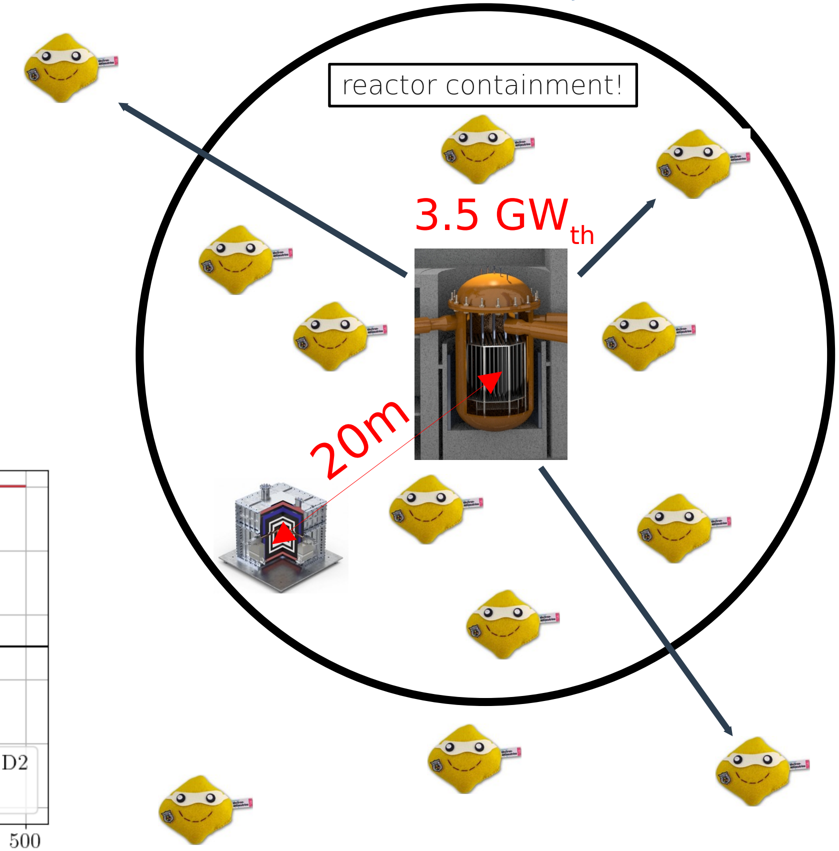
Backup

Assume a CONUS-like experiment

[Bonet et al., 10.1007/JHEP05(2022)085, 2022]

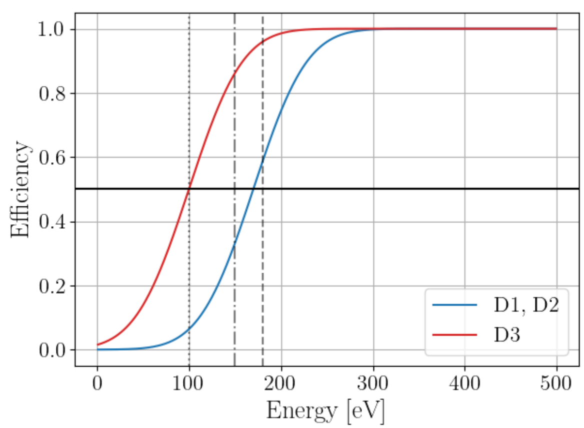
Reactor: commercial nuclear power plant

- Experimental site ~20 m to 3.5 GW_{th}
- ν flux: ~1.5 * 10^{13} /cm²/s (3% uncertainty)
- Typical PWR fuel composition:
  56.1% U235, 7.6% U238, 30.7% Pu239, 5.6% Pu241



Background

- No critical reactor-correlated bkg!
- Background levels:
  - 10 cnts/keV/d/kg for $E_{ion} \leq$ 1keV
  - 0.5 cnts/keV/d/kg for E_{ion} >1keV



[Bonhomme et al., 10.1140/epjc/s10052-022-10768-1, 2022]

Detectors:

- Data collection: t_{OFF}= 0.5 * t_{ON}:

  R1 – exp_{ON} = 5 kg*yr
  R2 – exp_{ON} = 50 kg*yr

- CONUS HPGe detectors with improved trigger efficiency:
  $\mathbf{E_{thr} \sim 3 \cdot FWHM_{pulser}}$
- Quenching according to Lindhard model (1% uncertainty)

Detector	Threshold E_{thr}
D1 (conservative)	180 eV
D2 (expected)	150 eV
D3 (optimistic)	100 eV

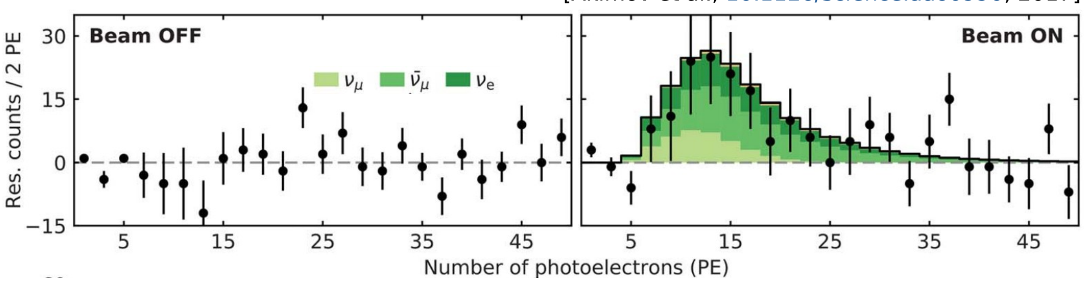
[particlezoo.net, 2023]

CEνNS observations and constraints

Observations:

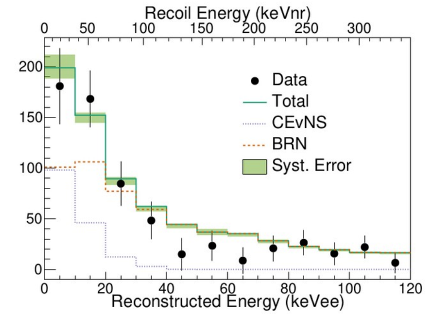
COHERENT CsI[Na] (2017): 5 * 10^{20} POT
obs. 134+-22, pred. 173+-48

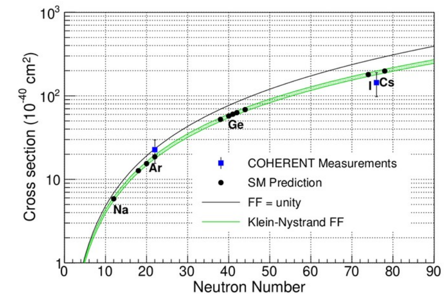
[Akimov et al., 10.1126/science.aao0990, 2017]



COHERENT LAr (2021): 13.7 * 10^{22} POT
obs. 159+-43, pred. 128+-17

[Akimov et al., 10.1103/PhysRevLett.126.012002, 2021]

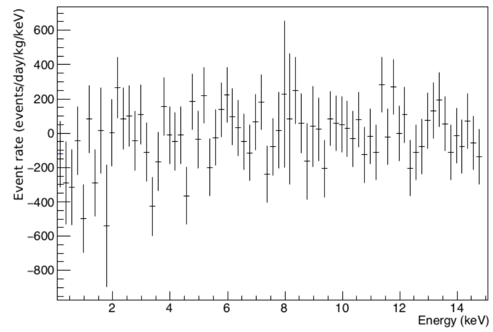




Limits:

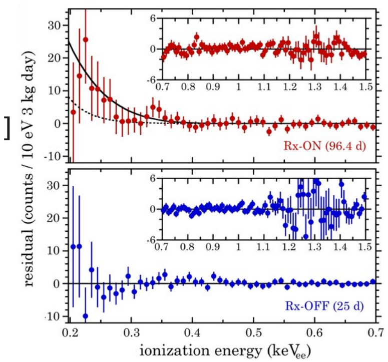
CONNIE Si (2019):
R_{NP}<40*R_{SM} *@ 95% C.L.*
2.1kg*d ON + 1.6kg*d OFF

[Aguilar-Arevalo et al., 10.1103/PhysRevD.100.092005, 2019]



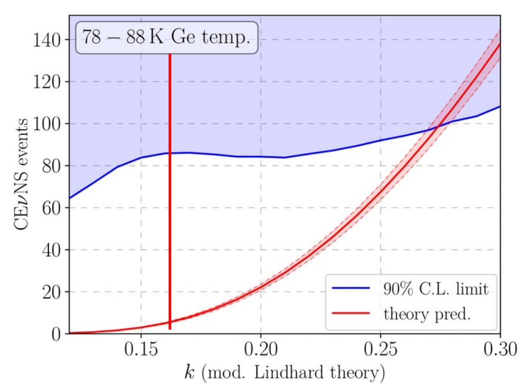
"Measurement […] Reactor Antineutrinos"
[Colaresi et al., 10.1103/PhysRevLett.129.211802 , 2022]

NCC-1701 Ge:
289kg*d ON + 75kg*d OFF



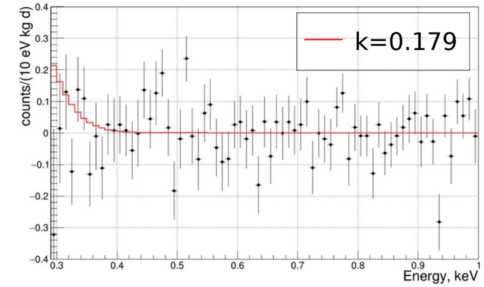
CONUS Ge (2020):
R_{SM}*<0.4/kg/d @ 90% C.L.*
(x17 lower then prediction)
249kg*d ON + 59kg*OFF

[Bonet et al., 10.1103/PhysRevLett.126.041804, 2020]



νGEN Ge (2022):
no excess,
k<0.177 @ 90% C.L.
133kg*d ON + 66kg*d OFF

[Alekseev et al., 10.1103/PhysRevD.106.L051101 , 2022]



Outlook: Future Ge detectors at reactor sites

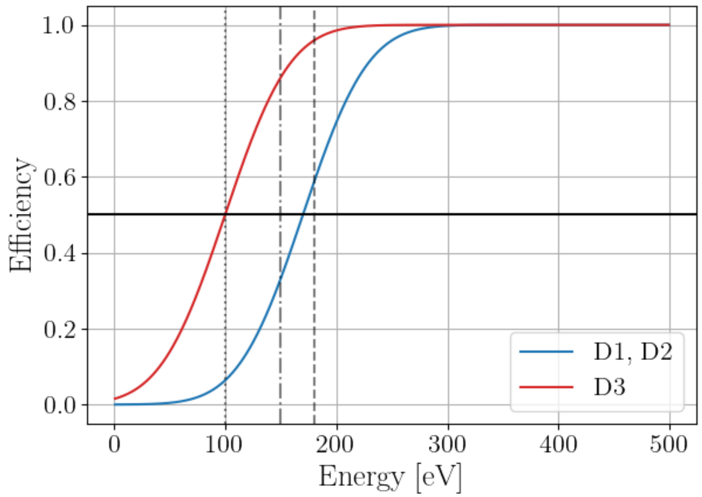
Progress for kg-size Ge detectors @ reactor sites

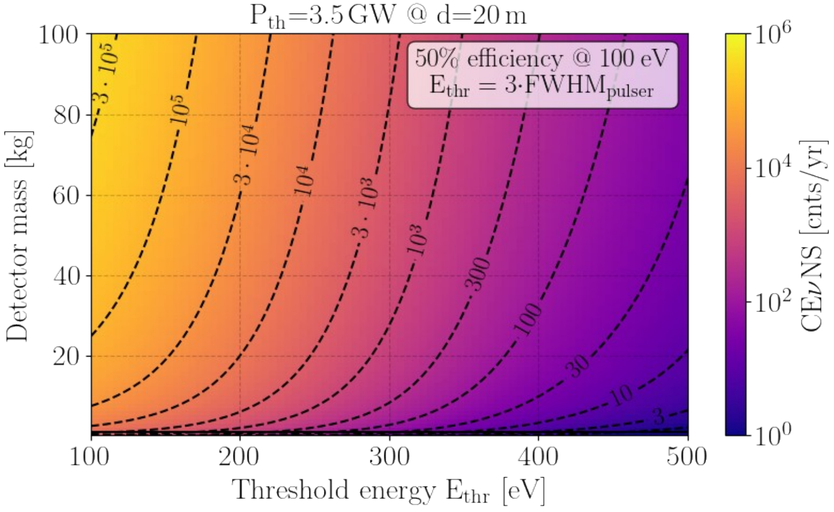
Experimental perspective (single diode):

- Improve pulser width $\text{FWHM}_{\text{pulser}}$
  → improves $E_{thr} \sim 3 \cdot \text{FWHM}_{\text{pulser}}$!
- Improve trigger efficiency
  → record more events in critical region!
- Background and environmental stability at experimental site
  → increases exposure

Theoretical perspective (whole set-up):

- Energy threshold and exposure are key for a strong CEνNS signal / BSM reach
- Trade-off between reactor flux and background
- Incorporate major uncertainties in SM and BSM studies!

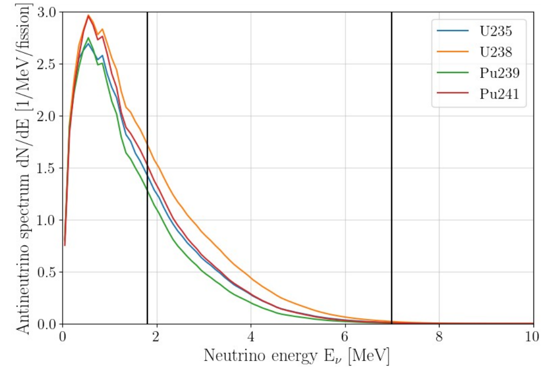




HPPC Ge detectors offer a scalable technology also in critical environments
→ energy threshold and trigger efficiency are crucial! exposure via multiple diodes?
→ quenching (description) strongly affects CEνNS prediction

Reactor antineutrino spectrum: data-driven approach

[Estienne et al., 10.1103/PhysRevLett.123.022502, 2019]



1) Low energy region E<1.8 MeV:

Summation spectra of Estienne et al. (2019)

2) Intermediate energy 1.8 MeV≤E<7 MeV

Daya Bay (2021):
- unfolded IBD spectra of U235, (Pu239+ Pu241), total
- method to construct data-based predictions

$$S_{\mathrm{pred}} = R \cdot \begin{pmatrix} S_{\mathrm{total}} \\ S_{235} \\ S_{\mathrm{combo}} \\ S_{238} \\ S_{241} \end{pmatrix}$$

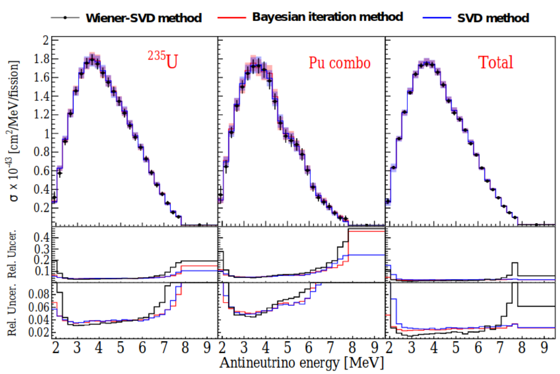
$$R = \left(I_{25} \mid \Delta f_{235} I_{25} \mid \Delta f_{239} I_{25} \mid \Delta f_{238} I_{25} \mid (\Delta f_{241} - 0.183 \times \Delta f_{239}) I_{25} \right)$$

Difference in fission fractions

S_{238} → Mueller

S_{241} → Huber

Extend with bin-to-bin uncorrelated uncertainties: 10% Huber, 15%Mueller

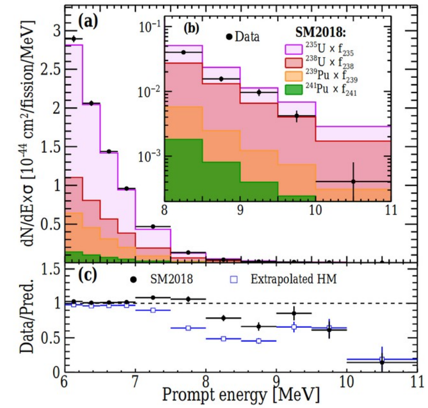


[An et al., 10.1088/1674-1137/abfc38, 2021]

3) High energy E≥7 MeV:

Daya Bay measurement of combined high energy spectrum (2022)

→ Application of Daya Bay data-based method with Estienne et al. spectra



[An et al., 10.1103/PhysRevLett.129.041801, 2022]

Spectrum also used in current CONUS analysis!

Sensitivity determination

(Binned log-) Likelihood function:

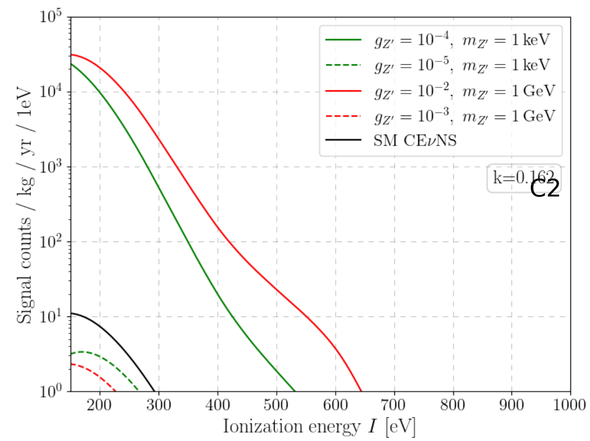
- ON and OFF data are fitted together:

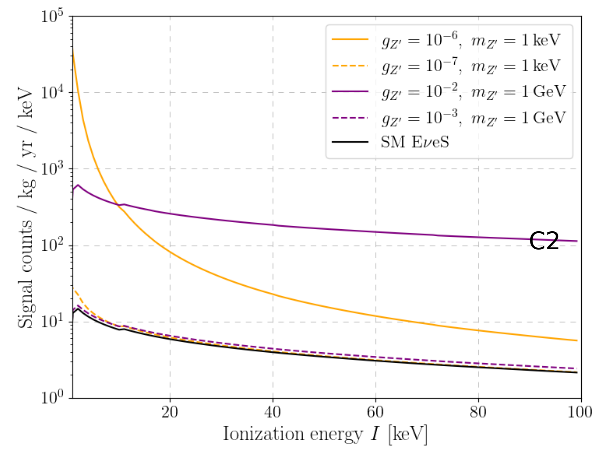
$$\log\,\mathcal{L} = \log\,\mathcal{L}_{\mathrm{ON}} + \log\,\mathcal{L}_{\mathrm{OFF}} + \text{pull term}$$

with $\log\mathcal{L}_{\mathrm{ON}}(\sin^2\theta_W,\ g_{Z'},\ m_{Z'};\ b_{\mathrm{CE}\nu\mathrm{NS}},\ b_{\mathrm{E}\nu\mathrm{eS}},\ \Phi_{\bar{\nu}},\ k)$

$\log\mathcal{L}_{\mathrm{OFF}}(b_{\mathrm{CE}\nu\mathrm{NS}},\ b_{\mathrm{E}\nu\mathrm{eS}})$

- Parameter list:
  - Weinberg angle $\sin^2\theta_W$
  - Z' model parameters $g_{Z'},\ m_{Z'}$
  - bkg normalizations $b_{\mathrm{CE}\nu\mathrm{NS}},\ b_{\mathrm{E}\nu\mathrm{eS}}$
  - reactor neutrino flux (~3%) $\Phi_{\bar{\nu}}$
  - parameter of Lindhard model (~1%) k
- profile LH ratio for limits + χ^2-distribution of test statistic
- Sensitivity estimates via two methods:
  - Asimov data set
  - MC sampling + median average of limits





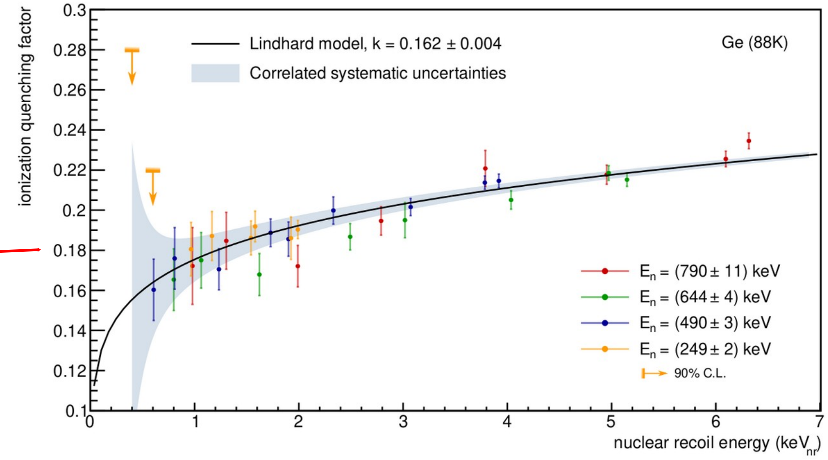
Sensitivity to the Weinberg angle
CEνNS - E_{ion}< 1keV

Sensitivity to a light vector boson:
CEνNS - E_{ion}< 1keV
EνeS - E_{ion}<100kev

Experimental requirements at reactor site

Goal: Detecting CEνNS with high accuracy!

[Bonhomme et al., arXiv:2202.03754, 2022]



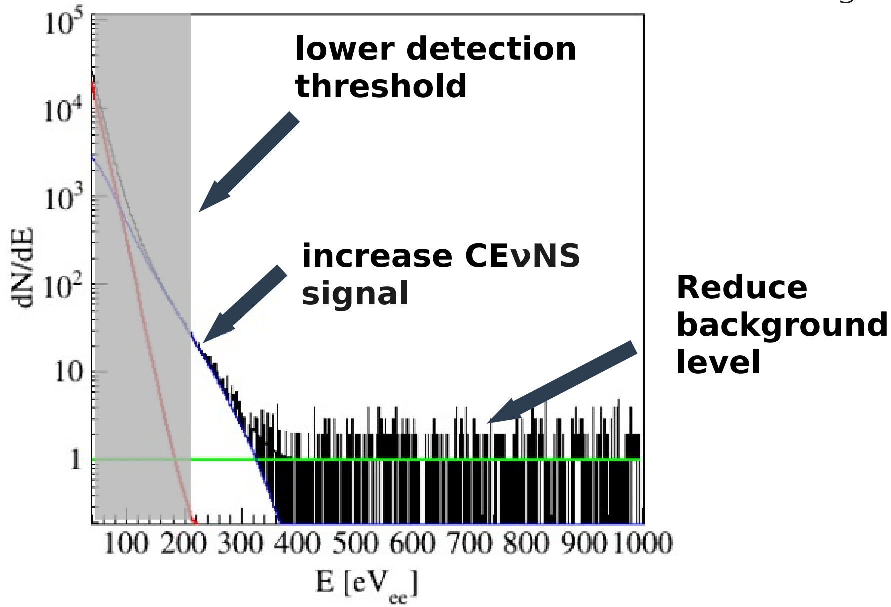
Several obstacles to overcome:

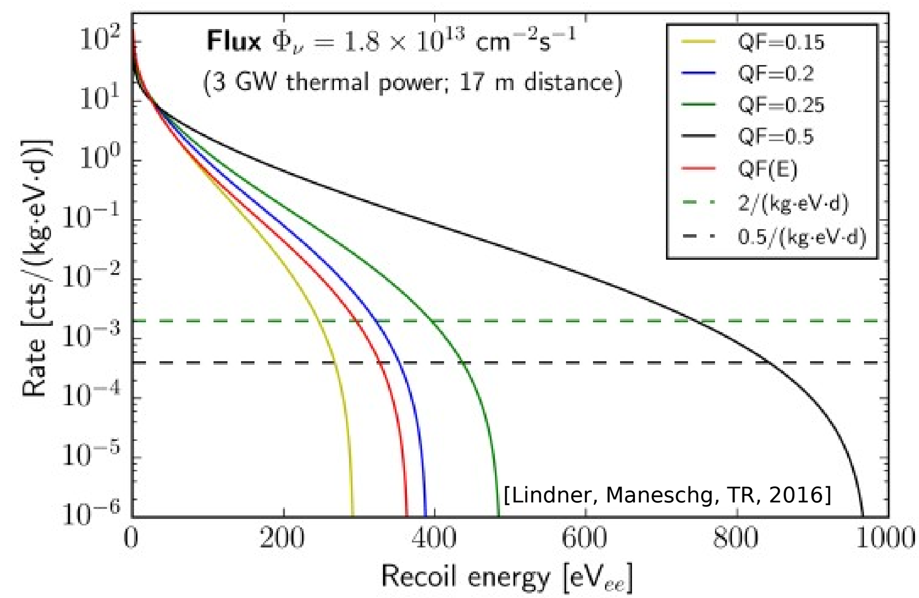
1) Beat $1/R^2$ factor
   → strong (= commercial) power plant, close to reactor core

2) Compensate quenching (E_{recoil} → E_{ion})
   → lowest possible detection threshold

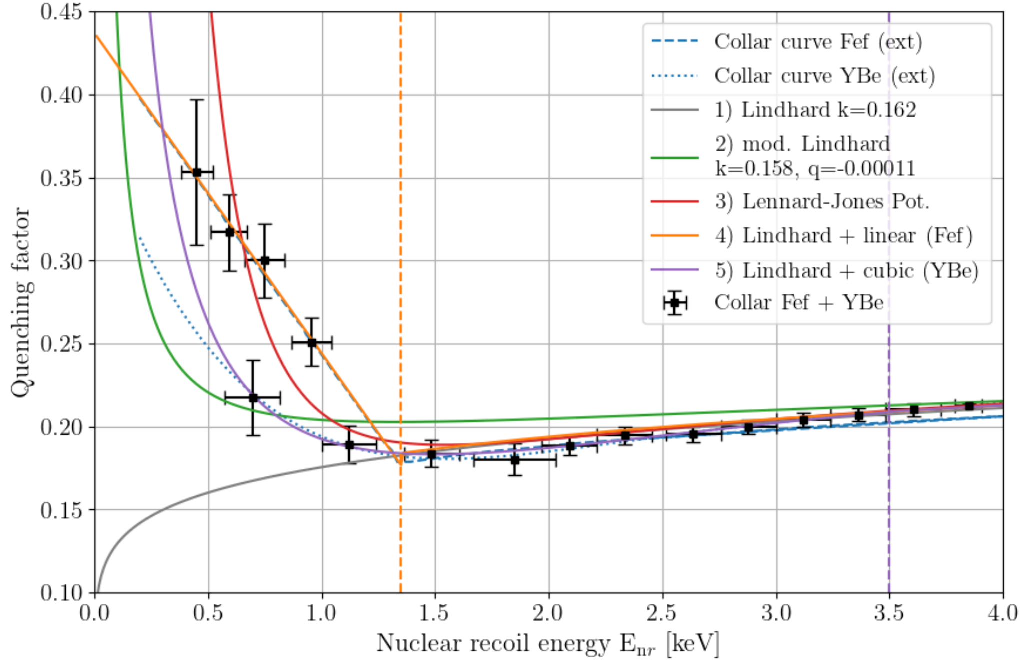
E_ν: 10MeV
max E_{Recoil}: 3keV
maxE_{ion}: ~600eV

3) Low background outside lab condition
   → moderate overburden & limited shielding capacities

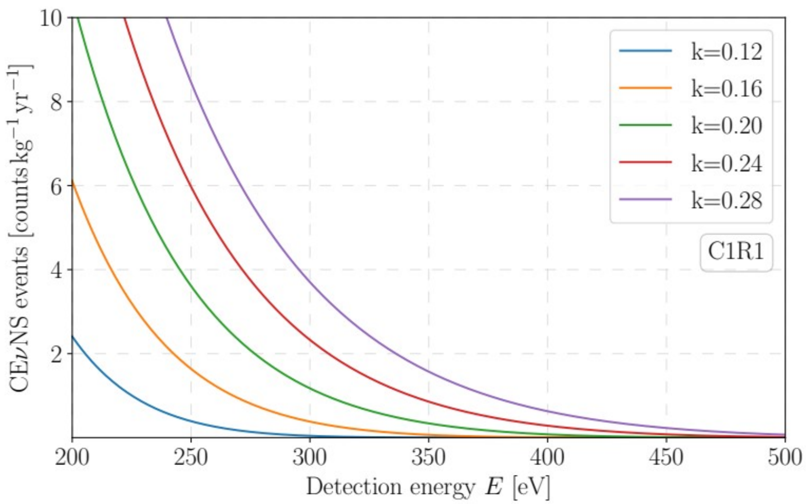




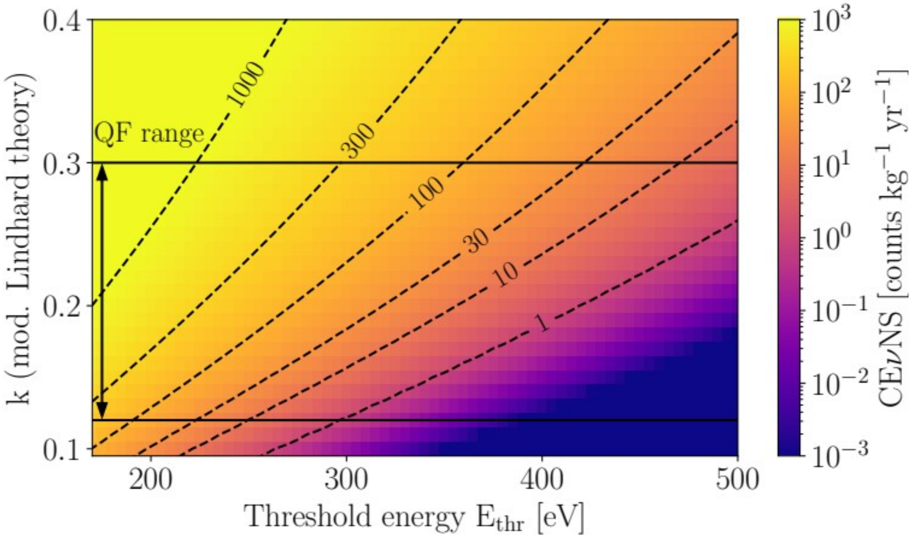
Impact of quenching at low energy



Quenching according to mod. Lindhard model:

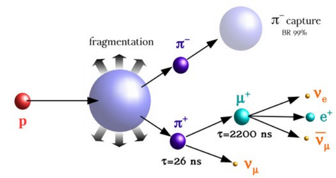


[TR, PhD thesis, 2022]



Two complementary approaches

π-decay-at-rest neutrinos:



- Pulsed GeV-proton beam hitting heavy target
  → multiple ν flavors
- Time correlation of events
  → background suppression x(10^3-10^4)
- Higher ν energies
  → larger cross section, but reduced coherence

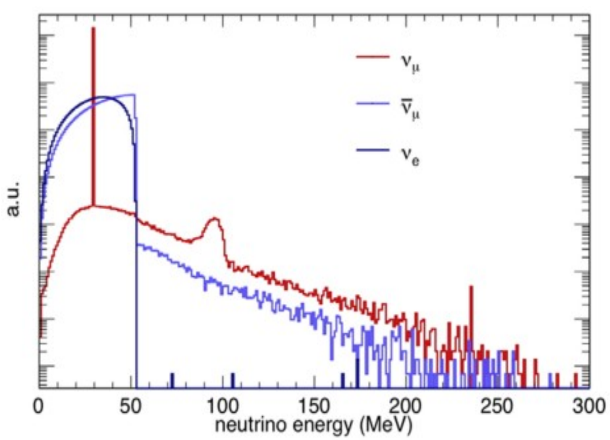
→ COHERENT, CCM, "CEνNS@ESS"...

Reactor antineutrinos:

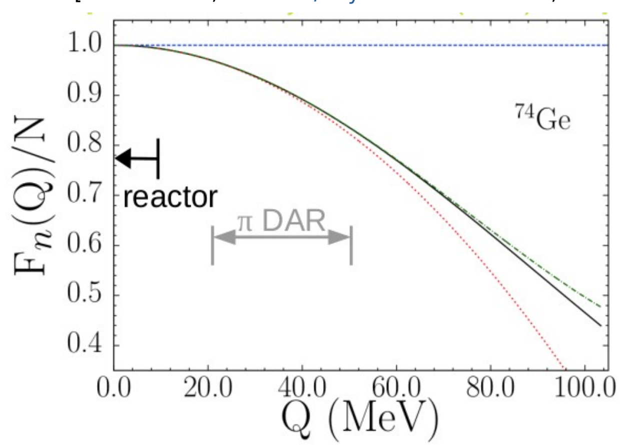
- β decays in nuclear reaction chains → only $\bar{\nu}_e$
- Strongest artificial ν source on earth:
  ~10^{20} $\bar{\nu}_e$'s/GW/s
- ν energies up to 10 MeV → coherent regime!
- Close to reactor core: no lab conditions!
  → no cryogenic liquids, no remote control

→ CONNIE, CONUS, NCC-1701, νGEN ...

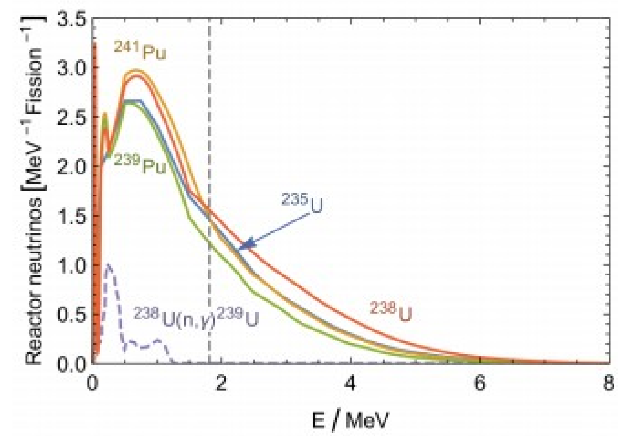
[Akimov et al., arXiv:1509.08702, 2015]



[Patton et al., 10.1103/PhysRevC.86.024612, 2012]



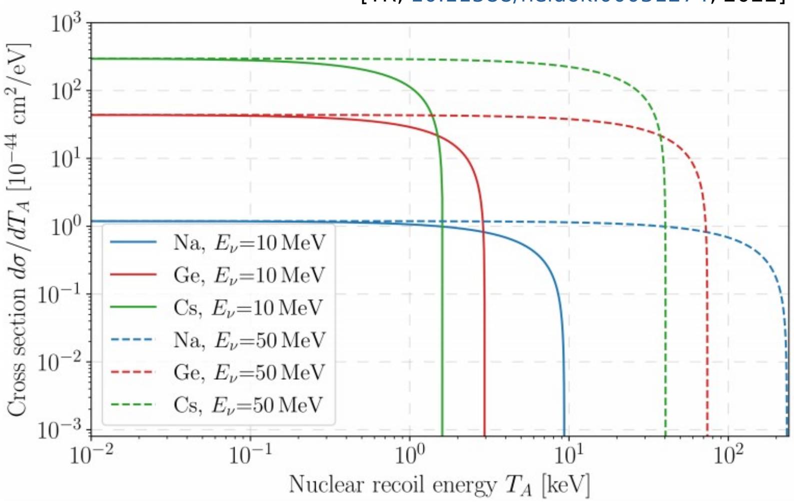
[Vitagliano et al., 10.1103/RevModPhys.92.045006, 2020]



Beam-reactor complementarity:
CEνNS at reactor site as high statistic baseline for multi-target and multi-flavored beam investigations!

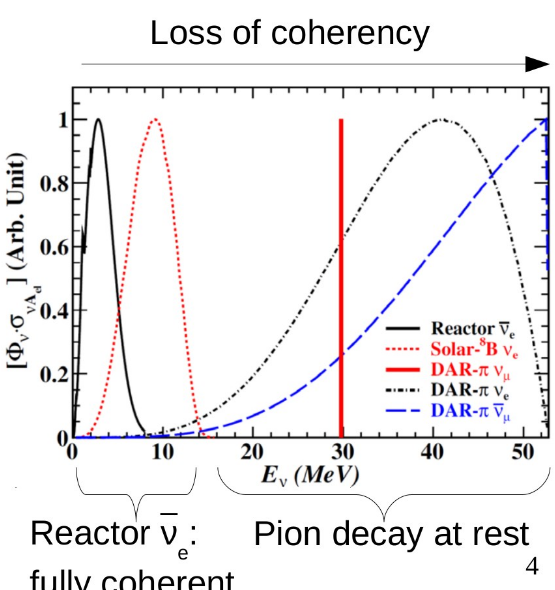
CEνNS with different sources and targets

[TR, 10.11588/heidok.00031274, 2022]



Element	N	r_A [fm]	$E_\nu^{\max}$ [MeV]	$T_A^{\max}$ [keV]
Na	12	3.6	27.7	71.5
Si	14	3.8	25.9	51.3
Ar	22	4.4	23.1	28.5
Ge	38/40/42	5.2	18.9	10.5
I	74	6.3	15.7	4.16
Xe	75/77/78	6.4	15.5	3.93
Cs	78	6.4	15.4	3.85

[TR, 10.11588/heidok.00031274, 2022]



[W. Maneschg, 2017]

Neutrino source	Target	$T_A^{\max}$ [keV]	E (QF $\in \{0.1, 0.15, 0.2\}$) [keV]
Nuclear reactor (10 MeV)	Na	9.33	0.93 / 1.40 / 1.87
	Si	7.64	0.76 / 1.15 / 1.53
	Ar	5.37	0.54 / 0.81 / 1.07
	Ge	2.96	0.30 / 0.44 / 0.59
	I	1.69	0.17 / 0.25 / 0.34
	Xe	1.64	0.16 / 0.25 / 0.33
	Cs	1.62	0.16 / 0.24 / 0.32
π-DAR source (50 MeV)	Na	232.4	23.2 / 34.9 / 46.5
	Si	190.4	19.0 / 28.6 / 38.1
	Ar	134.0	13.4 / 20.1 / 26.8
	Ge	73.8	7.38 / 11.1 / 14.8
	I	42.3	4.23 / 6.34 / 8.45
	Xe	40.9	4.09 / 6.13 / 8.17
	Cs	40.4	4.04 / 6.03 / 8.07