CsI[Na] scintillation response to nuclear recoils in the energy range of 3-20 keV

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Energy deposition channels

Ionizing radiation energy depostion → ionisation, excitation, heat

ionisation → excitation → heat

Energy fraction deposited to a certain channel depends on a projectile type

Gamma and beta particles transfer energy to recoil electrons

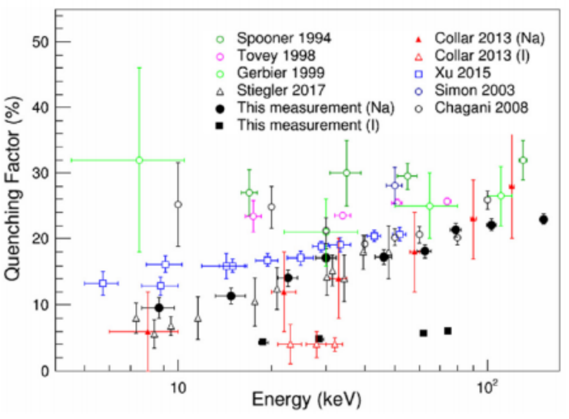
Neutrons, neutrino and hypothetical WIMPs transfer energy to nuclear recoils

Higher ionization density at a cite of interaction cause intense recombination and quenching of nuclear recoil signals relative to electron recoils

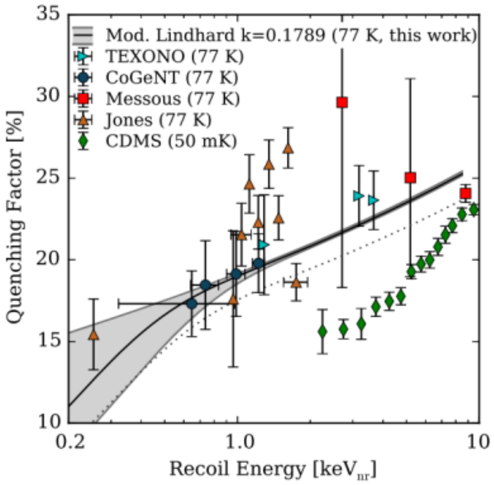
$$\text{Nuclear recoil quenching factor (QF)} = \frac{\text{Nuclear recoil signal yield}}{\text{Electron recoil signal yield}}$$

NR QF in various materials

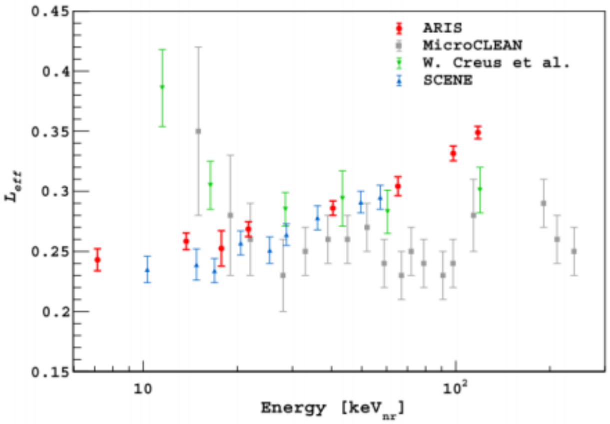
NaI[Tl], H.W. Joo et al., Astr.Ph.,v.108 (2019)



HPGe, B.J. Scholz et al., PRD 94 (2016)



LAr, P. Agnes et al., PRD 97 (2018)



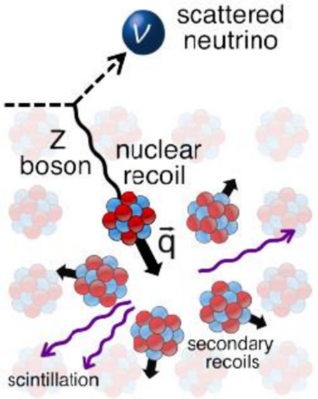
Large variations in published values of QF, amomg possible reasons — complications in calibration of a neutron beam energy, NR energy, multiple scattering and inelastic scattering contributions, small signals analysis

Motivation — studying response of materials to hypothetical dark matter particles (WIMPs), doesn't necessarily require high experimental accuracy of obtained QF values. Direct dark matter search experiments evaluate upper limits on WIMPs mass and coupling to matter.

CEvNS and CsI[Na] QF

D. Freedman, PRD v.9, n.5 (1974)

V. Kopeliovich, L. Frankfurt, Zh.ETF Pis. Red., v.19 n.4 (1974)

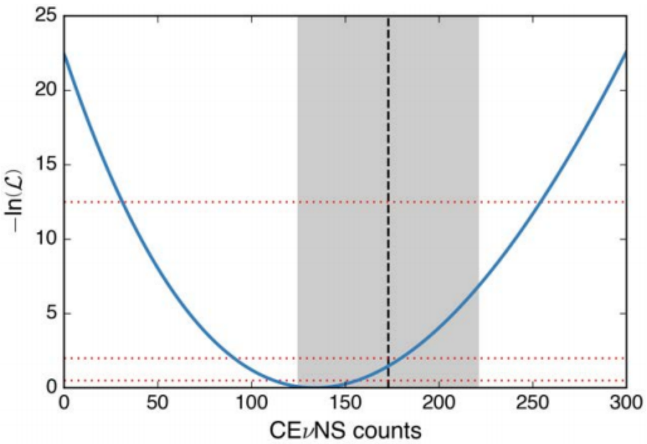


Coherent elastic neutrino-nucleus scattering — a weak neutral current process in the SM

The first observation was performed in 2017 by the COHERENT collaboration at SNS (ORNL)

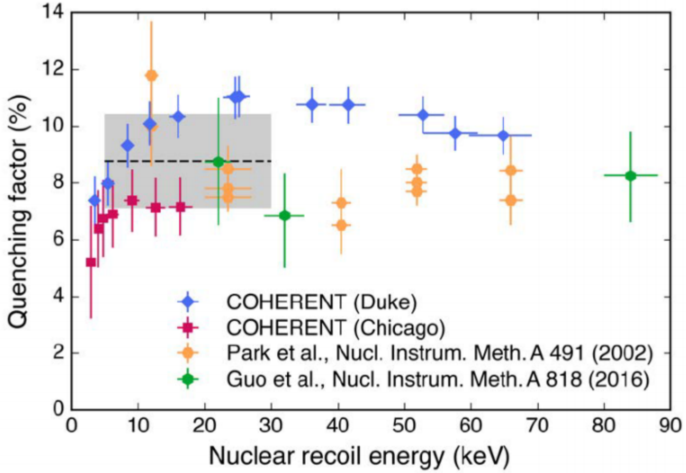
D. Akimov et al., Science v. 357 (2017)

Observed — 134±22, predicted — 173±48 events



Large discrepancy in the QF measurements performed by COHERENT dominates the uncerainty

In 2017 we used 8.8±1.7% as a representative QF value



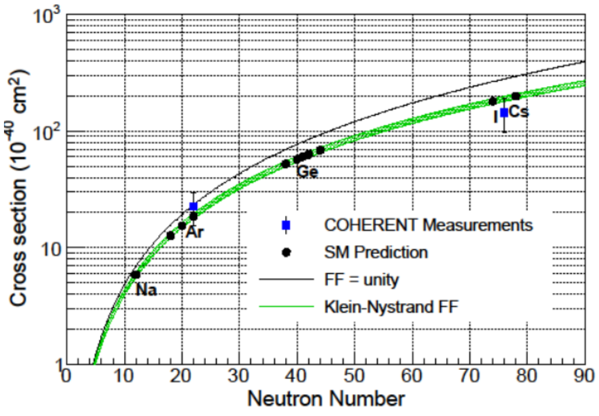
What is interesting about CEvNS

CEvNS cross section in the SM:

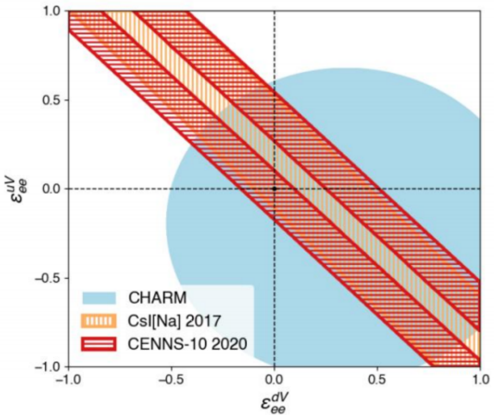
$$\frac{d\sigma}{dT} = \frac{G_F^2 M}{4\pi}\left([1-4\sin^2\theta_W]Z - N\right)^2\left[1-\frac{T}{T_{max}}\right]F_{nucl}^2(q^2)$$

$$T_{max} = 2E_\nu^2/(M+2E_\nu)$$

Test of CEvNS rate N² dependence



Combined NSI exclusion limits



Assuming vector current-like NSI couplings:

$$(g_V^p + 2\epsilon_{ee}^{uV} + \epsilon_{ee}^{dV})\ Z + (g_V^n + \epsilon_{ee}^{uV} + 2\epsilon_{ee}^{dV}\ )N$$

Non-standard neutrino interactions and properties

J.Liao, D. Marfatia., PLB 775 (2017)

O. G. Miranda et al., JHEP 07 (2019)

P.Coloma et al., PRD 96 (2017)

M. Caddedu et al., PRD 101 (2020)

D. Papoulias and T. Kosmas, PRD 97 (2018)

Y. Farzan et al., JHEP 66 (2018)

Nuclear structure

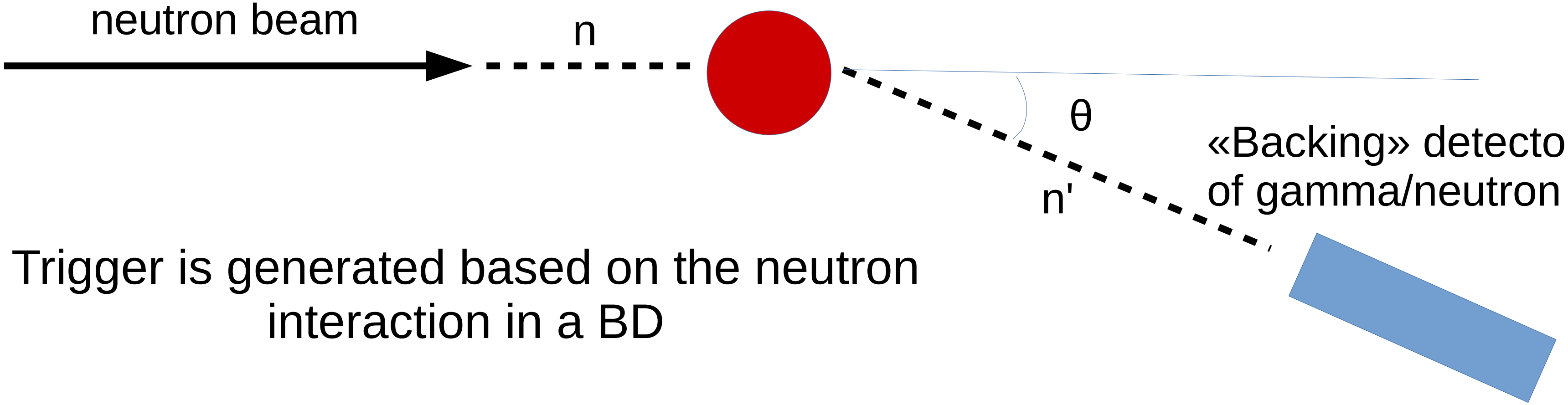
M. Caddedu et al., PRL 120 (2018)

Xu-Run Huang, Lie-Wen Chen, PRD 100 (2019)

D. Papoulias et al., Physics Letters B 800 (2020)

How does one measure NR QF?

Usually the neutron calibration data are used to obtain QF values



Trigger is generated based on the neutron interaction in a BD

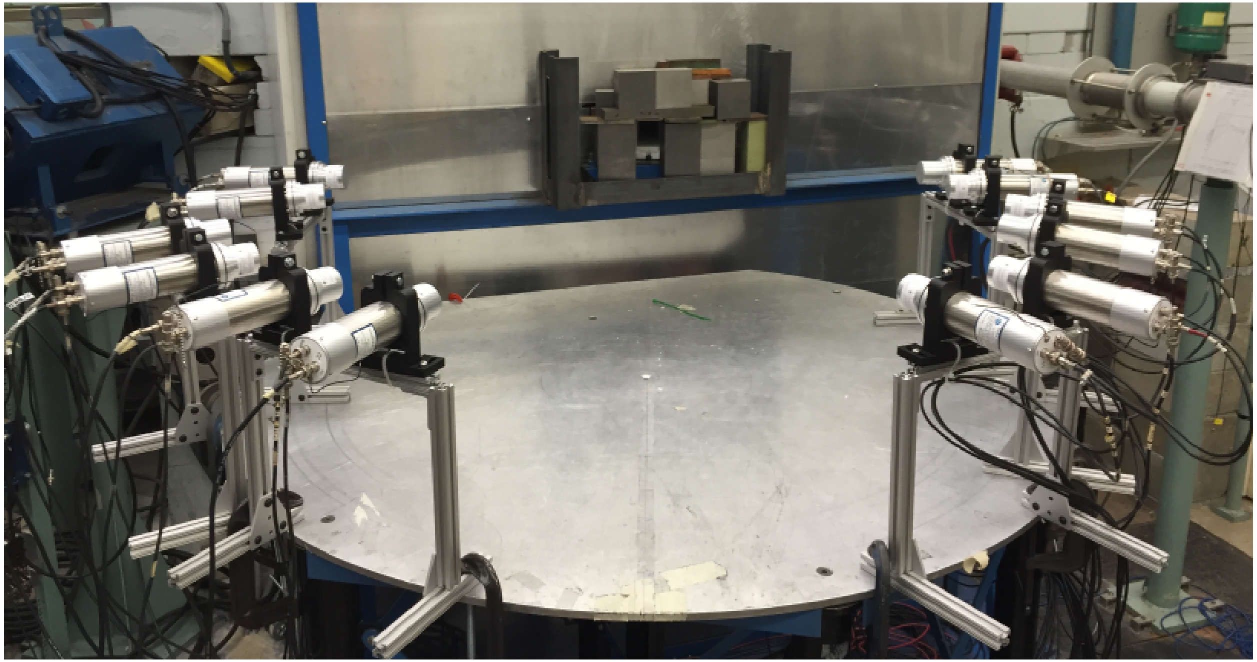
Nuclear recoil energy $$\Delta E \approx \frac{2E_n M_n M_T}{(M_n + M_T)^2}(1 - \cos\theta)$$ for $M_T >> M_n$

CsI[Na] NR QF measurements in TUNL

TUNL (Triangulat Universities Nuclear Lab.) - a laboratory in NC USA, a Van der Graaf generator accelerates light ions, which can be used to produce neutron beams based on $^{7}Li(p,n)$, $D(D,n)^{3}He$, $^{3}H(p,n)^{3}He$, $^{3}H(D,n)^{4}He$ reactions

CsI[Na] crystal (*l*=51mm, Ø=19mm)

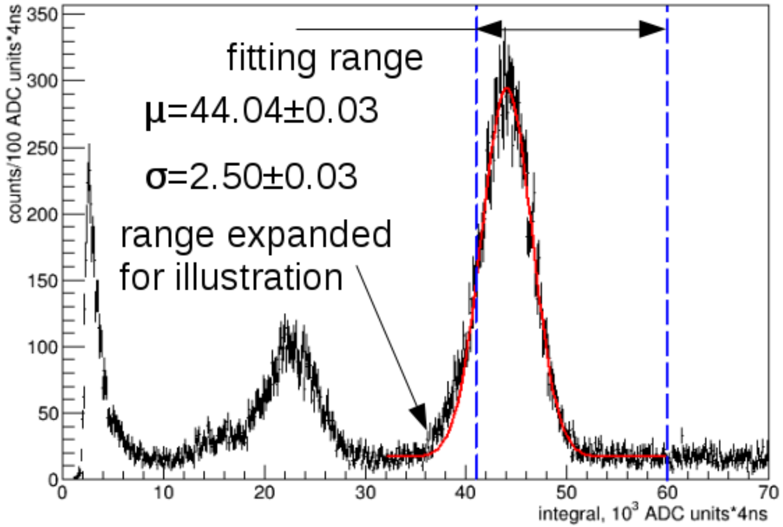
SSA area: neutron beam window and backing detectors



COHERENT measurements in 2016-2018

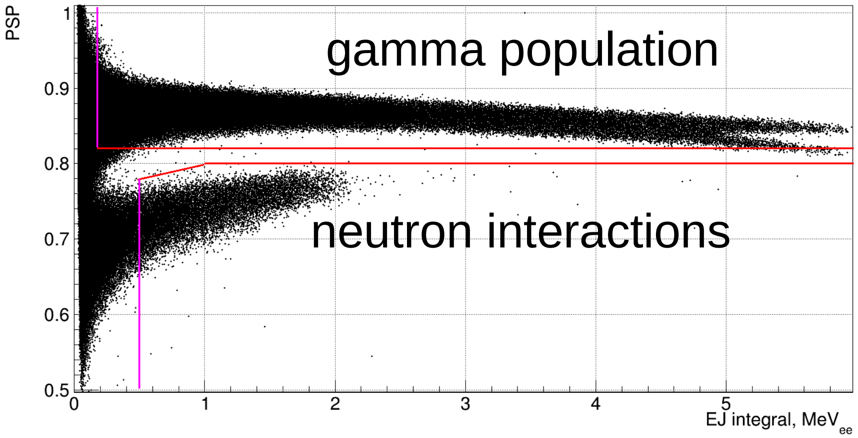
Dataset	Data / Results	n prod.	E_n, MeV	E_{nr}, keV	BD type	BD positions
COHERENT-1	2016 / 2017	$D(D,n)^3He$	3.8	3-70	EJ-301 LS	12
COHERENT-2	2016 / 2017	$D(D,n)^3He$	3.8	3-20	EJ-299-33A	7
COHERENT-3	2018 / 2020	$D(D,n)^3He$	4.55	17.5	EJ-301 LS	1
COHERENT-4	2017 /2020	$^7Li(p,n)$	0.92 / 1.23	<28.2/<37.3	n/a	n/a

All measurements used 59.5 keV line of an ^{241}Am source as a reference point for ER scale

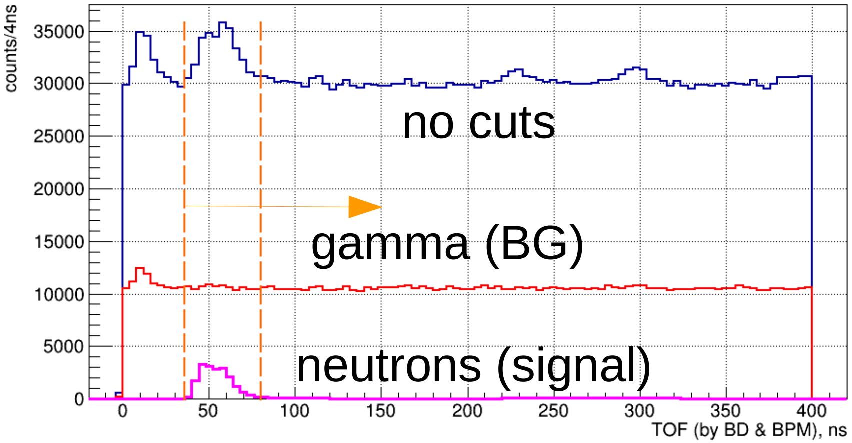


COHERENT-3 measurement (2020)

BD energy deposition and PSP



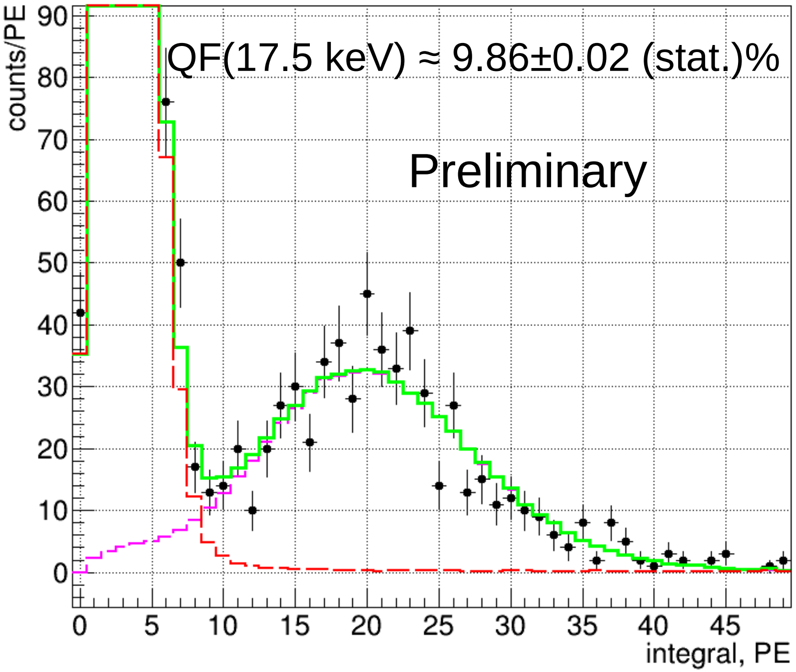
Ограничения на время пролёта для сигнала и фона



NR energy prediction take into account:

1. Neutron beam energy (based on TOF)
2. MCNP of CsI[Na] and EJ-301 response
3. CsI[Na] resolution (photostat.)

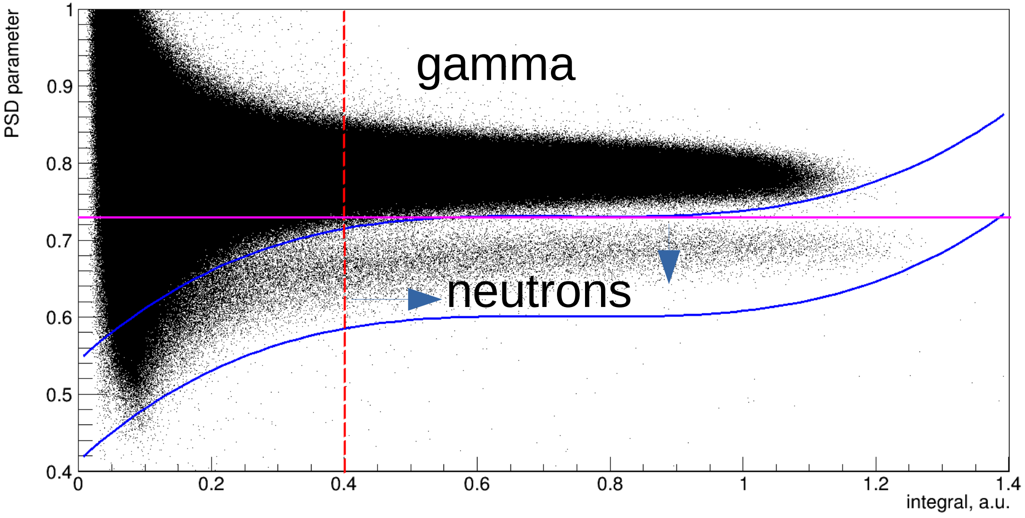
Results:



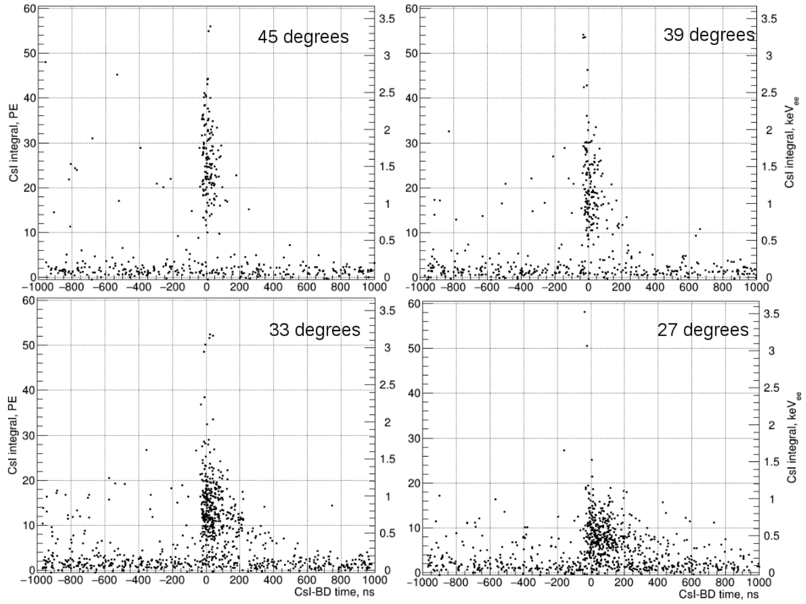
Uncertainties: En - ±4%, CsI[Na] response - ±4%

COHERENT-2 data re-analysis (2016/2020)

BD (EJ-299-33A) energy depositions and PSP



TOF: CsI — EJ



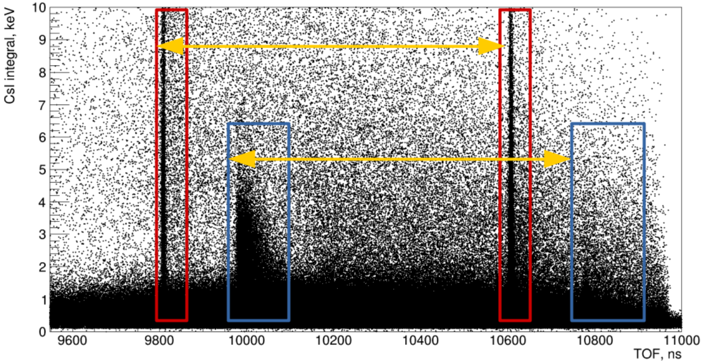
Preliminary results:

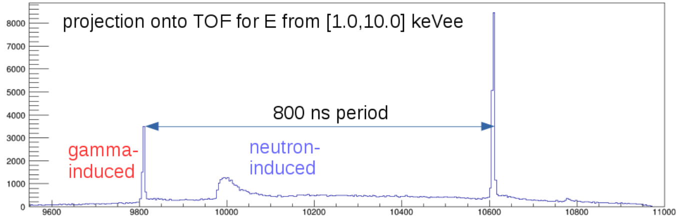
Scat. Angle, deg.	18	21	24	27	33	39	45
E_{nr}, keV ± RMS width	2.9±0.6	4.0±0.7	4.8±0.8	6.3±0.9	2.9±0.6	2.9±0.6	2.9±0.6
QF,% (old)	5.2±1.7	6.4±0.9	6.8±0.8	6.9±0.7	7.4±0.5	7.1±0.7	7.2±0.6
QF,% re-nalysis	5.4±1.1	7.2±0.4	7.9±0.4	8.0±0.4	8.7±0.4	9.0±0.5	9.4±0.5

COHERENT-4 — the «endpoint» measurement

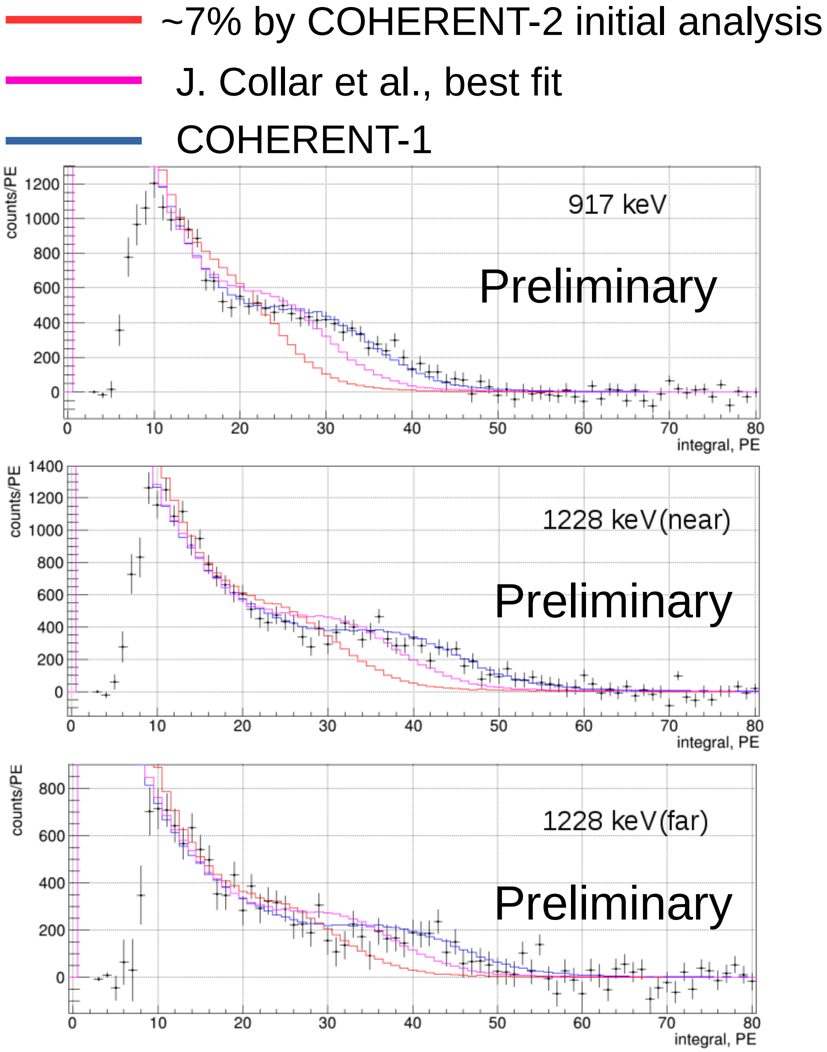
Measurement by the energy deposition endpoint

- no BD (all scattering angles)
- CsI[Na] self-trigger
- TOF-based selection of NR signals



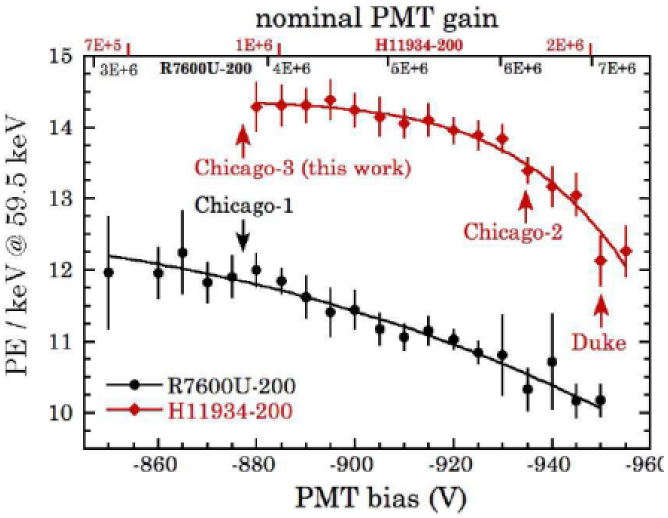


«Endpoint» energy deposition: $$E_{\rm nr}^{\rm max} = \frac{4E_{\rm max}m_{\rm nuc}m_n}{(m_{\rm nuc}+m_n)^2}$$



J. Collar et al., PRD 100 (2019)

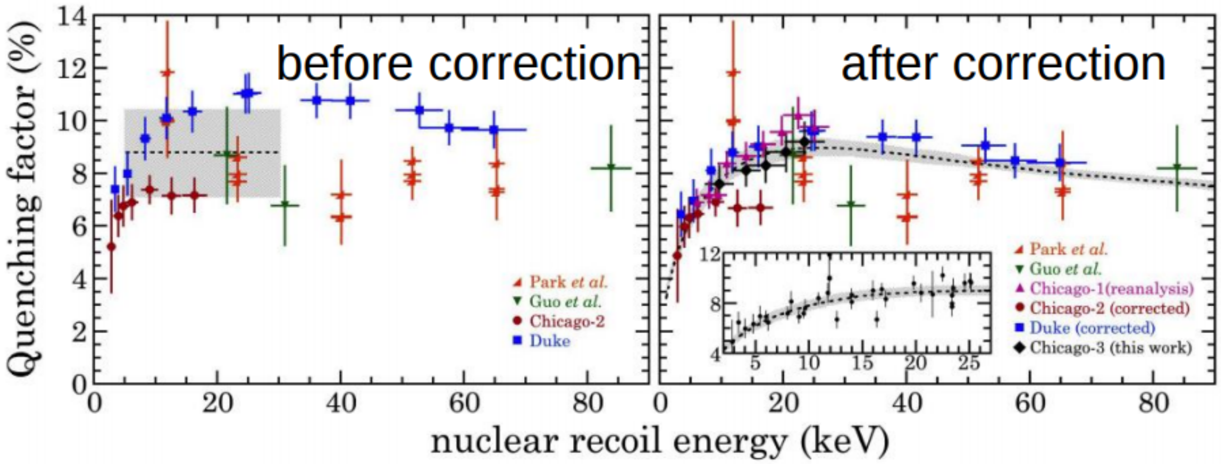
In 2019 the J.Collar et al., PRD (100) paper is published. Authors provide new QF measurements results and claim the non-linear behavior of the PMT used by COHERENT (at 59.5 keV signal)



Authors observed decreasing light yield of a CsI[Na] on the 59.5 keV line of ^{241}Am with increase of the H11934-200 PMT bias voltage

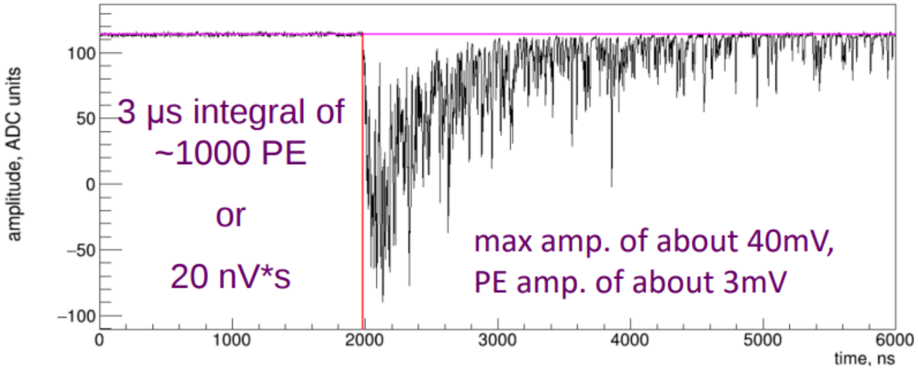
Authors applied the correction suggested by their findings to COHERENT data and evaluated updated QF model and uncertainty

COHERENT performed scrutiny of the J. Collar et al. claim by multiple test of H11934-200 PMT unit



H11934-200 linearity tests

Scale of a 59.5 keV signal (COHERENT-2):



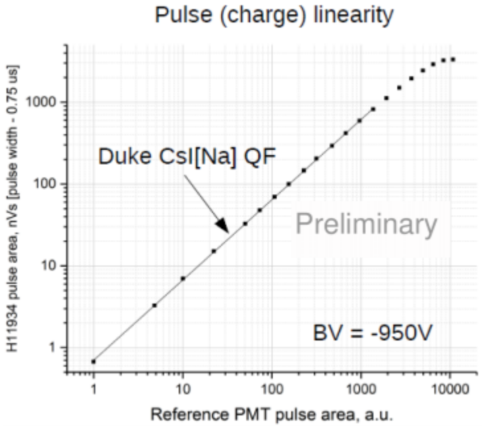
Crude estimate

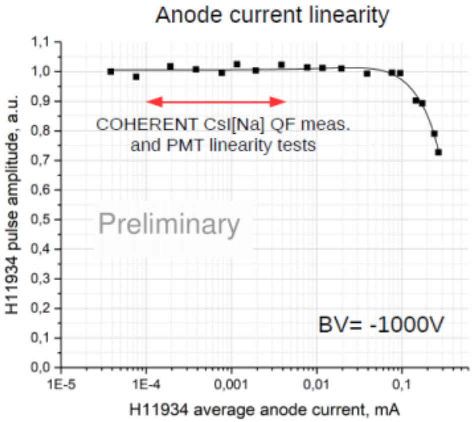
1200 PE signal at -950V and a gain of $2*10^6$ (Hamamatsu info)

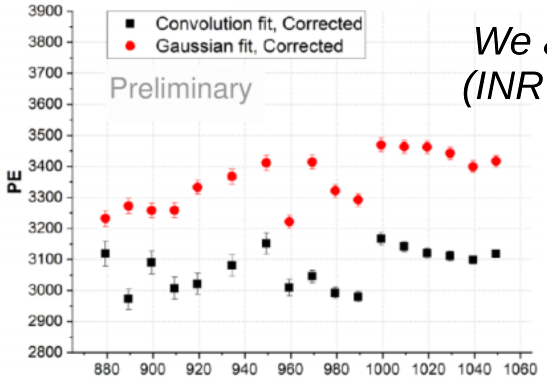
$$\frac{2.4\cdot 10^9\ e \approx 4\cdot 10^{-10}\ C}{300\ ns\ (vs.\ 3\mu s)} = 1.3\ mA$$

vs. ± 2% at 20mA from Hamamatsu info

Tests both with a CsI[Na] crystal and controlled light sources (LED/laser) refute the H11934-200 non-linearity claim. We observe non-linearity effects on the scale 40 times large than CsI[Na] response to 59.5 keV







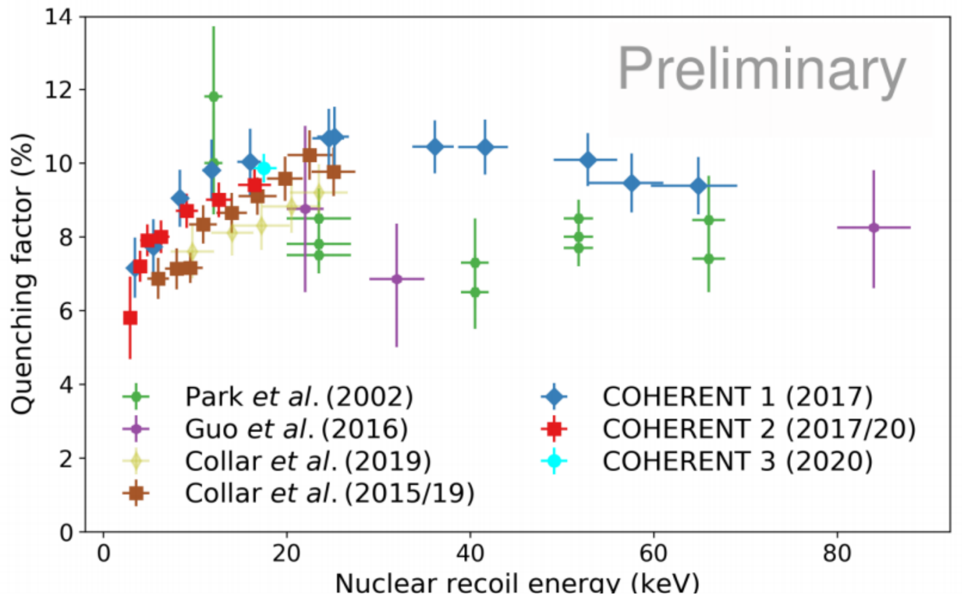
We are grateful to Yu. Melikyan (INR RAS) for help with the PMT characterisation

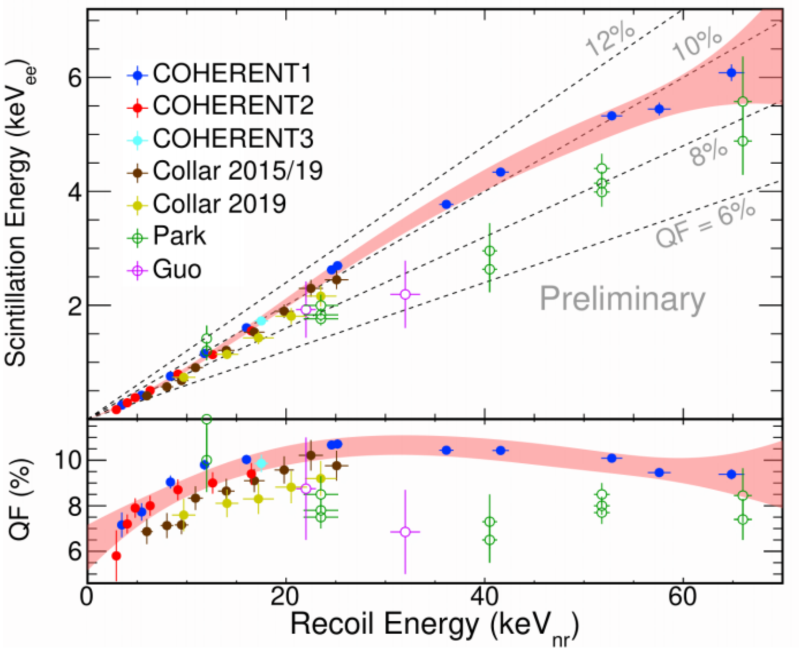
COHERENT refutes the H11934-200 non-linearity claim and doesn't agree with corrections applied to COHERENT data in J. Collar et al., PRD 100 (2019)

Global fit

Updated plot with world data on CsI[Na] QF

We use Chicago-1/3 and COHERENT-1/2/3 data for the global fit



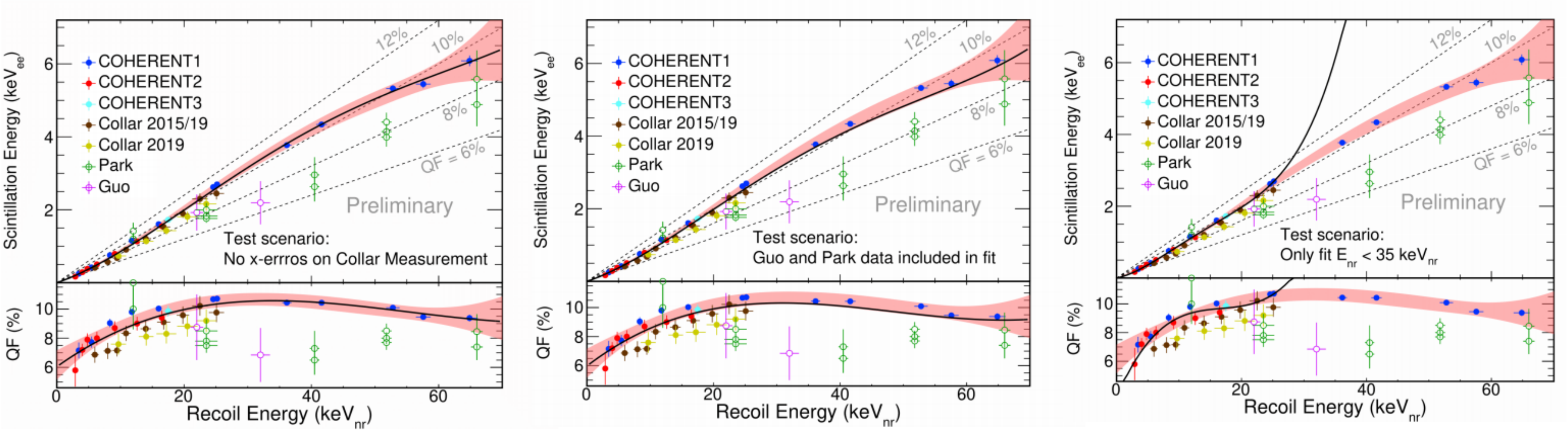


We fit in E_{ee} vs. E_{nr} space

$$Sc(E_{nr}) = 0.0616006 \times E_{\rm nr} + 3.37111 \times E_{\rm nr}^2 - 77.9909 \times E_{\rm nr}^3 + 519.958 \times E_{\rm nr}^4$$

Width of E_{nr} distribution is not included in COHERENT data y-axis uncertainty of E_{ee} vs. E_{nr}

Systematic excursion tests



Systematic excursion tests central values are contained by «default» scenario unc-ty band

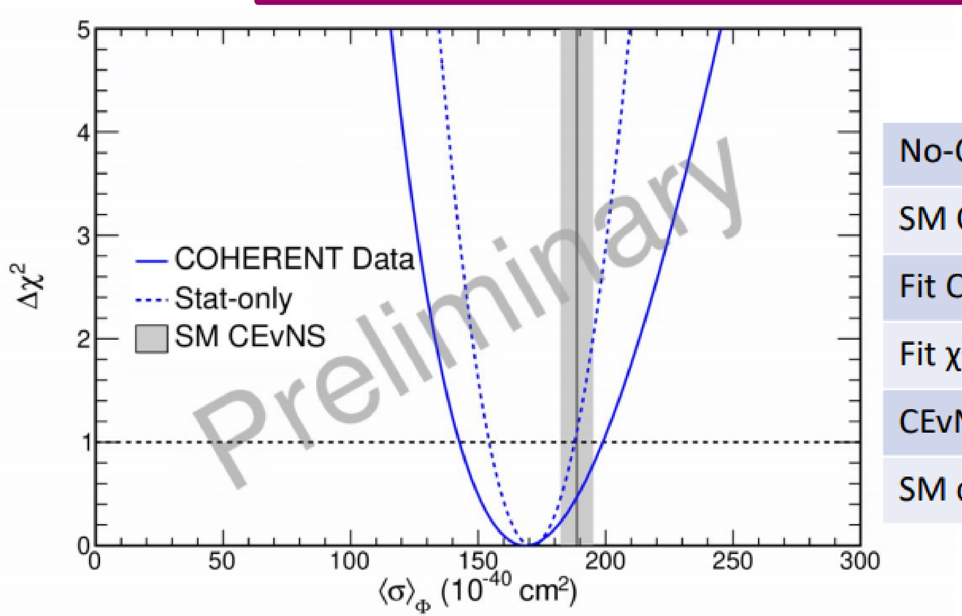
The possibility of raw QF data release is discussed within COHERENT collaboration to address possible concerns

Conclusion

Results of the COHERENT QF measurement efforst allow us to reduce the CEvNS uncertainty depending on the QF from 28% to 4%

On Monday November 16 of 2020 COHERENT has presented results of full dataset analysis of the CsI[Na] experiment (blind analysis) taking into account new QF estimate, observed CEvNS cross-section is consistent with the SM prediction within the uncertainty

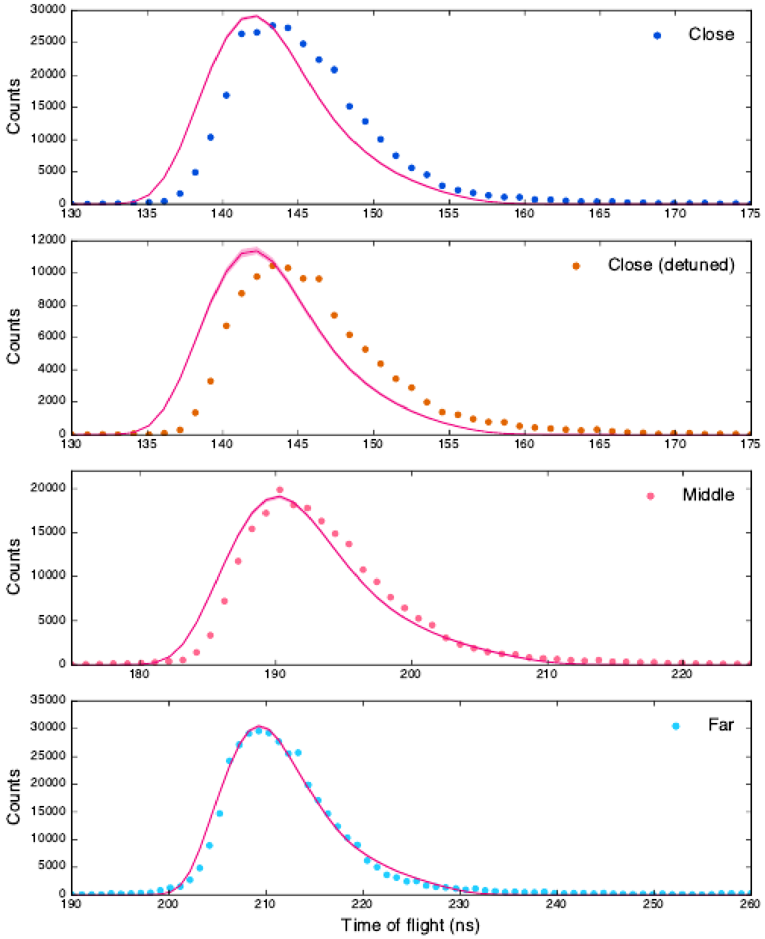
From D. Pershey, Magnificent CevNS worksop (2020)

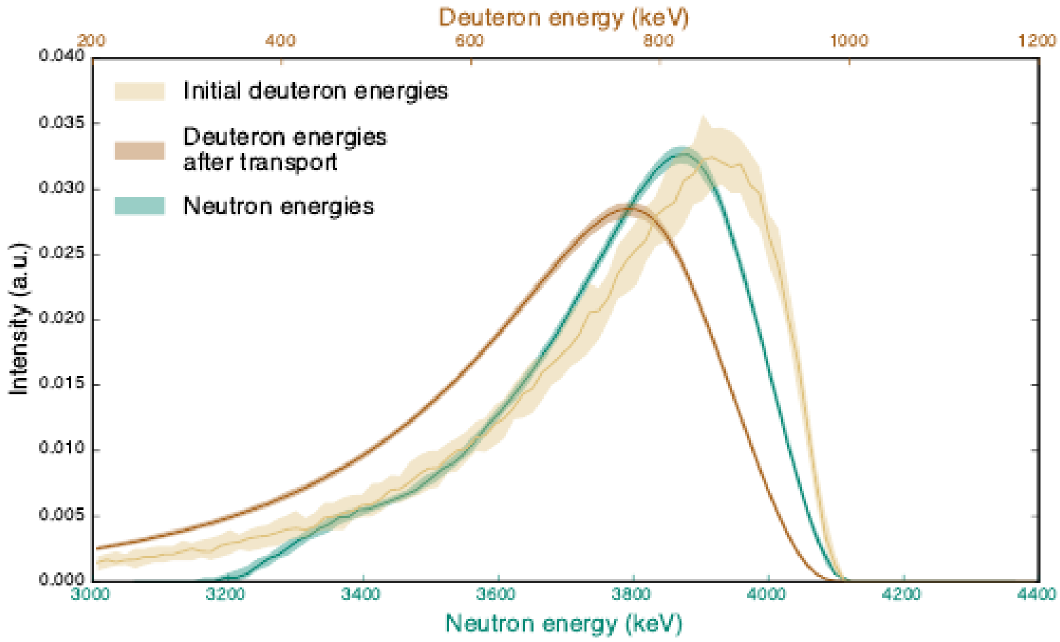


No-CEvNS rejection	11.6 σ
SM CEvNS prediction	$333 \pm 11(\text{th}) \pm 42(\text{ex})$
Fit CEvNS events	306 ± 20
Fit χ^2/dof	82.4/98
CEvNS cross section	$169^{+30}_{-26} \times 10^{-40}$ cm^2
SM cross section	$189 \pm 6 \times 10^{-40}$ cm^2

Backup: beam energy calibration

TOF test and the model





From G.C. Rich PhD thesis
(University of North Carolina, 2017)