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Search for Double-Beta Decay of ^{136}Xe to the 0^+_1 Excited State of ^{136}Ba with Complete EXO-200 dataset

第二届“无中微子双贝塔衰变及相关物理研讨会, 5.19-5.22, 2023

arxiv: 2303.01103

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On behalf of the EXO-200 Collaboration

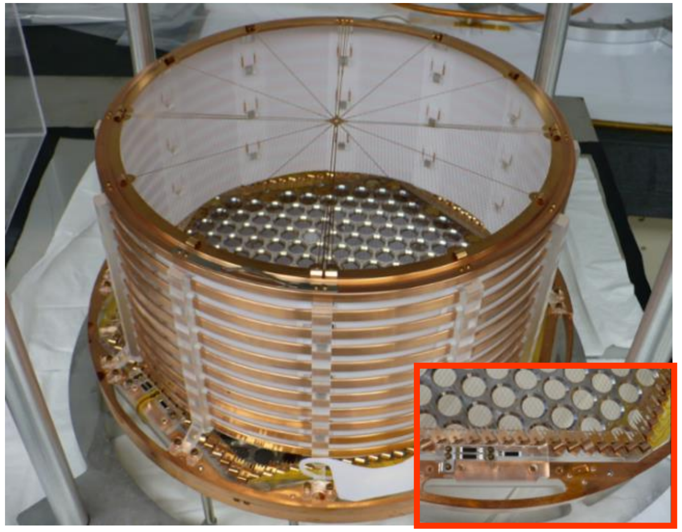
May 22@珠海

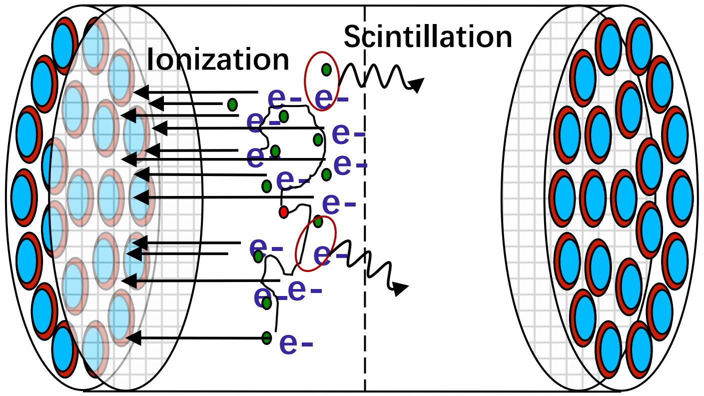
Outline

- **EXO-200**
- **$2\nu\beta\beta$ decay of ^{136}Xe to the 0^+_1 Excited State of ^{136}Ba**
- **Sensitivity and unblind data result**
- **Summary**

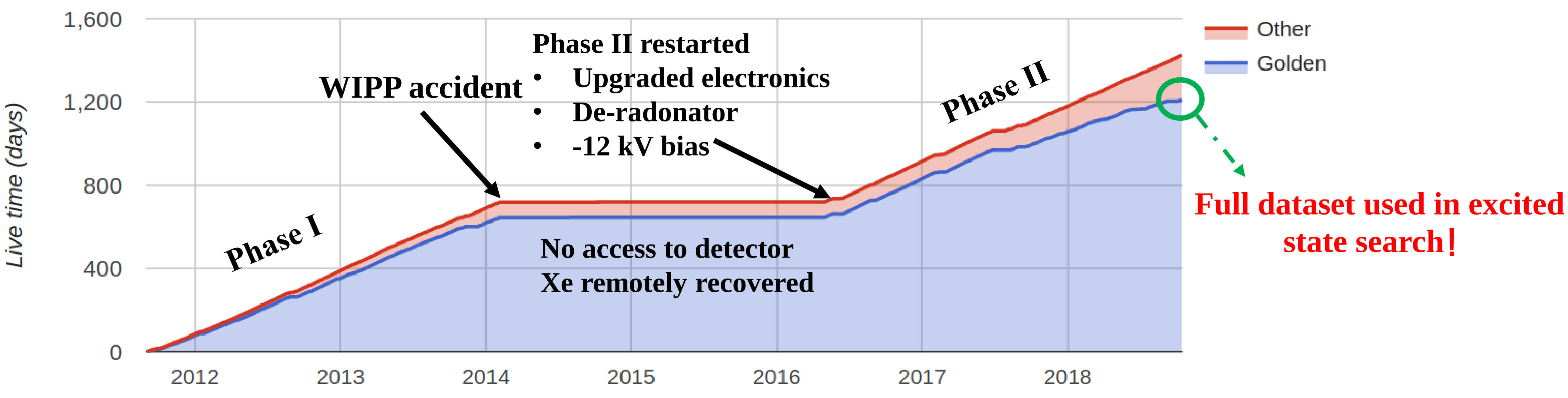
EXO-200 Detector

- Search Neutrinoless Double Beta Decay ($0\nu\beta\beta$) of ^{136}Xe
  - A Liquid Xenon Time Projection Chamber (TPC)
  - ~175kg Liquid Xenon (LXe) with ^{Enrich}Xe (80.6%)
  - Two identical back-to-back TPCs made from radio-pure copper
- Energy measured using two signals
  - Ionization signal drifted to crossed wire planes
    - Shielding plane (V-wires)
    - Collection plane (U-wires)
  - Scintillation light (178nm) readout by arrays of large area avalanche photodiodes (LAAPDs)





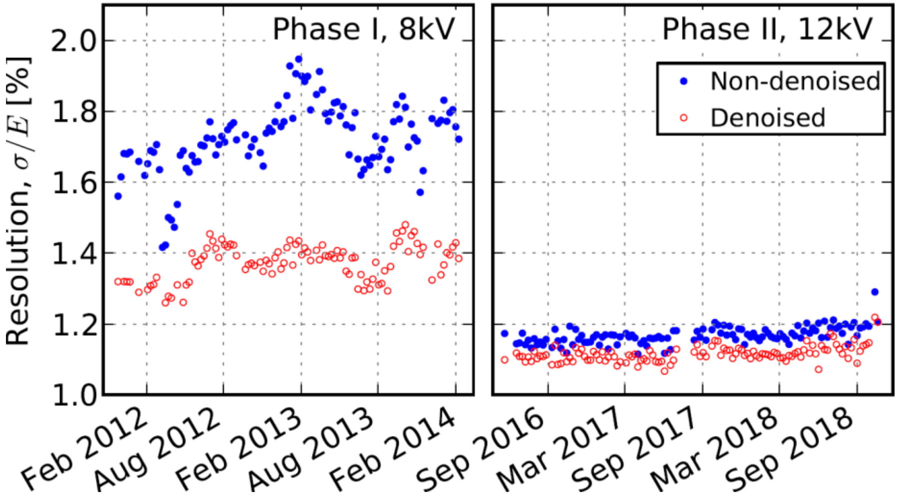
EXO-200 Timeline



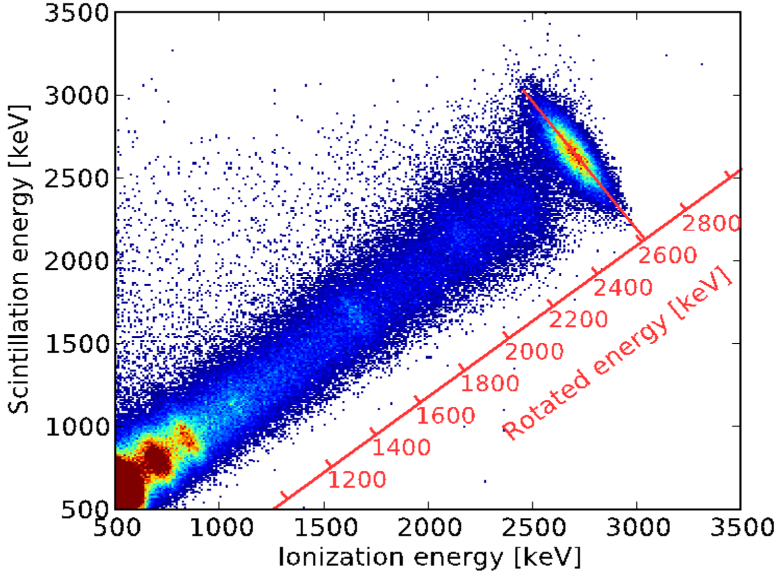
- Phase I from *Sep 2011 to Feb 2014*
  - Most precise $2\nu\beta\beta$ measurement, *PRC. 89, 015502 (2013)*
  - Stringent limit for $0\nu\beta\beta$ search, *Nature 510, 229 (2014)*
- Phase II from *Jan 2016 to Dec 2018*
  - First results with Phase II data from upgraded detector, *PRL. 120, 072701 (2018)*
  - Final $0\nu\beta\beta$ results with full dataset, *PRL. 123, 161802 (2019)*
- A total of 1181.3 days of livetime

Energy reconstruction

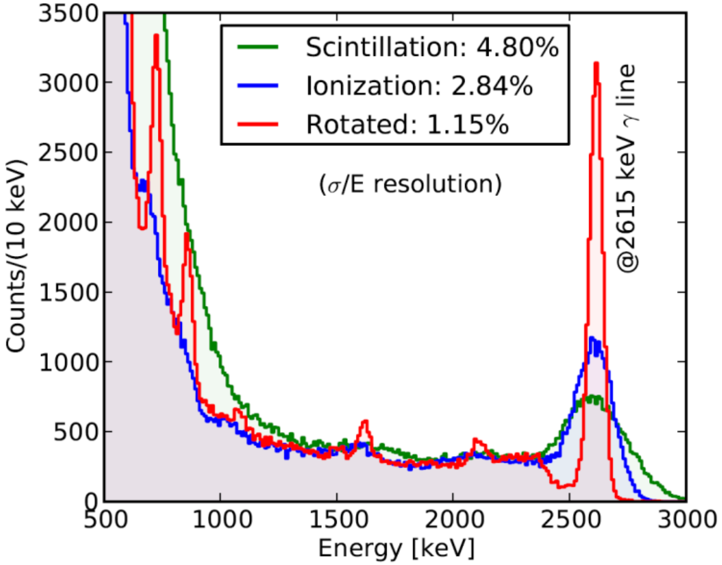
- Anti-correlation between signals from scintillation light and ionization charge
- Linear combination of Light/Charge energy gives optimal event energy (“Rotated” energy)
- Energy resolution (σ/E) at $Q_{\beta\beta}$
  - Software De-noising to optimize energy calibration
  - Phase I (Phase II): 1.35 ± 0.09% (1.15 ± 0.02%)



^{228}Th calibration data at cathode

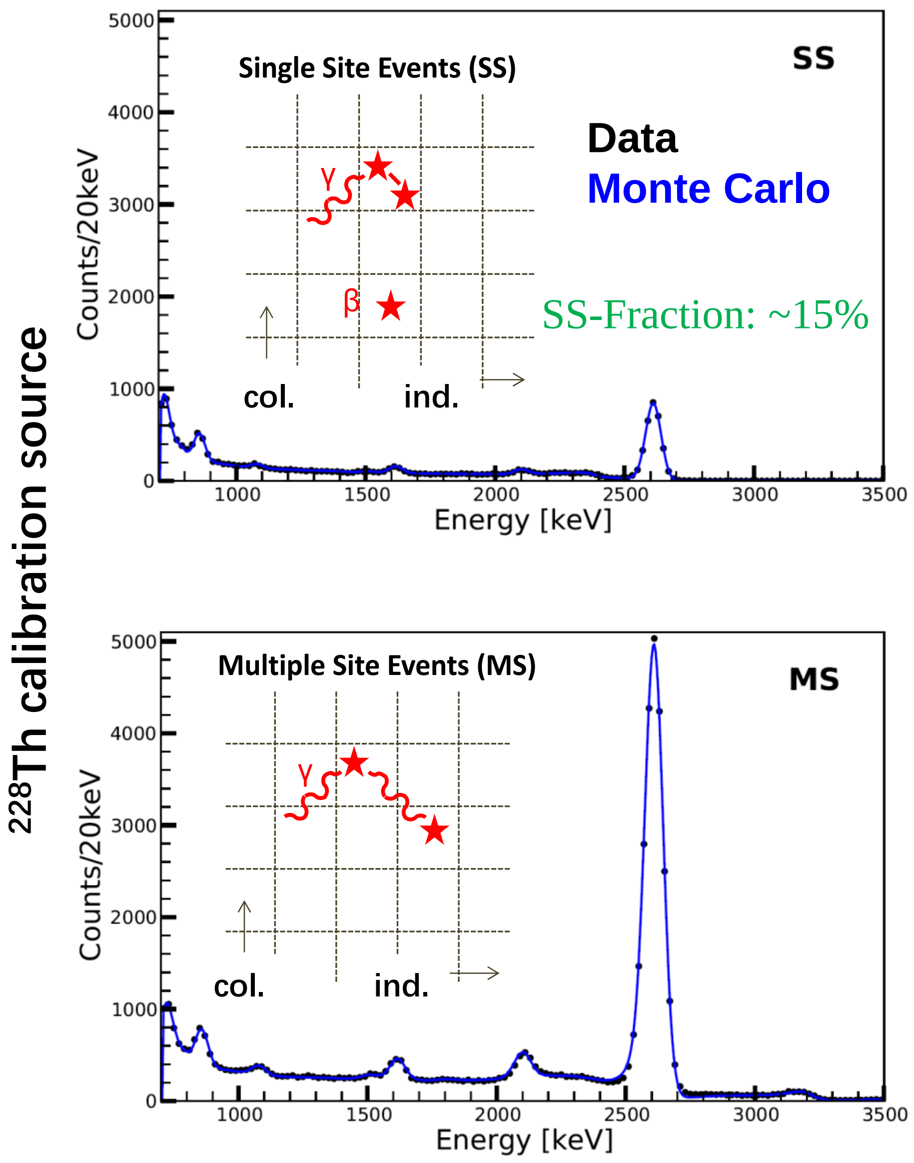


Reconstructed energy, ^{228}Th calibration



Vertex reconstruction and SS/MS classification

- Vertex reconstruction
  - X/Y position: Determined by the signals in cross wire planes
  - Z position: Time delay between light signal and collection signals in wires
- TPC allows for 3D reconstruction of energy deposits
- Event type
  - ββ decay mostly deposits energy (cluster) at single location (Single-Site)
  - γ backgrounds deposits at multiple locations (Multi-Site) from Compton scattering
- SS/MS classification is very powerful in background rejection



EXO-200 $0\nu\beta\beta$ decay results

No statistical significant signal observed

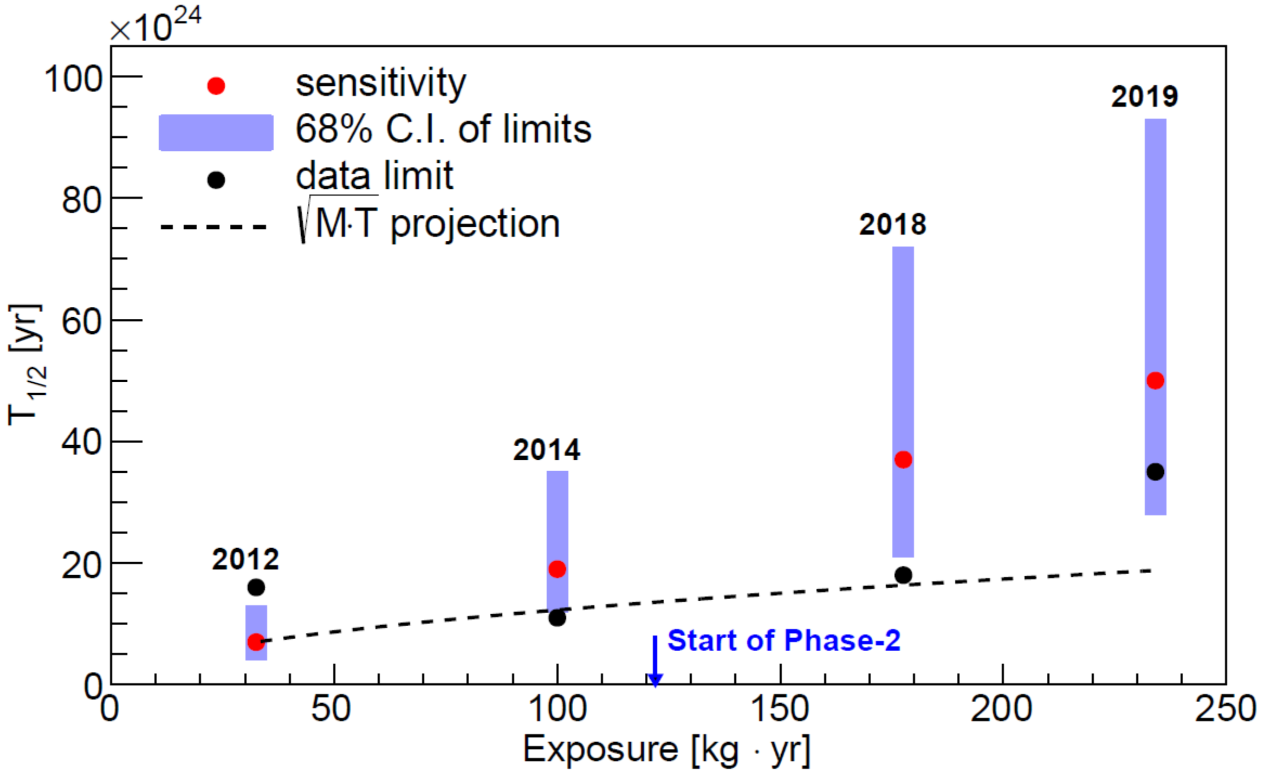
Phase I+II: 234.1 kg · yr ^{136}Xe exposure

Limit: $T_{1/2}^{0\nu\beta\beta} > \mathbf{3.5 \times 10^{25}}\ \boldsymbol{yr}$ (90% C.L.)

$\langle m_{\beta\beta} \rangle < (93 - 286)$ meV

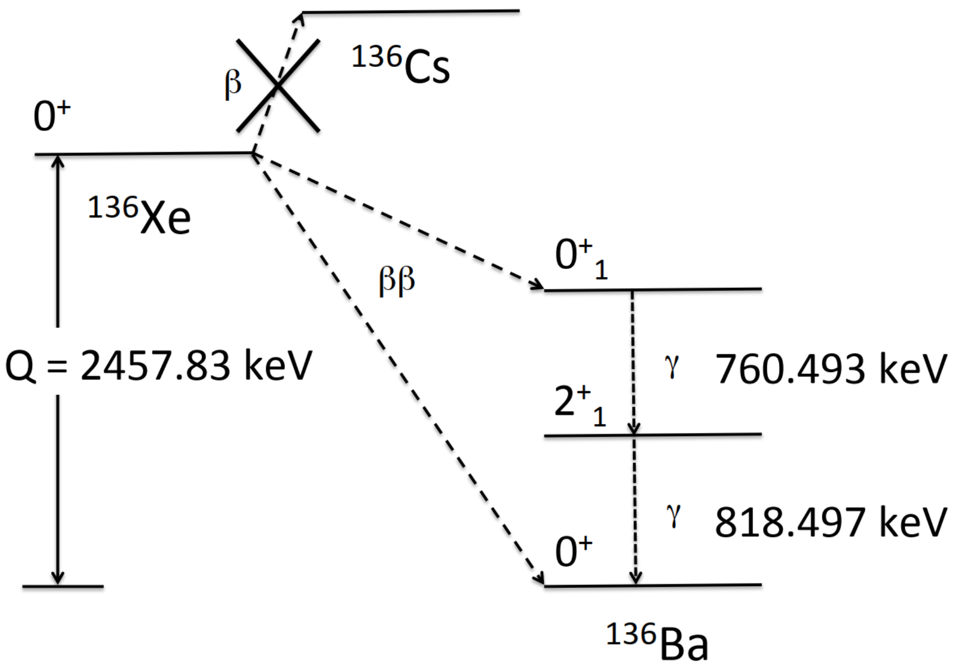
Sensitivity: $5.0 \times 10^{25}\ yr$ (90% C.L.)

EXO-200 $0\nu\beta\beta$ search results



2012: Phys.Rev.Lett. 109 (2012) 032505
2014: Nature 510 (2014) 229-234
2018: Phys. Rev. Lett. 120, 072701 (2018)
2019: arXiv 1906.02723

$\beta\beta$ decays to the Excited state



Level scheme of the $\beta\beta$ decay of 136Xe

Phys. Rev. C 93 (2016), 035501

- $\beta\beta$ decays to the Excited State
  - The nuclear matrix elements (NMEs) of the transition to the ground state (GS) and to the excited state (ES) may have common uncertainties
  - Measuring the decays to the ES offers additional experimental input to the calculation of $2\nu\beta\beta$ NMEs
  - Contributing to the precise determination of the effective Majorana neutrino mass from $0\nu\beta\beta$ half-life measurements
  - Theoretically predicted half-life 10^{23-26} yr[1,2]

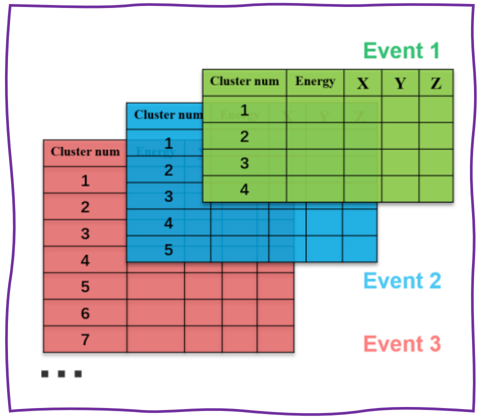
[1] *arXiv:2211.03764*
[2] *Phys. Rev. C 91, 054309 (2015)*

Highlights in this new analysis

The 2016 paper :

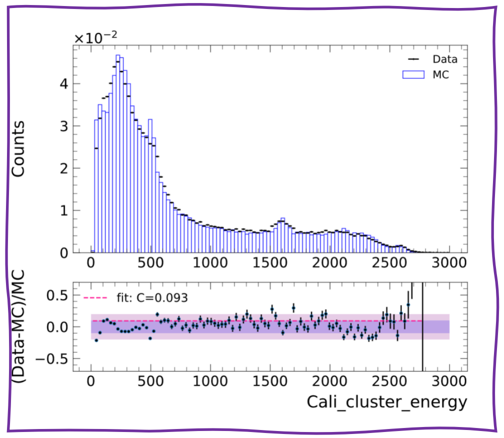
- Total exposure 100kg·yr. in Phase-I
- Sensitivity study using E+BDT
- Sensitivity 1.7×10^{24} yr. (90% CL)
- Lower limit $>6.9 \times 10^{23}$ yr. (90% CL)

- Refined cluster energy calibration
  - Using cluster energy of SS events to calibrate cluster energy of MS events

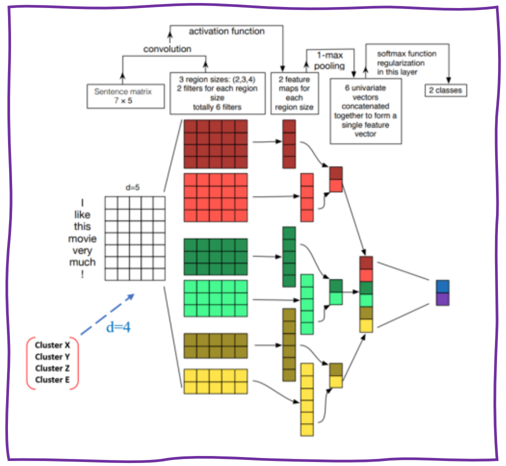


Input data

- Large exposure:
  - Phase I → Phase I + II
- Event selection optimization
  - Signal efficiency doubled

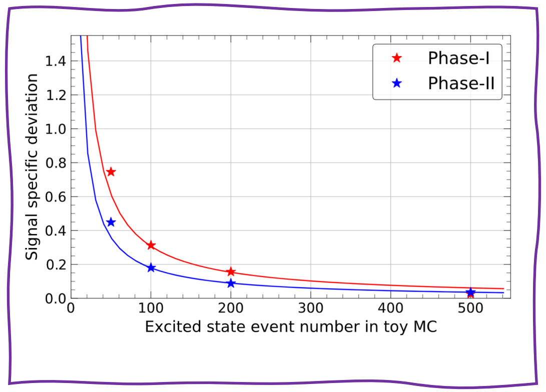


Calibration



Discriminator

- Background identification
  - New ML techniques

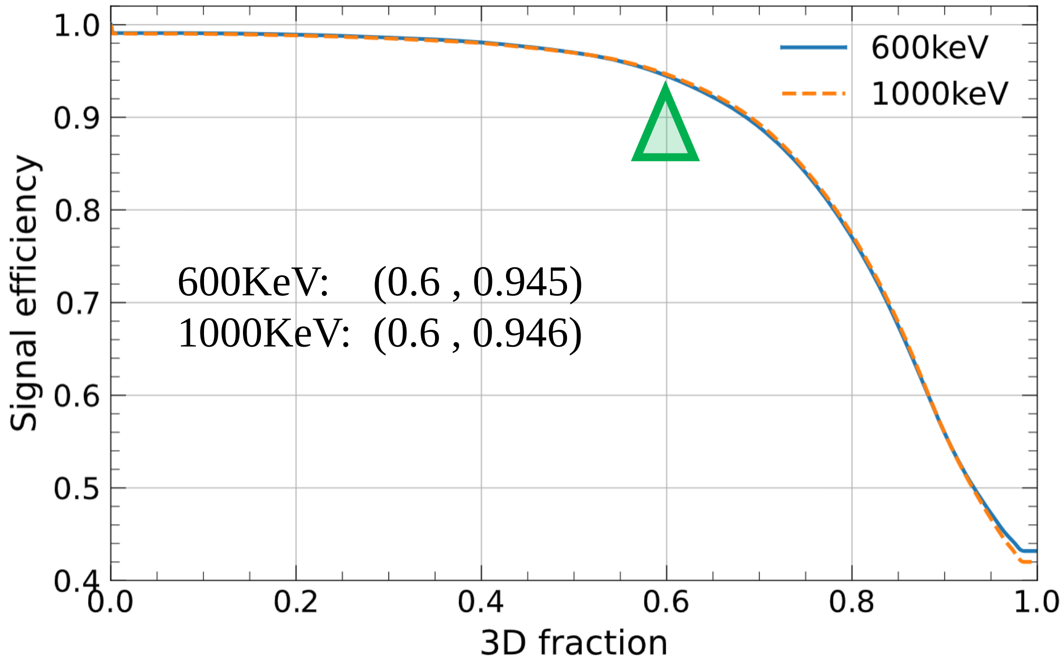


Error Analysis

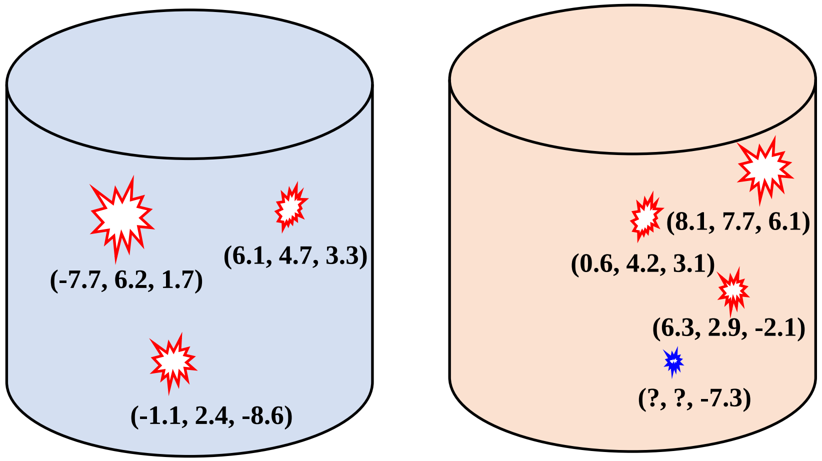
- Fitting
  - Optimized the evaluation method of systematic uncertainly

Event selection optimization

Signal efficiency vs 3D fraction



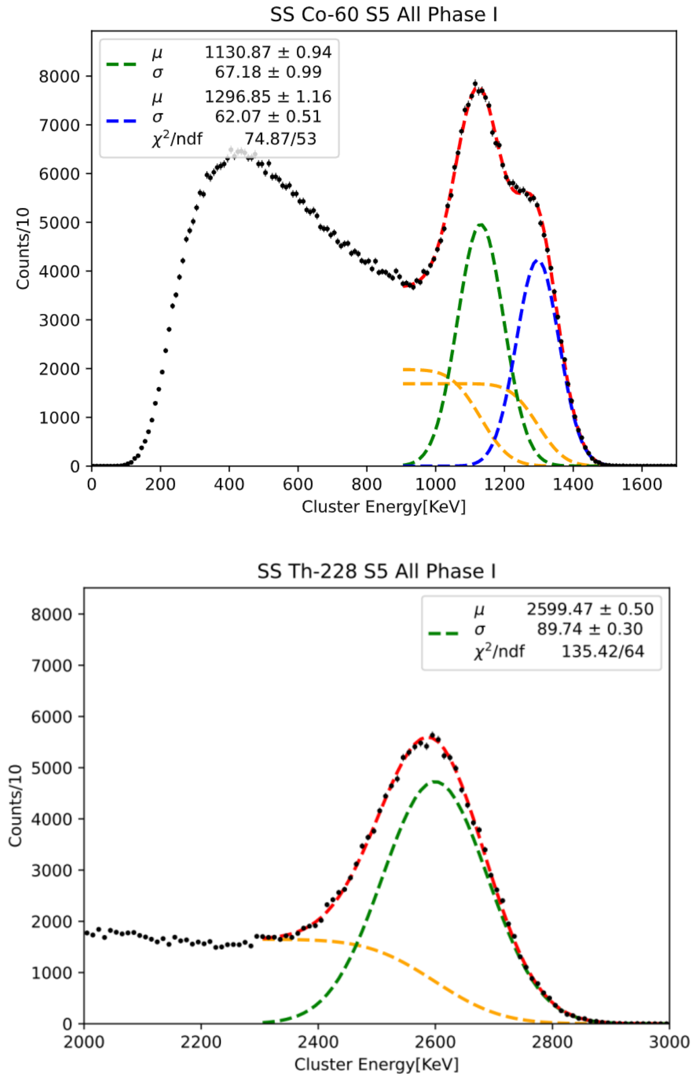
Cut condition	2016 paper (P1/P2)	This work (P1/P2)
Event coincident	0.930	0.995
3D fraction	0.420 (0.443)	0.946 (0.957)
FV & Energy	0.627 (0.617)	0.617 (0.616)
Total efficiency	0.245 (0.254)	0.580 (0.587)



Full 3D event **Partial 3D event**

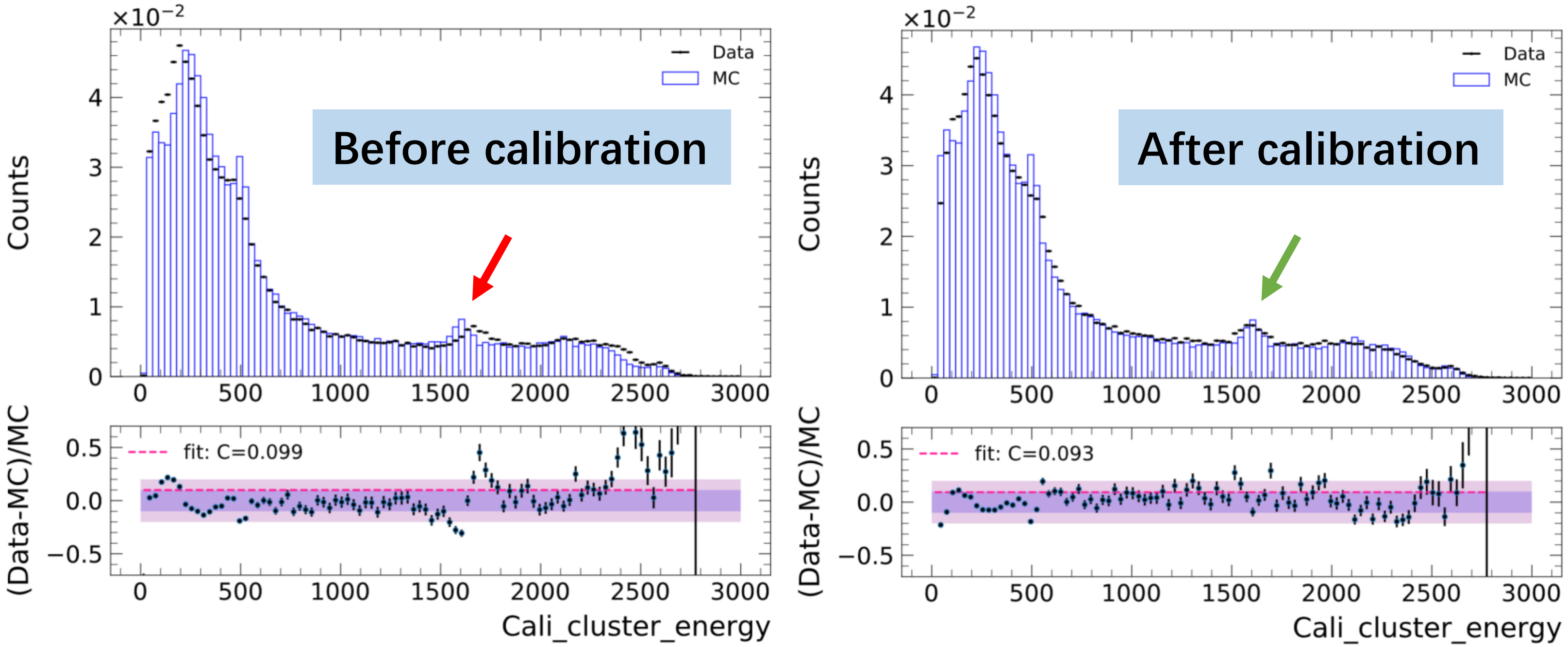
- Partial 3D events due to small energy may deposit without "V-wires signals"
- Require > 60% of energy deposits to be 3D reconstructed
- Doubles the 3D efficiency to ~95%

Cluster energy Calibration



Energy Peak Fit example for Co60 (top) and Th228 (bottom) in Phase I

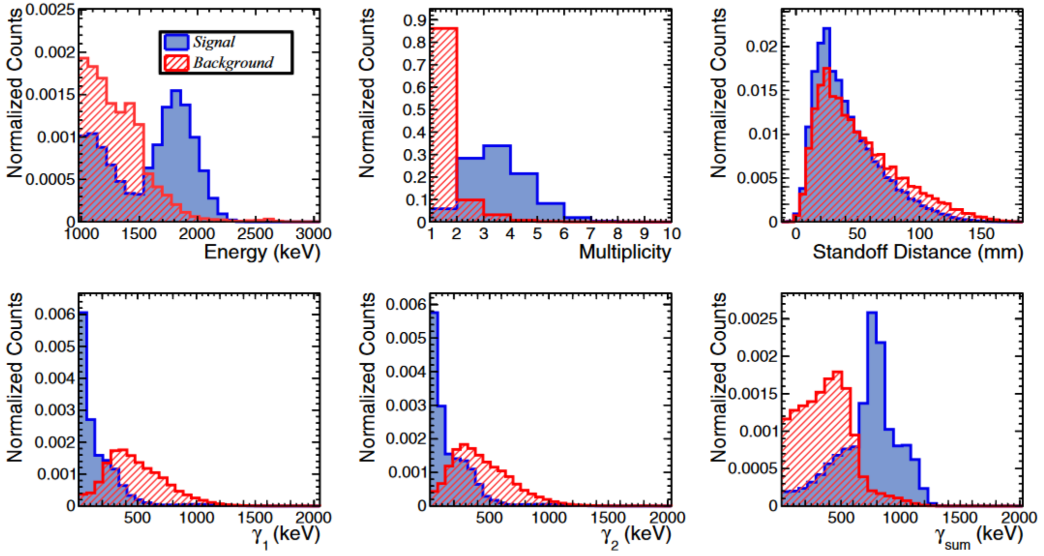
Th-228 MS, Phase-I



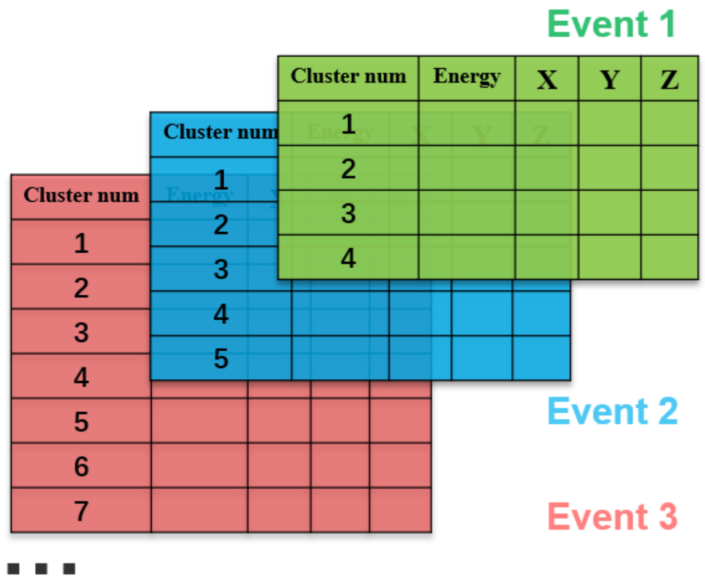
- Cluster energy, important inputs to ML
- In MC, no charge yield dependence on energy, while it is clear non-linear in data
- Obtain cluster energy calibration curve using SS event samples
- Significantly improved the data/MC agreement, with any residual properly taken into account in the shape error evaluation later

Background separation improvement

- BDT used several derived event-level variables (2016)
  - No information on spatial correlation among clusters
  - Maybe incomplete information on energy correlation among clusters
- Lower level information retains more intrinsic correlations
  - Realistic technical difficulties if using waveforms
- Choose Cluster (e, x, y, z) as ML input (this work)



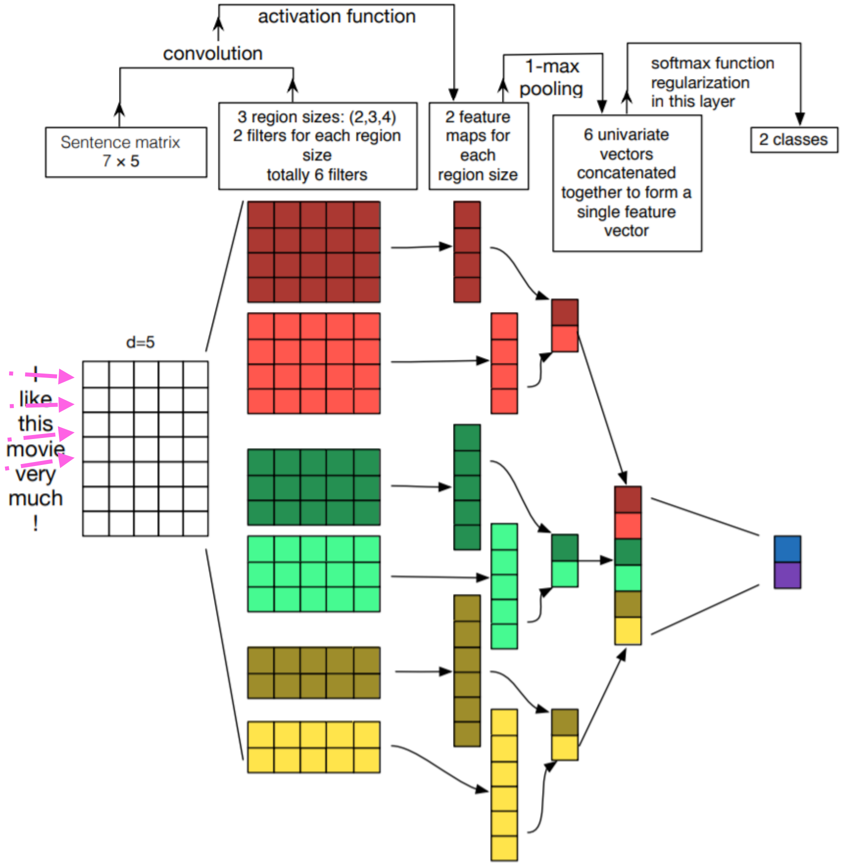
Phys. Rev. C 93 (2016), 035501



ML algorithm for background discrimination

Cluster num	Energy	X	Y	Z
1	301.3	-27.7	33.2	63.4
2	422.1	61	0.8	23.6
3	1072.6	13.6	16.1	67.7
4	722.3	133.1	-9.5	0.6

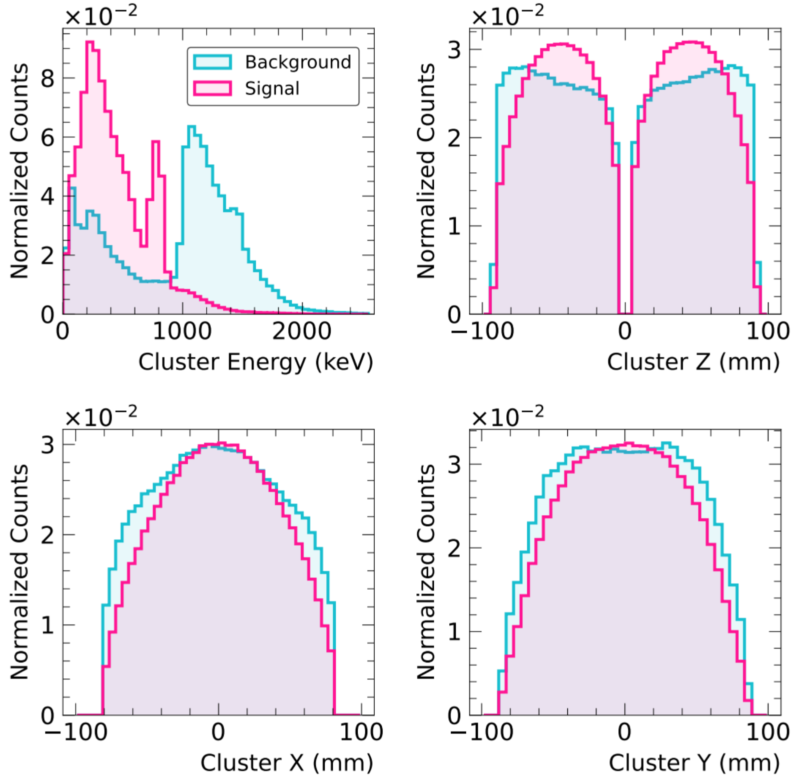
Event input

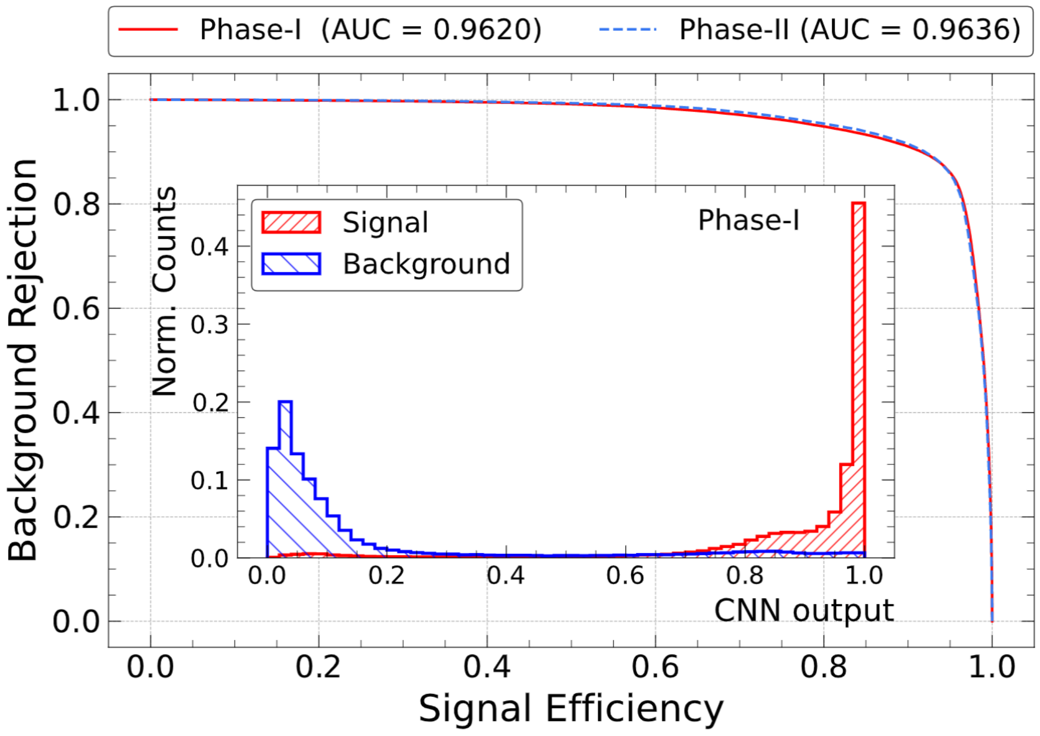


Schematic diagram of TextCNN

- ML input: cluster (e, x, y, z)
- TextCNN usually for natural language processing, suitable for input of cluster (e, x, y, z)

Network training





Distributions of the input variables in Phase II

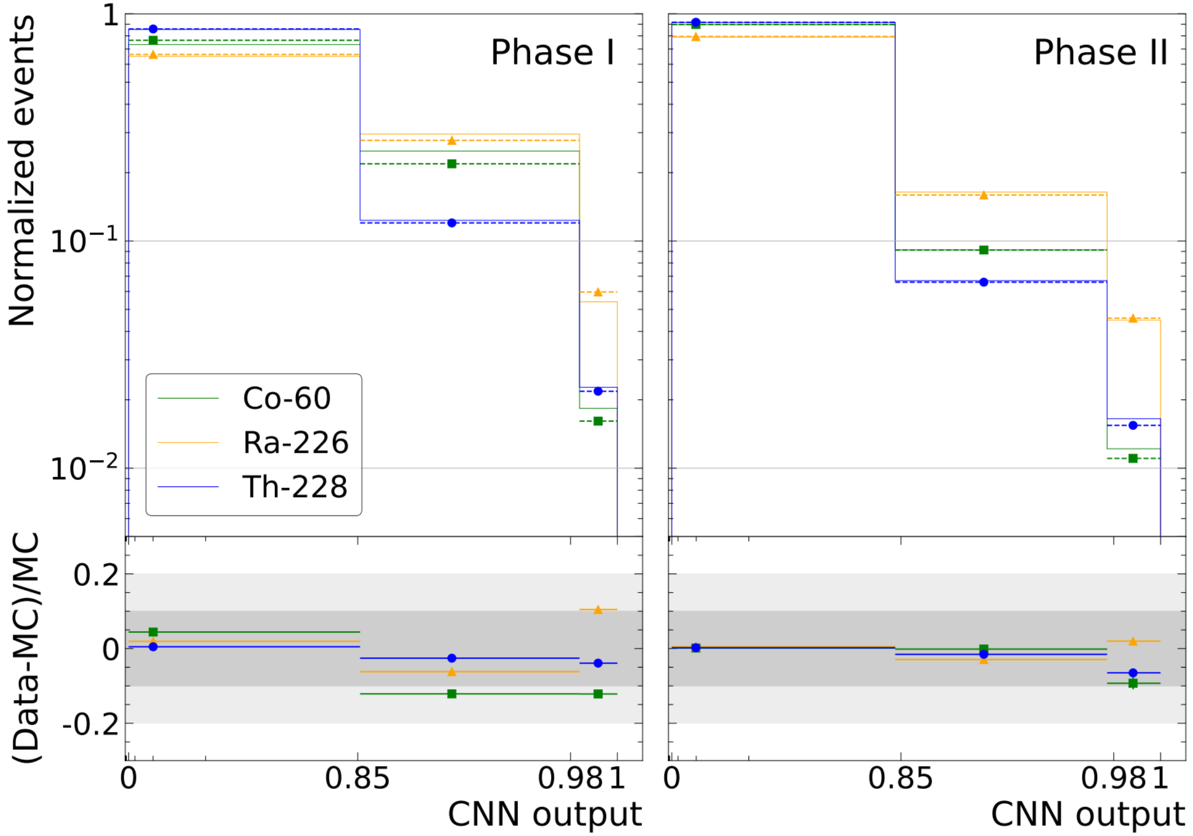
ROC curves of CNN discriminators in Phase I and Phase II

- Training dataset
  - 1.8M events for training, with equal stats for signal and background
  - Background fractions determined by the e-only fit to the low background data

- The network performance of the two phases is very similar
- Performance on partial 3D events is comparable to full 3D events, though slightly worse

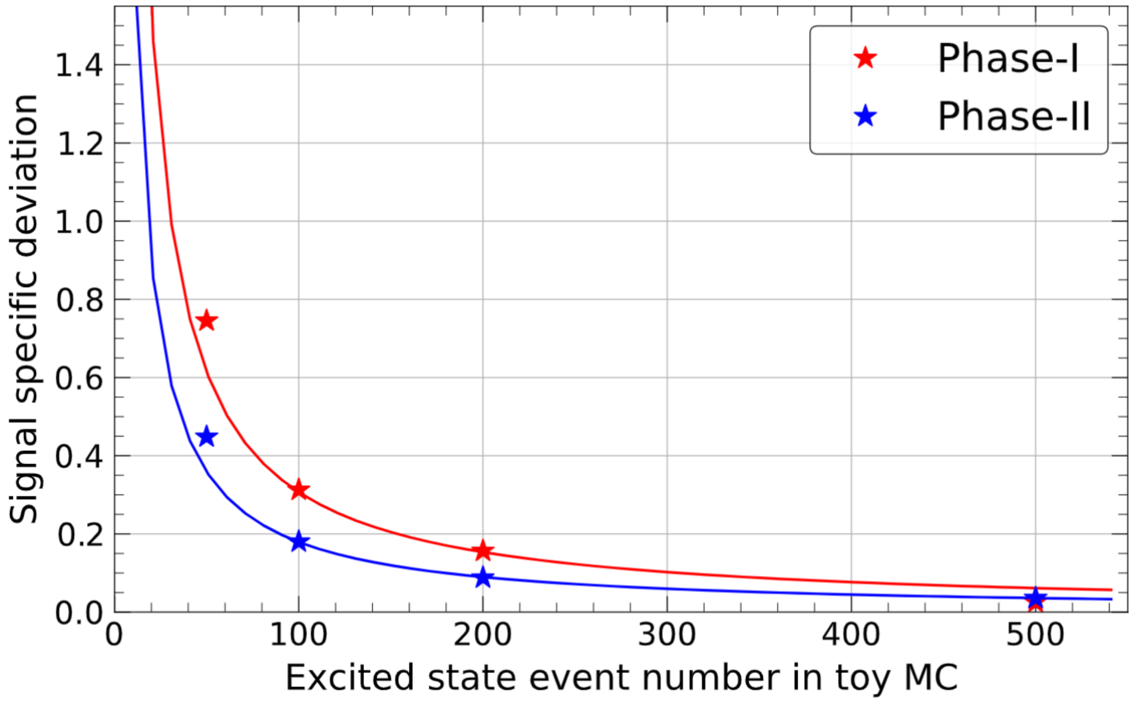
ML shape agreement

- Binning method: equal signal counts in CNN output bins (3 bins)
- Discrepancies in the shape agreement between data/MC are checked with calibration sources
  - agreement within ~15%
  - Phase-II agrees better than Phase-I over the full spectrum
- Residuals are taken into account as systematic uncertainties on normalization of signals



Shape agreement plots for CNN

Signal specific error



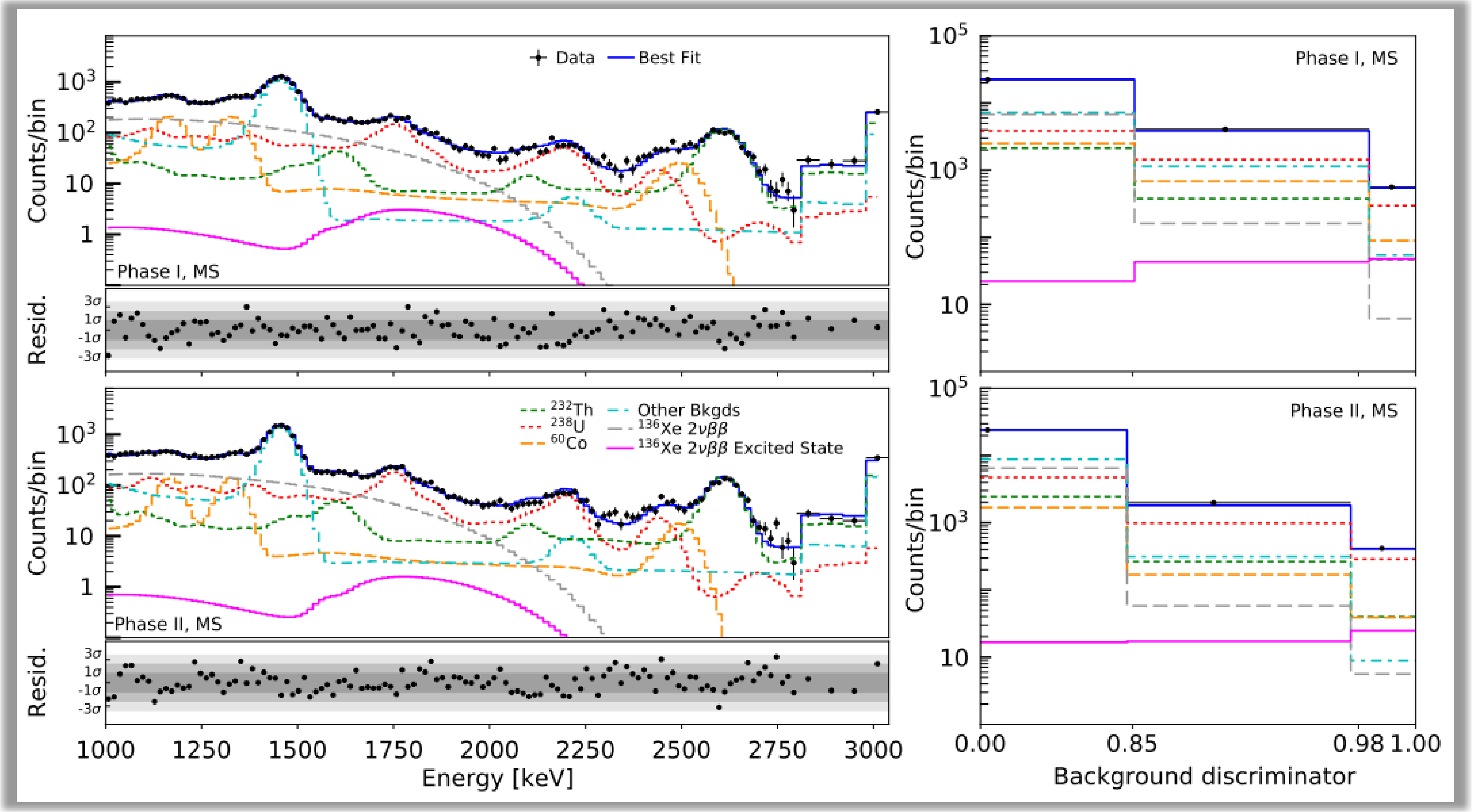
The signal specific error vs excited state event

Summary of systematic errors

	Phase-I	Phase-II
Common normalization	3.1%	2.9%
SS fraction	5.8%	4.6%
nCap fractions	20%	20%
^{222}**Rn**	10%	10%
Signal-specific normalization	a=30.7	a=17.9

- Get spectral shape error by weighted toy dataset observed data/MC ratio based on the calibration data
- Signal specific error dominant by shape error
- The signal-specific error is fit with the expression: $\sigma_{signal}/N = a/N$,where N is signal counts
- Other systematic error as in the final $0\nu\beta\beta$ paper: 2019 $0\nu\beta\beta$Analysis

Unblinded data fit



- 2-dimension fit in both SS and MS: **E + DNN**
  - SS, MS relative contributions constrained by SS fraction
- Background model + data → maximum likelihood fit

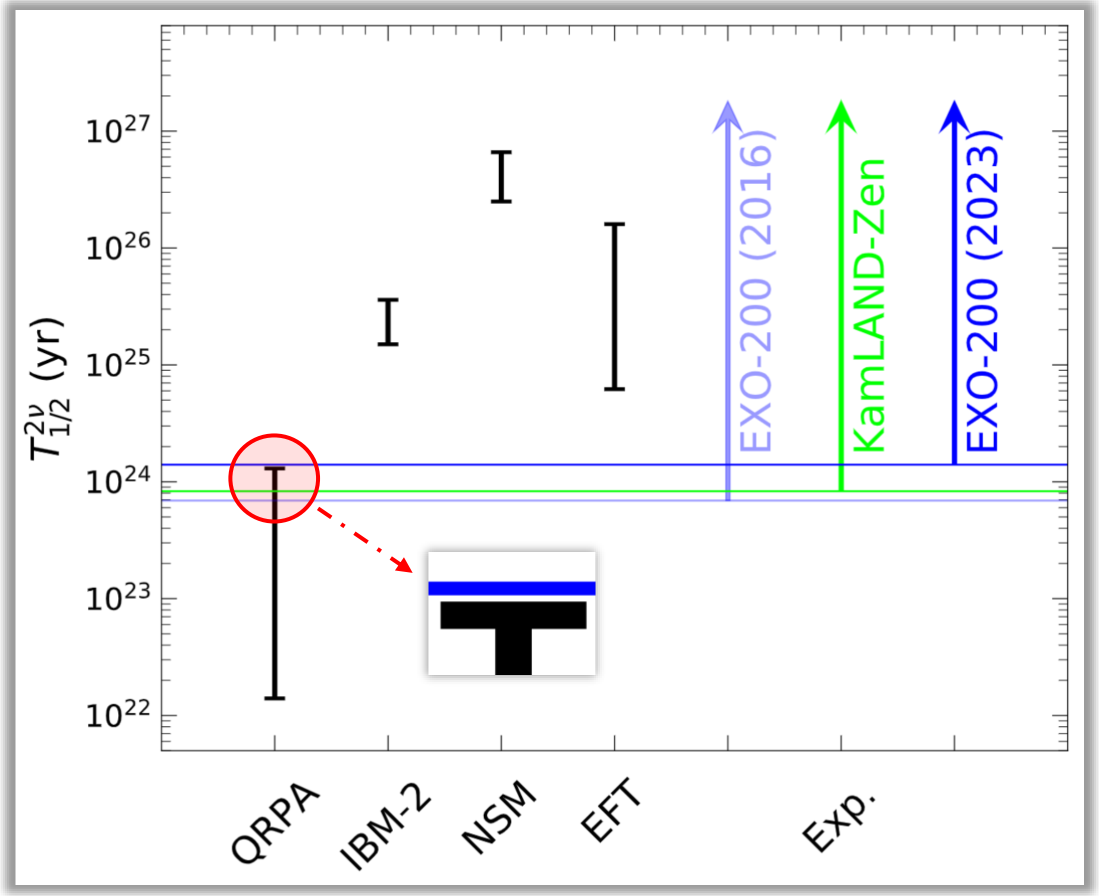
arXiv:2303.01103

Unblinded data fit

- The combined profile obtained by profiling each phase over $n/\epsilon L$, then adding the profiles together
- **No statistical significant signal observed**
- Limit: $T_{1/2}^{2\nu\beta\beta(ES)} > 1.4 \times 10^{24}$ yr (90% C.L.)
- Sensitivity: 2.9 $\times 10^{23}$ yr (90% C.L.)
- 1.7 improvement over the current world's best constraint (KL-Z 2016)
- In tension with the values predicted by QRPA

Unblinded data fit results

	Data limit($\times 10^{24} yr$)		
	P1	**P2**	**Combined**
E + CNN	**0.93**	**1.38**	**1.36**



Summary

- EXO-200 has concluded its successful operation as of December 2018
- New results highlighted in this talk:
  - The ^{136}Xe $(0^+ \rightarrow 0_1^+)$ process is searched : $T_{1/2}^{2\nu\beta\beta(ES)} > 1.4 \times 10^{24} yr$ (90% C.L.)
- The next generation 5-ton nEXO will improve the search capability for this process (with lower backgrounds and more exposure) in addition to the 10^{28} yr sensitivity to $0\nu\beta\beta$

Thanks for listening!

Sensitivity study

Combined sensitivity results

	Asimov dataset		~1k toy datasets		Sensitivity($\times 10^{24} yr$)		
Phases	**P1**	**P2**	**P1**	**P2**	**P1**	**P2**	**Combined**
E + CNN	103.8	87.1	105.6	94.8	$\mathbf{2.0^{+1.1}_{-0.7}}$	$\mathbf{2.2^{+1.5}_{-0.8}}$	2.9

- 2-dimension fit in both SS and MS: **E + DNN**
  - SS, MS relative contributions constrained by SS fraction
- The Phase I sensitivity is improved by 15% from the BDT-based approach in 2016 paper.