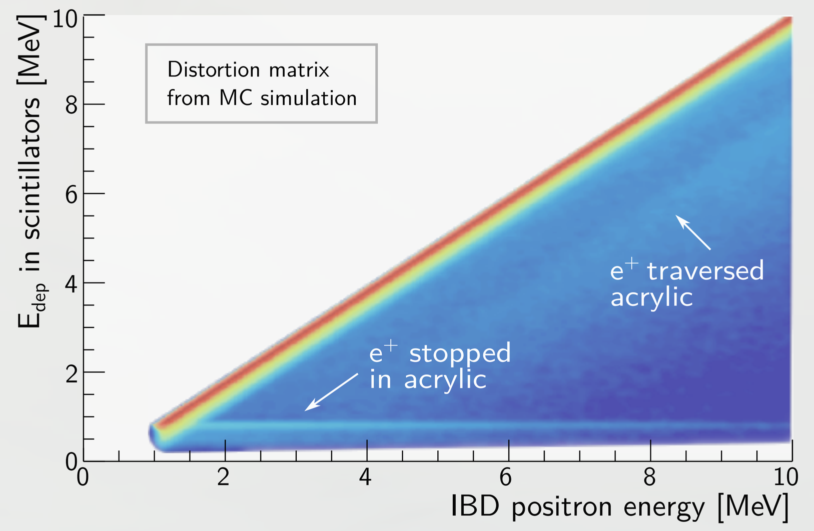
Modeling the energy response of the Daya Bay antineutrino detectors

Goal: establish positron energy scale from inverse beta decay (IBD) interactions in a 1-8 MeV energy range

Sören Jetter, IHEP, CAS, Beijing

on behalf of the Daya Bay collaboration

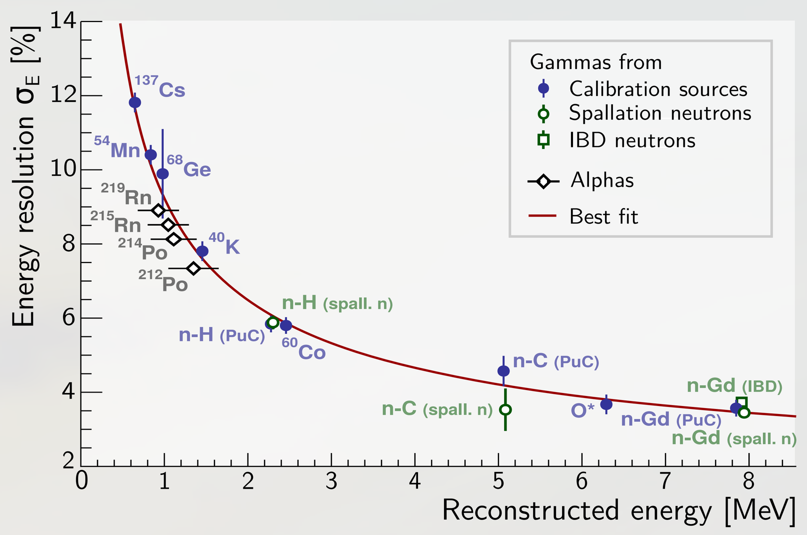
Energy losses in acrylic vessels



- Detector targets enclosed by non-scintillating acrylic vessels
- Kinetic energy of positrons near acrylic vessels not fully converted to scintillation light (~13% of all IBD positrons)
- Positron annihilation gammas with longer range can also deposit energy in scintillators
- Introduces spectral distortion at around 1 MeV

Extracted from MC simulation

Energy resolution



$$\frac{\sigma_E}{E} = \sqrt{a^2 + \frac{b^2}{E} + \frac{c^2}{E^2}}$$

a = 0.015: Spacial/temporal resolution
b = 0.087: Photon statistics
c = 0.027: Dark noise

- Radioactive calibration sources at detector center
- Additional data from IBD + spallation neutrons, uniformly distributed in scintillators
- Alpha source data used to cross-check result

Constrained by gamma data

Particle kinetic energy E_{true}

↓

Energy deposited in scintillating volumes E_{dep}

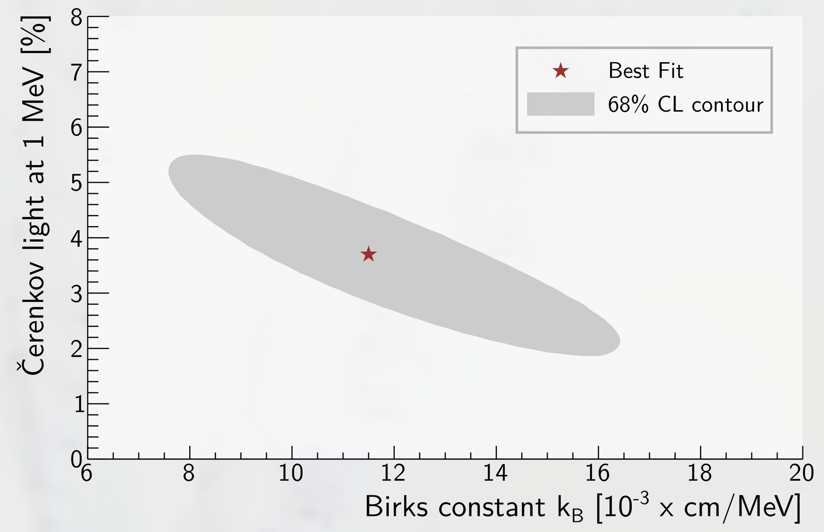
↓

Energy converted to visible light E_{vis}

↓

Energy seen by readout electronics E_{rec}

Non-linear response from liquid scintillators



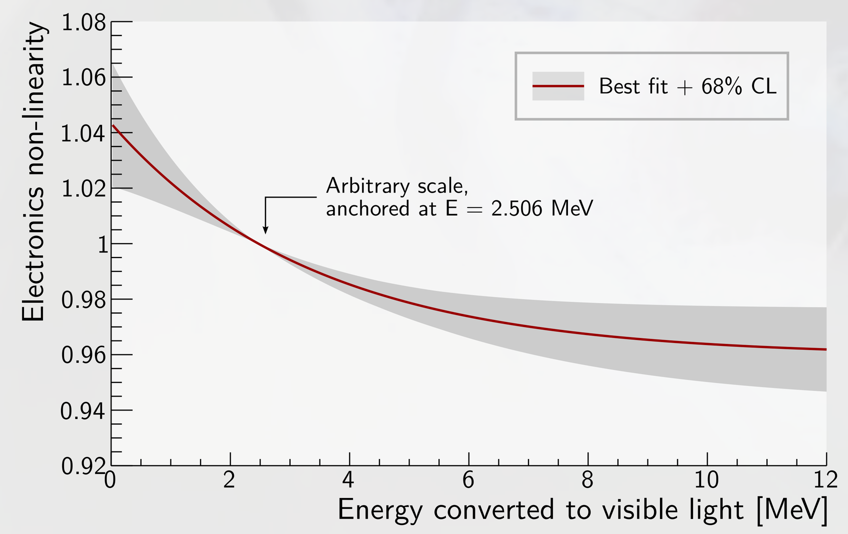
- Decrease in light yield due to ionization quenching
- Emission and absorbtion/re-emission of Čerenkov light

Semi-empirical electron response model based on Birks law:

$$\frac{E_{vis}}{E_{true}} = f_q(E_{true}, k_B) + k_C \cdot f_c(E_{true})$$

k_B: Birks constant
k_C: Contribution from Čerenkov light

Non-linear response from PMT readout electronics



Electronics does not fully capture late secondary PMT hits
⇒ Slow scintillation light missed at high energies
⇒ Charge collection efficiency decreases with visible lighty

Cannot be easily calibrated out on single channel level
⇒ Use effective exponential model as a function of total visible energy

Scintillator and readout electronics model parameters constrained by fit to gamma+boron calibration data

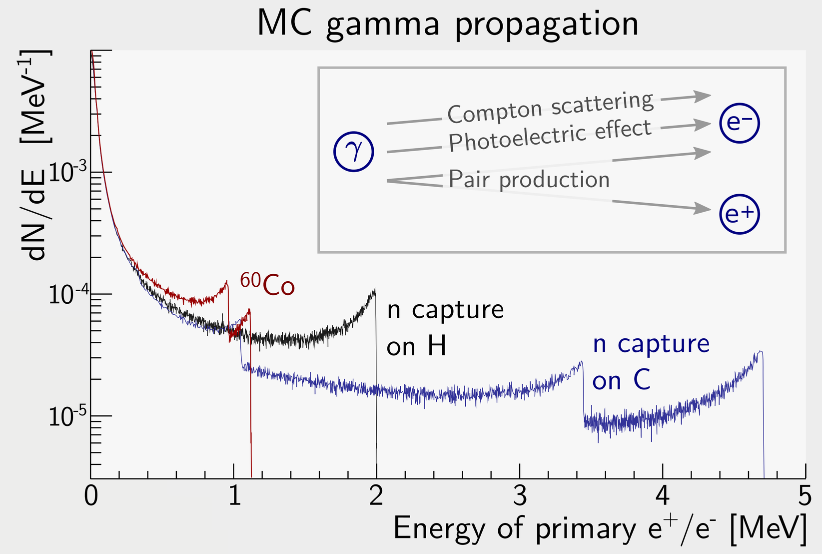
Unconstrained 5-parameter fit to γ+^{12}B data:

- Absolute energy scale
- Birks constant
- Relative contribution from Čerenkov light
- Size and decay constant of electronics model

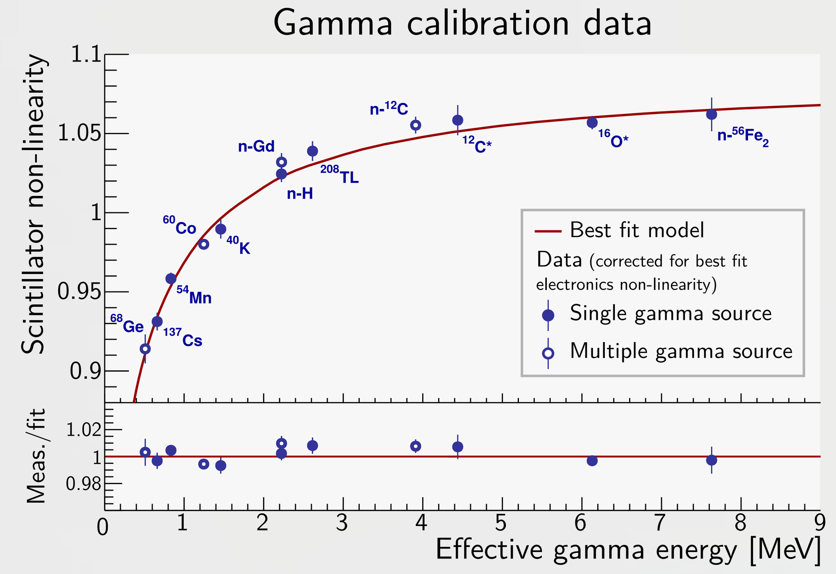
Gammas connected to electron scintillator model through MC:

$$E^{\gamma}_{vis} = \int E^{e^-}_{vis}\left(E^{e^-}_{true}\right) \cdot \frac{dN}{dE}\left(E^{e^-}_{true}\right) dE^{e^-}_{true}$$

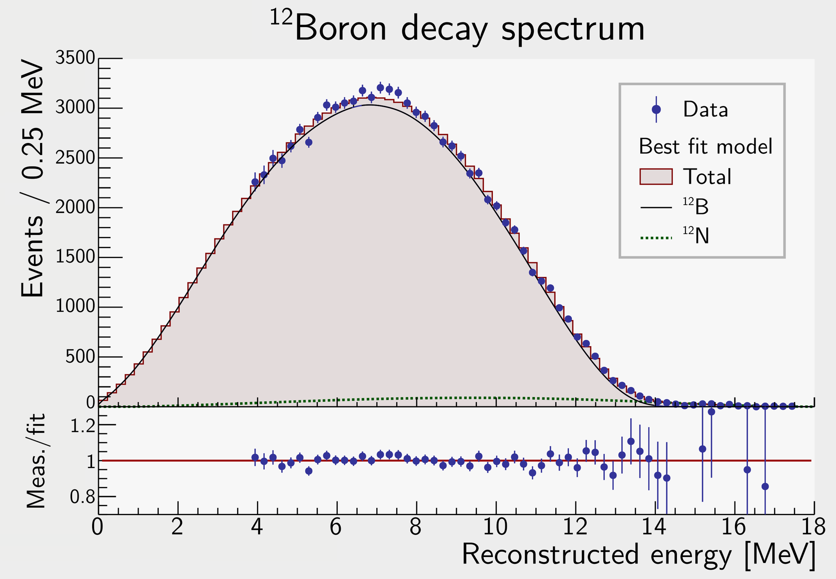
MC gamma propagation



Gamma calibration data



^{12}Boron decay spectrum

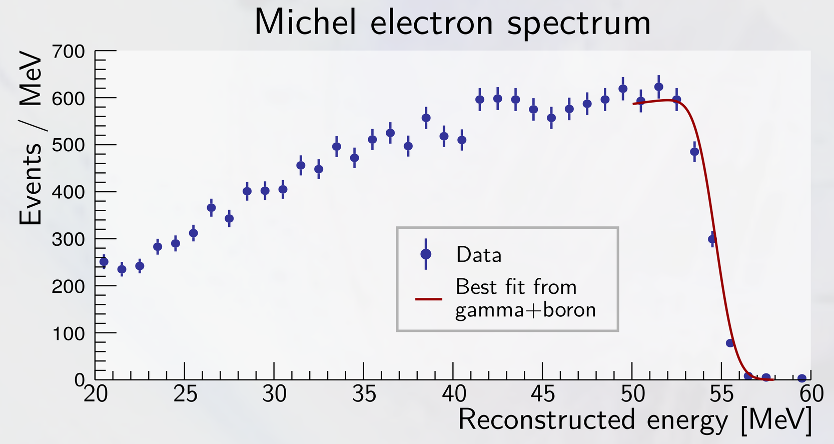


1. Monoenergetic gamma lines from various sources
   - Radioactive calibration sources employed regularly: ^{68}Ge, ^{60}Co, ^{241}Am^{13}C
   - Sources employed during special calibration periods: ^{137}Cs, ^{54}Mn, ^{40}K, ^{241}Am^{9}Be, Pu^{13}C
   - Singles and correlated spectra in regular physics runs: ^{40}K, ^{208}Tl, neutron capture on H, C, Gd
2. Continuous spectrum from ^{12}B produced by muon spallation inside scintillating volumes

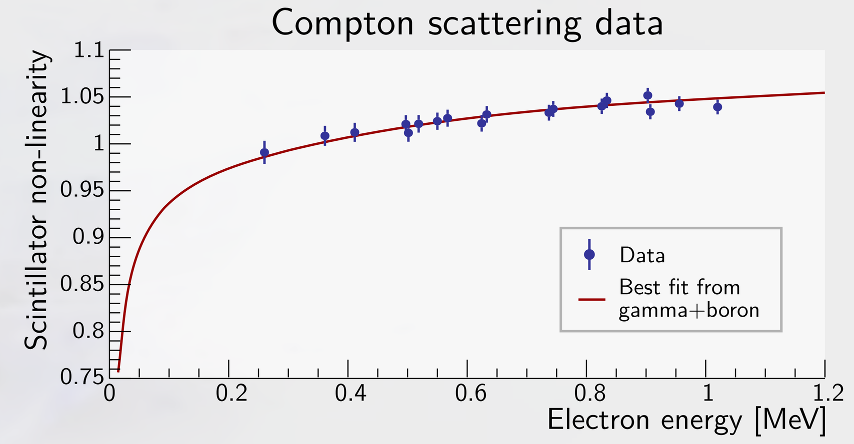
Validation with additional calibration data

- 53 MeV cutoff in michel electron spectrum from muon decays
- Continuous beta+gamma spectra from bismuth and thallium decays
- Benchtop scintillator response measurement using compton electrons
- Calibration of readout electronics response using flash ADC

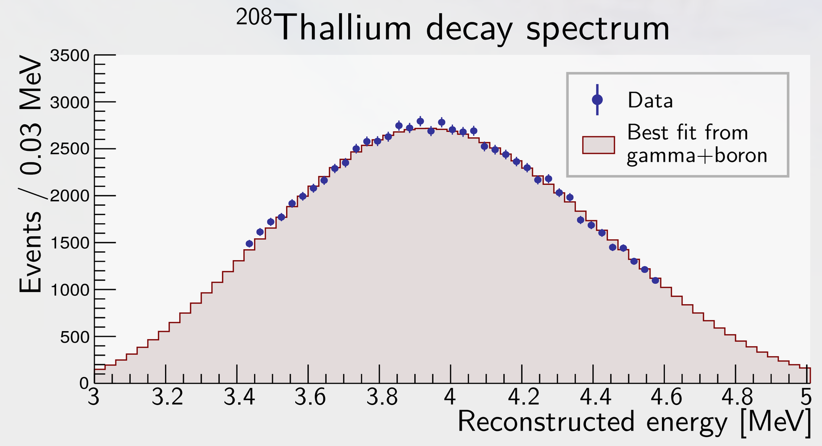
Michel electron spectrum



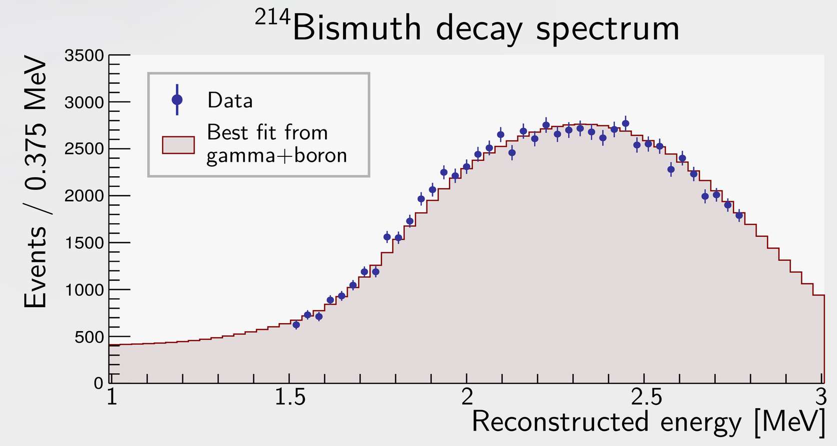
Compton scattering data



^{208}Thallium decay spectrum

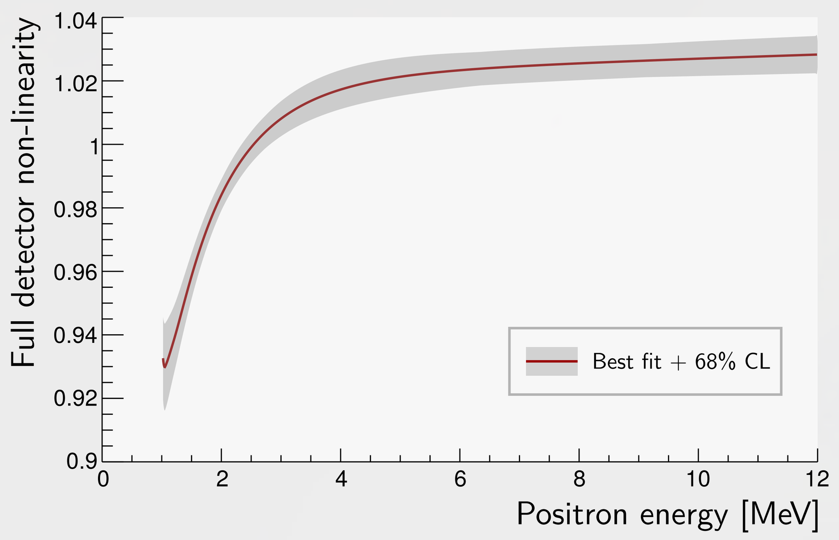


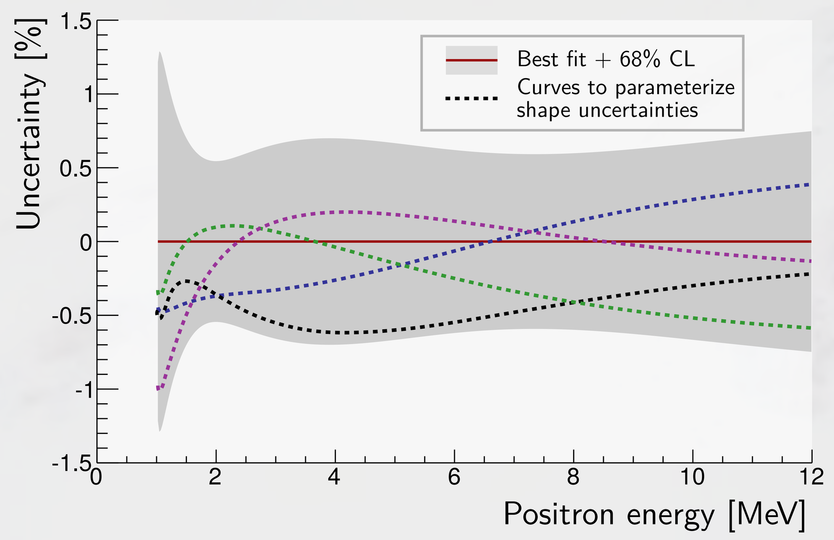
^{214}Bismuth decay spectrum



- **All data consistent with prediction from gamma+boron constrained energy model**
- **Best fit model stable within 68% CL when including additional data constraints**

Full IBD positron non-linearity model





- Ionizing positrons assumed to interact with scintillator in same way as electrons, full response computed from electron curve + 2 annihilation gammas:
  $$E^{e^+}_{vis} = E^{e^-}_{vis} + 2 \cdot E^{\gamma}_{vis}(0.511\,\mathrm{MeV})$$
- 4 curves numerically selected from 1-sigma phase space to parameterize shape uncertainties
- **Sub-percent overall uncertainty from non-linear response model**
- **Reduced dependency on reactor models in oscillation analysis**
- **Crucial for measurement of reactor spectrum**

contact: jetter@ihep.ac.cn

background image: interior of one of the Daya Bay antineutrino detectors