ISS-RAD Fast Neutron Detector (FND) Simulation and Data Unfolding- Status Report

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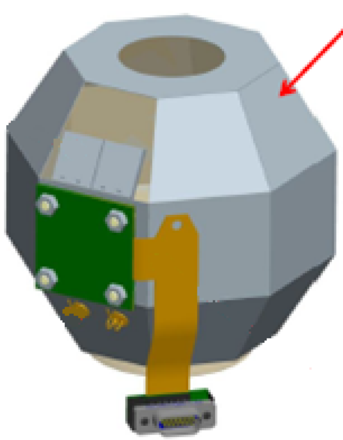
on behalf of the NASA SRAG ISS-RAD team

Workshops on Radiation Monitoring for the International Space Station

09/10/15

Outline:

1. **Introduction: Light function formalism**
2. **Light function calibration**
3. **Regularized unfolding**
4. **Validation on generated data**
5. **Summary & Outlook**



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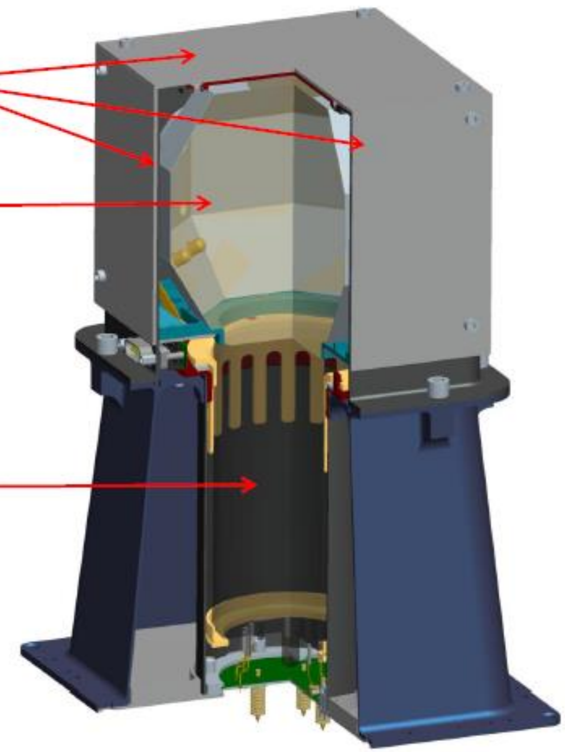
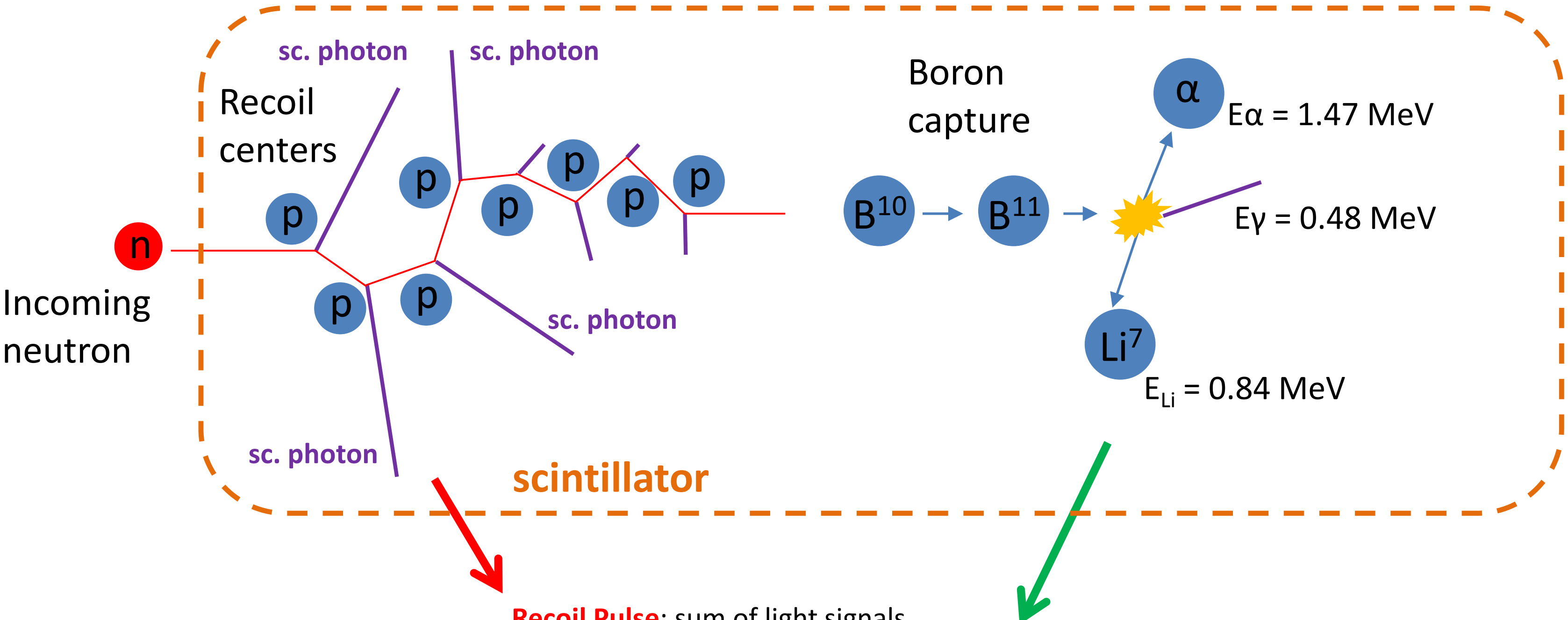


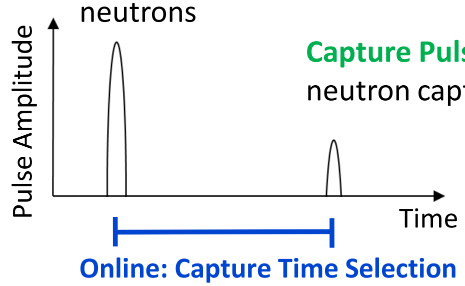
1. Introduction: Detection/Selection Mechanism: Boron-loaded Scintillator

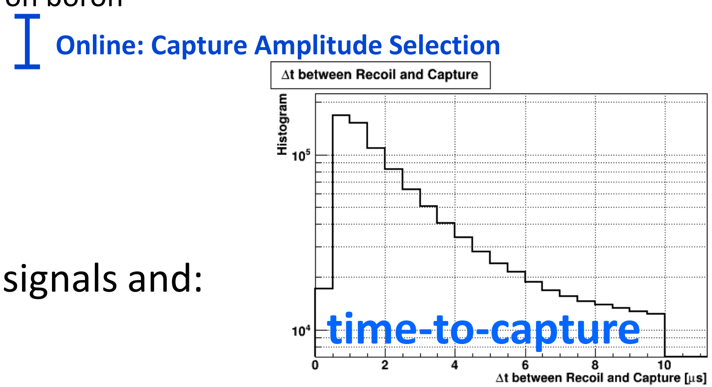
- Neutrons deposit energy in plastic scintillator, some captured by ^{10}B atoms:



Recoil Pulse: sum of light signals produced during deceleration of neutrons

Capture Pulse: light produced by neutron capture on boron



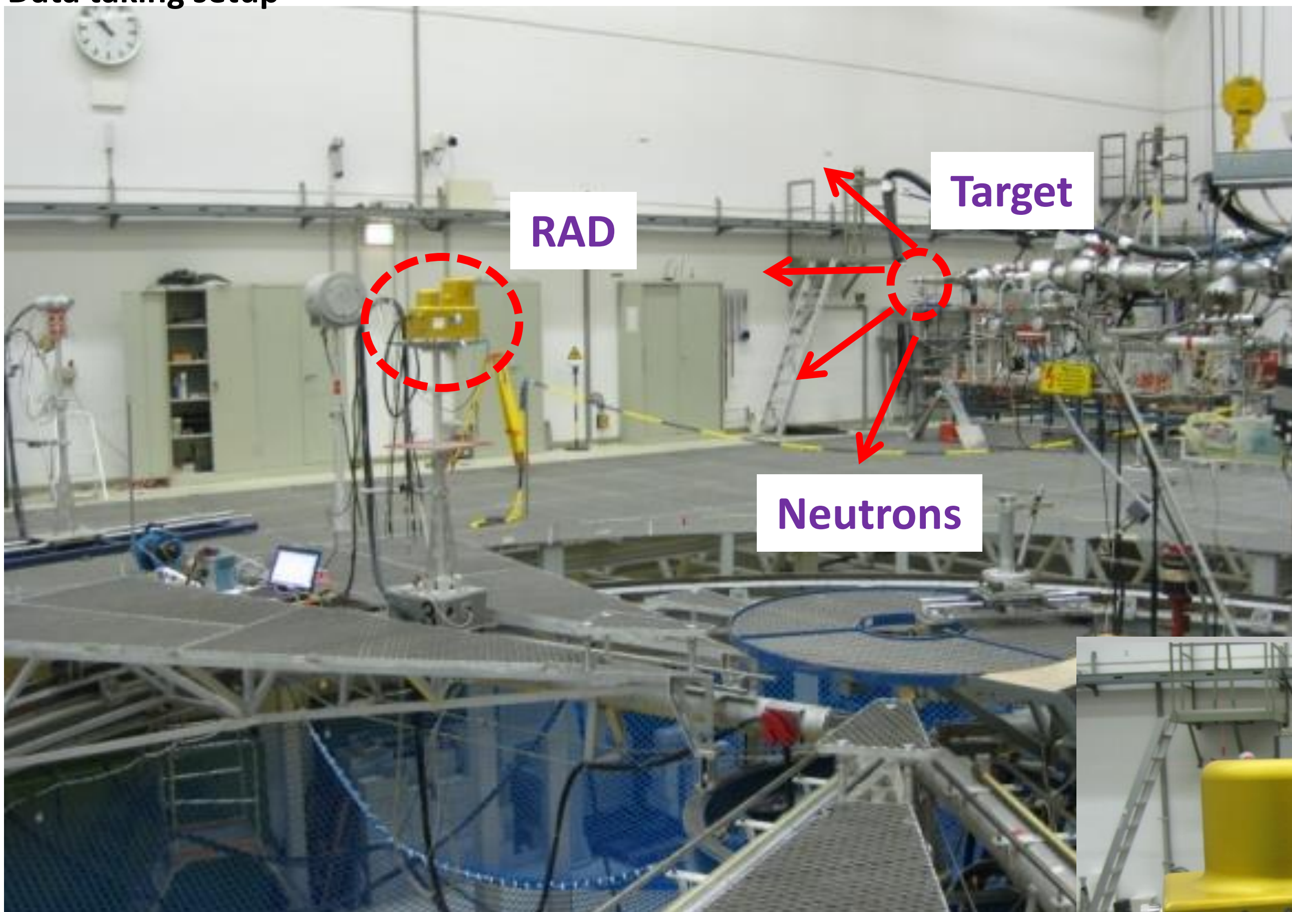


- Measurements of **recoil** and **capture** photon signals and:

1. Introduction: Response Spectrum Shape

- ‘Monoenergetic’ neutron calibration (ΔE < 5%) at PTB, Germany:

Data taking setup

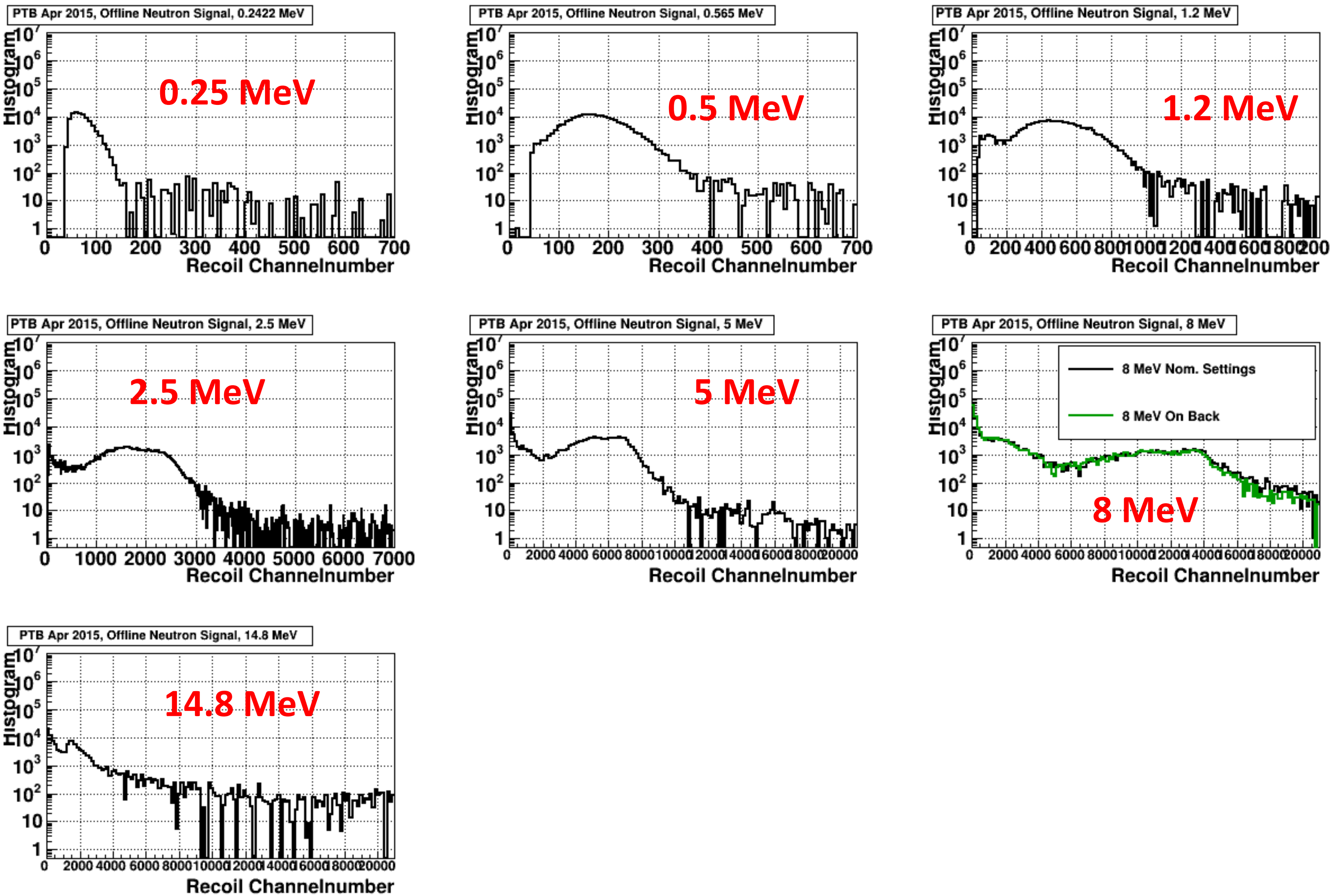


p, d Beamline

FND on beam axis/in forward scattered field at 2.5m from target

1. Introduction: Response Spectrum Shape

- Filtered ADC spectrum in response to monoenergetic neutron fields (after background subtraction):



1. Introduction: Scintillation Light Creation/Propagation: Light Function Formalism

- Shape of response spectra dominated by factors impacting collected light:

a) Multiple scattering of neutron with scintillator material nuclei: multiple pulses of scintillation light per neutron

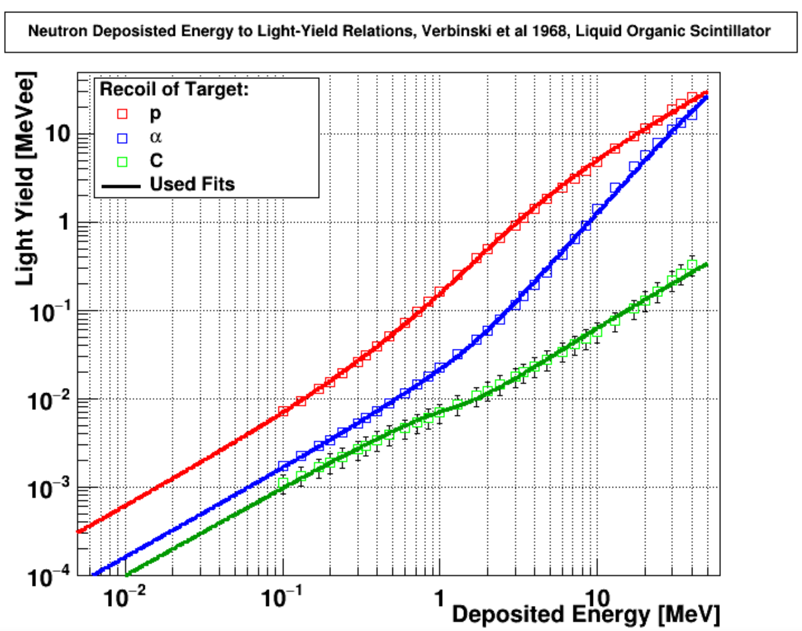
b) Scintillation light quenching (ionization quenching- Birk's law): nonlinear amount of collected scintillation light per interaction depending on energy deposit & scattering target

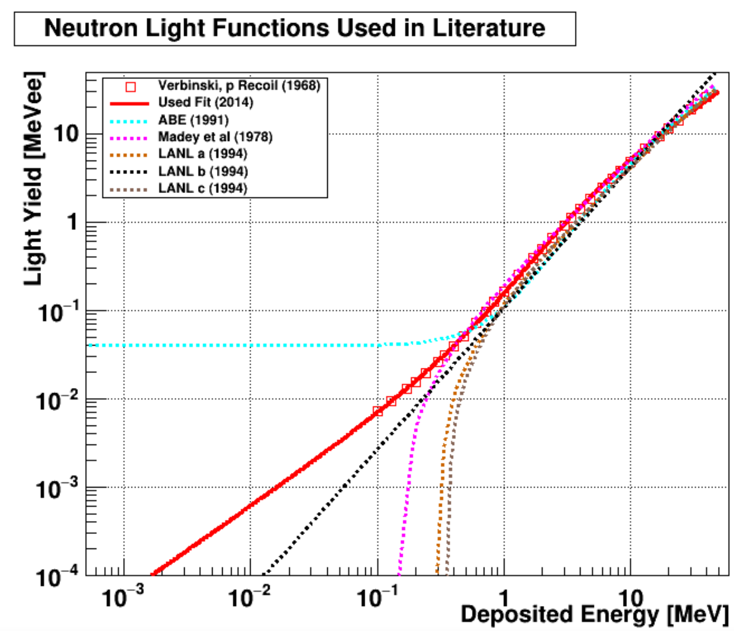
Even monoenergetic neutrons create broad distribution in light deposit/FND recoil spectra.

- Approach describing scintillation light generation in multiple scattering: Light function formalism
- Measurements/parameterization of light functions: Verbinski et al, 1968 (liquid scintillator):

Literature: Neutron recoils on...

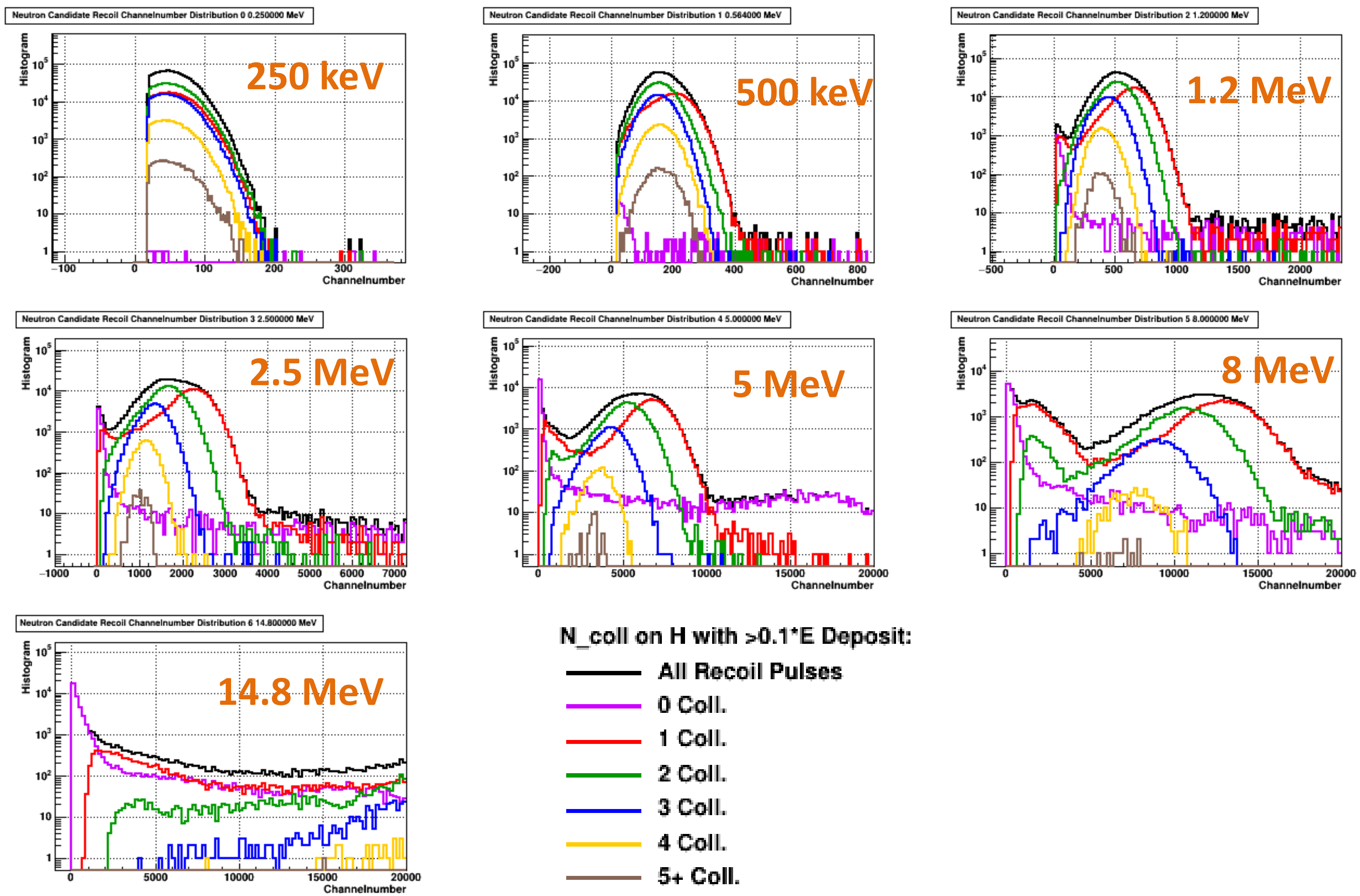
V.V. Verbinski et al, NIM 65 (1968) 8 ff





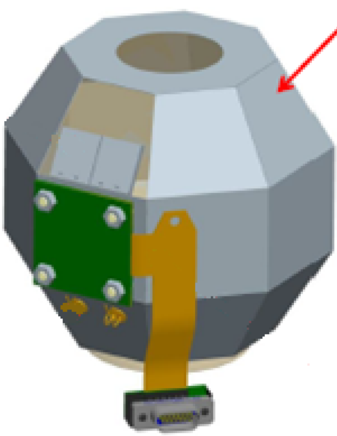
1. Introduction: Scintillation Light Creation/Propagation: Light Function Formalism

- Example: End-to-end FND simulation (MCNP-PoliMi and FND signal processing algorithms) for monoenergetic neutron fields at PTB (FM002 calibration)
- Spectral shape driven by number of high energy deposit neutron collisions off hydrogen:



- For result with finer energy binning than experimental data: apply light function formalism

2. Light function calibration



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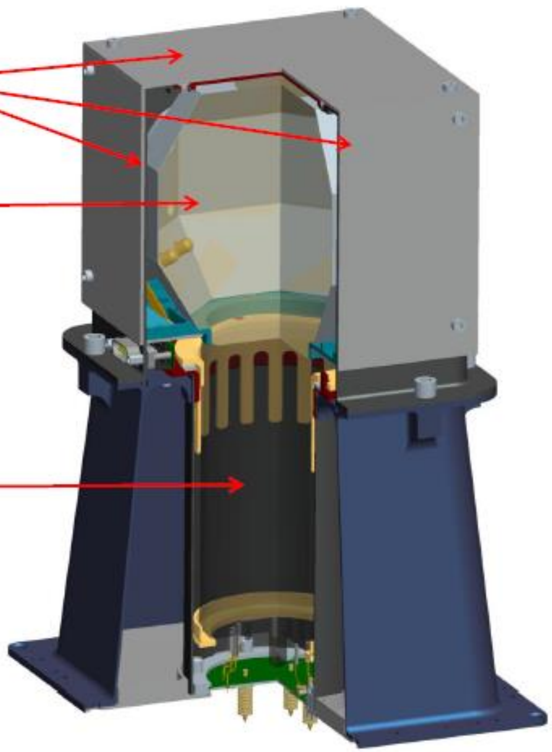


2. Light Function Calibration- Flowchart

- Goal: Extract continuous light function describing scintillator behavior to freely choose energy binning
- For each experimental monoenergetic data sample, start from first principles:

a) Create energy deposit files

a.1) Generate MCNP-PoliMi energy deposits per neutron-target interaction vs. time, for experimental energies

→ a.2) 'Time-connect' independent MCNP source events for respective Poisson-distributed event rate

b) Light function calibration

Create recoil spectra

→ b.1) Convert energy deposits to light yield with **light function**

→ b.2) Apply **resolution** (scintillator, PMT, pulse processing electronics)

→ b.3) Simulate light collection and pulse digitization in FND PMT and electronics

→ b.4) Convert to channelnumber values using photon calibration results

→ b.5) Apply FND FPGA pulse pair selection logics

→ Fill recoil spectrum

for each energy deposit (~5M per energy)

Check against experimental spectra

→ b.6) Apply chance coincidence subtraction, scale factor (efficiency not part of optimization, just product)

→ Check match to experimental data

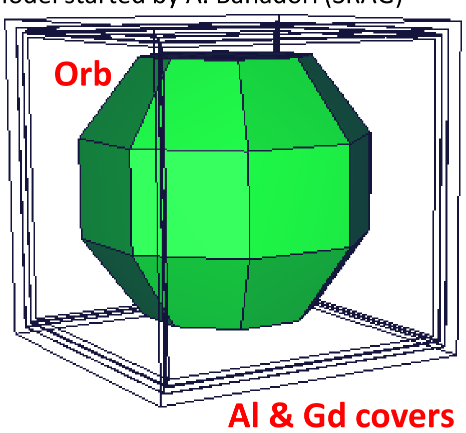
→ **Adjust light function and resolution**

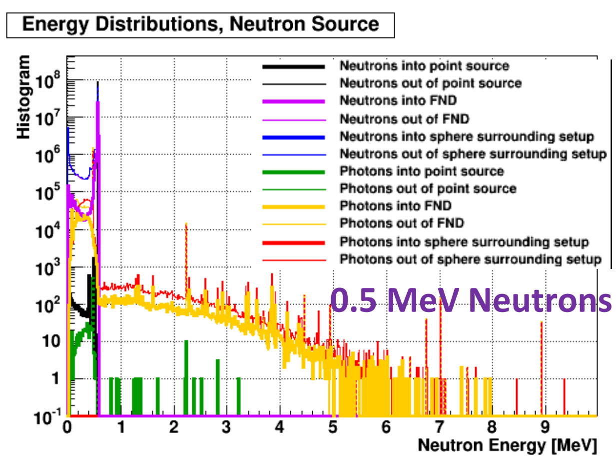
optimization loop for each energy sample

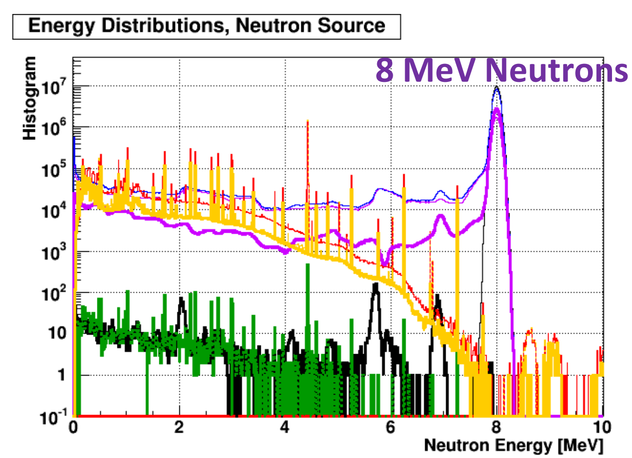
2.a.1 Generation of Neutron Energy Deposits: MCNP-PoliMi

- Use MCNP-**PoliMi** package:
    * MCNP limitations for neutron propagation and fission/inelastic scattering simulation:
        @ only returns total energy deposition of each neutron in target volume for conversion to light
        @ photon and neutron productions in fission/inelastic collision events not correlated in time/energy/multiplicity
    * PoliMi package writes out each interaction of single neutrons and photons
        @ time correlation within each single history, resolution in 100 ps
        => energy-to-light conversion possible on per-interaction-basis
        @ elastic, (n,gamma) and (n,n') interactions accurately modeled/propagated
    * Generations of 1e+08 n per experimental energy in bias cone around FND

Model started by A. Bahadori (SRAG)







2.a.2 'Time-connect' Neutron Energy Deposits from MCNP-PoliMi

- Output of PoliMi: ASCII file containing interactions of neutrons and photons with target material:

	History	Particle Number	Particle Type	Interaction	ZAID	Cell	Energy Deposited [MeV]	Time [Shakes]	X-Coord.	Y-Coord.	Z-Coord.	Weight	Generation Nr	Number of Scatters	Code	Energy Prior to Collision [MeV]
H-scatter	2805	1	1	-99	1001	10	3.589902	8.08	2.05	-1.30	-3.78	1.000E+00	0	0	0	4.958E+00
	2805	1	1	-99	1001	10	1.112997	8.28	0.39	0.26	-1.68	1.000E+00	0	1	0	1.368E+00
	2805	1	1	-99	1001	10	0.003554	8.79	2.27	2.43	0.51	1.000E+00	0	2	0	2.549E-01
	2805	1	1	-99	1001	10	0.181367	8.82	2.39	2.53	0.64	1.000E+00	0	3	0	2.514E-01
	2805	1	1	-99	6000	10	0.004136	8.82	2.39	2.53	0.65	1.000E+00	0	4	0	7.007E-02
	2805	1	1	-99	1001	10	0.043889	9.05	2.41	1.76	0.89	1.000E+00	0	5	0	6.590E-02
B10 Capture!	2805	1	1	0	5010	10	2.789669	24.20	-0.40	2.31	2.63	1.000E+00	0	14	0	1.375E-04
Capture photon	2805	2	2	1	6	10	0.099156	24.22	-1.92	0.93	-2.22	1.000E+00	0	0	801	4.776E-01

- Limitation in PoliMi: no transport of non-neutron/photon decay products of capture/fission reactions -> manually distribute recoil energy among decay products & convert to light

- To create realistic succession of neutron events in scintillator: 'time-connect' PoliMi events to experimental flux (30-310 /s/cm^2):

History	Particle Type	Interaction	ZAID	Energy Deposited [MeV]	Absolute Time [μs]
15	1	-99	6000	0.3258	200.9430278347747105272
15	1	-1	6000	1.223006	200.9446278347747067983
15	1	-99	1001	1.19312	200.9471278347747045245
20	1	-1	6000	1.153536	249.6897651601931613641
21	1	-99	6000	2.070328	258.0006369570315882811
35	1	-99	6000	0.027568	372.9355042009522662738
...					
99999932	1	-99	6000	0.009083	943205800.4175952672958
99999958	1	-99	1001	1.209701	943206036.2944241762161
99999988	1	-1	6000	0.332827	943206258.0235788822174
99999988	1	-99	1001	0.772745	943206258.0235788822174
99999997	1	-99	1001	1.429591	943206423.4481251239777

→ ~15 min

2.b.1 Convert Energy Deposit to Light- Function Parameterization

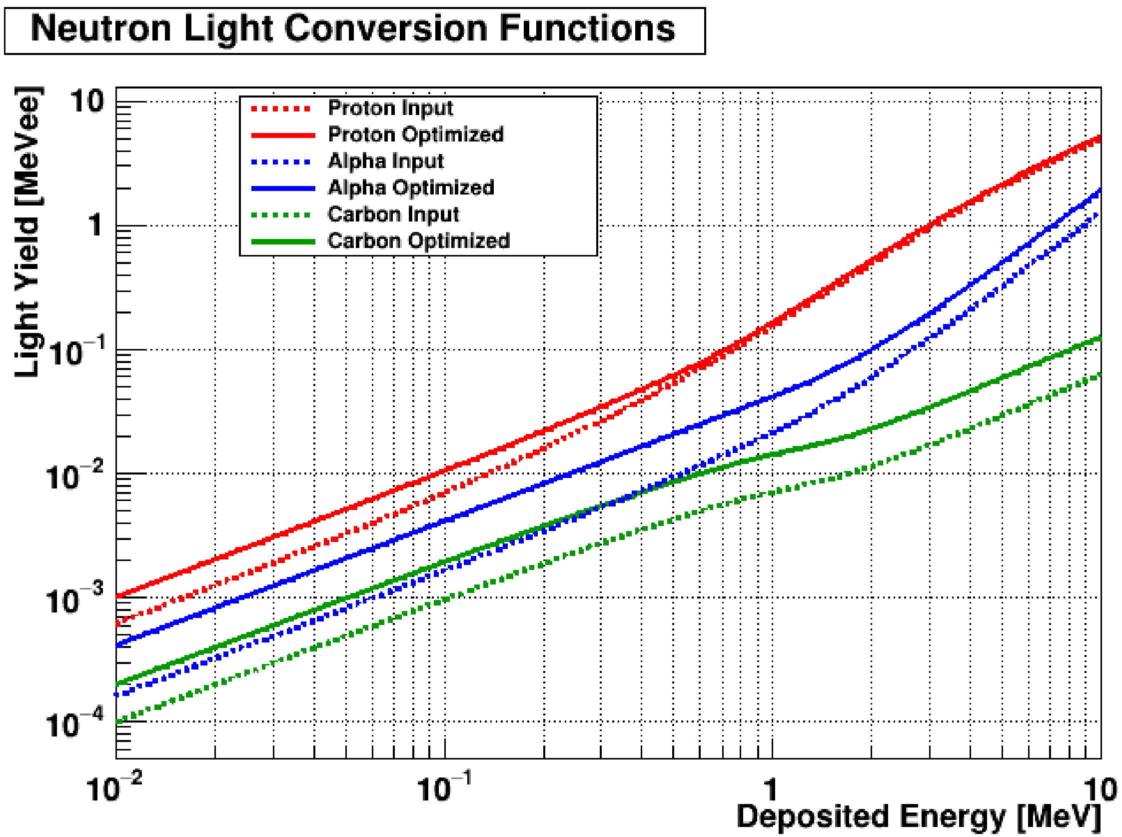
- Fit to Verbinski data parameterized as: 2nd order polynomial at low deposited energy; sqrt(const+E^2) at high energy
- Change 5 parameters to optimize match with experimental data

$$L(x_{ED}) = \begin{cases} \dfrac{a x_{ED} + b x_{ED}^2}{c + d\sqrt{e^2 + f^2 x_{ED}^2}} & \text{for x < g} \\ & \text{for x >= g, where} \end{cases}$$

$$a = \frac{d f^2 g}{\sqrt{e^2 + f^2 g^2}} - 2bg$$

$$c = ag + bg^2 - d\sqrt{e^2 + f^2 g^2}$$

Continuity requirements for 1st and 2nd derivative

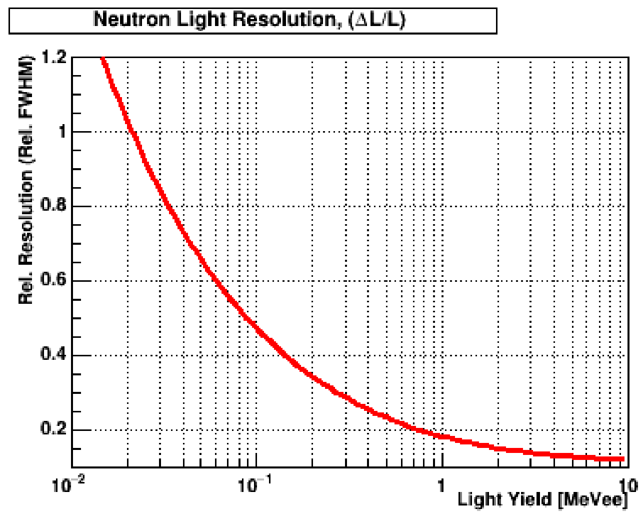


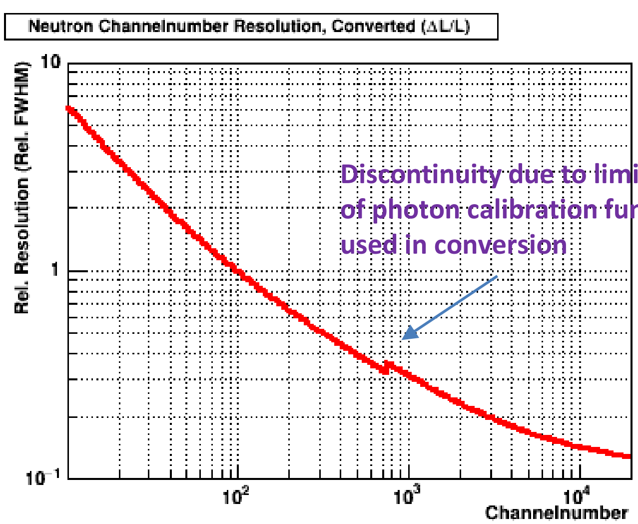
2.b.2 Apply Resolution- Implementation

- Single-point implementation of all experimental resolution contributions:
    * light production/quenching/reflections in plastic,
    * light coupling scintillator to PMT
    * PMT photon detection
    * electronic noise (PMT/amplifier) etc
- Optimize 3 parameters to match experimental data

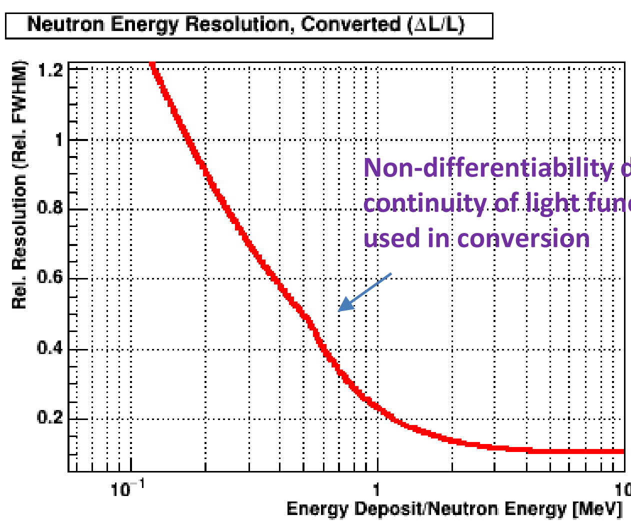
ΔL / L (rel. FWHM):

$$\frac{\Delta L}{L} = \left(\alpha^2 + \frac{\beta^2}{L} + \frac{\gamma^2}{L^2}\right)^{1/2}.$$





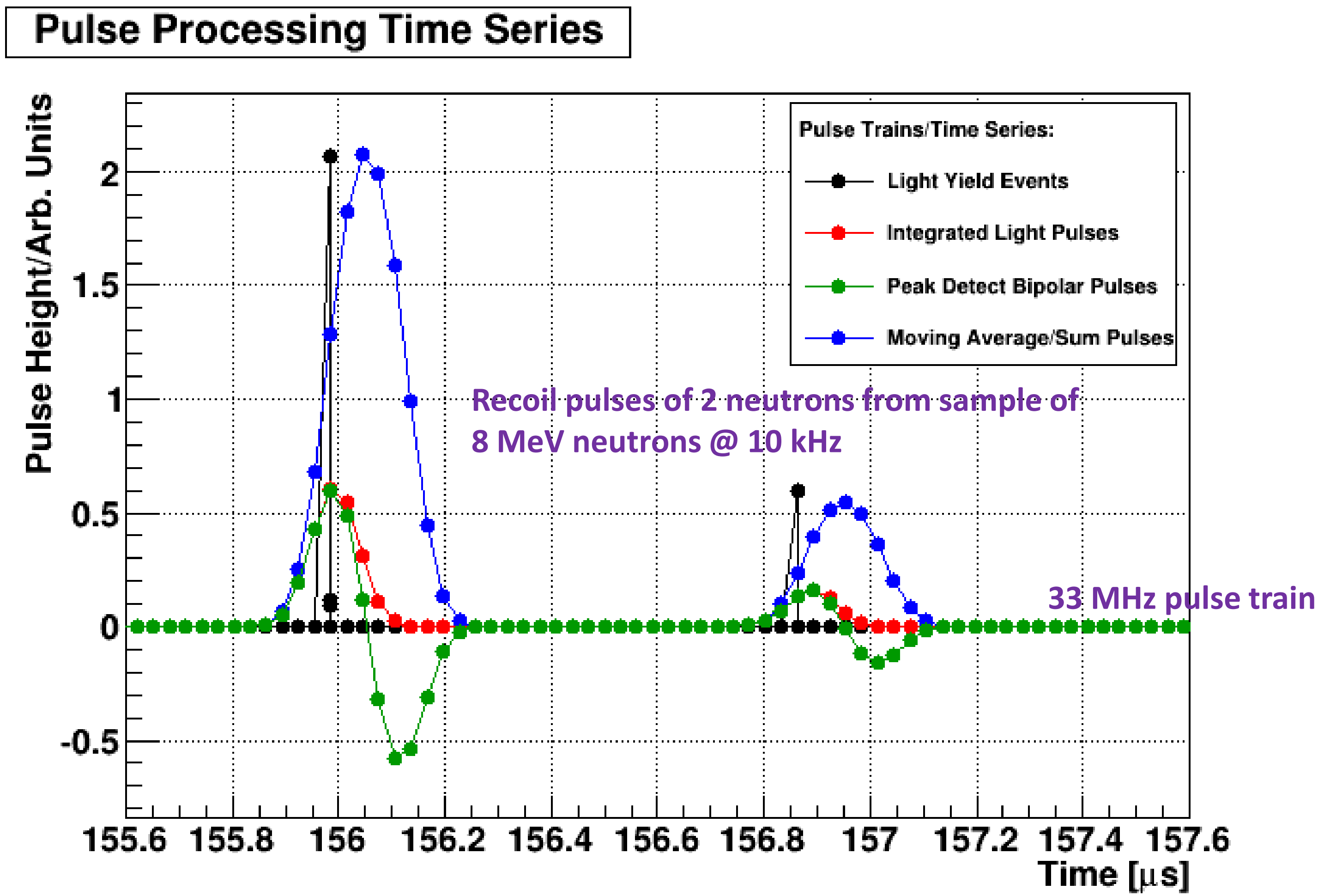
Discontinuity due to limited continuity of of photon calibration function (1st order) used in conversion



Non-differentiability due to limited continuity of light function (2nd order) used in conversion

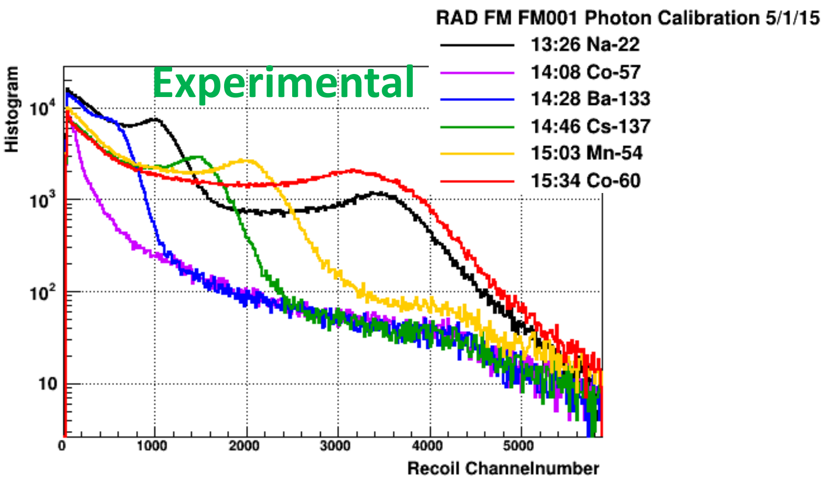
2.b.3 Light Collection/Pulse Digitization (see Michael V.'s talk)

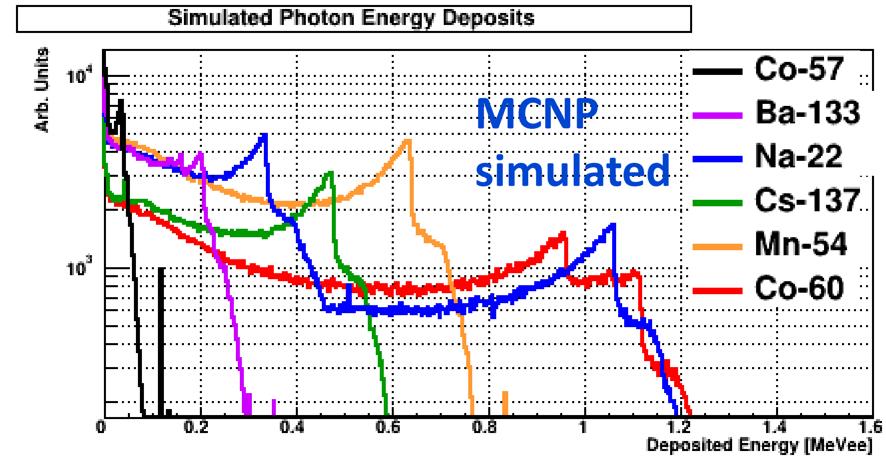
- Convert light yields to corresponding **electronics signal pulses** via Gaussian function sampled by 33 MHz clock; area normalized to light yield
- Two filters create **bipolar signals** for peak detection and '**moving average (sum)**' for signal height
- Time width of Gaussian chosen to match experimental signal processing pulse width (full width ~390 ns)



2.b.4 Light to Channelnumber Conversion: Photon Calibration

- Inputs: experimental photon source and MCNP-simulated energy deposit spectra
- Perform global fit of conversion function parameters: create channelnumber spectra from generated deposited energy spectra





experimental

$$N_{\mathrm{Exp.\,Gamma}}(x_{CHN}) = N_{\mathrm{Exp.\,Bg}}(x_{CHN}) + \int R(x_{CHN}, x_{ED})\, N_{\mathrm{Sim.\,MC}}(x_{ED})\, dx_{ED}$$

$$R(x_{CHN}, x_{ED}) = e^{-\frac{(ED(x_{CHN}) - x_{ED})^2}{2\sigma^2}}$$

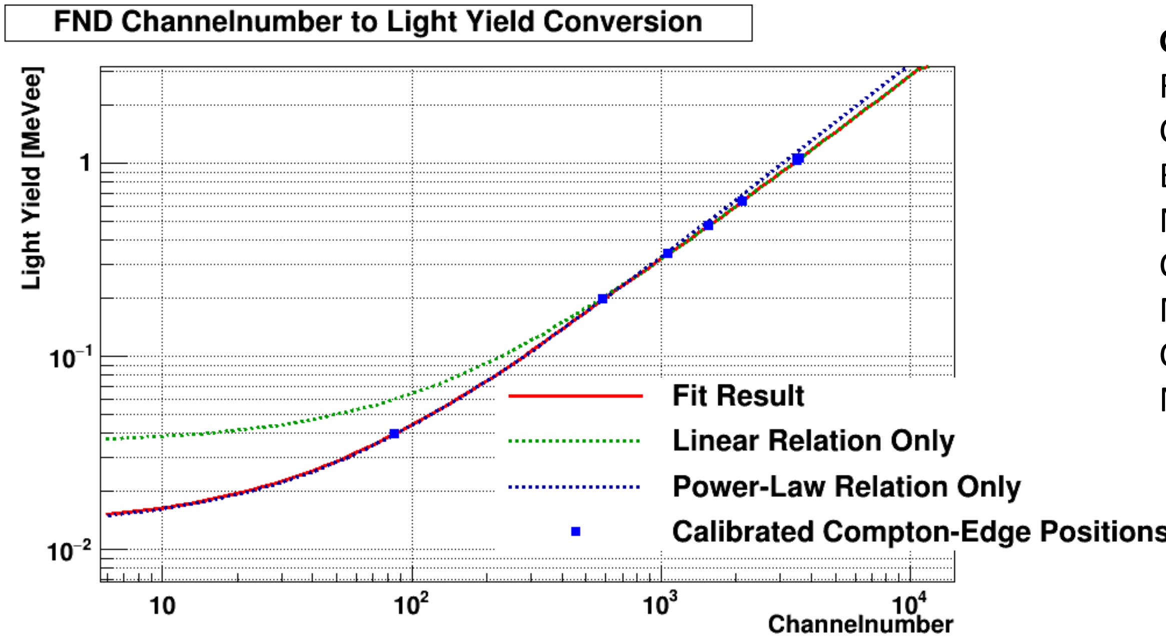
Channelnumber-to-light yield conversion:

$$ED(x_{CHN}) = \begin{cases} a + b x_{CHN}^{c} & \text{for x < e} \\ d + b x_{CHN} & \text{for x >= e, where } d = a + b e^{c} - b e \end{cases}$$

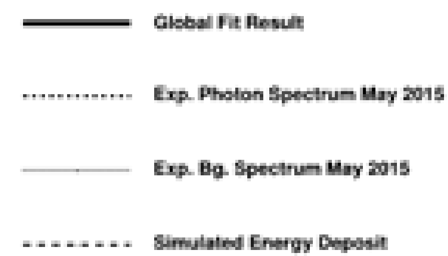
Continuity requirement

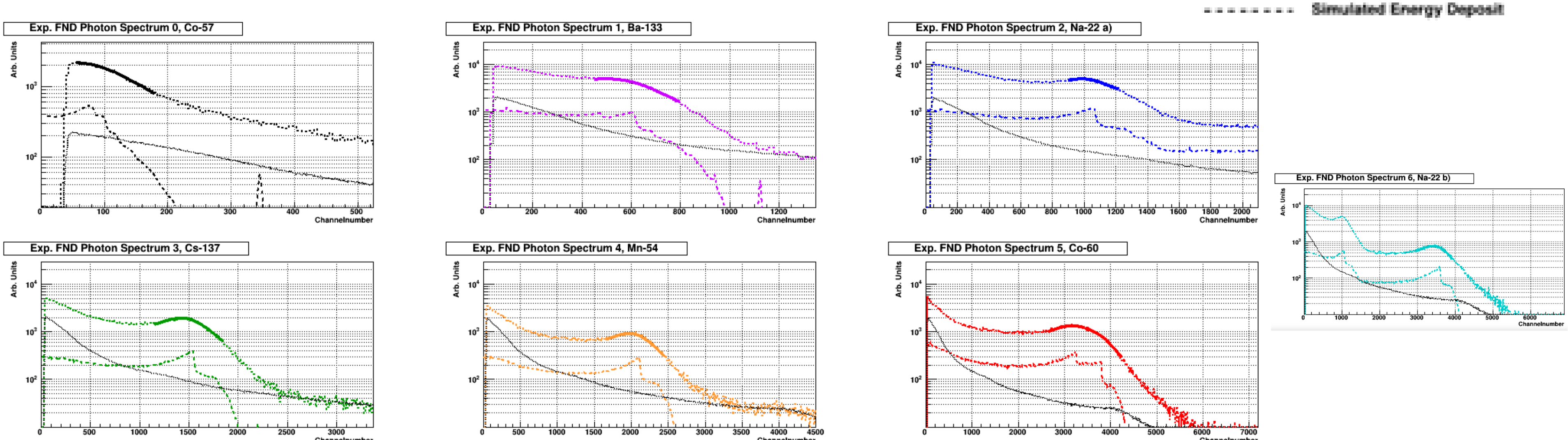
2.b.4 Light to Channelnumber Conversion: Photon Calibration

- Result: Low light yield region prefers nonlinear (power law) shape (also seen in other literature):



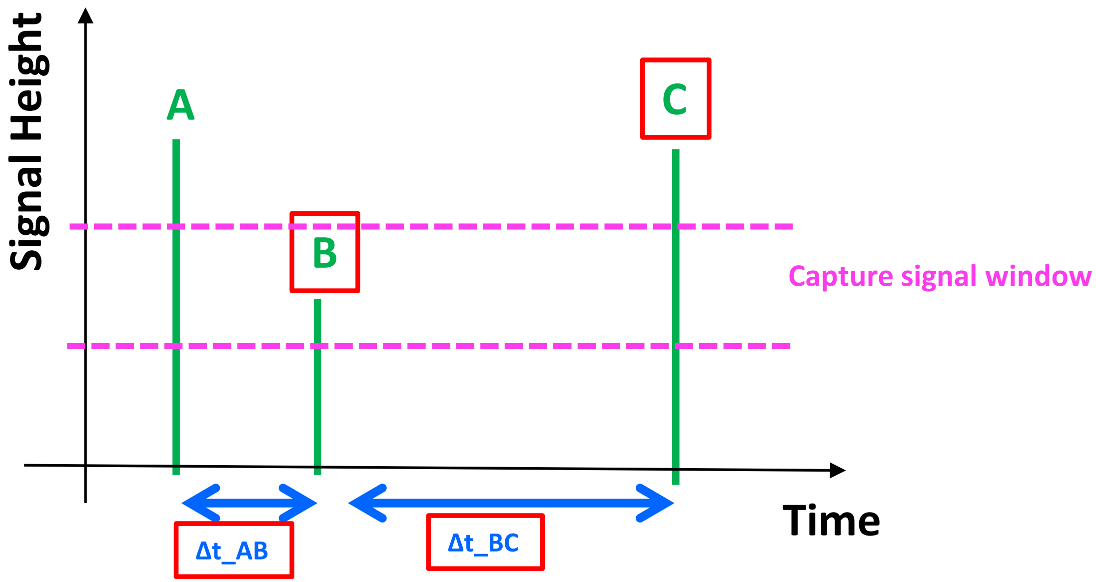
Global red. chisq. = 695 / 490 = 1.42
Red. chisq. for single plots:
Co-57: 27/31 = 0.86
Ba-133: 63 / 35 = 1.80
Na-22 a): 53 / 32 = 1.67
Cs-137: 108 / 70 = 1.54
Mn-54: 69 / 80 = 0.86
Co-60: 211 / 160 = 1.32
Na-22 b): 164 / 100 = 1.64





2.b.5 FND Pulse Pair Selection (see Michael V.'s talk)

- Apply same selection as FND FPGA
- Algorithm considers three latest detected pulse amplitudes (moving averages) and time intervals between them (zero crossing of bipolar signal)



- **Pulse selection logics**: accept A, B as pulse pair:

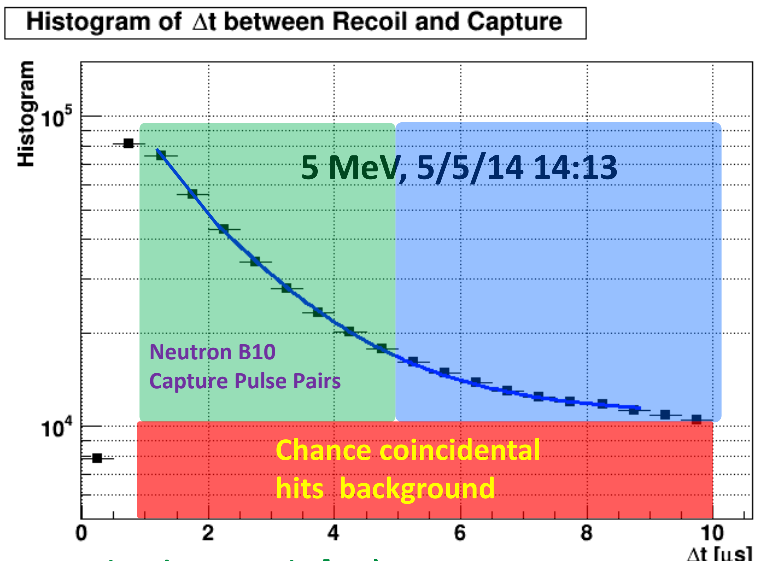
I) SH_B in capture signal window &&
II) Δt_AB in capture time window &&
III) Δ t_AB < Δ t_BC ||
(SH_C outside of capture signal window || Δ t_BC outside of capture time window)

2.b.6 Background/Chance Coincidence Subtraction

- Poisson time correlation between recoil and capture pulses for B10 capture event allow to subtract backgrounds

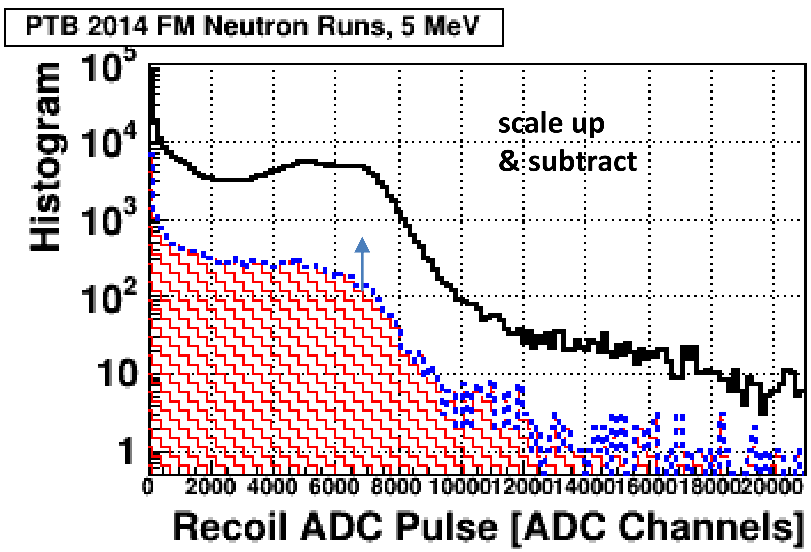
- Oversubtraction ensures all backgrounds subtracted; rejected neutron pairs recovered via efficiency correction

- Performed in both experimental and simulated samples for consistency



Signal + Bg: Δt in [1;5) μs

"Background": Δt in [5;10) μs

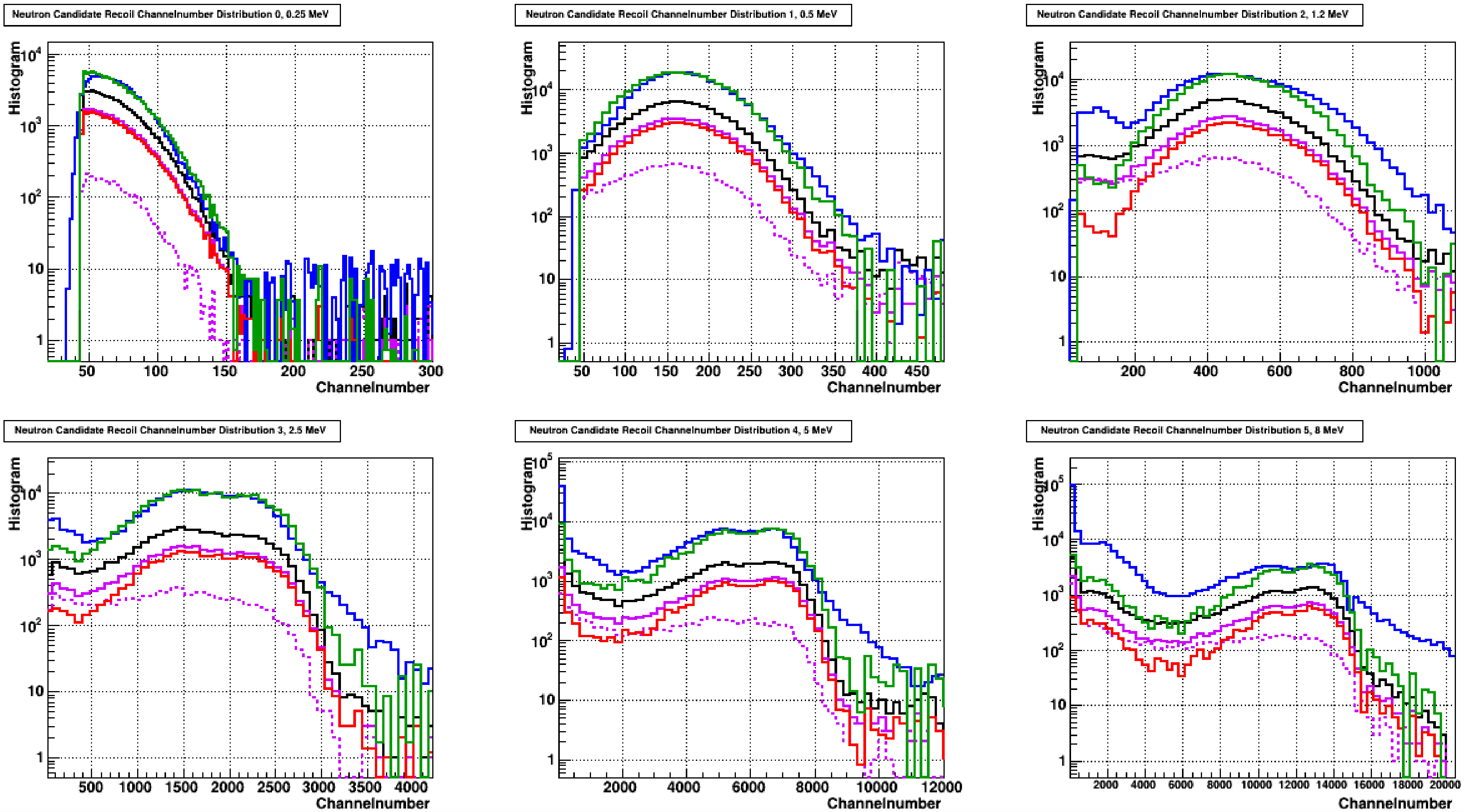


Subtract scaled chance background from recoil spectrum

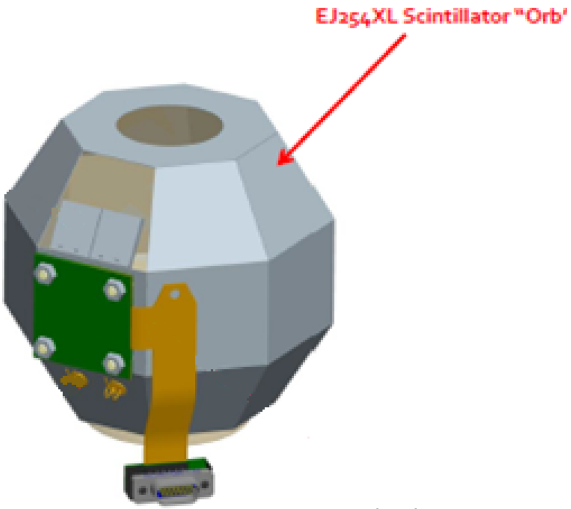
2. Preliminary Calibration Results- Recoil Spectra Match

- Deviations for low channelnumbers at mid to high energies- further analysis to be done to identify missing process/incorrect treatment of neutron interactions; resolution to be adjusted as well

Simulated Selected Recoil Pulses
Sim. Sel. Recoil Pulses, $\Delta t_{Capt.}$ in [1;5) μs
Sim. Sel. Recoil Pulses, $\Delta t_{Capt.}$ in [5;10) μs
Sim. Final Background-Subtracted
Sim. Fit Result to Exp.
Exp. PTB 15, Bg.-Sub.



3. Regularized Unfolding



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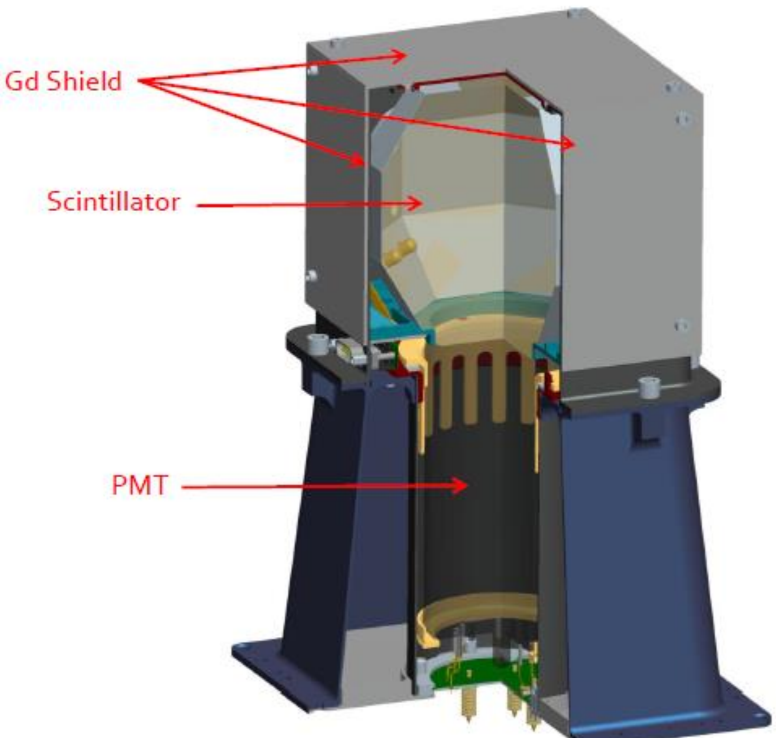


3.1 Unfolding Procedure: Regularized SVD Unfolding

A. Hoecker, V. Kartvelishvili, NIM A372, 469 (1996) [arxiv:hep-ph/9509307]

- Uncertainties on data distributions and response matrix

=> use regularized, singular vertex decomposition-based unfolding algorithm (ROOT: TSVDUnfold)

- **Advantages**:

* correct treatment of uncertainty-equipped input quantities (detector response matrix, input distribution)
* full uncertainty propagation; fast

- **Limitations**:

* 'strength' of regularization described by free parameter, needs to be determined from simulation and pre-launch data (systematic uncertainty)
* dependence on input distribution (to be studied)

general problem formulation:

$$\hat{A}\, x^{\mathrm{ini}} = b^{\mathrm{ini}}, \qquad \sum_{i=1}^{n_b} \Big(\sum_{j=1}^{n_x} \hat{A}_{ij} x_j - b_i \Big)^2 = \min$$

but: Δb != 0

$$\sum_{i=1}^{n_b} \Big(\frac{\sum_{j=1}^{n_x} \hat{A}_{ij} x_j - b_i}{\Delta b_i} \Big)^2 = \min \qquad (\hat{A}x - b)^T B^{-1} (\hat{A}x - b) = \min$$

rescaling and regularization:

$$(\tilde{A}\, w - \tilde{b})^T\, (\tilde{A}\, w - \tilde{b}) + \tau \cdot (C\, w)^T C\, w \;=\; \min$$

regularization parameter: chosen from rank of response matrix/problem

-> need response matrix for given recoil channelnumber and chosen neutron energy binning

3.2 Neutron Energy Binning

- Neutron energy binning:
  * low and high limits: approach from detector side:
    @ **lower limit: 200 keV** (electronics lower pulse cutoff/arming threshold)
    @ **upper limit: 8.5 MeV** (corresponding pulses start to saturate 12-bit ADC)
  * bin width:
    @ FND orbit data histograms hardcoded to 512 channel width (29 bins)
    @ light function nonlinearity: first recoil bin contains most of all < 1 MeV neutrons
    @ choose second bin such that contains majority of peak for 1.2 MeV
    => 12 bins, bin width 0.7 MeV

- Boundary effects:
  * Neutrons < 200 keV contribute to low bins of recoil distributions (finite detector resolution, fixed-amplitude capture signals)
  * Neutrons > 8.5 MeV contribute to all bins in recoil spectra (scattering, capture signals)

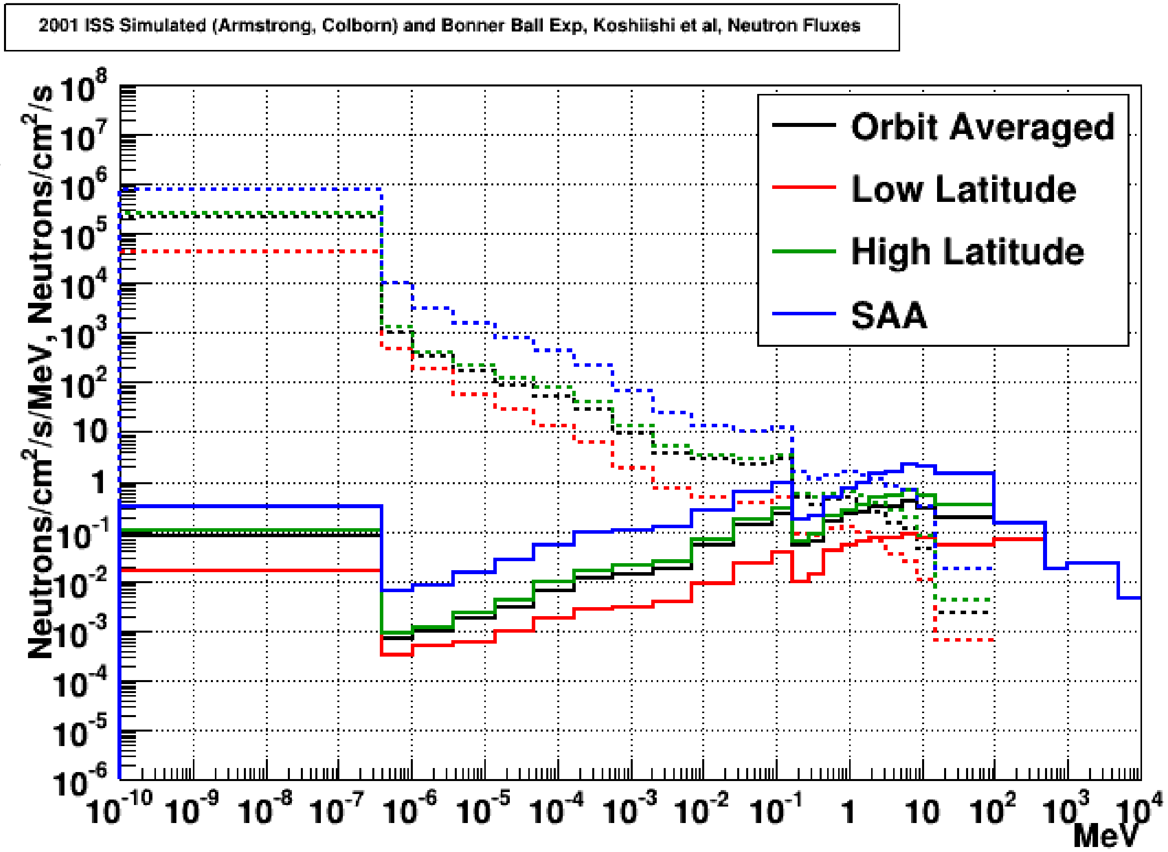
  -> include under- and overflow bins in neutron energy:

  * reason to believe that low energies correctly modeled
  * fidelity of simulation/physics models for energies > 8.5 MeV not as high -> additional systematic uncertainties

3.3 Response Matrix Assembly

- Choose 'input spectrum' close to expected truth:
  * Koshiishi et al, published 2007 (data from 2001);
  * three data points filled for energies [100 MeV; 10 GeV) from simulation
- Integral orbit averaged flux (black line):
  * thermal to 200 keV: ~0.6 n/cm^2/s, > 8.5 MeV: 0.6 n/cm^2/s
  * total ~3.0 n/cm^2/s

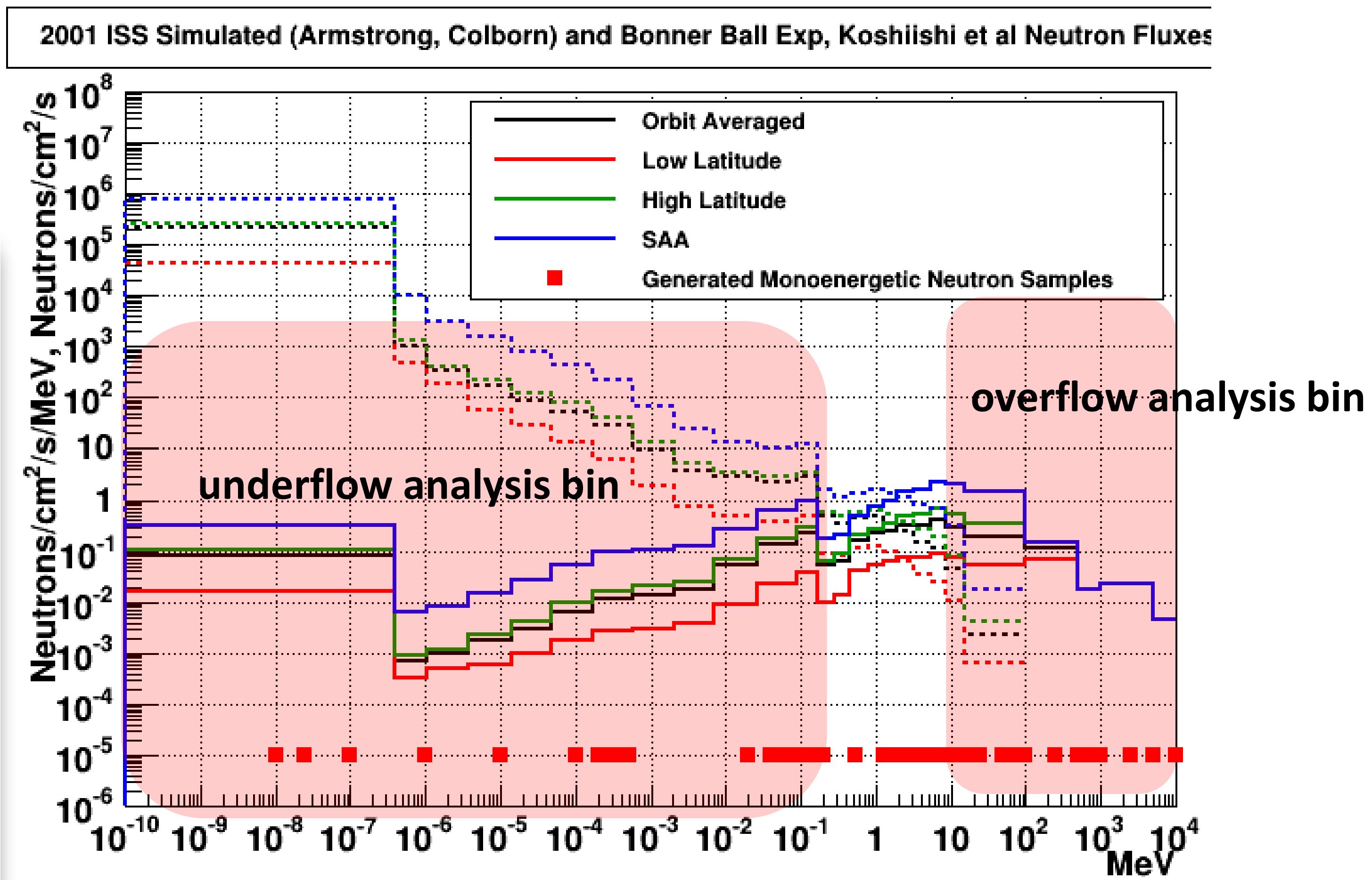
H. Koshiishi et al,
Rad. Meas. 42 (2007), 1510ff



3.3 Response Matrix Assembly

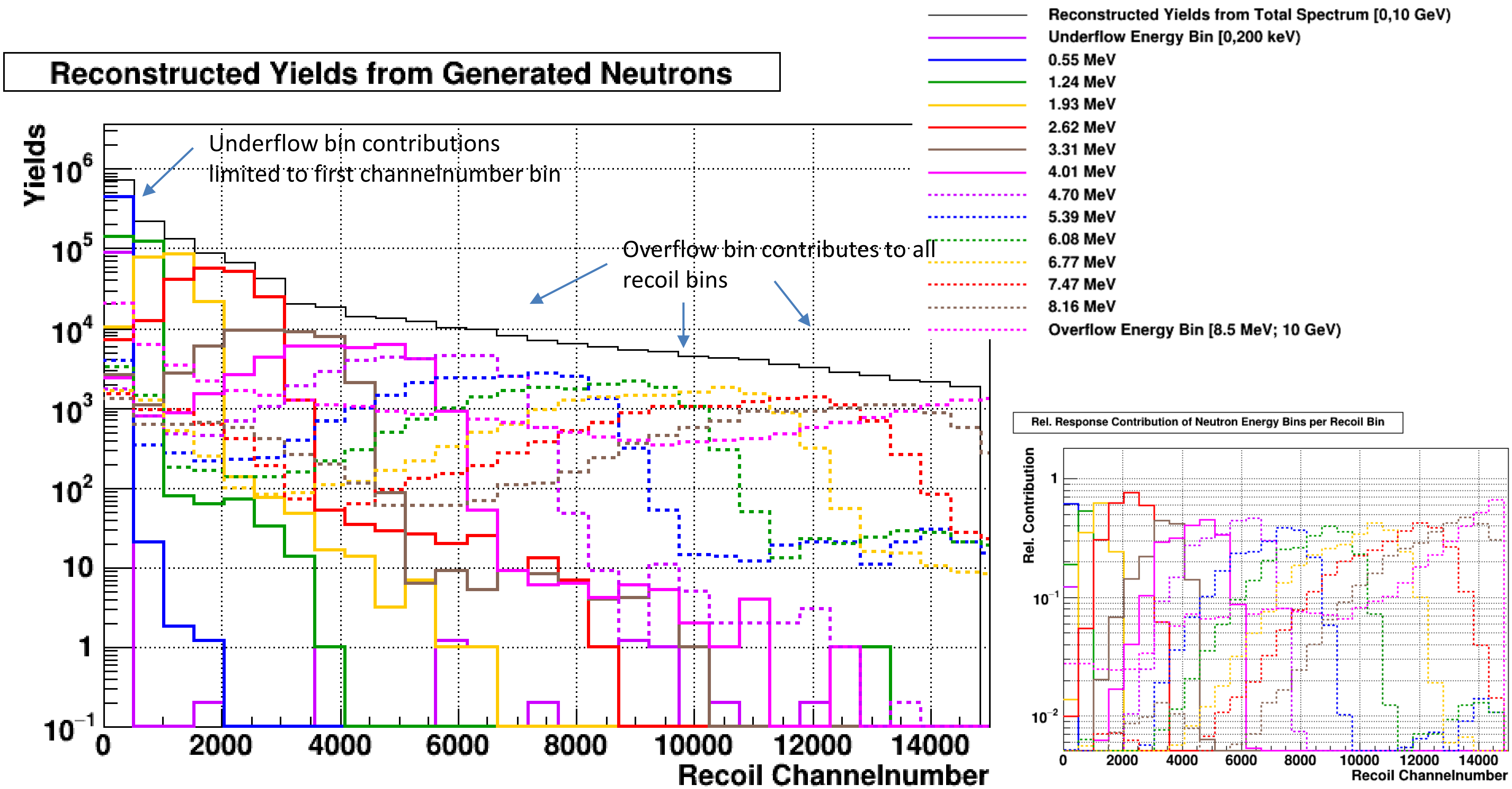
- Generated energies from thermal to maximum energies to have representative neutron spectra of each kinematic region (MCNP-PoliMi)

- Scale relative statistics/time for each neutron energy analysis bin according to measured orbit averaged fluxes reported in Koshiishi et al, to be close to expected environment



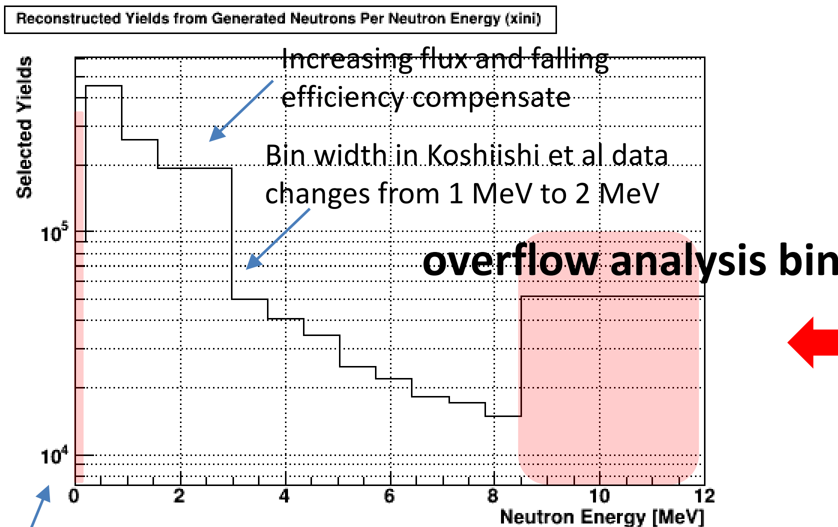
3.3 Response Matrix Assembly

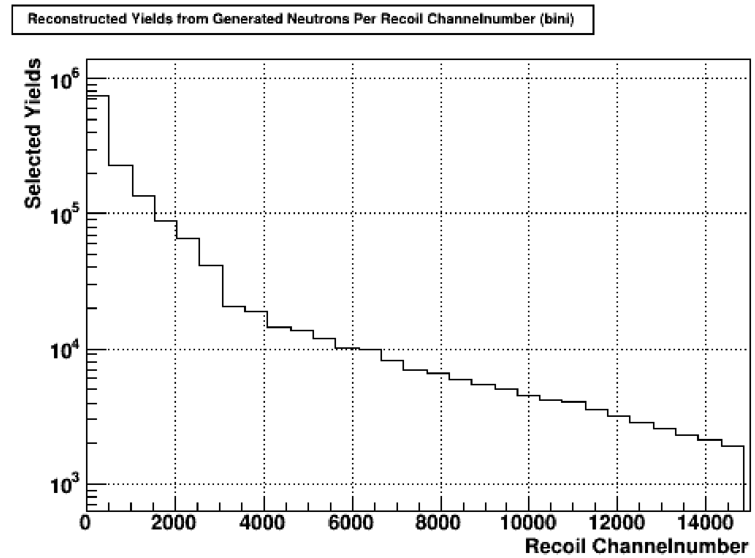
- Response recoil spectra for chosen neutron binning; fluxes acc. to Koshiishi et al
- Underflow contributions only in first channelnumber bin: 12%
- Overflow neutron energies contribute to all channelnumber bins: dominates highest two bins; >10% contribution to bins >11000; few % down to first bin
-> unfolding removes contributions



3.3 Response Matrix Assembly

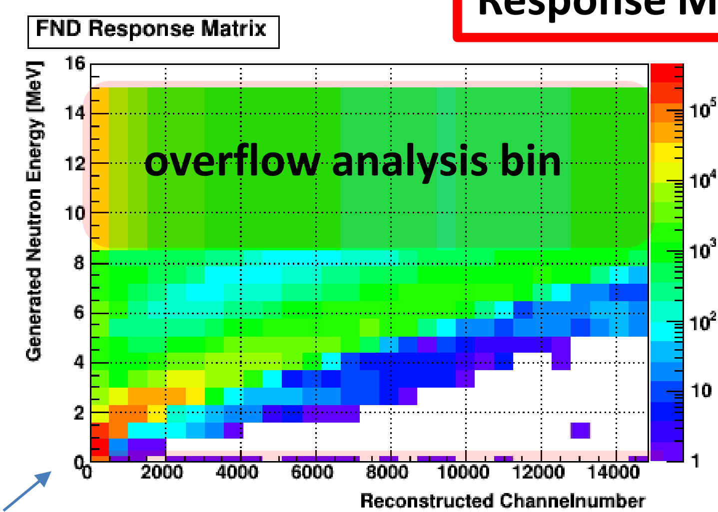
- Line and row integrals of response matrix;
- Recoil channelnumber distribution represents simulation of detector response to on orbit spectrum from 0.1 meV to 10 GeV measured by Koshiishi et al + simulation



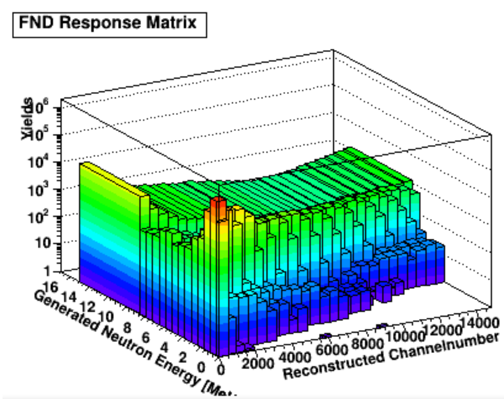


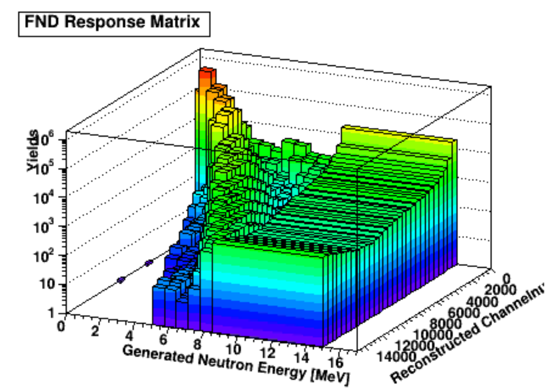
underflow analysis bin

Response Matrix



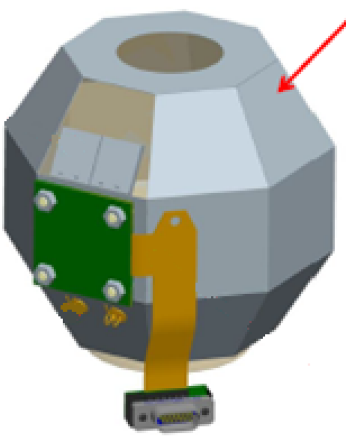
underflow analysis bin



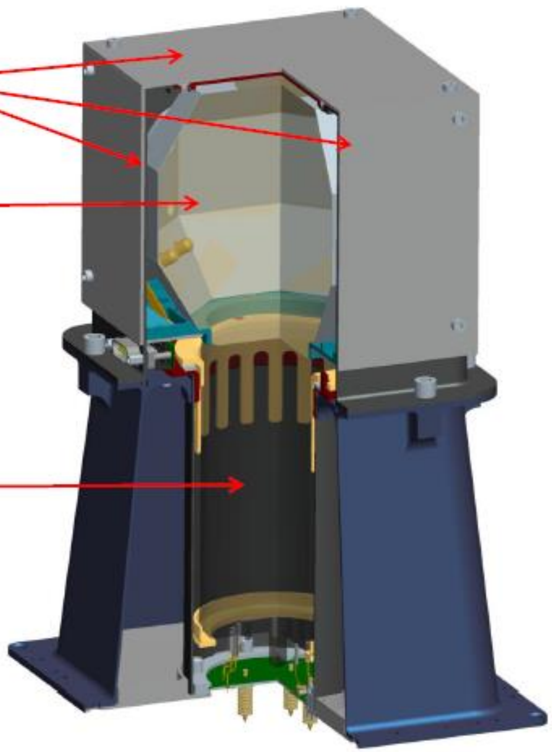


likely: hard photons from Gd capture coincidental with other neutrons

4. Validation on generated data



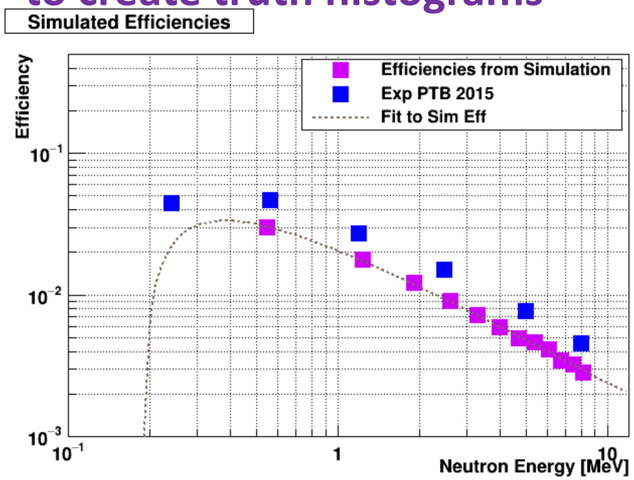
graphics modified from SwRI

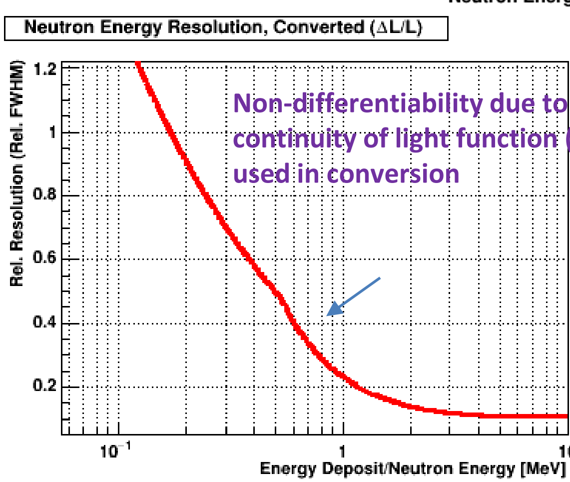


4.1 Validation on Generated Monoenergetic Data

- MCNP-PoliMi-generated monoenergetic energies encountered at PTB
- Apply energy resolution of FND light function calibration, simulated efficiencies
- Tuning necessary for single energies- resolution mismatch

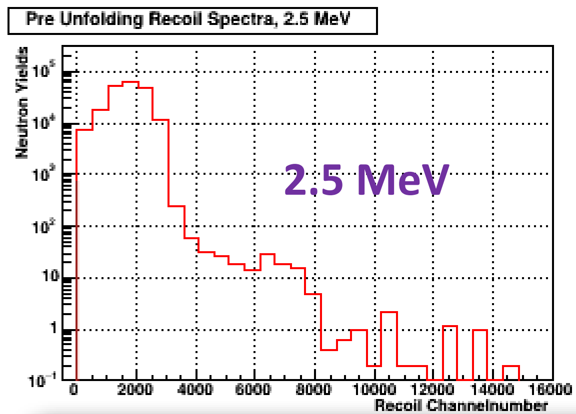
Efficiencies, resolution used to create truth histograms

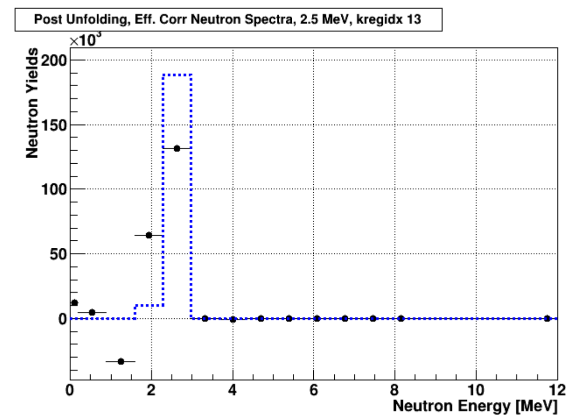


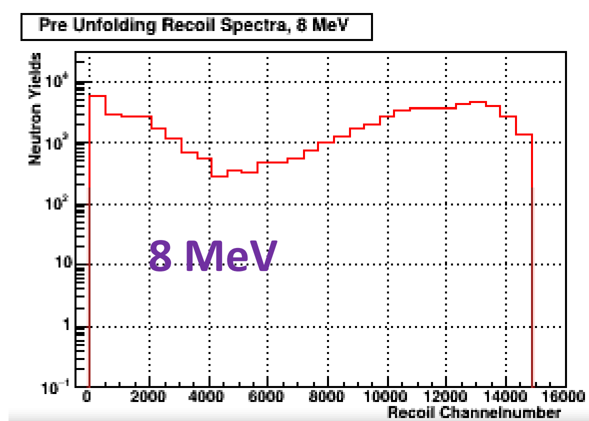


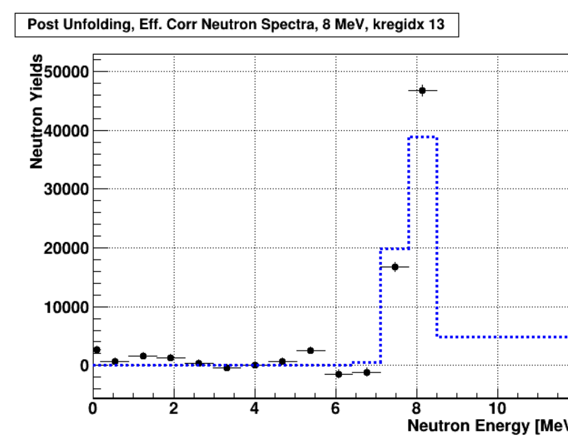
Non-differentiability due to limited continuity of light function (2^{nd} order) used in conversion

reconstructed → **unfolded**



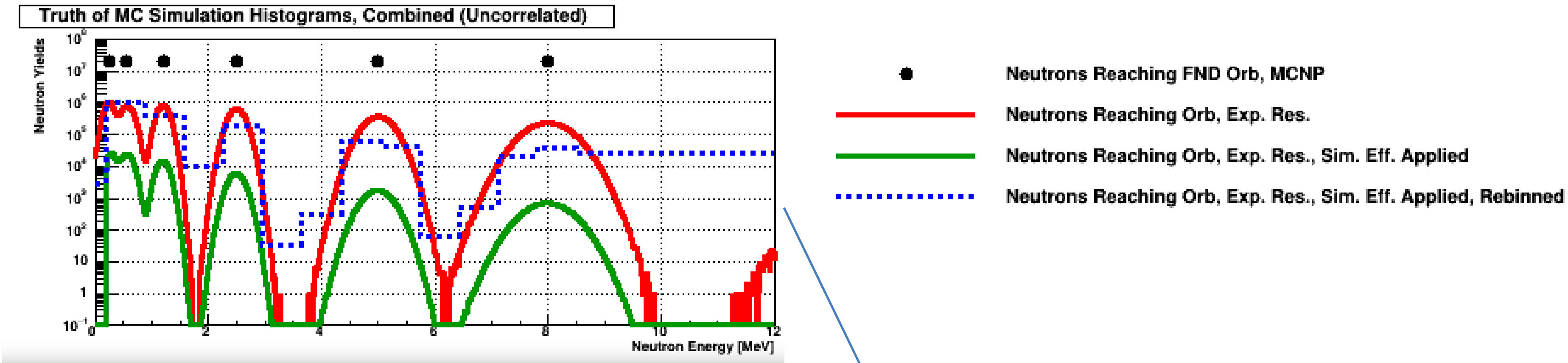




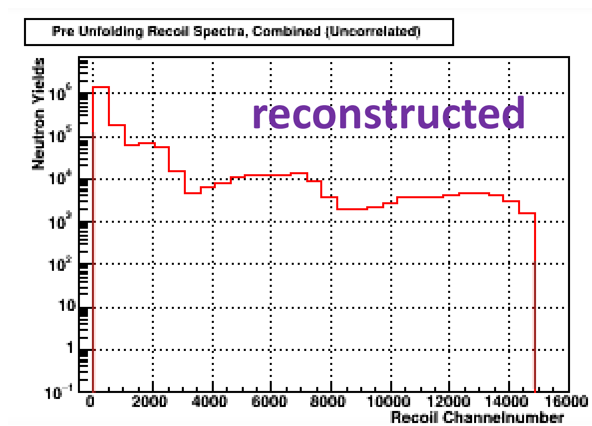


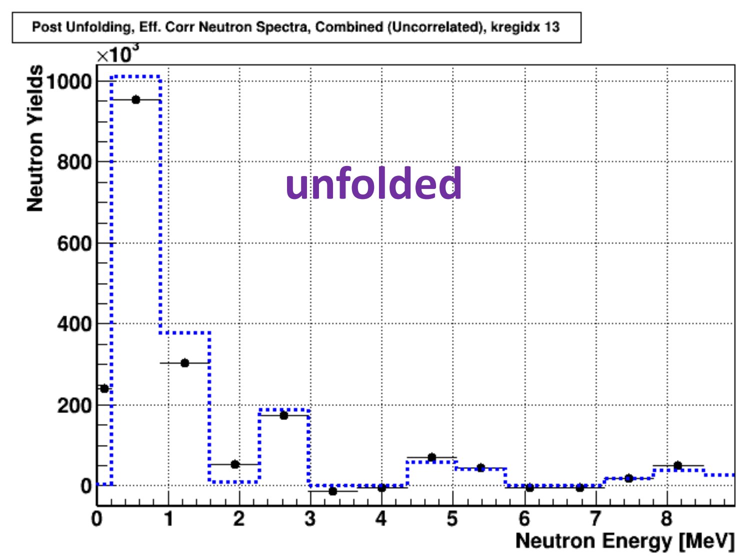
4.1 Validation on Generated Monoenergetic Data

- Extreme case: combine all single energies in one reconstructed histogram, unfold;
- Differences <~25% for most part



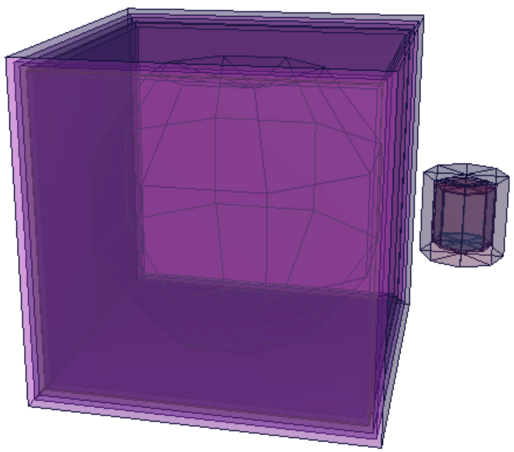
Mixed monoenergetics

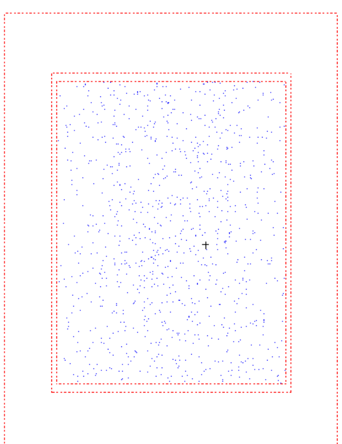


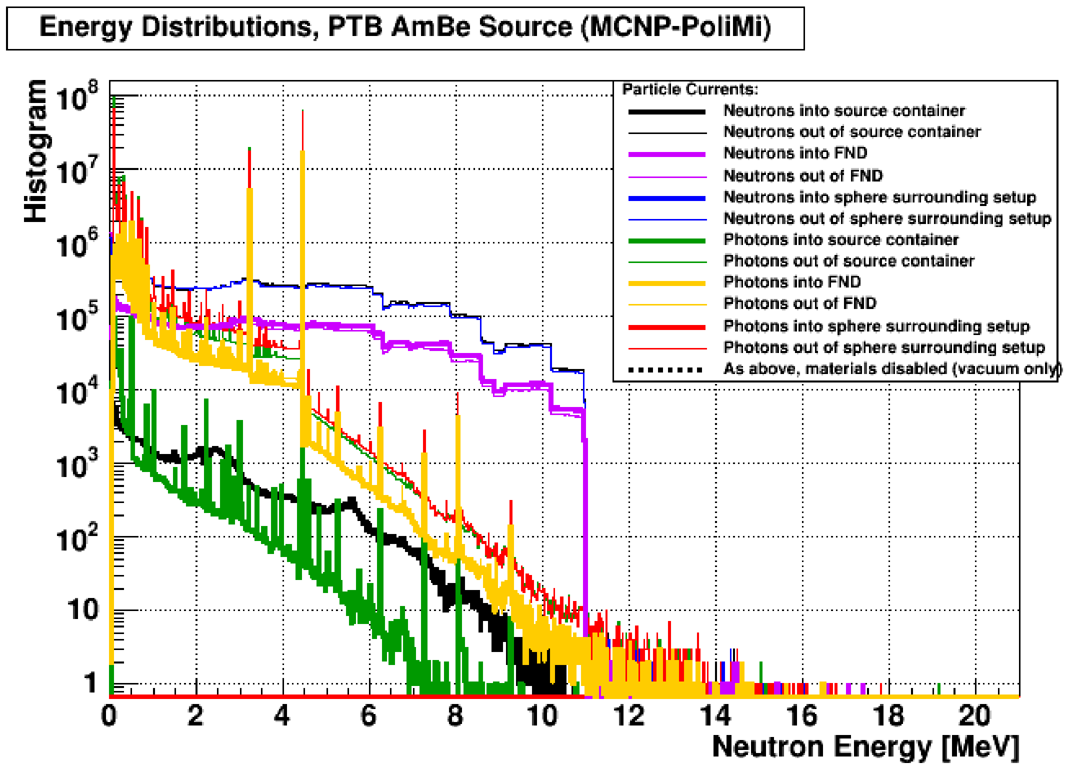


4.2 Validation on Generated Data- AmBe

- Built-in MCNP-Polimi AmBe spectrum, generated inside simulated source as volume source
- Deviations to ISO AmBe spectrum ~30%, but benchmarking rather for functional relation to original true spectrum

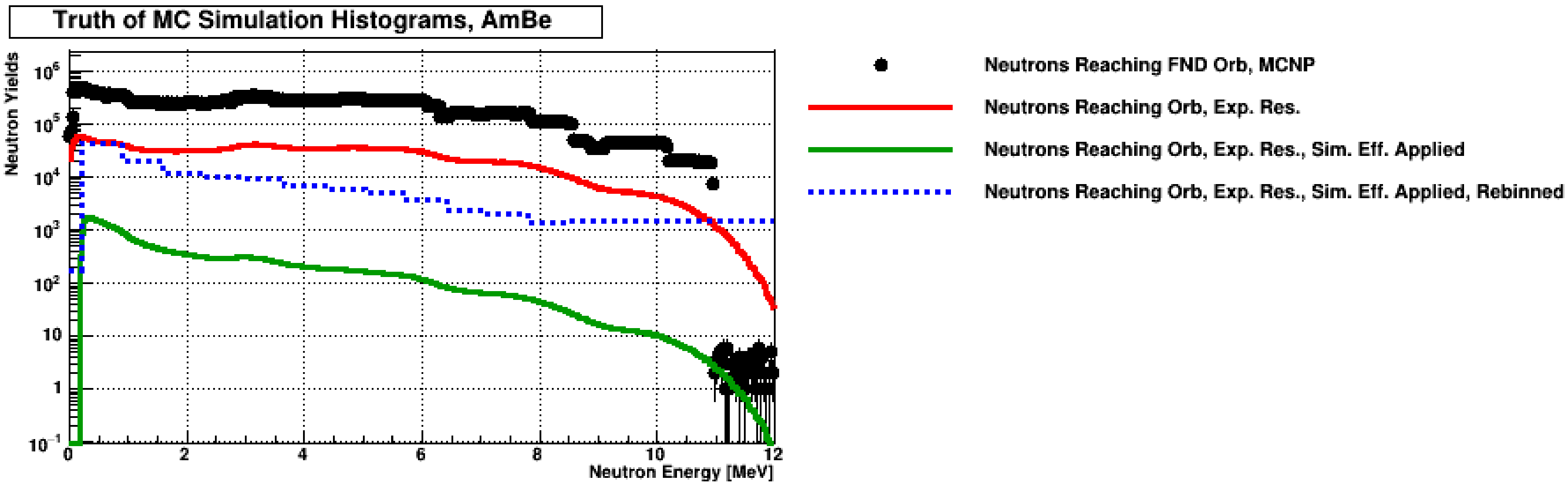




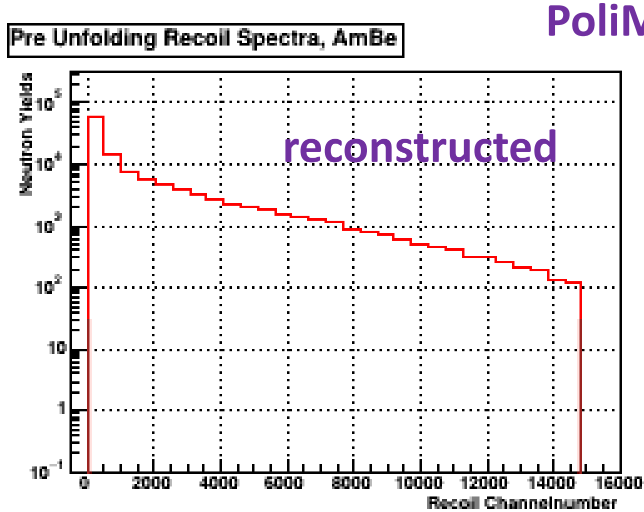


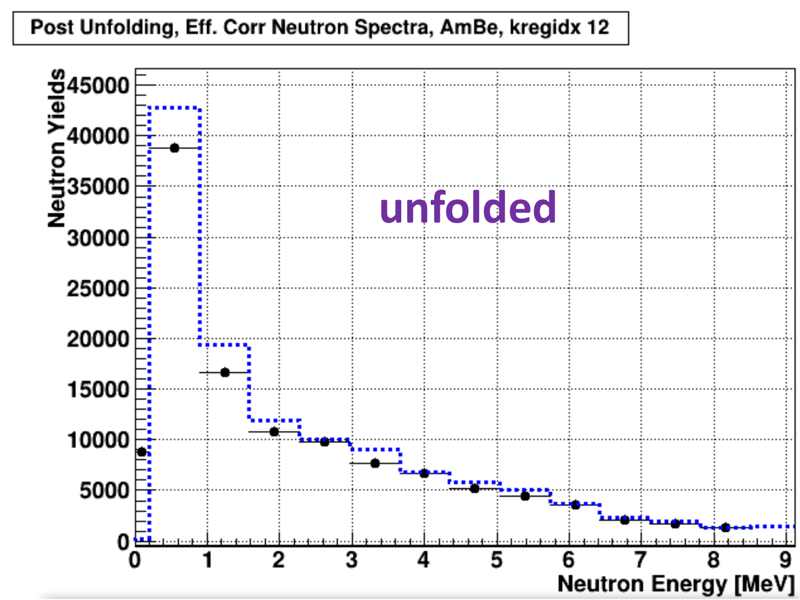
4.2 Unfolding Benchmarking- Generated AmBe Data

- Largest deviations 18%, general undershoots truth (possibly normalization tuning necessary)



PoliMi AmBe



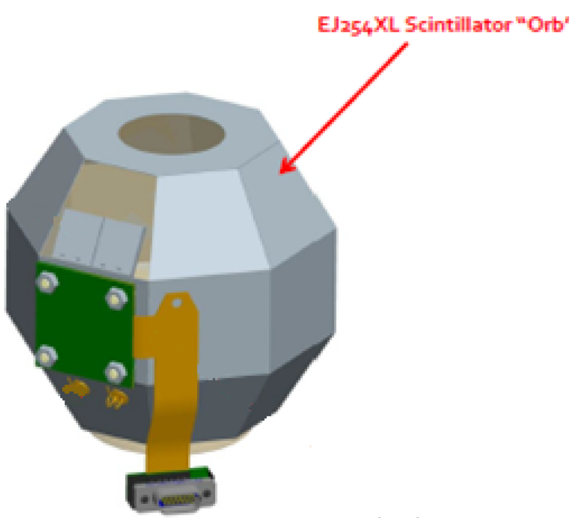


5. Plan Ahead

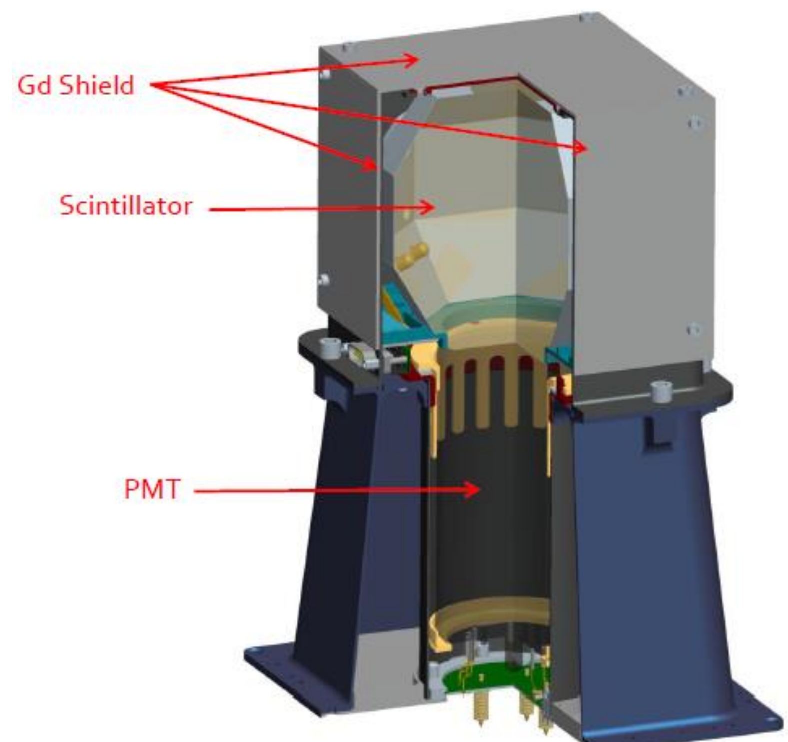
- **Improve match** of calibration to experimental data and of unfolding to generated data; unfold experimental data

- Systematic studies: other unfolding algorithms

- Study FND **response and recoil spectrum contributions** of **mixed radiation field** on ISS: protons, alphas, photons (simulations/ experimental measurements: TRIUMF, NSRL)



graphics modified from SwRI

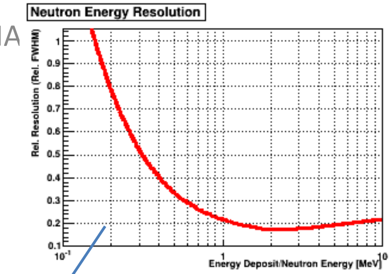


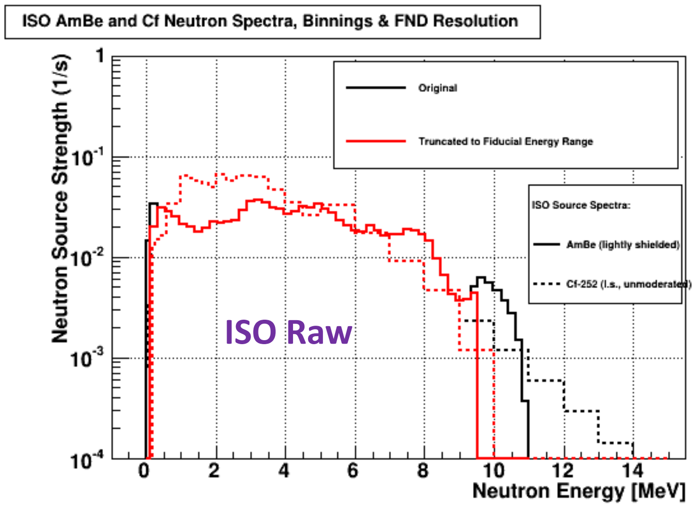
Backup

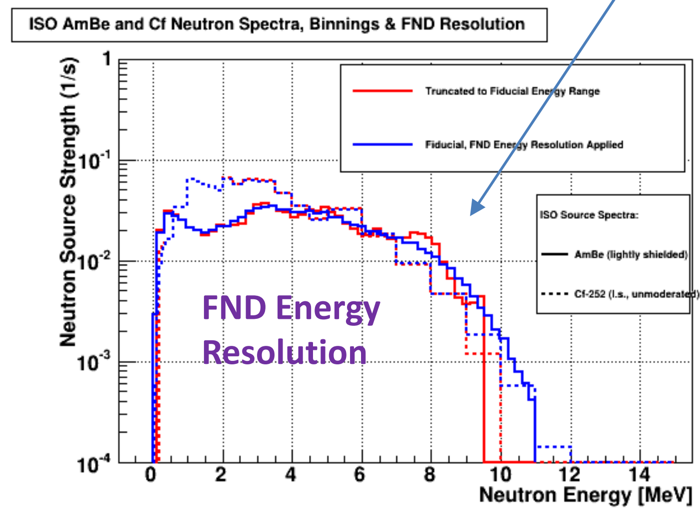
M. Leitgab, NA

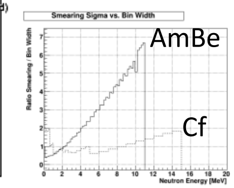
2c) Direct Mapping/Conversion Spectral Match Test

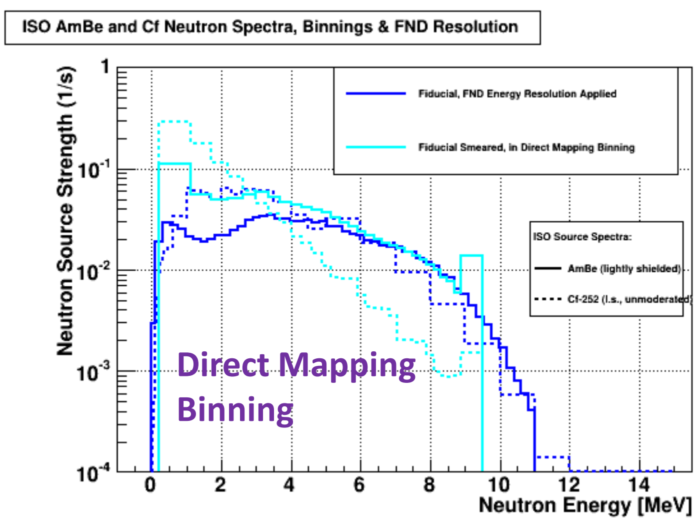
- Created ‘truth’ distributions from ISO for AmBe and Cf sources:
apply detector resolution, direct mapping binning and energy range selection (0.5-8 MeV)
* Cf ISO binning mostly too wide for smearing to have effect;

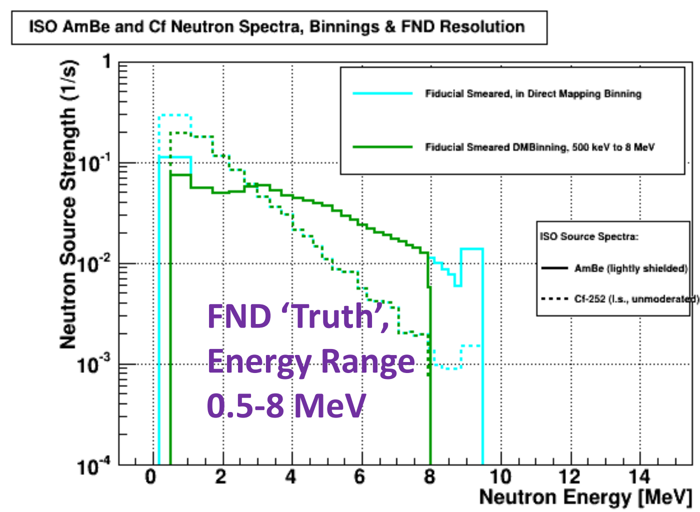












2c) Direct Mapping/Conversion Spectral Match Test

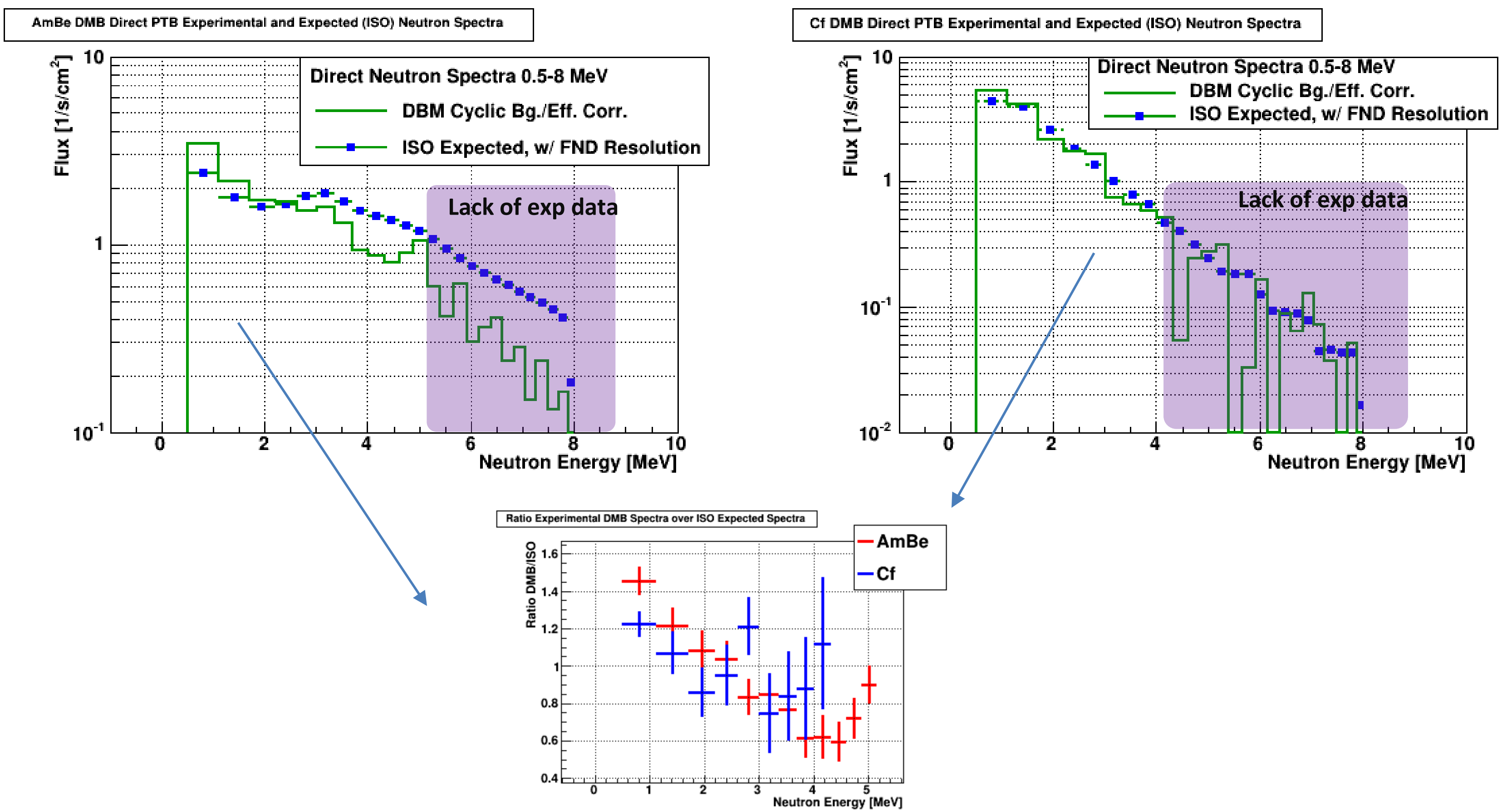
- Scale 'truth' histograms with PTB reported (adjusted) neutron flux
- Comparison with GAS analysis results statistics-limited to <~ 5 MeV (only spotty shadow cone and background subtraction data at higher chn bins):

@ Expected: Low energy spectrum overestimated, medium/high energy spectrum underestimated

@ AmBe spectrum shows structure in ISO-truth, not reflected in DBM spectrum: deviations +45% to -41%;

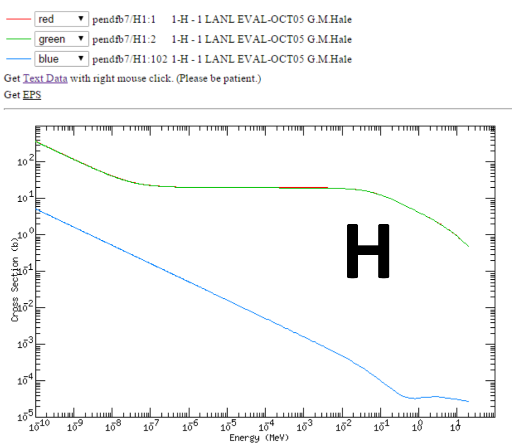
@ Cf spectrum closer (statistics limited): overestimate at low bins ~22%, medium energy bins large uncertainties, in part consistent;

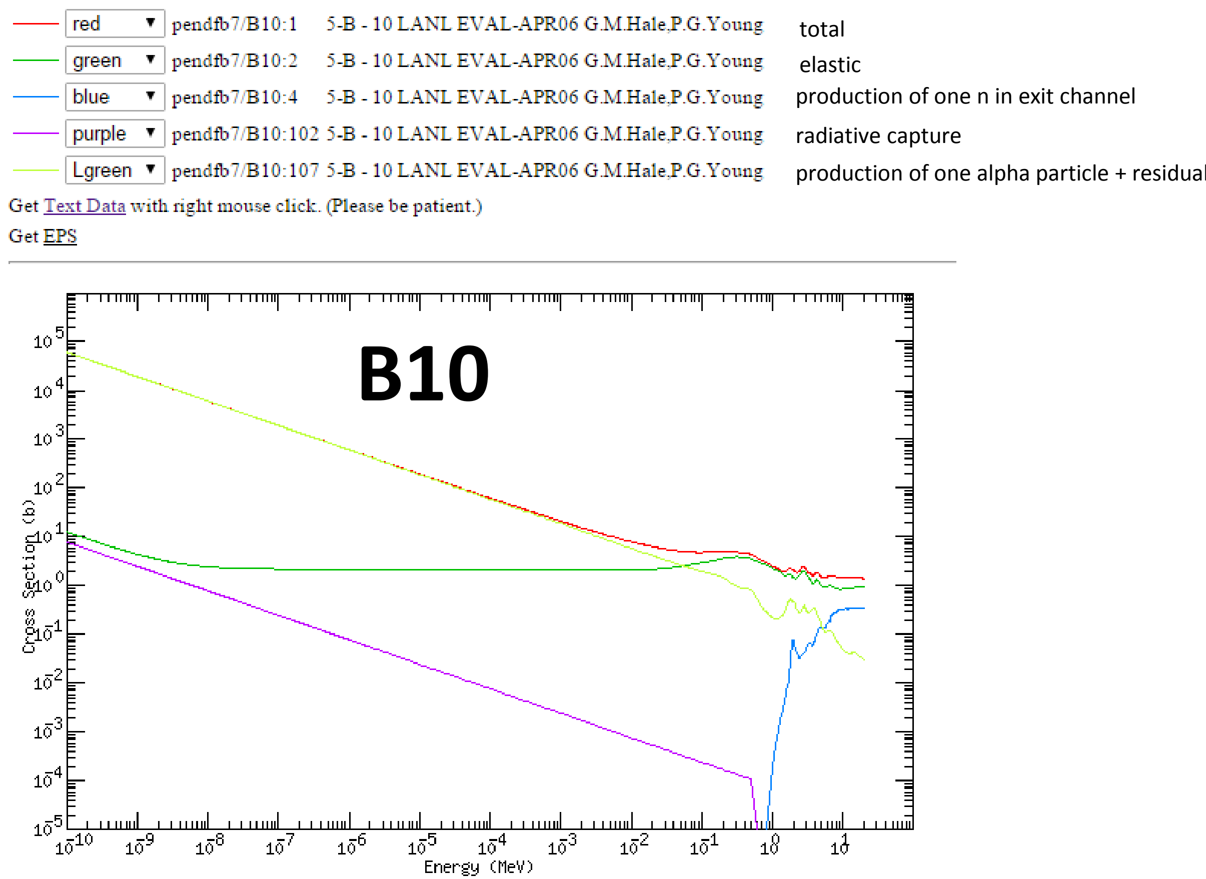
- Conclusion: Direct Mapping/Conversion analysis method by design shows limitations in reproducing neutron energy spectra.



4.1a Simulation of Neutron Energy Deposits: MCNP-PoliMi

- for all materials use ENDF-VII library at 300 K, assembled in 2005; max energy 20 MeV, 500-3500 energies depending on material





4.1a Simulation of Neutron Energy Deposits: MCNP-PoliMi

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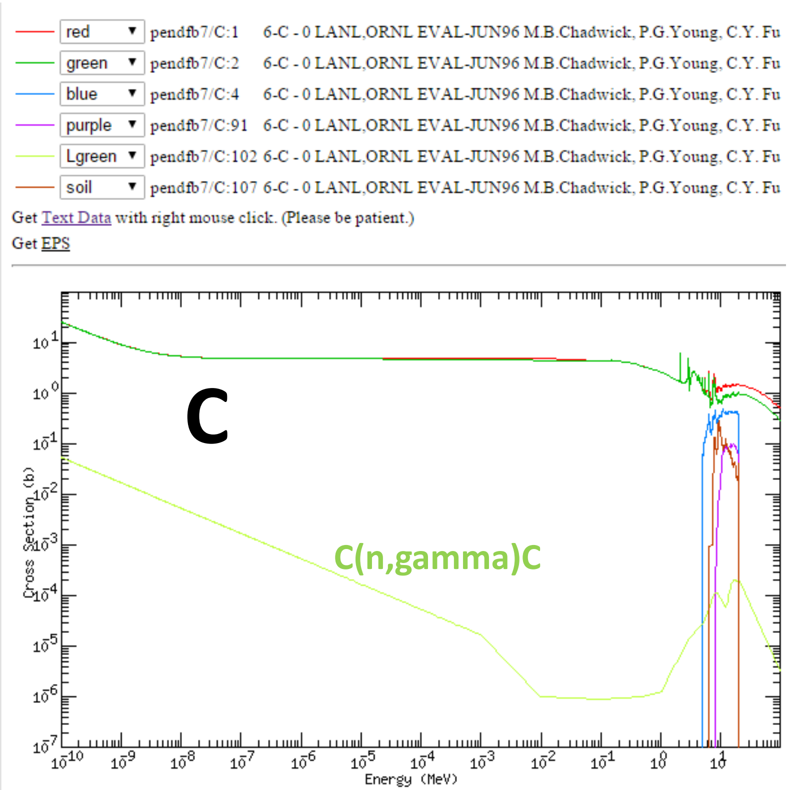
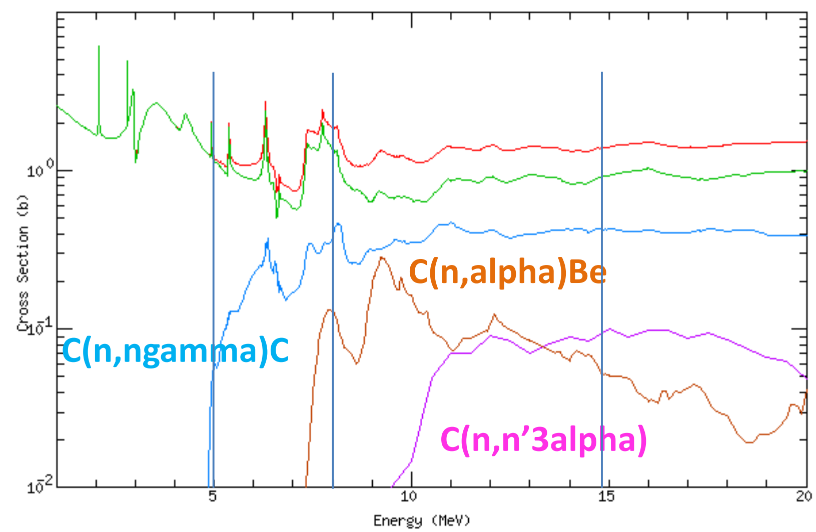


total
elastic
production of one n in exit channel
production of one n in continuum not included in separate listings
radiative capture
production of one alpha particle + residual



6) Low Energy Nonlinear Light Output in Literature

Literature c)

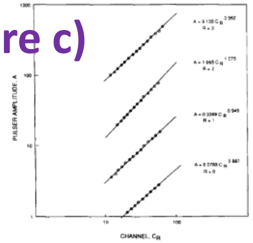
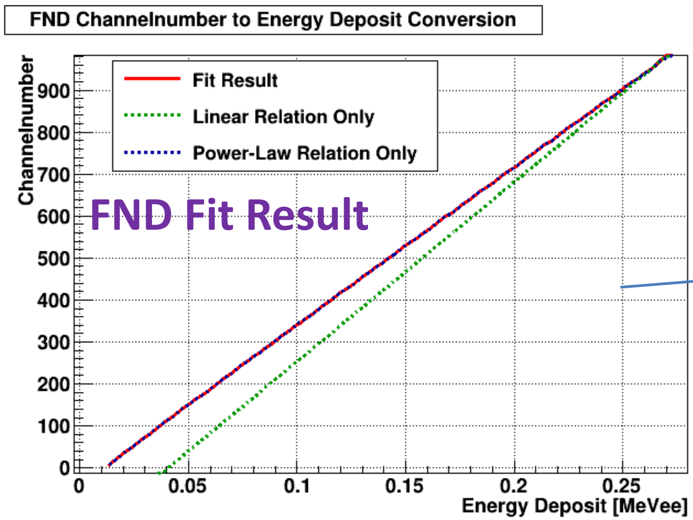


Fig. 4. Pulser calibration data for the rod-1 ADC and the associated gated-integrator assembly of the ABE detector. R denotes the range of amplification fed to the 6-bit ADC.

Feldman et al, NIM A 306 (1991) 350 ff

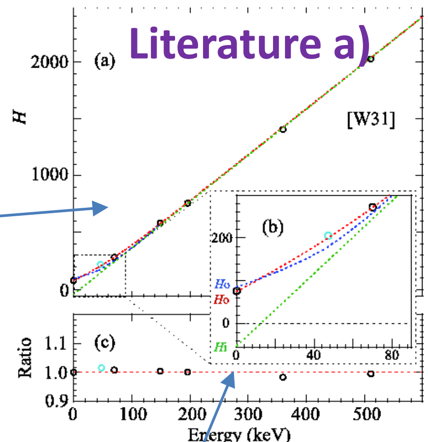
FND Fit Result:
A ~ C^(1.02)

Energy deposit -> Light Yield -> Channelnumber



FND Fit Result

Literature a)



Literatureb)

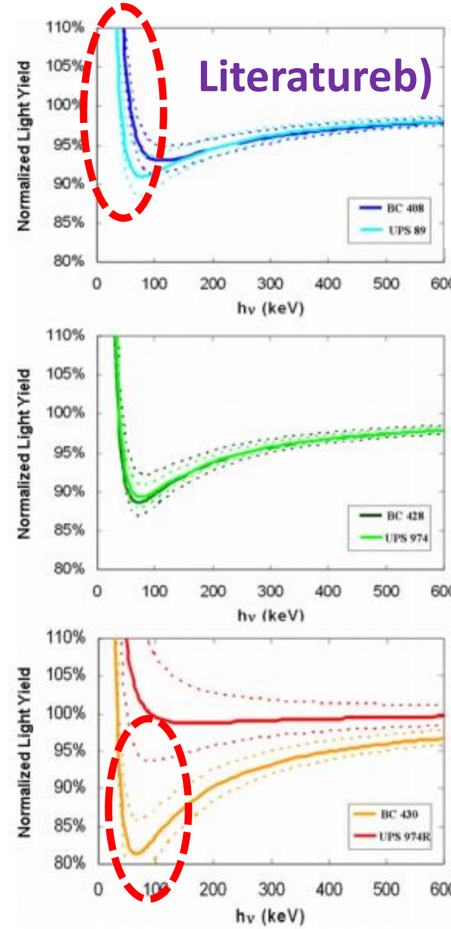
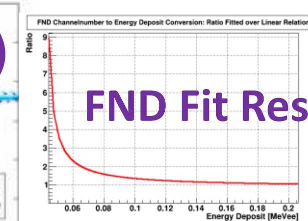
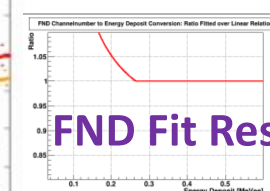


Fig. 11. Mean light amount for photons for the blue, green, and red scintillators (from top to bottom). The dotted lines represent the experimental uncertainties.



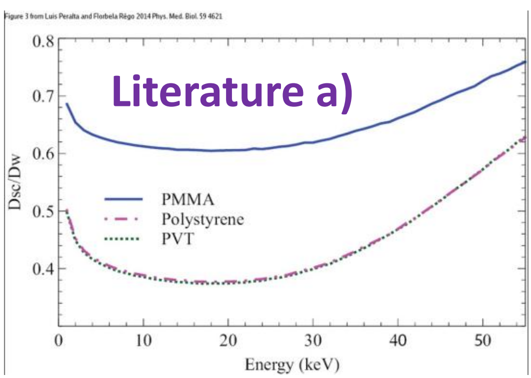
FND Fit Resu

Assumed linear



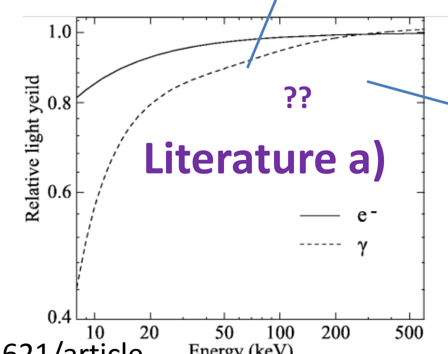
FND Fit Resul

Literature a)



??

Literature a)



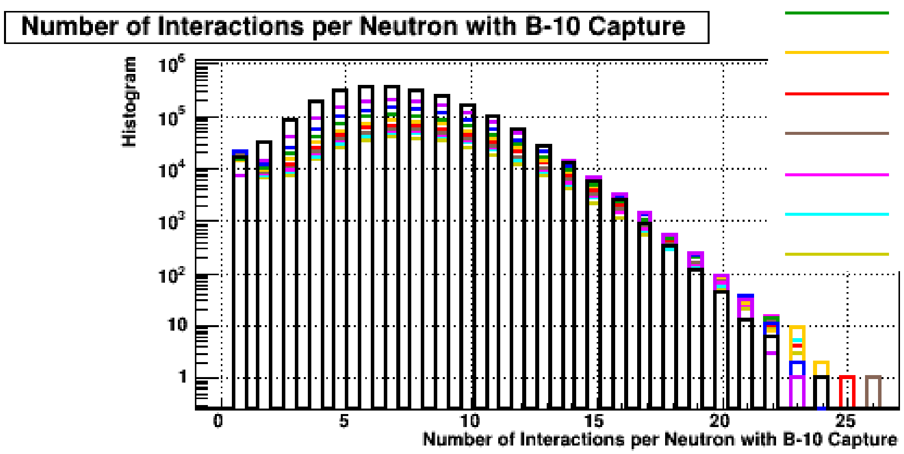
http://iopscience.iop.org/0031-9155/59/16/4621/article

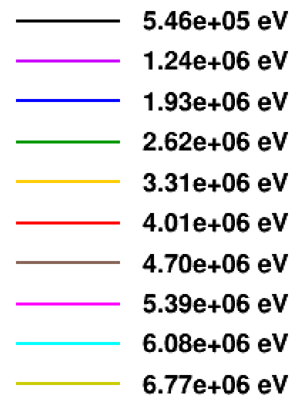
http://pasj.asj.or.jp/v63/sp3/63s303/63s303-frame.html

http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=4696573

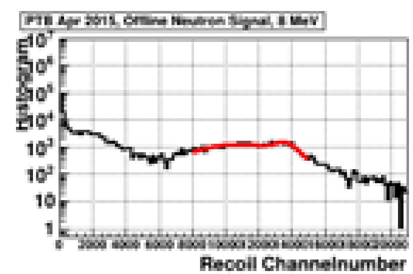
4. Scintillation Light Creation/Propagation: Light Function Formalism

MCNP-PoliMi Scintillator Simulations





Exp. Recoil of 8 MeV Monoenergetic



3.1 Unfolding Procedure: Regularized SVD Unfolding

A. Hoecker, V. Kartvelishvili, NIM A372, 469 (1996)
[arxiv:hep-ph/9509307]

general problem formulation:

$$\hat{A}\, x^{\text{ini}} = b^{\text{ini}}, \qquad \sum_{i=1}^{n_b} \Big(\sum_{j=1}^{n_x} \hat{A}_{ij} x_j - b_i\Big)^2 = \min$$

with SVD:

$$\hat{A} = U\, S\, V^T \qquad z = V^T x \qquad d = U^T b$$

$$x = V z = V S^{-1} d = V S^{-1} U^T b = \hat{A}^{-1} b \qquad \hat{A}^{-1} = V\, S^{-1} U^T$$

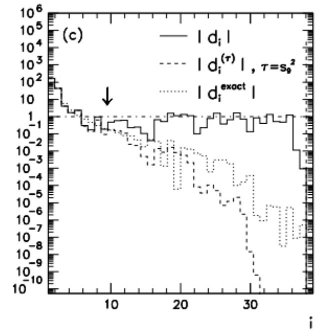
but: delta b != 0

$$\sum_{i=1}^{n_b} \Big(\frac{\sum_{j=1}^{n_x} \hat{A}_{ij} x_j - b_i}{\Delta b_i}\Big)^2 = \min \qquad (\hat{A}x - b)^T B^{-1} (\hat{A}x - b) = \min$$

rescaling and regularization:

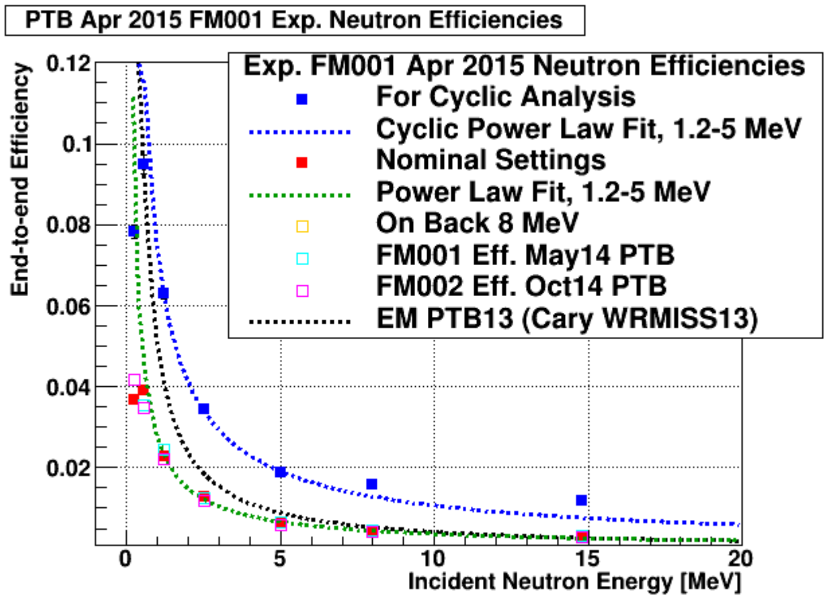
$$(\tilde{A}\, w - \tilde{b})^T\, (\tilde{A}\, w - \tilde{b}) + \tau \cdot (C\, w)^T C\, w \;=\; \min$$

regularization parameter: chosen from rank of response matrix/problem

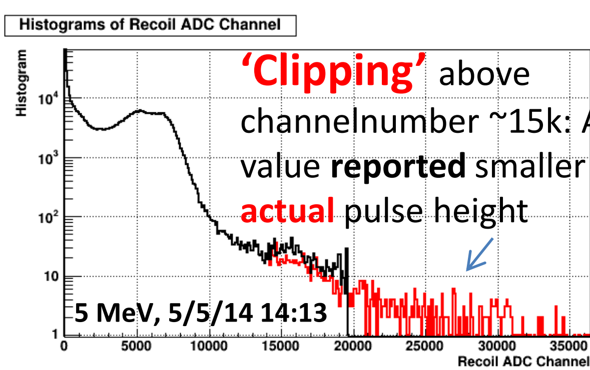


2) Neutron Efficiency Results, ADC Saturation

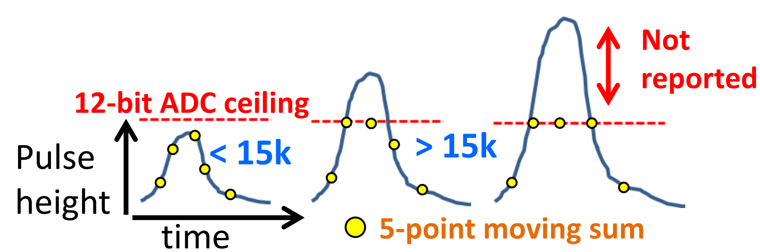
- Efficiencies from PTB datasets: Rel. uncertainties 2-3%;



- ADC saturation for high pulse heights

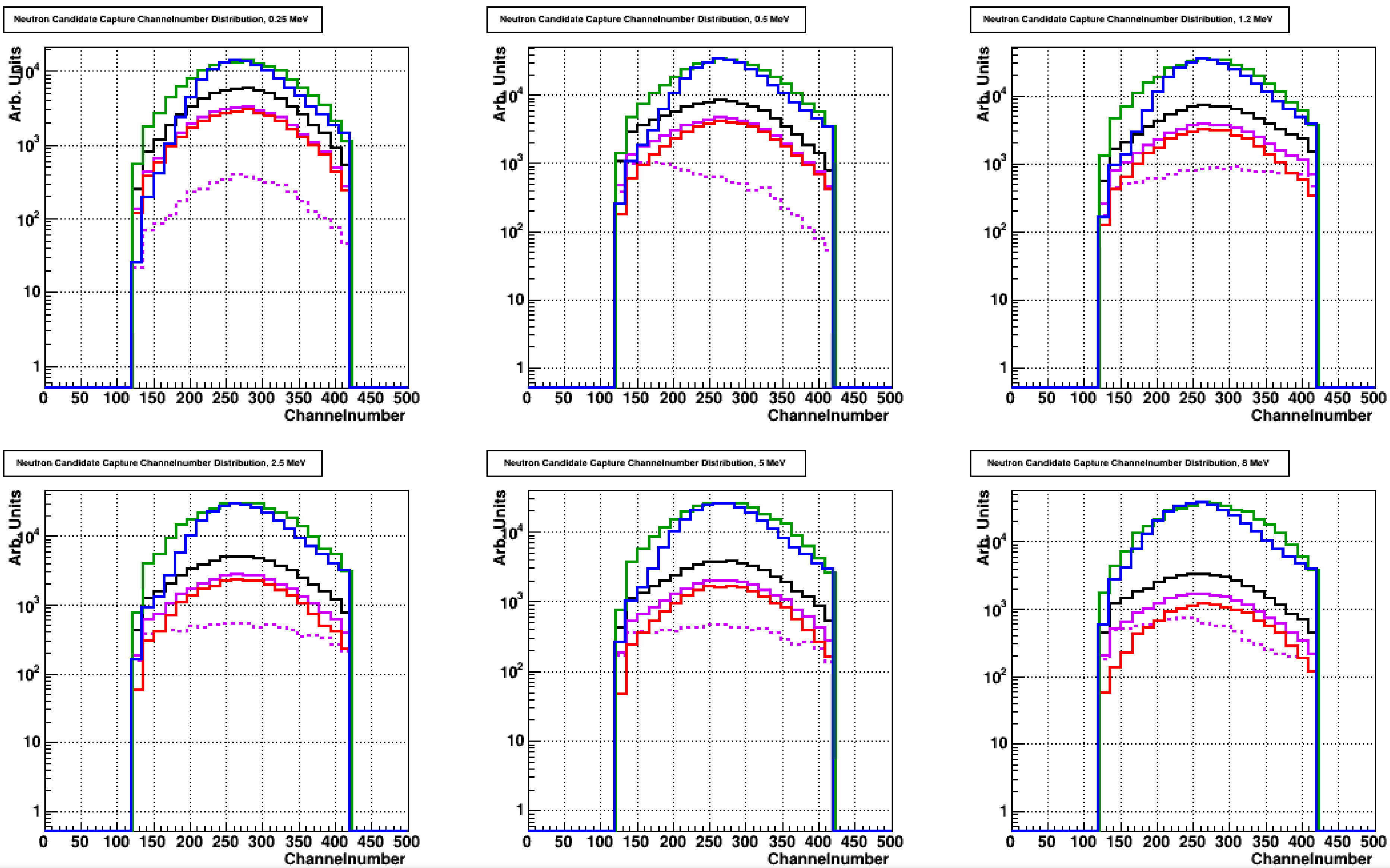


'Clipping' above channelnumber ~15k: ADC value **reported** smaller than **actual** pulse height



2) Preliminary Fit Result to Capture Pulse Distributions

- Experimental data not corrected for beam background/room return



2) Preliminary Simulation Result for Delta t Capture Distribition

- Experimental data not corrected for beam background/room return