

# Neutron Scattering Cross-Section Measurements of $^{208}\text{Pb}$ with ELISA

**J.K. Knijpstra – University of Groningen**

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C. Paradela

A. Plompen



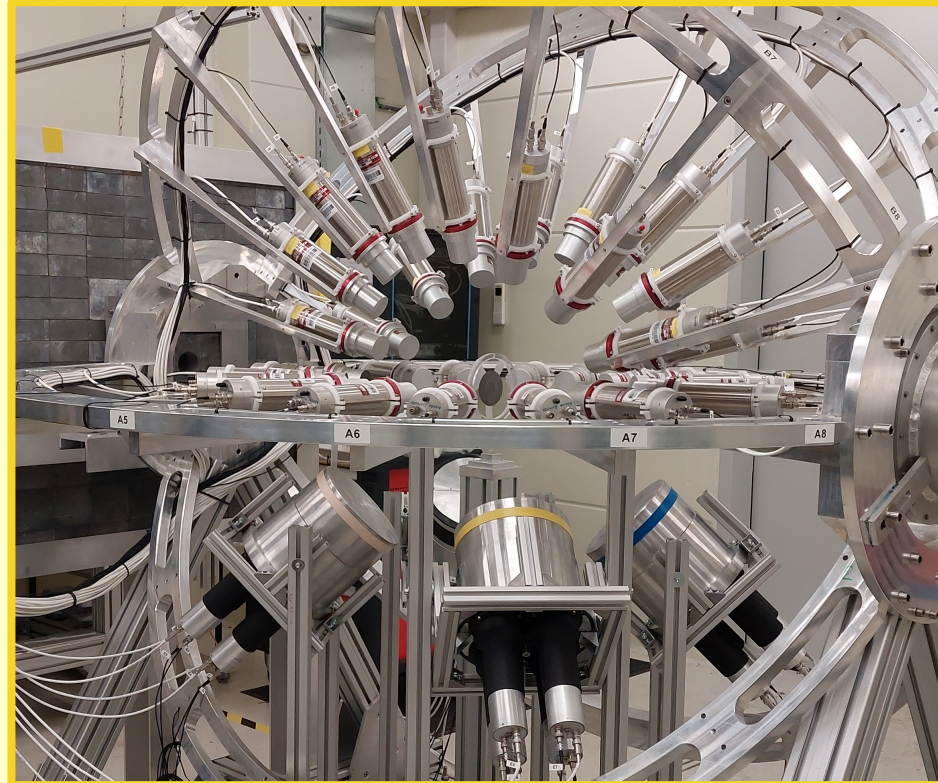
[Wonder 2026: 7th edition of the International Workshop  
On Nuclear Data Evaluation for Reactor Applications](#)



# The ELISA Spectrometer at GELINA

**32 organic liquid scintillators  
at 8 angles**

- 16 EJ301 / EJ309 ( $C_8H_{10}$ )
- 16 EJ315 ( $C_6D_6$ )



**ELISA  
@ 27 m**

The GELINA Facility at EC-JRC Geel

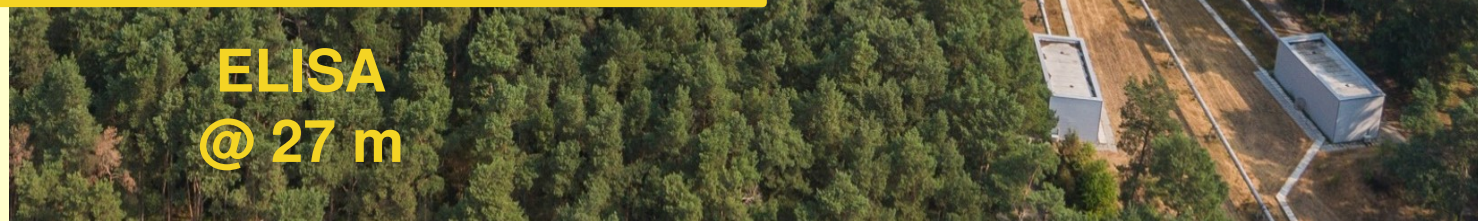
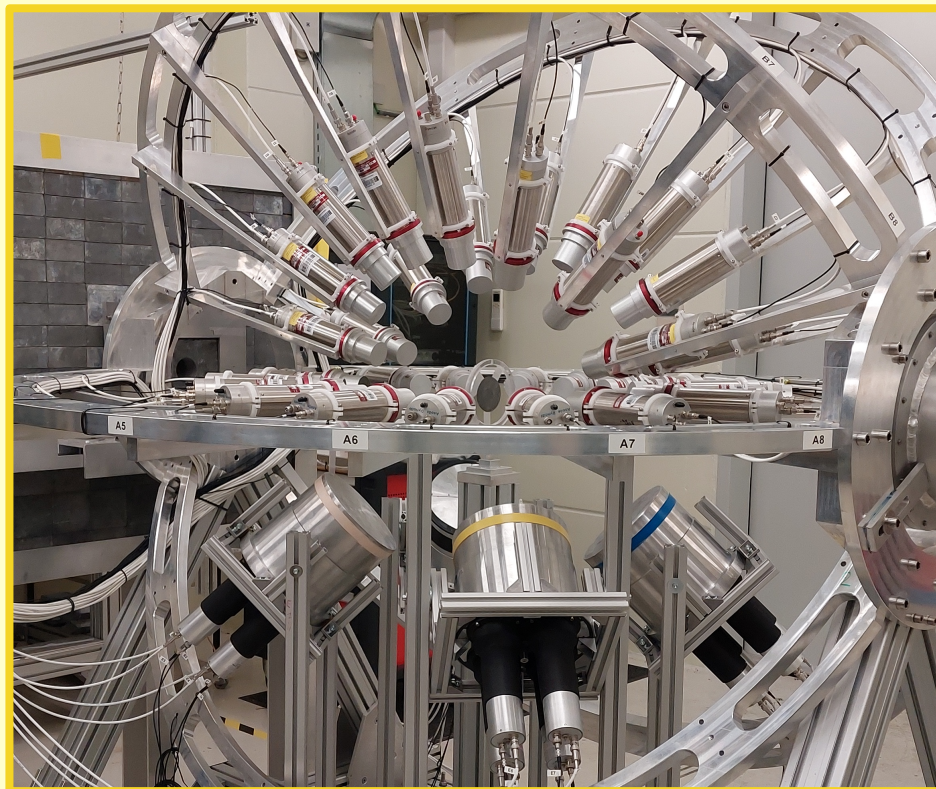
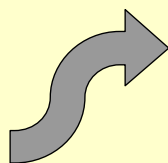


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**$^{235}U$  parallel plate  
fission chamber (FC)**



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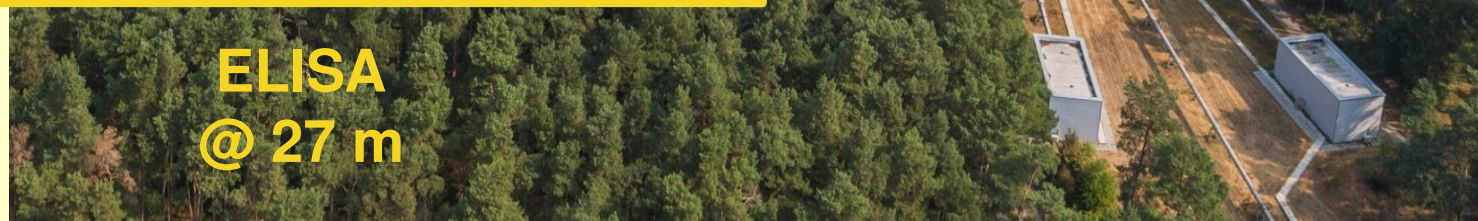
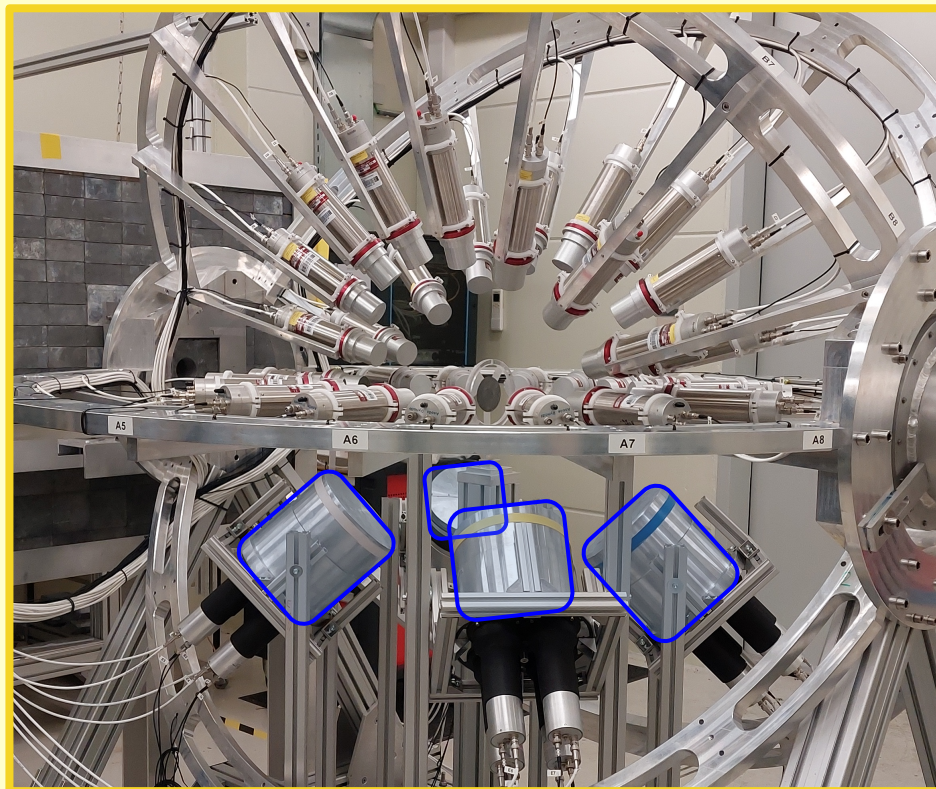
- 16 EJ301 / EJ309 ( $C_8H_{10}$ )
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**$^{235}U$  parallel plate  
fission chamber (FC)**



**Modification: 4 NaI(Tl)**

- Ø25 cm x 30 cm
- Enables n- $\gamma$  coincidence techniques



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# The ELISA Spectrometer at GELINA

## Targets:

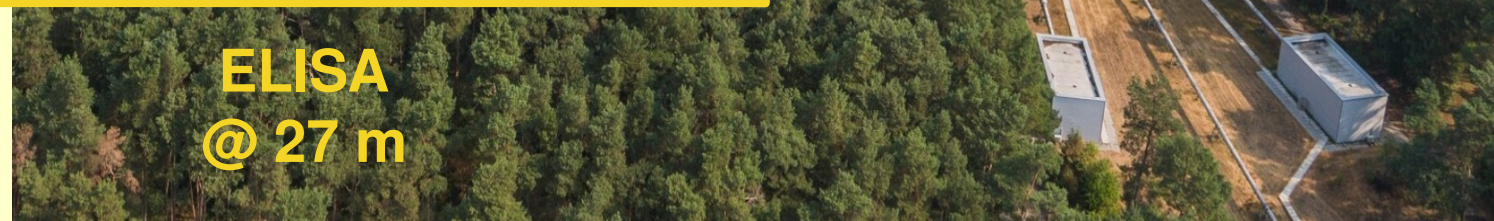
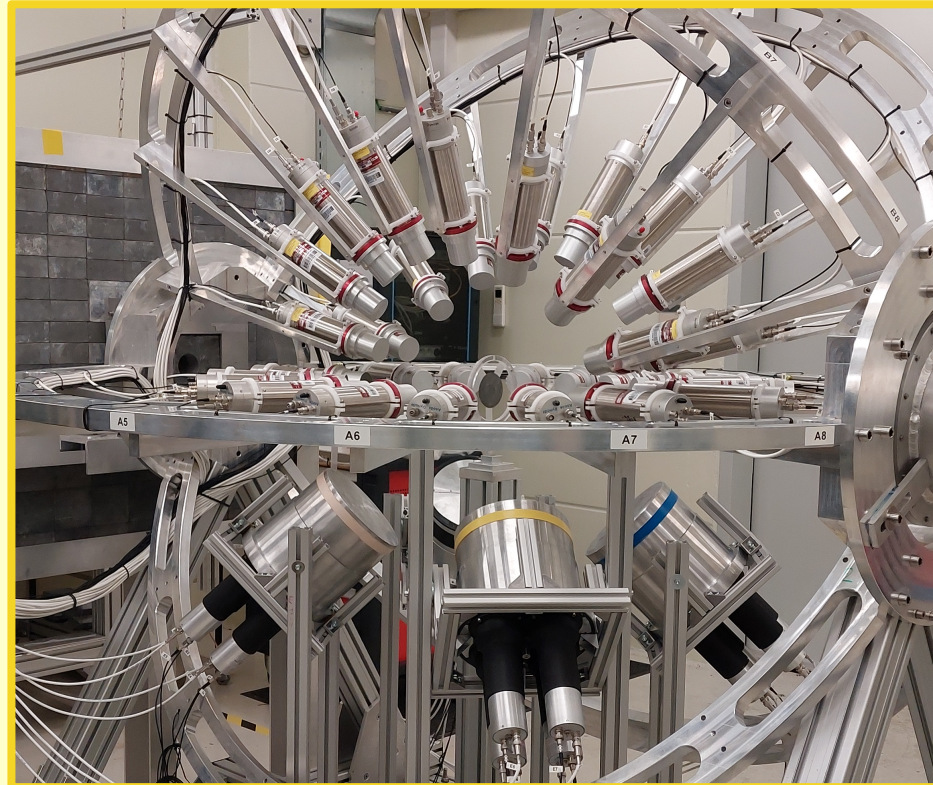
$^{nat}\text{C}$  – 11 mm

$^{208}\text{Pb}$  – 1 mm

$^{208}\text{Pb}$  – 3 mm

Isotope	ENR [%]
$^{208}\text{Pb}$	<b>88.110</b>
$^{207}\text{Pb}$	0.8943
$^{206}\text{Pb}$	10.988
$^{204}\text{Pb}$	0.00758

$^{206}\text{Pb}$  – not yet analysed

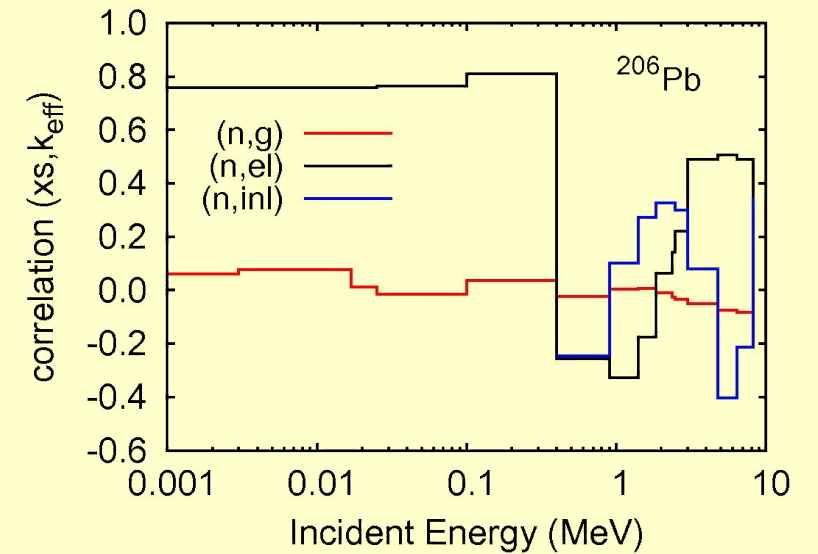
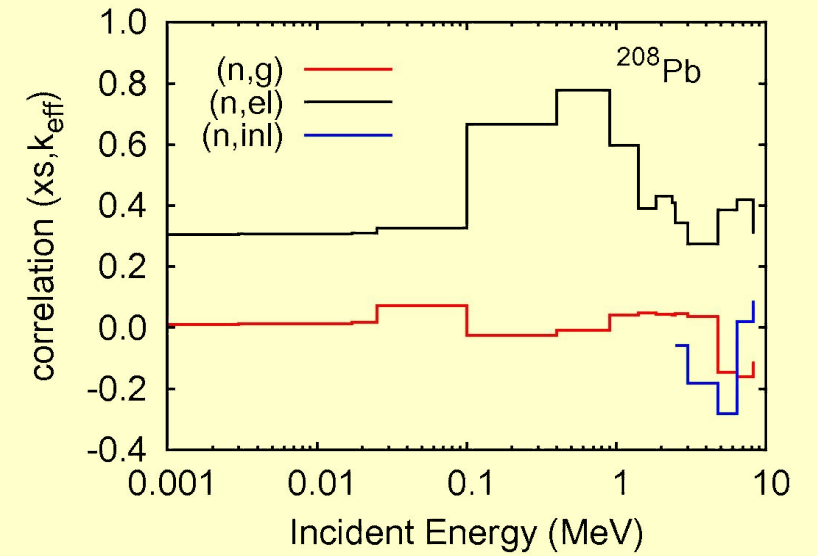


**ELISA  
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The GELINA Facility at EC-JRC Geel

# Motivation

- Lead-cooled fast reactor (LFR) development
- Scattering affects criticality calculations



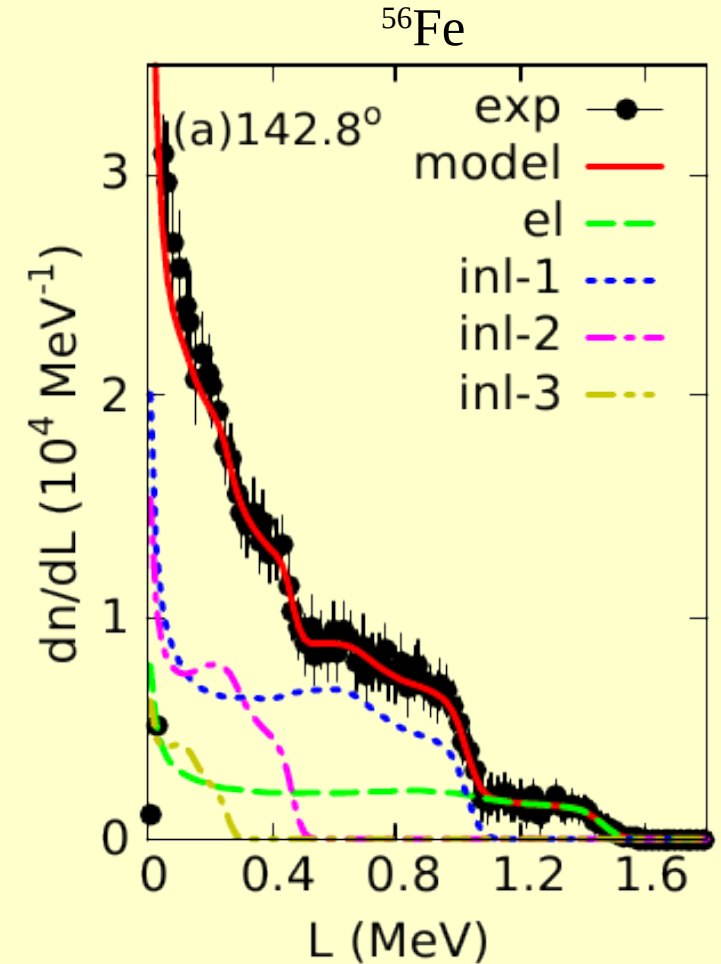
E. Alhassan *et al.*

[10.1016/j.anucene.2014.07.043](https://doi.org/10.1016/j.anucene.2014.07.043)



# Motivation

- Lead-cooled fast reactor (LFR) development
- Scattering affects criticality
- **Test n- $\gamma$  coincidence technique**
- Inelastic at ELISA restricted to nuclei with spaced levels:  $^{12}\text{C}$ ,  $^{54}\text{Fe}$ , etc.
- Coincidence analysis may allow (n,n' $\gamma$ ) measurement for formerly inaccessible nuclei



TOF = [976,986] ns

G. Gkatis, PhD thesis

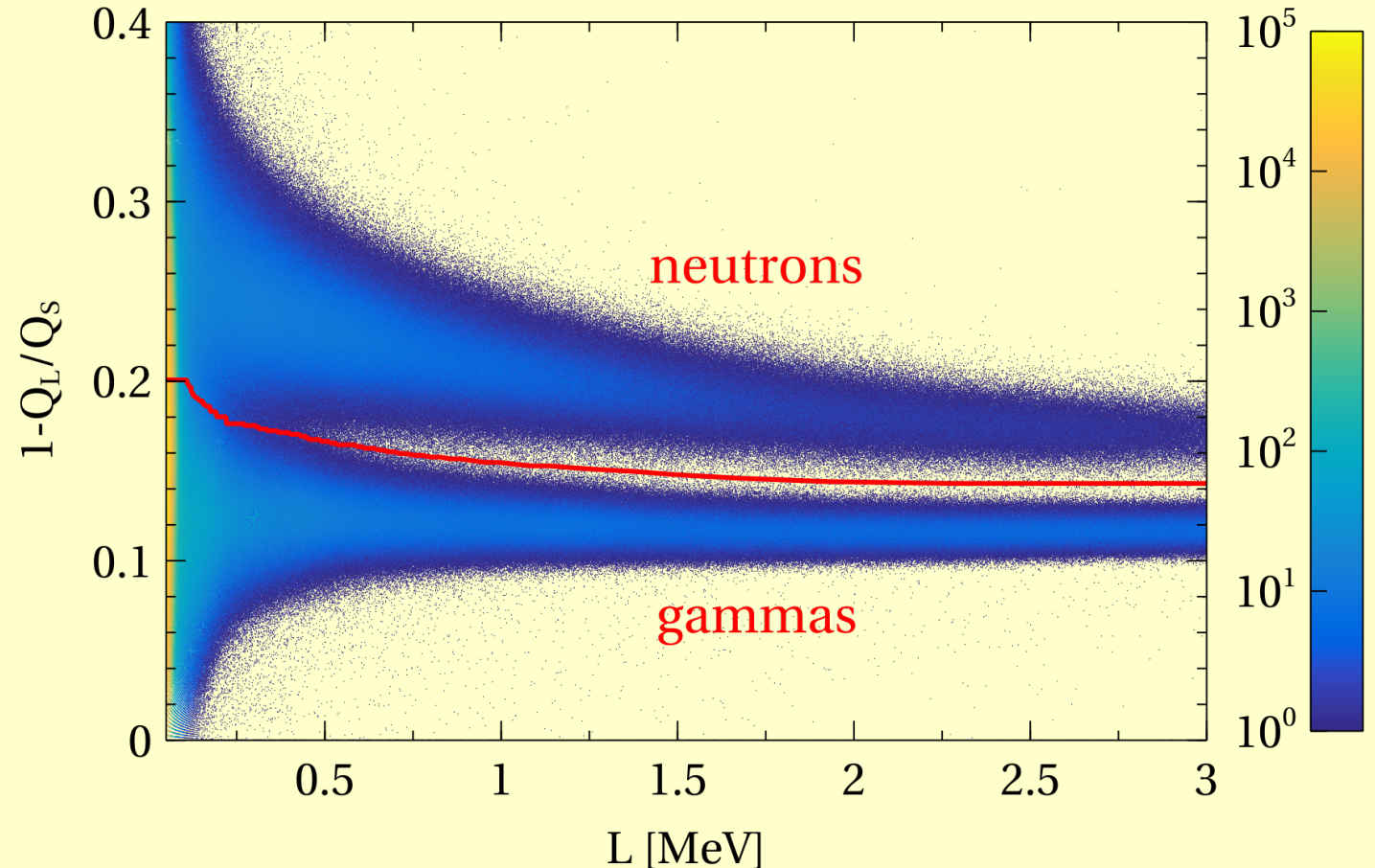


# Data Analysis Procedure – Elastic Scattering

- 1) Neutron/gamma separation
- 2) Subtract sample-out data
- 3) Detector response
- 4) Neutron fluence
- 5) Elastic/inelastic separation
- 6) Multiple scattering correction
- 7) Extract cross sections

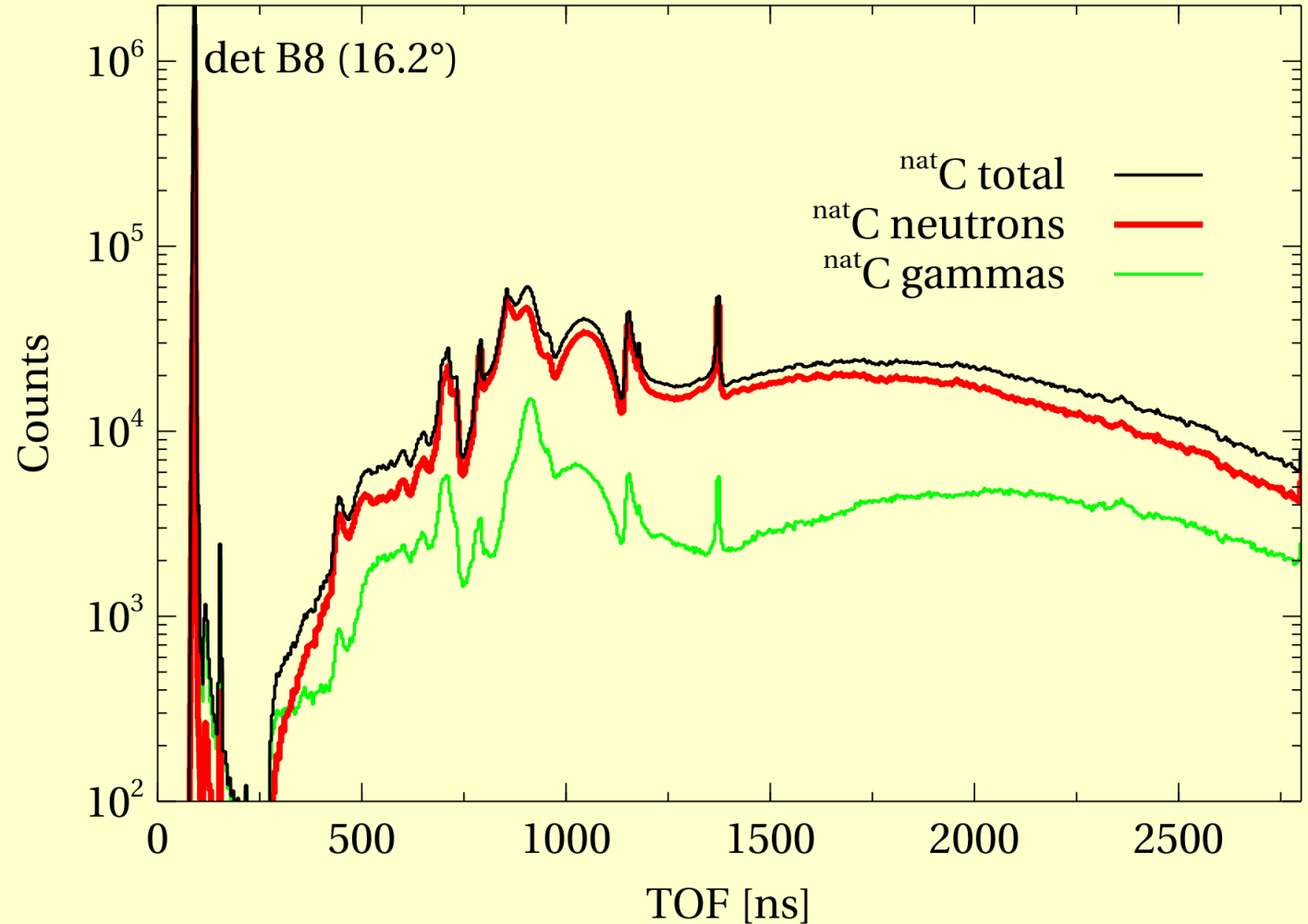
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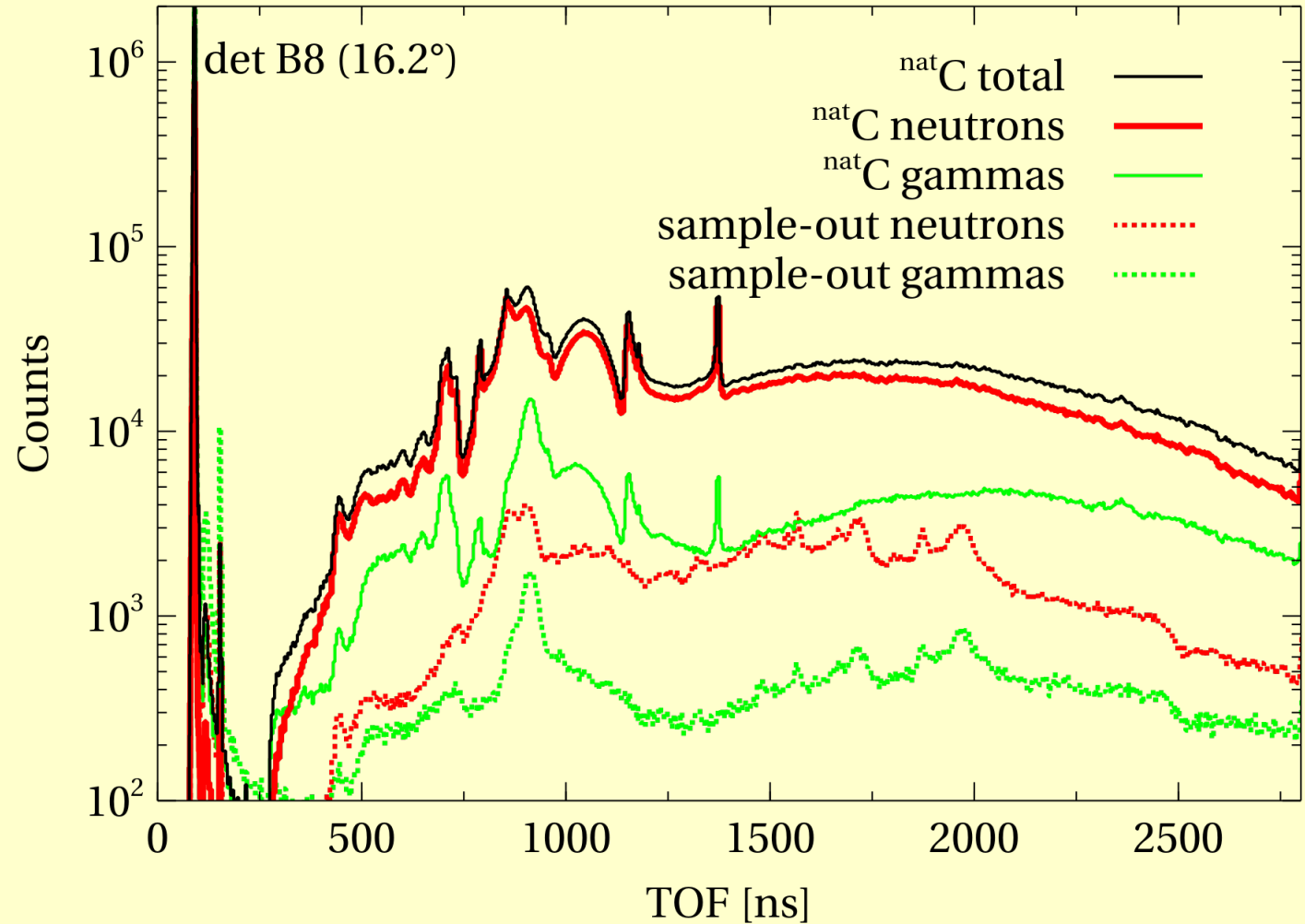
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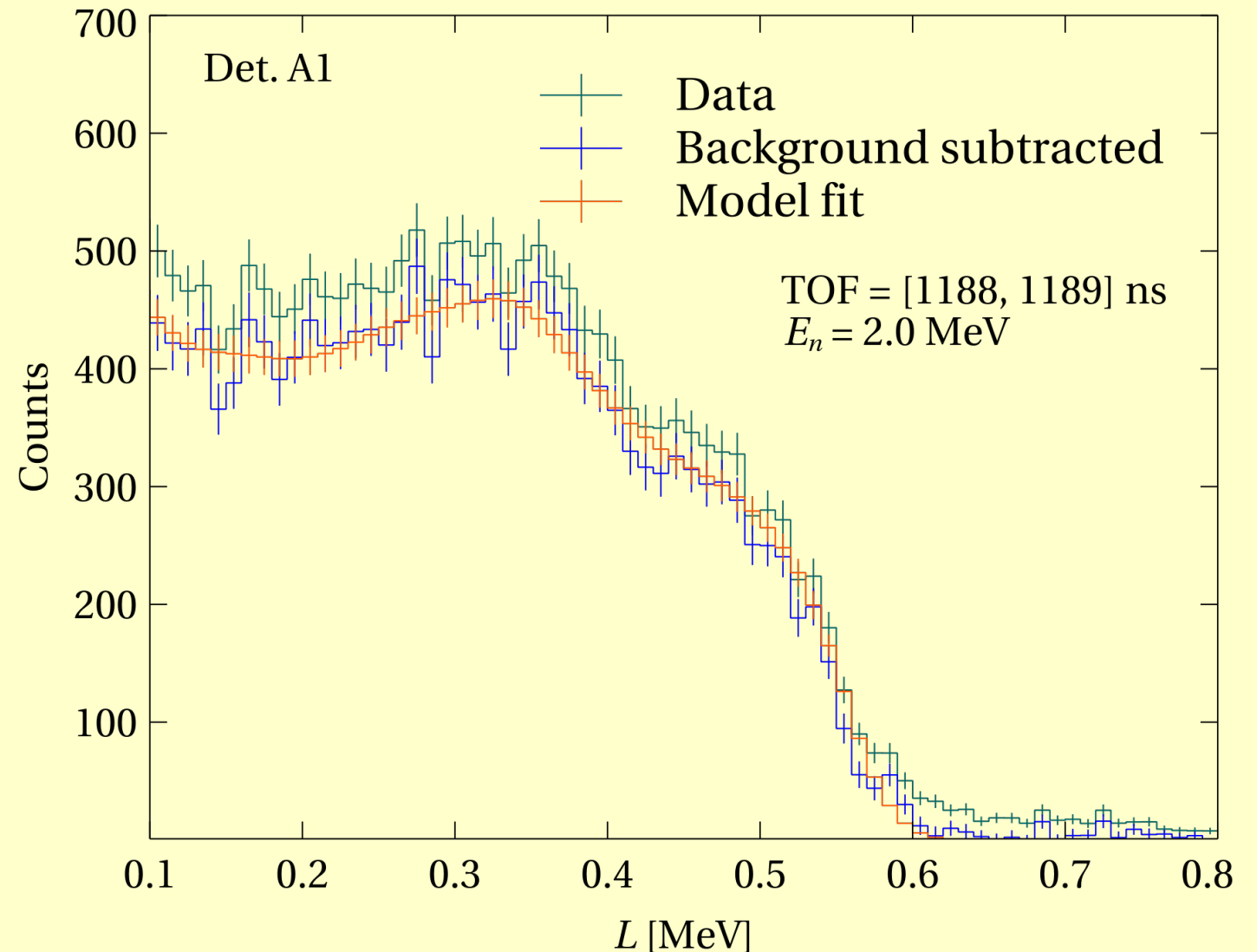
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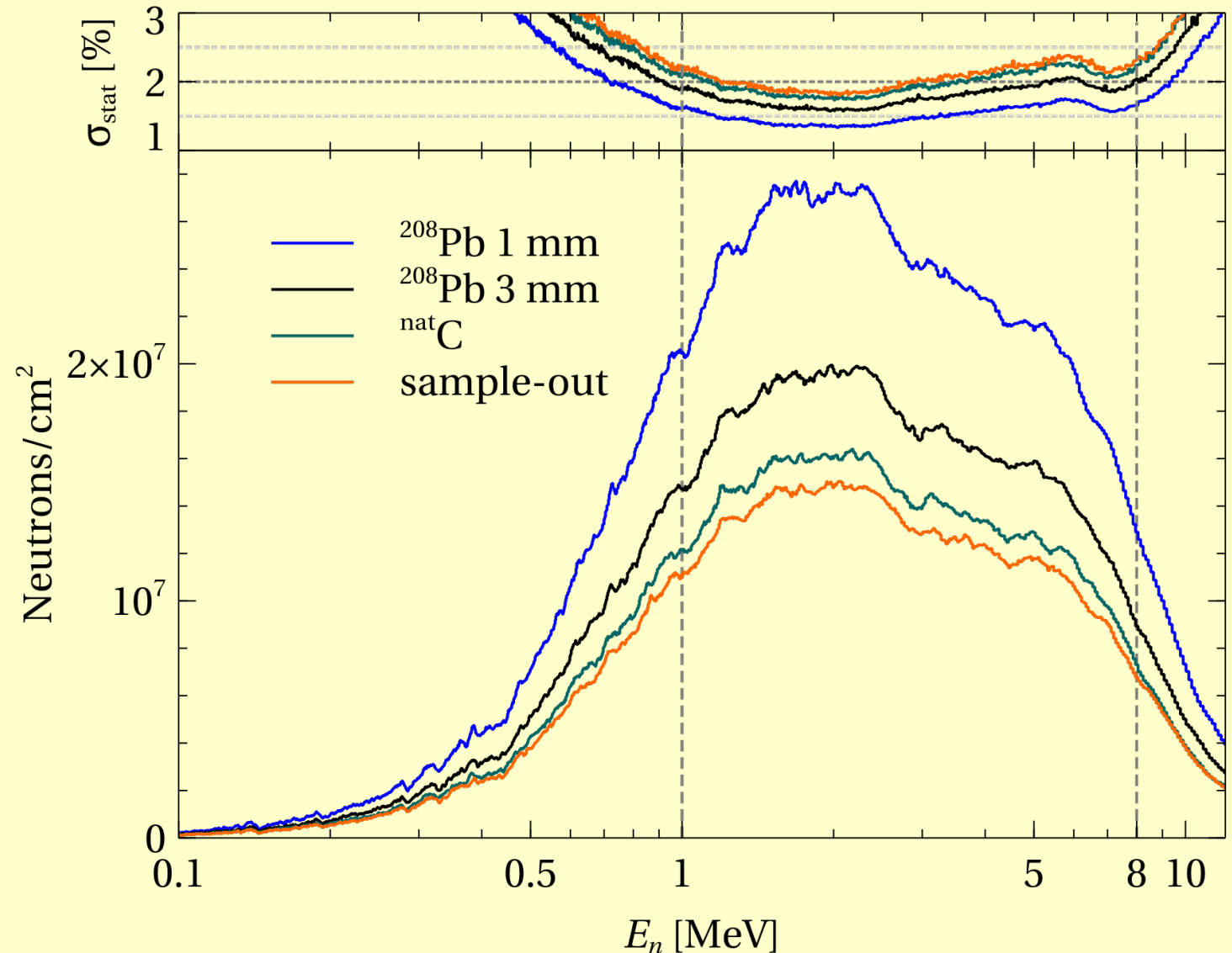
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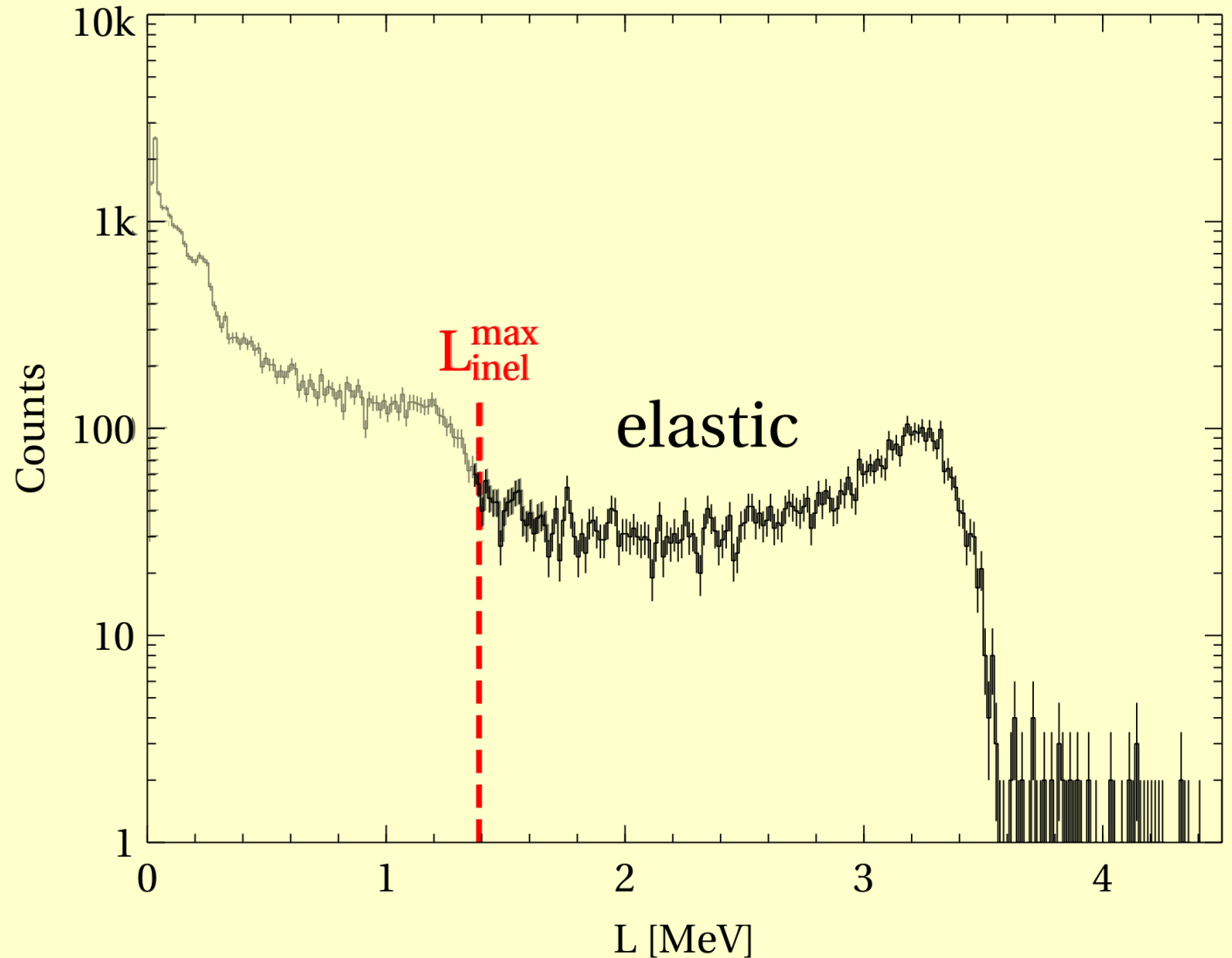
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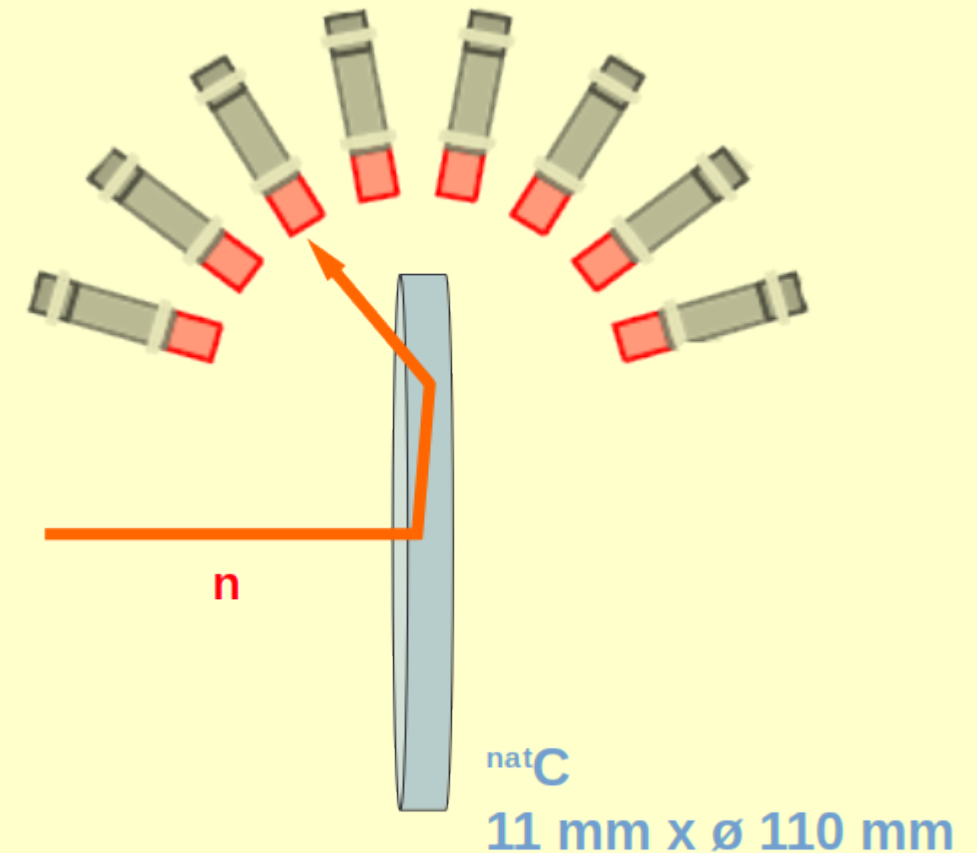
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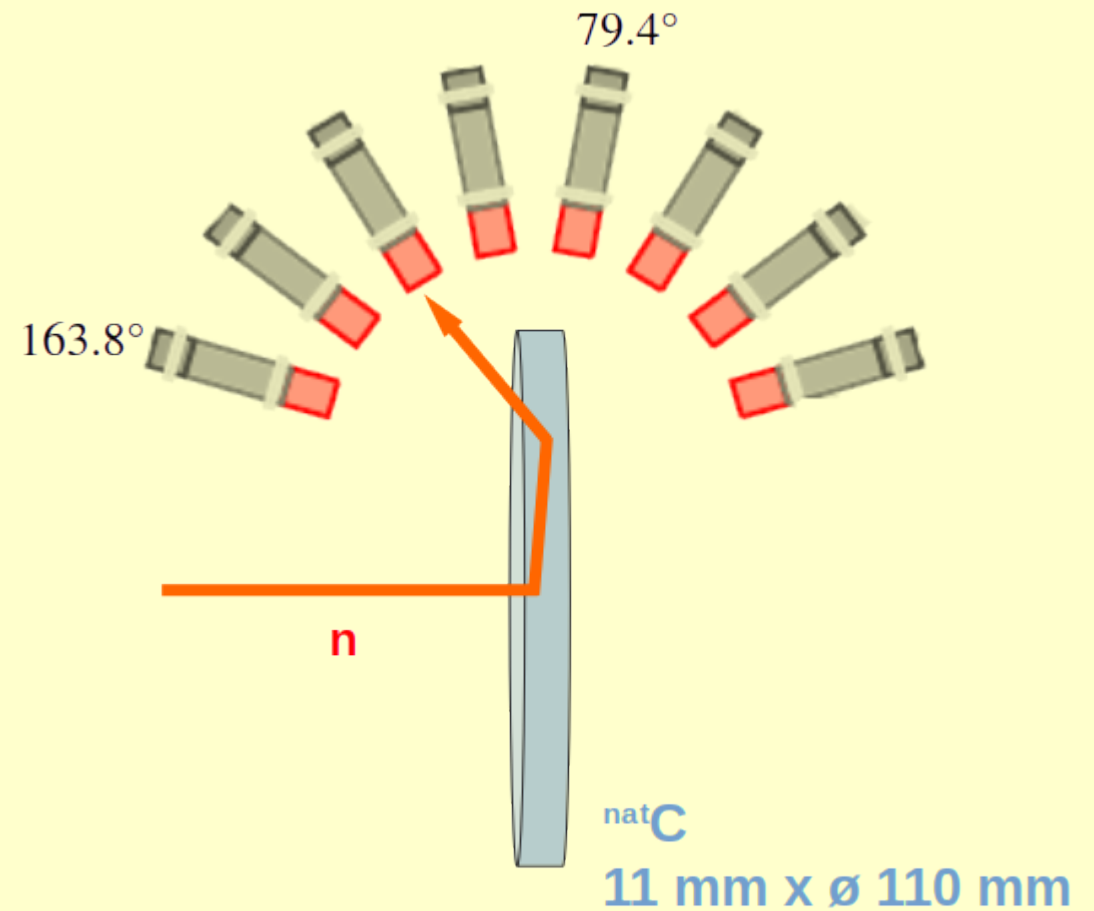
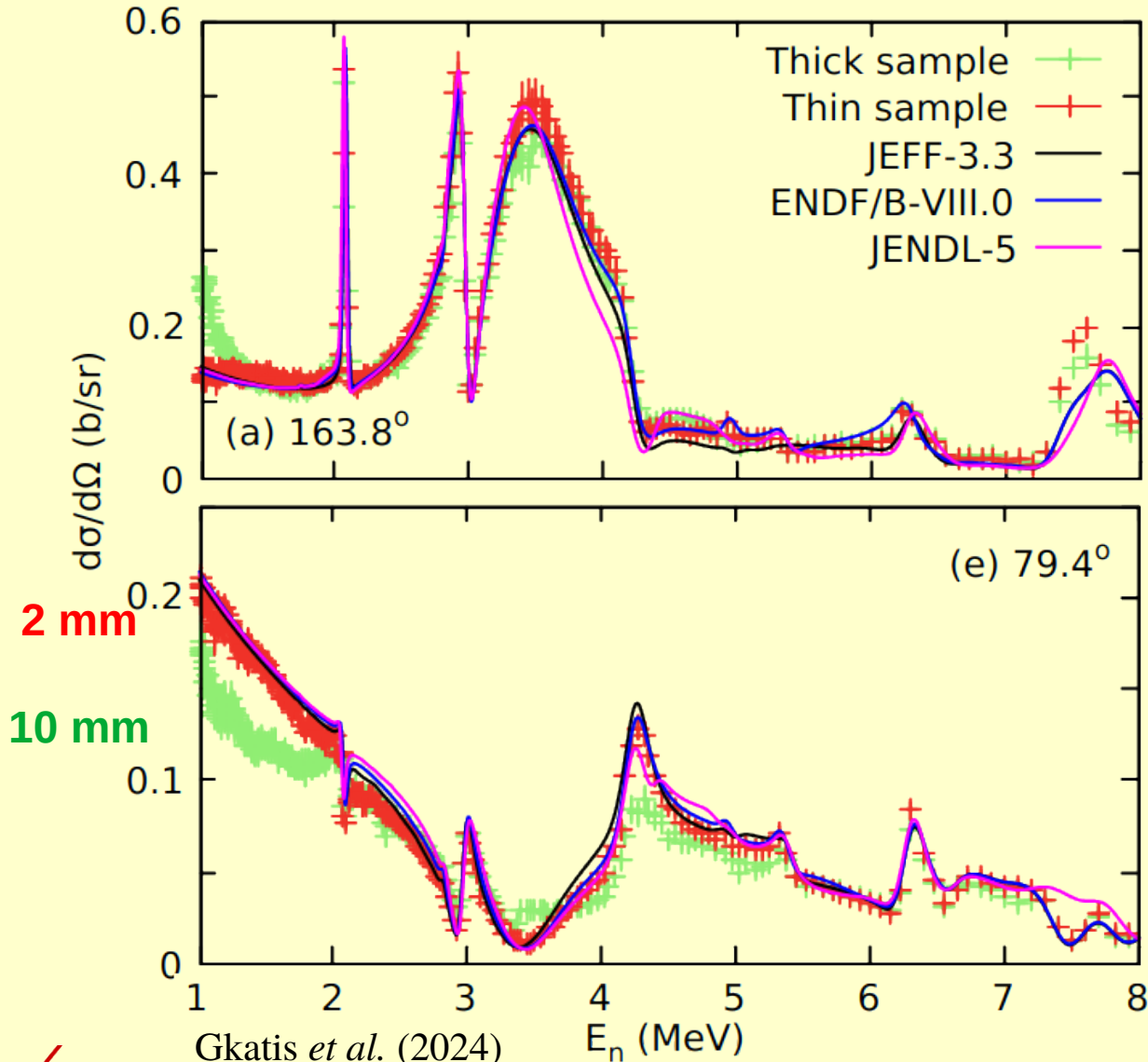
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# $^{nat}\text{C}(n,e)$ Multiple Scattering

MC corrections unreliable for thick samples:

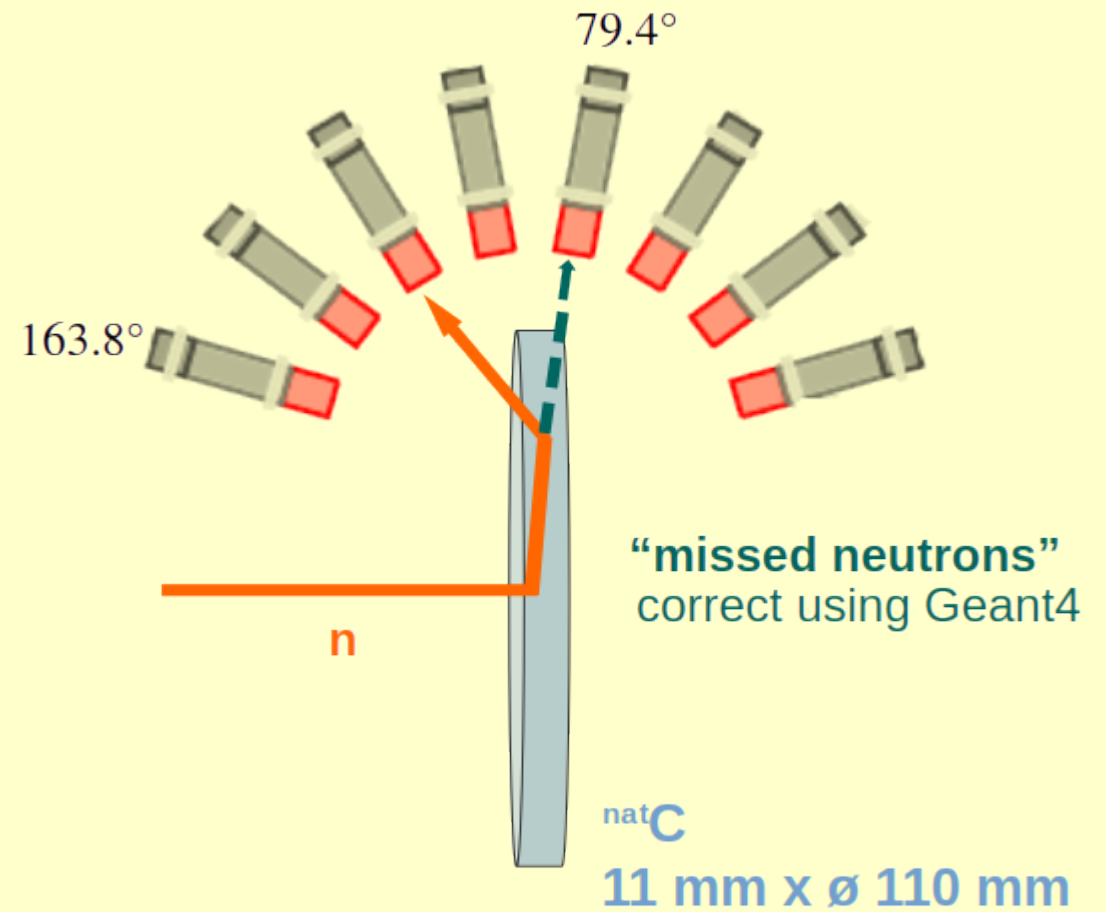
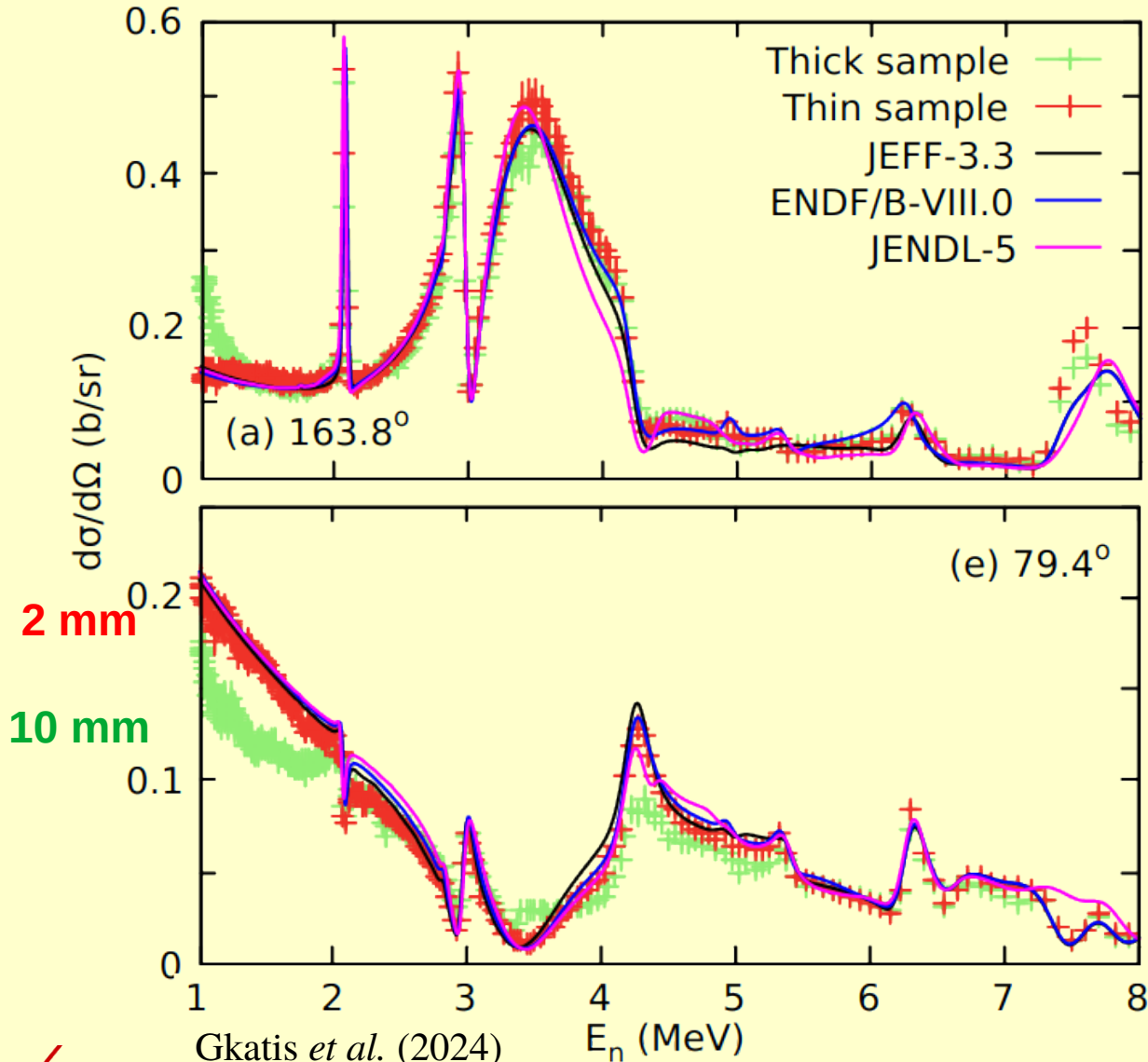


Gkatis *et al.* (2024)

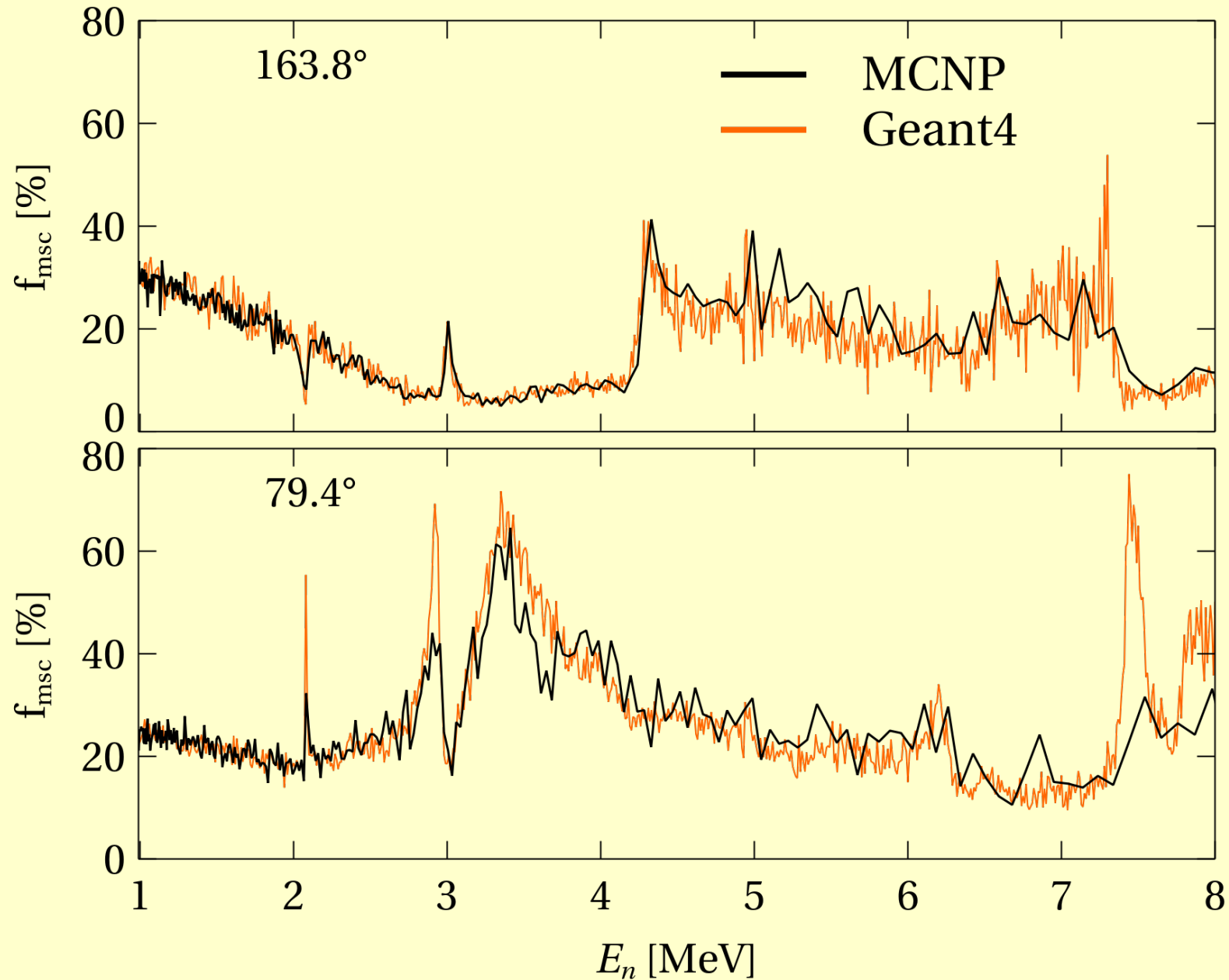
<https://doi.org/10.1103/PhysRevC.110.034609>

# <sup>nat</sup>C(n,e) Multiple Scattering

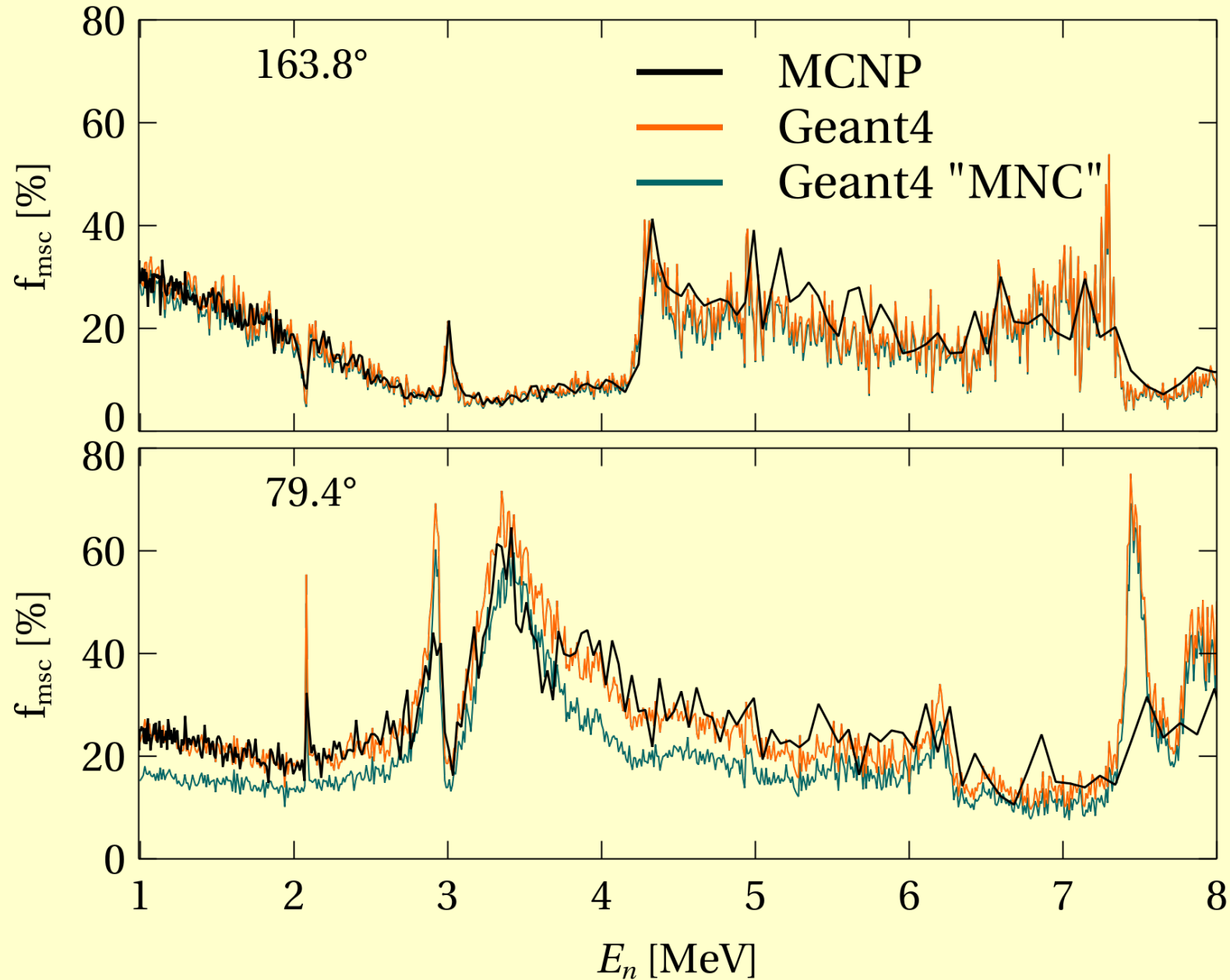
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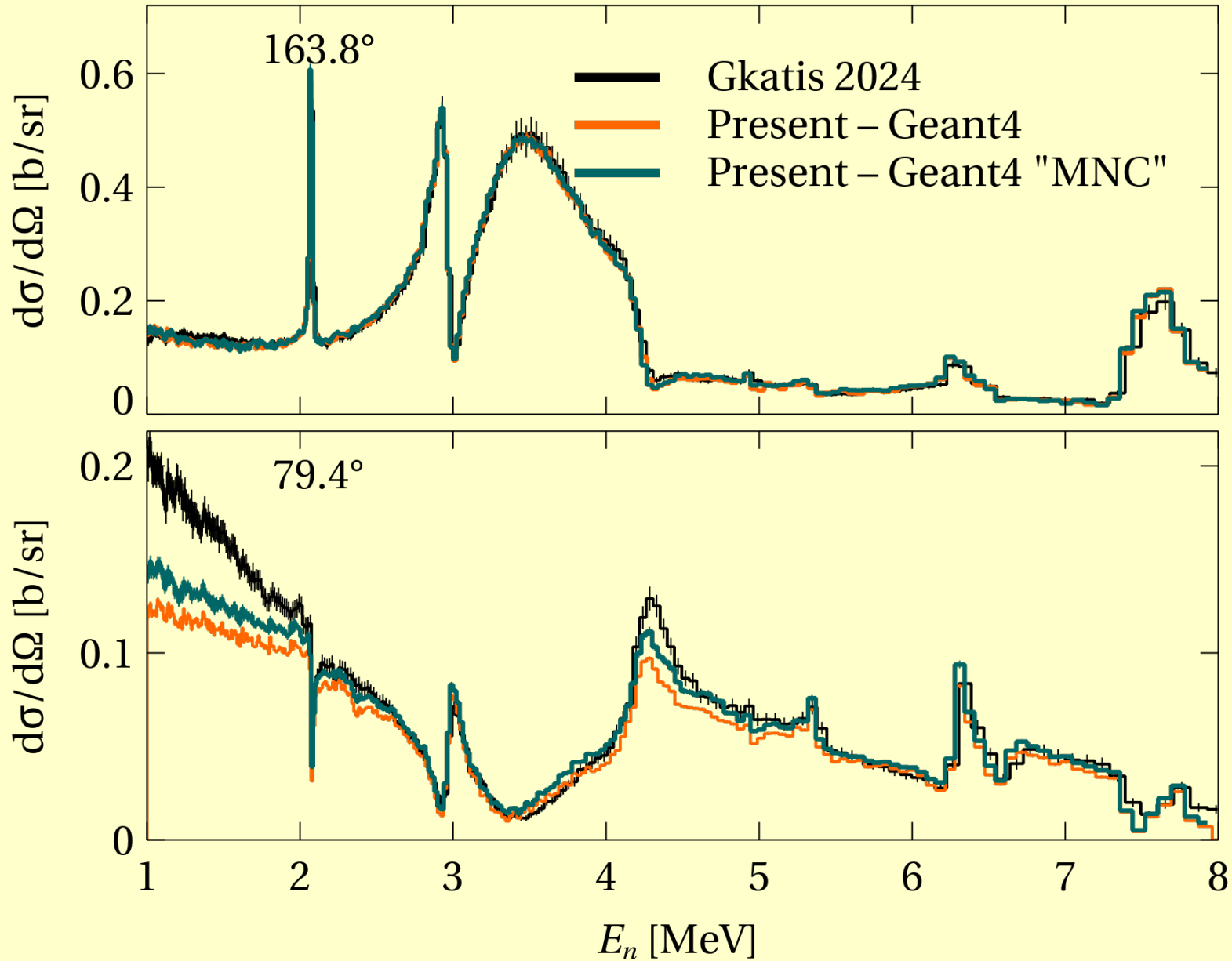
# <sup>nat</sup>C(n,e) Multiple Scattering



“MNC”  
missed-neutron  
correction



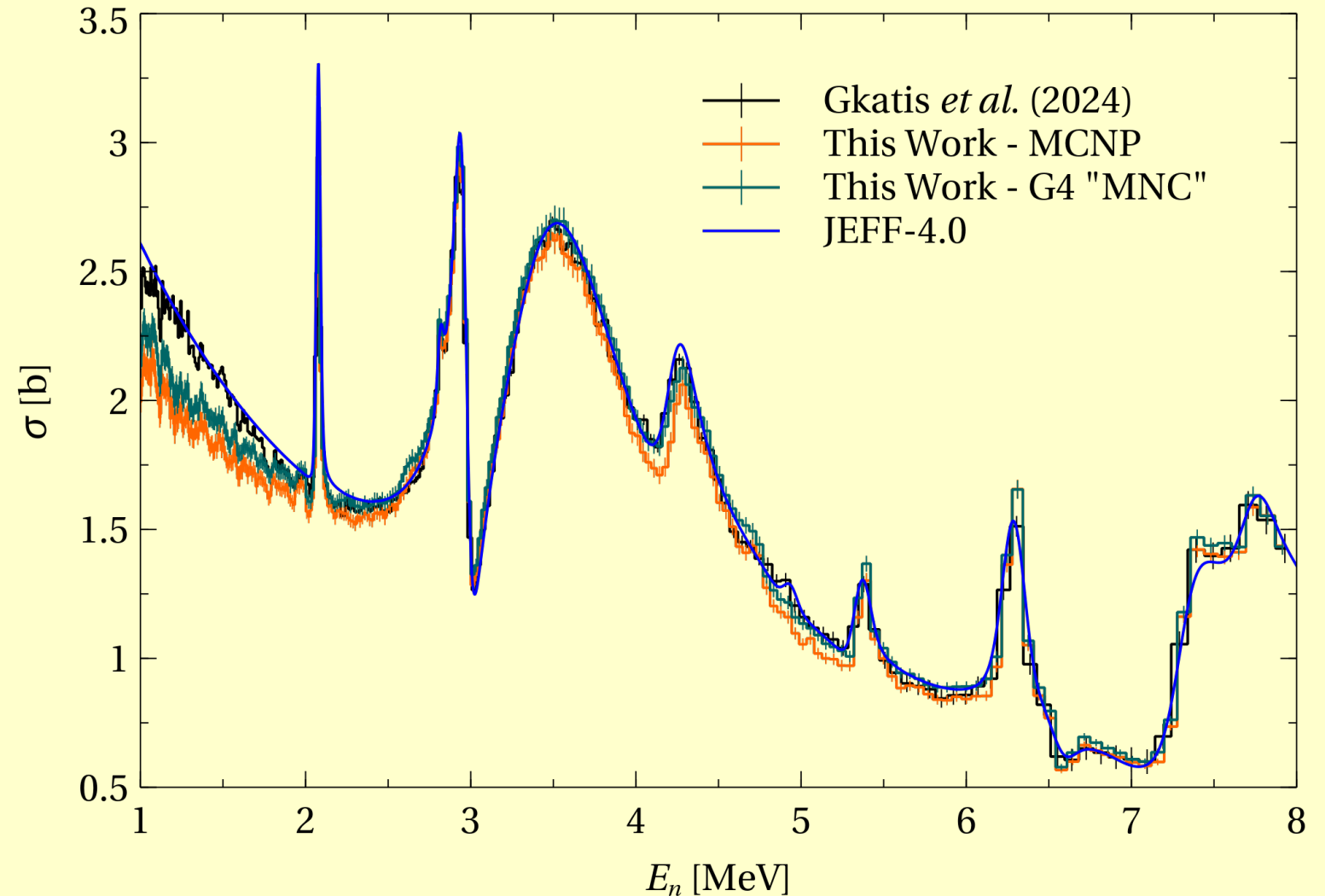
# <sup>nat</sup>C(n,e) Differential Cross Sections



# <sup>nat</sup>C(n,eI) Angle Integrated Cross Section

Gauss-Legendre quadrature:

$$\sigma(E) = 2\pi \sum_{i=1}^8 w_i \frac{d\sigma}{d\Omega}(E, \cos \theta_i)$$

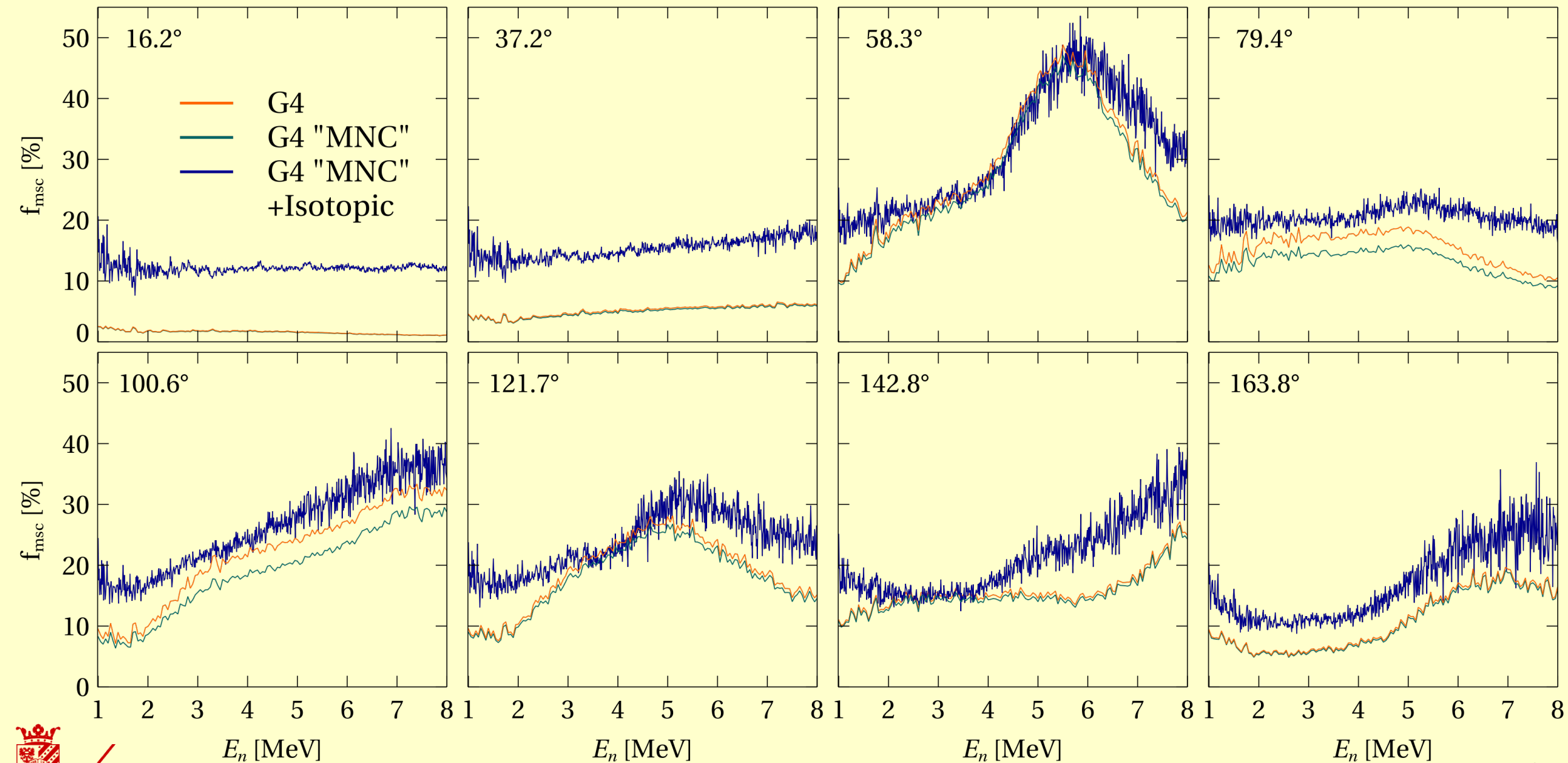


# $^{208}\text{Pb}(n,e\ell)$ Analysis

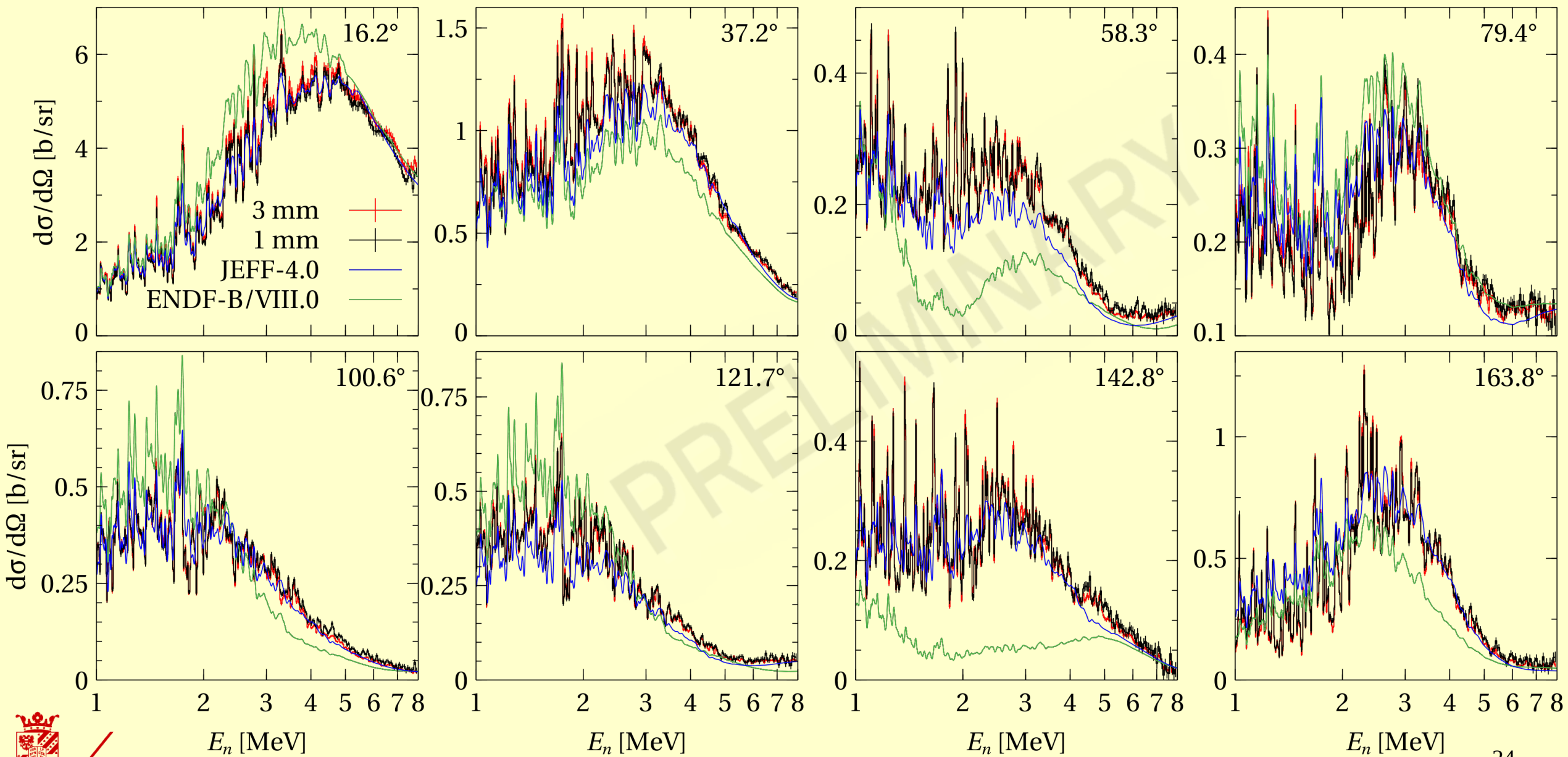
**Correction** required for scattering on **non- $^{208}\text{Pb}$**  isotopes



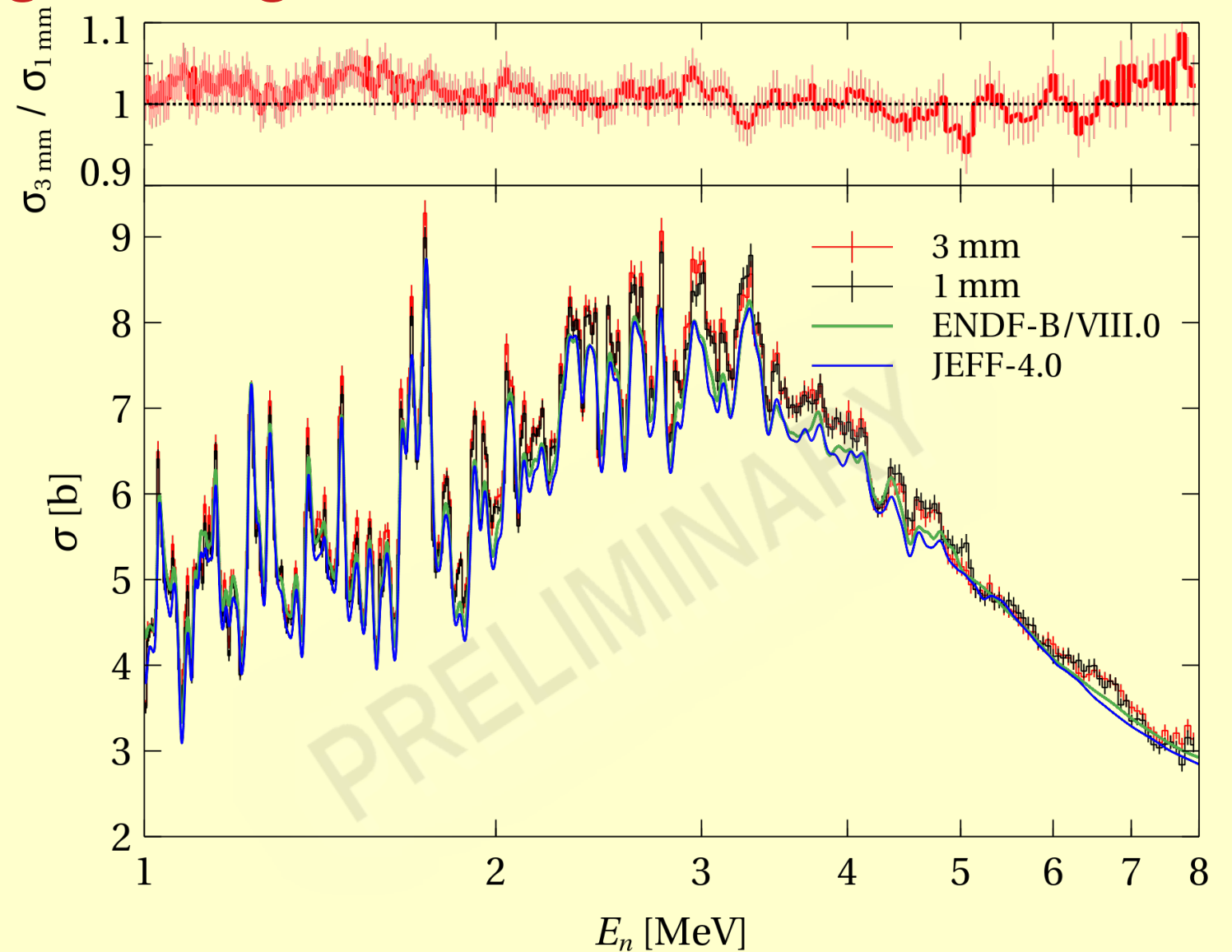
# $^{208}\text{Pb}(n,e)$ Multiple Scattering + Isotopic Corrections – 3 mm



# $^{208}\text{Pb}(n,e)$ Differential Cross Sections



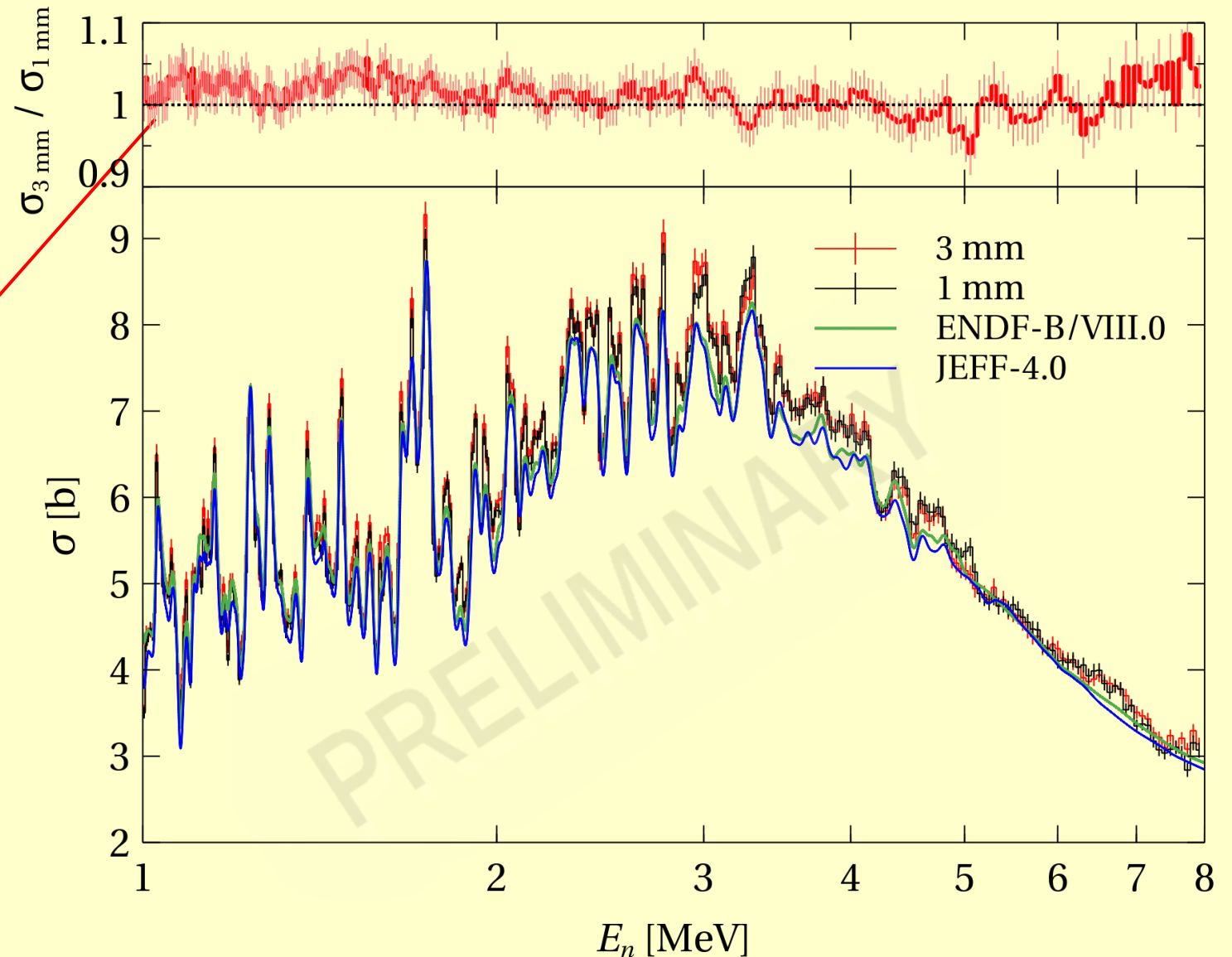
# $^{208}\text{Pb}(n,e)$ Angle-Integrated Cross Section



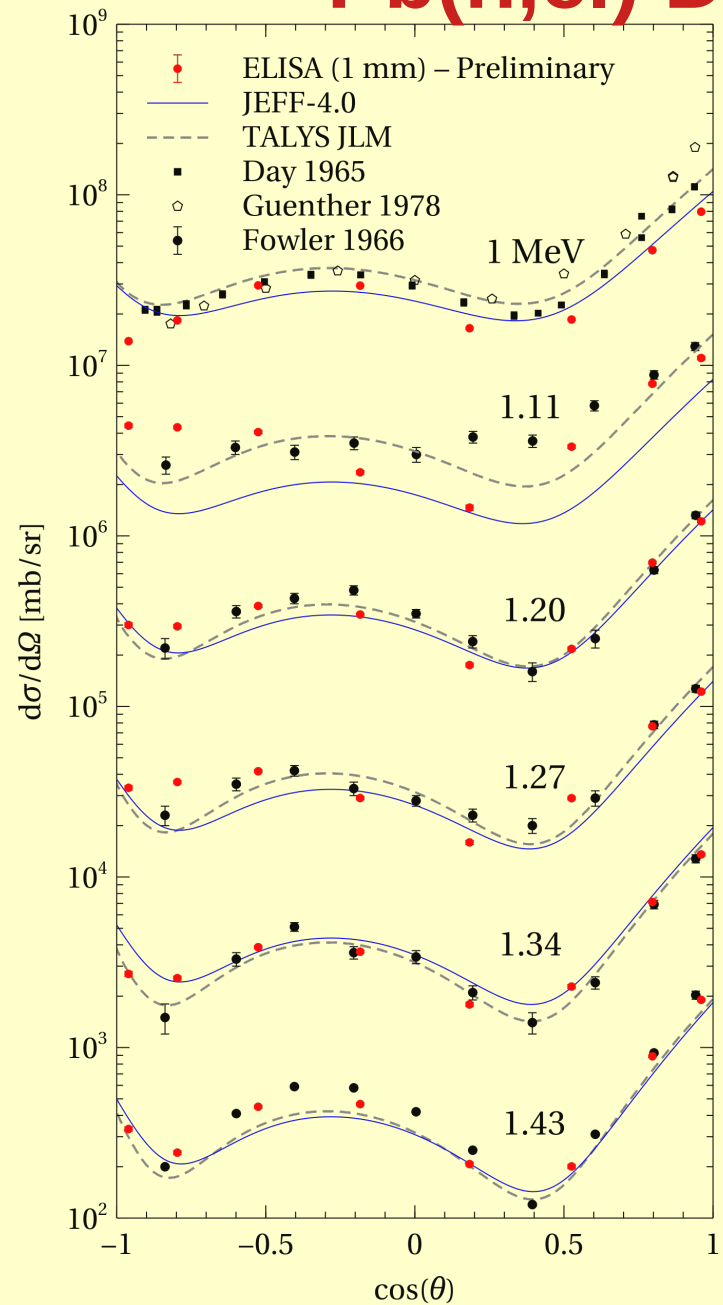
# $^{208}\text{Pb}(n,e\ell)$ Angle-Integrated Cross Section

## Systematic uncertainties

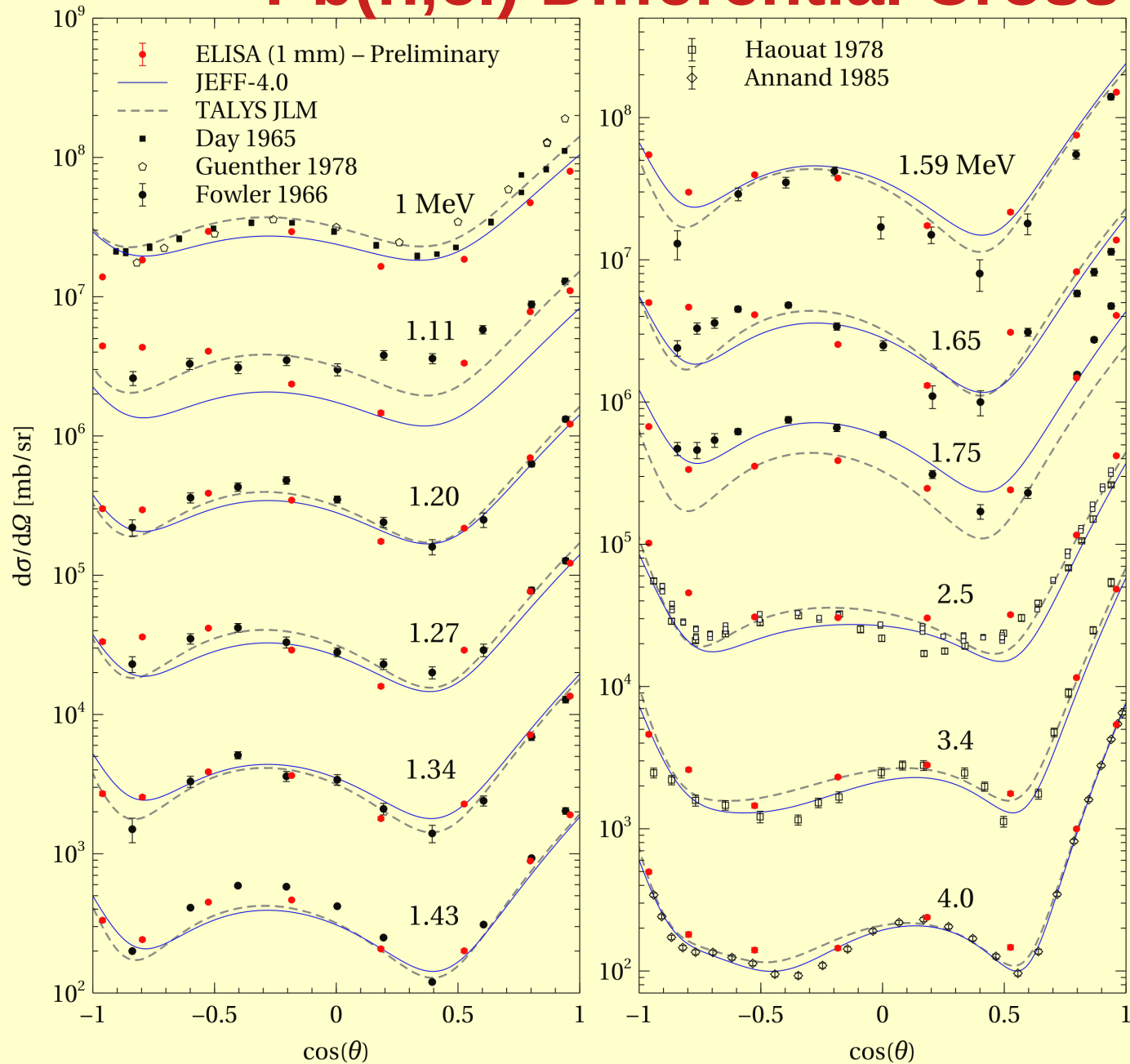
Multiple scattering correction	0 – 5%
Isotopic correction	?
FC efficiency	1%
$^{235}\text{U}(n,f)$ cross section	1.1 – 1.2%



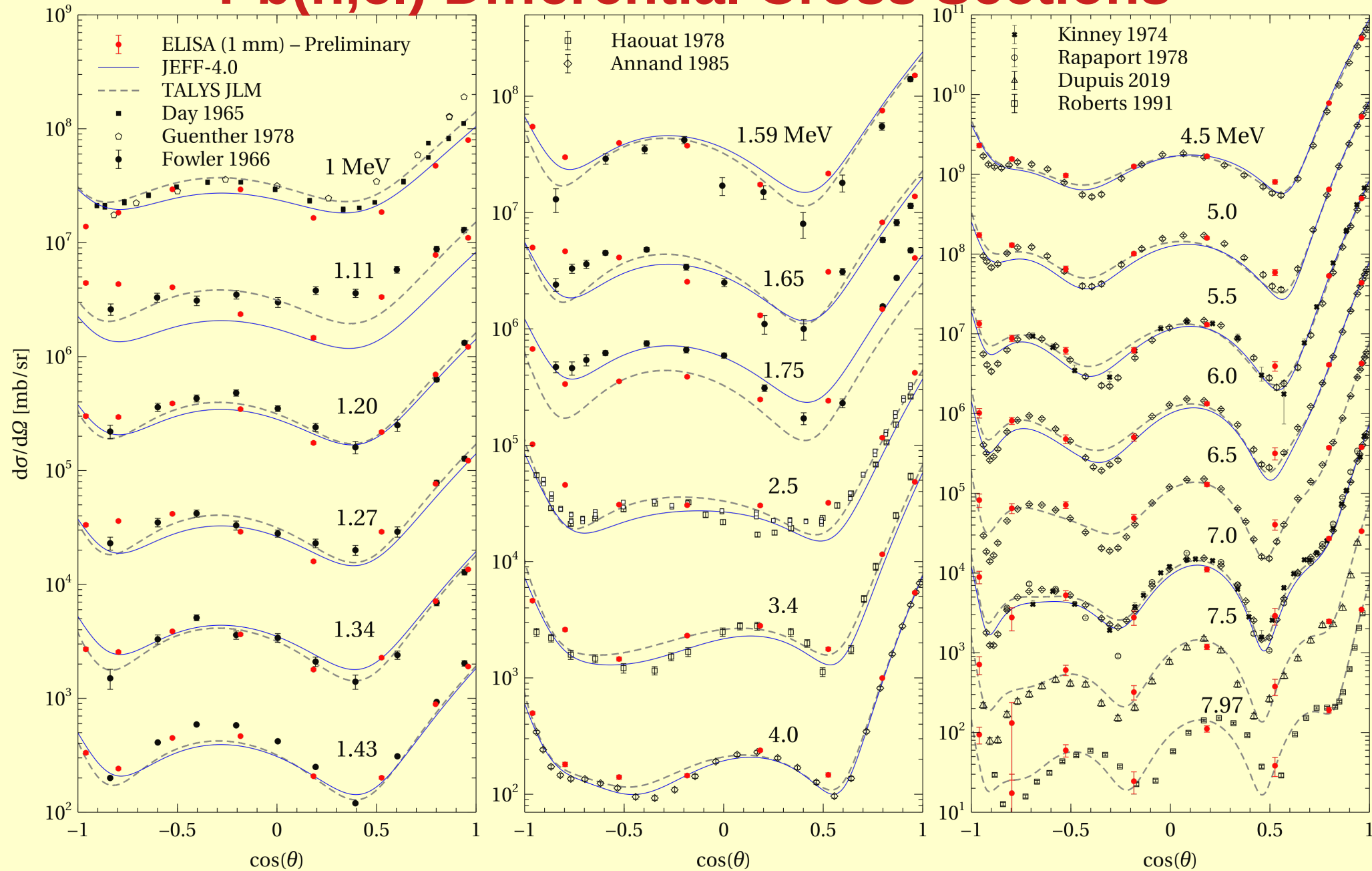
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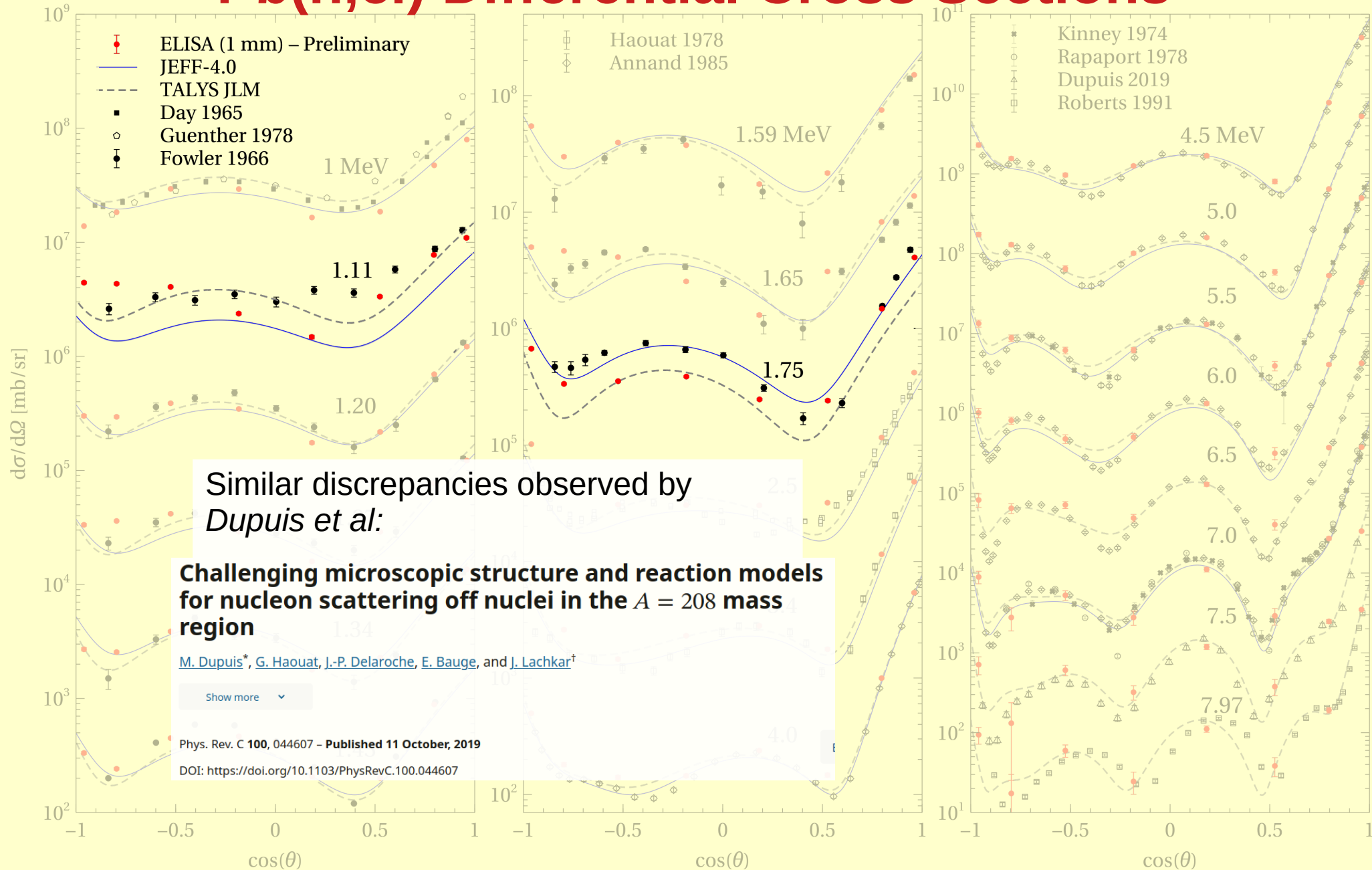
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# Conclusions

- **Improved multiple scattering corrections**
  - ▷ Verified with  $^{nat}\text{C}(n,el)$  cross sections
- **$^{208}\text{Pb}(n,el)$  differential cross sections measured from 1 to 8 MeV**
  - ▷ Reasonable coherence with JEFF-4.0 and exp. data at most energies/angles
  - ▷ Disagreements at certain energies



# Conclusions

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  - ▷ Reasonable coherence with JEFF-4.0 and exp. data at most energies/angles
  - ▷ Disagreements at certain energies

# Outlook

- Analyse  $^{206}\text{Pb}(n,\text{el})$ 
  - ▷ Improve isotopic corrections in  $^{208}\text{Pb}$  analysis
- Analyse  $^{206,208}\text{Pb}(n,n'\gamma)$  through coincidence analysis



# Extra Slides

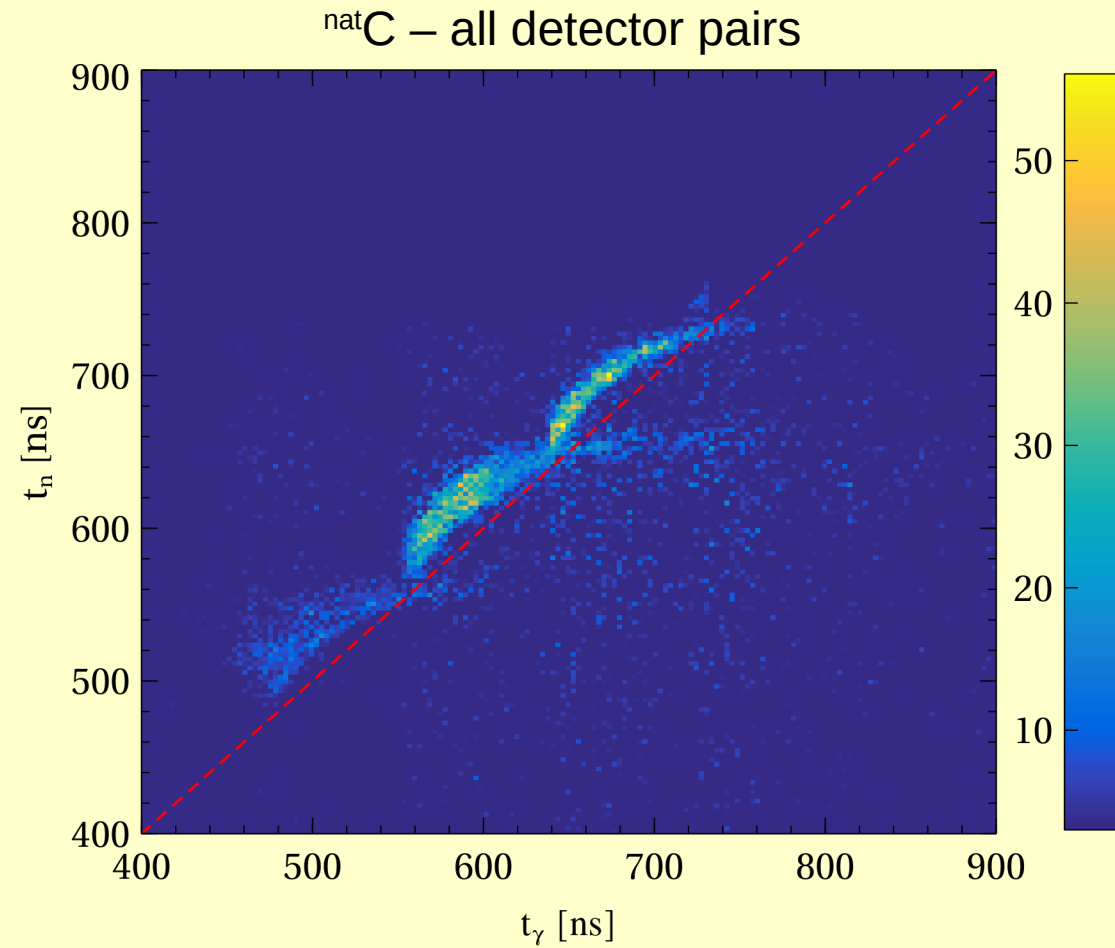


# n- $\gamma$ coincidence data

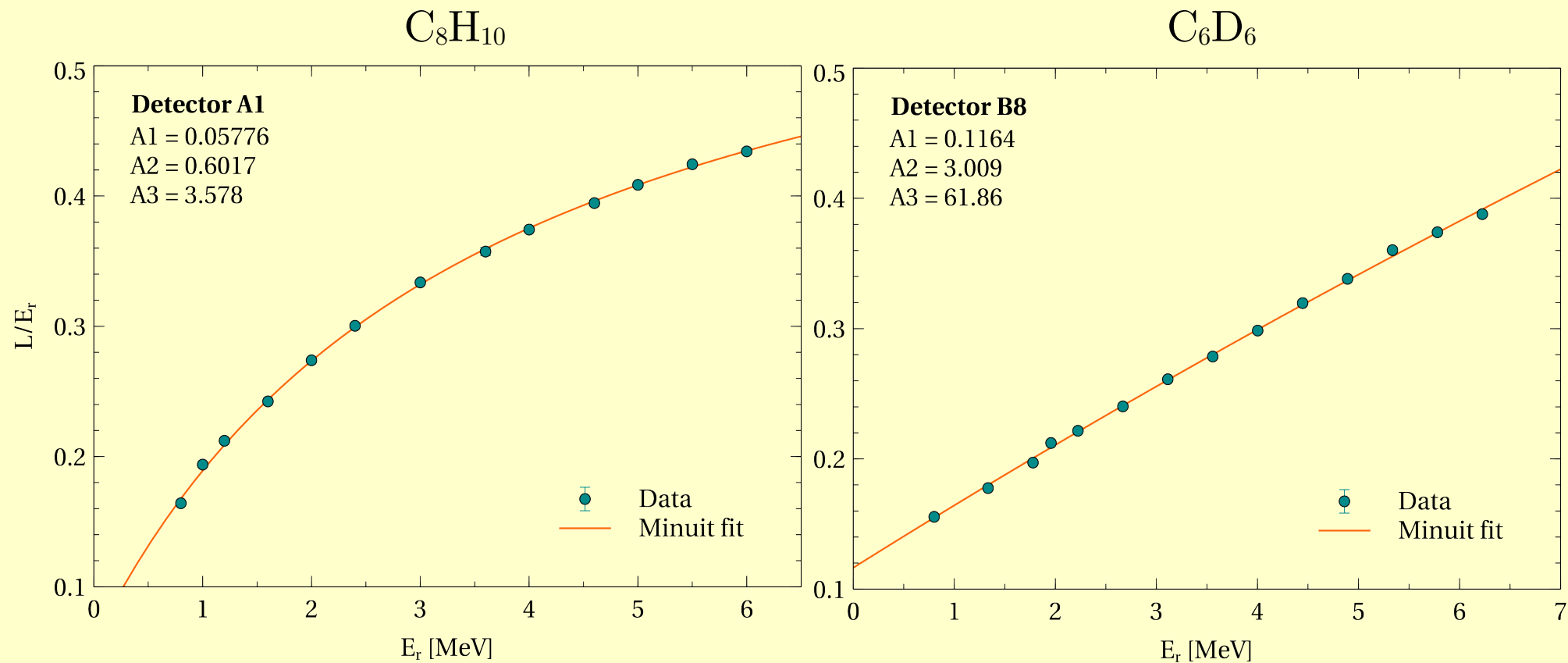
Gate on  $E_\gamma$  in NaI detectors

Random coincidence background

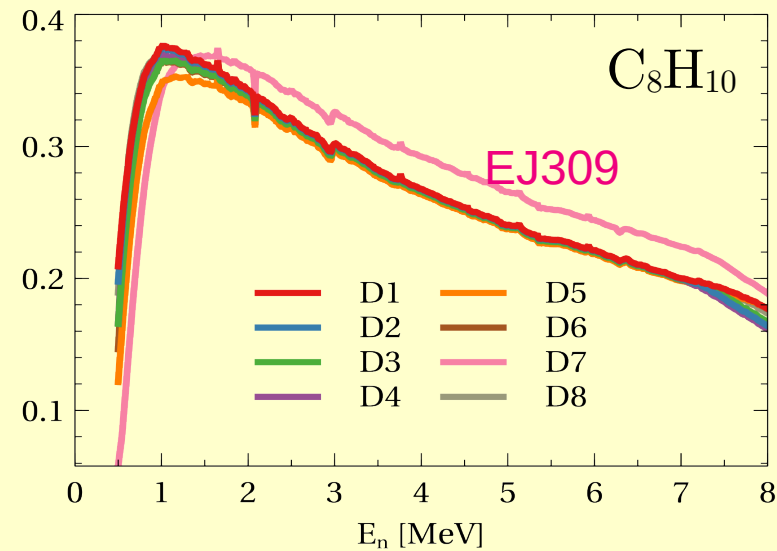
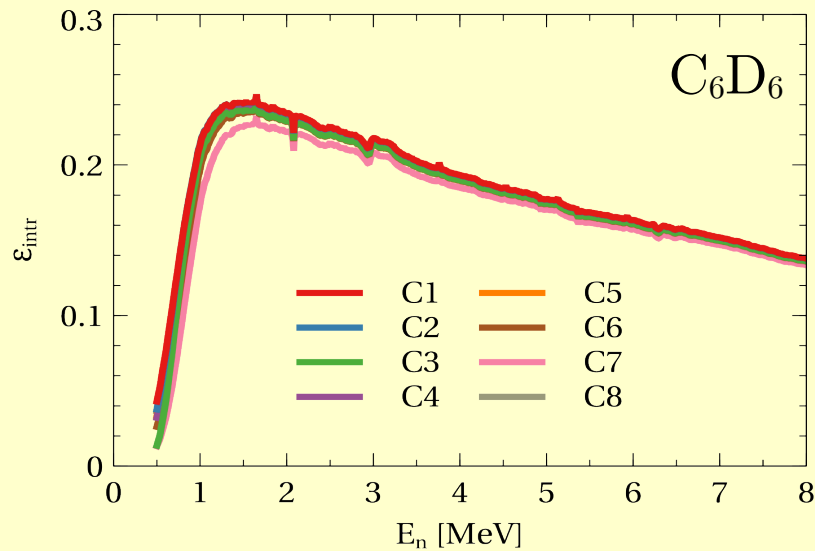
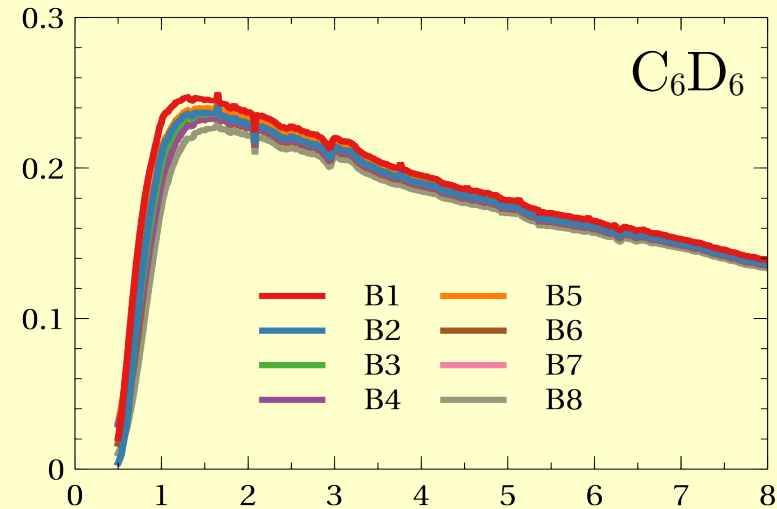
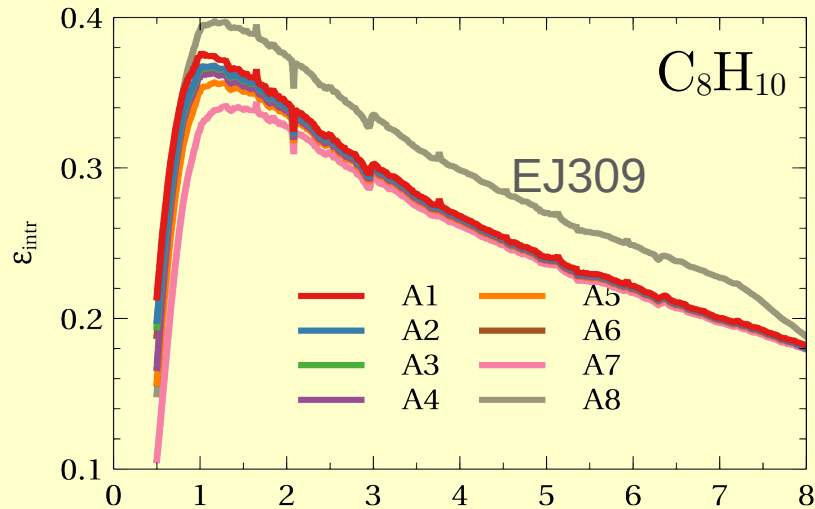
- Estimate from singles data\*



# Global response functions



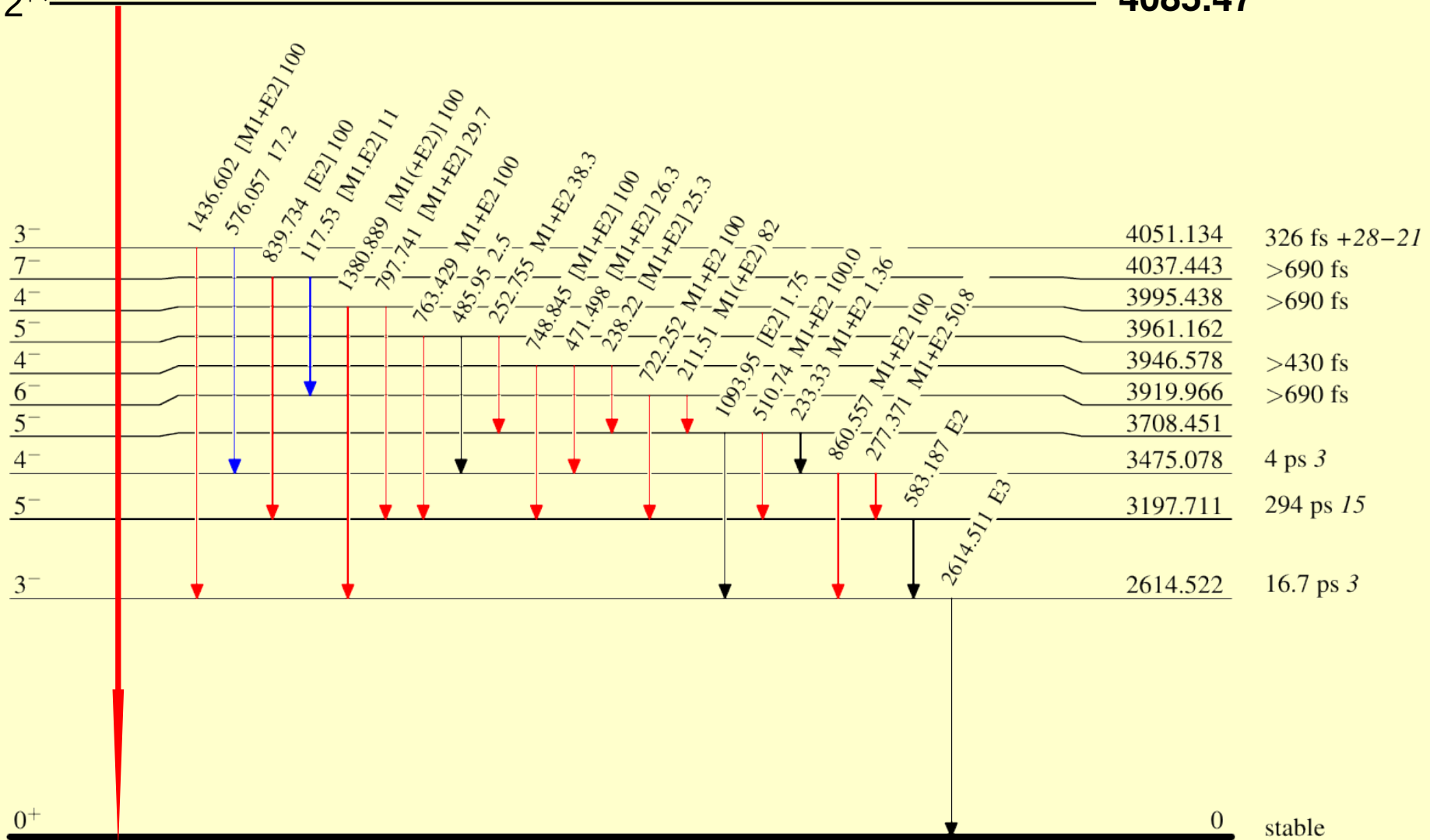
# Neutron Detection Efficiency



# $^{208}\text{Pb}$ Adopted Levels

$2^+$  4085.47 [E2] 100

4085.47



$J^\pi$

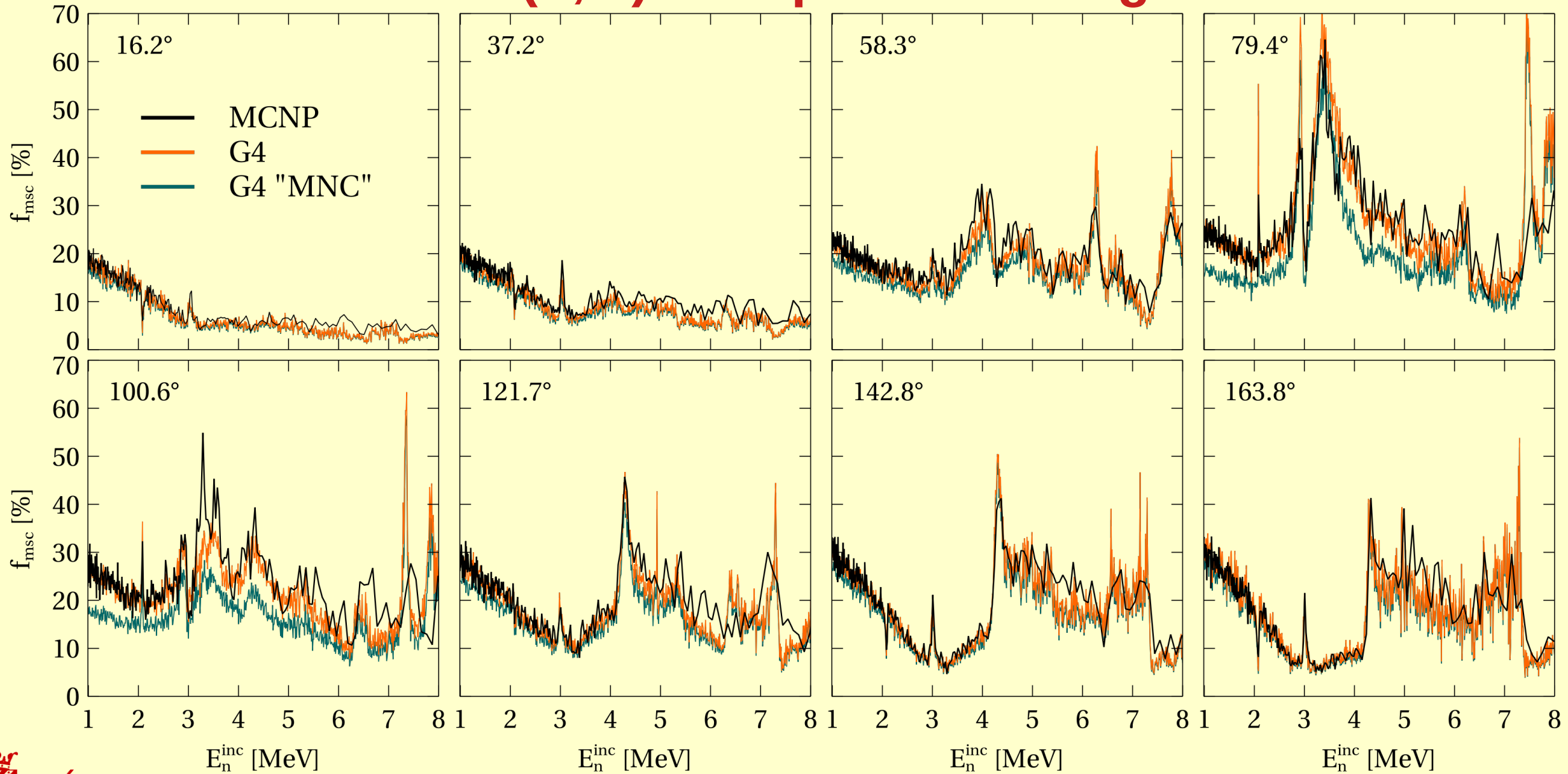
$^{208}_{82}\text{Pb}_{126}$

$E^*$

$T_{1/2}$



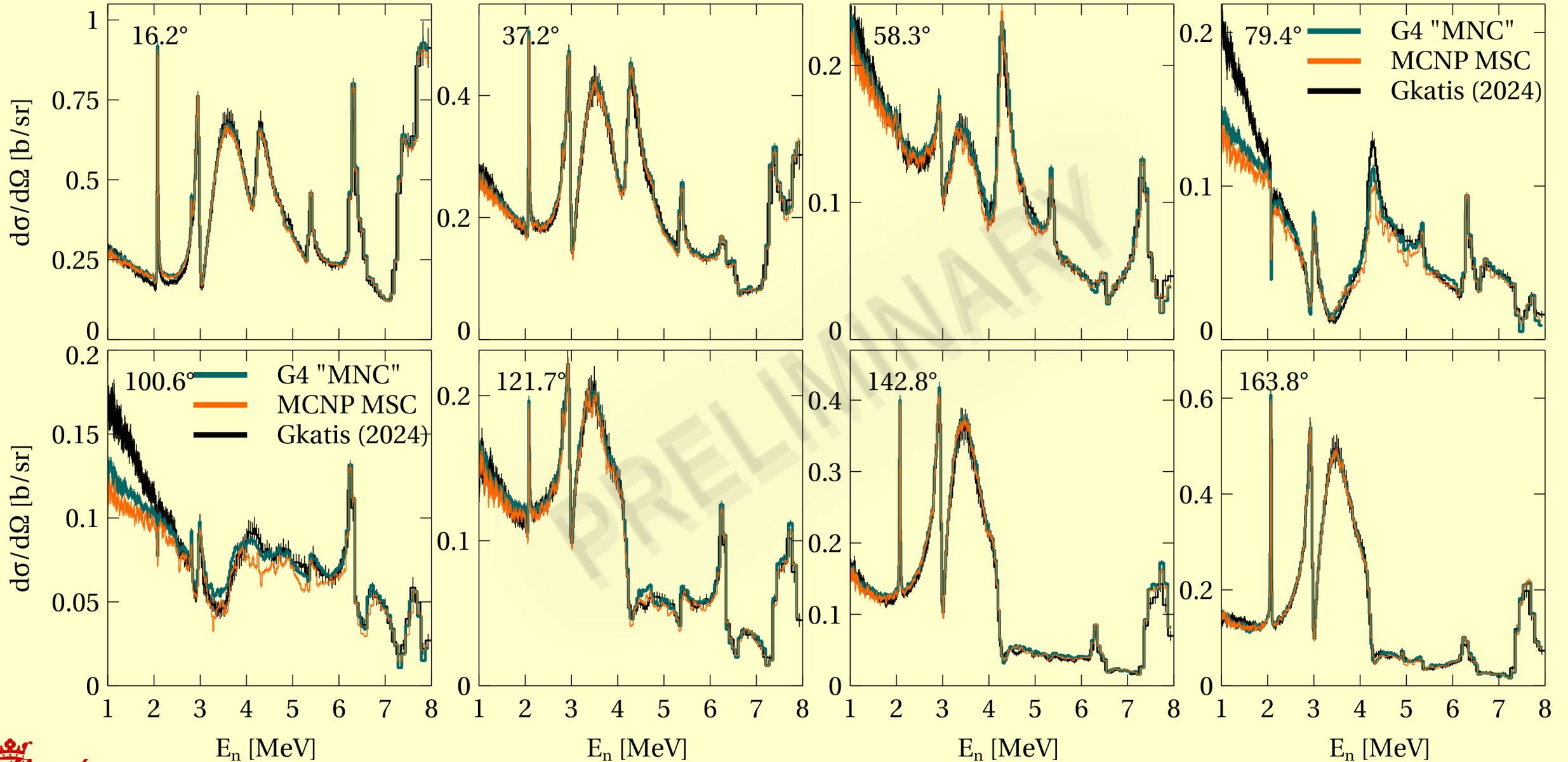
# <sup>nat</sup>C(n,e) Multiple Scattering



"MNC" (Missed-neutron-corrected)



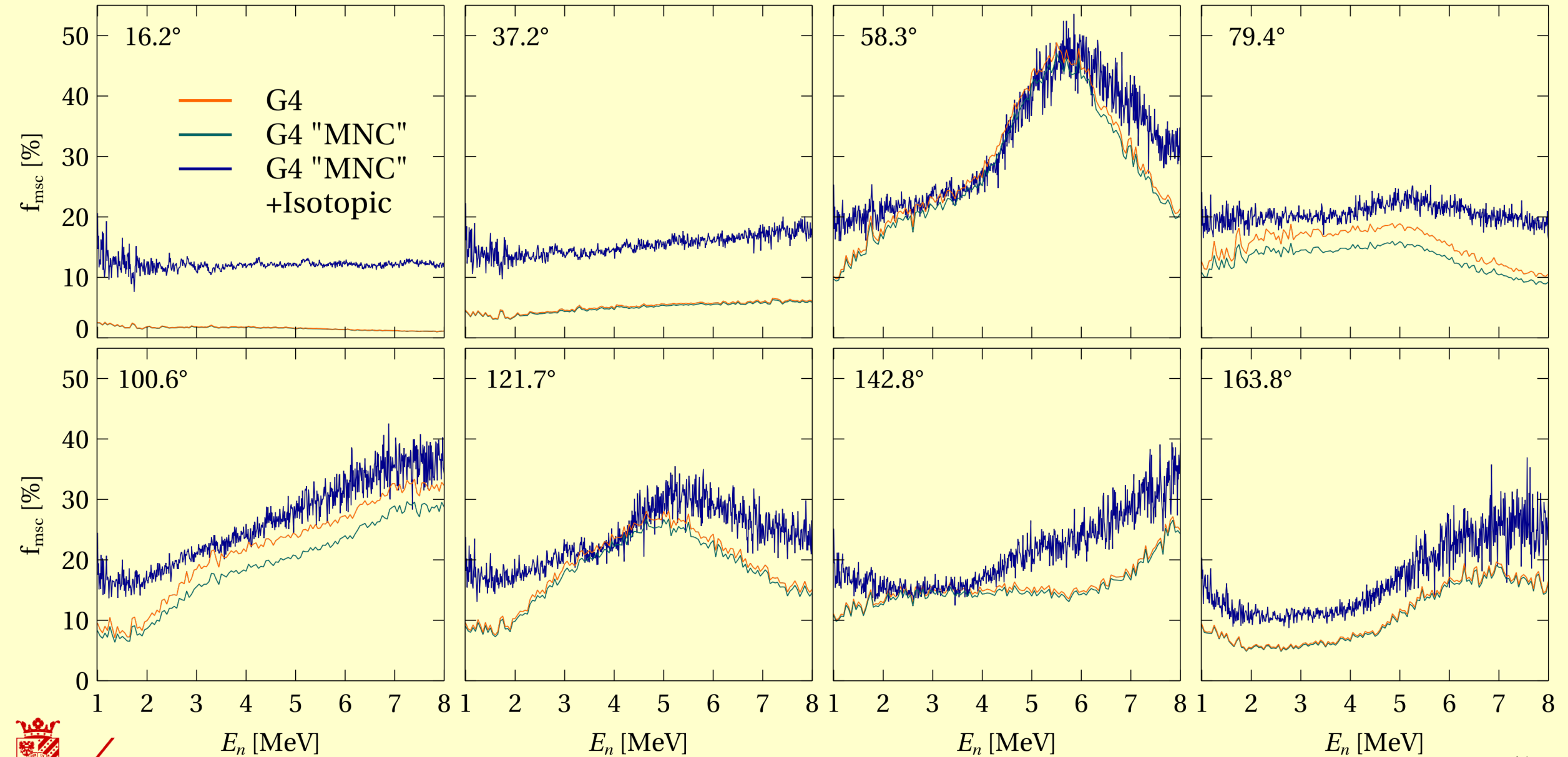
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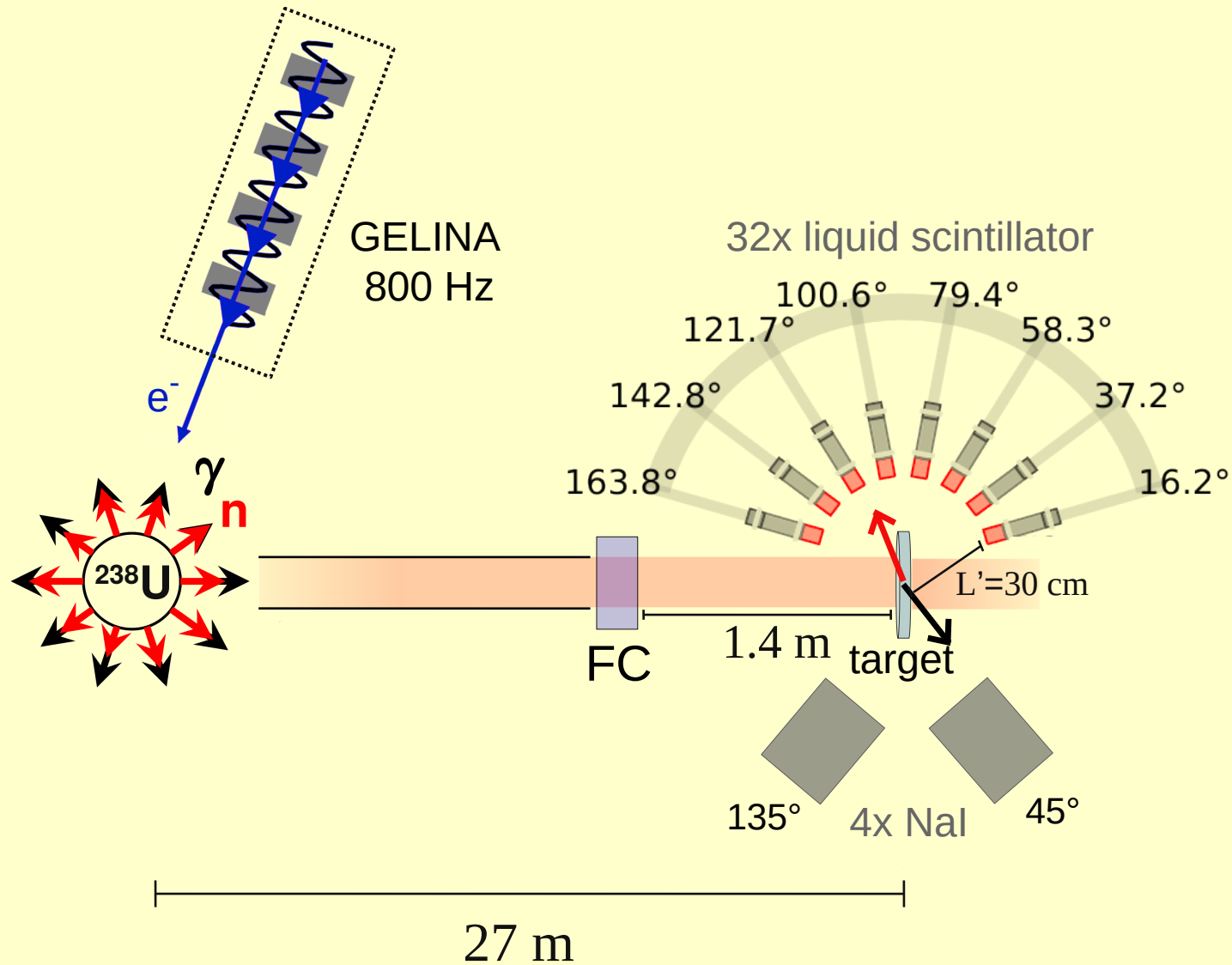
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# $^{208}\text{Pb}(n,e)$ Multiple Scattering + Isotopic Corrections



# ELISA: schematic

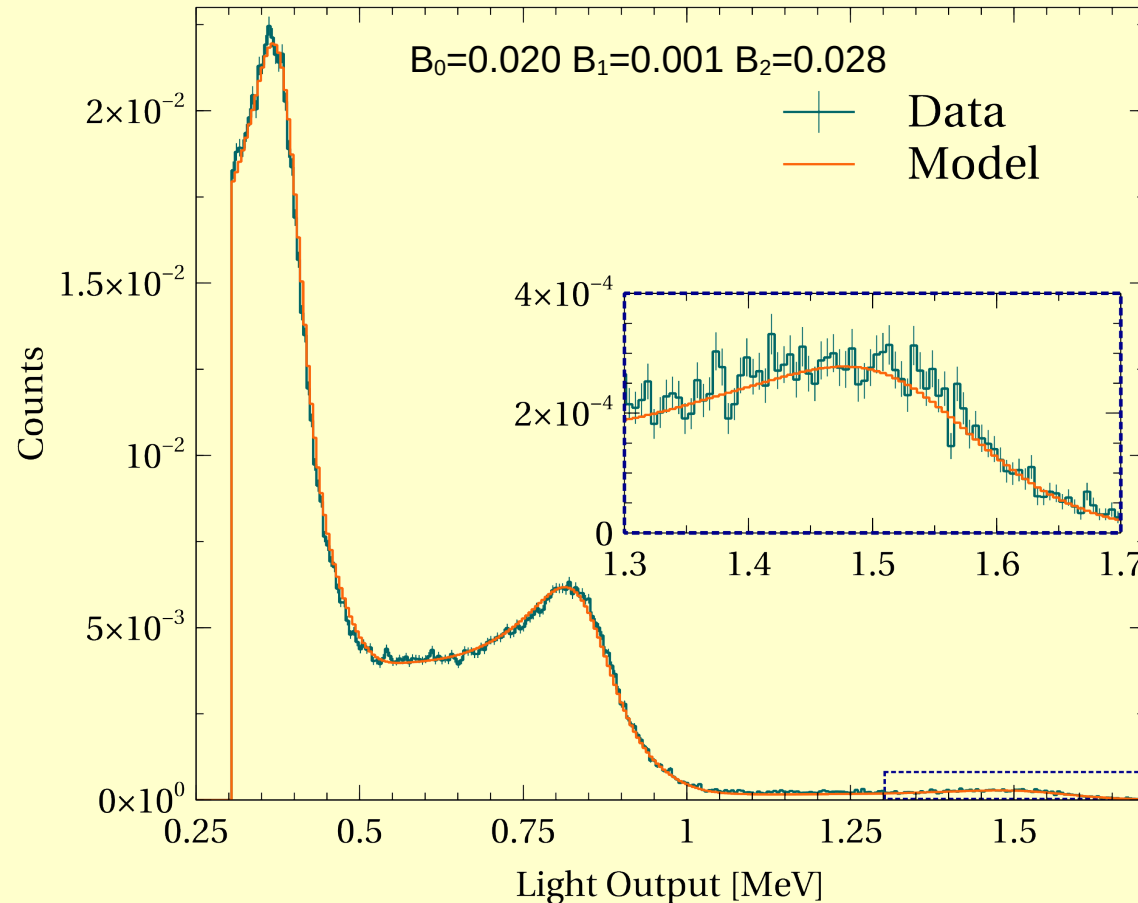


- Neutrons from  $^{238}\text{U}(\gamma, xn)$  &  $^{238}\text{U}(\gamma, f)$
- $^{235}\text{U}(n, f)$  monitor (FC)
- $E_n$  detection range: 1 - 8 MeV

# Calibrating Light Output & Resolution

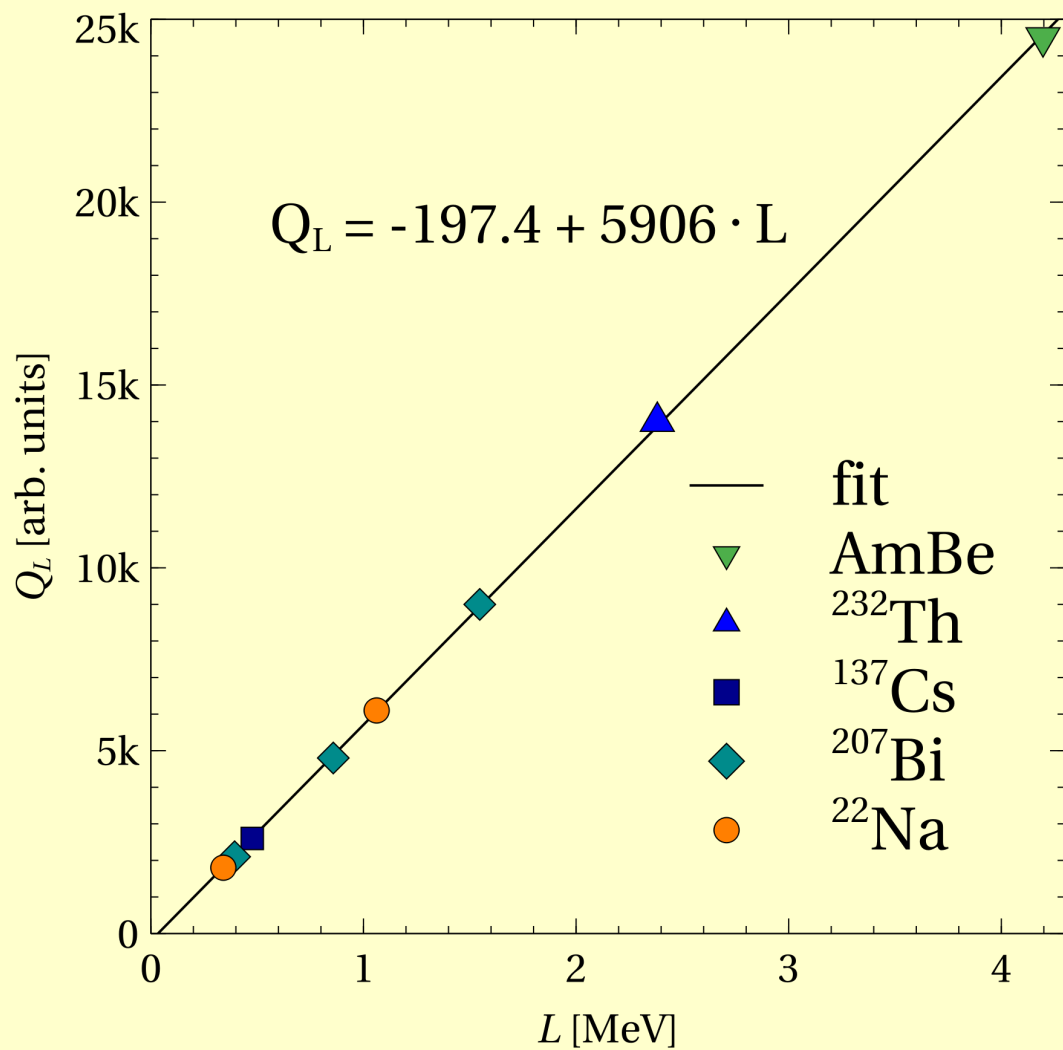
$$\sigma_{L'}^2 = B_0^2 + B_1^2 L' + B_2^2 L'^2$$

<sup>207</sup>Bi



Source	$E_\gamma$ (keV)	$E_c$ (keV)
<sup>137</sup> Cs	662	477
<sup>207</sup> Bi	570	394
	1064	858
	1770	1547
<sup>22</sup> Na	511	341
	1275	1062
<sup>232</sup> Th	2615	2382
AmBe	4438	4196

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# Response to Neutrons

Simulate monoenergetic neutrons

- Convert recoil energy to  $L$  [MeV]
- theor.  $L$ -distribution
- Fit to quasi-monoenergetic neutrons from  $^{nat}\text{C}$  sample

- EJ-301 / EJ-309 ( $\text{C}_8\text{H}_{10}$ )  
or EJ-315 ( $\text{C}_6\text{D}_6$ )

