Energy response model from first principles

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on behalf of Padova group

JUNO Italia meeting, Rome

28-29/03/2023

INFN PADOVA

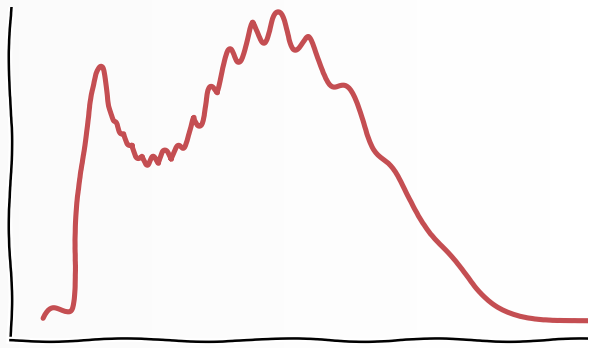
UNIVERSITÀ DEGLI STUDI DI PADOVA

JUNO

ORSA (Oscillated Reactor Spectrum Analysis)

Model

- Reactor model
- Backgrounds model
- Covariances
- SNIPER
- Detector response



Data processing

- Energy reconstruction
- Event selection

Cost function

- χ^2 (Pearson, Neyman, combined)
- Likelihood (binned, extended)

Fitter

- Minuit
- Markov Chains MC
- Nested sampling

Results

- Best fit values
- Posteriors
- Correlations
- Model selection

Why study the energy response?

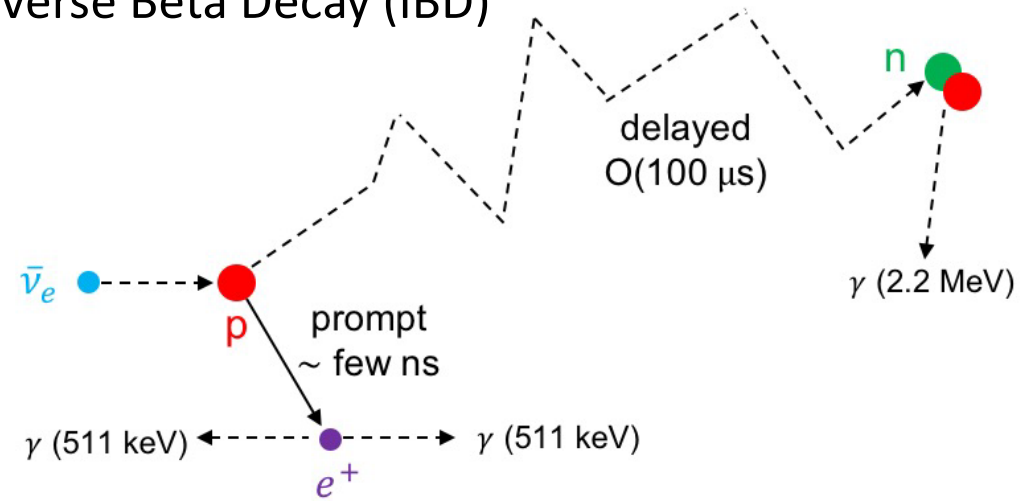
$E_{\bar{\nu}}$ [MeV] → (IBD cross section) → E_{dep} [MeV] → (E_{vis} [# OP]) → E_{rec} [PE or MeV]

- $e^{\pm}/\gamma$ interaction with the medium
- light production

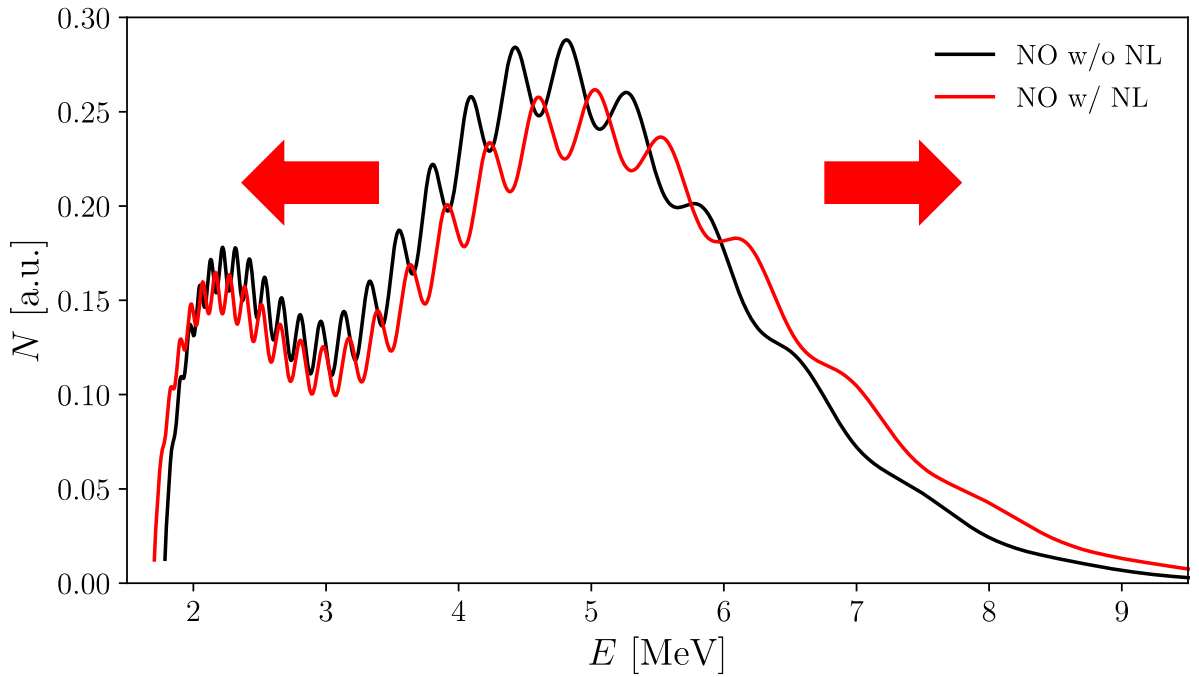
- energy resolution
- non-uniformity
- instrumental effects

$$E_{\mathrm{dep}} = T^{e^+} + 2 \cdot 511\ \mathrm{keV}\ \gamma \cong E_{\bar{\nu}} - 0.8\ \mathrm{MeV}$$

Inverse Beta Decay (IBD)



Effect on IBD spectrum → oscillation analysis



MODEL

IBD → neutron → $2.22\ \mathrm{MeV}\ \gamma$

↓

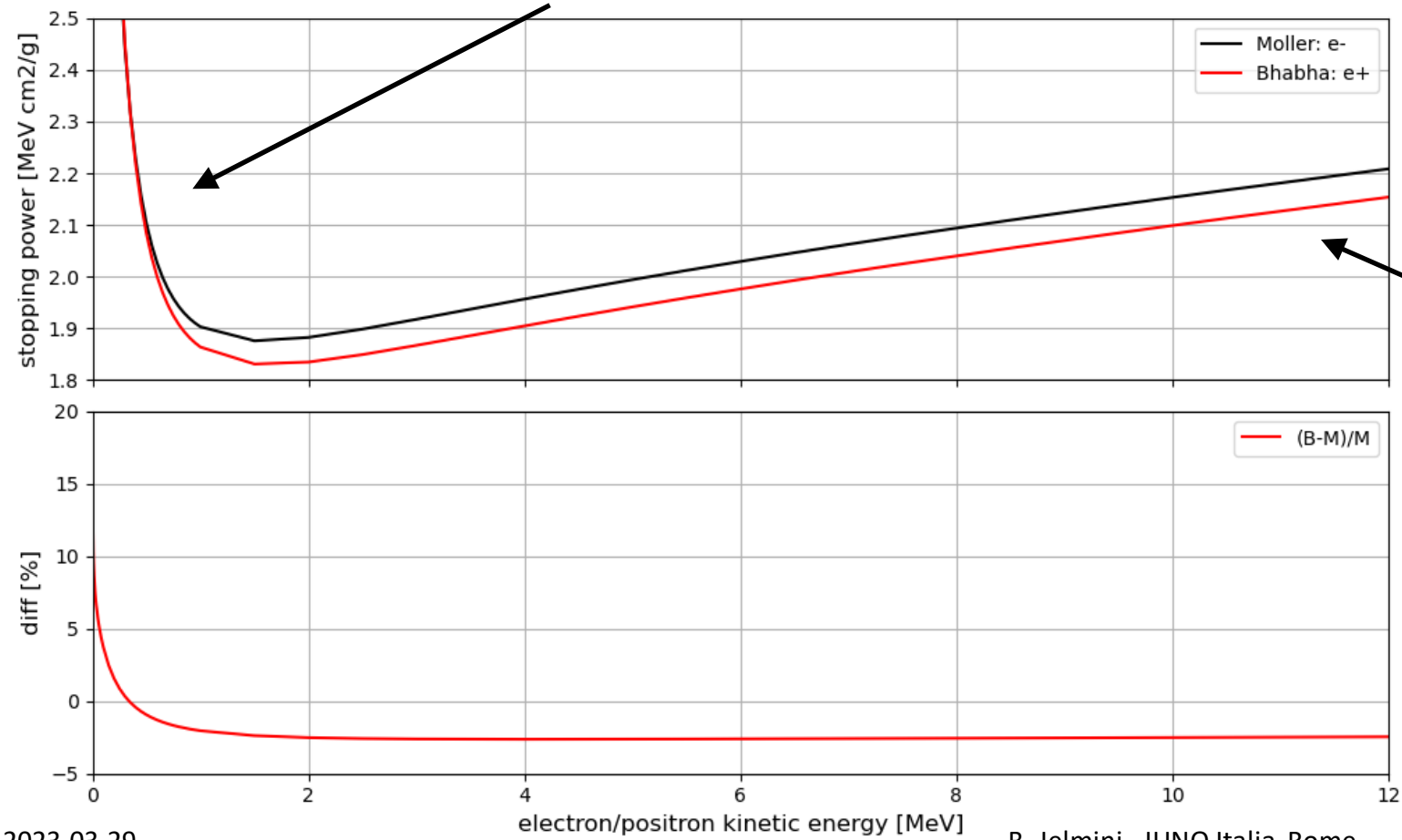
$e^+: E_{\mathrm{dep}} = T^{e^+} + 2 \cdot 511\ \mathrm{keV}\ \gamma$

Electron/positron stopping power

Dependence on material - JUNO LS:
Z/A = 0.56
I = 59.3 eV

Energy loss through collisions – Moller model for electrons

$$\left\langle -\frac{dE}{dX} \right\rangle = \frac{1}{2} K \frac{Z}{A} \frac{1}{\beta^2} \left[\ln \frac{m_e c^2 \beta^2 \gamma^2 m_e c^2 (\gamma - 1)}{2 I^2} + (1 - \beta^2) - \frac{2\gamma - 1}{\gamma^2} \ln 2 + \frac{1}{8} \left(\frac{\gamma - 1}{\gamma} \right)^2 - \delta(E) \right]$$



Density effect correction:
- energy dependent
- from ESTAR tool

Radiative energy loss:
- up to 10% difference @ 12 MeV
- from ESTAR tool

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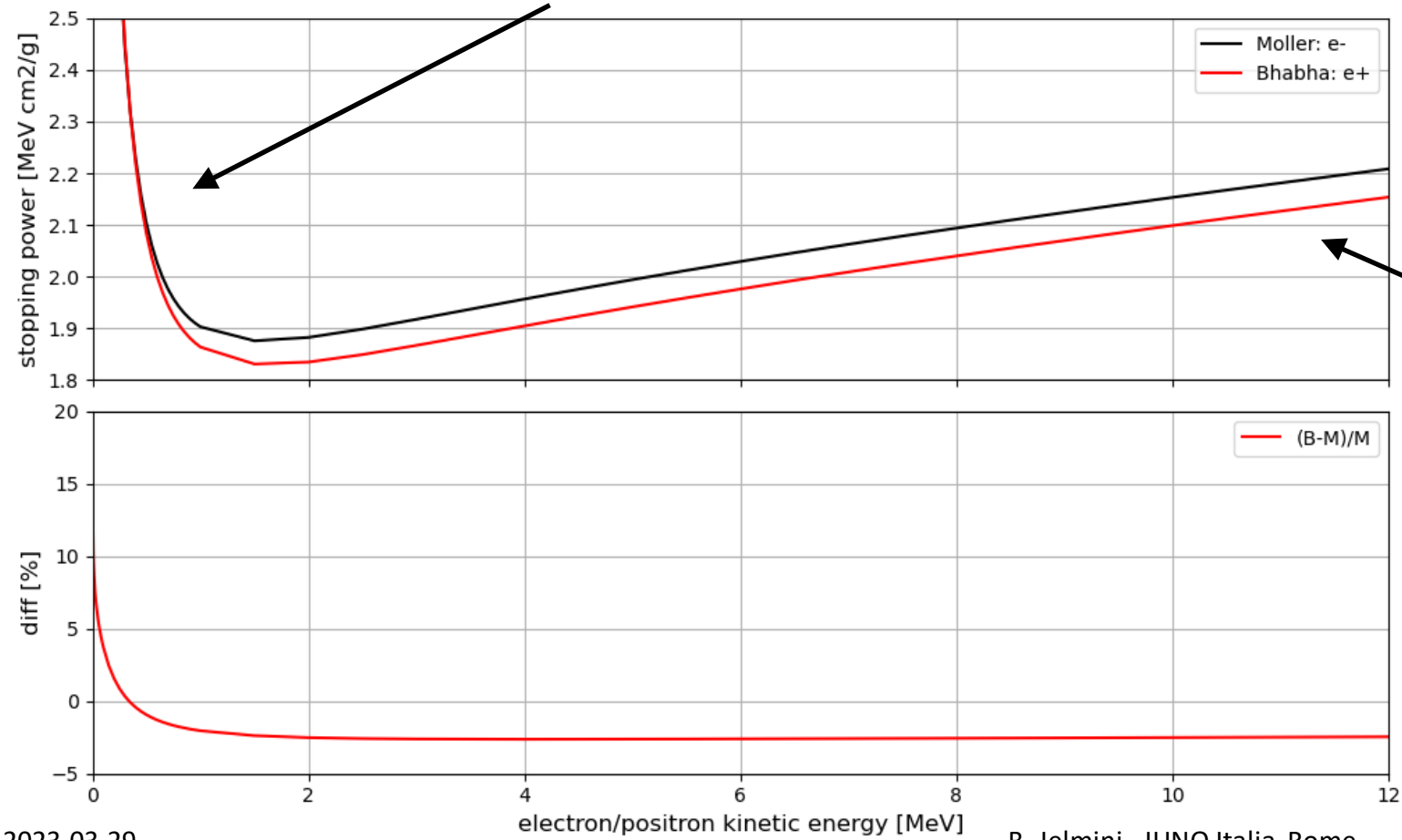

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For positrons:
- Bhabha model for collision term
- same $\delta(E)$
- same radiative term

Energy response to electrons/positrons

Integration of Birks' law:

from previous slide

$$\frac{E_{\text{scint}}}{E_{\text{dep}}} = A \cdot f_q\left(E_{\text{dep}}, k_B\right) = A \cdot \int_0^{E_{\text{dep}}} \frac{dE}{1 + k_B \cdot \frac{dE}{dX}}$$

$k_B = 6.5 \cdot 10^{-3}\ \text{cm}^2/\text{MeV/g}$

physics parameter

$A = 1$ (absolute scale)

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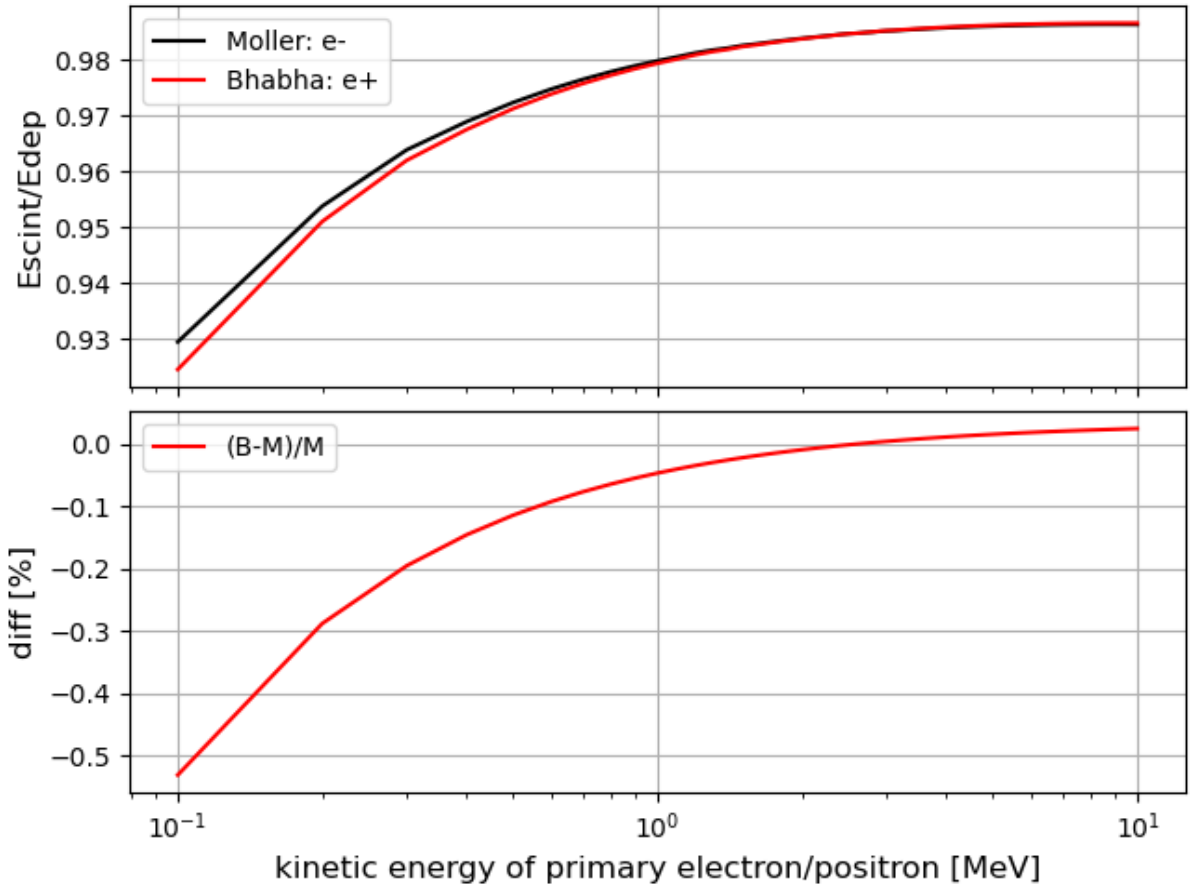
For simplicity, same quenching curve for e- and e+



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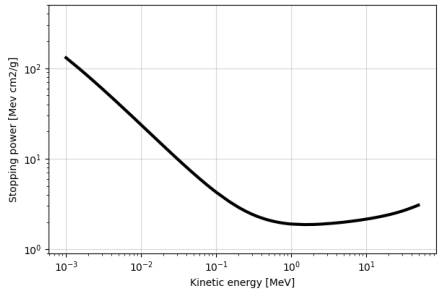
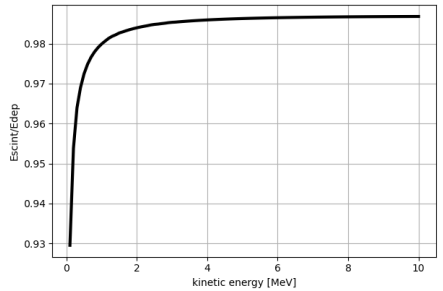
Particle interaction



Scintillation

Cerenkov

Light production



TODO

k_B

$$E_{\text{vis}} = E_{\text{scint}} + E_{\text{cerenkov}}$$

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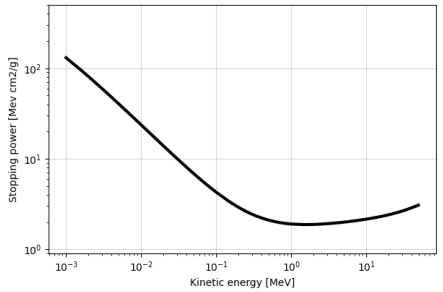

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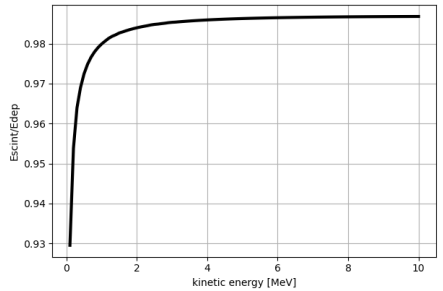

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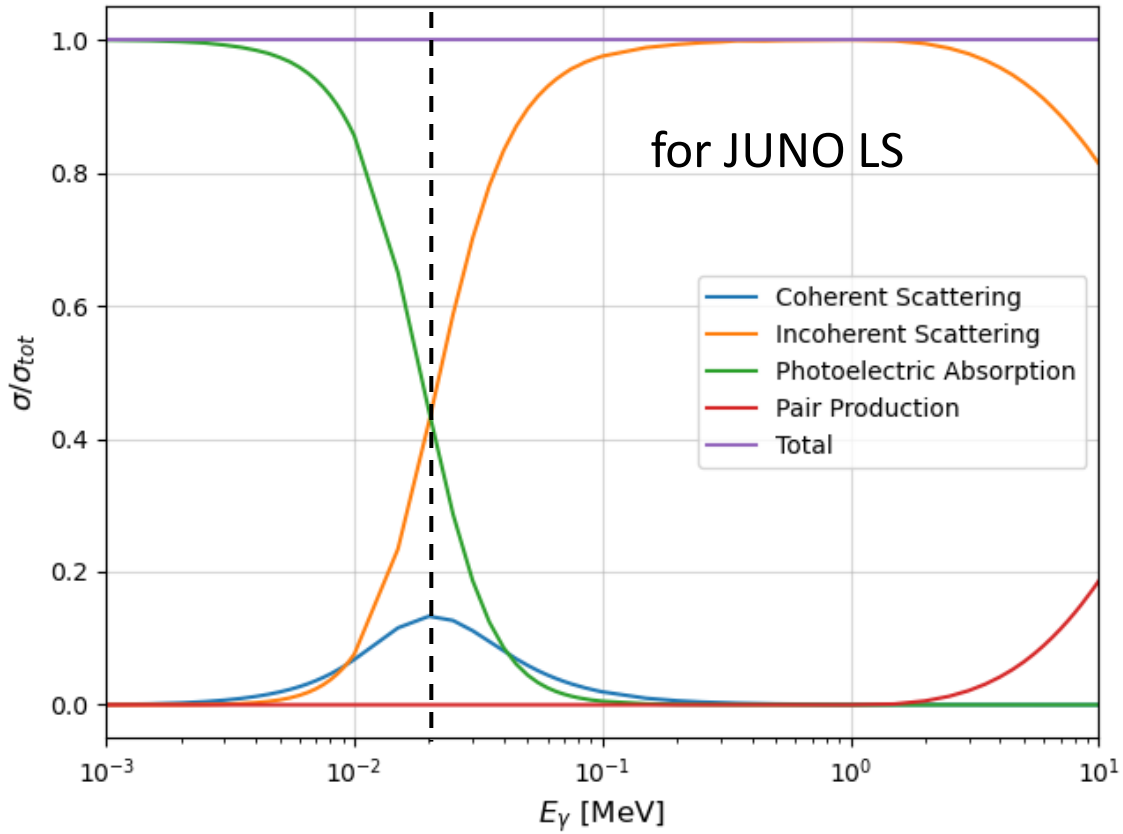
k_B

Gamma interactions

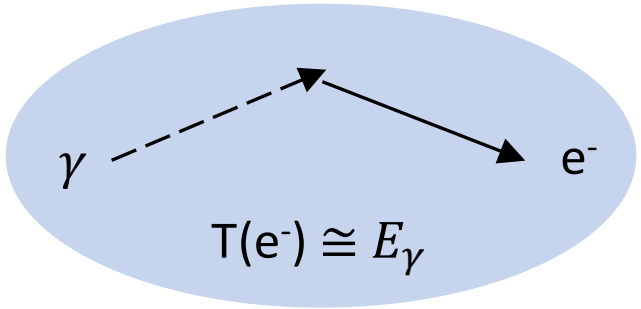
XCOM tool



Gamma interactions

Photoelectric effect

$E_\gamma \lesssim 0.02$ MeV



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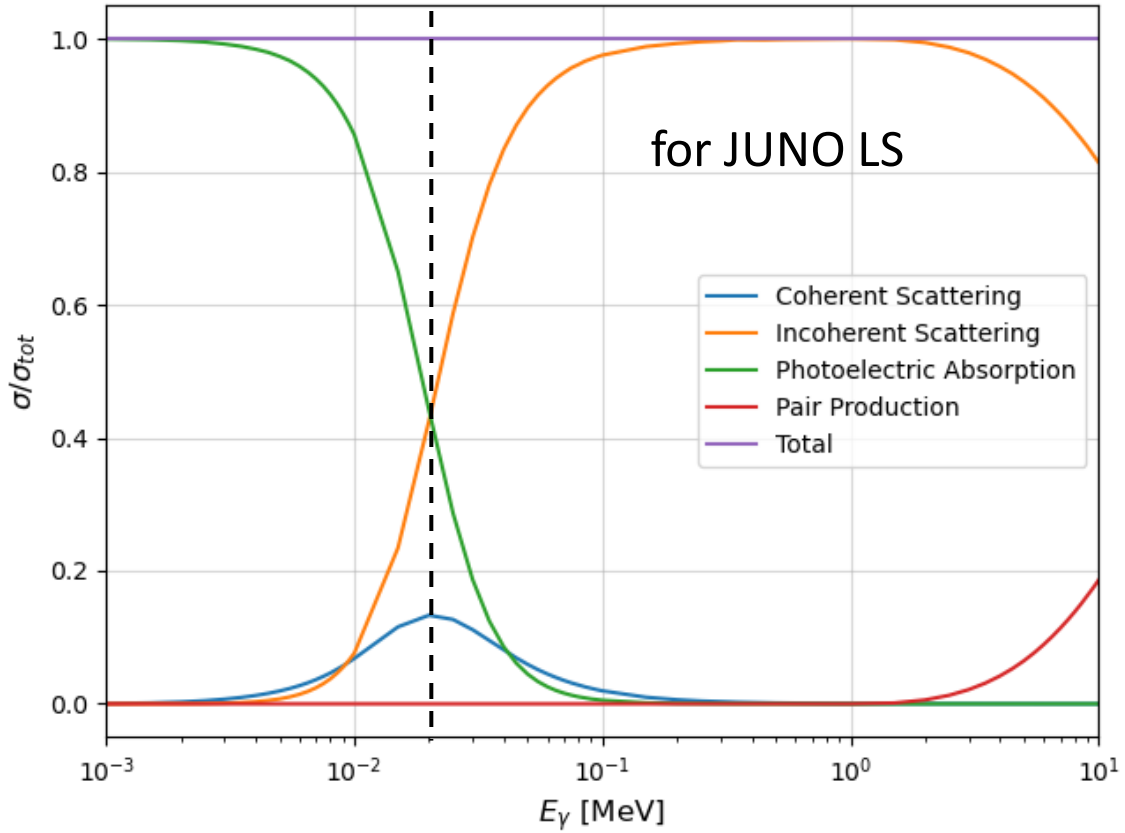

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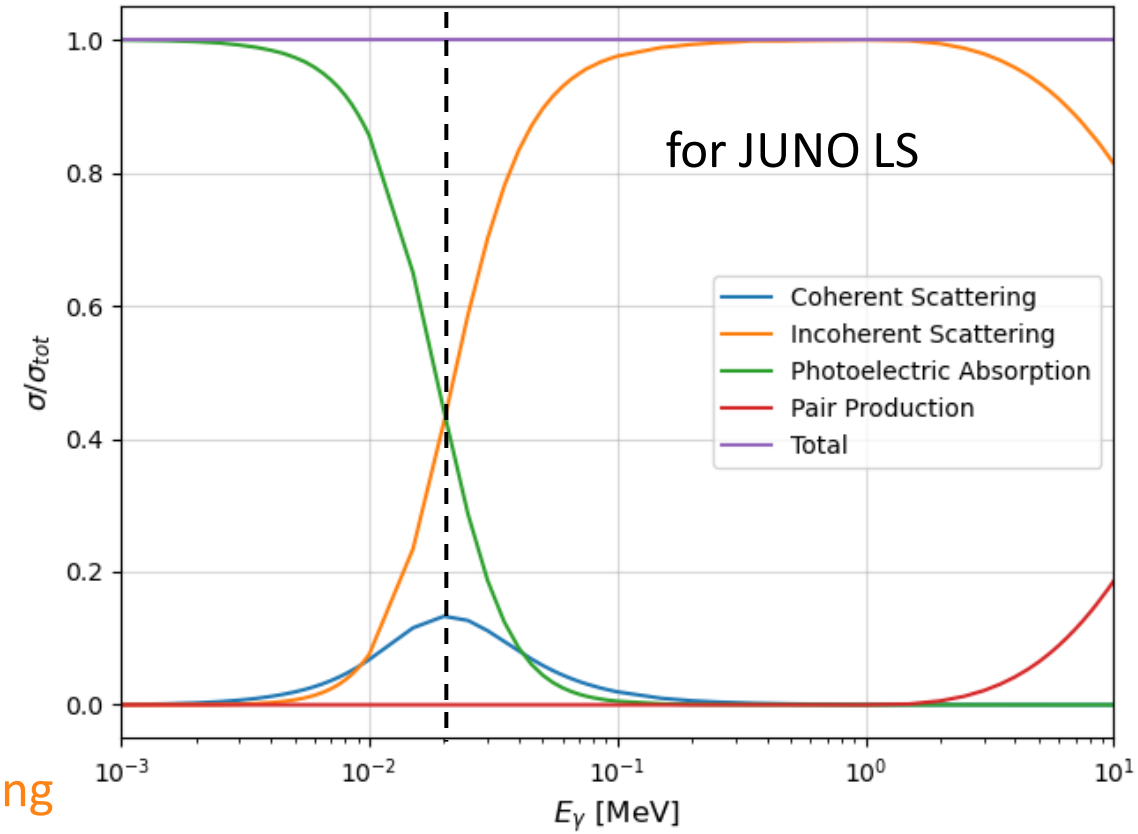

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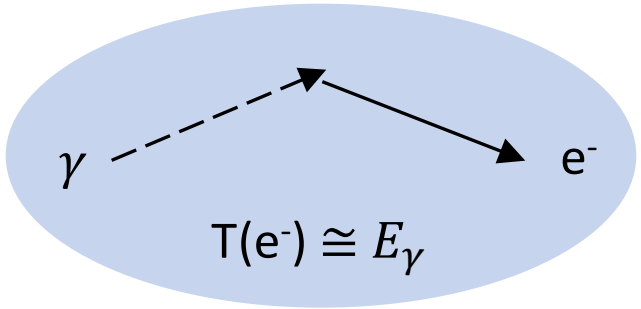

Incoherent or Compton scattering

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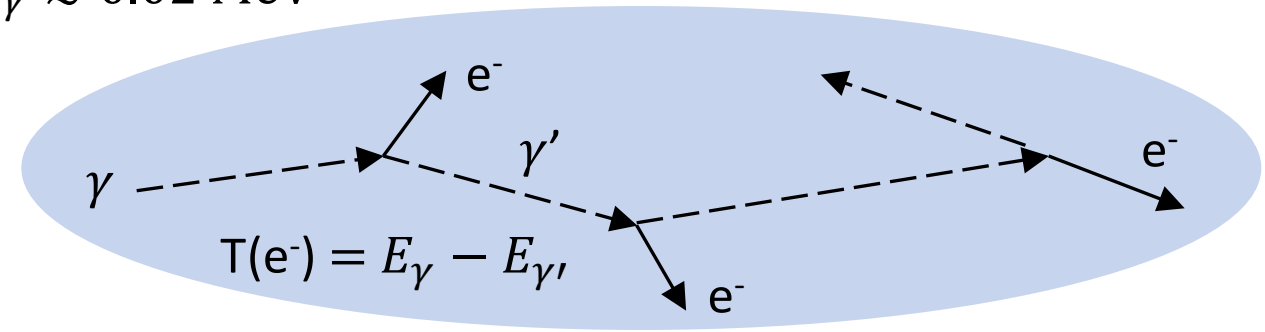

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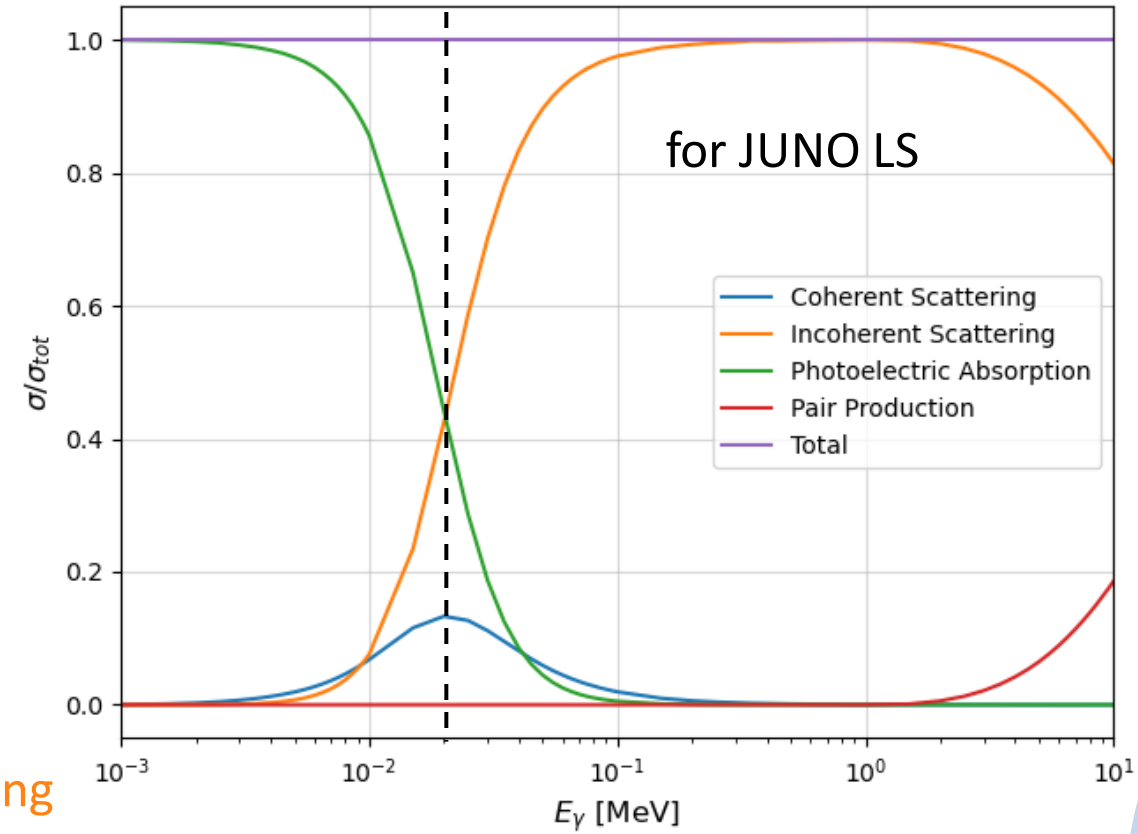

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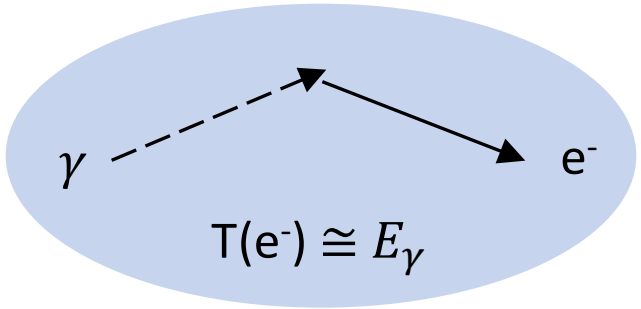

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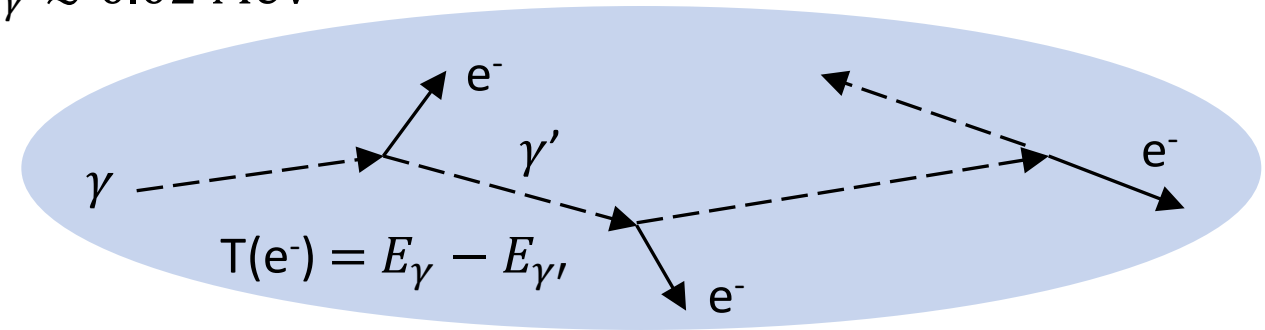
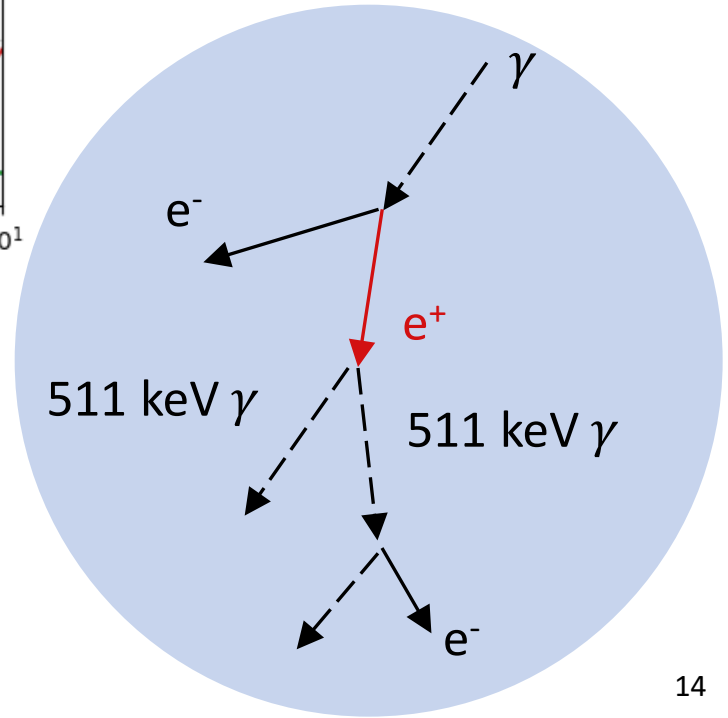


Pair production

$E_\gamma \gtrsim 1.022$ MeV



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Coherent or Rayleigh scattering

γ absorbed and re-emitted with same energy

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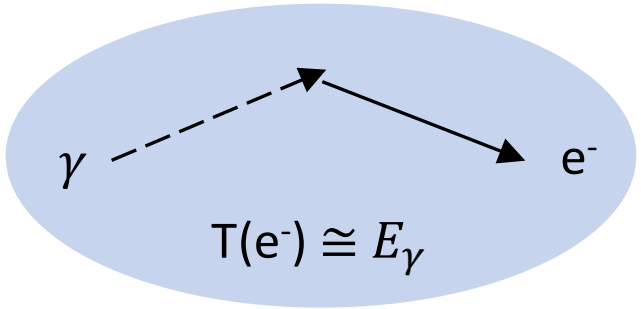

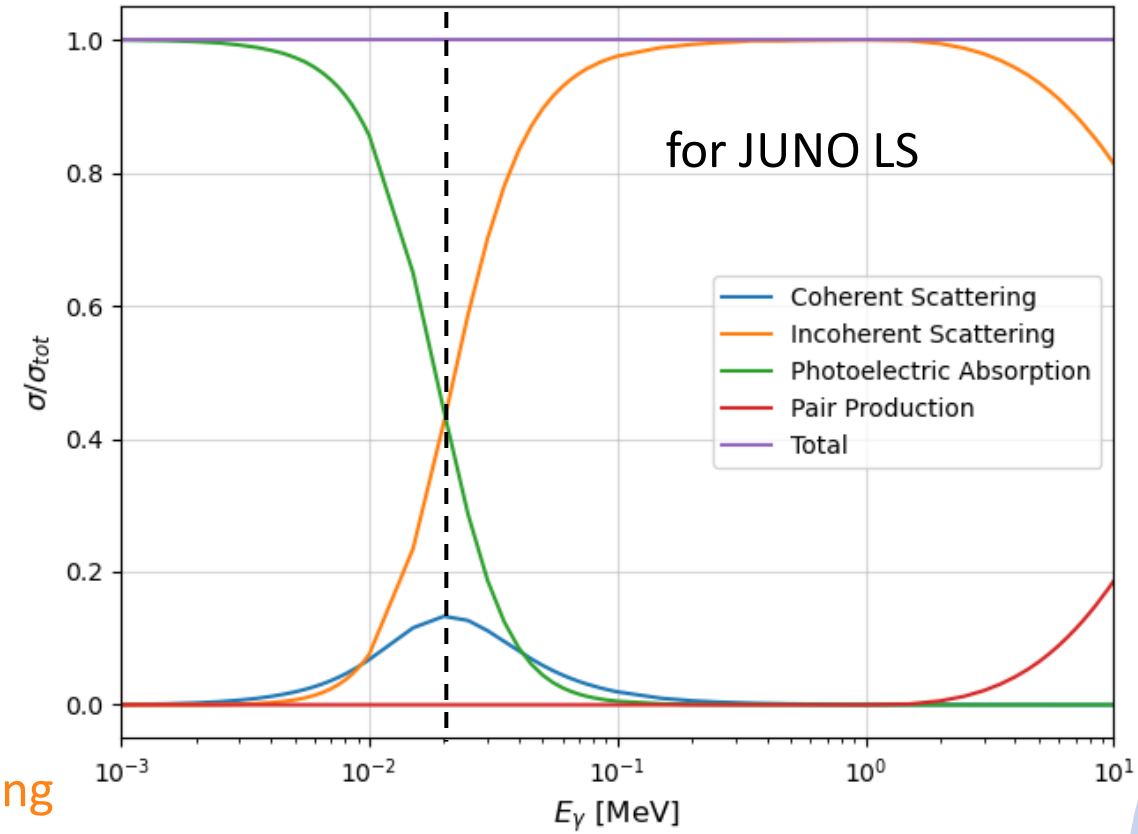

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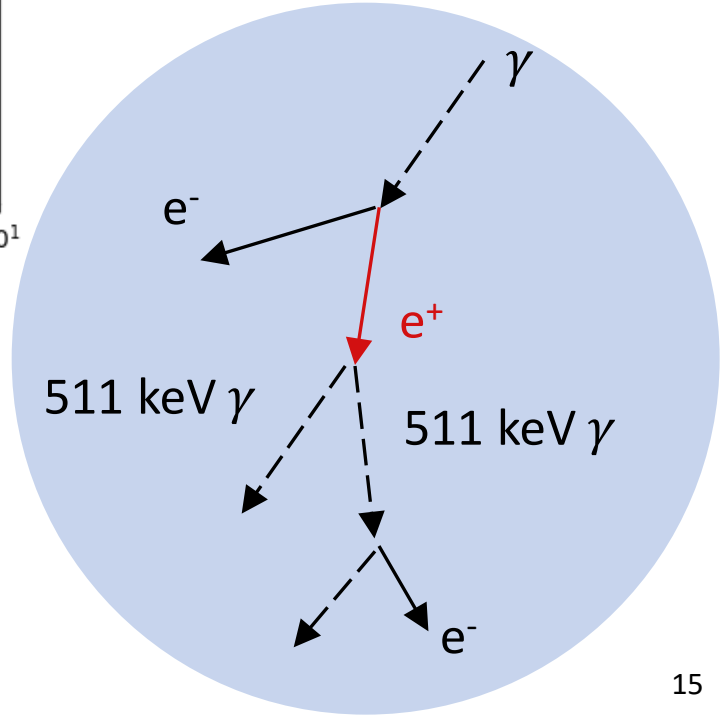

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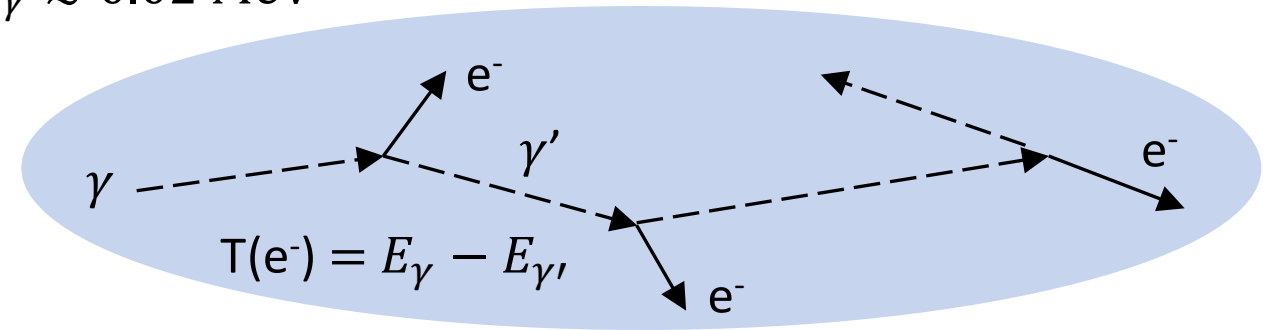

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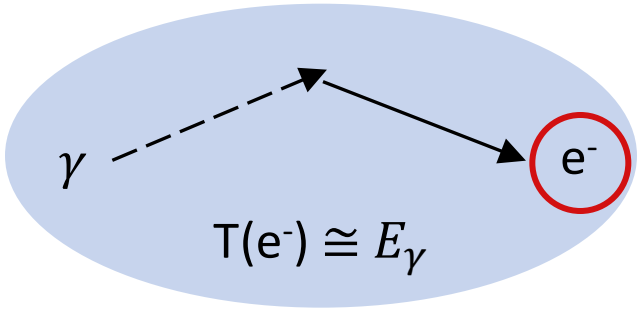

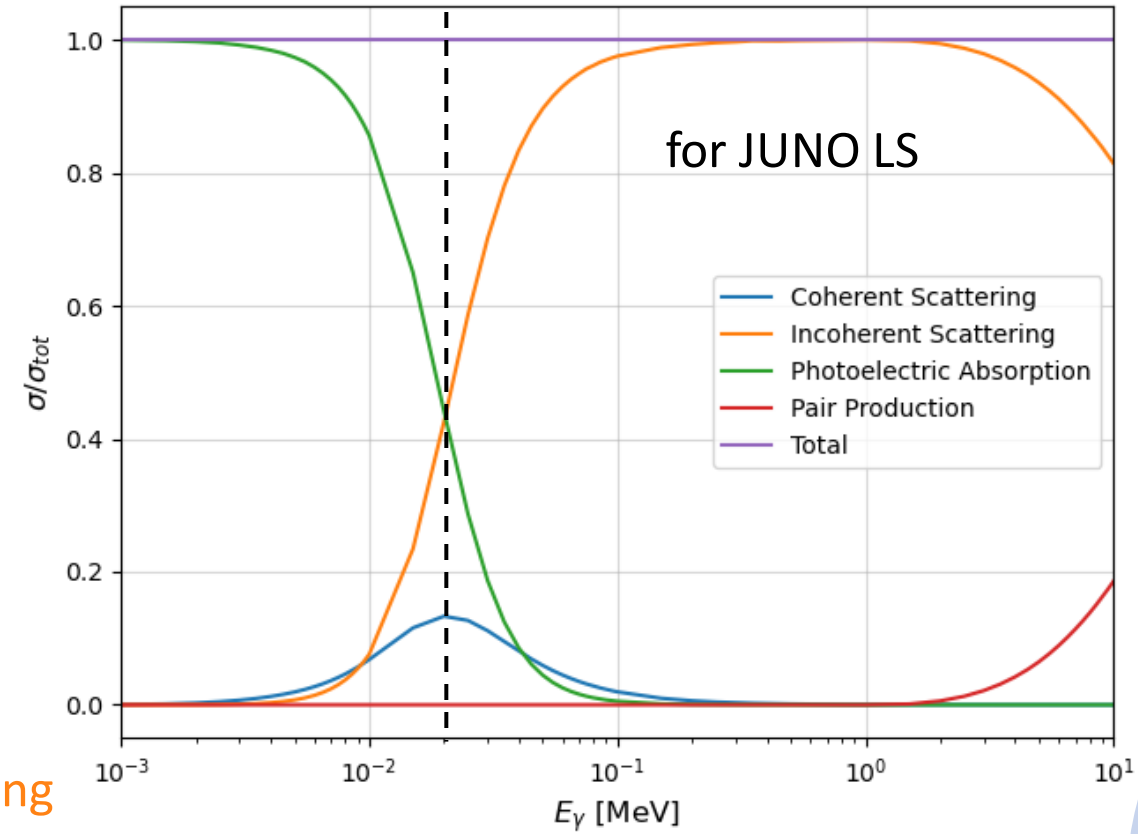

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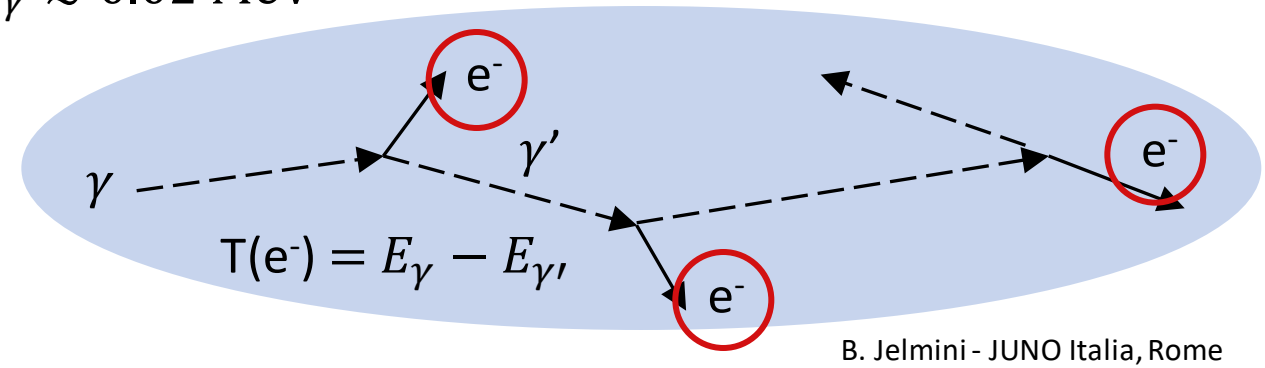

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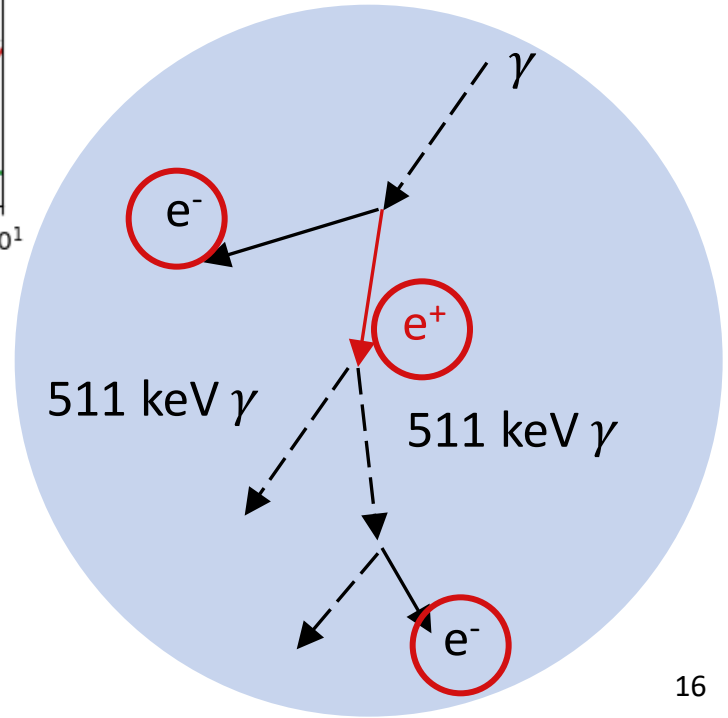
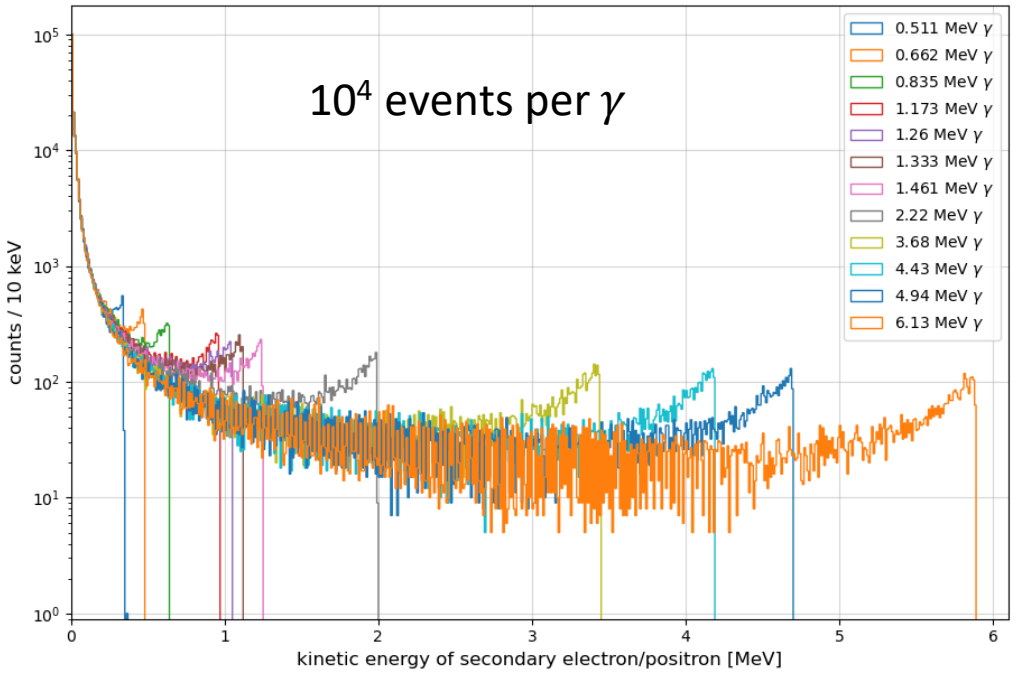


Energy distribution of secondaries e^-/e^+

Analytical+ToyMC distributions [1]

- T(e^-) ≅ E_γ for photoelectric effect
- Based on Klein-Nishina cross section for Compton scattering
- Pair production not included (yet)
- Slow (not optimized yet)



[1] P. Kampmann *et al* 2020 *JINST* **15** P10007

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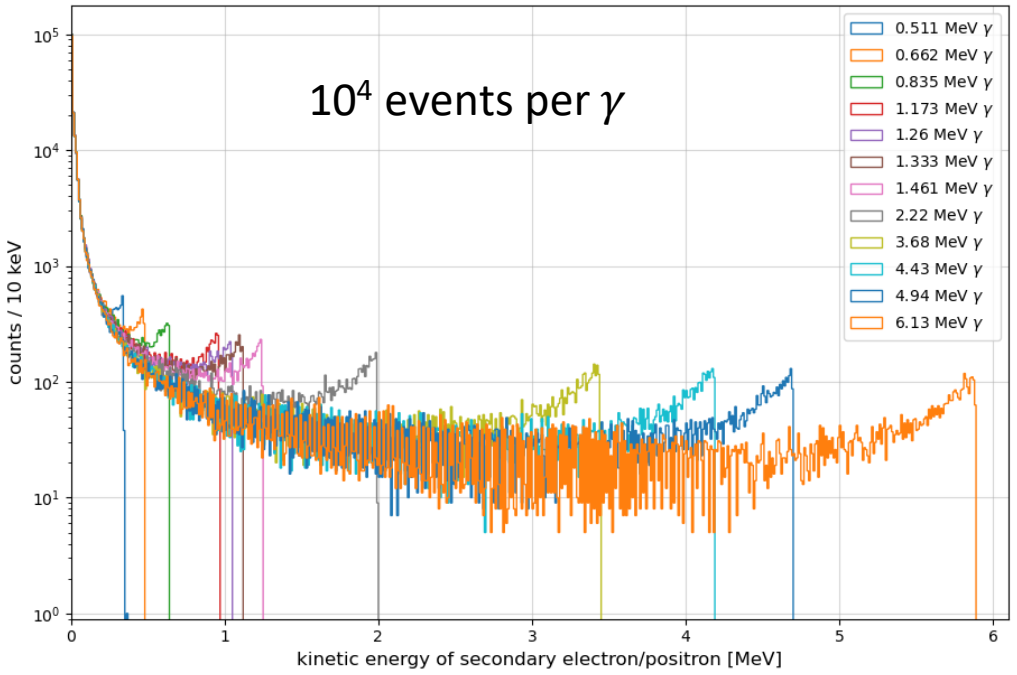
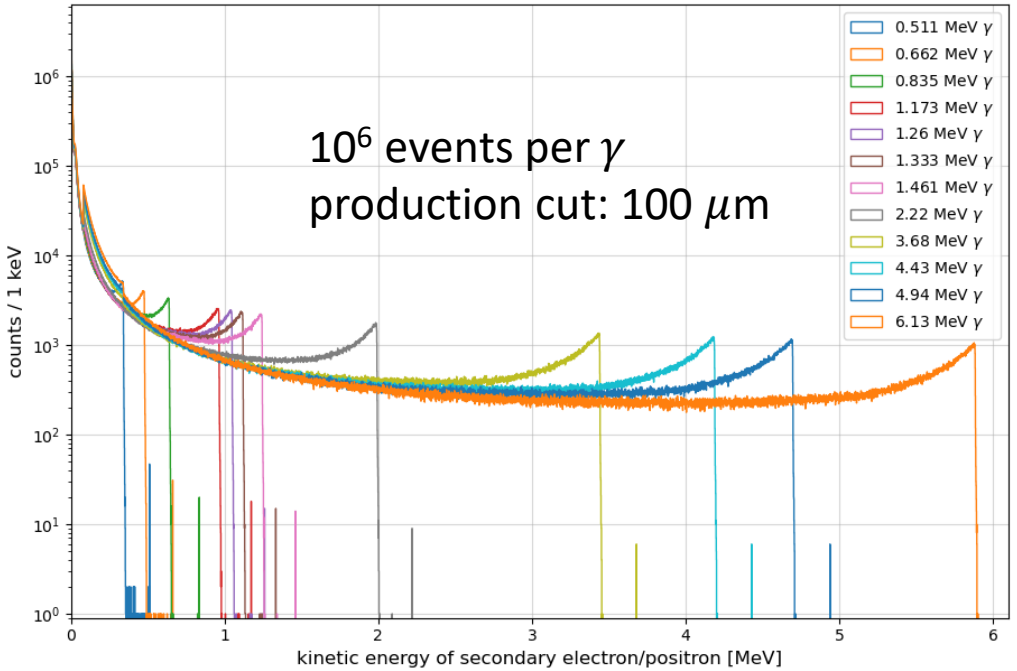
Geant4-based distributions

- All physics included in G4 simulation
- Stand-alone: particle gun in LAB box
- Fast
- Depends on production cut





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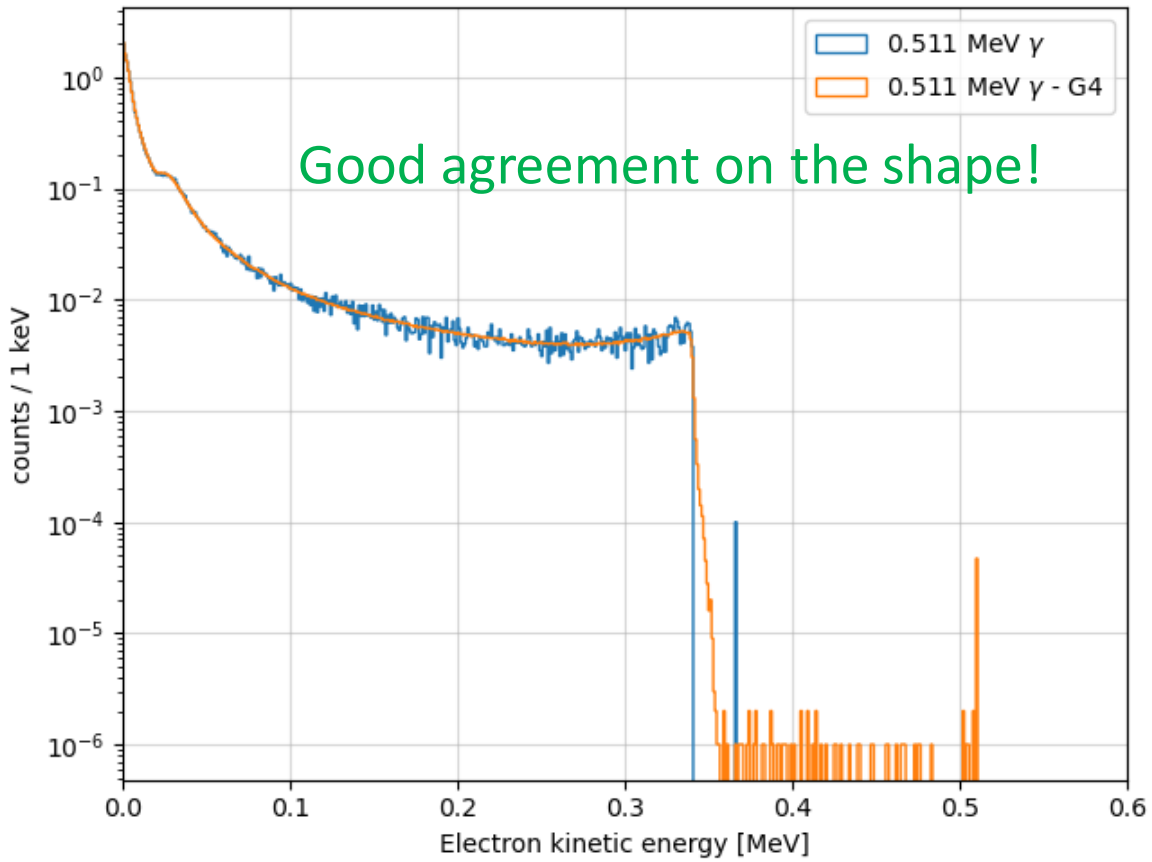
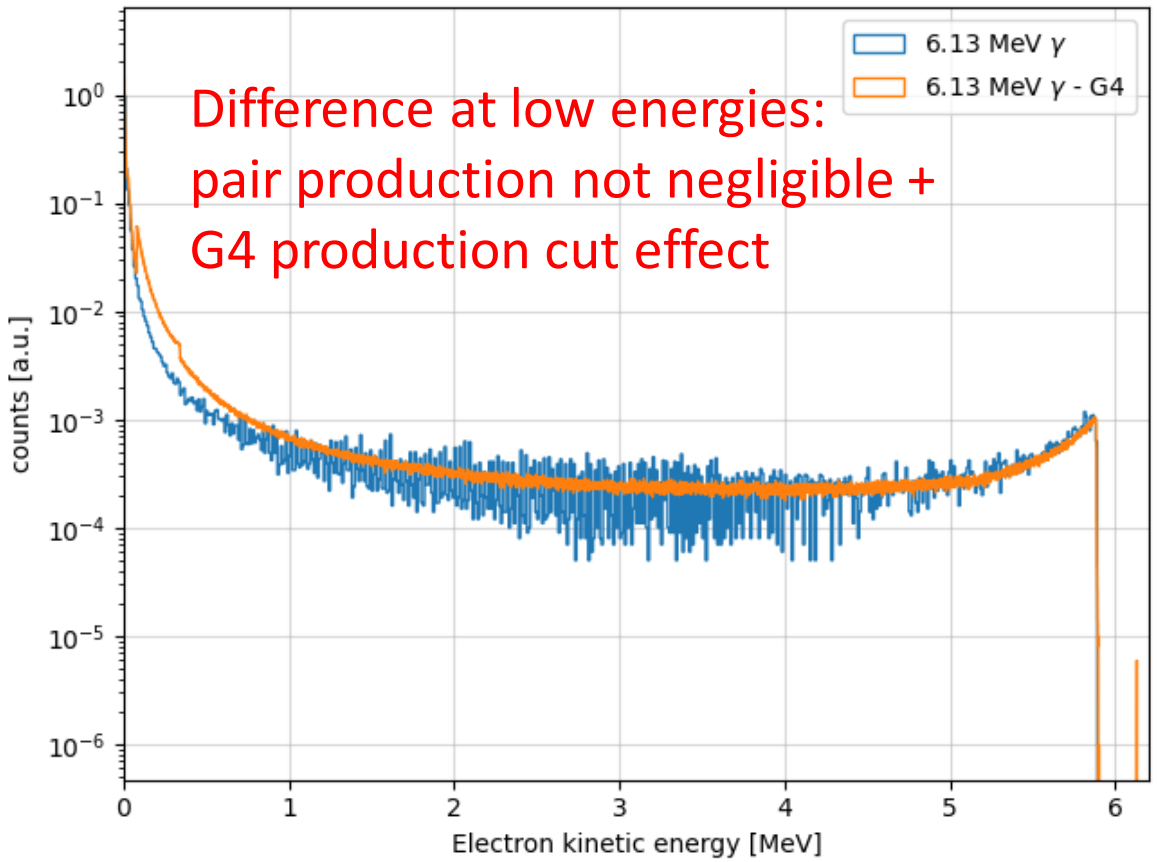
Analytical vs Geant4-based: energy distributions of secondaries e^-/e^+

0.511 MeV γ



6.13 MeV γ



Use G4 distributions in what follows

Following DYB collaboration, NIMA 940 (2019) 230–242

Energy response to gammas

Energy distribution of secondaries $e^{\pm}$

Quenching curve for $e^{\pm}$

$$\frac{E^{\gamma}_{\mathrm{vis}}}{E^{\gamma}_{dep}} = \frac{\int_0^{E^{e^{\pm}}_{\max}} P^{\gamma}\left(E^{e^{\pm}}\right) \cdot E^{e^{\pm}} \cdot A \cdot f_q^{e^-}\left(E^{e^{\pm}}, k_B\right) dE^{e^{\pm}}}{\int_0^{E^{e^{\pm}}_{\max}} P^{\gamma}\left(E^{e^{\pm}}\right) \cdot E^{e^{\pm}}\, dE^{e^{\pm}}}$$

Normalization constant for energy scale

$$A = 1$$

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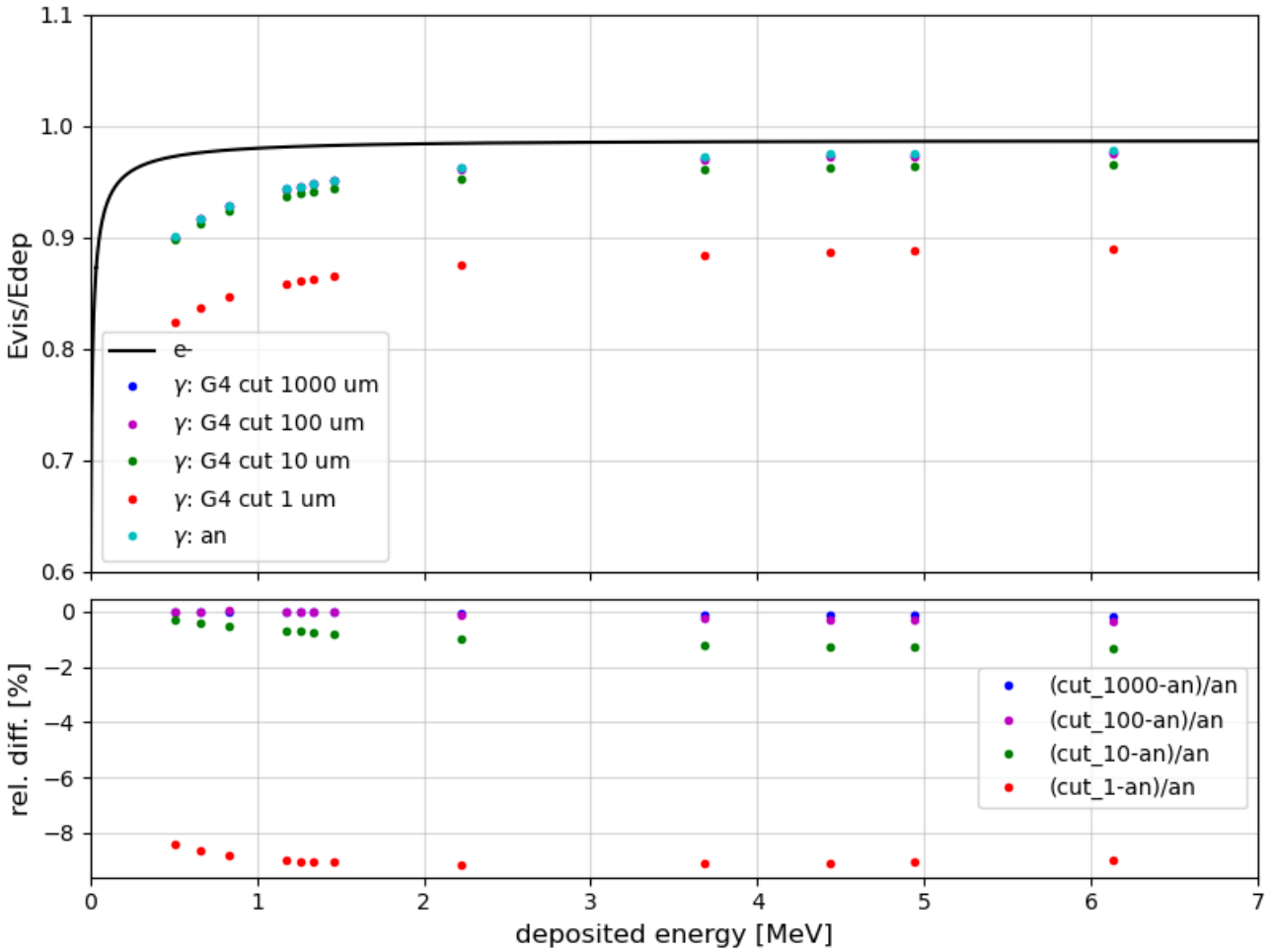

Production cut in G4 affects gamma non-linearity

→ keep cut at 100 μm as default one

As expected, gamma NL curve is below electron NL curve

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↓

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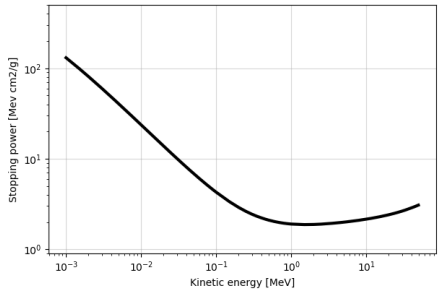
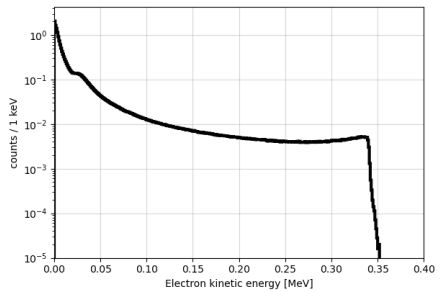
Particle interaction





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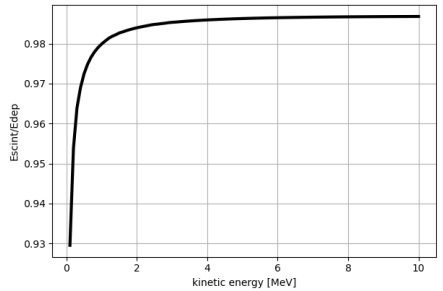
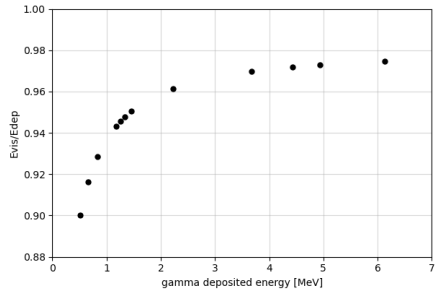


TODO



k_B

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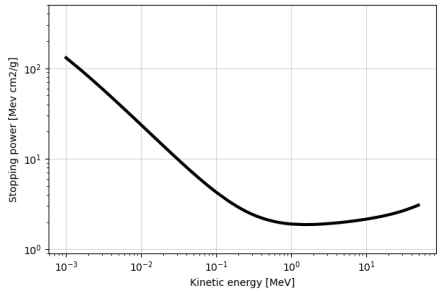

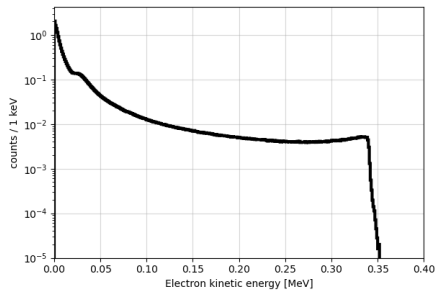

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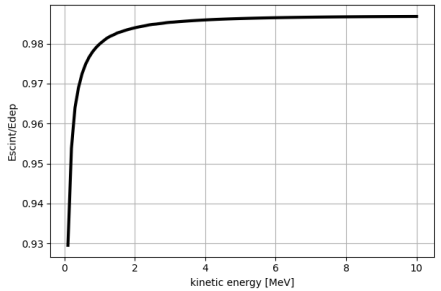

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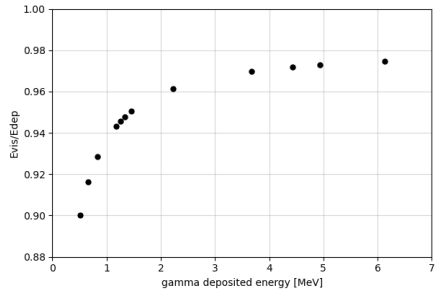


k_B

DATA

Calibration sources

Simulate calibration sources with JUNOSW:

- @ CD center
- with enclosure
- detsim level – no Cerenkov

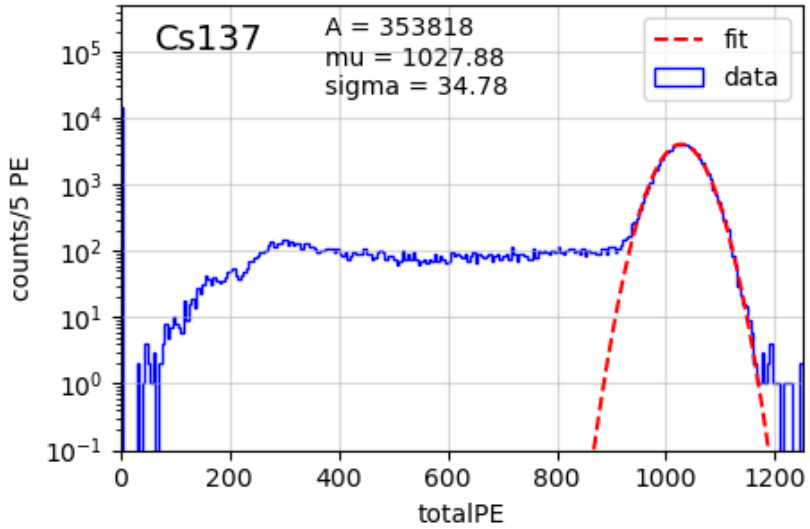
For neutron sources:

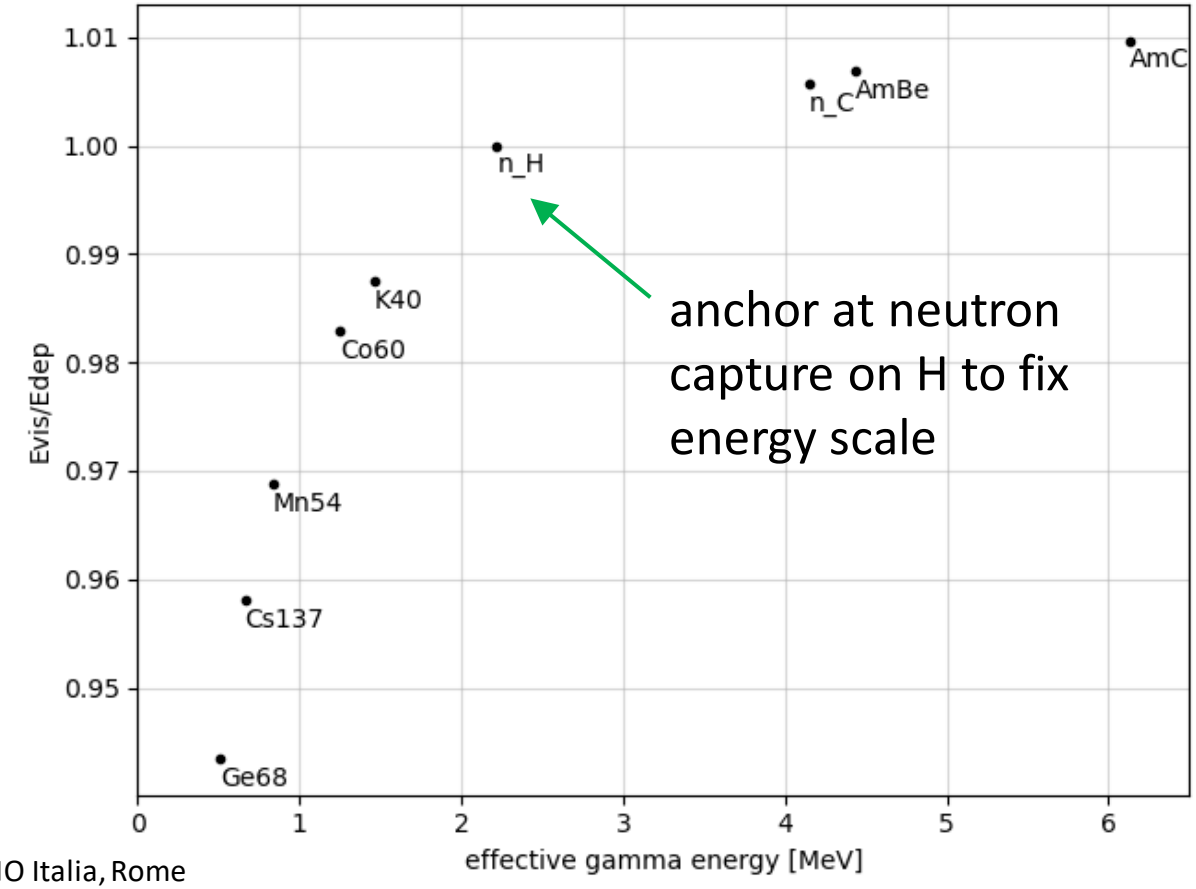
- 1 MeV neutrons
- 4.43 MeV and 6.13 MeV γ's

Sources/Processes	Type	Radiation
^{137}Cs	γ	0.662 MeV
^{54}Mn	γ	0.835 MeV
^{60}Co	γ	1.173 + 1.333 MeV
^{40}K	γ	1.461 MeV
^{68}Ge	e^+	annihilation 0.511 + 0.511 MeV
^{241}Am-Be	n, γ	neutron + 4.43 MeV (^{12}C*)
^{241}Am-^{13}C	n, γ	neutron + 6.13 MeV (^{16}O*)
(n,γ)p	γ	2.22 MeV
(n,γ)^{12}C	γ	4.94 MeV or 3.68 + 1.26 MeV

The JUNO collaboration., *J. High Energ. Phys.* **2021**, 4

Gaussian fit on totalPE spectrum





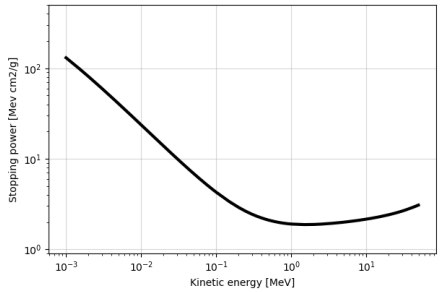
MODEL

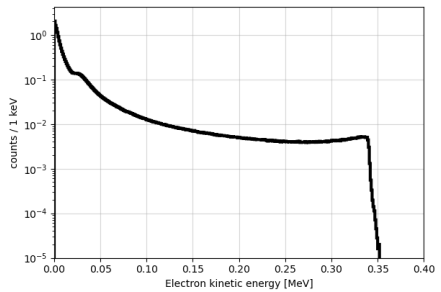
IBD → neutron → 2.22 MeV γ

↓

e^+: $E_{\text{dep}} = T^{e^+} + 2 \cdot 511\ \text{keV}\ \gamma$

Particle interaction

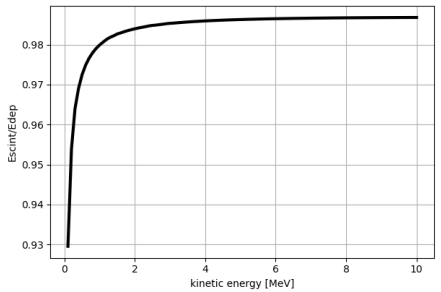




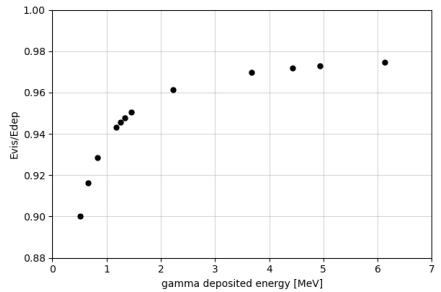
Scintillation

Cerenkov

Light production



TODO

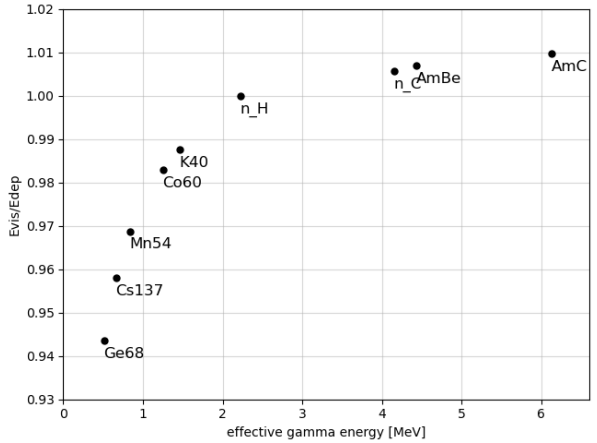


k_B

Fit

DATA

Calibration sources



Fit of gamma non-linearity curve

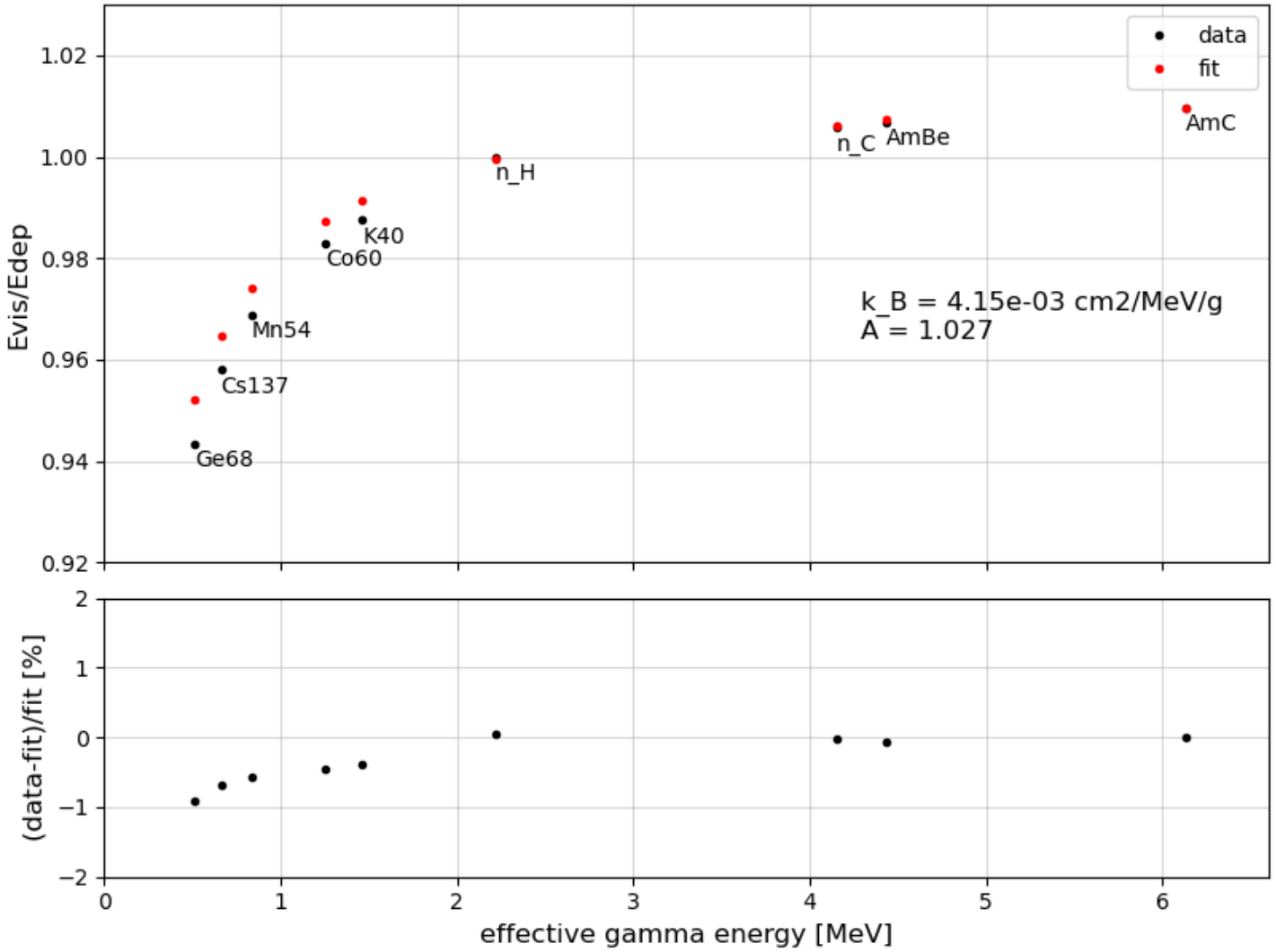
$$\chi^2 = \sum_{i \in \mathrm{src}} \frac{(M_i^\gamma - D_i^\gamma)^2}{(\sigma_i^\gamma)^2}$$

src = {^{68}Ge, ^{137}Cs, ^{54}Mn, ^{60}Co, ^{40}K, nH, nC, AmBe, AmC}

D_i^γ, σ_i^γ: Data, from Gaussian fit on calibration sources

M_i^γ: Model prediction
free parameters: A, k_B

Residuals within 1%



MODEL

IBD → neutron → 2.22 MeV γ

↓

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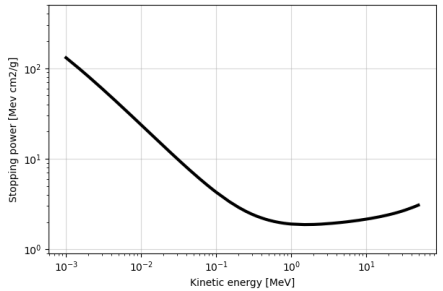
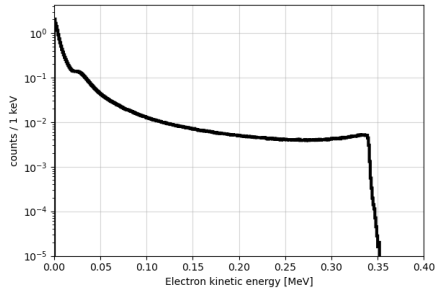
Particle interaction

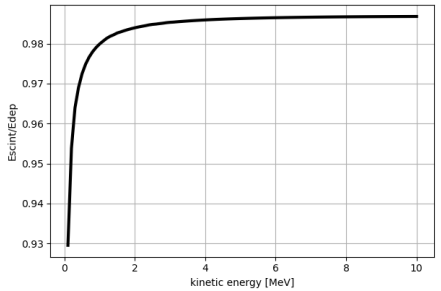




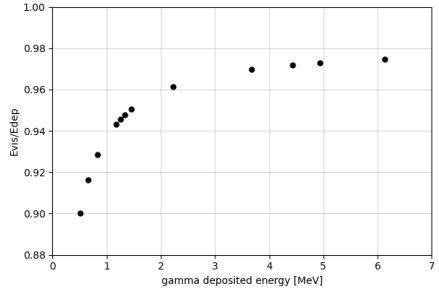
Scintillation

Cerenkov

Light production



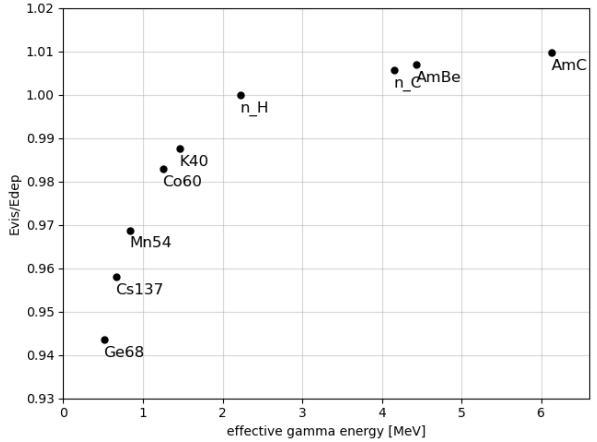
TODO



Fit

DATA

Calibration sources



k_B ⟷ k_B

JUNOSW input

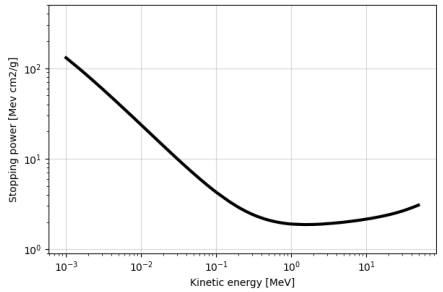
MODEL

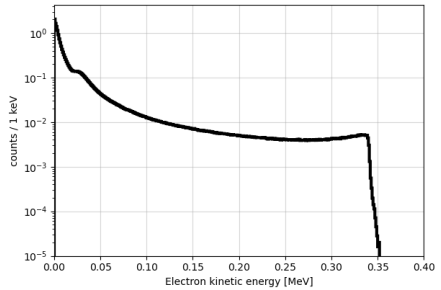
IBD → neutron → 2.22 MeV γ

↓

e^+: $E_{\text{dep}} = T^{e^+} + 2 \cdot 511\ \text{keV}\ \gamma$

Particle interaction

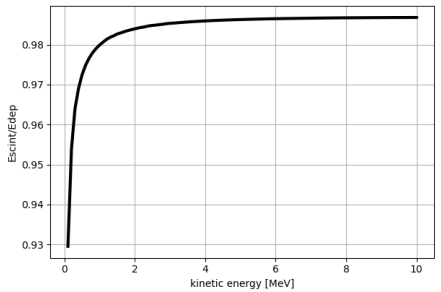




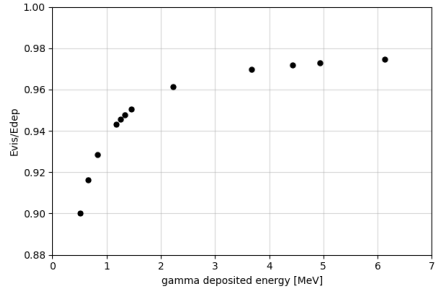
Scintillation

Cerenkov

Light production



TODO



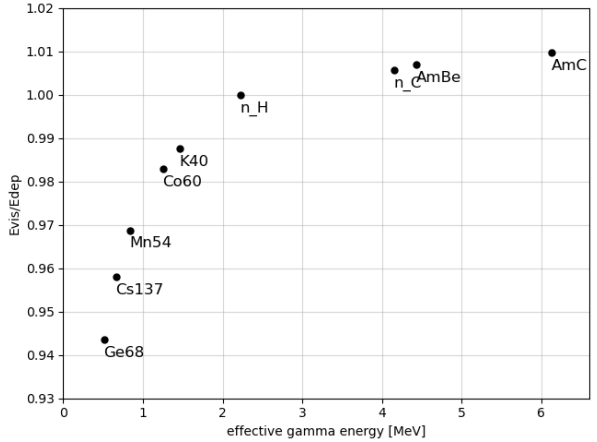
k_B ⟷ k_B

JUNOSW input

Fit

DATA

Calibration sources



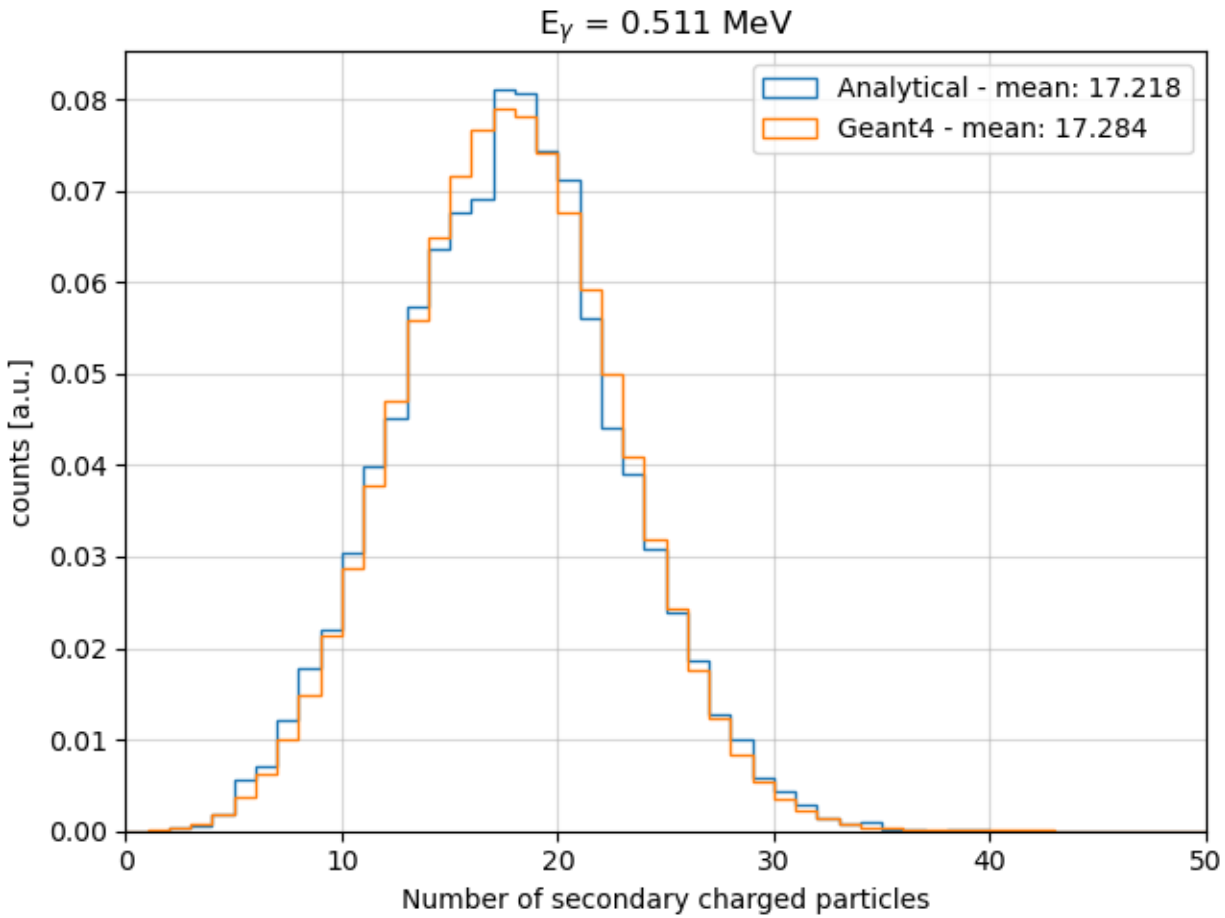
Future work:

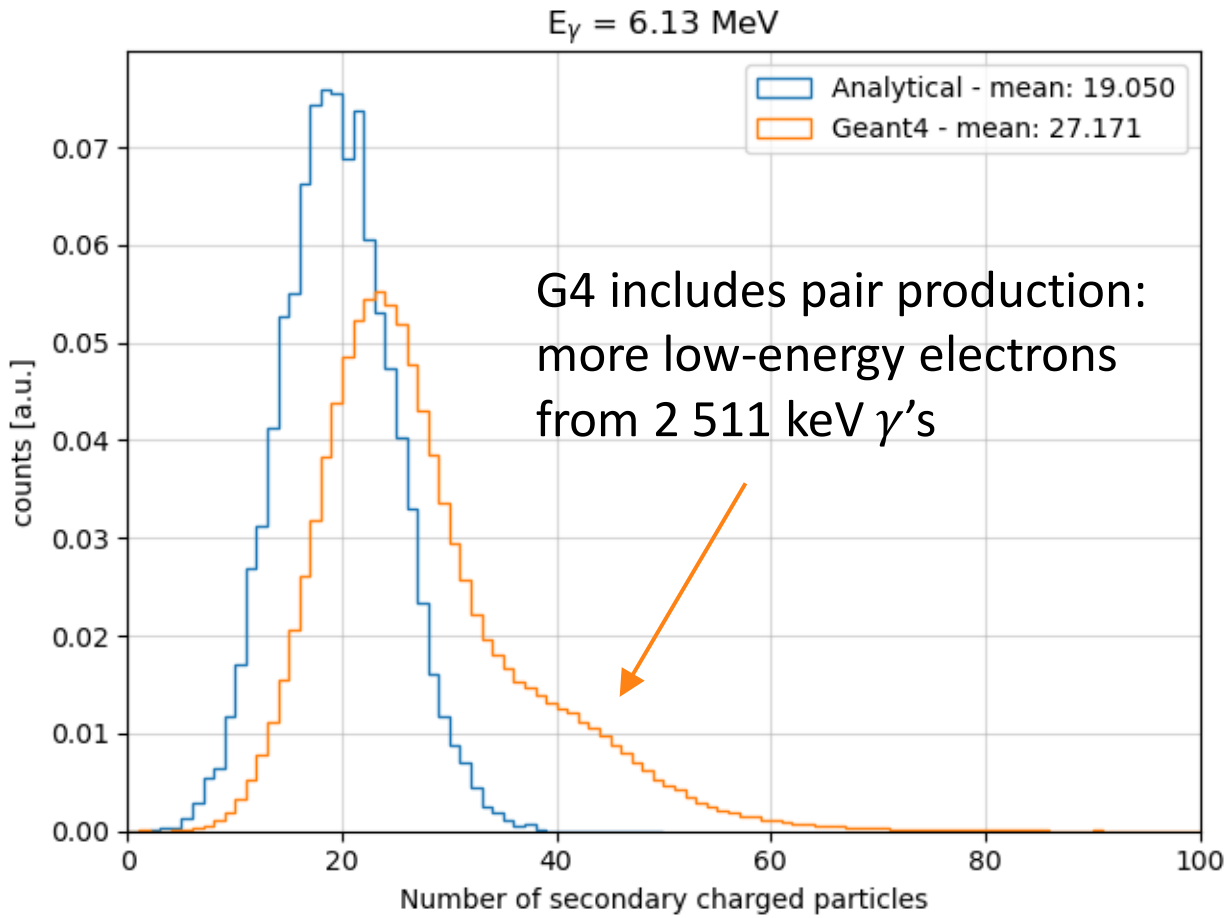
- Include Cerenkov
- Apply to positrons
- Include enclosure effects
  → Rosa Maria's work

Thank you for listening!

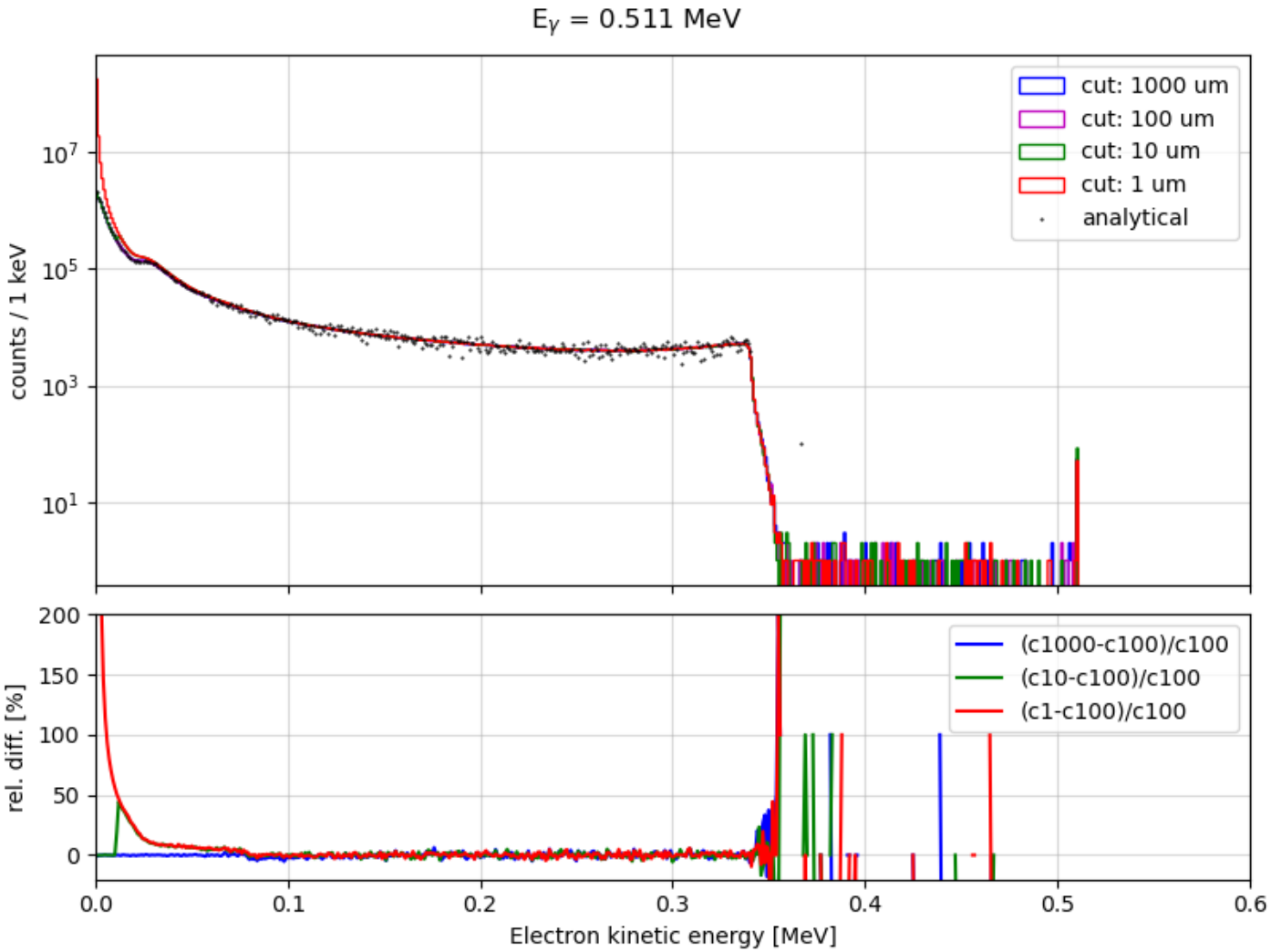
Backup

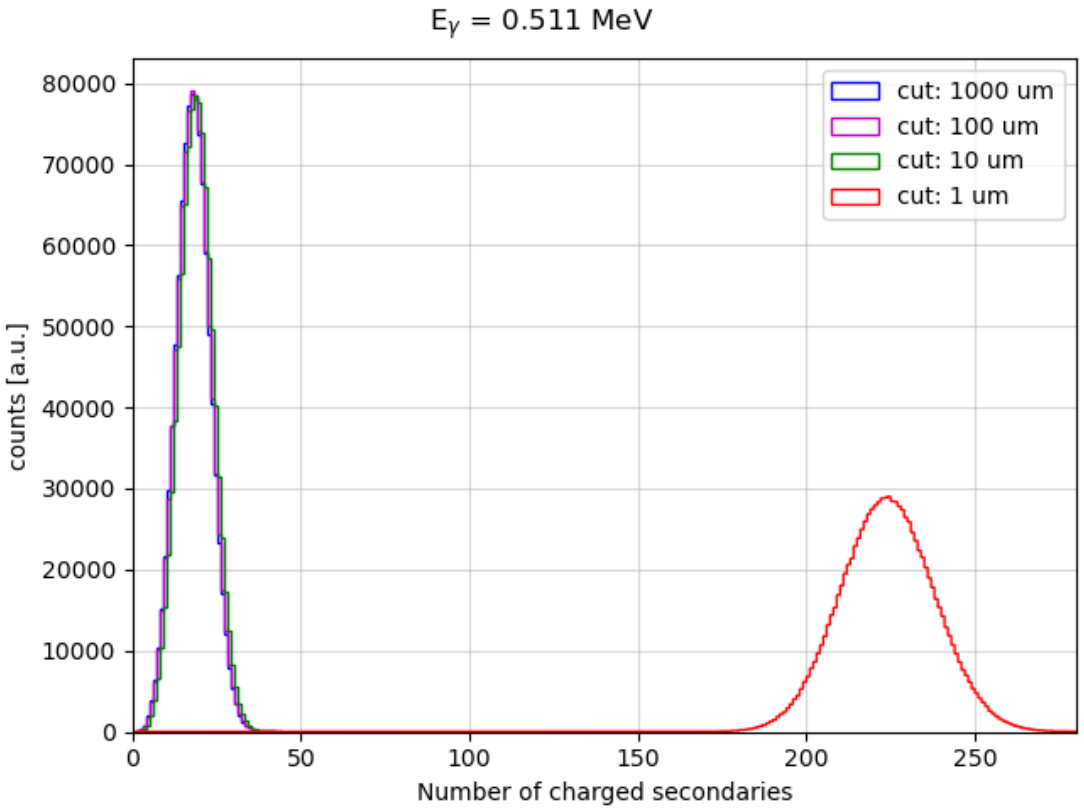
Analytical vs Geant4-based: number of secondaries e^-/e^+



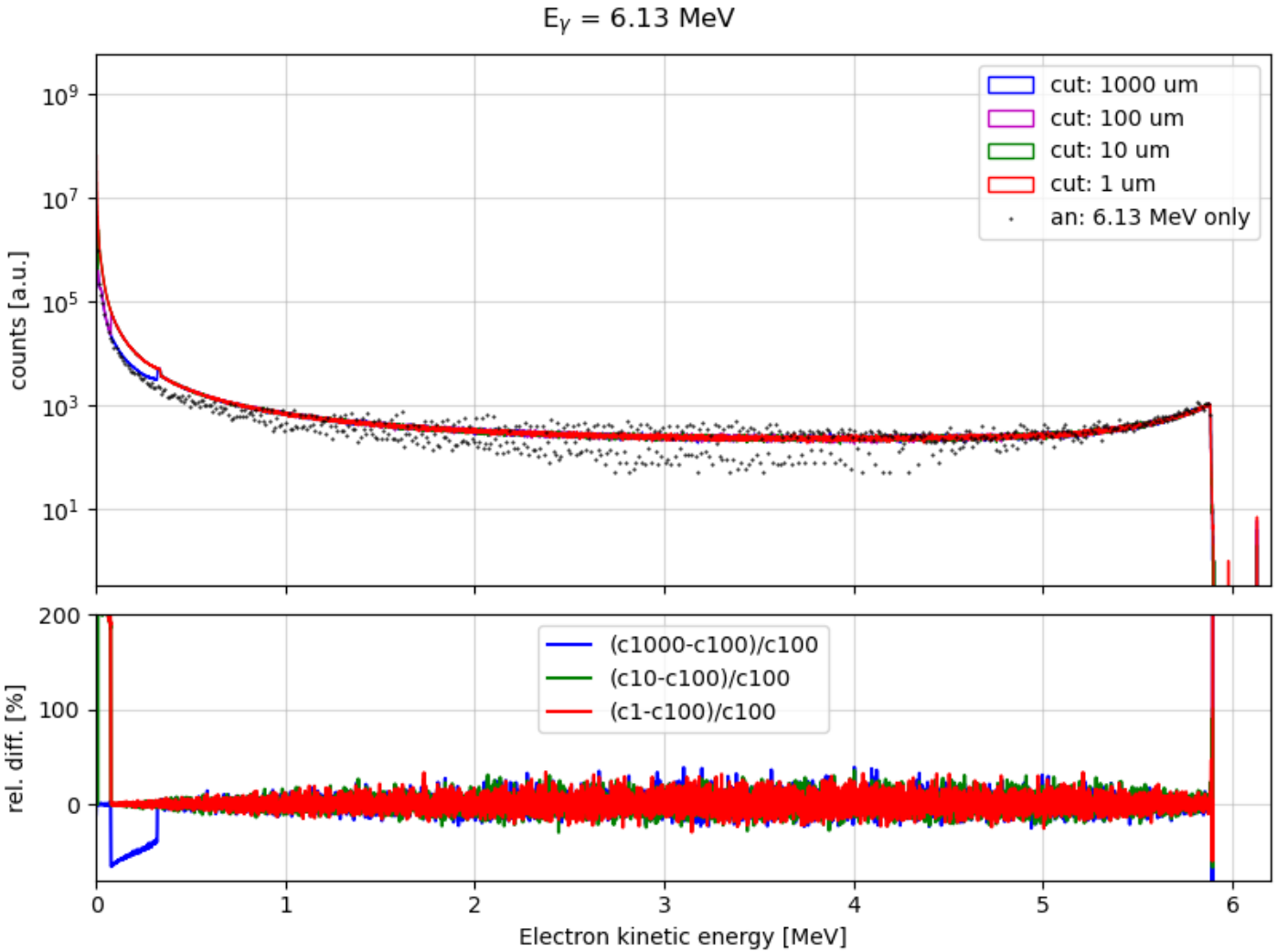


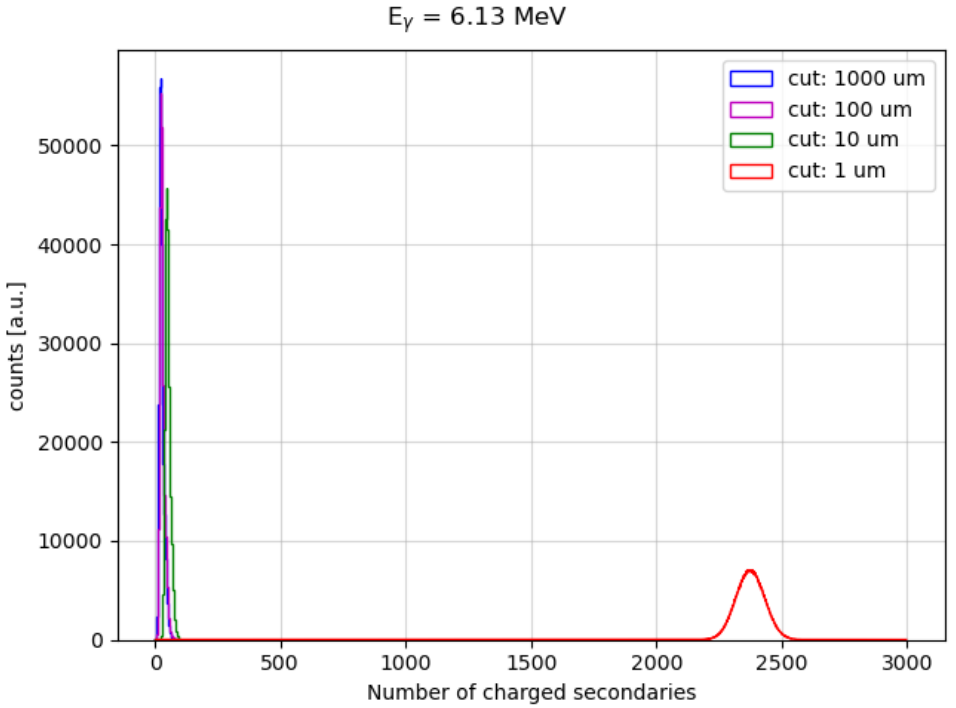
G4 production cuts (1)

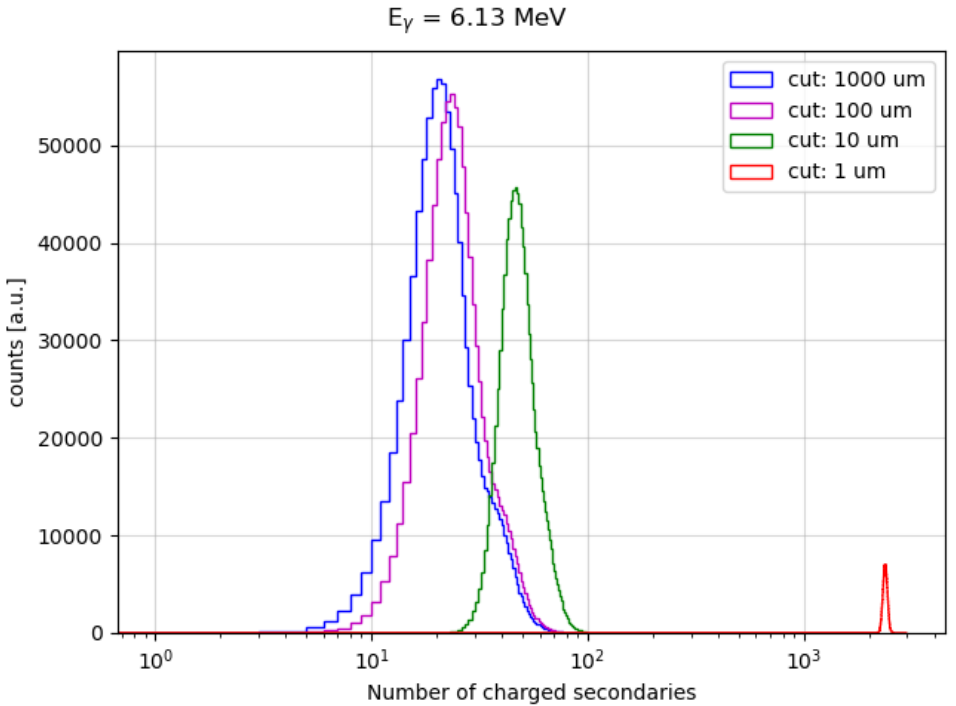


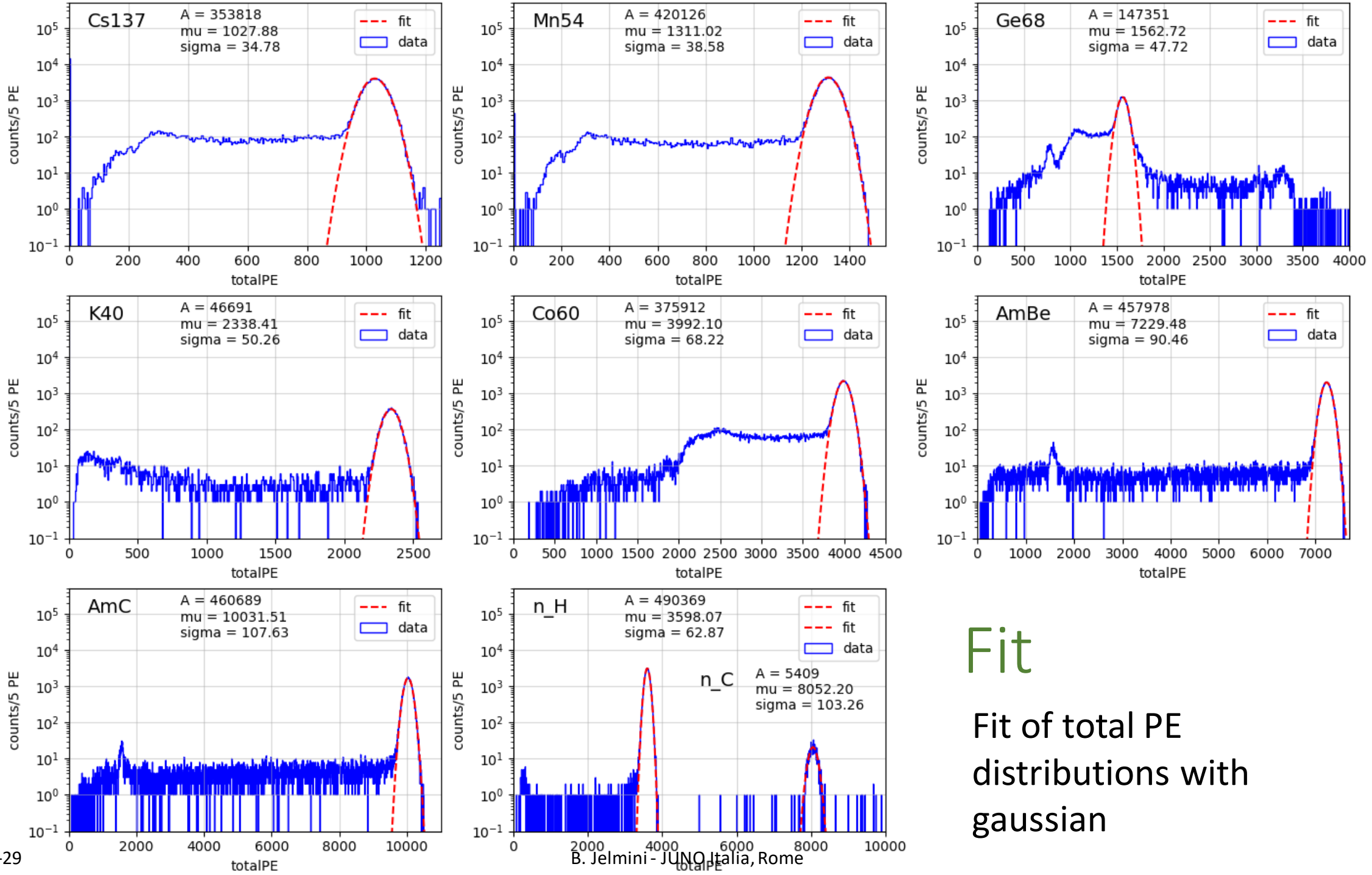


G4 production cuts (2)









Fit

Fit of total PE distributions with gaussian

Check stopping power with ESTAR