Energy resolution with different MC configurations

Yongbo Huang

IHEP

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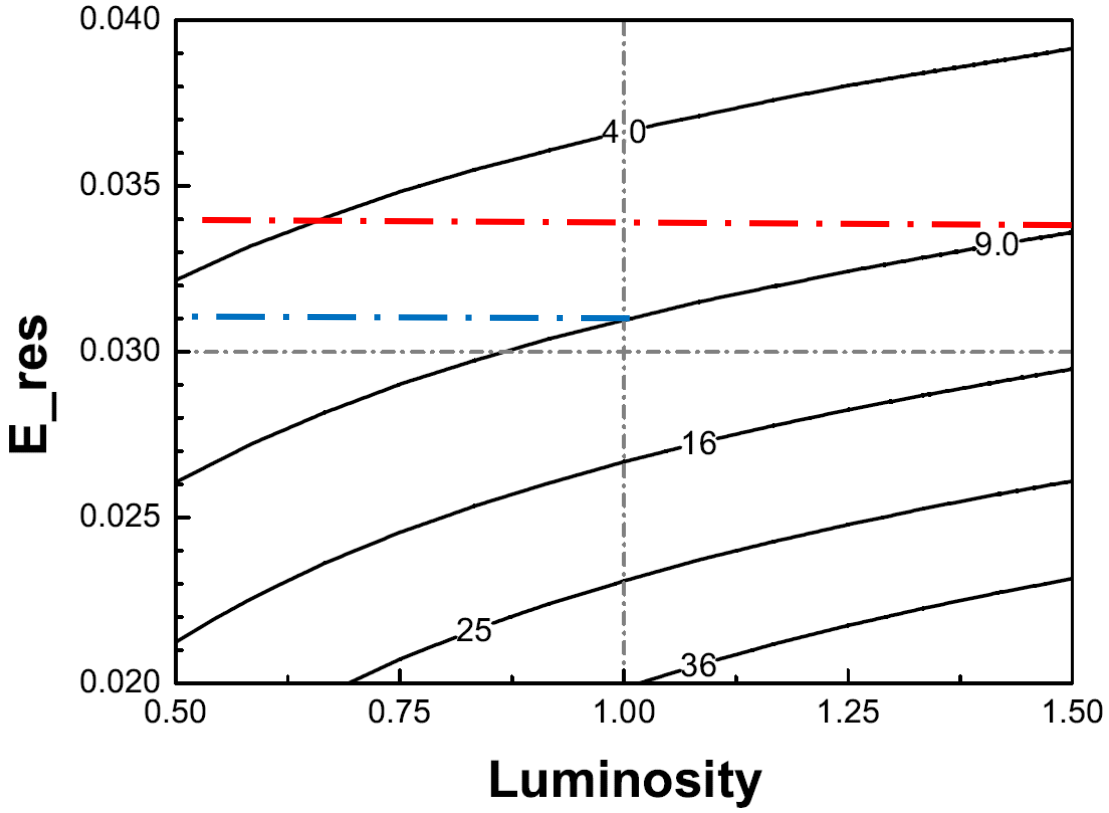
Introduction

- In the study of electron response
  - MC generation threshold affected:
    - Secondary electron
    - The resolution of quenched energy
  - Different KB resulted in different quenched energy distribution

- Simulation threshold and KB will introduce larger resolution ?
  - For JUNO (~3% at 1 MeV), the energy resolution is very important, need to check

JUNO's requirement on the Energy Resolution

- Baseline: ~3%/sqrt(E(MeV)), corresponding to 6 years data taking
- Affected by photon-electron statistics, the dark noise from PMT and electronics, the detector non-uniformity and vertex resolution, and the PMT charge resolution…..



Quenching

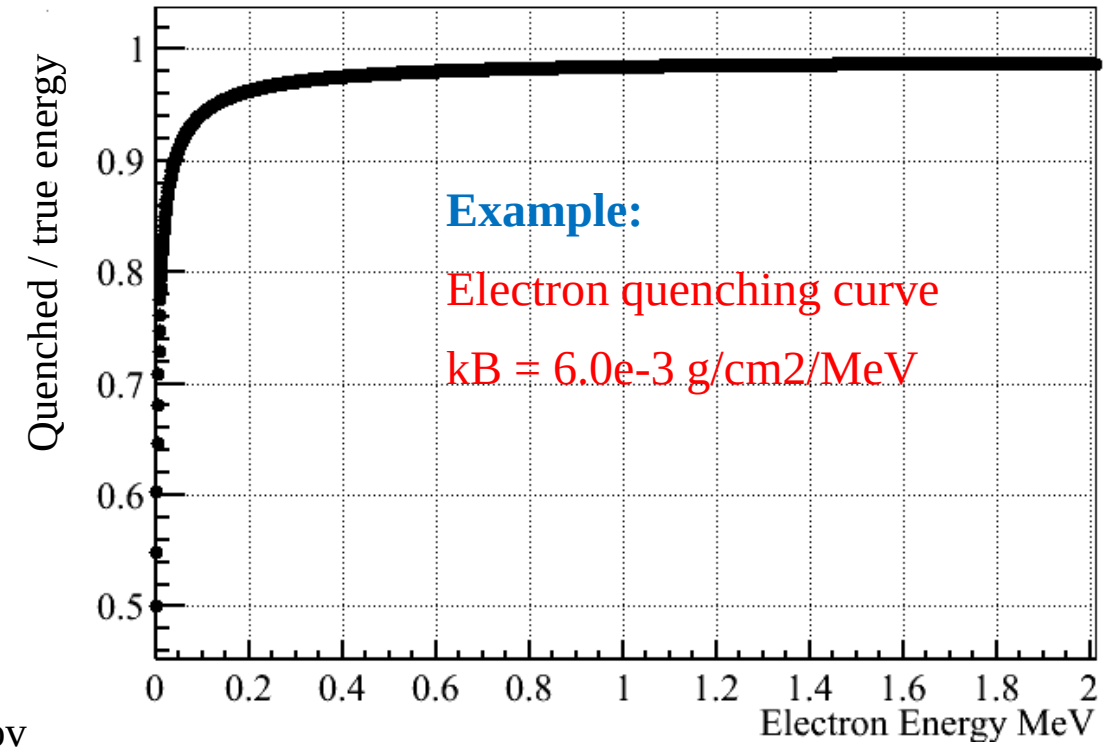
- Birks' formula (semi-empirically):

$$\frac{dL}{dx} \propto \frac{\frac{dE}{dx}}{1 + KB * \frac{dE}{dx} + c * \left(\frac{dE}{dx}\right)^2}$$

$$E_{quenched} = \int_0^{E_{true}} \frac{dE}{1 + KB * \frac{dE}{dx} + c * (\frac{dE}{dx})^2}$$

  - For electron and positron, $(\frac{dE}{dx})^2$ term can be ignored

- Quenched energy corresponding to visible energy
  - Total visible energy also with the contribution from Cerenkov



Quenching

- In geant4, from User Guide:

> Total energy deposited during the step - this is the sum of
> - the energy deposited by the energy loss process, and
> - the energy lost by secondaries which have NOT been generated because each of their energies was below the cut threshold

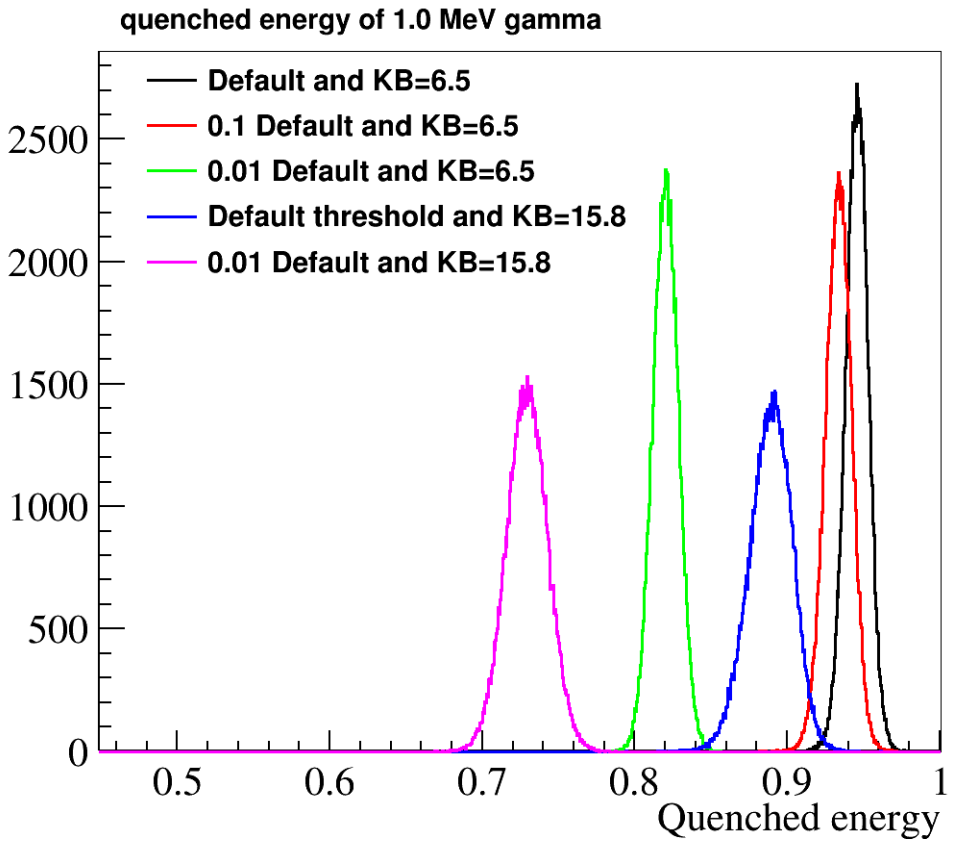
- So the loss energy is independent to cut threshold
- With low threshold, the secondary electron is generated and tracked
  - For a step which with secondary electron
  - $dE = dE_1 + dE_2$, dE_1 is ionization, and dE_2 is for secondary electron
  - Without secondary electron: $dE_{quenched} = \frac{dE}{1+KB*\frac{dE}{dx}}$
  - With secondary electron: $dE'_{quenched} = \frac{dE_1}{1+KB*(\frac{dE}{dx})_1} + \frac{dE_2}{1+KB*(\frac{dE}{dx})_2}$
  - $dE_{quenched}$!= $dE'_{quenched}$

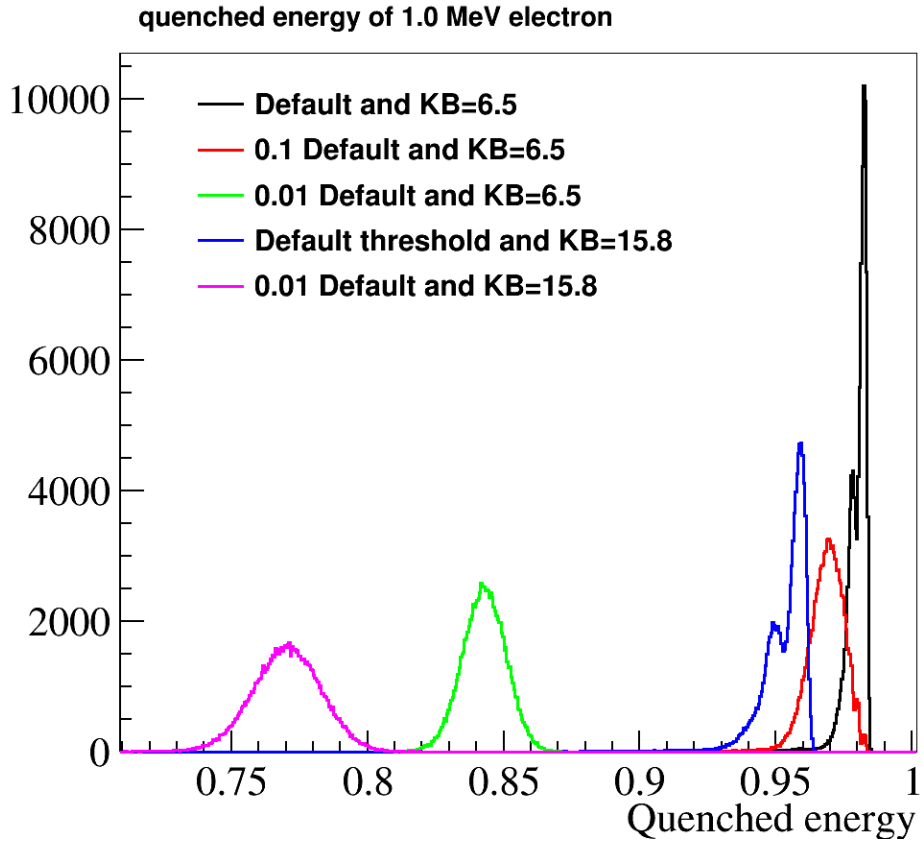
Setting in MC

- JUNO's Geant4 software framework
- Light Yield: 11523 (nominal)
- The current KB = 6.5e-3 g/cm^2/MeV
- Particle gun: gamma / **e**$^-$
- Position: (0,0,0)
- Kinetic energy: 0.5, 1.0, 1.5, 2.0 MeV
- Event: 99K for each kinetic energy
- Threshold in MC:
  - Default: cutForGamma 1.0mm, cutForElectron 0.1mm, cutForPositron 0.1mm
  - Modify threshold to 0.1*default and 0.01*default

Quenched energy

- Low threshold corresponding to small quenched energy and large resolution
- Large KB result in small quenched energy and large resolution
- In the case of default threshold, quenched energy distribution of electron with low energy tail





Simulation results (gamma)

- Low simulation threshold will result in a larger resolution compare to the case of nominal setting

Table 2: For KB = 6.5e-3 g/cm2/MeV, quenched energy resolution in the case of different simulation thresholds.

gamma Energy[MeV]	Threshold	Parameters		
		quenched energy	RMS	Resolution[%]
0.5	Default	0.4576	6.162e-03	1.346
	0.1 Default	0.4511	6.542e-03	1.4502
	0.01 Default	0.4000	6.113e-03	1.5284
1.0	Default	0.9455	7.609e-03	0.805
	0.1 Default	0.9335	8.653e-03	0.927
	0.01 Default	0.8201	8.550e-03	1.043
1.5	Default	1.4363	8.859e-03	0.617
	0.1 Default	1.4185	1.0477e-02	0.739
	0.01 Default	1.2420	1.0469e-02	0.843
2.0	Default	1.9276	1.0219e-02	0.530
	0.1 Default	1.9042	1.2116e-02	0.636
	0.01 Default	1.6642	1.2232e-02	0.735

Simulation results (gamma)

- Default threshold and KB=6.5, resolution = 0.805%
- Large KB will introduce large resolution

Table 3: For KB = 15.8e-3 g/cm2/MeV, quenched energy resolution in the case of different simulation thresholds.

gamma Energy[MeV]	Threshold	Parameters		
		quenched energy	RMS	Resolution[%]
0.5	Default	0.4165	1.0444e-02	2.508
	0.01 Default	0.3465	9.452e-03	2.728
1.0	Default	0.8888	1.4065e-02	1.582
	0.01 Default	0.7292	1.3504e-02	1.852
1.5	Default	1.3674	1.6991e-02	1.243
	0.01 Default	1.1152	1.6822e-02	1.508
2.0	Default	1.8477	1.9905e-02	1.077
	0.01 Default	1.5023	1.9736e-02	1.314

Simulation results (electron)

- Low simulation threshold will result in a larger resolution compare to the case of nominal setting

Table 4: For KB = 6.5e-3 g/cm2/MeV, quenched energy resolution in the case of different simulation thresholds.

electron kinetic Energy[MeV]	**Threshold**	**Parameters**		
		quenched energy	**RMS**	**Resolution[%]**
0.5	Default	0.4869	2.428e-03	0.499
	0.1 Default	0.4816	4.060e-03	0.843
	0.01 Default	0.4197	5.484e-03	1.307
1.0	Default	0.9797	4.122e-03	0.421
	0.1 Default	0.9684	6.575e-03	0.679
	0.01 Default	0.8426	7.992e-03	0.948
1.5	Default	1.4725	5.750e-03	0.390
	0.1 Default	1.4554	8.587e-03	0.590
	0.01 Default	1.2658	9.966e-03	0.787
2.0	Default	1.9651	7.240e-03	0.368
	0.1 Default	1.9423	1.0339e-02	0.532
	0.01 Default	1.6889	1.1730e-02	0.695

Simulation results (electron)

- Default threshold and KB=6.5, resolution = 0.421%
- Large KB will introduce large resolution

Table 5: For KB = 15.8e-3 g/cm2/MeV, quenched energy resolution in the case of different simulation thresholds.

electron kinetic Energy[MeV]	**Threshold**	**Parameters**		
		quenched energy	**RMS**	**Resolution[%]**
0.5	Default	0.4702	4.710e-03	1.002
	0.01 Default	0.3818	8.435e-03	2.209
1.0	Default	0.9532	8.098e-03	0.849
	0.01 Default	0.7701	1.2561e-02	1.631
1.5	Default	1.4366	1.1272e-02	0.785
	0.01 Default	1.1588	1.5922e-02	1.374
2.0	Default	1.9197	1.4172e-02	0.738
	0.01 Default	1.5473	1.8740e-02	1.211

Simulation results (gamma)

- When we modify the simulation threshold, totalPE for 1 MeV gamma is also change
  - Need to modify the Light Yield to ensure the totalPE is almost identical in different cases

Table 6: Before modified light yield, for KB = 6.5e-3 g/cm2/MeV, totalPE resolution in the case of different simulation thresholds.

gamma Energy[MeV]	Threshold	Parameters		
		totalPE	Sigma	Resolution[%]
0.5	Default	616.82	26.32	4.267
	0.1 Default	607.76	26.33	4.332
	0.01 Default	539.16	24.70	4.581
1.0	Default	1290.38	40.38	3.129
	0.1 Default	1274.14	40.85	3.206
	0.01 Default	1122.36	38.32	3.414
1.5	Default	1982.43	53.29	2.688
	0.1 Default	1958.49	53.80	2.747
	0.01 Default	1722.07	50.70	2.944
2.0	Default	2681.75	40.38	2.410
	0.1 Default	2649.96	65.24	2.462
	0.01 Default	2329.64	61.75	2.651

The change of resolution comes from both quenched energy distribution and photon-electron statistics

Simulation results (gamma)

- After modified Light Yield
  - Photon number is almost the same
  - The change of resolution only comes from quenched energy distribution

Table 7: After modified light yield, for KB = 6.5e-3 g/cm2/MeV, totalPE resolution in the case of different simulation thresholds.

gamma Energy[MeV]	Threshold	Parameters		
		totalPE	Sigma	Resolution[%]
0.5	Default	616.82	26.32	4.267
	0.1 Default	615.65	24.54	4.297
	0.01 Default	619.78	26.76	4.318
1.0	Default	1290.38	40.38	3.129
	0.1 Default	1290.26	41.22	3.194
	0.01 Default	1287.42	41.18	3.198
1.5	Default	1982.43	53.29	2.688
	0.1 Default	1982.80	54.39	2.743
	0.01 Default	1971.96	54.03	2.740
2.0	Default	2681.75	40.38	2.410
	0.1 Default	2682.99	65.91	2.457
	0.01 Default	2664.26	65.62	2.463

Simulation results (gamma)

- Default threshold and KB=6.5, resolution = 3.129%
- Large KB will introduce large resolution

Table 8: After modified light yield, for KB = 15.8e-3 g/cm2/MeV, totalPE resolution in the case of different simulation thresholds.

gamma Energy[MeV]	Threshold	Parameters		
		totalPE	Sigma	Resolution[%]
0.5	Default	594.47	28.79	4.843
	0.01 Default	602.48	29.64	4.919
1.0	Default	1285.20	45.69	3.555
	0.01 Default	1284.42	46.87	3.649
1.5	Default	1998.97	61.05	3.054
	0.01 Default	1986.75	62.045	3.123
2.0	Default	2721.99	74.03	2.720
	0.01 Default	2697.72	75.71	2.807

Simulation results (electron)

Table 9: After modified light yield, for KB = 6.5e-3 g/cm2/MeV, totalPE resolution in the case of different simulation thresholds.

electron kinetic energy[MeV]	Threshold	Parameters		
		totalPE	Sigma	Resolution[%]
0.5	Default	668.94	26.31	3.933
	0.1 Default	670.12	26.90	4.014
	0.01 Default	663.35	27.53	4.150
1.0	Default	1372.83	39.07	2.846
	0.1 Default	1374.39	40.18	2.924
	0.01 Default	1359.05	40.94	3.013
1.5	Default	2083.51	49.76	2.388
	0.1 Default	2085.32	51.09	2.450
	0.01 Default	2061.94	51.74	2.509
2.0	Default	2796.24	59.00	2.110
	0.1 Default	2798.31	60.39	2.158
	0.01 Default	2766.94	61.45	2.221

Simulation results (electron)

- Default threshold and KB=6.5, resolution = 2.846%
- Large KB will introduce large resolution

Table 10: After modified light yield, for KB = 15.8e-3 g/cm2/MeV, totalPE resolution in the case of different simulation thresholds.

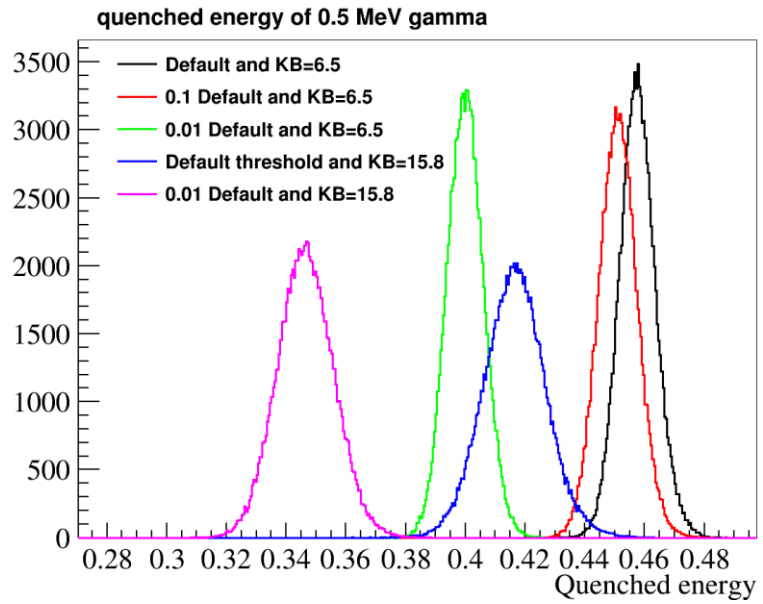
electron kinetic energy[MeV]	Threshold	Parameters		
		totalPE	Sigma	Resolution[%]
0.5	Default	683.99	27.42	4.008
	0.01 Default	676.80	307.19	4.539
1.0	Default	1413.69	41.40	2.928
	0.01 Default	1392.56	46.48	3.338
1.5	Default	2150.19	53.40	2.483
	0.01 Default	2115.31	58.97	2.788
2.0	Default	2889.65	63.75	2.206
	0.01 Default	2840.19	70.048	2.466

Summary

- For relative comparison (the above values are not absolute value), low simulation threshold and large KB will result in larger resolution compare to the result of nominal setting

- Need to consider which setting is more reliable

- Even if we get gamma’s resolution, we can’t naive apply it to electron directly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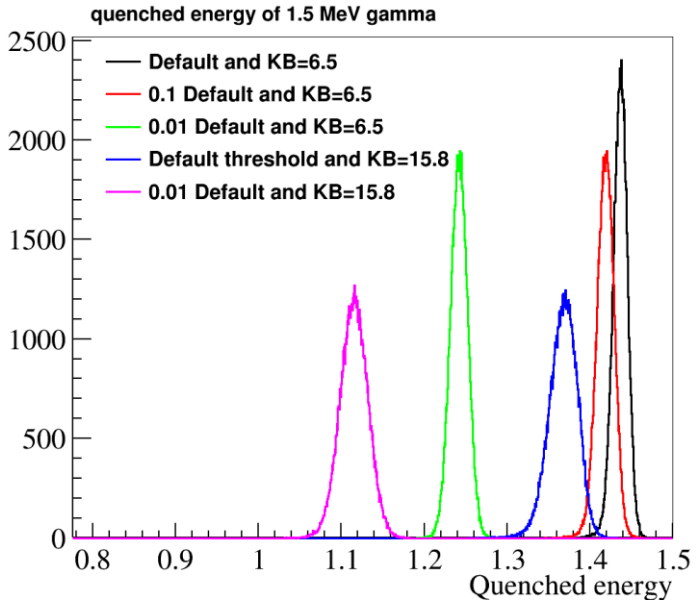
Quenched energy


quenched energy of 1.5 MeV gamma
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0.01 Default and KB=6.5
Default threshold and KB=15.8
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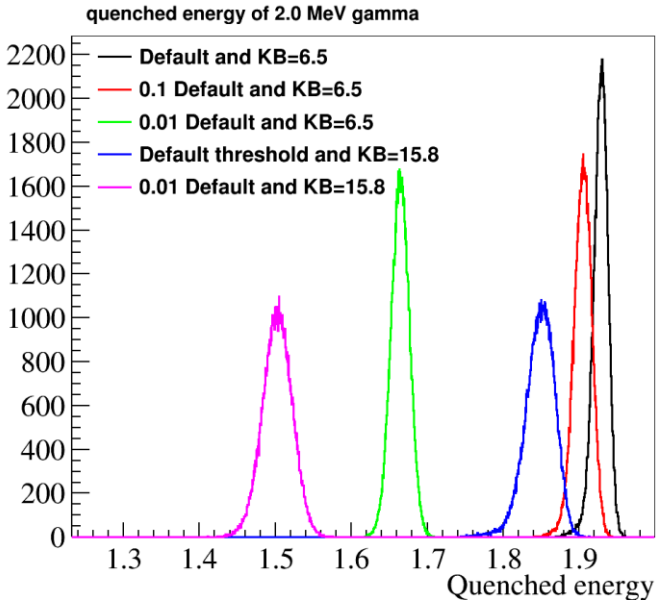
Quenched energy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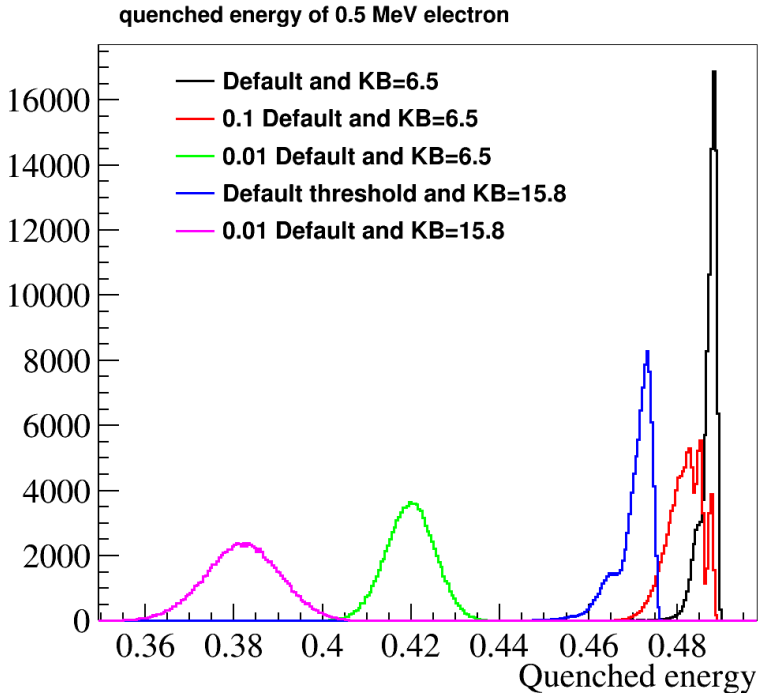
Quenched energy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Default threshold and KB=15.8
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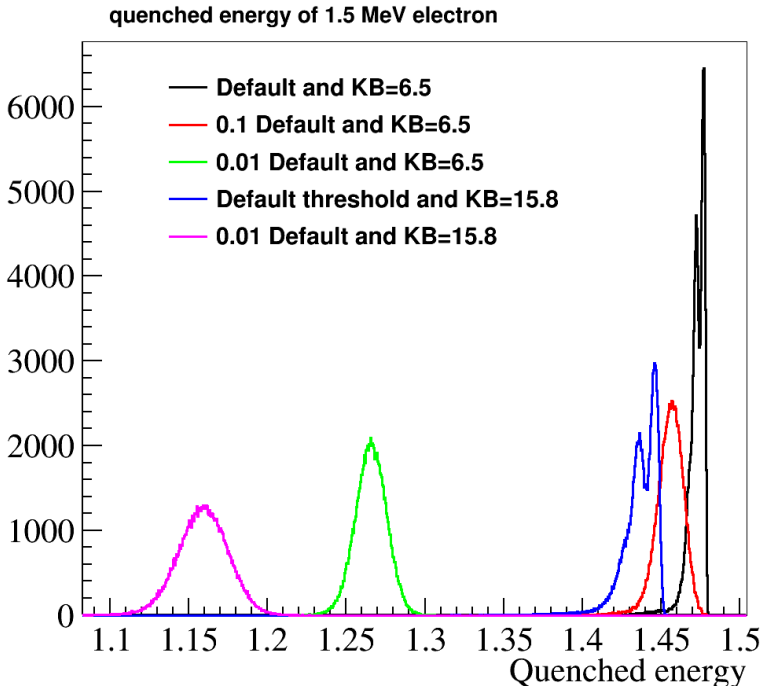
Quenched energy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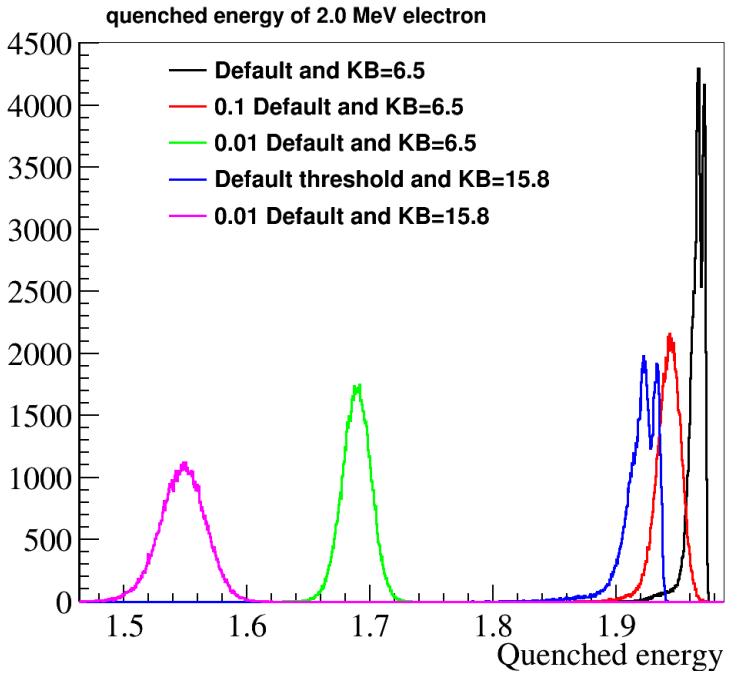
Quenched energy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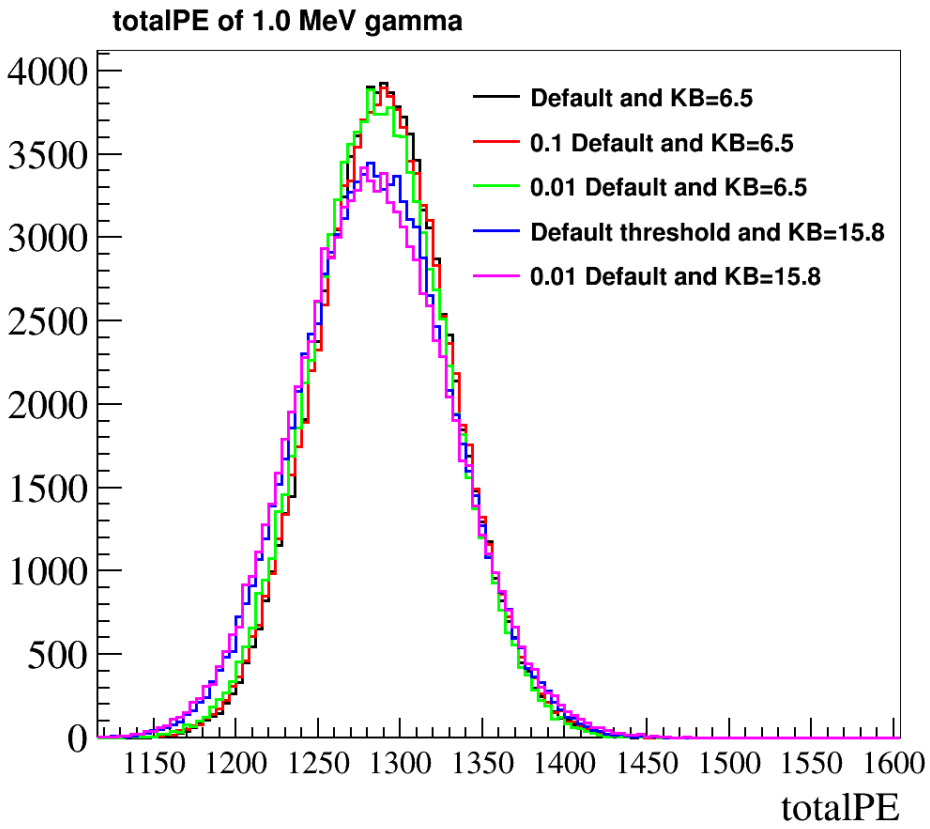
Quenched energy

totalPE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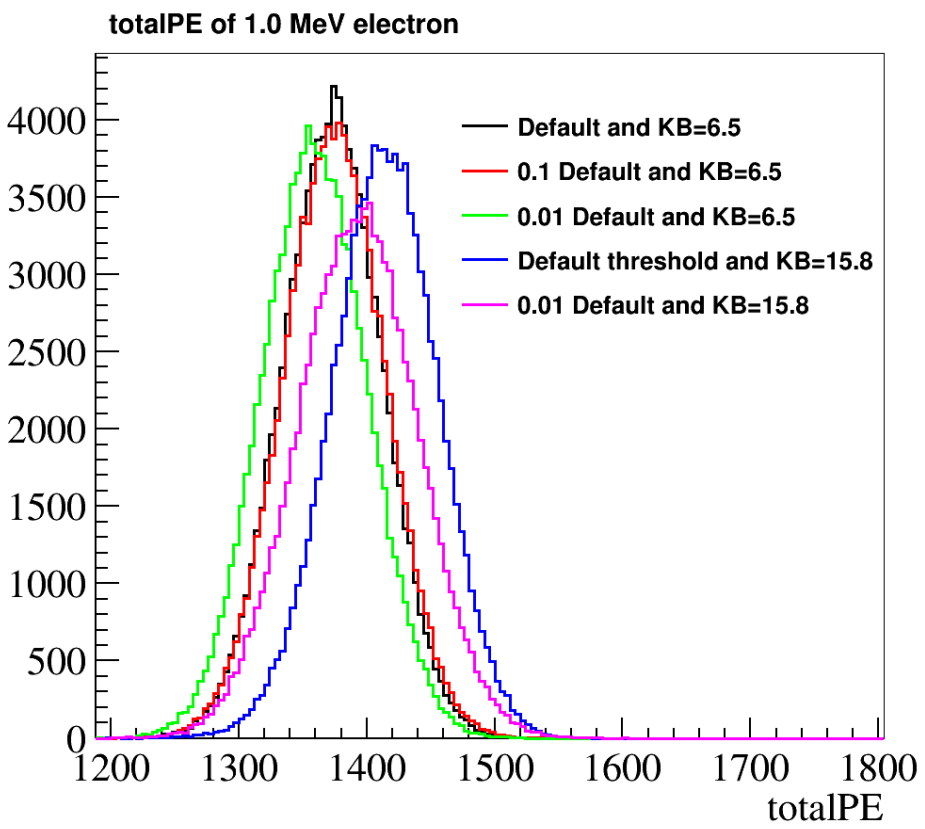
totalPE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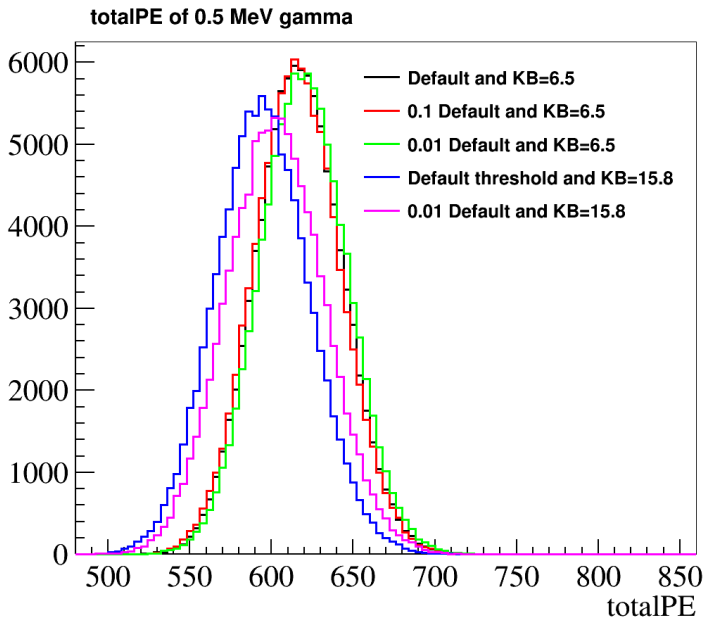
1200 1300 1400 1500 1600 1700 1800
totalPE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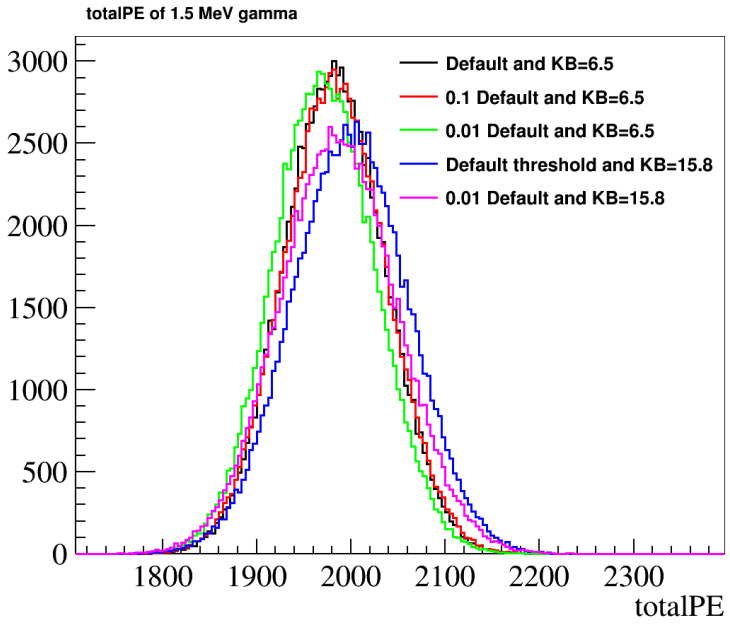
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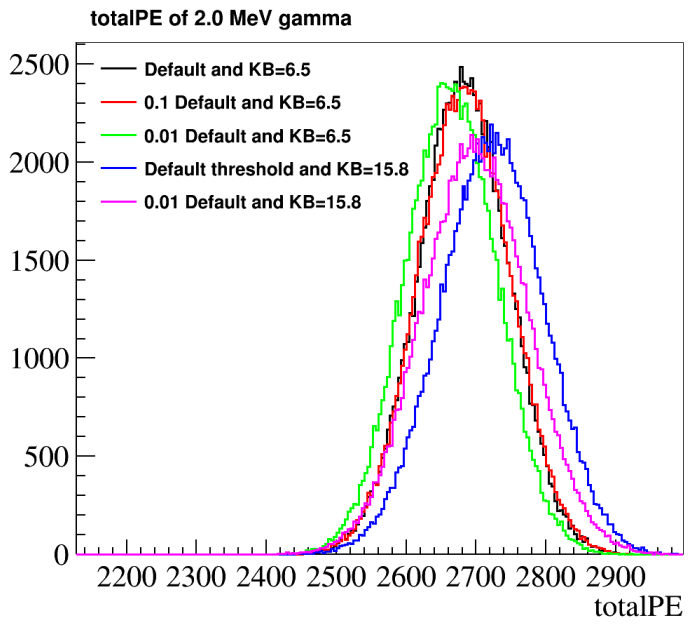
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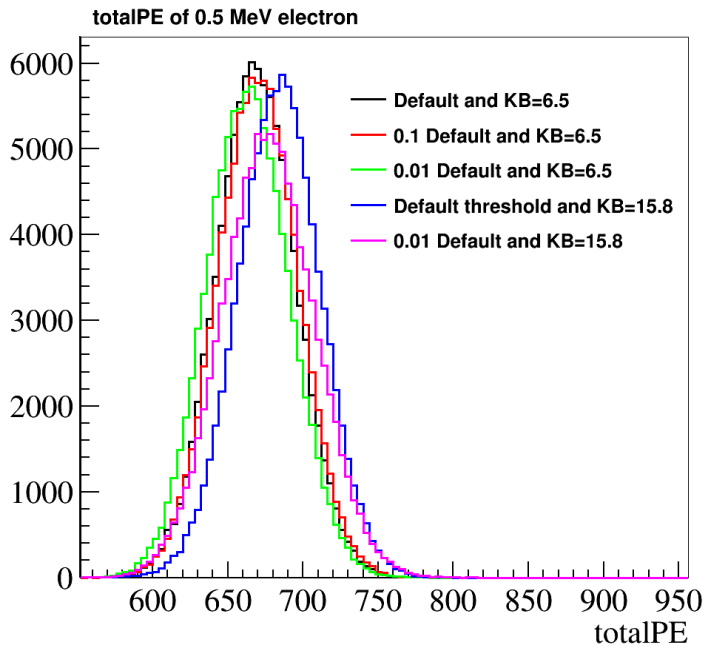
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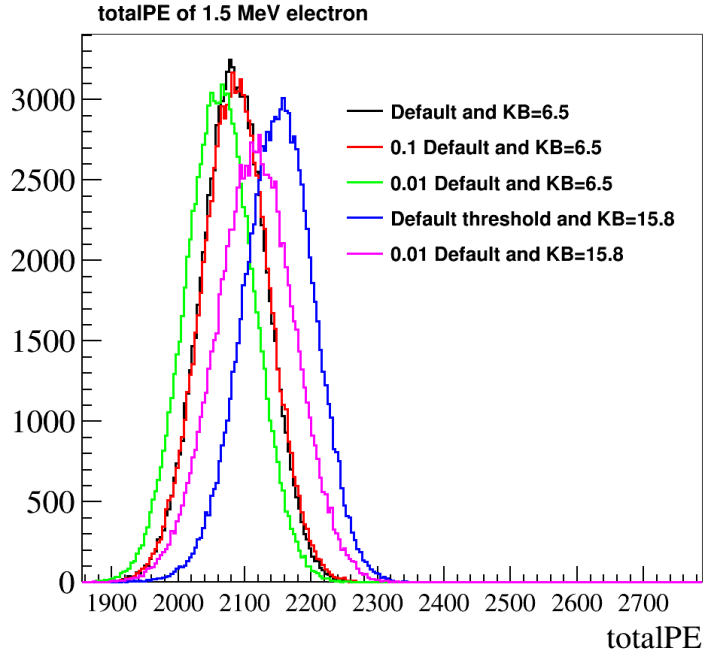
totalPE of 1.5 MeV electron
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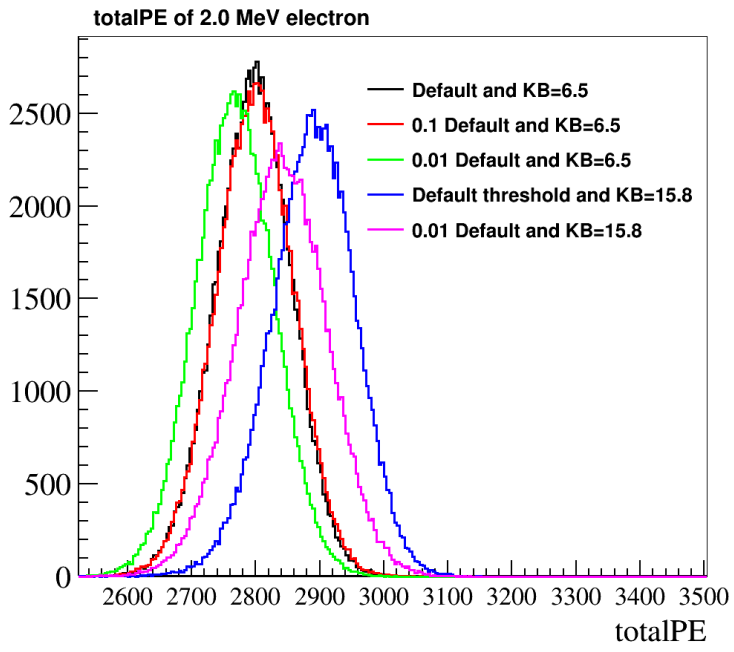
totalPE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