The impact of the liquid scintillator optical properties on the energy resolution

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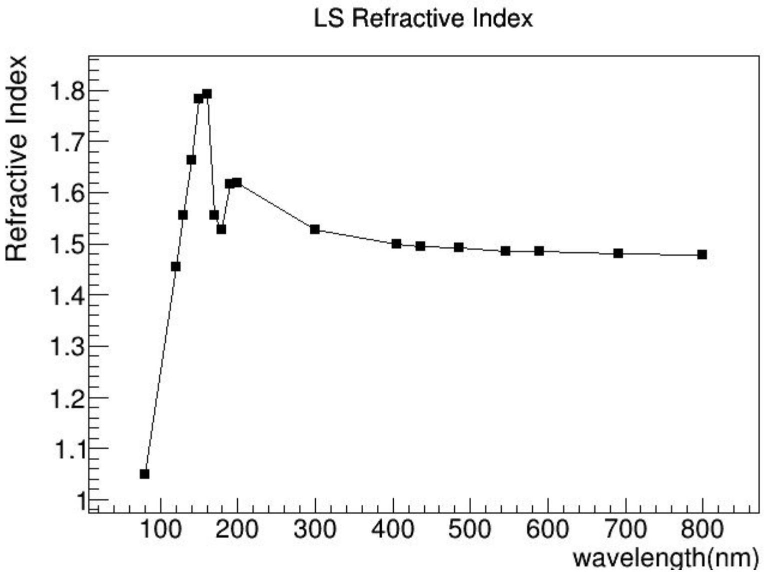
OUTLINE

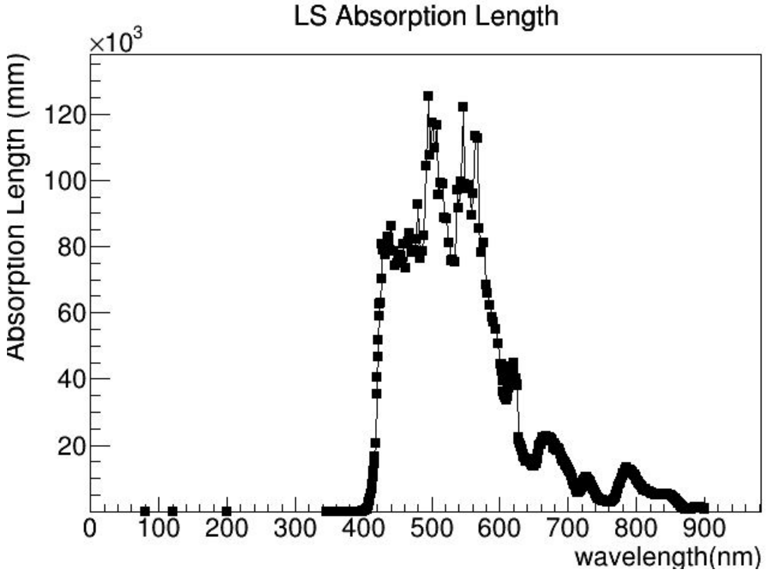
- **Liquid scintillator properties:**
  - ➔ Optical phenomena implemented in SNiPER;
  - ➔ SNiPER Monte Carlo simulations;
  - ➔ Impact of a few optical properties on the energy resolution;

- **Experimental measurements in Milan:**
  - ➔ Impact of the refractive index;
  - ➔ Impact of the newly measured spectrum;

LS PARAMETERS

Plots from the JUNOwiki page: https://juno.ihep.ac.cn/mediawiki/index.php/Analysis:Basic_Distributions_of_JUNO





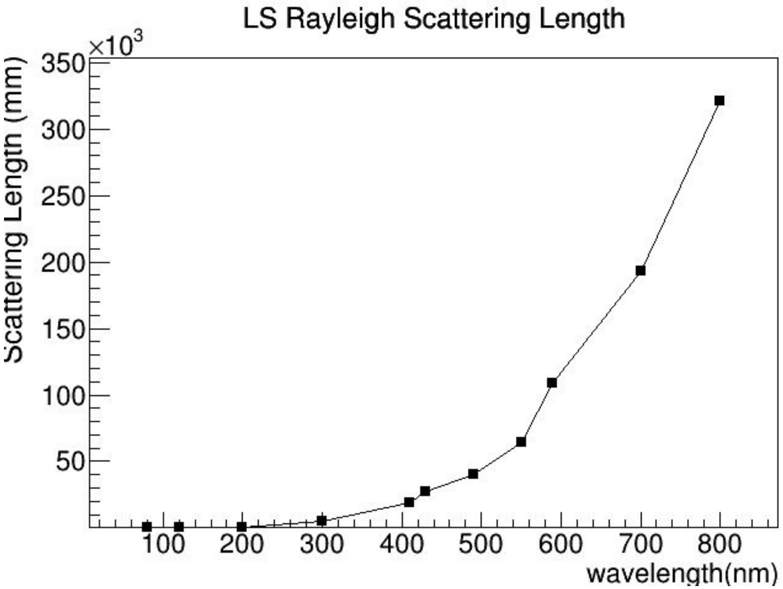
From: >400nm experimental results;
200-400nm dispersion formula;
120-200nm Kamland inherited;
80-120nm linear extrapolation

When: 2021

From: Daya Bay inherited, rescaled due to different transparescence

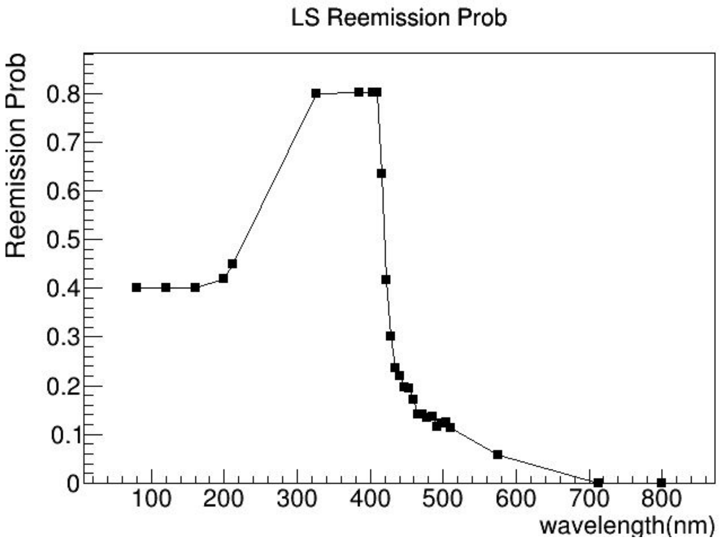
When: <2015

A PLOT OF THE LS PARAMETERS



From: Daya Bay inherited

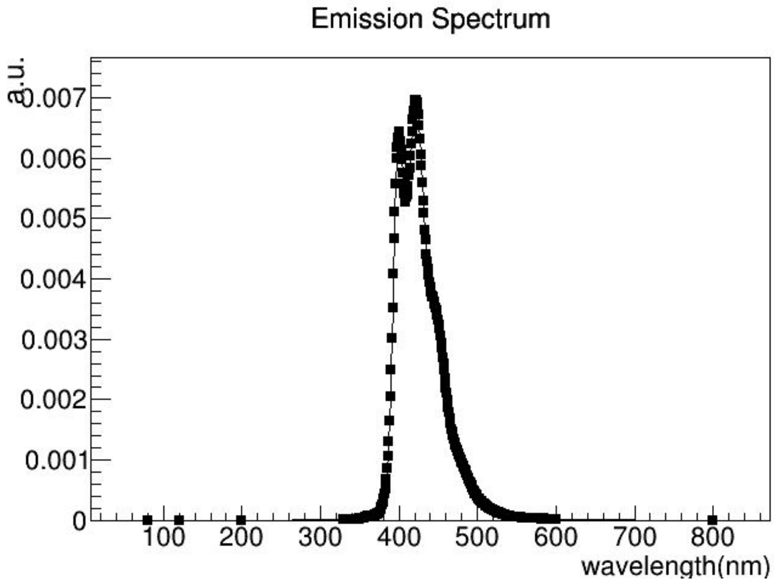
When: <2015



From: Daya Bay inherited

When: <2015

A PLOT OF THE LS PARAMETERS



From: Daya Bay inherited

When: <2015

Fluorescence times

PARTICLE	τ_1 [ns] / ratio	τ_2 [ns] / ratio	τ_3 [ns] / ratio	τ_4 [ns] / ratio
e^-, e^+, γ	4.6 / 70.7%	15.1 / 20.5%	76.1 / 6.0%	397 / 2.8%
p, n	4.5 / 61.4%	15.7 / 23.2%	76.2 / 9.0%	367 / 6.4%
α	4.345 / 49.82%	17.64 / 27.39%	89.045 / 14.67%	544.48 / 8.12%

From: e^- and p Munich
α unknown

When: e^- and p 2021
α recent

SNiPER SIMULATIONS

To evaluate the impact of the scattering, absorption, re-emission, Cherenkov and quenching:

1. “Ideal” liquid scintillator (no scattering, absorption, re-emission, quenching and Cherenkov)
2. Scattering, absorption and re-emission enabled;
3. All the optical phenomena enabled;

SNiPER SIMULATIONS: THE METHOD

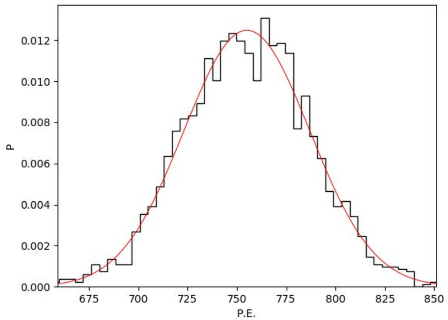
- Version of SNiPER used: J22.1.0-rc4 with the new parameters; (LY=9846/MeV, fC=0.51, k_B= 12.05e3*g/cm2/MeV, k_c=0) (see doc-DB 8400);
- All the primary particles were generated near the center of the detector (r=25cm).

PARTICLE	E_{kin}
e+	[0 - 9] MeV
e-	[0.5 - 9] MeV

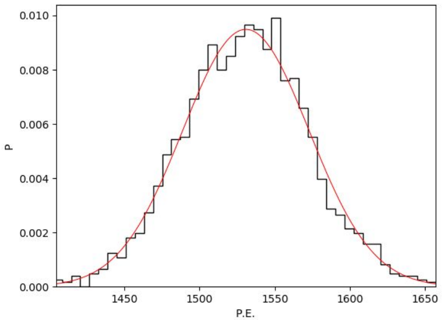
ENERGY RESOLUTION STUDIES: THE METHOD

For configuration, each energy and each particle, 2000 simulations were performed

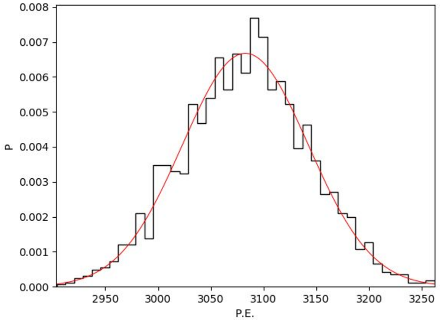
E(e-)=0.5MeV



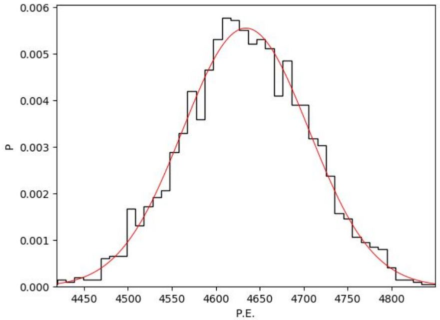
E(e-)=1MeV



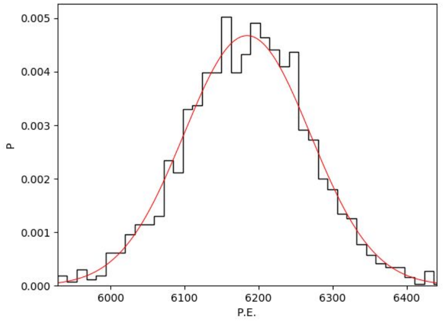
E(e-)=2MeV



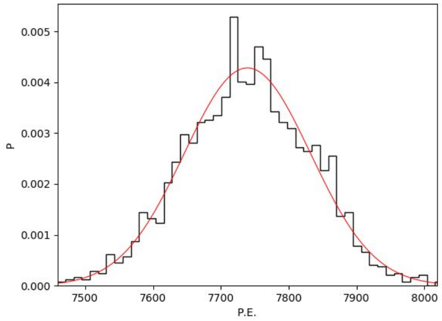
E(e-)=3MeV



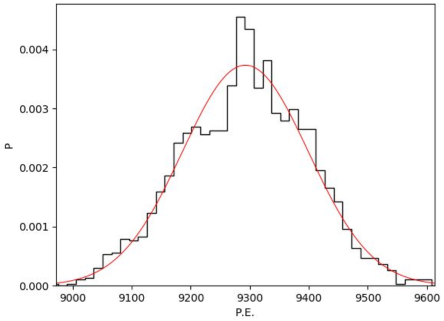
E(e-)=4MeV



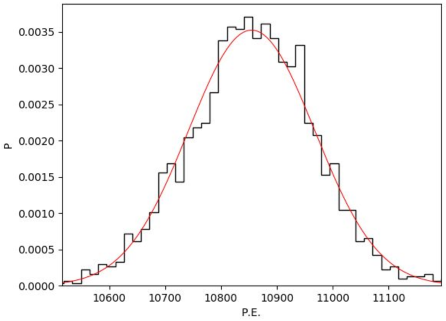
E(e-)=5MeV



E(e-)=6MeV

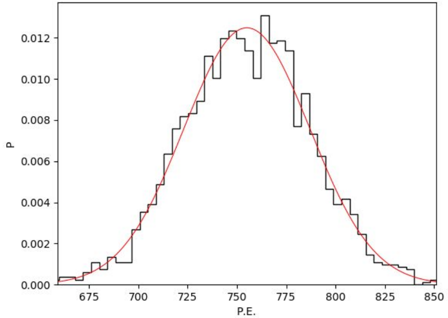


E(e-)=7MeV



ENERGY RESOLUTION STUDIES: THE METHOD

E(e-)=0MeV



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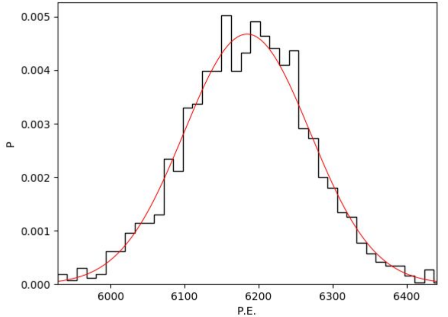

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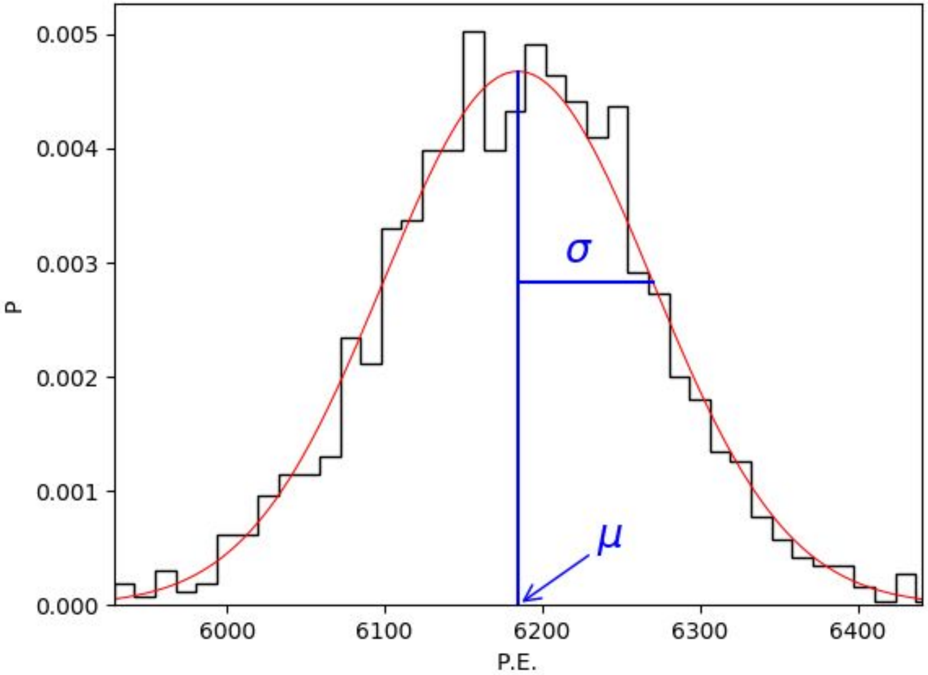

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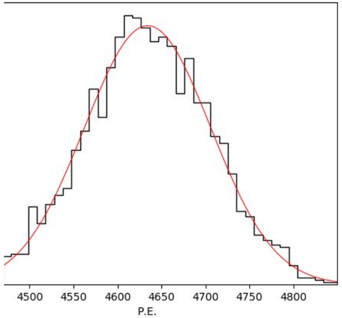

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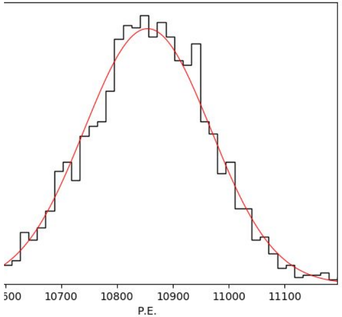
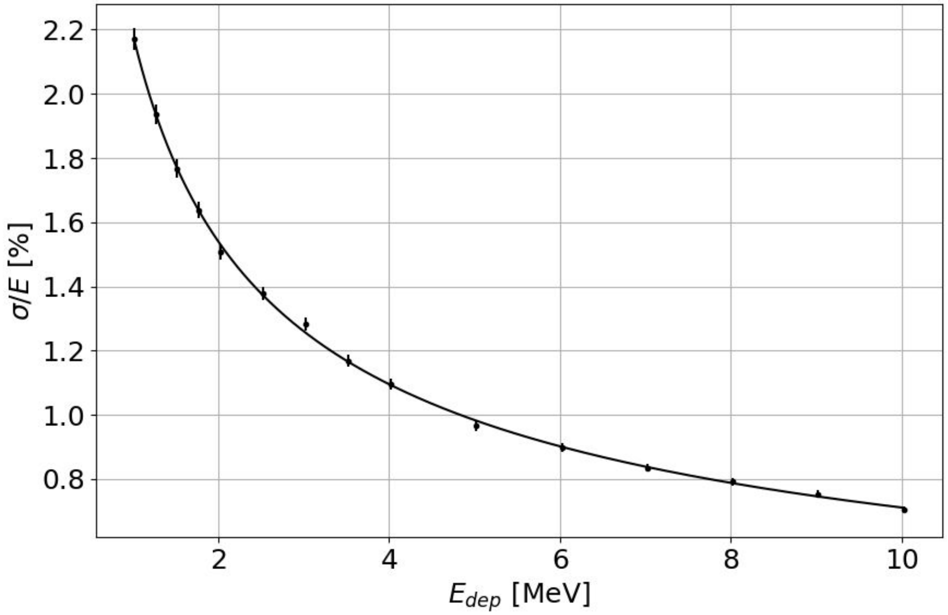


ENERGY RESOLUTION WITH AN IDEAL SCINTILLATOR

Positron results



Energy resolution @ 1.022MeV:
(2.17 ± 0.03) %

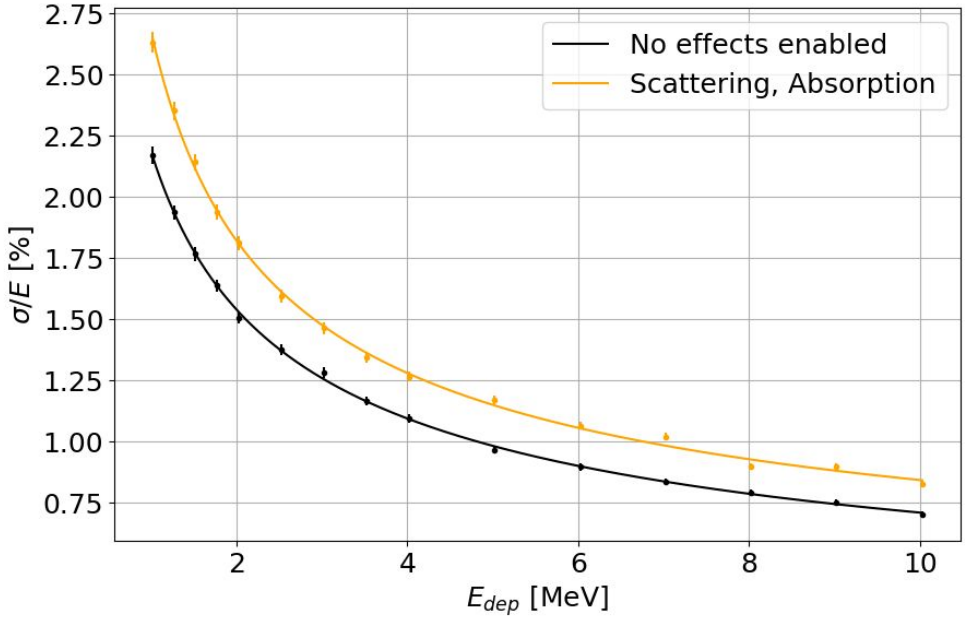
a = (2.14± 0.05) %
b = (0.22 ± 0.06) %
c = (0.43 ± 0.33) %

Elisa Percalli's talk

With **7 years** of **data-taking,** the **neutrino mass ordering sensitivity** is **5.0σ**

ENERGY RESOLUTION WITH PROPAGATION EFFECTS

Positron results



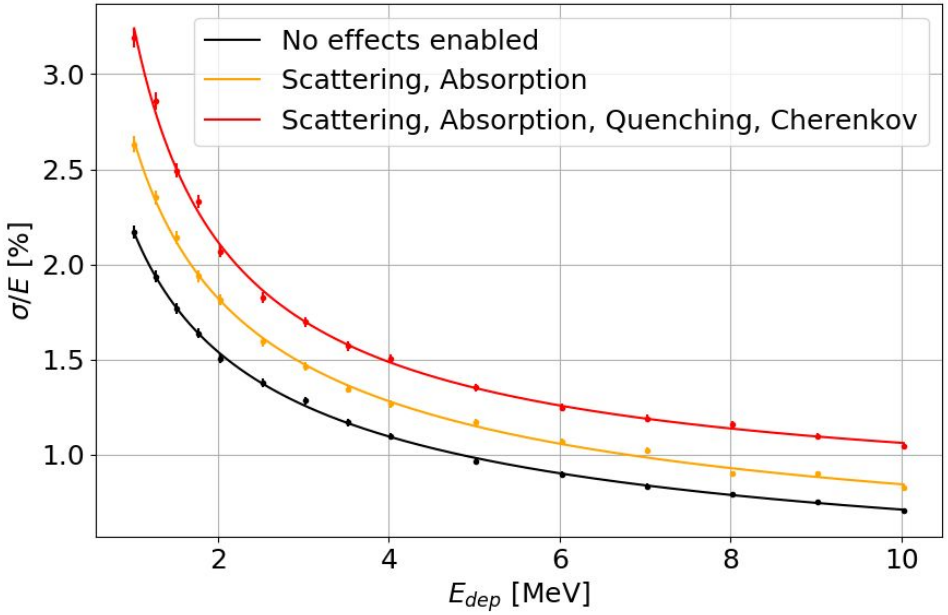
Energy resolution @ 1.022MeV:
(2.63 ± 0.04) %

a = (2.39± 0.06) %
b = (0.36 ± 0.05) %
c = (1.16 ± 0.17) %

With **7 years** of **data-taking,** the **neutrino mass ordering sensitivity** is **3.9σ**

ENERGY RESOLUTION FOR POSITRONS

Positron results

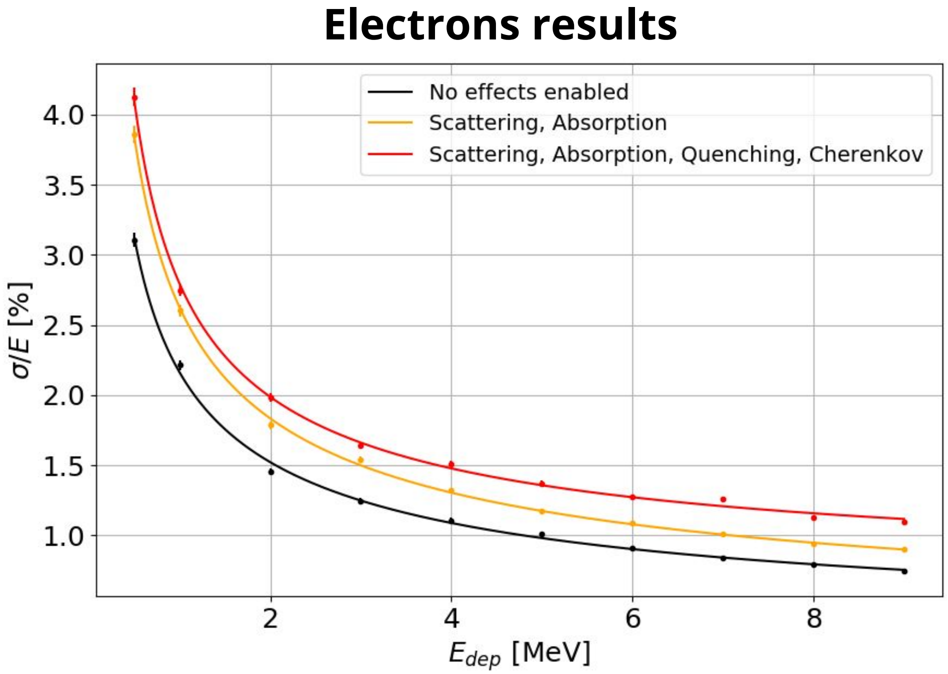


Energy resolution @ 1.022MeV:
(3.19 ± 0.05) %

a = (2.36± 0.09) %
b = (0.72 ± 0.04) %
c = (2.17 ± 0.13) %

With **7 years** of **data-taking,** the **neutrino mass ordering sensitivity** is **3.0σ**

ENERGY RESOLUTION FOR ELECTRON



Energy resolution @ 1MeV:
(2.21 ± 0.03) %
a = (2.09 ± 0.06) %
b = (0.29 ± 0.07) %
c = (0.49 ± 0.19) %

Energy resolution @ 1MeV:
(2.60 ± 0.04) %
a = (2.50± 0.05) %
b = (0.33 ± 0.06) %
c = (0.73 ± 0.13) %

Energy resolution @ 1MeV:
(2.74 ± 0.05) %
a = (2.53± 0.09) %
b = (0.72 ± 0.04) %
c = (2.92 ± 0.17) %

LS OPTICAL PROPERTY MEASUREMENTS

The currently implemented **LS optical properties** are **outdated** and were measured for different scintillators and they impact on JUNO energy resolution

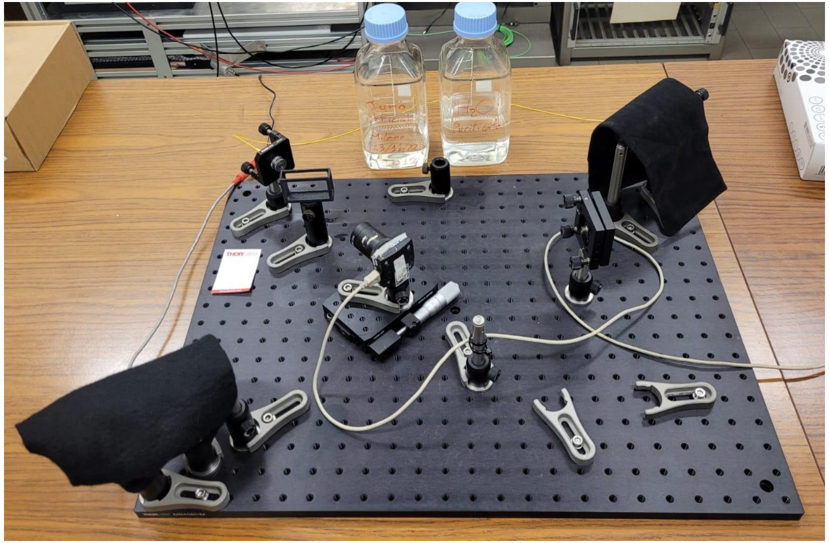
⇒ Many groups are **working** on **new measurements** of **JUNO LS** optical **properties**

In Milan we are working on the measurements of:

- **refractive index**;
- **emission spectrum** (with the collaboration of Perugia's group);
- **fluorescence times**;
- **absorption**;

THE GOAL OF THE SIMULATION STUDIES

In Milan we are measuring the JUNO LS refractive index in the range ~400nm - ~1000nm with a refractometer



→ Gioele Reina's talk

THE GOAL OF THE SIMULATION STUDIES

In Milan we are measuring the JUNO LS refractive index in the range ~400nm - ~1000nm with a refractometer

The refractive index since is a very important parameter as it is related with the Cherenkov radiation which:

- has a **huge impact** on the **energy resolution**;
- carries information on the event directionality.

THE GOAL OF THE SIMULATION STUDIES

In Milan we are measuring the JUNO LS refractive index in the range ~400nm - ~1000nm with a refractometer

We want to **understand** through simulations:

- How much the **refractive index impacts** on the **energy resolution**;

  When we will have our data we will be able to **provide** a **better energy resolution** estimate

- How much the **refractive index impacts** on the **event reconstruction** (energy and position).

  We can **understand** the **precision needed** for the measurement

SIMULATIONS VARYING THE REFRACTIVE INDEX

To study the **impact** of the **refractive index on** the **energy resolution** the refractive index was modified: its **default values were changed of various percentages**

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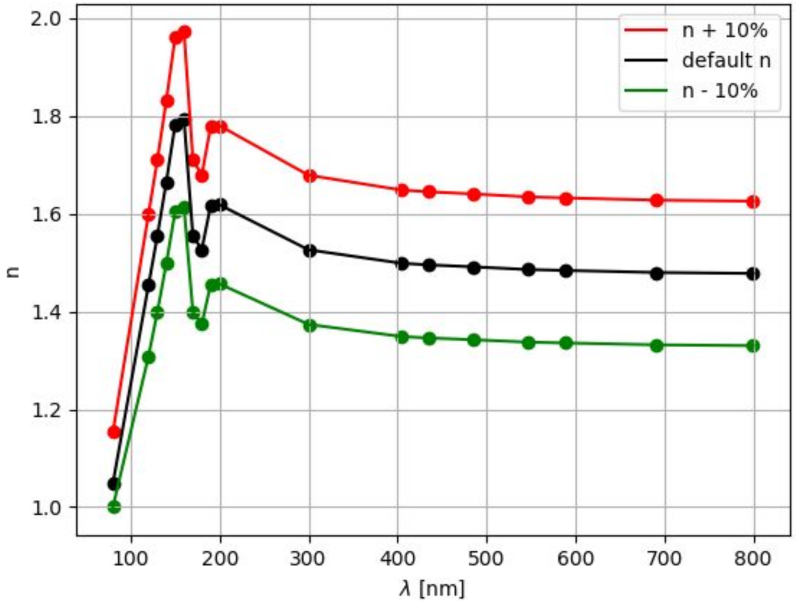

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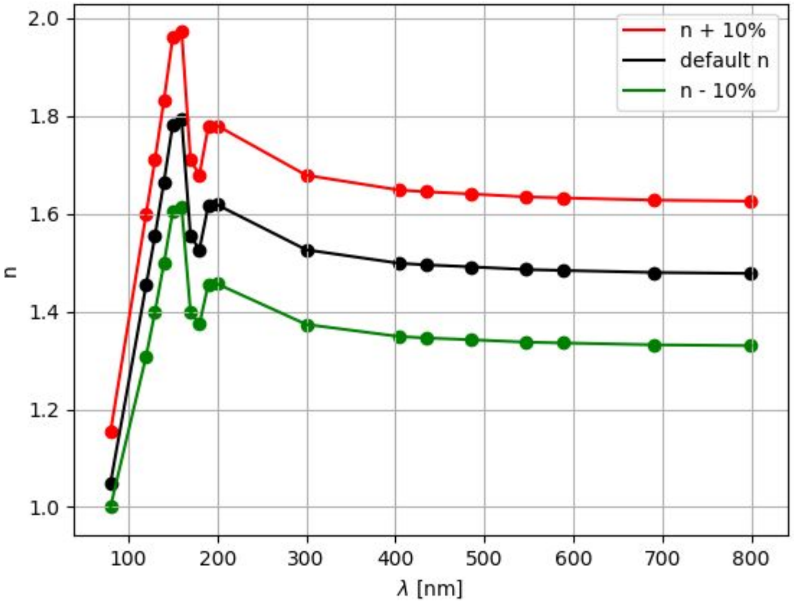


Such huge variations are **still possible**, especially at **low wavelength**

The variations were executed at high wavelength as well to be as conservative as possible

HOW TO CHANGE THE DEFAULT REFRACTIVE INDEX

python tut_detsim.py --no-gdml --evtmax 500 --seed 8684843 --output [detsim_rootfile] --user-output [detsim_user_rootfile] –cerenkov-yield 0.51 **--replace-param** Material.LS.ConstantProperty.ScintillationYield:9846/MeV,Material.LS.scale.LSLY_NewPMTModelScale:1.0,Material.LS.ConstantProperty.BirksConstant1:0.01205*g/cm2/MeV,Material.LS.ConstantProperty.BirksConstant2:0.0,**Material.LS.RINDEX**:RINDEX_MODIFIED_MINUS_5_PERCENT --anamgr-normal-hit gun --particles e- --momentums 1.0 --momentums-interp KineticEnergy --volume pTarget --material LS --volume-radius-max 250

HOW TO CHANGE THE DEFAULT REFRACTIVE INDEX

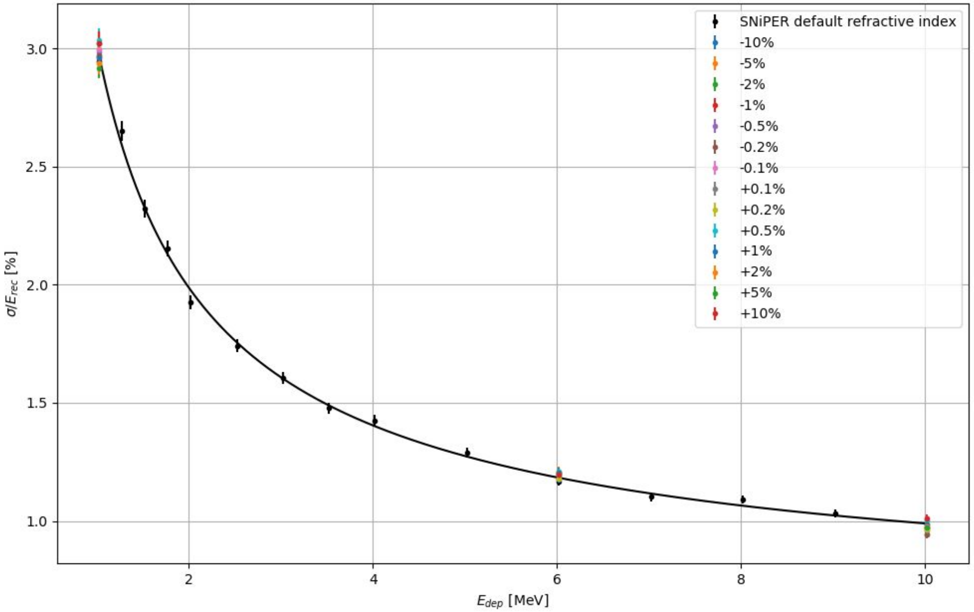
python tut_detsim.py --no … ed 8684843 --output
[detsim_rootfile] --user-ou … le] –cerenkov-yield 0.51
--replace-param
Material.LS.ConstantProp … 46/MeV,Material.LS.scale.LSL
Y_NewPMTModelScale:1.(… operty.BirksConstant1:0.012
05*g/cm2/MeV,Material.L … sConstant2:0.0,**Material.LS.**
RINDEX:RINDEX_MODIFIE … anamgr-normal-hit gun
--particles e- --momentum … rp KineticEnergy --volume
pTarget --material LS --vol

```
1.55 *eV 1.404195
1.79505 *eV 1.406
2.10499 *eV 1.40999
2.27077 *eV 1.411795
2.55111 *eV 1.416925
2.84498 *eV 1.420725
3.06361 *eV 1.42386
4.13281 *eV 1.45008
6.2 *eV 1.537575
6.526 *eV 1.53672
6.889 *eV 1.45065
7.294 *eV 1.476775
7.75 *eV 1.70335
8.267 *eV 1.69347
8.857 *eV 1.58099
9.538 *eV 1.476775
10.33 *eV 1.38092
15.5 *eV 1.0
```

RESULTS VARYING THE REFRACTIVE INDEX

THE IMPACT OF THE REFRACTIVE INDEX ON THE ENERGY RESOLUTION

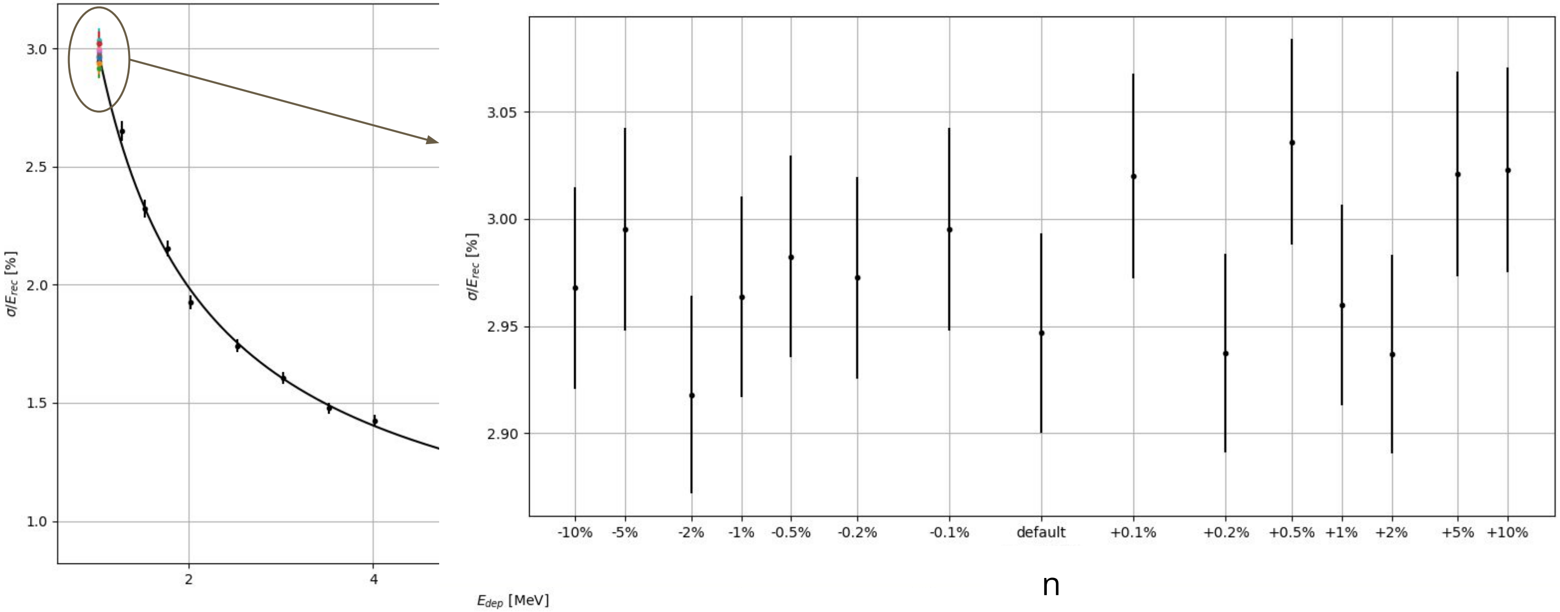
e+ results



THE IMPACT OF THE REFRACTIVE INDEX ON THE ENERGY RESOLUTION

Very small impact

e+ results



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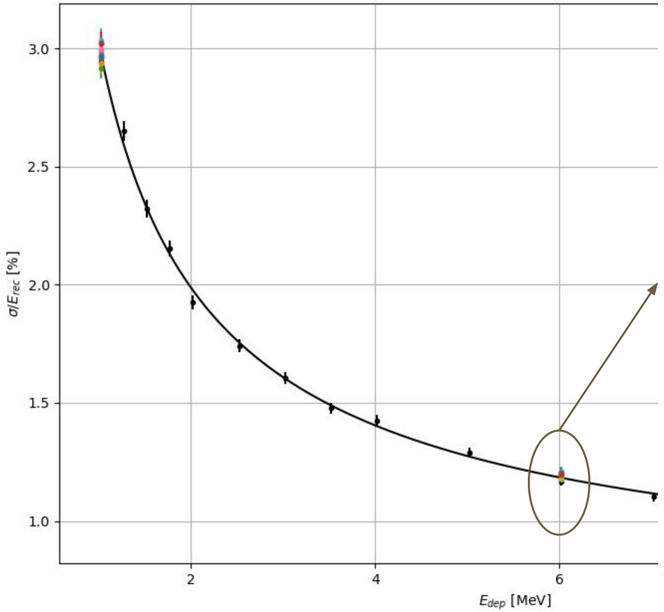
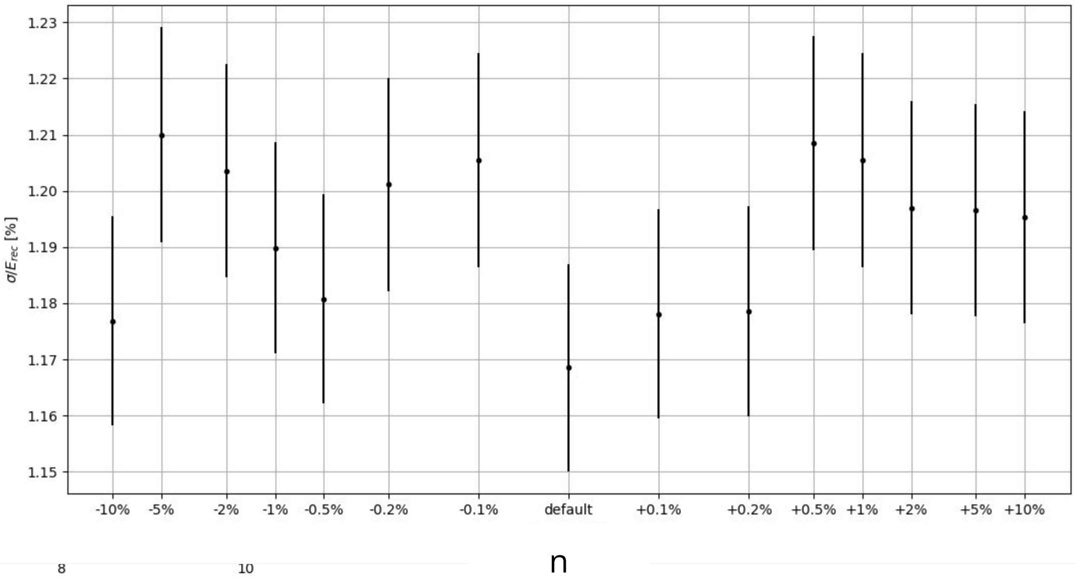
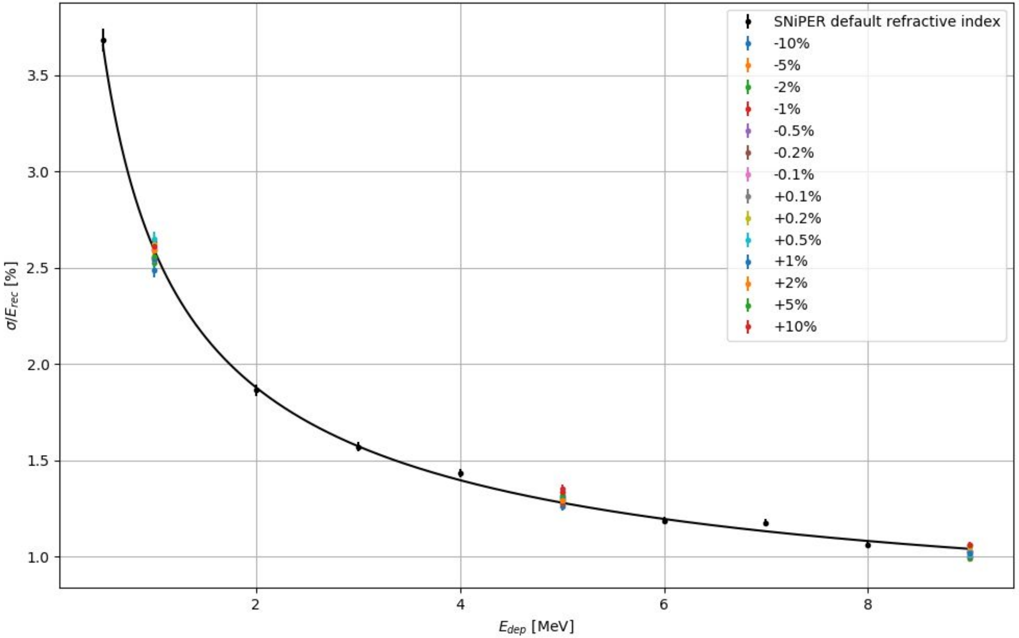




THE IMPACT OF THE REFRACTIVE INDEX ON THE ENERGY RESOLUTION

e- results



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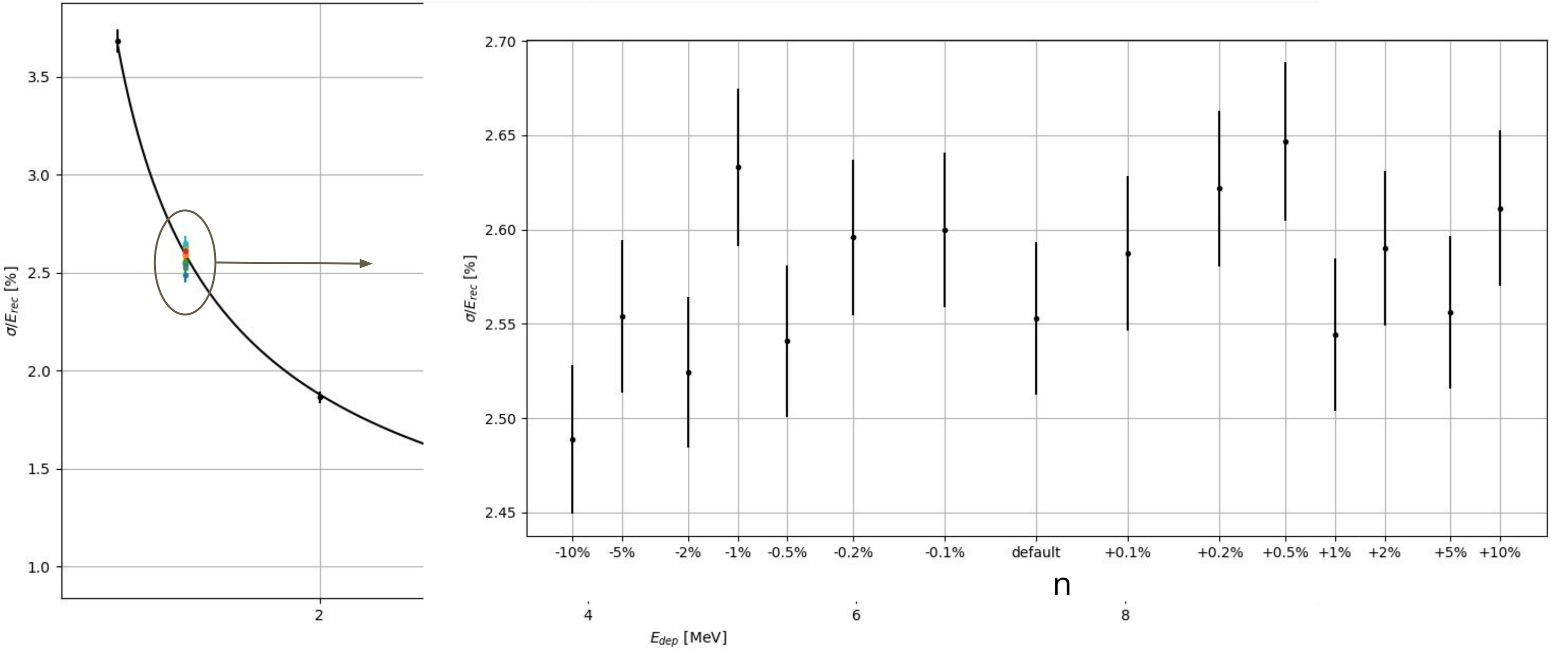

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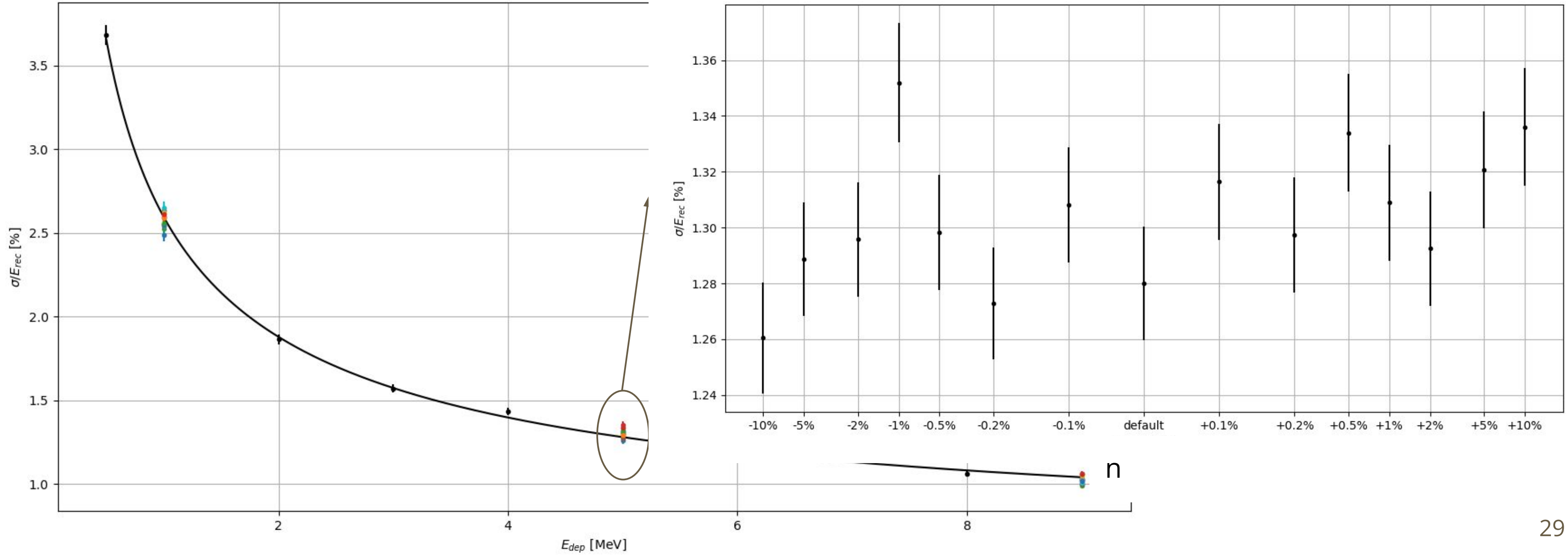

THE EMISSION SPECTRUM

SIMULATIONS VARYING THE EMISSION SPECTRUM

With the precious collaboration of Perugia's group we have recently measured the emission spectrum of JUNO LS as well:

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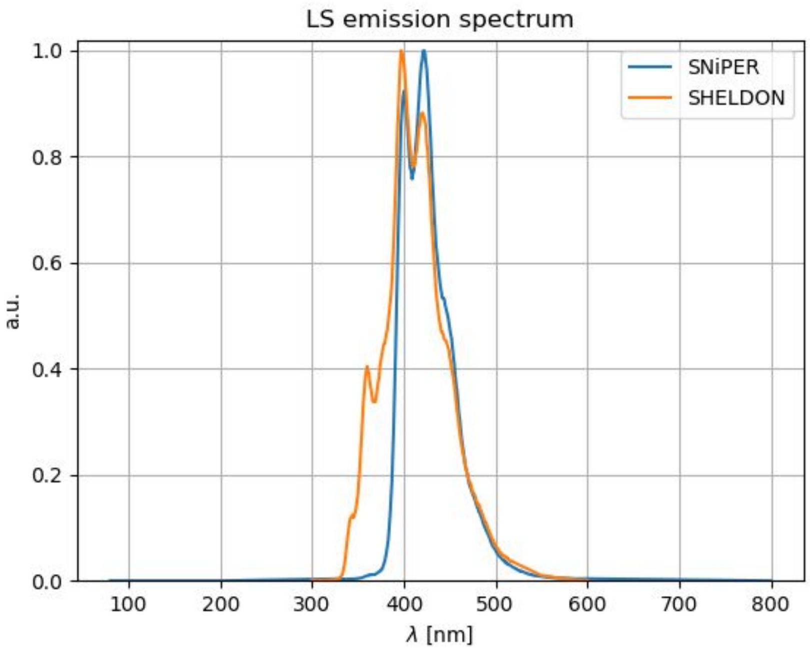

SIMILARITIES:

- Double peak, 1st at ~400nm, 2nd at ~425nm;
- Very similar descending profiles after the second peak.

DIFFERENCES:

- Main peak;
- Different ascending profile.

→ Federico Ferraro's talk

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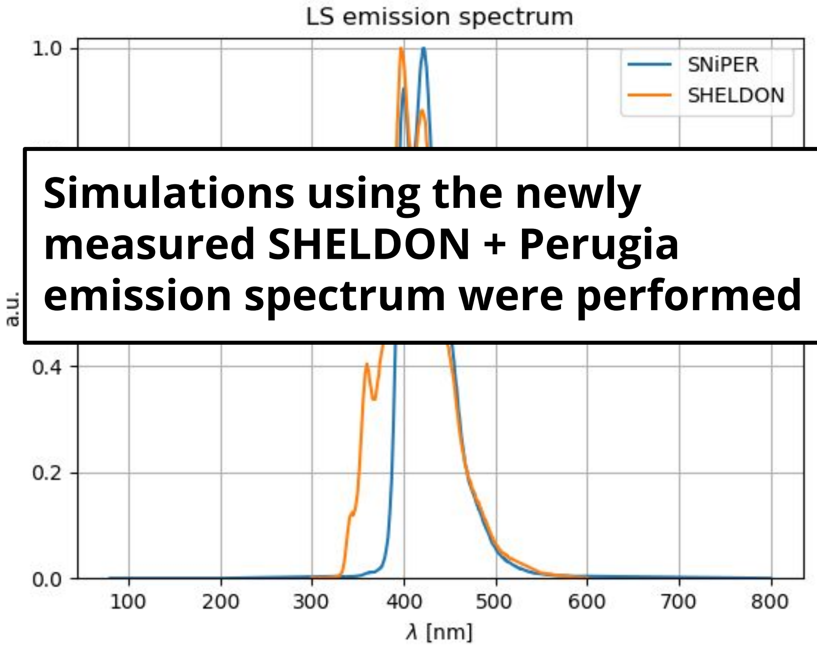


Simulations using the newly measured SHELDON + Perugia emission spectrum were performed

SIMILARITIES:

- Double peak, 1st at ~400nm, 2nd at ~425nm;
- Very similar descending profiles after the second peak.

DIFFERENCES:

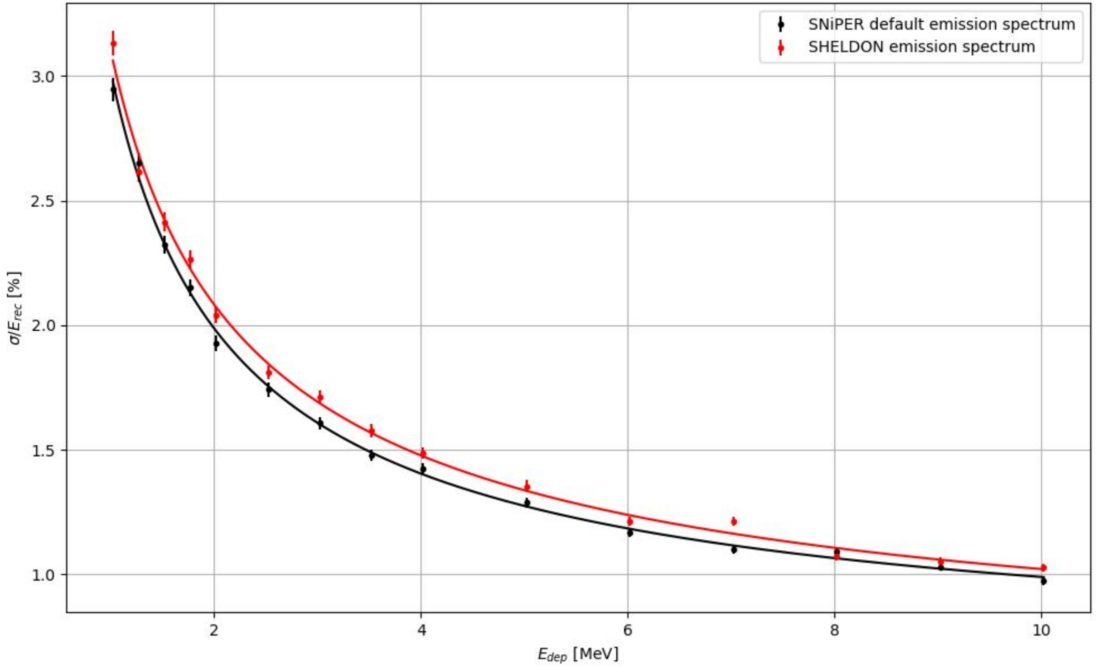
- Main peak;
- Different ascending profile.

HOW TO MODIFY THE EMISSION SPECTRUM

python tut_detsim.py --no-gdml --evtmax 500 --seed 8684843 --output [detsim_rootfile] --user-output [detsim_user_rootfile] –cerenkov-yield 0.51 **--replace-param** Material.LS.ConstantProperty.ScintillationYield:9846/MeV,Material.LS.scale.LSLY_NewPMTModelScale:1.0,Material.LS.ConstantProperty.BirksConstant1:0.01205*g/cm2/MeV,Material.LS.ConstantProperty.BirksConstant2:0.0,**Material.LS.FASTCOMPONENT**:EMISSION_SHELDON,**Material.LS.SLOWCOMPONENT**:EMISSION_SHELDON --anamgr-normal-hit gun --particles e- --momentums 1.0 --momentums-interp KineticEnergy --volume pTarget --material LS --volume-radius-max 250

THE IMPACT OF THE EMISSION SPECTRUM ON THE ENERGY RESOLUTION

Positron results



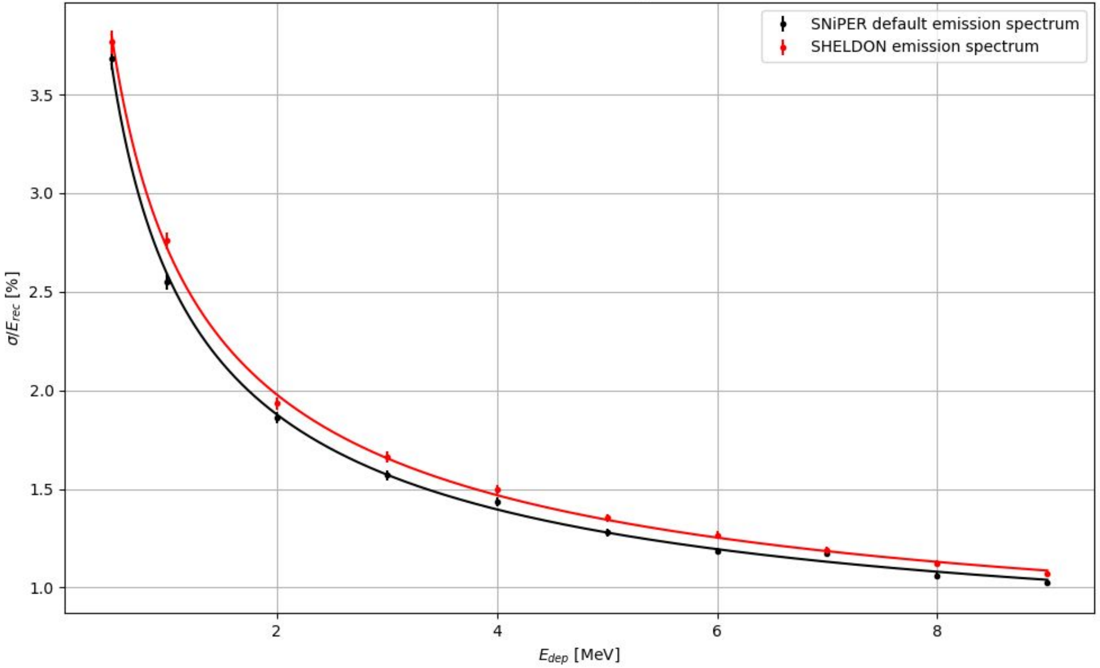
Energy resolution worsens with the newly measured spectrum

Energy resolution @ 1.022MeV: (2.95± 0.05) %
a = 2.34 ± 0.08
b = 0.63 ± 0.04
c = 1.80 ± 0.14

Energy resolution @ 1.022MeV: (3.13 ± 0.03) %
a = 2.59 ± 0.08
b = 0.59 ± 0.04
c = 1.61 ± 0.17

THE IMPACT OF THE EMISSION SPECTRUM ON THE ENERGY RESOLUTION

Electron results

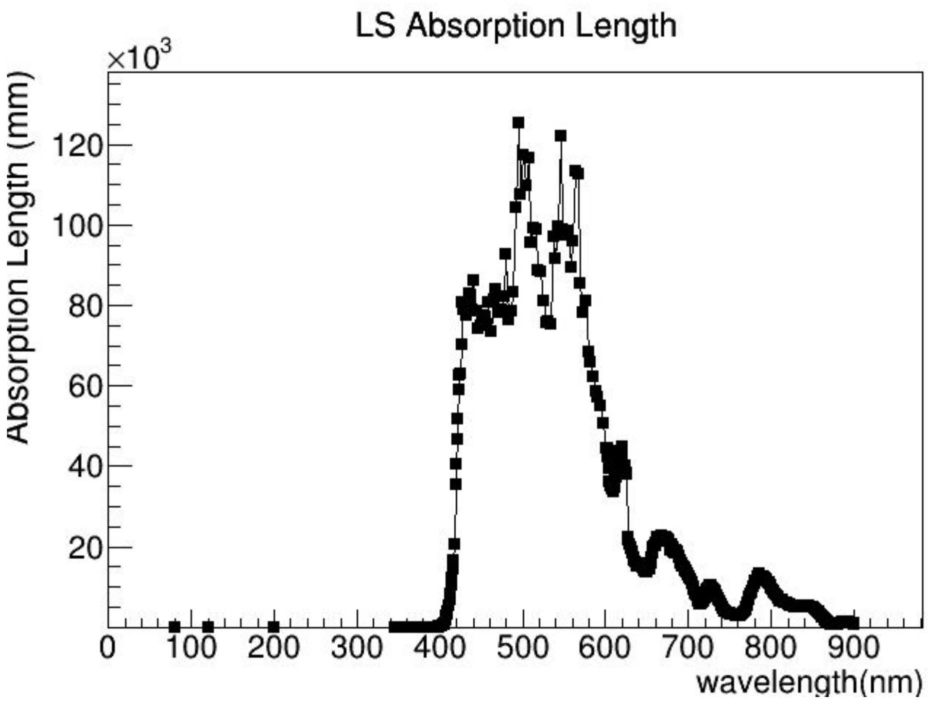


Energy resolution worsens with the newly measured spectrum

Energy resolution @ 1MeV: (2.55 ± 0.04) %
a = 2.49 ± 0.06
b = 0.62 ± 0.04
c = 0.36 ± 0.27

Energy resolution @ 1MeV: (2.76 ± 0.04) %
a = 2.65 ± 0.03
b = 0.63 ± 0.03
c = 0.0 ± 0.4

AN EXPLANATION FOR THE RESULTS



The absorption length at 360nm is < 1cm

We **observe**, on average, **fewer photoelectrons** at the end of the simulations with our emission spectrum

Energy resolution worsens

Could the effect be mitigated with an higher light-yield?

CONCLUSIONS

- Many **liquid scintillator optical properties** have a significant **impact** on the **energy resolution** and hence on neutrino mass ordering sensitivity: their precise measurements are required;

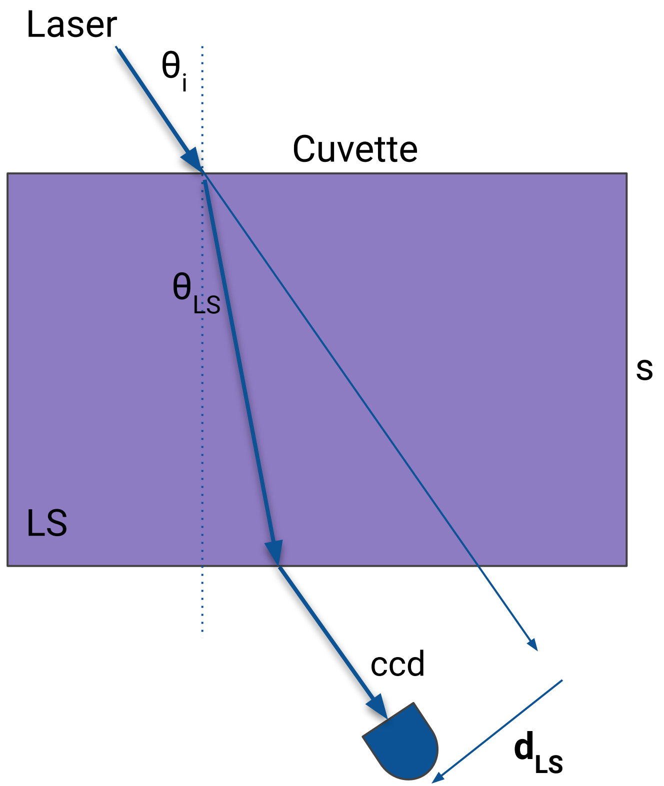
- We are currently measuring JUNO LS refractive index and emission spectrum;

- The refractive index has **a small impact on the energy resolution**;

- With the collaboration of Perugia's group we **measured** the LS **emission spectrum** as well. Due to a small peak around 360nm, the simulations with our spectrum show that the **energy resolution worsens significantly**.

BACKUP

THE MEASUREMENT OF THE REFRACTIVE INDEX



n: Arrival time measurement + Cherenkov contribution

For this measure we use a **refractometer**:

- Laser source with incident angle θ_i on empty cuvette (width s)
- Detect light with CCD camera
- Fill cuvette with LS
- Different refractive angle with/without LS
- Measure the displacement of the beam propagation d_{LS}

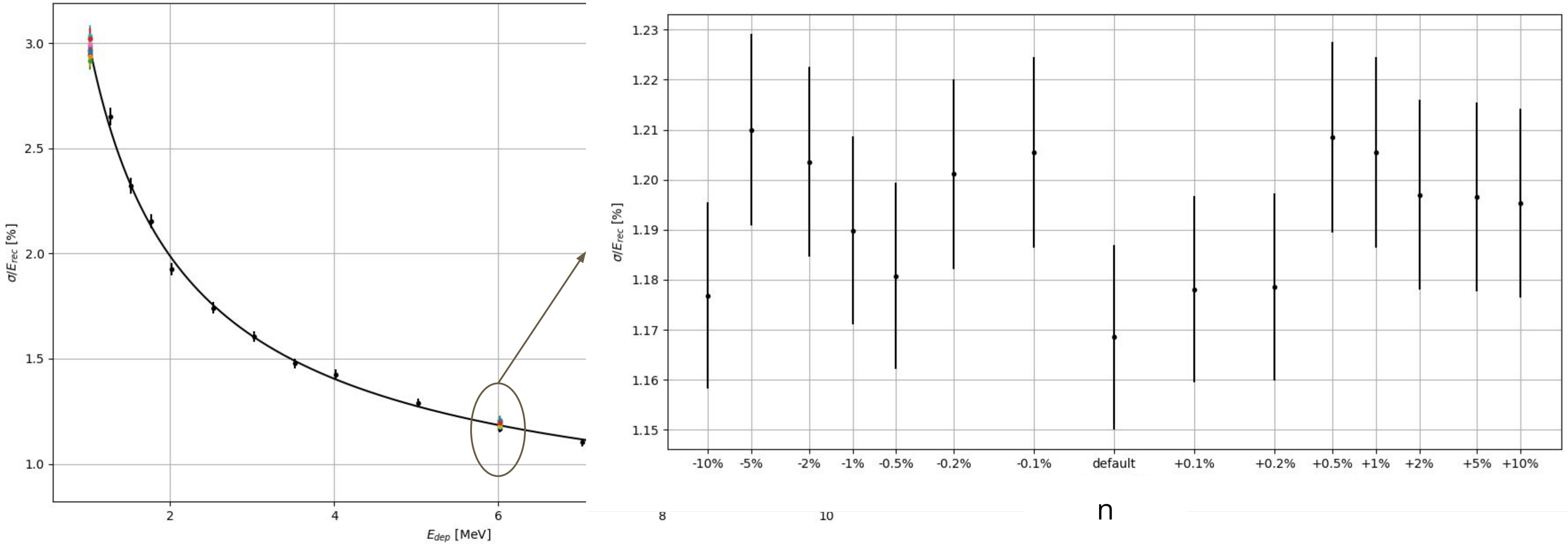
$$d_{LS} = \frac{s \sin\left[\theta_i - \arcsin\left(\frac{n_{air}}{n_{LS}} \sin\theta_i\right)\right]}{\cos\left[\arcsin\left(\frac{n_{air}}{n_{LS}} \sin\theta_i\right)\right]} \rightarrow \mathbf{n_{LS}}$$

Refer to: Gioele Reina (gioele.reina@mi.infn.it), Marco Beretta (marco.beretta@unimi.it), Davide Basilico (davide.basilico@mi.infn.it) for further details

THE IMPACT OF THE REFRACTIVE INDEX ON THE ENERGY RESOLUTION

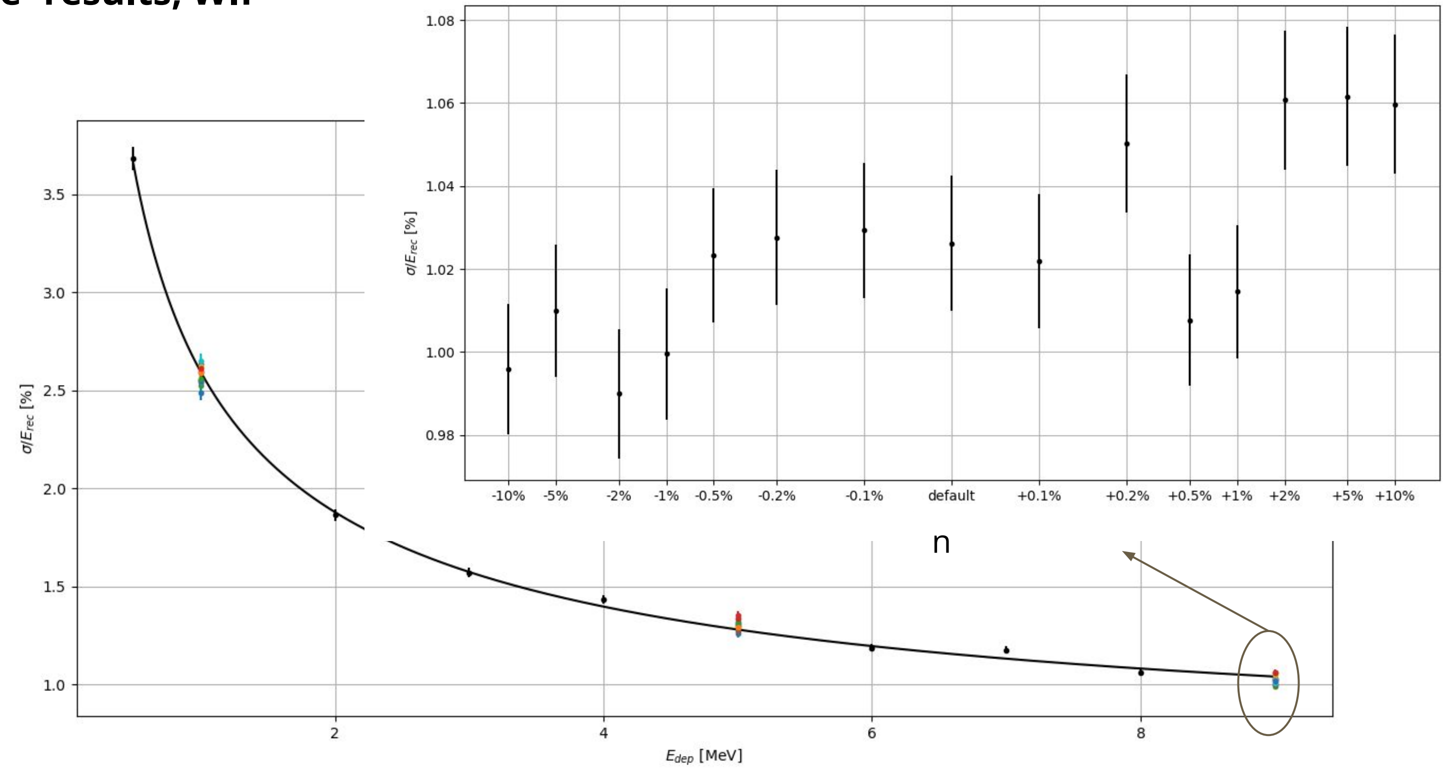
The Cherenkov, the Rayleigh scattering and the absorption were turned on again:

e+ results, WIP



THE IMPACT OF THE REFRACTIVE INDEX ON THE ENERGY RESOLUTION

e- results, WIP



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