Update of EPICS simulation: Direct pair production by heavy nuclei

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- Pre-history
- Implementation
- Summary, Problems, ToDo

TIM @ Firenze
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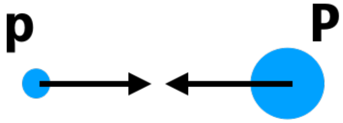
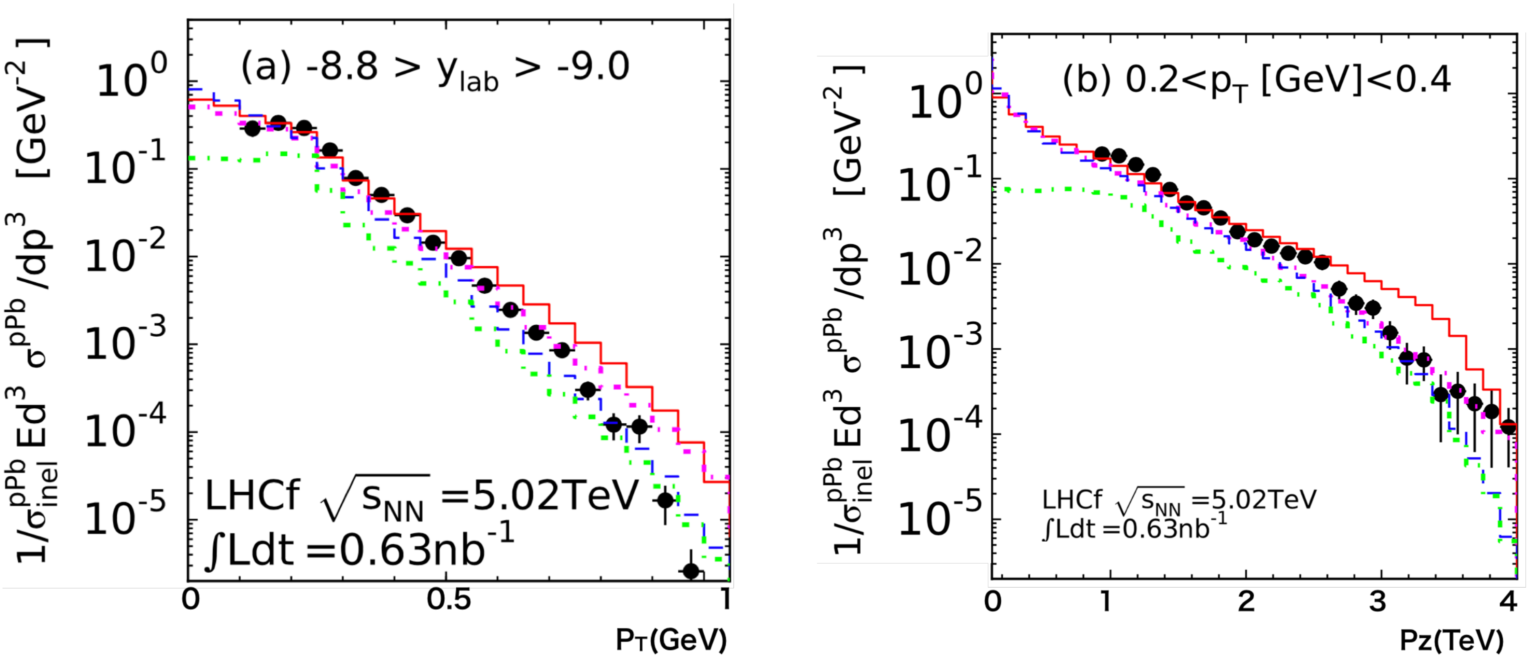
Pre-history:

- Experience before the implementaion:
  - LHCf experiment at CERN in 2013 and 2016.
  - p+Pb at $\sqrt{s_{NN}} = 5.02$ TeV (Equiv. $E_{lab} \sim 1.3 \times 10^{16}$ eV)



  - Observation: pi0 at proton remnant side
  - Experimental data: ∼ 2 times higher than predictions by hadronic interactions of popular models.
  - We should add UPC (Ultra Peripheral Collsion) !
  - STARlight, dpmjet3 (phojet), pythia were employed for UPC. Pb's $E \rightarrow$ photon by Wiz-Wil $\rightarrow$ photo-hadron production (γp interaction).
  - We simply added hadronic interaction results and UPC results to compare with the data.
  - That is: no implementation of UPC in Epics.

- Any UPC effect on AS (Air Shower) development ?
- Discussion with CERN theoretician (D): Target Nitrogen (or Oxigen) is not ionized so that UPC effect should be very small.
- After that, I became not to pay attention to UPC.
- However, Paolo pointed out direct pair production due to UPC seems to be important (Fluka seems to implemente it. I first doubted Target Brems).



Implementation

- Basic reference:
  ELECTROMGNETIC PROCESSES IN RELATIVISTIC HEAVY ION COLLISIONS, By Carlos A. BERTULANI and Gerhard BAUR. PHYSICS REPORTS (Review Section of Physics Letters) 163, Nos. 5 & 6 (1988) 299-408.
  - More than 100 pages. THICK ! Versatile and treats many UPC effects. Non-ionized (i.e, neutral, screened) target can be treated
  - BAUR seems an expert of this field and wrote many similar papers[1]
  - HOWEVER, the paper contains many careless mistakes, typos, misleading sentences etc.
  - One example is:

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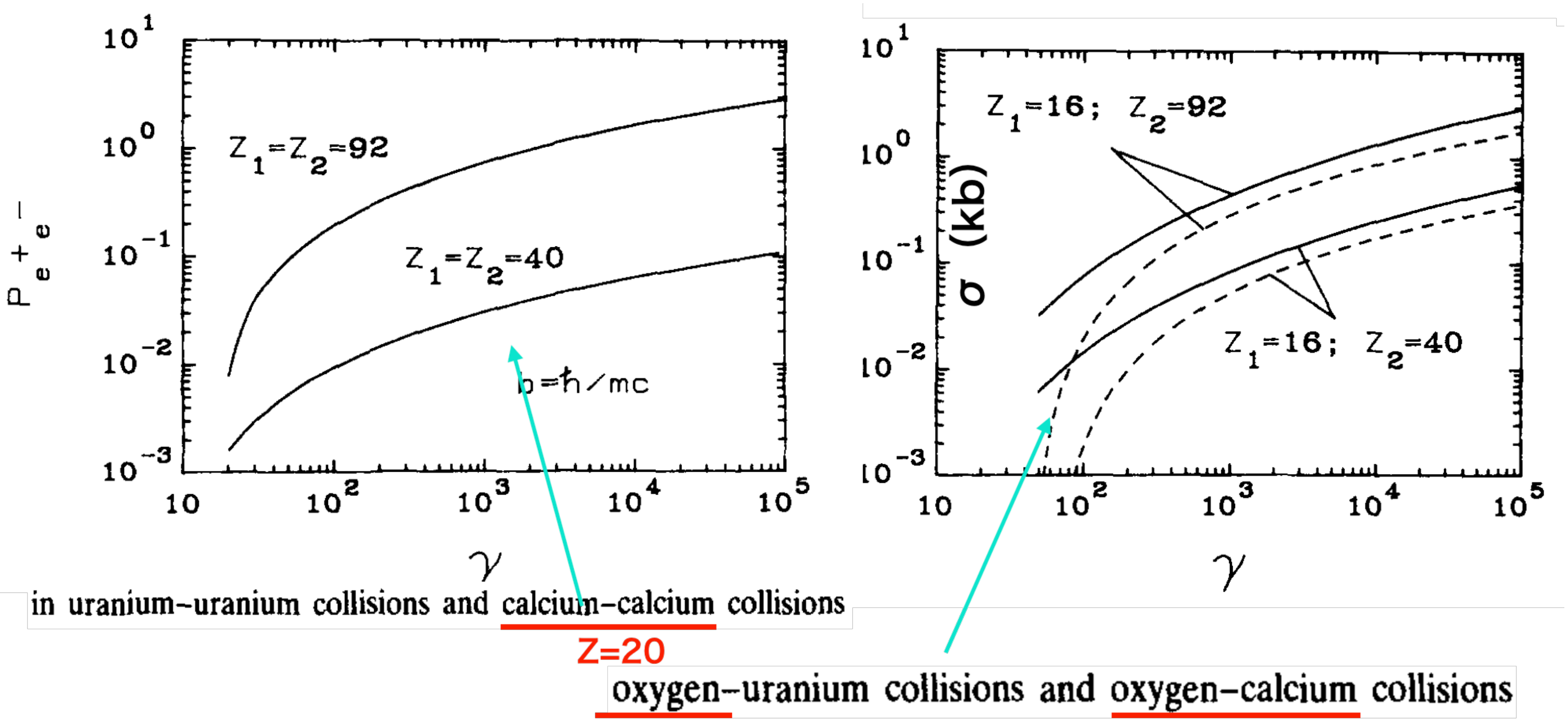
[1] He is the same author of a paper (Physics Reports 453 (2007) 1 – 27) which Paolo introduced to me



in uranium–uranium collisions and calcium–calcium collisions

Z=20

oxygen–uranium collisions and oxygen–calcium collisions

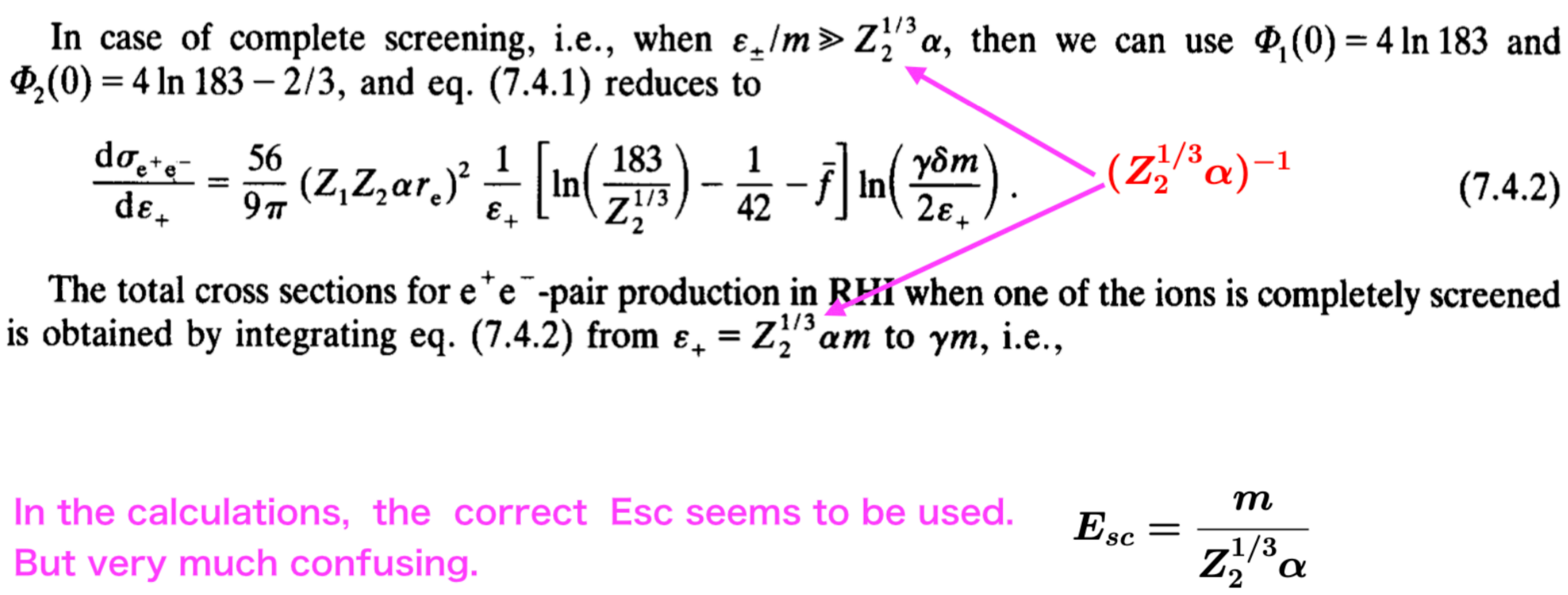
Z=8 Z=8 20

One may suspects 16 and 40 are mass numbers? Answer is No!

S and Zr

Figure 1: Confusion in Z and nucleus names. Probably they intended to use Oxigen and Calcium but wrong norminal Z's might be used. The ratio of the two curves should be the ratio of $Z_1^2 Z_2^2$ and it is 28 for the left figure and the right one 5.3 and is consistent with a such treatment.

– **Another example**



In case of complete screening, i.e., when $\varepsilon_\pm/m \gg Z_2^{1/3}\alpha$, then we can use $\Phi_1(0) = 4\ln 183$ and $\Phi_2(0) = 4\ln 183 - 2/3$, and eq. (7.4.1) reduces to

$$\frac{d\sigma_{e^+e^-}}{d\varepsilon_+} = \frac{56}{9\pi}(Z_1Z_2\alpha r_e)^2\,\frac{1}{\varepsilon_+}\left[\ln\left(\frac{183}{Z_2^{1/3}}\right) - \frac{1}{42} - \bar{f}\right]\ln\left(\frac{\gamma\delta m}{2\varepsilon_+}\right). \tag{7.4.2}$$

$(Z_2^{1/3}\alpha)^{-1}$

The total cross sections for e^+e^--pair production in RHI when one of the ions is completely screened is obtained by integrating eq. (7.4.2) from $\varepsilon_+ = Z_2^{1/3}\alpha m$ to γm, i.e.,

In the calculations, the correct Esc seems to be used.
But very much confusing.

$$E_{sc} = \frac{m}{Z_2^{1/3}\alpha}$$

Figure 2: This is probably another careless mistake the readers could be embarrassed and spend some time to get rid of it

- **More difficult problems**
  As to the screened cross-section, more complex situation waited. we describe them in Appendix
- **We show results after having fixed the problems.**

- **The basic equations:**
  Bare target case (non-screened) case: Eq. 7.3.9 of the paper.

$$f(E) = C_x \frac{1}{E}\left[\log\left(\frac{E}{m}\right) - \frac{1}{2} - \bar{f}(Z_1, Z_2)\right] \log\left(\frac{\gamma m \delta}{2E}\right) \tag{1}$$

Completely screened target case: Eq. 7.4.2 of the paper,

$$f(E) = C_x \frac{1}{E}\left[\log\left(\frac{183}{Z_2^{1/3}}\right) - \frac{1}{42} - \bar{f}(Z_1, Z_2)\right] \log\left(\frac{\gamma m \delta}{2E}\right) \tag{2}$$

where

- $f(E) = \frac{d\sigma}{dE}$ (mb/GeV): the differential cross-section for producing e^+ or e^- of energy E.
- E: electron or positron total energy (GeV. not kinetic). (ϵ_- or ϵ_+ in the paper).
- m: electron mass, α: fine structure constant (1/137)), r_e: classical electron radius.
- $C_x = \frac{56}{9\pi}(Z_1 Z_2 \alpha r_e)^2$
- $\bar{f}$: Coulomb Correction (C.C)) function (bit different from orginary one).
- Notations
  - Indefinite integral
    $F(E) = \int^E f(E) dE$

- ∗ **Total cross-section: Definite integral**

  $$\sigma = \int_a^b f(E)dE = F(b) - F(a)$$

  where $a = E_{min}$ and $b = E_{max}$
- ∗ **Z_1 the charge number of the projectile and Z_2 that of the target. A_1 and A_2 their mass number. (A_2 will not be needed at all.)**
- ∗ **γ: Lorenz factor of the projectile.**
- ∗ **$\delta = 0.681$ is a constant.**
- ∗ **E_{screen} (or E_{sc}): Screening energy.**

  $$E_{sc} = \frac{m}{Z_2^{1/3}\alpha}$$

  At energies $E \gg E_{sc}$, complete screening holds for the non-ionized target. (For $Z_2 = 74$, 16.7 MeV and for $Z_2 = 6$, 38.5 MeV).

The difference between Eq.1 and 2 is simple: only [...] part. It is constant in Eq.2.

- **γm is the maximum possible electron energy if we suppose it cannot run faster than the projectile (about this, we will be back later).**
- **Important feature**

  $f(E), Ef(E)$, and σ are proportional to $(Z_1 Z_2)^2$ (see C_x) if we plot them as a function of γ (or energy per nucleon, not totatal energy).

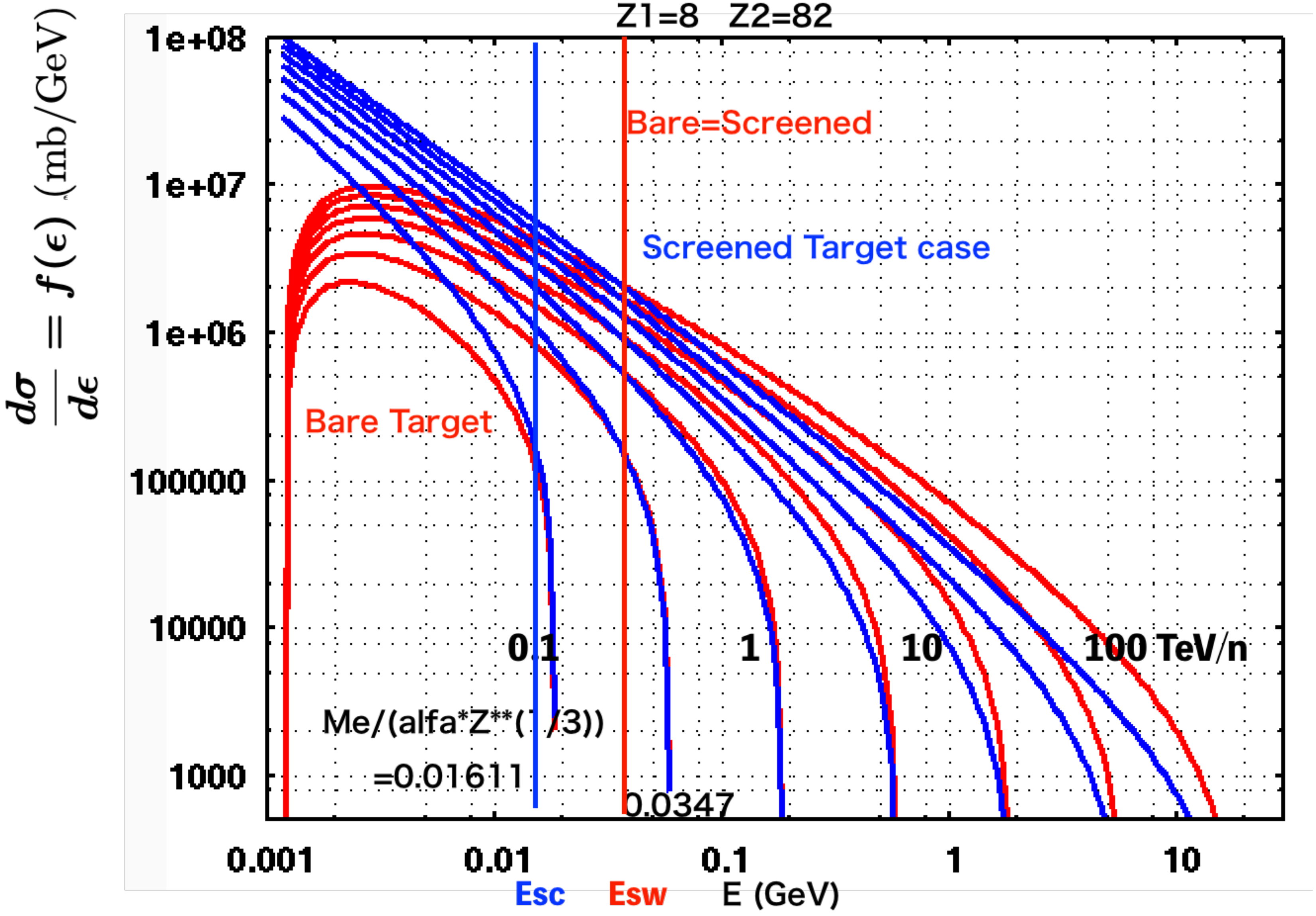


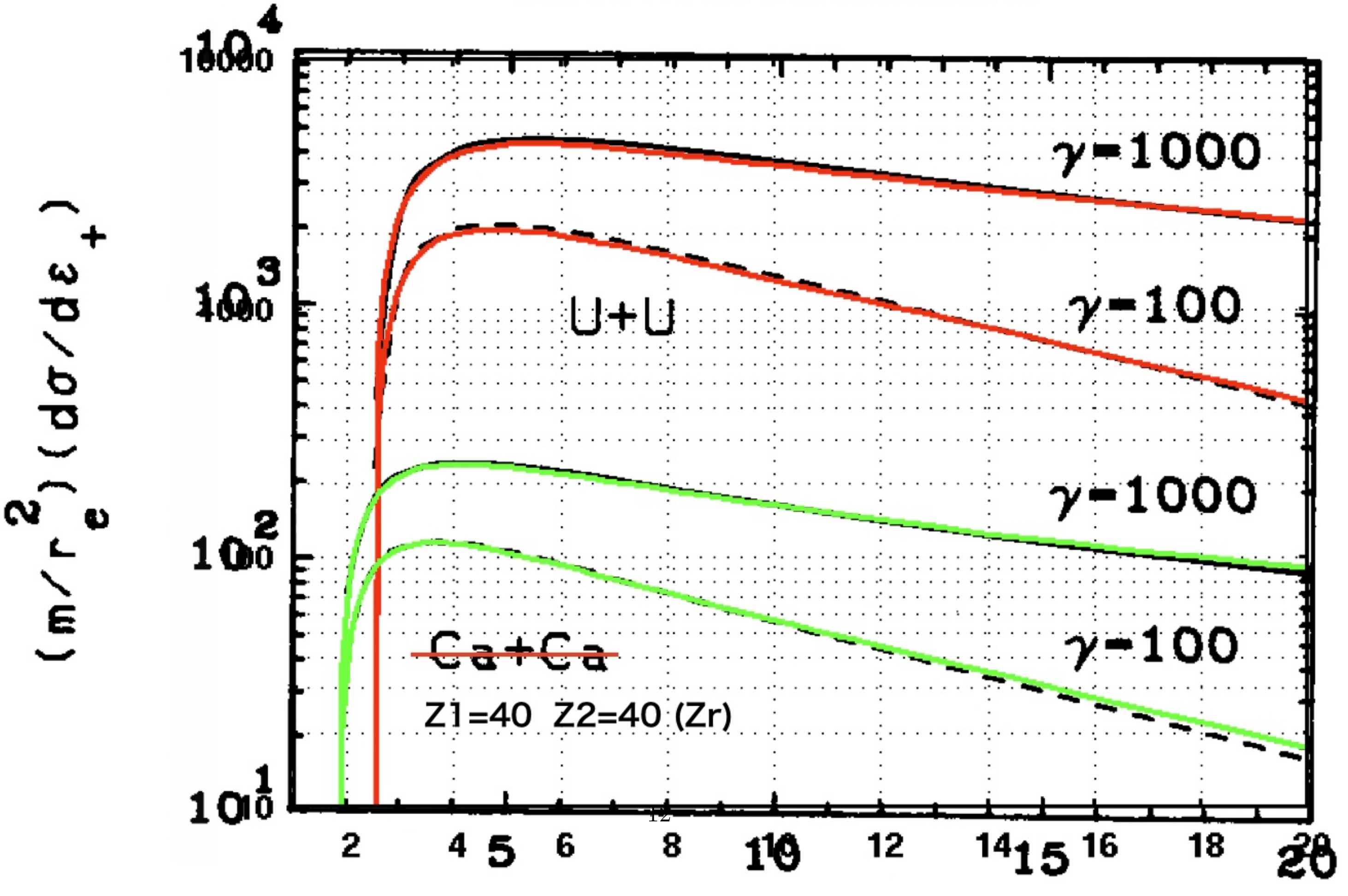
Figure 3: Differential cross sections for $Z_1 = 8, Z_2 = 82$. The cross-sections are switched at $E = E_{sw}$ where the screened and non-screened cross-section becomes equal. E_{sw} is $> E_{sc}$.

- E_{switch} (or E_{sw}): The energy where $f(E)$ of the screened target and that of the non-screened (bare) target becomes equal:
  $E_{sw} = m \exp(\log(183/Z_2^{1/3} + 20/42))$
  $E_{sw} = 22.5, 51.7$ MeV for $Z_2 = 74, 6$, respectively. Normally $E_{sw} > E_{sc}$ and independent of the projectile energy.

  Our standard treatment is to use the complete screening cross-scetion if $E > E_{sw}$, otherwise non-screened (bare) target cross-section.

First we check whether every cross-section figure on the paper can be reproduced or not.

Fig 7.4 is well reproduced



$m/r_e^2 = 6.435\times10^{-6}$ (GeV/mb)

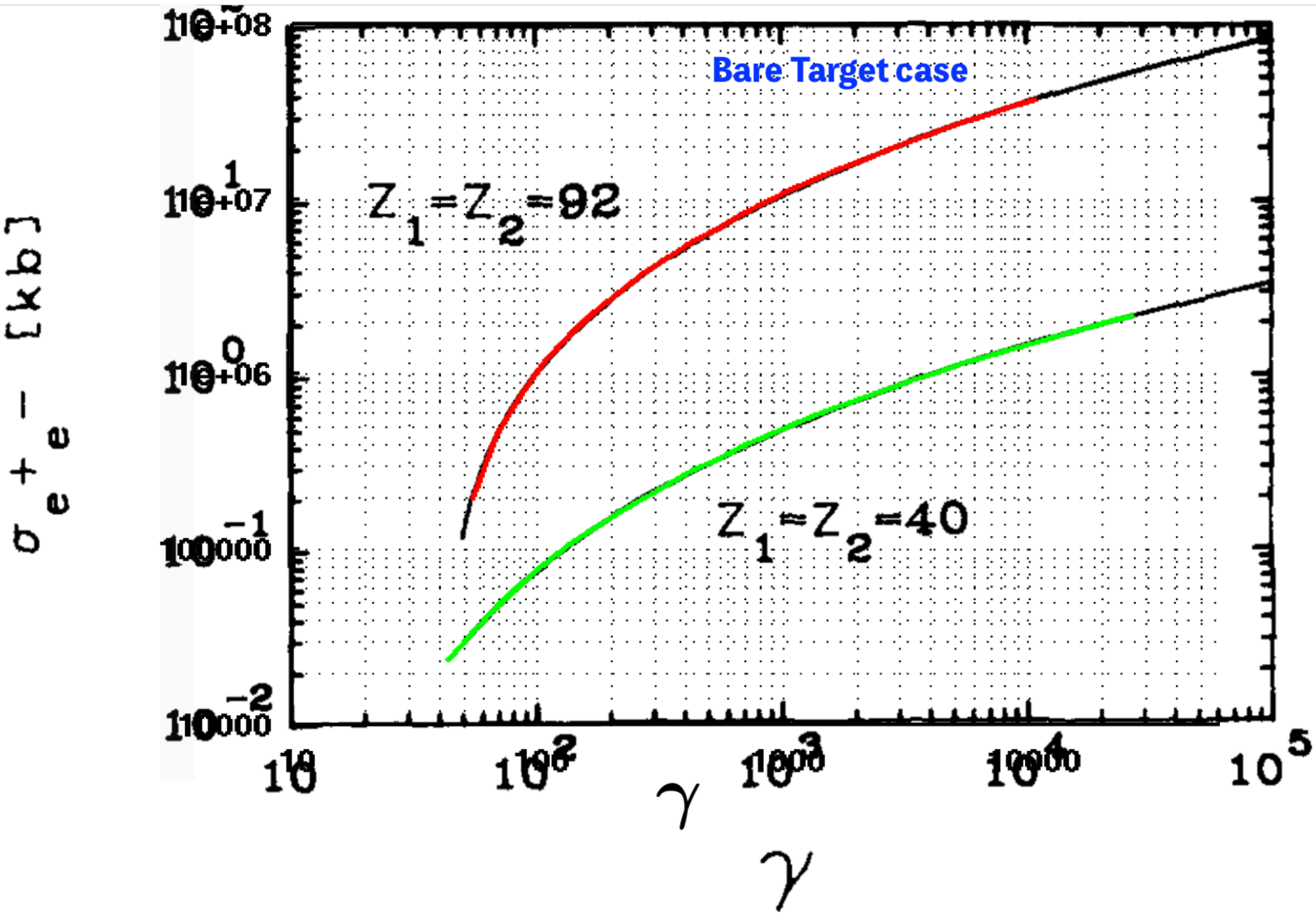


Figure 5: Fig7.6 of the paper: $\boldsymbol{\sigma}$ of U+U and Zr+Zr. Bare (non-screened) target. Former is 28 times higher as prevous one. At low $\boldsymbol{\gamma}$'s the ratio becomes smaler, since $\boldsymbol{\gamma} \rightarrow \mathbf{1}$ $\boldsymbol{f}$ becoms 0.

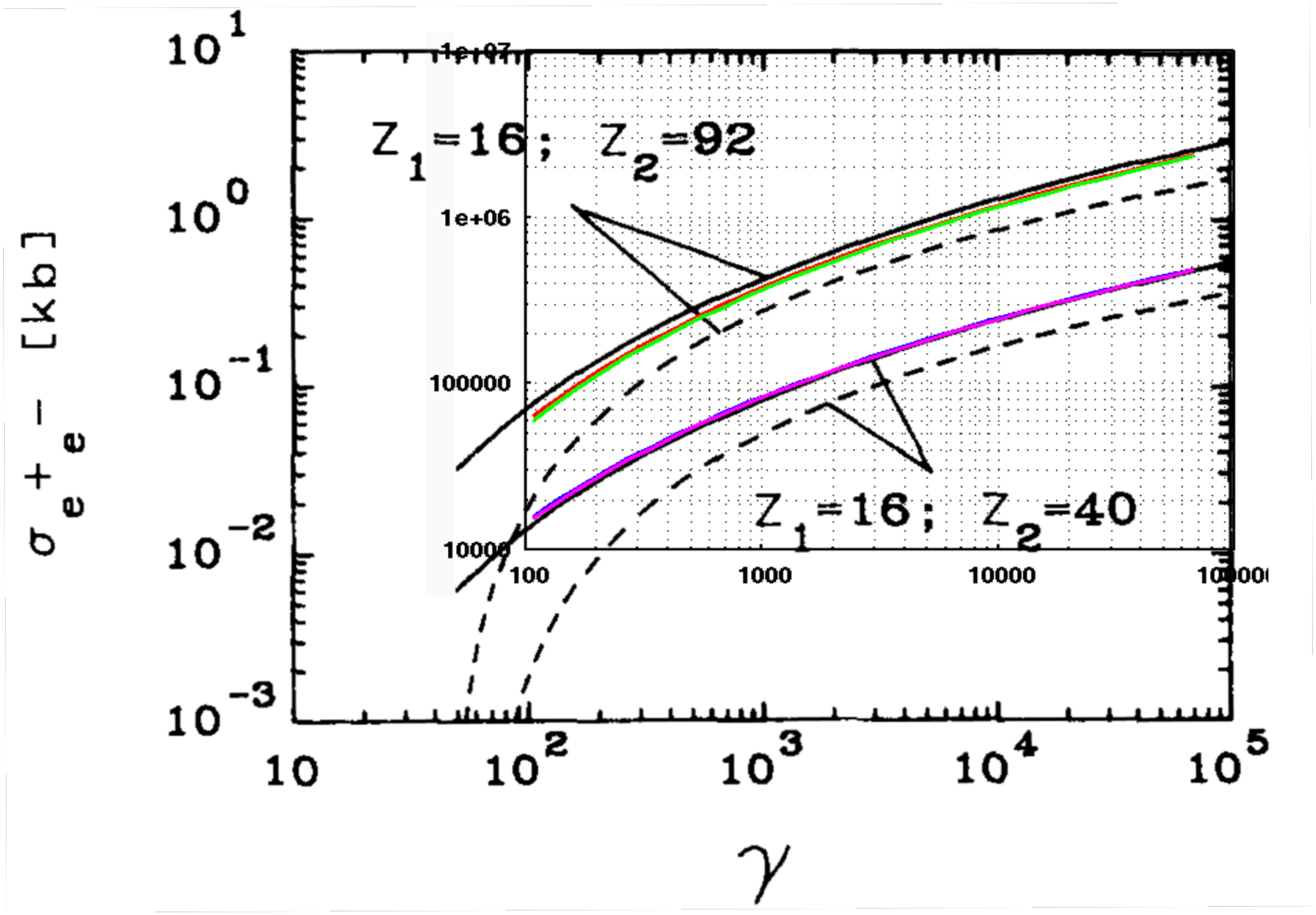


Figure 6: Fig7.7 of the paper: $\boldsymbol{\sigma}$ of S+U and S+Zr. Bare (non-screened) target. Former is $\mathbf{(92/40)^2} \sim \mathbf{5.3}$ times higher. There seems to be a little bit discrepancy for S+U case. Some difference seen in two color lines for this case comes from $\boldsymbol{f}$ and $\bar{\boldsymbol{f}}$.

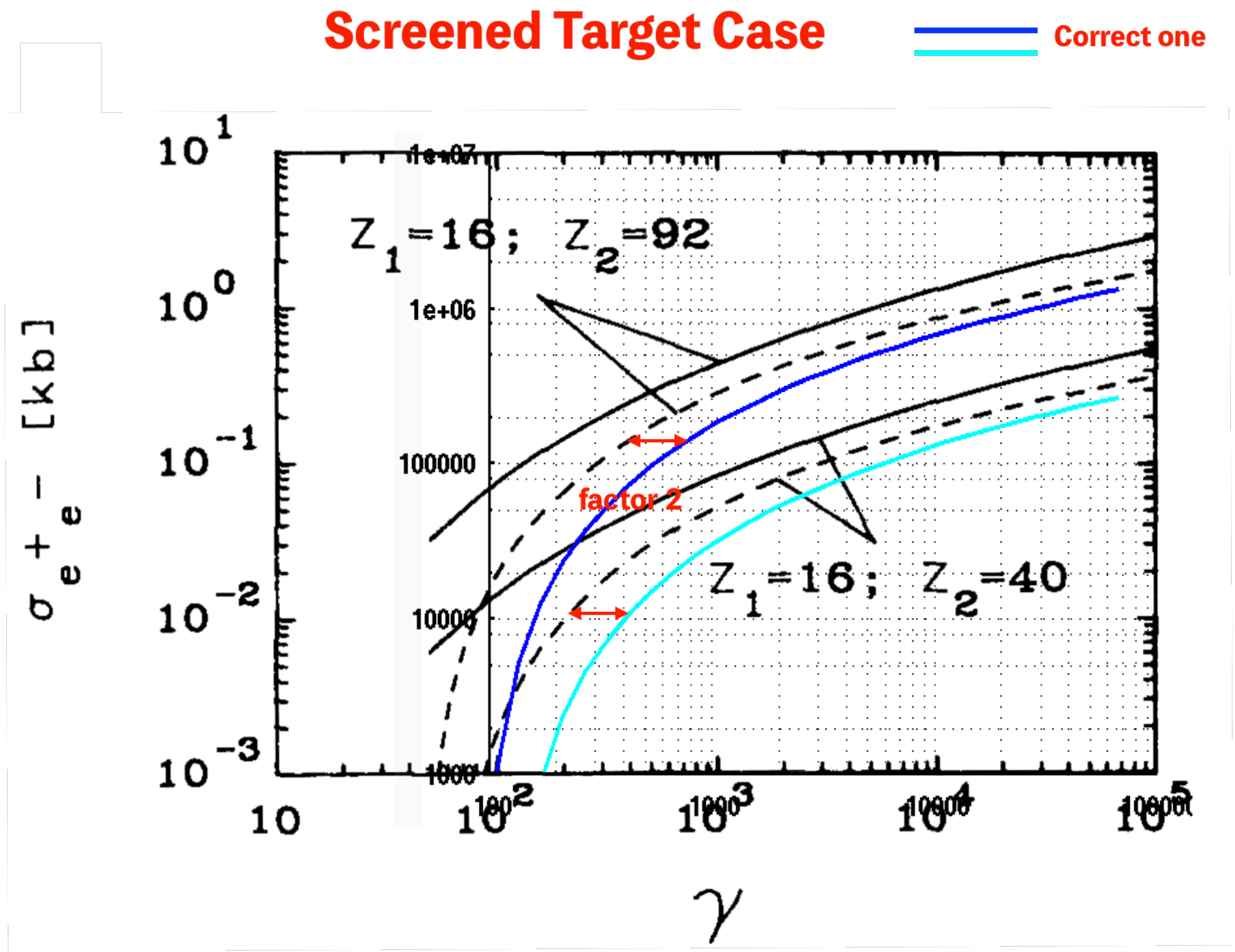


Figure 7: Fig7.7 of the paper: $\boldsymbol{\sigma}$ of $\boldsymbol{Z_1 = 16, Z_2 = 92}$ and $\boldsymbol{Z_1 = 16, Z_2 = 40}$. The dashed lines can be reproduced by using the formula in the papger, but it has mistake (γ must be rpelaced by $\boldsymbol{\gamma/2}$) so the correct one must be shifted by factor 2 to the right as colored lines.

- **Where DP becomes improtant ?**
  The amount of the electron energy emitted by DP is an important key and it is expressed as $\Delta E = \int_a^b E f(E) dE$ The unit is GeV mb. This can be convrted to GeV/(g/cm^2) if the target media information (such as density) is available. In the GeV/(g/cm^2) unit, Z_2^2 dpendence of ΔE becomes Z_2 dependence. Therefore, if we noramalize $DeltaE$ by $Z_1^2 Z_2$, we will get a neary universal curve as a function of per-nucleon energy of the projectile. Then, the standard $2Z_1^2$MeV/(g/cm^2) value may be treated as 2 MeV/Z_2)/(g/cm^2), and the threshold energy to consider DP interaction may be set to the energy correspoinding to $\sim 1\%$ of that value.

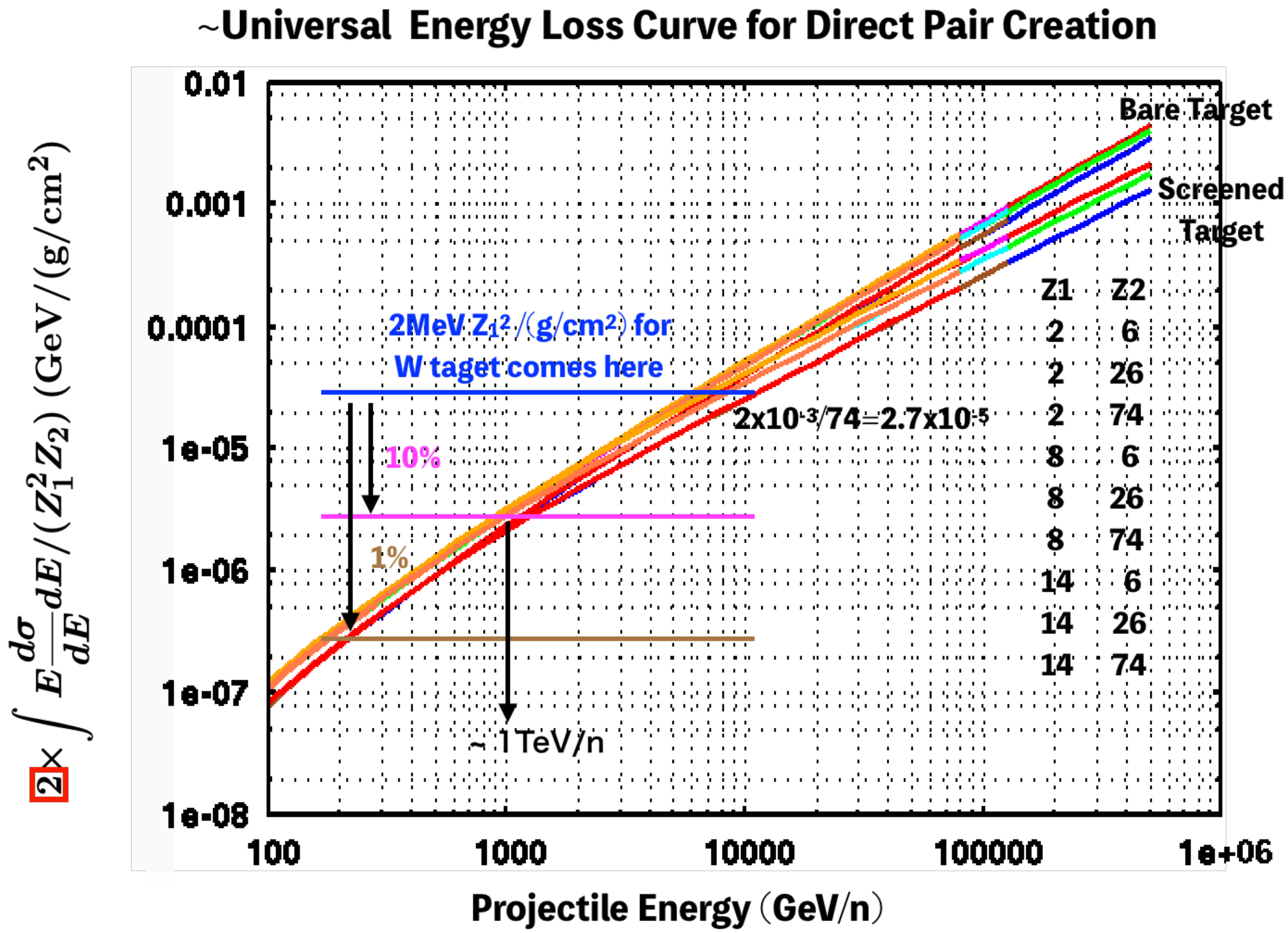


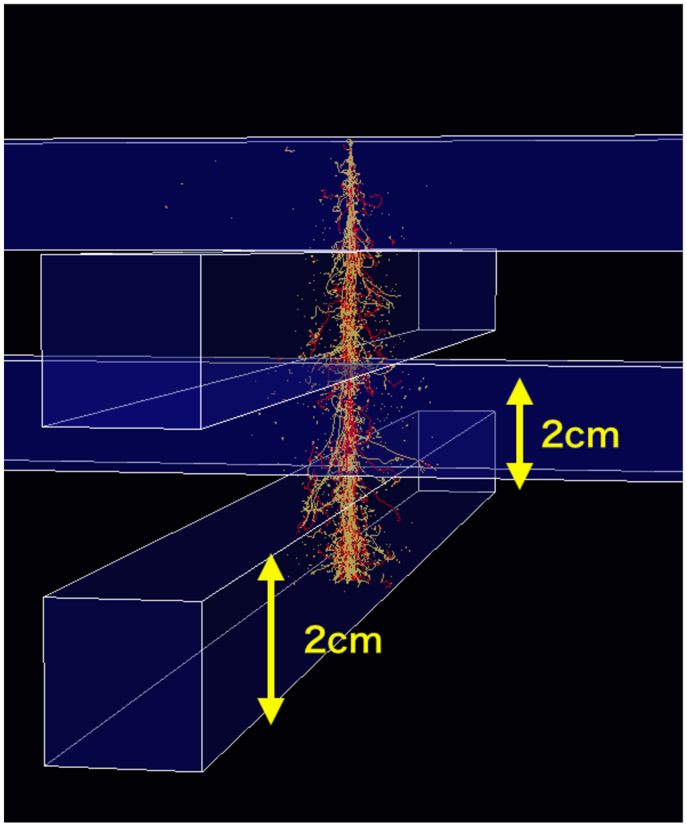
Figure 8: $\Delta E/(Z_1^2 Z_2)$ as a function of projectile energy in per nucleon

On the fly test

That is, information is extracted during execution of EPICS (using epUI).

Next one is to have a quick look of the DP effect by showing the particle tracking images.

Quick Look of the DP Effect by Trace View

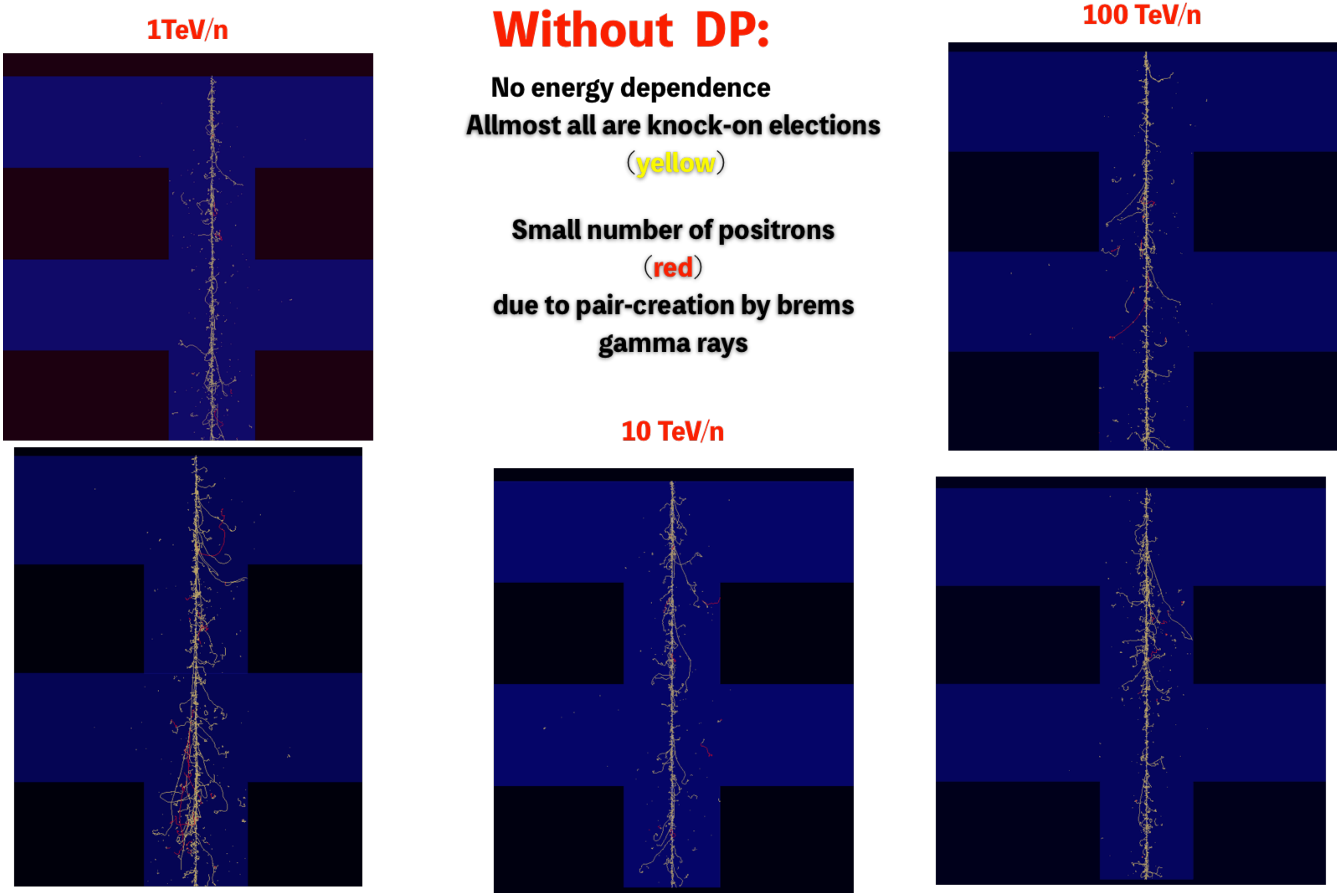


Inject Oxgen vertically into a simple PWO config.

4 layers of 32 cm x 1.9 cm x 2 cm log

Show trace data of events which made no hadronic collision

Figure 9: Oxgen is injected at the center of 4 lyaers of PWO log.

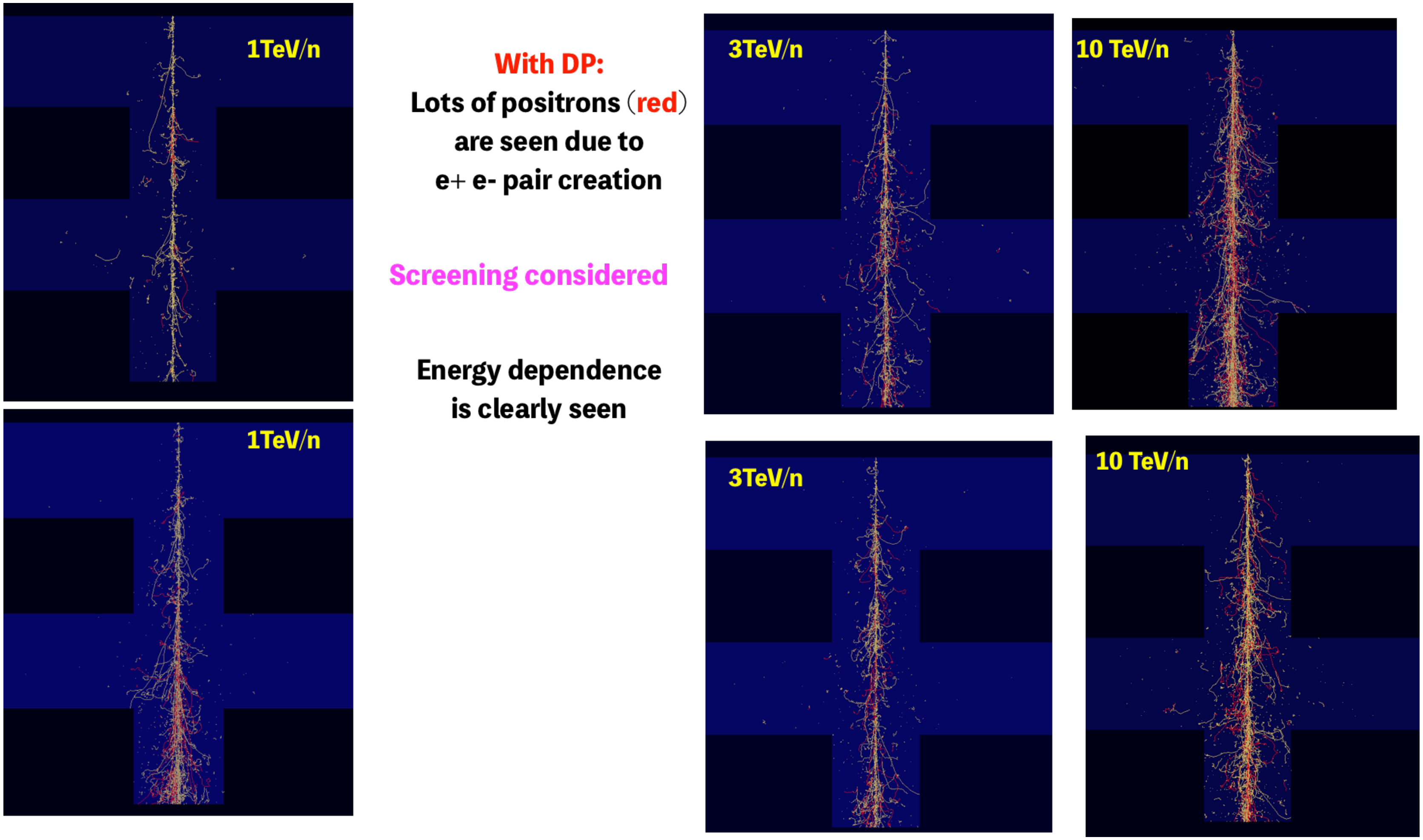


Without DP:

No energy dependence
Allmost all are knock-on elections
(yellow)

Small number of positrons
(red)
due to pair-creation by brems
gamma rays

Figure 10: NO DP case

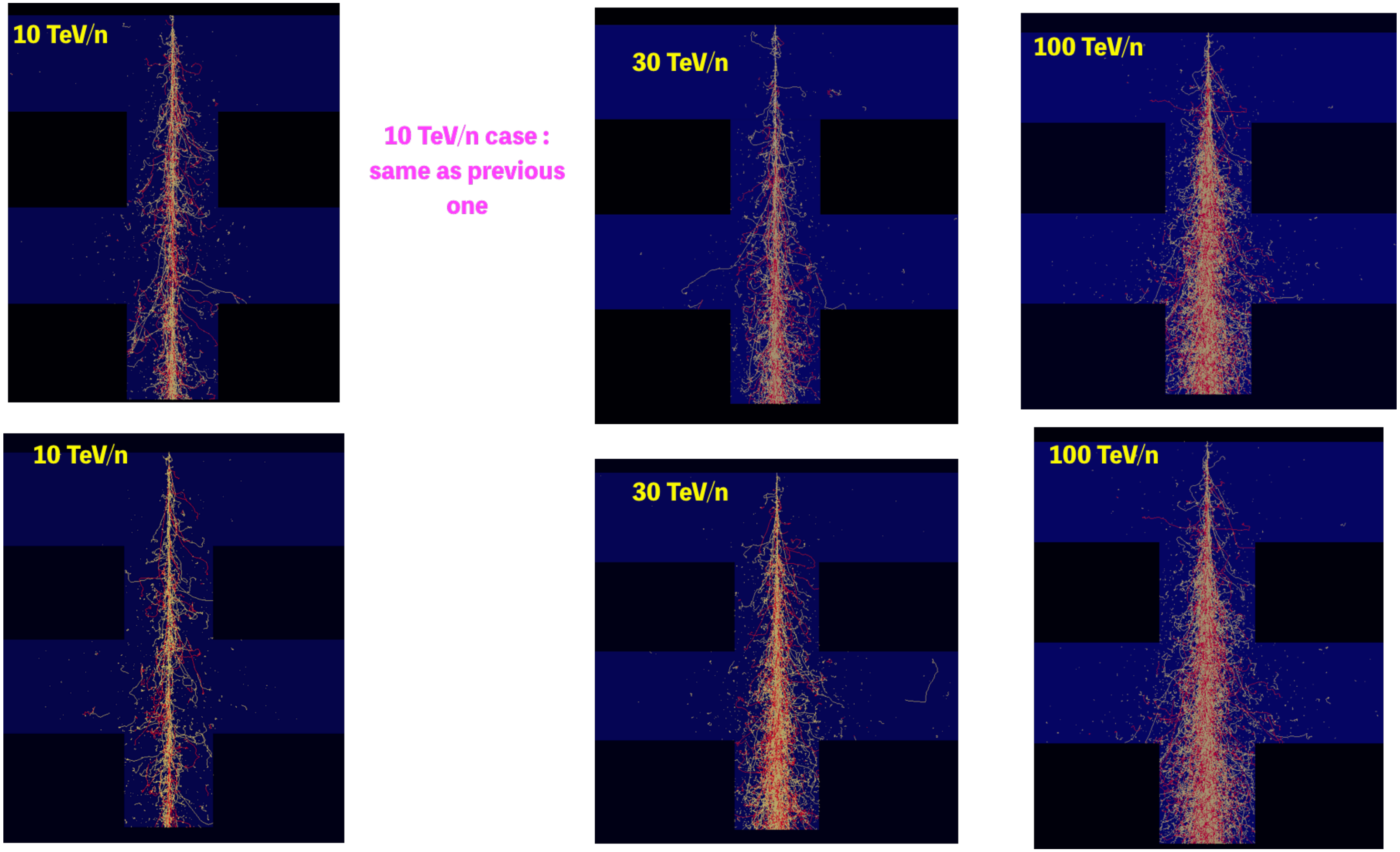


With DP:
Lots of positrons (red)
are seen due to
e+ e- pair creation

Screening considered

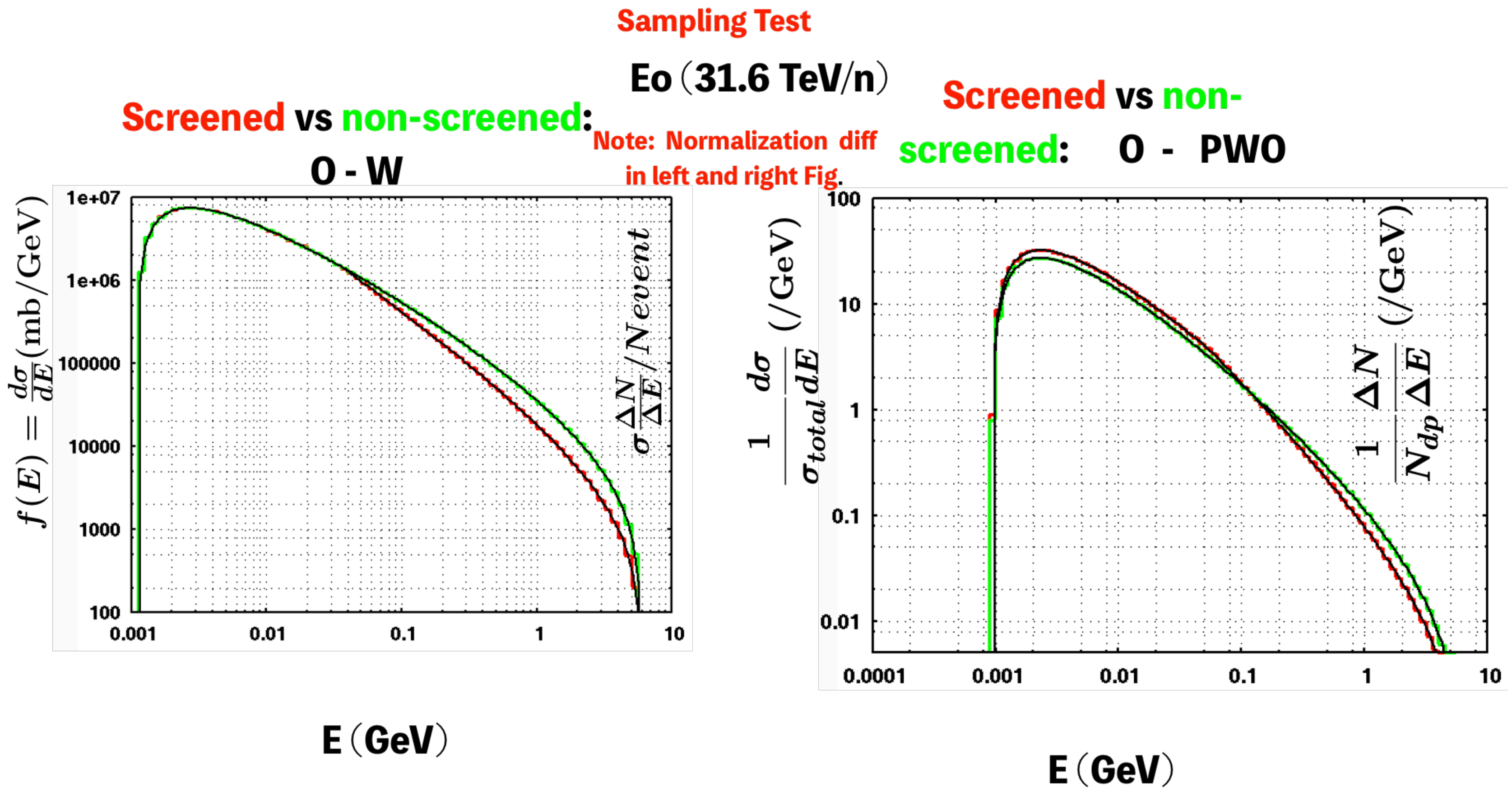
Energy dependence
is clearly seen

Figure 11: With DP



10 TeV/n case : same as previous one

Figure 12: With DP



Sampling Test

Eo（31.6 TeV/n）

Note: Normalization diff in left and right Fig.

Screened vs non-screened: O - W

Screened vs non-screened: O - PWO

Figure 13: Sampling of DP elecrtons

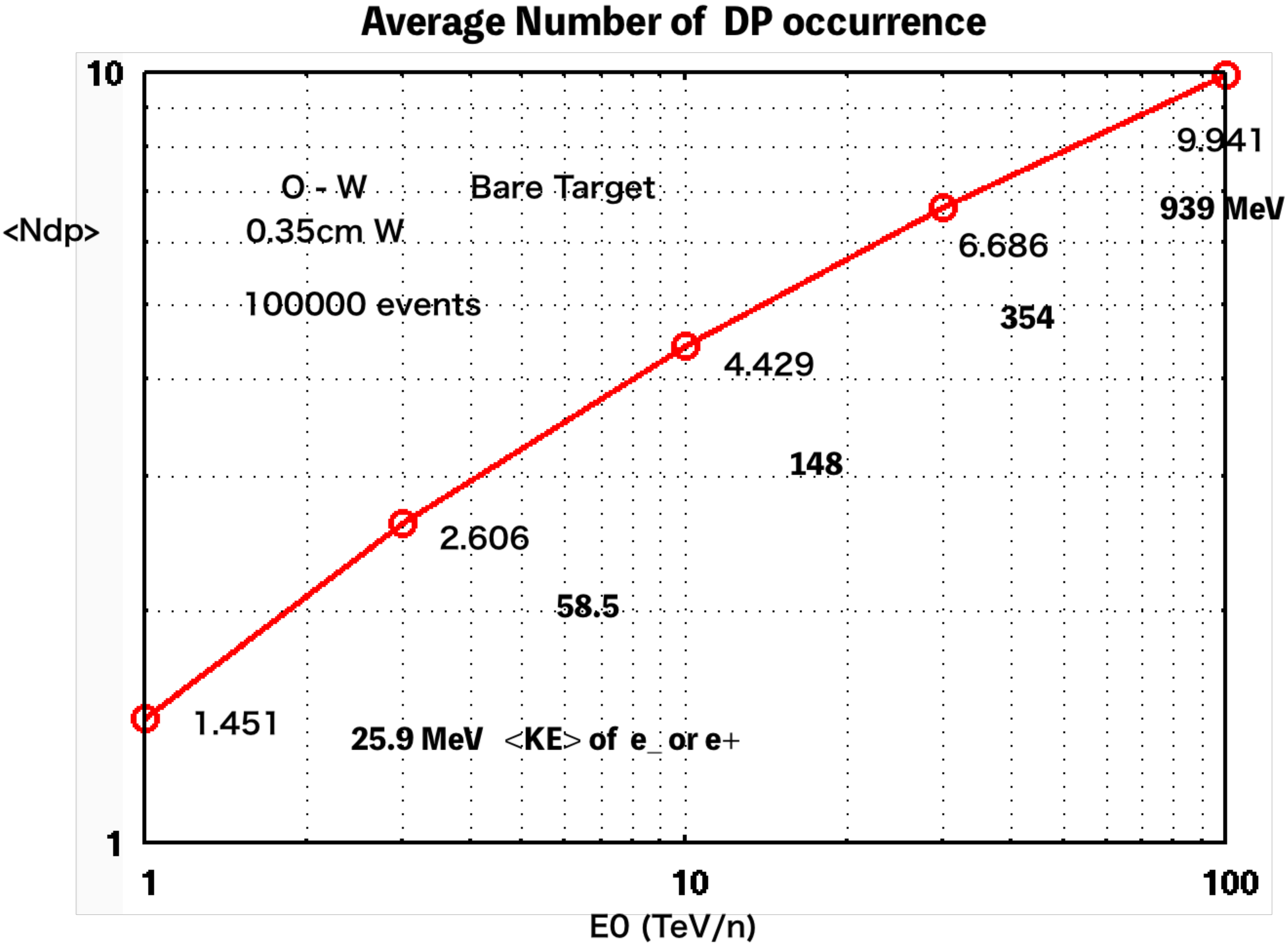


Figure 14: $\boldsymbol{E_0}$ vs Average number of DP

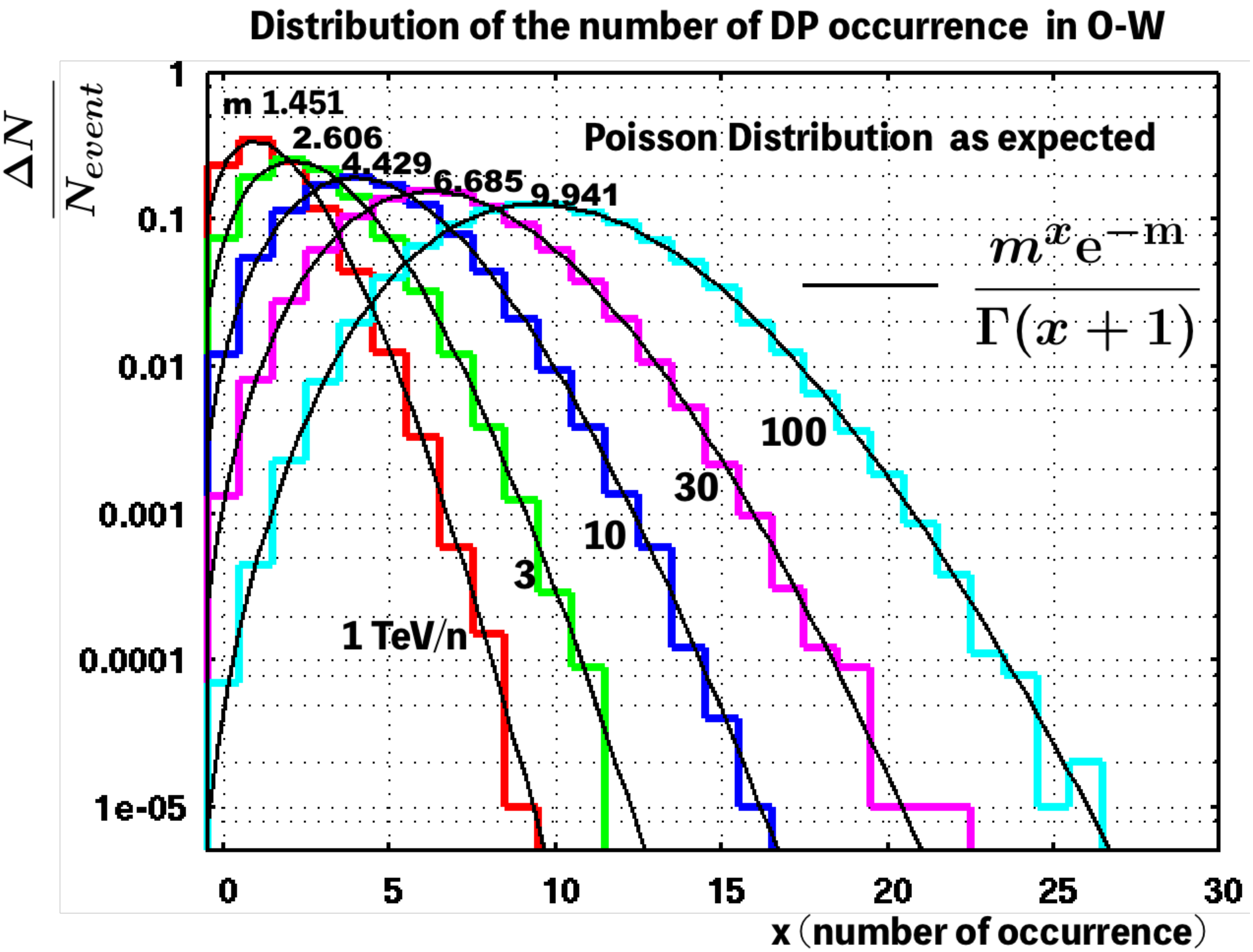


Figure 15: DP occurence number distribution: Possison as expected

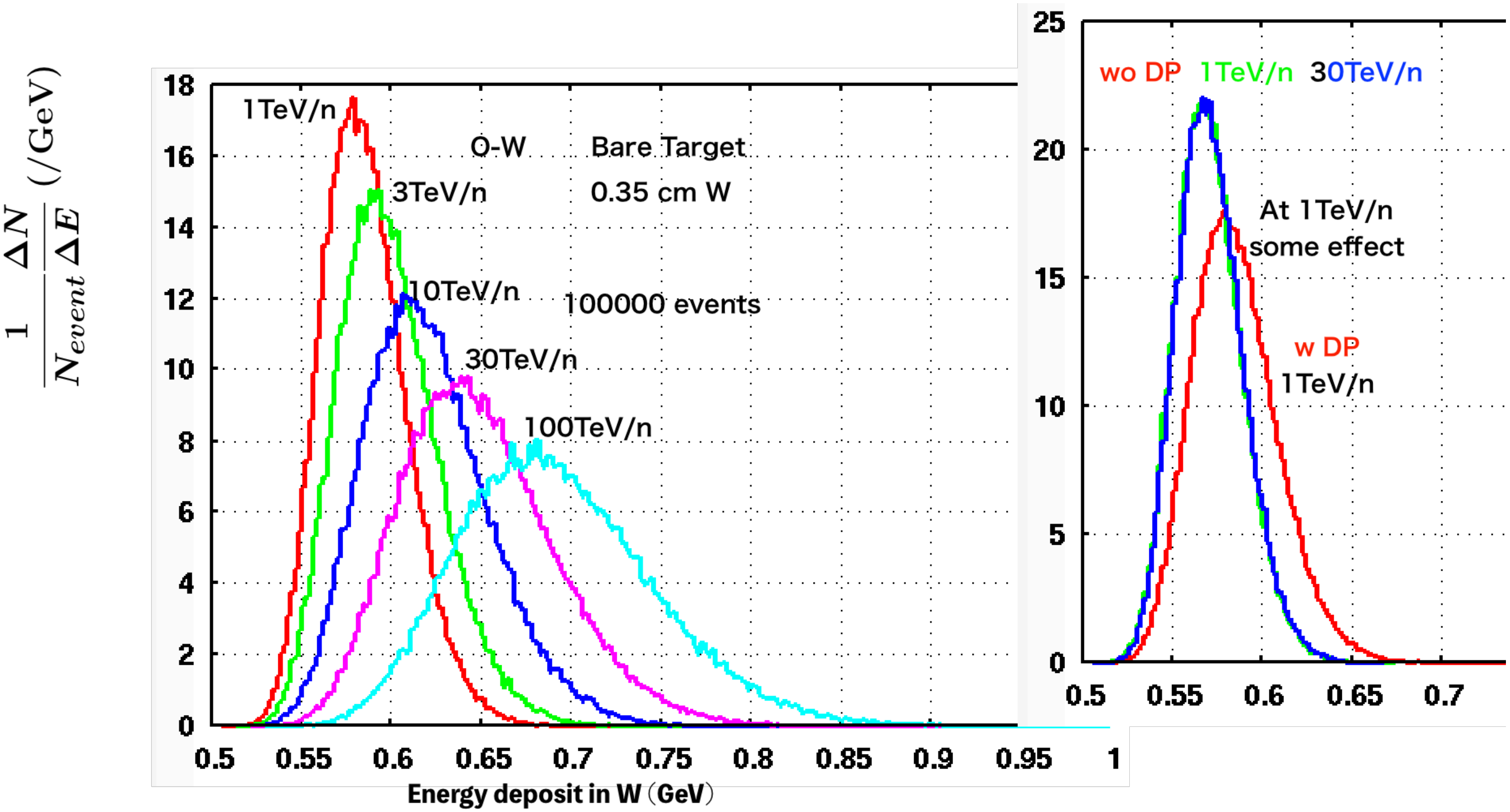


Figure 16: Energy deposit in 0.35 cm W. Right one shows if W/O DP, $\boldsymbol{E_0}$ independent (blue and green). At 1 TeV/n, some effect of DP (blue or green vs red). Left energy dependence is clear.

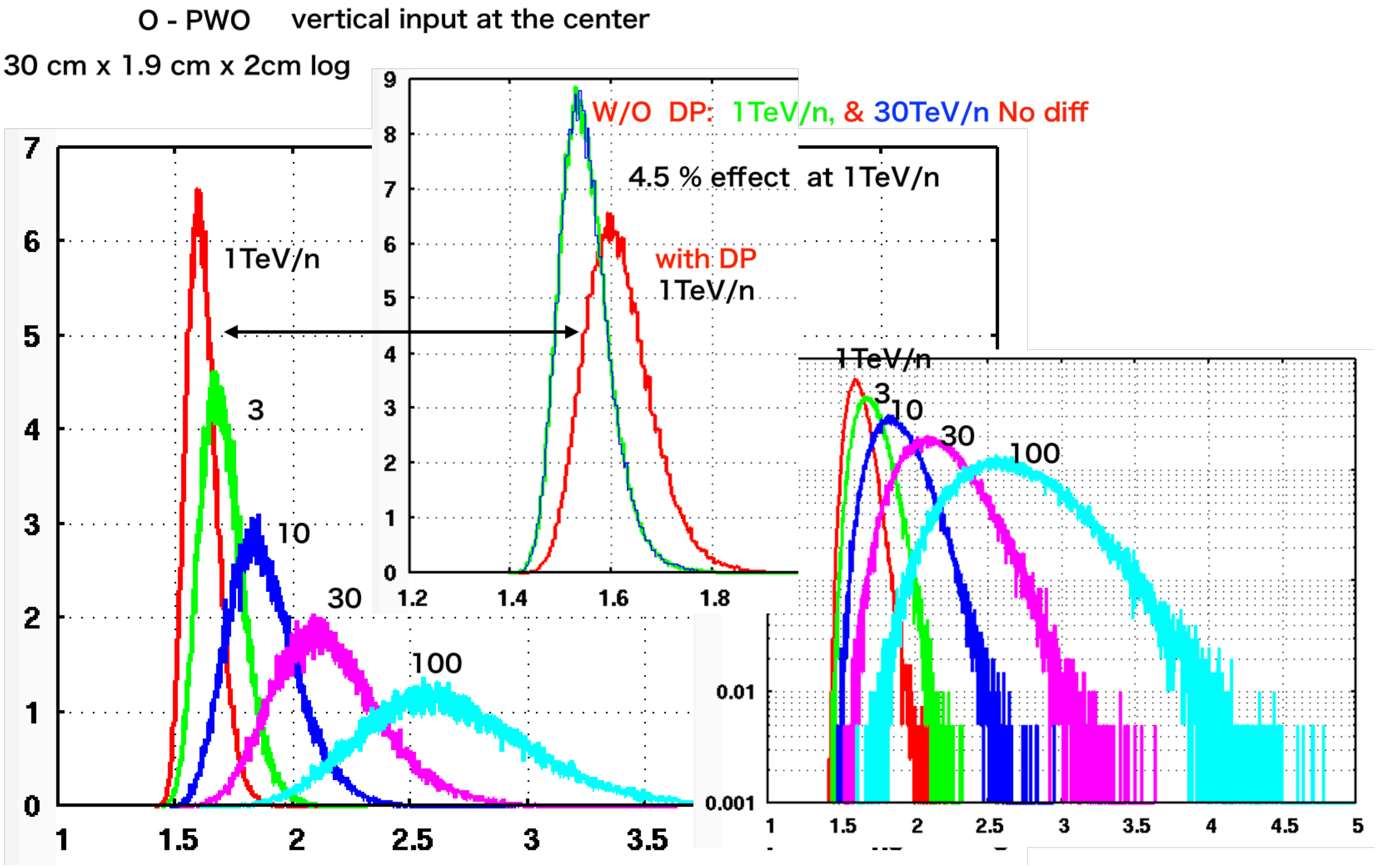


Figure 17: Simlar one for 1 PWO log.

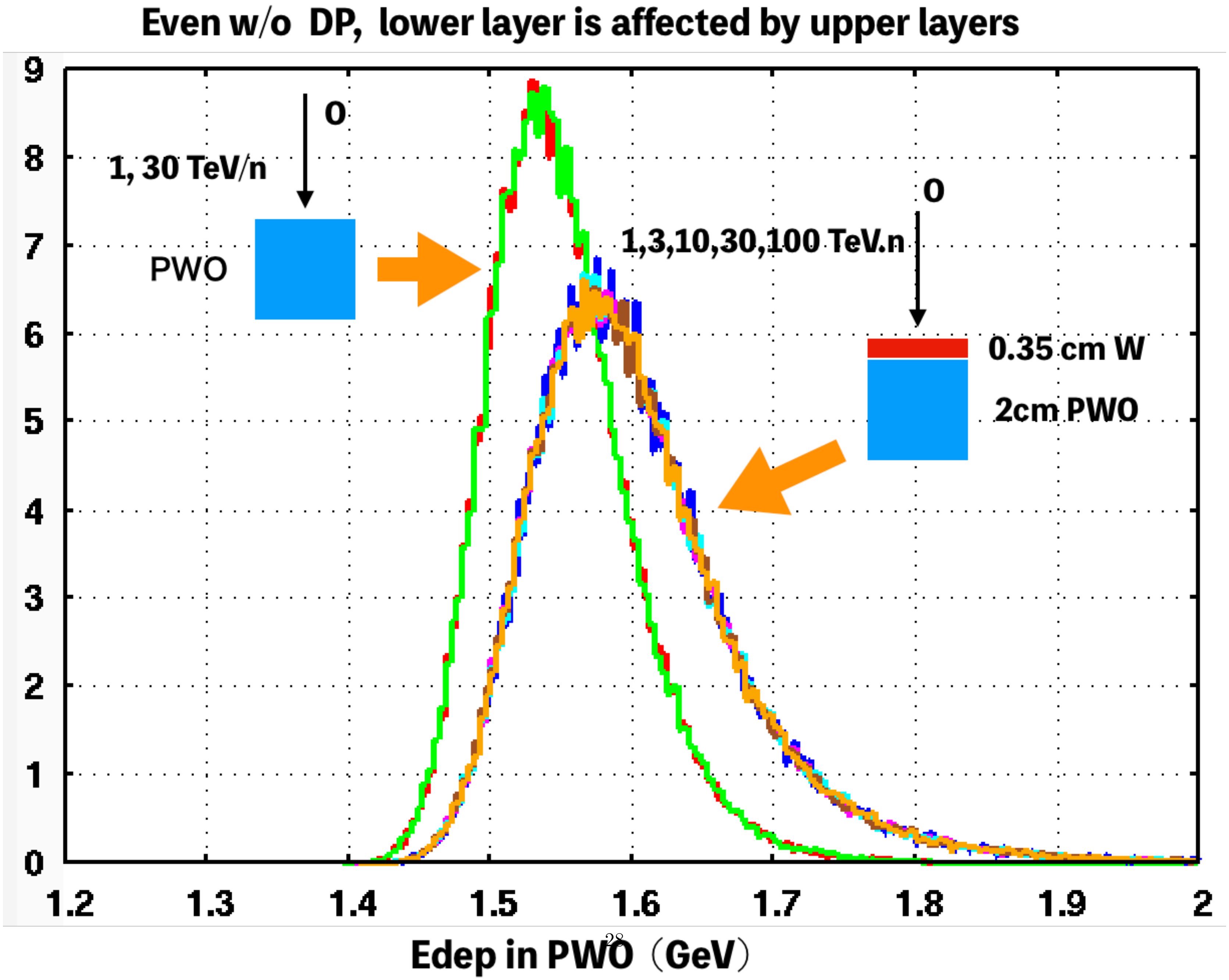


Figure 18: Upper layer effect. Even w/o DP, lower layer is affected but energy independent.

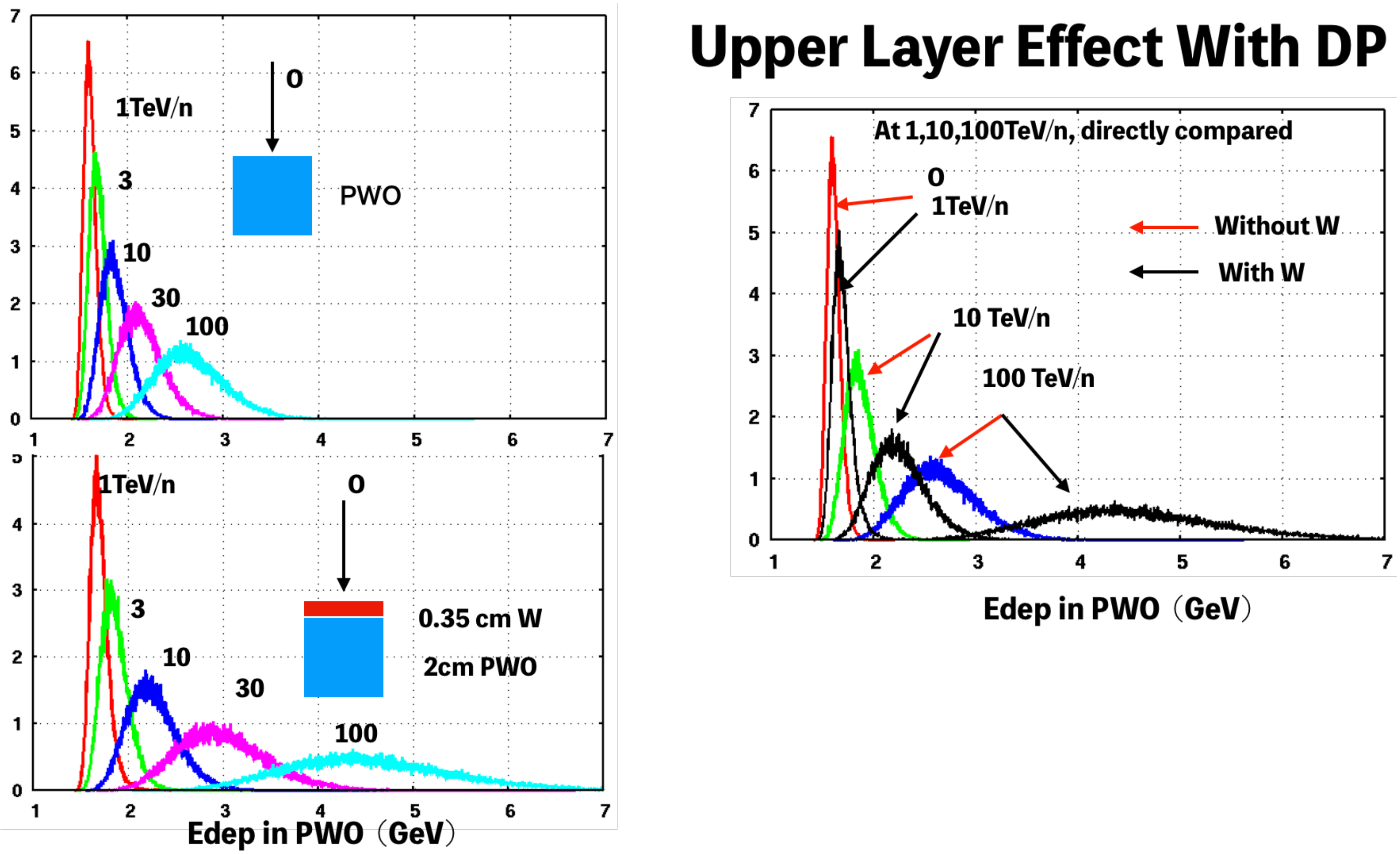


Figure 19: W DP. Upper layer effect is larger.

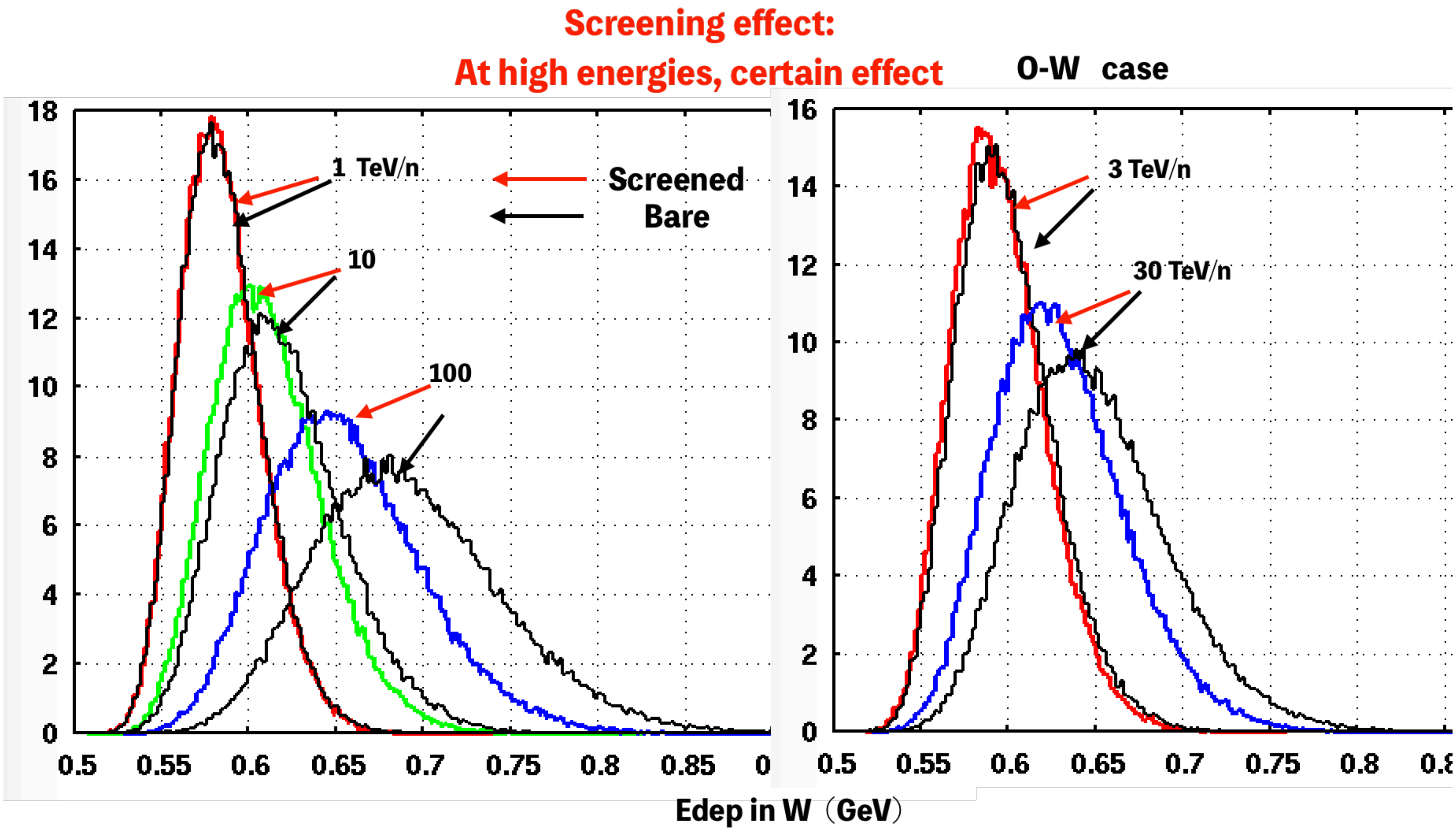


Figure 20: Screening effect makes effect bit smaler but surely exist.

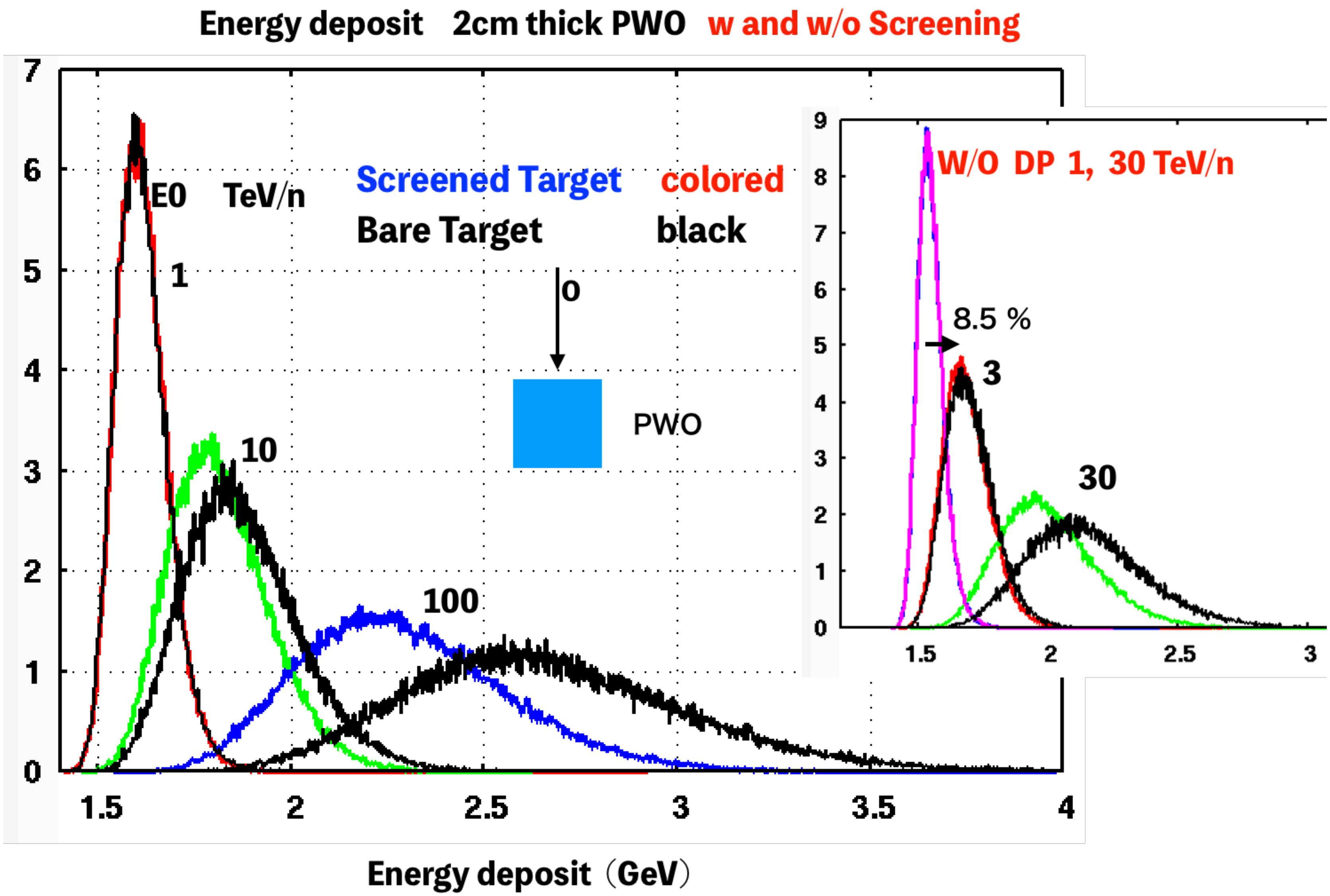


Figure 21: Same for PWO single log

Summary, Problems, ToDo

- **The DP cross-section given in the basic reference paper (`B & B`) was successfully implemented in Epics.**
- **Its effect should be seen clearly over few TeV/n even in a sigle PWO log.**
- **Problems**
  - **Are the cross-sections reliable ?**
    There are papers which employed a numerical method
    (Decker: Phys.Rev.A, Vol.41 No.5 (1991))
    or M.C method
    (Bottcher & Strayer:Phys Rev. D 39, 1330(1989))
    to integrate basic cross-section formulas (which are different and based on different assumptions).

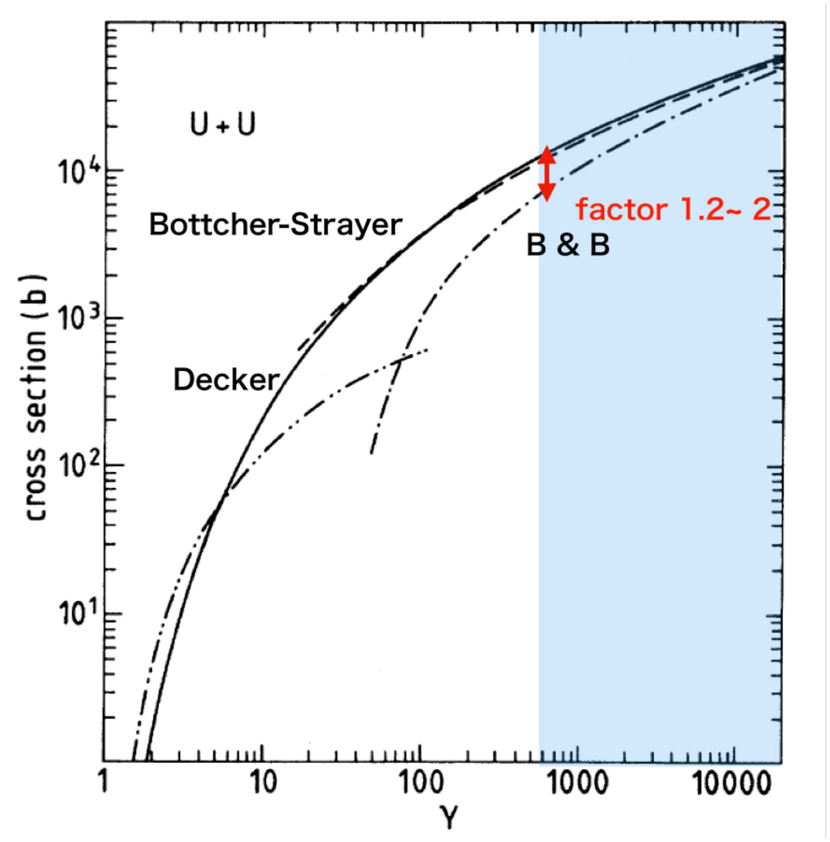


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Figure 22: Comparison with other two calculations. for bare U+U case. In our interested region, factor of ∼ **1.5** seems to exist.

As shown in Fig.22, `B&B` gives lower total cross-section for bare target U+U case (in our interested region, factor of ∼1.5).
We don't know what happens for O+W etc, esp. with screened

target case.
They don't treat the screened target case. Also it is probably very difficult to apply their methods for arbitrary combination of projectile and target.

- Partial screening
  Currently the unscreened cross-section is switched to the completely screened cross-section at E_{sw}. But partial screening should happen between them to decrease the cross-section at around E_{sc} (althougth the effect is expected to be small)
- Other UPC effect ?
  Such as photo-hadron production.
- Inclusive treatment.
  When sampling the energy of pair electrons, we use the same inclusive distribution for e- and e+. But the energy of e- and e+ should have some loose correlation (say, probabilty of both e- and e+ are very high energy would be smaller than those sampled as above).
  This is probably not important for our purpose since DP will takes

place many times. We need some verification for safety.

- **EPICS interface**
  - **Three parameters in epicsfile.**
  - **DirectPair: T or F. Default T**
  - **BareTarget: T or F. Defaut F**
  - **AdjFac: 1.0 or .. Default is 1.0. This factor is multiplied to the threshold value for the DP production.**
  - **Interaction name of DP: dpair**

Appendix:
Copmplex misleading stuffs

Screened Target Case **Dash lines**

Z1=16 Z2=92

σ based on Eq.7.4.3 (red) Should reprouce dashed curve but not ! The integration upper bound in the Eq. seems wrong.

The Eq. is modified to use the correct upper bound. Now OK. (green)

Z1=16 Z2=40

Blue and magenta correspond to red and green above

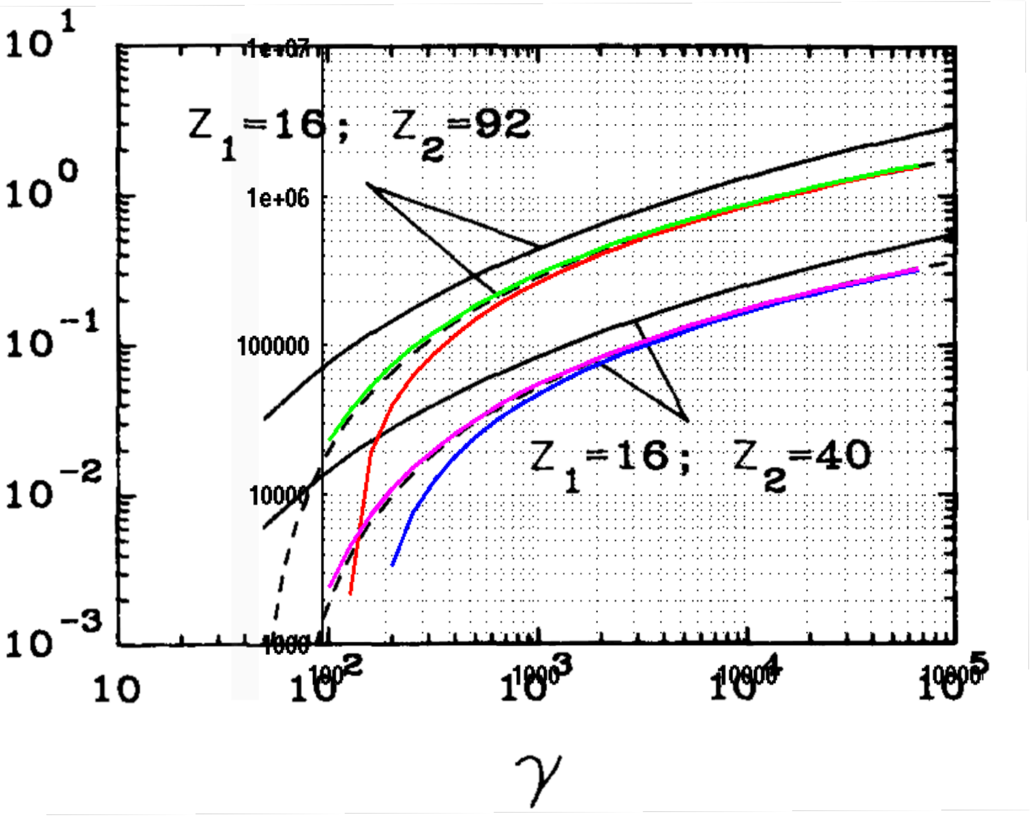

Figure 23: Fig7.7 of the paper: σ of $Z_1 = 16, Z_2 = 92$ and $Z_1 = 16, Z_2 = 40$

As to Eq. 7.4.3 exprssing σ, there are problems in

$$\text{Indefinite integral: } F(E) = \int^{E} f(E)dE$$

$$\text{Definite integral: } \sigma = \int_{a}^{b} f(E)dE = F(b) - F(a)$$

a is said to be $E_{sc} = mZ^{1/3}\alpha$. This should be typo[2] and in the actual calculation in the paper, correct $E_{sc} = m/(Z^{1/3}\alpha)$ seems to be used (but very much confusing). $b = \gamma m$ is used in Eq. 7.3.4. For this b, f beomes negative. b must be $\gamma m\delta/2$ After changing b, we could get consistent results with the dashed lines (green and magenta) curves were obtained!

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[2] If this E_{sc} is correct, it becomes as low as 16 keV for $Z = 74$. (but must be $\geq m$ as a)

But the story didn't end here.

$\boldsymbol{F(E)}$ **itself seems to have a mistake: γ in the formula must be replaced by $\gamma/2$.**

So the lines are shifted by a factor of 2 as shown in Fig.7