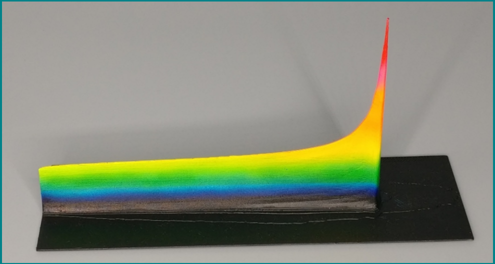
15th Varenna Conference on Nuclear Reaction Mechanisms
Varenna, 11-15 June 2018

MONET code: evaluation of the dose in Hadrontherapy



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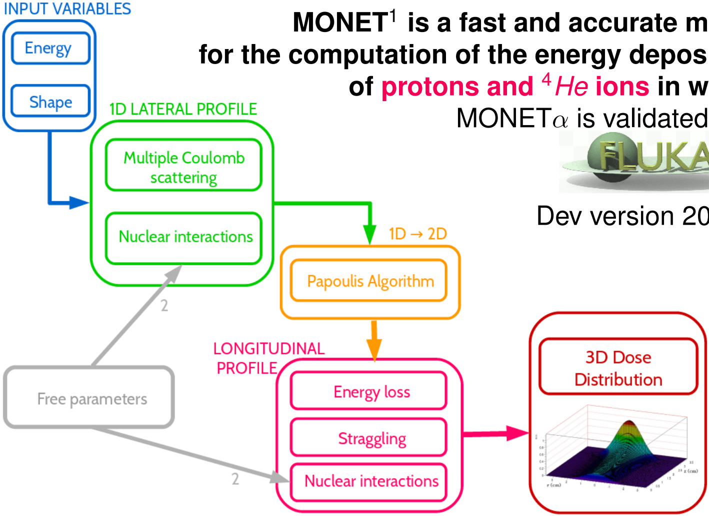
MONET[1] is a fast and accurate model for the computation of the energy deposition of protons and ^4He ions in water.

MONETα is validated with FLUKA

Dev version 2017.0



[1] Embriaco, A model for the fast and accurate dose evaluation in hadrontherapy, *PhD thesis*

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Helium ions

From a physical point of view, ^{4}He **ions** seem to fill the gap between protons and ^{12}C.

The most important advantages of ^{4}He beams are a reduction of:

- **multiple Coulomb scattering** compared to protons,
- **energy straggling** compared to protons,
- **projectile fragmentation** than Carbon ions.

Lateral profile

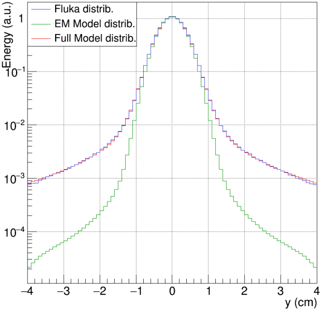
The lateral distribution is calculated as the sum of **multiple Coulomb scattering** and **nuclear interactions**[2 3]:

$$f_x(x) = W_p f_M(x) + (1 - W_p) \frac{t(x)}{\int t(u) \mathrm{d}u}$$

- f_M Molière distribution
- W_p primary particle weight
- $t(x)$ is a **Cauchy-Lorentz function:**

$$t(x) = \frac{1 - A \exp\left[-\frac{x^2}{2b^2\sigma^2}\right]}{\pi b \left(\frac{x^2}{b^2} + 1\right)}$$

- $1 - W_p$ nuclear contribution



^4He ions of 150 MeV/u at z=15 cm

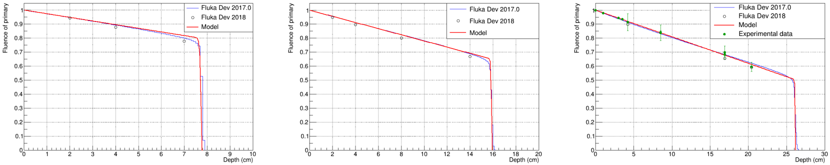
[2] Bellinzona et al. 2016 *Physics in Medicine and Biology* **61** N102

[3] Embriaco et al. 2017 *Physica Medica* **40** 51–58

Attenuation of ^4He ions

The attenuation curves of ^4He ions are fitted using an **error function multiplied by a linear parametrization**[4]:

$$W_p = (\alpha z + \beta) \times \mathrm{erf}\left(\frac{R - z}{\gamma}\right)$$



The energy analyzed are left: E=100 MeV/u, middle: E=150 MeV/u and right: E=200 MeV/u.

For energy of 200 MeV/u, the experimental data[5] are added for the validation of the curve.
The black dots are the results of new development version of FLUKA 2018(Thanks to Giulia Aricò).

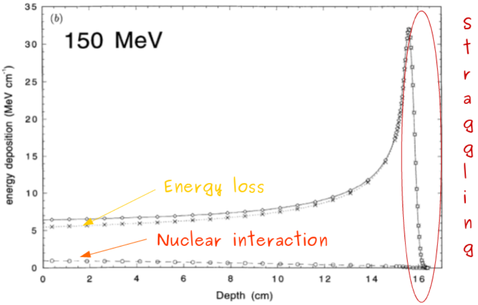
[4] Embriaco, A model for the fast and accurate dose evaluation in hadrontherapy, *PhD thesis*

[5] Rovituso et al. 2017 *Physics in Medicine and Biology* **62**(4):1310

Longitudinal profile

The longitudinal profile is characterized by the sum of **three effects**[6]:

1. Average energy loss
2. Straggling
3. Nuclear interaction



[6] Carlsson et al. 1997 *Phys. Med. Biol.* **42** 1033-1053

Average energy loss

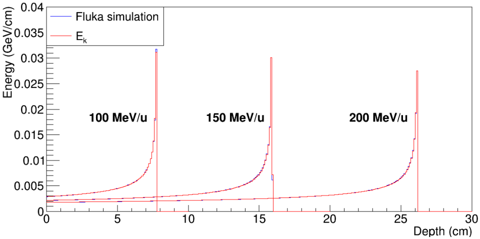
We have implemented a **new formula** of the average energy loss:

$$E_K(z) = -m + \frac{F(z)}{2} + \sqrt{m^2 + \frac{F^2(z)}{4}}$$

where $F(z)$ is:

$$F(z) = p\beta \left(1 - \frac{z}{R}\right)^{k/2}$$

and $k = 1.07$.



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Straggling

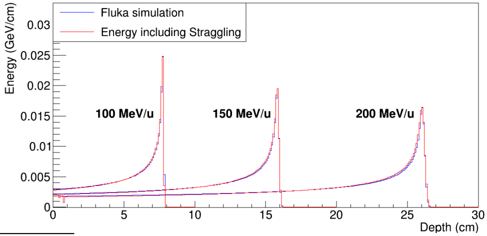
The energy deposed at the actual depth z can be obtained by the **convolution of the energy loss with a Gaussian** function:

$$\hat{E}_K(z)0 = \int_0^R E_K(\bar{z}) \frac{e^{-(z-\bar{z})^2/2\sigma^2}}{\sqrt{2\pi}\sigma} d\bar{z}$$

Approximation for σ[6 7 8]:

$$\sigma \approx 0.012 R^s$$

E(MeV/u)	100	150	200
s	0.55	0.71	0.76



[6] Carlsson et al. 1997 *Phys. Med. Biol.* **42** 1033-1053

[7] Bortfeld 1997 *Med. Phys.* **24** 2024-2033

[8] Embriaco, A model for the fast and accurate dose evaluation in hadrontherapy, *PhD thesis*

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Nuclear interaction

Including the nuclear interaction, the total expression of the deposited energy becomes:

$$f_z(z) = W_p \hat{E}_K(z) + (1 - W_p) E_N(z)$$

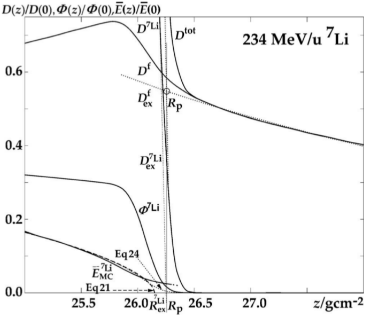
where W_p is the primary particle weight and $E_N(z)$ is a **linear parametrization** for the nuclear contribution:

$$E_N(z) = az + b$$

with the coefficients a and b are obtained by fitting FLUKA simulations.

After Bragg peak

The depth dose curve from FLUKA simulations are analyzed, focusing in the few centimeters after the peak.



Practical range[9]: the depth corresponding to the intersection point between the tangent at the inflection point of the descending part of the depth dose profile and the exponentially extrapolated tail.

[9] Kempe et al. 2008 *Medical Physics* **35(1)** 159–70

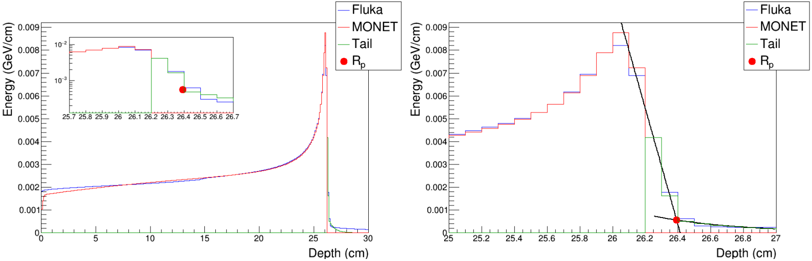
After Bragg peak

Therefore the **total energy deposition** for ^4He ions is given by:

$$f_z(z) = \begin{cases} W_p \hat{E}_k(z) + (1 - W_p)(a'z + b') & 0 < z < R \\ mz + q & R < z < R_p \\ \exp(p_0 + p_1 z) & z > R_p \end{cases}$$

where m and q are the parameter of the tangent at the inflection point and the p_0 and p_1 the parameters of the exponential fit of the tails.

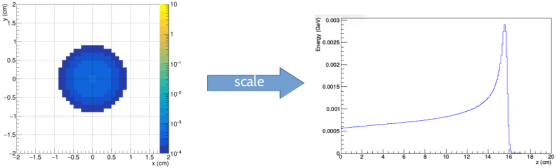
Total energy deposition



Bragg curves including nuclear contributions of ^{4}*He* ions calculated with MONETα compared with FLUKA simulations for 200 MeV/u.

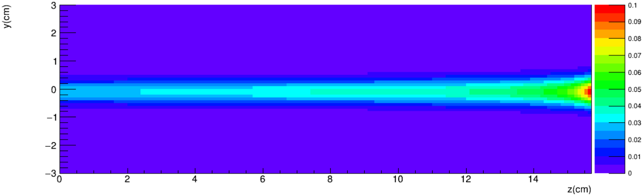
[8] Embriaco, A model for the fast and accurate dose evaluation in hadrontherapy, *PhD thesis*

3-dimensional dose distribution



$$D(x, y, z) = f(z)f(r)$$

^4He ions of 150 MeV/u



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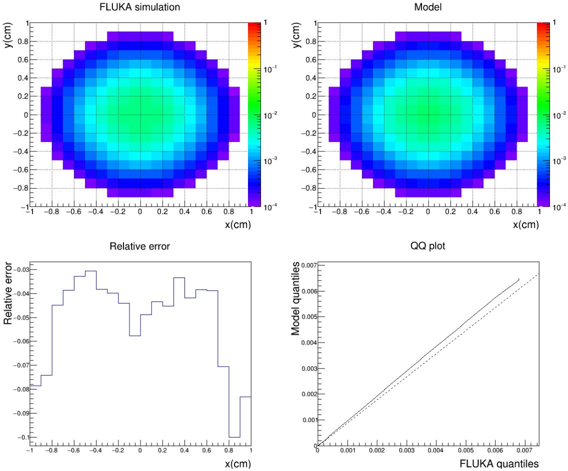
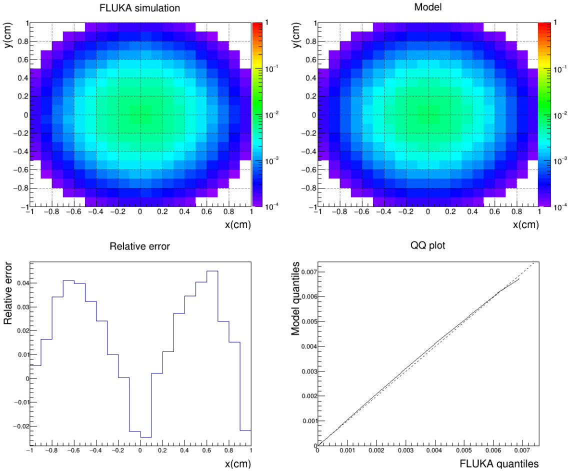
^4He Single Gaussian beam



Energy 100 MeV/u at depth z=4 cm (Bragg peak at 7.8 cm).

[8] Embriaco, A model for the fast and accurate dose evaluation in hadrontherapy, *PhD thesis*

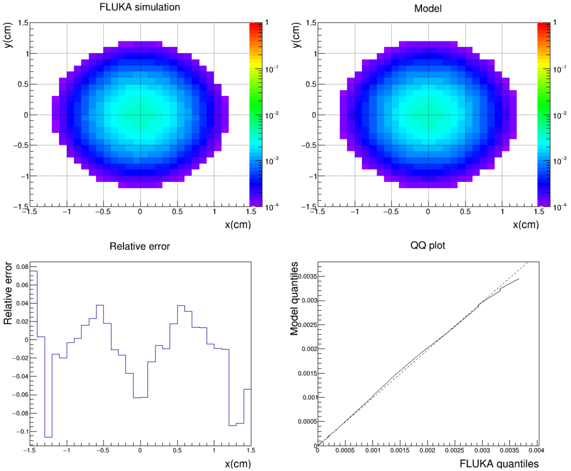
^{4}He Single Gaussian beam



Energy 150 MeV/u at depth z=15 cm (Bragg peak at 15.9 cm).

[8] Embriaco, A model for the fast and accurate dose evaluation in hadrontherapy, *PhD thesis*

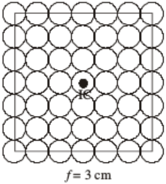
^4He Single Gaussian beam



Energy 200 MeV/u at depth z=25 cm (Bragg peak at 26.1 cm).

[8] Embriaco, A model for the fast and accurate dose evaluation in hadrontherapy, *PhD thesis*

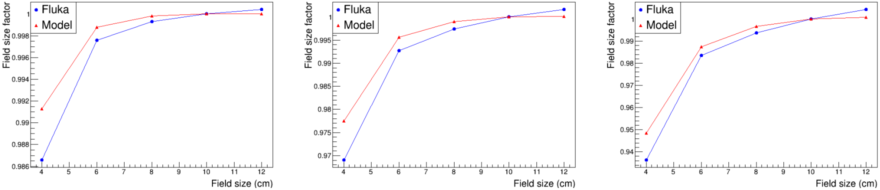
Field size factor test



The field size factor is defined as:

$$FSF(f) = \frac{D_f}{D_{10}}$$

where f assumes the values $4, 6, 8, 10, 12$ cm.



Field size factor for ^4He ions:(left) 100 Mev/u at z=6 cm, (middle) 150 MeV/u at z=15 cm and (right) 200 MeV/u at z=25 cm.

[8] Embriaco, A model for the fast and accurate dose evaluation in hadrontherapy, *PhD thesis*

Field size factor test

FSF differences between the model and FLUKA for four fields, three depths and three energies:

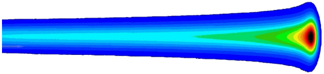
E(MeV)	100/u			150/u			200/u		
FSF	2	4	6	5	10	15	10	15	25
4	0.4%	0.6%	0.5%	0.9%	1.2%	0.9%	1.8%	1.9%	1.3%
6	0.1%	0.1%	0.1%	0.3%	0.6%	0.3%	1.1%	1.2%	0.4%
8	0.0%	0.1%	0.0%	0.1%	0.3%	0.2%	0.6%	0.7%	0.3%
12	0.0%	-0.0%	-0.0%	-0.1%	-0.2%	-0.2%	-0.4%	-0.6%	-0.3%

The FSF tests show a **good evaluation of the low dose contributions** with MONETα code.

[8] Embriaco, A model for the fast and accurate dose evaluation in hadrontherapy, *PhD thesis*

MONET code

The results of the model for Helium ions are validated with FLUKA.



Advantages

- Physical foundation
- only 4 free parameters for energy
- accuracy
- fast calculation time
  (for each depth 2/4 s for single beam/lateral scan)

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MONET code

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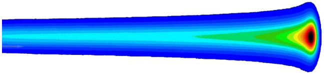

Advantages

- Physical foundation
- only 4 free parameters for energy
- accuracy
- fast calculation time
  (for each depth 2/4 s for single beam/lateral scan)

Developments

- dose database of interest for the clinical use
- online/in-room fast dose evaluation tool

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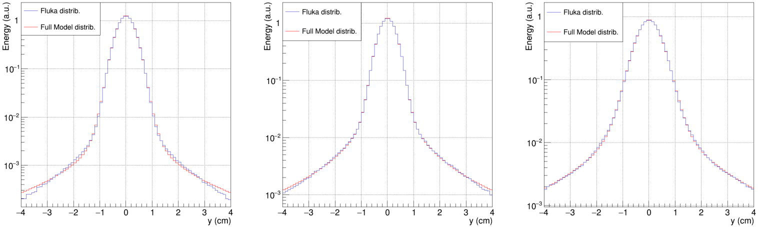
Backup Slides

Lateral profile of ^4He ions



Lateral profile: E=100 MeV/u z=7 cm, middle: E=150 MeV/u z=7cm and right: E=200 MeV/u z=25 cm.

From 1D to 2D: Papoulis Algorithm

The projected distribution f_x and f_y are uncorrelated, but not independent."[8]

$$f(x, y) \neq f_x(x) \times f_y(y)$$

In case of **cylindrical symmetry:**[9]

Transform $f_x(x)$ into $\mathbf{f}(r)$:

$$h(r) = 2\int_0^{+\infty} f_x(\sqrt{r^2 + y^2})dy$$

$$\mathbf{f}(r) = \frac{1}{2\pi r}\frac{dh(r)}{dr}$$

[8] Fruhwirth & Regler, Nucl. Instr.Meth. Phys. Res. A 456 (2001) 369-389

[9] Papoulis 1968 *IEEE Transactions on Information Theory*

Papoulis algorithm

Let us consider a distribution $f(x)$ in the xy plane with circular symmetry [4]:

$$f(x,y) = f(r) \qquad r = \sqrt{x^2 + y^2}$$

The marginal distribution $f_x(x)$ corresponding to $f(x,y)$ is:

$$f_x(x) = \int_{-\infty}^{+\infty} f(x,y)dy = \int_{-\infty}^{+\infty} \mathbf{f}(r)dy = 2\int_0^{+\infty} \mathbf{f}(\sqrt{x^2+y^2})dy$$

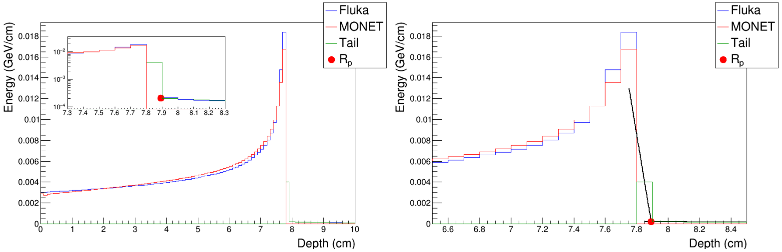
Transform $f_x(x)$ into $\mathbf{f}(r)$:

$$h(r) = 2\int_0^{+\infty} f_x(\sqrt{r^2+y^2})dy$$

$$\mathbf{f}(r) = \frac{1}{2\pi r}\frac{dh(r)}{dr}$$

[4] Papoulis 1968 *IEEE Transactions on Information Theory*

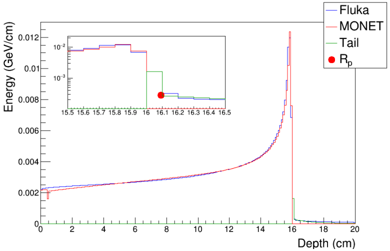
Total energy deposition

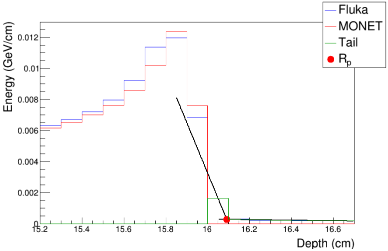


Bragg curves including nuclear contributions of ^4He ions calculated with MONETα compared with FLUKA simulations for 100 MeV/u. The bullet point represent the practical range R_p. In the inset plot, fragmentation tail is reported in log scale. The practical range as the intersection between tangent at inflection point and the exponential tail is reported in linear scale.

[6] Embriaco, A model for the fast and accurate dose evaluation in hadrontherapy, *PhD thesis*

Total energy deposition

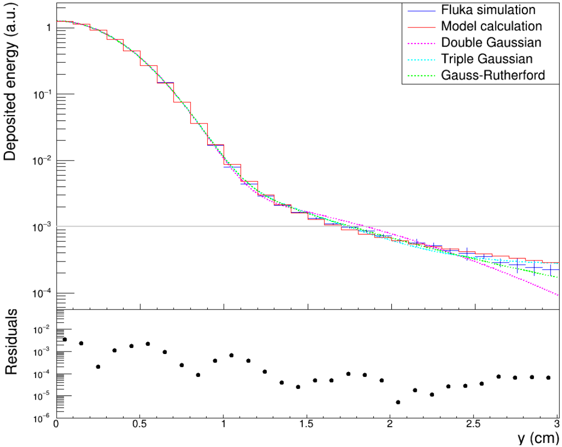




Bragg curves including nuclear contributions of ^4He ions calculated with MONETα compared with FLUKA simulations for 150 MeV/u.

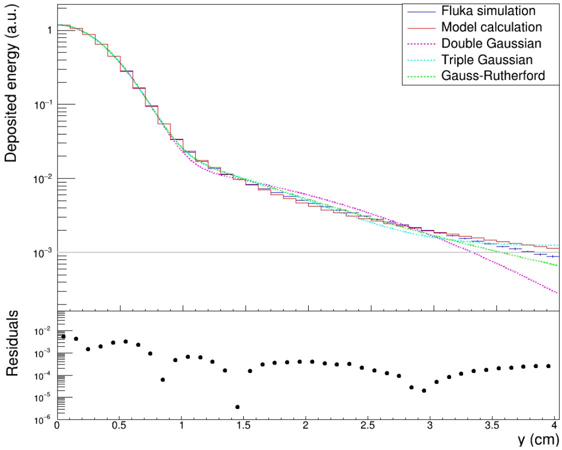
[6] Embriaco, A model for the fast and accurate dose evaluation in hadrontherapy, *PhD thesis*

Helium lateral profile



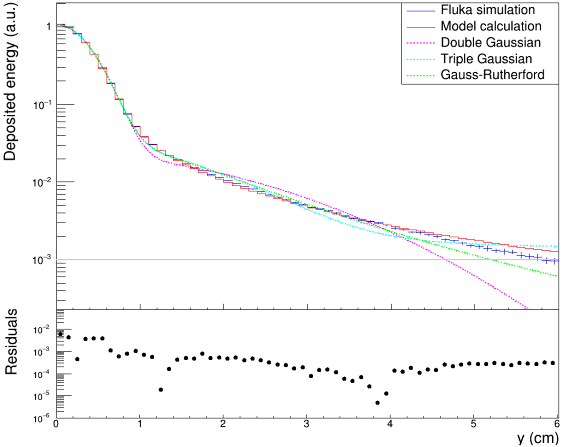
Energy of 100 MeV/u in water at a depth $z = 7$ cm.
Lateral distribution of Helium beam with the different models. The plotted residuals are calculated between the FLUKA simulation and the model.

Helium lateral profile



Energy of 150 MeV/u in water at a depth $z = 10$ cm.
Lateral distribution of Helium beam with the different models. The plotted residuals are calculated between the FLUKA simulation and the model.

Helium lateral profile



Energy of 200 MeV/u in water at a depth $z = 15$ cm.
Lateral distribution of Helium beam with the different models. The plotted residuals are calculated between the FLUKA simulation and the model.

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