# 基于REST的无中微子双β衰变实验的蒙特卡洛模拟

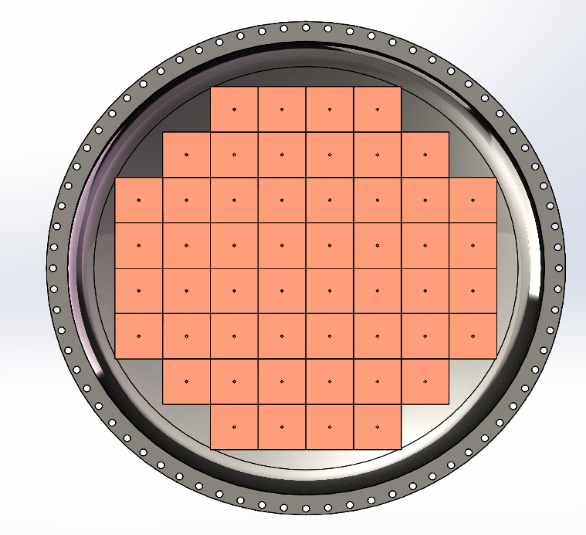
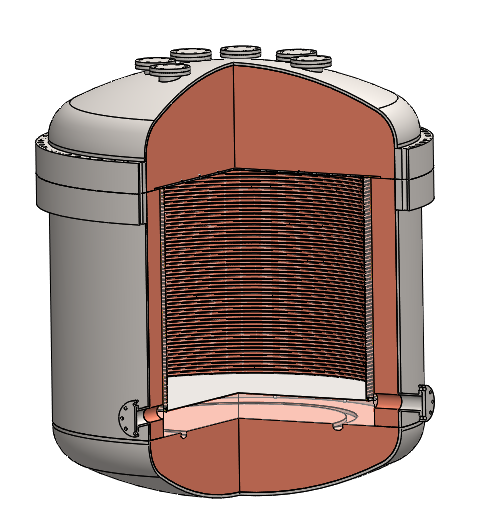
## 1.介绍

PandaX-III实验计划在中国锦平地下实验室进行无中微子双β衰变实验。该实验利用高压气体时间投影室(TPC)记录实验过程中的能量沉积和电子轨道的拓扑信息。为了实物实验在缺乏先前经验的情况下能够以更高的精确度开展，提高检测效率，我们计划使用基于Rare Event Searches with TPCs Software(后称REST)软件的蒙特卡洛模拟，重建本实验中使用的TPC模型，和相关实验步骤。我们后续将使用机器学习分析模拟的结果，并对于实验参数的选择进行调整，以更好得抑制背景信号，增加目标信号的检测效率。

## 几何模型

PandaX-III实验正在研发百公斤量级富集Xe-136的高压气氙TPC来寻找NLDBD过程。 探测器的设计如图-1所示，读出平面由52块20×20 cm2的Microbulk Micromegas（MMs）组成，探测器有效区域尺寸为直径1.6米，漂移总长度1.2米，读出条尺寸是3毫米，能量分辨率指标是3%半高全宽（2.5MeV）。

The PandaX-III experiment is developing a high-pressure gas TPC enriched with Xe-136 in the order of 100 kg to find the NLDBD process. The design of the detector is shown in Figure -1. The readout plan is composed of 52 Microbulk Micromegas (MMs) of 20\*20 cm^2. The effective area of the detector is 1.6 meters in diameter and 1.2 meters in total drift. The size of each strip is 3mm, the energy resolution index is 3% full width at half maximum which is 2.5MeV.



图‑1：左图为PandaX-III探测器罐体设计图，中间有效区域TPC高度1.2m,直径1.6m。右图为读出平面设计图，由52块MMs组成。

This picture shows the design of the PandaX-III detector tank. The effective area of TPC is 1.2m in height and 1.6m in diameter.

This picture is the desing of the readout plan, which consists of 52 MMs

## 模拟

##模拟过程的流程图

### 3.1基于Geant4的蒙特卡洛模拟数据的生成

模拟过程的第一步就是使用Geant4进行数据的生成。依据上文中的几何模型，模拟粒子在Xe-136气体介质中的相互作用并记录所有作用过程中的process parameters，simulation conditions, readout definition, 和 gas properties。

本次模拟我们使用了基于Geant4的RestG4模拟包，在使用RestG4的过程中，TPC有效体积中电离出的电子的轨迹会随机生成，当这些粒子在轨迹上行进时会因为散射和一些特殊的物理过程沿着轨道沉积能量。而此时Geant4会跟踪这些轨迹，将时间戳、粒子类型、动量、能量沉积和位置等信息记录下来。由于背景事件的Geant4会将这些信息封装在一个TRestG4Event中。在REST架构下，TRestG4Event能够被转换为TRestHitsEvent，从而进行更具体的处理和分析。（这部分可以加一个Geant4出来的探测器几何模型）

The first step of the simulation process is to use the underlying Geant4 framework for data generating. According to the geometric model above, we have simulated the interaction of particles in the Xe-136 gas and have recorded the process parameters, simulation conditions, readout definition, and gas properties during all the interactions.

In this simulation, we used the RestG4 simulation package based on Geant4. In the process of using RestG4, the trajectories of ionized electrons in the effective volume of the TPC will be randomly generated. The process deposits energy along the track. At this time, Geant4 will track these trajectories and record information such as timestamp, particle type, momentum, energy deposition, etc. We have used the RestG4 package as an interface to define the simulation conditions through a REST metadata structure named TRestG4Metadata, and to store all event information in a TRestG4Event that can be further processed inside REST.

##如果到这一步就有图的话就分别把本底和信号的图片选取一张比较好看的放上去

## 3.2基于REST 的物理学模拟

模拟过程的第二步是利用REST已经封装好的一些接口进行数据的进一步处理。此阶段主要对打到readout平面的电子进行更精确的物理学模拟。下面将详细介绍每一个处理步骤的物理意义和一些重要处理手段对应的结果。

The second step of the simulation process is to use interfaces which have been already encapsulated in REST to implement further data processing. At this subsection, we mainly performs phisical simulations. The physical meaning of each step and the results of some important processes will be described in the details below.

3.2.1 TRestG4AnalysisProcess:

此过程作用于TRestG4Event。因为之后我们将进行的TRestG4ToHitsProcess会导致大量Geant4有关的数据丢失，所以在进行事件转换之前需要将这些会被丢失的数据存储进分析树以便后续的研究。通过这个过程，我们能够把一些重要数据保留下来，在不影响对于数据进行处理的基础上使得数据具备一定完整性。

本次数据处理记录了以下参数：Energy deposited in the gas volume in keV、Total energy deposited in all the volumes in keV、photoelectric(Its value will be 1 if the event contains a photoelectric interaction.)即是否存在photoelectric interaction 、compton (Its value will be 1 if the event contains a compton scattering process.) 即是否存在康普顿散射、bremstralung (Its value will be 1 if the event contains a bremstralung physics process)即是否存在bremstralung过程。除此之外我们还手动设定了最低能量阈值和最高能量阈值，分别为2390keV和2520keV。

This process implements to TRestG4Event. Since the TRestG4ToHitsProcess that we will carry out later will cause a lot of Geant4 related data to be lost, it is necessary to store these data into the analysis tree. Through this process, we can keep some important data and make the data complete without affecting the data processing.

This data processing recorded the following parameters: Energy deposited in the gas volume in keV, total energy deposited in all the volumes in keV, photoelectric (Its value will be 1 if the event contains a photoelectric interaction.That is to say, whether there is photoelectric interaction), Compton (Its value will be 1 if the event contains a compton scattering process. That is to say, whether there is a Compton scattering), bremstralung (Its value will be 1 if the event contains a bremstralung physics process. That is to sayis whether there is a bremstralung process.)

In addition, we also manually set the minimum energy threshold and the maximum energy threshold, respectively 2390keV and 2520keV.

【不确定阈值这个概念合不合适，或许是energy cut？】这个主要是基于我们找的Xe-136无中微子双贝塔衰变的Q值是2458keV, 我们探测器的能量分辨率是3%半高全宽，我们取中心值附近2倍sigma筛选事例， 正好是2395~2520

3.2.2 TRestG4ToHitsProcess

此过程将TRestG4Event转换为TRestHitsEvent，在进行此步骤的过程中，所有和Geant4相关的信息如上文介绍那样，都会丢失，转换成仅保留了部分信息的数据点。这些数据点的集合就是TRestHitsEvent。这个结构包含了粒子在反应过程中被存储在三维坐标系中的x，y，z的数据，我们将使用这个数据类型来描述探测器中的能量沉积。

This process converts TRestG4Event to TRestHitsEvent. During this process, all the information related to Geant4 will be lost as described above, and it will be converted to a data point that only retains part of the information. The collection of these data points is TRestHitsEvent. This structure contains the x, y, z data of the particles stored in the three-dimensional coordinate during the reaction. We will use this data to describe the energy deposition in the detector.

##放三张图像

3.2.3TRestElectronDiffusionProcess

该过程使用实验中的Xe-136气体的扩散系数模拟电子从初始位置到最终读出平面过程中产生的相对偏差，这个相对偏差是由一级电离产生的。TRestHitsEvent中发现的每一次碰撞都会有一个相对应的能量被记录，我们把这个能量当做电离过程产生的能量，那么我们可以计算出在这次碰撞中产生了多少因电离而出现的电子，我们将每一个电子都当成是TRestHitsEvent 结构中的一个新的Hits点，它们的坐标将按照Xe-136固有的参数、它的纵向和横向扩散系数以及发生碰撞的点到读出平面的距离等，进行高斯分布后得出。

本次实验在这个Process中设定了以下参数：电场强度设定为1keV/cm，气压设定为10个大气压，并且使用读出平面上收集到的能量作为观测器。

This process uses the diffusion coefficient of the Xe-136 gas to simulate the relative deviation of electrons from the initial position to the final readout plane. This relative deviation is caused by the first stage ionization. Each collision found in TRestHitsEvent has a corresponding energy recorded. We regard this energy as the energy generated by the ionization process, then we can calculate how many electrons appear in this collision due to ionization. Each electron is regarded as a new Hits point in the TRestHitsEvent structure. With the inherent parameters of Xe-136, longitudinal and lateral diffusion coefficients, and the distance from the collision point to the reading plane, after a Gaussian distribution we can obtain their coordinates.

The following parameters were set in this process: the electric field strength was set to 1 keV per cm, the air pressure was set to 10 atmospheres, and the energy collected on the readout plane was used as an observer.

【Xe-136的扩散系数是在root里面吗？Myprocess.rml的代码里没有找到】这个扩散系数是REST耦合的Garfield自动算出来的，计算完之后直接给程序运行了。也可以在配置文件中自定义个扩散系数。

下面三张图分别为信号事件、和两个背景事件经过电子扩散模拟后的图像，和初始的图像进行对比可以发现。。。

##三张图片

3.3.1TRestAvalancheProcess

该过程是为了在模拟过程中添加探测器本身引入的电荷信号增益，故依据探测器能量分辨率，对每个hit点的沉积能量添加一个探测器增益的随机涨落，近似于模拟电子在读出平面内的放大过程。

该过程中添加的参数有energyreference 为2458keV，resolutionreference 为3，

其物理意义为在2.458MeV能量下，探测器的误差为3%的半高全宽。以及detectorGain为1，即本次模拟使用的探测器的电荷信号增益定为1。

This process is to add the charge signal gain introduced by the detector itself in the simulation process. According to the detector energy resolution, a random fluctuation of the detector gain is added to the deposition energy of each hit point, which is similar to the simulation of the amplification process of electrons in readout plane.

The following parameters were set in this process: energy reference is 2458keV, resolution reference is 3, its physical meaning is that under the energy of 2458keV, the deviation of the detector is 3% full width at half maximum. And detectorGain is 1, that is to say, the charge signal gain of the detector used in this simulation is set to 1.

3.3.2 TRestFiducializationProcess

从TPC的几何模型我们可以看出，我们在模拟过程中使用的灵敏体积为以直径1.6m的圆为底，1.2m为高的圆柱体，即我们的读出平面被设定为了直径为1.6m的圆。但是实际情况是，我们使用了52个尺寸为192mm\*192mm的MMs进行拼接，最终得到近似于圆形的读出平面。该过程就是用于对被readout平面检测到的电子进行筛选，删除没有打在实际readout plane的points。

From the geometric model of TPC, we can see that the active volume we used in the simulation process is a cylinder, its base is a circle with a diameter of 1.6m and with a height of 1.2m, that is to say, our readout plane is set to a circle with a diameter of 1.6m. But the actual situation is that we used 52 MMs with a size of 192mm \* 192mm for splicing, and finally get a readout plane that is approximately circular. This process is used to filter the electrons detected by the readout plane and delete those points which did not hit the readout plane.

3.3.3 TRestHitsSmearingProcess

该过程模拟了电子响应过程中的拖尾效应，本次模拟中定义了以下参数：energyReference = 2458keV 和resolutionReference =3.0。其物理意义为在2.458MeV能量下，探测器的误差为3%的半高全宽。

This process simulates the tailing effect in the electronic response process. The following parameters are defined in this simulation: energyReference is 2458keV and resolutionReference is 3.0. Its physical meaning is that under the energy of 2.458 MeV, the deviation of the detector is 3% of the full width at half maximum.

3.3.4 TRestHitsShuffleProcess

该过程通过对电子进行一次shuffle，使得生成的电子数据的顺序打乱，以达到更加真实的效果，本次模拟中我们定义了以下参数：迭代次数定为1000.

This process shuffles the electrons to disrupt the sequence of the electronic data to achieve a more realistic result. In this simulation, we defined the following parameters: The number of iterations is set to 1000.

## 3.4基于REST的电子学模拟

模拟过程的第三步也是最后一步，是对转换成信号事件的数据进行电子学模拟。我们引入了一些方法如：添加噪声、零位抑制、信号成形等。基于此阶段的数据处理是针对信号事件的，所以在最开始需要进行事件类型转换以得到TRestTimeSignalEvent和TRestRawSignalEvent。在数据处理的最后我们将把事件类型重新转换为TRestHitsEvent以便之后机器学习的顺利进行。

The third and final step of the simulation process is the electronic simulation which were implemented to signal events. We introduced some methods such as: adding noise, zero suppression, signal shaping, etc. The data processing based on this stage is for signal events, so at the beginning, an event type conversion is required to obtain TRestTimeSignalEvent and TRestRawSignalEvent. At the end of the data processing, we will convert the event type back to TRestHitsEvent so that machine learning can be proceed.

3.4.1 TRestHitsToSignalProcess

该过程主要目的是得到 TPC 中初级电子所在位置到探测器读出平面的时间投影，从而得到TRestTimeSignalEvent。

TRestHitsEvent在三维坐标系中的坐标（xi，yi，zi）将被转换为TRestTimeSignalEvent。该过程使用读出平面的metadata结构，将每个坐标(xi，yi)与检测器的某个读出通道相关联，并利用读出平面的位置和气体中电子的漂移速度将zi属性转化为时间属性。在本次模拟中，我们在输入参数中给定特定气压和飘逸速度，从而在名为TRestGas的metadata中找到气体属性。

该过程使用的参数为：采样时间：200ns、electricField：1kV/cm、气压：10个大气压、和飘逸速度。

The main purpose of this process is to obtain the time projection of electrons which float from the initial position to the readout plane, and the time projection we obtained is called TRestTimeSignalEvent.

The coordinates (xi, yi, zi) of TRestHitsEvent in the three-dimensional coordinate will be converted to TRestTimeSignalEvent. This process uses the metadata structure of the readout plane, associates each coordinate (xi, yi) with a certain readout channel of the detector, and uses the position of the readout plane and the drift velocity of electrons in the gas to convert zi to Time attributes. In this simulation, we gave specific gas pressure and drift velocity in the input parameters, by doing so, we can find gas properties in the metadata named TRestGas.

The parameters used in this process are: sampling time: 200 ns, electricField: 1 kV per cm, air pressure: 10 atm, and drift velocity which have been calculated by Garfield.

其中飘逸速度将在模拟过程中生成？漂移速度也是软件计算好的，气体比分固定，漂移电场确定，漂移速度和扩散系数就都有了

3.4.2 TRestSignalToRawSignalProcess

该过程将 TRestTimeSignalEvent 作为输入，并将其数据采样到与 TRestRawSignalEvent 的输出类型兼容的数组中，如采样时间 dt和采样点总数。它们作为输入参数提供给该过程。TRestRawSignalEvent的输出类型使我们能够使用REST自带的API的，所以这一步是必要的。

该过程使用的参数为：采样时间：200ns、采样点数量：512、触发模式：第一个产生沉积能量的点、触发延迟：100采样点、gain:1、integralThreshold：10ADC。

This process takes TRestTimeSignalEvent as input and samples its data into an array compatible with the output type of TRestRawSignalEvent, such as the sampling time dt and the total number of sampling points. They are provided as input parameters . The output type which is TRestRawSignalEvent enables us to use the API which are encapsuled in REST, so this process is necessary.

The parameters used in this process are: sampling time: 200 ns, number of sampling points: 512, trigger mode: the first point to generate deposited energy, trigger delay: 100 sampling points, gain: 1, integralThreshold: 10 ADC.

（这里可以给出一个信号的波形）

3.4.3 TRestRawSignalShapingProcess

该过程模拟了 TRestRawSignalEvent中电子信号整形器的仿真。它将我们设定好的分析响应函数和输入的TRestRawSignalEvent做了一次卷积，从而获得检测器中的原始电荷分布。这一过程提供了引入任意波函数作为响应函数的可能性，为生成的输出增加了真实性。

该过程涉及到的参数为：shapingType：Gaus、shapingTime：1.014us、gain1000

This process simulates the electronic signal shaper in TRestRawSignalEvent. It does a convolution of the analysis response function we set and the input TRestRawSignalEvent, thus we obtain the original distribution of charge in the detector. This process provides the possibility of introducing an arbitrary wave function as a response function, adding authenticity to the generated output.

The parameters involved in this process are: shapingType: Gaus, shapingTime: 1.014us, gain: 1000

3.4.4 TRestRawSignalAddNoiseProcess

该过程用于模拟电子噪声的影响，同时模拟采集过程中时间信号的波动。我们在使用过程中会引入噪声的幅度这个变量，我们将在metadata中定义这个变量。在该过程中，我们使用的添加噪声方法为：给TRestRawSignalEvent 中的每个bin分配一个高斯分布后的独立的随机值。

该过程涉及到的参数为：noiselevel：10/4096\*120 fC。

This process is used to simulate the influence of electronic noise and to simulate the fluctuation of the time signal during the acquisition. We will introduce the variable of the amplitude of noise in this process, we will define this variable in metadata. In this process, we assign an independent random value after Gaussian distribution to each bin in TRestRawSignalEvent as the method of adding noise.

The parameters involved in this process are: noiselevel: 10/4096 \* 120 fC.

3.4.5 TRestZeroSuppresionProcess

该过程的目的是将接近零位的信号进行筛选删除，手动提高零位。

从理论结果我们可以得知，信号强度在一定timebin范围内的振幅远高于其余timebin。为了使得在零位附近振动的信号经过转换之后不会对信号事件的机器学习产生负面影响，我们将设置偏移零位，以删除无用信号。

该过程涉及到的参数有：baseLineRange：20-40ADC、integralRange：(100,512)、pointThreshold：3.5ADC、pointsOverThreshold：5ADC、signalThreshold：2.8ADC、sampling：200ns

需要特别说明的是，TRestZeroSuppresionProcess的输入是TRestRawSignalEvent，而输出是TRestTimeSignalEvent，即通过这个过程我们将对数据类型进行一次转换，简化了process的步骤。

The purpose of this process is to filter and delete signals close to zero, and manually increase the zero position.

From the theoretical results, we can tell that the amplitude of the signal intensity in a certain timebin is much higher than those in other timebins. In order to make the signal vibratings near the zero position do not implement huge affect to the machine learning, we will reset the offset zero position to delete those useless signals.

The parameters involved in this process are: baseLineRange: 20-40 ADC, integralRange: (100,512), pointThreshold: 3.5 ADC, pointsOverThreshold: 5 ADC, signalThreshold: 2.8 ADC, sampling: 200ns

Need of sprcial note is that the input of TRestZeroSuppresionProcess is TRestRawSignalEvent, and the output is TRestTimeSignalEvent, that is to say, through this process we will convert the data type, simplifying the steps of the simulation.

3.4.6 TRestSignalToHitsProcess

该过程是TRestHitsToSignalProcess的逆过程，我们输入TRestTimeSignalEvent ，利用其中的时间信息和气体属性来恢复或重建TRestHitsEvent中的Hits点。具体过程为：每一个信号的ID都会对应readout的metadata中的特定描述，同时会对应到特定的读出通道。从而可以获得重建的坐标，

该过程使用的参数有：电场强度：1kV/cm、气压：10个大气压、飘逸速度：由Garfield计算得出。此处参数和TRestHitsToSignalProcess相匹配，确保作为逆过程，经过此步骤不会改变数据真实性。

This process is the inverse process of TRestHitsToSignalProcess. We input TRestTimeSignalEvent and use the time information and gas attributes to restore or reconstruct the Hits point in TRestHitsEvent. The specific process is: the ID of each signal will correspond to a specific description in the metadata of readout, and will also correspond to a specific readout channel. So that the reconstructed coordinates can be obtained,

The parameters used in this process are: electric field strength: 1 kV per cm, air pressure: 10 atm, and drift velocity: calculated by Garfield. The parameters here match TRestHitsToSignalProcess, so we can ensure that this process is exactly the reverse process, and the data authenticity will not be changed after this process.