LHAASO
高海拔宇宙线观测站

中国科学院高能物理研究所
Institute of High Energy Physics
Chinese Academy of Sciences

LHAASO对宇宙线能谱的测量及CORSIKA模拟软件使用

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LHAASO暑期学校・昆明

主要内容

- 在地面测量宇宙线能谱的意义及困难
- LHAASO在宇宙线能谱测量中的优势
- **LHAASO的全粒子能谱的测量**
- **LHAASO的成分及成分能谱的测量**
- **LHAASO的绝对能标**
- CORSIKA软件的使用

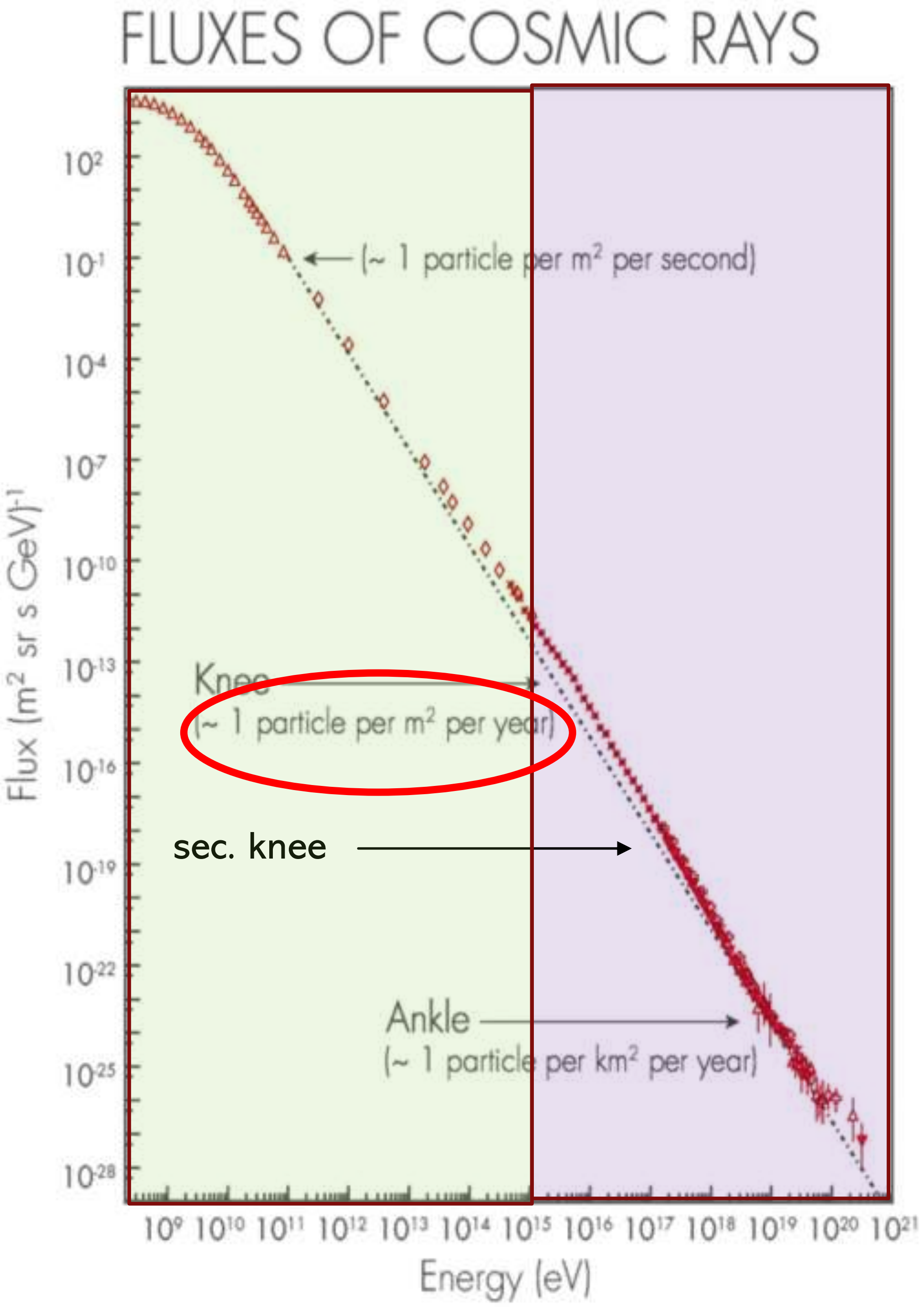
地面测量宇宙线的意义

- 能谱存在精细结构:(宇宙线能谱指数的变化)
  - 膝：3PeV （-2.7变为-3.1）
  - 第二膝：100PeV （-3.1变为-3.3）
  - 踝：5EeV （谱指数变回-2.7）
  - GZK截断：50EeV

$$F = E^{\gamma}$$

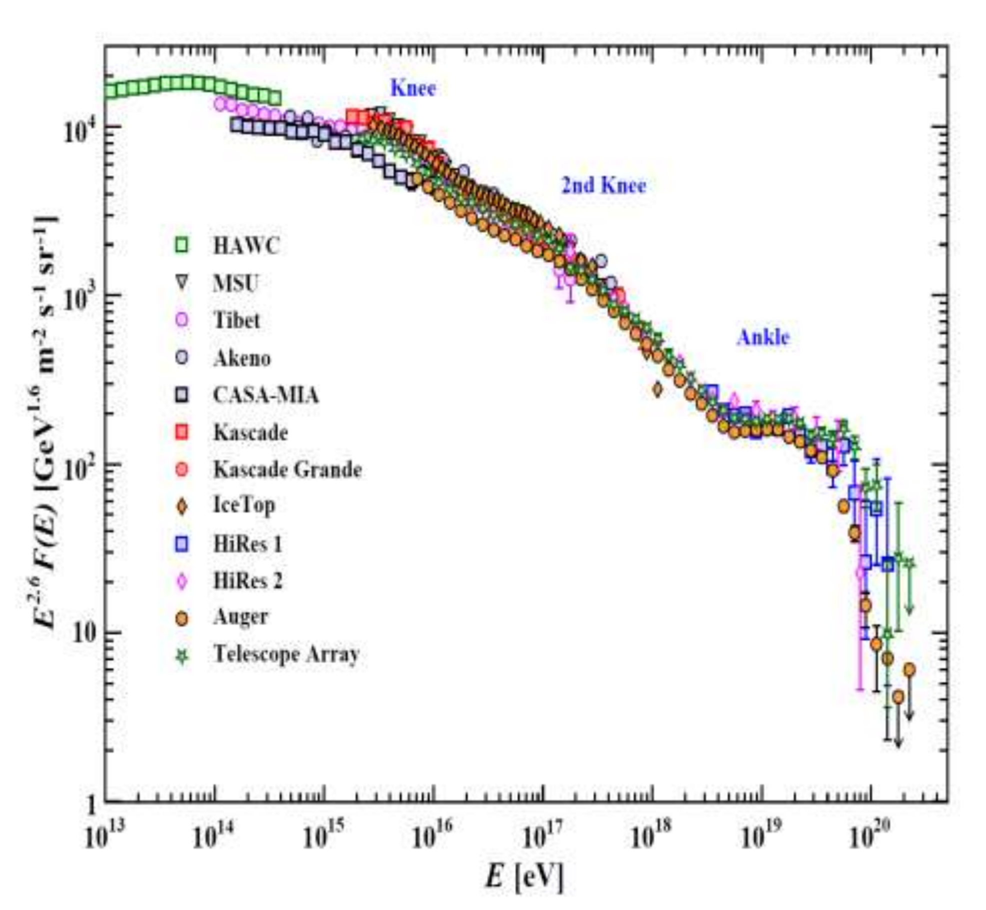
- “燕过留痕”
  - 膝：银河系加速源对宇宙线加速能力的上限，质子的膝最先出现，然后为氦核等更重的核子，并且不同核子的膝的位置呈现Z依赖
  - 第二膝：银河系加速源对铁核加速能力的上限

对宇宙线能谱及成分的测量有助于解决宇宙线起源这一世纪难题



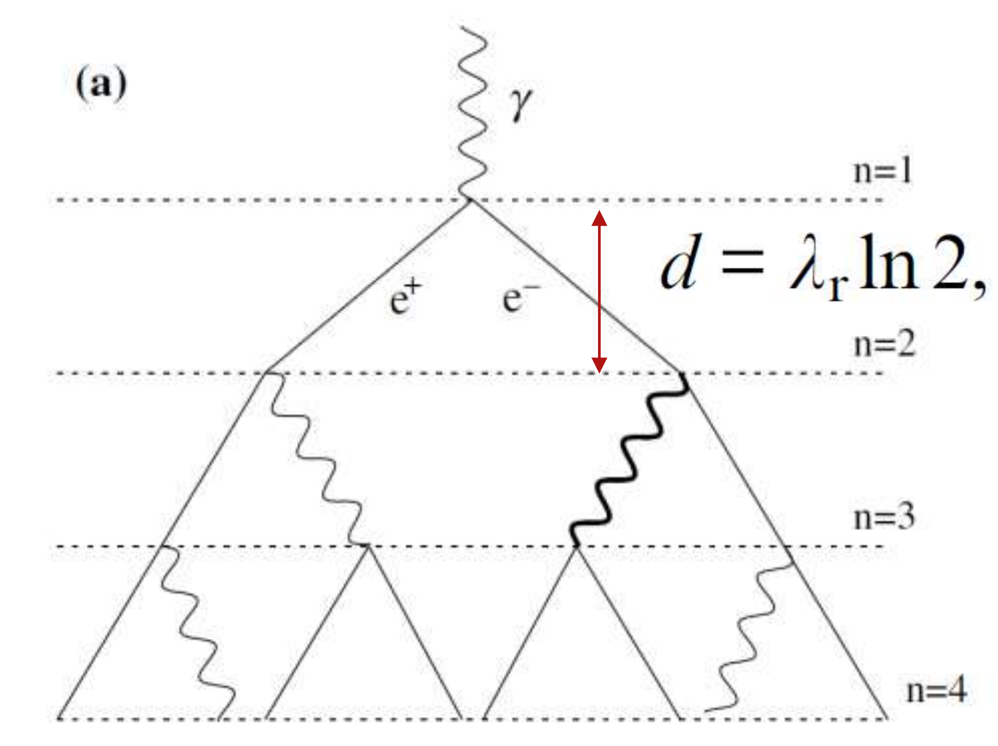
地面测量宇宙线的困难

- 间接测量 通过广延大气簇射间接测量，巨大的有效面积
- 能量，成分信息都已丢失，只能通过大气簇射的特征来判断
  - 不同成分之间特征的差异很小，并伴随有巨大的统计涨落
  - 能量和成分的重建互相依赖
  - 受强相互作用模型的影响
  - 探测器绝对能标无法标定
    - 自然界中缺少能量和成分已知束流对探测器进行绝对能量标定



广延大气簇射

广延大气簇射 电磁级联



$d = \lambda_r \ln 2,$

高能伽马进入大气层之后和大气相互作用产生正负电子对；

正负电子在大气的库仑场中通过韧致辐射，有辐射出光子；

级联不断发展，直到电子的能量降低到产生韧致辐射的阈能时，簇射发展到极大。

此后电离能损占主导地位，簇射开始衰减

$$N_{\max} = 2^{n_c} \qquad E_\circ = \xi_c^e N_{\max}$$

$$\xi_c^e = 85\ \mathrm{MeV}$$

$$n_c = \ln[E_\circ/\xi_c^e]/\ln 2,$$

$$X_{\max}^{\gamma} = n_c \lambda_r \ln 2 = \lambda_r \ln[E_\circ/\xi_c^e].$$

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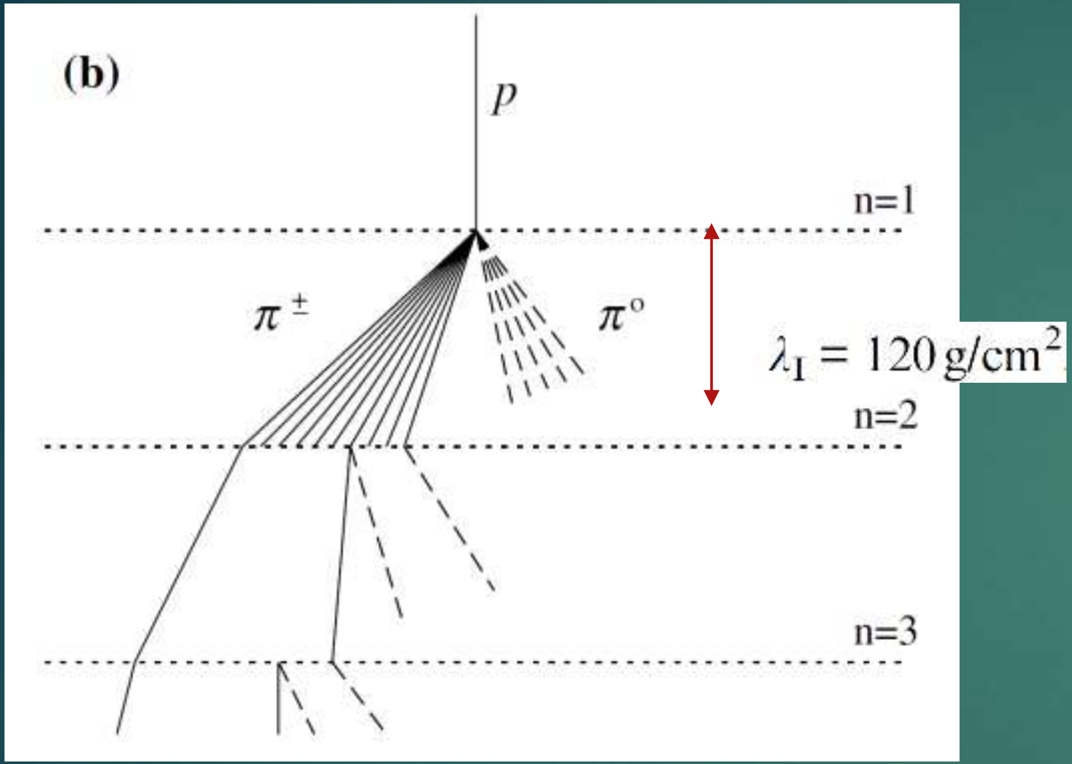
广延大气簇射 强子级联



- 高能宇宙线进入到大气层之后和大气相互作用产生π^0， $\pi^{\mp}$，
- 多重数：$3/2N_{ch}$
- π^0：衰变，引发电磁级联，产生e,γ
- $\pi^{\mp}$： 进一步发生相互作用，或者衰变产生 μ,
  - 当衰变长度$\gamma c\tau\rho$小于相互作用长度时则发生衰变

$$E_\pi = \frac{E_\circ}{\left(\frac{3}{2}N_{ch}\right)^n}$$

$$n_c = \frac{\ln[E_\circ/\xi_c^\pi]}{\ln\left[\frac{3}{2}N_{ch}\right]} = 0.85\log_{10}[E_\circ/\xi_c^\pi]$$

$$\xi_c^\pi = 20\ \mathrm{GeV}$$

$$N_\mu = N_\pi = (N_{ch})^{n_c}$$

$$E_\circ = \xi_c^e N_{max} + \xi_c^\pi N_\mu$$

$$X_{max}^p = X_\circ + \lambda_r \ln\left[E_\circ/(3N_{ch}\xi_c^e)\right]$$

$$X_{max}^\gamma = n_c\lambda_r \ln 2 = \lambda_r \ln[E_\circ/\xi_c^e]$$

叠加模型 (重核产生的大气簇射的特点)

原子核(A,E) = A个能量为E/A的质子

$$N_\mu^A = N_\mu^p \left(\frac{E}{A}\right)^\beta \quad \beta \sim 0.85$$

$$N_e^A = N_e^p \left(\frac{E}{A}\right)^\alpha \quad \alpha \sim 1.05$$

$$X_{max}^A = X_{max}^p - \lambda_r lnA$$

能量相同时，越重的核子缪子数越多，电磁粒子数越少，Xmax的位置越高

簇射中的光---切伦科夫光

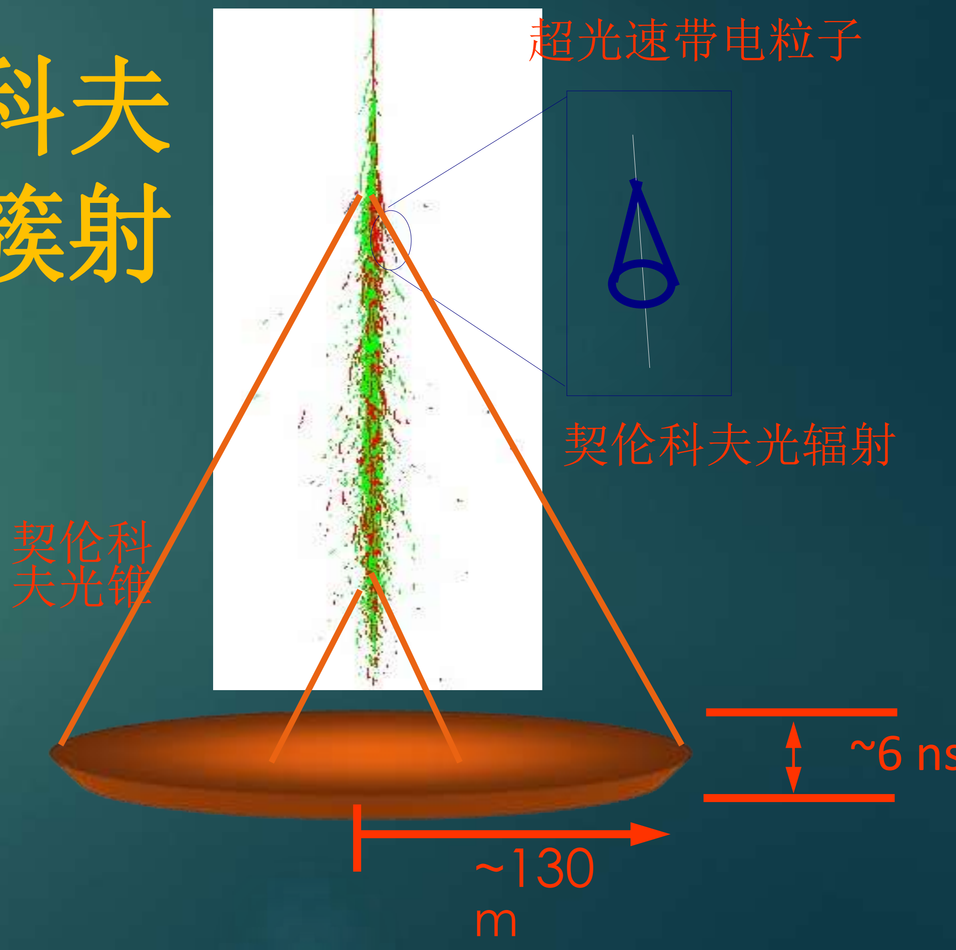
- 产生机制，当次级粒子的速度大于光在空气中的速度时
- 产生契伦科夫光的阈能

$$E_{th} = \frac{m_0 c^2}{\sqrt{1-1/n^2}}$$

- 契伦科夫光的方向性

$$\cos\theta = 1/\beta n$$

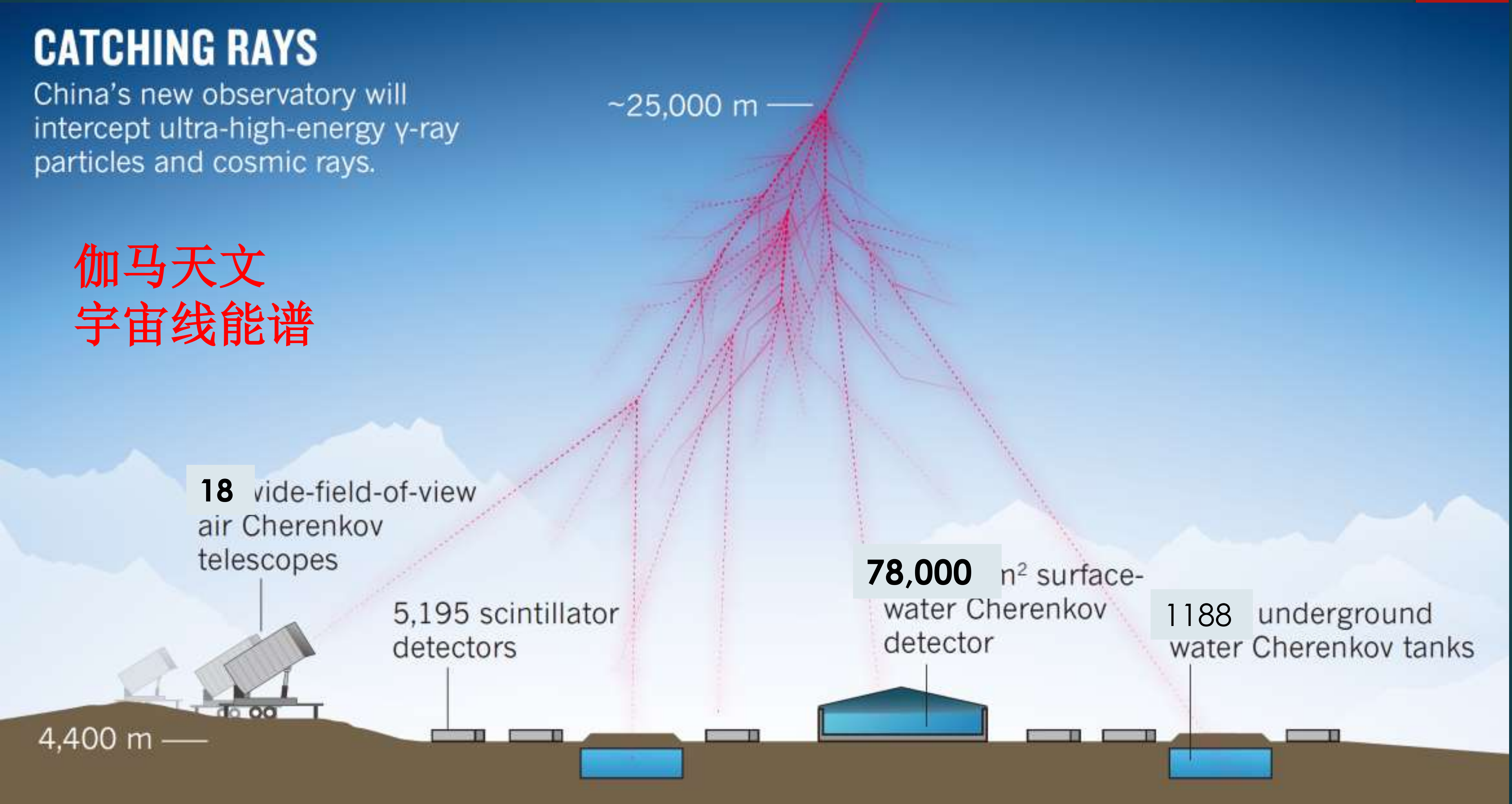
簇射中的切伦科夫光主要产生自簇射中的正负电子



Medium	Index of refraction (n)	Particle threshold energy in MeV[a]		
		Electron[b]	Muon[c]	Proton[d]
Air	1.00027712[e]	21.2	4380.9	38925.9
Silica aerogel[f]	1.05	1.16	240.7	2139.0
Water	1.332	0.263	54.3	482.1
Glass[g]	1.47	0.186	38.5	341.9
Plastic[h]	1.52	0.167	34.6	307.6
Ceramic[i]	2.1	0.070	14.5	128.7
Diamond	2.4	0.051	10.6	93.9

LHAASO的挑战与机遇

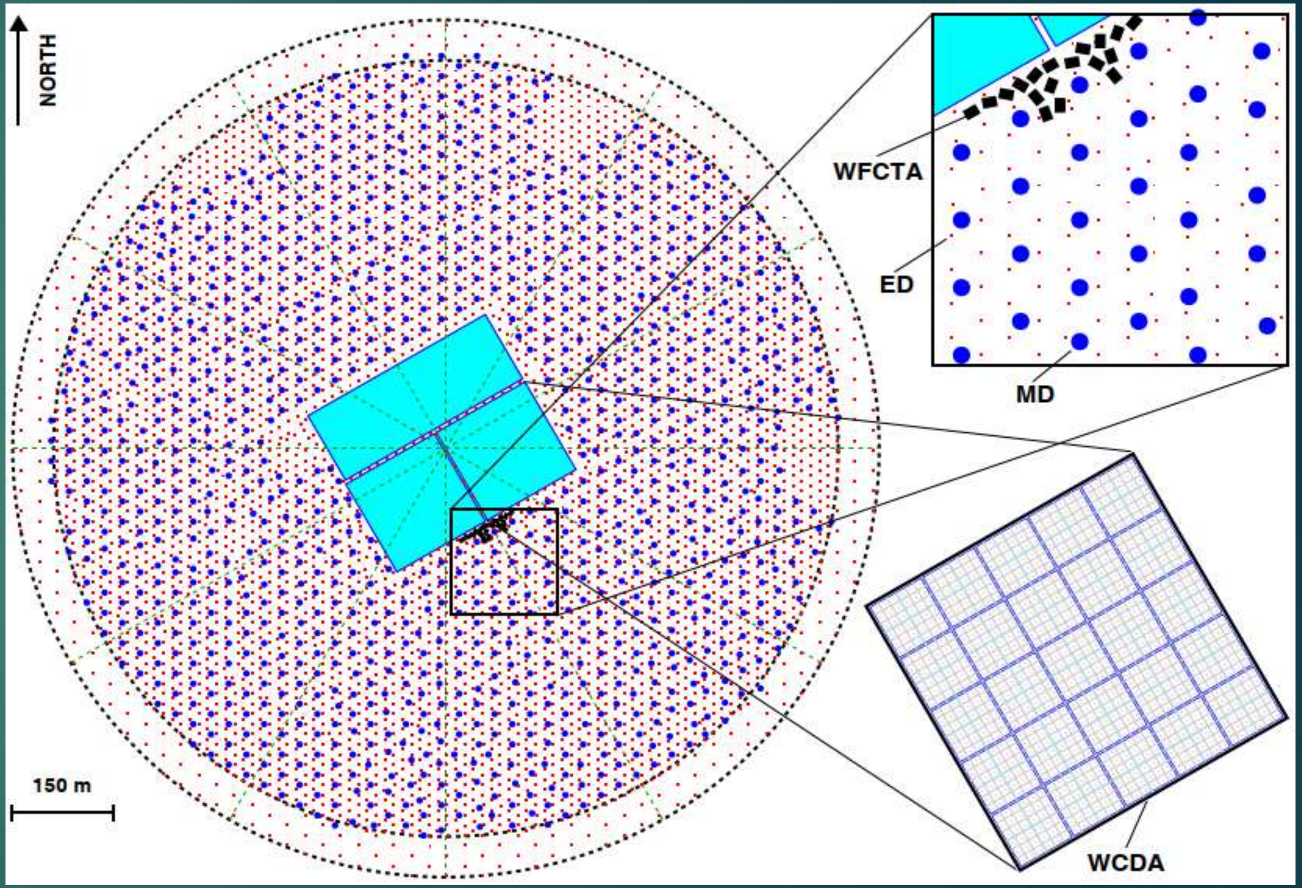
LAASO对宇宙线的探测



伽马天文
宇宙线能谱

LHAASO对宇宙线能谱的测量

- 多参数测量
- KM2A：
  - 测量簇射中的电磁粒子数和缪子数
- WFCTA：
  - 测量簇射中**带电粒子**所辐射出的契伦科夫光子



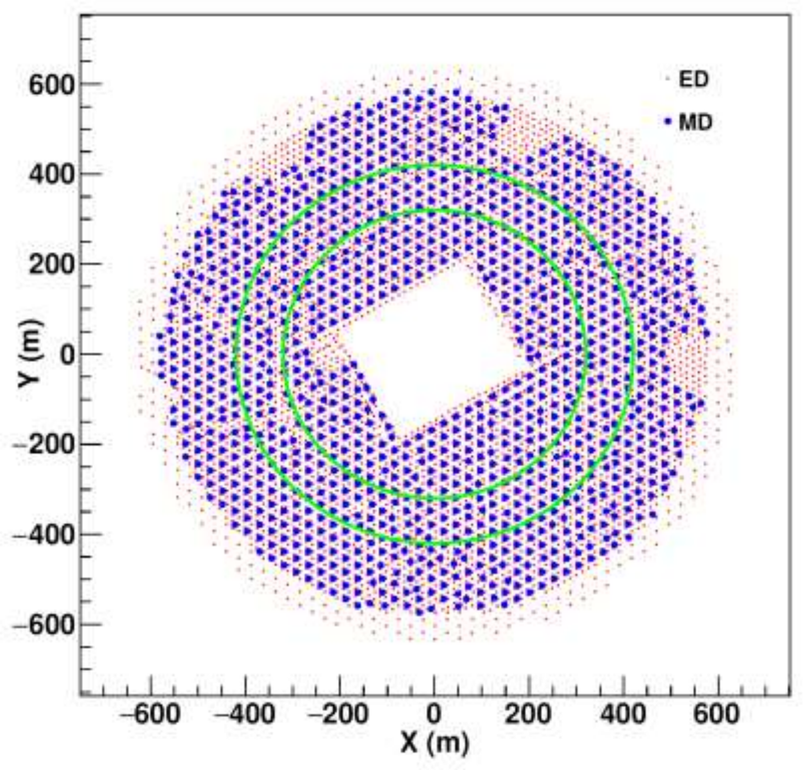
LHAASO对宇宙线全粒子谱的测量

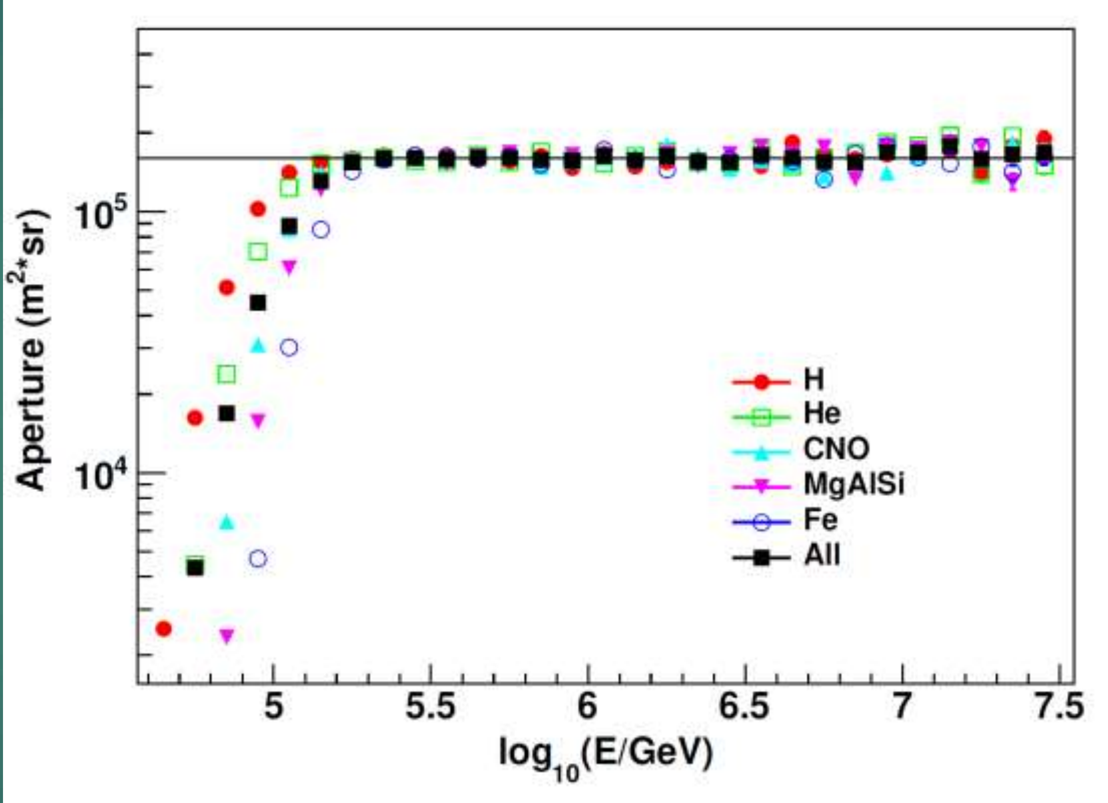
全粒子能谱测量

$$f = \frac{dN}{ATdE}$$

有效面积

能量重建





芯位：320m-420m

天顶角：10°-30°

$$A = S\int_{\theta_1}^{\theta_2} \sin\theta\cos\theta\, d\theta \int_0^{2\pi} d\varphi$$

0.16km²sr

能量重建

E

E_e E_h

$$E_\circ = \xi_c^e N_{max} + \xi_c^\pi N_\mu$$

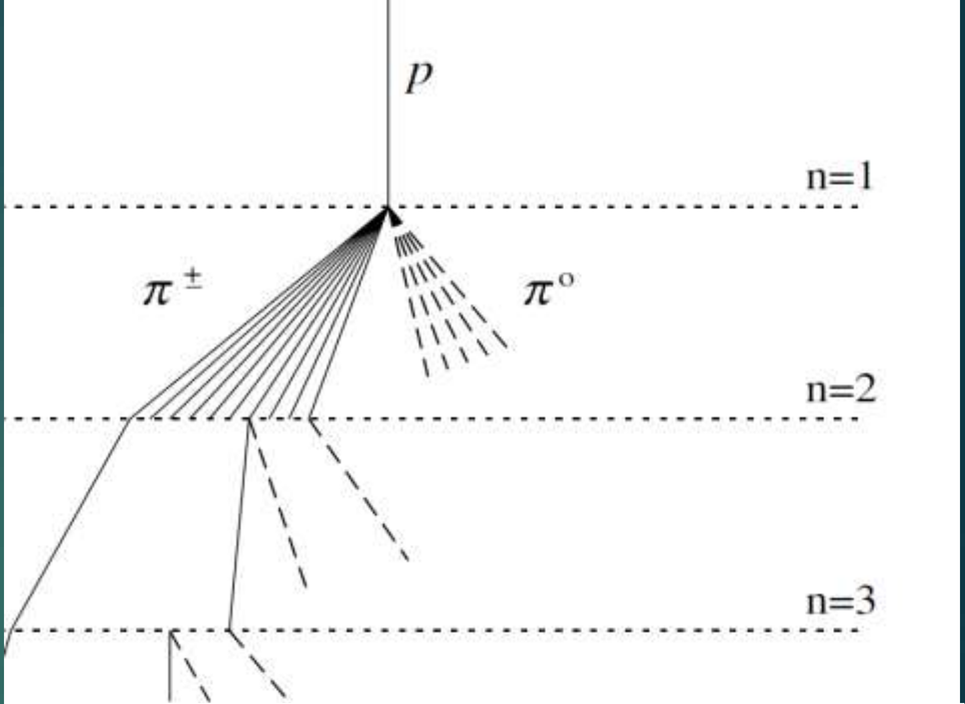
簇射极大时的电磁粒子数和缪子数

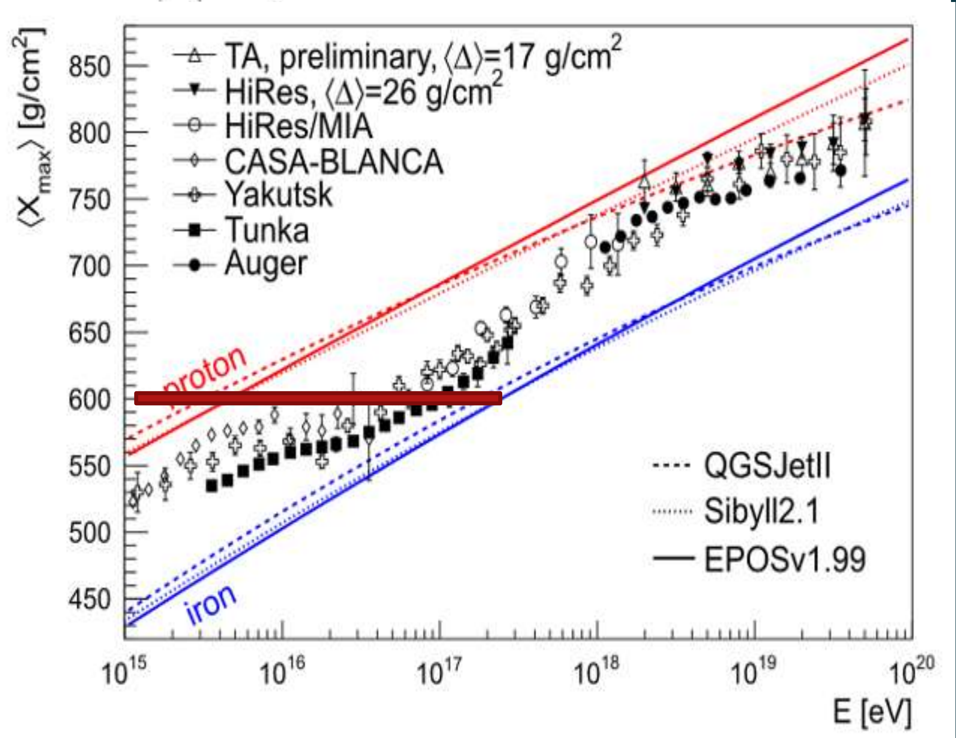
LHAASO的优势：

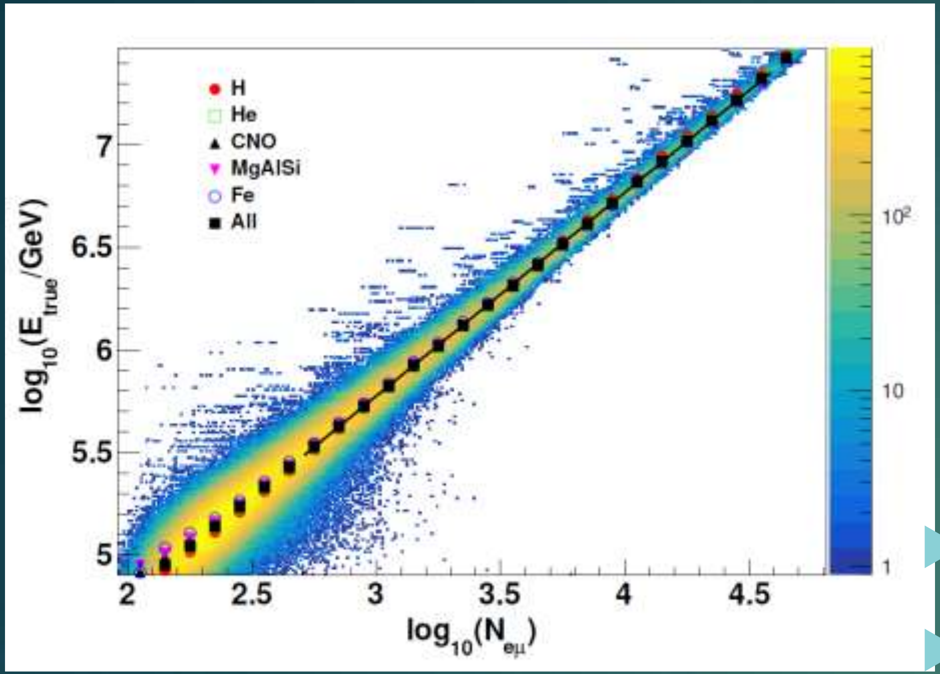
高海拔， 4410米，600g/cm²，位于簇射极大附近

多参数： 实现成分弱依赖的能量重建

$$\boxed{N_{e\mu} = N_e + 2.8N_\mu}$$

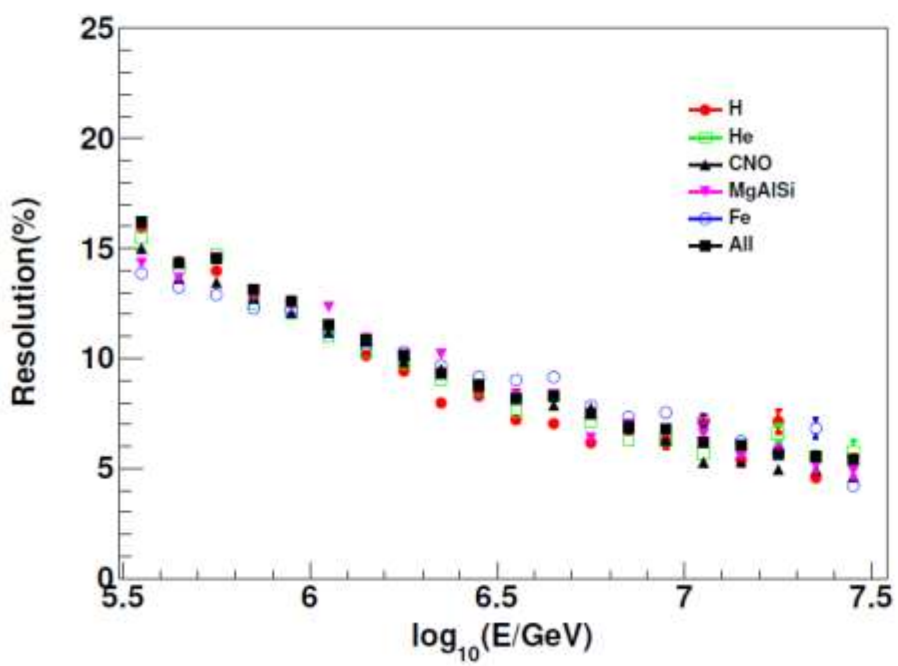


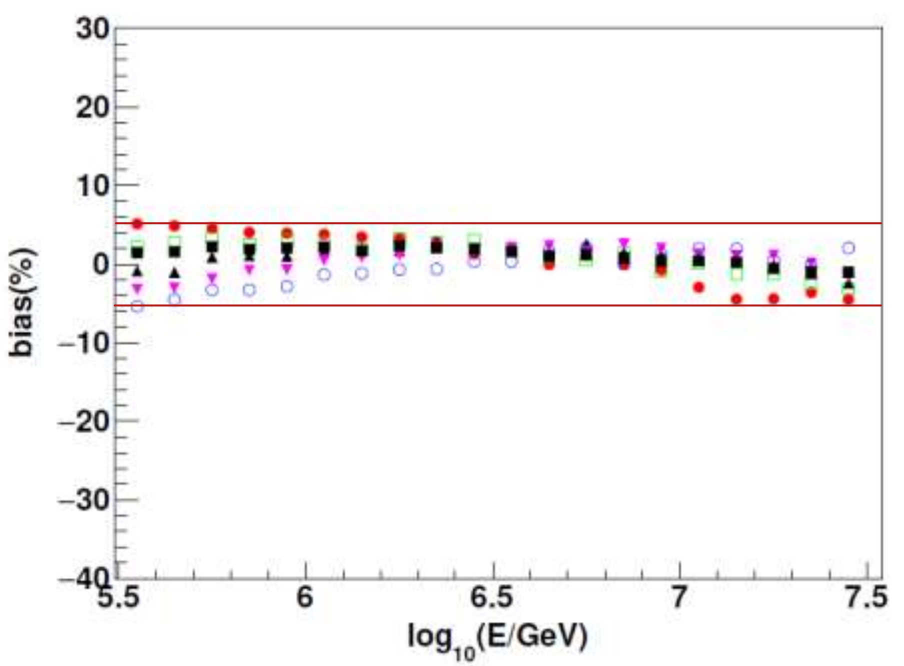




$$log_{10}E = p_1 log_{10}N_{e\mu} + p_0$$

- 分辨率：重建能量和真实能量之间相对差异的分布宽度
- 重建偏差：重建能量和真实能量之间相对差异的平均值





能量重建对成分模型和相互作用模型的依赖性

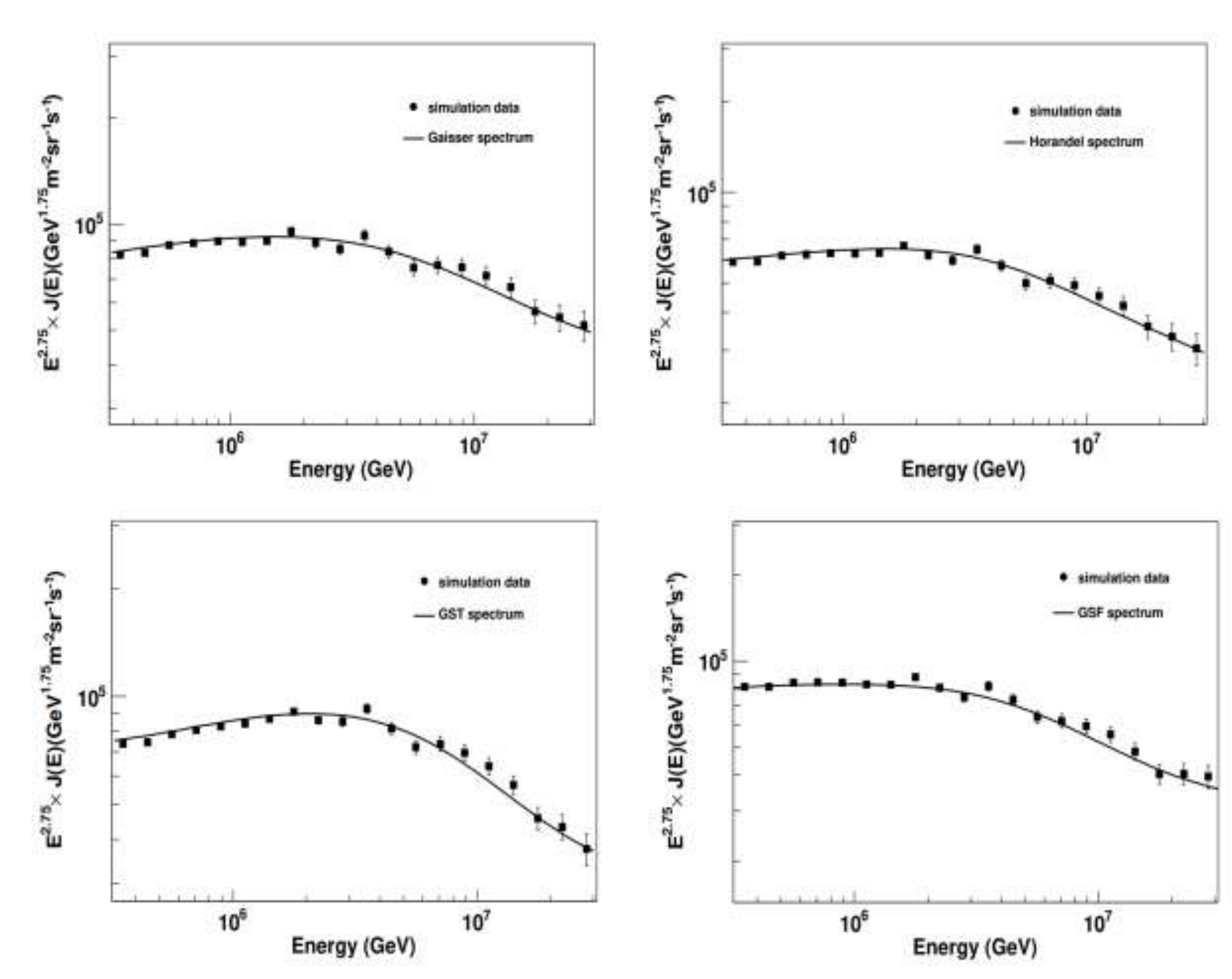
$$log_{10}E = p_1 log_{10}N_{e\mu} + p_0$$

Model	p_0	p_1
Gaisser	2.799	0.992
Horandel	2.798	0.992
GST	2.802	0.992
GSF	2.797	0.992

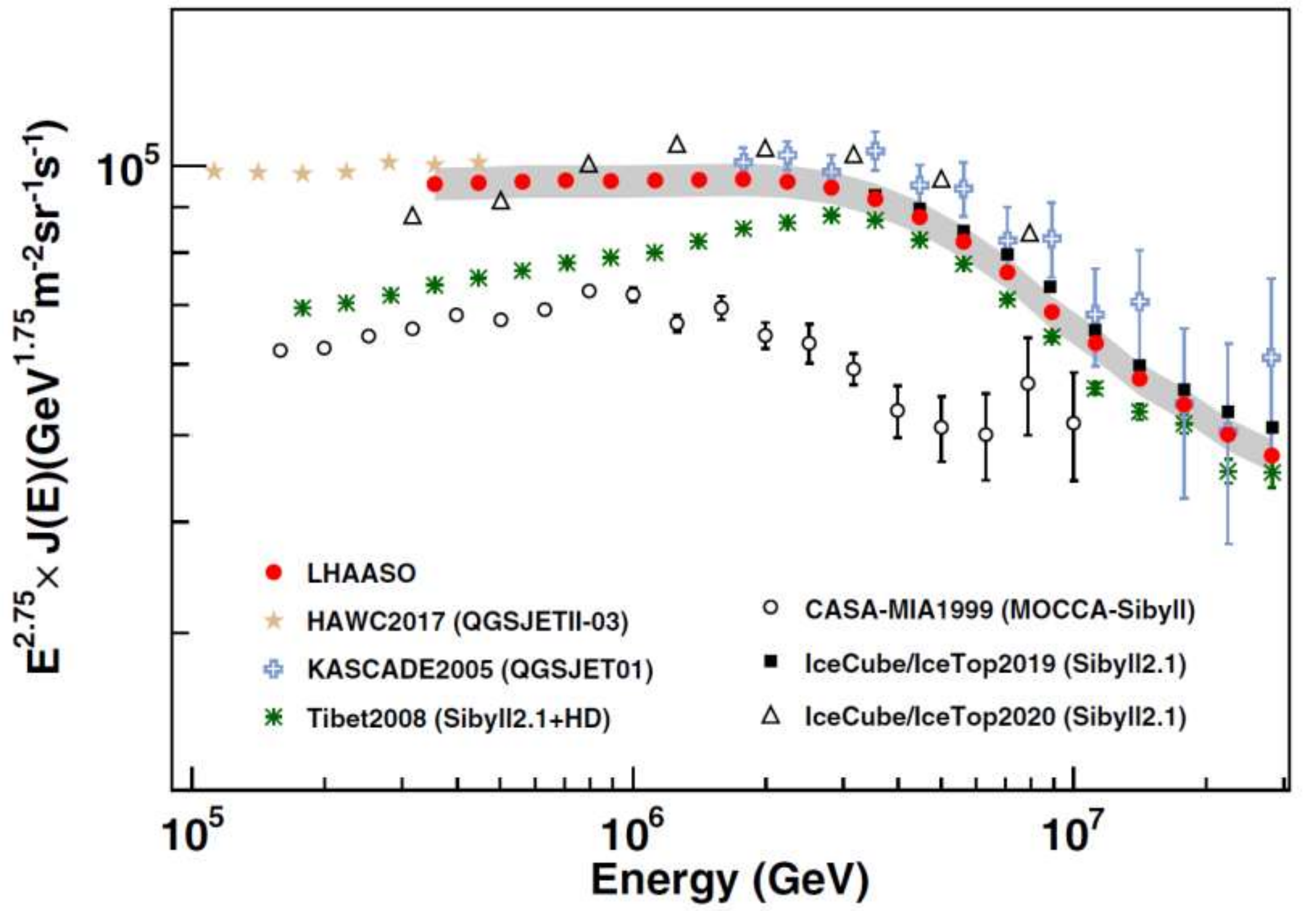
不同成分模型所得到的能量重建参数

Model	p_0	p_1
QGSJETII-04	2.799	0.992
EPOS-LHC	2.789	0.992
SIBYLL-2.3d	2.784	0.995

不同相互作用模型所得到的能量重建参数

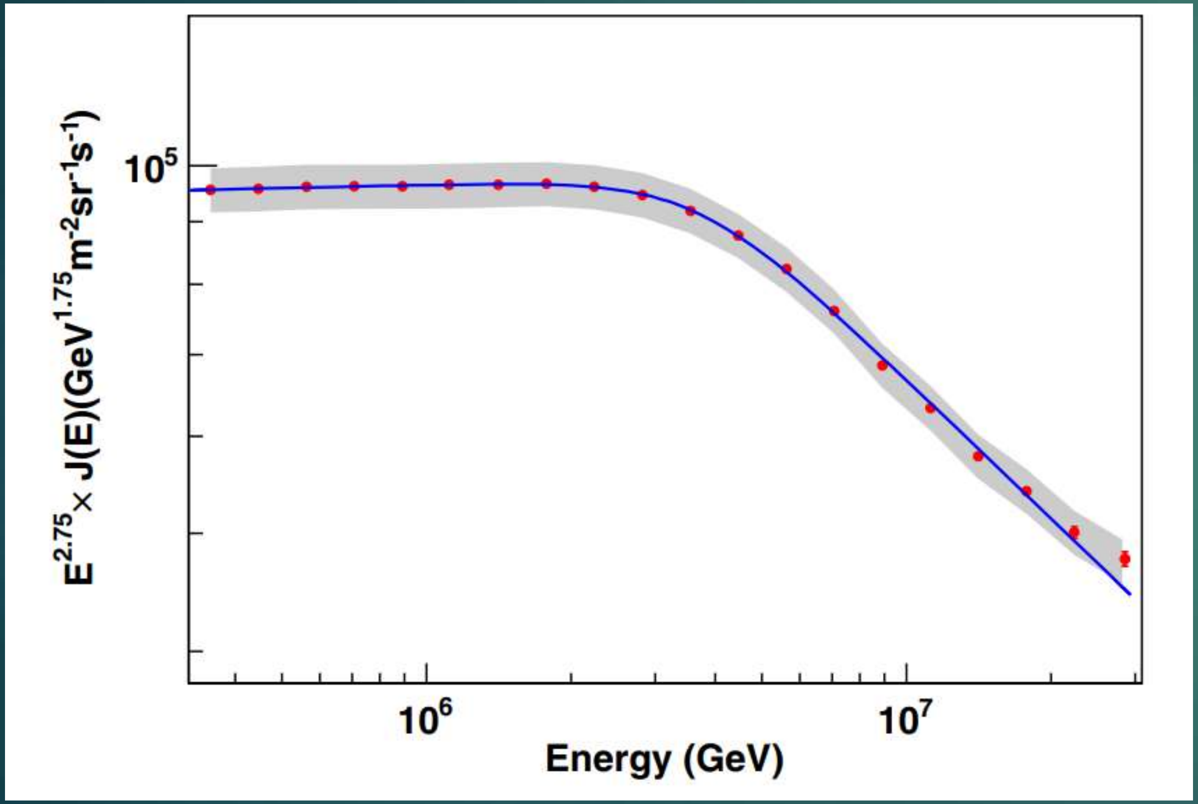


$$\log_{10}(E/\mathrm{GeV}) = 2.791 + 0.993 \cdot \log_{10}(N_{e\mu})$$



- 成分模型引入的系统误差 +-1.5%
- 强相互作用引入的系统误差 +-2.5%
- 气压变化引入的系统误差 +-3%

Phys. Rev. Lett. 132, 131002 (2024)



$$J(E) = \Phi_0 \cdot (E)^{\gamma_1} \left(1 + \left(\frac{E}{E_b}\right)^s\right)^{(\gamma_2 - \gamma_1)/s}$$

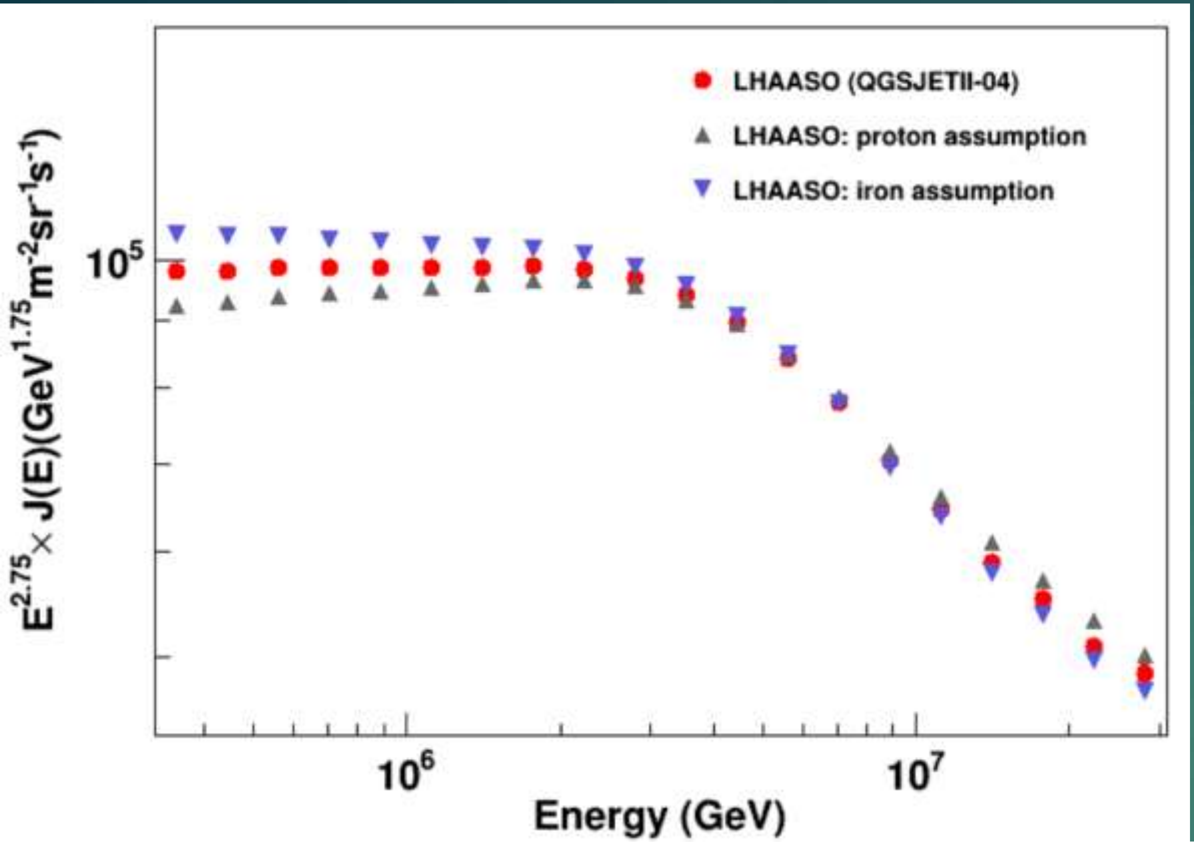
$E_b = 3.67 \pm 0.05 \pm 0.15$ PeV

$\gamma_1 = -2.7413 \pm 0.0004 \pm 0.0050$

$\gamma_2 = -3.128 \pm 0.005 \pm 0.027$

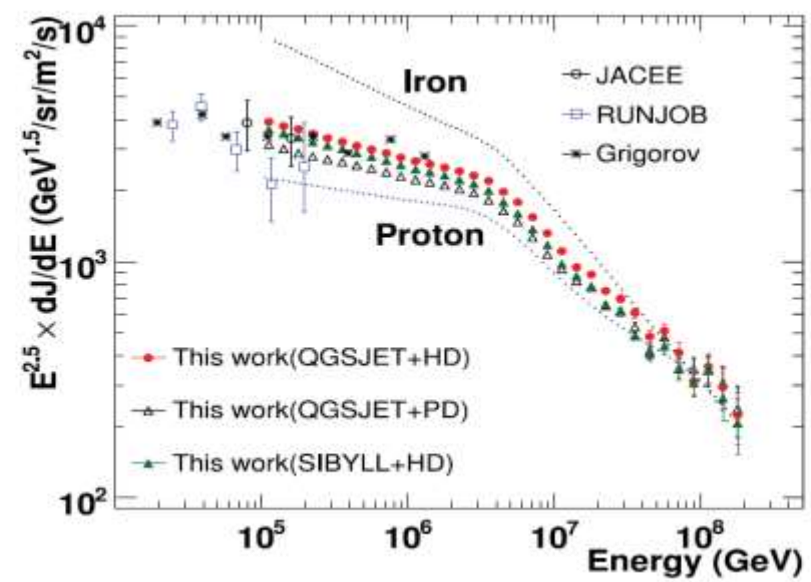
$s = 4.2 \pm 0.1 \pm 0.5$

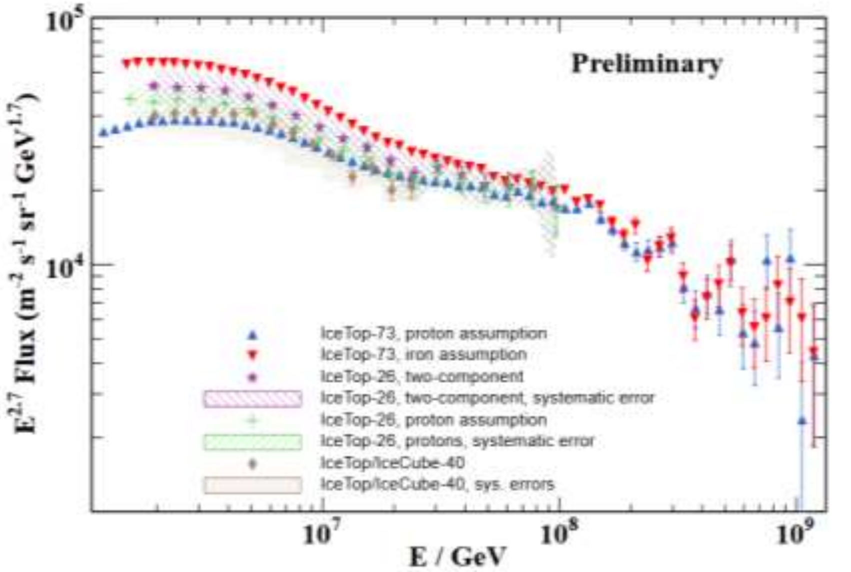
没有成分依赖的能量重建的优势



在极端成分模型（纯质子及纯铁核）假设下，LHAASO所得到的差异为12%

Asgamma为300%，IceTop为200%



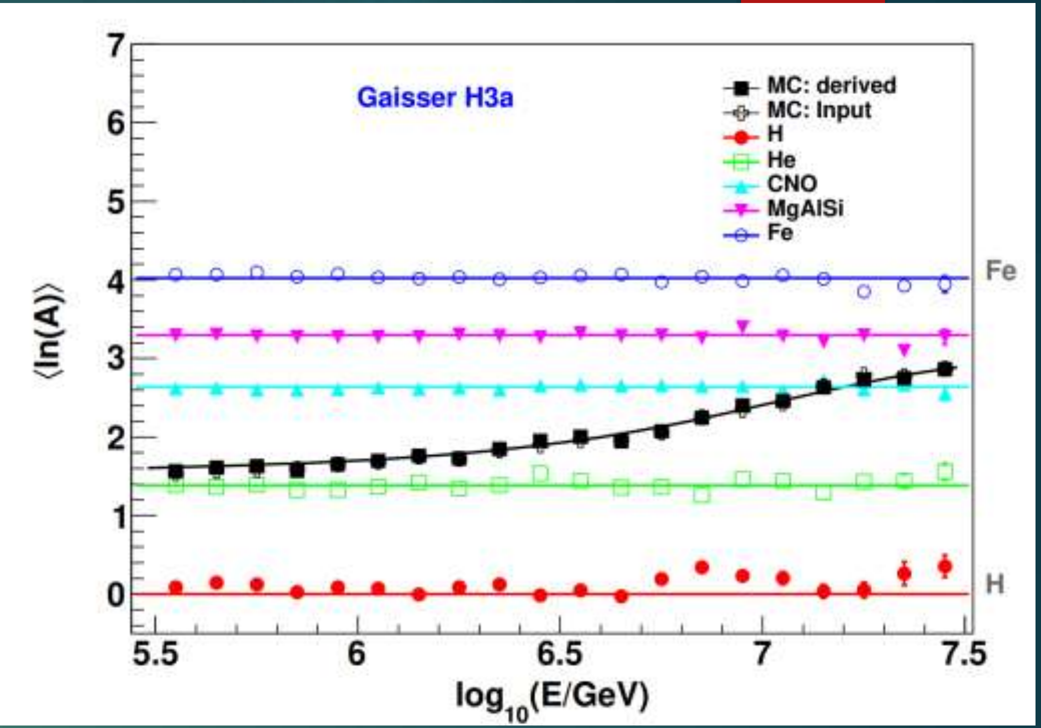


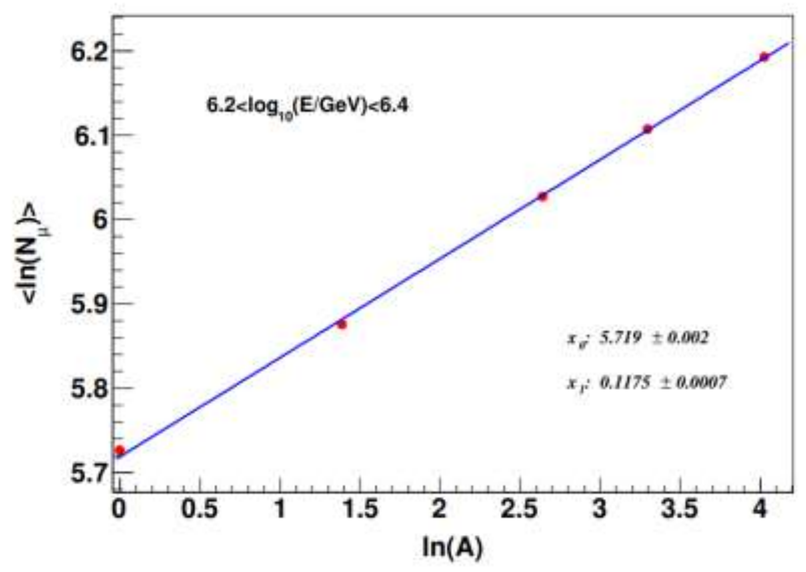
利用LHAASO-KM2A测量平均对数质量 <lnA>

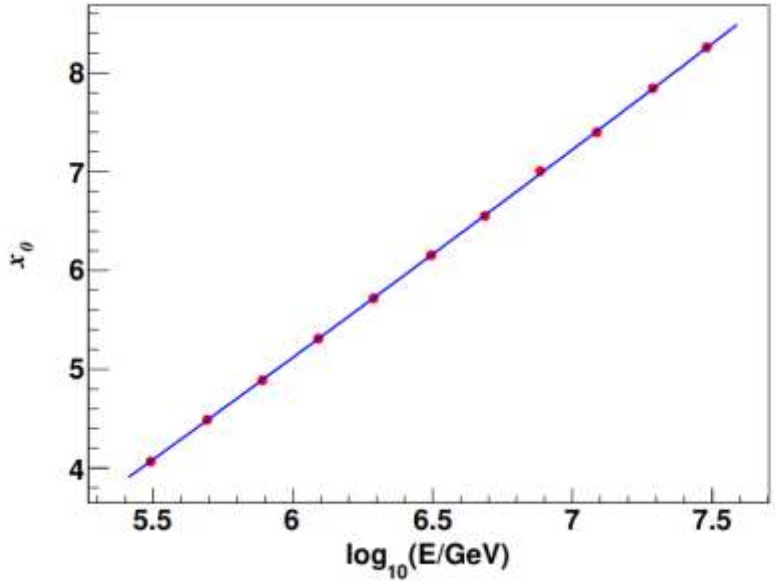
叠加模型

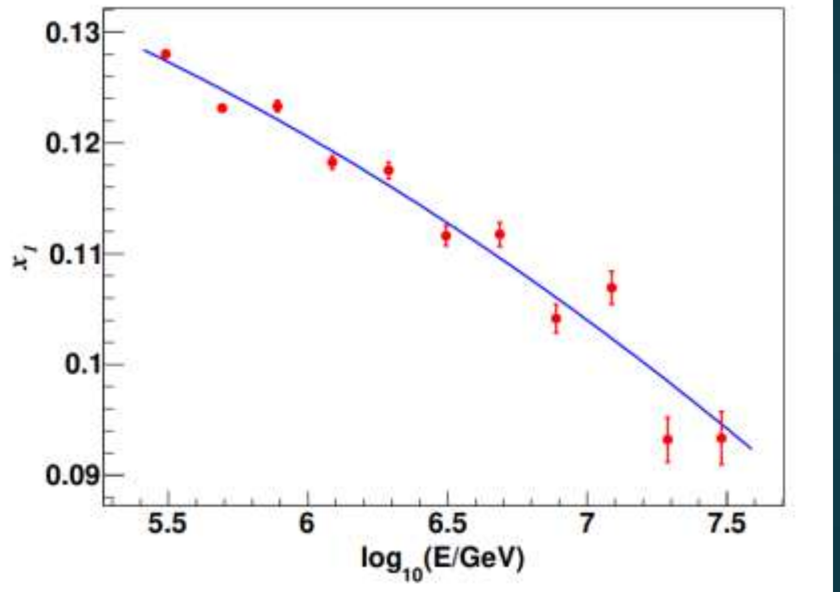
- 原子核(A,E) = A个能量为E/A的质子

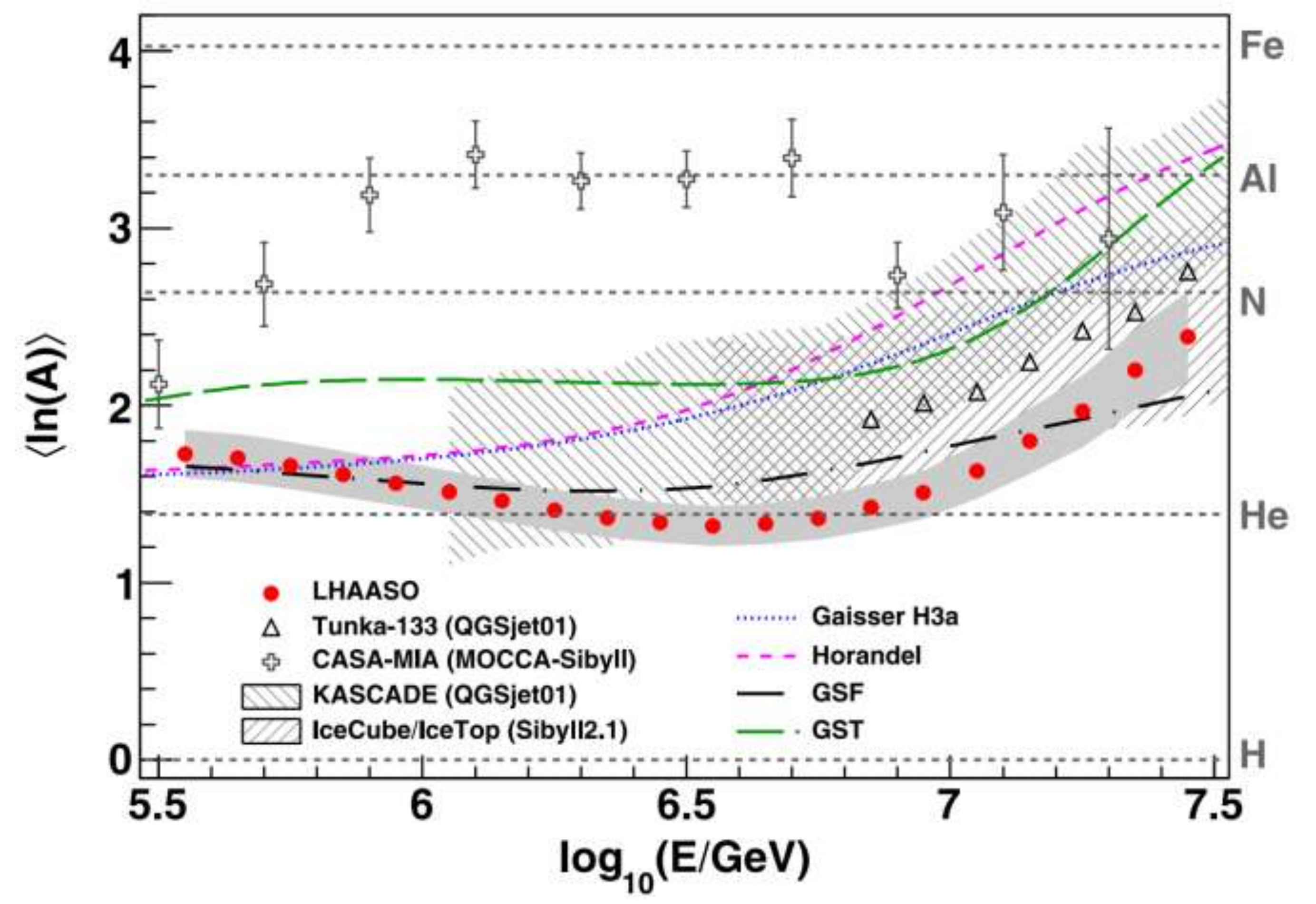
$N_\mu \propto A \cdot (\frac{E}{A})^\beta$ ⟶ $\langle \ln(N_\mu) \rangle = x_0 + x_1 \cdot \langle \ln(A) \rangle$











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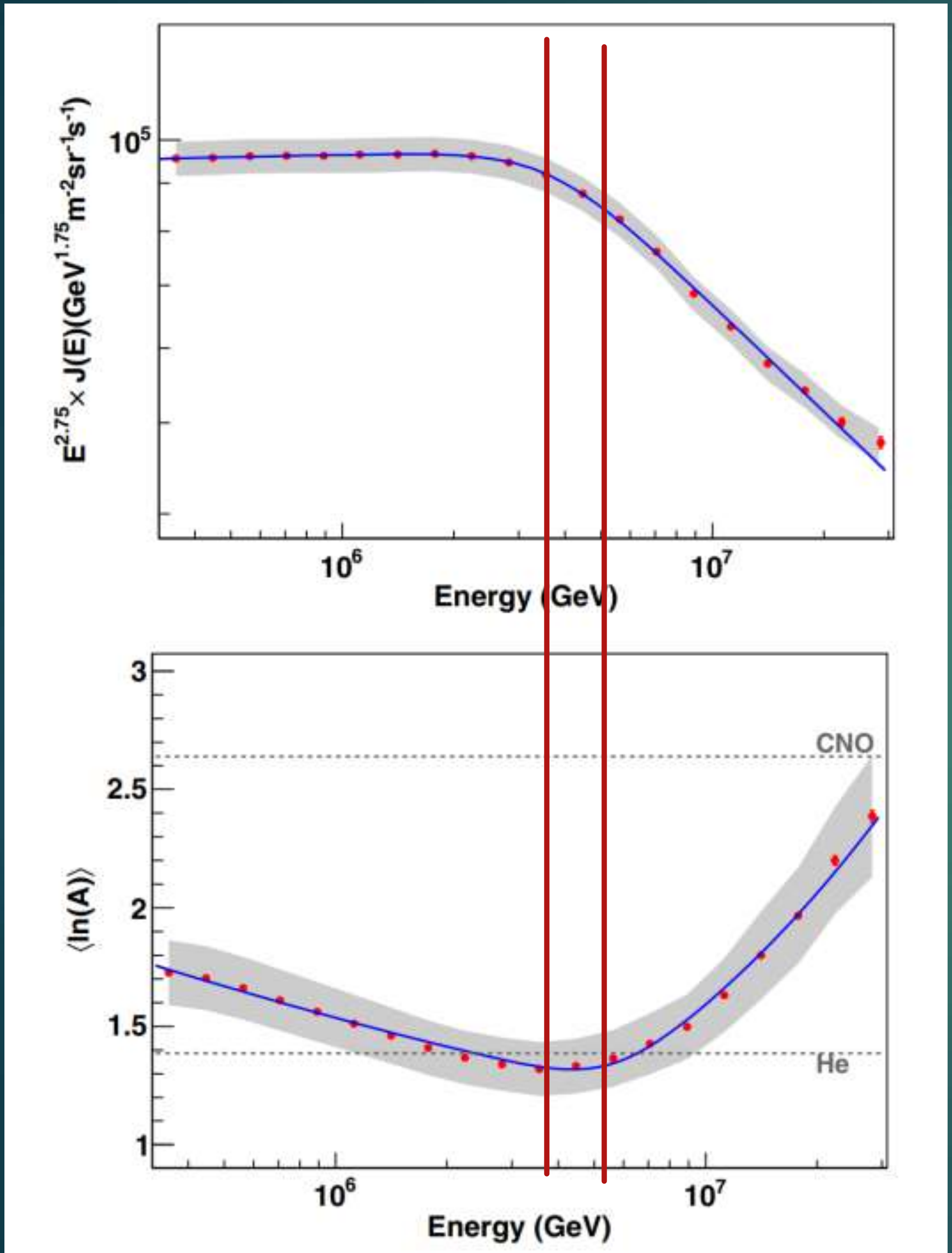


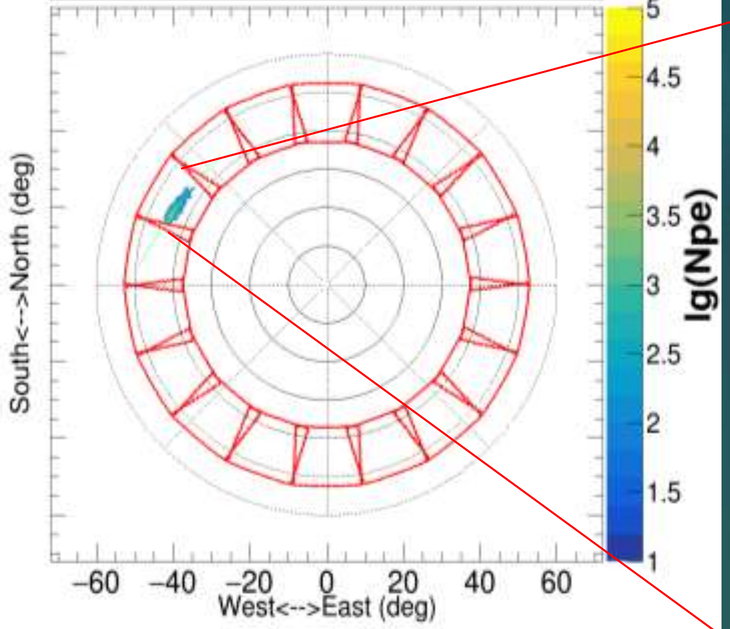
$$J(E) = \Phi_0 \cdot (E)^{\gamma_1}\left(1+\left(\frac{E}{E_b}\right)^s\right)^{(\gamma_2-\gamma_1)/s}$$

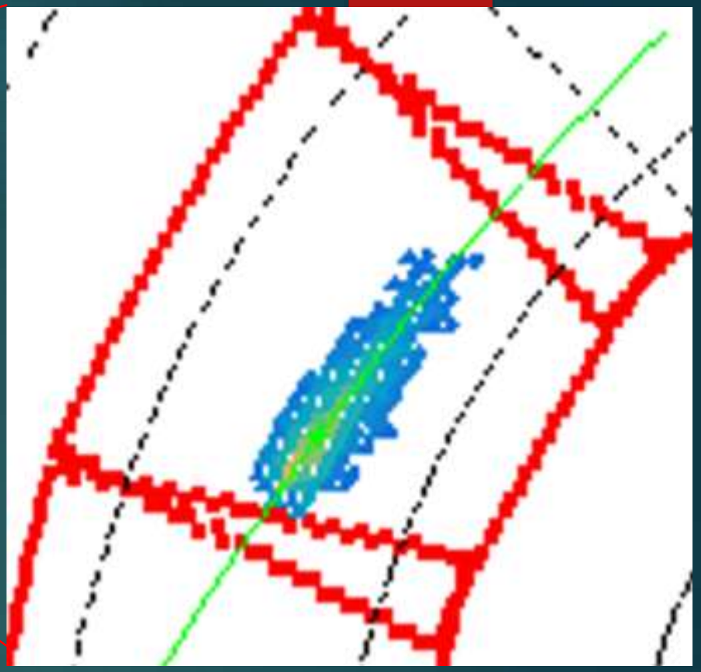
- 膝前，<lnA>与能量的关系，服从谱指数-0.12
- 膝后，谱指数变为了0.497
- 暗示膝为轻成分的膝，膝前谱指数为：$-2.74-(-0.12)=-2.62$

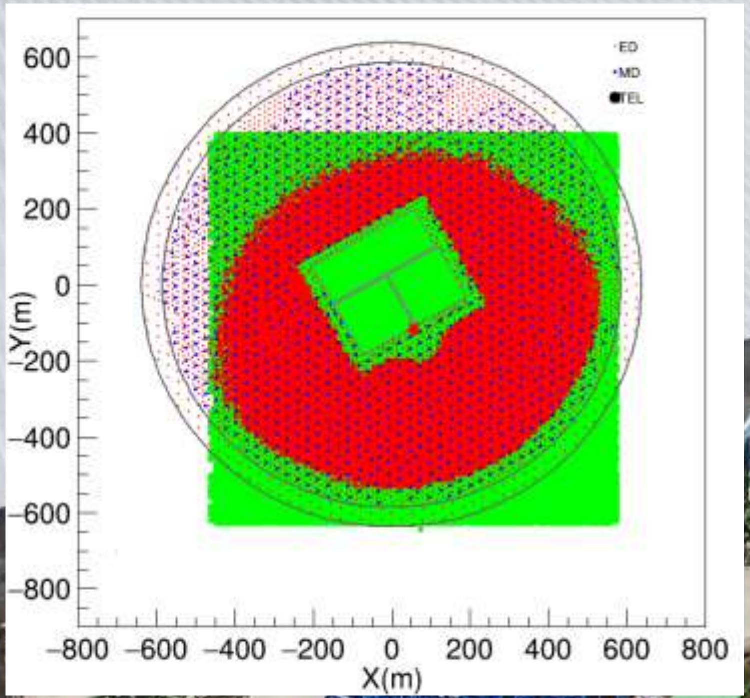
利用KM2A,WFCTA测量宇宙线轻成分能谱

事例筛选条件

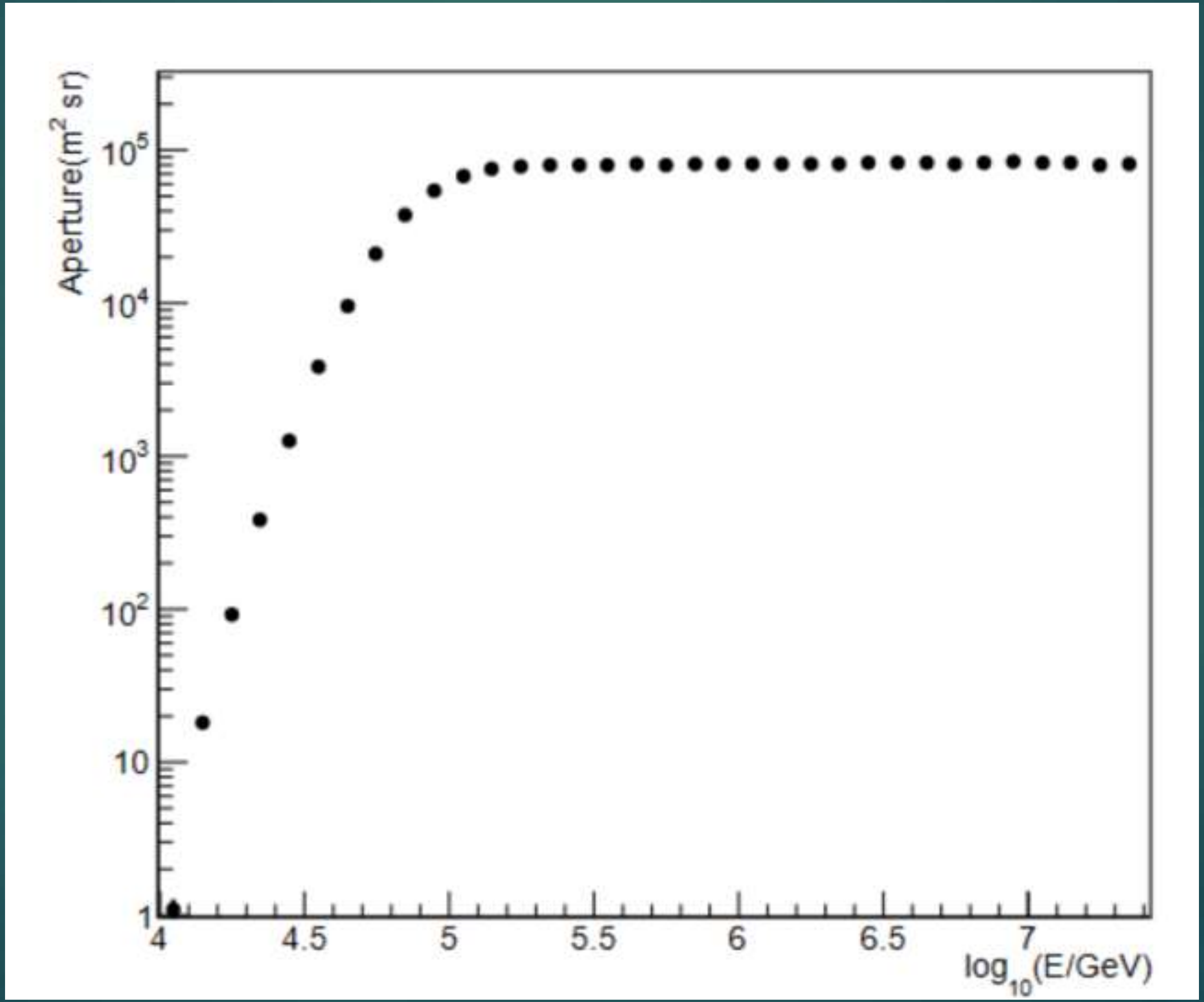
- WFCTA指向45°
- 300m<Rp<100m
- |MeanX(Y)|<5°
- Npix>10 && NtrigE>20
- NhitM>0 && NpE1>0





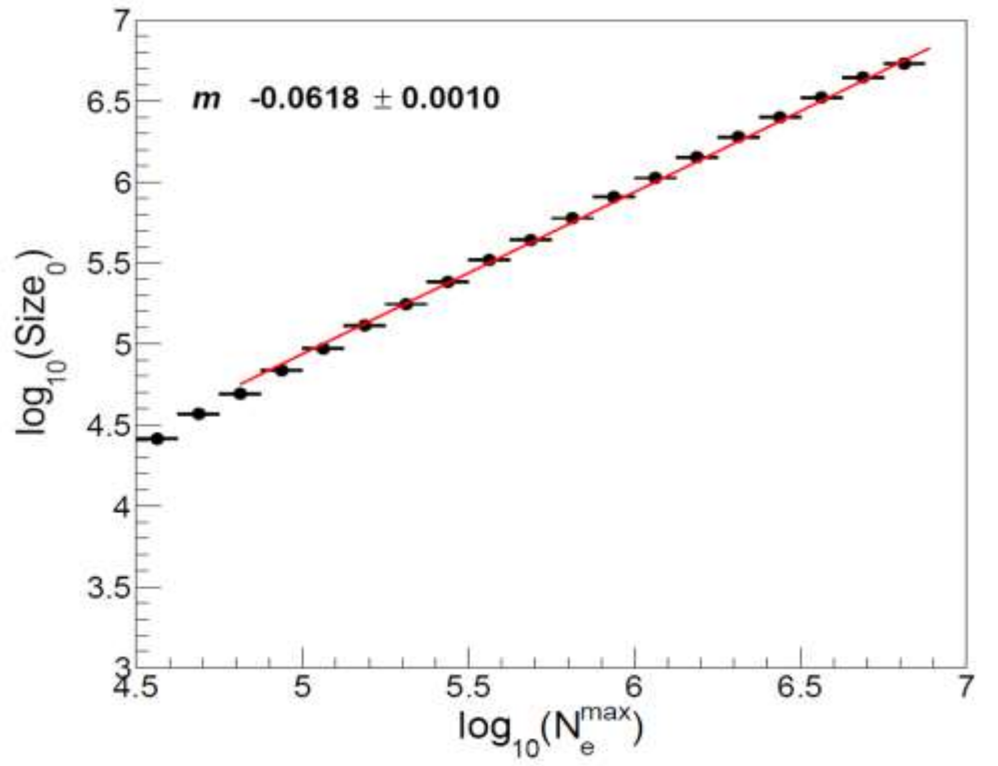


有效面积



KM2A,WFCTA联合能量重建

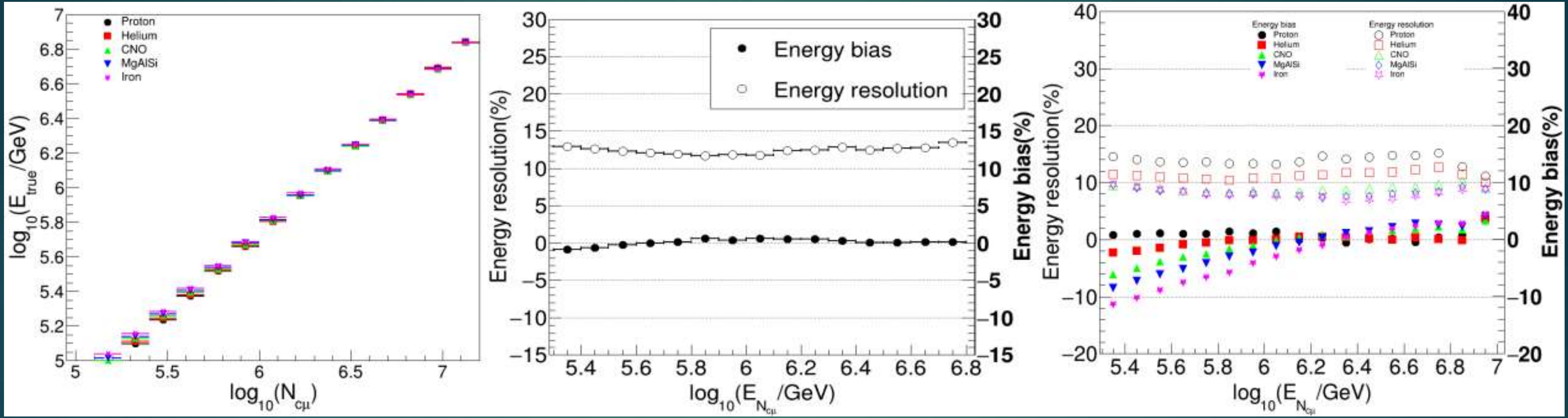
- 天顶角45°对应的大气厚度为850g/cm2
- 此时，膝区宇宙线已过簇射极大
- Ne！= Nemax
- 绝大多数切伦科夫光产生于簇射极大时的正负电子
- Nc正比于Nemax



$$N_{e\mu} = N_e + 2.8N_\mu$$

$$N_{c\mu} = N_c + 110N_\mu$$

KM2A,WFCTA联合能量重建



不依赖于能量的成分鉴别参数

叠加模型

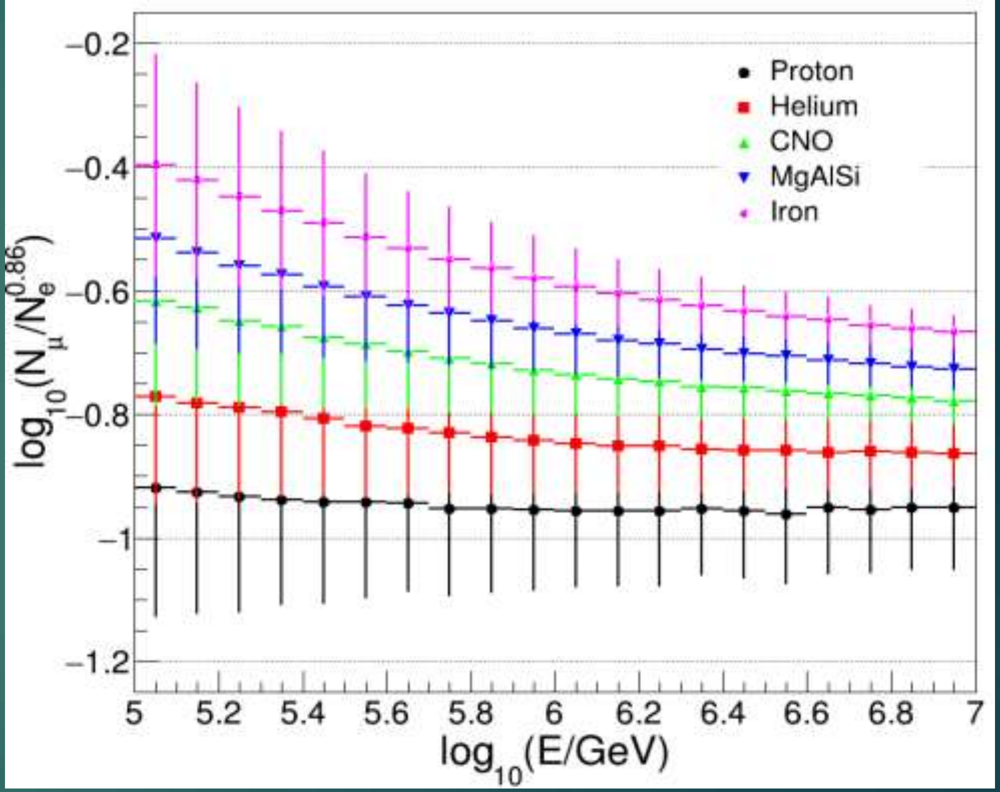
- 原子核(A,E) = A个能量为E/A的质子

$$N_\mu^A = N_\mu^p \left(\frac{E}{A}\right)^\beta$$

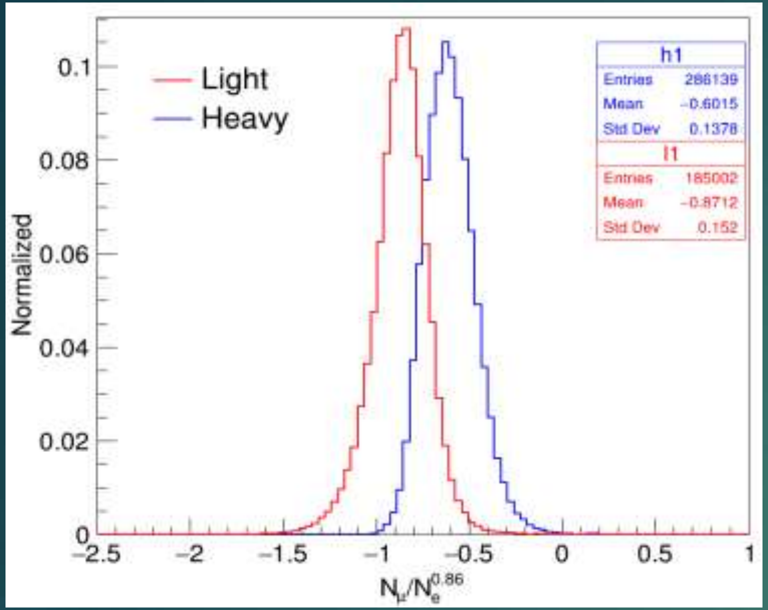
$$N_e^A = N_e^p \left(\frac{E}{A}\right)^\alpha$$

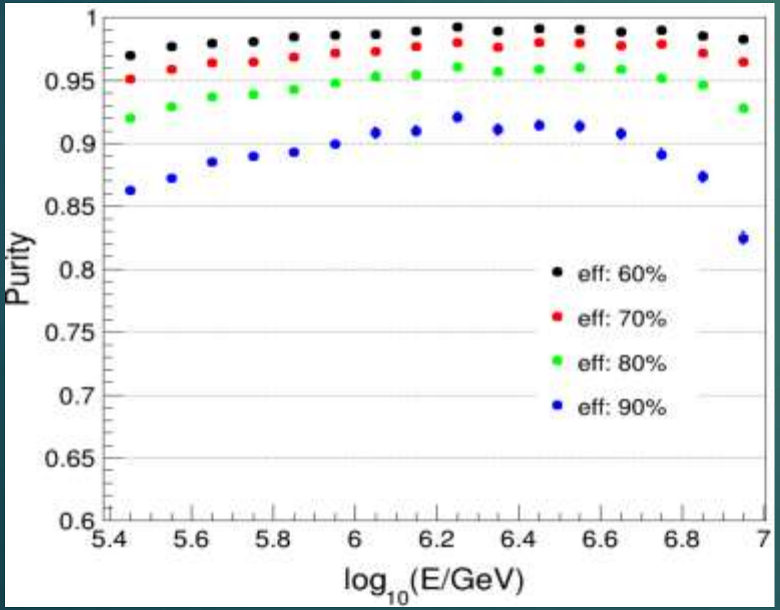
成分鉴别参数：N_μ / N_e^γ

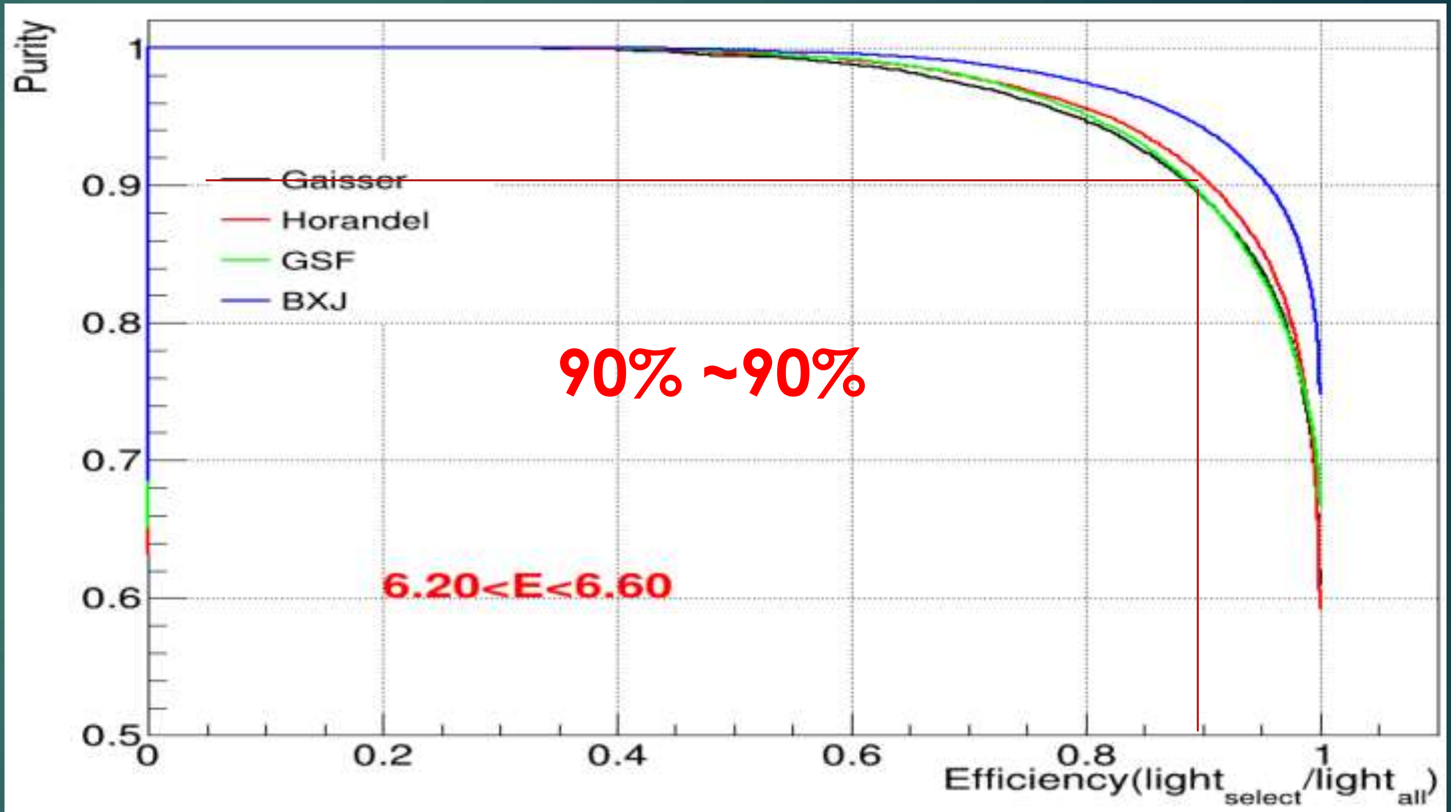
γ ~0.86



挑选轻成分的能力

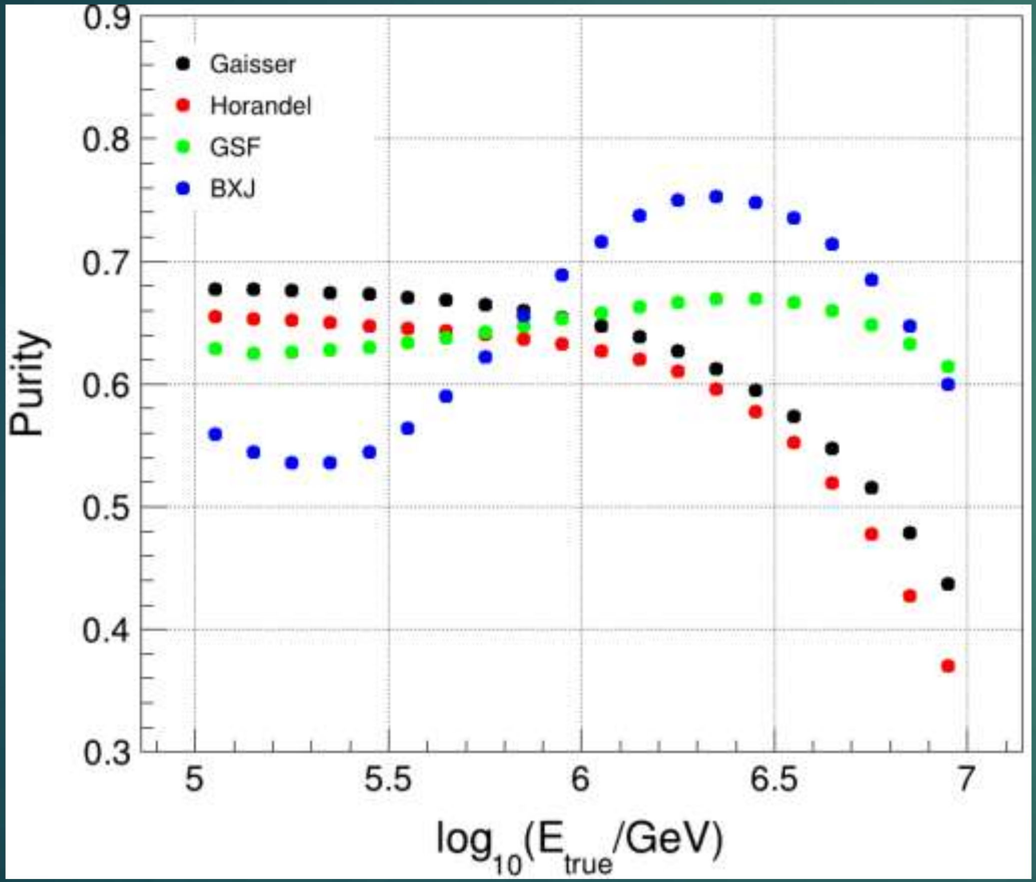


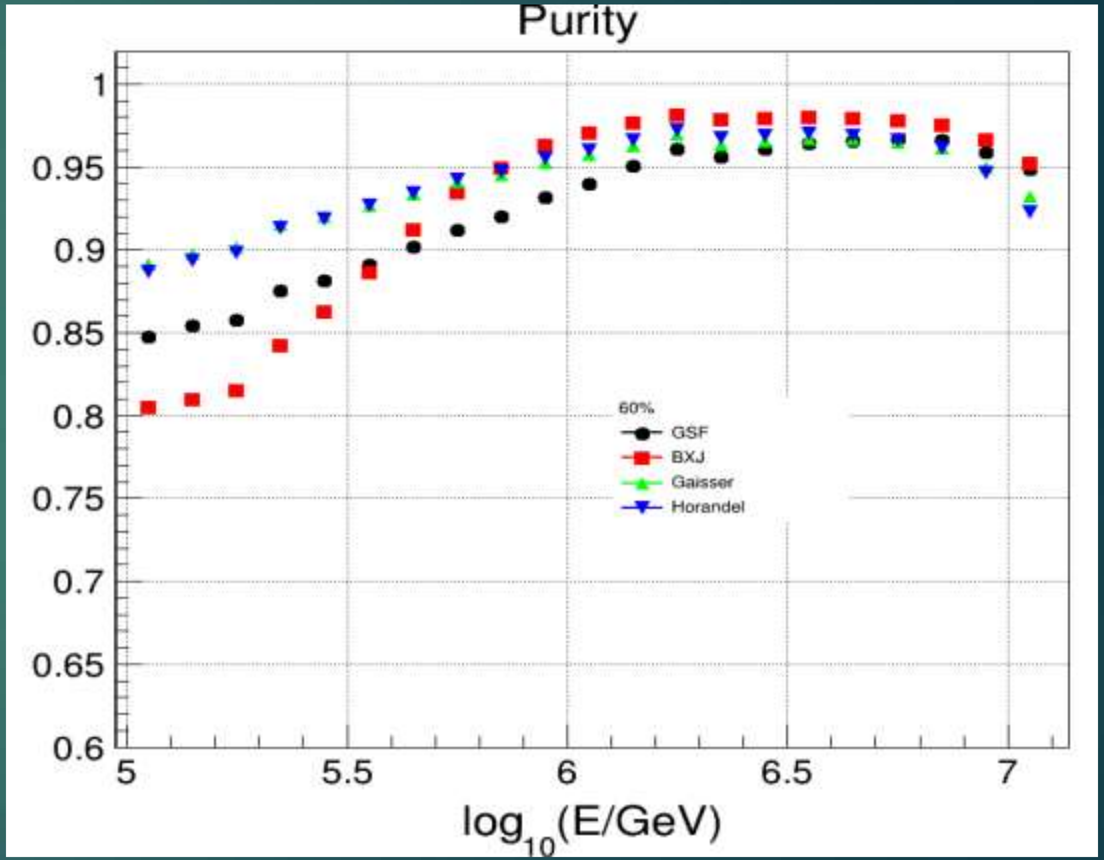


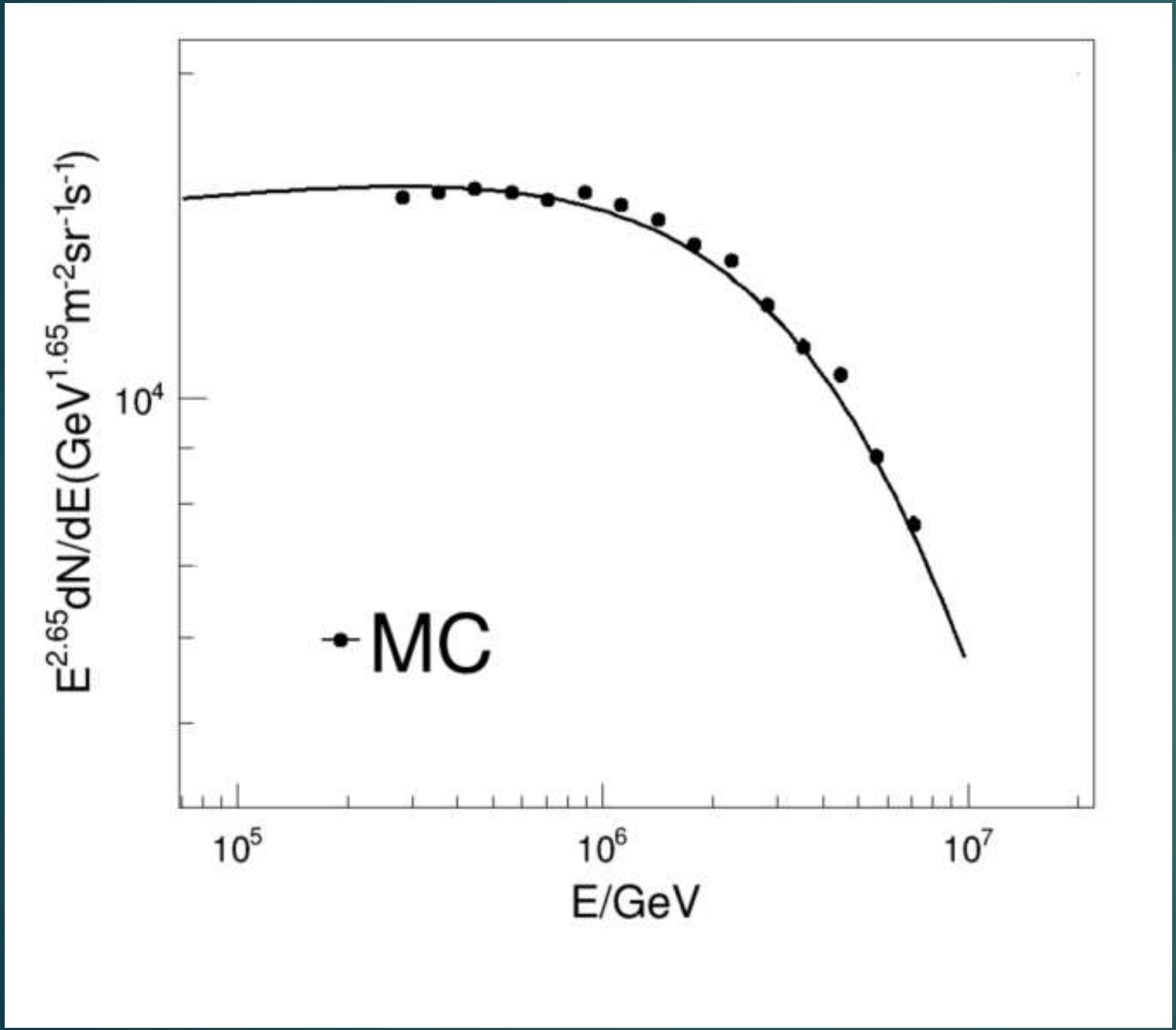


P: 挑选出样本，真正轻成分的比例，纯度

ϵ：挑选轻成分的效率


Gaisser
Horandel
GSF
BXJ
Purity
$\log_{10}(E_{true}/GeV)$

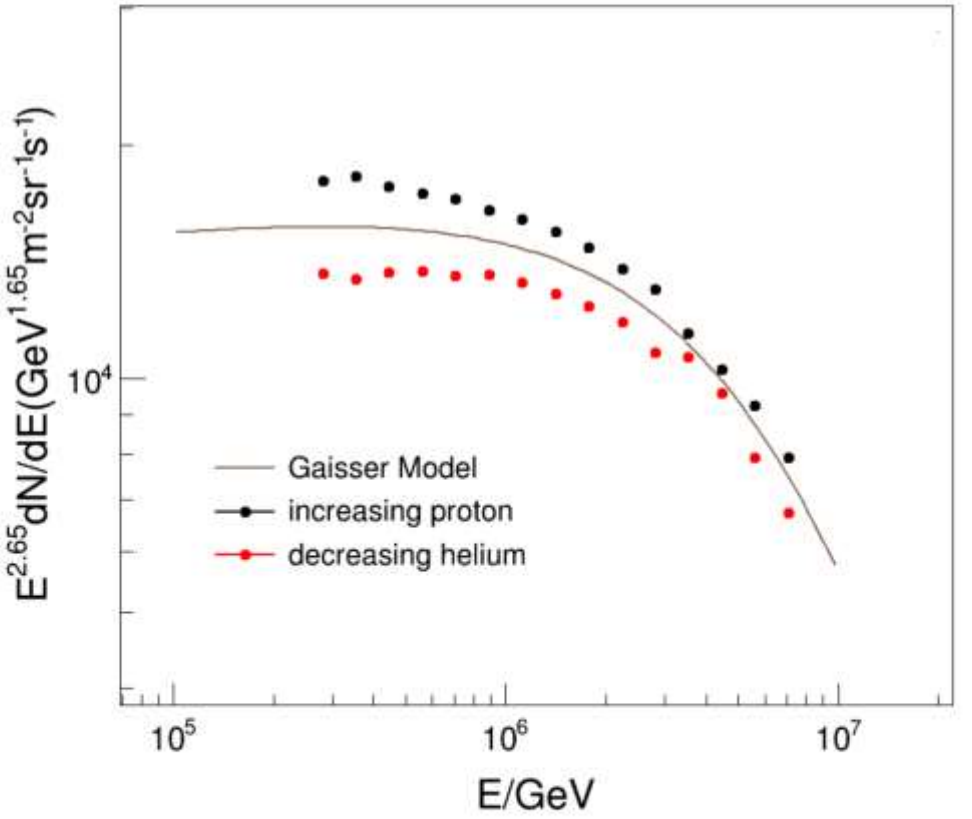

Purity
60%
GSF
BXJ
Gaisser
Horandel
$\log_{10}(E/GeV)$



$$F = \frac{dN}{A \cdot T \cdot dE} \cdot \frac{P}{\epsilon}$$

成分模型不确定引入的系统误差

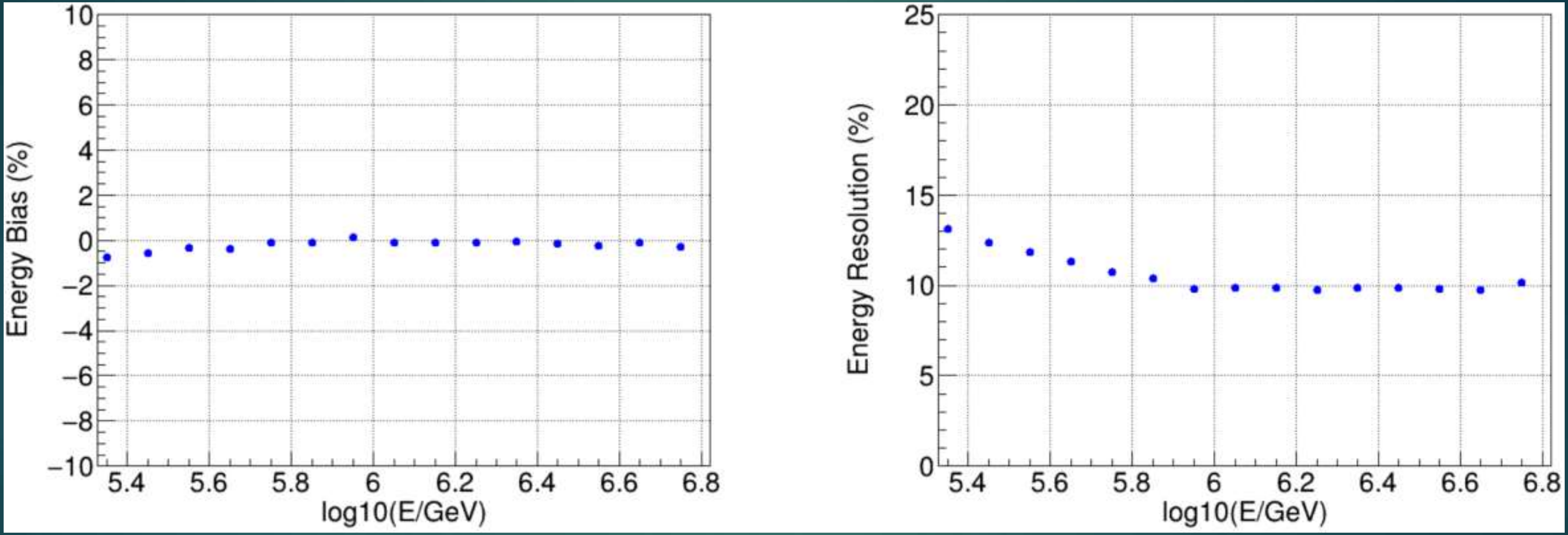
- 成分中模型中质子氦核的比例，会影响挑选效率
- 在现在流行的模型基础上增加质子的比例(50%)或者增加氦核的比例(50%)，所得结果的差异为15%
- 用纯质子或者纯氦核的极端模型所的结果的差异为23%



利用KM2A,WFCTA测量宇宙线质子能谱

能量重建 by Ncμ

质子

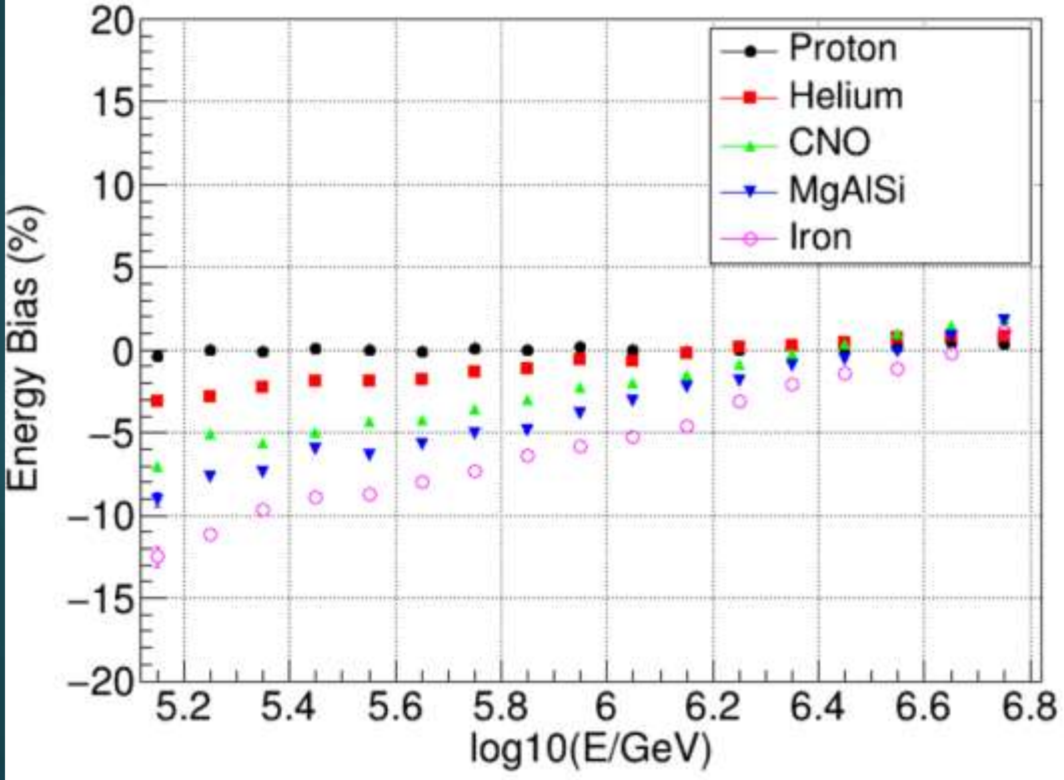


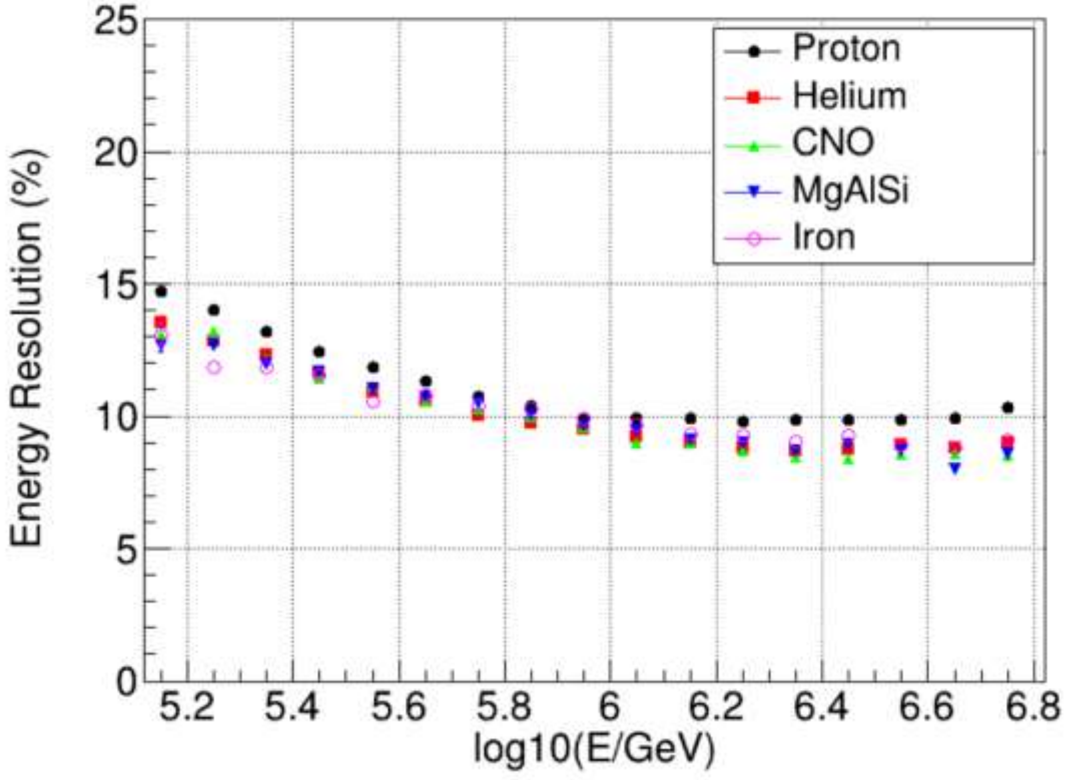
能量重建偏差: <2%

能量分辨率: <15%

对其他重成的能量重建

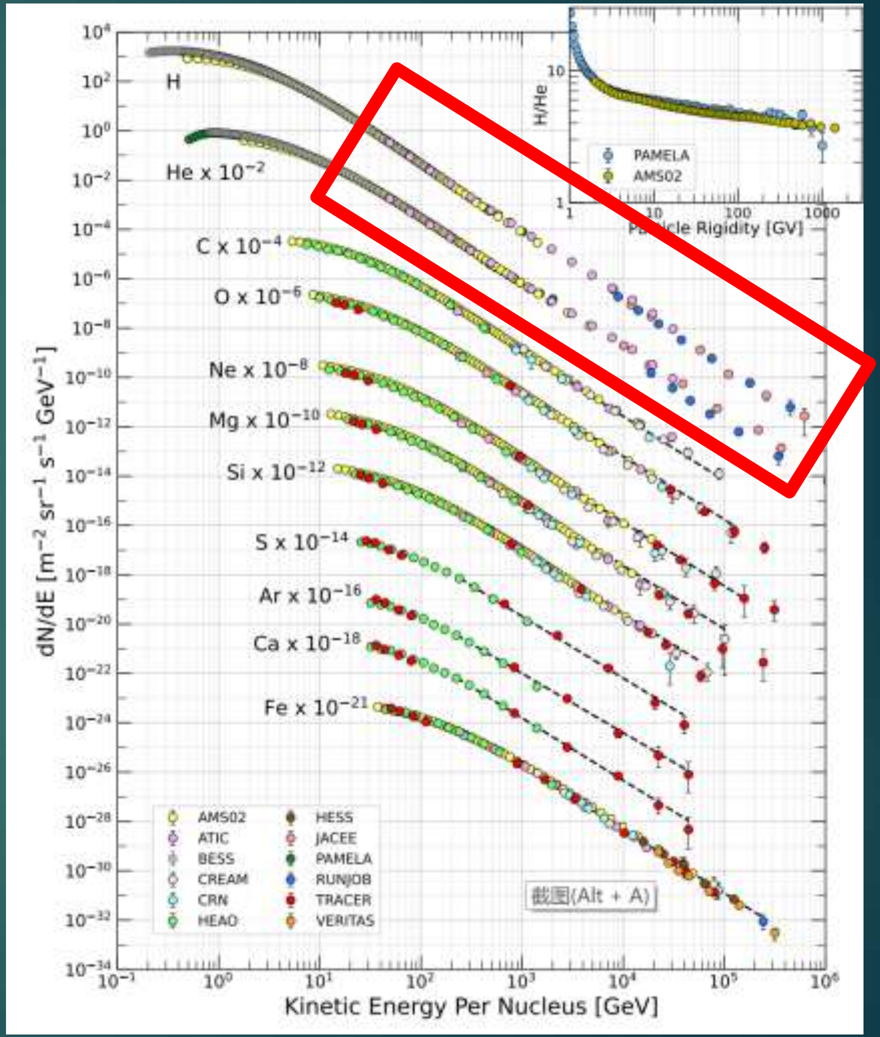
对其他重成分能量重建偏小，由于能谱的急剧下降，使得其他重成分的污染变小，相应的增加了对质子的挑选能力。





挑选质子最大的困难

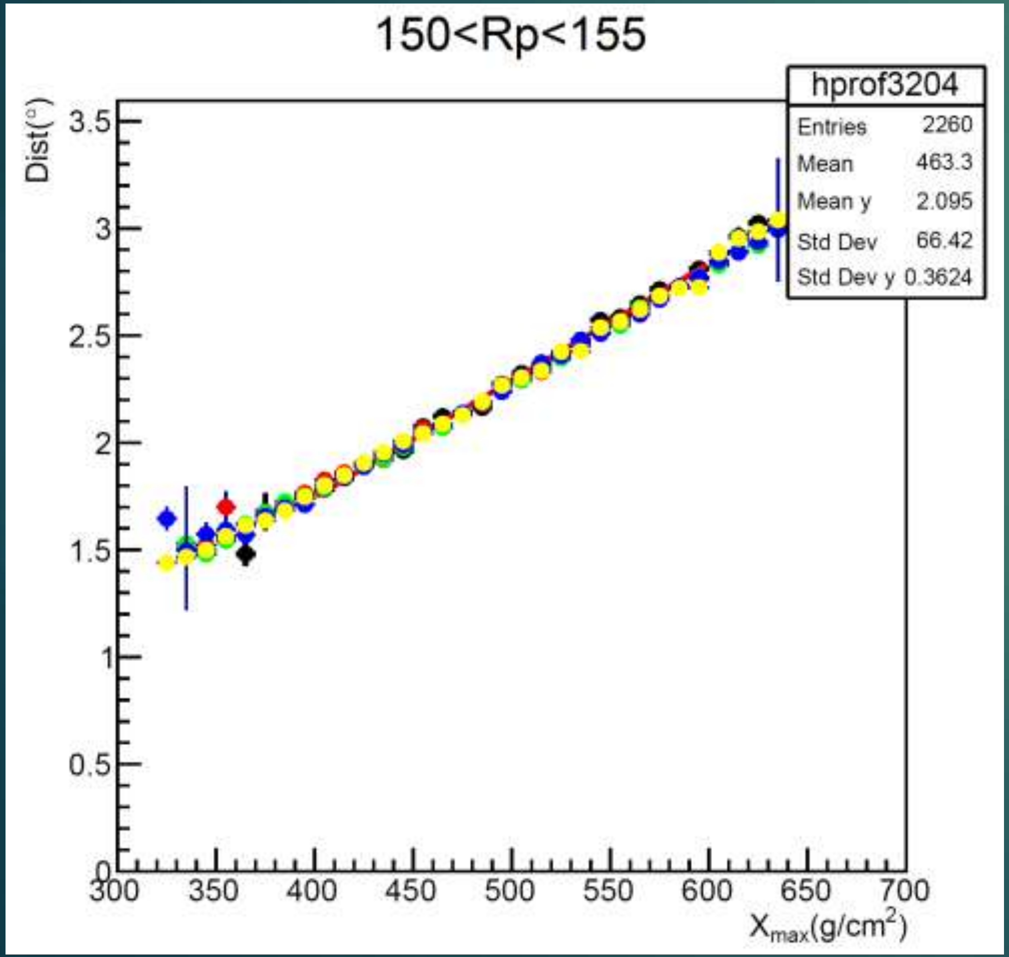
- 如何压低氦核的污染
- 更强的成分挑选能力
- 更多的鉴别参数

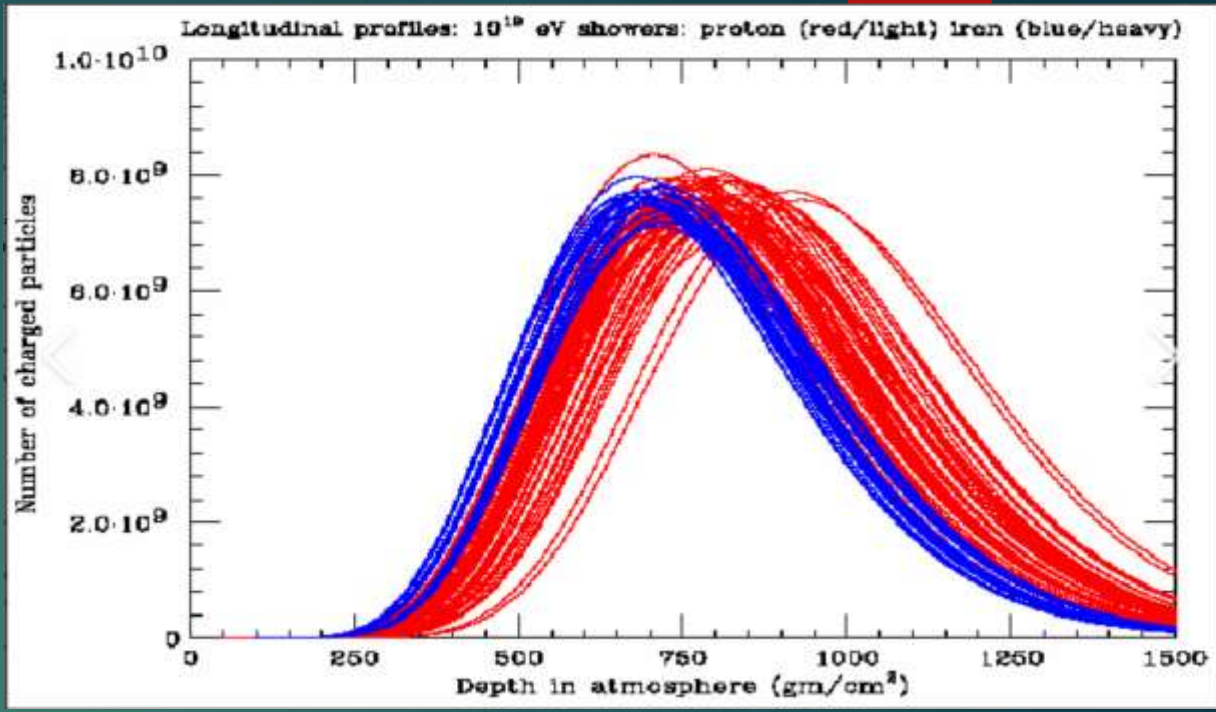


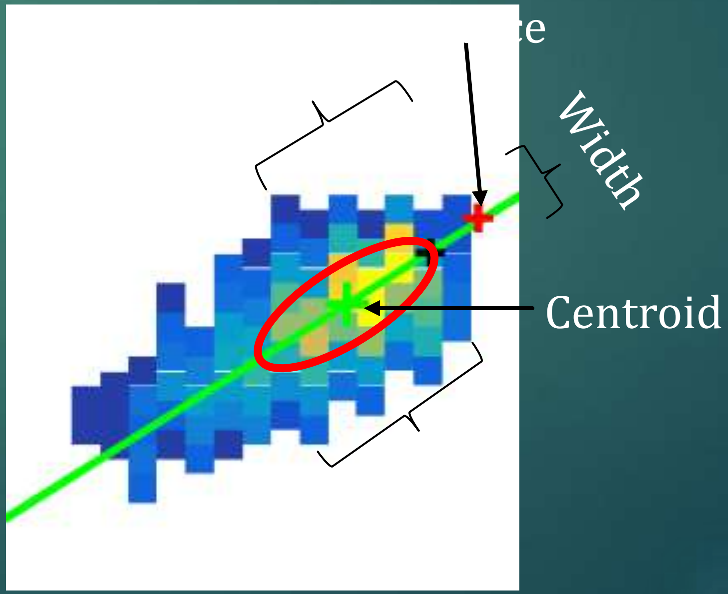
叠加模型

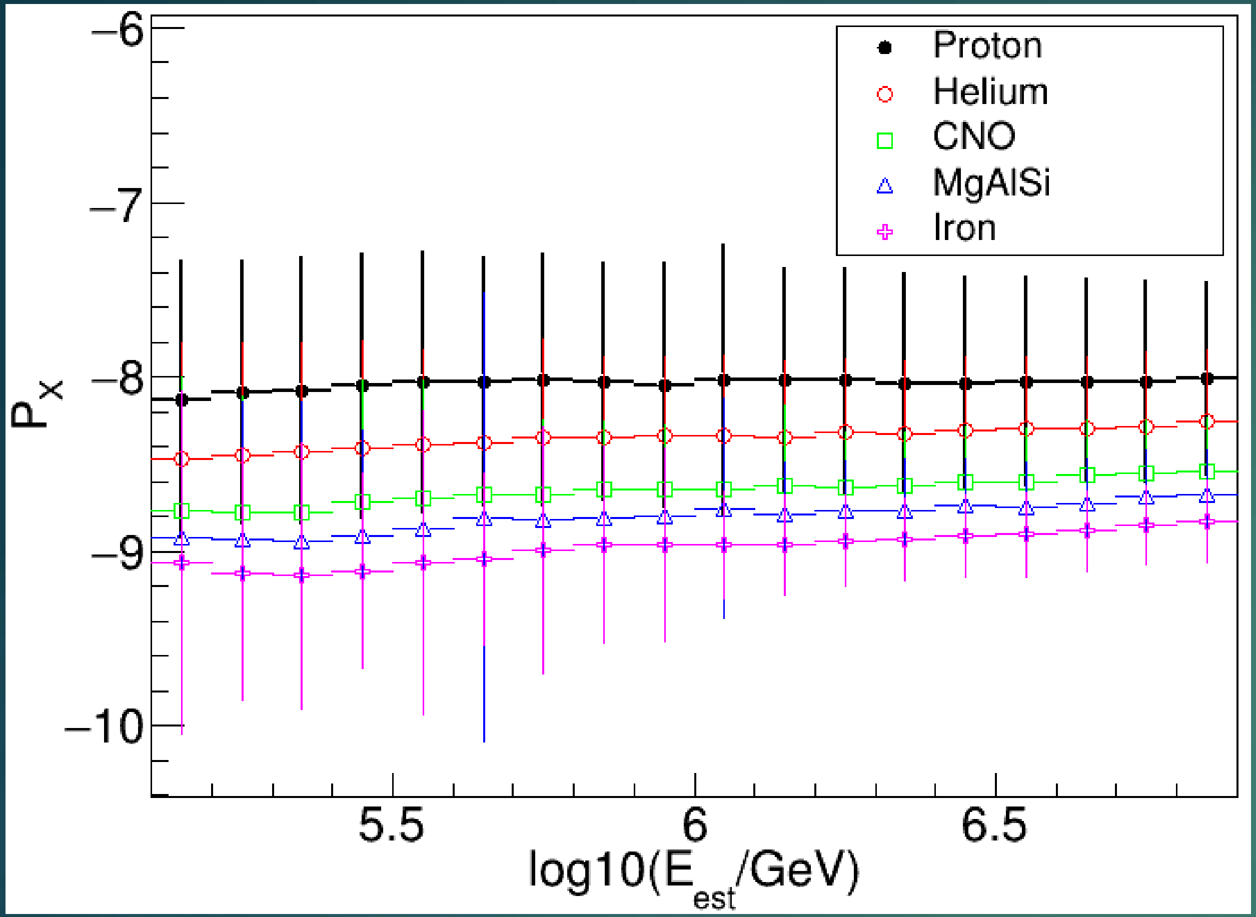
原子核(A,E) = A个能量为E/A的质子

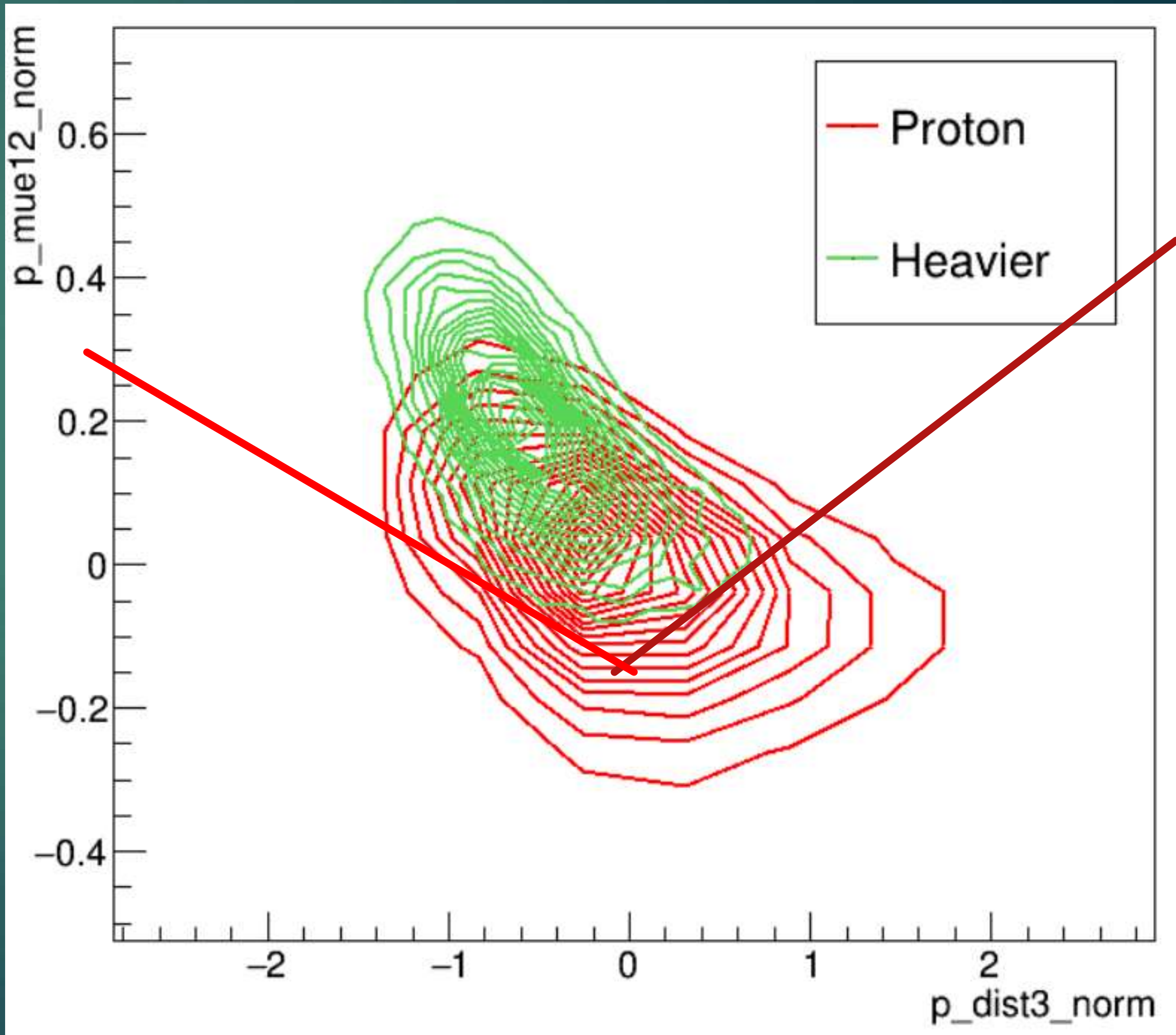
$$X_{max}^{A}=X_{max}^{p}-\lambda_r lnA$$







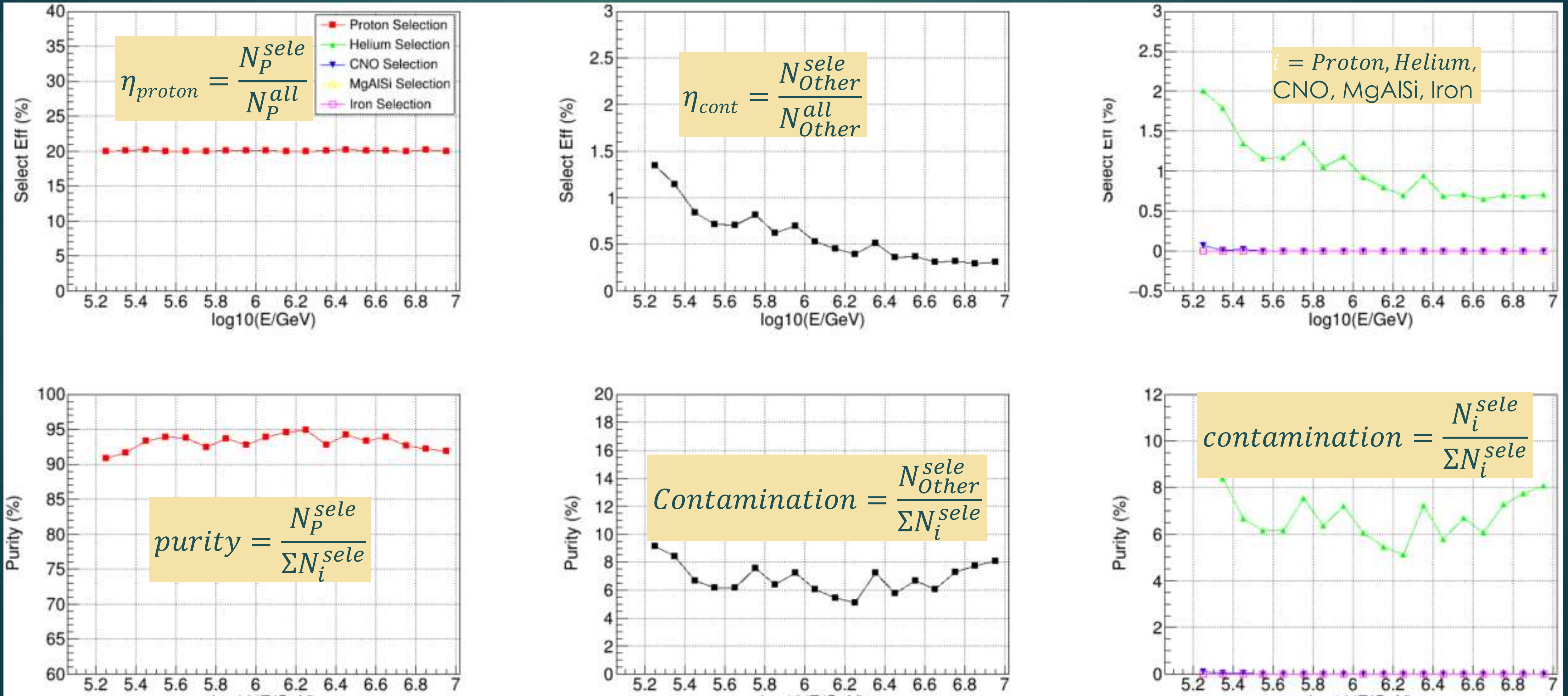

Proton
Helium
CNO
MgAlSi
Iron
P_X
−6
−7
−8
−9
−10
5.5
6
6.5
log10(E_est/GeV)


Proton
Heavier
p_mue12_norm
0.6
0.4
0.2
0
−0.2
−0.4
−2
−1
0
1
2
p_dist3_norm

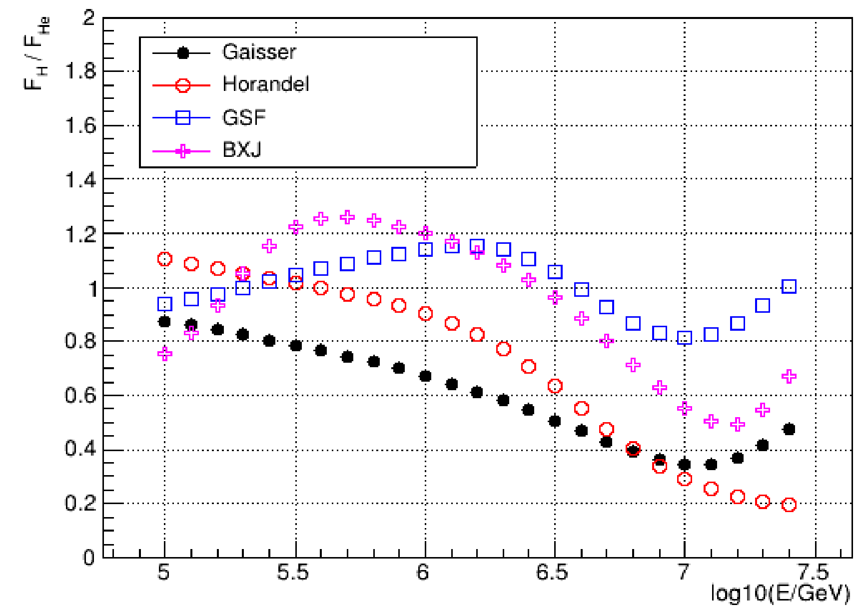
Selection Efficiency versus Purity of the Proton Sample (20%)

$$N * \frac{purity}{\eta} = N * \frac{N_P^{sele}}{\Sigma N_i^{sele}} / \frac{N_P^{sele}}{N_P^{all}}$$

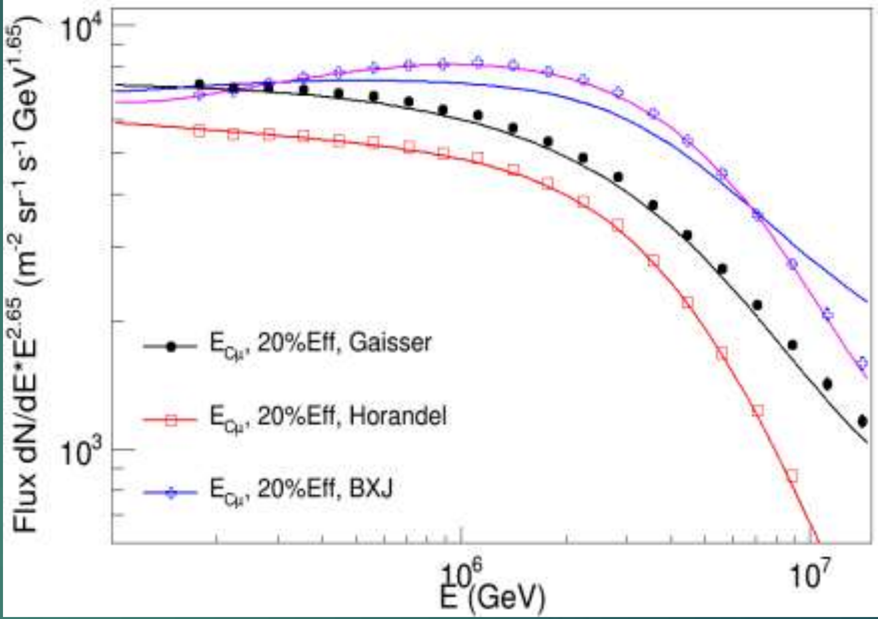
$$\eta = \frac{N_i^{sele}}{N_i^{all}}$$



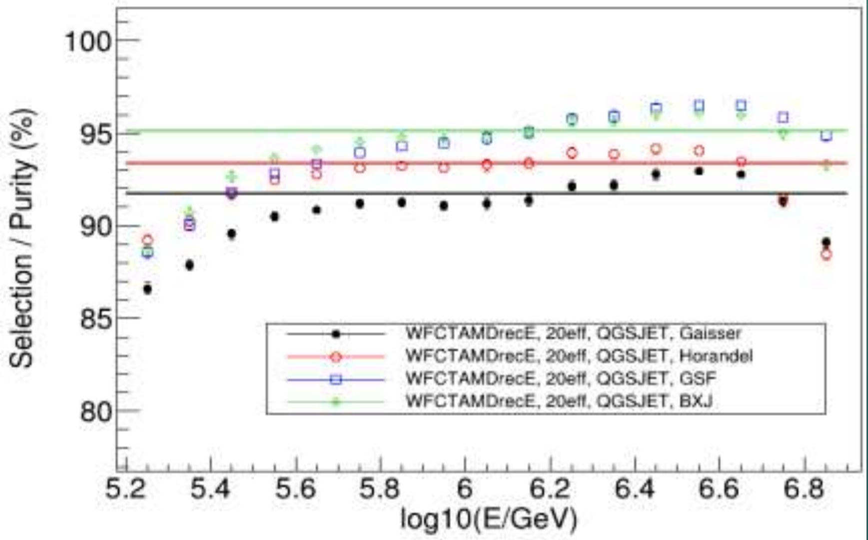
成分模型的系统误差



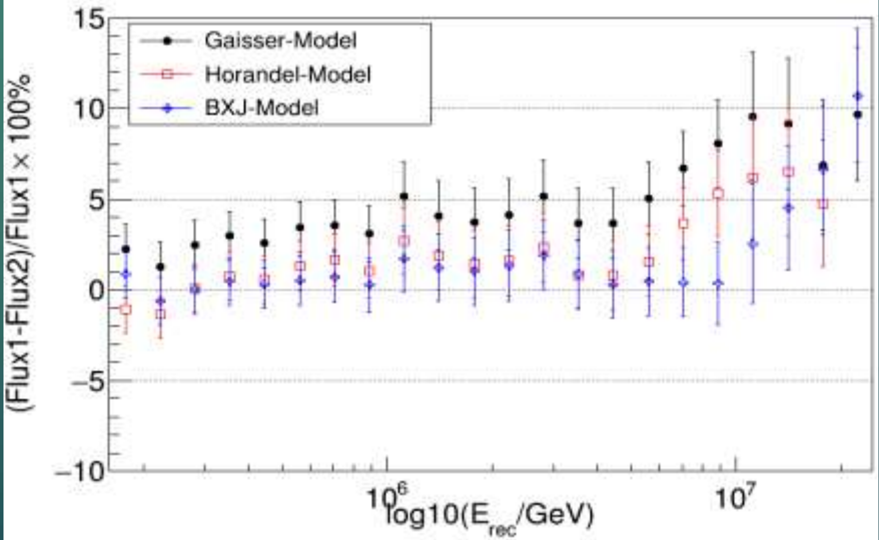
F_H / F_He
Gaisser
Horandel
GSF
BXJ
log10(E/GeV)



Flux dN/dE*E^2.65 (m^-2 sr^-1 s^-1 GeV^1.65)
E_Cμ, 20%Eff, Gaisser
E_Cμ, 20%Eff, Horandel
E_Cμ, 20%Eff, BXJ
E (GeV)



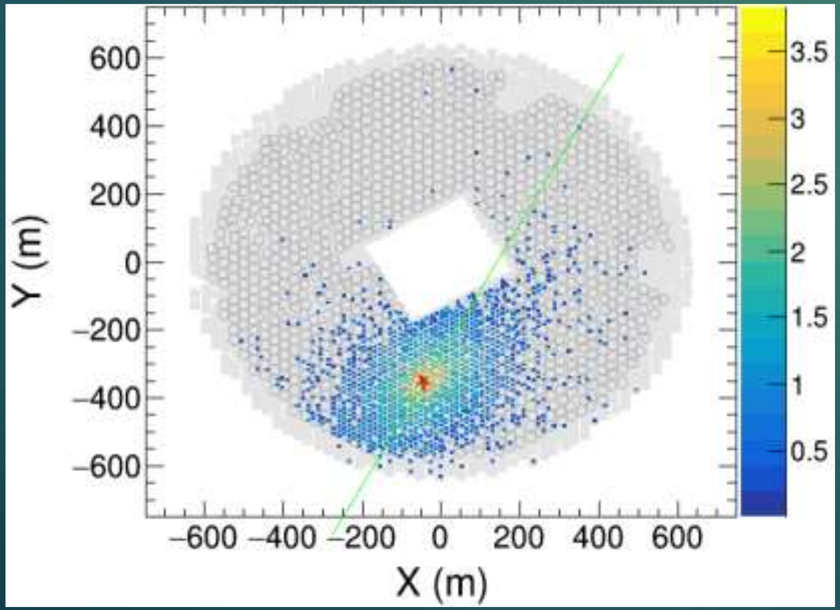
Selection / Purity (%)
WFCTAMDrecE, 20eff, QGSJET, Gaisser
WFCTAMDrecE, 20eff, QGSJET, Horandel
WFCTAMDrecE, 20eff, QGSJET, GSF
WFCTAMDrecE, 20eff, QGSJET, BXJ
log10(E/GeV)

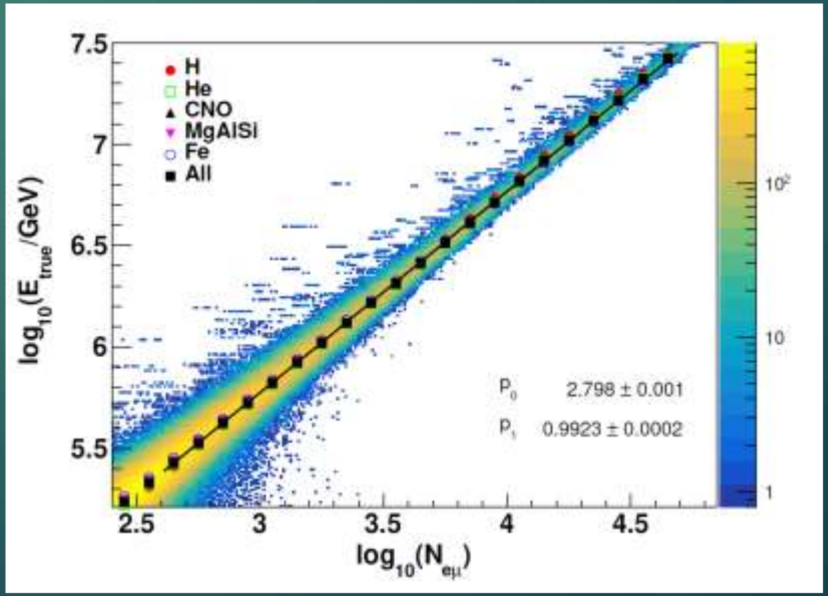


(Flux1-Flux2)/Flux1 × 100%
Gaisser-Model
Horandel-Model
BXJ-Model
log10(E_rec/GeV)

LHAASO探测器的绝对能标

- 能量估计参数和真实能量的关系需要进行标定
- 缺少成分和能量已知的宇宙线束流
- 绝大多数地面宇宙线实验，无法标定自己的绝对能标





地-月磁谱仪

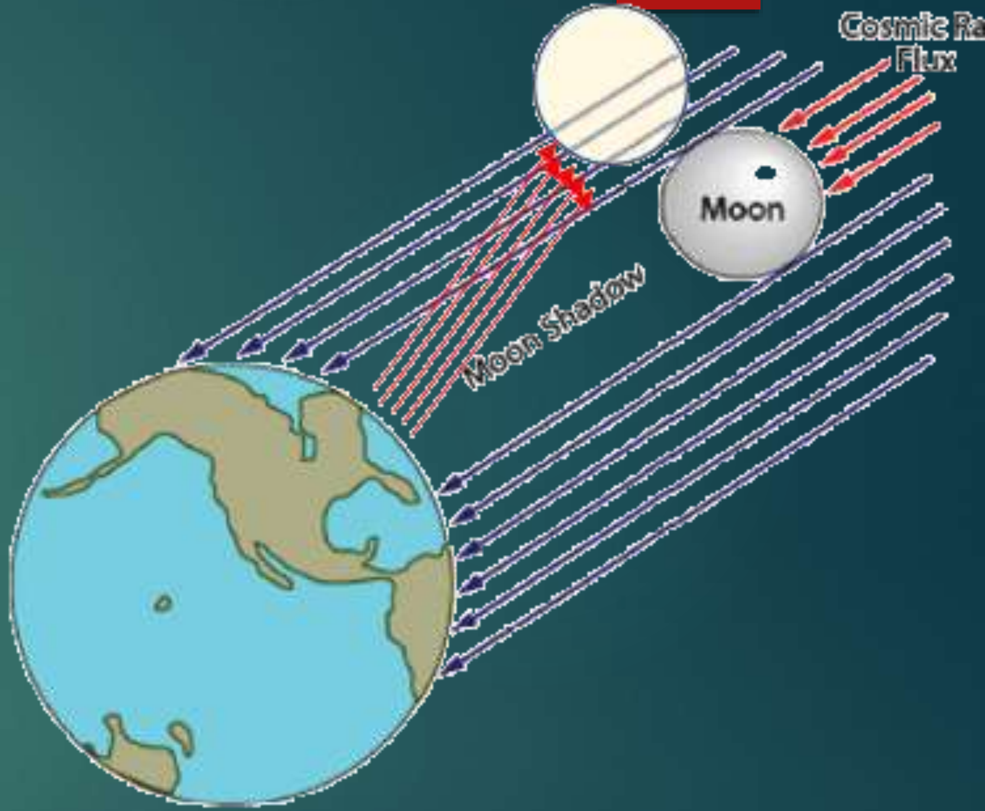
- 观测月影与月球真实位置的偏移

$$\Delta = z * 1.59°/E(TeV)$$

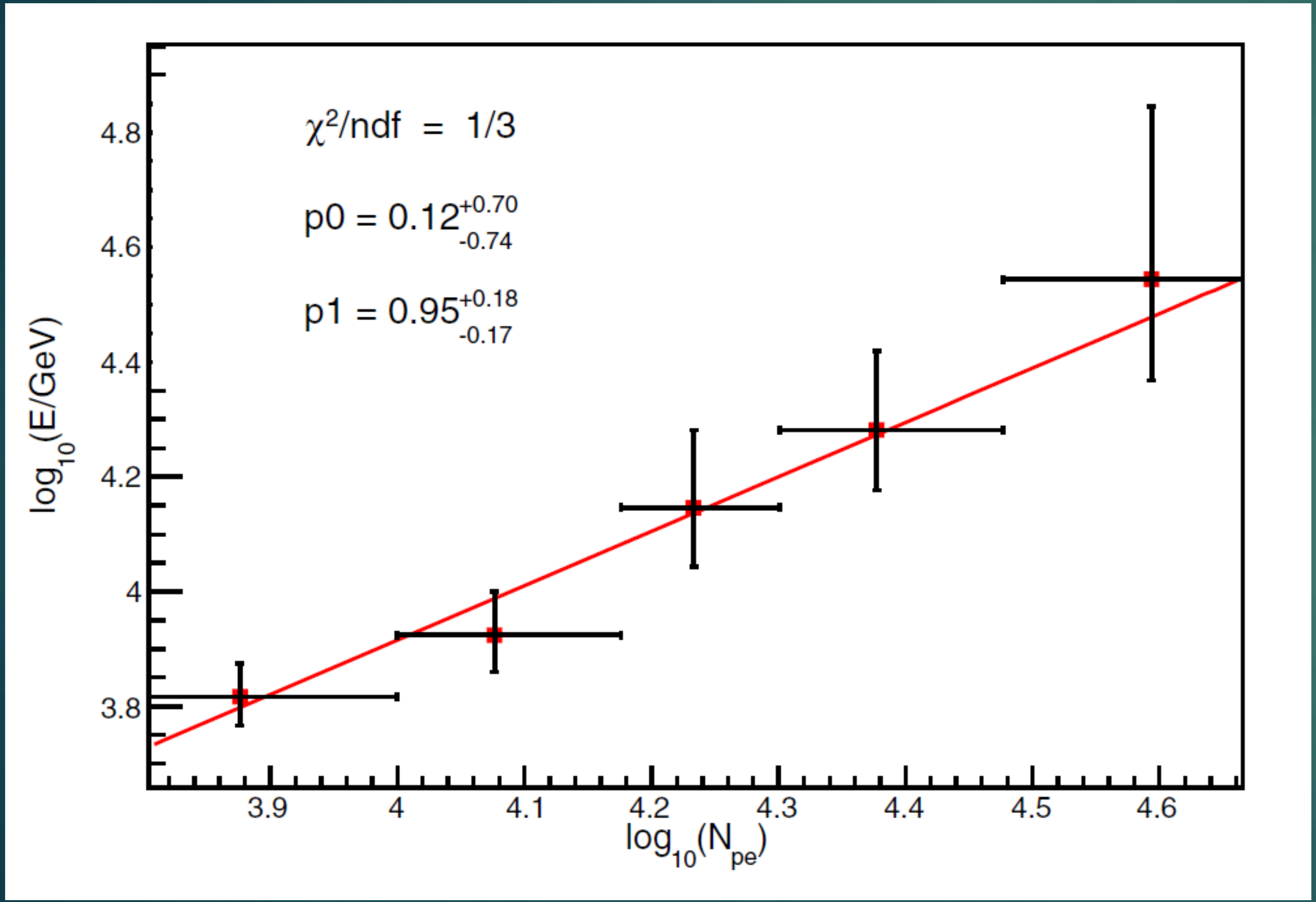
Shift of the Moon Δ

z of cosmic rays used to measure the Moon shadow

The median energy of cosmic rays can be obtained



利用月影偏移量，在35TeV一下对WCDA的绝对能量进行了标定



$\Delta = z * 1.59°/E(TeV)$

对于更高能量标定非常困难

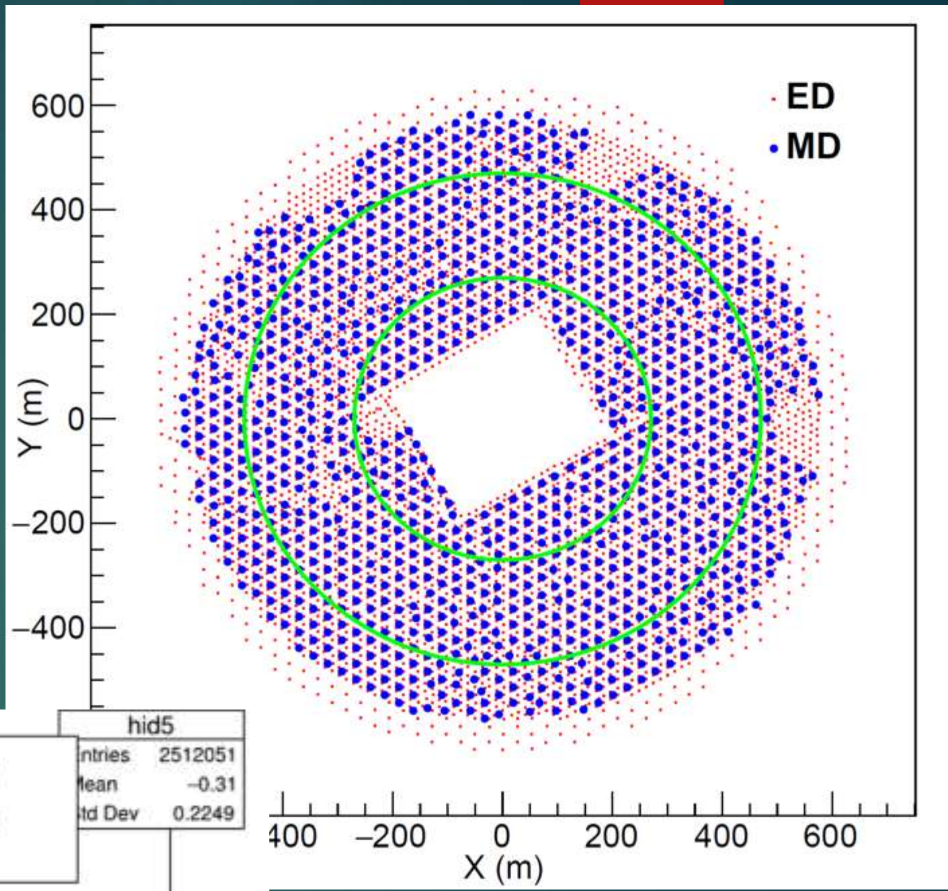
- Proton：Δ=0.032@50TeV，
  Δ= 0.016@100TeV
- Helium：Δ=0.064@50TeV，
  Δ= 0.032@100TeV

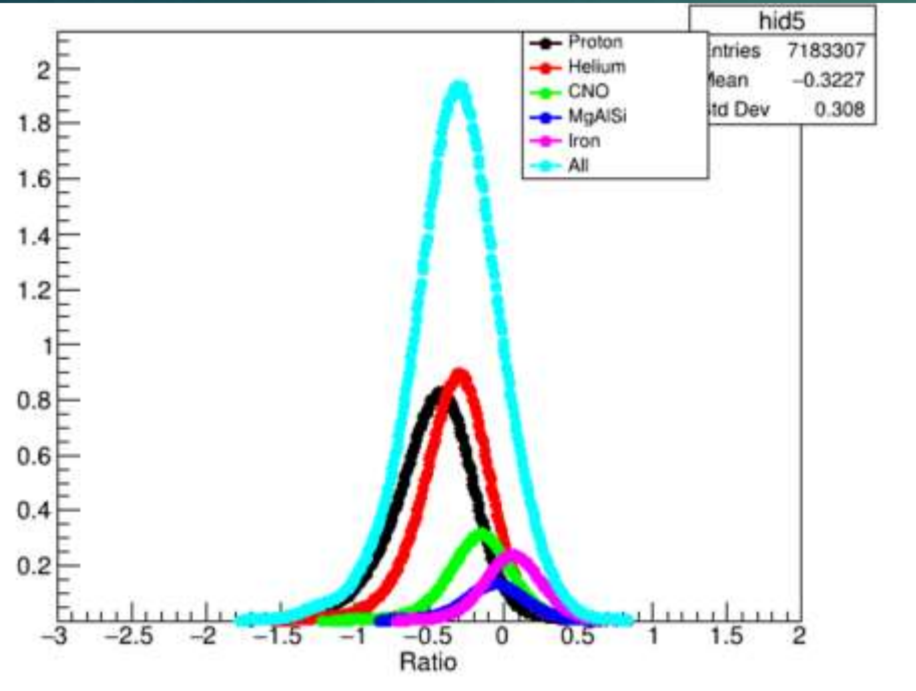
100TeV时，月影的偏移量接近探测器的指向精度

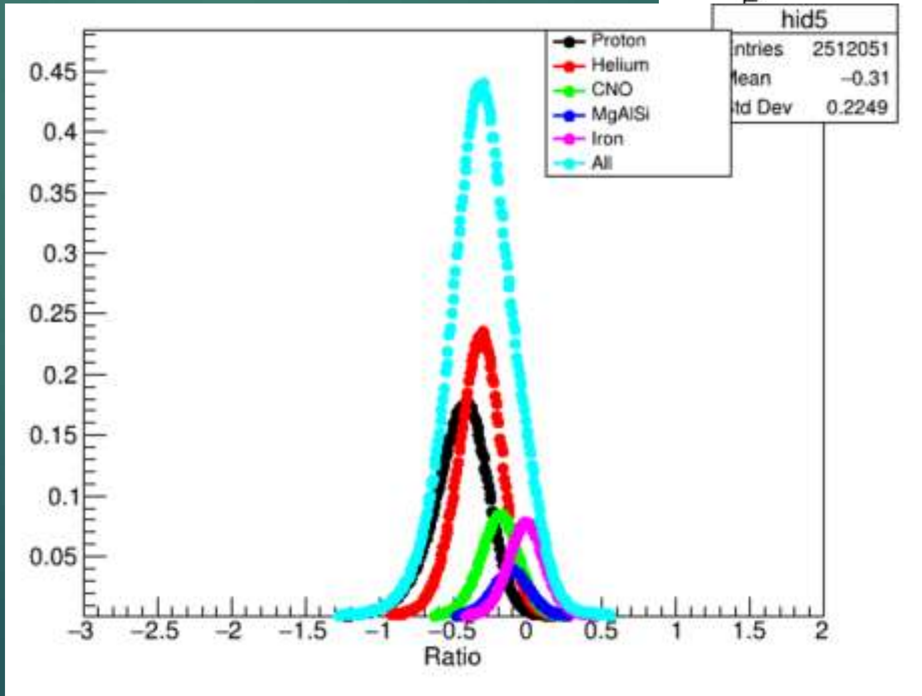
统计量低，测量月影位置的统计误差大

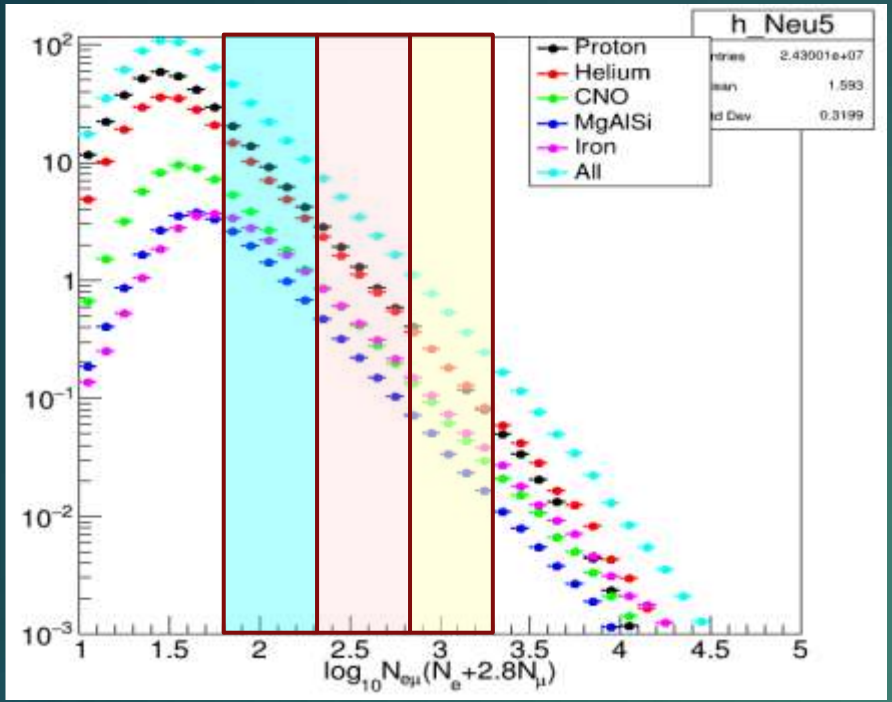
100TeV~200TeV标定KM2A的绝对能标

Iron: Δ=0.82@50TeV,
Δ=0.43@100TeV,

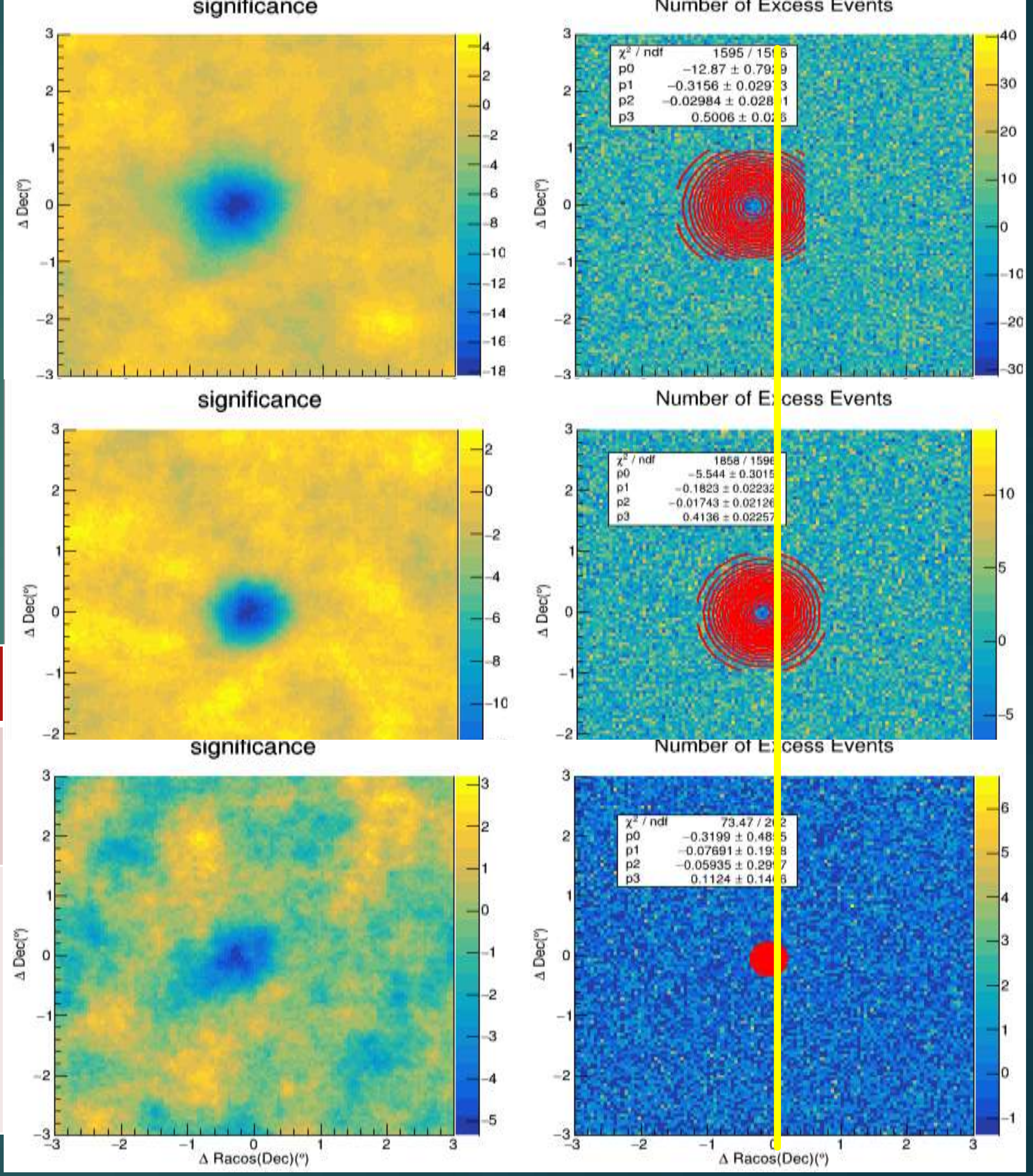








Range	[1.8,2.3]	[2.3,2.8]	[2.8,3.3]
Significance	-17	-12	-5
Shift and the error	-0.32+-0.03 6%	-0.18+-0.02 11%	-0.07+-0.20 285%



总结

- LHAASO以最高的精度测量了全粒子的膝区能谱，及平均对数质量
- LHAASO具备强大的成分鉴别能力，能够实现对质子能谱和轻成分能谱的测量
- LHAASO巨大的有效面积和成分鉴别能力，能够实现在100~200TeV的绝对能量标定

CORSIKA软件的使用

EAS模拟思路

- 假设未知：
  - 宇宙线流强、成份、
  - 相互作用模型、
- 模拟物理过程：
  - shower在大气中的发展过程 （大气模型）
  - EAS次级粒子到达探测器后的探测器响应
- 分析模拟数据：
  - 模拟数据重建
- 和实验数据对比：

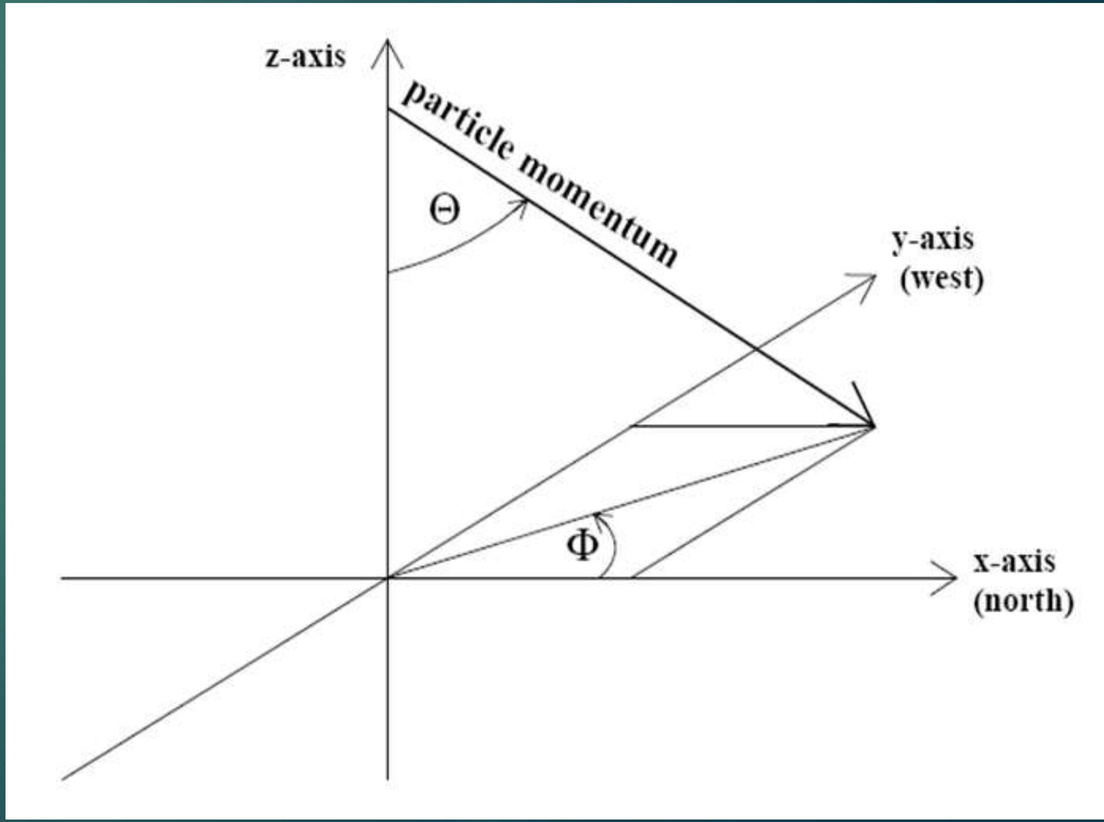
COsmic Ray Simulation for KAscade

- KASCADE实验组开发的EAS模拟软件，现已广泛应用与宇宙线模拟领域
- 随机数产生器（RM48）
  - Sequence length: 2^{144}
  - **在运行CORSIKA程序时应设置随机种子，如随机种子相同，得到的模拟结果相同**
- 相互作用模型
  - 高能强相互作用模型： **QGSJET，EPOS-LHC，SIBYLL，DPMJET，**
  - 低能强相互作用模型： FLUKA，GHEISHA
  - 电磁相互作用模型：EGS4
- 大气模型
  - 多种模型选择（参见guide）
  - 常用美国标准大气模型
  - 也可以建立自己的大气模型

CORSIKA的坐标系定义

- 坐标系定义
  - X轴：地磁北极； Y轴：向西；Z轴：向上
- 方位角定义：
  - 事例方位角0° 时指向X轴正方向
  - 事例方位角90° 时指向Y轴正方向

一定要保证探测器的坐标系定义和CORSIKA一致。



CORSIKA中的单位

Quantity	CORSIKA	EGS4	FLUKA GHEISHA UrQMD HERWIG PYTHIA	SIBYLL	DPMJET EPOS NEXUS QGSJET VENUS	CONEX
length	cm	cm				m
energy	GeV	MeV	GeV	GeV [3])	GeV	GeV
mass	GeV	MeV	GeV	GeV	GeV	GeV
time	sec [1])	sec				sec
magn. field	μT					[4])
density	g/cm^3	g/cm^3				g/cm^3
mass overburden	g/cm^2					g/cm^2
angle	rad [2])	rad				rad
wavelength	nm					

[1]) For output files also nsec is used.

[2]) For in- and output files also ° is used.

[3]) In some subroutines also TeV is used.

[4]) No Earth magnetic field considered.

CORSIKA中的粒子

Identification	Particle	Identification	Particle
1	γ	51	ρ°
2	e^+	52	ρ^+
3	e^-	53	ρ^-
		54	Δ^{++}
5	μ^+	55	Δ^+
6	μ^-	56	Δ°
7	π°	57	Δ^-
8	π^+	58	$\overline{\Delta}^{--}$
9	π^-	59	$\overline{\Delta}^-$
10	K_L°	60	$\overline{\Delta}^\circ$
11	K^+	61	$\overline{\Delta}^+$
12	K^-	62	$K^{*\circ}$
13	n	63	K^{*+}
14	p	64	K^{*-}
15	$\overline{p}$	65	$\overline{K^*}^\circ$
16	K_S°	66	ν_e
17	η	67	$\overline{\nu}_e$
18	Λ	68	ν_μ

CORSIKA中有200多种粒子，其它的可以参考COSIKA手册

核子：A*100+Z
如铁核： 5626

常用Corsika选项及关键字

- 高能相互作用模型选项
  - Option　　key words

Option	key words
DPMJET	DPMJET T 0
	DPJSIG T
EPOS	EPOS T 0
	EPOSIG T
QGSJET	QGSJET T 0
	QGSSIG T
SIBYLL	SIBYLL T 0
	SIBSIG T

低能相互作用模型选项

Option

FLUKA，　GHEISHA

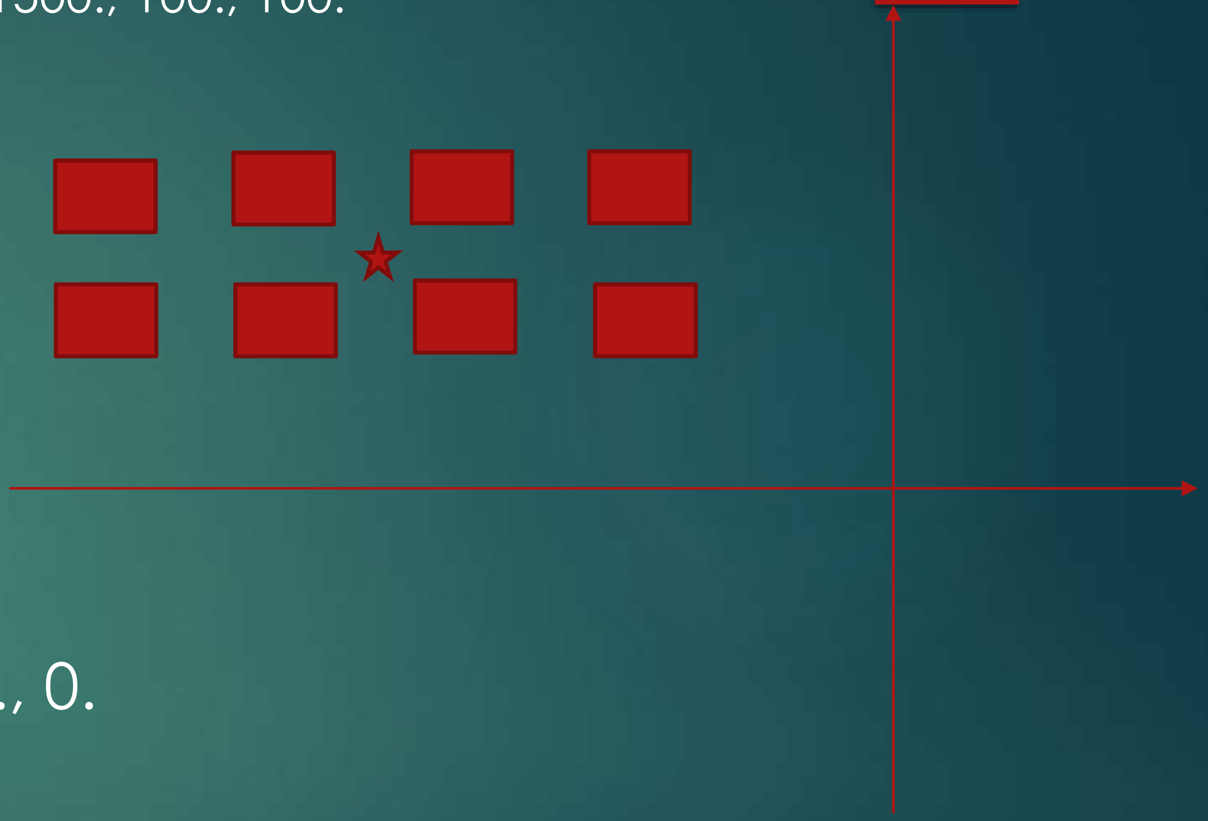
电磁相互作用

NKG	RADNKG 200.E2 ELMFLG T T
EGS4	

Cherenkov选项及关键字

- Cherenkov光子波长选项 CERWLEN
  - 如选用此选项契伦科夫光子波长依赖于大气的折射系数。但是对极端相对论粒子来说此选项影响较小，只有对阈能附近的粒子影响较大。
- 大气吸收选项 CEFFIC
  - 如不选此选项CORSIKA则不会考虑大气吸收。
- 关键字：
  - CWAVLG WAVLGL WAVLGU 波长范围
    - Defaults = 300., 450.
    - Limits are: 100. < WAVLGL < WAVLGU < 700.
  - CERSIZ CERSIZ
    - Default = 0. (如果是0，会选择适合HEGRA-array的size)
    - Limit is: CERSIZ >= 0.
  - CERQEF CERQEF CERATA CERMIR (需要选用CEFFIC选项)
    - Defaults = F, F, F
    - CERQEF : If .true., 考虑探测器的量子效率，调用*quanteff*.dat 文件
    - CERATA : If .true., 考虑大气对光子的吸收，调用 *atmabs*.dat 文件
    - CERMIR : If .true., 考虑反射镜的反射率，调用*mirreff*.dat 文件
    - **可根据探测器自身的特点修改这三个文件**

- CERARY NCERX NCERY DCERX DCERY ACERX ACERY
  - Format = (A6, 2I, 4F), Defaults = 27, 27, 1500., 1500., 100., 100.
  - NCERX : x方向望远镜的个数.
  - NCERY : y方向望远镜的个数.
  - DCERX : x方向望远镜之间的间距.
  - DCERY : y方向望远镜之间的间距
  - ACERX : x方向望远镜的边长.
  - ACERY : y方向望远镜的边长



- CSCAT ICERML XSCATT YSCATT
  - Format = (A5, I, 2F), Defaults = 1, 0., 0.
  - ICERML :对事例重复利用的次数.
  - XSCATT : x方向投点范围 –XSCATT<x<XSCATT
  - YSCATT : y方向投点范围 –YSCATT<y<YSCATT

THIN选项

- 当所要模拟的事例能量高于10^{16}eV时，需要很长时间和存储空间。为了节省时间和存储空间CORSIKA提供了THIN选项。
- 关键字
- THIN EFRCTHN WMAX RMAX
  - EFRACTHN：当次级粒子的能量小于EFRCTHN*E0（原初宇宙线的能量）时，THIN开始发挥作用。用其中一个次级粒子来代表一束粒子来做追踪，相应给出这个粒子的权重。 WMAX为最大权重，当权重超出此值时，将不进行THIN。
  - RMAX：为了节省磁盘空间，对于靠近芯位的次级粒子可以有选择的存储。选择按照$prob \propto (r/rmax)^4$，相应的权重再乘以1/prob.
- THINH THINPAT WEITRAT
- THINEM THINPAT WEITRAT
  - THINRAT = E_{them}/E_{thhadr} and WEITRAT = $WMAX_{em}/WMAX_{hadr}$
  - **THINH 与THINEM只能选择其中之一。如选择THINH，THIN关键字中的EFRACTHN指的是电磁粒子的能量阈值，如选择THINEM， THIN关键字中的EFRACTHN指的是强子的能量阈值。**

其他常用关键字

- RUNNR NRRUN 用作输出文件的文件名
- EVTNR SHOWNO 所模拟的第一个事例的编号
- SEED ISEED（1,2,3）随机种子
- NSHOW NSHOW 本次模拟的事例数
- PRMPAR PRMPAR 模拟事例的成份
- ERANGE LLIMIT ULIMIT 模拟事例的能量范围（GEV）
- ESLOPE PSLOPE 谱指数
- THETAP THETPR(1) THETPR(2) 天顶角范围
- PHIP PHIPR(1) PHIPR(2) 方位角范围
- ATMOD MODATM 大气模型（30个模型可选参见手册）
- MAGNET BX EX 地磁场强度 （水平磁场，垂直磁场）
- ELMFLG TNKG FEGS 电磁相互作用
  - TNKG: (T)利用NKG函数计算电磁级联
  - FEGS: (T)利用EGS4模型计算电磁级联（需提供随机种子）
  - 如果选择了Cherenkov选项，则程序会自动选择EGS4

其他常用关键字

- STEPFC STEPTC 电子多次散射长度
  - Format = (A6, F), Default = 1.
  - Limits are: 0. < STEPFC < 10.0
  - 如果此参数值增大能有效的减少模拟时间，但是会使电子的分布宽度变窄。
  - STEPFC = 10.， CPU可以节省1.7倍的时间
  - STEPFC = 0.1， CPU需要增加5倍的时间
- RADNKG RADNKG NKG函数的作用范围（外圈半径）
  - Format = (A6, F), Default = 200.E2
  - Limit is: RADNKG > 100.
  - 内圈半径为100cm

其他常用关键字

ECUTS ELCUT(i), i=1... 4

Format = (A5, 4F), Defaults = 0.3, 0.3, 0.003, 0.003

Limits are: ELCUT(1)>=0.05 ; ELCUT(2)>=0.01;

ELCUT(3), ELCUT(4) >= 0.00005

ELCUT(3)<0.08 同时作为NKG函数计算的阈值

Hadron，Muon，electron，photon

根据探测器的阈值选择

LONGI LLONGI THSTEP FLGFIT FLONGOUT

Format = (A5, L, F, 2L), Defaults = F, 20.0, F, F

LLONGI : If .true., 在簇射发展过程中，每个阶段的光子数，电子数，契伦科夫光子数等都会记录下，并且各种粒子所沉积的能量也会记录下来

THSTEP：记录纵向发展的步长（g/cm^2）

FLGFIT: if .true., 对纵向发展曲线进行拟合，

FLONGOUT：If .true.， 写入到一个独立的文件，*DATnnnnnn*.long，

if .false：写入*DATnnnnnn文件中LONG的subblock内*

其他常用关键字

- MUMULT FMOLI muon的多次散射
  - Format = (A6, L), Default = T
  - FMOLI : If .false. Muon的多次散射利用高斯近似来计算，If .true: 对于大步长散射采用莫里尔理论，对于小步长又添加了很多单次库伦散射。
- OBSLEV OBSLEV(i) 观测面的海拔高度
  - Format = (A6, F), Default = 110.E2
- MAXPRT MAXPRT 输出详细信息的事例数
  - Format = (A6, I), Default = 10
- DIRECT DSN 输出文件的路径，**路径一定要以“/”结束**

输入卡

```
RUNNR   1                              number of run
EVTNR   100400                         no of first shower event
SEED    100401  0  0                   seed for hadronic part
SEED    100402  0  0                   seed for EGS4 part
SEED    100403  0  0                   seed for Cherenkov part
NSHOW   10                             no of showers to simulate
PRMPAR  5626                           primary particle code (iron)
ERANGE  2.00E4  4.00E4                 energy range of primary (GeV)
ESLOPE  -2.7                           slope of energy spectrum
THETAP  0.  10.                        range zenith angle (deg)
PHIP    -180.  180.                    range azimuth angle (deg)
QGSJET  T  0                           QGSJET for high energy & debug level
QGSSIG  T                              QGSJET cross-sections enabled
HADFLG  0  0  0  0  0  2               HDPM interact.flags & fragmentation fla
ELMFLG  T  T                           elmag. interaction flags NKG, EGS4
STEPFC  1.                             multiple scattering step length factor
RADNKG  200.E2                         outer radius (cm) of NKG elect. distrib
MAGNET  20.4  43.23                    magnetic field central Europe (/uT)
ECUTS   .3  .3  .015  .015             energy cuts: hadr. muon elec. phot. (Ge
LONGI   T  20.  T  T                   longitud, stepsize(g/cm^2), fit, out
MUMULT  T                              muon multiple scattering by Moliere
MUADDI  T                              additional muon information
OBSLEV  110.E2                         observation level (cm)
ARRANG  18.25                          angle between north to array-grid (deg)
MAXPRT  10                             max. no of printed events
ECTMAP  1.E2                           printout gamma factor cut
DIRECT  /home/user/corsika/run/        directory of particle output
CERARY  10 8 1200. 1500. 80. 50.       Cherenkov detector grid (cm)
CWAVLG  300.  450.                     Cherenkov wavelength band (nm)
CERSIZ  5.                             bunch size Cherenkov photons
CERFIL  F                              Cherenkov output file
CSCAT   5  1000.  1000.                scatter Cherenkov events (cm)
DATBAS  T                              write data base file
USER    you                            user name for data base file
HOST    your_host                      host name for data base file
DEBUG   F  6  F  999999999             debug flag, log. unit, delayed debug
EXIT
```

编译CORSIKA (./coconut)

STEP 1: 选择编译机器的位数

```
Compile in 32 or 64bit mode ?
   1 - Force 32bit mode [CACHED]
   2 - Use compiler default ('-m64' on a 64bit machine)
```

STEP 2: 选择高能相互作用模型

```
Which high energy hadronic interaction model do you want to use
   1 - DPMJET 2.55
   2 - EPOS LHC
   3 - NEXUS 3.97
   4 - QGSJET 01C (enlarged commons)
   5 - QGSJETII-04 [CACHED]
   6 - SIBYLL 2.1
   7 - VENUS 4.12
```

STEP 3: 选择低能相互作用模型

```
Which low energy hadronic interaction model do you want to use ?
   1 - GHEISHA 2002d (double precision)
   2 - FLUKA  [CACHED]
   3 - URQMD 1.3cr
```

STEP 4: 选择探测器几何

```
Which detector geometry do you have ?
   1 - horizontal flat detector array [CACHED]
   2 - non-flat (volume) detector geometry
   3 - vertical string detector geometry
```

STEP 5: 其它选项

```
Which additional CORSIKA program options do you need ?
   1 - Cherenkov version for rectangular detector grid
   2 - Cherenkov version for telescope system (using bernlohr IACT C-routines)
   3 - apply atm. absorption, mirror reflectivity & quantum eff.
   4 - external atmosphere functions (table interpolation)
        (using bernlohr C-routines)
   5 - THINning version
   6 - NEUTRINO version
   7 - shower PLOT version (PLOTSH) (only for single events)
   72 - shower PLOT(C) version (PLOTSH2) (only for single events)
   8 - interaction test version (only for 1st interaction)
   9 - SLANT depth instead of vertical depth for longi-distribution
   a - CURVED atmosphere version
   b - UPWARD particles version
   c - view-cone version
   d - ANALysis HISTos & THIN (instead of particle file)
   e - Auger-info file instead of dbase file
   f - Auger-histo file & THIN
   g - Auger Cherenkov longitudinal distribution
   h - PRESHOWER version for EeV gammas
   i - MUPROD to write decaying muons
   j - COMPACT particle output file
   k - annitest cross-section version (obsolete)
   l - LPM-effect without thinning
   m - STACK INput of secondaries, no primary particle
   n - primary neutrino version with HERWIG (NUPRIM)
   p - PARALLEL treatment of subshowers
   q - CHARMed particle/tau lepton version with PYTHIA
   qt - TAU LEPton version with PYTHIA
   s - preHISTORY of muons: mother and grandmother
   u - TRAJECTory version to follow motion of source on the sky
```

STEP 6: Cherenkov选项 纵向发展

```
Cherenkov light vertical (longitudinal) distribution option ?
   1 - Photons counted only in the step where emitted
   2 - Photons counted in every step down to the observation level
       (compatible with old versions but inefficient)
   3 - No Cherenkov light distribution at all [CACHED]
```

STEP 7: Cherenkov发射角与波长的关系

```
Do you want Cherenkov light emission angle wavelength dependence ?
   1 - Emission angle is wavelength independent [DEFAULT]
   2 - Emission angle depending on wavelength
```

STEP 8：选择结束，检查各种选项

corsika会记录上一次编译时的选项，如不需要则要删除

```
Your final selection to build CORSIKA is:

options:    QGSJETII FLUKA FLUKADIR HORIZONTAL TIMEAUTO M32
selection:  CERENKOV INTCLONG CERWLEN CEFFIC
```

STEP 8: 编译

```
Configuration is finished. How do you want to proceed ?
   f - Compiling and remove temporary files [DEFAULT]
   k - Compile and keep extracted CORSIKA source code
   n - Just extract source code. Do not compile!
```

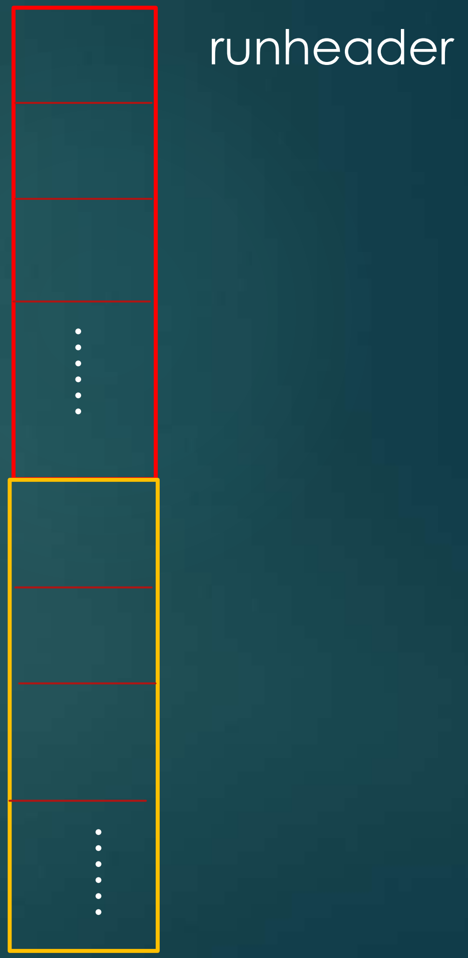
→ corsika73700Linux_QGSII_fluka

Corsika运行及输出文件

- 运行
  - corsika73700Linux_QGSII_fluka <*****.input
- 输出文件格式: 二进制，root
- 输出文件名：CERnnnnnn， DATnnnnnn， DATnnnnnnn.long
- 二进制文件有许多block组成
- 每个block包含21个sub-block。
- sub-block 包含273 word，每个word长度为4bites
  - 如sub-block第一个word为 RUNH， 则为 RUN header sub-block，记录了本次模拟最基本的信息（table 7）
  - 如sub-block第一个word为 EVTH， 则为 event header sub-block，记录了模拟事例的信息（table 8）
  - 如sub-block第一个word为LONG， 则为Long sub-block， 记录了事例的纵向发展信息（table12）
  - 如sub-block第一个word为 EVTE， 则为Event end sub-block，记录了事例模拟结束时的信息
  - 如sub-block第一个word为 RUNE， 则为run end sub-block，记录了模拟结束时的信息
  - 在data 所在的sub-block中，每个sub-block有39sub-sub-block组成，每个sub-sub-block包含7个word。簇射中次级粒子的信息就存储于此。（table 10， 11）
  - 如选择了thin选项， 每个sub-sub-block包含8个word，而每个sub-block的长度变为：312

Runheader sub-block

Run header sub-block: (once per run)	
No. of word	Contents of word (as real numbers R*4)
1	'RUNH'
2	run number
3	date of begin run (yymmdd)
4	version of program
5	number of observation levels (maximum 10)
$5+i$	height of observation level i in cm
16	slope of energy spectrum
17	lower limit of energy range
18	upper limit of energy range
19	flag for EGS4 treatment of em. component
20	flag for NKG treatment of em. component
21	kin. energy cutoff for hadrons in GeV
22	kin. energy cutoff for muons in GeV
23	kin. energy cutoff for electrons in GeV
24	energy cutoff for photons in GeV



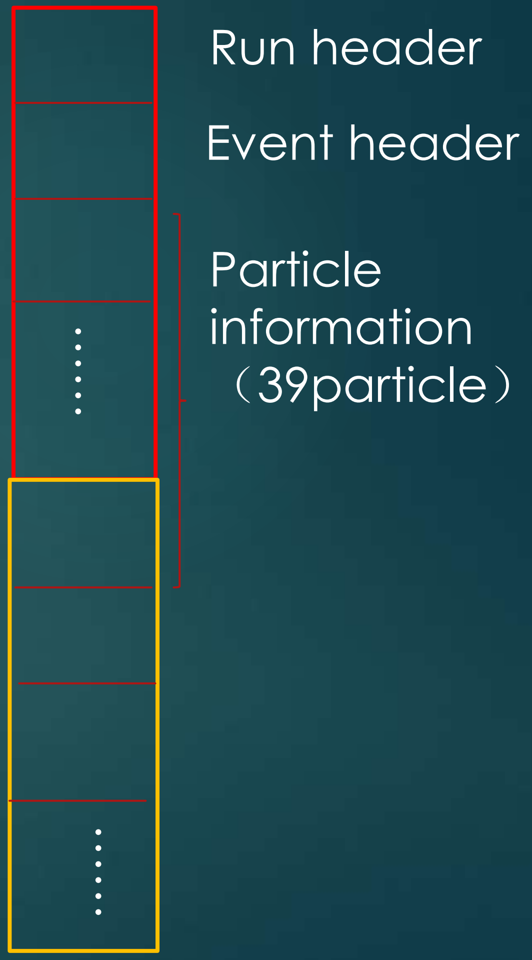
EventHeader sub-block

Event header sub-block: (once per event)	
No. of word	Contents of word (as real numbers R*4)
1	'EVTH'
2	event number
3	particle id (particle code or $A \times 100 + Z$ for nuclei)
4	total energy in GeV
5	starting altitude in g/cm^2
6	number of first target if fixed
7	z coordinate (height) of first interaction in cm (negative, if tracking starts at margin of atmosphere, see TSTART)
8	px momentum in x direction in GeV/c
9	py momentum in y direction in GeV/c
10	pz momentum in -z direction in GeV/c (pz is positive for downward going particles)
11	zenith angle θ in radian
12	azimuth angle ϕ in radian

Particle data sub-block

Particle data sub-block : (up to 39 particles, 7 words each)	
No. of word	Contents of word (as real numbers R*4)
$7 \times (n-1)+1$	particle description encoded as: part. id$\times$1000 + hadr. generation[85] $\times$ 10 + no. of obs. level
$7 \times (n-1)+2$	px, momentum in x direction in GeV/c
$7 \times (n-1)+3$	py, momentum in y direction in GeV/c
$7 \times (n-1)+4$	pz, momentum in -z direction in GeV/c
$7 \times (n-1)+5$	x position coordinate in cm
$7 \times (n-1)+6$	y position coordinate in cm
$7 \times (n-1)+7$	t time since first interaction (or since entrance into atmosphere)[86] in nsec [for additional muon information: z coordinate in cm]
	for $n = 1 \ldots 39$ if last block is not completely filled, trailing zeros are added

如果选择了THIN选项，则每个sub-block为8word，最后一个为权重



Cherenkov data sub-block

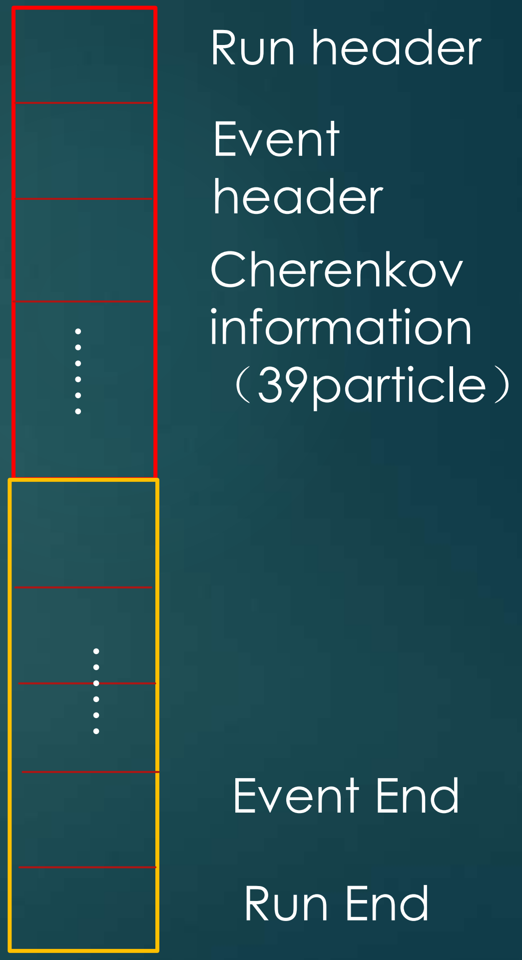
Cherenkov photon data sub-block : (up to 39 bunches, 7 words each)	
No. of words	Contents of word (as real numbers R*4)
$7 \times (n-1) + 1$	number of Cherenkov photons in bunch [in case of output on the particle output file: $99.E5 + 10 \times \mathrm{NINT}$(number of Cherenkov photons in bunch) + 1]
$7 \times (n-1) + 2$	x position coordinate in cm
$7 \times (n-1) + 3$	y position coordinate in cm
$7 \times (n-1) + 4$	u direction cosine[87] to x-axis
$7 \times (n-1) + 5$	v direction cosine[87] to y-axis
$7 \times (n-1) + 6$	t time since first interaction (or since entrance into atmosphere)[86] in nsec
$7 \times (n-1) + 7$	height of production of bunch in cm
	for $n = 1 \ldots 39$ if last block is not completely filled, trailing zeros are added

如果选择了THIN选项，则每个sub-block为8word，最后一个为权重

EventEnd sub-block

Event end sub-block : (once per event)

No. of word	Contents of word (as real numbers R*4)
1	'EVTE'
2	event number
	statistics for one shower :
3	weighted number of photons arriving at observation level(s)
4	weighted number of electrons arriving at observation level(s)
5	weighted number of hadrons arriving at observation level(s)
6	weighted number of muons arriving at observation level(s)
7	number of weighted particles written to particle output file MPATAP. (This number includes also Cherenkov bunches, if Cherenkov output is directed to MPATAP, but excludes additional muon information.)



谢谢大家