利用LHAASO实验多参数测量100TeV-10PeV宇宙线轻成分能谱展望

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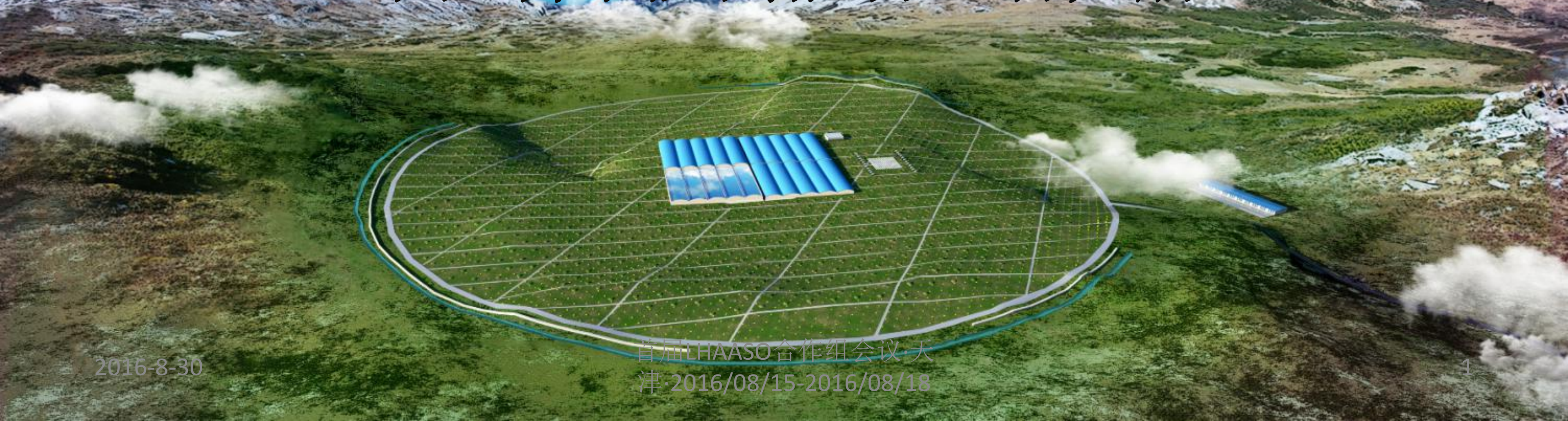
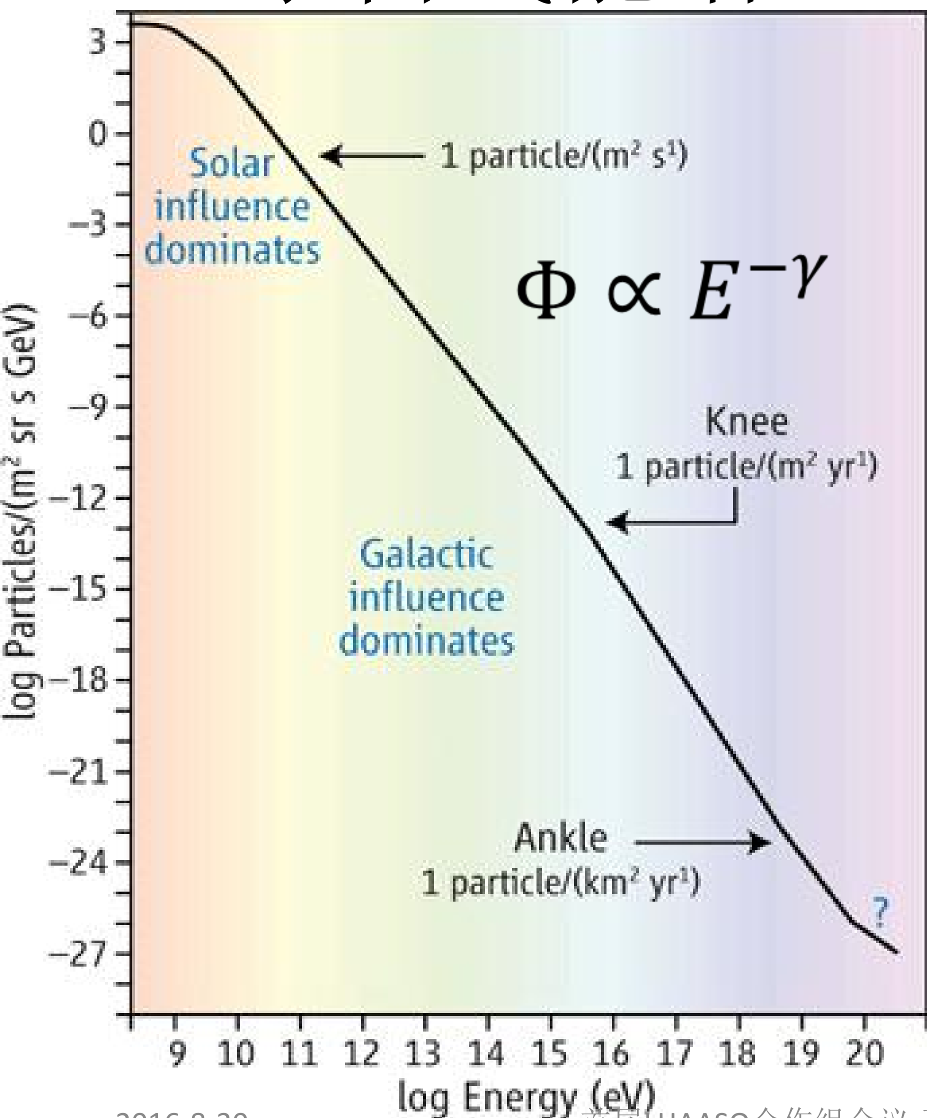


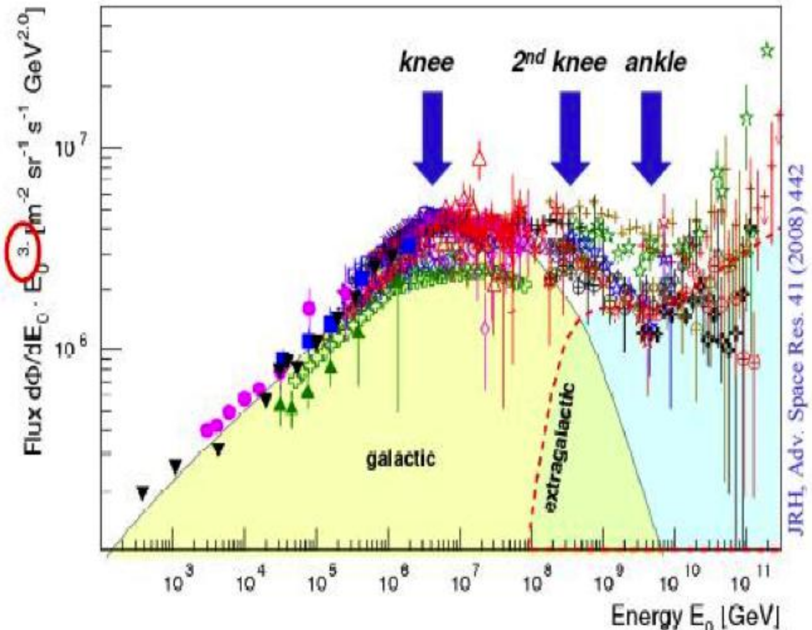
主要内容

- 背景
  - 宇宙线的“膝”
  - WFCTA样机和ARGO-YBJ复合实验
- LHAASO宇宙线轻成分能谱测量展望
  - 探测器阵列和参数化模拟
  - 位置和能量重建
  - 成分敏感变量与预期
- 总结和展望

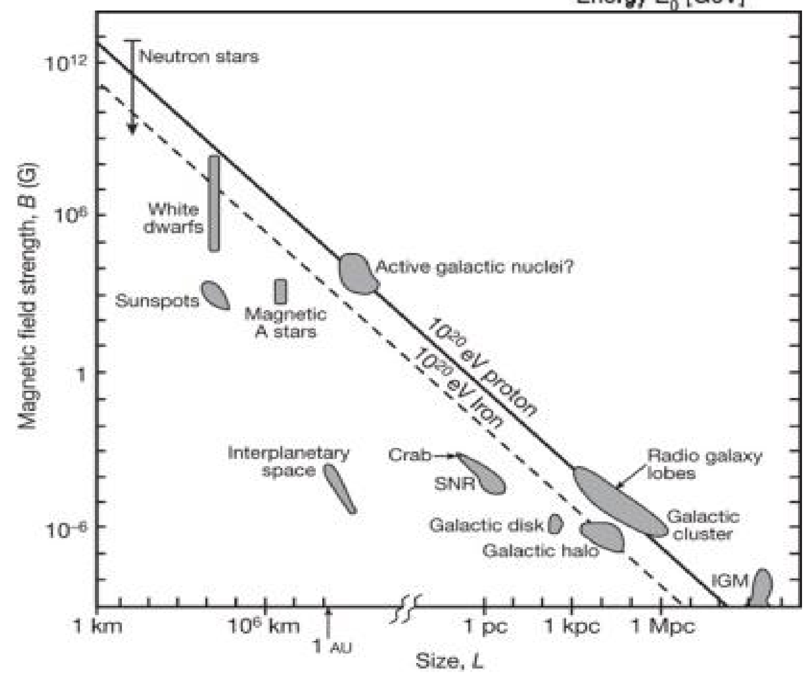
宇宙线能谱



$\Phi \propto E^{-\gamma}$
Solar influence dominates
1 particle/(m² s¹)
Knee
1 particle/(m² yr¹)
Galactic influence dominates
Ankle
1 particle/(km² yr¹)
?
log Particles/(m² sr s GeV)
log Energy (eV)

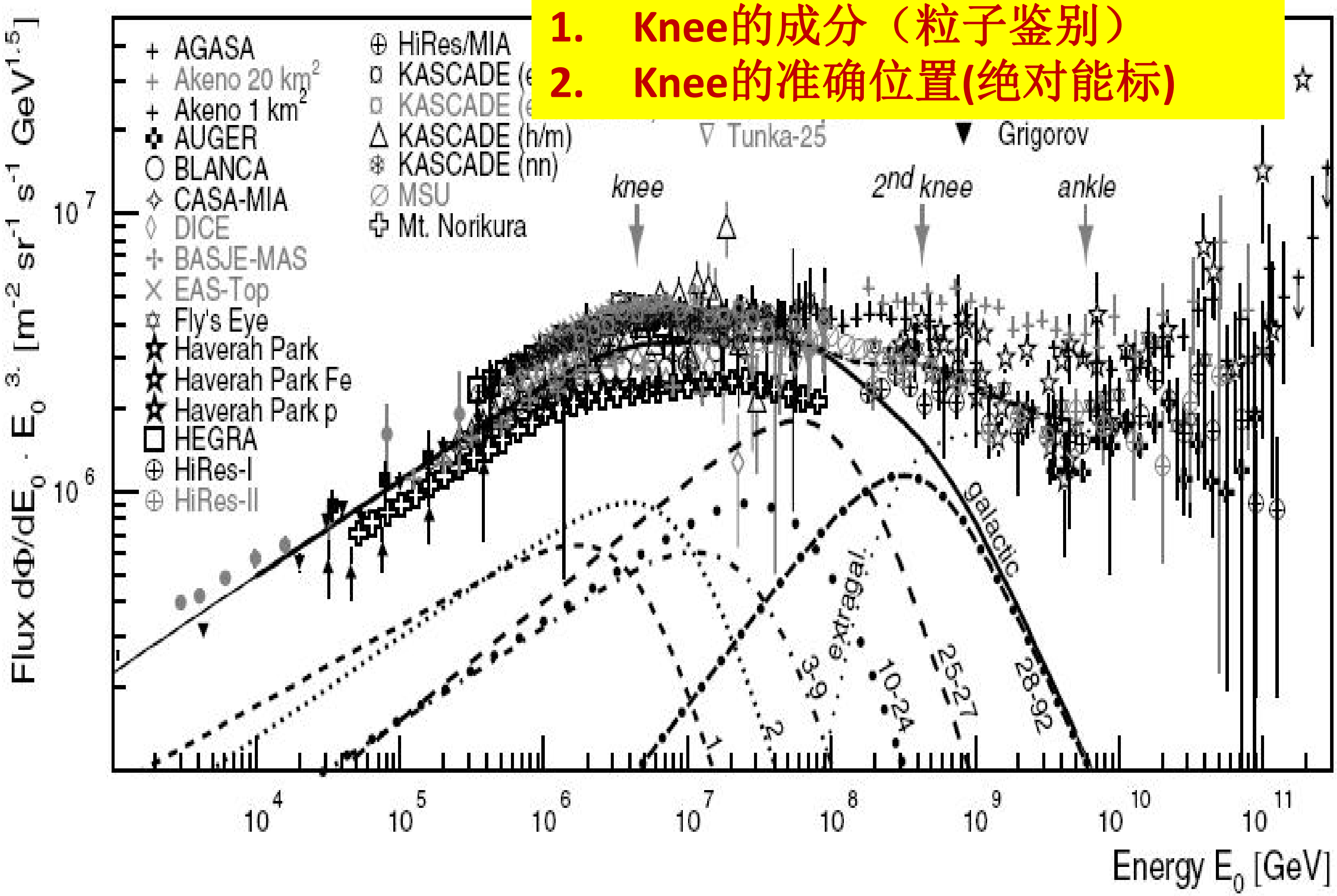


knee
2nd knee
ankle
galactic
extragalactic
Flux dΦ/dE0 · E0^3. [m^-2 sr^-1 s^-1 GeV^2.0]
Energy E0 [GeV]
JRH, Adv. Space Res. 41 (2008) 442



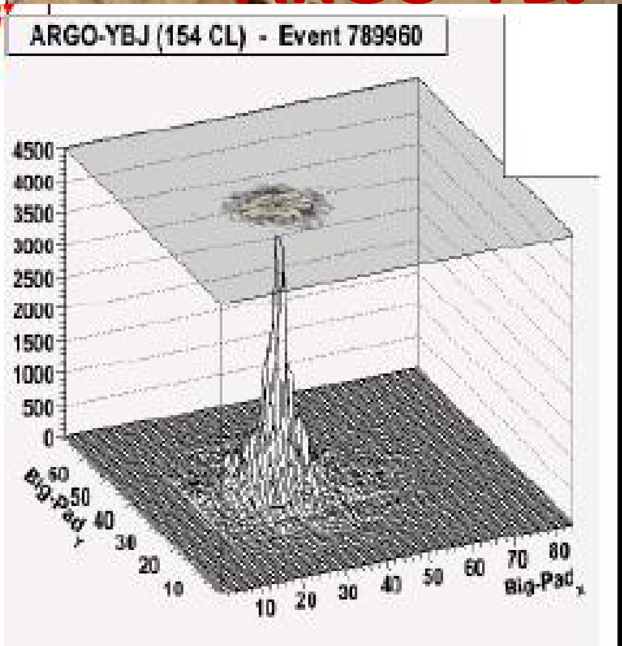
Neutron stars
White dwarfs
Active galactic nuclei?
Sunspots
Magnetic A stars
10^20 eV proton
10^20 eV iron
Interplanetary space
Crab
SNR
Radio galaxy lobes
Galactic disk
Galactic halo
Galactic cluster
IGM
Magnetic field strength, B (G)
Size, L
1 km
10^6 km
1 AU
1 pc
1 kpc
1 Mpc

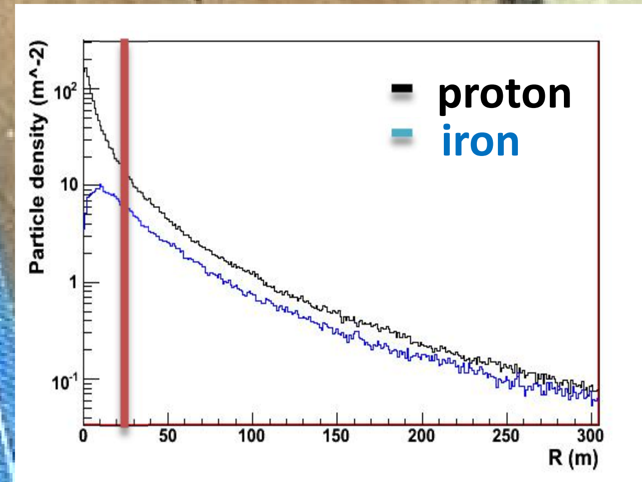
膝区物理面临的问题

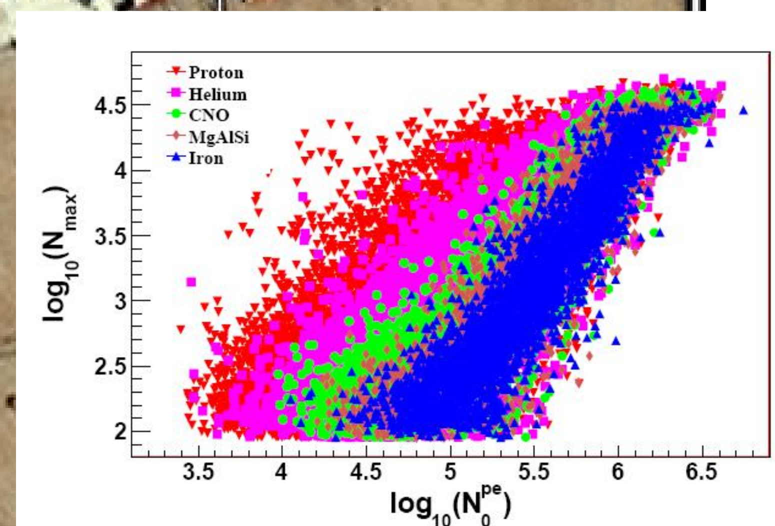


1. **Knee的成分（粒子鉴别）**
2. **Knee的准确位置(绝对能标)**

ARGO-YBJ experiment @ 4300 m a.s.l.

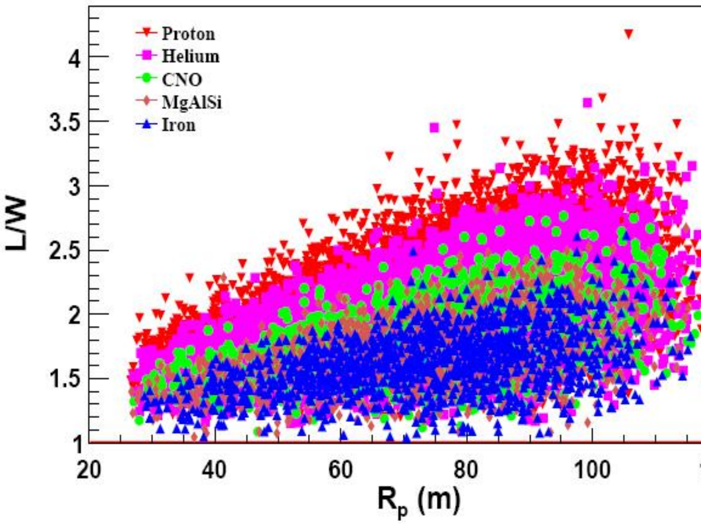


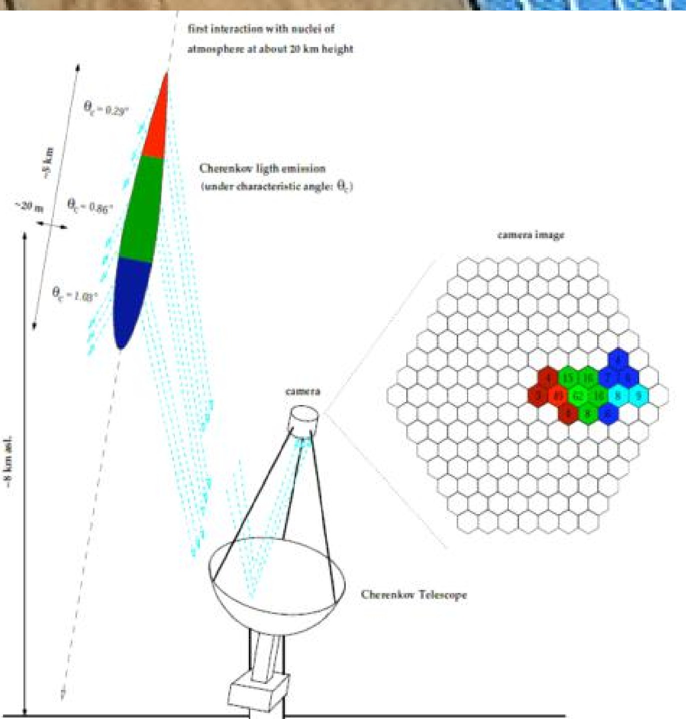


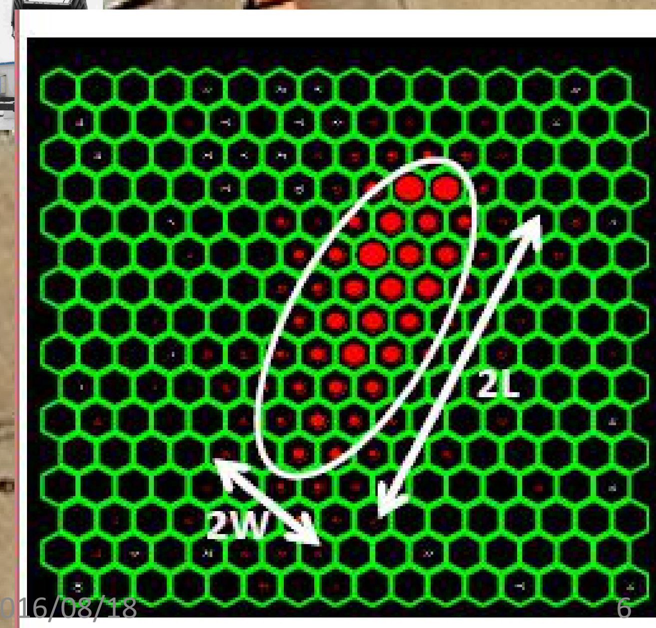


Wide Field of View Cherenkov Telescope (WFCTA)

- 5m² spherical mirror;
- 16×16 PMT array
- Pixel size 1°;
- FOV: 14°× 16°;
- Elevation angle: 60°.

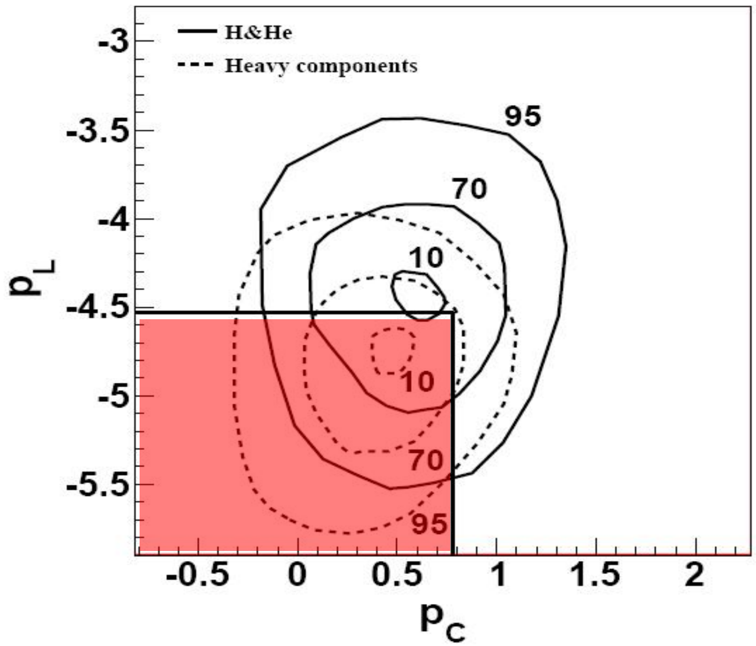




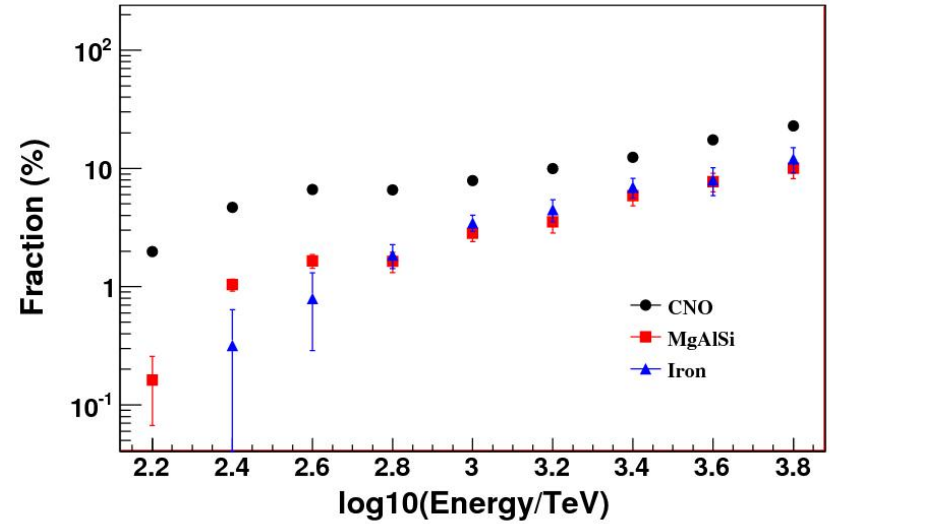


ARGO-YBJ 与 WFCTA样机联合观测结果

$$p_C = L/W - R_p/109.9m - 0.1log_{10}N_0^{pe}$$
$$p_L = log_{10}N_{max} - 1.44log_{10}N_0^{pe}$$



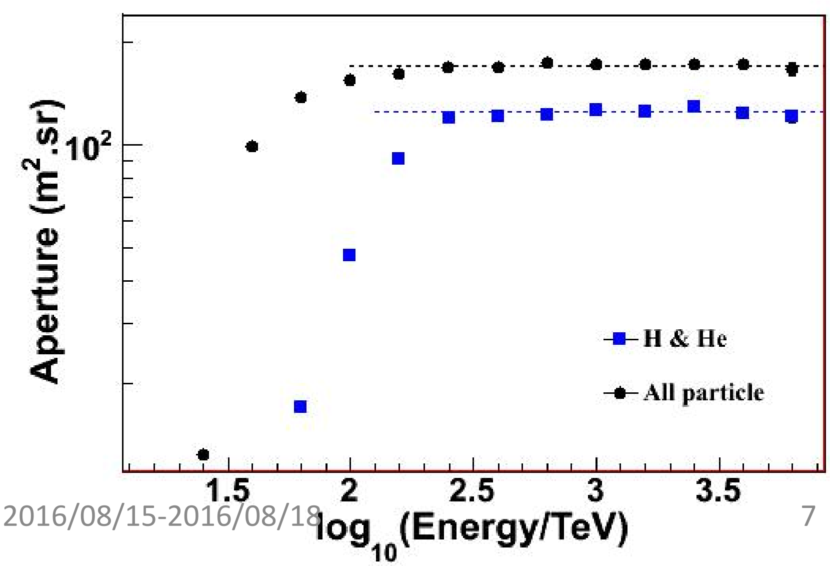
J.R. Hörandel, Modern Physics Letter A, 22, 1533 (2007)



➢The aperture of H&He: ~120 m² sr above 300 TeV;

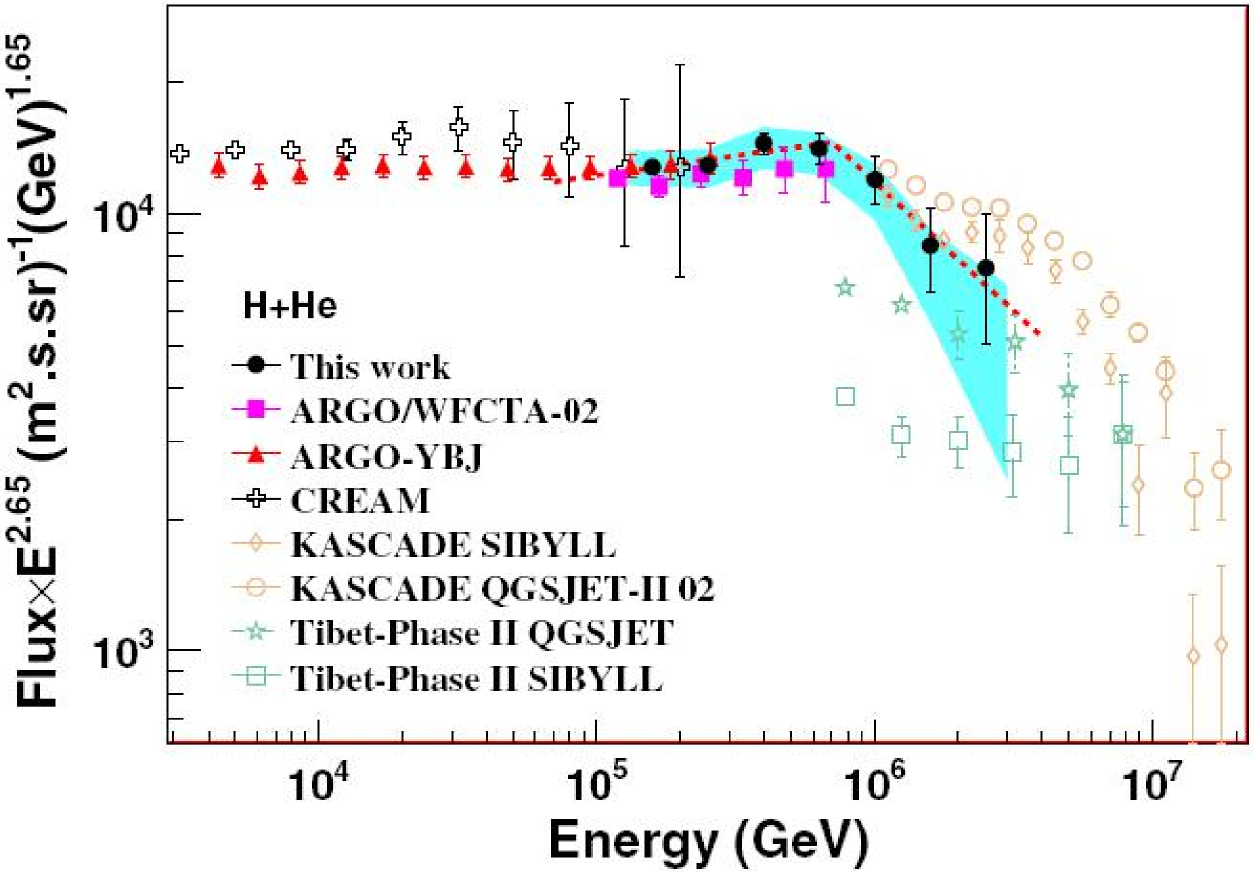
➢ The purity of H&He showers: ~93% below 700 TeV;

➢ The contamination of heavy nuclei increases with energy: 13% @ 1 PeV, gradually increases to 27% @ 3 PeV;



B. Bartoli, et al.， PHYSICAL REVIEW D 92, 092005 (2015)

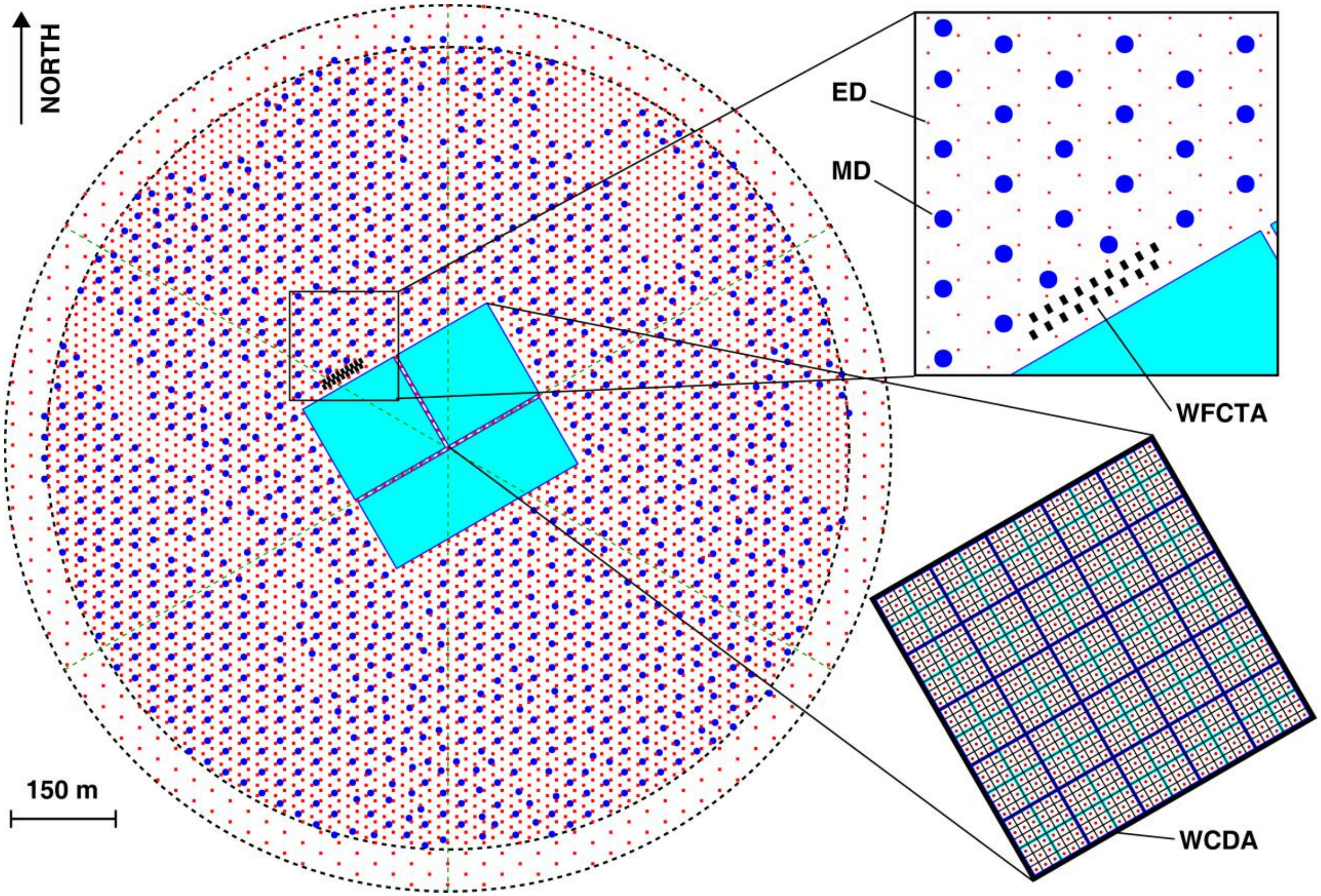
The spectrum of H & He with its knee below 1PeV



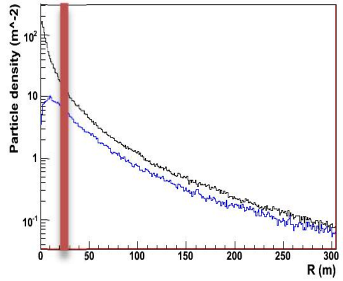
- 测量了100TeV-3PeV的质子+氦核能谱；
- 在（640±87）PeV处发现了非常重要的质子+氦核能谱“膝”，远低于人们根据之前实验结果推断的结果（4PeV）。

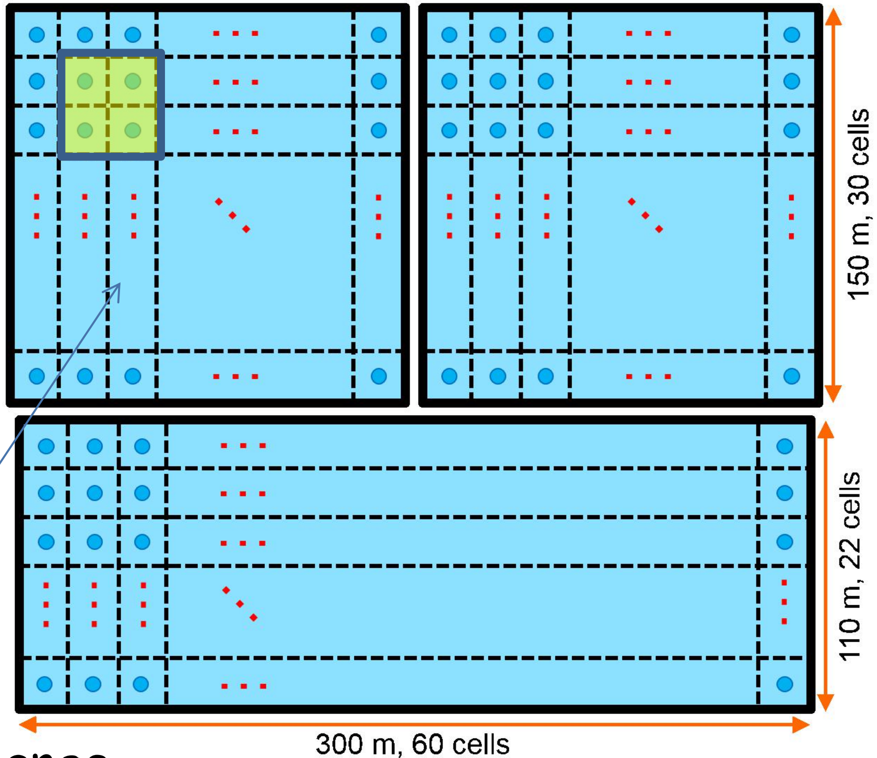
LHAASO 海拔：~4400m

大型高海拔空气簇射观测站 四川稻城海子山

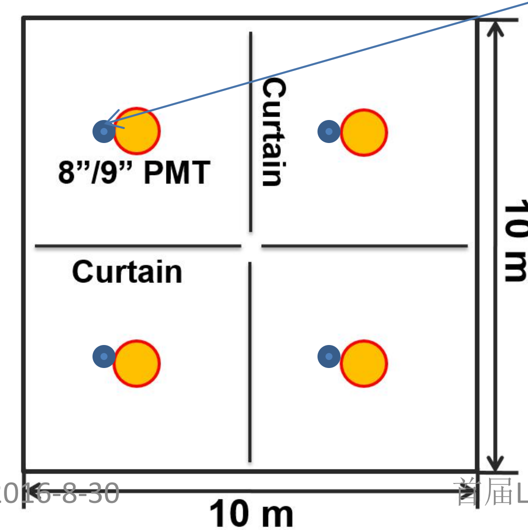


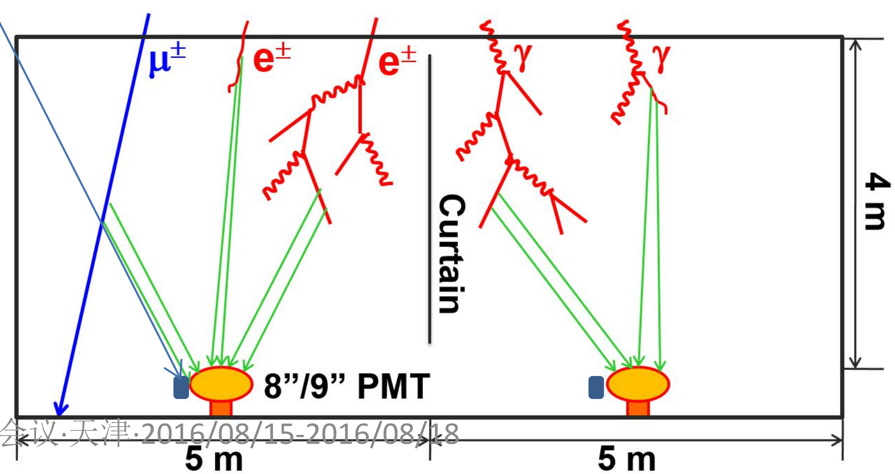
WCDA++

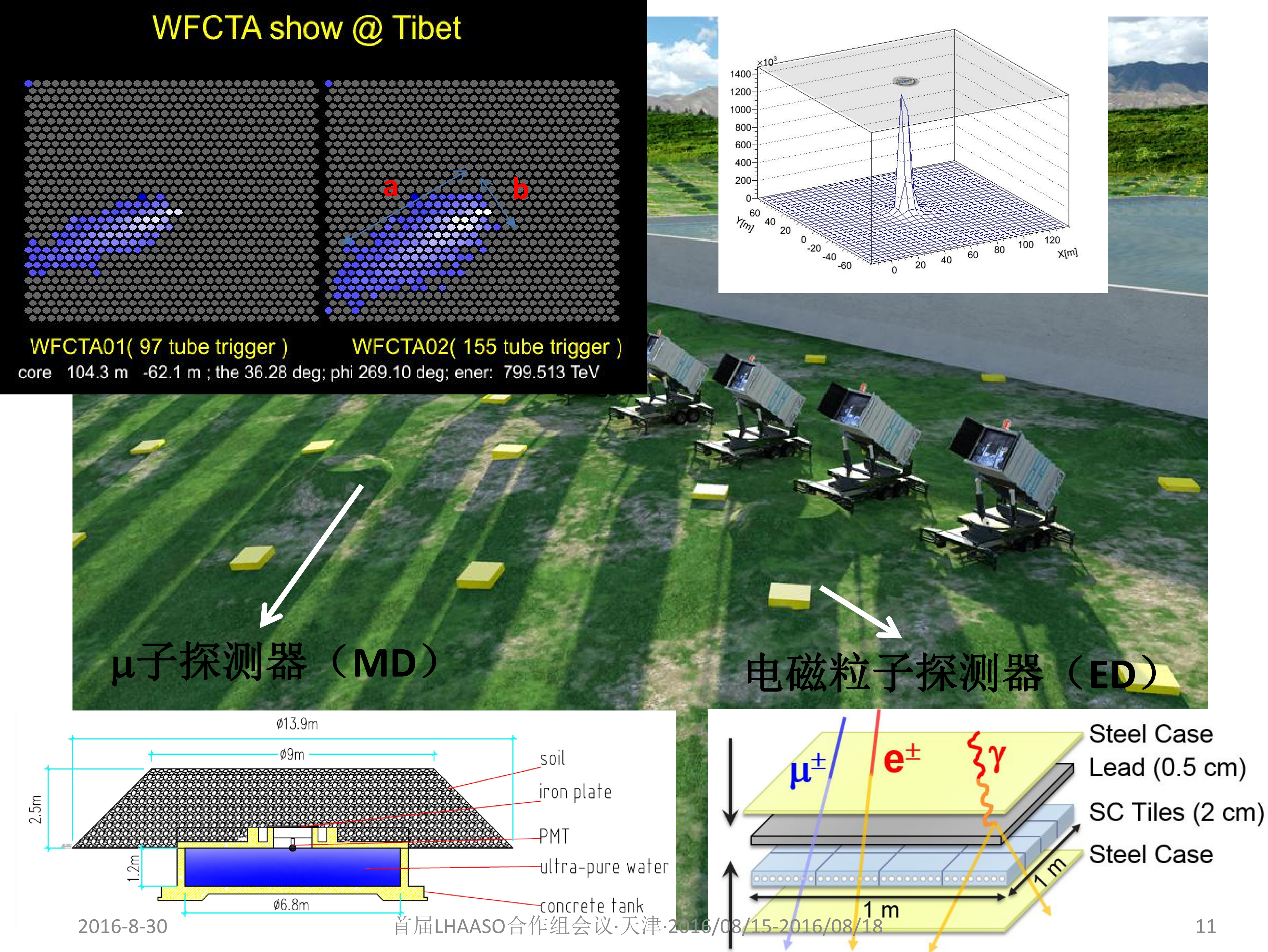




- 3 water ponds:
  - 78,000 m² in total;
  - 4 m effective depth;
  - 3120 cells, with an 8"/9" PMT in each cell;
  - Cells are partitioned with black curtains.
- WCDA++: 1"PMTs enhance Dynamic Range

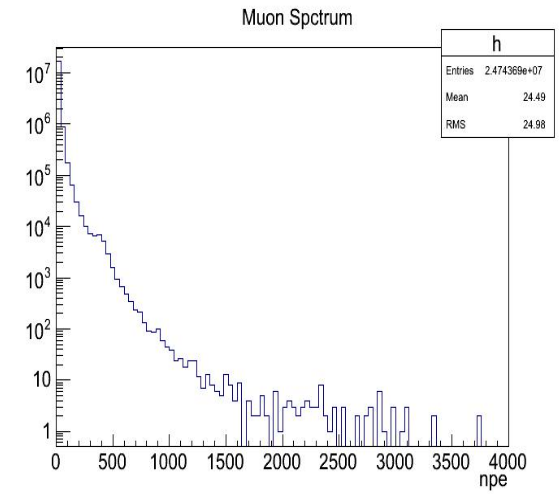


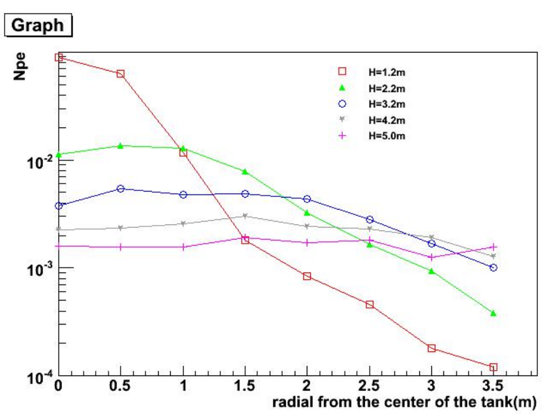


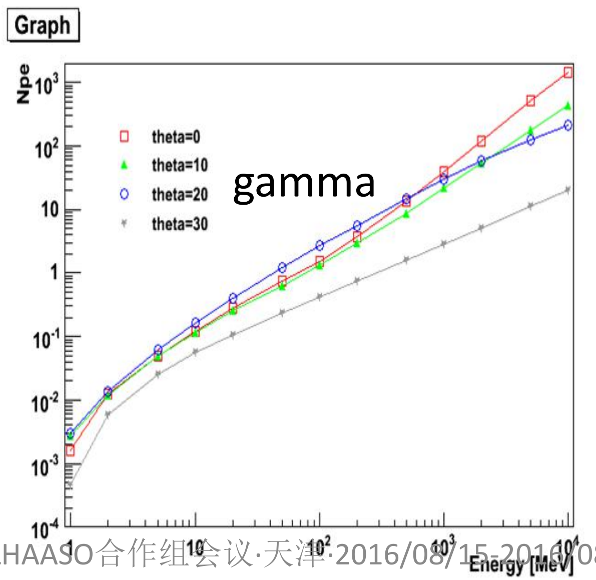

WFCTA show @ Tibet
a
b
WFCTA01(97 tube trigger)
WFCTA02(155 tube trigger)
core 104.3 m -62.1 m ; the 36.28 deg; phi 269.10 deg; ener: 799.513 TeV
×10³
1400
1200
1000
800
600
400
200
0
Y[m]
60
40
20
0
-20
-40
-60
0
20
40
60
80
100
120
X[m]
μ子探测器（MD）
电磁粒子探测器（ED）
ø13.9m
ø9m
2.5m
1.2m
ø6.8m
soil
iron plate
PMT
ultra-pure water
concrete tank
μ±
e±
γ
Steel Case
Lead (0.5 cm)
SC Tiles (2 cm)
Steel Case
1 m
1 m

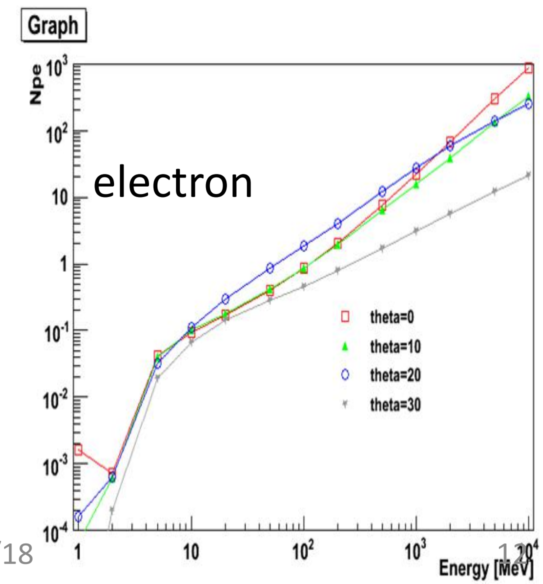
探测器模拟

- Cherenkov望远镜
  - WFCTA现有模拟程序
- KM2A-MD
  - 对于能量大于1GeV的$\mu^{\pm}$计数，加25% smear
- WCDA
  - 对γ和电子，采用平均光电子数求和（研究表明和集中水池的位置关系不大，主要依赖于能量）（Wu Hanrong）
  - 对$\mu^{\pm}$，从单μ的光电子分布中抽样（Li Huicai）



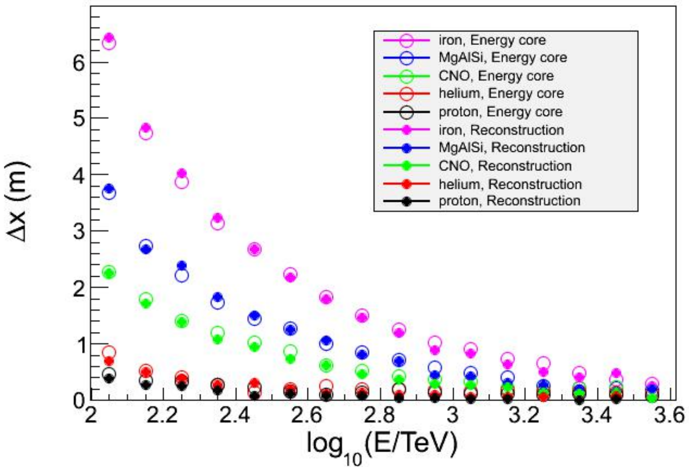


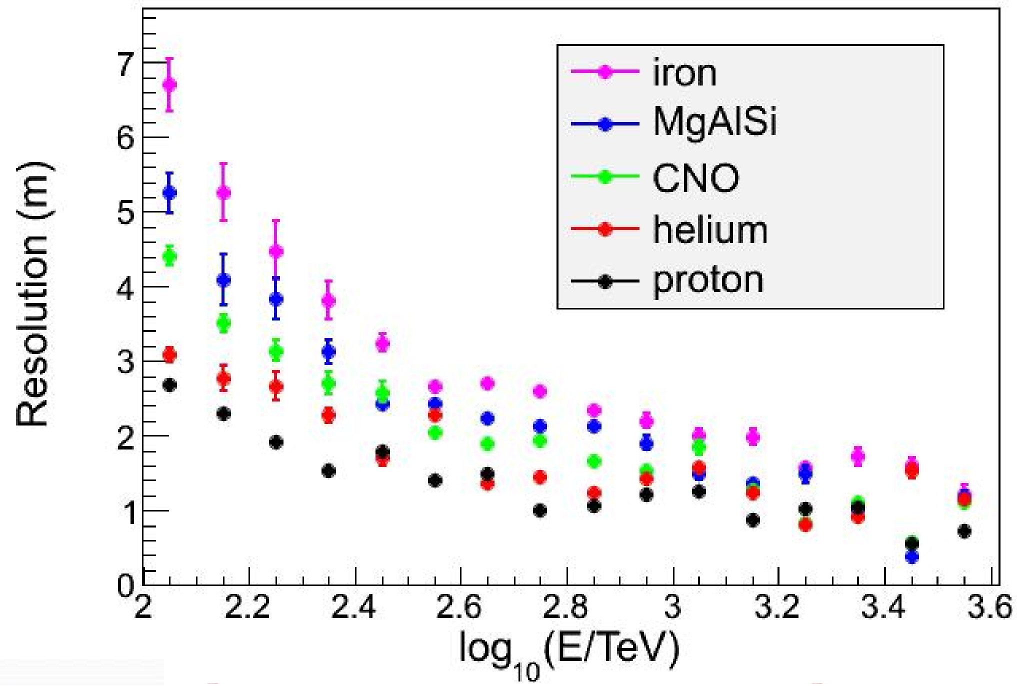




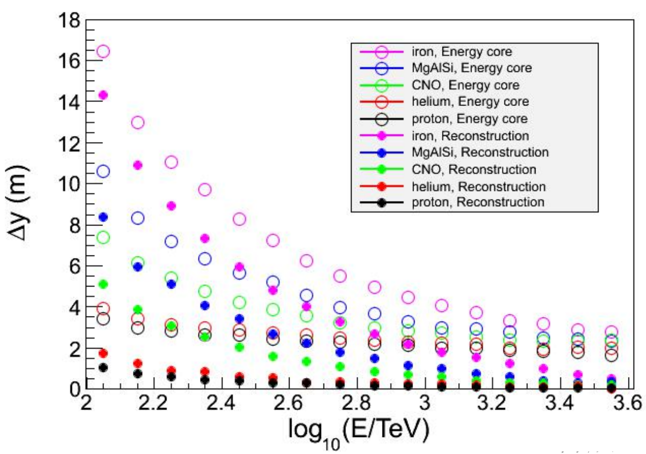
$$\rho(r) = N \times \left(\frac{r}{rm}\right)^a \times \left(1 + \frac{r}{rm}\right)^b$$

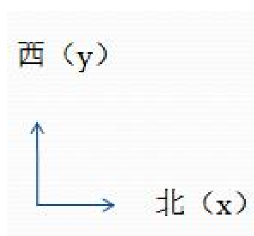
芯位重建分辨





- 地磁场的影响导致shower的能量重心不在预期的(0,0)点
- x,y两个方向芯位重建的偏差和能量重心的偏差基本是符合的



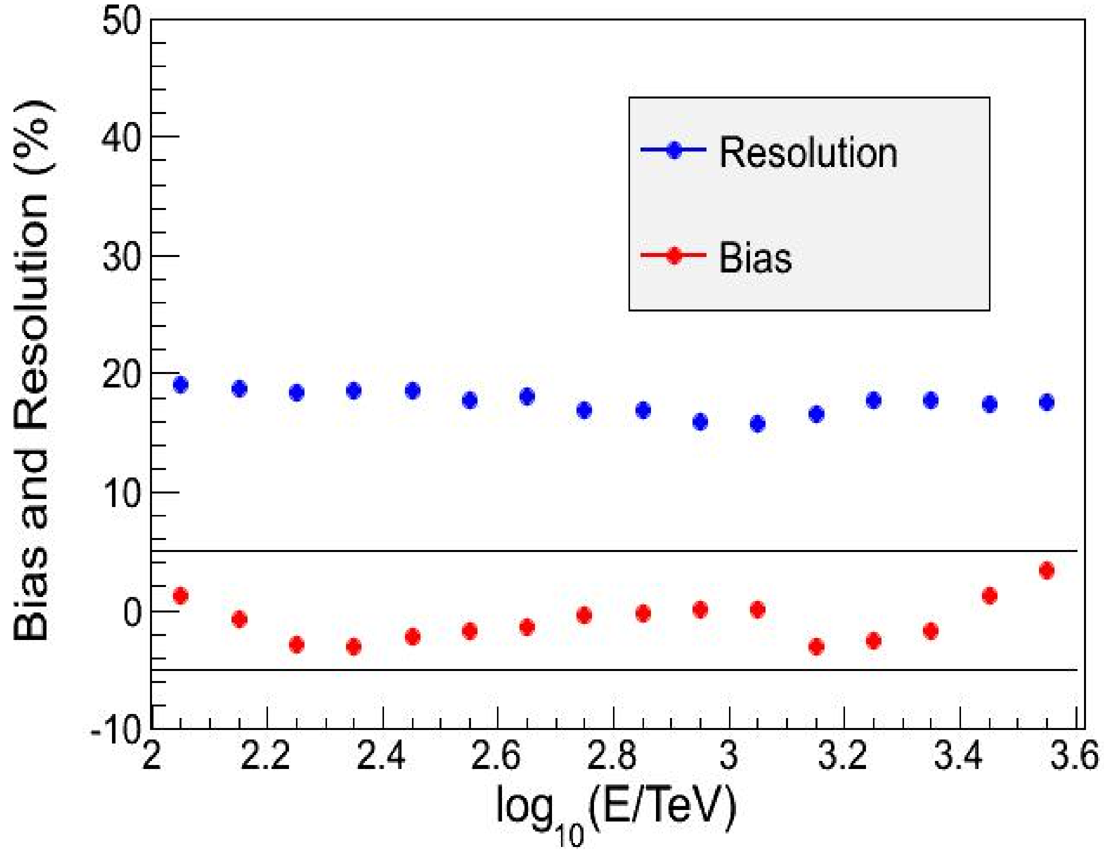


$$Reolution = \sqrt{\sigma_x^2 + \sigma_y^2}$$

对轻成分（proton and helium）的芯位重建分辨好于3m

能量重建

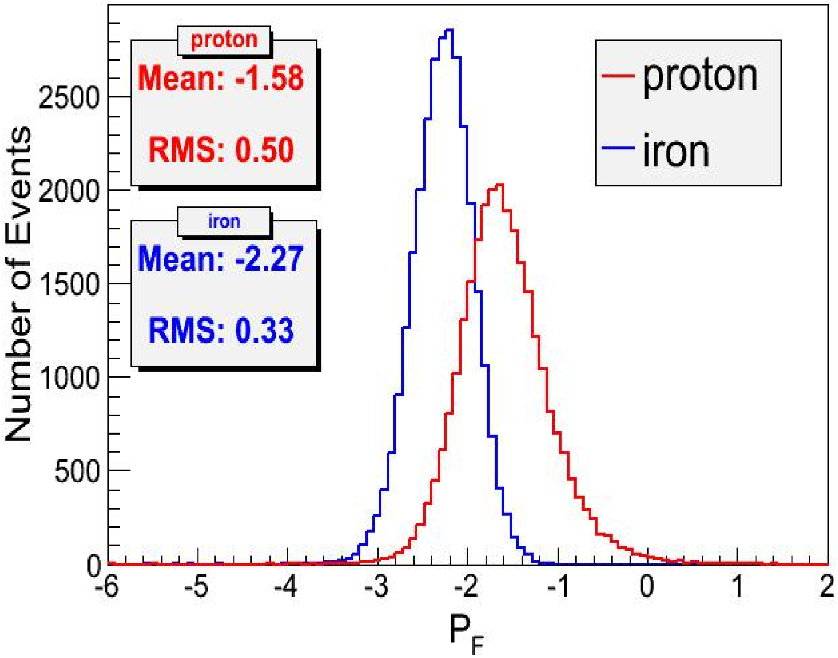
- Cherenkov望远镜对观测平面以上的所有Cherenkov光子进行积分
- 有量能器的特点
- Bias < ±5%
- Resolution ~ 20%



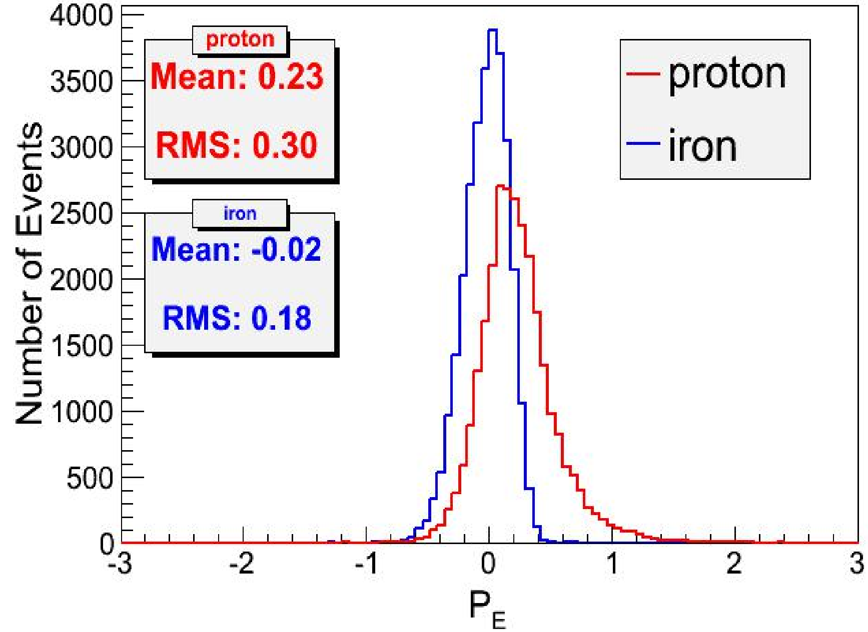
WFCTA（观测平面以上簇射发展过程沉积能量）&WCDA++（簇射的剩余能量）结合在一起可能提供更好的能量重建方案

成分敏感的参数

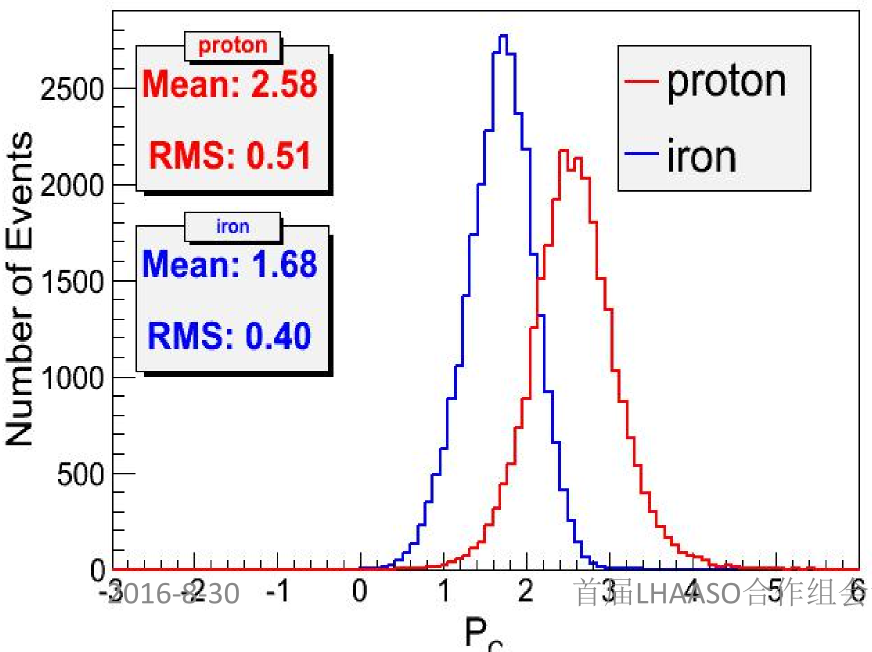
- 用Rp和α修正望远镜的光子数
  - $\log_{10}(N_{pe}^0) = \log_{10}(N_{pe}) + 0.0092 \times R_p + 0.0182 \times \alpha$
- $P_F = \log_{10}(W_{max}) - 1.392 \times \log_{10}(N_{pe}^0)$
  - 芯区能流密度，WCDA++提供簇芯最亮的PMT光电子数
- $P_E = \log_{10}(\Sigma W) - 1.16 \times \log_{10}(N_{pe}^0)$
  - 簇射剩余能量，WCDA++中的总光电子数
- $P_C = \frac{L}{W} - 0.0139 \times R_p + 0.267 \times \log_{10}(N_{pe}^0)$
  - 契伦科夫像的长宽比，WFCTA提供簇射的纵向发展信息
- $P_\mu = \log_{10}(N_\mu) - 0.9823 \times \log_{10}(N_{pe}^0)$
  - MD提供簇射的μ子信息，$N_\mu \propto E^{0.9} A^{0.1}$



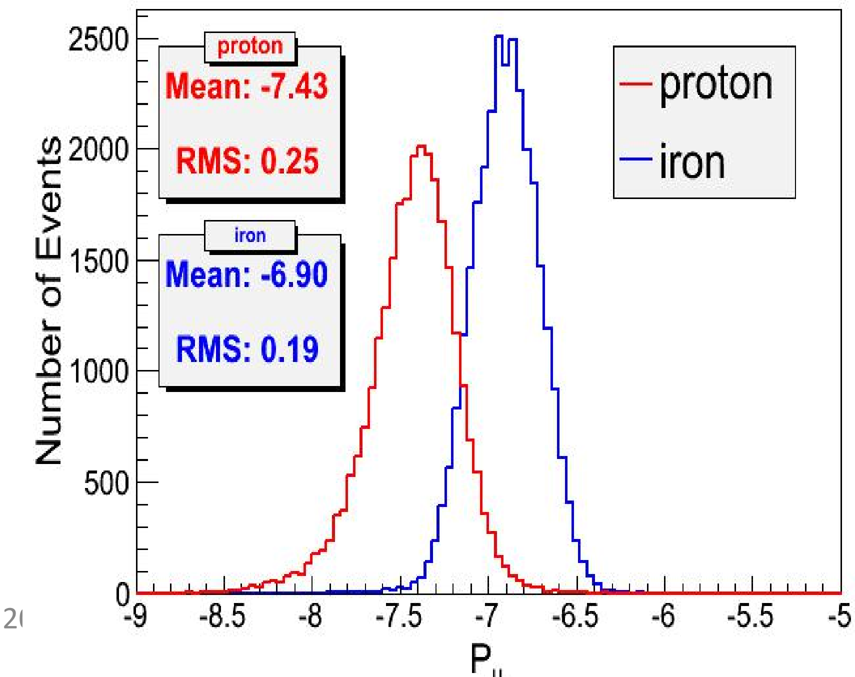
proton
Mean: -1.58
RMS: 0.50
iron
Mean: -2.27
RMS: 0.33
proton
iron
Number of Events
P_F



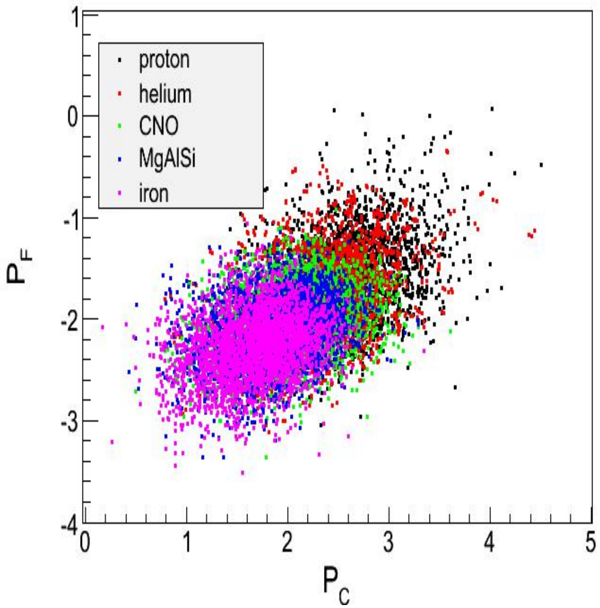
proton
Mean: 0.23
RMS: 0.30
iron
Mean: -0.02
RMS: 0.18
proton
iron
Number of Events
P_E

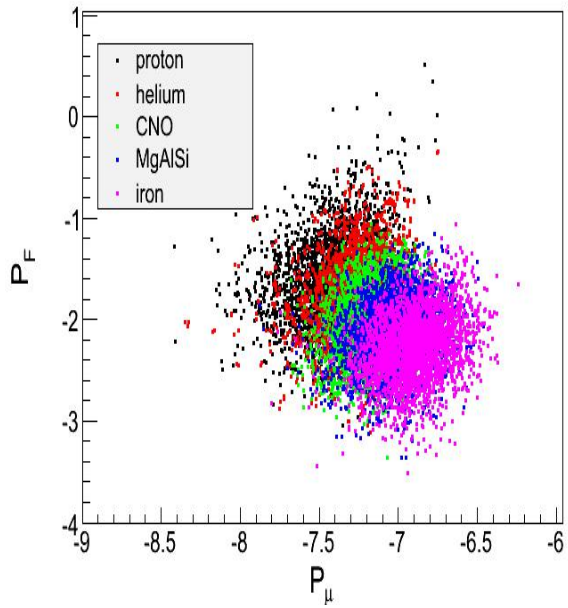


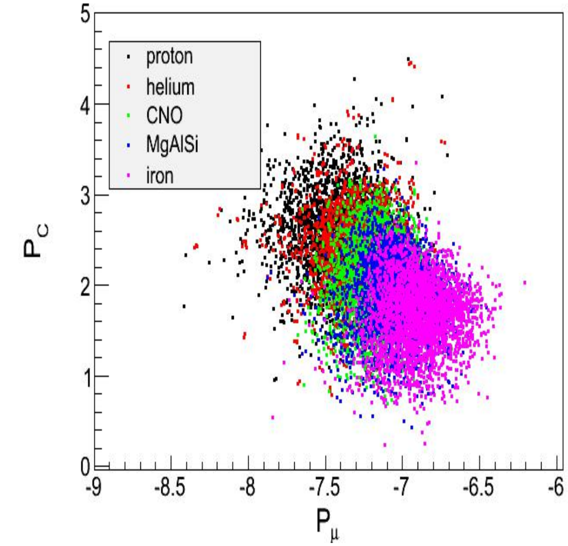
proton
Mean: 2.58
RMS: 0.51
iron
Mean: 1.68
RMS: 0.40
proton
iron
Number of Events
P_C

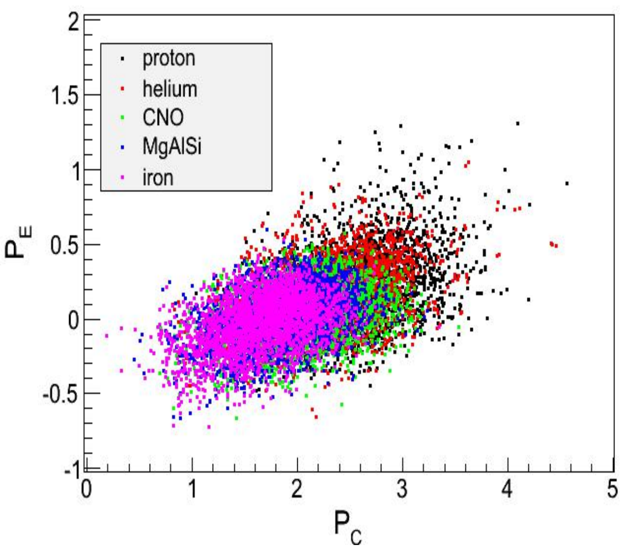


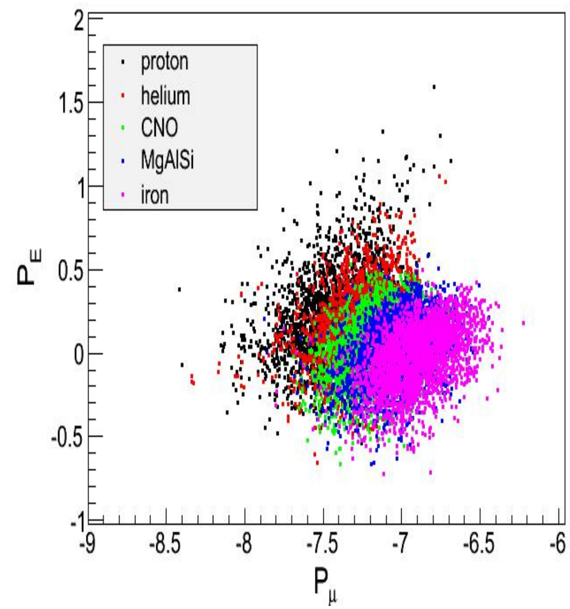
proton
Mean: -7.43
RMS: 0.25
iron
Mean: -6.90
RMS: 0.19
proton
iron
Number of Events
P_μ





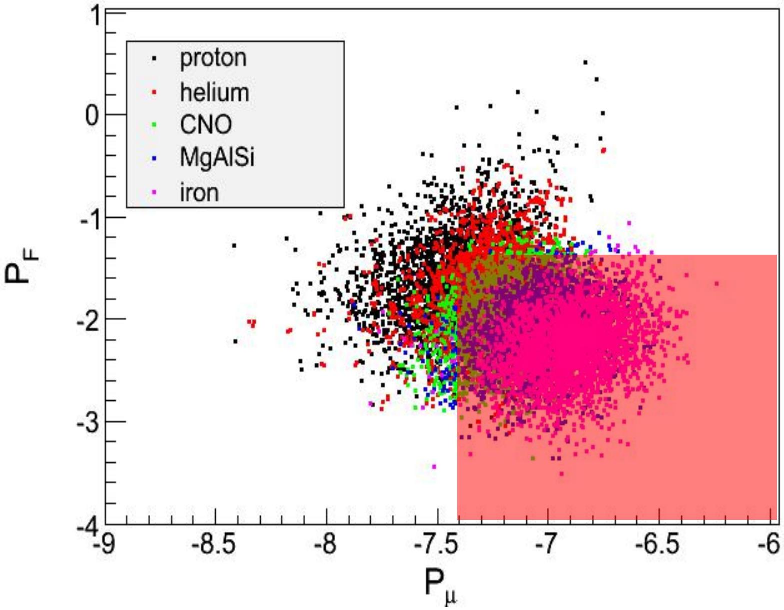


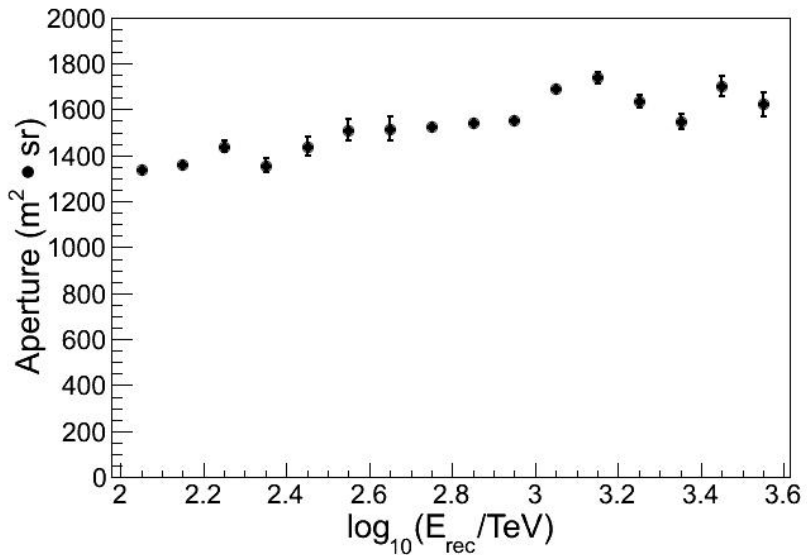




除了P_F v.s. P_E的外，其他的变量之间是相互独立的

对proton+helium的挑选



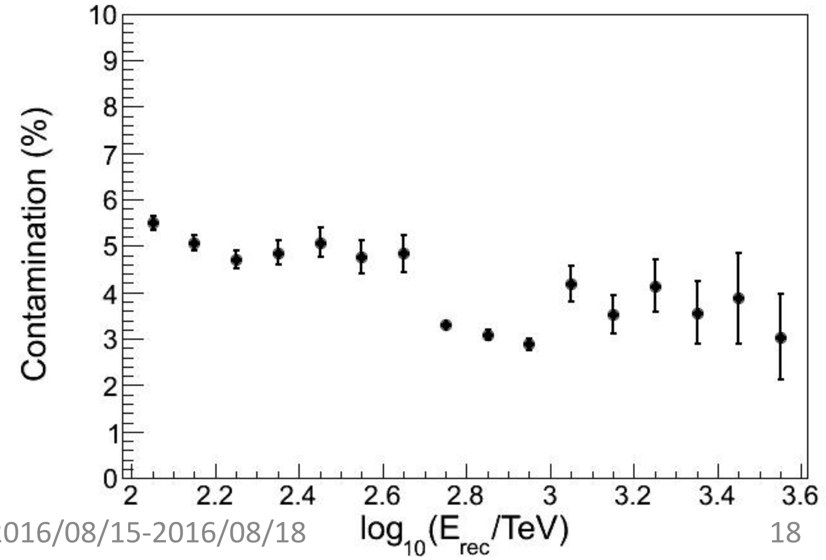


6台望远镜，3%duty cycle

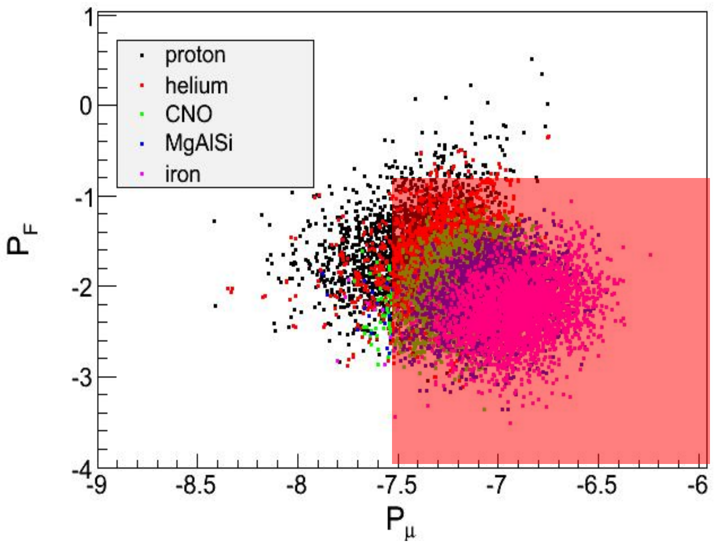
Aperture ~ 1600m^2·sr

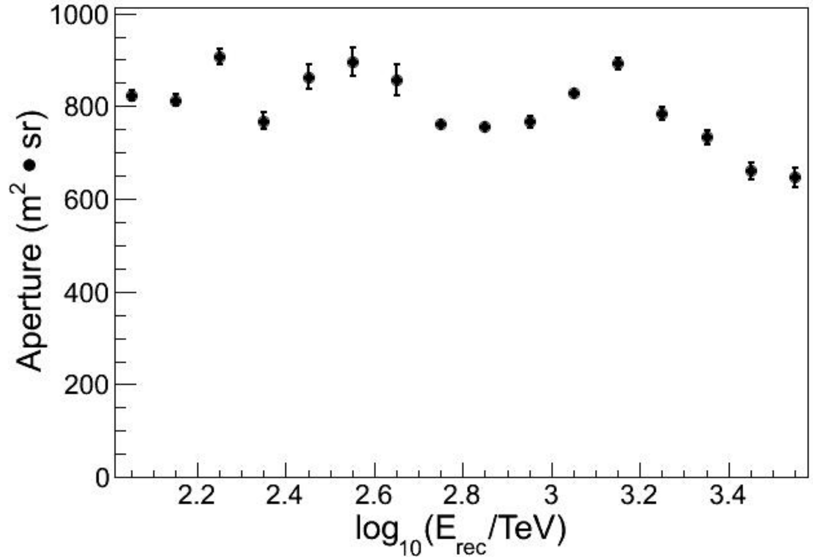
Efficiency ~ 70%

Contamination < 10%



对proton的挑选



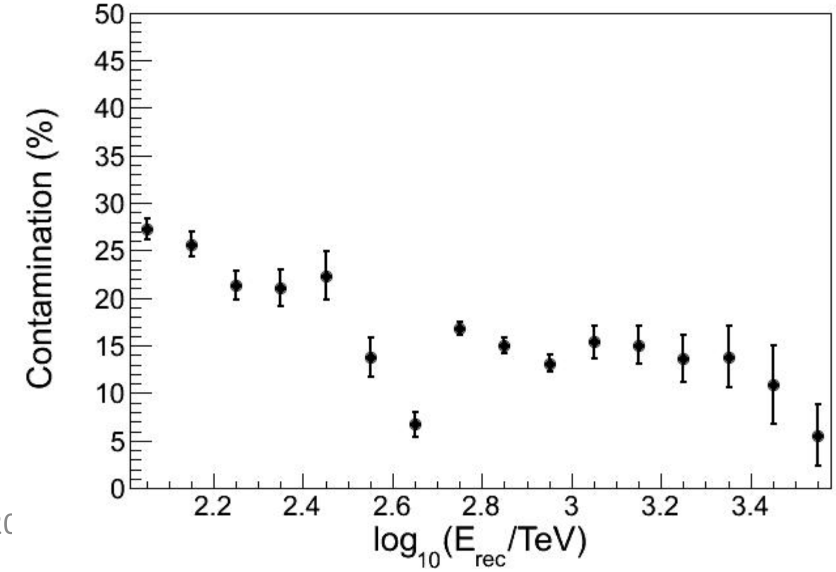


6台望远镜，3%duty cycle

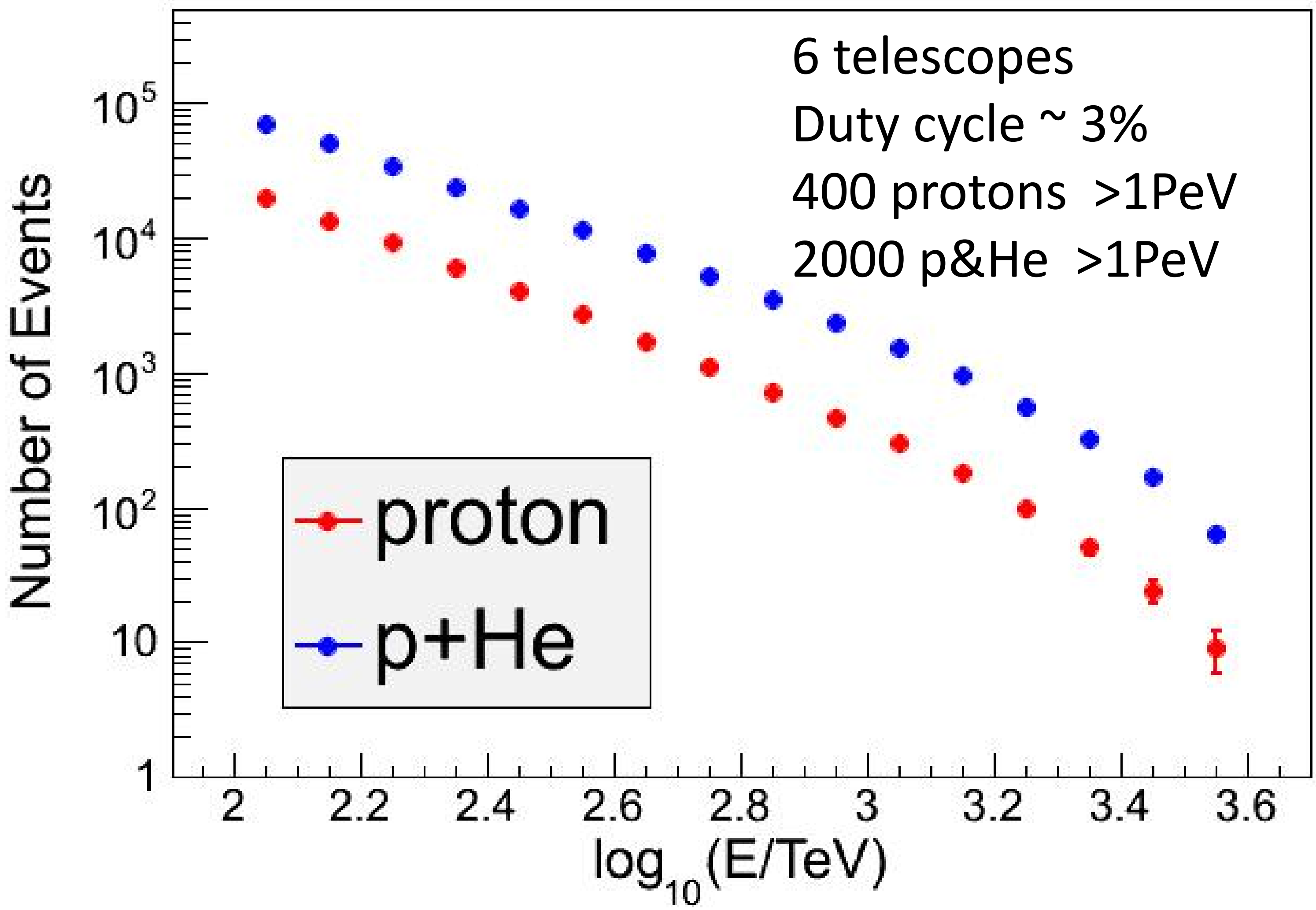
Aperture ~ 800m^2·sr

Efficiency ~ 30%

Contamination < 25%



观测统计量的估计



6 telescopes
Duty cycle ~ 3%
400 protons >1PeV
2000 p&He >1PeV
proton
p+He
Number of Events
10^5
10^4
10^3
10^2
10
1
2
2.2
2.4
2.6
2.8
3
3.2
3.4
3.6
$\log_{10}(E/TeV)$

总结与展望

- 位置分辨和能量分辨：
  - 对轻成分，位置分辨好于3m
  - 能量bias<±5%，分辨率好于20%
- 成分分辨和统计量估计
  - P_F、P_E、P_C、P_μ有区分成分的能力
  - 6台望远镜，3%的duty cycle下
  - 400 proton, E>1PeV, contamination<20%
  - 2000proton&helium, E>1PeV, contamination<10%
- 更好的分析方法可能带来更好的结果
  - WFCTA&WCDA可能提供更好的能量分辨
  - 引入多参数分析方法可能带来更好的成分分辨能力
  - 或许有更多的成分敏感参量有待发掘
  - ……………………