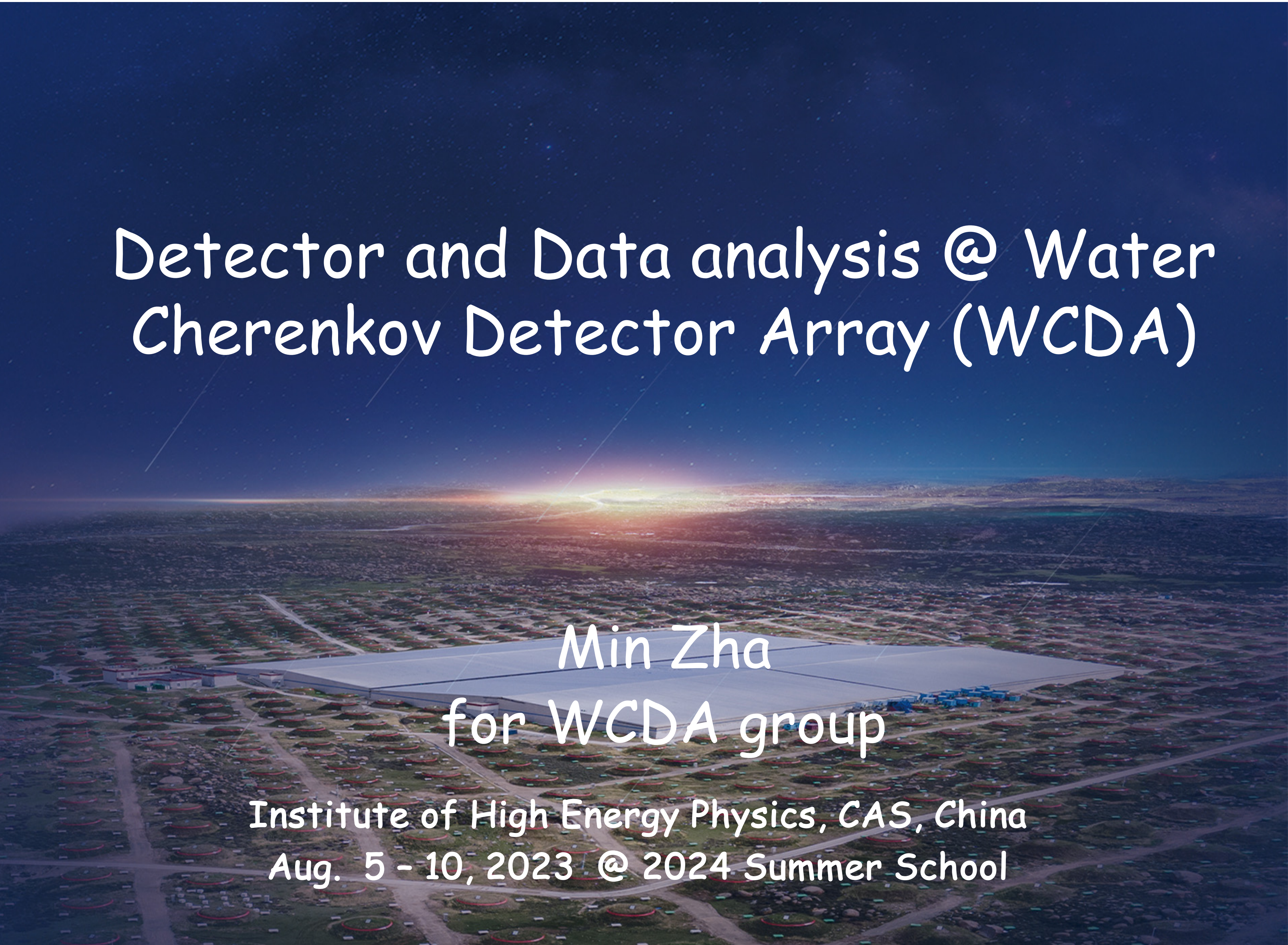


Detector and Data analysis @ Water Cherenkov Detector Array (WCDA)

Min Zha
for WCDA group

Institute of High Energy Physics, CAS, China

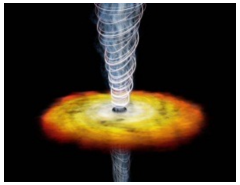
Aug. 5 – 10, 2023 @ 2024 Summer School

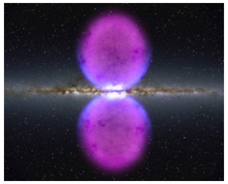
outline

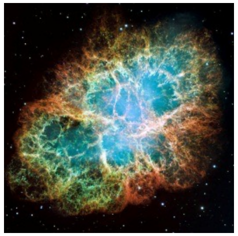
- WCDA detector
- WCDA data production details
- Summary and outlook

Scientific targets

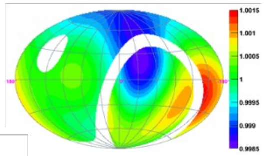
- V/UHE gamma sky survey (100 GeV-1 PeV)
  - Galactic sources;
  - Extragalactic sources & flares;
  - VHE emission from Gamma Ray Bursts;
  - Diffused Gamma rays.



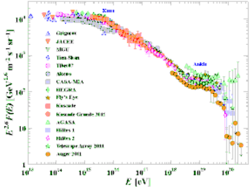


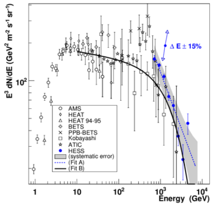


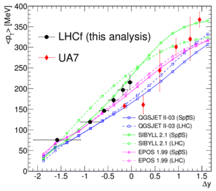
- Gamma ray Spectrum measurement at the high end:
  - Nature of the acceleration: leptonic or hadronic;
  - Origin of cosmic rays – 100 years' mystery.



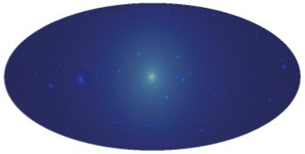
- Cosmic rays
  - Anisotropy of VHE cosmic rays;
  - Cosmic electrons / positrons;

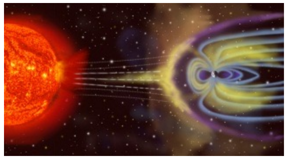




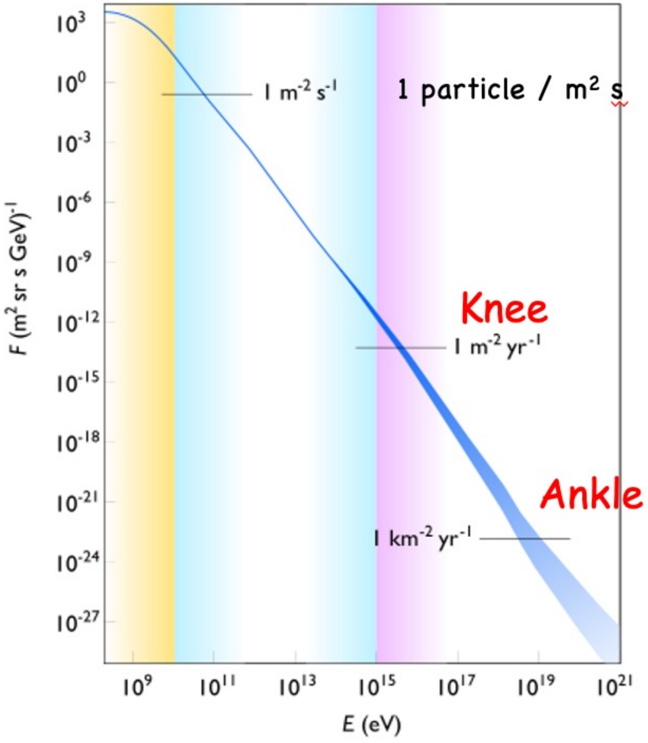


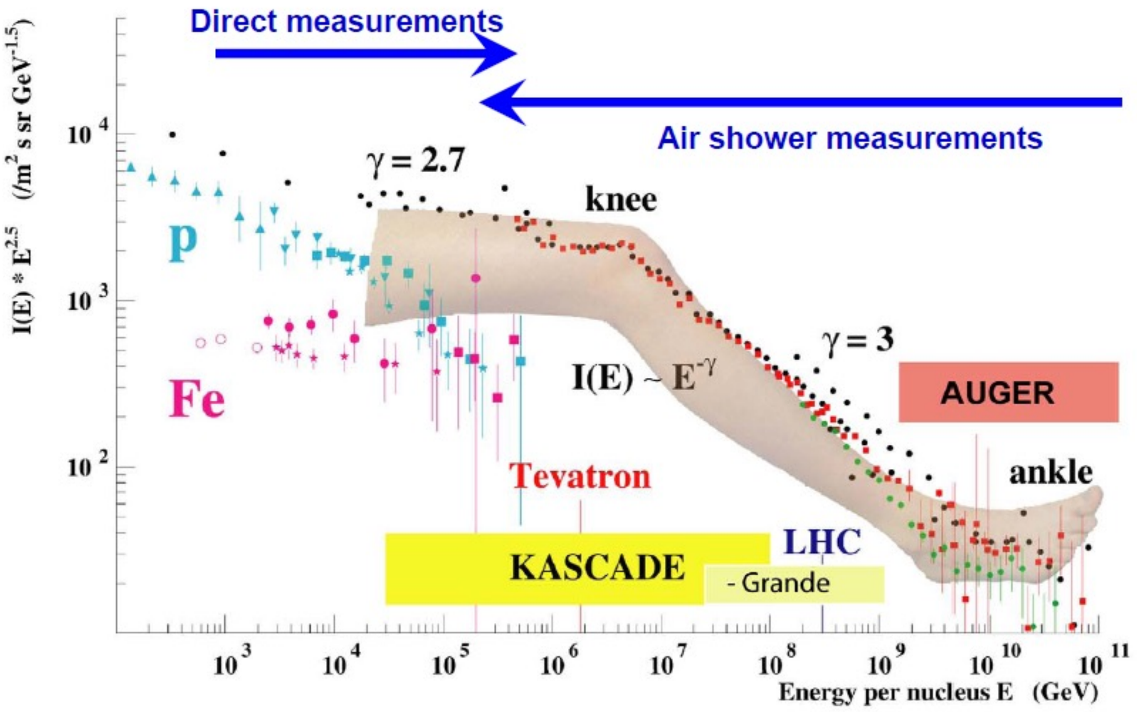
- Miscellaneous:
  - Gamma rays from dark matter;
  - Sun storm & IMF.





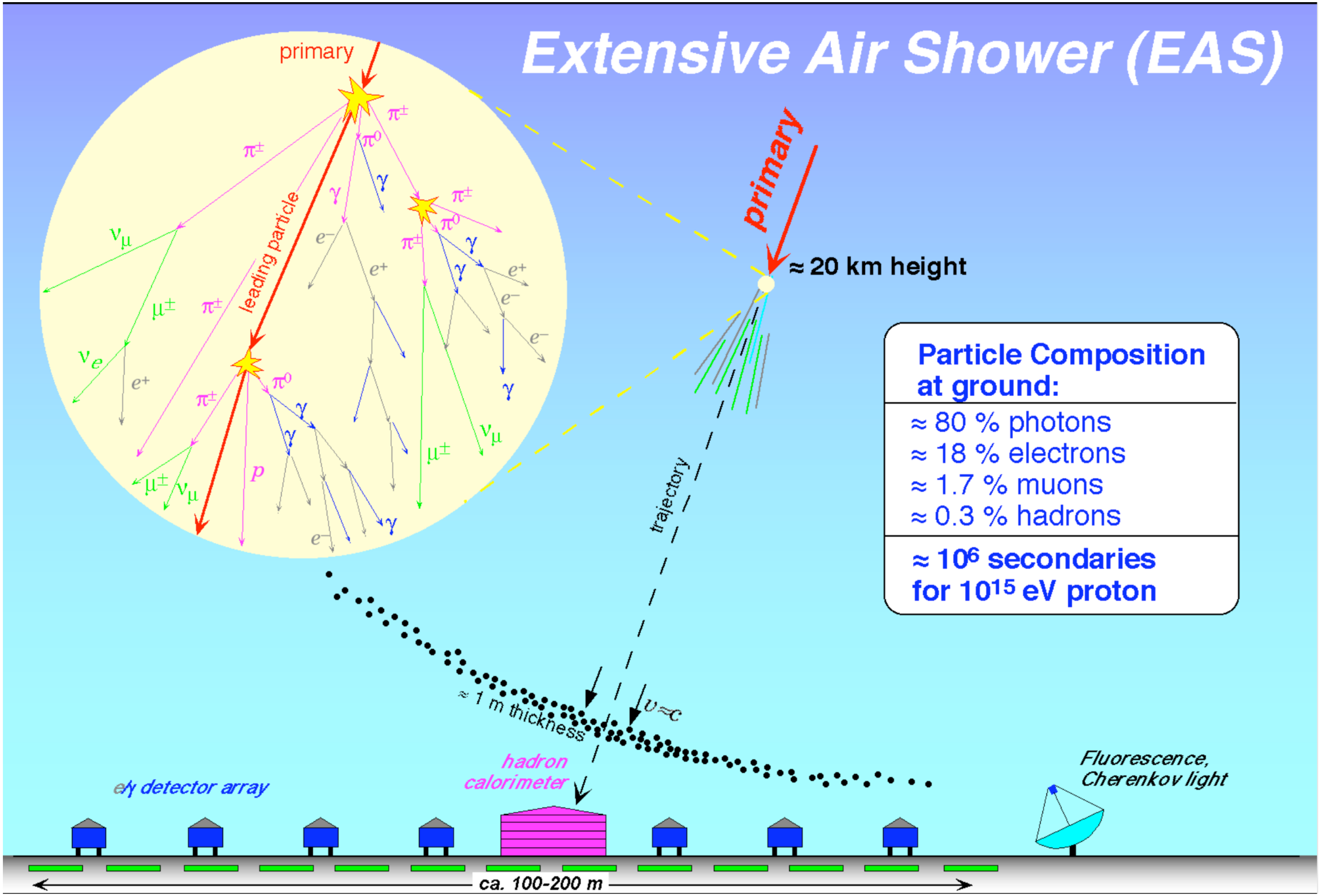
The Energy Spectrum for Cosmic Ray





- 跨越12个量级；
- 最高能可达10^{20} eV！
- 近似幂指数 (power law)分布；
- 能量越高，流强越小。
- 加速机制？

Extensive Air Shower (EAS)



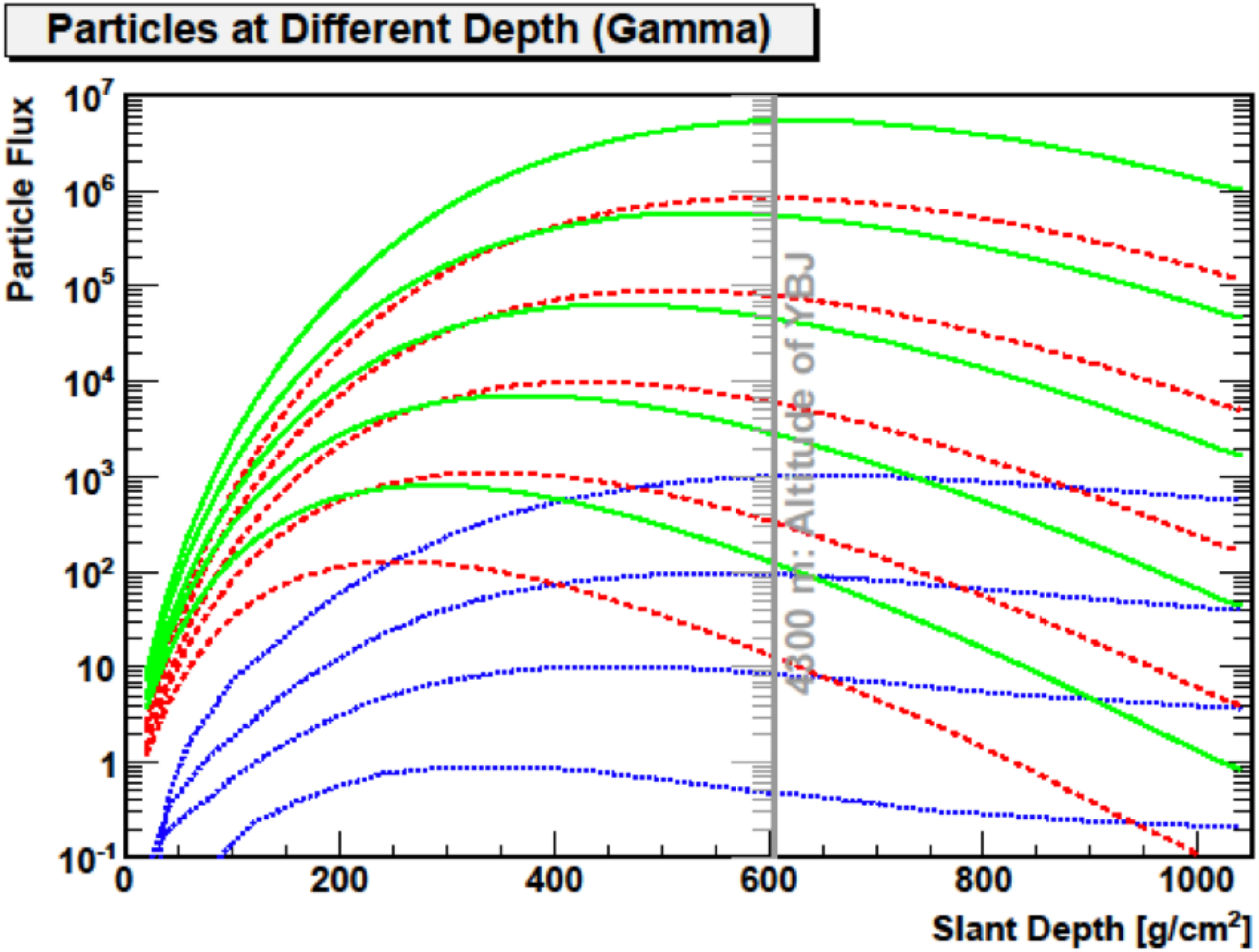
Particle Composition at ground:

- ≈ 80 % photons
- ≈ 18 % electrons
- ≈ 1.7 % muons
- ≈ 0.3 % hadrons

≈ 10^6 secondaries for 10^{15} eV proton

通过测量簇射中的次级粒子来获取原初宇宙线的信息（方向、能量、成分）

高海拔: 降低阈能 + 膝区宇宙线的极大发展深度

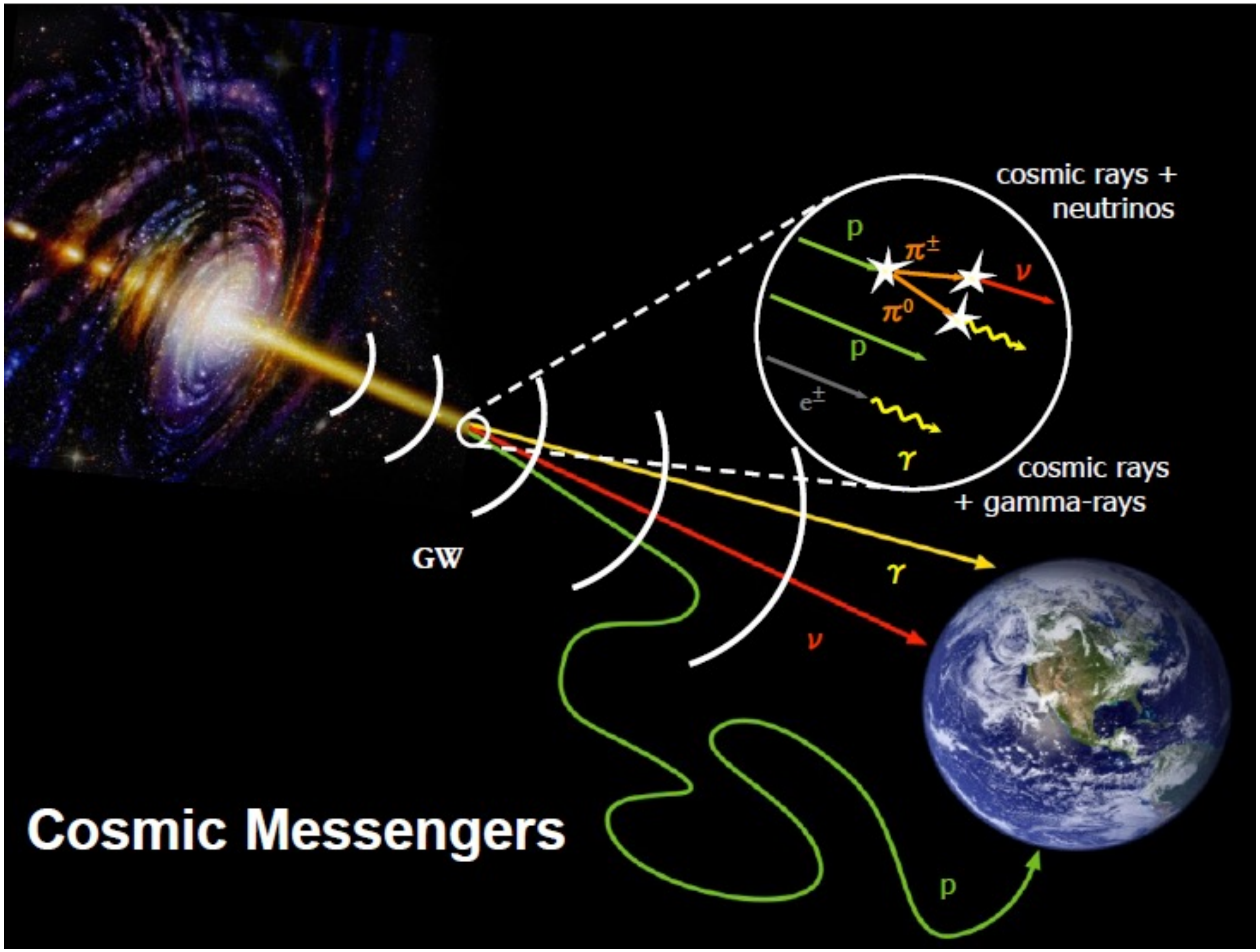


- Green: gamma;
- Red: electron;
- Blue: muon.

- From top to bottom:
  - 1 PeV;
  - 100 TeV;
  - 10 TeV;
  - 1 TeV;
  - 100 GeV.

Site @~ 4400 a.s.l

伽马射线是重要的宇宙信使之一



- 伽马不受磁场偏转，从而可以确定发生源的位置！
- 伽马探测是天体物理研究的重要手段之一。

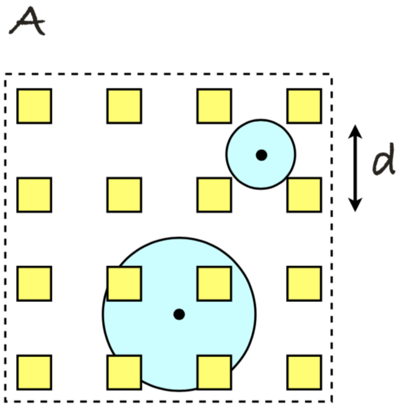
$N_{evts} = \text{flux} \times \text{area} \times \text{time}$

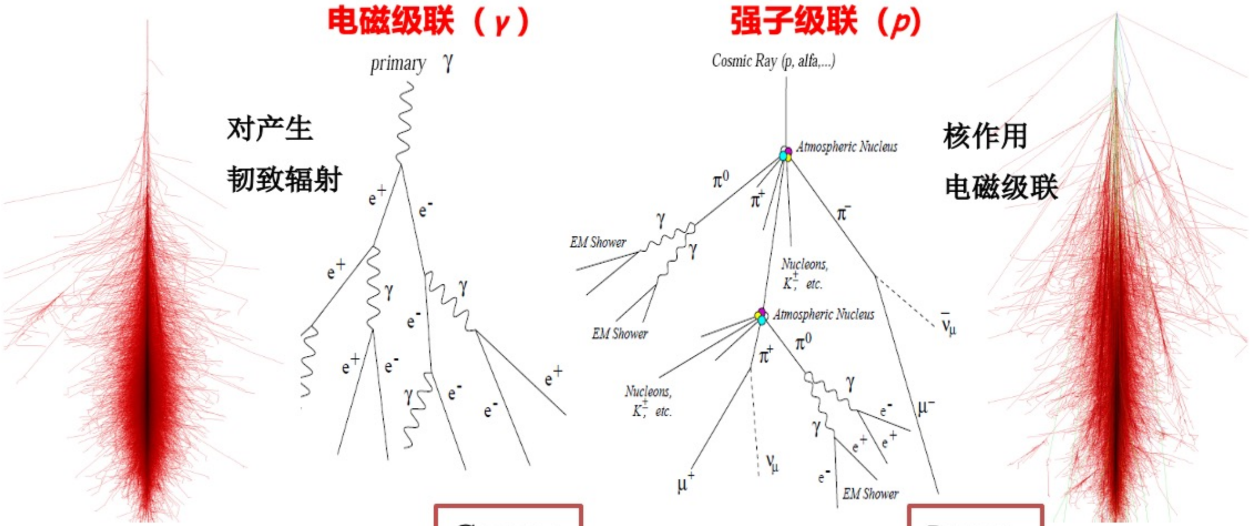
> 100 for $<10\%$ stat. error

low, given by nature

$\approx 1\ m^2$ for space exp.

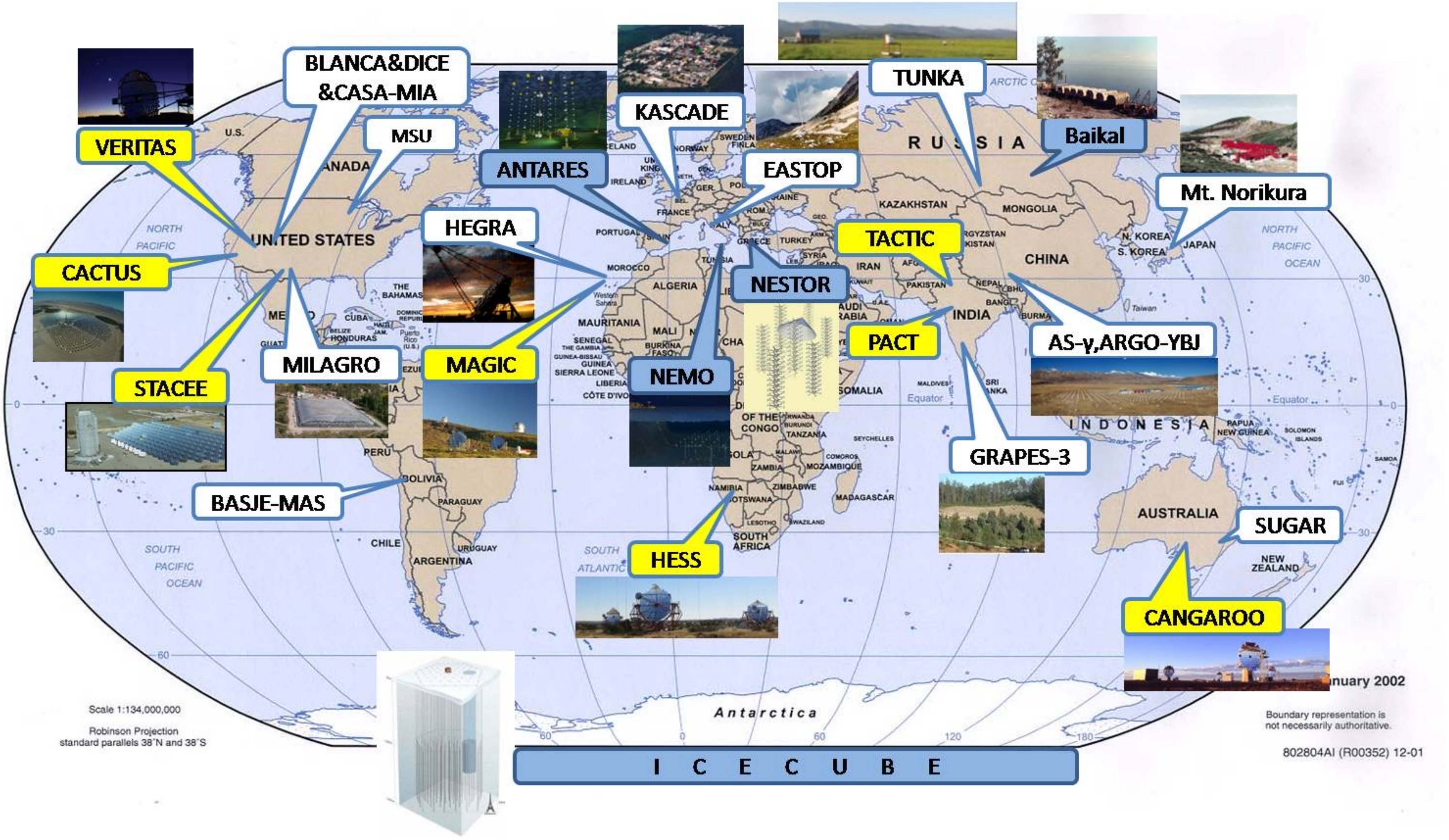
≈ 3 yrs for a PhD



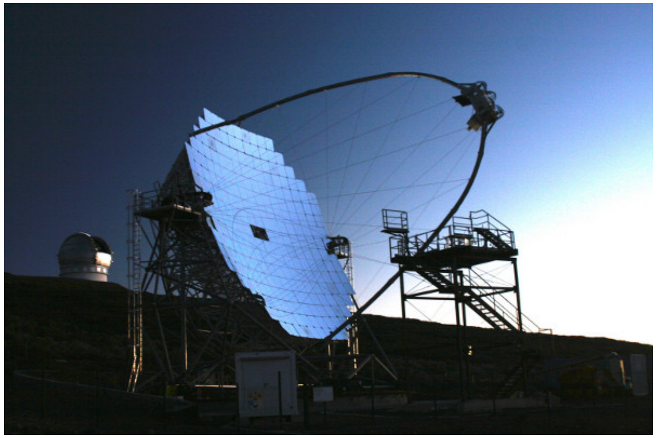


	Gamma	**Proton**
次级粒子分布：	单芯对称；集中分布；	多芯或单芯不对称；杂乱分布；
主要成分：	e± ; γ ;	e±; γ; 核子; **μ子;**
首次作用点：	离地面较低；	离地面较高；

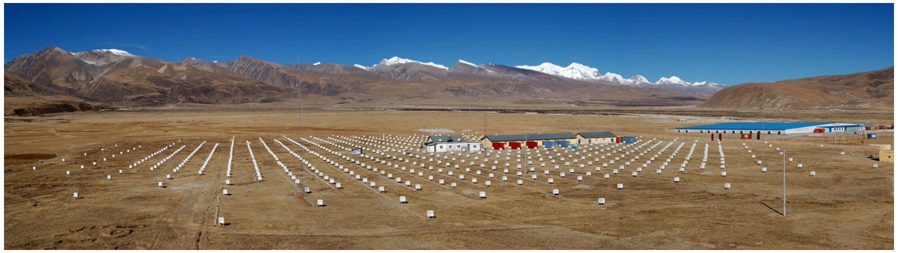
World-wide Distribution of EAS Experiments for $E <\sim 10^{16}$eV



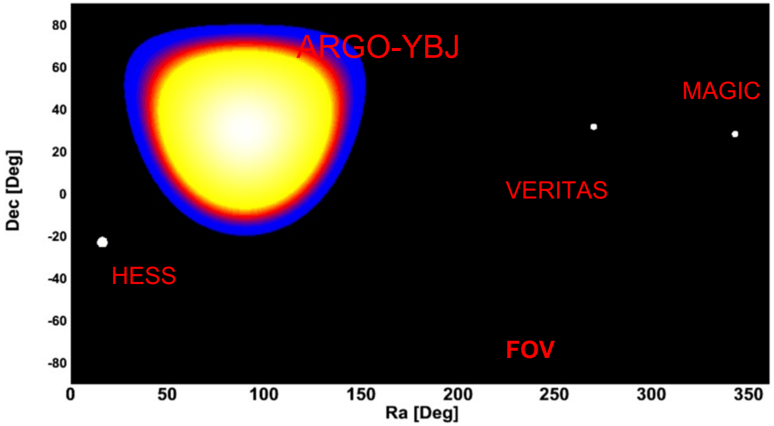
Detection techniques @ VHE gamma-ray astronomy



- IACT: HESS, VERITAS, MAGIC, …
  - Better angular resolution;
  - Fair background rejection;
  - Low duty cycle;
  - Narrow FOV.
- More focused on deep observation.



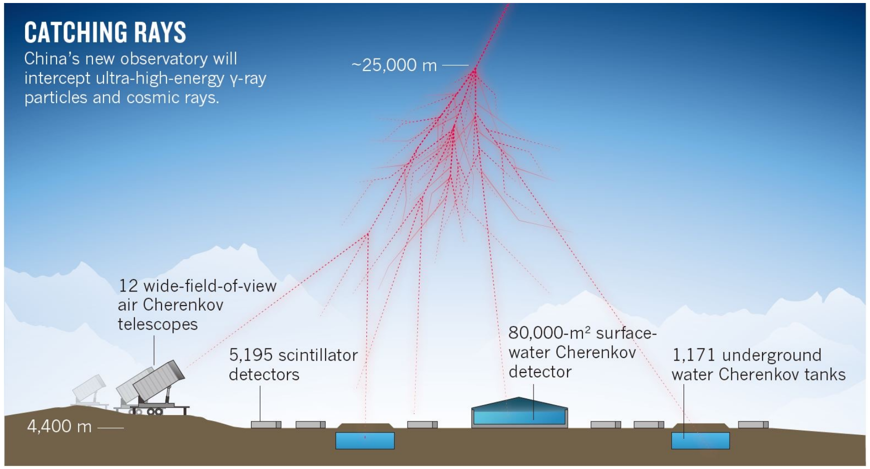
- Ground-based EAS array: ASγ, ARGO-YBJ, MILAGRO, …
  - Not-so-good angular resolution;
  - Poor background rejection;
  - Full duty cycle;
  - Wide FOV.
- More oriented on all sky survey and flares detection.

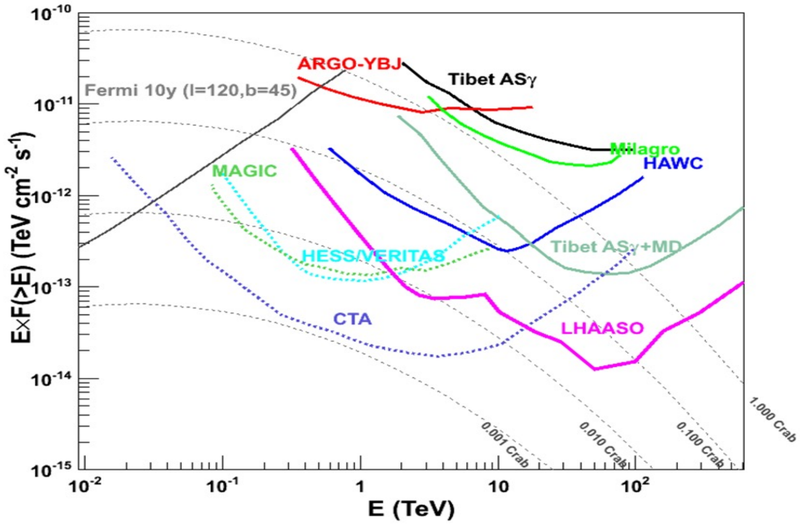


Ground-based air shower detection

伽玛观测灵敏度度提高20-30倍;宇宙线能谱100GeV-EeV

- High sensitivity: ~2% Crab @3TeV@100TeV
- Wide energy range: sub-TeV to 10 PeV
- Large FOV:~1.8 sr



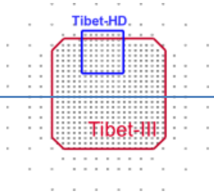


- Detect air shower secondary particles: Gammas, electrons/positrons, muons, photons, hadrons, ...
- Measure the numbers / (or energy eqv.), arrival time, as well as the lateral / longitudinal distribution.
- So that obtainning the direction, energy, type of the primary particle.

Instrumentation History

Whipple
(0.2 Crab)

1980



Tibet-ASγ
(1.5 Crab)

Crab detected!

1989

HEGRA, CANGAROO, CAT ... 0.04 Crab

2001

Milagro
(0.9 Crab)

H.E.S.S.
(0.01 Crab)

2004

VERITAS
(0.01 Crab)

2007

ARGO-YBJ
(0.6 Crab)

MAGIC
(0.02 Crab)

2009

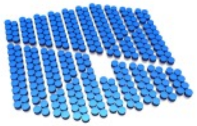
~150 Sources observed

2014

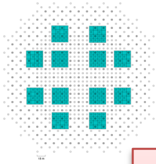
~10 Sources

IACTs are typically 10× better in sensitivity, gained from the lower energy threshold (stat.)

2015

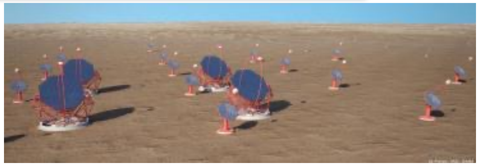


HAWC
0.06 Crab

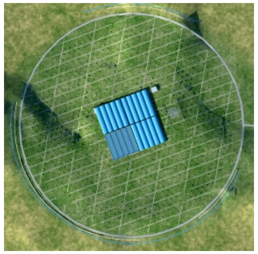


ASγ+MD
0.06 Crab

CTA
(0.001 Crab)



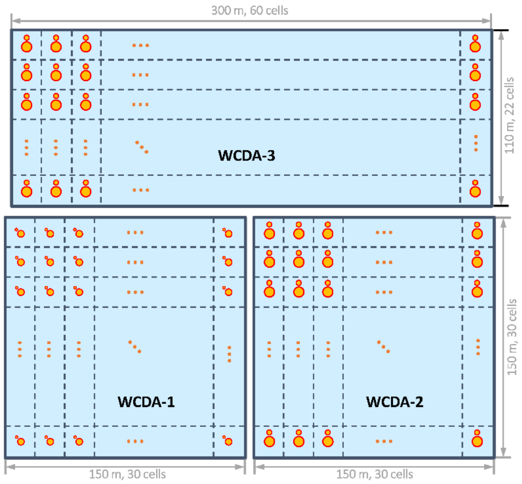
2019

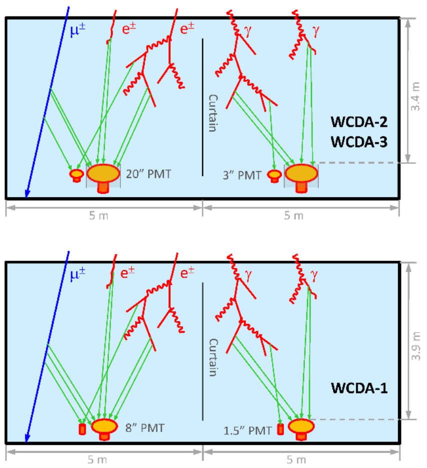


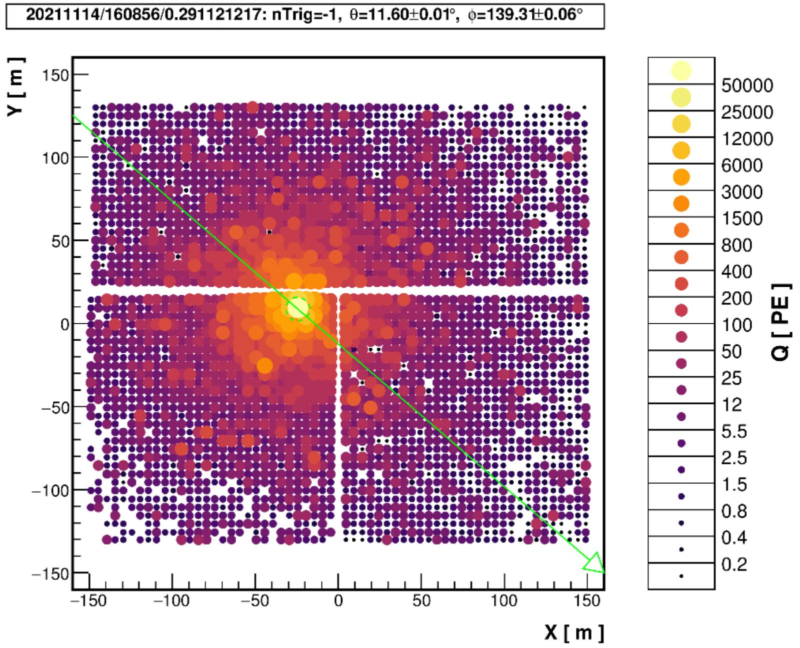
LHAASO
(0.01 Crab)

Largely to improve Gamma/Proton separation power

20 years delay!





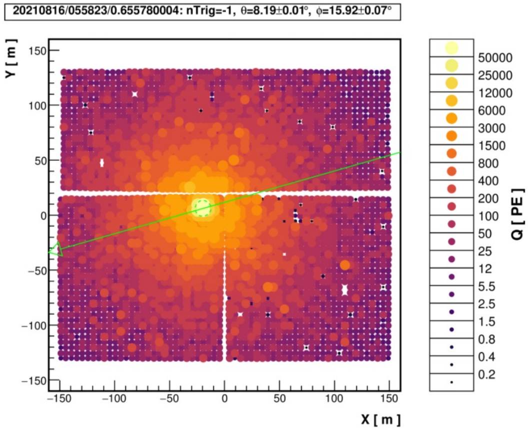


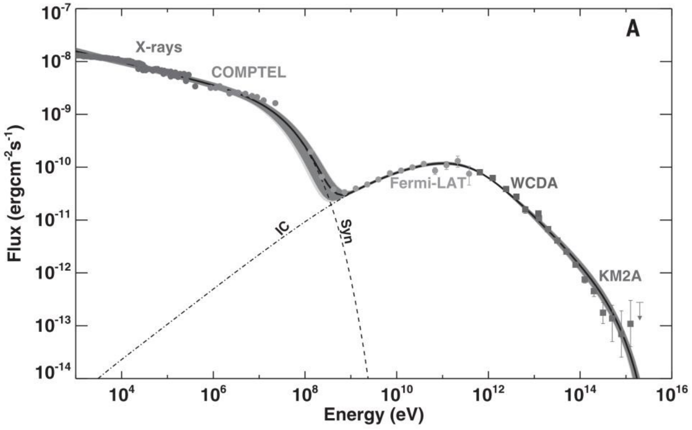
WCDA

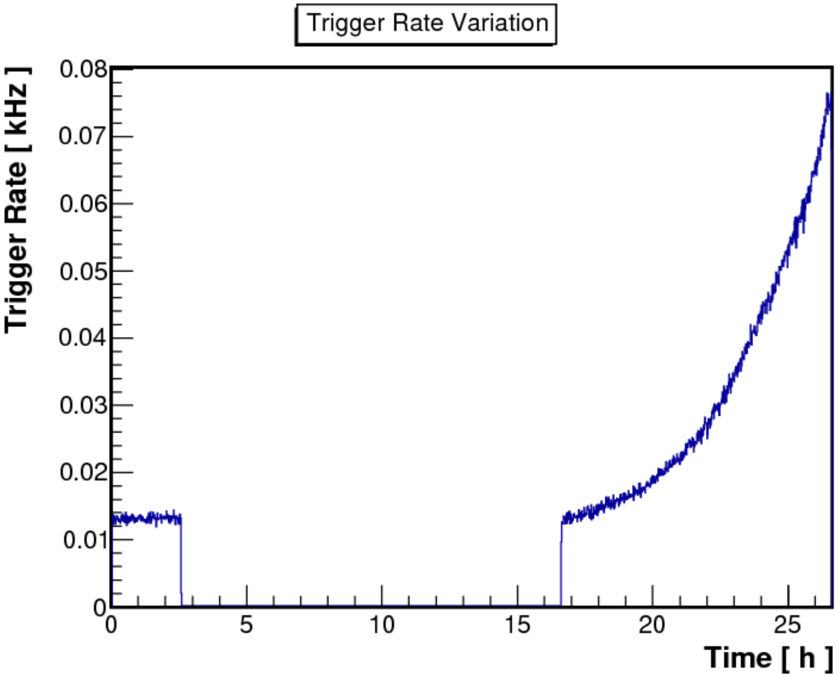
- Time resolution of a cell: ~2 ns;
- Dynamic range: 1 – 50000 PEs;
- Charge resolution: <50% (@ 1 PE), <10% (>2000 PE)

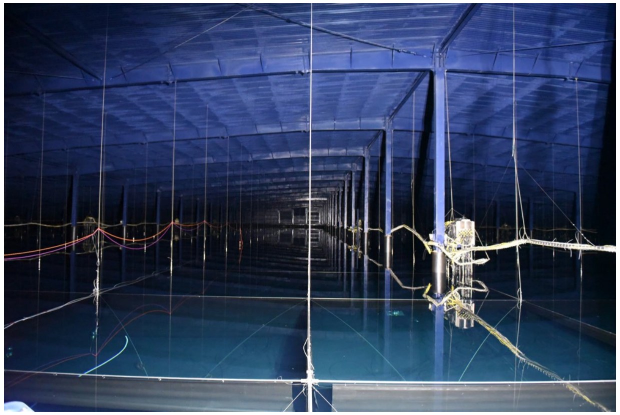
LHAASO-WCDA

- 50 GeV - 50 TeV的一个伽马天文观测
- 物理目标丰富：
  - 河内伽马源、河外伽马源、耀变源（Blazar、GRB、FRB、引力>波对应体）、时变现象、新物理（暗物质）
- 低阈能、全天候、宽视场，聚焦于发现和精确测量两方面
- 多波段、多信使观测不可或缺的环节
- 先进数据获取理念：
  - 无触发、软触发，可以实现针对物理目标的数据获取
  - 数据量大
    - 6 PB/年。需要强大的数据处理技术和物理分析技能

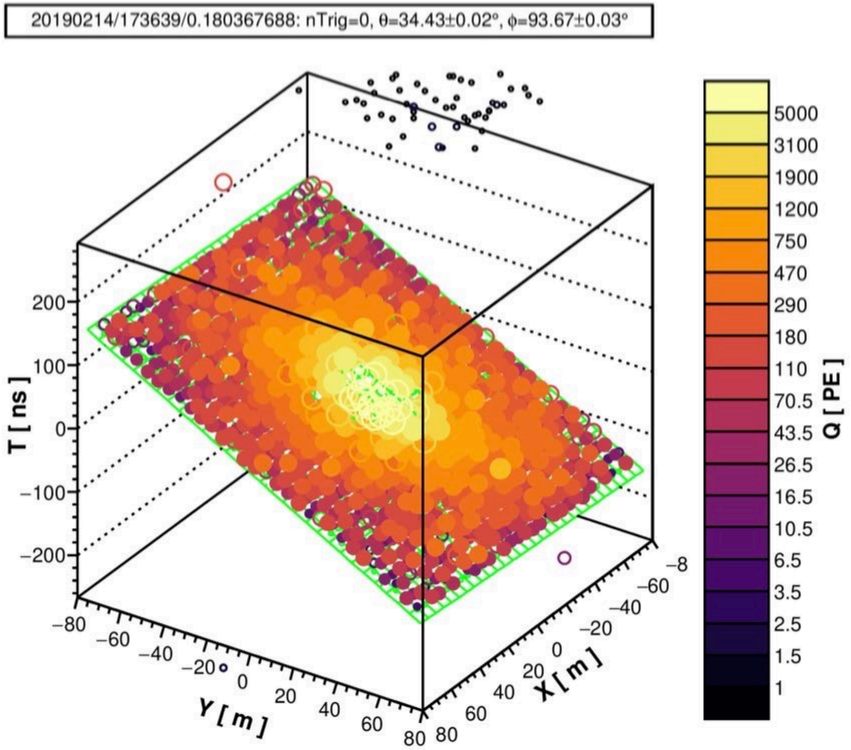


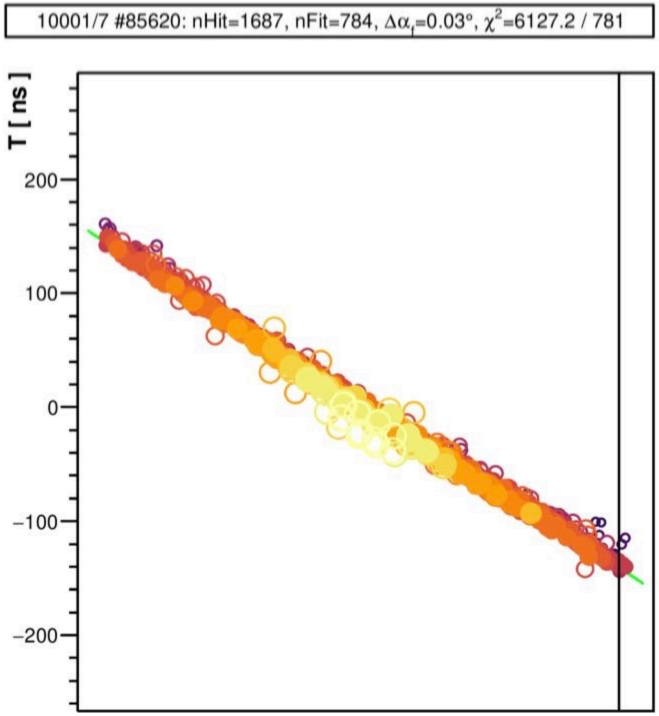



Trigger Rate Variation
Trigger Rate [kHz]
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
0
5
10
15
20
25
Time [h]



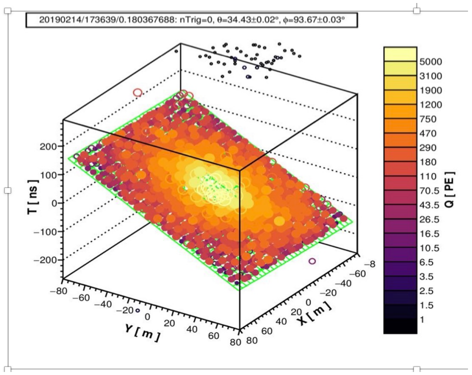
Valentine day event

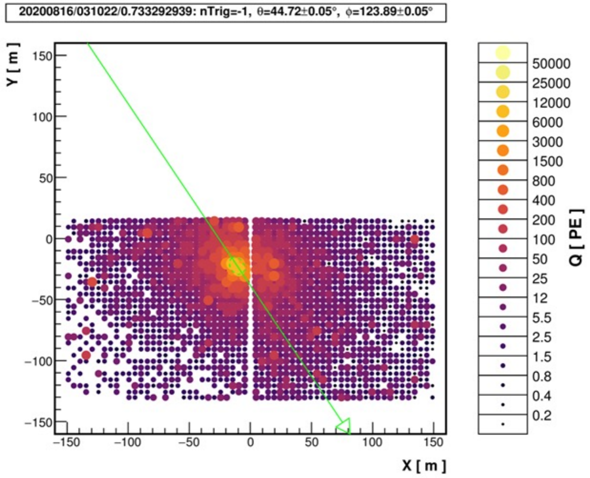


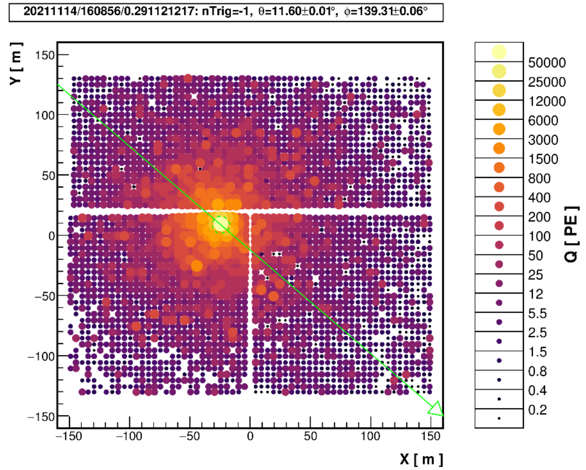


Timeline of WCDA

- wcda-1
  - 20190426-20200228
- wcda-u = wcda-1+ wcda-2:
  - 20200312-20210228
- Phase 1: ~40 KHz
  - 2020/03/12: nfee trigger
- Phase 2: ~45 KHz
  - 2020/05/25: npmt trigger
- Phase 3: ~65 KHz
  - 2020/06/08/: pattern trigger
  - 12X12 PMTs = 60 m X 60 m area trigger
- Phase 4: ~ 90 KHz
  - 2020/11/01 - 2021/02/28
  - wcda-1 cleaning + wcda-2 shielding
  - Raw data: 12 T /day
- Phase 5: ~ 35kHz
  - 2021/03/05 – now
  - WCDA full array running with 1PE @20inch + 0.3 pe@8inch

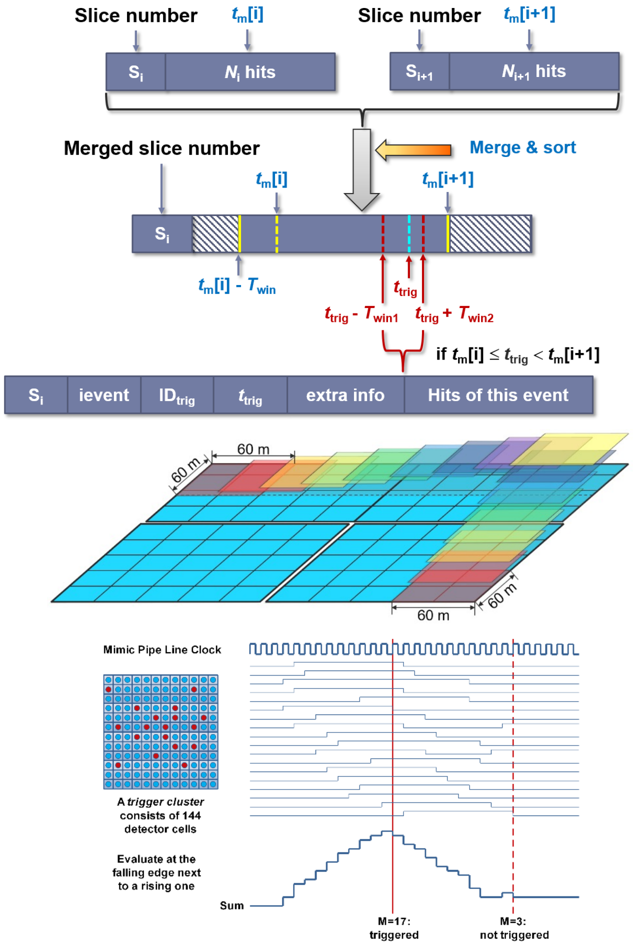






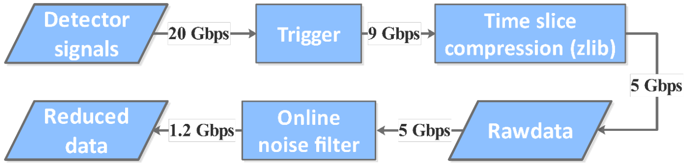
Trigger

- Implemented on a computing cluster:
  - Soft trigger.
- Basic triggers:
  - KM2A (EDA + MDA), WCDA and WFCTA, independently;
  - 3 parallel data streams;
  - for every stream, other detector hits in a time window are collected and stored.
- Special triggers:
  - Calibration;
  - For some special physics goals.
- Triggerless data:
  - Compact single counting signals (with precision lost) are cached;
  - Stored for up to 2 weeks;
  - For follow-up observations at very low energy threshold, on GRBs, Blazers, FRBs, neutrino counterparts, GW counterparts, etc.



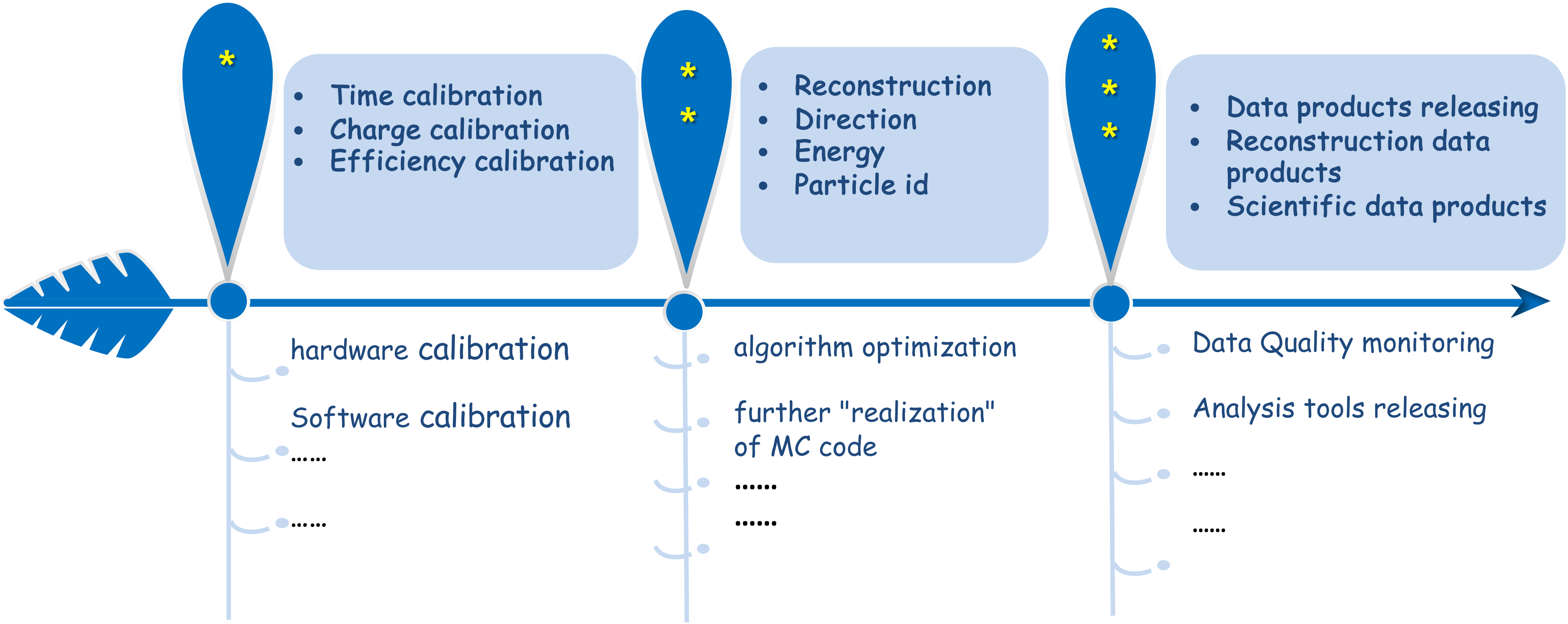
Trigger logic of WCDA

LHAASO数据量：~12 PB/yr


Detector signals → 20 Gbps → Trigger → 9 Gbps → Time slice compression (zlib) → 5 Gbps → Rawdata → 5 Gbps → Online noise filter → 1.2 Gbps → Reduced data

- KM2A原始数据：
  - 触发率：2.6 kHz
  - 数据量：0.20 Gbps = 2.2 TB/day = 760 TB/yr
- WFCTA原始数据：
  - 触发率：1.1 Hz/telescope * 18 = 20 Hz
  - 数据量：100 TB/yr （注意：1400 hour/yr）
- WCDA原始数据：
  - 触发率：34 kHz ➔ 160 kHz（降低单道阈值及触发多重度阈值）
  - 数据量（噪声过滤前）：1.1 Gbps = 12 TB/day = 4.4 PB/yr ➔ 3.9 Gbps = 42 TB/day = 15 PB/yr
  - 数据量（噪声过滤后）：0.42 Gbps = 4.5 TB/day = 1.6 PB/yr ➔ 1.2 Gbps = 12 TB/day = 4.3 PB/yr
  - GRB数据（~3 triggers/week，LAT GCN only）：8.7 TB/burst = 1.3 PB/yr ➔ 30 TB/burst = 4.6 PB/yr

Data Analysis Chain



*

- Time calibration
- Charge calibration
- Efficiency calibration

hardware calibration

Software calibration

……

……

**

- Reconstruction
- Direction
- Energy
- Particle id

algorithm optimization

further "realization" of MC code

……

……

***

- Data products releasing
- Reconstruction data products
- Scientific data products

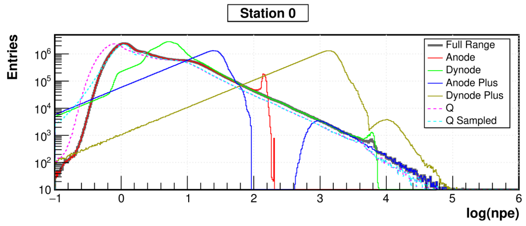
Data Quality monitoring

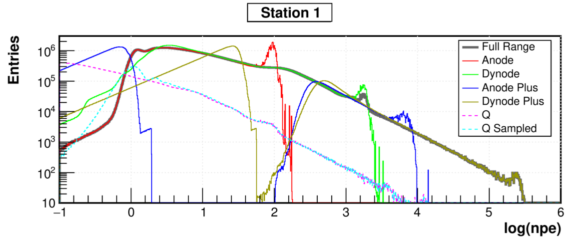
Analysis tools releasing

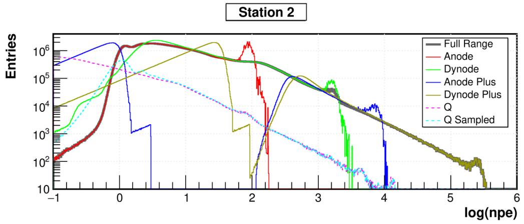
……

……

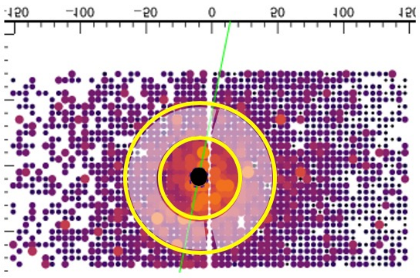
Calibration @ WCDA



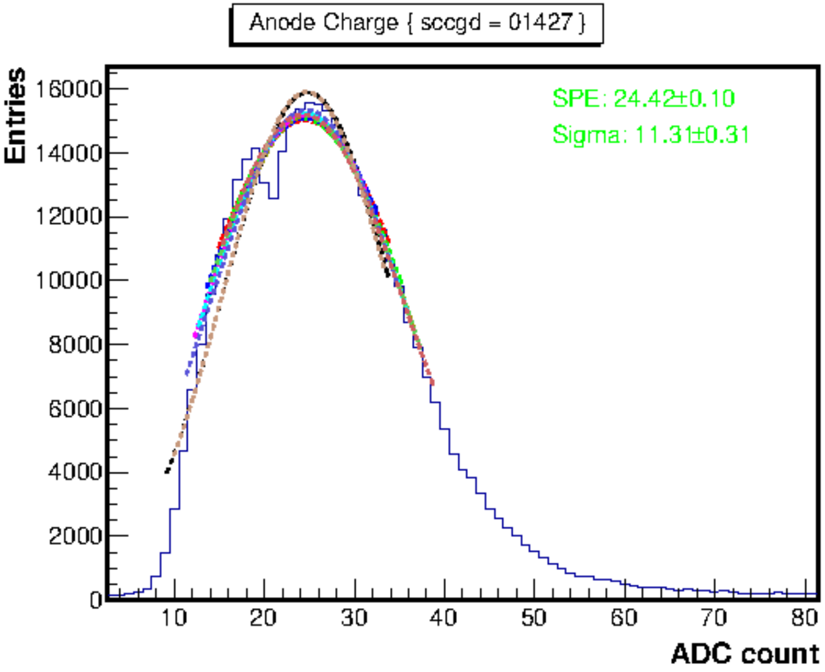


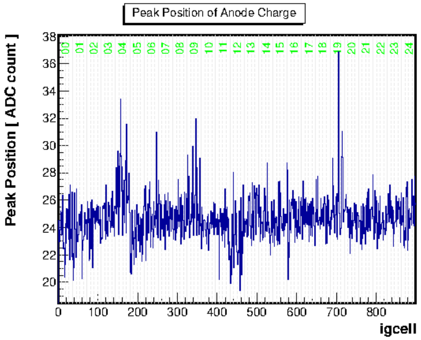


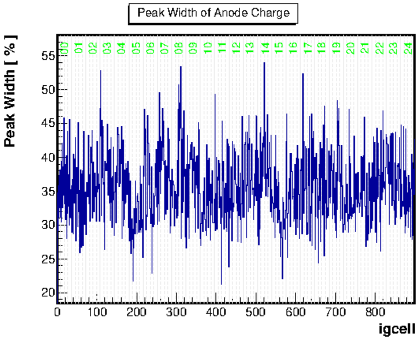
- 特色和难点：
  - 电荷标定：
    - 4种不同类型PMT，每个PMT又分阳极（高增益）和打拿极（低增益）需要把8种信号归为一种
  - 时间标定：
    - 探测器存在明显的Q-T（电荷与时间）关系，而且还包含R-T（芯距与时间）甚至与簇射方向关联，修正极其复杂
  - 还有3个水池间的时间与电荷标定
  - 水质及污染物等原因造成的探测效率的变化
  - 探测器的复杂多变，需要定期或实时标定
- 解决方案：
  - 电荷标定：采用簇射信号，采用迭代拟合的方式；每次标定需要采用4天以上的数据；已经实现自动数据处理，得到标定结果。
  - 时间标定：基于硬件标定，采用天量级的簇射事例完成时间偏差、Q-T、R-T的修正参数的计算
  - 水池间标定：采用复杂算法，采用簇射事例的对称性，实现了每天一次的水池间的标定
  - 根据簇射信号的多峰结构进行标定，并提出了CRS的方法，实现了不同单元（共3120）间的效率的实时（天量级）标定

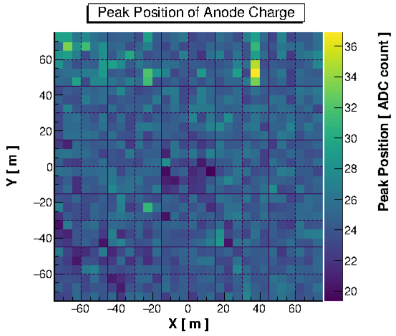


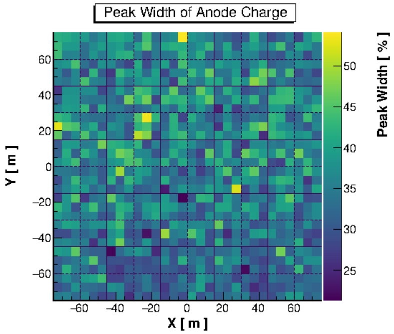
Charge calibration: SPE + AD ratio

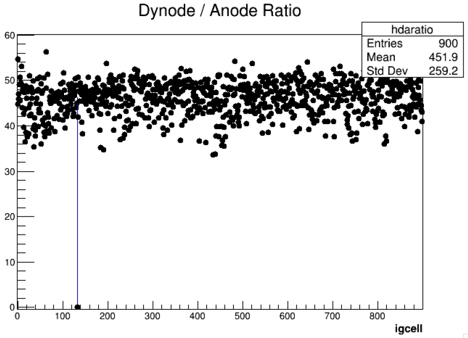


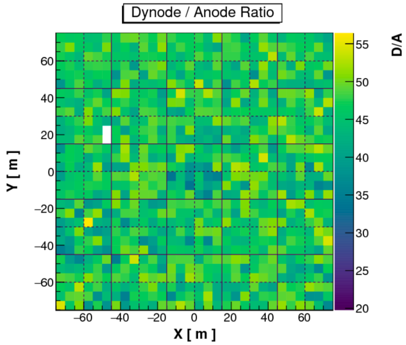




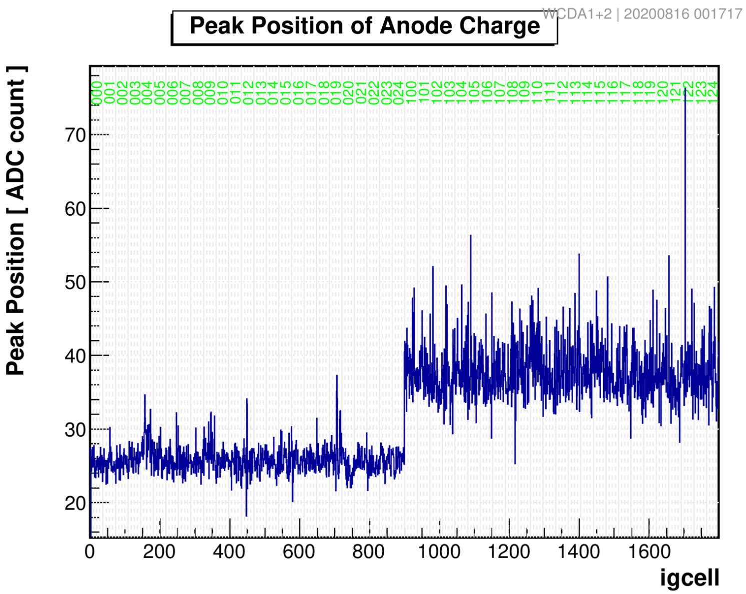


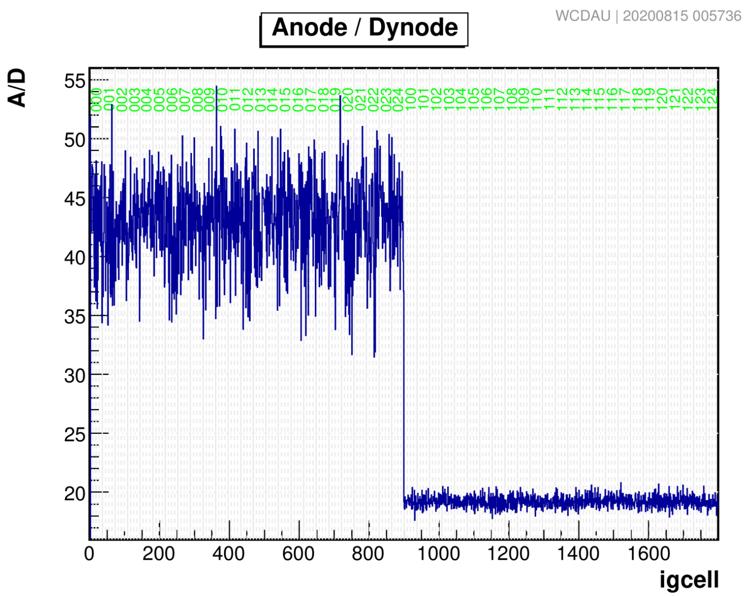




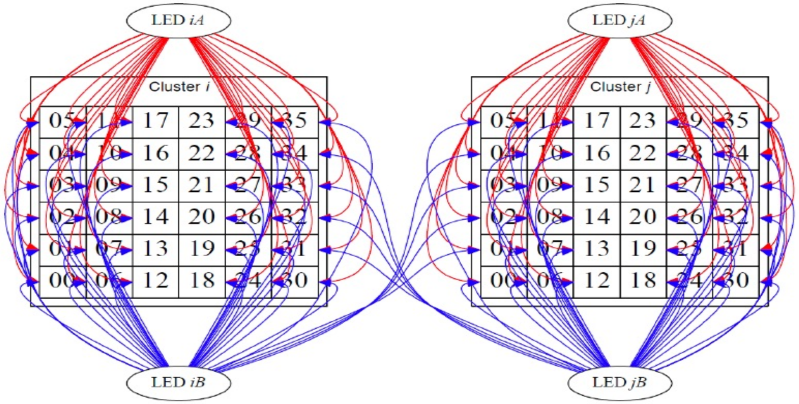


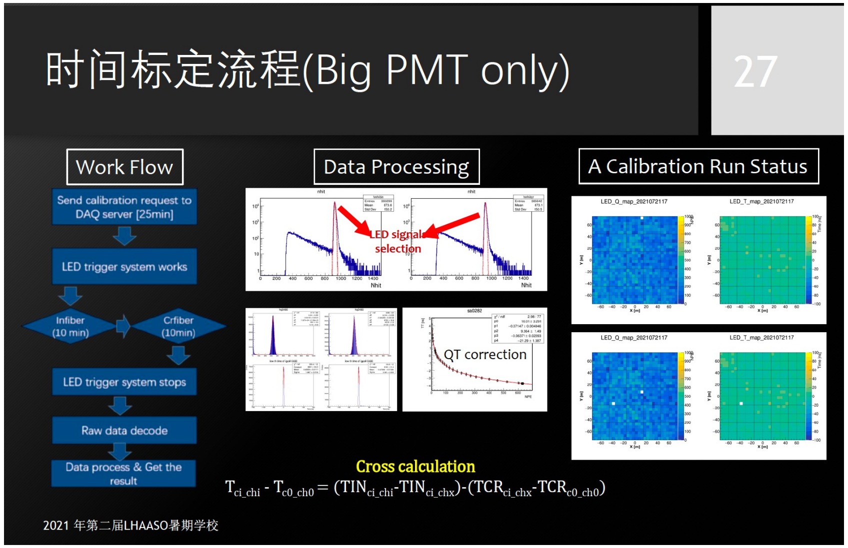
Charge calibration: SPE + AD ratio





Time calibration @ WCDA





时间标定流程(Big PMT only)

27

Work Flow

- Send calibration request to DAQ server [25min]
- LED trigger system works
- Infiber (10 min)
- Crfiber (10min)
- LED trigger system stops
- Raw data decode
- Data process & Get the result

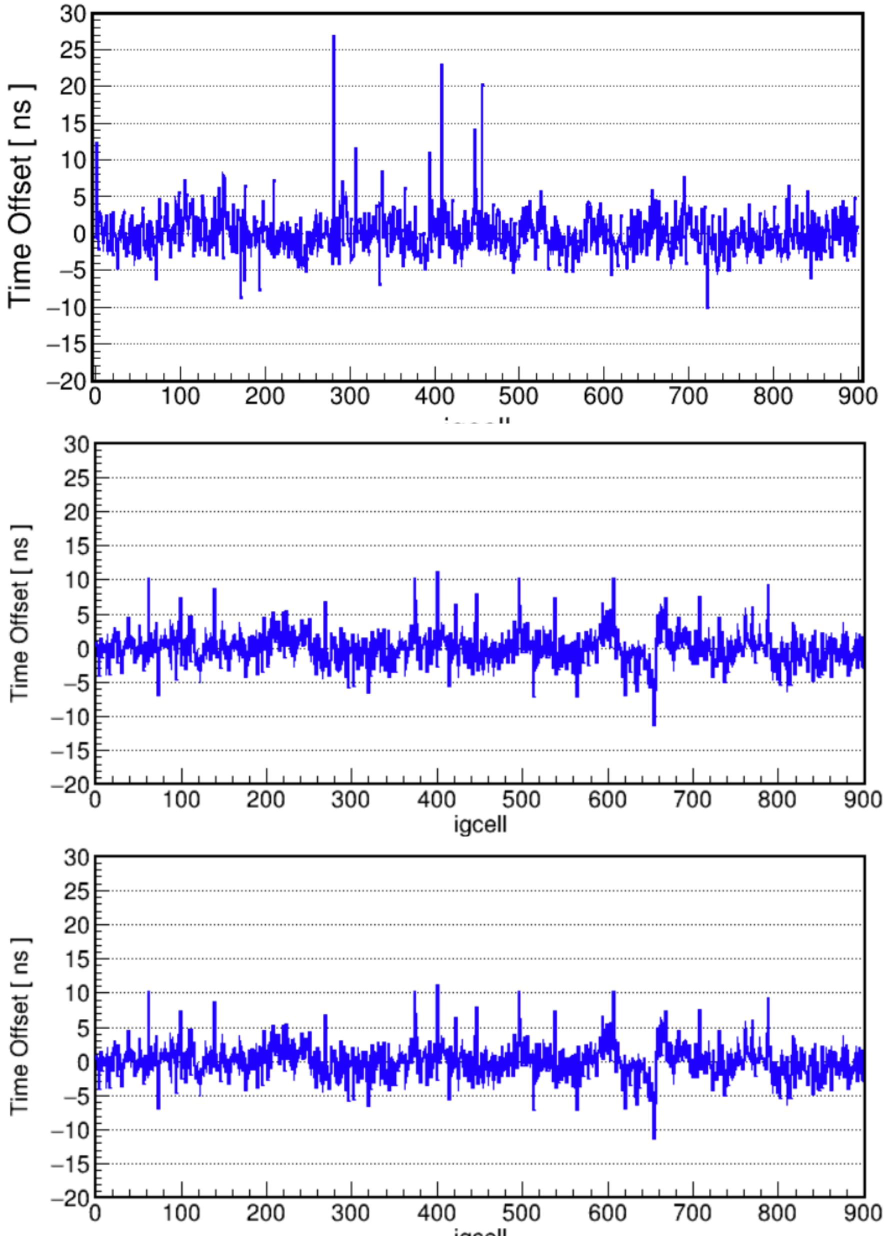
Data Processing

A Calibration Run Status

Cross calculation

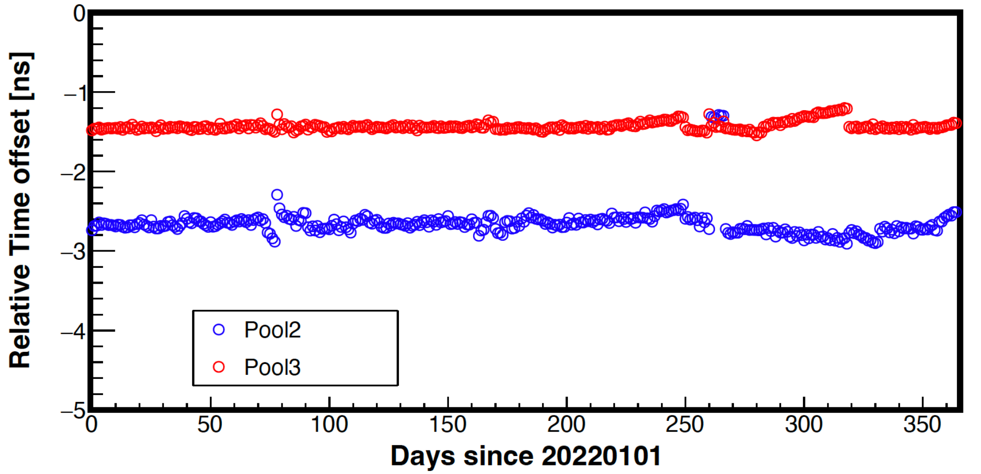
$T_{ci\_chi} - T_{c0\_ch0} = (TIN_{ci\_chi} - TIN_{ci\_chx}) - (TCR_{ci\_chx} - TCR_{c0\_ch0})$

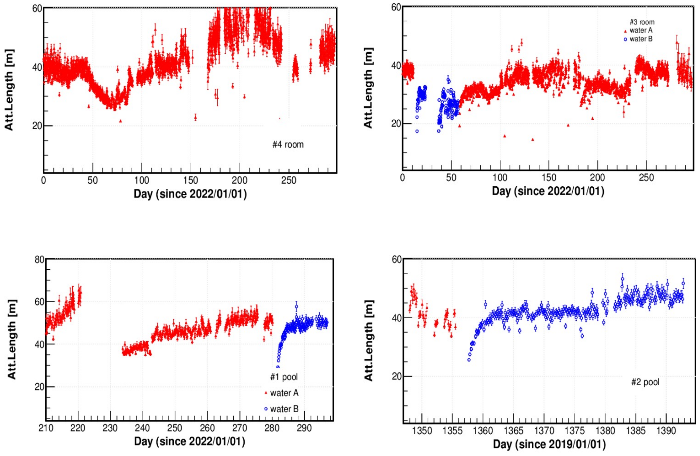
2021 年第二届LHAASO暑期学校



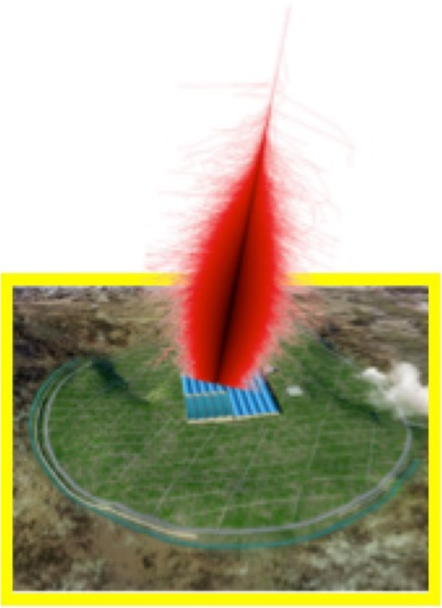
WCDA Calibration Status

- 对目前投入运行的三个水池的4类8个量程的共6240支PMT实现了定期（约5天）的电荷刻度，并实现了利用计算集群的自动处理；
- 已经通过硬件、簇射事例两种方法实现了三个水池3120支用于时间测量的PMT的时间刻度和每支PMT的高精度的电荷-时间依赖关系测量，也实现了计算集群的自动处理；
- 采用电荷谱和计数率两种方法实现了不同PMT之间的效率修正；
- 采用跨越两个水池的簇射事例实现了三个水池间的电荷和时间的每天的自动实时标定；
- 另外，实现了对水池水位和表征水质透明度的光衰减长度的实时测量。





Detailed data production and analysis chain



CORSIKA / AIRES

QGSJET / EPOS / SIBYLL/…….

Detector response simulation

Data

MC samples

Reconstruction / Analysis Chain

Comparison MC .vs Data

Air shower simulation:
CORSIKA Output:

WCDA : shower secondary particles

Geant4 based detectors simulation package

G4WCDA: two steps processing

Physics Data production
Level 1:
code + algorithm developer
Level 2:
user I/O to physics result

Simulation @ WCDA

- 特色和难点
  - 空气簇射的模拟：CORSIKA/COSMOS/AIRES……
    - 模拟样本多 （伽马、质子到铁核5组或56种元素；多种强相互作用模型的结合）
      - QGSJET， EPOS-LHC， SIBYLL， GHEISHA， FLUKA
    - 能量范围宽广（10 GeV - 1 PeV)
  - **探测器模拟**（GEANT4 为基础）
    - 切伦科夫光子数巨大，内存消耗量大、模拟缓慢
    - 实验大厅结构复杂，并存在结合KM2A（包括ED和MD）探测器模拟的必要
    - 探测器存在若干不确定的参数（多变的水质、国际首次使用的20-cin PMT等）

- 创新：
  - 创造了一种类似于GDML的探测器结构描述文本，可以用python等程序产生
  - 创造了hits流的概念，取代event流，解决了内存消耗问题，优化中间结果的存储，也使得并行单事例处理成为可能
  - 提出并实现了两步模拟的方案，把95%耗时的过程放在第一步，保存一些过程信息，把未定或多变的探测器参数放在第二步去调节，易于实现探测器的真实化

GEANT4 的简介

1. **Geant4开发：** Geant4 是欧洲核子中心(CERN)基于开发C++语言开发
2. **用途：** 模拟粒子在探测器中传输和相互作用的开源大型软件包。
3. **前身：** 在此之前主要使用EGS和GEANT3 (基于Fortran语言开发的)
1. **Geant4 优点：** 丰富相互作用模型，复杂的探测器结构及面向对象编程风格等。

庞大的开发维护团队

An internatonal collaboration

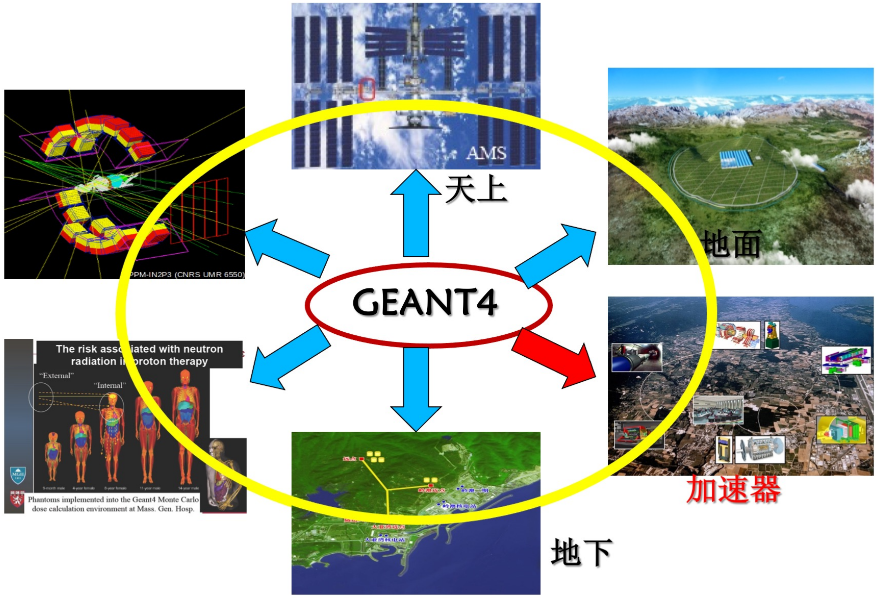
>100 active members

15 countries

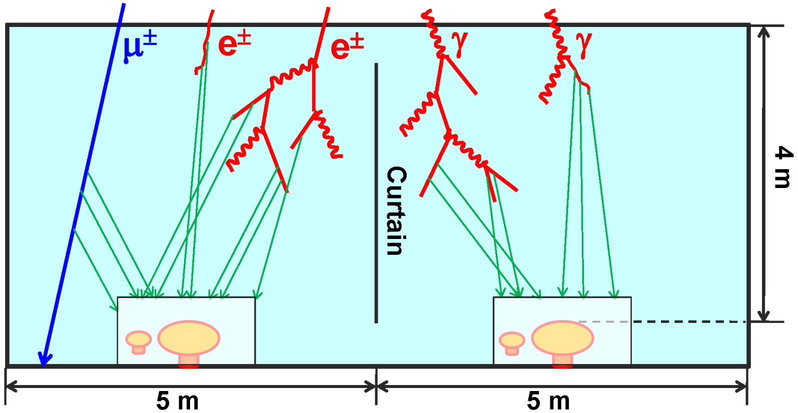
1998年12月第一个版本:Geant4.0.0.0

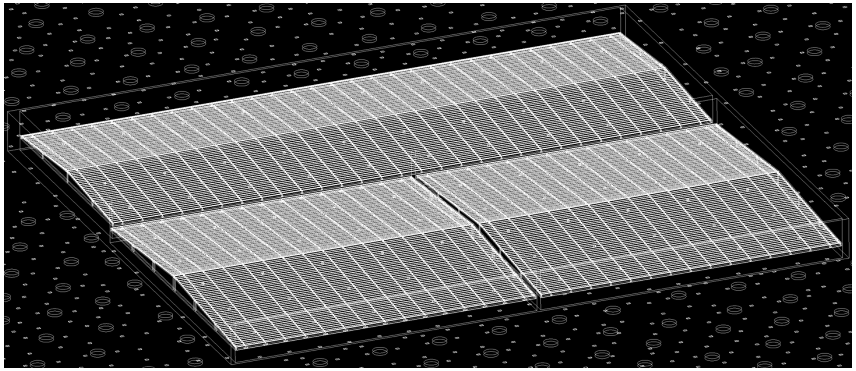
2015年6月:Geant4.10.1 (patch-02), 每年都有更新

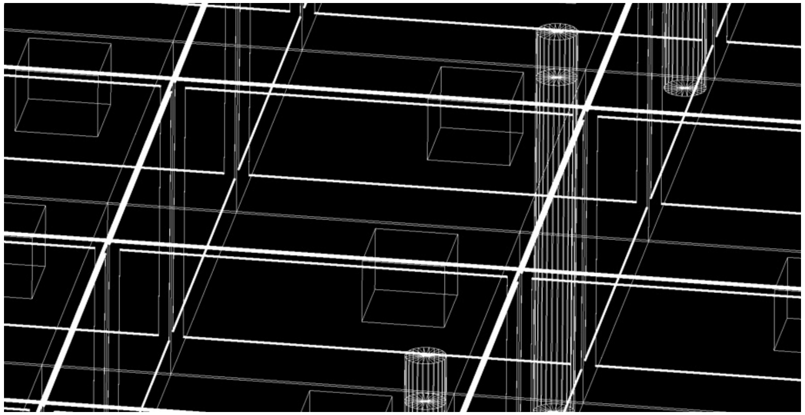
照片来自于Makoto.A., GEANT4 Tutorial, 2014, SLAC

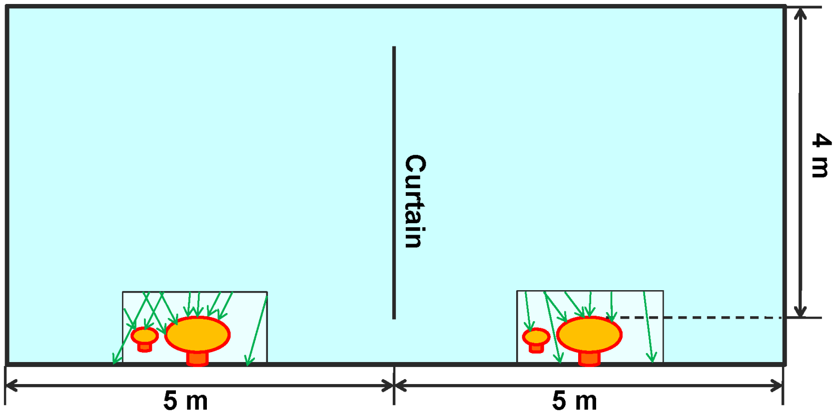


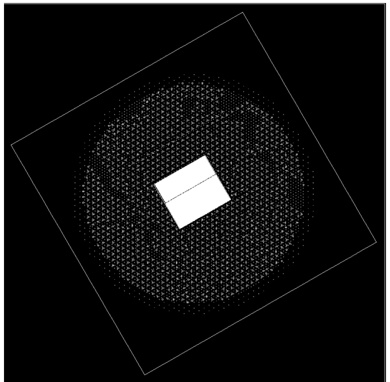
LHAASO-WCDA MC status

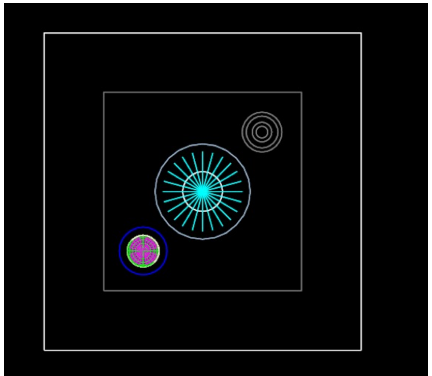




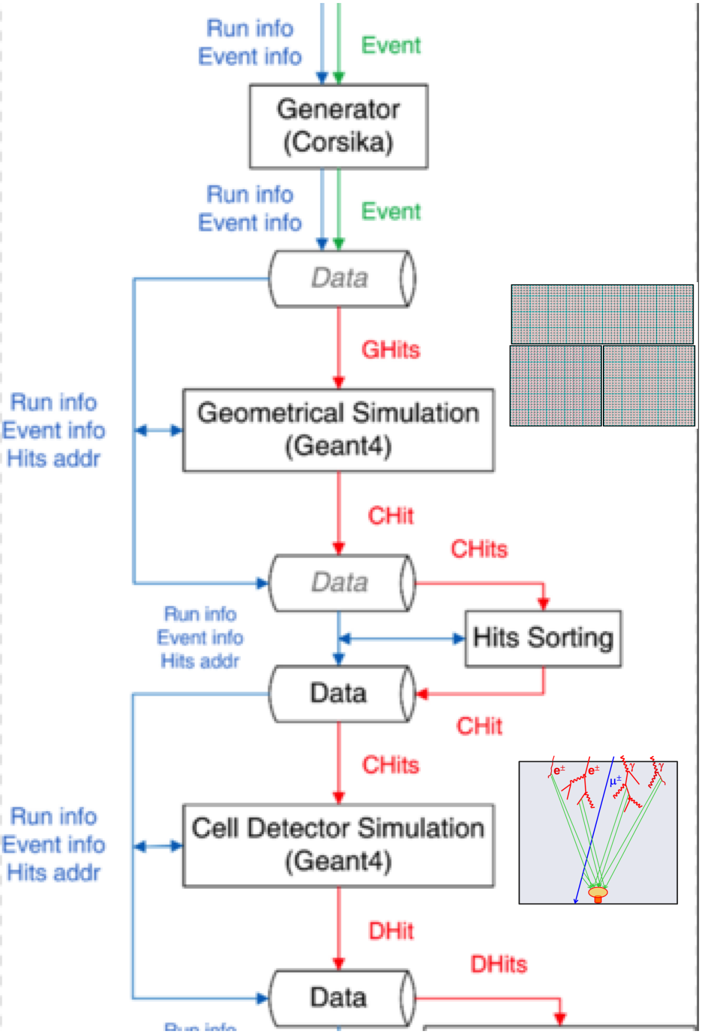








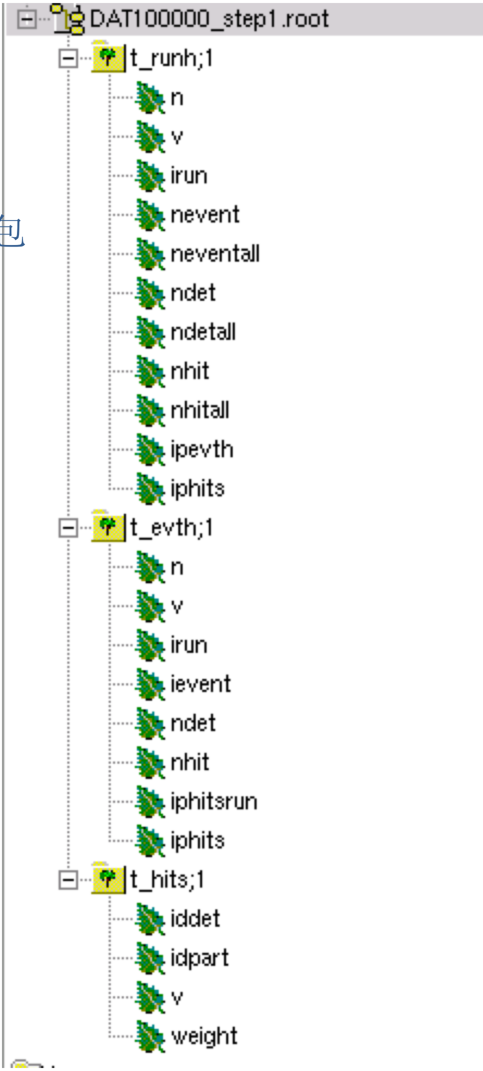
Update: Hits Stream



- Corsika数据的随机读取程（CorsikaReader）
- Hit流处理程序包（HitsReader）；
- 命令行解析、控制参数和数据库调用程序包（OptParser）。

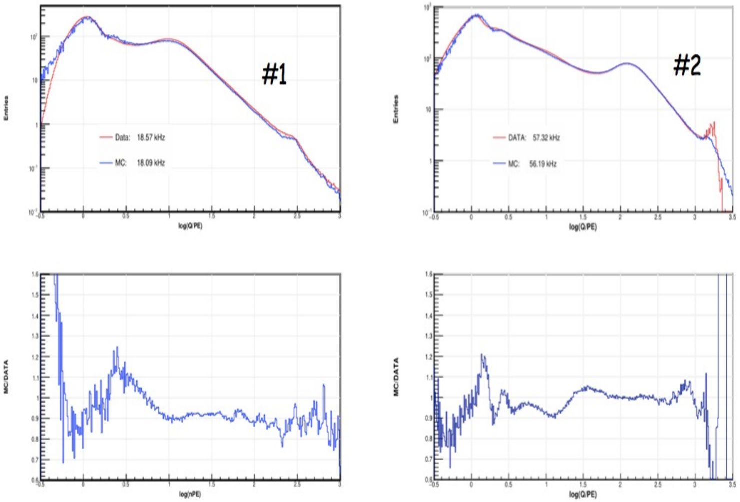
- 4 kinds of hits:
  - Ghit: generator hit;
  - Chit: cell hit;
  - Dhit: detector hit;
  - Fhit: final hit.
- Hit stream:
  - In: a batch of hits;
  - Out: a hit.
- Storage & buffering:
  - ROOT tree

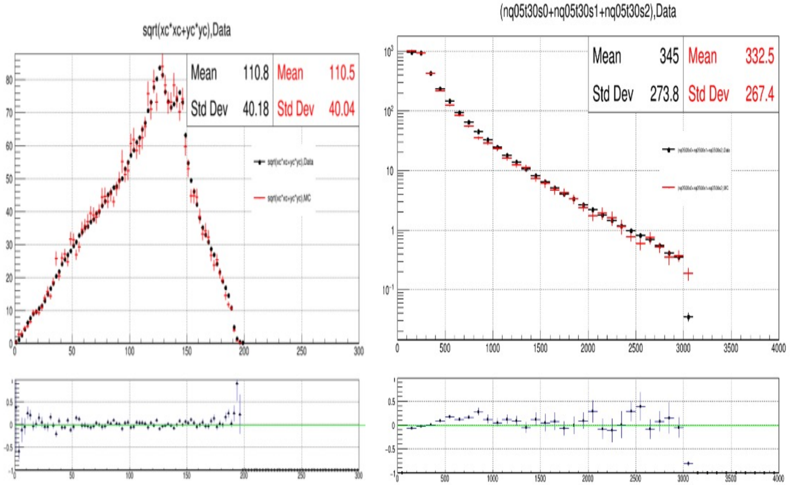
- 解决了内存耗尽
- 优化中间结果的存储
- 易于探测器真实化
- 简化各类探测器的统一模拟。
- Example: version >2.0



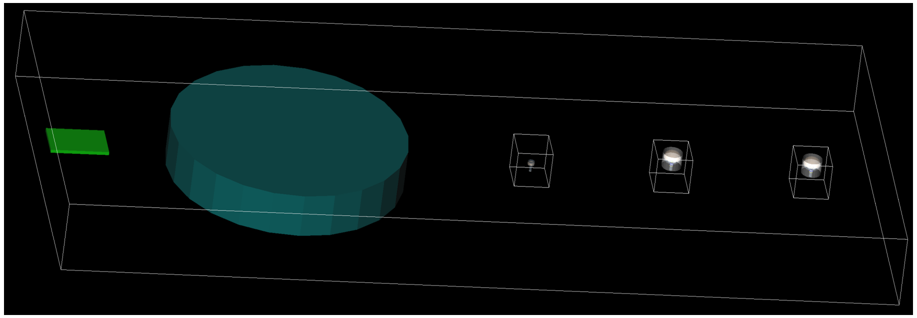
- DAT100000_step1.root
  - t_runh;1
    - n
    - v
    - irun
    - nevent
    - neventall
    - ndet
    - ndetall
    - nhit
    - nhitall
    - ipevth
    - iphits
  - t_evth;1
    - n
    - v
    - irun
    - ievent
    - ndet
    - nhit
    - iphitsrun
    - iphits
  - t_hits;1
    - iddet
    - idpart
    - v
    - weight

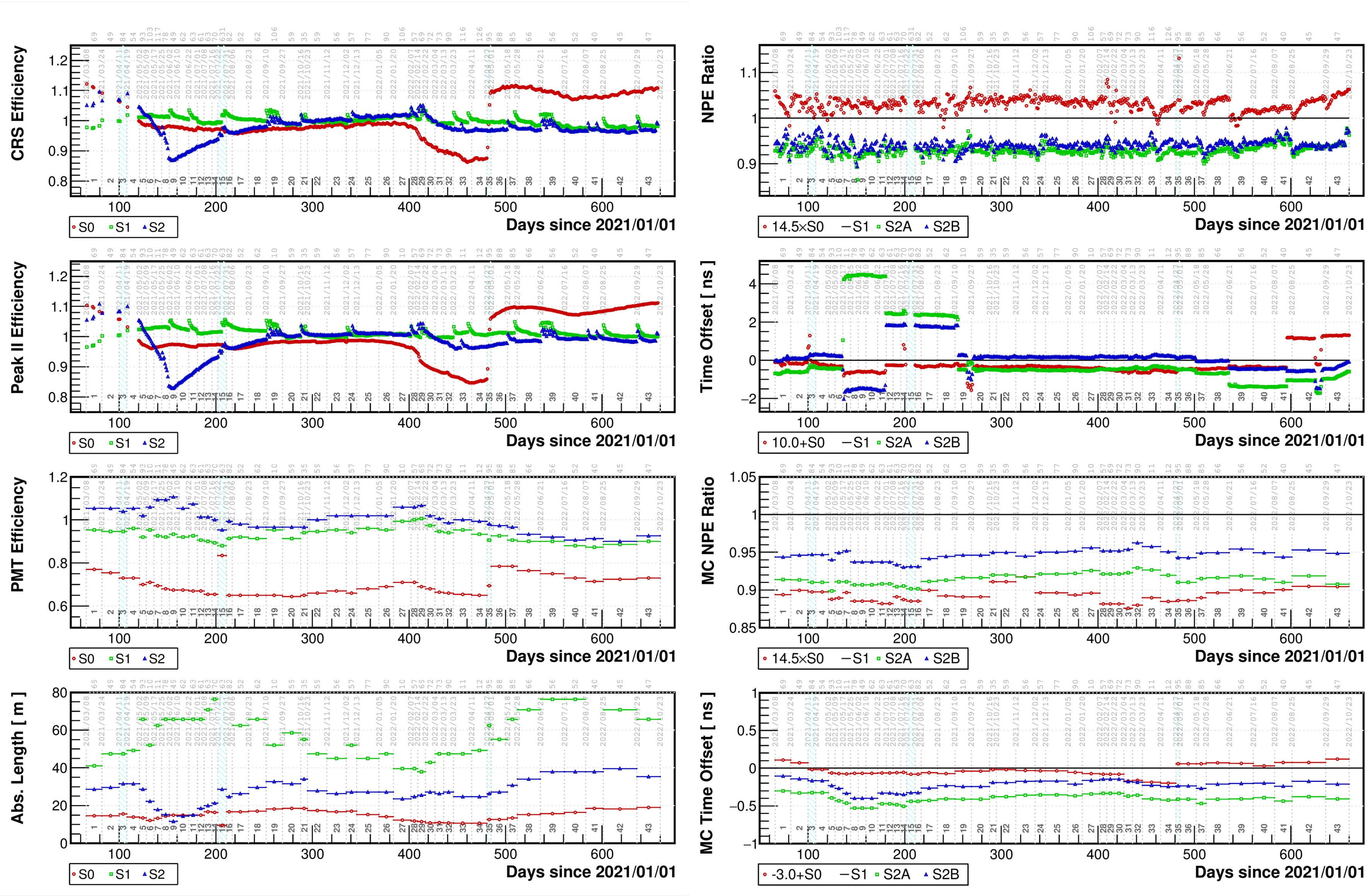
WCDA MC status





- MC samples
  - Multiple samples: Crab orbit and isotropic samples.
  - IO @ ED, MD detector unit




CRS Efficiency
1.2
1.1
1
0.9
0.8
100
200
300
400
500
600
Days since 2021/01/01
S0 S1 S2
Peak II Efficiency
1.2
1.1
1
0.9
0.8
Days since 2021/01/01
S0 S1 S2
PMT Efficiency
1.2
1
0.8
0.6
Days since 2021/01/01
S0 S1 S2
Abs. Length [m]
80
60
40
20
0
Days since 2021/01/01
S0 S1 S2
NPE Ratio
1.1
1
0.9
Days since 2021/01/01
14.5×S0 −S1 S2A S2B
Time Offset [ns]
4
2
0
−2
Days since 2021/01/01
10.0+S0 −S1 S2A S2B
MC NPE Ratio
1.05
1
0.95
0.9
0.85
Days since 2021/01/01
14.5×S0 −S1 S2A S2B
MC Time Offset [ns]
1
0.5
0
−0.5
−1
Days since 2021/01/01
-3.0+S0 −S1 S2A S2B
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43
2021/03/08
2021/03/24
2021/04/11
2021/04/19
2021/05/02
2021/05/09
2021/05/17
2021/05/25
2021/06/02
2021/06/10
2021/06/22
2021/07/01
2021/07/08
2021/07/16
2021/07/22
2021/08/06
2021/08/23
2021/09/10
2021/09/27
2021/10/16
2021/10/23
2021/11/12
2021/12/02
2021/12/13
2022/01/05
2022/01/20
2022/02/07
2022/02/14
2022/02/22
2022/03/04
2022/03/13
2022/03/23
2022/04/11
2022/04/27
2022/05/18
2022/05/28
2022/06/21
2022/07/16
2022/08/07
2022/08/25
2022/09/29
2022/10/23

Classic way to reconstruct the direction

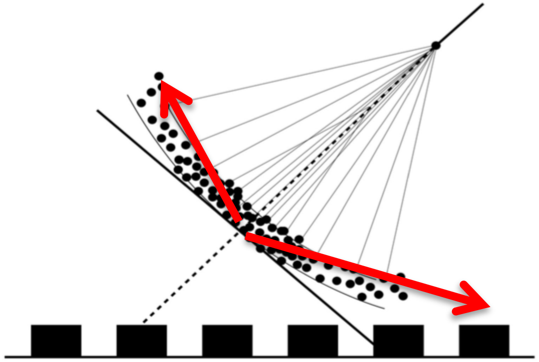
Direction reconstruction: 前锋面拟合

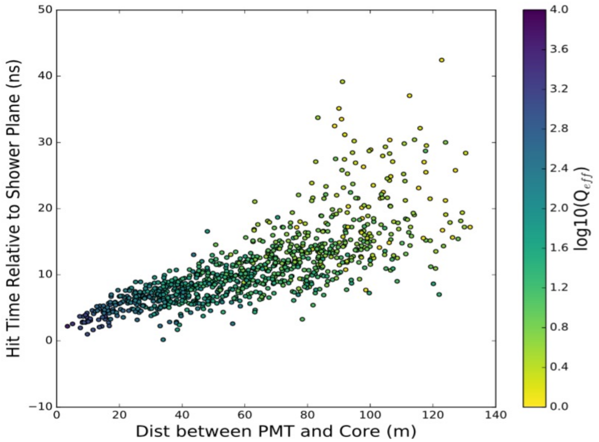
Plana fitting:

$$\chi^2 = \sum_i w_i (c\cdot(t_i - T_0) - x_i\cdot L - y_i\cdot M)^2$$

Conical correction:

$$\chi^2 = \sum_i w_i (c\cdot(t_i - T_0) - x_i\cdot L - y_i\cdot M - c\cdot(\alpha R_i))^2$$

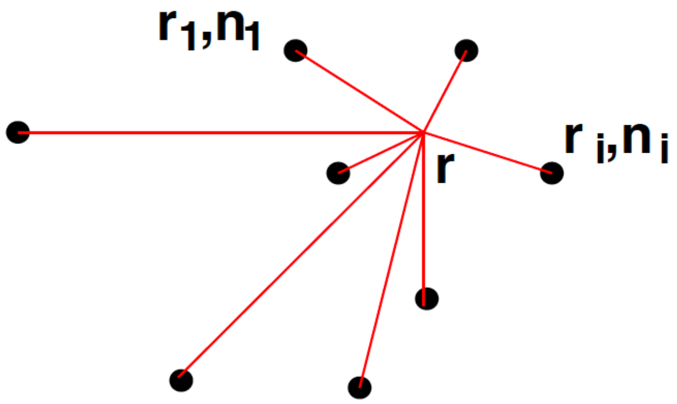




- 簇射前锋面到达阵列时，
- 第i个fired PMT 的坐标为 (x_i, y_i, t_i)
- 未知参量(L, M, T_0) L=sinθcosϕ, M=sinθsinϕ,

- Implementation tools
  - CERNLIB Minuit/ TMatrix /ROOT

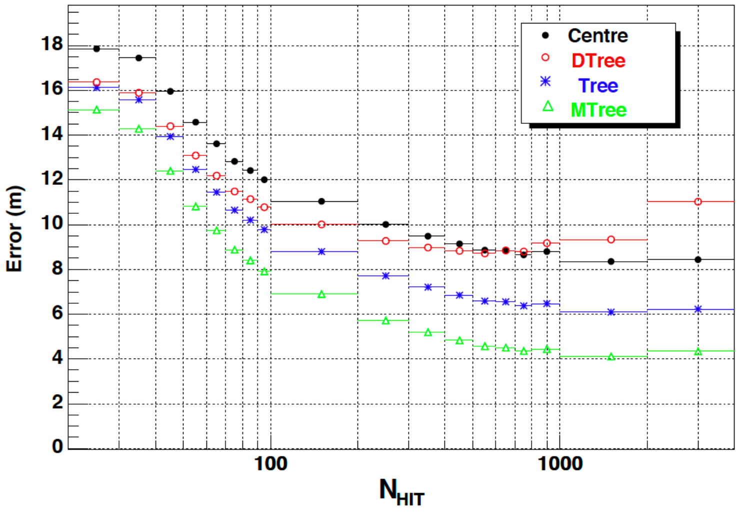
Classic way to reconstruct the core position

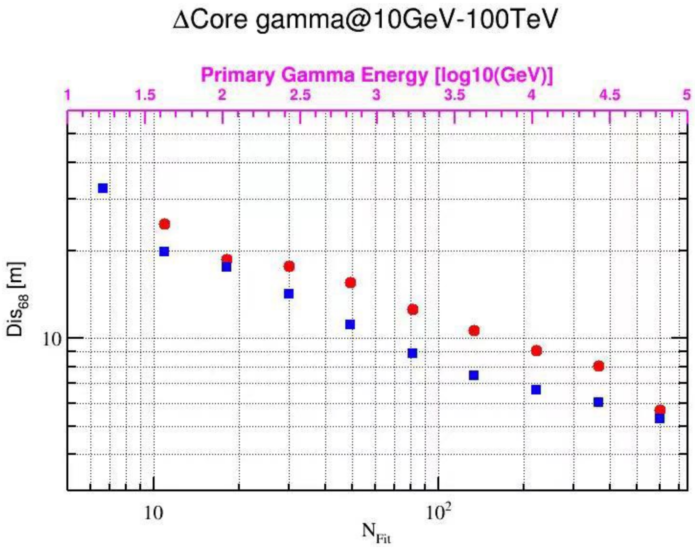


- Center of Gravity(COG)

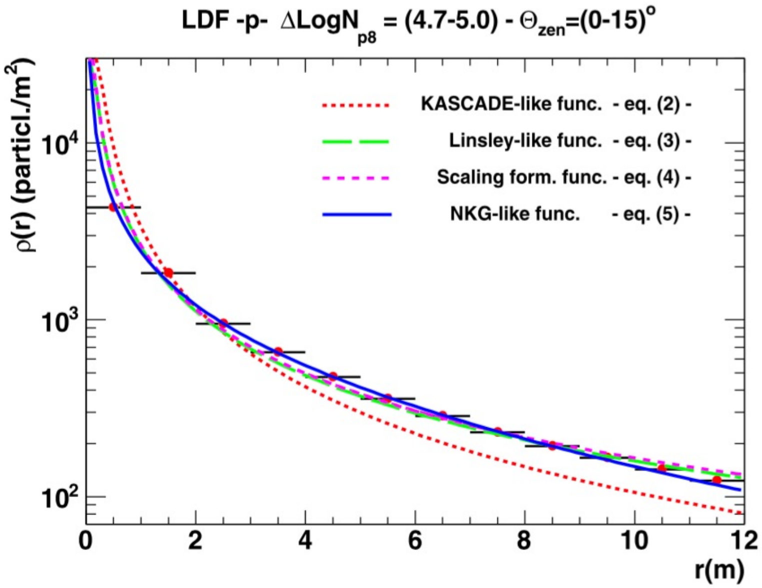
$$(X_c, Y_c) = \frac{\sum_{i=1}^{N} (x_i, y_i)\, n_i}{\sum_{i=1}^{N} n_i}$$

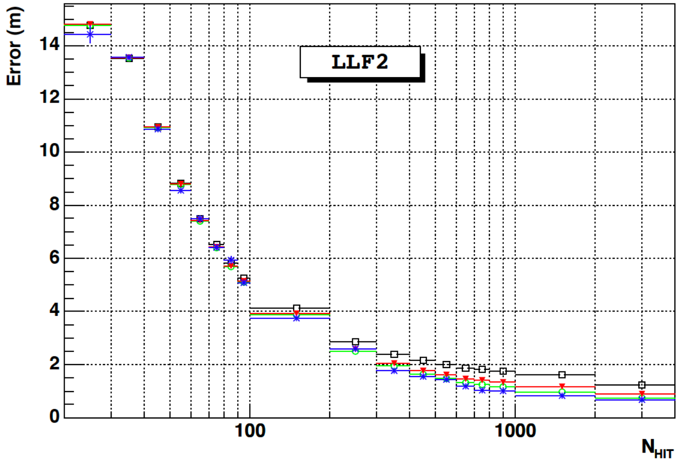
- Tree length algarithm





Core reconstruction





- COG is initial seed;
- NKG function is analytical function, in principle it is closely related with direction.(x_c, y_c, θ, φ)

$$\rho_2(r) = N_e C(s)\left(\frac{r}{r_0}\right)^{s-\alpha}\left(1+\frac{r}{r_0}\right)^{s-\beta}$$

- different experiments use different NKG-like or nkg-modified functions;
- AGASA

$$\rho_4(r) = \frac{N_e}{r_0^2} C\left(\frac{r}{r_0}\right)^{-\alpha}\left(1+\frac{r}{r_0}\right)^{-(\beta-\alpha)}\left[1+\left(\frac{r}{10r_0}\right)^2\right]^{-\delta}$$

- AGRO-YBJ BigPad data

$$\rho(r) = A\left(\frac{r}{r_0}\right)^{s'-2}\left(1+\frac{r}{r_0}\right)^{s'-4.5}$$

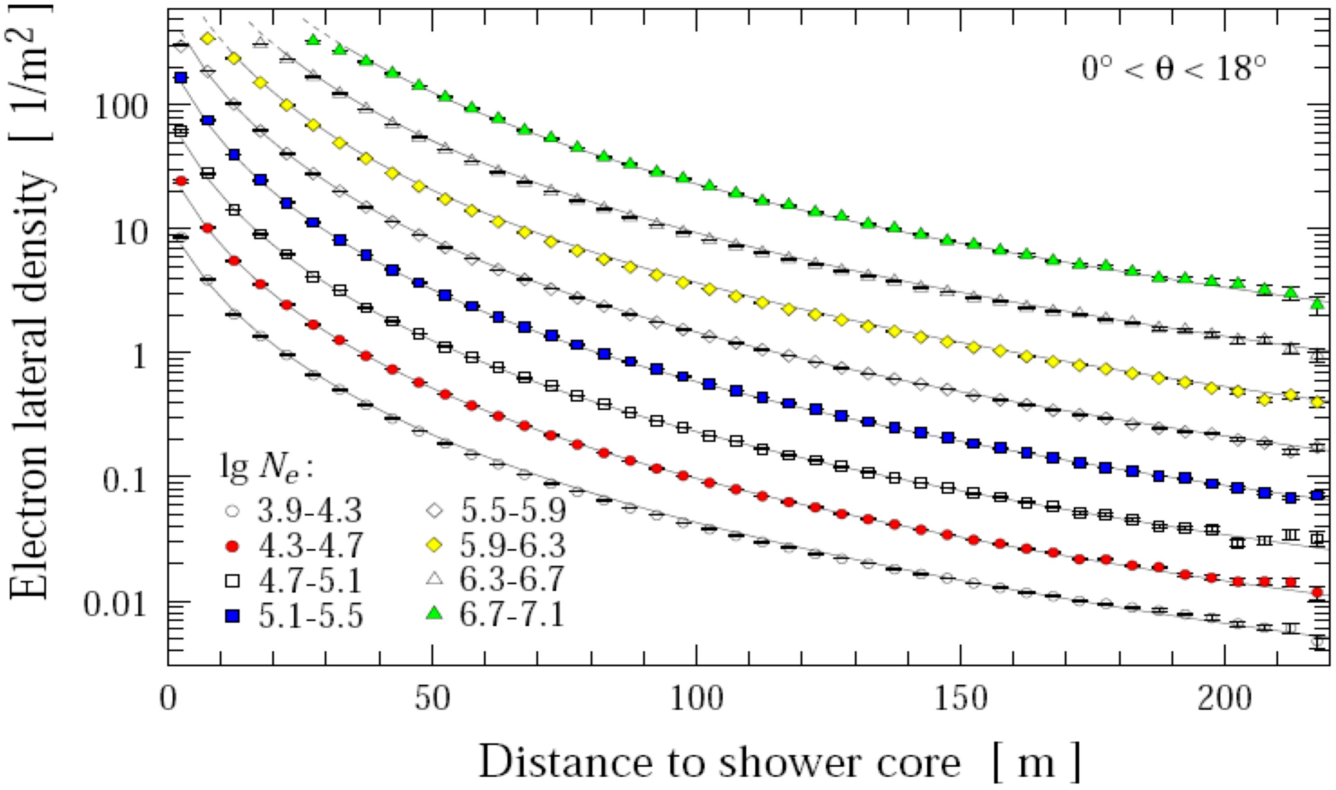
- Likelihood algorithm

$$LF2 = \prod_{k=1}^{N_S} p_k(m_k)$$

Classic way to reconstruct the direction

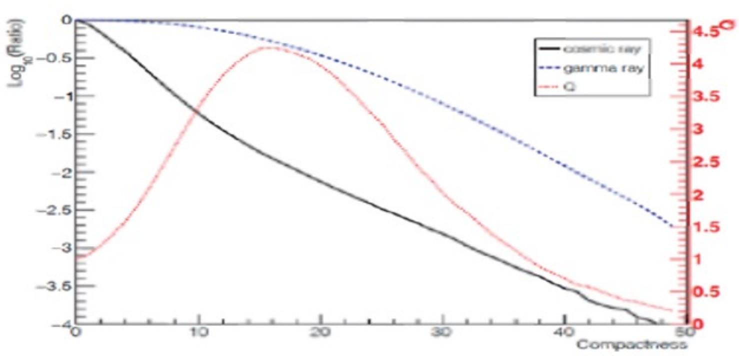
3. Lateral distribution(global fitting)
   - * To fit (xc, yc, theta, phi, Ne, rm, s)

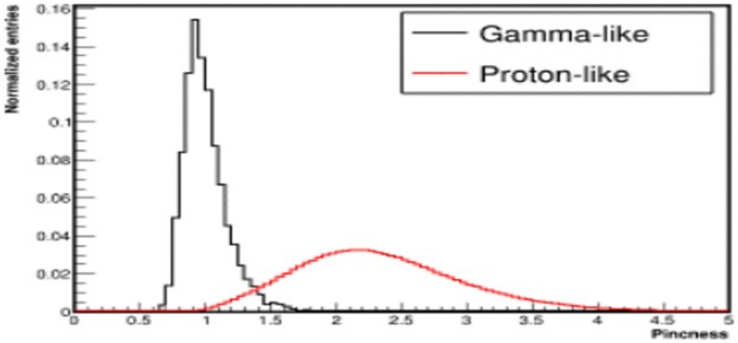
$$\rho(r)=Ne.A\left(\frac{r}{rm}\right)^{s-2}\left(1+\frac{r}{rm}\right)^{s-4.5}$$

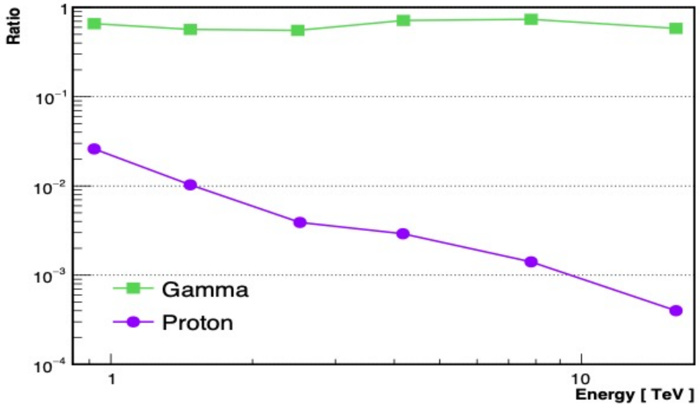


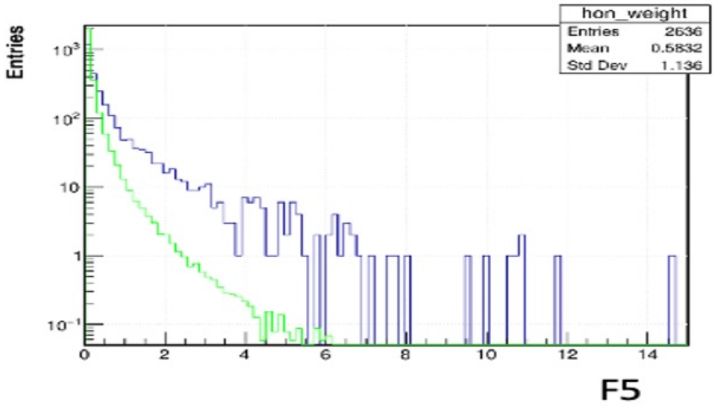
WCDA 粒子鉴别 （gamma/proton sepation)

- 借鉴并发展了多种质子伽马区分方法、F5权重方法、实现了对宇宙线背景事例的高排除率， 部分能区达到了6e-4，**达到了国际上同类实验的最高水平**

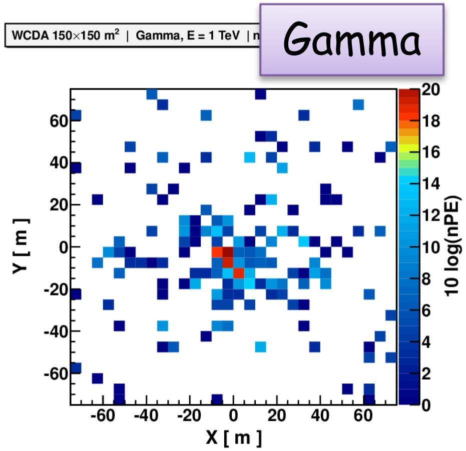


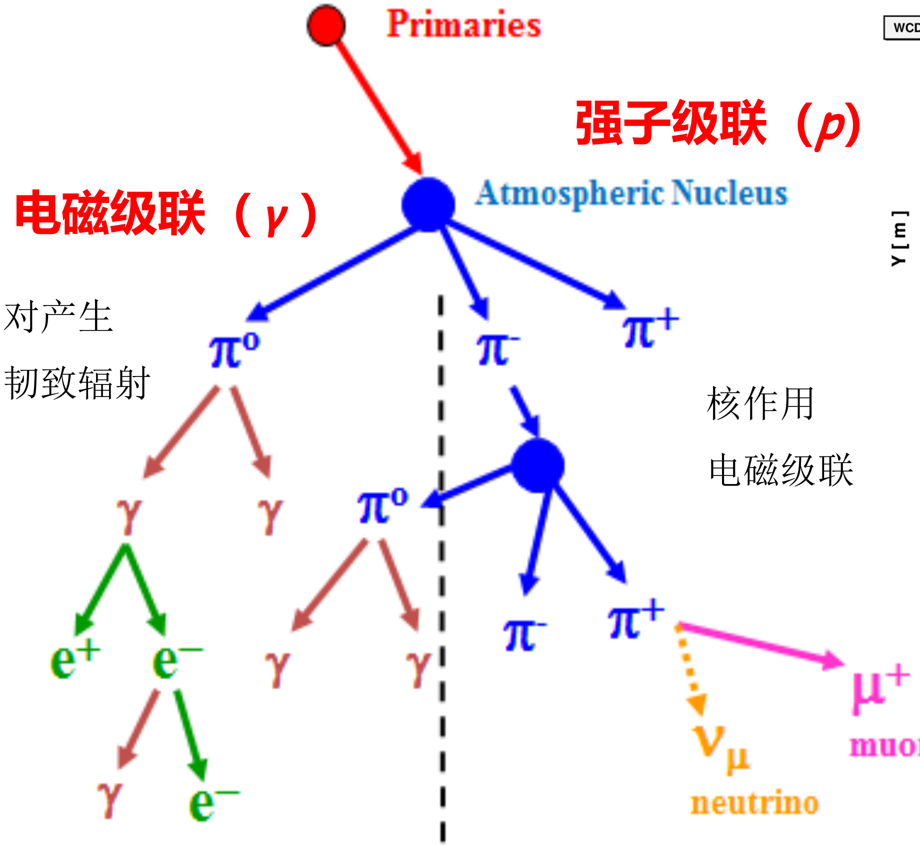


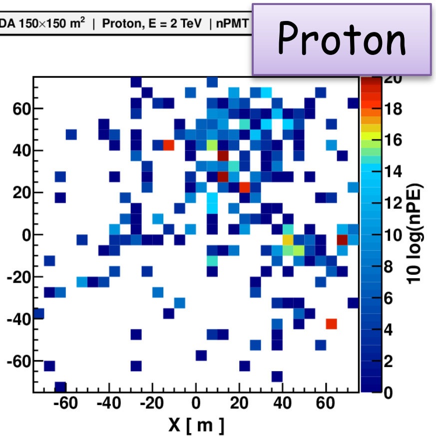




Gamma/Proton separation

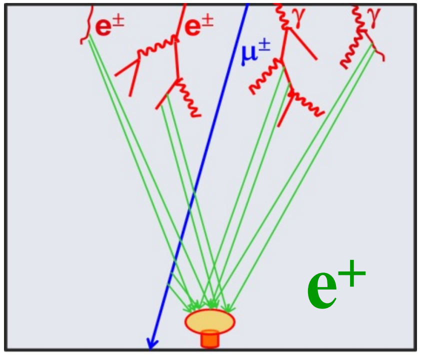






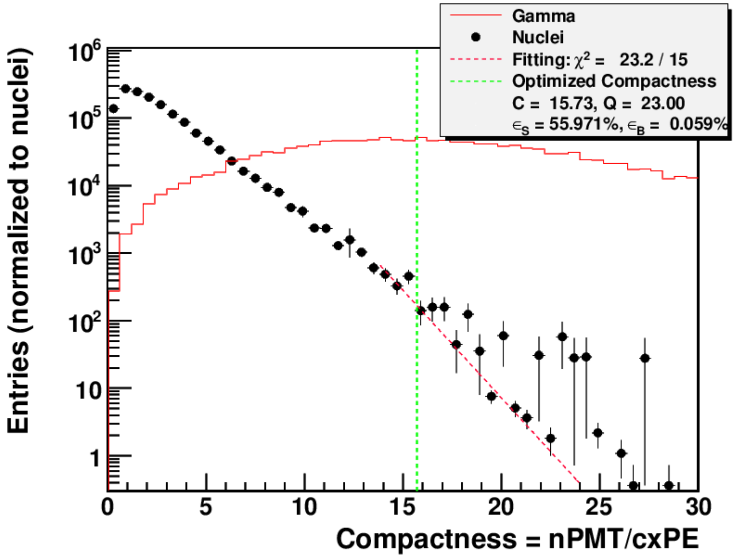
μ子与次芯粒子

产生大信号

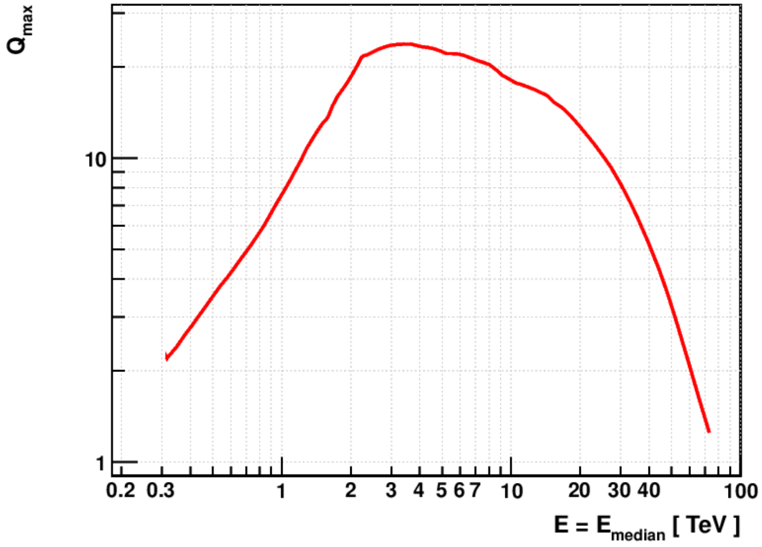


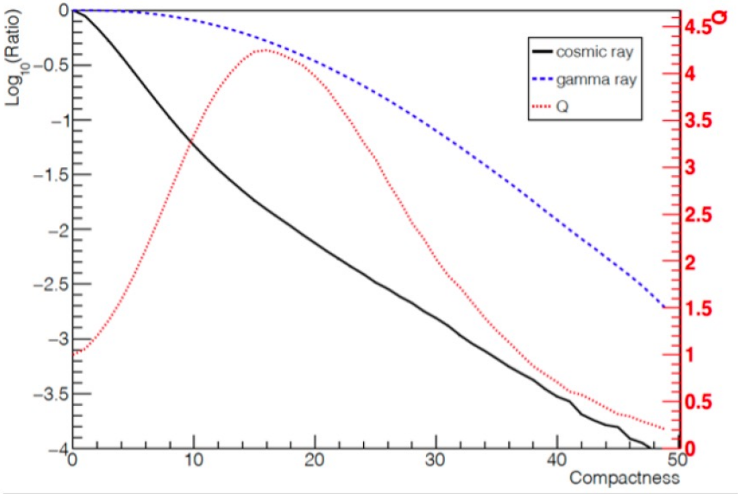
次级粒子分布：	单芯对称；集中分布；	多芯或单芯不对称；杂乱分布；
主要成分：	e±；γ；	e±；γ；核子；μ子；
首次作用点：	离地面较低；	离地面较高；

Compactness: C=Nhit/CXPE (Q_{max}>45)

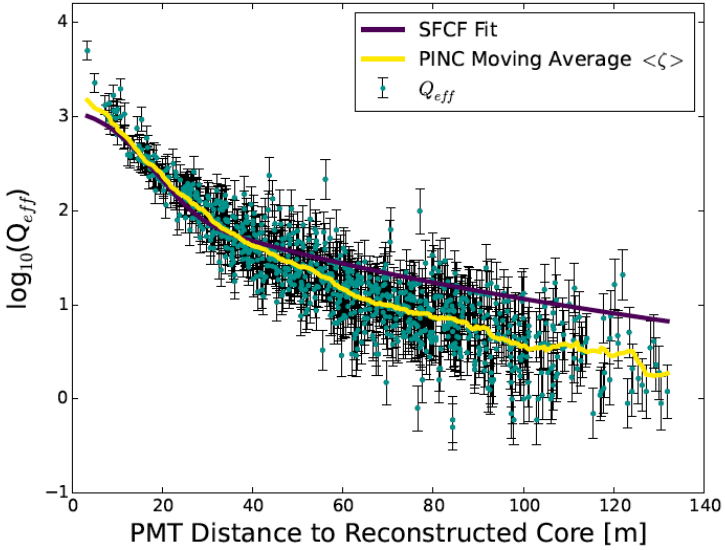


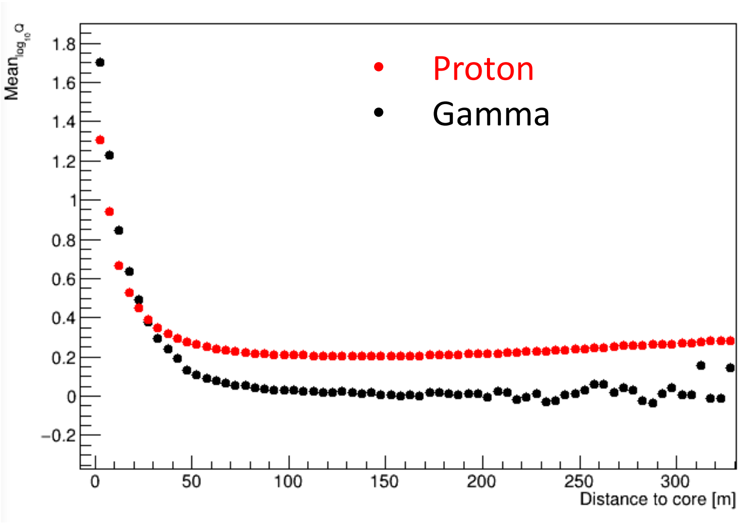
- “次芯” 的寻找:
  - Signal of the brightest PMT outside the shower core region (e.g., 45 m);
- “Compactness” can be employed to reject cosmic ray background efficiently.



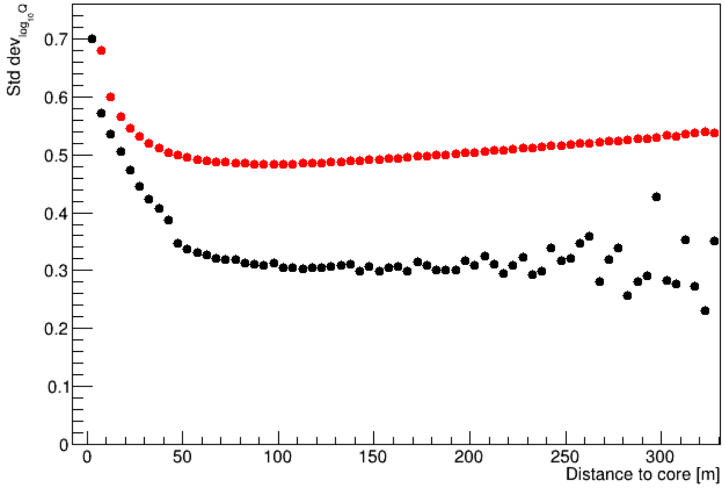


$$\mathcal{P}_{incness} = \frac{1}{N}\sum_{i=0}^{N}\frac{(\zeta_i - \langle\zeta_i\rangle)^2}{\sigma_{\zeta_i}^2}$$





- σ_{ζ_i} determination
  - Hit window optimization
  - R optimization
    - 离芯位越远，时间窗口越大
    - 45m <r <250m
  - A group of $(\langle\zeta_i\rangle, \sigma_{\zeta_i})$ is collected.

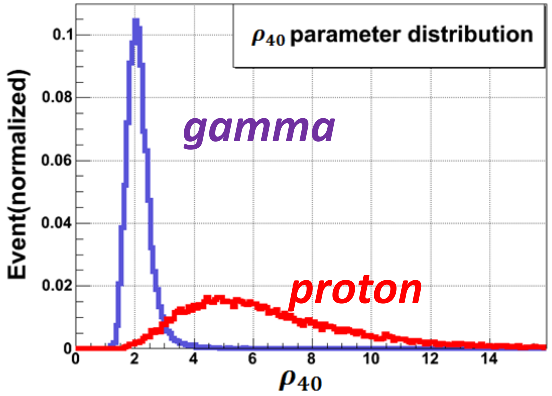


伽马/质子区分敏感参量

2、 Density out(ρ_{40}) = $\frac{\sum PE_{40}}{\sum PMT_{40}}$

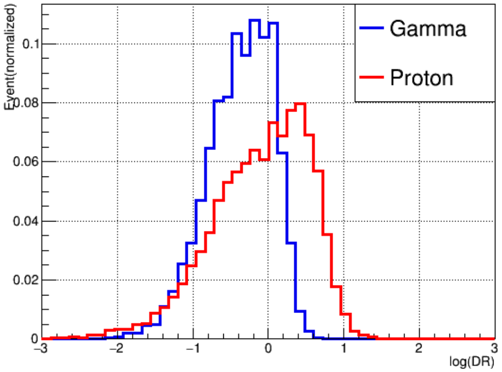
$\sum PE_{40}$：芯位40m之外所有光电子数；

$\sum PMT_{40}$：芯位40m之外所有着火PMT个数；



3、 Density raito(DR ）

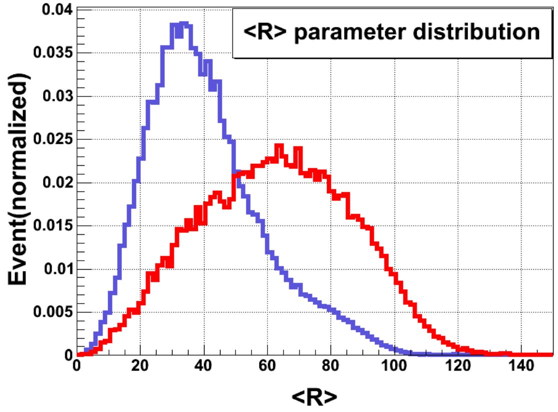
$$\mathrm{DR} = \frac{\sum PE_{50} / \sum PMT_{50}}{\sum PE_{10} / \sum PMT_{10}}$$



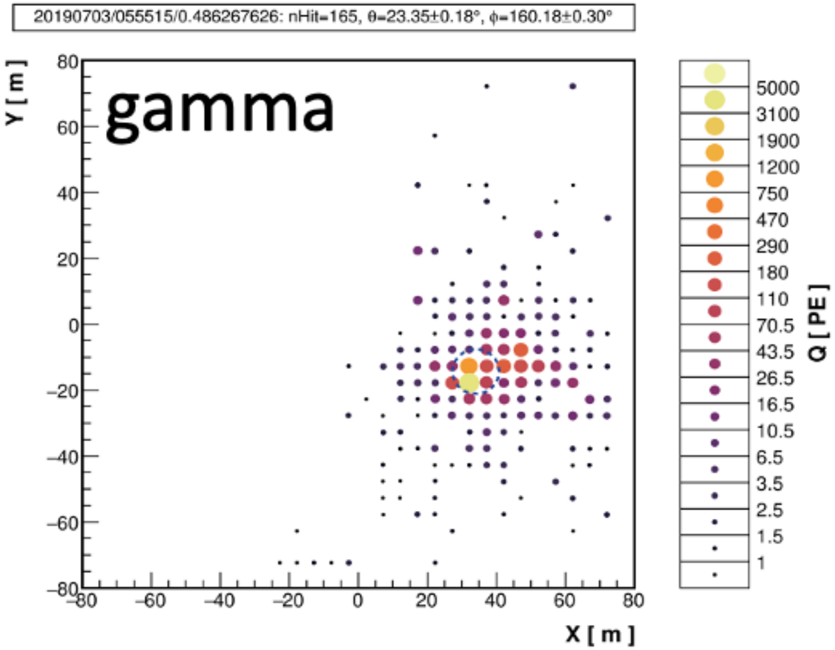
4、 <R> = $\frac{\sum PE_i R_i}{\sum PE_i}$ （平均横向扩展半径）

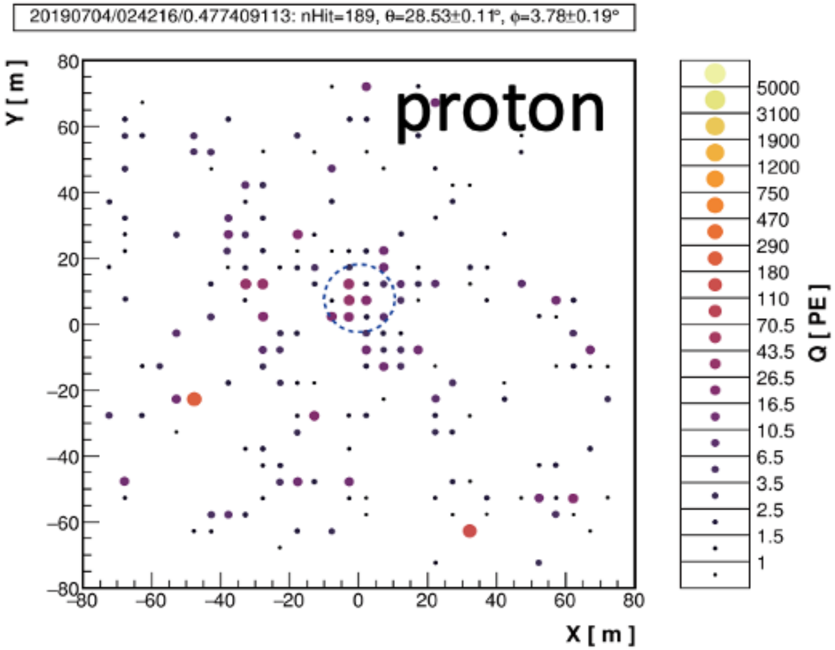
PE_i: 第i个着火PMT上光电子数；

R_i ： 第i个着火PMT 到芯位距离；

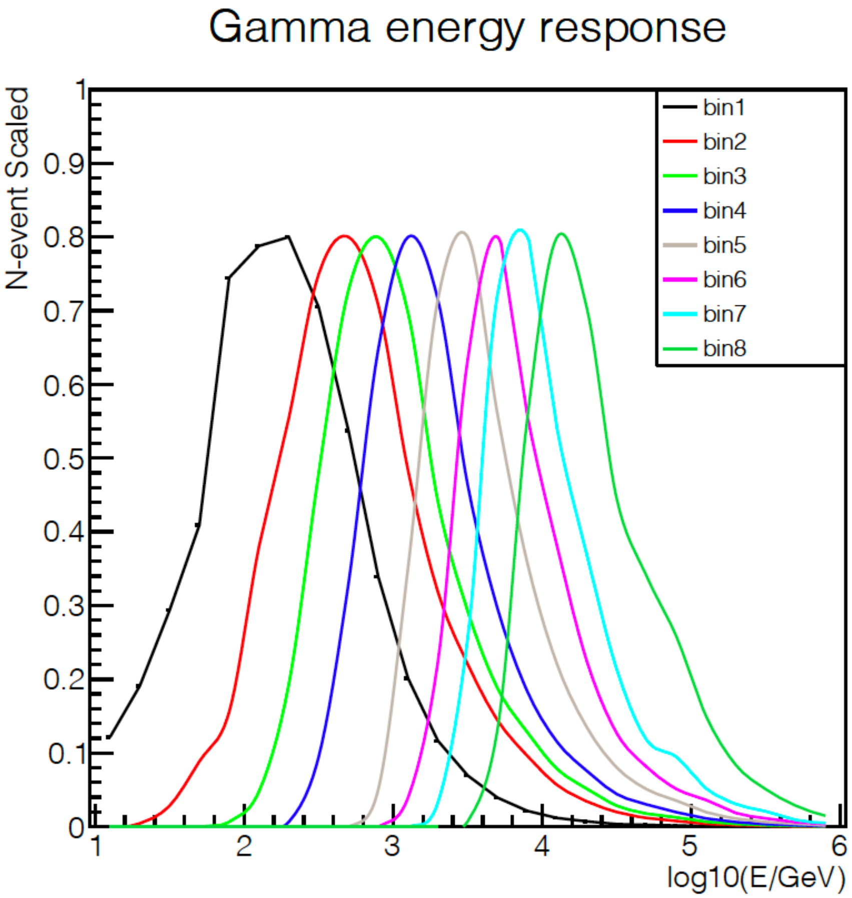


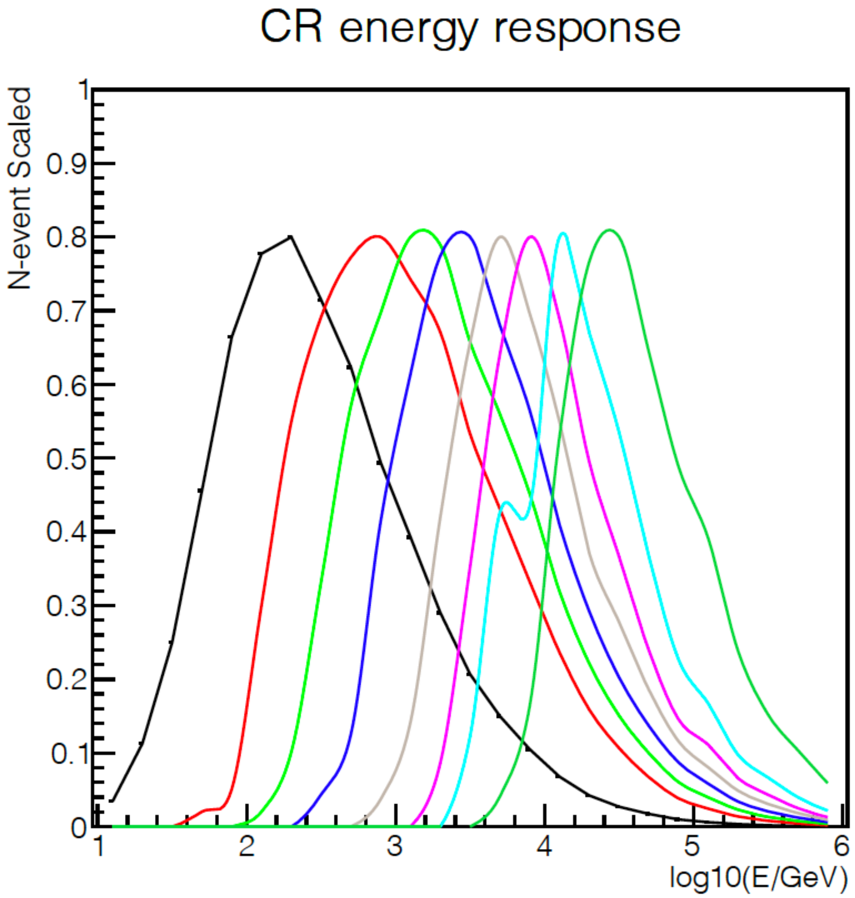
CR Background Rejection Power @ WCDA



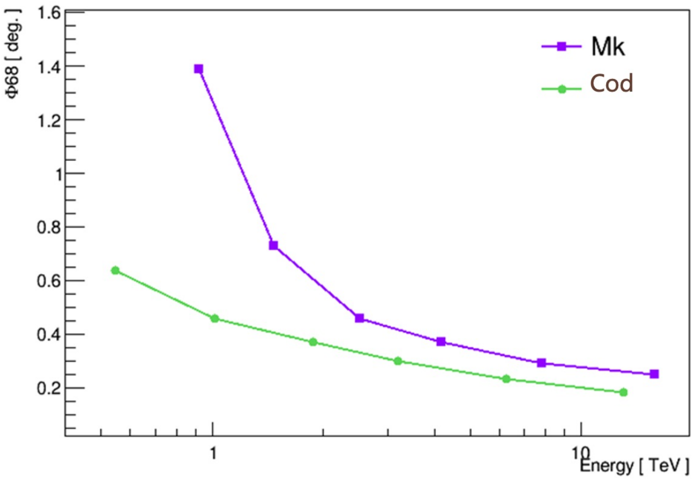


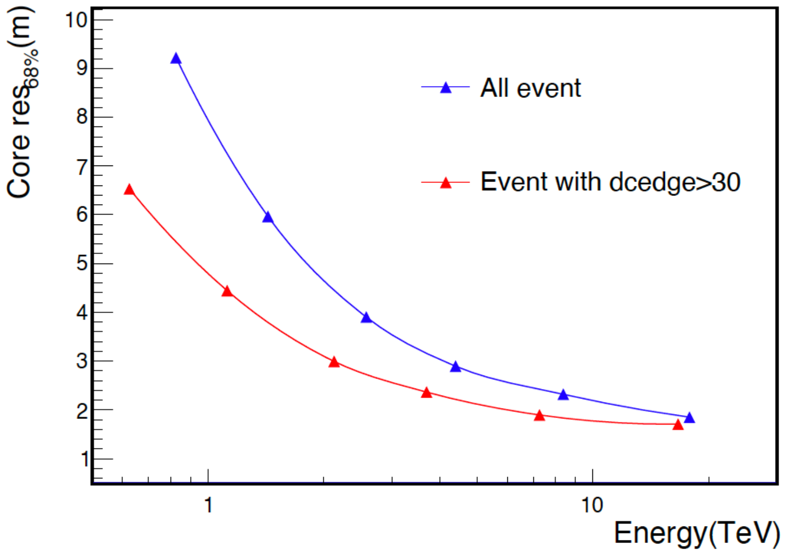
Energy determination base on MC





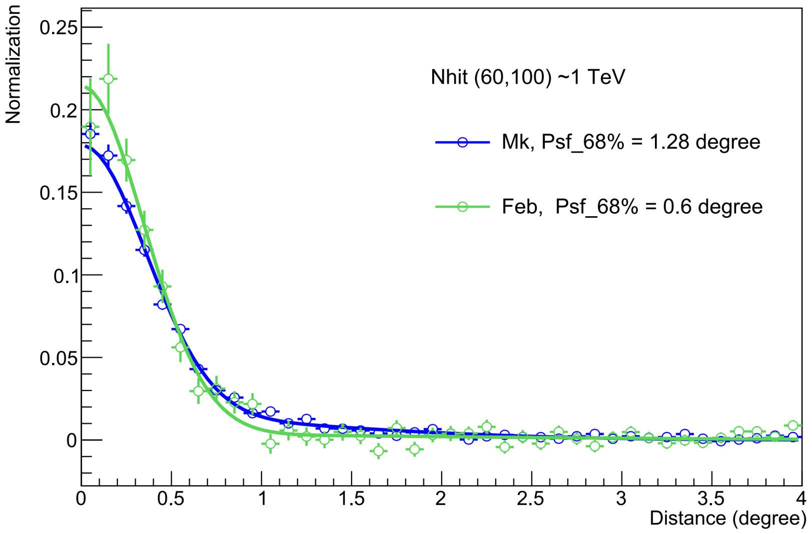
Shower reconstruction resolution

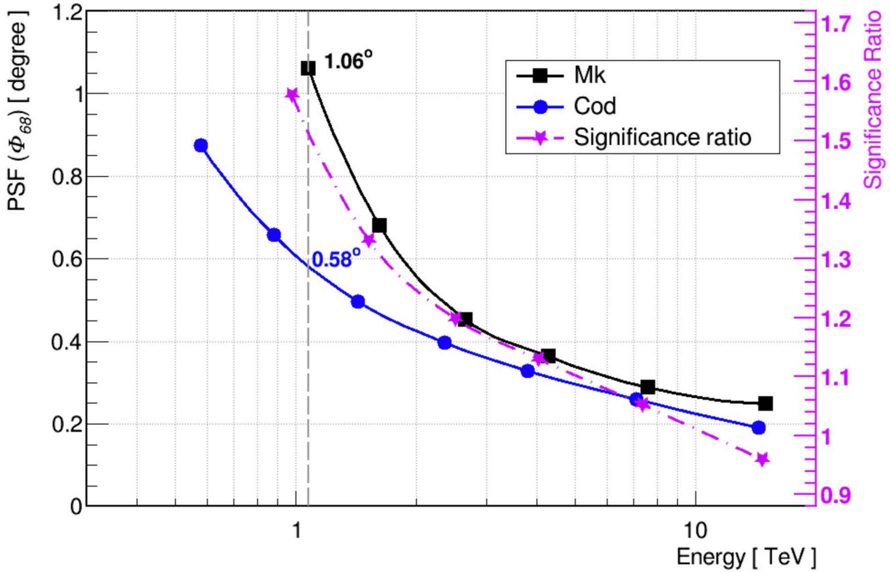




Reconstruction @ WCDA

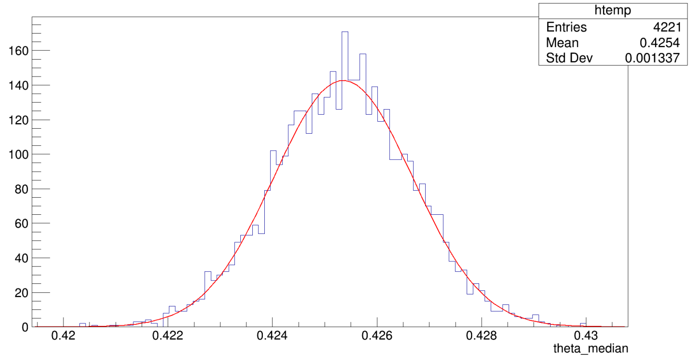
- 特色与难点：
  - 高噪声
  - 同类异构（3个水池，2种类型的PMT）探测器的联合重建
- 重建程序的发展和优化
  - Long term
    - G/P separation optimization;
    - Angular resolution optimization;
    - Energy resolution optimization;
    - further realistic implementation for MC database;
    - ……

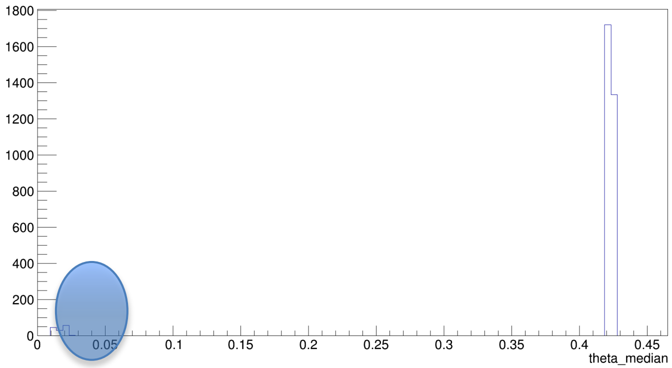


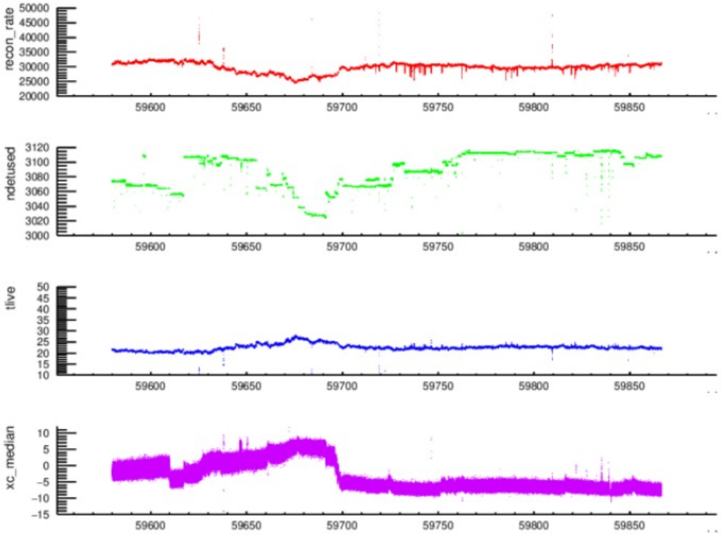


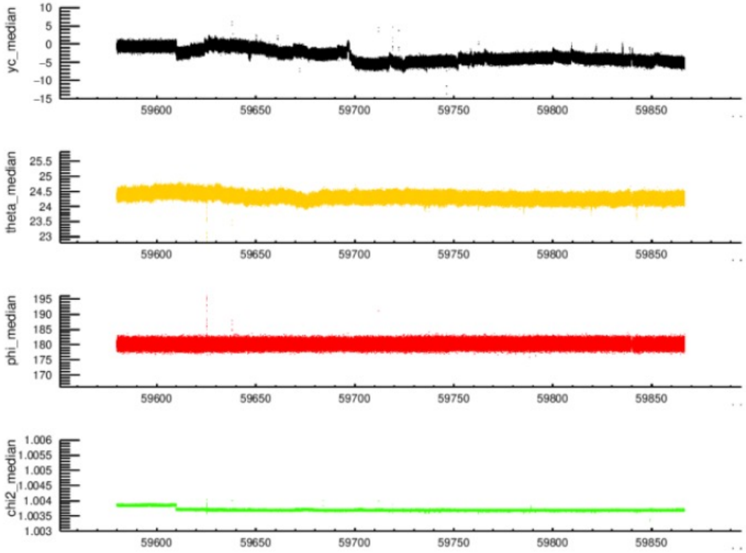
Data Quality Monitoring

- Done by monitoring some parameters related with the daily stability of detector running and reconstruction;
- t_{live}, n_{hit}, θ, φ, x_c, y_c, χ^2 @ Nq05t30>150
- Over 5 sigma file is marked as bad file;
- On average around 3% -6% file is marked as bad file.



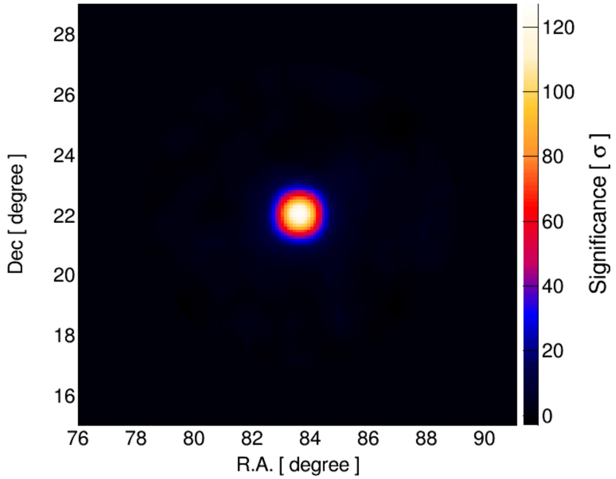


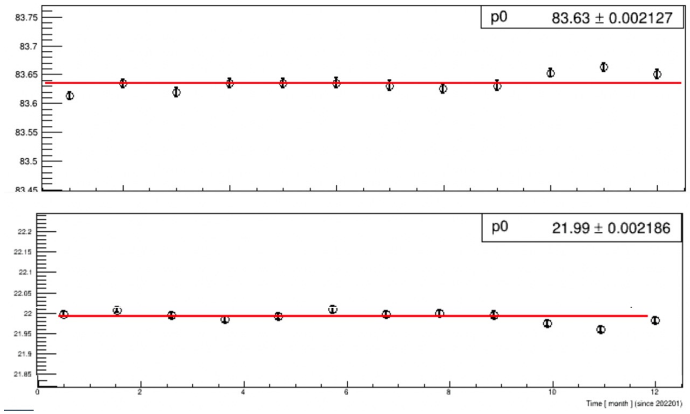


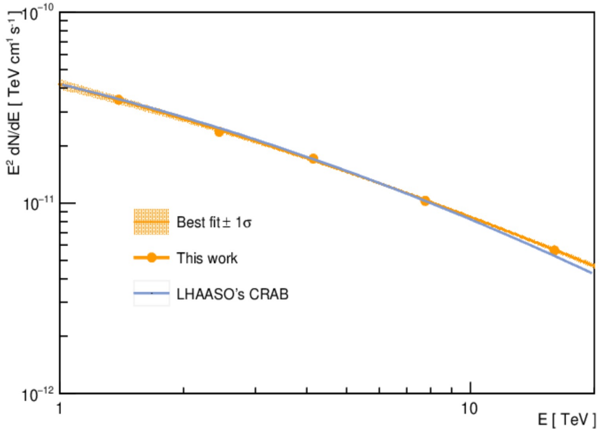


Crab Nebula monitoring

N_{hit}:[100-200]





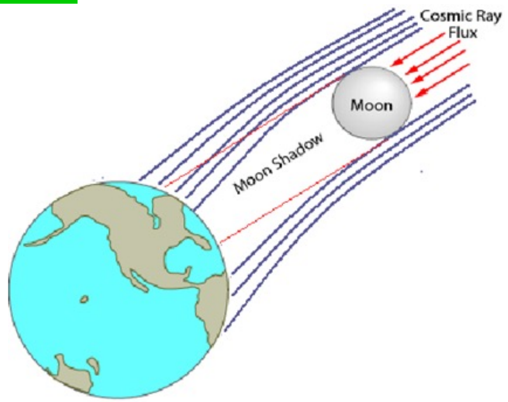


- Pointing error <0.02 deg && SED is consistent with LHAASO science result.

The Moon Shadow technique

Cosmic rays are blocked by the Moon → **Deficit of cosmic rays in the direction of the Moon**

- **Size of the deficit** → **Angular Resolution**
- **Position of the deficit** → **Pointing Error**



Moon diameter ~0.5 deg

Geomagnetic Field: positively charged particles are deflected towards the West.

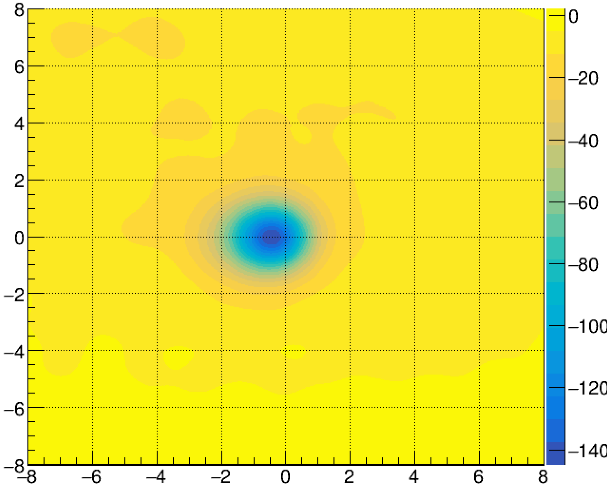
→ **Magneticspectrometer**

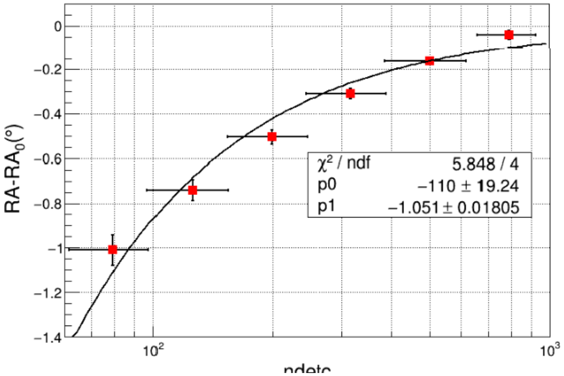
$$\Delta\alpha \approx \frac{1.6^{0} \cdot Z}{E(TeV)}$$

- **West displacement** → **Energy calibration**

利用地磁场的磁谱仪的作用，利用LHAASO高海拔、低阈能得特点，挑选由轻成分主导的月亮阴影数据来建立能标；再利用同一批数据测量宇宙线轻成分在低能端能谱来进一步的检验这一能标。

Moon shadow monitoring

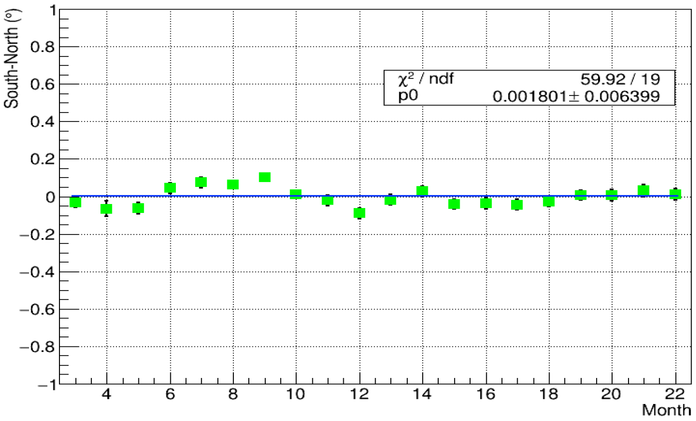


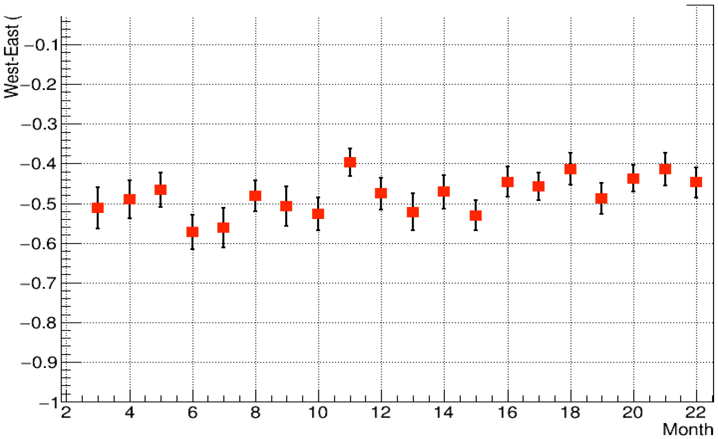


能标的误差主要来源于统计误差：

✓ 在 6.6TeV 误差为：12%

✓ 在 35 TeV 误差为：50%

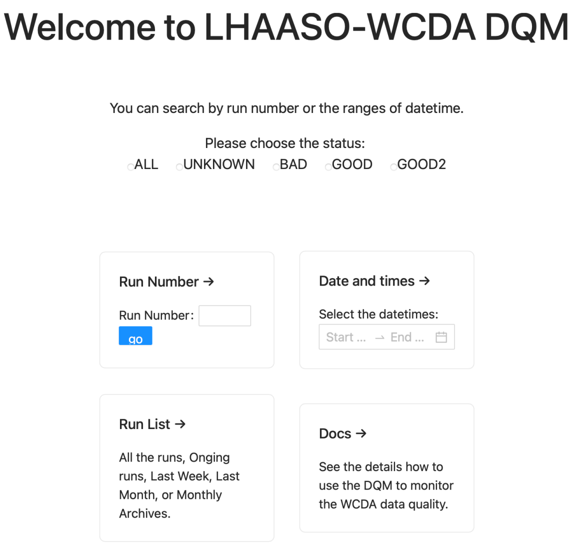




- N_{hit}>100 pointing error <0.01 deg @ moon shadow

Reconstruction Production version

- DAQ raw data
  - 11T/day
- Now working version: Mk
- 4 data products
  - Reducedata/
    - noise filter data 5 T/day
  - Recdata/
    - reconstruction datc 950 G/day
  - Recgdata/
    - potential gamma events 1.4 G/day
  - Sampdata/
    - specific data sample around the sources(crab) 200 G/day



Welcome to LHAASO-WCDA DQM

You can search by run number or the ranges of datetime.

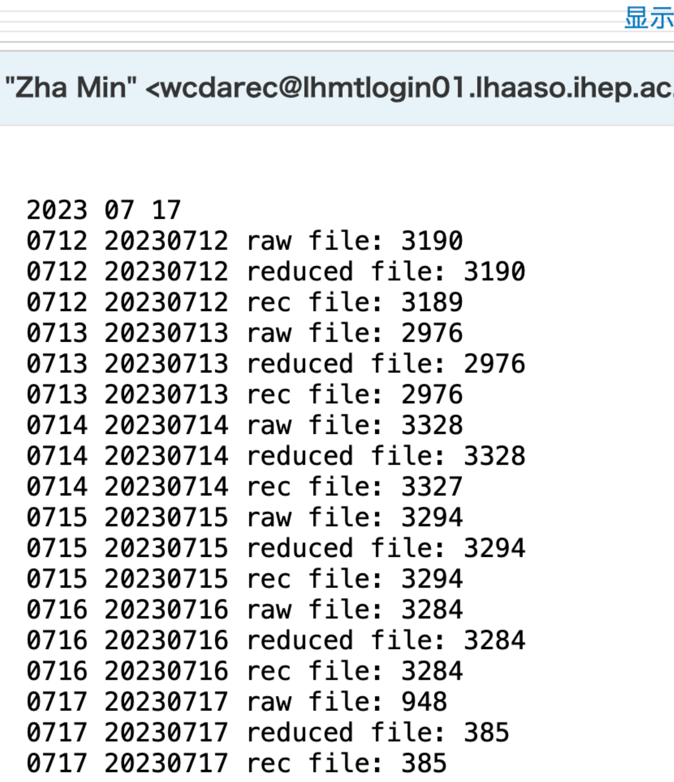
Please choose the status:
○ALL ○UNKNOWN ○BAD ○GOOD ○GOOD2

Run Number →
Run Number: ☐

Date and times →
Select the datetimes:
Start ... → End ...

Run List →
All the runs, Ongoing runs, Last Week, Last Month, or Monthly Archives.

Docs →
See the details how to use the DQM to monitor the WCDA data quality.



"Zha Min" <wcdarec@lhmtlogin01.lhaaso.ihep.ac

```
2023 07 17
0712 20230712 raw file: 3190
0712 20230712 reduced file: 3190
0712 20230712 rec file: 3189
0713 20230713 raw file: 2976
0713 20230713 reduced file: 2976
0713 20230713 rec file: 2976
0714 20230714 raw file: 3328
0714 20230714 reduced file: 3328
0714 20230714 rec file: 3327
0715 20230715 raw file: 3294
0715 20230715 reduced file: 3294
0715 20230715 rec file: 3294
0716 20230716 raw file: 3284
0716 20230716 reduced file: 3284
0716 20230716 rec file: 3284
0717 20230717 raw file: 948
0717 20230717 reduced file: 385
0717 20230717 rec file: 385
```

- A good-file-list can be collected;
- Some detailed parameters informaiton can be checked.

WCDA Data Production

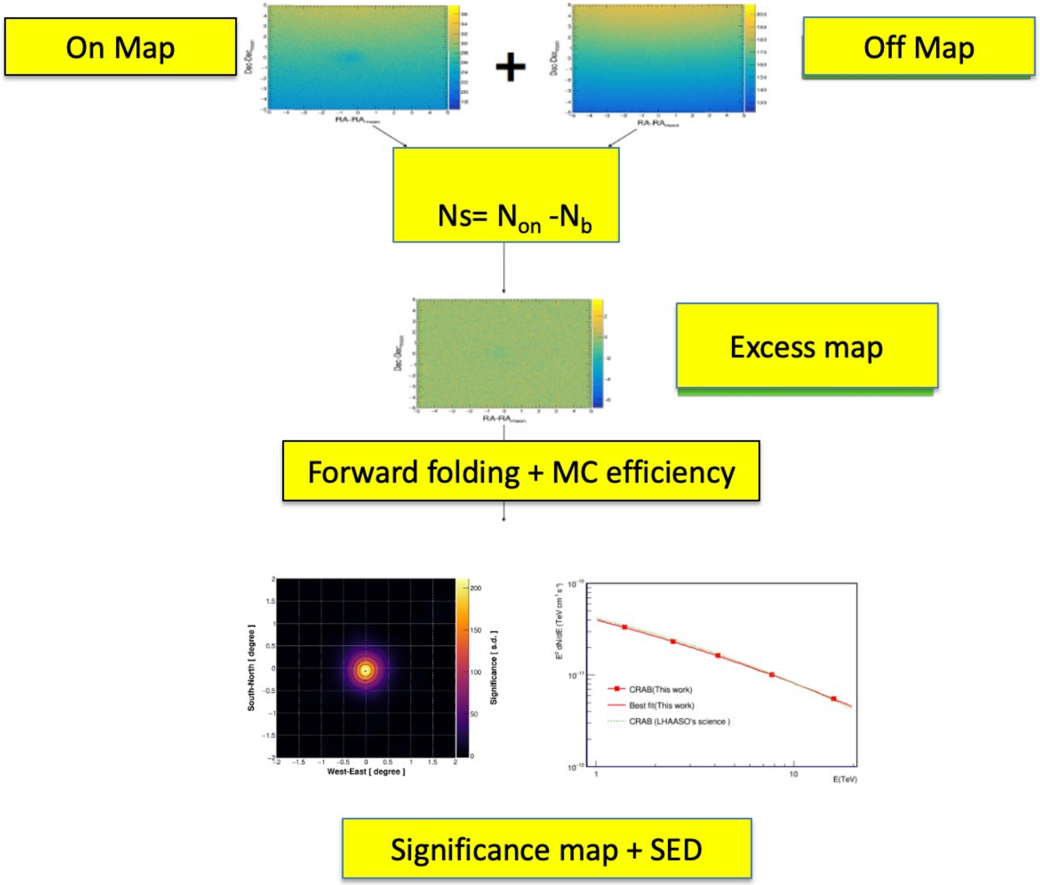
- Releasing directory @ /eos/lhaaso/rec/wcda/publish/
  - 1:progs/ 2:data/ 3:goodlist/ 4:Simulation/ 5:Skymap/
- Releasing working version: Mk
- Reconstruction and Simulation programme @ progs/
  - Reconstruction: Mk/ + test/test.sh
  - Simulation: g4wcda/8.02run + test1.sh && test2.sh
- Three physics data products in root format @ Mk/
  - yyyy/mmdd → 2023/0101
  - Readme.wcda → details about root elements
  - recdata/ -→ Standard reconstruction data 450 G/day
  - recgdata/ → Gamma-like reconstruction data 1.6 G/day
  - sampdata/ → specific sample data around the sources(crab) 100 G/day
- File-list about Data quality Check @ goodlist/
  - Txt format: yyyymmdd.dat → 20230101.dat
- Two scientific data products in root format @
  - One skymap data in root format @ skymap
  - One simulation samples in root format @ simulation/ (just gamma samples)
    - MC1Gamma is for data from 2021/03/05 to 2022/09/30;
    - MC2Gamma is for data from 2021/03/05 to 2023/12/31;

WCDA Data Production

- Releasing directory @ /eos/lhaaso/rec/wcda/publish/
  - 1:progs/ 2:data/ 3:goodlist/ 4:Simulation/ 5:Skymap/
- Releasing working version: Cod/
- Reconstruction and Simulation programme @ progs/
  - Detector Simulation package: g4wcda/8.03 + test1.sh && test2.sh
  - Reconstruction pacage: Cod/ + test/test.sh
- One Physics data products in root format @ Cod/
  - yyyy/mmdd → 2023/0101
  - Readme.wcda → details about root elements
  - recdata/ -→ Standard reconstruction data 450 G/day
- File-list about Data quality Check @ goodlist/
  - Txt format: yy/mmdd.dat → 2023/0101.dat
- Two scientific data products in root format @
  - One skymap data in root format @ skymap

  - One simulation samples in root format @ simulation
    - To estimate efficiency of WCDA detector
    - MCCR/ is the samples for Cosmic Ray composition with 26 elements;
    - MC2Gamma/ is for Gamma samples

A 3D tool on source Analysis



On Map

Off Map

Ns= N_{on} -N_b

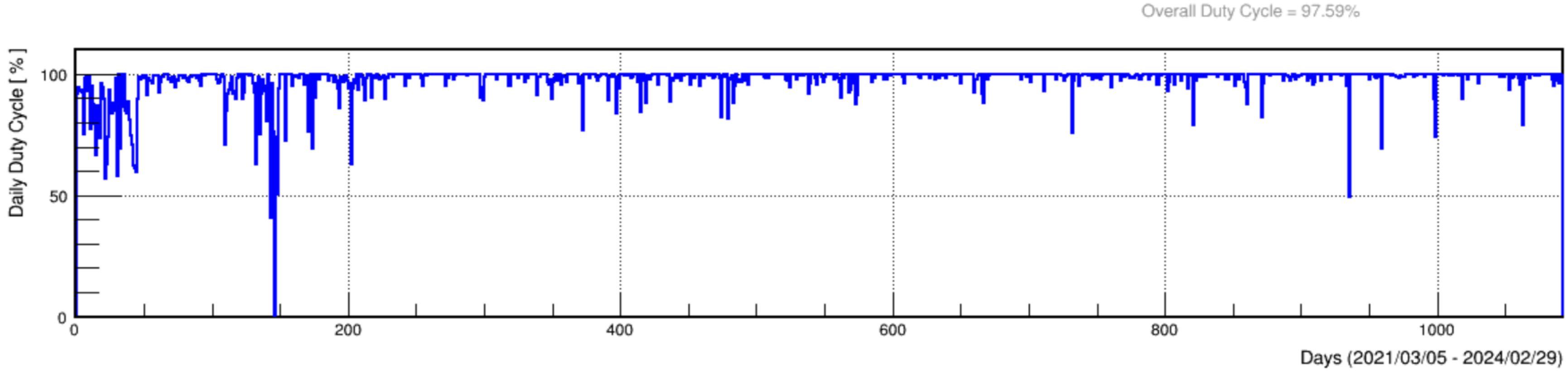
Excess map

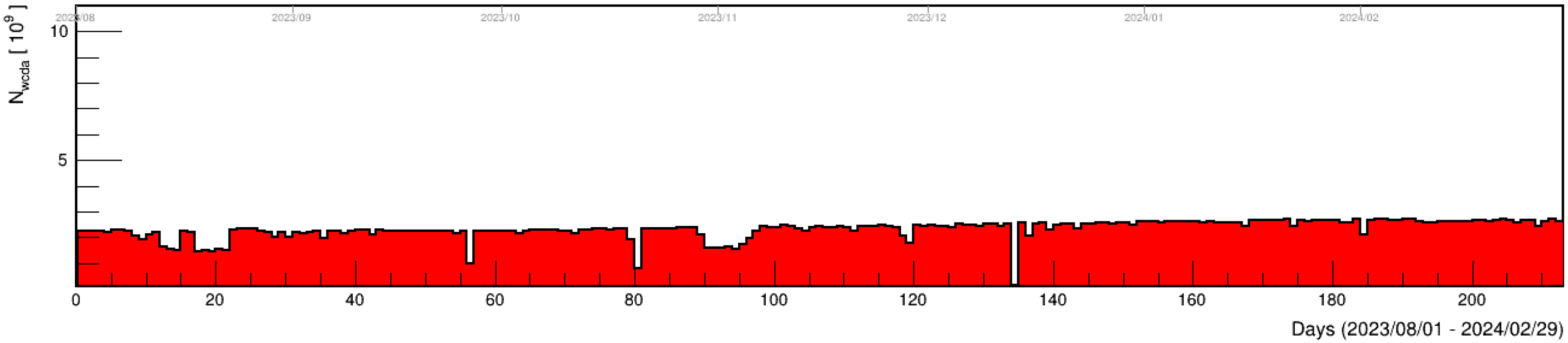
Forward folding + MC efficiency

Significance map + SED

Details can be seen talk by Shicong Hu

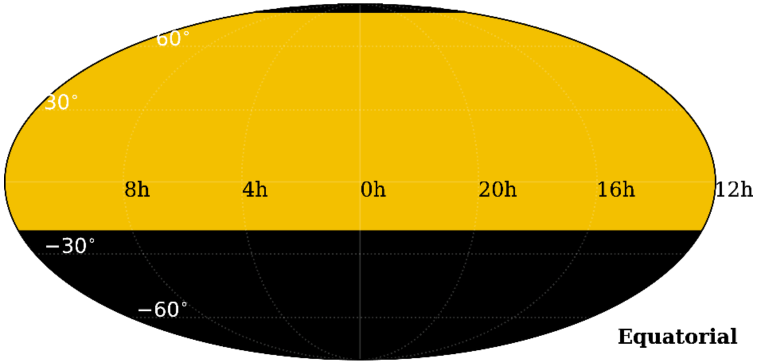
Features: full duty cycle



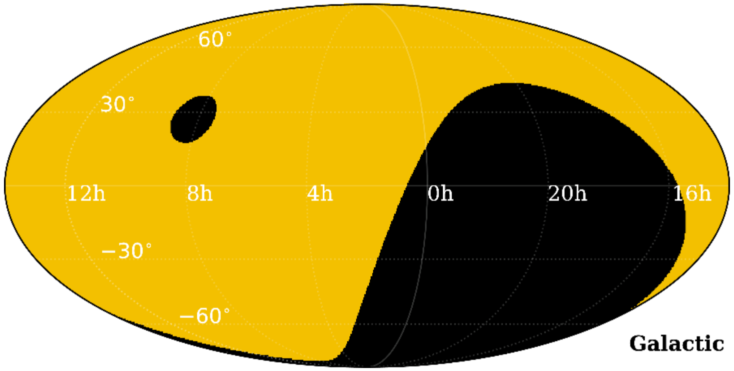


Features: wide field of view

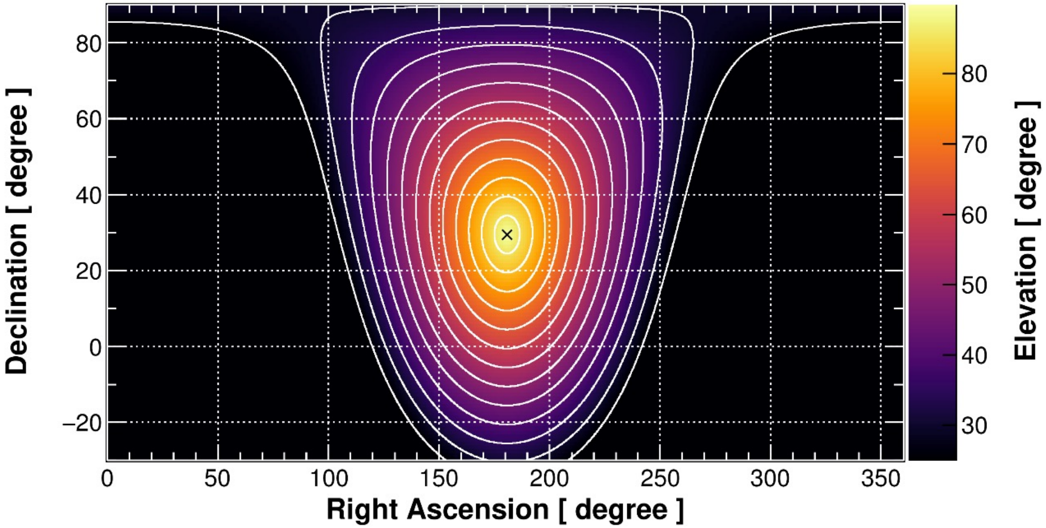
Daily/yearly FOV



LHAASO FOV



LHAASO FOV

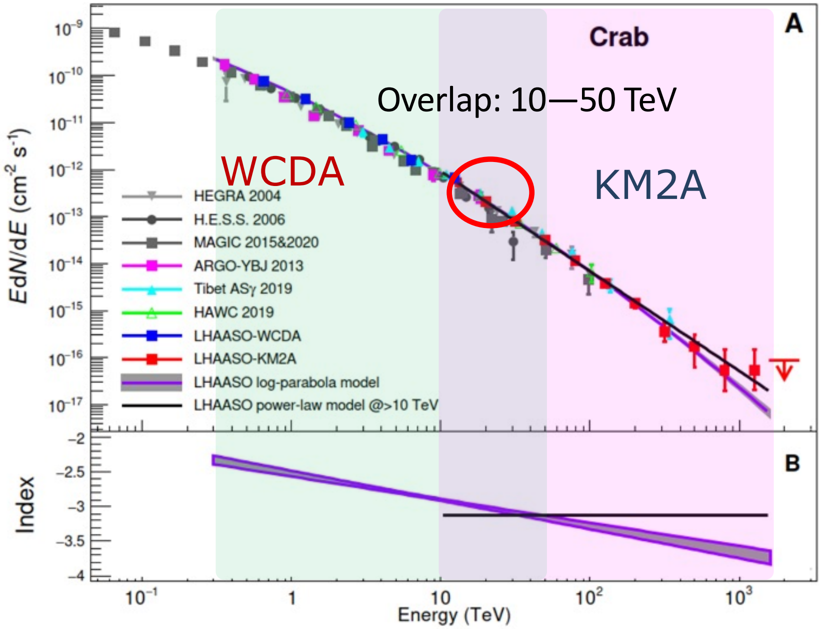


Instant FOV

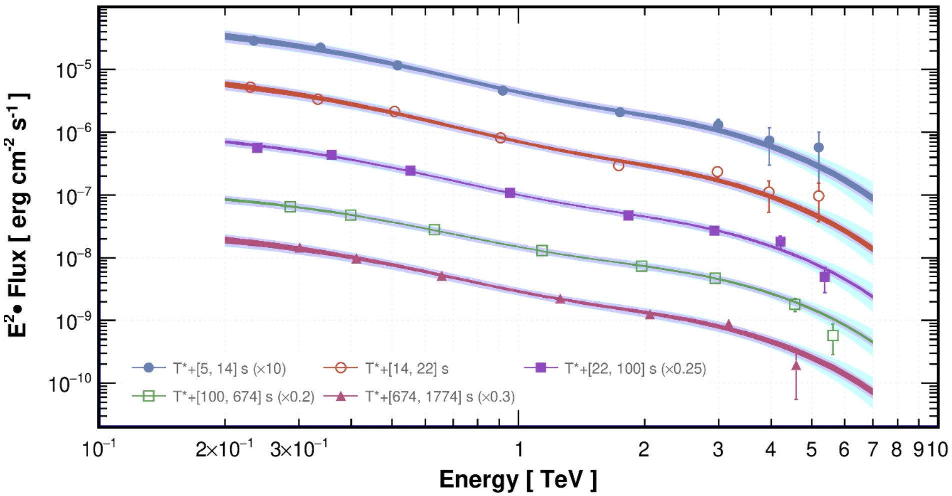
1/6 of the entire sky at any given moment.

The Earth's rotation further enables a 3/4 sky coverage

Features: wide energy range coverage



GRB 221009A

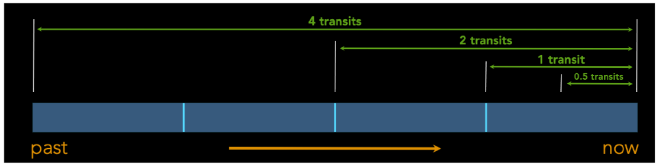


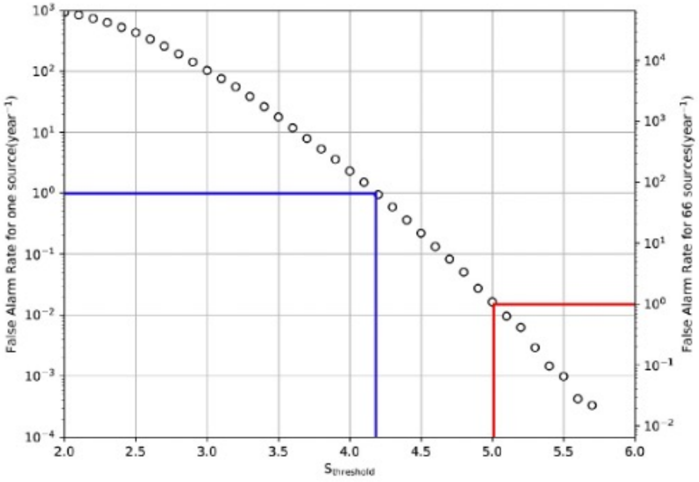
The lowest can reach < ~100 GeV?

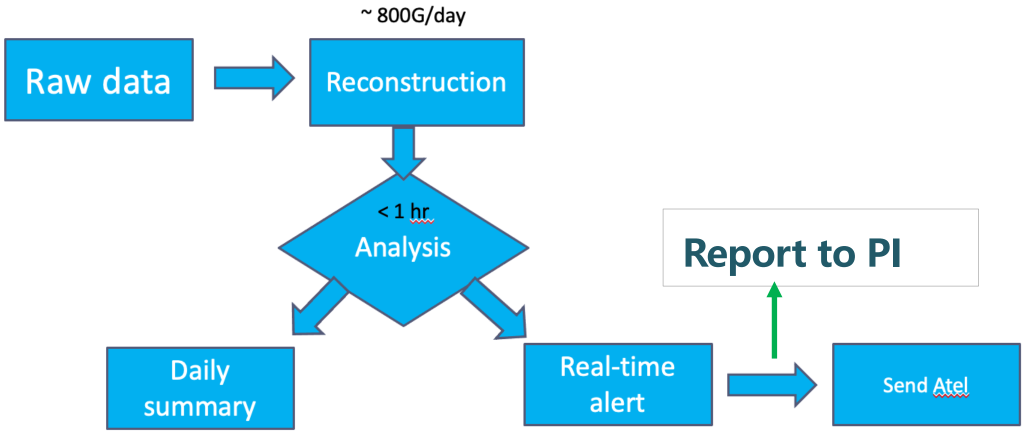
- For the first time covering 3.5 ~ 4 decdades of energy (300 – 1.5 PeV)
  - Consistent with others < 100 TeV
  - Self cross-check between WCDA and KM2A; KM2A and WFCTA

A real-time monitoring @ selected AGN

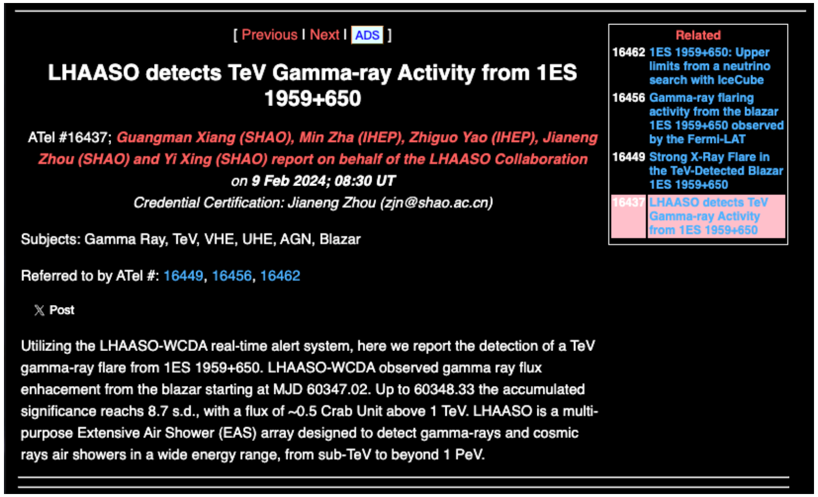
- Space
  - The maximum searching distance between the source and grid center is set as 0.1 deg;
- Duration: 0.5,1,2,4 transits
- Alert threshold ←→ the false alarm rate
  - Based on MC simulation







LHAASO-WCDA 河外候选AGN耀变现象的实时监测



[Previous | Next | ADS]

LHAASO detects TeV Gamma-ray Activity from 1ES 1959+650

ATel #16437; *Guangman Xiang (SHAO), Min Zha (IHEP), Zhiguo Yao (IHEP), Jianeng Zhou (SHAO) and Yi Xing (SHAO) report on behalf of the LHAASO Collaboration*
on 9 Feb 2024; 08:30 UT
Credential Certification: Jianeng Zhou (zjn@shao.ac.cn)

Subjects: Gamma Ray, TeV, VHE, UHE, AGN, Blazar

Referred to by ATel #: 16449, 16456, 16462

𝕏 Post

Utilizing the LHAASO-WCDA real-time alert system, here we report the detection of a TeV gamma-ray flare from 1ES 1959+650. LHAASO-WCDA observed gamma ray flux enhancement from the blazar starting at MJD 60347.02. Up to 60348.33 the accumulated significance reaches 8.7 s.d., with a flux of ~0.5 Crab Unit above 1 TeV. LHAASO is a multi-purpose Extensive Air Shower (EAS) array designed to detect gamma-rays and cosmic rays air showers in a wide energy range, from sub-TeV to beyond 1 PeV.

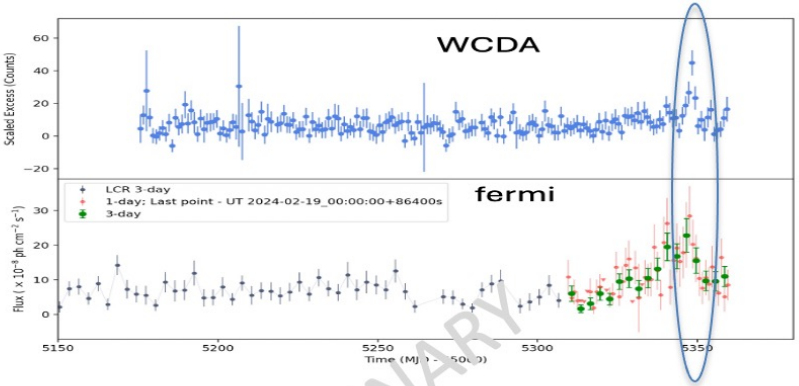
Related

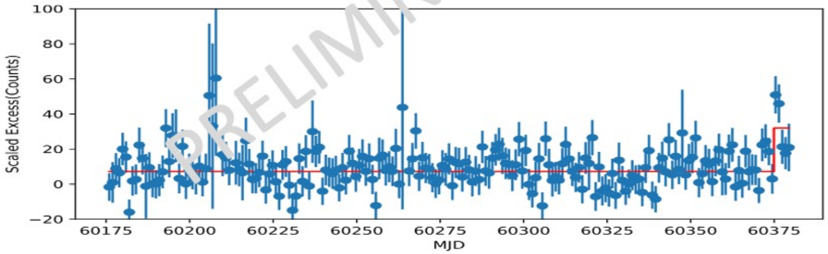
16462 1ES 1959+650: Upper limits from a neutrino search with IceCube

16456 Gamma-ray flaring activity from the blazar 1ES 1959+650 observed by the Fermi-LAT

16449 Strong X-Ray Flare in the TeV-Detected Blazar 1ES 1959+650

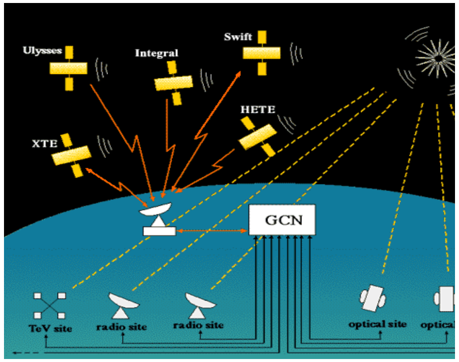
16437 LHAASO detects TeV Gamma-ray Activity from 1ES 1959+650

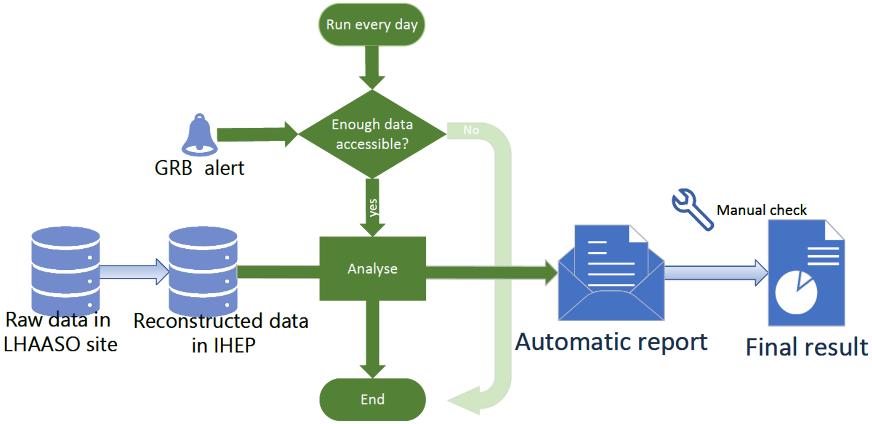


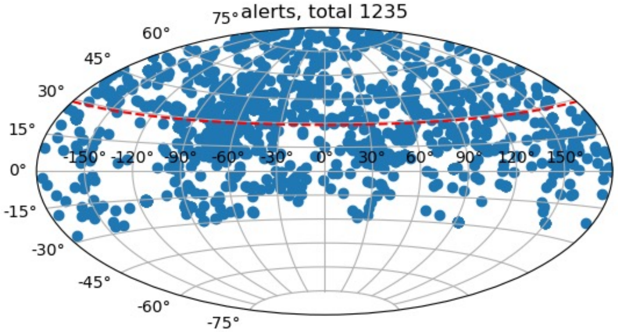


- 在2024.02.08探测到1ES1959+650的耀变行为，发布了Atel预警，Swfit-XRT, Fermi-LAT, IceCube 都进行了后续多波段，多信使的观测和分析；
- IC 310 在 2024/03/08 发布了ATel 的预警， VERITAS 进行了有效的后续观测

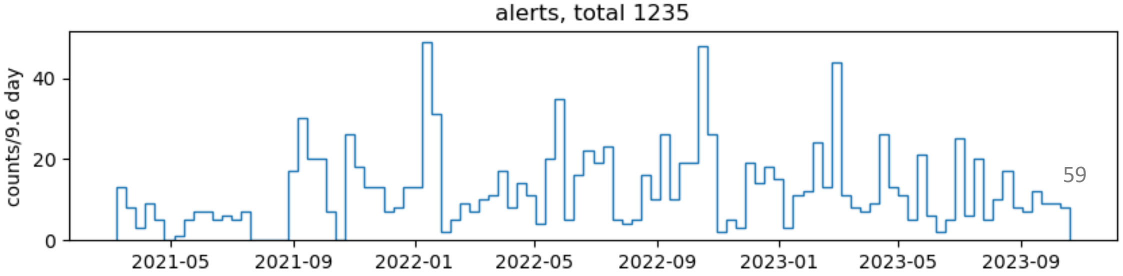
GRB/transient/GW candidate follow-up @ trigger and triggerless data







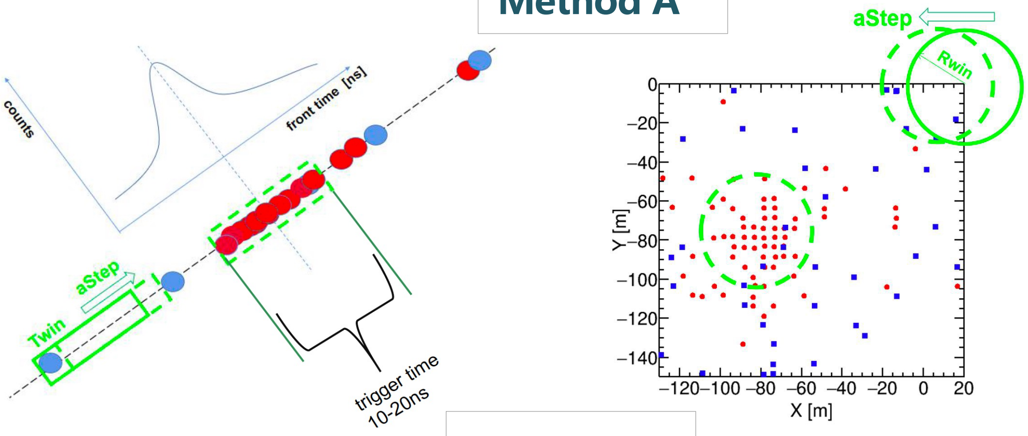
- Receive a GCN alert inside LHAASO FOV
    - Alert rate: 2.5/week
- Save (T0-0.5 h, T0 + 2 h) hours of data
- (Npe, T) of 3120 detector units
- Big data size → 8 TB/alert
- Touching low energy band



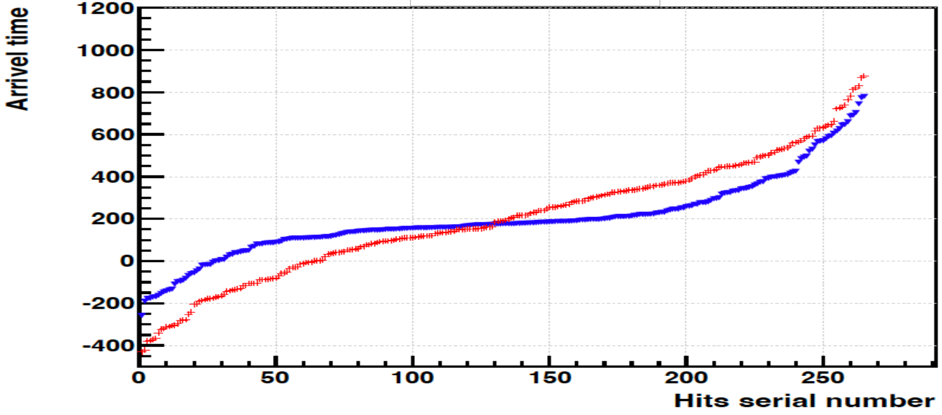
Analysis pipeline

- Hits-to-Events re-trigger (A)
    - Time & window selection
    - 20 ns Twindow + 20 ns Tgap
    - R=20 m
- Hits-to-Events re-triger (B)
    - Twin=1000 ns + half overlap
- Event reconstruction/No reconst.
- Background estimation
- Searching excess
- Physics analysis
    - Flux upper limits

Method A



Method B



Results

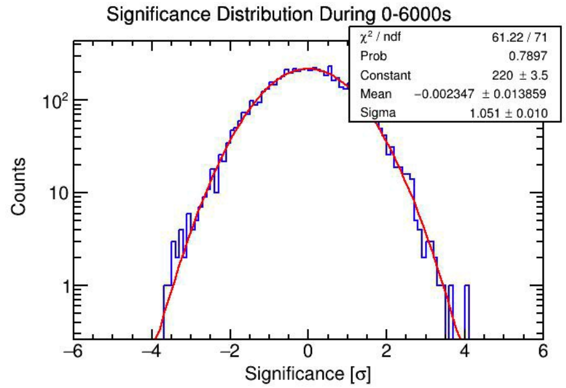
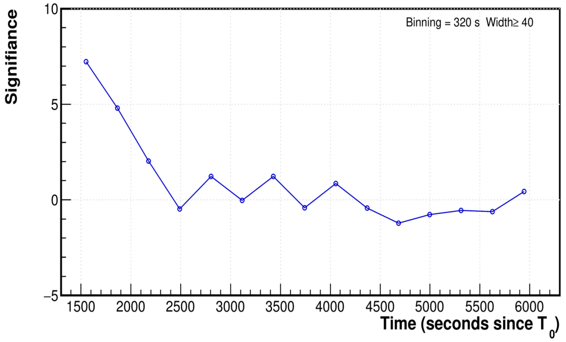
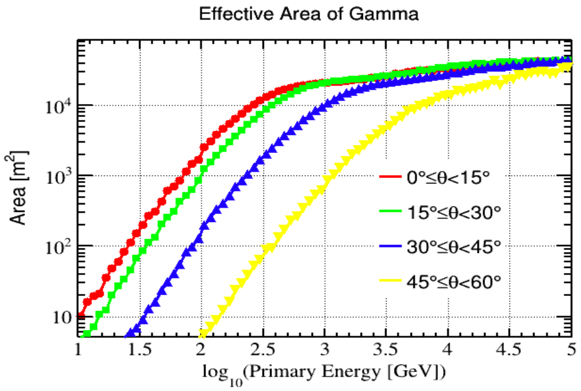


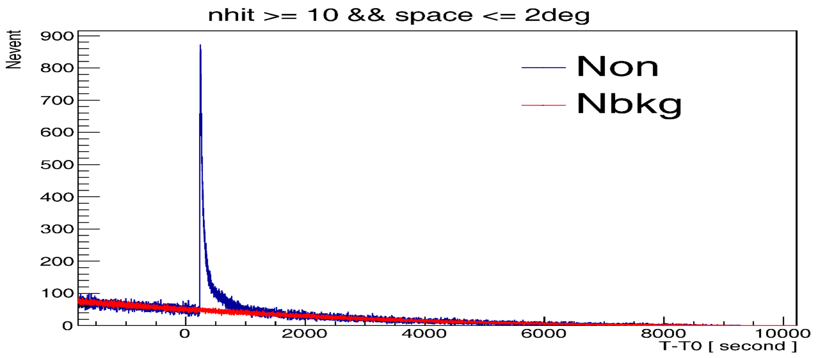
表 4.2 不同红移下T_0-T_{90}和T_{90}−6000s时间范围内低能和高能流强上限列表

取数日期	天顶角	T90	T_{90}, nfitc < 60		T_{90}, nfitc ≥ 60		0 − 6000s, nfitc < 60		0 − 6000s, nfitc ≥ 60	
			F (z=0.1)	F (z=0.5)	F(z=0.1)	F (z=0.5)	F (z=0.1)	F(z=0.5)	F(z=0.1)	F (z=0.5)
	[o]	[s]	[erg cm^{-2}]	[erg cm^{-2}]	[erg cm^{-2}]	[erg cm^{-2}]	[erg cm^{-2}]	[erg cm^{-2}]	[erg cm^{-2}]	[erg cm^{-2}]
20190619	27.73	/	5.20E-05	1.23E-02	8.08E-07	1.91E-04	3.27E-04	7.71E-02	3.23E-06	7.63E-04
20190620	24.92	/	4.74E-04	1.08E-01	3.84E-06	8.74E-04	2.86E-03	6.52E-01	1.58E-05	3.59E-03
20190703	4.48	/	2.36E-04	1.18E-02	1.85E-06	9.18E-05	1.08E-03	5.38E-02	1.08E-05	5.39E-04
20191004	31.43	/	1.20E-03	5.49E-01	7.87E-06	3.60E-03	4.53E-03	2.07E+00	3.75E-05	1.72E-02
GRB191011A	31.33	/	1.09E-03	4.98E-01	4.15E-06	1.90E-03	5.46E-03	2.50E+00	4.38E-05	2.00E-02
GRB191017C	36.1	/	1.95E-03	1.57E+00	1.17E-05	9.42E-03	2.05E-02	1.65E+01	9.96E-05	8.01E-02
GRB191101B	47.09	/	1.14E-03	9.13E-01	1.67E-06	1.35E-03	9.42E-03	7.57E+00	7.20E-05	5.79E-02
GRB191115A	29.23	/	1.17E-03	5.16E-01	8.11E-06	3.59E-03	4.81E-03	2.13E+00	2.10E-05	9.29E-03
GRB191122A	25.29	/	3.14E-04	7.16E-02	3.45E-06	7.87E-04	3.25E-03	7.41E-01	2.44E-05	5.55E-03
GRB191125A	33.42	/	7.70E-04	3.52E-01	3.58E-06	1.64E-03	3.89E-03	1.78E+00	1.89E-05	8.65E-03
GRB200903C	34.93	/	5.25E-03	4.22E+00	2.41E-06	1.94E-03	2.89E-02	2.32E+01	5.62E-06	4.52E-03
GRB200906A	39.13	67.3	1.20E-02	1.59E+01	/	/	5.78E-02	7.67E+01	2.15E-05	2.85E-02
20200913	38.93	/	6.27E-03	8.32E+00	4.00E-06	5.31E-03	9.07E-02	1.20E+02	2.00E-05	2.66E-02
20200915	40.9	/	7.35E-03	9.87E+00	/	/	6.34E-02	8.53E+01	2.80E-05	3.77E-02
GRB200916A	35.49	76	1.72E-03	1.38E+00	/	/	4.71E-03	3.78E+00	8.20E-07	6.59E-04
GRB200919A	36.39	/	8.05E-03	6.47E+00	2.54E-06	2.04E-03	3.73E-02	3.00E+01	2.37E-05	1.90E-02
GRB201021A	31.73	/	3.15E-03	1.44E+00	1.41E-06	6.45E-04	1.10E-02	5.03E+00	1.32E-05	6.02E-03
20201030	26.48	/	1.26E-03	2.98E-01	7.70E-07	1.82E-04	2.24E-02	5.28E+00	1.03E-05	2.42E-03
GRB201031B	29.06	/	2.74E-03	1.21E+00	2.56E-06	1.13E-03	1.80E-02	7.97E+00	8.42E-06	3.72E-03
GRB201116A	34.09	/	1.50E-03	6.88E-01	1.59E-06	7.27E-04	1.23E-02	5.65E+00	4.77E-06	2.18E-03
20201119	37.75	/	4.23E-03	3.47E+00	3.03E-06	2.48E-03	2.28E-02	1.87E+01	6.06E-06	4.96E-03
20201123	41.47	/	6.90E-03	9.27E+00	/	/	6.87E-02	9.23E+01	4.05E-05	5.45E-02
GRB201128A	36.47	/	1.05E-02	8.47E+00	3.39E-06	2.73E-03	5.00E-02	4.02E+01	5.93E-06	4.77E-03
20201213	35.91	/	6.50E-03	8.62E+00	8.17E-06	1.08E-02	1.34E-01	1.78E+02	1.36E-05	1.81E-02

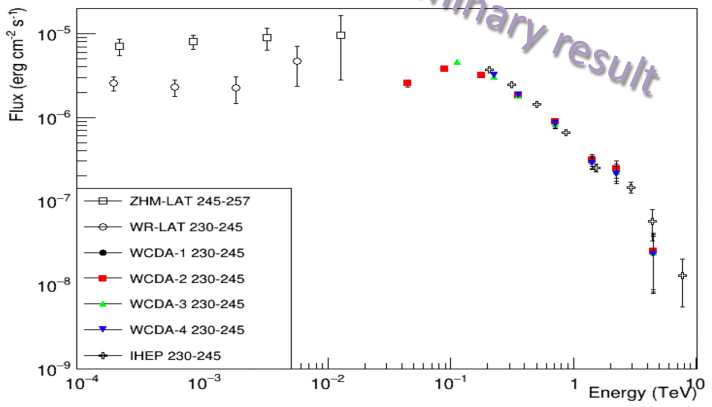


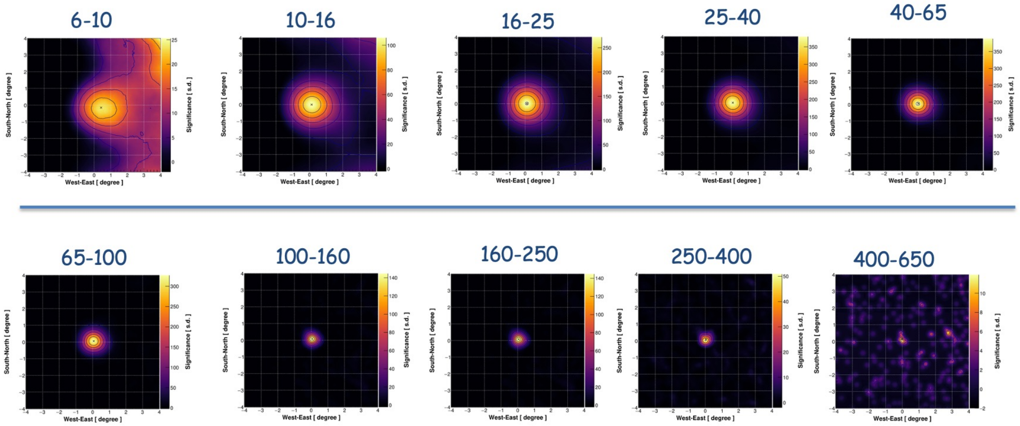


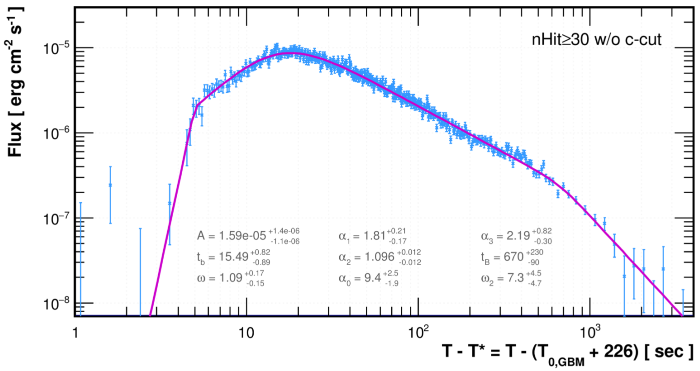
GRB221009A：史上最亮GRB



preliminary result







Big events @ VHE/UHE gamma-ray astronomy

1961

Explorer XI

The first detection of cosmic gamma rays

1983

St. Hopkins

The claim of detecting VHE gamma rays from Cygnus X-3 trigger a surge of interest.

1989

Whipple

The detection of VHE gamma rays from the Crab Nebula is seen as the dawn of VHE gamma ray astronomy.

1992

Whipple

Mrk 421 is the first detected extragalactic source

2004

H.E.S.S.

The resolved image of J1713.7-3946 has been measured

2019

MAGIC

The First GRB 190114C detected by ground-based experiment.

2021

LHAASO

The discovery of 12 Ultra High Energy (UHE) gamma ray sources and open the window for UHE gamma ray astronomy

2022

LHAASO

The detection of Bright Of All Time GRB 221009A and open a 10 TeV photon window

2024

LHAASO

Release 1st LHAASO catalogue, 32 new VHE sources and 43 UHE sources

Summary and outlook

- LHAASO从2021年7月进入全阵列模式，在此后的20年内将采用四种探测技术，全方位、多变量地测量来自于北天区的高能天体的伽马射线和宇宙线；
  - 甚高能区（1 TeV – 30 TeV）灵敏度最优的伽马巡天探测器；
  - 超高能区（30 TeV – 1 PeV）灵敏度最好的伽马天文探测器；
  - 能区跨度范围（10 TeV – 1 EeV）最大的宇宙线探测器。

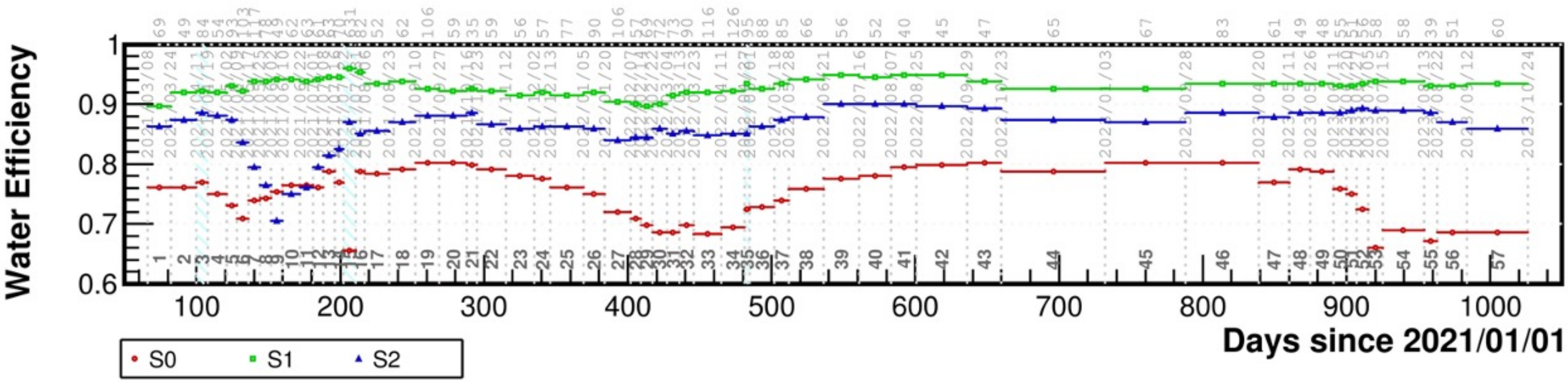
- WCDA 定期释放数据产品，**面向合作组提供三种**数据产品、两类科学数据产品和相应的科学数据分析软件；

- Any suggestions and comments about reconstruction and simulation code and analysis tools are very welcome Email to Min Zha/ Zhiguo Yao/ Shicong Hu
  - zham@ihep.ac.cn/ yaozg@ihep.ac.cn/ hushicong@ihep.ac.cn

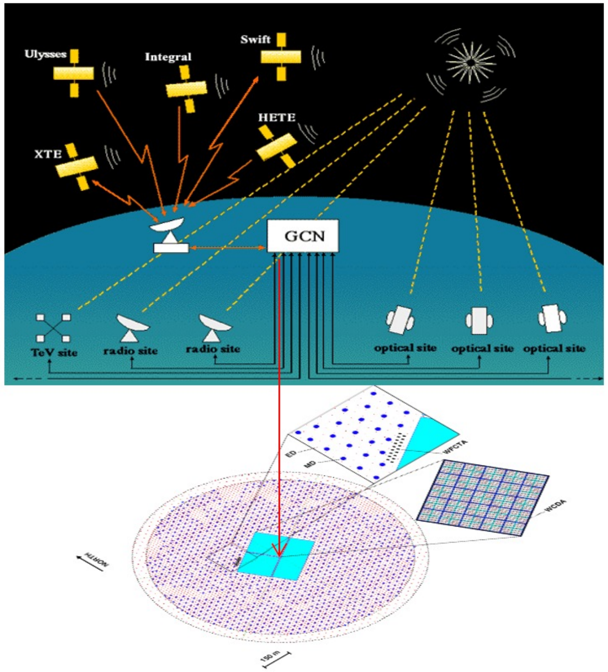
- 在重建和数据分析等方面，中小模型AI，获得比传统方法更优的结果；
- 开展大模型AI的使用，最终在探测器研发、运行控制、标定与数据分析、多波段多信使联合研究等多方面获得重大突破

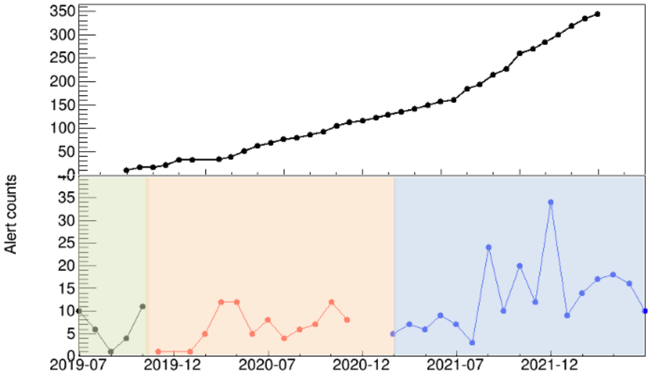
backup

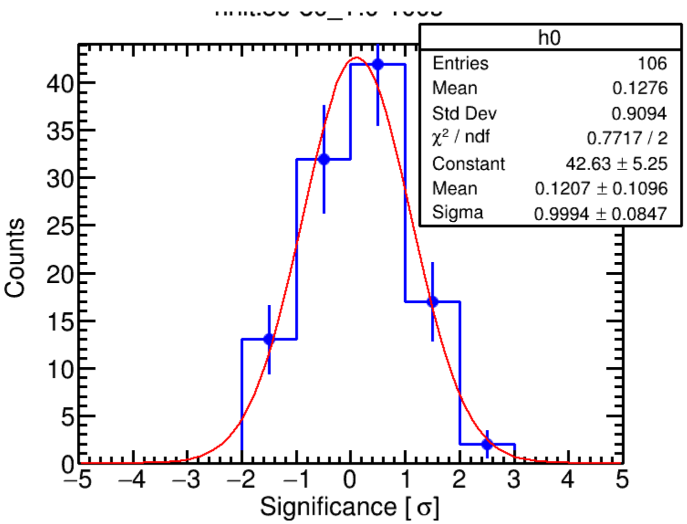
Calibration on Data and Simulation in periods



GRB follow-up by LHAASO-WCDA triggerless data + shower data







- GCN alerts from Fermi-GMB/LAT and Swift experiments
- Data-taken criteria： zenith < 60°
- Triggerless Data：hits information on each PMT are stored between T0-0.5h and T0+2h
- 2019/06-2022/6: ~ 330 follow-ups
- No significant emission is found neither in triggerless date nor triggered data taken from 2021/3 to 2022/6.

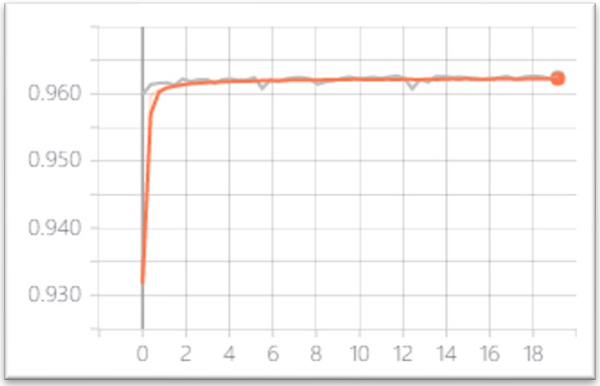
WCDA信号监测--基于CNN的分割方法概述

- CNN是一种数据驱动的算法，数据和计算力是CNN的关键。基于大量数据，CNN利用反向传播算法优化网络中的参数，自动学习到输入数据的特征表达，避免了显示地设计和提取特征的过程。

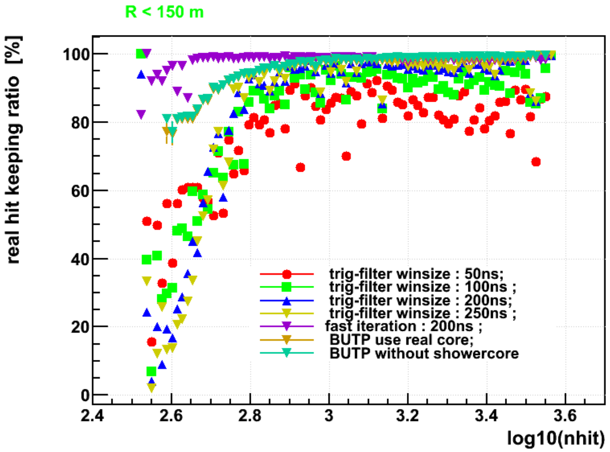
- 15757个事例，随机选取10000个事例进行实验，按照8:1:1的比例分为训练集、验证集和测试集。

- 在(x,y,t)三维坐标系下，借鉴图像实例分割的思路，通过粒子邻域内的空间结构，对粒子类别进行判断。

- 共训练了50轮次，总共19个小时。橙色曲线为训练集Accuracy，灰色曲线为验证集Accuracy，可以发现模型很快收敛。
- 选择在验证集Accuracy最高的模型，对测试集中1000个事例进行测试，总共需要11s左右，平均每秒处理91个事件。

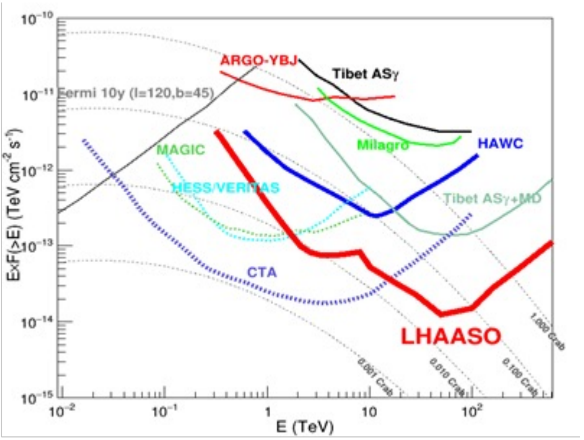


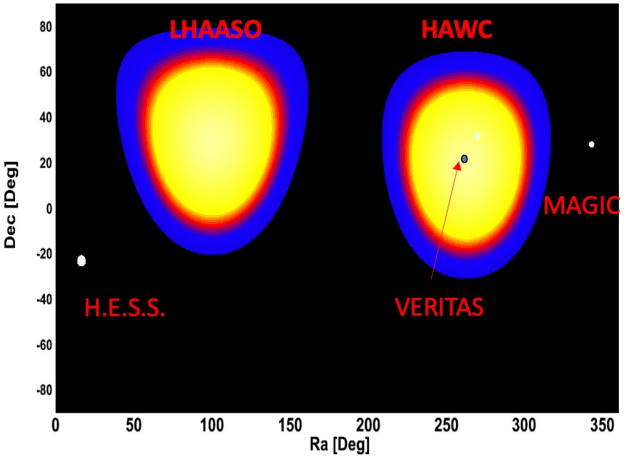
实验机器配置信息	
CPU	Intel(R) Core(TM) i7-4790K CPU @ 4.00GHz
内存	32G
GPU	GeForce GTX TITAN

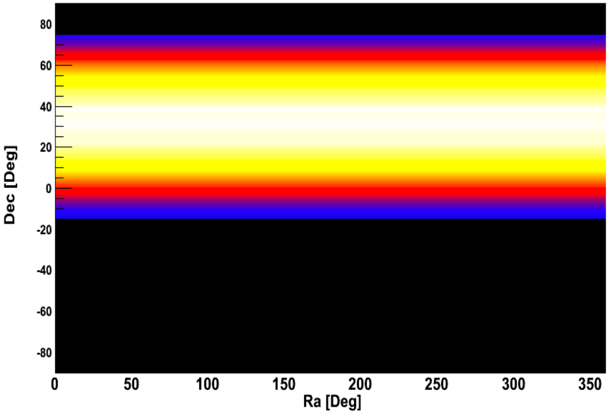


- 测试集所有粒子统计结果
  - Accuracy=96.27%　　Precision=96.94%　　Recall=97.07%

LHAASO advantage







LHAASO is a good facility to do sky survey at VHE + UHE and monitor transient

多源分析 I/O

- **Forward folding**
  - 假设源的能谱形式，卷积探测效率匹配数据得到能谱参数的估计值

$$N_i^{\mathrm{exp}} = \iint I(E)\cos(\theta)\,\eta(\theta, E)\mathrm{S_0 T_0} f(\theta)\mathrm{d}\theta\mathrm{d}E$$

$$\chi^2 = \sum_i \left(\frac{N_i^{\mathrm{obs}} - N_i^{\mathrm{exp}}(\Theta_S)}{\sigma_i^{obs}} \right)^2$$

- **Maximum likelihood**
  - Binned：将事例的某一维或多维信息分成区间，假设每个区间内事例数服从的分布，将多个区间的概率连乘构造似然函数；
  - Unbinned：已知或假设事例的每一维信息的分布函数形式或关联密切的多维信息的联合分布函数形式；

- 对于WCDA，这里的多位信息就是事例的空间位置和N_{hit}

任一空间格子中的事例数服从泊松分布

$$P\left(N_{i,j}^{\mathrm{on}} \middle| \lambda_{i,j}\right) = \frac{{\lambda_{i,j}}^{N_{i,j}^{\mathrm{on}}} e^{-\lambda_{i,j}}}{N_{i,j}^{\mathrm{on}}!} \qquad \lambda_{i,j} = N_{i,j}^{\mathrm{bk}} + \sum_{k=1}^{N_{\mathrm{src}}} N_{k,i,j}^{\mathrm{s}}$$

假设源本身的信号空间分布为$f_k(x, y|\Theta_k^{\mathrm{M}})$，卷积PSF后

$$f_{k.i}^{\mathrm{D}}\left(x, y \middle| \Theta_k^{\mathrm{M}}\right) = f_k(x, y|\Theta_k^{\mathrm{M}}) * PSF_i$$

$$N_{k,i,j}^{\mathrm{s}} = N_{k,i}^{\mathrm{exp}}(\Theta_S) \times f_{k.i}^{\mathrm{D}}\left(x, y \middle| \Theta_k^{\mathrm{M}}\right)$$

从而将所有格子的概率连乘构造似然函数

$$\boxed{\ln L(\Theta|N_{\mathrm{on}}) = \sum_i^{N_{\mathrm{bins}}} \sum_j^{\mathrm{ROI}} \left(N_{i,j}^{\mathrm{on}} \ln\lambda_{i,j} - \lambda_{i,j} - \ln N_{i,j}^{\mathrm{on}}!\right)}$$

基于上述推导，单个源的模型相对于背景涨落的显著性可由无源模型下$\ln L_0$的和单源模型的$\ln L_1$计算得到

$$\boxed{TS = -2(\ln L_0 - \ln L_1)}$$

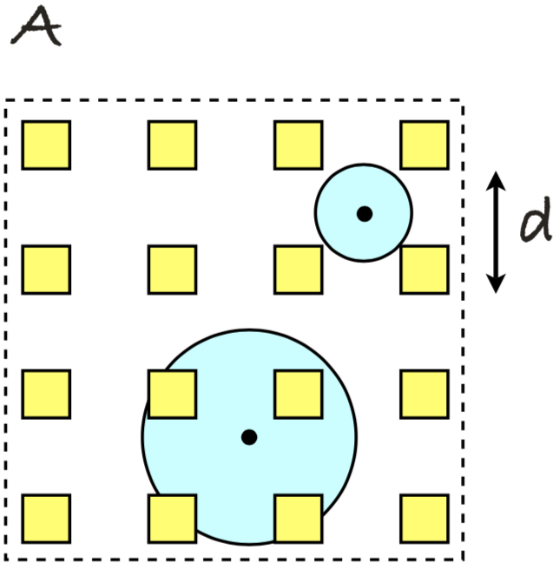
N_{evts} = flux x area x time

> 100
for <10% stat. error

low, given
by nature

≈ 1 m²
for space exp.

≈ 3 yrs
for a PhD



A: area of the array
determines the rate of high energy events recorded

d: grid distance
determines the low energy threshold

Cd: cost per detector
determines quality, size, efficiency, resolution, i.e. details of measurement

For best physics: A: large, d:small, Cd: high. But cost rises with AC_d/d^2

Always compromise needed