Cosmic-ray MC simulation studies in IACT field

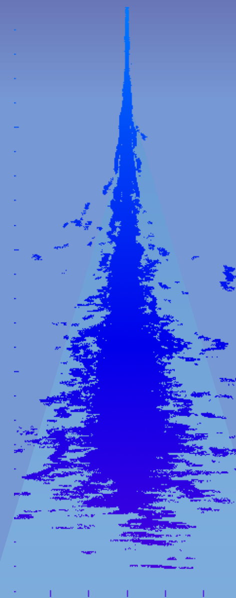
Michiko Ohishi (ICRR)

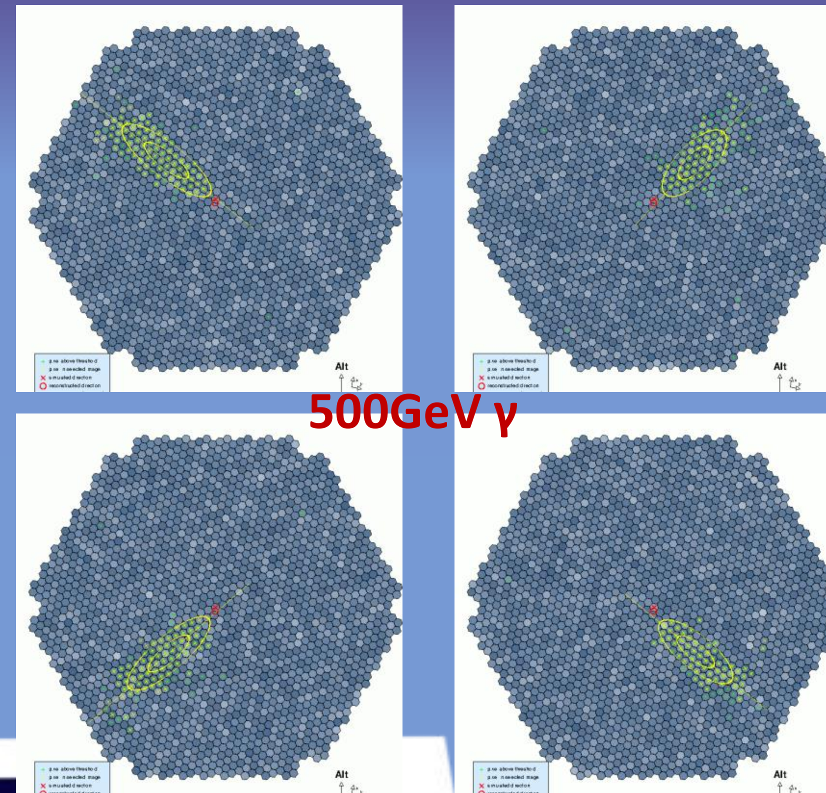
Outline

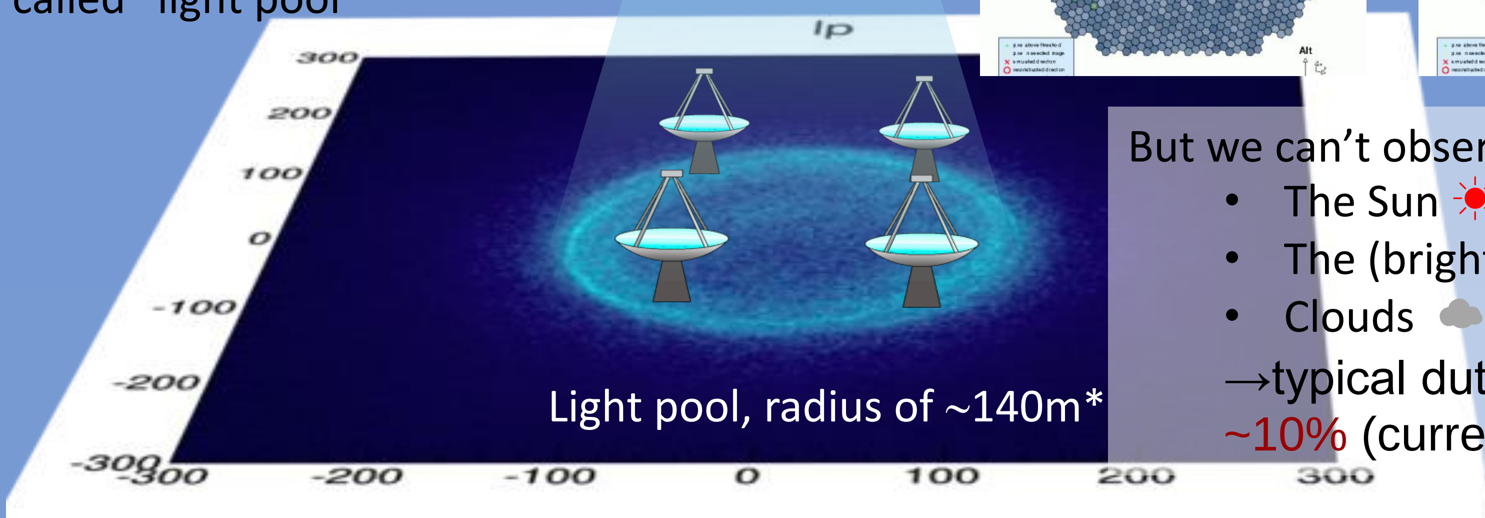
- ●Gamma-ray (+CR) detection principle of IACT(Imaging Atmospheric Cherenkov Telescope)
- ●Current IACT systems and CTA
- ●Simulation studies related to CTA, which I involved
  - Definition of the "gamma-ray sensitivity" (in CTA)
  - ➢ Effect of uncertainty of hadronic interaction models on the estimated CTA sensitivity (proton)
  - ➢Cosmic-ray heavy nuclei composition (Fe, Si....)

Gamma-ray (+CR) Detection principle of IACT

- Detect Cherenkov photons (in visible light wavelength) emitted by charged particles in the air showers by a large telescope
- Lower energy threshold than air shower array (if the observation altitude is same)
- If the primary is gamma (or electron), Cherenkov photons make a symmetric pattern called "light pool"







Light pool, radius of ~140m*

But we can't observe under
- The Sun ☀
- The (bright) moon ☽
- Clouds

→typical duty cycle of ~10% (current systems)

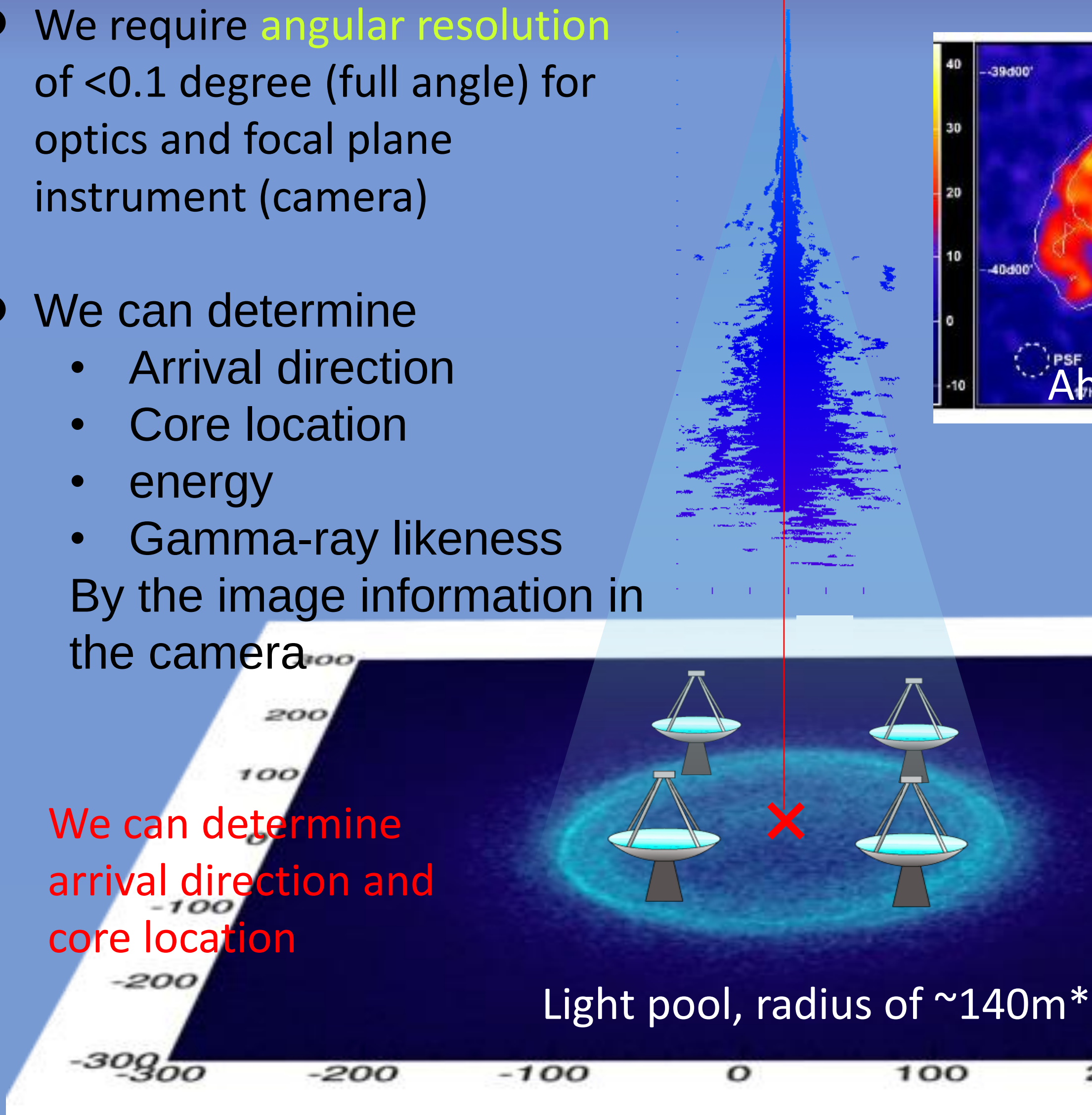
*depends on the observation altitude

Imaging: arrival direction reconstruction

- We require angular resolution of <0.1 degree (full angle) for optics and focal plane instrument (camera)

- We can determine
  - Arrival direction
  - Core location
  - energy
  - Gamma-ray likeness

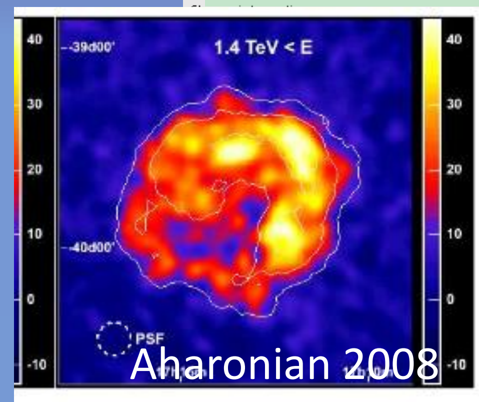
  By the image information in the camera



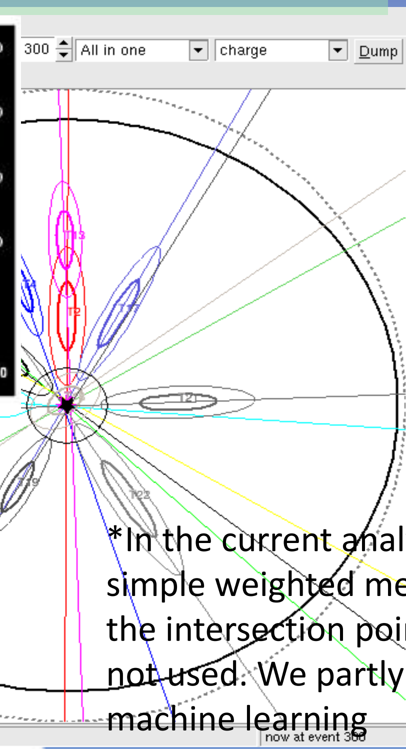
We can determine arrival direction and core location

Light pool, radius of ~140m*

Arrival direction reconstruction in the focal plane



Aharonian 2008



*In the current analysi simple weighted mean the intersection point i not used. We partlyuse machine learning regression analysis.

To achieve <0.1 deg resolution for we need a fine optics → FOV is small (typically ~10^{-3} str)

*depends on the observation altitude

Imaging：Energy reconstruction

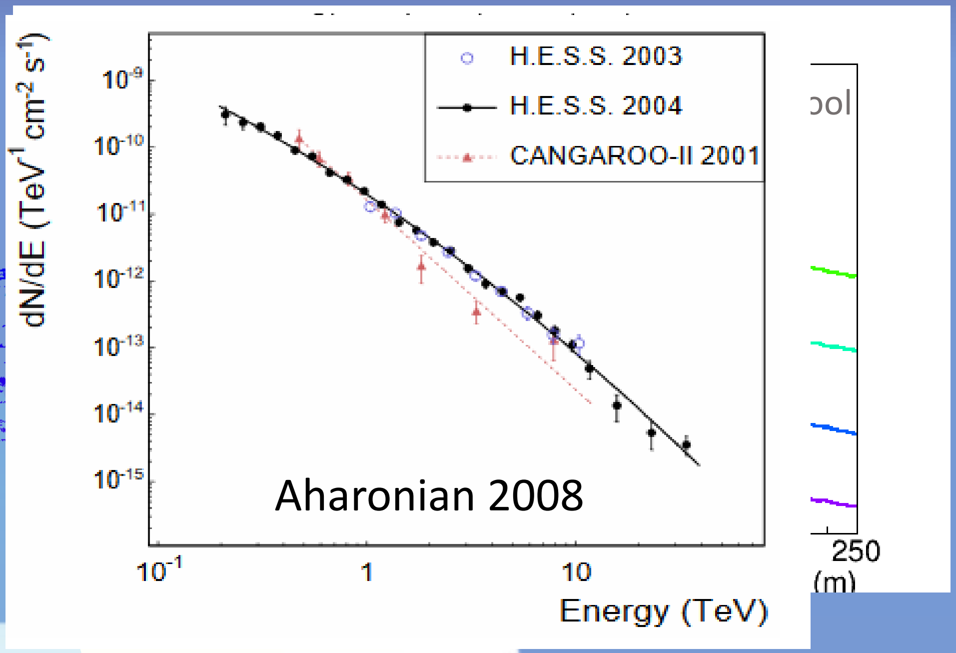
- Core location reconstruction

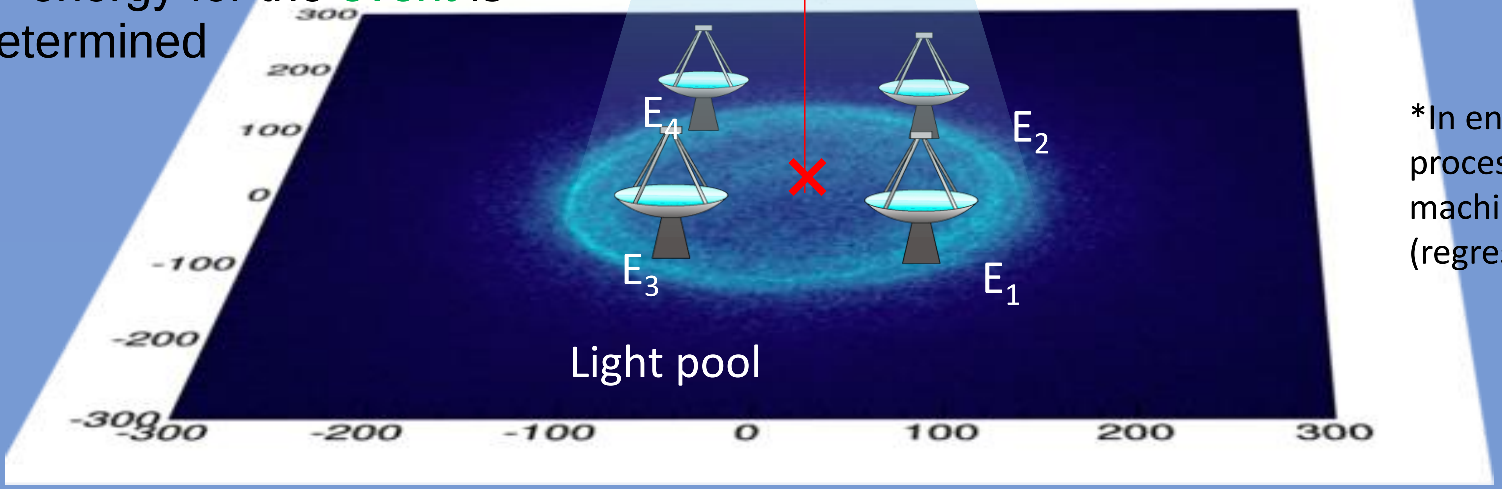
  → Impact parameter of each telescope is known

- Look-up-table (LUT) is prepared from MC gamma-ray events; we can extract “expected” p.e. counts from this LUT for a reconstructed impact parameter and Size (sum of p.e.s of the image)

- Take an average over telescopes

→ energy for the event is determined





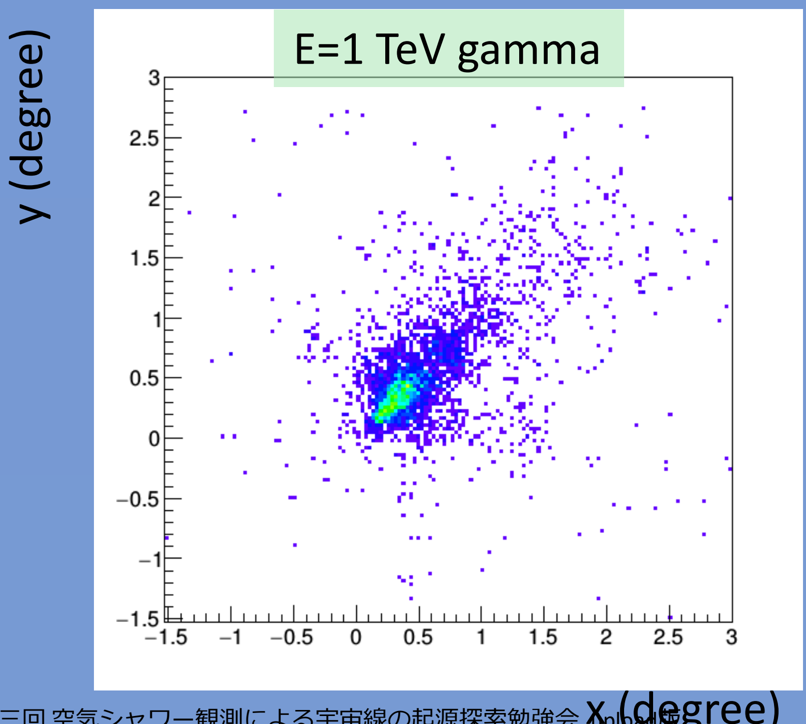
*In energy determination process we partly use machine learning (regression)

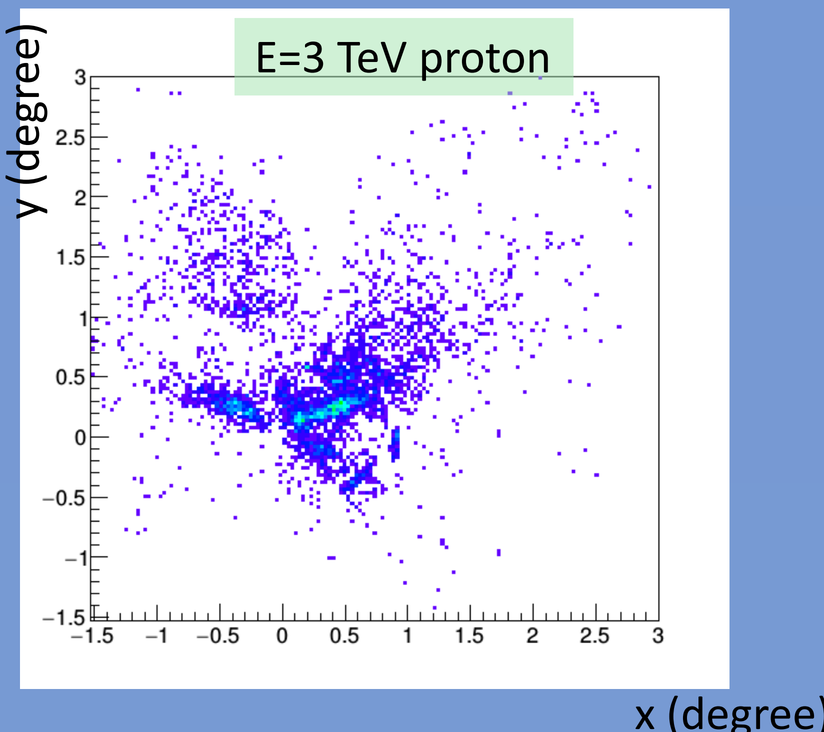
Imaging :Particle identification

- CR nuclei (background) are also easily detected and much more in number than gamma-rays (signal)

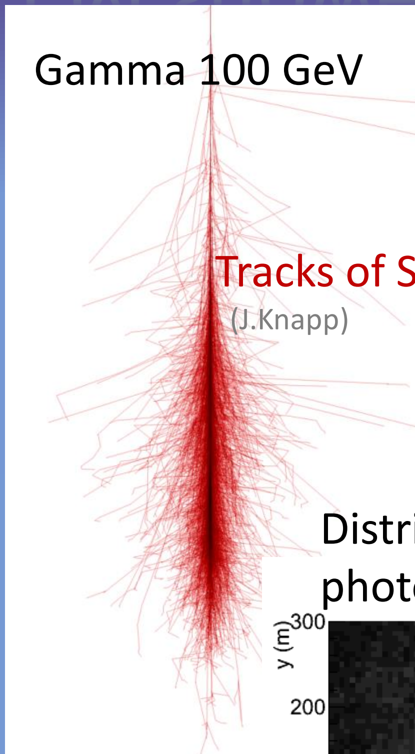
→High background reduction ability is essential for the usage of gamma-ray detector

- Indirect detection on the ground→we don't know charge of the primary
- Only shower image information is used to separate γ from hadrons

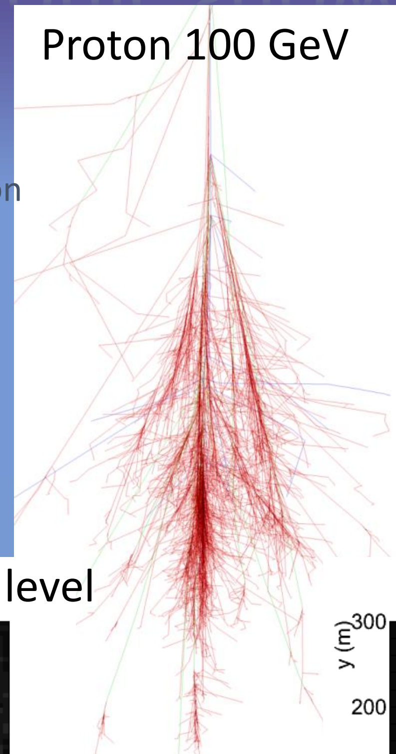




EM showers and hadronic showers



CORSIKA simulation

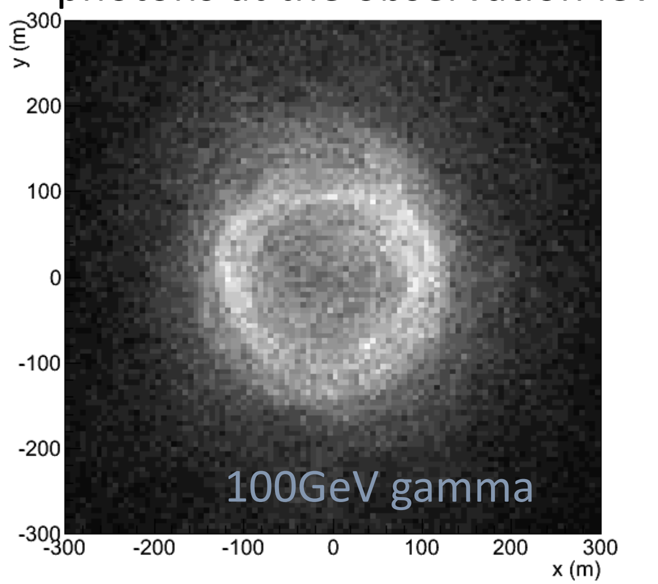


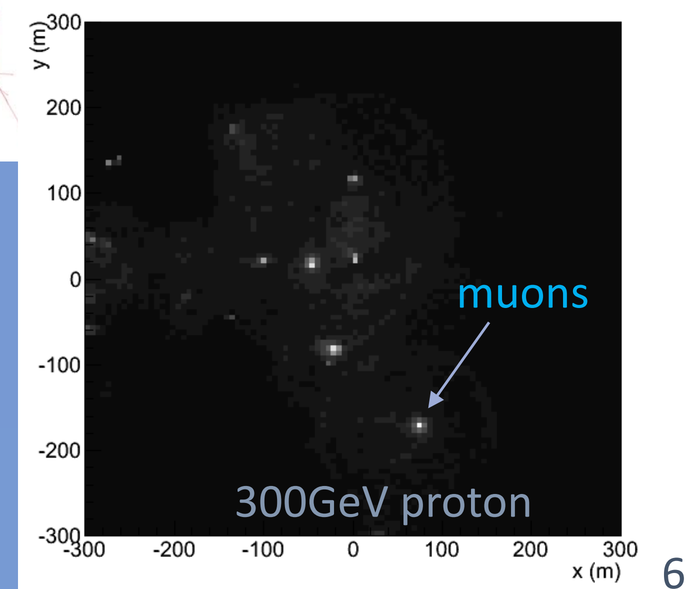
Tracks of Secondary particles

(J.Knapp)

Characteristics of the shower is different from EM shower (mostly in transverse direction)
→will lead to the difference in Cherenkov photon pattern

Distribution of Cherenkov photons at the observation level

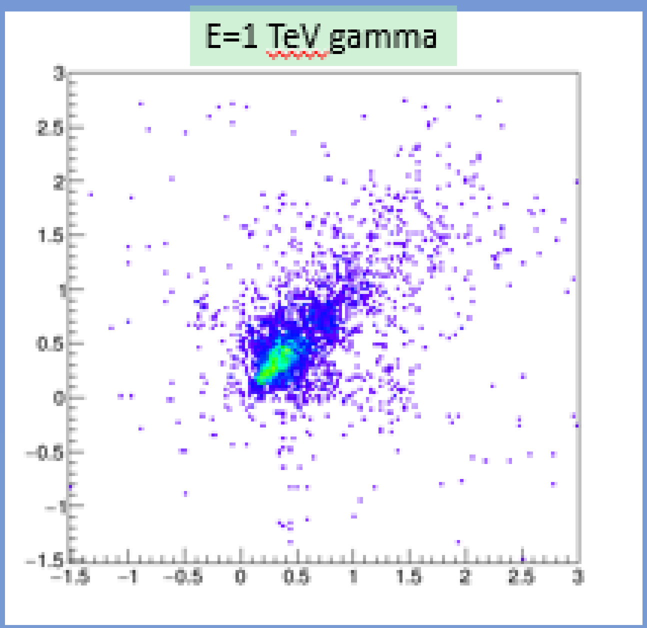


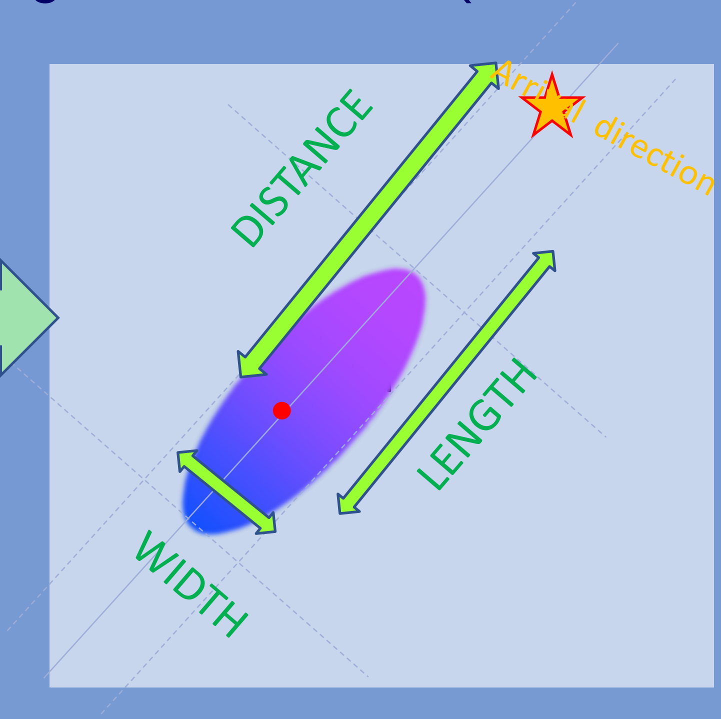


Imaging：Extracting shower characteristics

- Extracting shower characteritics＝Hillas Parameters are well known
- Most powerful parameter: WIDTH (transverse size of the shower)
- Recently we use many other new parameters in addition to Hillas and put them in to machine learning MultiVariate Analysis (MVA, Boosted Decision Tree, RandomForest etc.)

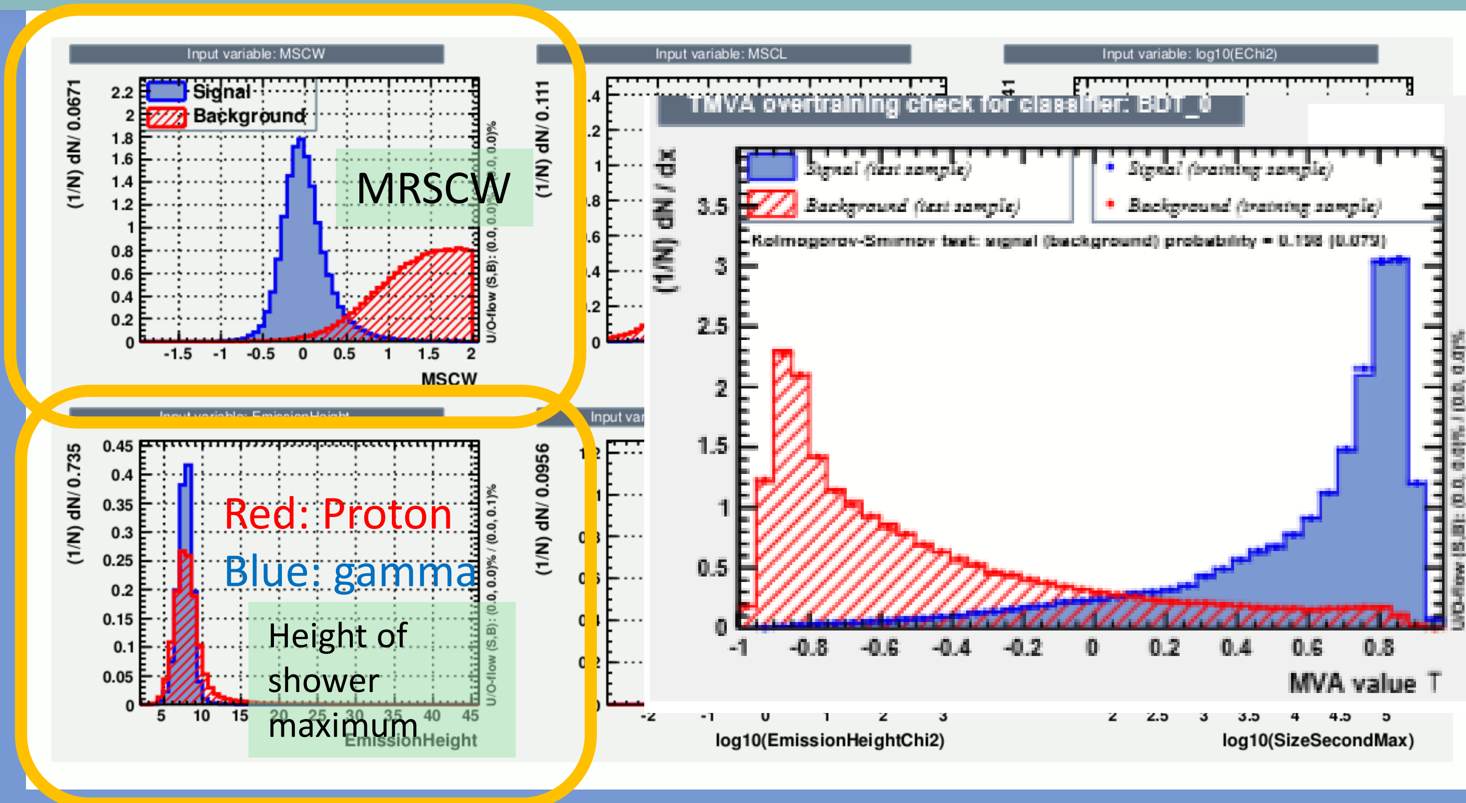
→ Introduce a single index as "gamma-likeness (or hadroness)





Imaging：γ-hadron separation, MVA

Parameters used in gamma-hadron separation MVA currently in CTA (not all)



Maier, 2017

- Separation efficiency depends on energy（Upper figure corresponds to ~10 TeV）
- Harder to distinguish in low energy

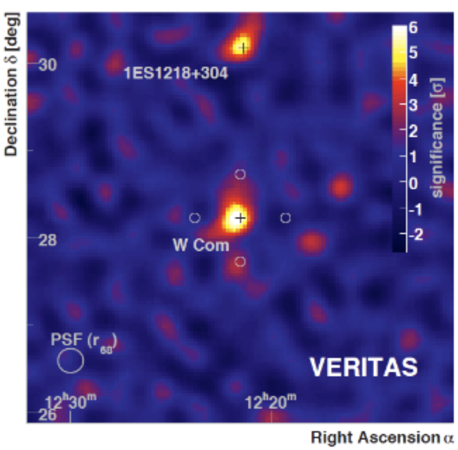
"Beam test" is not available for us, air shower experiments
→ We are paying much effort to tune parameters in the simulation so that it is close to the reality

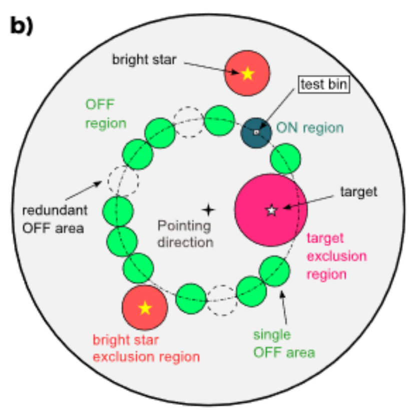
Residual background level estimation

- We cannot remove background protons perfectly
- So we estimate background level from “OFF-source data”, using regions where no known gamma-ray source exist
- Subtract this background level

Gamma-ray Measurements & Hadronic Interaction Models

OFF-source subtraction





In General: only primary gamma rays are simulated.
Hadronic Interactions not relevant!

Maier, ISVHECRI2018

DESY. | IACTs & Hadronic Interaction Models | Gernot Maier   18

How do you subtract background for
- **Isotropic gamma-ray emission…?**
- **CR electron…?**

We can’t subtract BG. So we have trust background MC simulation for that case.

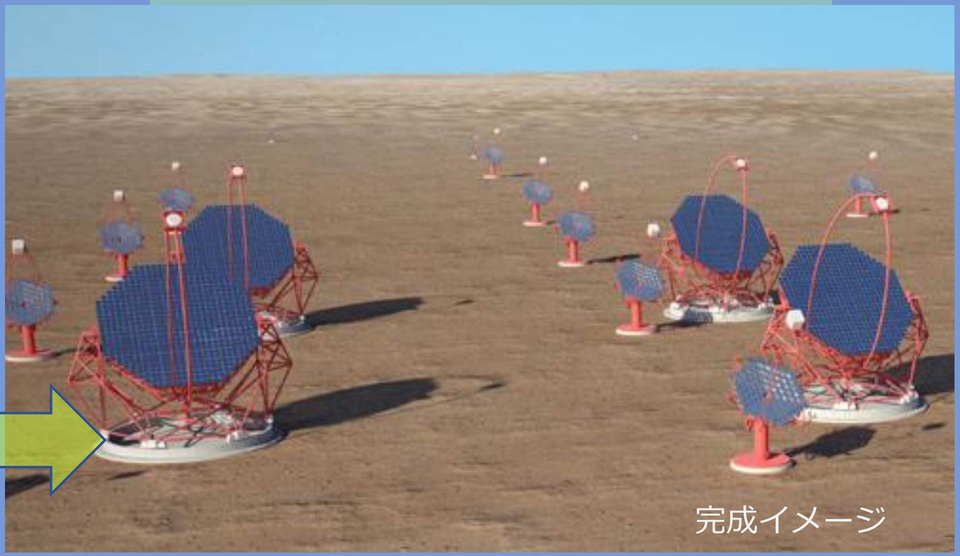
Current IACT systems and CTA

Current systems

"10m-class reflector,stereo" generation

Covers roughly 100 GeV – 20 TeV

Next generation project (construction) CTA



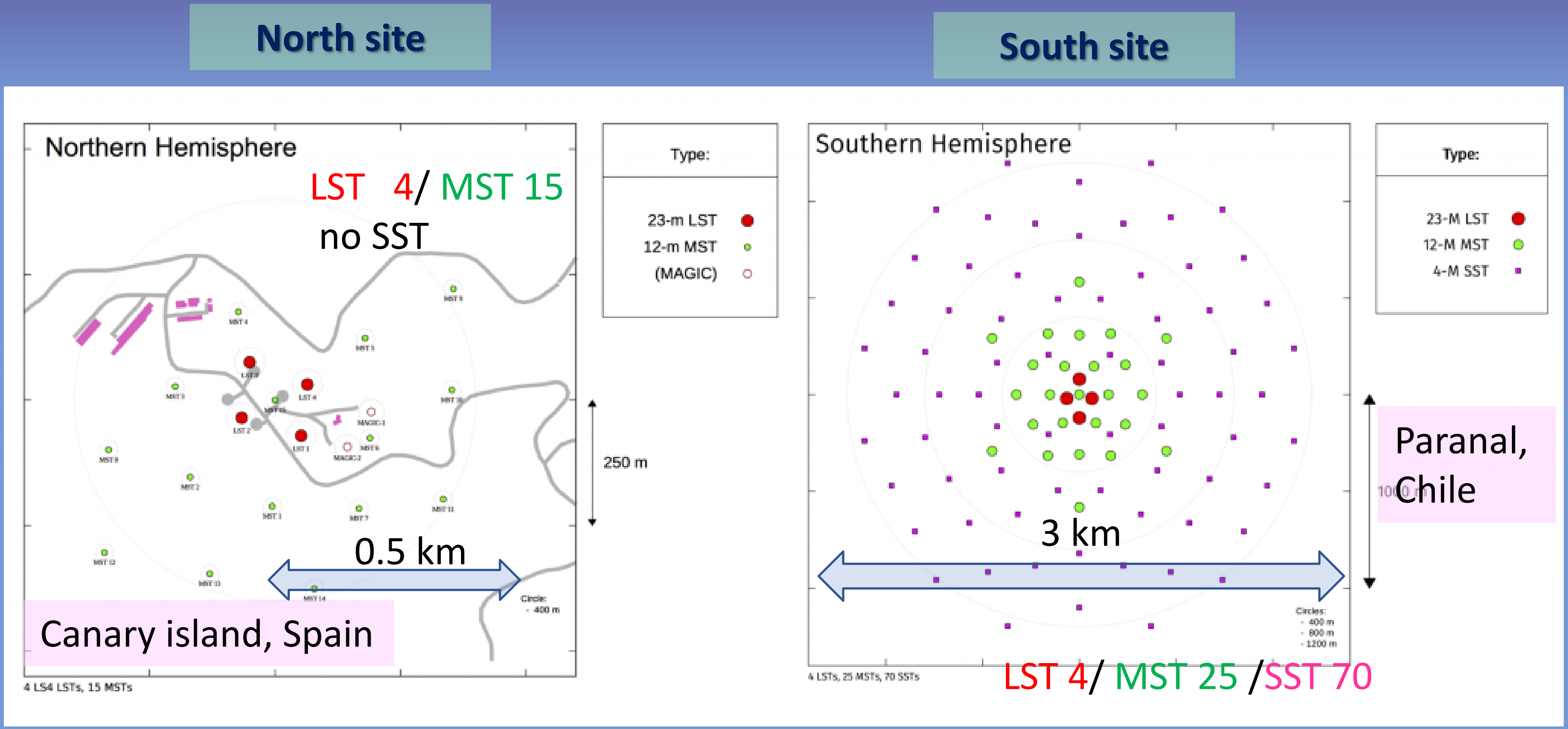
- 99 telescopes, 3 types
- Cover wider energy range

  20 GeV -300 TeV

>1,400 members

Gigantic collaboration…

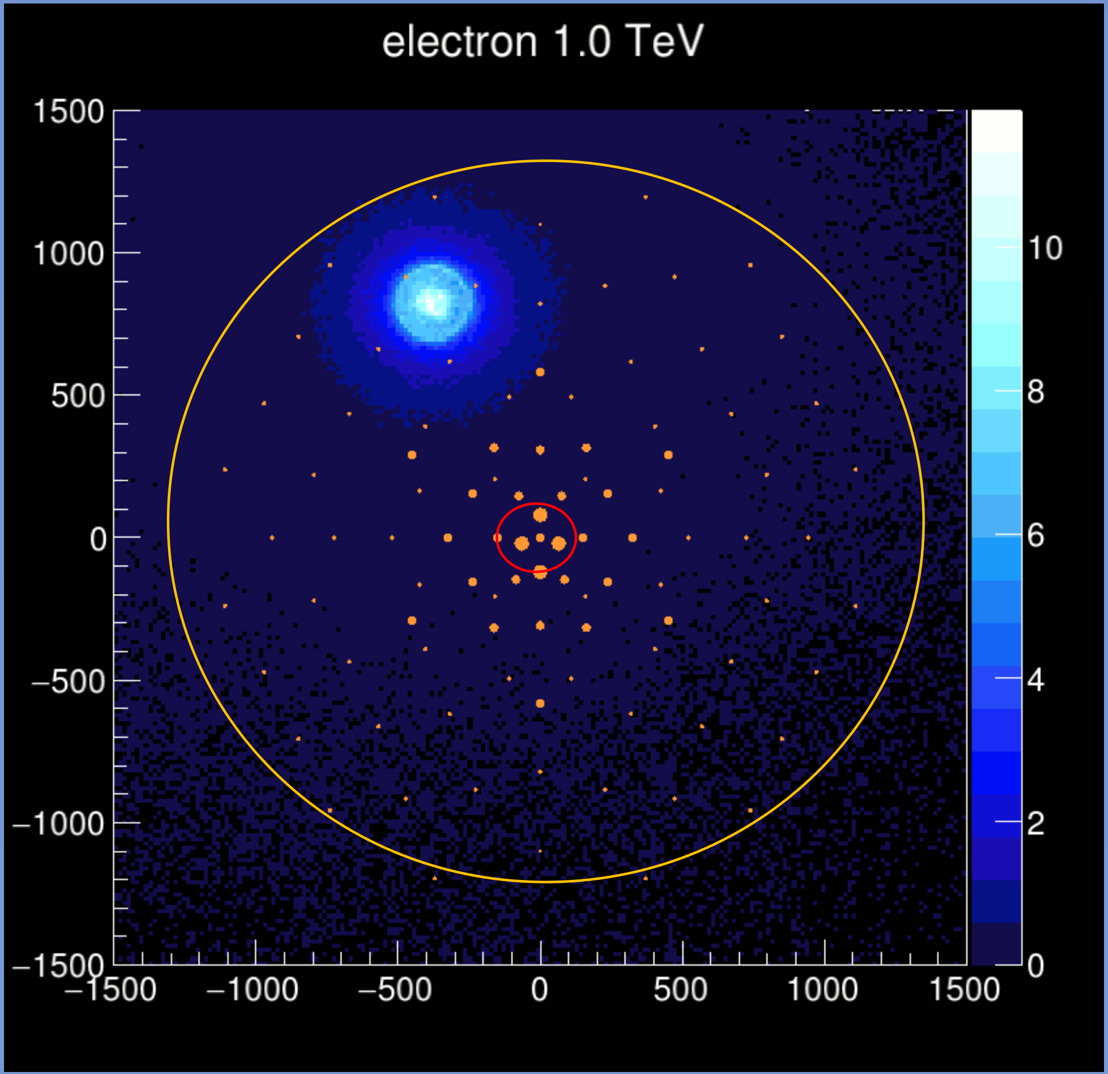
CTA planned array configuration (baseline)



- We also defines a smaller array as "Implementation threshold"
- North site→ Extragalactic sources are main targets
  → focusing on low energy threshold → no small-sized telescopes
- South site → Galactic sources are main targets
  → >10 TeV high energy region is also important → large array with SSTs

Array size and light pool scale

~ km-scale large array

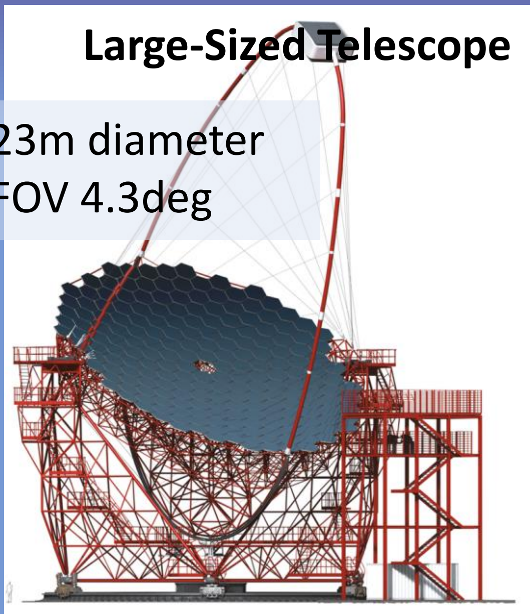


→ increasing effective area of the gamma-ray and improving identification of the particle type

- Current systems
  - Light-pool size > array size
  - Large zenith angle observation increase the effective area
- CTA
  - Light-pool size << array size
  - Large zenith angle observation is not so effective

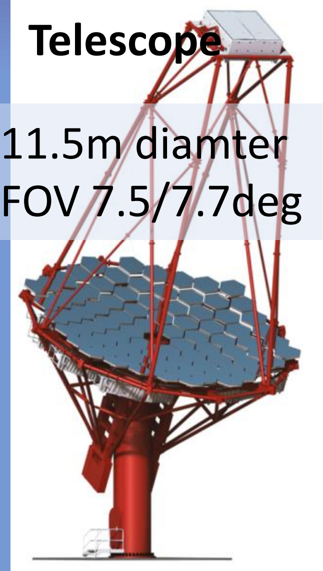
CTA ： telescopes

Large-Sized Telescope



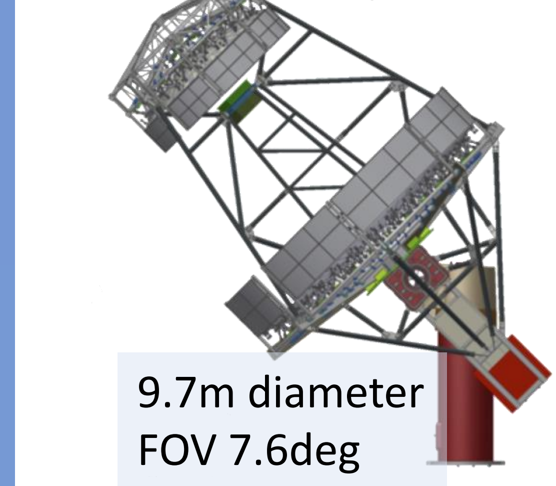
23m diameter
FOV 4.3deg

Medium-Sized Telescope



11.5m diamter
FOV 7.5/7.7deg

Medium-Sized Telescope (SCT)



9.7m diameter
FOV 7.6deg

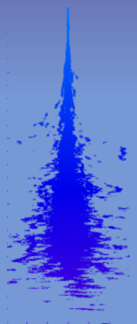
Small-Sized Telescope

第三回 空気シャワー観測による宇宙線の起源探索勉強会, upload版

Diameter 4.0 m /4.3 m /4.0 m
FOV 8.3 deg / 10.5 deg / 8.8 deg

Detailed specification：
https://www.cta-observatory.org/project/technology/

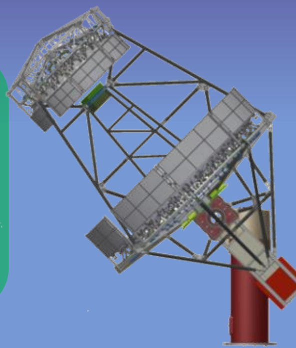
Simulation codes used in IACT experiments



Air shower description
Cherenkov photon
generation
(CORSIKA)

➕

Detector response
（optics・photon
detector・electronics）



●Air shower description + Cherenkov photon generation

→ **CORSIKA** (H.E.S.S., MAGIC, VERITAS,+CTA)

interaction models used (currently in CTA) in CORISKA6.990

Electromagnetic : **EGS4**

Hadronic : **QGSJET-II-03 (high energy model)**
UrQMD（low energy model）

Switches at 80 GeV/nucleon

●Detector response

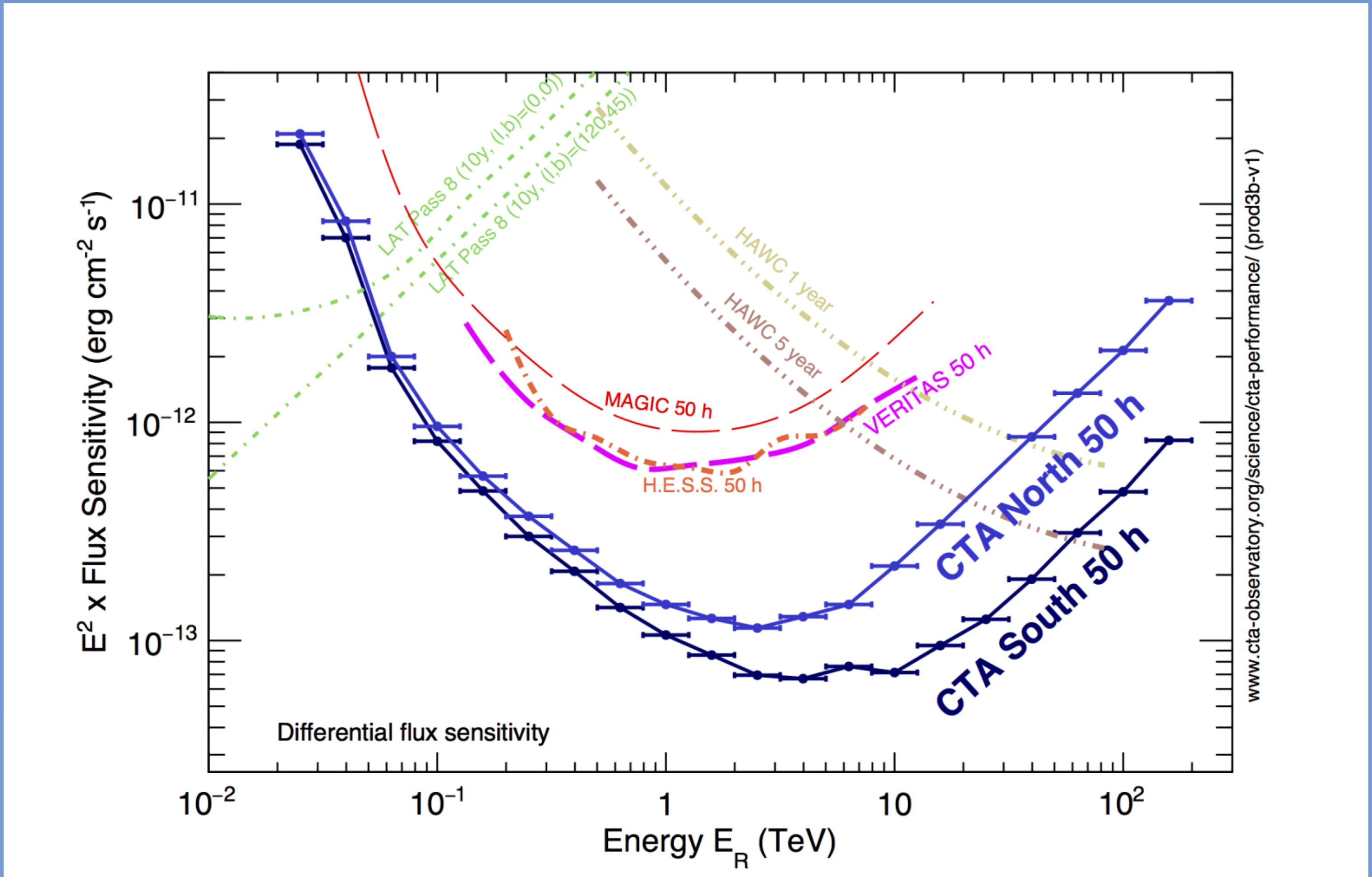
→ original codes called sim_telarray (inherited from the one use in H.E.S.S.)

- MC data mass production for sensitivity curve is (basically) done on EU-GRID
- Computing resources in 20 institutes over 7 countries (as of 2018)
- ~ 2 PB MC data were produced in the last 1.5 year
- Most computing resource is consumed in Cherenkov photon generation

CTA full-array public sensitivity curve

- https://www.cta-observatory.org/science/cta-performance

  we provide data files in FITS,ROOT, TXT too.



3 conditions to determine sensitivity curve (CTA case)

- Signal event statistics (N_γ>10)

Acceptance in the analysis

$$N_\gamma = F_\gamma A_{0\gamma}\epsilon_\gamma t \quad > 10 \quad \Rightarrow \quad F_\gamma = \frac{1}{A_{0\gamma}}\frac{1}{\epsilon_\gamma} N_\gamma t^{-1}$$

User definition

- Significance of signal to background (5σ)

parameter

$$N_\sigma = \frac{1}{\sqrt{1+\alpha}}\frac{N_\gamma}{\sqrt{N_B}} = \frac{1}{\sqrt{1+\alpha}}\frac{F_\gamma A_{0\gamma}\epsilon_\gamma t}{\sqrt{F_B A_{0B}\epsilon_B \Omega t}} > 5$$

- This is approximated formula
- Li&Ma (1983) Eq.(17) is the standard

Literature value

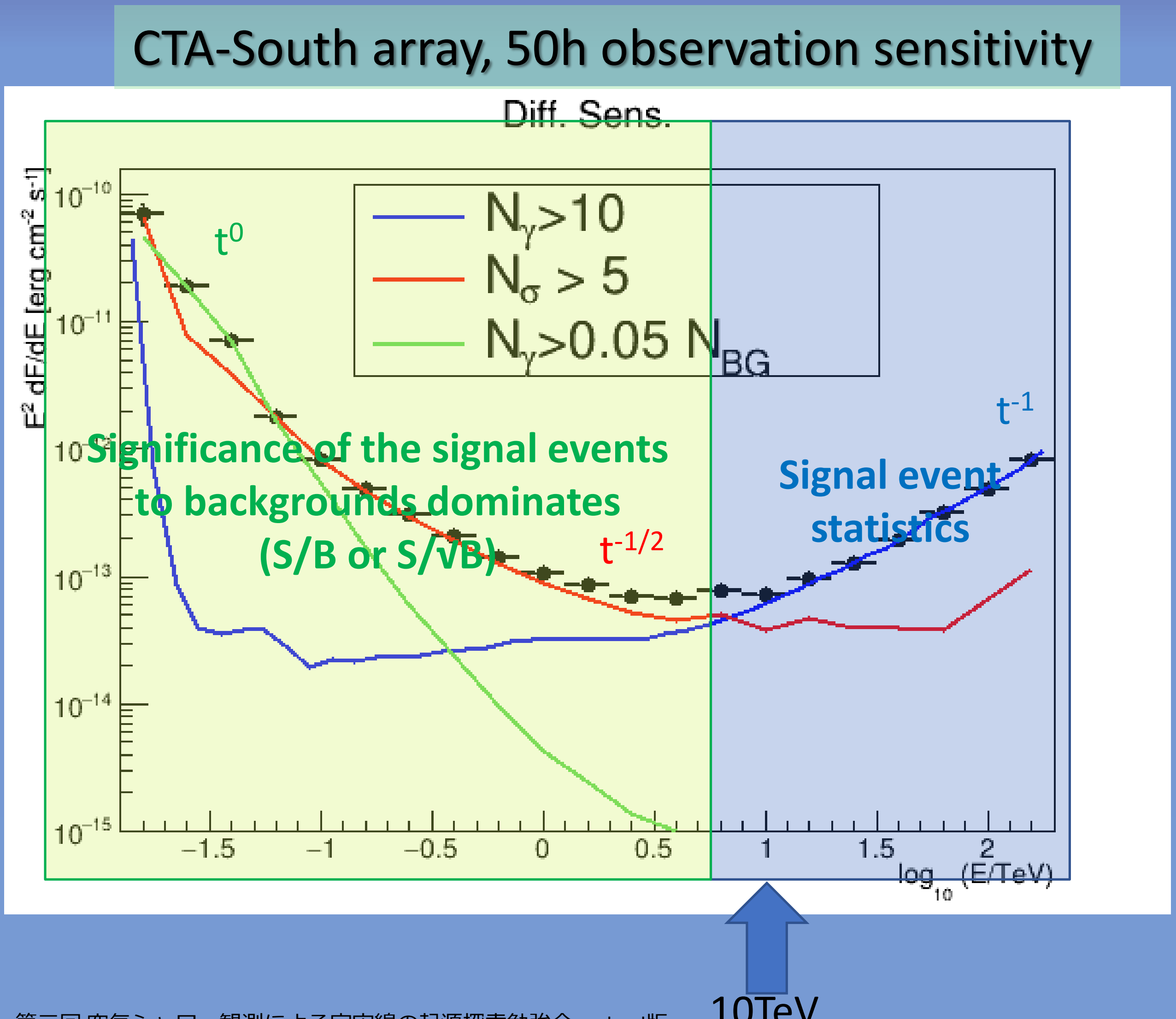
$$\Rightarrow \quad F_\gamma = \sqrt{F_B}\frac{\sqrt{A_{0B}\Omega}}{A_{0\gamma}}\frac{\sqrt{\epsilon_B}}{\epsilon_\gamma}\sqrt{1+\alpha} N_\sigma t^{-1/2}$$

- ✓ Dependence on the observation time is different
- ✓ Strongly depends on the efficiency in the analysis which reject backgrounds

- Signal ratio to background(>5%)

$$R_{\gamma B} = \frac{N_\gamma}{N_B} = \frac{F_\gamma A_{0\gamma}\epsilon_\gamma}{F_B A_{0B}\epsilon_B \Omega} \quad > 0.05 \quad \Rightarrow \quad F_\gamma = F_B \frac{A_{0B}\Omega}{A_{0\gamma}}\frac{\epsilon_B}{\epsilon_\gamma} R_{\gamma B}$$

Sensitivity curve and 3 conditions(2)



- E>10 TeV
  Signal event statistics dominates
  → We need to enlarge effective area(or exposure) to increase sensitivity

- E< 10 TeV
  Signal to noise ratio condition dominates
  → High resolution camera and relatively dense array helps to improve sensitivity

Proton simulation in IACT field…..

If you have real telescopes….

We have real telescopes and real background data. Why do we need to rely on hadron simulations? Real data is enough!

IACT people basically don't simulate protons (except for special studies)

"Image for illustration purposes only"

….we need proton simulations until we will get new telescopes….

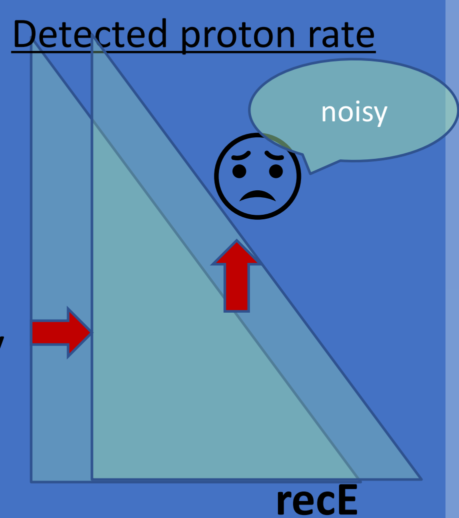
We only simulate protons and electrons for background

How the uncertainty of hadronic interaction model affects the "sensitivity"

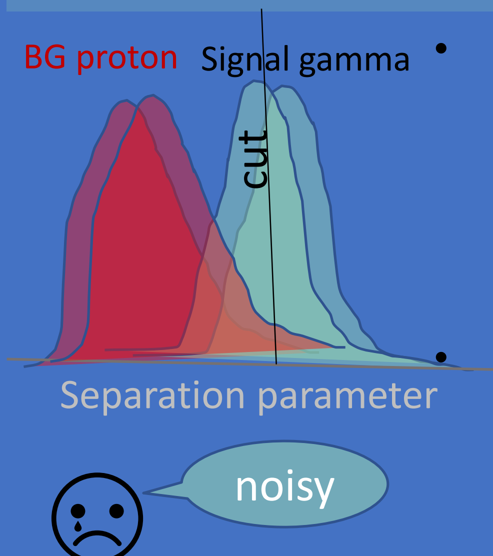
- As for proton background, there are several interaction models
- We apply a tight cut to select gamma-ray(-like) events in the sensitivity curve derivation.
- "Gamma-ray likeness" almost means "EM-shower likeness". We can't distinguish electrons from gamma-rays.
- In the sensitivity derivation, difference of "gamma-ray likeness" works in 2-stages:

Difference in reconstructed energy

- EM like showers consume more energy in e- (major emitter of Cherenkov)
- More Cherenkov yield→ higher recE



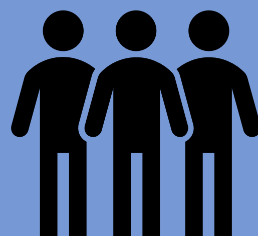
Difference in γ-hadron separation efficiency



- Models which generate more EM-like showers show bad separation from gamma-rays
- After optimized cut, residual proton number increases

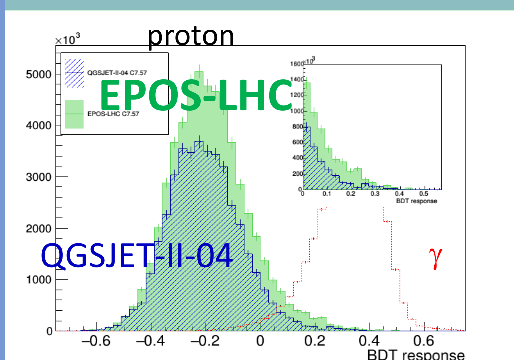
Study about hadronic interactions in TeV range…

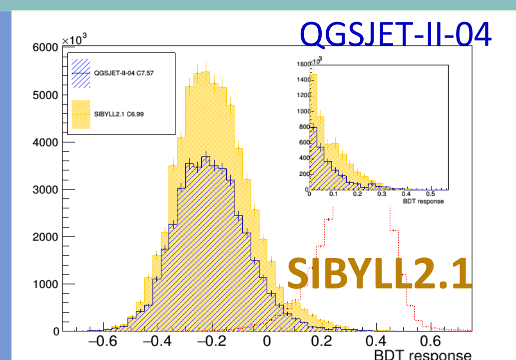
- Very good summary at ISVHECIR
  https://indico.cern.ch/event/639198/contributions/2965268/attachments/1655072/2649093/DESY-20180525-ISVHECRI.pdf

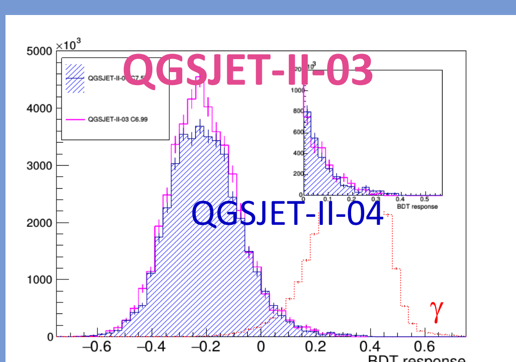


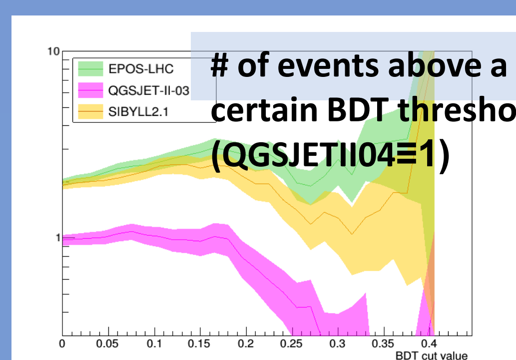
We are VHE people, uncertainty in hadronic interaction is a matter of UHE. Maybe we don't need to take it too seriously……

CTA full array image analysis, E>1 TeV focused MC data









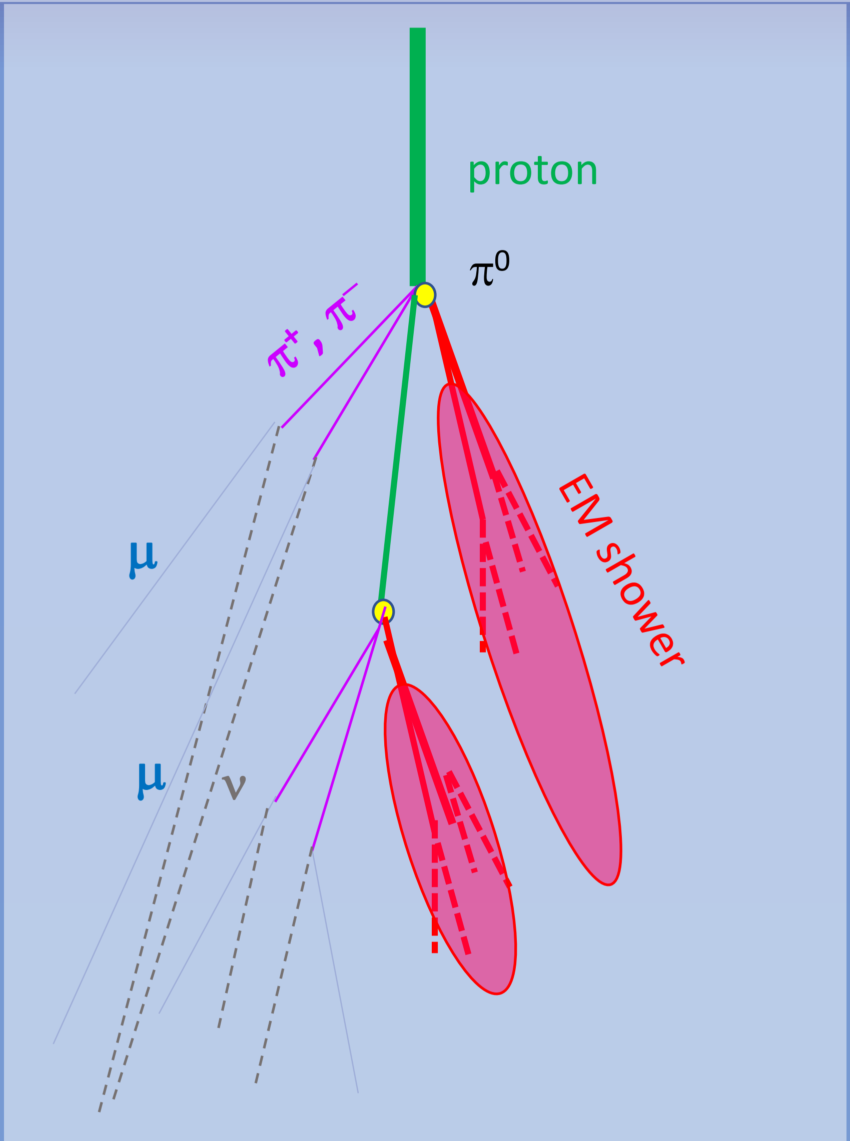
..but

- CTA has a better separation ability of γ-hadron than current systems
- Difference in models may be seen more clearly
- Actually there seems to be factor2 difference in # of gamma-ray like proton events between recent models…

Nature of "gamma-ray" like showers

- How the primary energy was consumed
  ← **If consumption in electromagnetic components is large, it looks like a gamma-ray**
- Major supplier of EM components ←π^0 (→2γ, life=8.5×10^{-17} sec)
- Events which emit high energy π^0 in early stage of shower evolution →looks gamma-ray like
  Maier+(2007), Sitarek+(2017)
- But pi0 spectra in simulation differs model to model…

Schematic diagram of a proton induced shower



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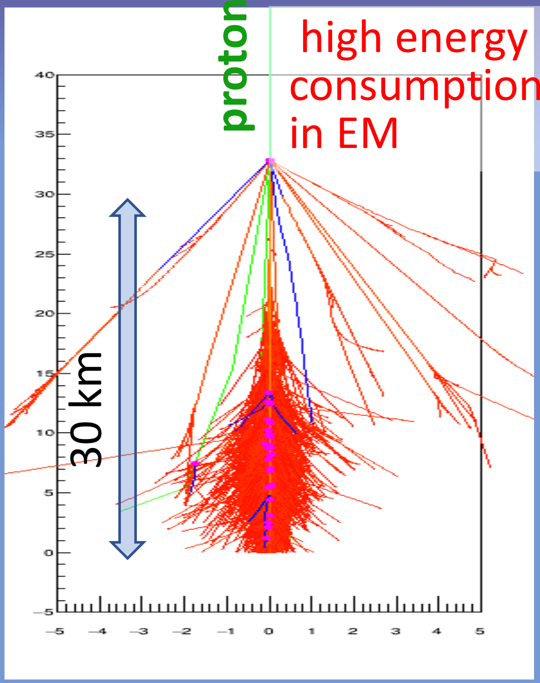
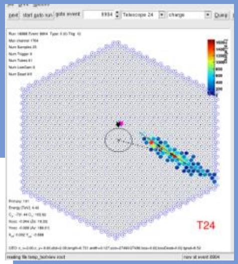


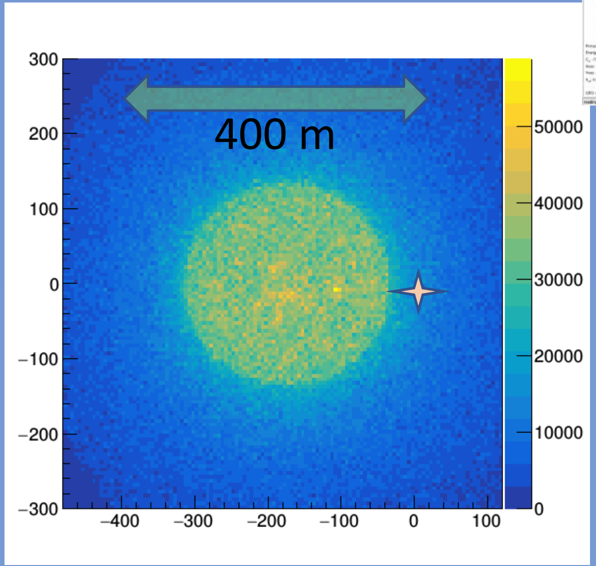
E_p=4.42 TeV

Red: EM

Blue: μ

Green: hadron





Cherenkov Light pool for this event

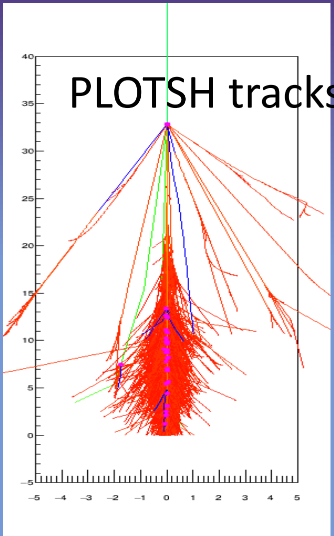
Particle track info in CORSIKA simulation

- PLOTSH options was used to extract particle track information
- Used high-energy interaction models

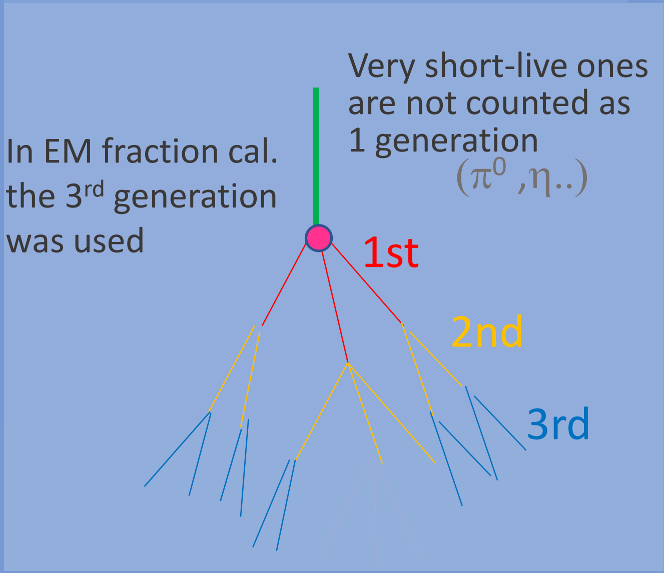
  QGSJET-II-04, EPOS-LHC v3.4, SIBYLL2.3 (COR 7.64*1)

  QGSJET-II-03, SIBYLL2.1 (COR 6.99)
- Low energy model is fixed as UrQMD
- CERENKOV options was turned off (just to reduce output file size)
- Injection particle: proton, mono energy : 10, 3.16, 1, 0.316, … (TeV)
- Target is fixed as Nitrogen nucleus (A=14)
- ECUT for EM particles were set to 0.1% of primary (to suppress output file size)
- Other CORSIKA parameters are basically inherited from corsika_simtelarray baseline simulation

Non-Cherenkov simulation in TeV range



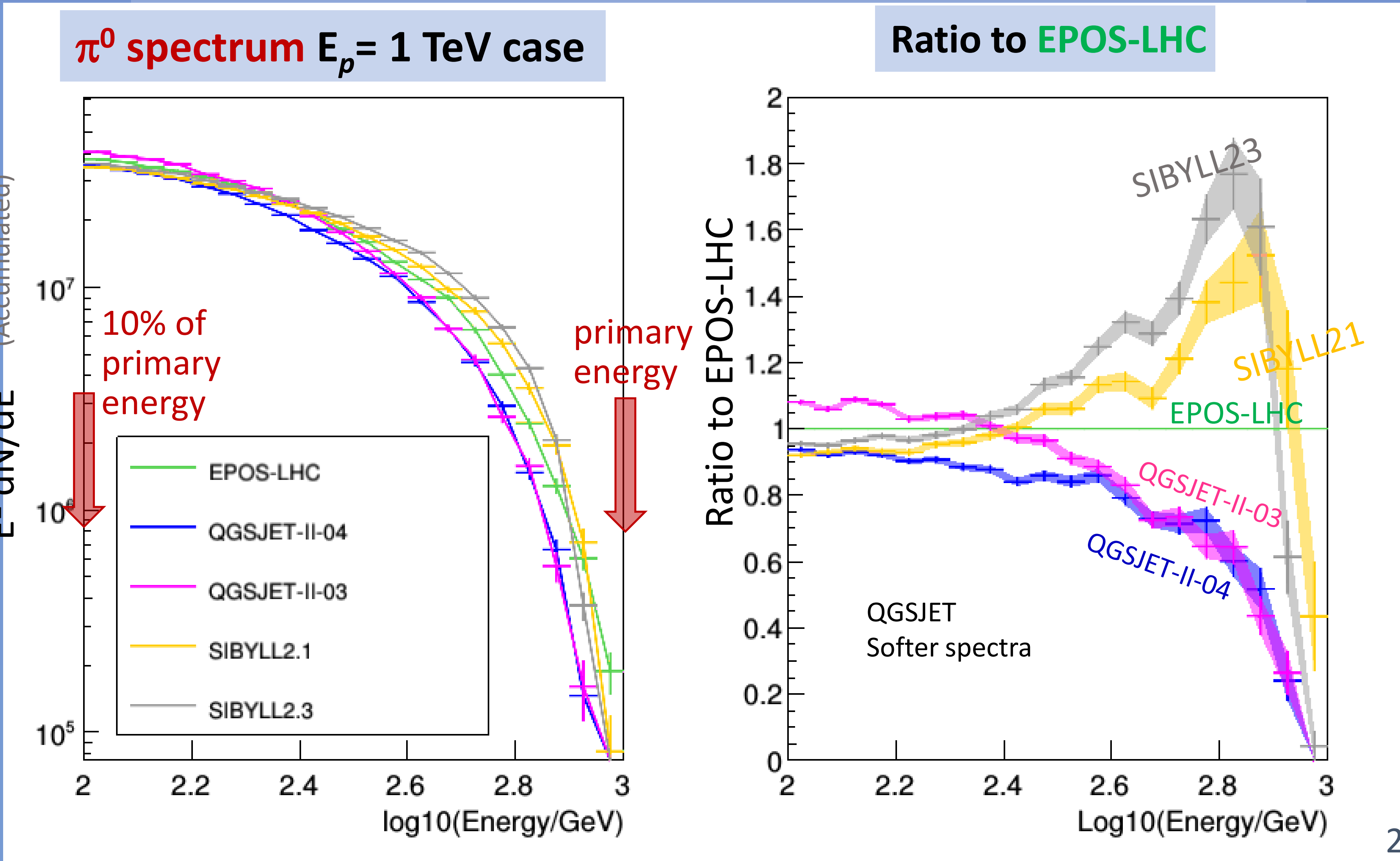
Schematic view of a shower
(Explanation for the fig. in p.5)



*1 Results at Barcelona meeting are from C7.57, but it seems no large difference in interaction model between 7.57/7.64

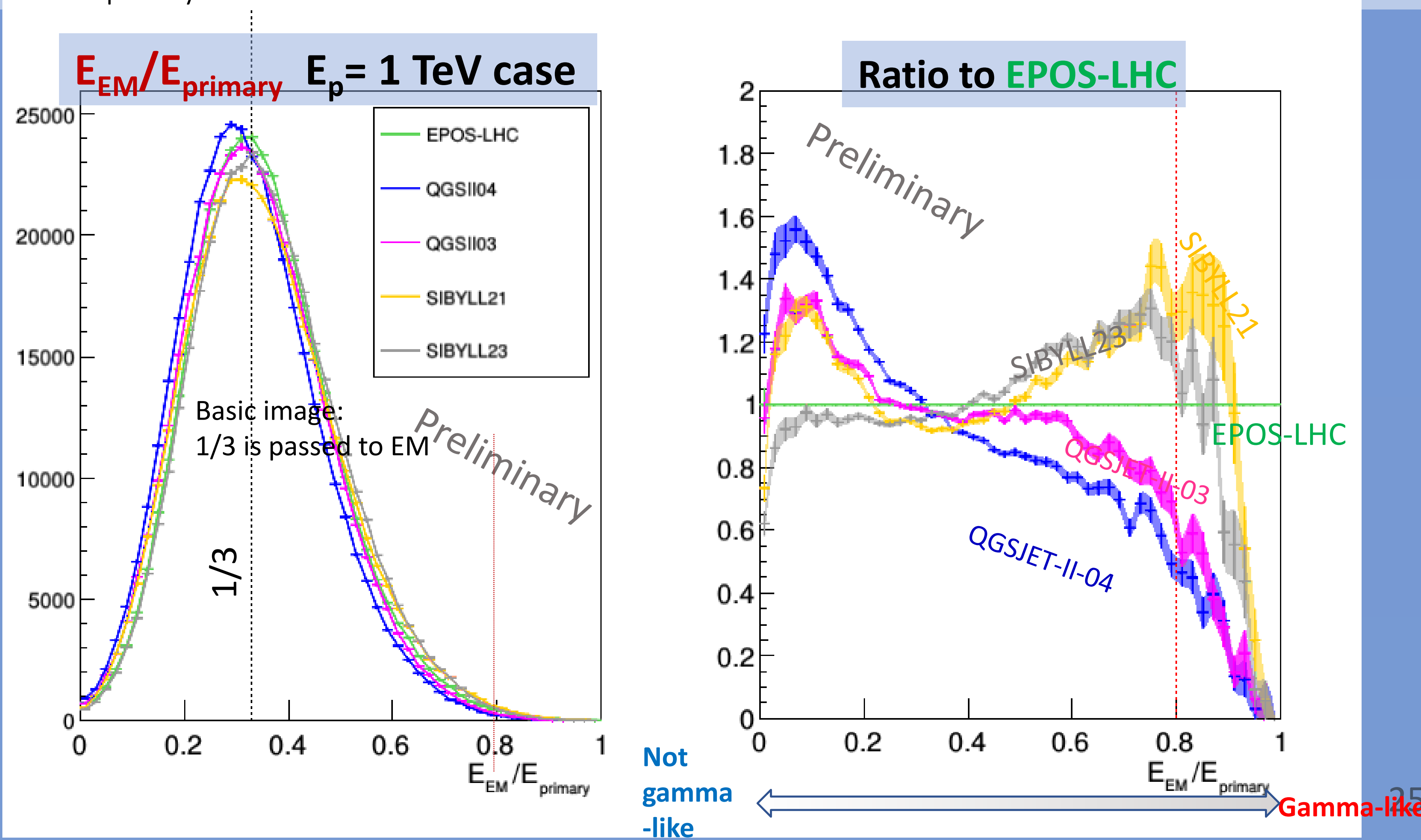
Difference between interaction models: π^0

- Collected all the π^0s in the shower (above ECUTS value)
- Harder spectrum for EPOS-LHC is known in UHE region



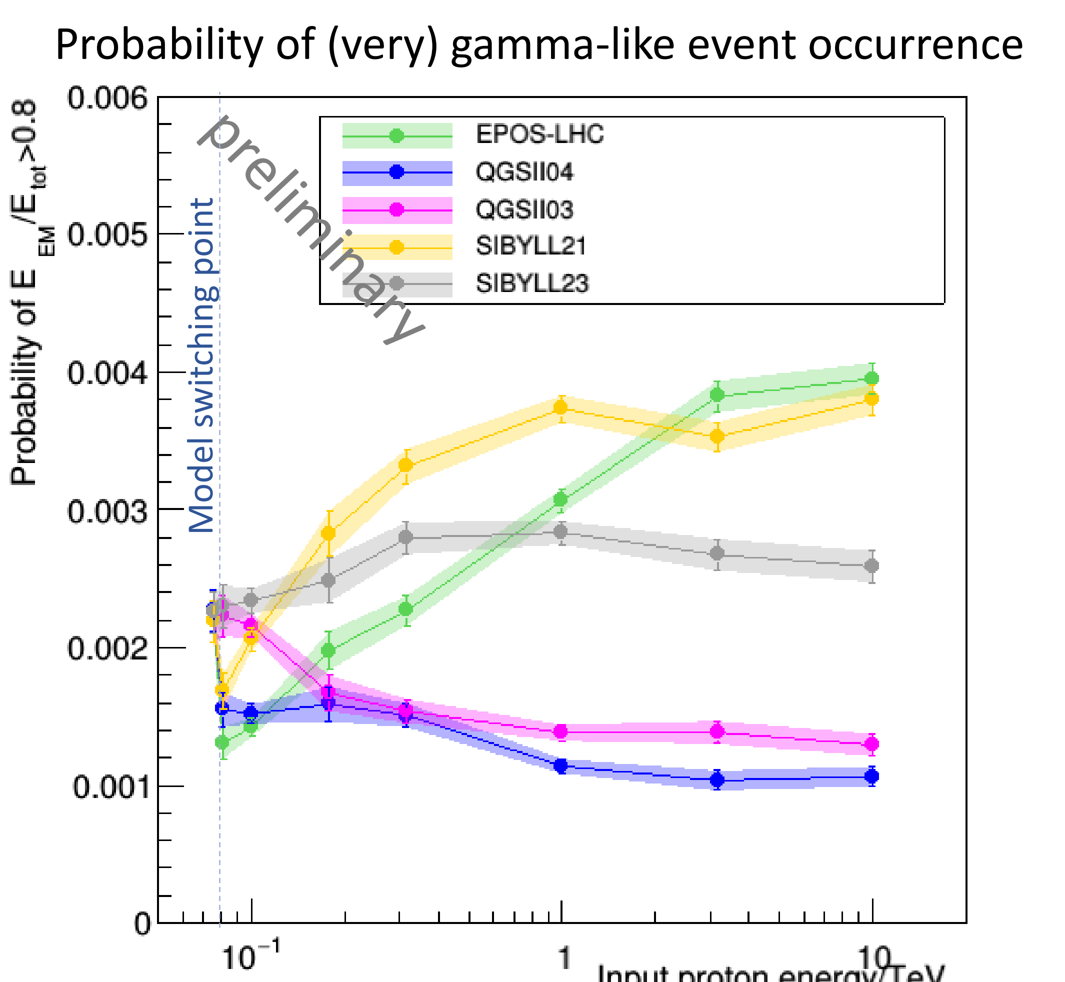
Difference between interaction models: EM part.

- Learned from Maier & Knapp (2007)
- Energy fraction which carried by EM particles (e^-,e^+,γ) after the 3rd interaction ($E_{EM}/E_{primary}$).



EM components: energy dependence

Probability of $E_{EM}/E_{primary}$>0.8 VS input primary energy

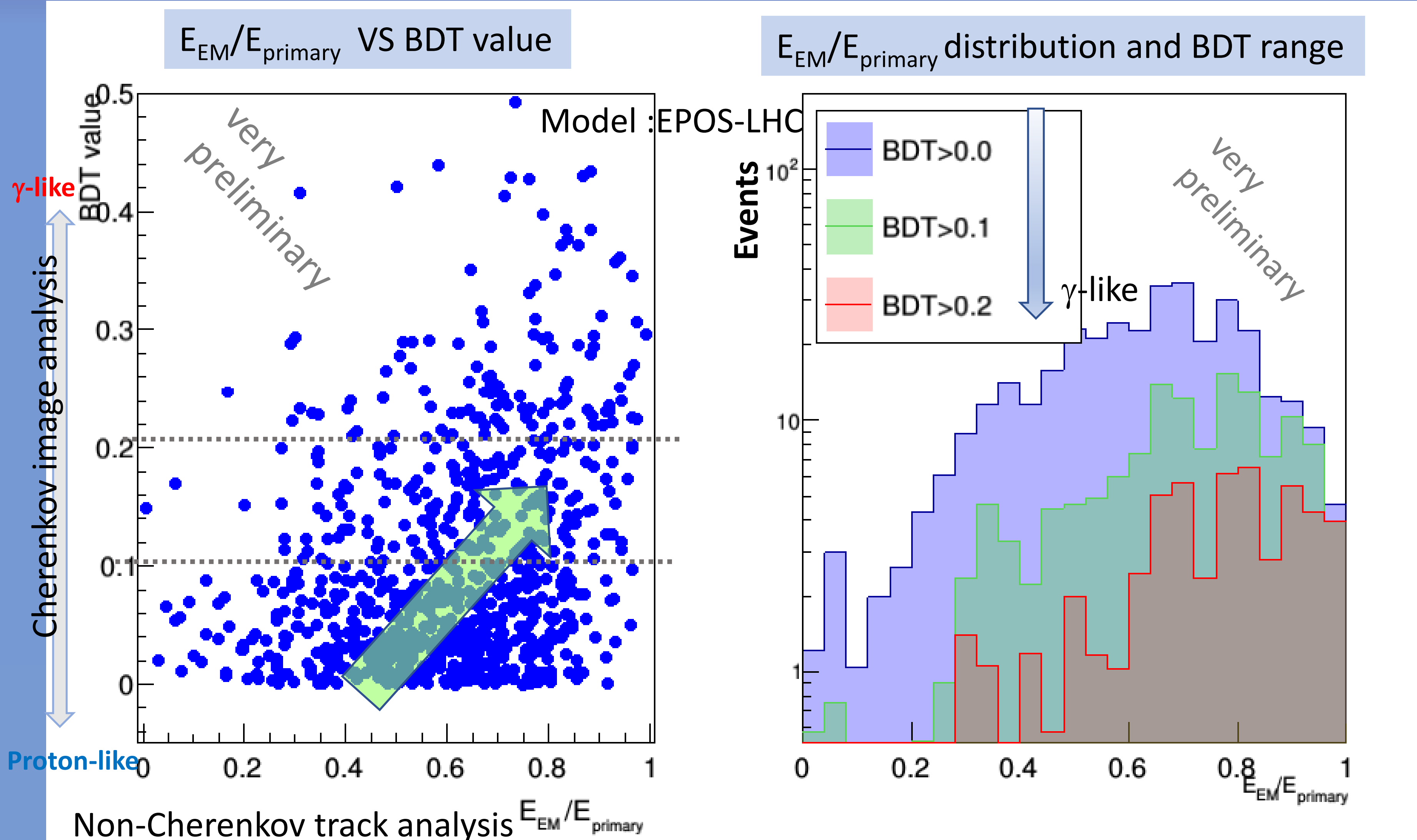


第三回 空気シャワー観測による宇宙線の起源探索勉強会, upload版

- Low energy model is fixed as UrQMD, switching point is at 80 GeV /nucleon (so the results are naturally converged in low energy region).
- As for Ep > 3 TeV (thus E_γ > 1.0 TeV) region, EPOS-LHC has a significantly higher probability of $E_{EM}/E_{primary}$>0.8 than QGS, which can be an indirect clue for factor ~2 difference in # of gamma-ray like events.
- There is a small discontinuity for some models in $E_{EM}/E_{primary}$ at the model switching point.

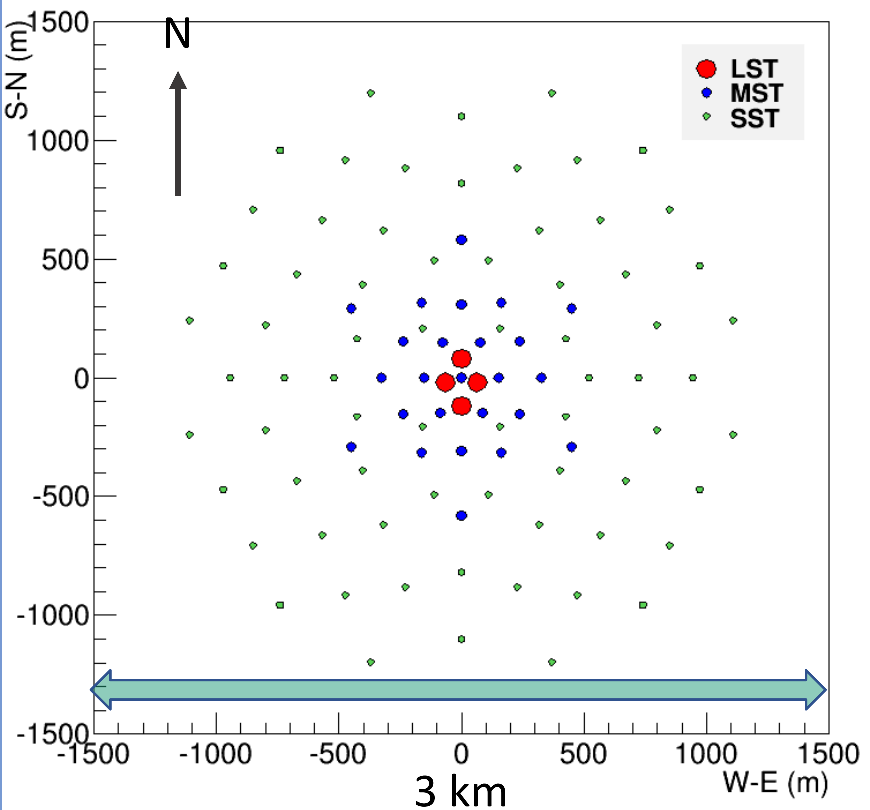
Correlation between BDT value in image analysis and $E_{EM}/E_{primary}$

- Picking up Random Seed at the beginning of event for (a part of)dataset shown in p.2 (power-law, baseline sim.) and reproduced the same air shower with track information



Additional simulation for full CTA energy range

Array configuration, South Site

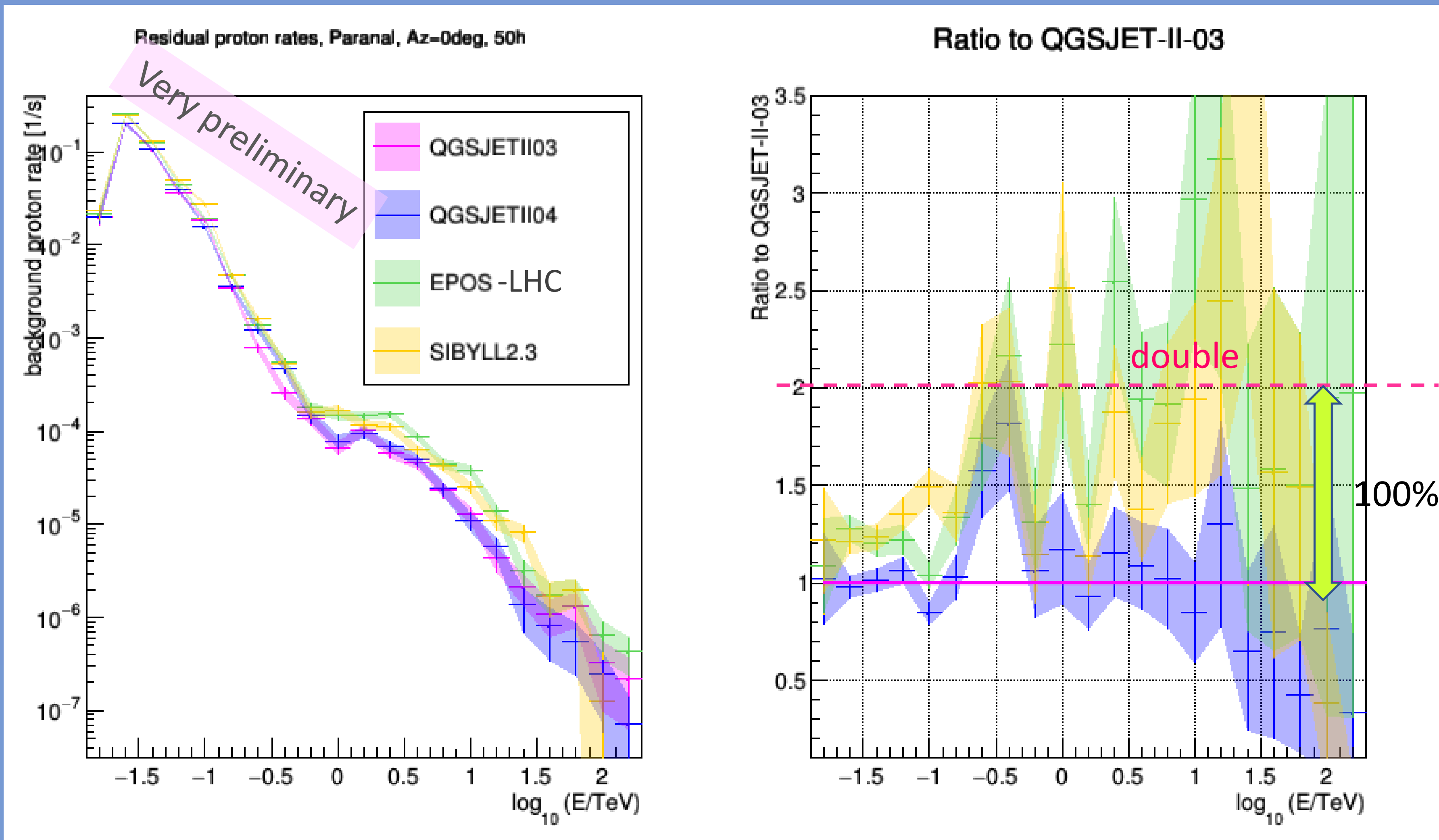


Parameter	Value
Sute	Paranal (Chile)
Array	"Baseline" 4 LSTs, 25 MSTs, 70 SSTs
Particle	Gamma, e-, Proton:QGSJET-II-03 *1 Proton: QGSJET-II-04*1/EPOS-LHC /SIBYLL2.3c*2 Low energy model is fixed as UrQMD
Core range	2500 m
Viewcone	0 - 10 deg, uniform
Energy range	0.003 - 330 TeV (e-, gamma) 0.004 - 600 TeV (proton)
Spectral index	-2.0 *3

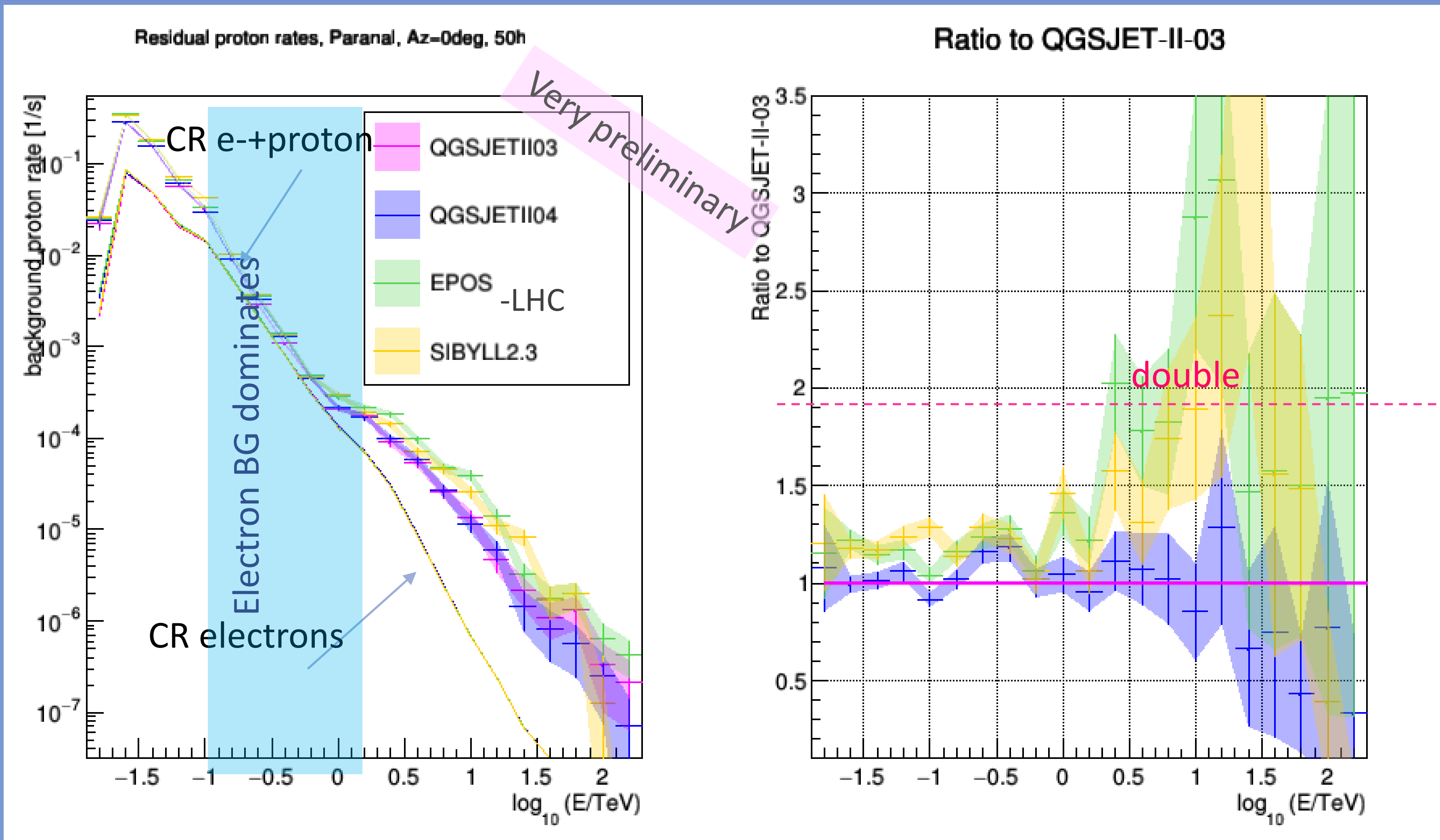
*1 in CORSIKA 6.99
*2 in CORSIKA 7.69
*3 Reweighted in the analysis procedure to be -2.6

Residual proton rates

- Both of direction cut and shape(BDT) cut were applied
- If we just want to test the difference between models, we can loose direction cut, which makes event statistics improved largely.

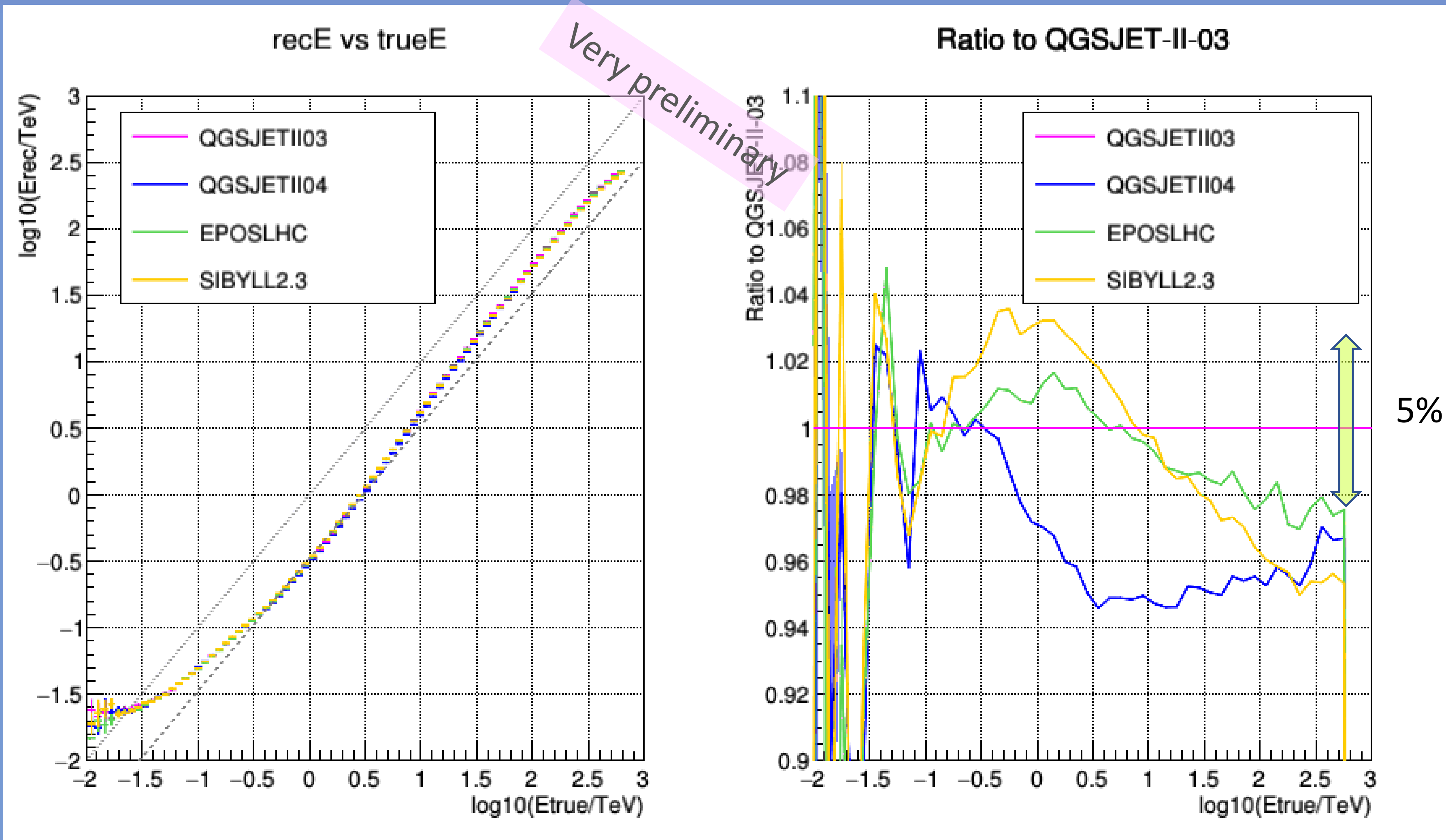


Residual proton + e- rate



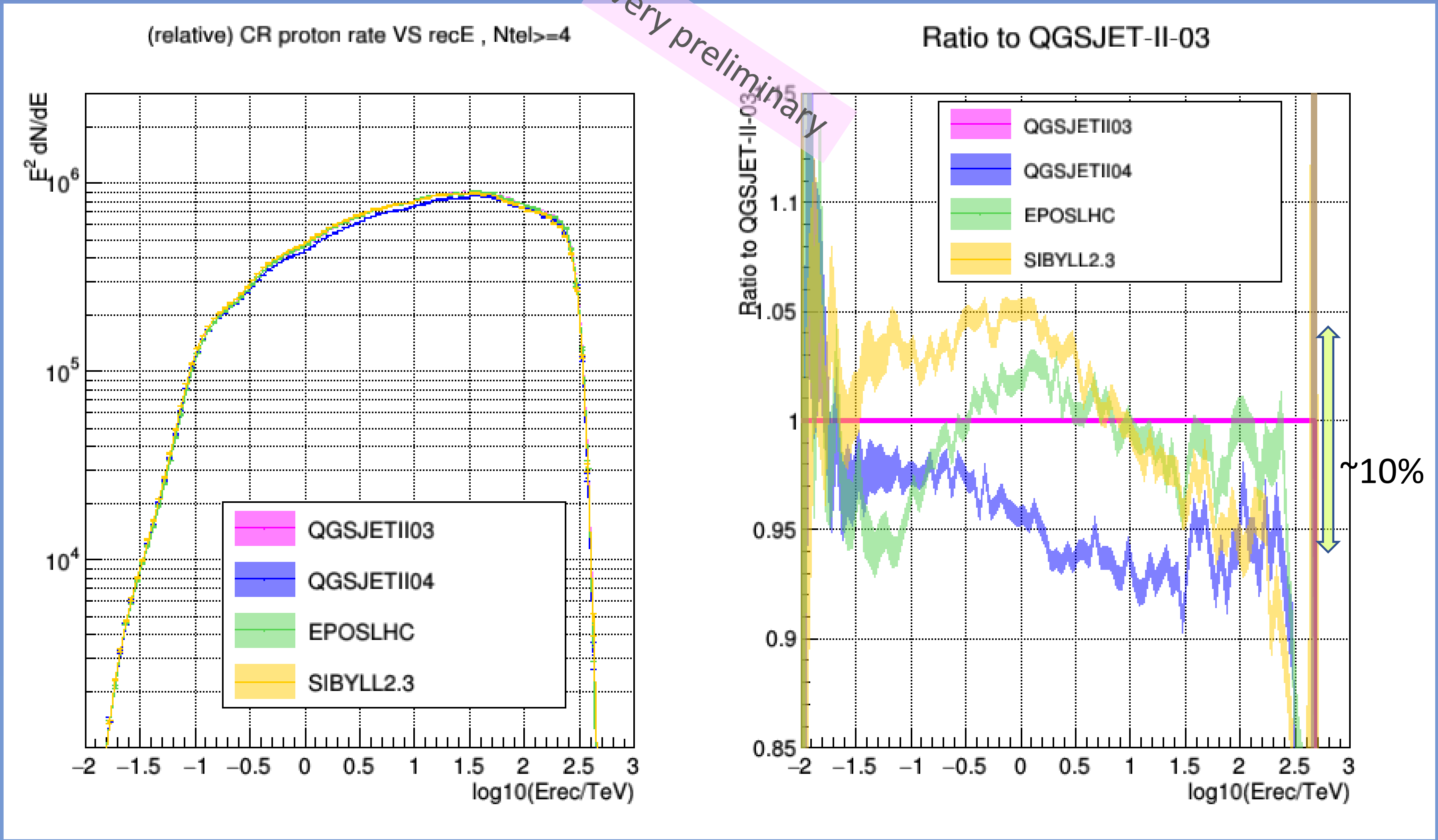
Difference in reconstructed energy

- No direction cut, no shape cut
- All “detected” proton events



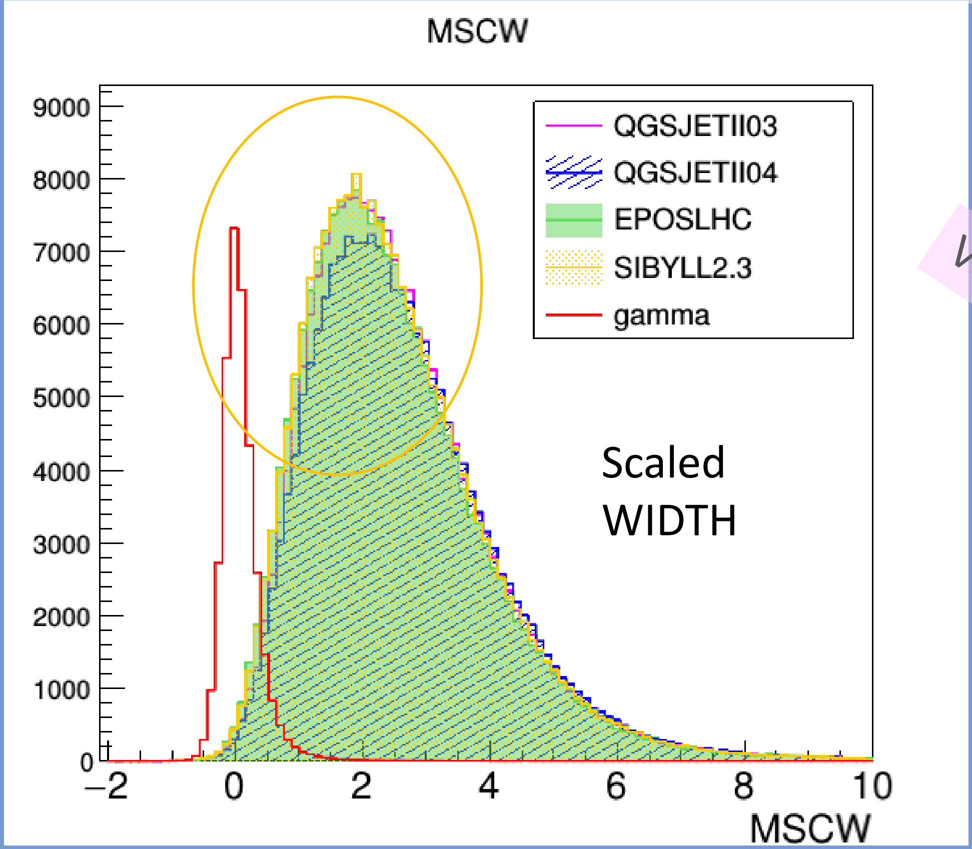
(relative) CR proton rate

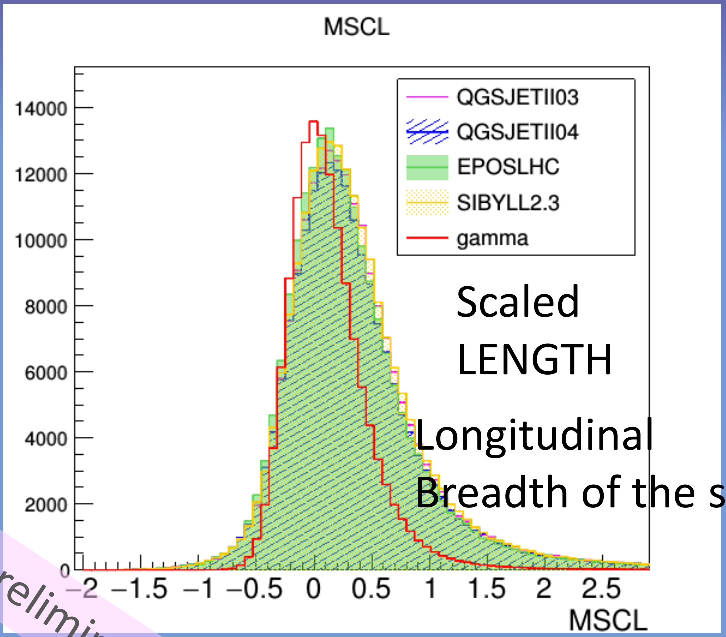
- No direction cut, no shape cut
- All “detected” proton events

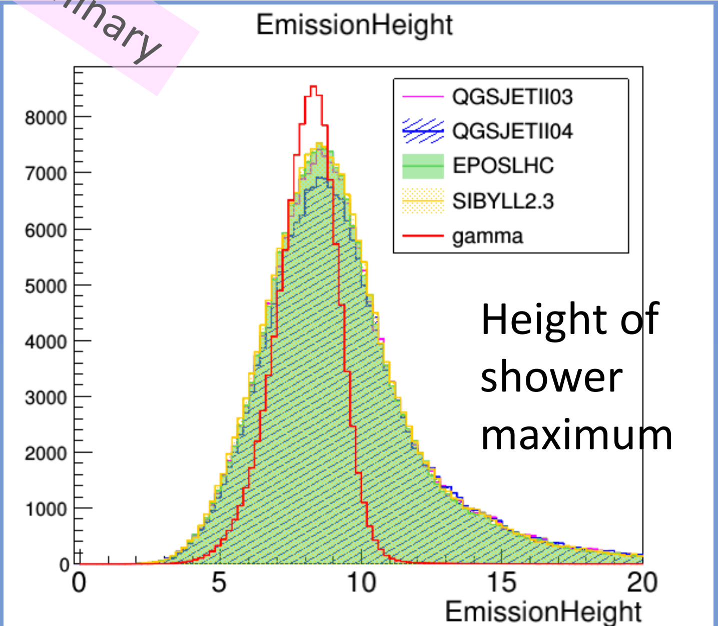


Difference in basic shower parameters

- Most important parameter for the gamma-hadron separation is WIDTH (transverse breadth of the shower)
- Distributions for 1.0 < log10(Erec)<10.0



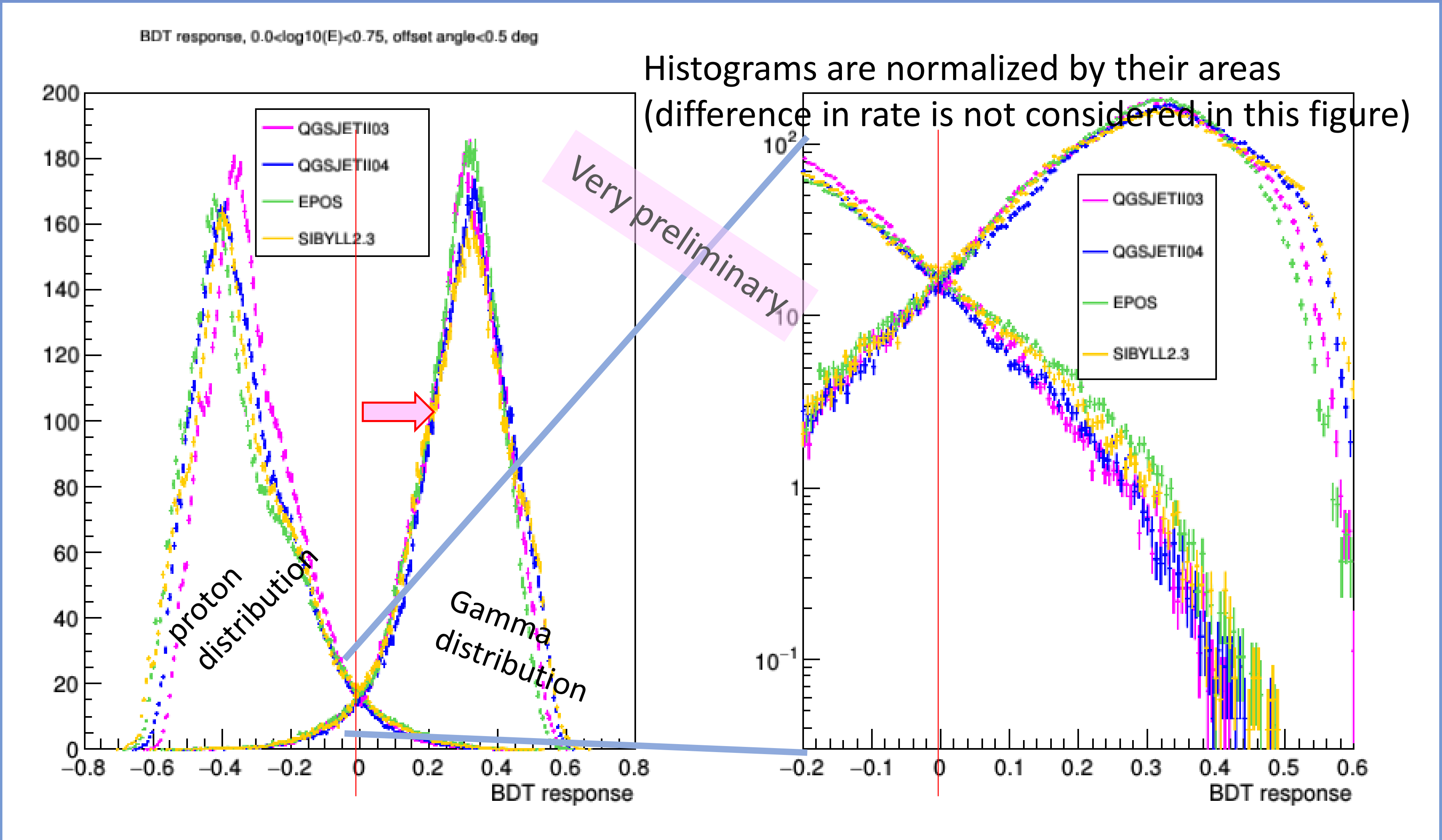




Difference in MVA separation parameter

Separation parameter, 0.0<log10(E)<0.75, offset angle <0.5 deg

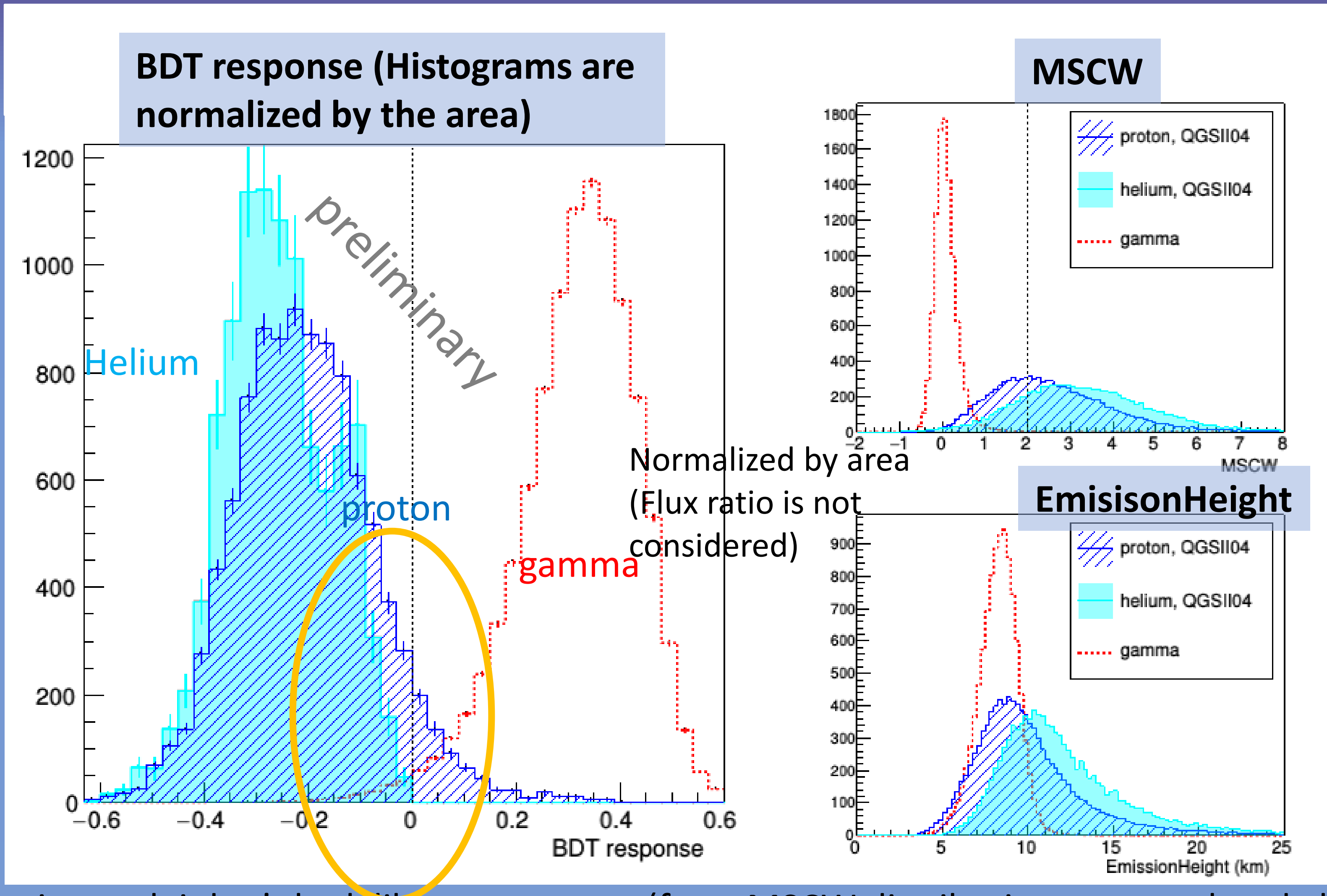
Histograms are normalized by their areas
(difference in rate is not considered in this figure)



Summary so far

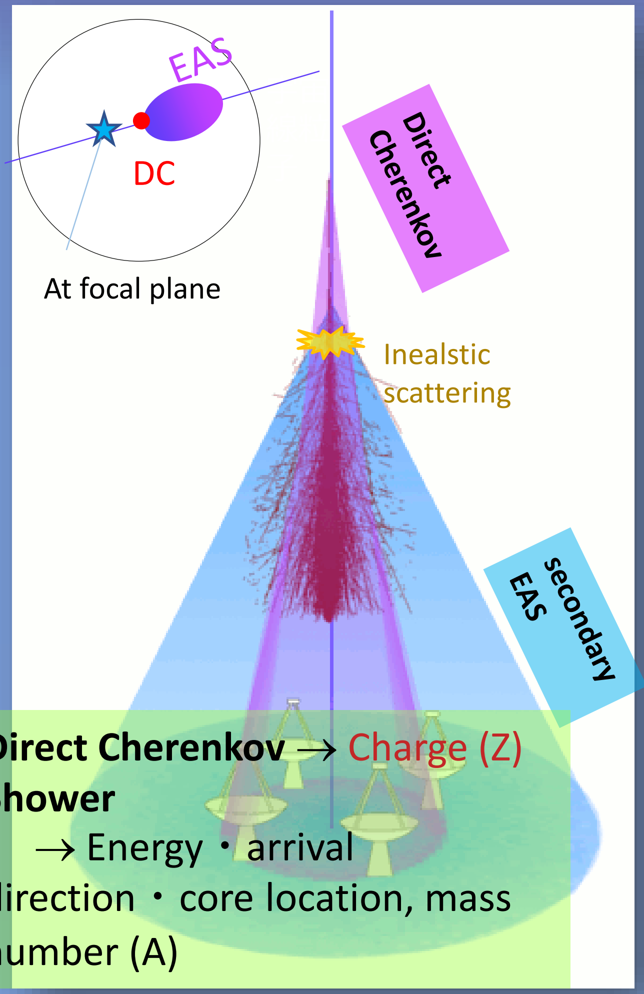
- There is factor ~2 difference in the number of gamma-ray like protons (determined by BDT) among 4 hadronic interaction models.
- EPOS-LHC has a harder π^0 spectrum than QGS . As for SIBYLL, the spectra are also hard, but with a very sharp cutoff.
- Thus this difference in $E_{EM}/E_{primary}$ in the models can (partly) explain the factor ~2 level difference of num. of gamma-ray like events, in recE > 1 TeV region. (But at the same time difference level depends on energy.)
- Effect on the gamma-ray sensitivity is expected to be ~30% between models, only appear in 1- 10 TeV region, where 5-sigma condition dominates.
- Anyhow, we think we will be able to give useful feedbacks to the existing models. Difference in shape parameters are small, but defining proper parameter which is sensitive to the model difference is possible.

Contribution of heavier nuclei? Uncertainty of the composition?



- Heavier nuclei don't look like gamma-rays (from MSCW distributions so on, already known by HESS electron paper)
- So contribution of heavier nuclei can be neglected. Almost free from uncertainty of the CR composition.

Cosmic-ray chemical composition measurement using IACT



Direct Cherenkov → Charge (Z)
Shower
→ Energy・arrival direction・core location, mass number (A)

Schematic diagram of Direct Cherenkov method using an IACT array

- Direct Cherenkov method: Detect Cherenkov photons emitted before the inelastic scattering

Frank-Tamm Formula

$$\frac{dN_c}{ds} = 2\pi Z^2 \alpha \int \frac{\sin^2\theta_c}{\lambda^2} d\lambda$$

$$\alpha : \frac{e^2}{4\pi\varepsilon_0 \hbar c} \qquad \cos\theta_c = \frac{1}{n\beta}$$

Free from interaction model uncertainty

- We can estimate primary charge from the Cherenkov photons detected on the ground

- The first idea is proposed by Kieda et al. (2001)
- H.E.S.S. and VERITAS reported iron spectra(>13 TeV) measured with this method
- Secondary showers also include information of primary mass number.

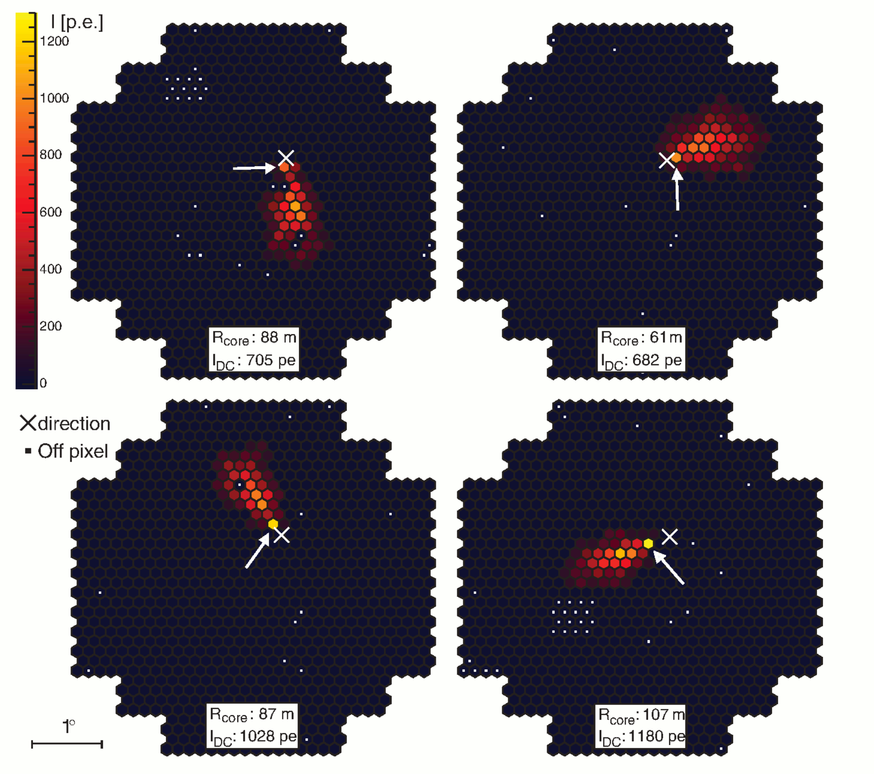
Much larger effective area, no energy upper limit

H.E.S.S. measurement results

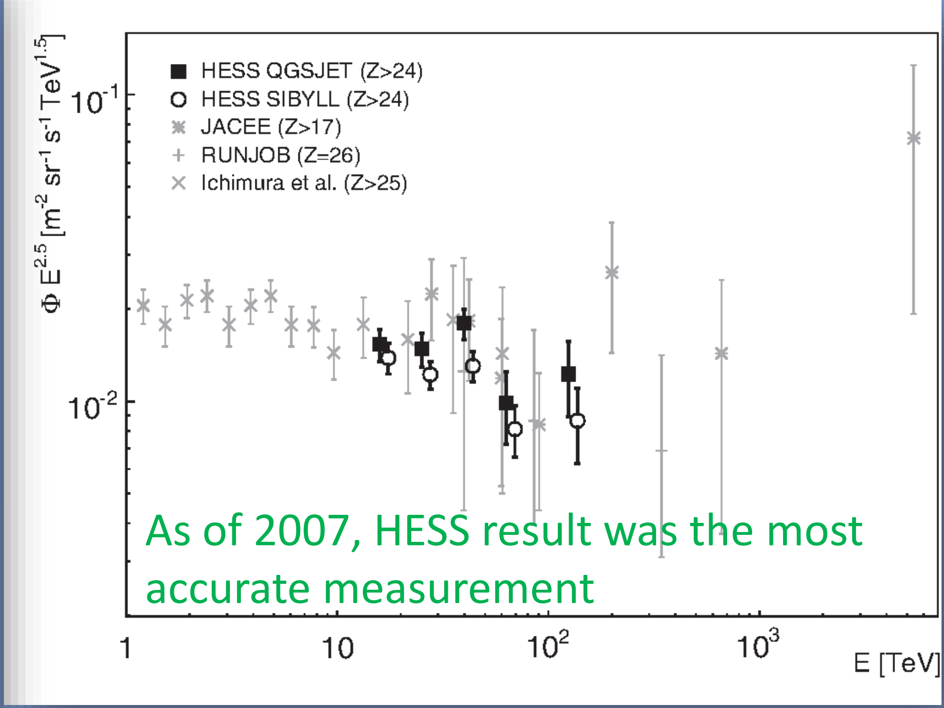
- Aharonian et al., Phys. Rev. D 75 042004 (2007)
- 12m-Diameter x4 system
- z<22 deg data selection

→ net observation time of 357 hours, 1899 events were identified as DC events

A DC event sample (all the 4 telescope include DC)



Sub-PeV iron spectrum measured by H.E.S.S. and balloon results



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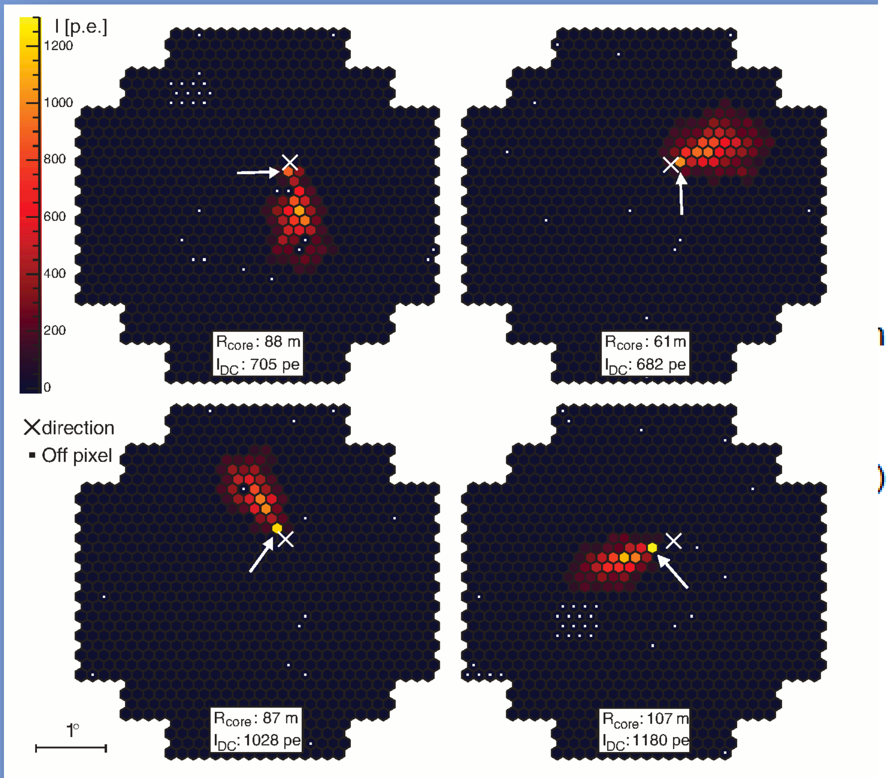

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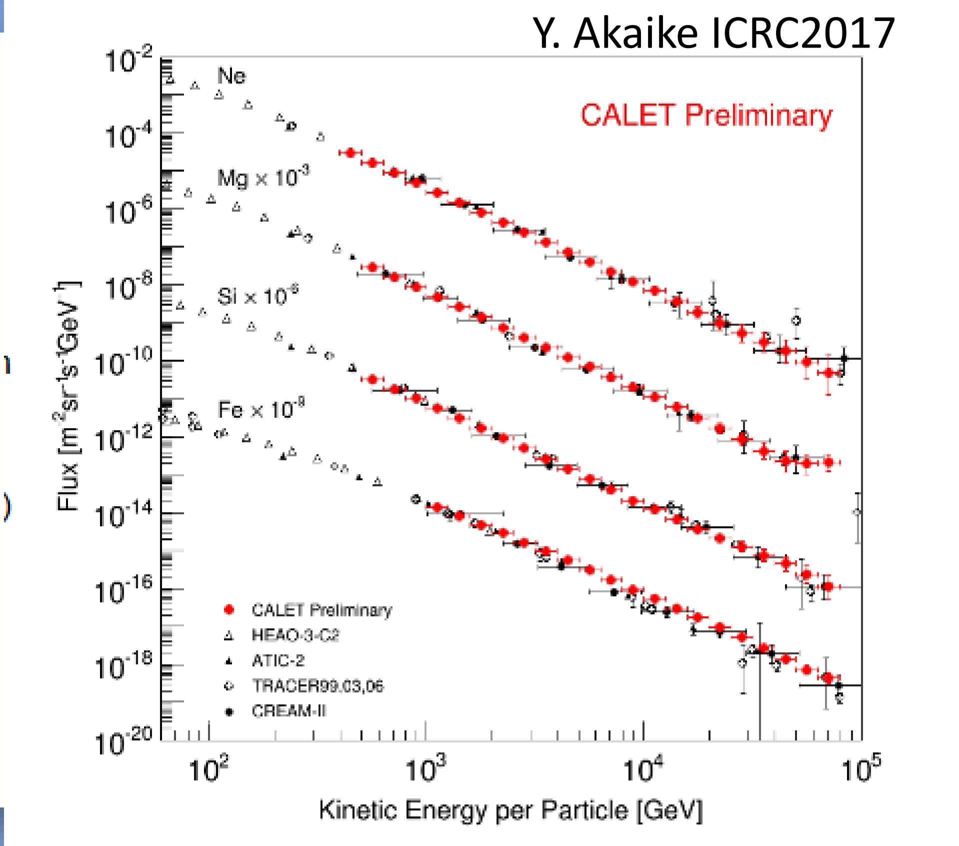
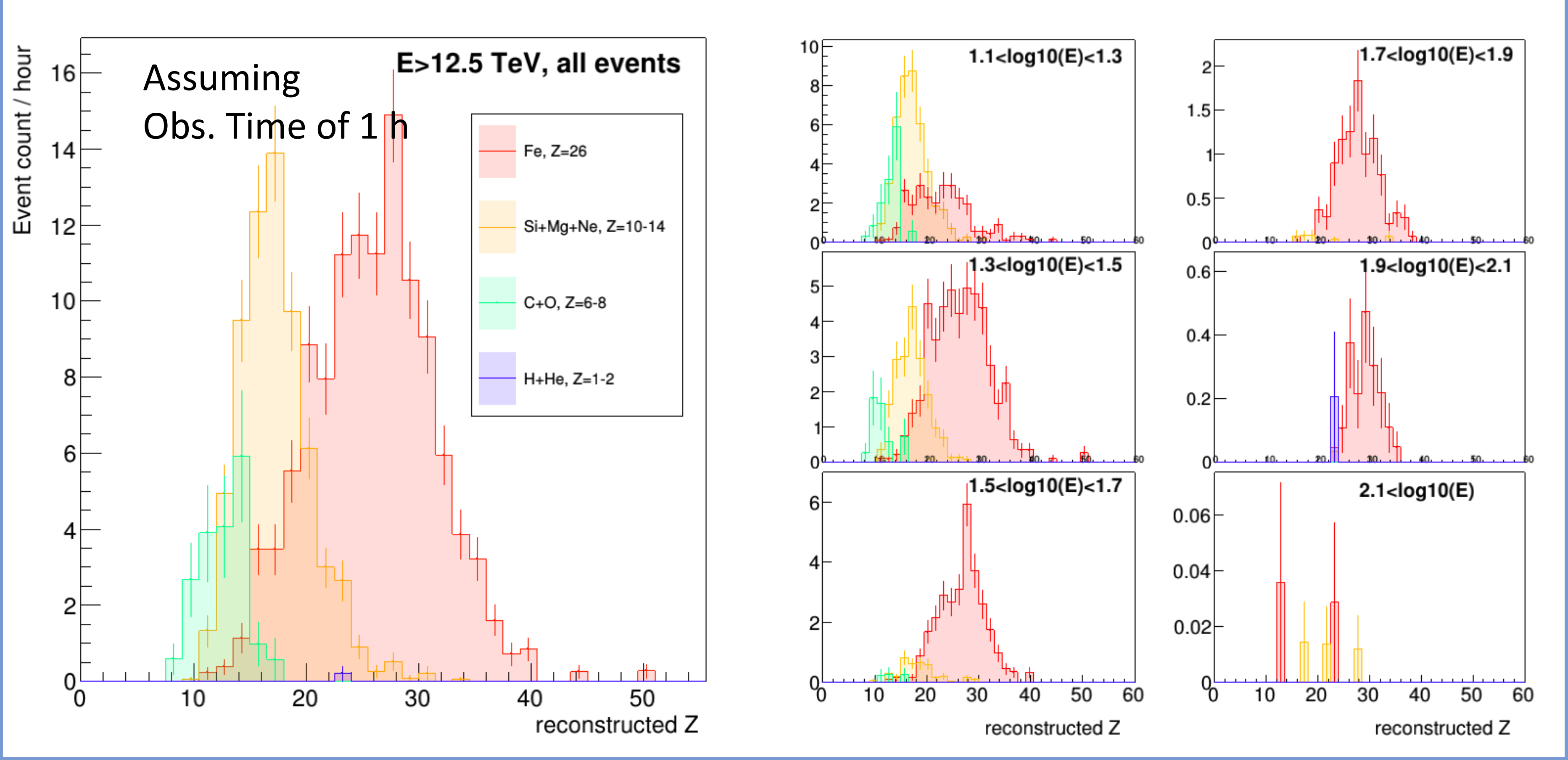


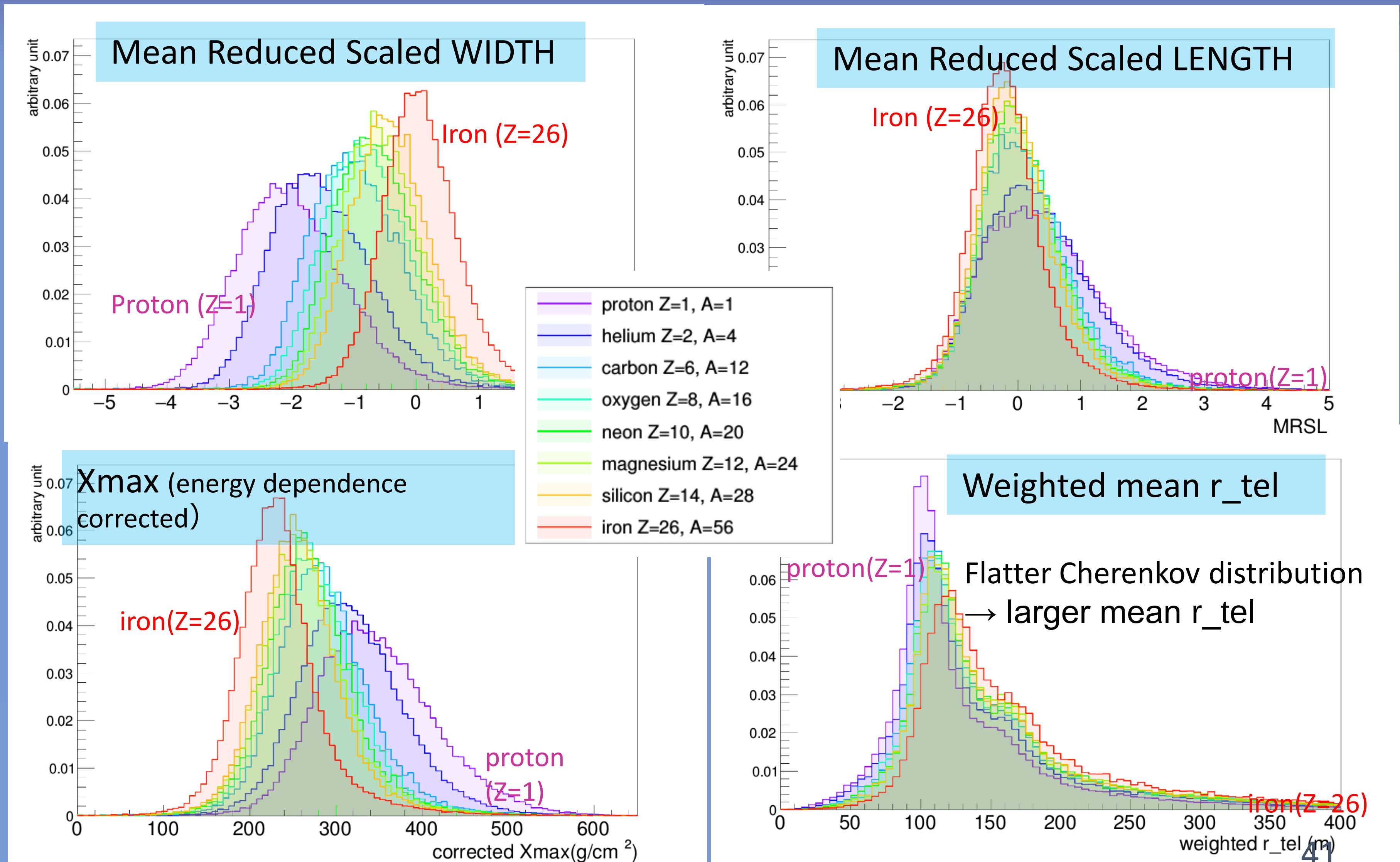
Particle identification ： only using Direct Cherenkov

- Assuming CTA array, only MSTs are used in simulation
- Light nuclei as H,He were rejected in the Direct Cherenkov(D.C.) event selection
- Only telescope close to the shower core (r<140m) can be used for D.C. analysis
- Effective area for DC events is much smaller than shower analysis



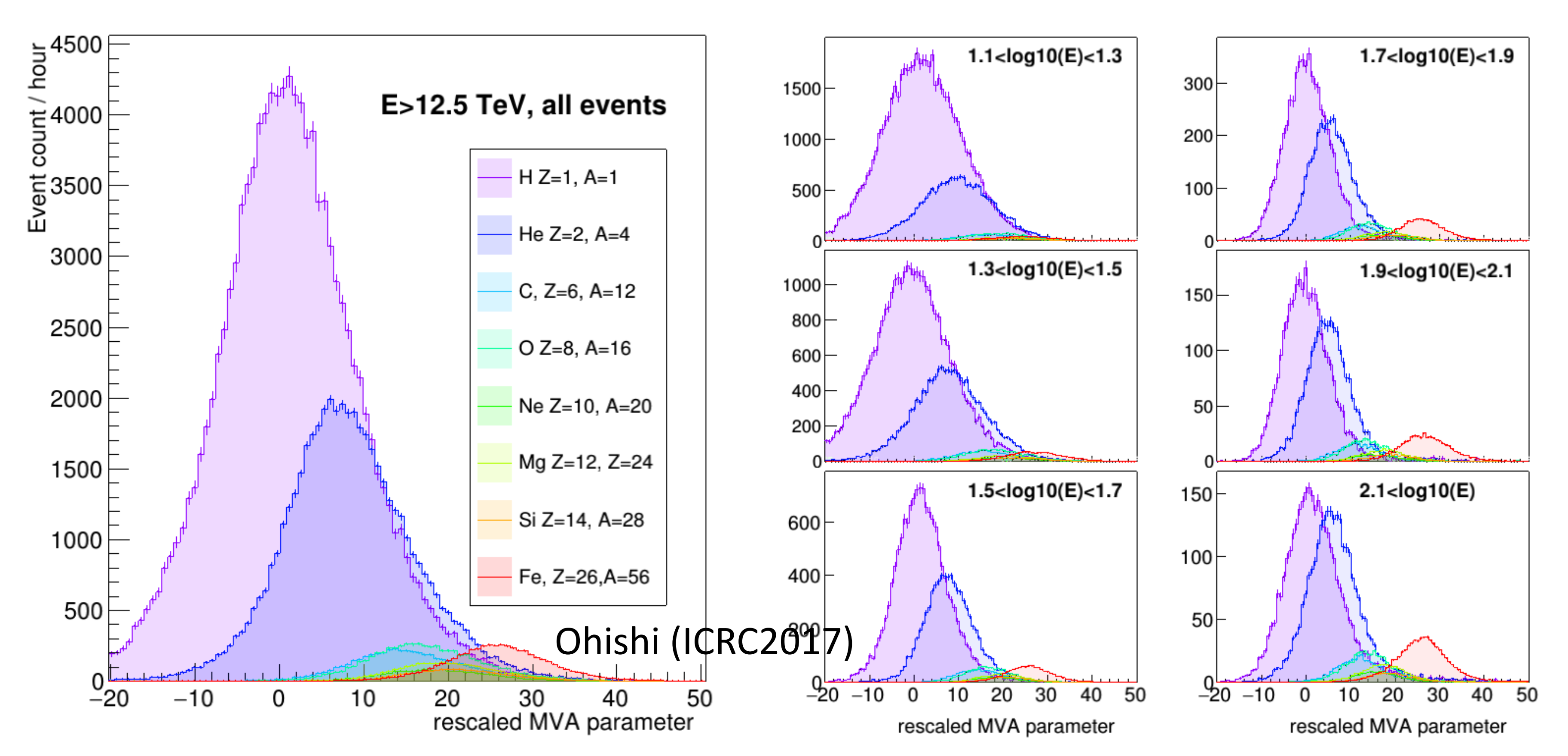
Particle identification: shower parameter analysis

- Typical shower parameters (MRSW,MRSL, XMAX, r_tel_mean)



Particle identification ： using only shower parameters

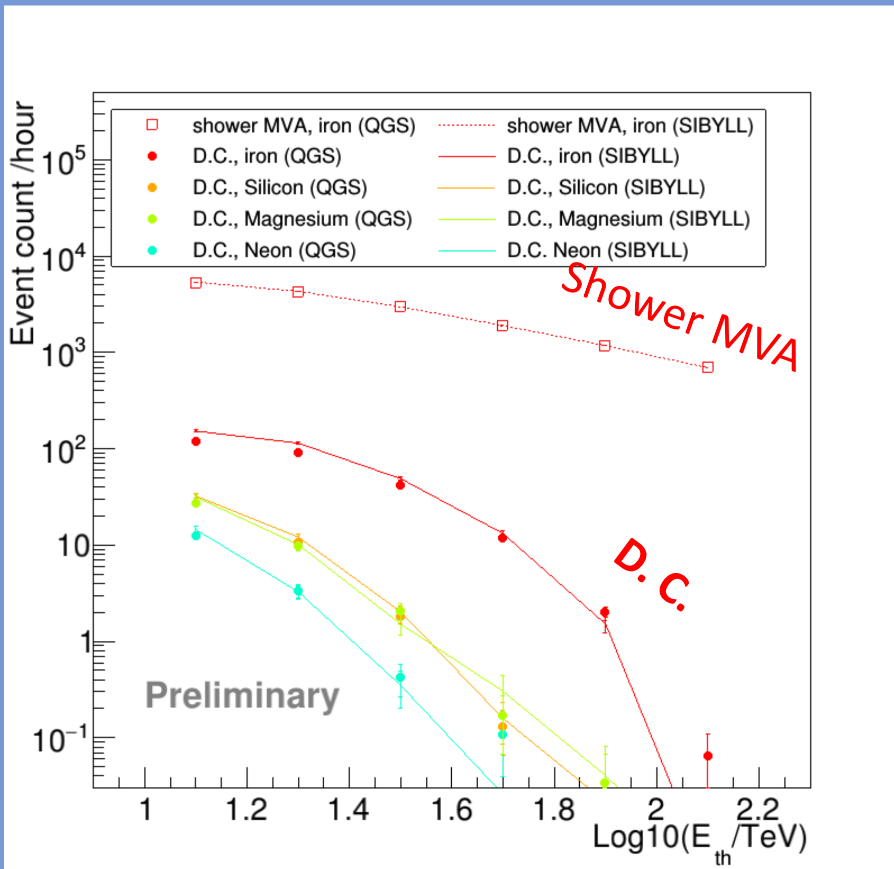
- Literature flux value from HÖrandel(2003) is used for weighting
- Assumed obervation time is 1 hour
- Energy is reconstructed assuming iron (LUT prepared from iron events)



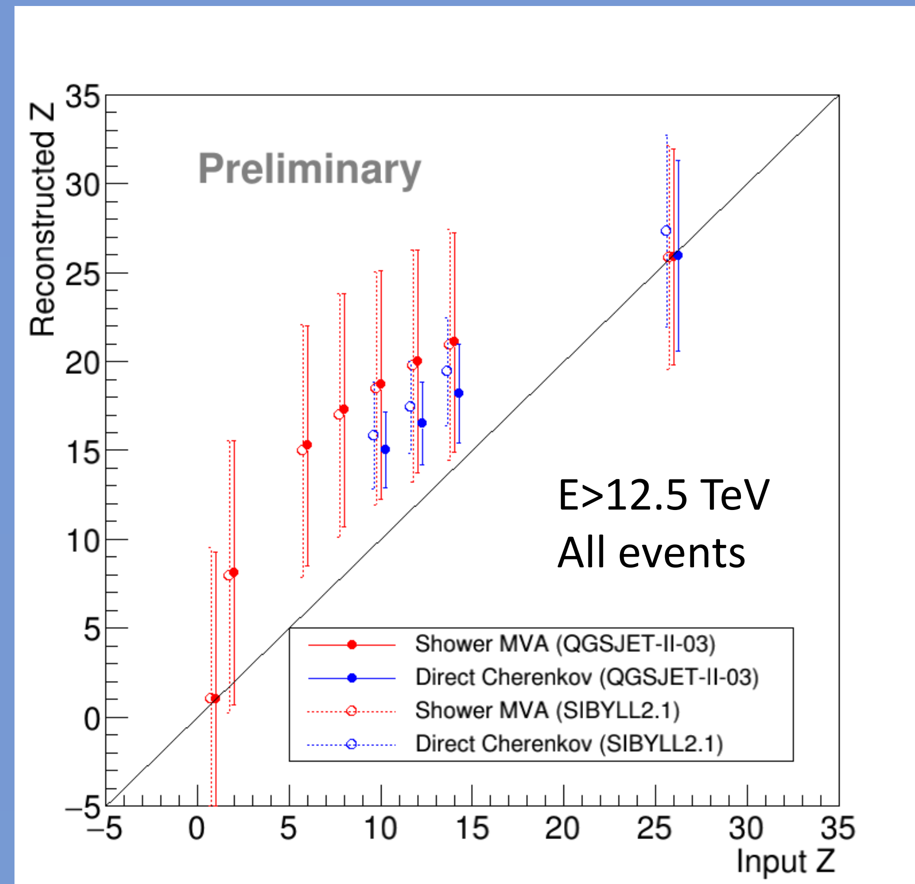
Ohishi (ICRC2017)

Expected event rate and charge resolution

Expected event rate



Charge resolution vs input Z

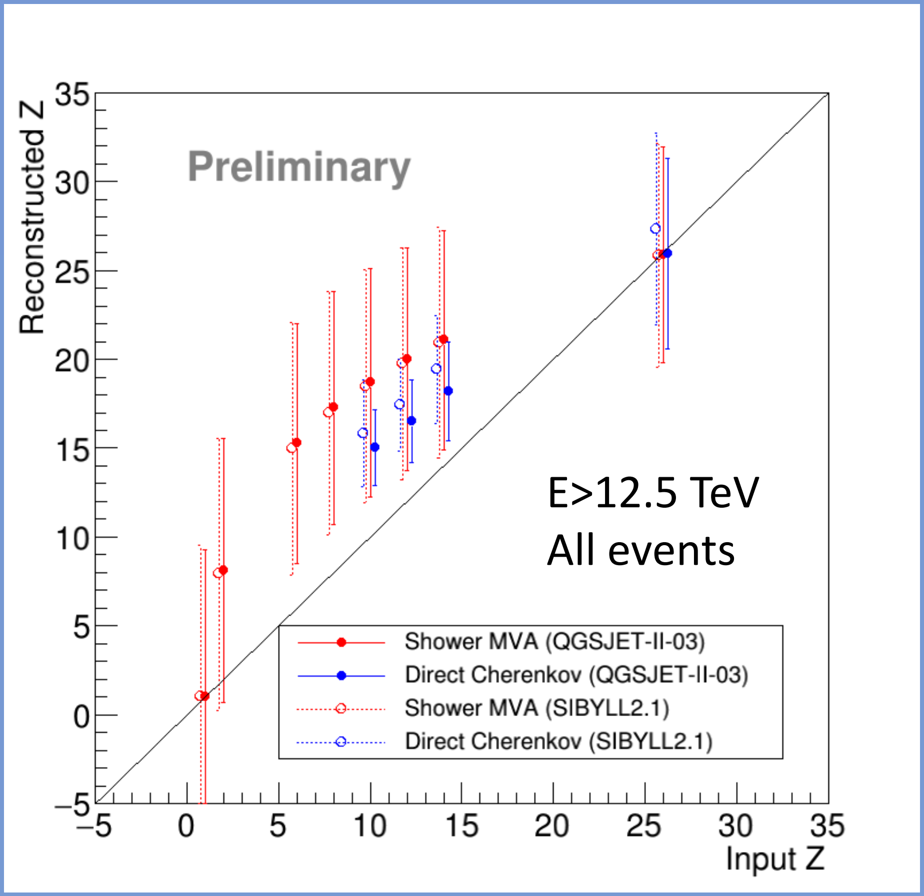


Expected event rate and charge resolution

Expected event rate

	Direct Cherenkov		Shower MVA	
	QGS	SIB	QGS	SIB
Fe	5.38	5.41	6.05	6.30
Si	2.77	3.02	6.16	6.50
Mg	2.33	2.59	6.24	6.54
Ne	2.14	2.99	6.44	6.55
O	-	-	6.55	6.84
C	-	-	6.74	7.08
He	-	-	7.41	7.66
H	-	-	8.30	8.53

Charge resolution vs input Z



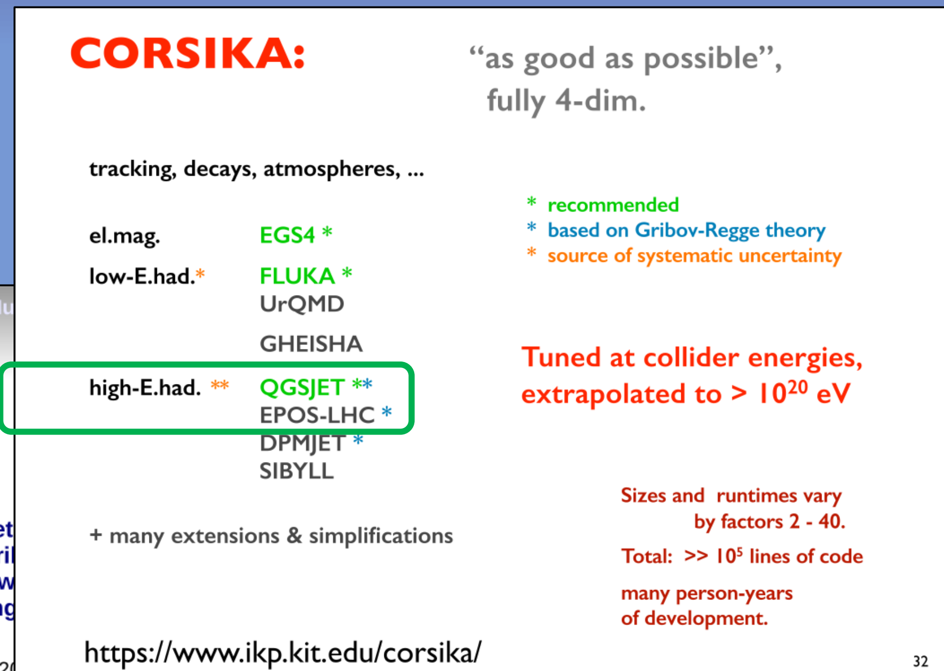
Summary

- Monte carlo simulation of hadronic components is relatively not well studied yet. There a number of things to do ….
- Proton: major background for gamma-ray observation and residual background event rate is significantly different depending on current interaction models.
- Proton: Once the telescopes are completed, we will not need proton simulation for gamma-ray observation. But at the same time we will be able to provide feedbacks to model builders from IACT measurement.
- As for the heavy nuclei and electron (CR) study, we will need hadron simulation anyway. As a preparation for those studies, we had better understand interaction first.
- There may be a lot of approaches to improve the analysis methods for CR composition.. Your help is very welcome!

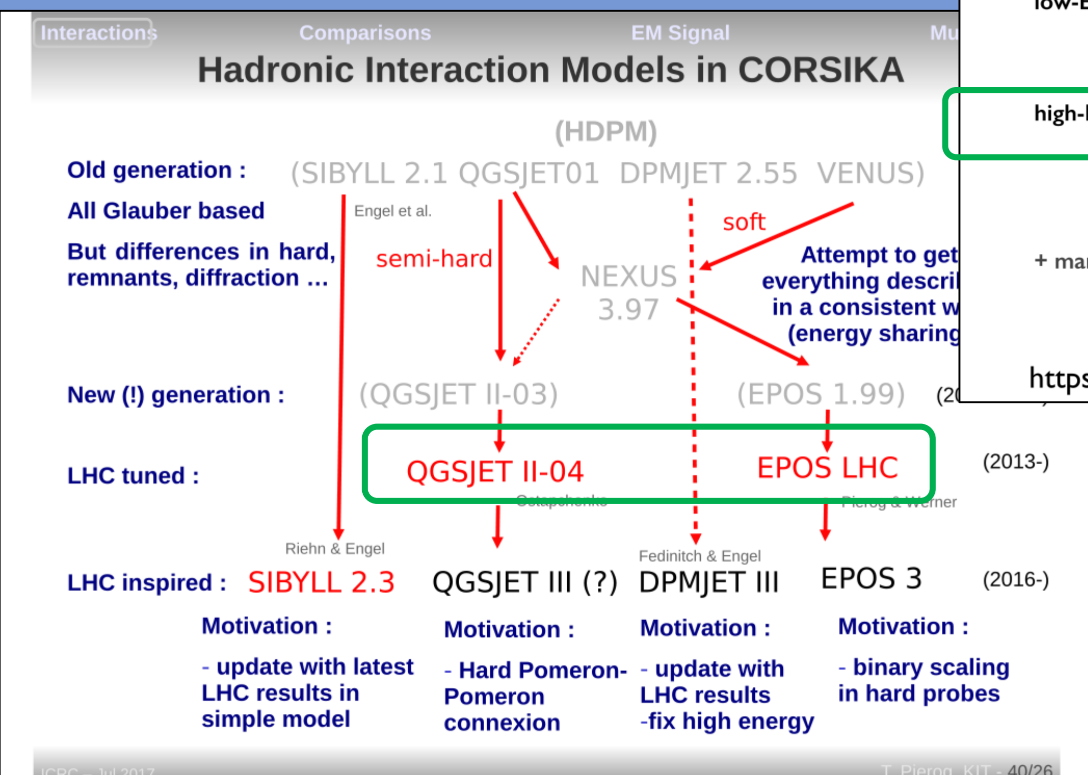
Backup

Post-LHC hadron interaction model in CORSIKA

J. Knapp, CTA AS Boot camp 2017

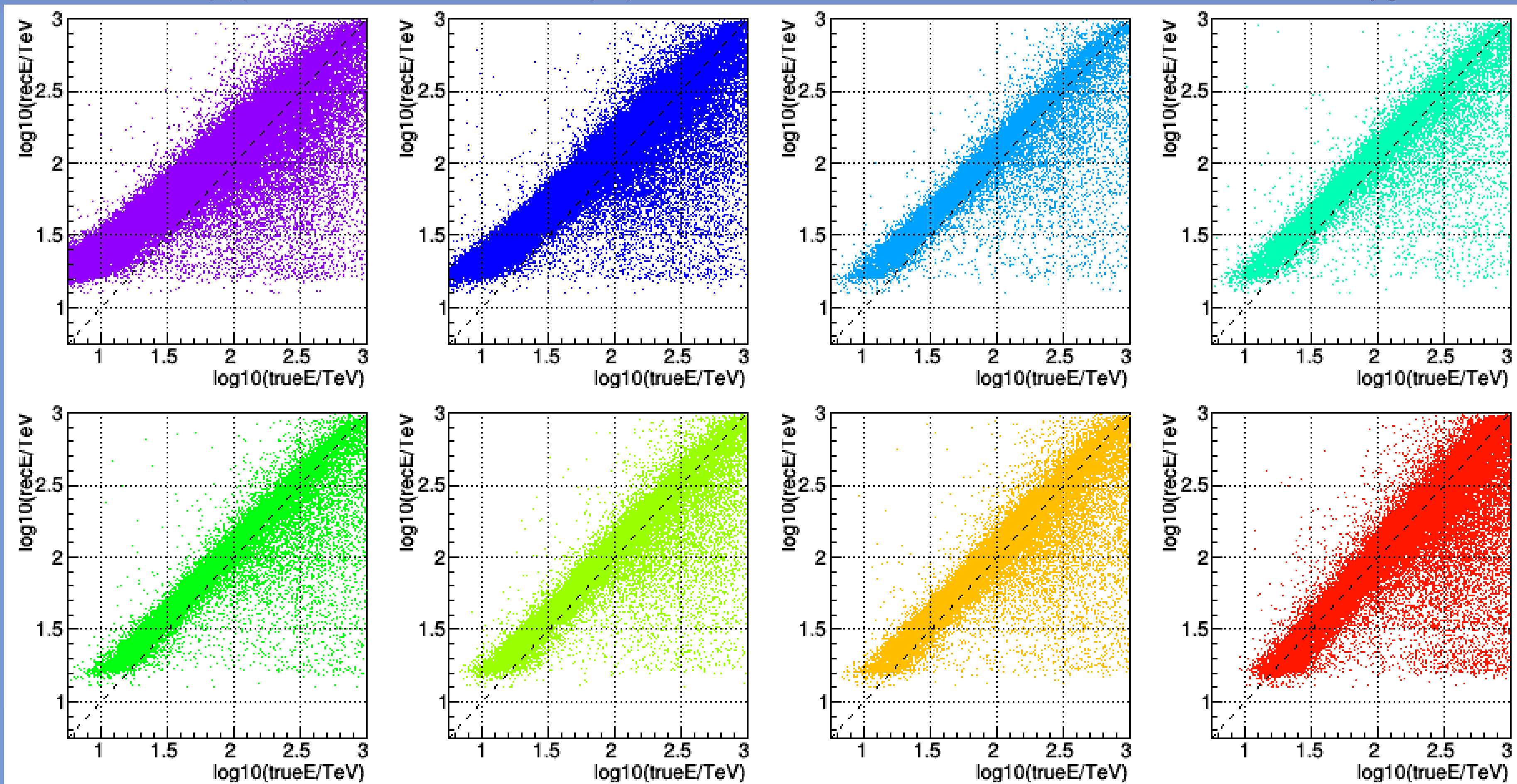


T. Pierog, ICRC2017 highlight talk



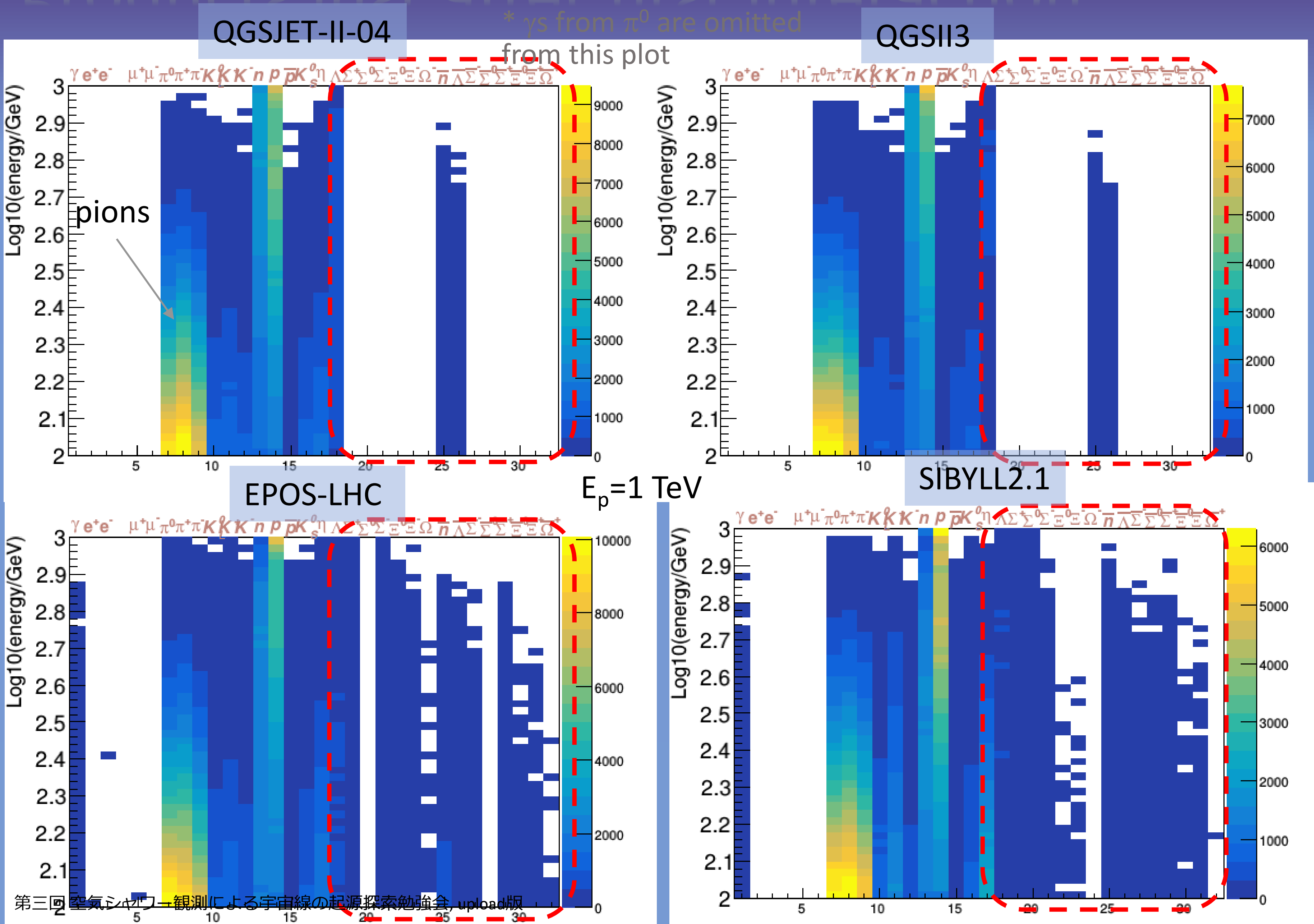
Energy scale

Proton Helium Carbon Oxygen

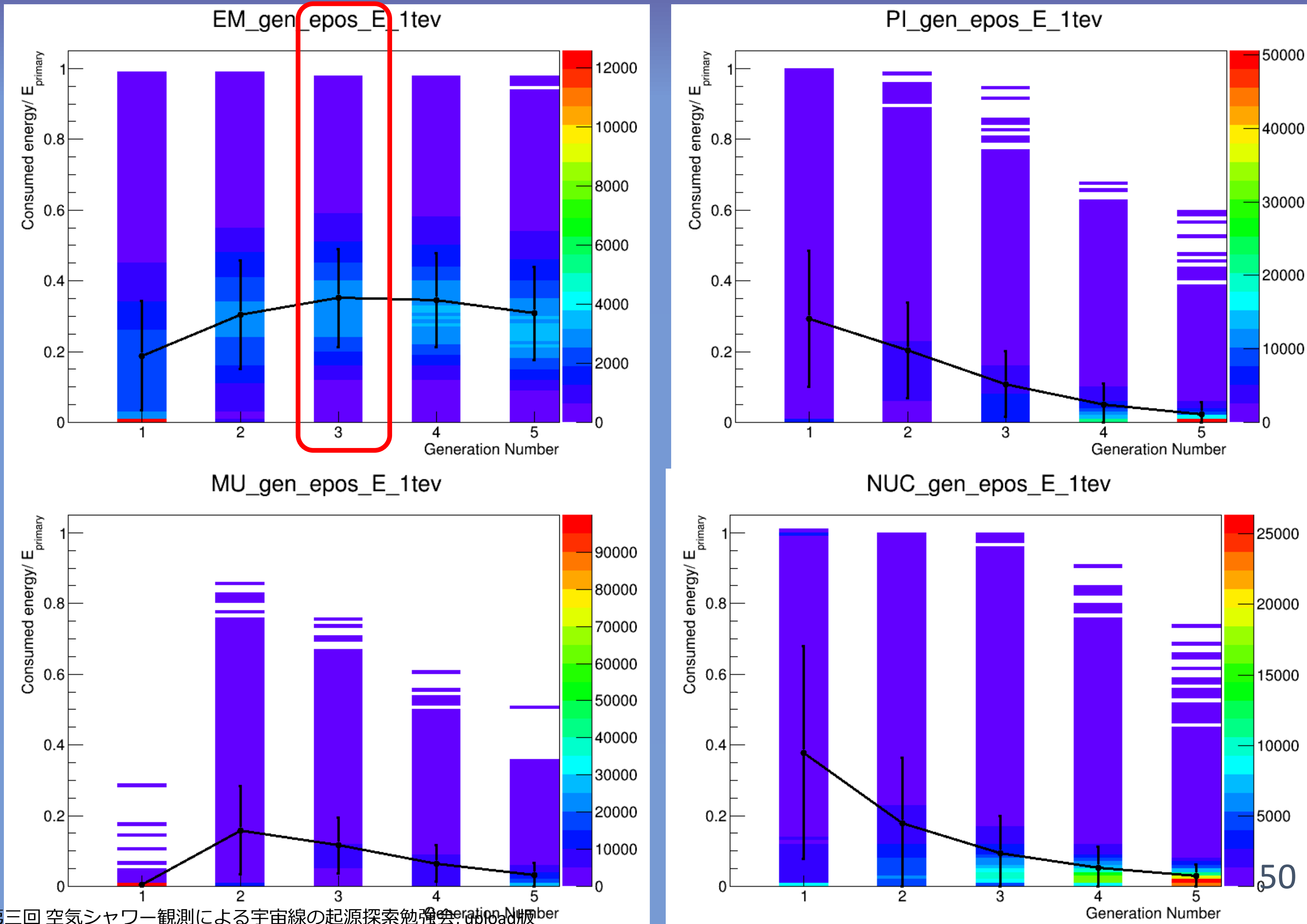


Neon Magnesium Silicon Iron

Products just after first interaction



Generation and consumed energies

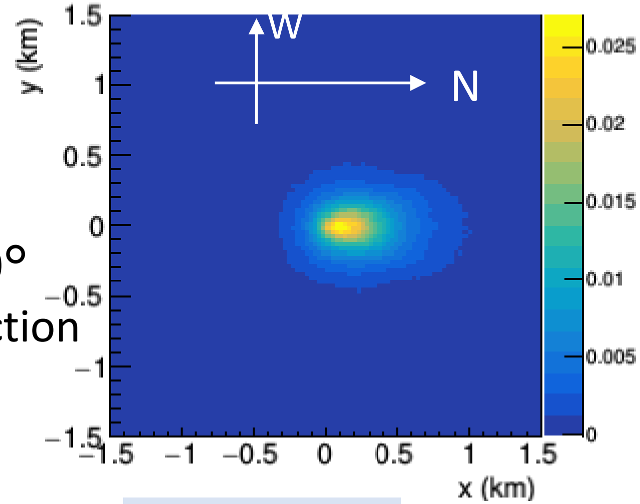


Difference in muon number density on the ground

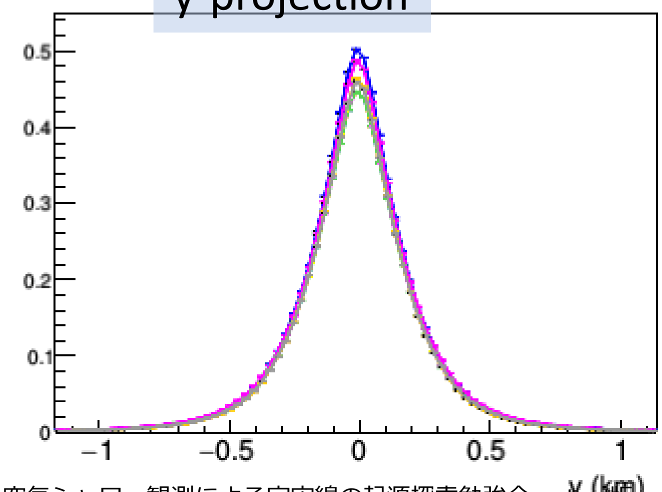
E_p=1.0 TeV

E> 10 GeV muons number density on the ground

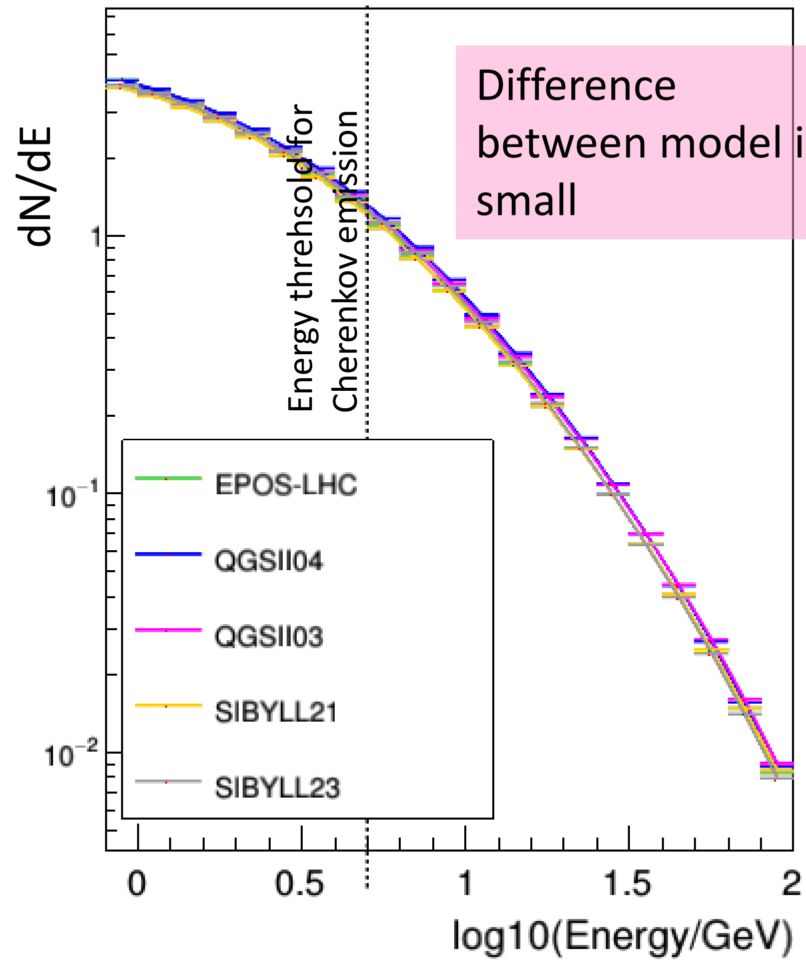
z=20° injection



y-projection



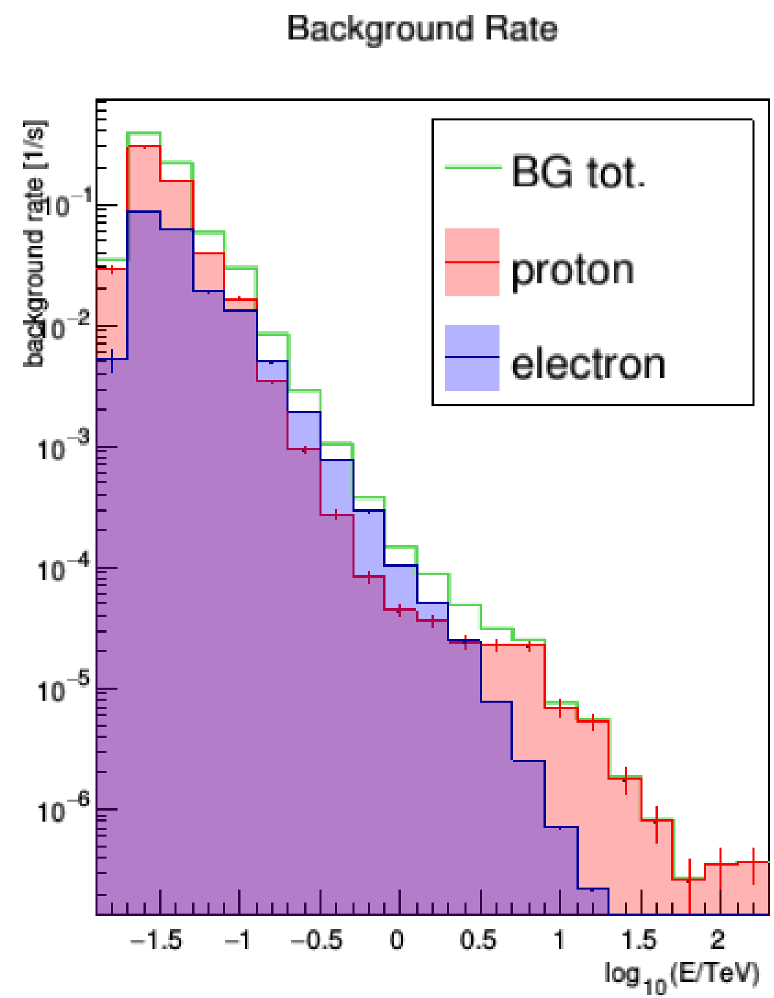
Muon energy spectral at the ground level

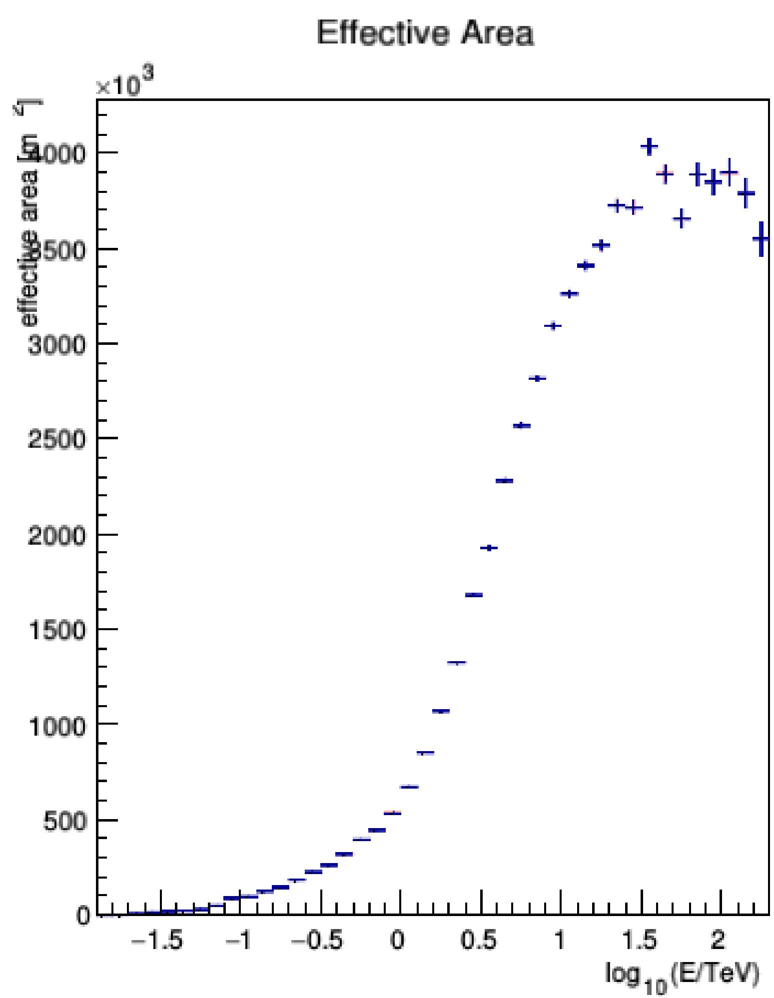


Difference between model is small

Other information contained In IRF

of residual background events/ effective area





Model dependence check: deposited energy in EM shower

of events (normalized by total event number) VS fraction of energy deposited in EM component

The probability that more than 50% of the primary energy deposited in the EM component

Maier & Knapp, 2007