Cosmic ray physics at MATHUSLA

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Cosmic ray physics at MATHUSLA

Content

Introduction

Cosmic rays

Energy spectrum extends from $\mathcal{O}(100)$ MeV up to ZeV

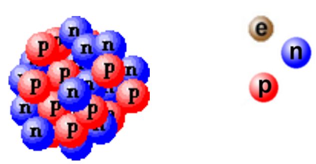
> Spectrum:

$F(E) = E^{-\gamma}$

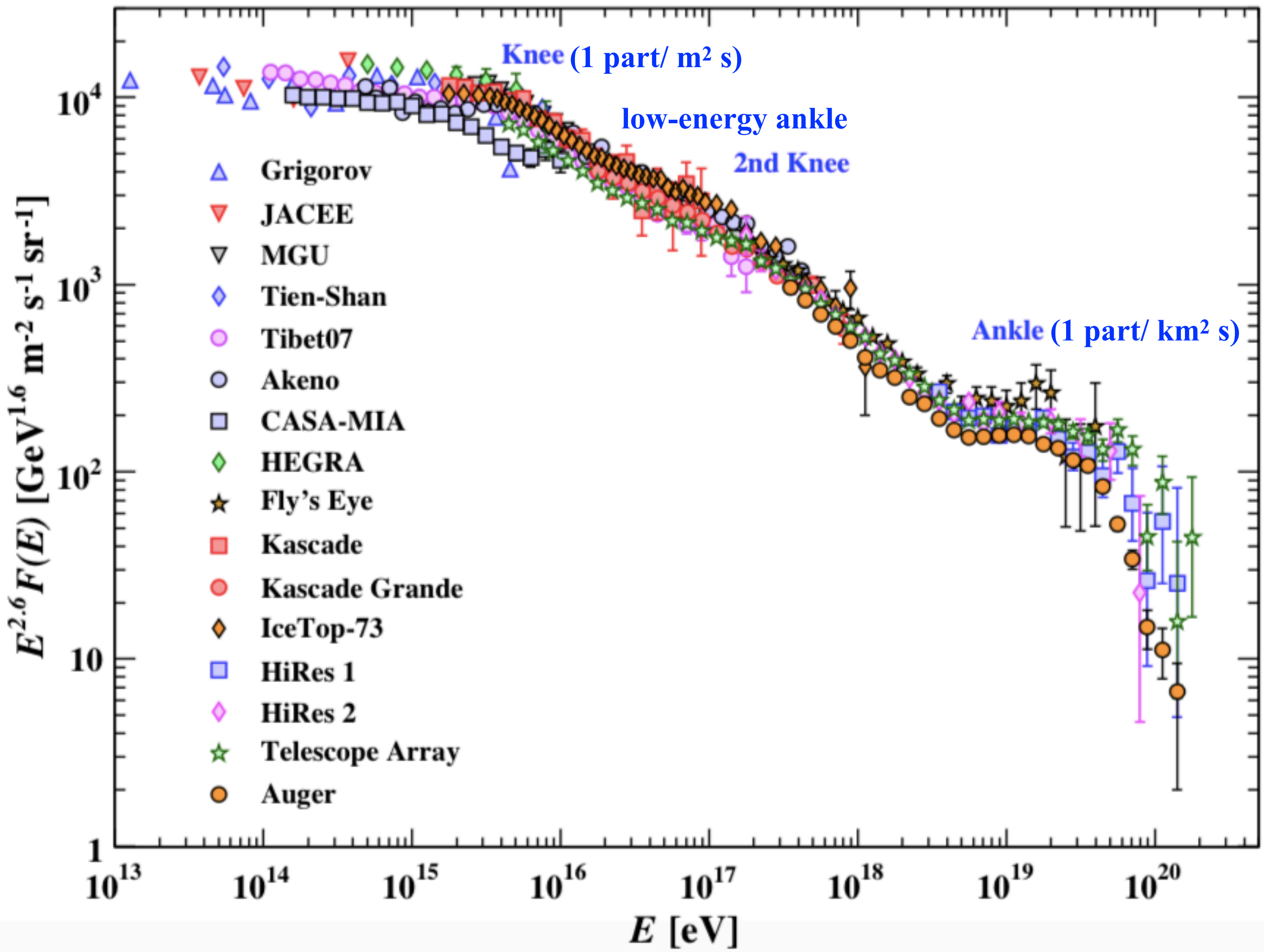
> Composition:

1) Electrons (2 %)
2) Atomic nuclei and
3) Neutrons (98 %)

Mainly H (83 %), He (11%)



PDG 2017



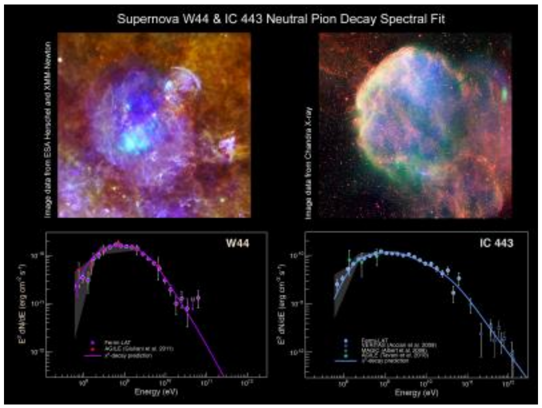
Introduction

Cosmic rays

> Origin:

Galactic:

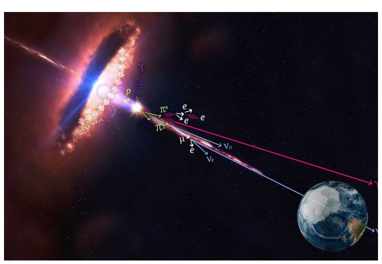
1) Sun
2) Supernovae Remnants
3) ?



M. Ackermann et al., Science Mag. 339 (2013) 807

Extragalactic:

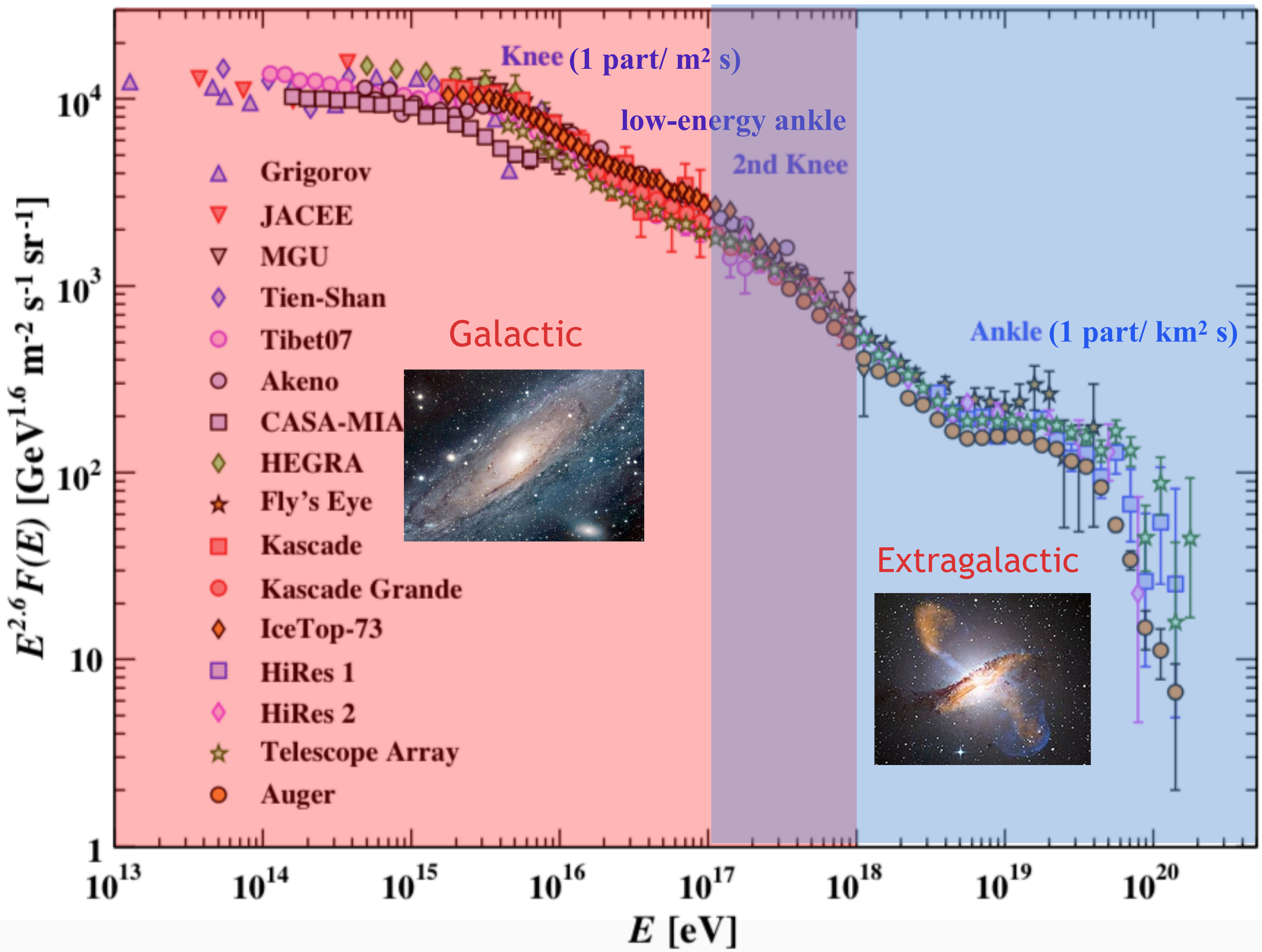
1) Blazars
2) ?



ICECUBE/NASA

Energy spectrum extends from O(100) MeV up to ZeV

PDG 2017



Introduction

Cosmic rays

Energy spectrum extends from O(100) MeV up to ZeV

> Questions:

1) Origin of structures in spectrum

2) Composition

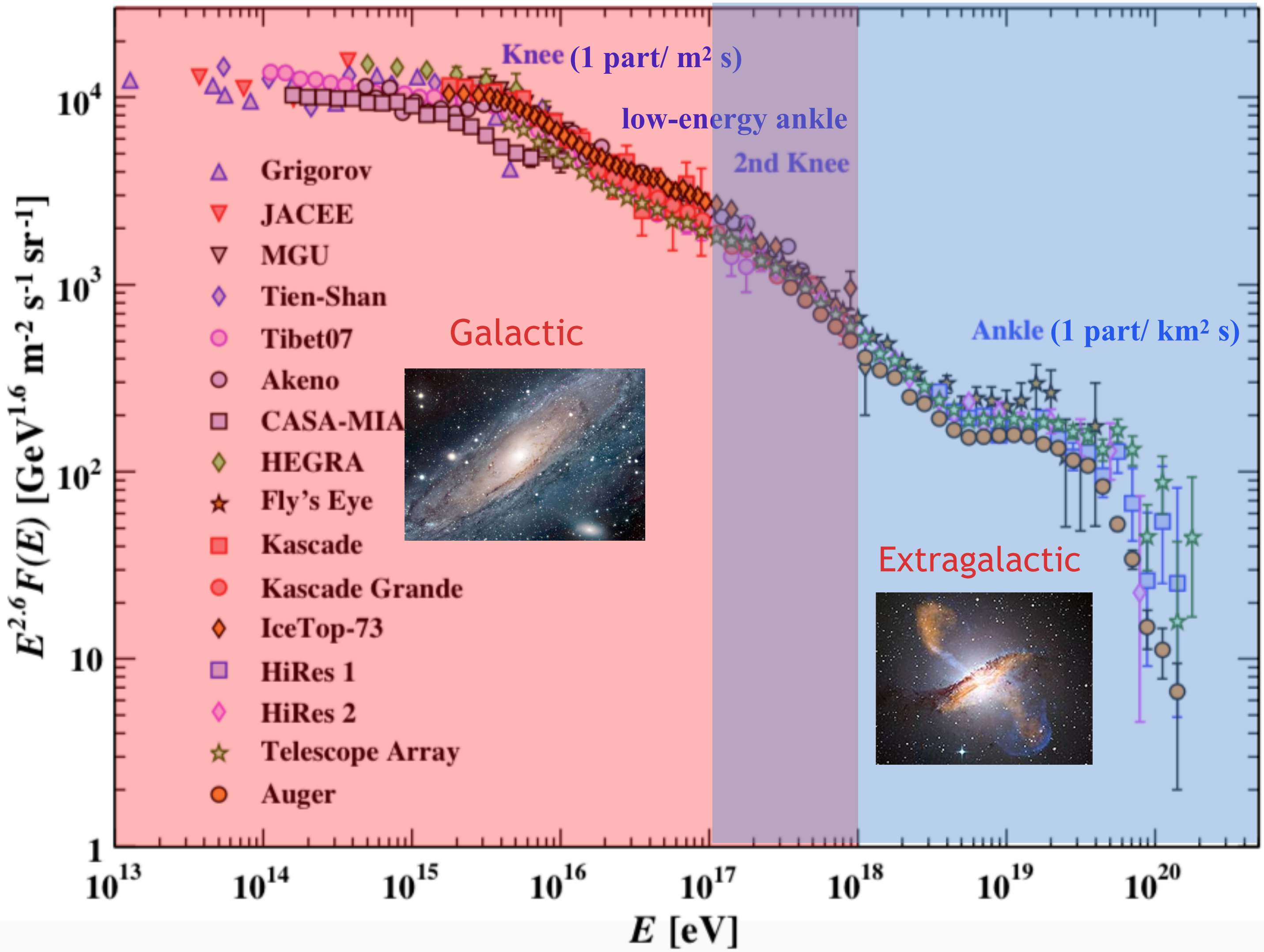
3) Sources

4) Propagation

5) Acceleration mechanism

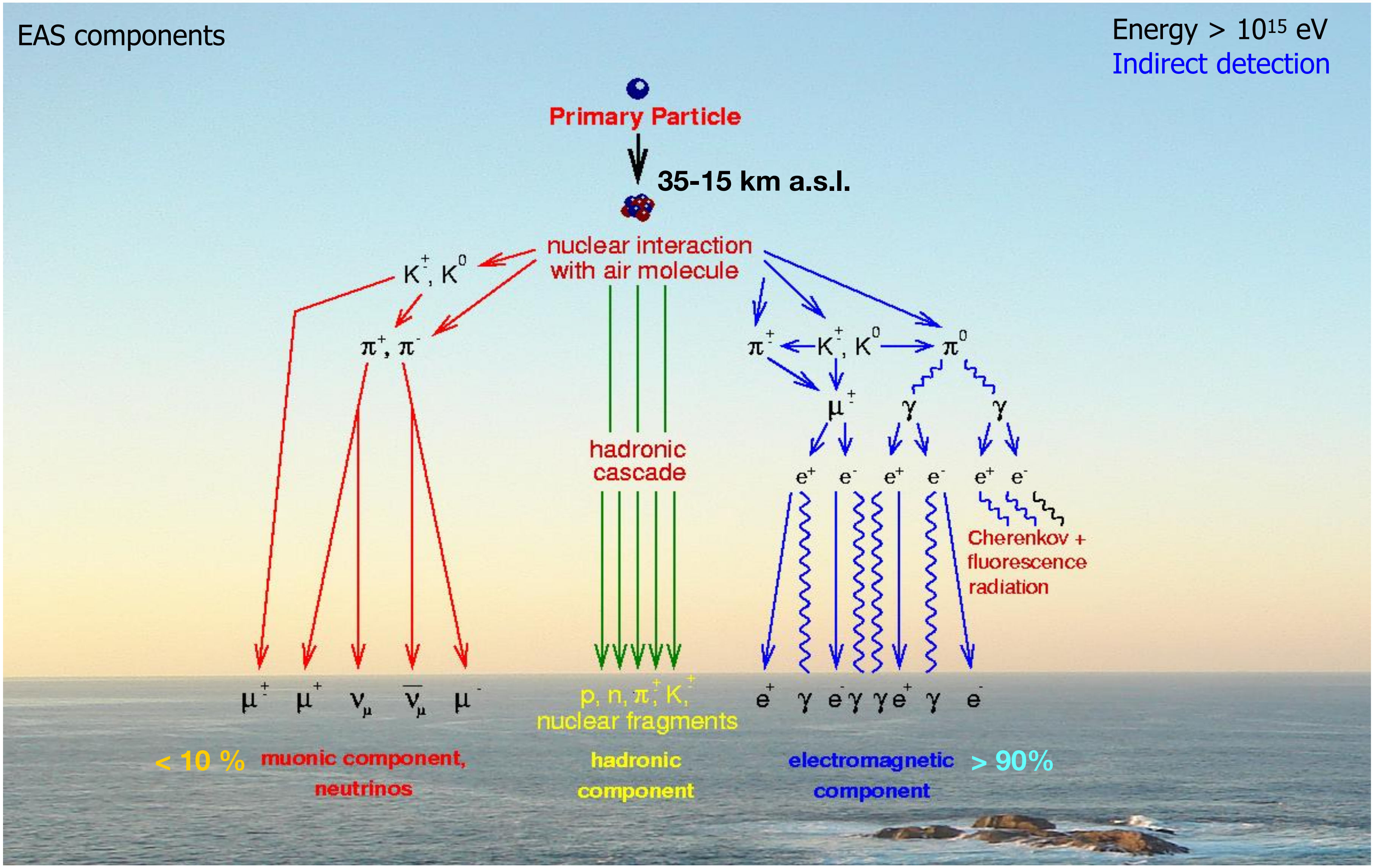
6) Galactic-extragalactic Transition

PDG 2017



Introduction

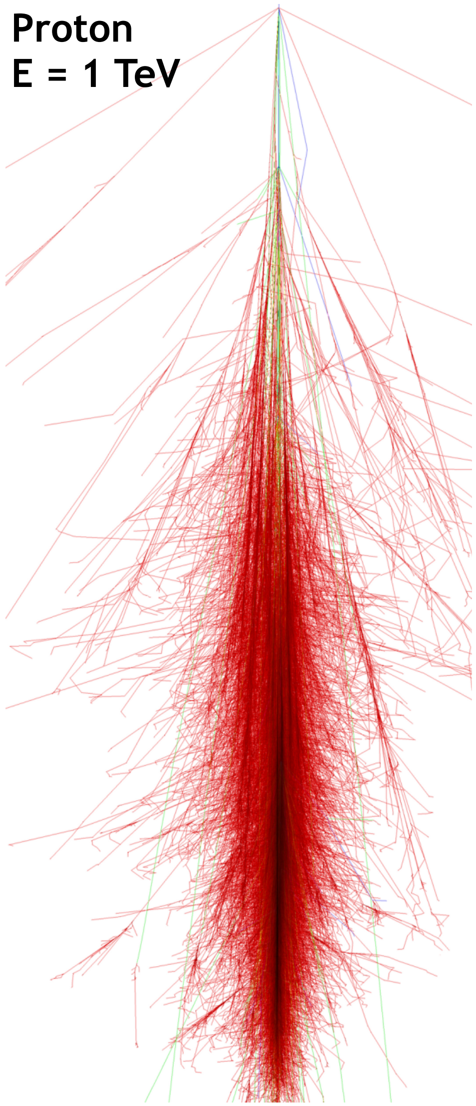
Indirect detection of cosmic rays through **extensive air showers** (EAS)



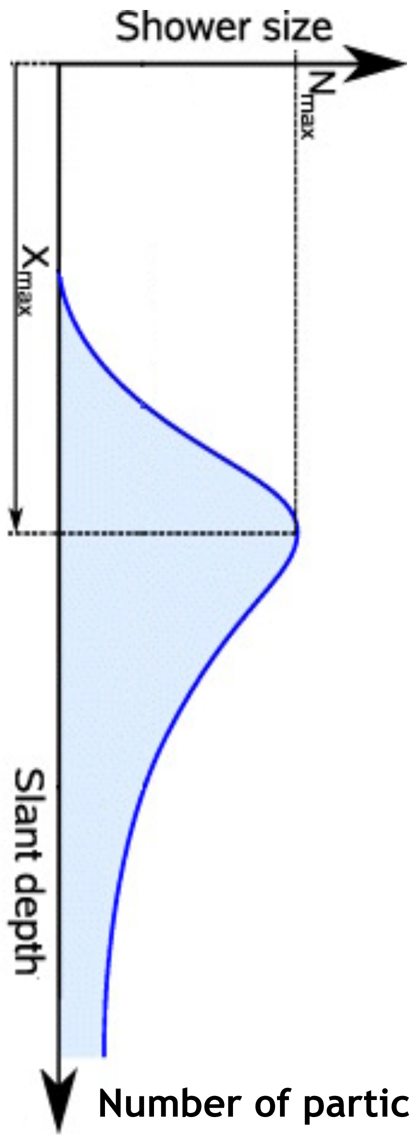
Introduction

Longitudinal development

Proton
E = 1 TeV



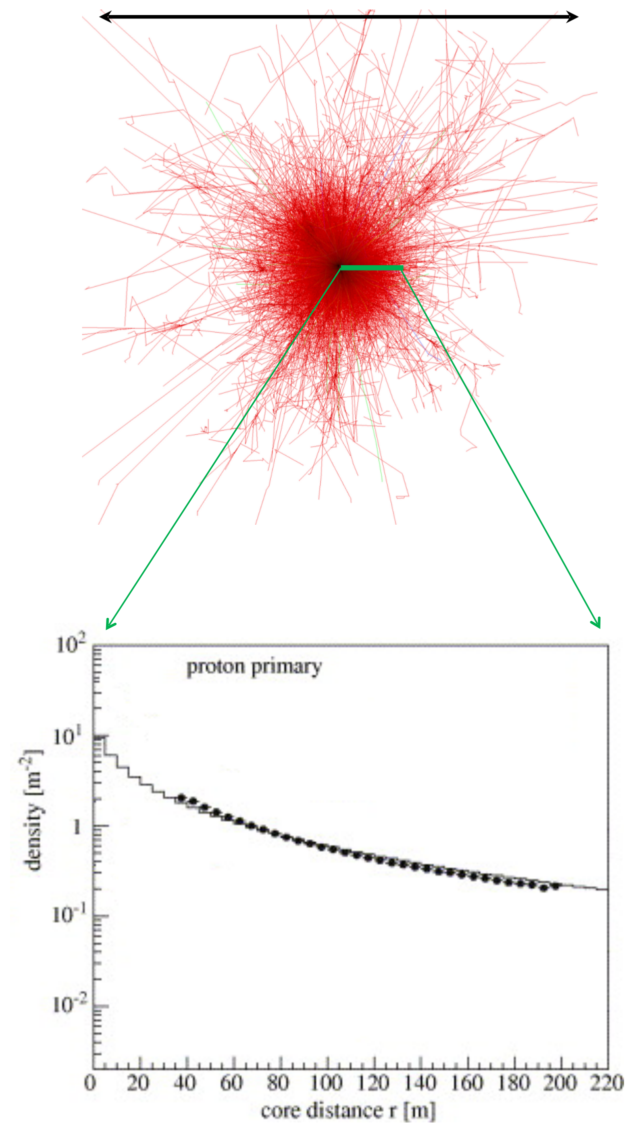
CORSIKA webpage



Number of particles at ground: $N \sim E^{\alpha}$

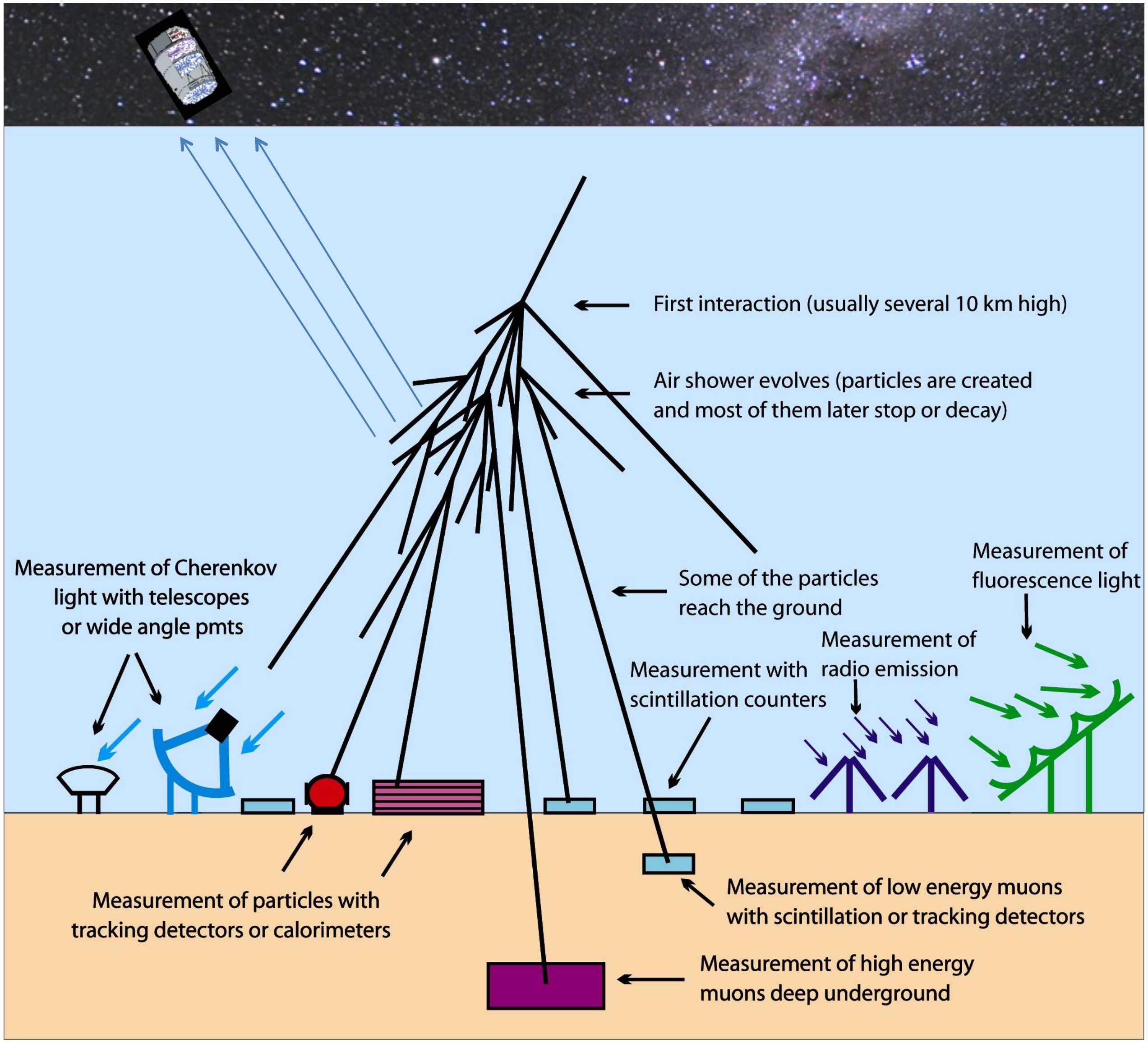
Lateral development

$\mathcal{O}$(0.1 - 1 km)



Introduction

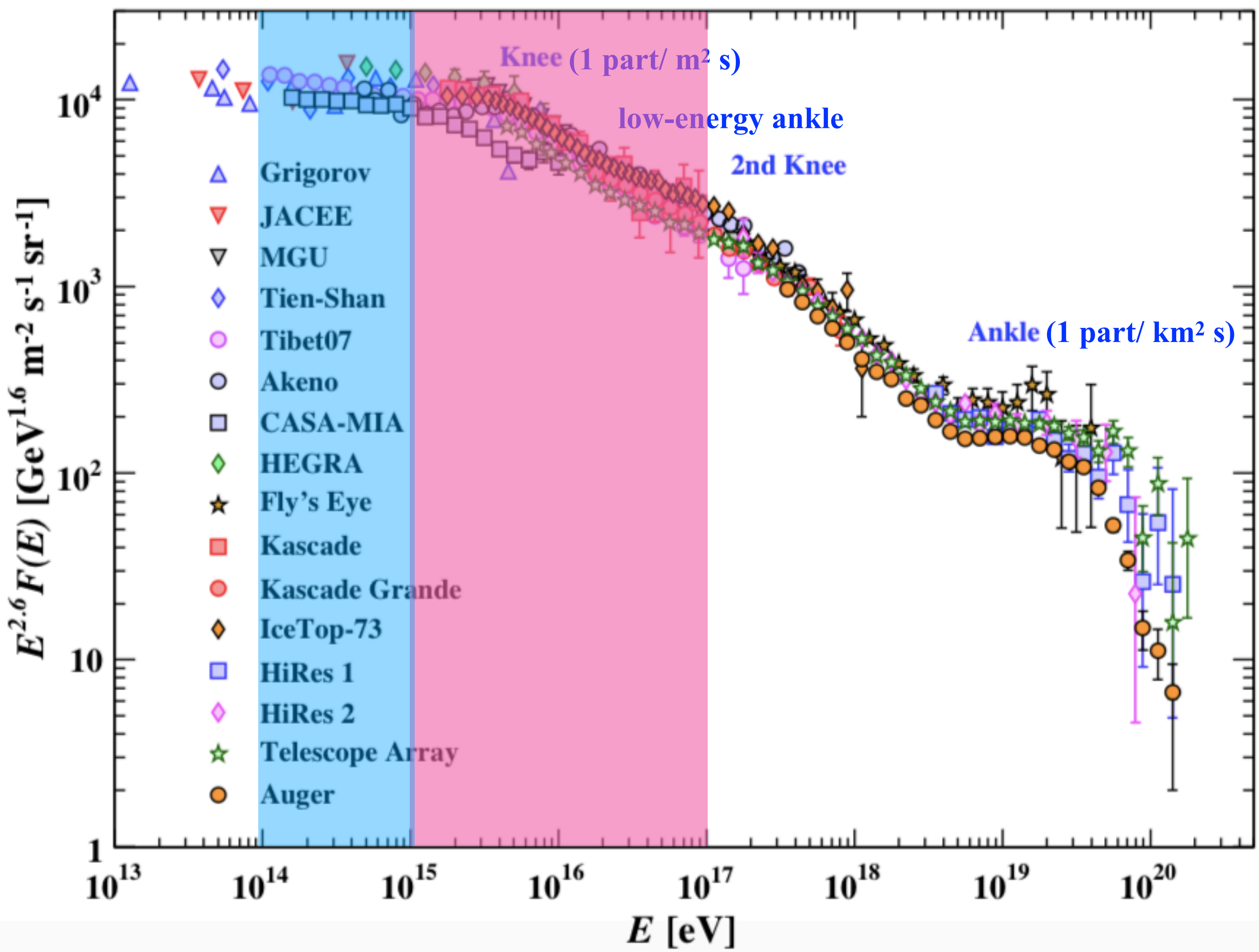
EAS detection from Earth and space



MATHUSLA as an EAS detector

Expected energy range sensitivity: 10^{14} - 10^{17} eV **Full efficiency > 10^{15} eV**

PDG 2017



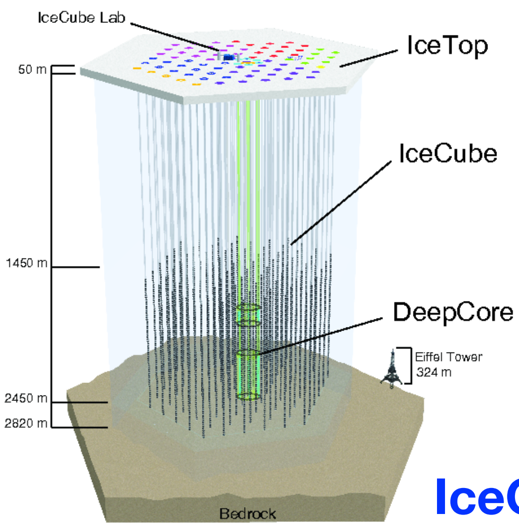
From the size of the instrument, altitude, and past CR detectors

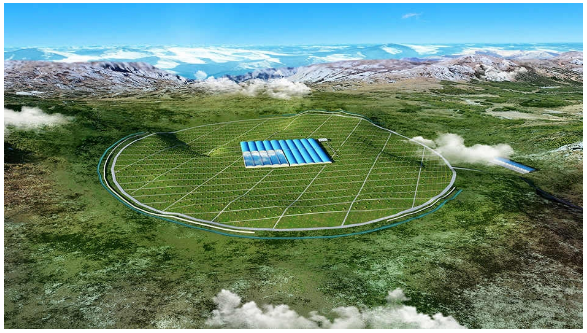
MATHUSLA as an EAS detector

Modern/future experiments sensitive to the energy range of MATHUSLA

Experiment	Energy range	Altitude (m a. s. l)	Size	Technique
Taiga	$>$ 30 TeV-γ's;$>$ 100 TeV-CR	675	0.25 km^2	IACTs
HAWC	100 GeV - 100 TeV	4100	22000 m^2	WCD
HAWC-Outrigger	100 GeV - PeVs	4100	$(8.8-11)\times 10^3\ m^2$	WCD
IceCube	TeV - PeV	-2450 to -1450	1 km^3	WCD
IceTop	10 TeV-1 EeV	2835	1 km^2	WCD
TALE (TA)	$10^{15.5}$ eV - $10^{18.5}$ eV	1550	700 km^2	FD, Sci.
LHAASO	10^{11} eV - 10^{17} eV	4410	1 km^2	WCD,AC,Sci.

HAWC (Mexico)





LHASSO (China)

IceCube/IceTop (Antartica)

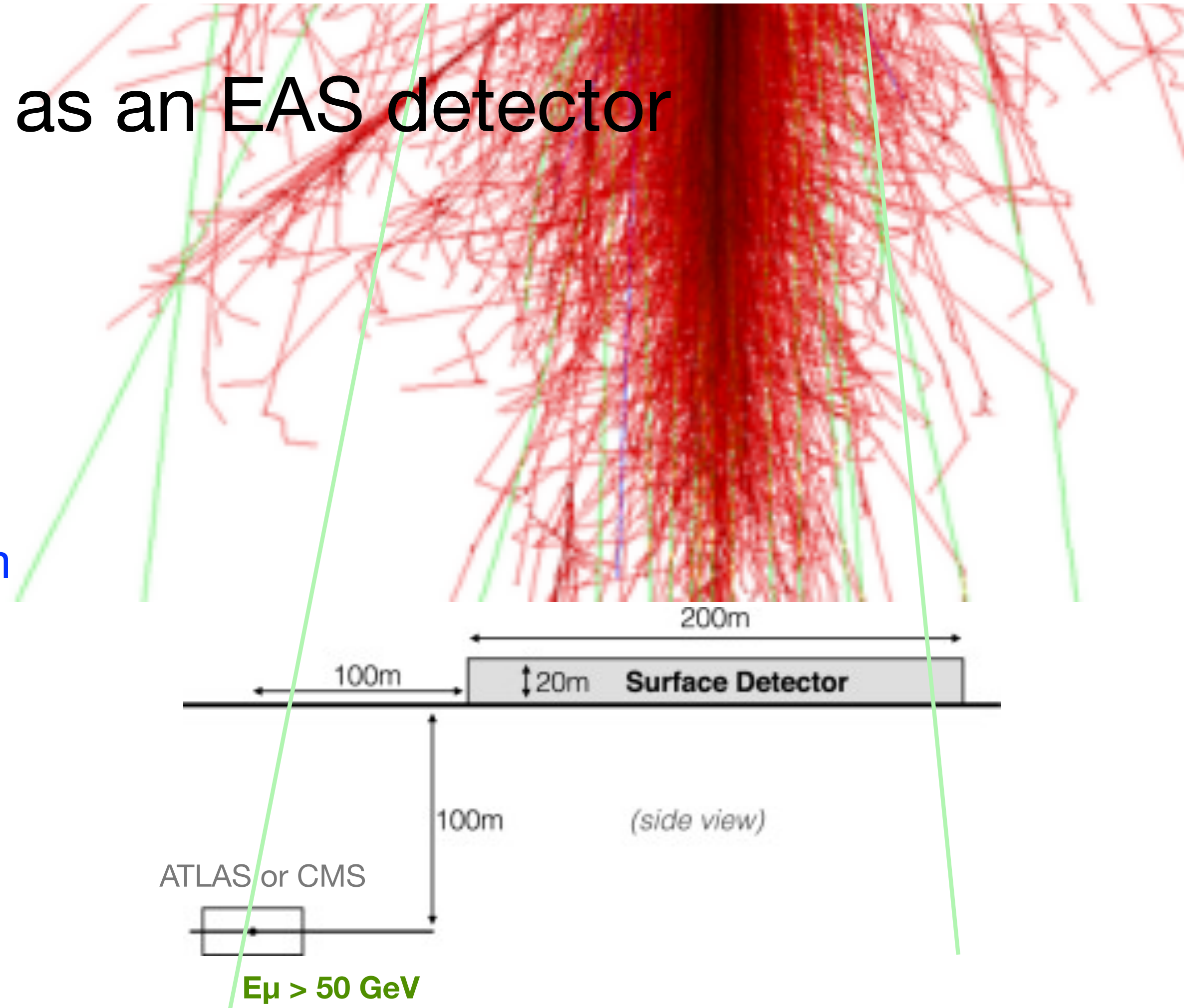
MATHUSLA as an EAS detector

Characteristics

$V = 8 \times 10^5\ m^2$

$h \sim 436$ m a.s.l. ($\sim 975\ g/m^2$)

Sampling EAS front after maximum



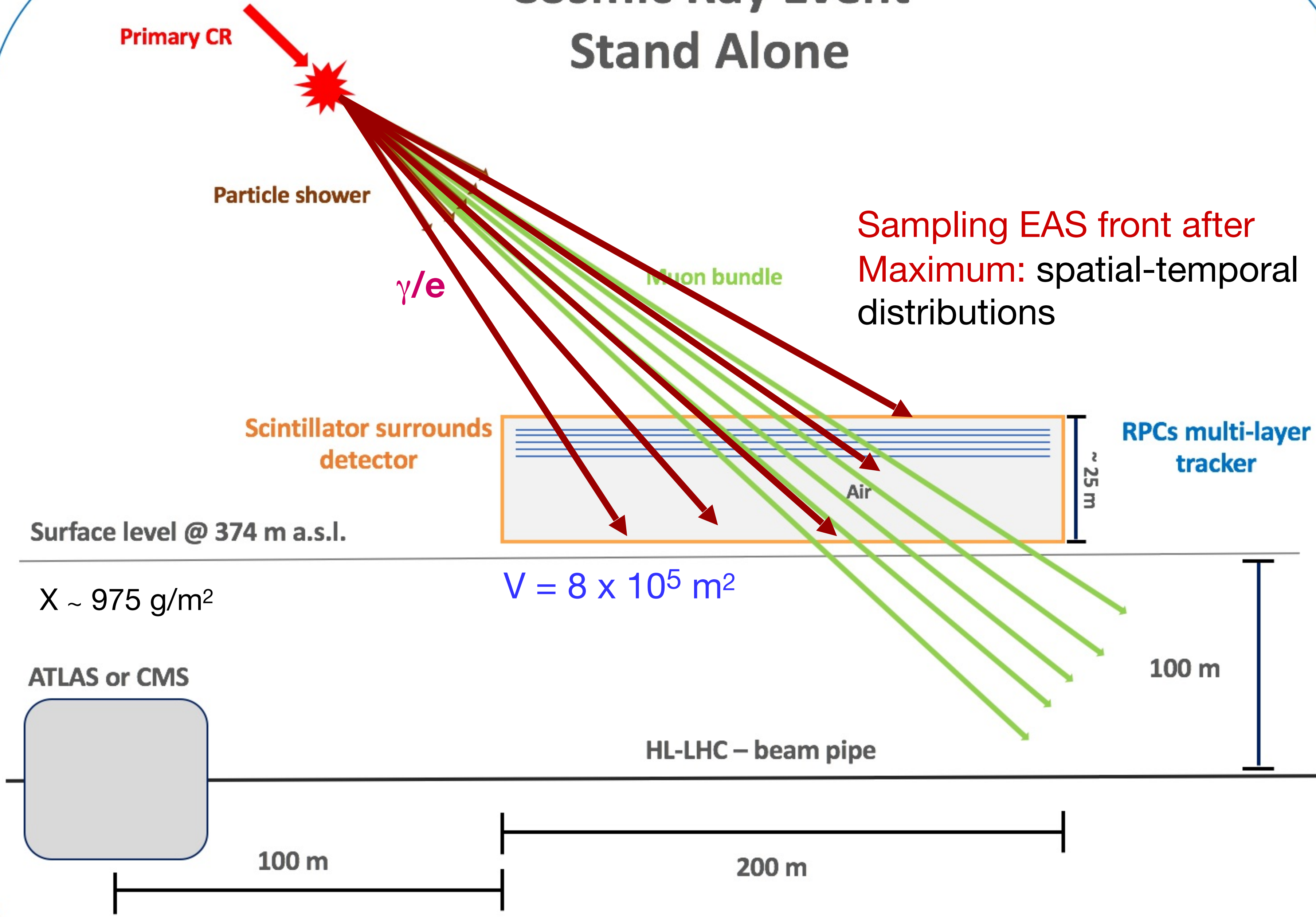
Two modes for EAS sampling:

Stand alone mode (STD): MATHUSLA (scintillator planes and RPC's) alone.

Combined mode (CB): MATHUSLA and the underground detector.

Golden events: Local shower μ's sampled with the collider detector for EAS with cores landing on MATHUSLA sensitive area.

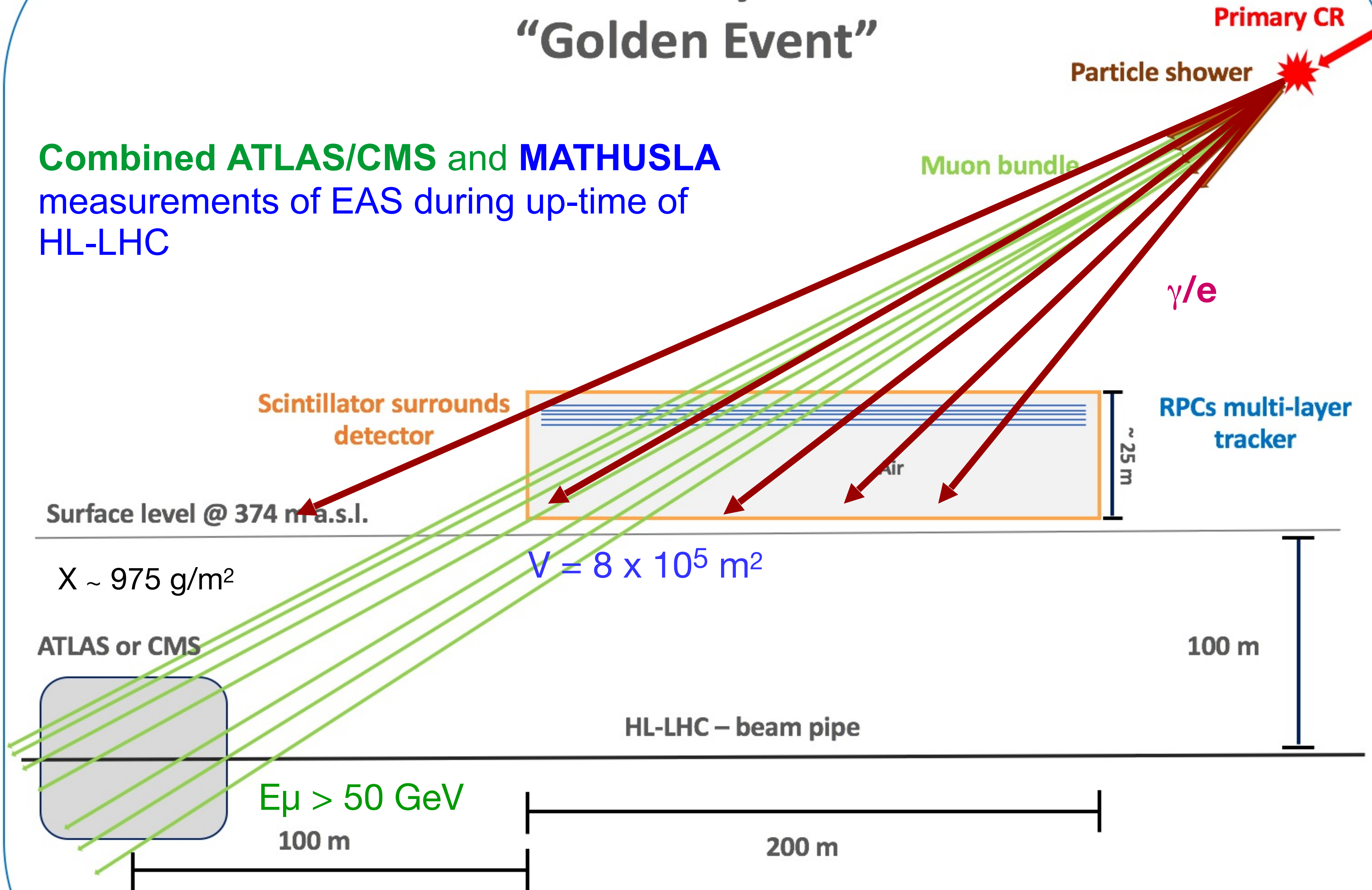
Cosmic Ray Event Stand Alone



Martin Subieta

Cosmic Ray Event
"Golden Event"

Combined ATLAS/CMS and **MATHUSLA** measurements of EAS during up-time of HL-LHC



Martin Subieta

MATHUSLA as an EAS detector

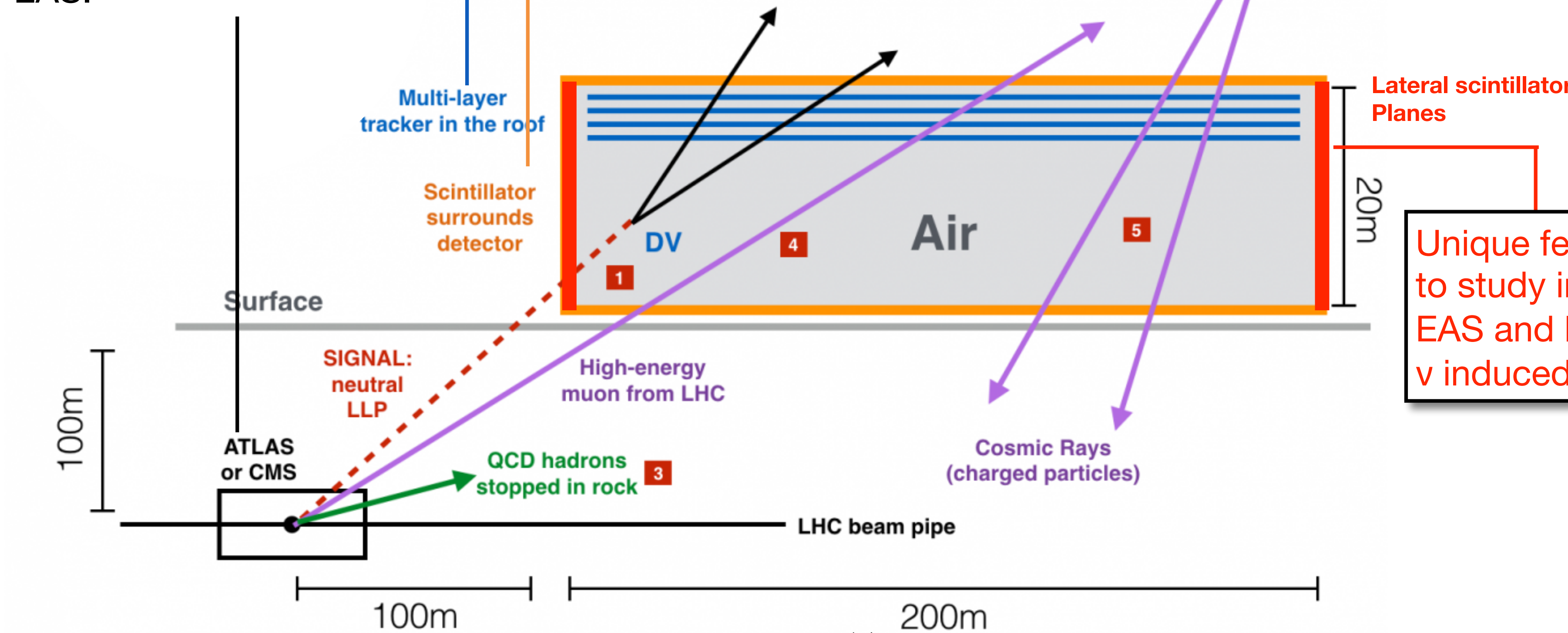
Monitor northern hemisphere, day and night, independent of weather conditions (increased statistics in comparison with Cherenkov arrays)

1.Enhanced angular resolution and better precision in EAS core location than other particles detector arrays.

2.Spatial-temporal measurements of EAS front at the finest level (**it could help for shower particle ID**).

1.Help in the study of μ-bundles.
2.In CB mode will complement MATHUSLA measurements of EAS.

1.Help in reconstruction of arrival direction and core location of air showers.
2.Help to check systematics on EAS observables.



Unique feature to study inclined EAS and look for ν induced events

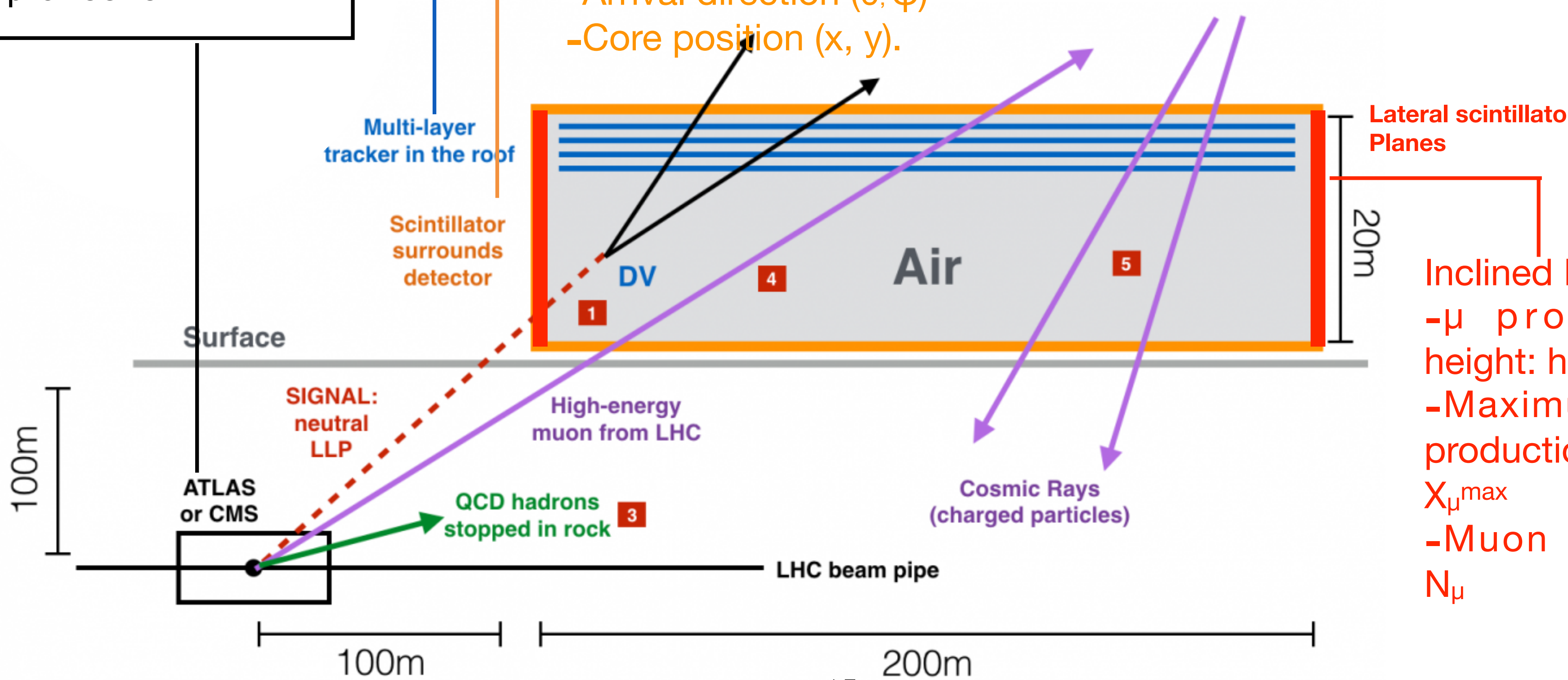
MATHUSLA as an EAS detector

With no e/μ separation

- Lateral density distribution: $\rho_{ch}(r)$.
- Total number of charged particles: N_{ch}.
- Arrival times: t(r).
- Lateral shower age: s.
- Arrival direction (θ, ϕ)
- Core position (x, y).

- μ densities
- μ^+/μ^- ratio
- μ energy spectrum
- μ direction

- Lateral density distribution: $\rho_{ch}(r)$.
- Total number of charged particles: N_{ch}.
- Arrival times.
- Lateral shower age: s.
- Arrival direction (θ, ϕ)
- Core position (x, y).



Inclined EAS
- μ production height: h_μ
- Maximum of μ production depth: X_μ^{max}
- Muon content: N_μ

Cosmic ray physics case

1. Cosmic rays

+ Energy spectrum of cosmic rays
    - Obtain fine details of spectrum
+ Composition
    - Spectra of individual chemical species
    - New light knee ~ 700 TeV as observed by ARGO-YBJ?
    - Fine spectrum of heavy component of CRs
+ Anisotropies
    - Look for point sources
    - Anisotropy maps vs composition? It depends on statistics

2. High energy neutrinos

+ Look for Earth-skimming/atmospheric/cosmic events.
    - Neutrino oscillations, atmospheric flux, neutrino interactions, etc

Cosmic ray physics case

3. Test of hadronic interaction models

+ Shower particles

- Correlation with N_{μ}, N_{h}, N_{e}
- Arrival times of particles
- High energy muon excess
- Attenuation length of shower muons
- Muon production height (MPH)
- Lateral distribution of muons/electrons/hadrons
- For events measured simultaneously with MATHUSLA/underground detector:
  > Muon bundles and relation with EAS primaries
  > Local ρ_{μ} (θ, E), μ+/μ- (θ, E) data for EAS

+ Shower properties

- Investigate fine spatial-temporal structure of EAS
- Study inclined EAS
- Look for exotic EAS events

4. VHE gamma rays

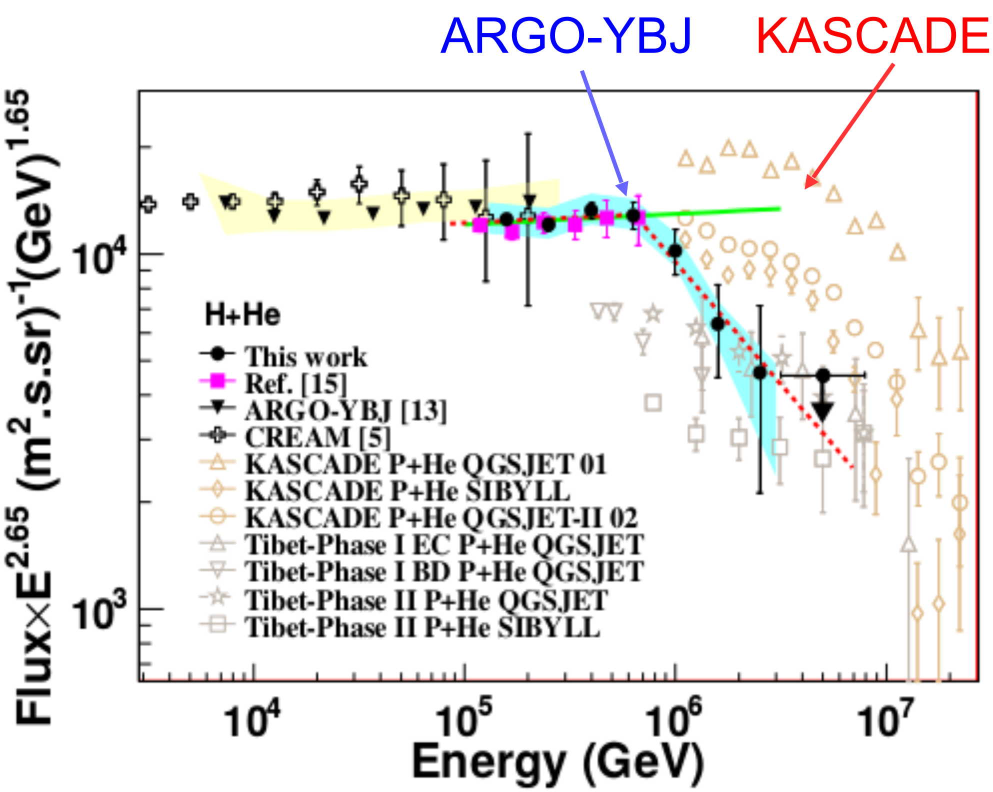
+ Look for γ-ra events —> upper limits

Cosmic ray physics case

Light spectrum of CRs

+ Two knees in the PeV light (H+He) spectrum?

+ Hidden systematic error?

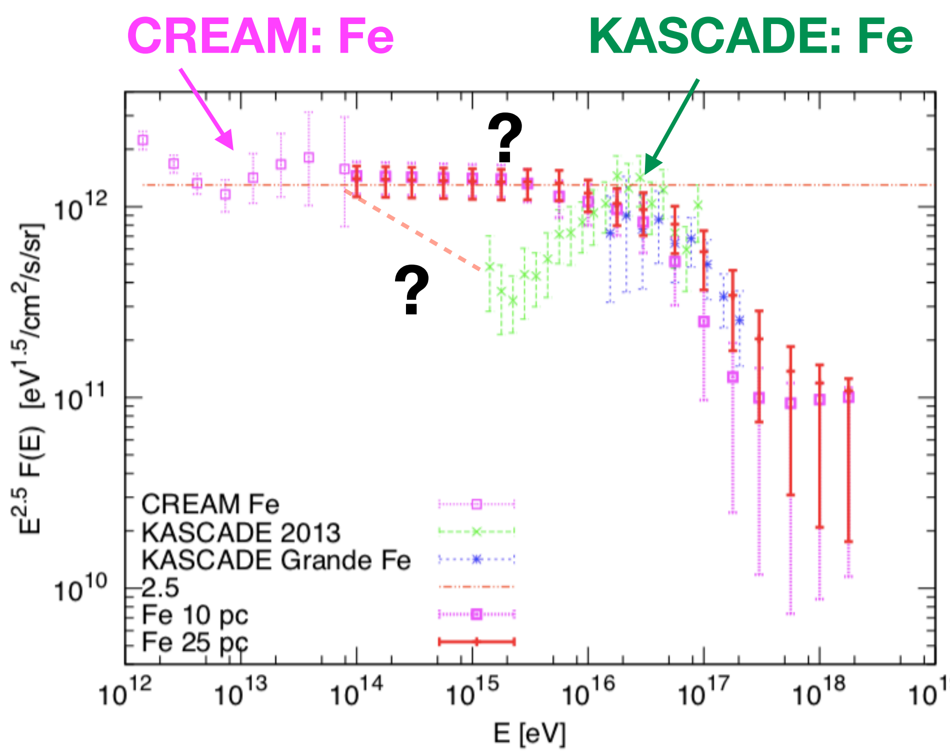


ARGO-YBJ Collab., astro-ph 1502.03164

Heavy spectrum of CRs

+ Fine structure in spectrum?

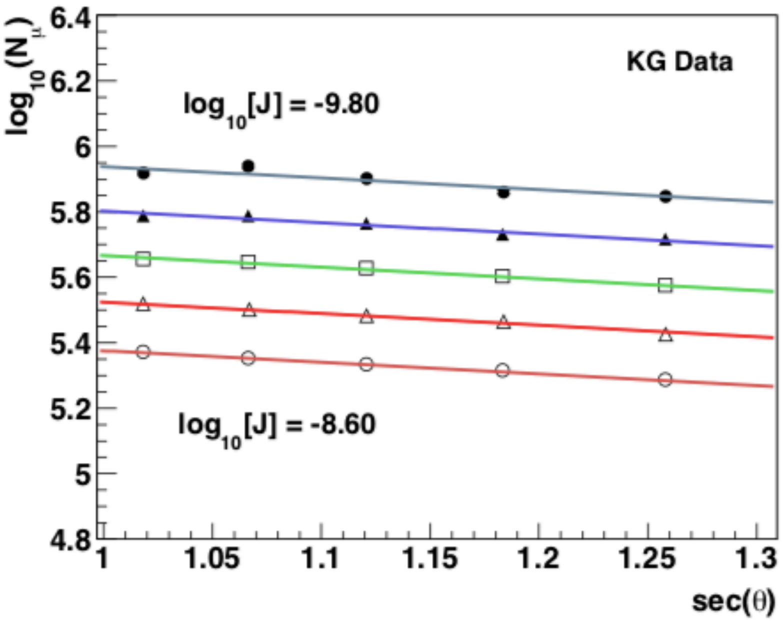
+ Systematic errors?



Giacinti et al., PRD 91 (2015) 083009

Cosmic ray physics case

KASCADE measurements



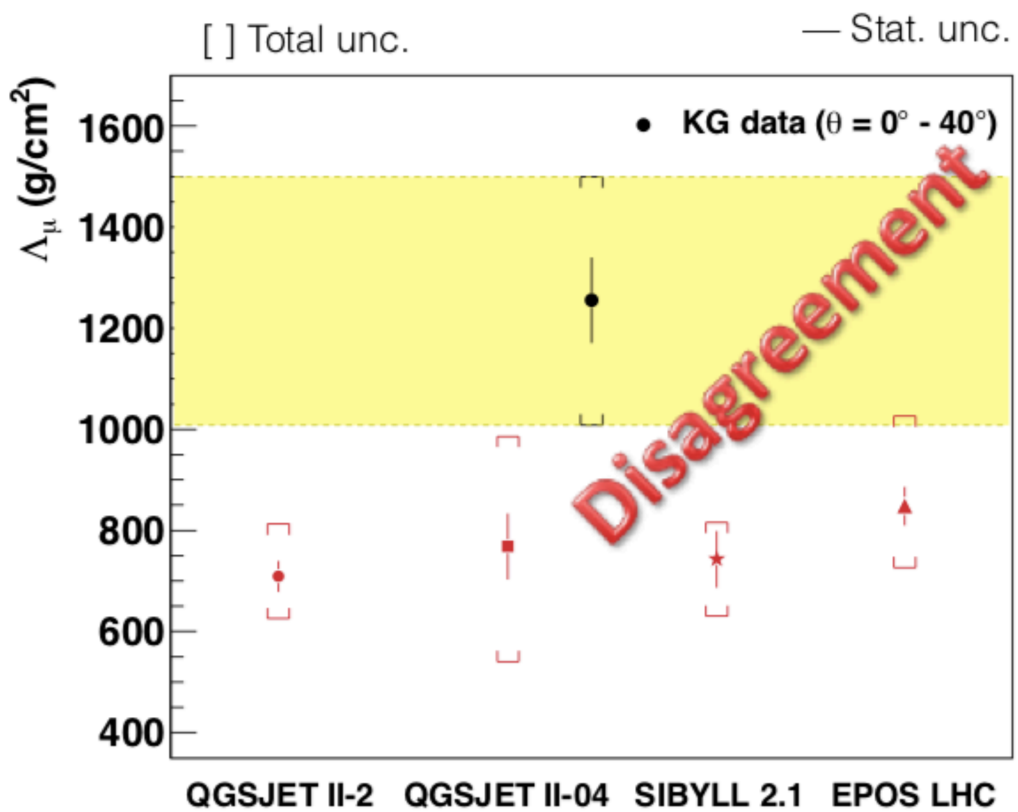
Muon attenuation length (Λ_μ):

$$N_\mu = N_\mu^0 \exp[-X_0 \sec(\theta)/\Lambda_\mu]$$

Measured muon attenuation length (E_{CR} ~ 10^{16} - 10^{17} eV) **is above** MC predictions .

Can we confirm the anomaly around the knee? E dependence?

Muon attenuation length

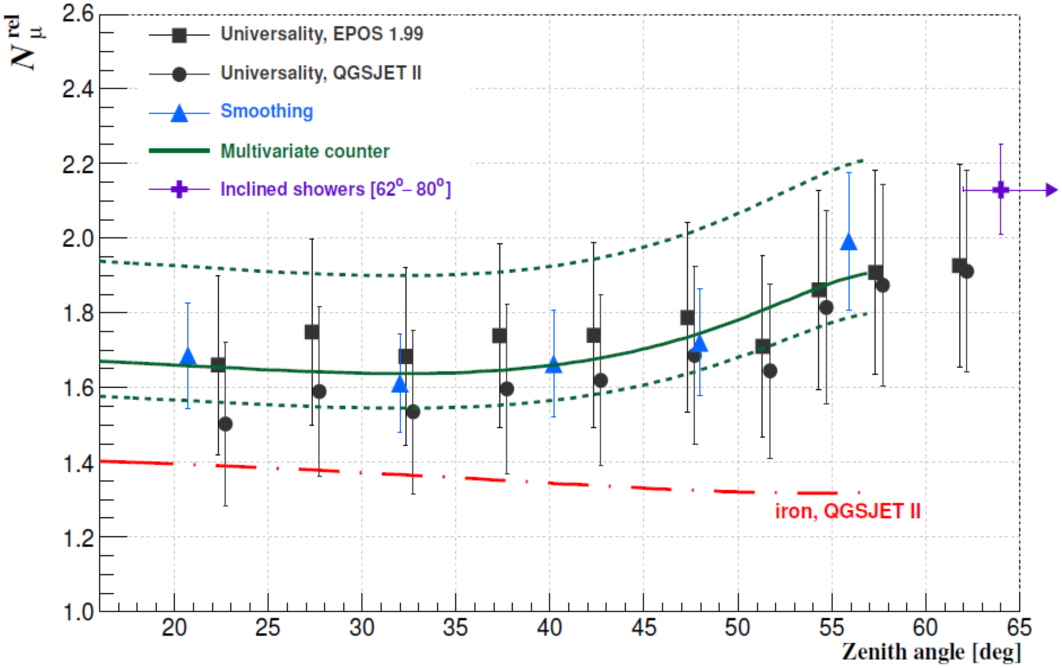


J.C. Arteaga et al., Astropar. Phys. 95 (2017) 25

Less effective attenuation in exp. data

Cosmic ray physics case

At ultra-high energies muon discrepancies have been observed by Auger:
Deficit of muons in MC predictions



Relative number of muons (measured data over protons QGSJET-II predictions at 10^{19} eV) at 1000 m from the EAS core.

A. Yushkov et al., Auger Collaboration, EPJ W. of Conf. 53 (2013)

Pierre Auger Observatory

Activities of the Cosmic Ray group

1. Investigate the capabilities of MATHUSLA as a cosmic ray detector

+ Write white document for CR physics case

  - 1st version has been written
  - Adding comments and correcting last version
  - Obtaining simulations and improving estimations

+ Produce data sets with MC simulations for cosmic rays

  - First data sets using **CORSIKA** with **QGSJET-II-04/GEISHA** were obtained
  - Different mass groups: **H, He, C, O, Si, Fe**

+ Investigate properties of CR in the MATHUSLA energy range

  - Preliminary analyses of shower size, particle content, event rates, etc… have been performed

Activities of the Cosmic Ray group

2. Estimate the background of secondary particles

+ Obtain the spectrum and event rate of muons, neutrinos and electrons
    - Preliminary estimations using CR's with E = $\mathcal{O}$(GeV) - 10 PeV were produced.
    - Study of the particle production at fixed energies.
    - Investigate the relevant energy CR range for MATHUSLA.
    - Study the effect of primary composition & shape of spectra of mass groups.
    - Zenith angle evolution
    - Effect of thinning

3. Obtain a generator to simulate background of secondary particles

+ Use results of own simulations and estimations from literature for comparison, for example,

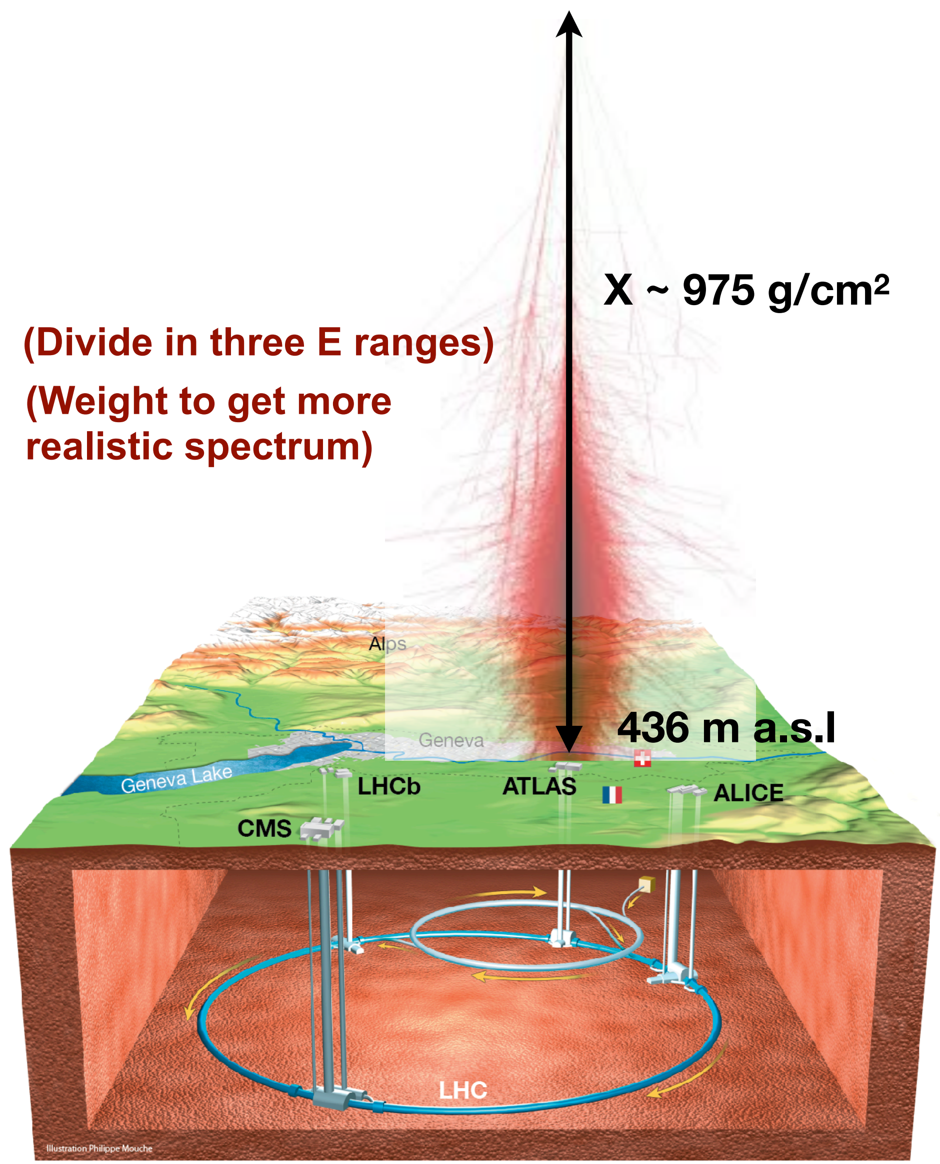
Honda et al., Phys. Rev. D 75, 043006 (2007)

V. Agrawal, T. K. Gaisser, P. Lipari, and T. Stanev Phys. Rev. D 53 (1996) 1314

Simulations

CORSIKA 7.6400	
High-energy hadronic model (E_h > 200 GeV)	QGSJET-II-04 EPOS-LHC SIBYLL 2.3
Low-energy model	Fluka Geisha
Mass groups	H, He, C, Si, O, Fe
Primary energy range	$\log_{10}$ (E/GeV) = 0.5 - 9
Primary spectrum	E^{-2}
Zenith angle range	0^o - 90^o
Energy cuts	hadrons (100 MeV) μ's(100 MeV) e's (3 MeV) ɣ's (3 MeV)
Atmosphere	Standard U.S. model, curved
Site	ATLAS
Magnetic field at site NOAA https://www.ngdc.noaa.gov/	(Bx, Bz) = (22.1, 41.6) μT
Detector Geometry	Flat/volume geometry

At the moment 14 x 10^6 simulations with QGSJET-II-04/Geisha



Simulations

> Vertical events

> Region of maximum efficiency (**E > 1 PeV**)

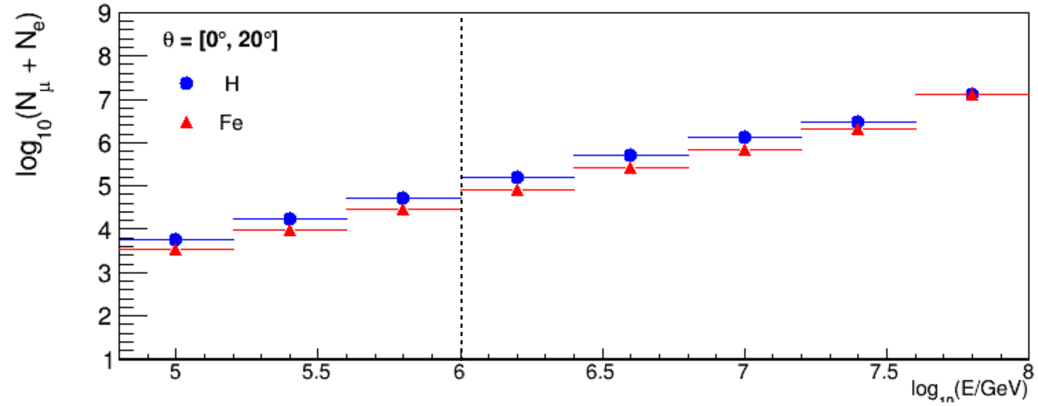
Shower size vs Energy

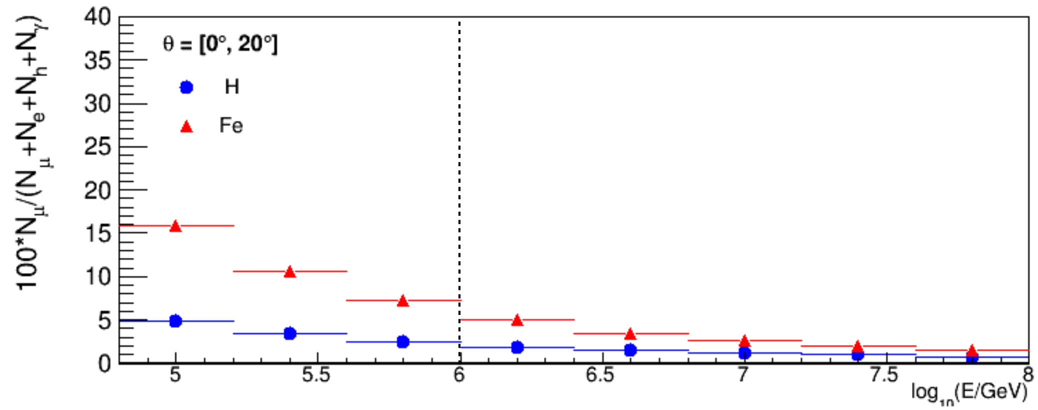
$N \sim E^a$

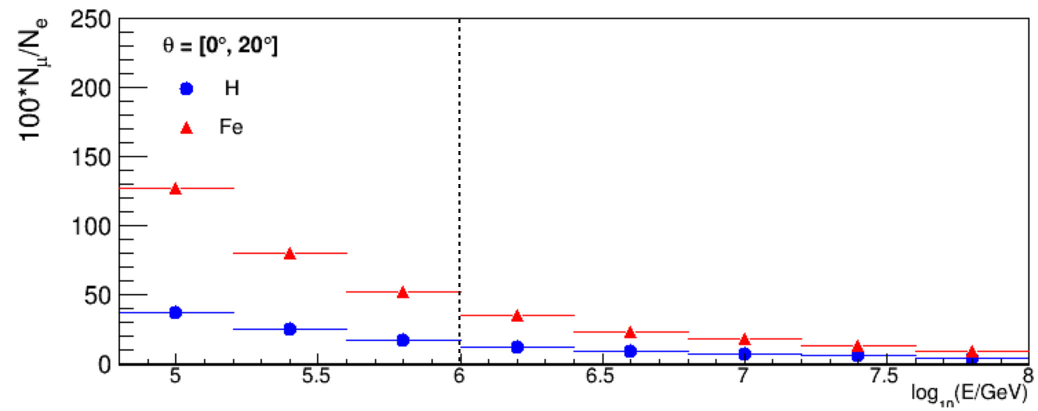
Muon content

$N_\mu/(N_{em} + N_h + N_\mu) < 7\%$

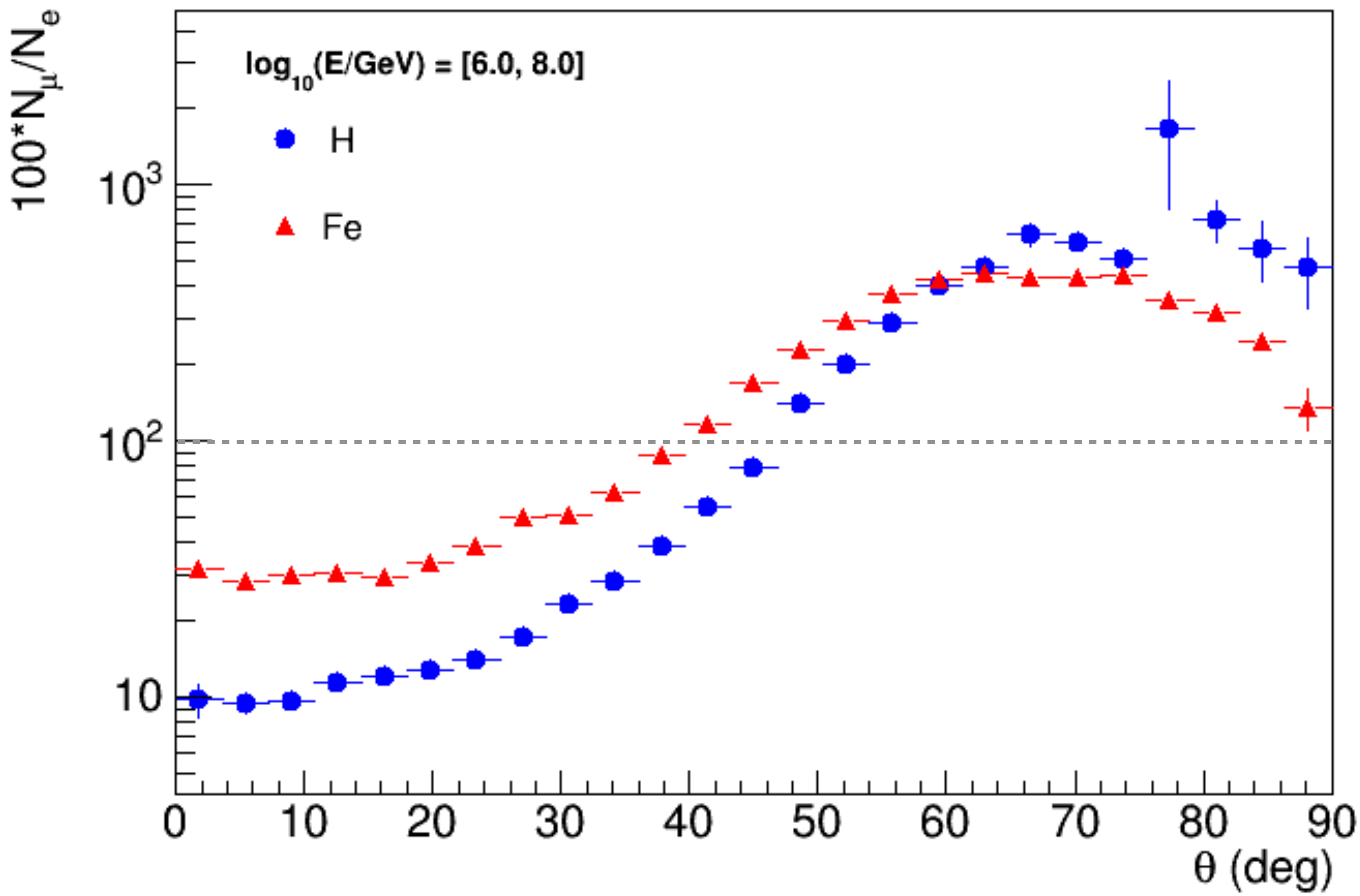
$N_\mu/N_e < 0.4$







Simulations



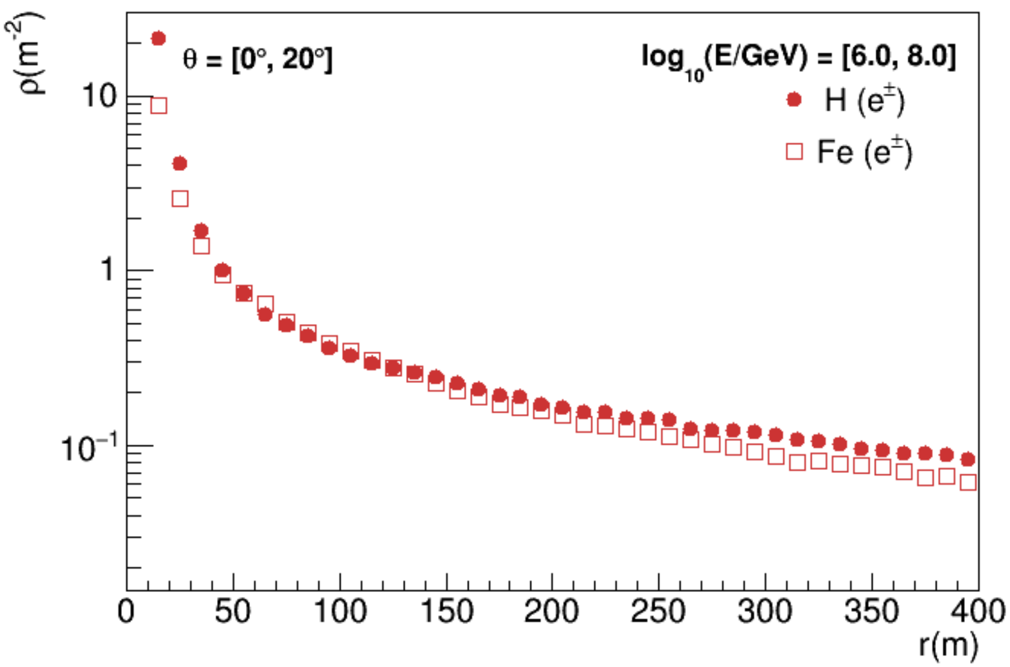
Zenith angle evolution of mean muon content

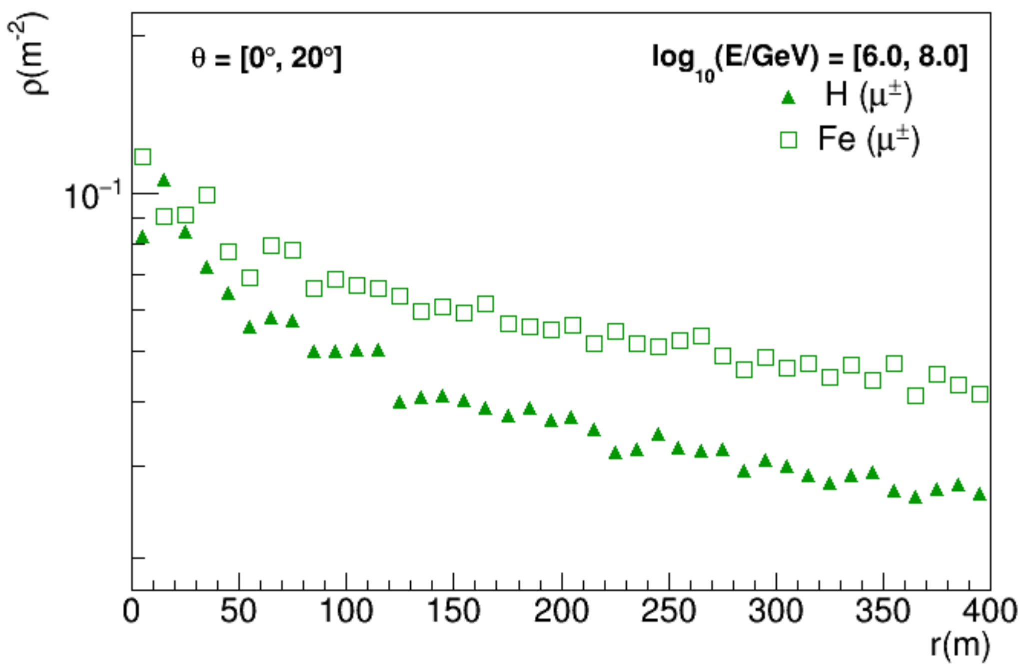
> Increases with θ up to 70º

> For θ > 70º atmospheric absorption has a relevant effect

Simulations

r: distance from EAS core at ground level





Mean electron lateral density distribution

> Decreases with **r**

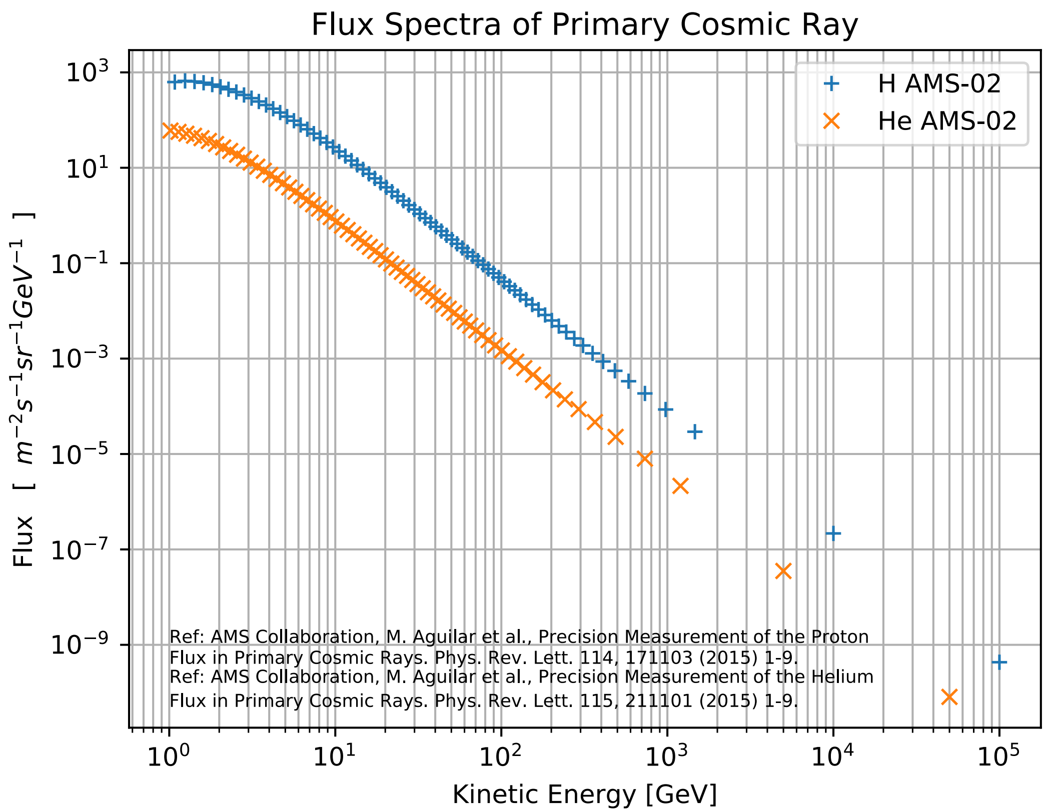
Mean muon lateral density distribution

> Flatter than **e** LDF

> Smaller than **e** component close to the core

> At large distances **μ** component Is larger than **e** component.

Secondary charged particles at fixed E



AMS-02 data was used at low energies in MC simulations:

- $\log_{10}(E/GeV) = [0.5, 5]$
- Only dominant elements:

  H (83%)
  He (11%)

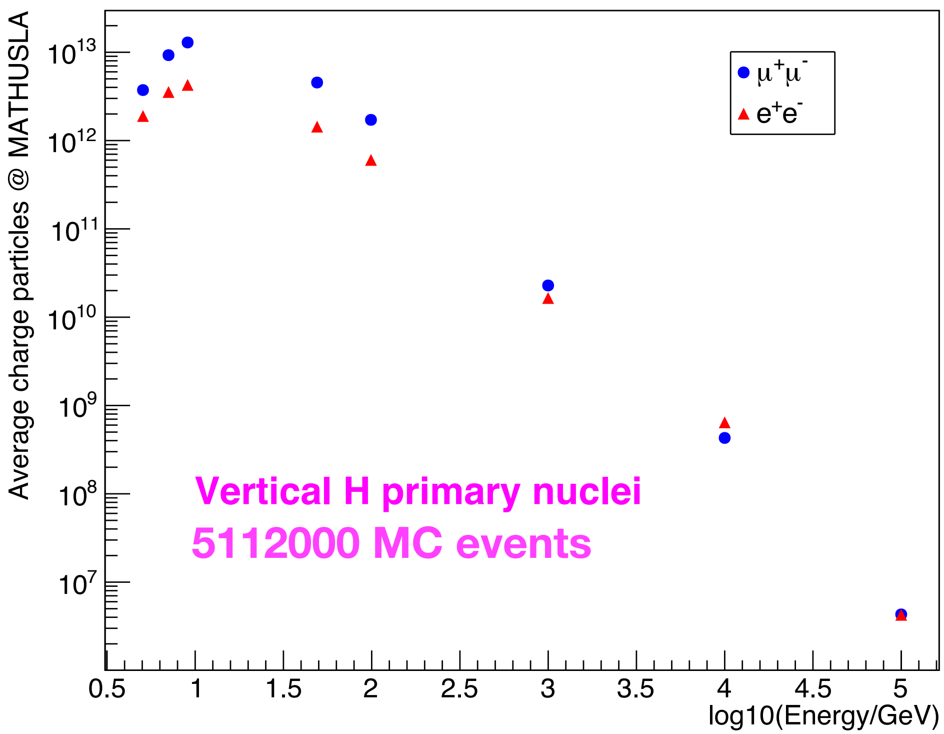
> Investigate production of secondaries at fixed E

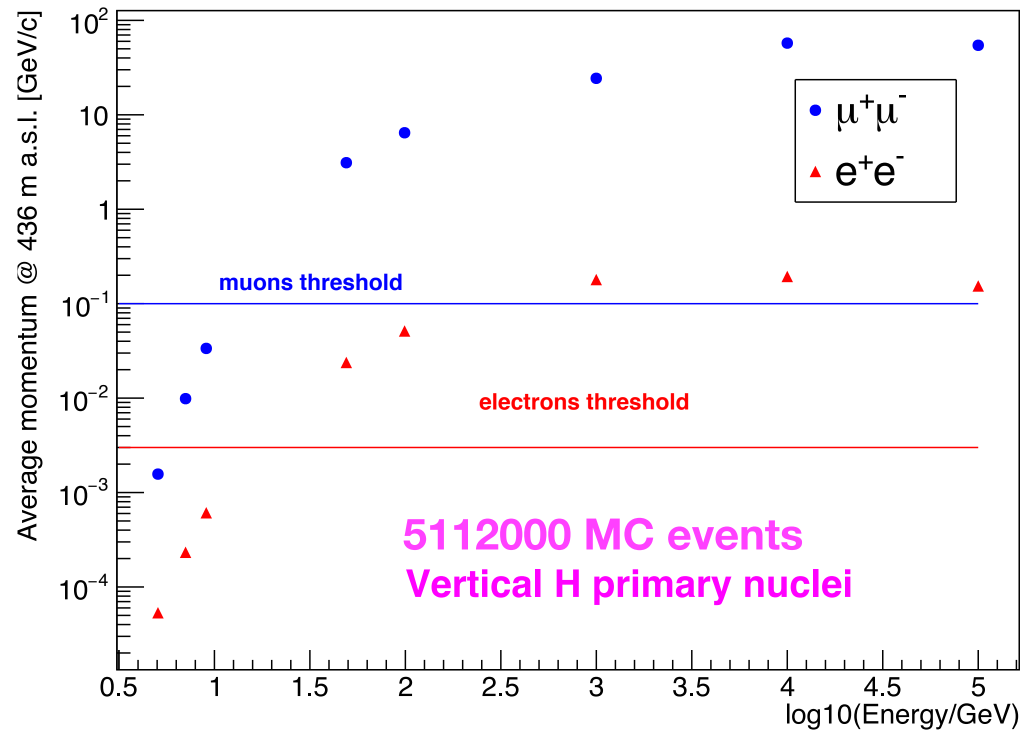
> Find lowest energy threshold for simulations

Secondary charged particles at fixed E

E: primary cosmic ray energy

θ = 0º





Secondary charged particles
@ MATHUSLA level

From **MC** simulations assuming
AMS-02 spectrum

Mean ***p*** for secondary charged particles
@ MATHUSLA level

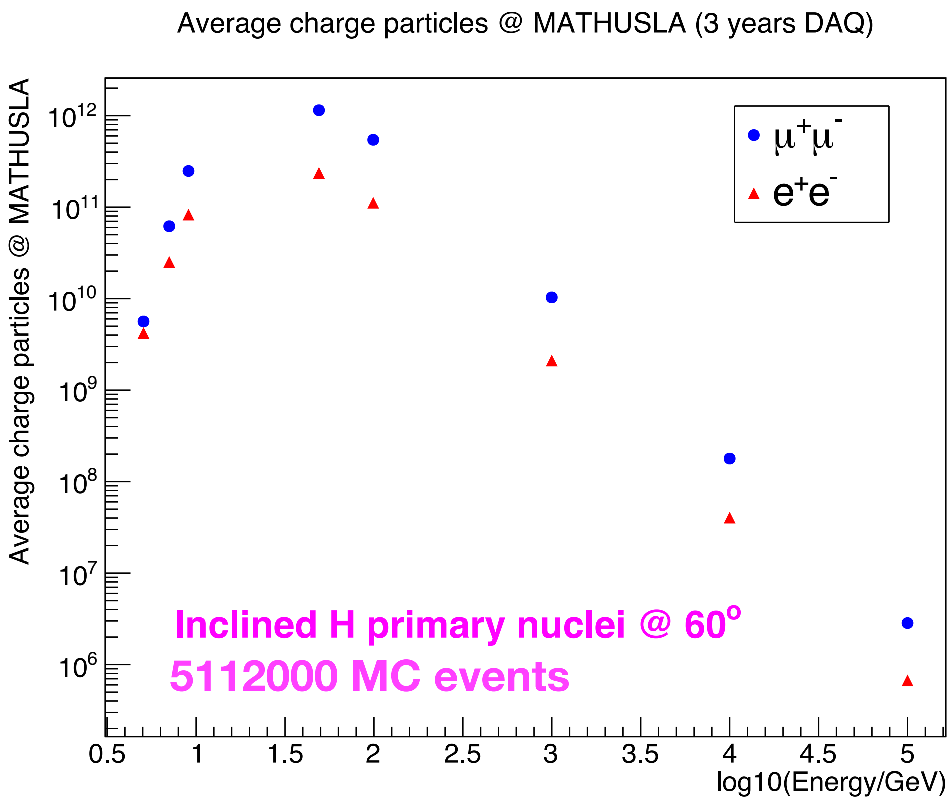
> More secondaries from LE primaries

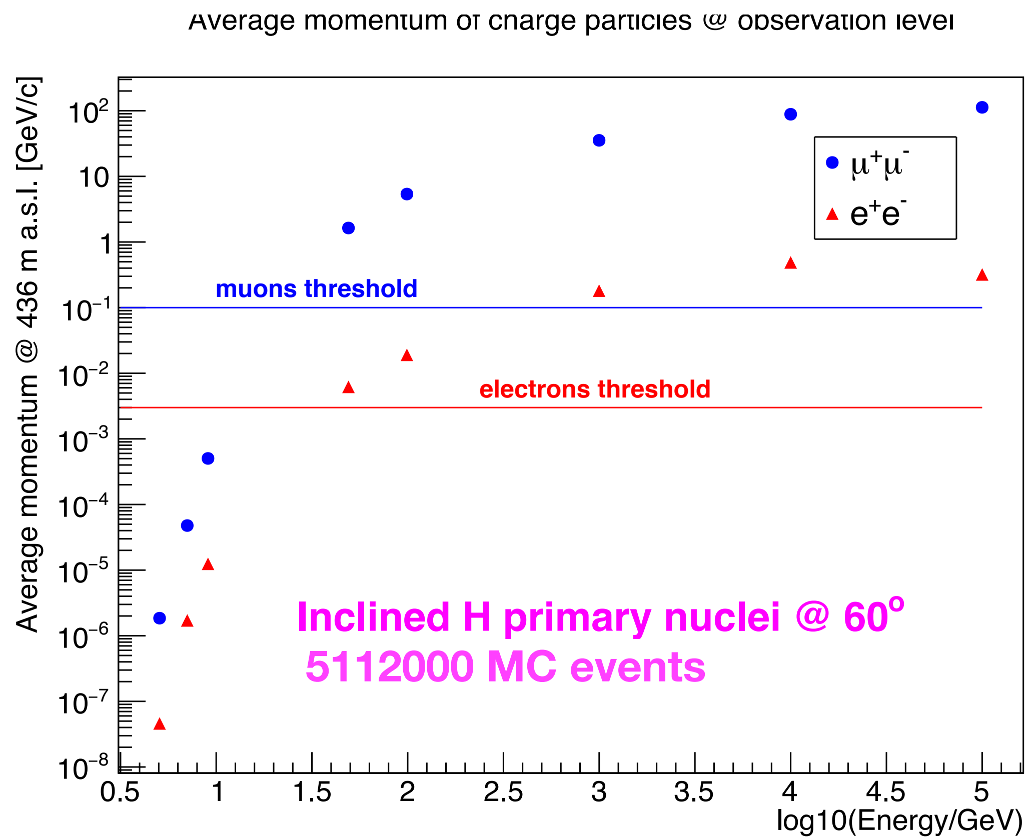
> mean *p* grows not linearly with E

Secondary charged particles at fixed E

E: primary cosmic ray energy

θ = 60°





Secondary charged particles
@ MATHUSLA level

From **MC** simulations assuming
AMS-02 spectrum

Mean ***p*** for secondary charged particles
@ MATHUSLA level

> Atmosphere attenuates the flux

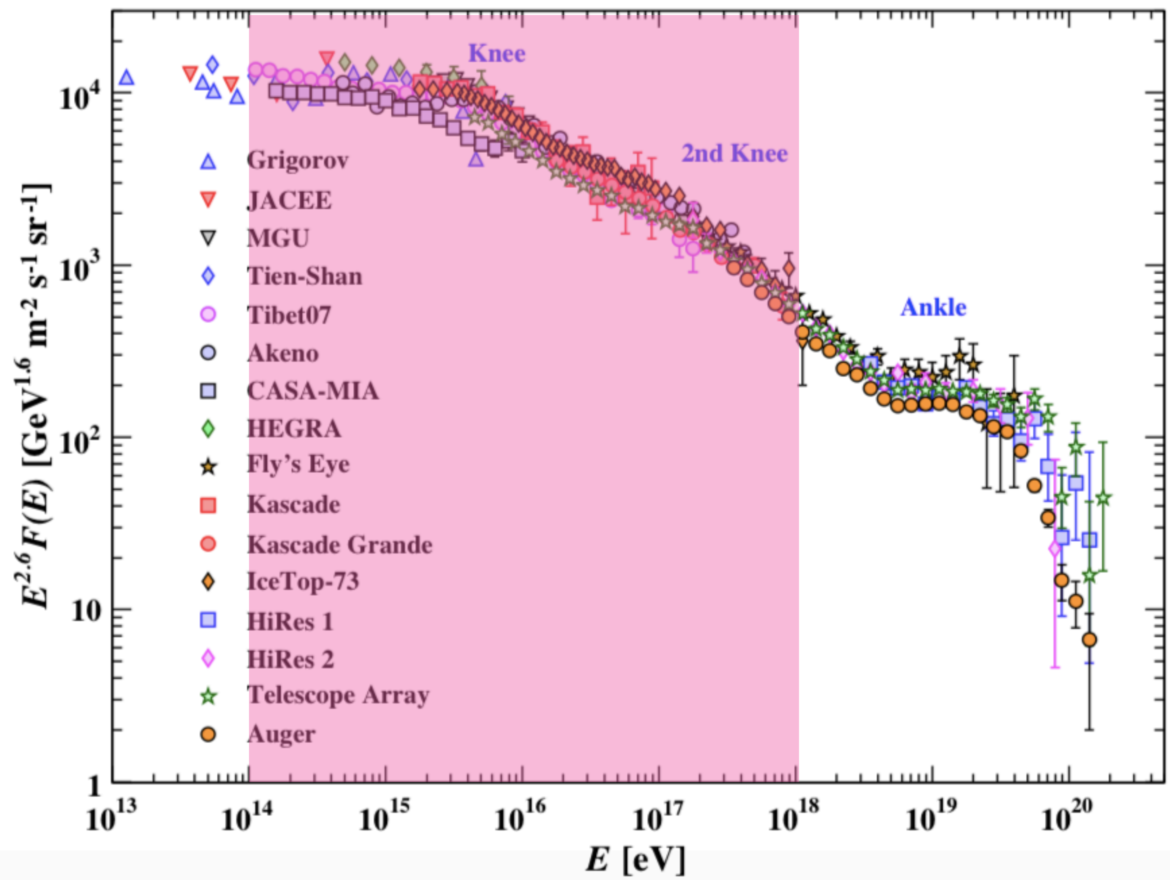
> Mean *p* is bigger at large θ

Event rates and fluxes

> Preliminary estimation of background rates, EAS rates, secondary spectra (μ, e, ν)

> Study the effect of uncertainties from composition model
- Different mass groups (2 millions per mass group)
- Consider evolution of spectrum
- Use two composition models

> Preliminary E range
- $\log_{10}(E/\mathrm{GeV}) = [3, 7]$



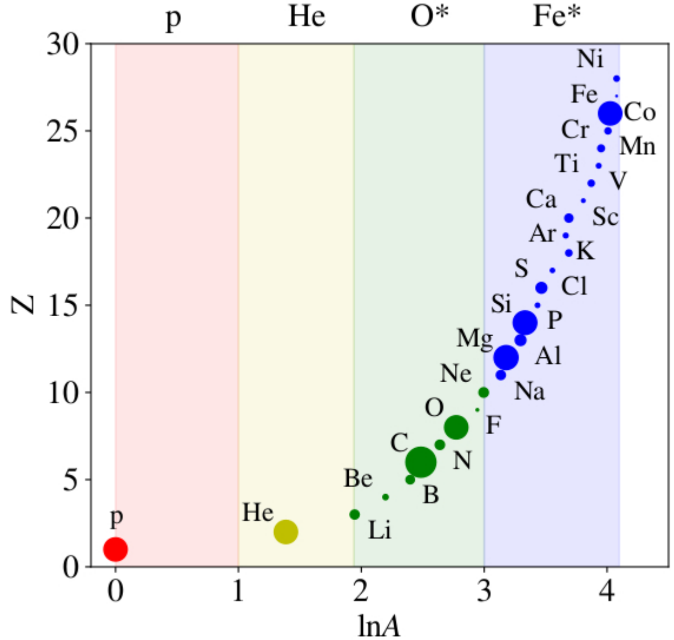
Event rates and fluxes

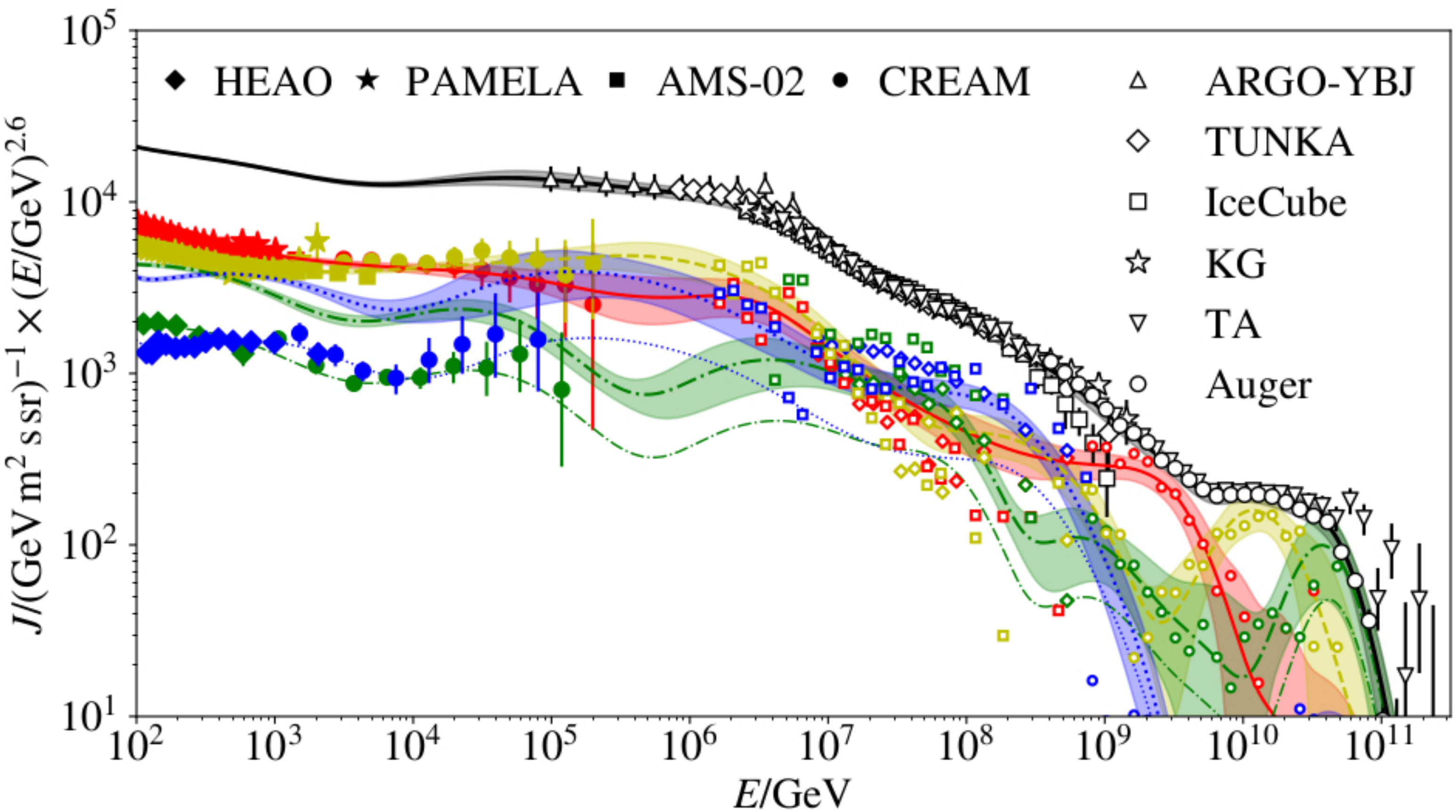
Global Spline Fit (GSF) model

H. P. Dembinski et al.,PoS(ICRC2017)533, astro-ph.HE 1711.11432

- Spline fits to the measured data from E = 3 GeV to 10^{11} GeV
- Only **four mass groups**:

    Use the most abundant element in each group
    as the representative for corresponding set



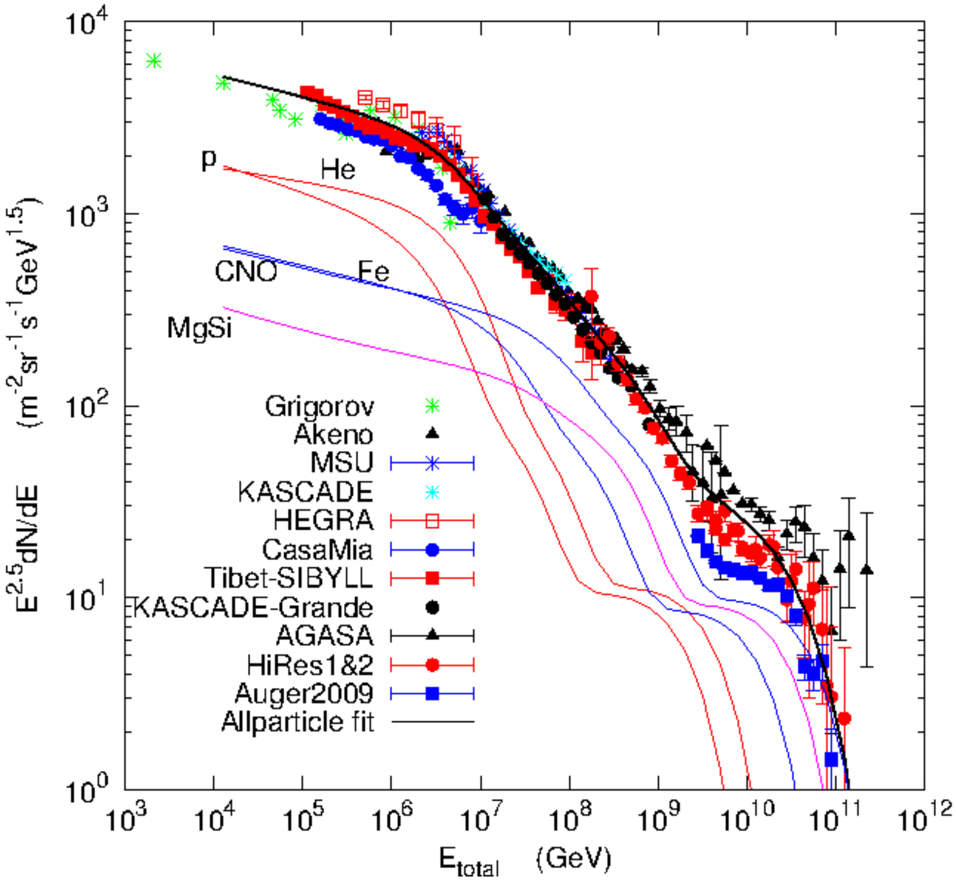


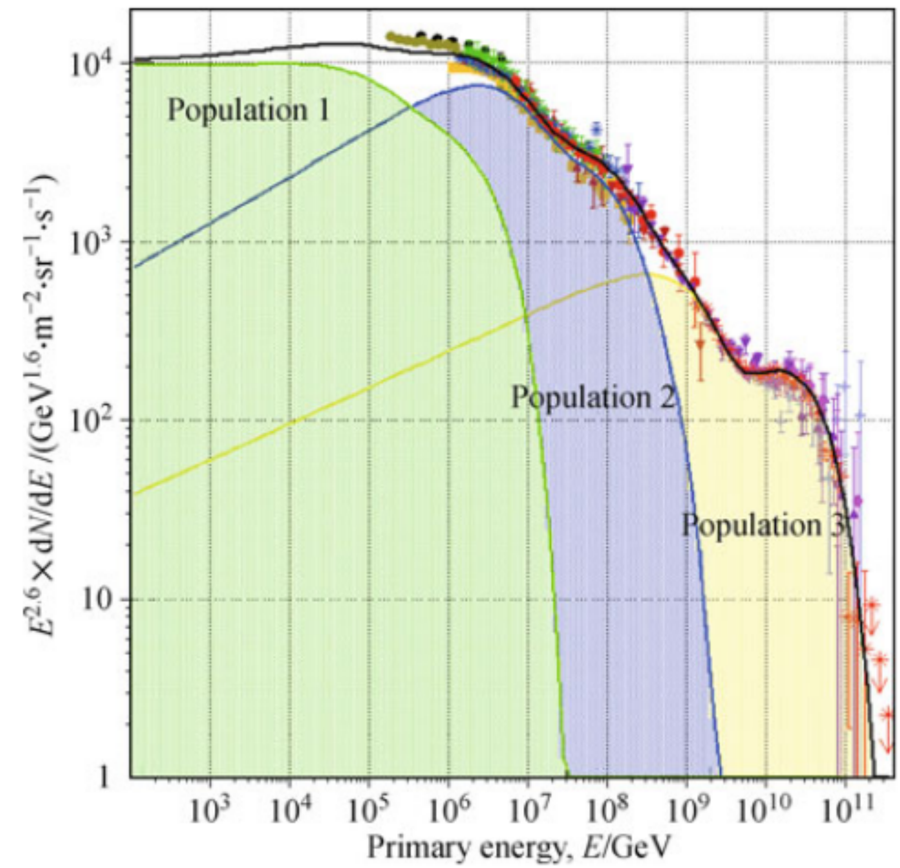
Event rates and fluxes

Hillas (H3a) model

T.K. Gaisser, Astrop. Phys. 35 (2012) 80; Frontiers of Physics 8 (2013)

$$\phi_i(E) \;=\; \Sigma_{j=1}^{3}\, a_{i,j}\, E^{-\gamma_{i,j}} \times \exp\left[-\frac{E}{Z_i R_{c,j}}\right].$$



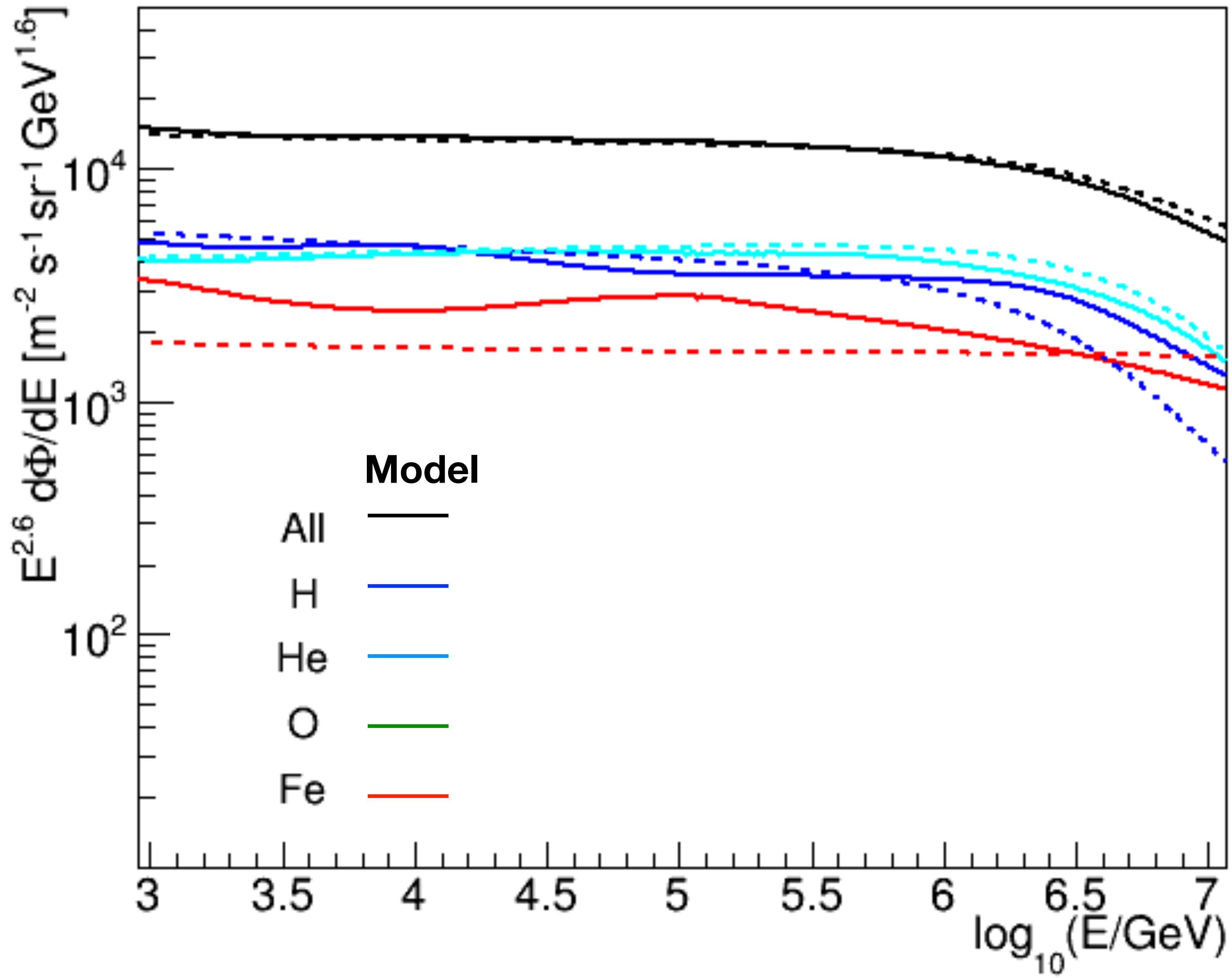


- Three cosmic populations
- Knees and other features produced by loss of magnetic confinement.
- Calibrated with measured data
- **Five mass groups**

- Population 1: SNR (E_{max} ~100 TeV)
- Population 2: Galactic pevatron (PWN, hypernovae, galactic center, etc.)
- Population 3: Extragalactic origin.

Event rates and fluxes

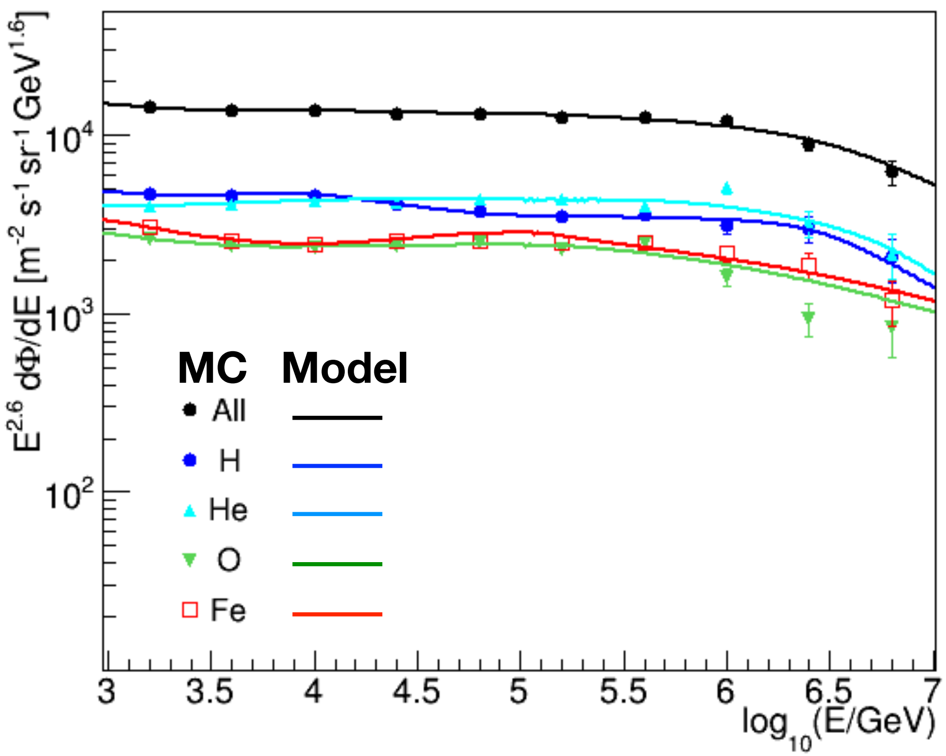
Comparison between GSF (continuos line) and H3a (dotted line) models

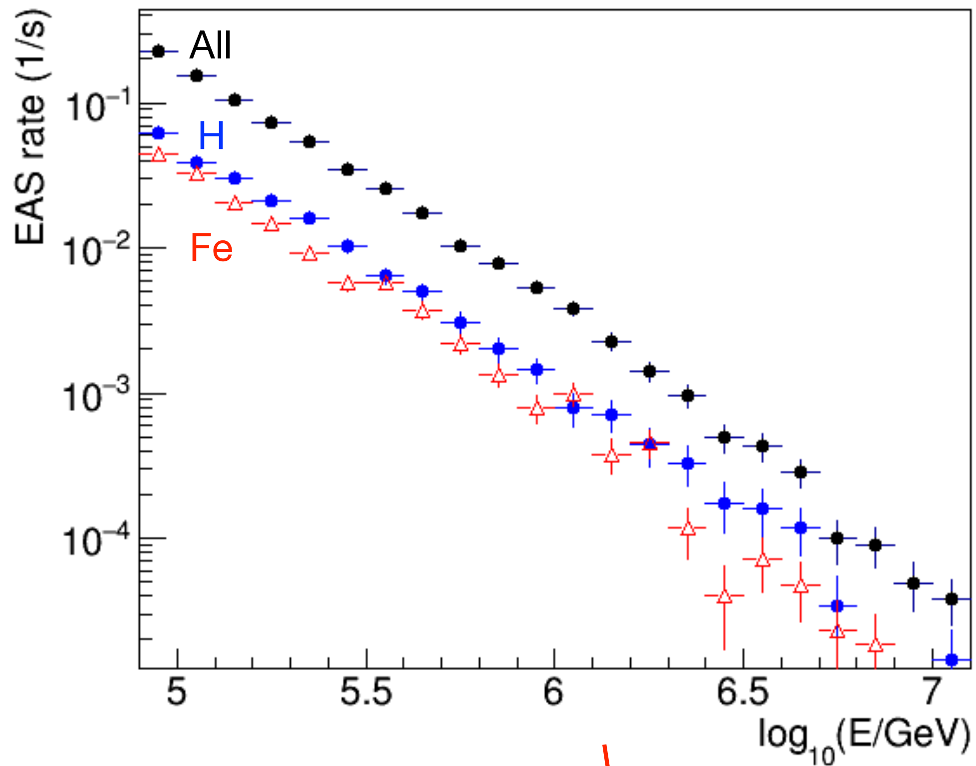


Event rates and fluxes

Results for the GSF model

θ = [0°, 12.8°]





Event rate of EAS primaries (horizontal geometry)

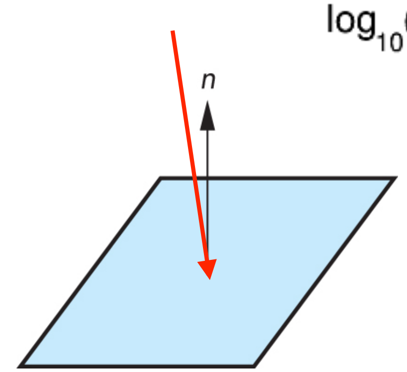
$N_{EAS}(E > 1\ \mathrm{PeV}) = 1 \times 10^{-2}/s$

Aeff ~ $4 \times 10^4\ m^2$

DAQ period = 3 yr (HL-LHC Run 4: 2027-2030)

Field of view = 0.155 sr

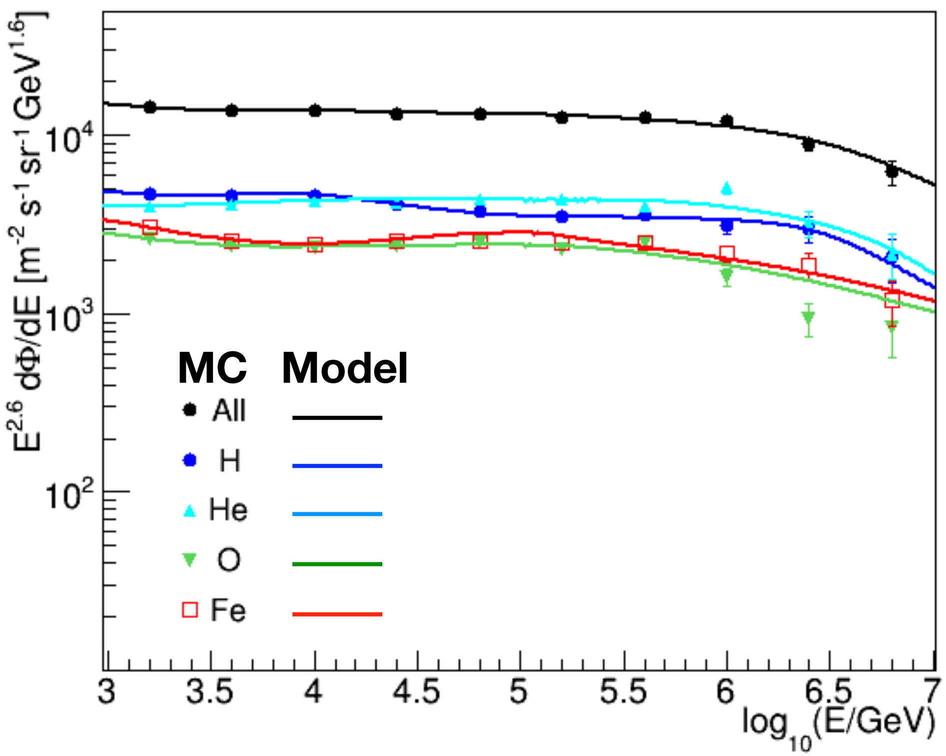
—> 9.5×10^5 CR events in 3 years

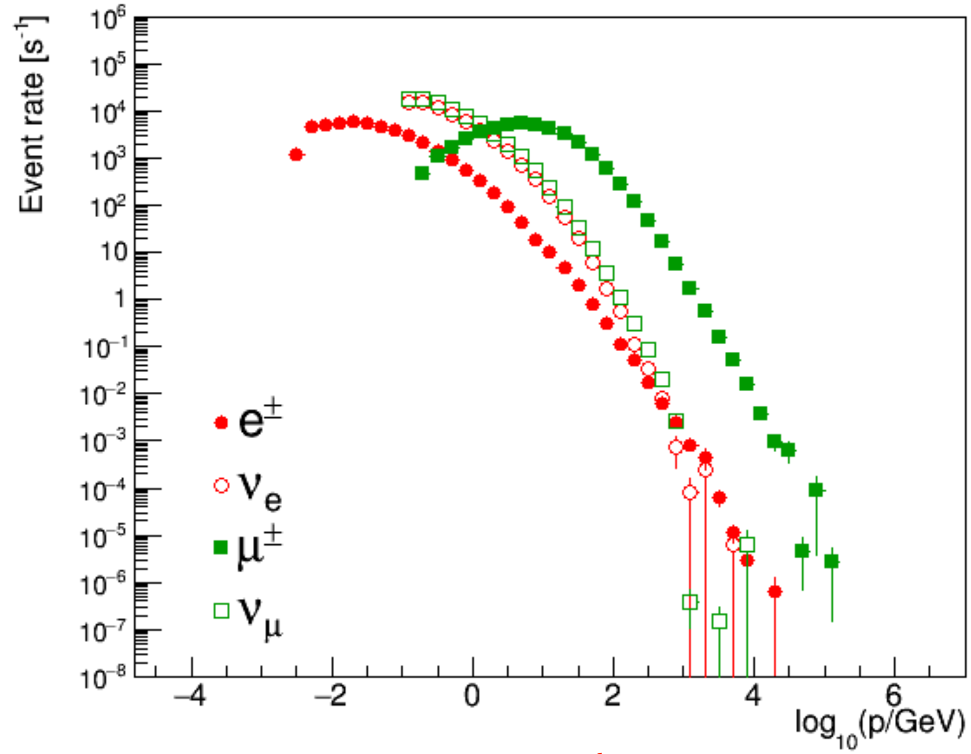


Event rates and fluxes

Results for the GSF model

θ = [0º, 12.8º]



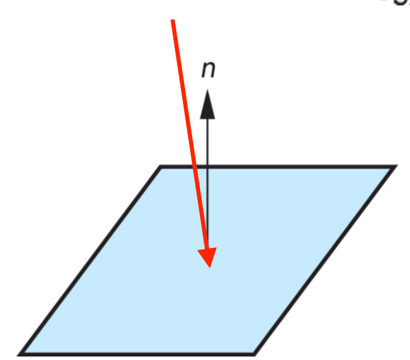


Event rate of secondaries (horizontal geometry)

N_e/s= 4.4 x 10^4

N_μ/s = 4.1 x 10^4

N_ν/s = 1.5 x 10^5

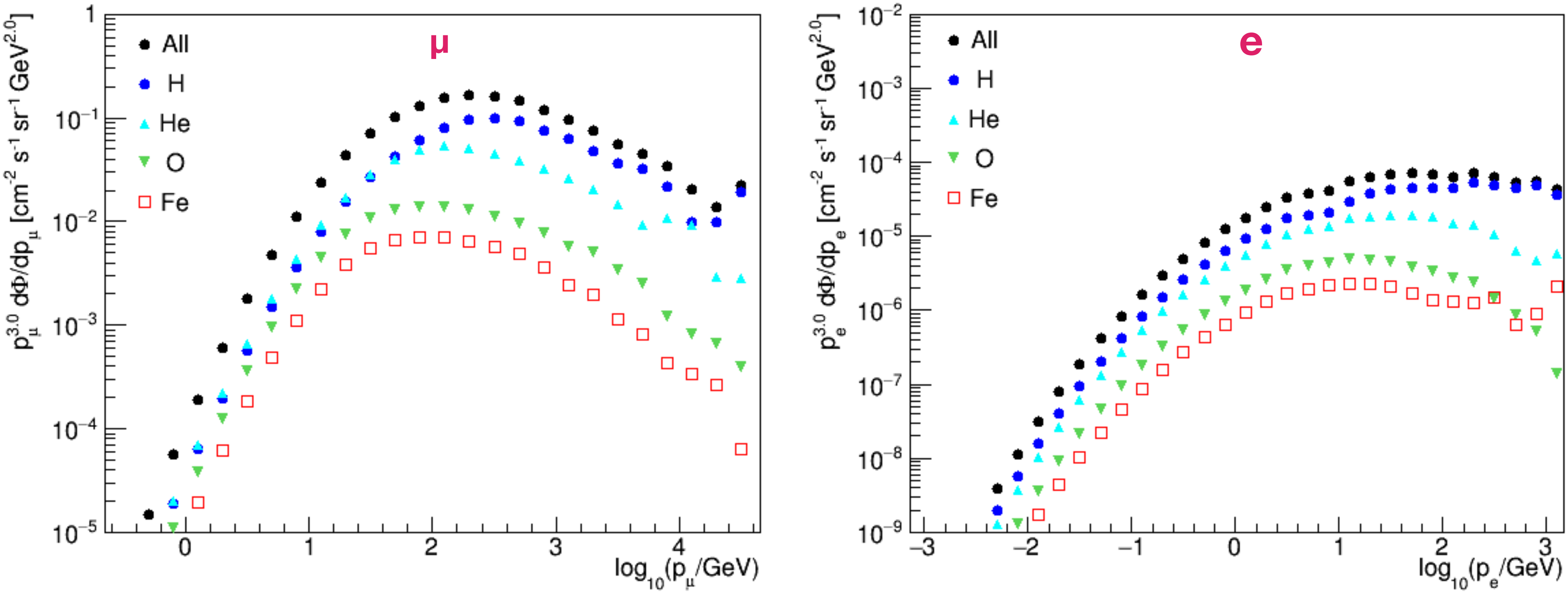


LE secondaries are more abundant

Event rates and fluxes

Results for the GSF model

θ = [0º, 12.8º]



Flux of secondaries (horizontal geometry)

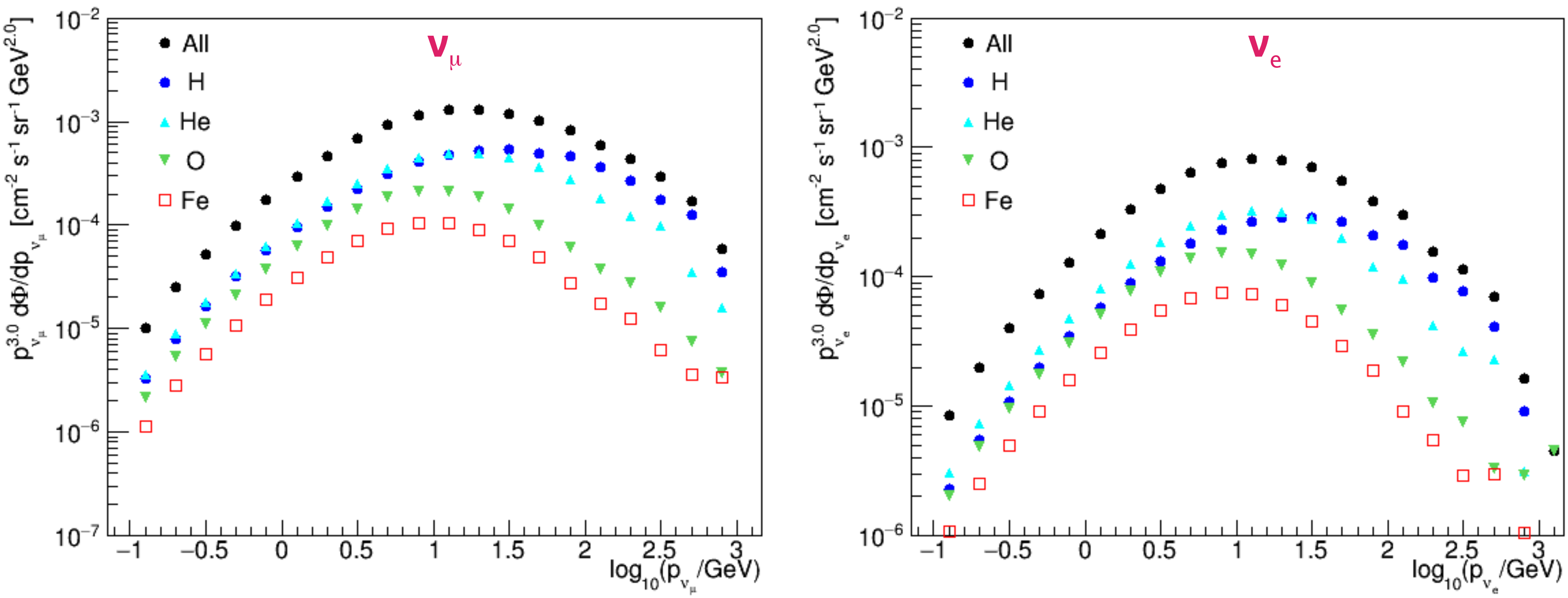
> The dominant contribution comes from **H** and **He**

> **Heavy component** produces more muons but not enough dominate secondary spectrum

Event rates and fluxes

Results for the GSF model

θ = [0°, 12.8°]



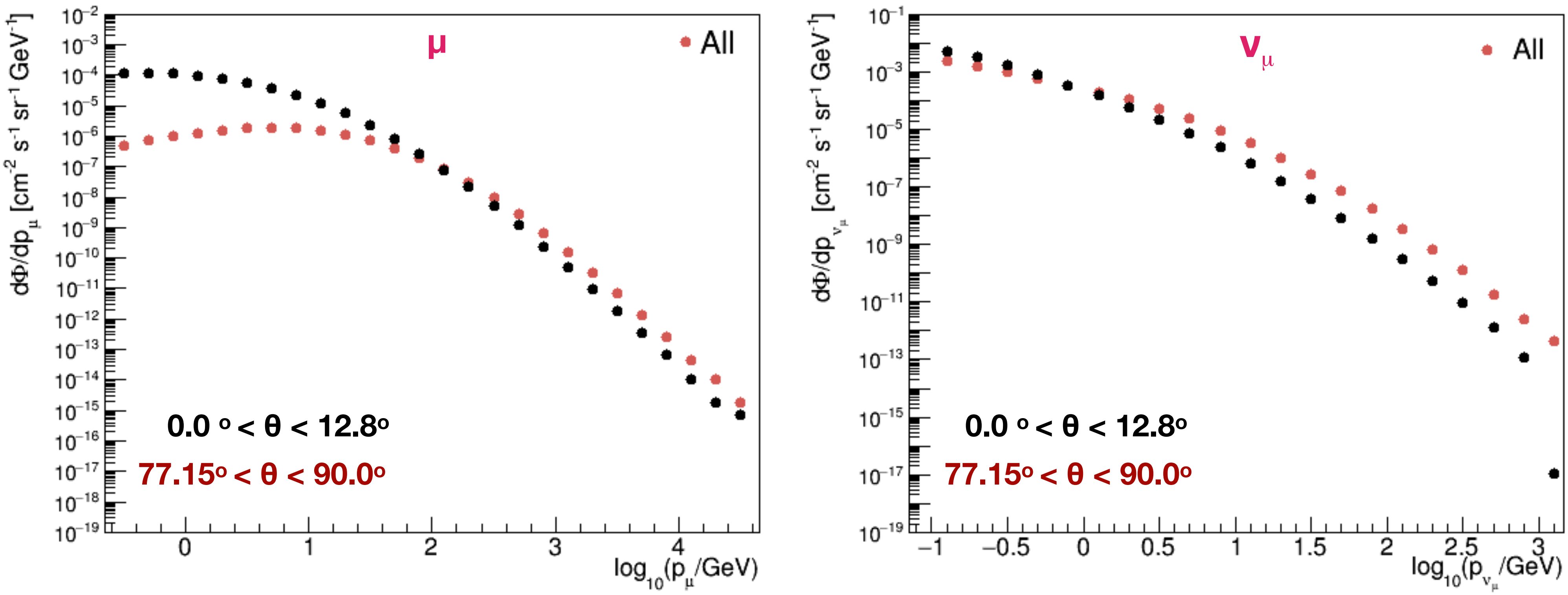
Flux of secondaries (horizontal geometry)

> The dominant contribution comes from **H** and **He**

> **Heavy component** produces more muons but not enough dominate secondary spectrum

Event rates and fluxes

Results for the GSF model



Flux of secondaries vs zenith angle (horizontal geometry)

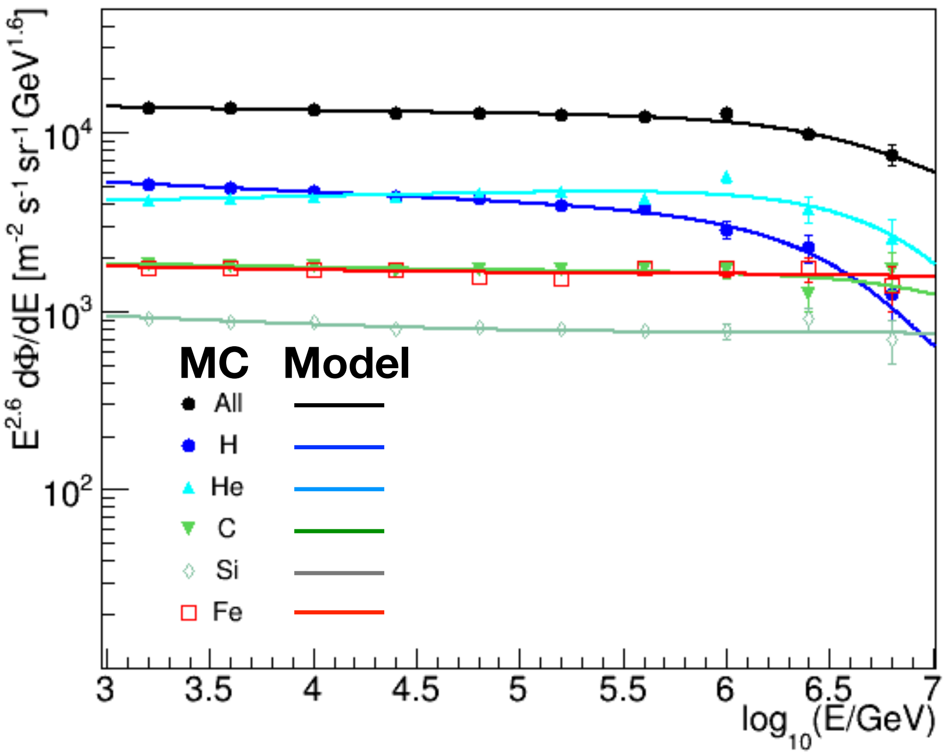
> LE penetrating component is attenuated by atmosphere for inclined EAS.

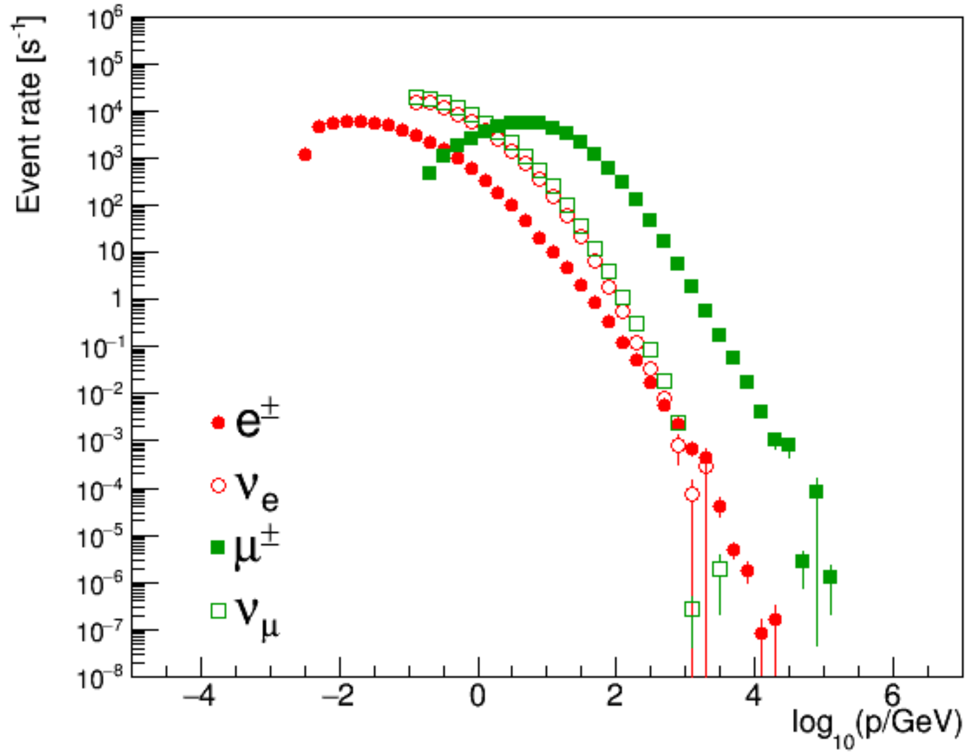
> HE penetrating component increases at high zenith angles

Event rates and fluxes

Results for the H3a model

θ = [0º, 12.8º]



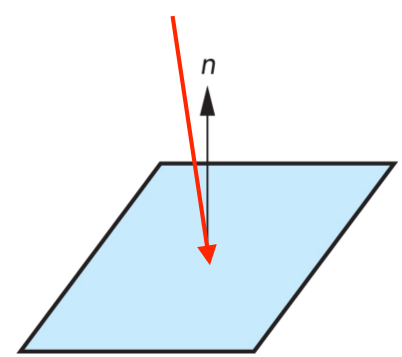


Event rate of secondaries (horizontal geometry)

N_e/s= 4.6 x 10^4

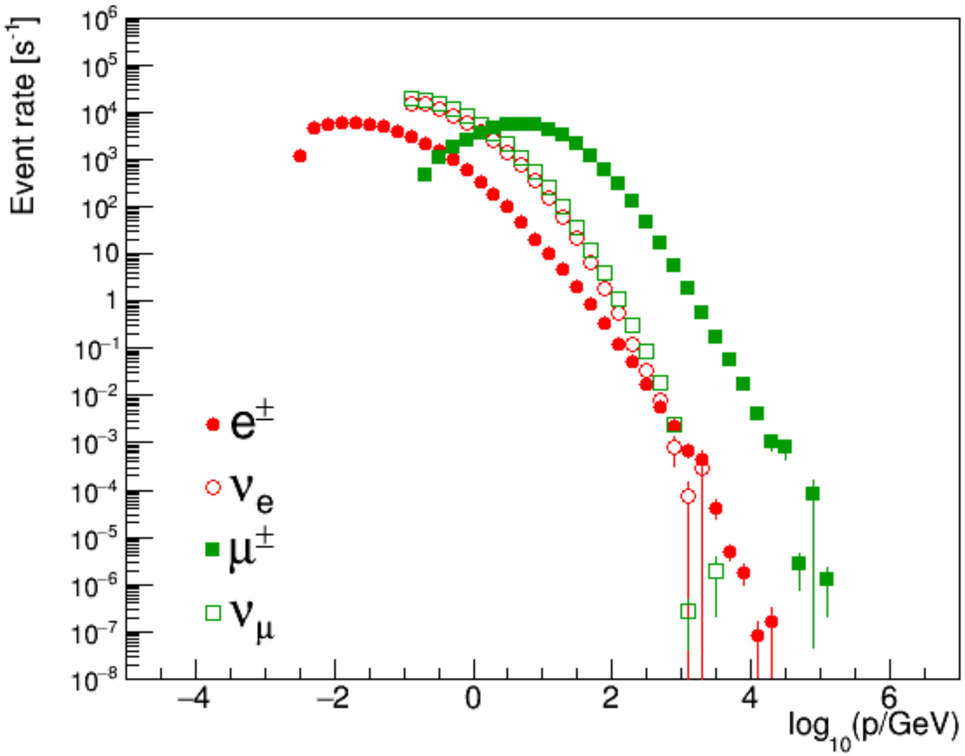
N_μ/s = 4.2 x 10^4

N_ν/s = 1.5 x 10^5

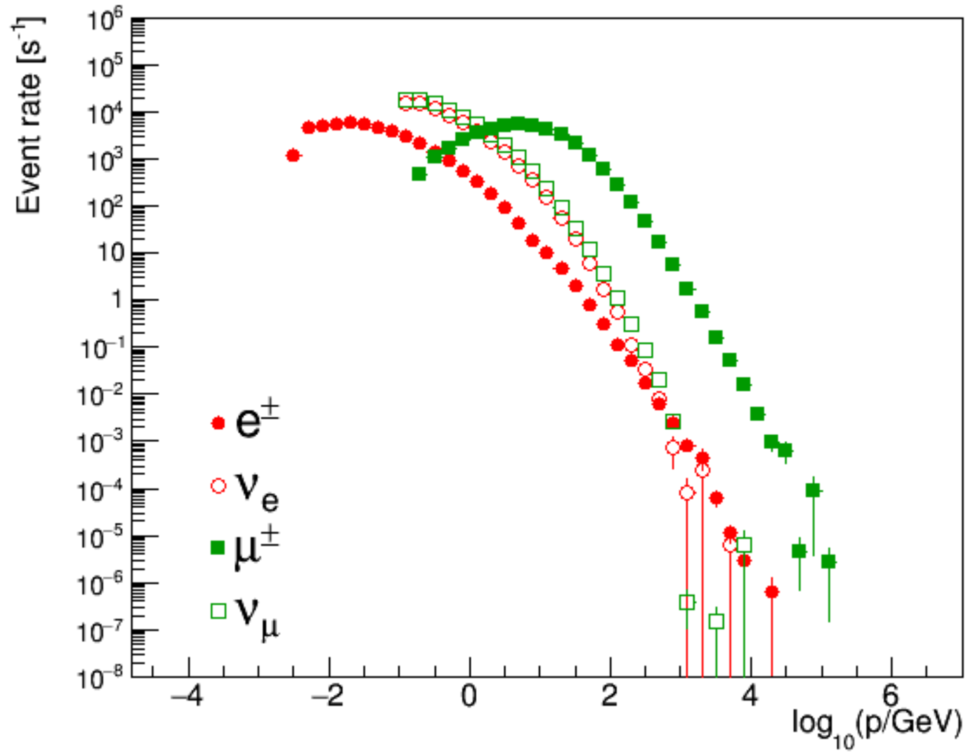


Event rates and fluxes

Results for the H3a model



Results for the GSF model



Event rate of secondaries (horizontal geometry)

H3a model:

N_e/s= 4.6 x 10^4

N_μ/s = 4.2 x 10^4

N_ν/s = 1.5 x 10^5

GSF model:

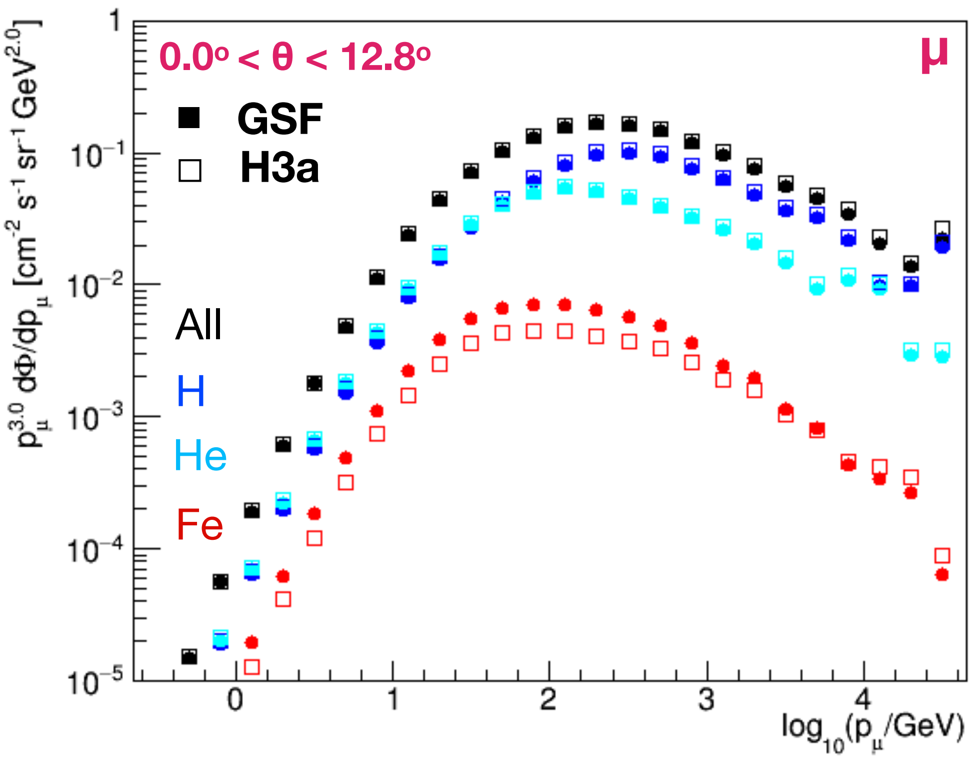
N_e/s= 4.4 x 10^4

N_μ/s = 4.1 x 10^4

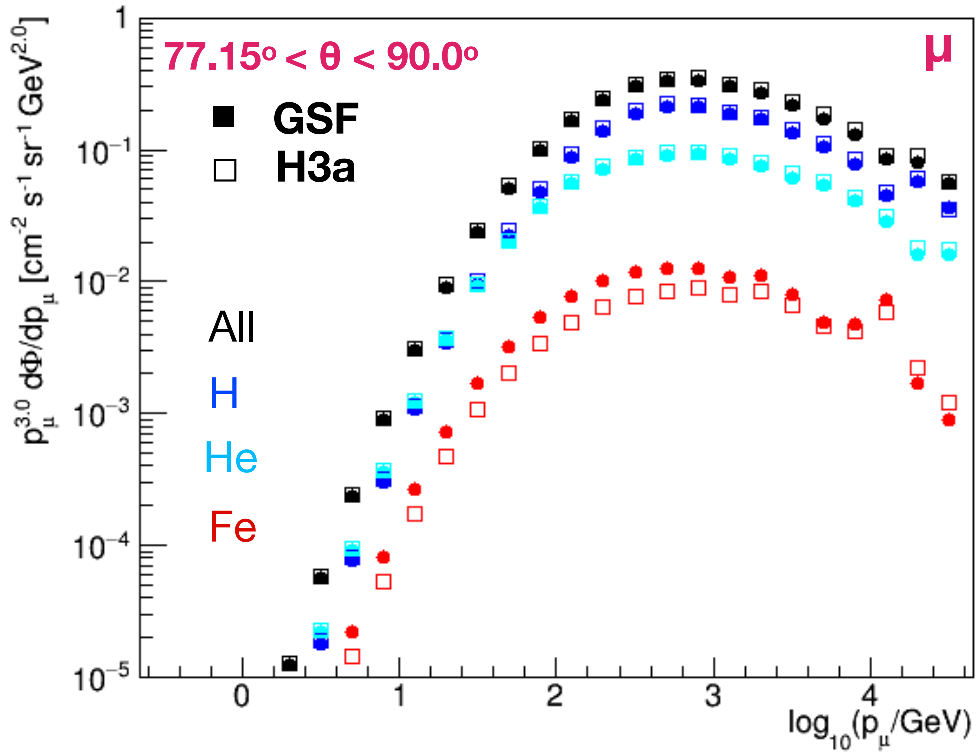
N_ν/s = 1.5 x 10^5

Event rates and fluxes

Comparison of μ results for H3a and GSF models



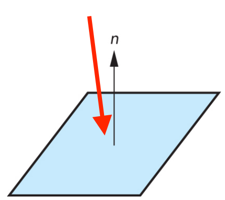
Secondary spectra from vertical direction

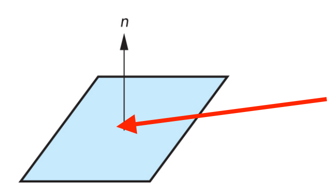


Secondary spectra from horizontal direction

> Flux differences < 10%

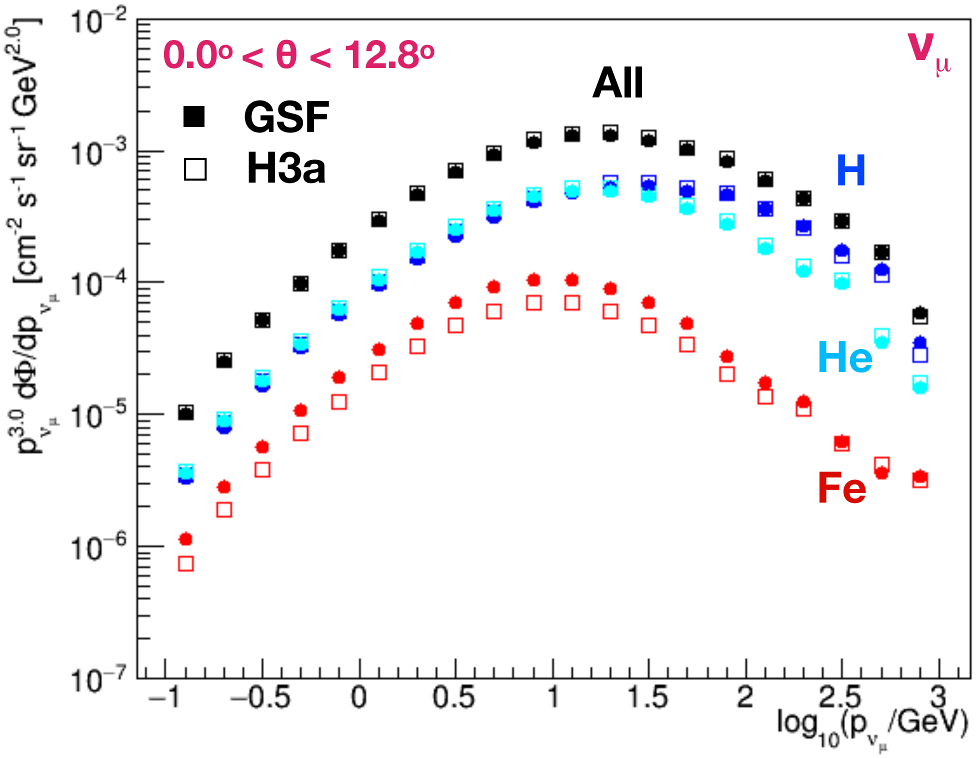
> Same differences for electrons



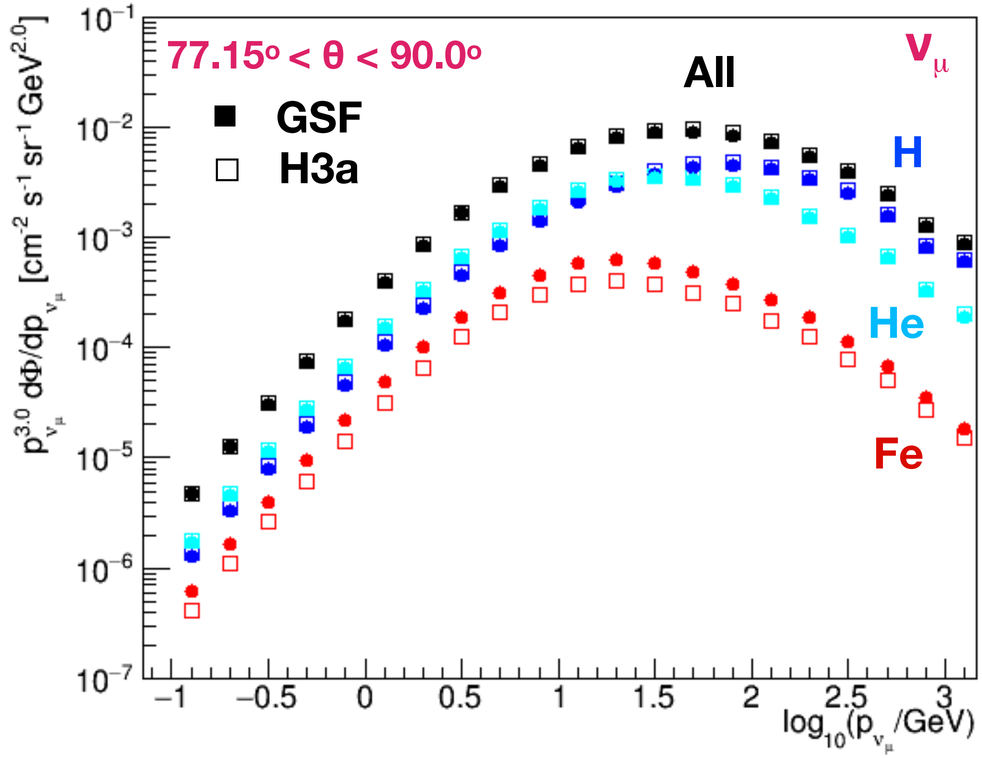


Event rates and fluxes

Comparison of ν results for H3a and GSF models



Secondary spectra from vertical direction



Secondary spectra from horizontal direction

> Flux differences < 10%

> Same differences for electron neutrinos

Final remarks

+ A detector like MATHUSLA would complement the **Long Lived Particle searches** at the LHC.

+ As pay-back MATHUSLA would also allow to **study several open issues** in astroparticle physics (Cosmic rays, dark matter, gamma-rays, neutrinos, …).

+ It would provide quality data on **extensive air showers** with **unprecedented precision at PeV energies**.

+ It would permit to **validate/test predictions of hadronic interaction models** at very high energies with cosmic rays.

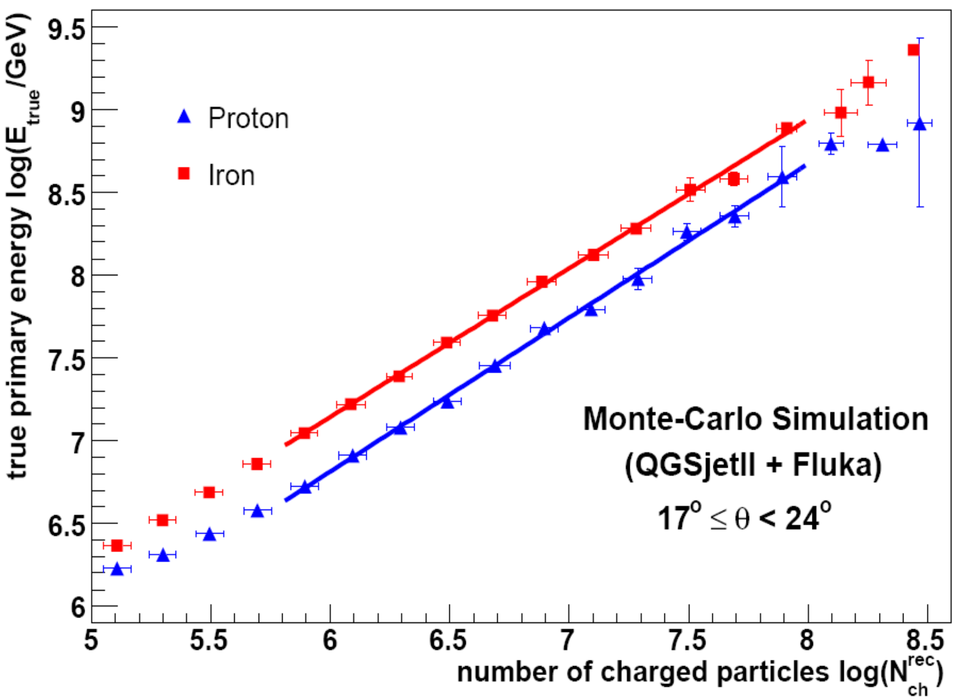
+ **White paper** for the MATHUSLA physics case (and intro to the Cosmic Ray potential) has been finished, **CR MATHUSLA white paper** is preparation.

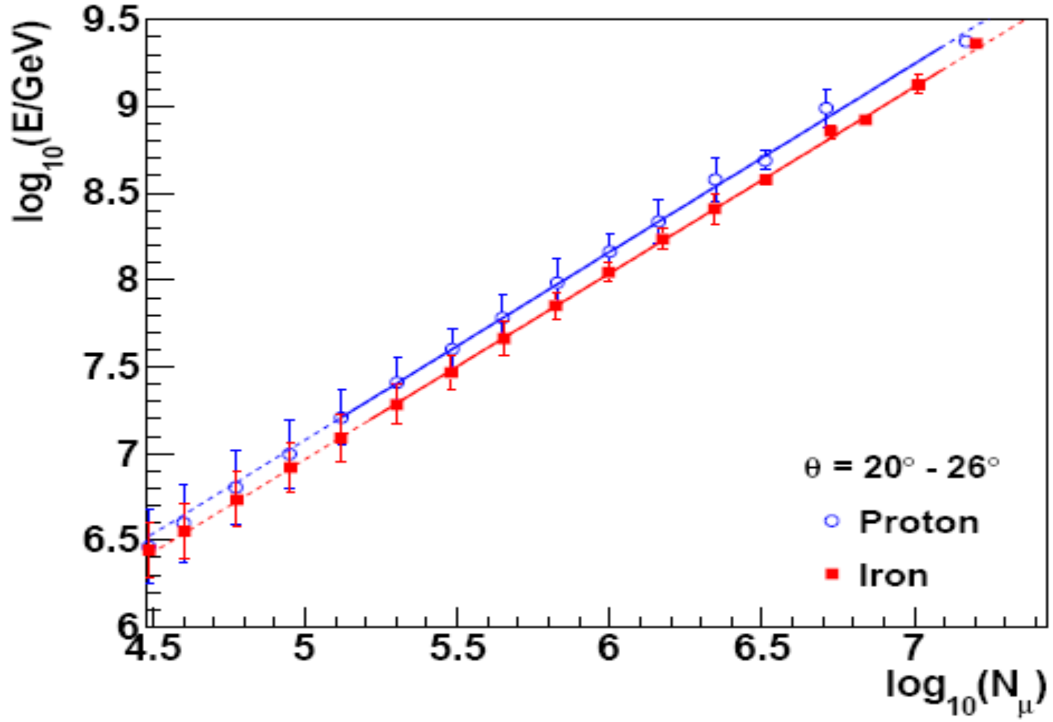
+ **CR simulations** and **background estimation** have started.

Backups

Introduction

Extensive air showers (EAS)





KASCADE-Grande Collaboration

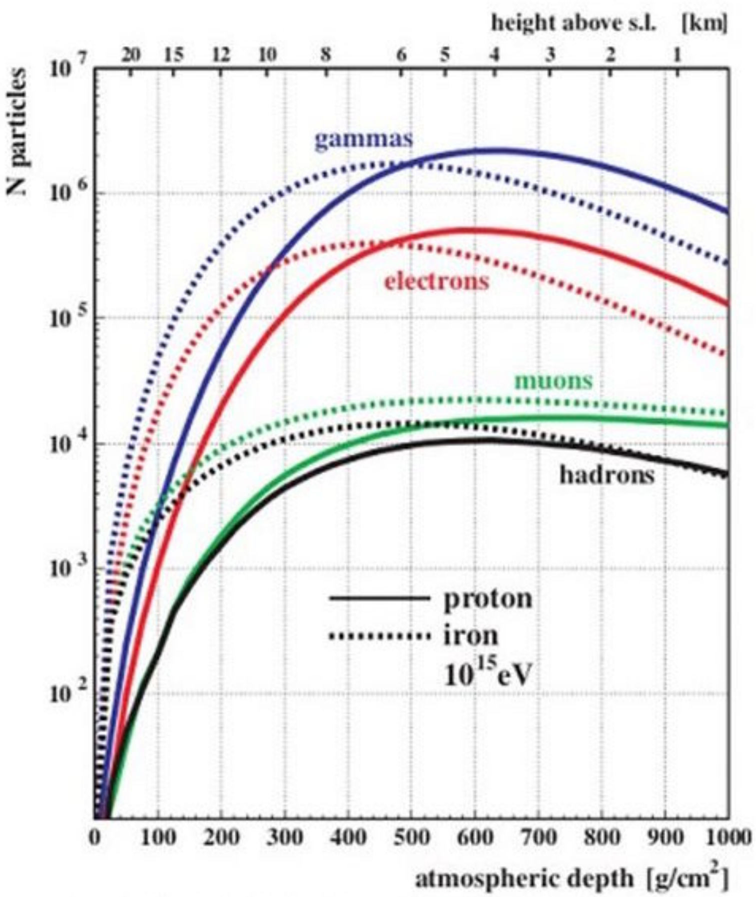
$$N^A \sim A \times (E/A)^a$$

A: Number of nucleons of primary
N: Shower size (number of particles)

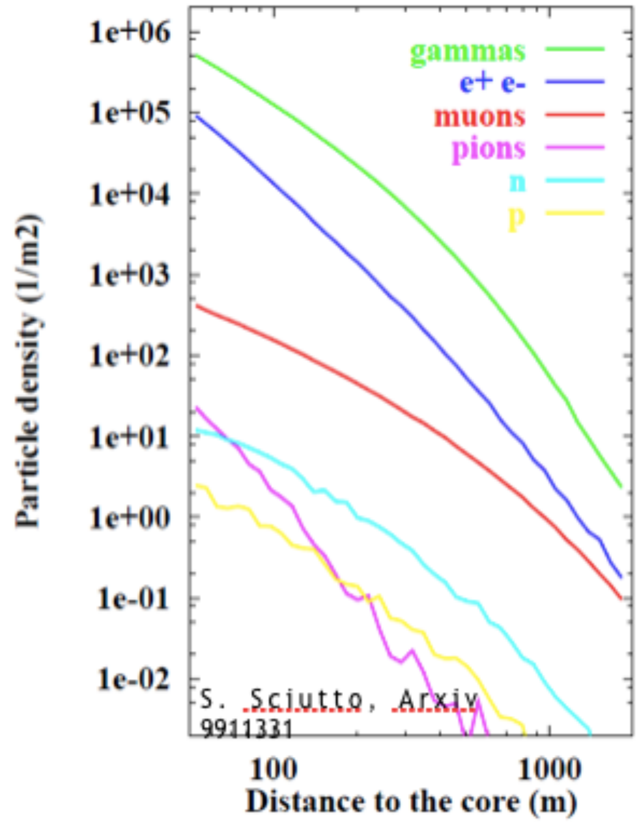
Introduction

Extensive air showers (EAS)

D. Heck (2006)

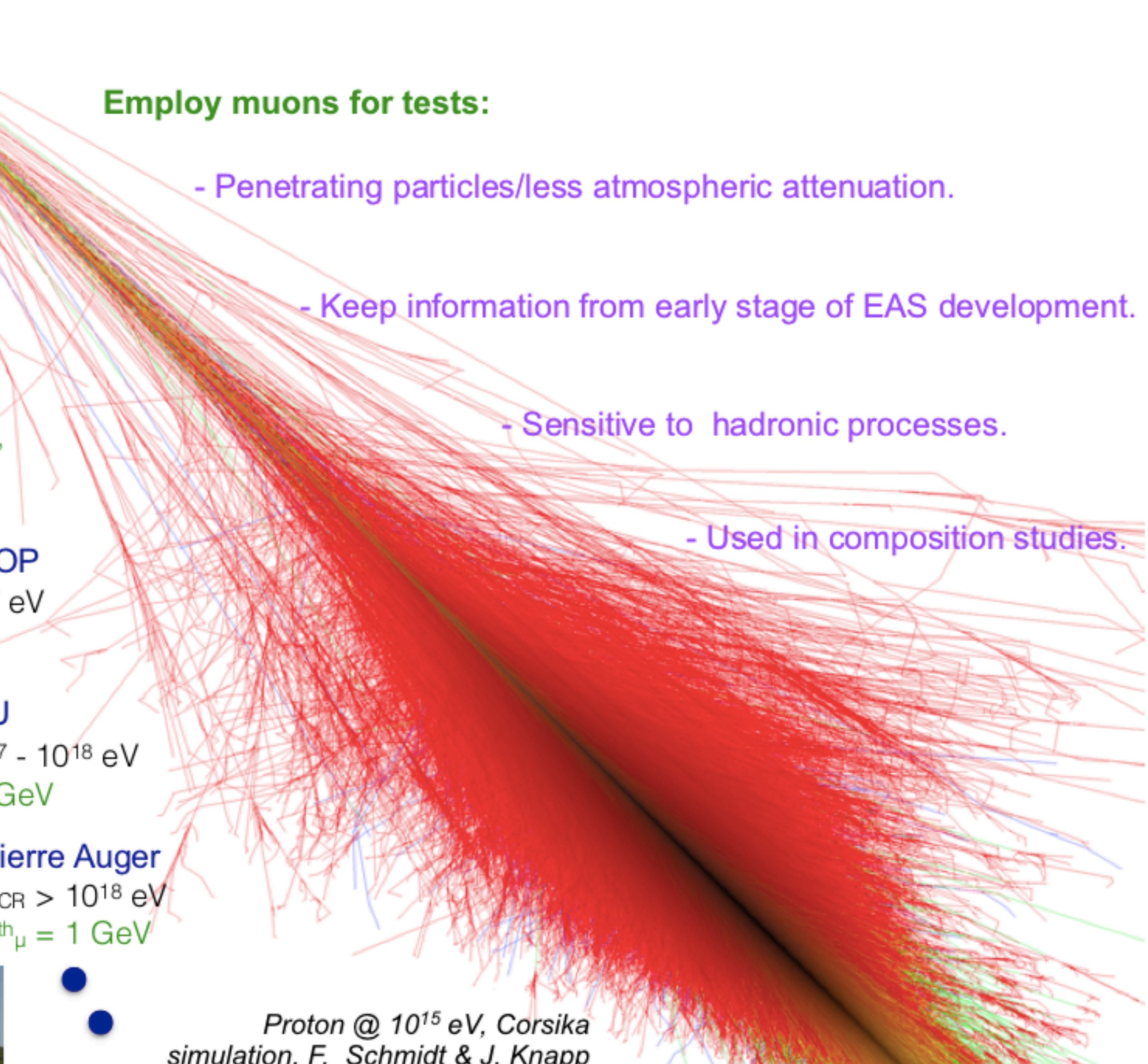


Proton E = 10 EeV



Cosmic ray physics case

Test of hadronic interaction models

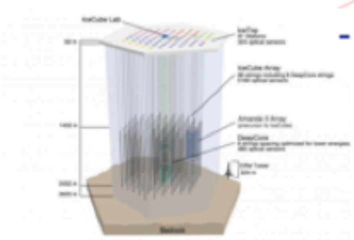


Employ muons for tests:

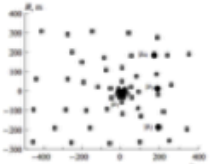
- Penetrating particles/less atmospheric attenuation.
- Keep information from early stage of EAS development.
- Sensitive to hadronic processes.
- Used in composition studies.

Use CR observatories to constrain/test models:

- KASCADE-Grande
  E_{CR} = 10^{15} - 10^{18} eV
  E^{th}_{μ} = 230 MeV, 490 MeV, 800 MeV, 2.4 GeV



- ICECUBE/ICETOP
  E_{CR} = 10^{15} - 10^{17} eV
  E^{th}_{μ} = 0.2 GeV



- EAS-MSU
  E_{CR} = 10^{17} - 10^{18} eV
  E^{th}_{μ} = 10 GeV

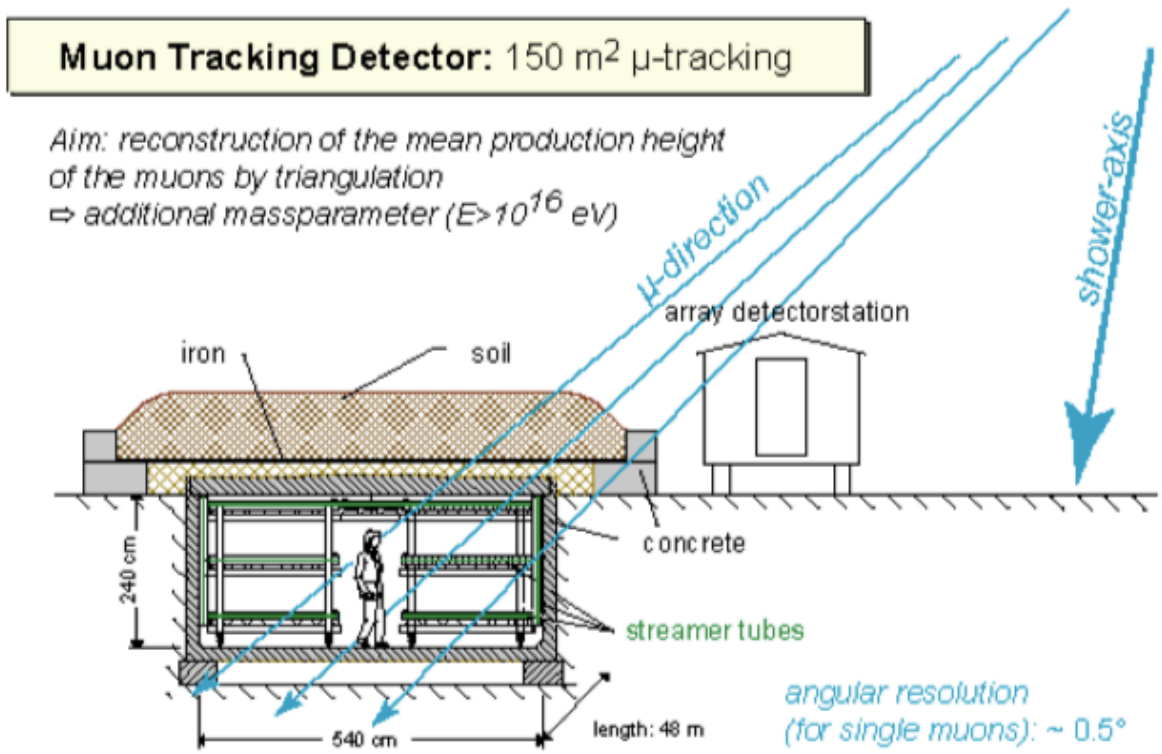
- Pierre Auger
  E_{CR} > 10^{18} eV
  E^{th}_{μ} = 1 GeV

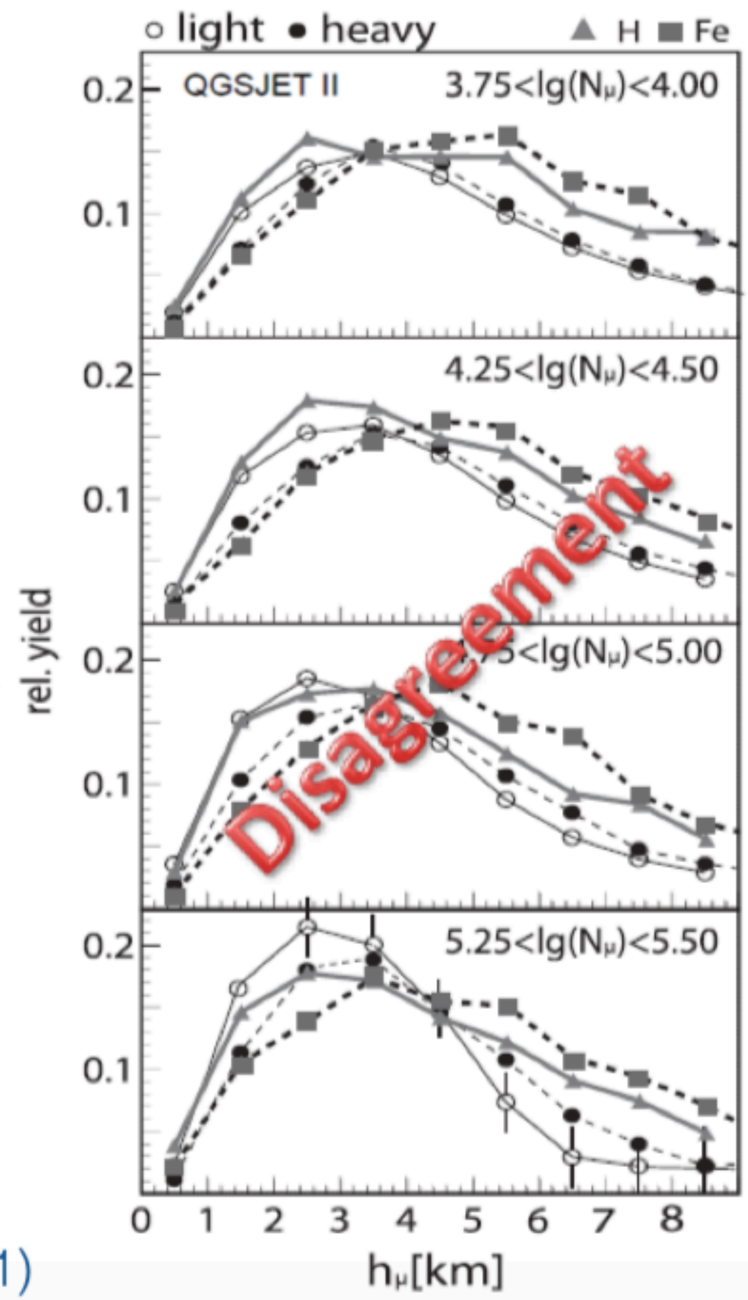
Proton @ 10^{15} eV, Corsika simulation, F. Schmidt & J. Knapp

Cosmic ray physics case

Muon production height

KASCADE measurements





Apel et al., Astropart. Phys. 34 (2011)

Simulations

> Development of EAS

CORSIKA package v 7.6400: Developed for the KASCADE experiment

D. Heck et al., Forschungszentrum Karlsruhe Report FZKA 6019 (1998)

> Hadron production and hadronic interactions

High Energy (E_h > 200 GeV):

QGSJET-II-04: S. Ostapchenko, Phys. Rev. D 83 (2011) 014018.

EPOS-LHC : T. Pierog, et al., Phys. Rev. C 92 (2015) 034906.

SIBYLL 2.3c : F. Riehn, et al., PoS (ICRC2017) 301

Low Energy (E_h < 200 GeV):

Fluka : A. Fassò, etal., 2005. Report CERN-2005-10

Geisha: H. Fesefeldt, Report PITHA 85/02, RWTH Aachen, 1985

> Mass groups

H, He, C, O, Si, Fe

Simulations

Primary energy range: $\log_{10}$ (E/GeV) = 0.5 - 9 **(Divide in E ranges)**

Primary spectrum: E^{-2} **(Weight to get more realistic spectrum)**

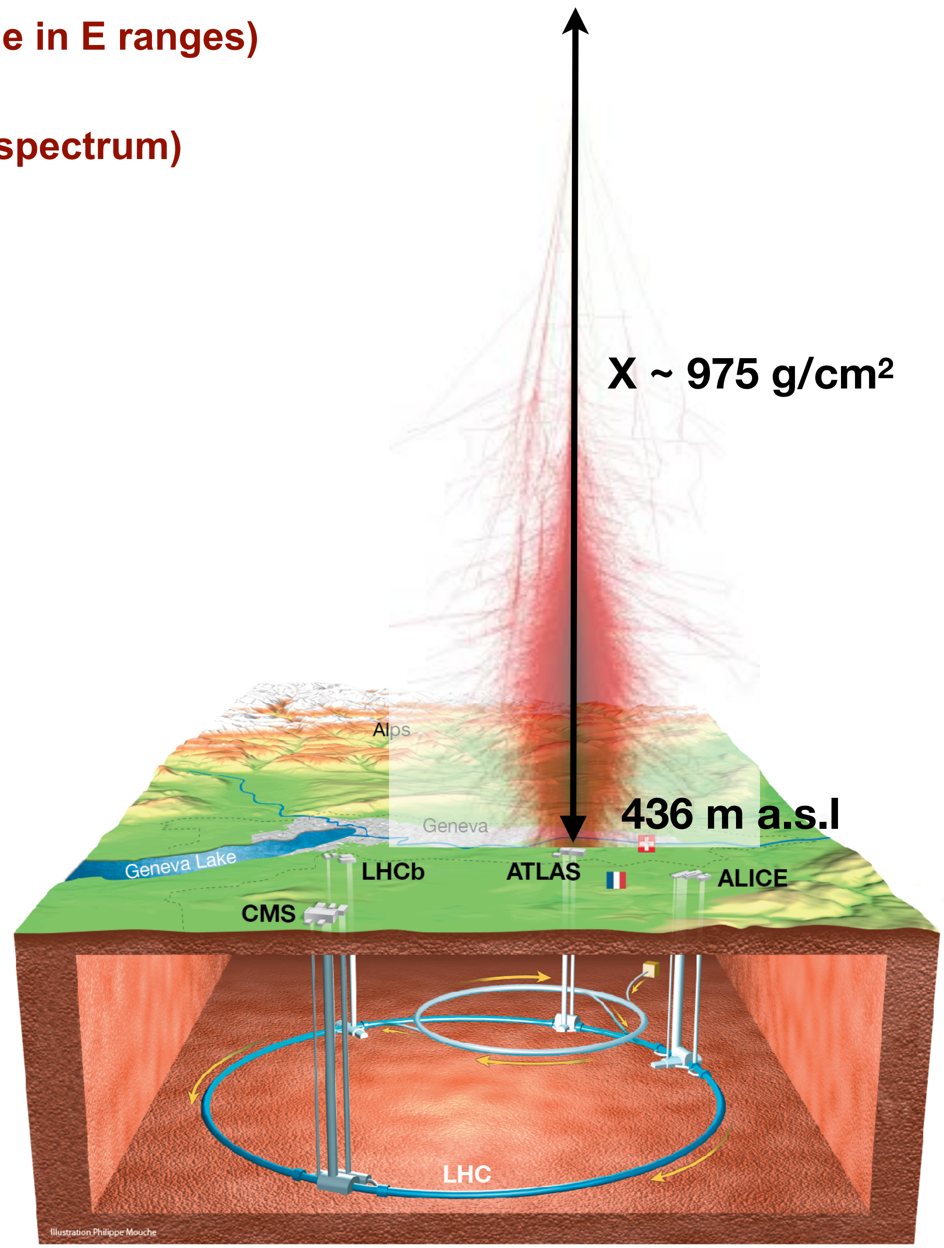
Zenith angle range: 0^{o} - 90^{o}

Energy cuts: hadrons (100 MeV)
μ's(100 MeV)
e's (3 MeV)
ɣ's (3 MeV)

Site: ATLAS

Magnetic field at site:
(Bx, Bz) = (22.1, 41.6) μT
NOAA https://www.ngdc.noaa.gov/geomag-web/#igrfwmm

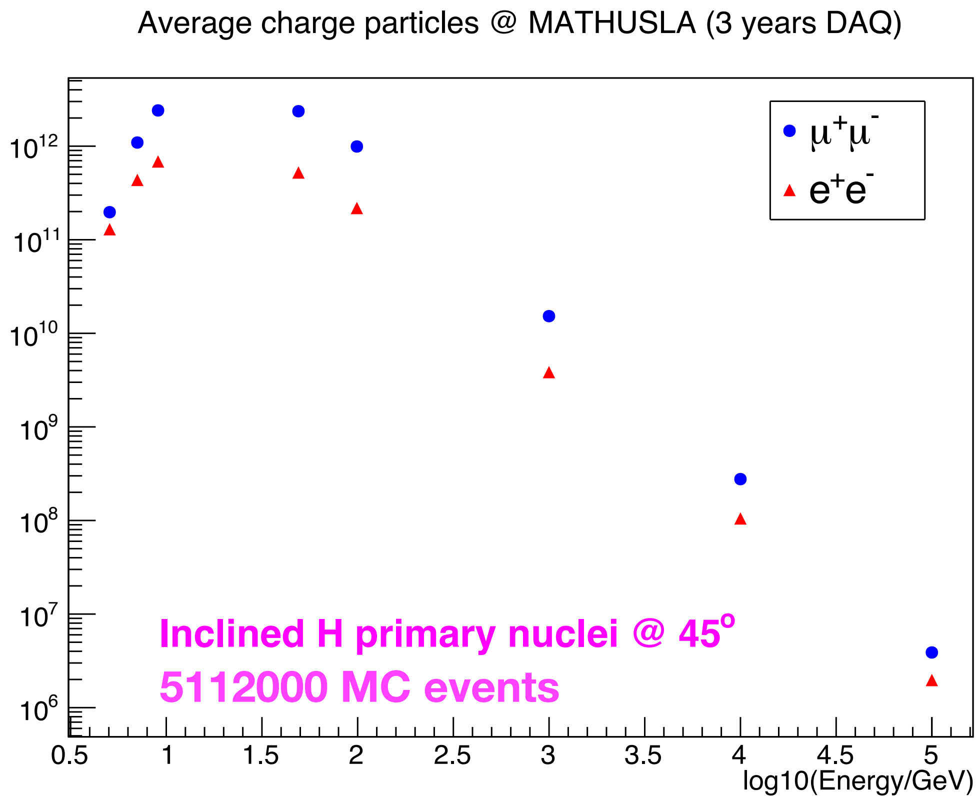
Detector Geometry: Horizontal/volume geometry

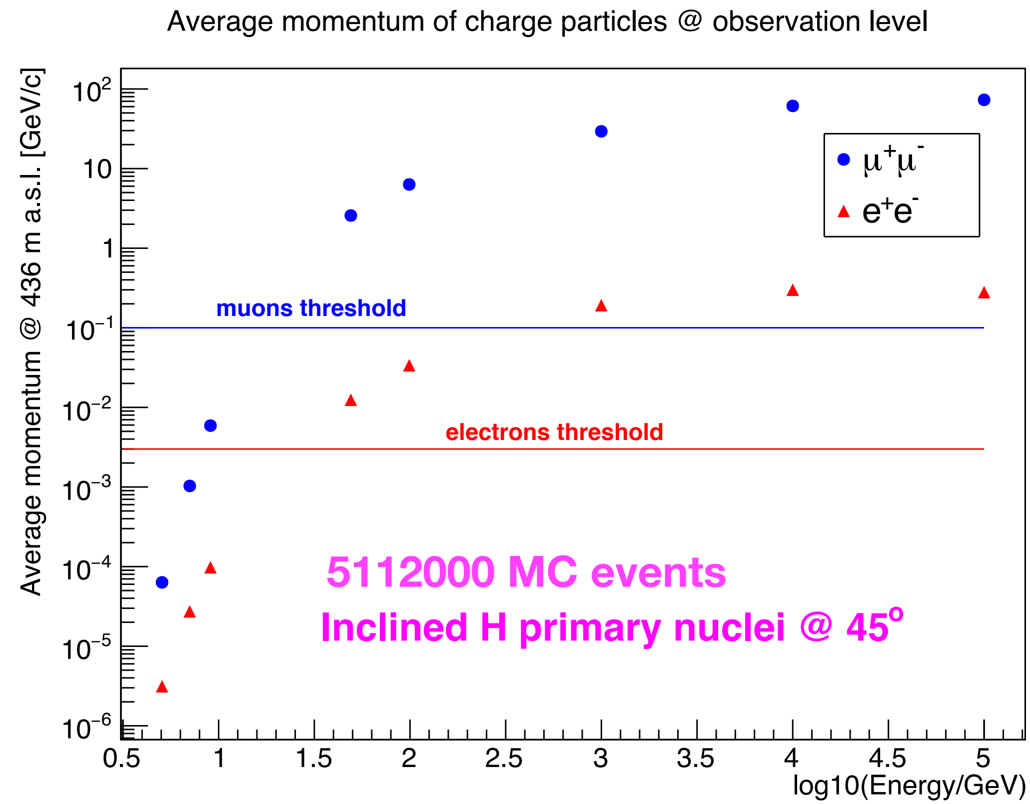


Secondaries charged particles at fixed E

E: primary cosmic ray energy

θ = 45°





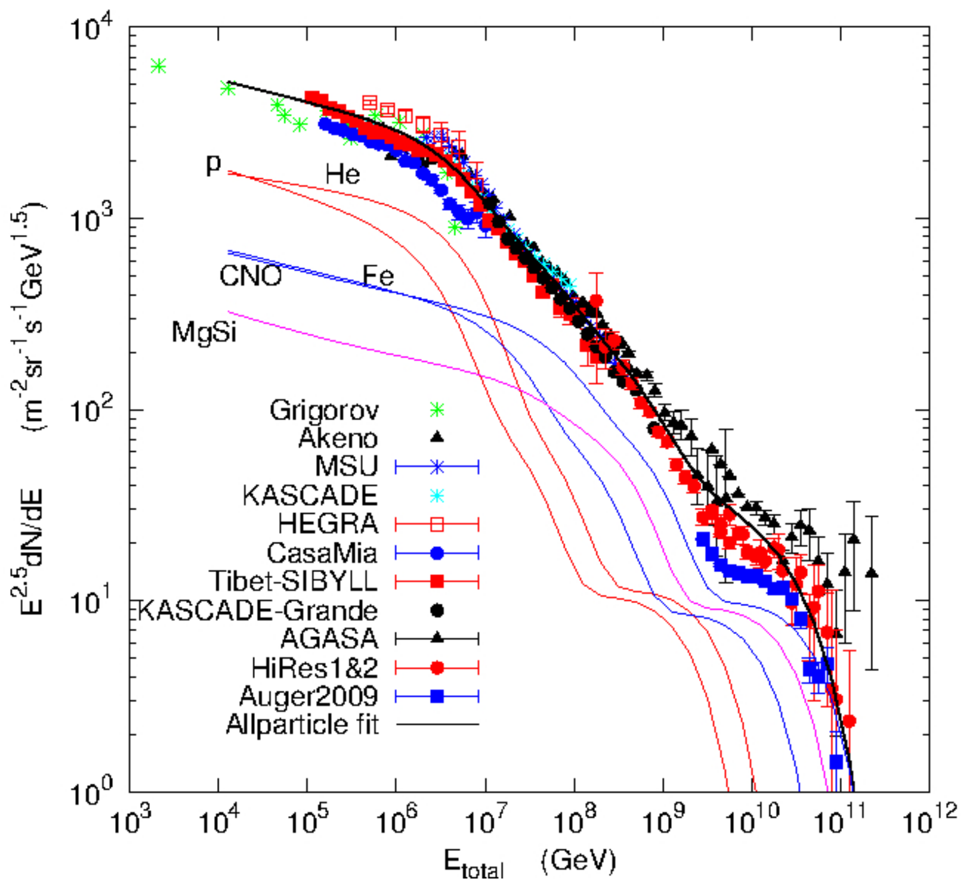
Secondary charged particles
@ MATHUSLA level

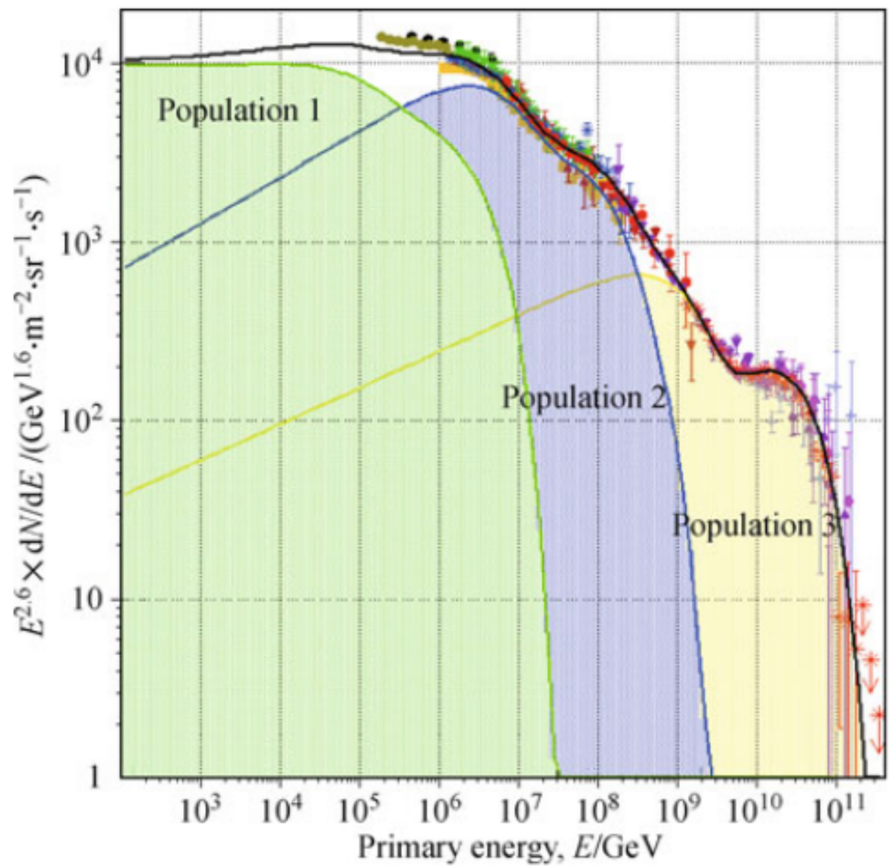
From **MC** simulations assuming
AMS-02 spectrum

Mean ***p*** for secondary charged particles
@ MATHUSLA level

Hillas (H3a) model

T.K. Gaisser, Astrop. Phys. 35 (2012) 80; Frontiers of Physics 8 (2013)





$$\phi_i(E) = \Sigma_{j=1}^{3} a_{i,j} E^{-\gamma_{i,j}} \times \exp\left[-\frac{E}{Z_i R_{c,j}}\right].$$

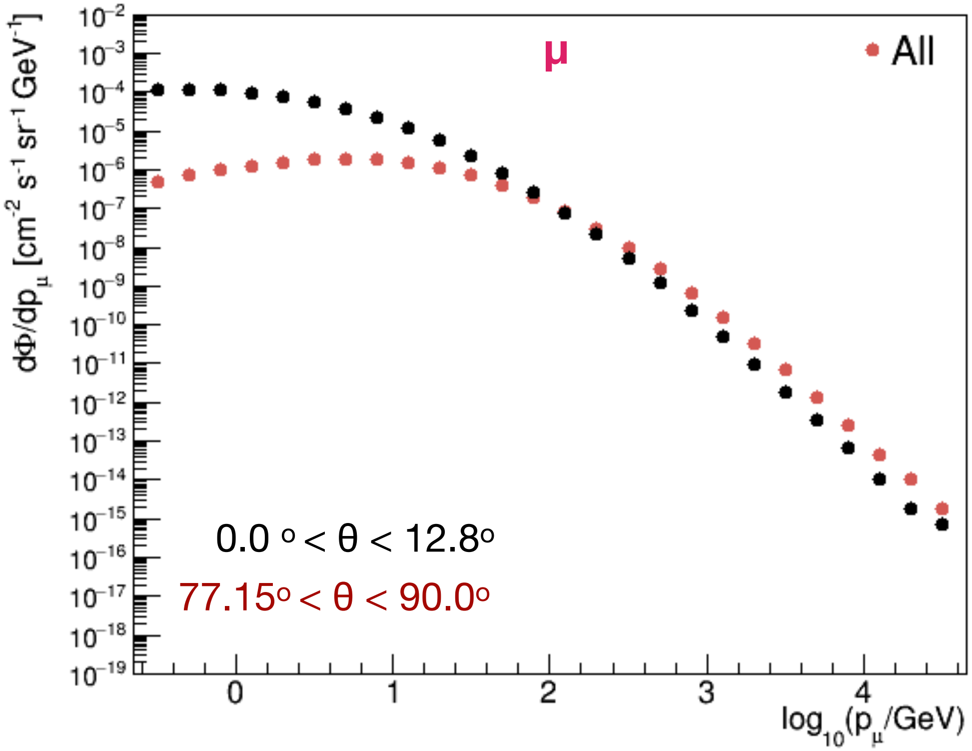
- Rc = Rigidity
- $E_{knees} \propto Z \times E_H$.

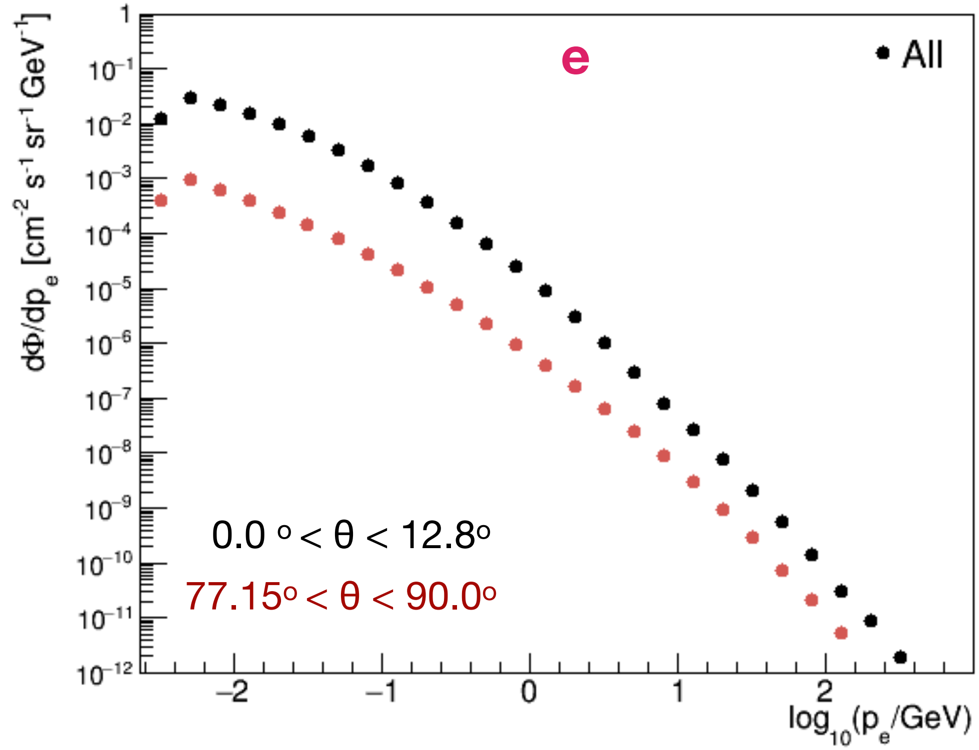
- Population 1: SNR (E_{max} ~100 TeV)
- Population 2: Galactic Pevatron (PWN, Hypernovae, galactiv center, etc.)
- Population 3: Extragalactic.

Event rates and fluxes

Results for the GSF model

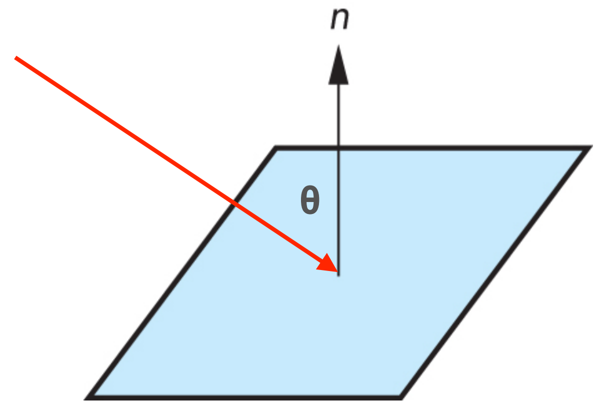
θ = [0º, 12.8º]





MATHUSLA as an EAS detector

Expected EAS events (STD mode)



Assuming:

Aeff ~ 4 x 10^4 m^2

DAQ period = 3 yr (LHC Run 4: 2027-2030)

Field of view (plane geometry) = π sr

—> Acceptance ~1.2× 10^{13} $m^2 \cdot s \cdot sr$. ($\theta < 90^o$)

If the integral intensity of primary cosmic ray nuclei is parameterized as

$$I(>E) \approx 10^{-7} \left(\frac{E}{10^{15}\,\mathbf{eV}}\right)^{-2.1} \mathbf{m}^{-2} \cdot \mathbf{s}^{-1} \cdot \mathbf{sr}^{-1},$$

Expected number of events

—> n(> 1 PeV) ~1.2× 10^6

—> n(> 10 PeV) ~9.4× 10^3

Golden events:

—> 0.4 x events in STD mode (70 % of DAQ period and $\theta < 50^0$)