Measured and simulated μ flux for the first KM3NeT Detection Units

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CORSIKA Cosmic Ray Simulation Workshop Karlsruhe, 17.06.2019

KM3NeT
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Outline

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1. KM3NeT
2. Simulations
   - Status
   - Additional productions
3. Summary

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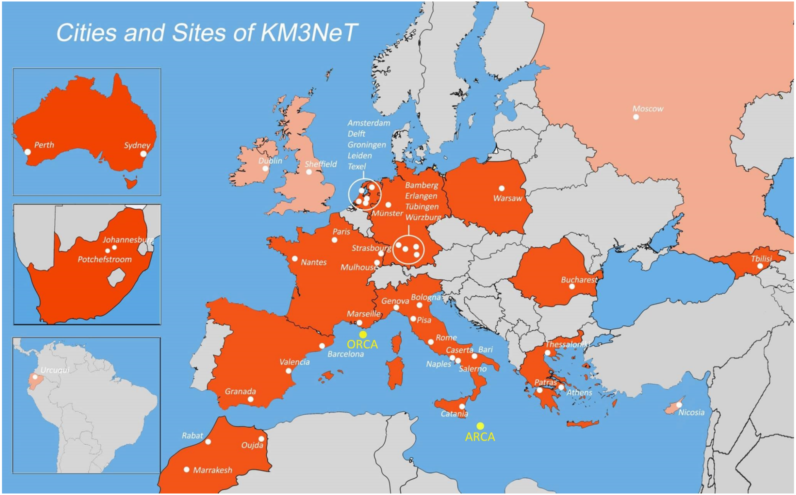
What is KM3NeT?



KM3NeT – The Cubic Kilometre Neutrino Telescope

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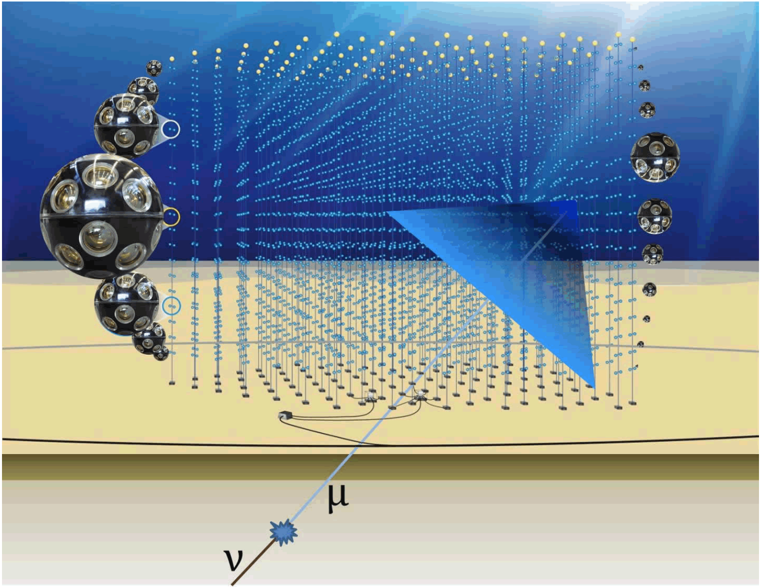
Principle of detection



Light sensors

PMT – Photomultiplier Tube

DOM – Digital Optical Module
(31 PMTs)

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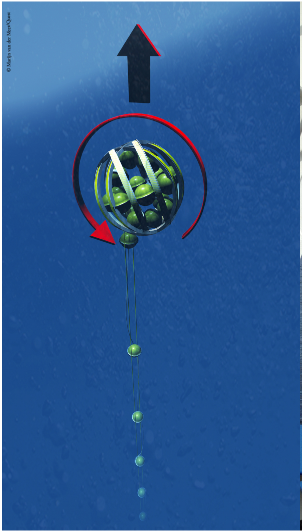
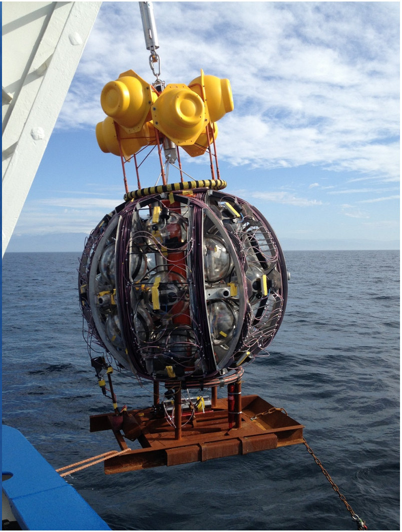
DOM arrangement





DU – Detection Unit (18 DOMs on a string)
LOM – Launcher of Optical Modules

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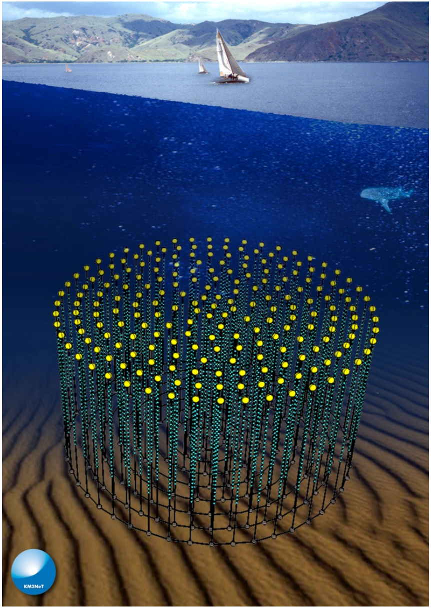
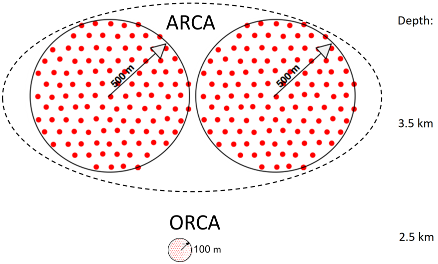
Detectors



ARCA – Astroparticle Research with Cosmics in the Abyss



ORCA – Ocillation Research with Cosmics in the Abyss

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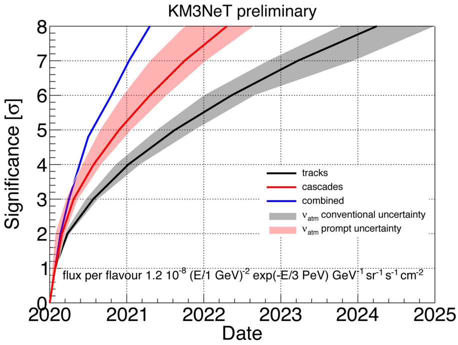
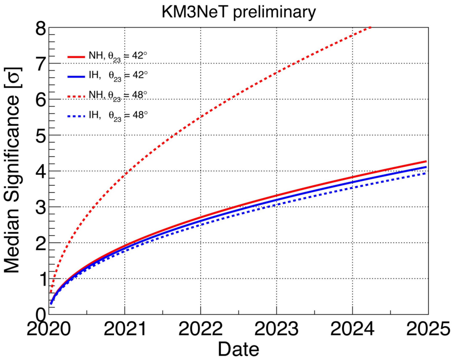
Expected performance (from LoI)

ARCA



ORCA



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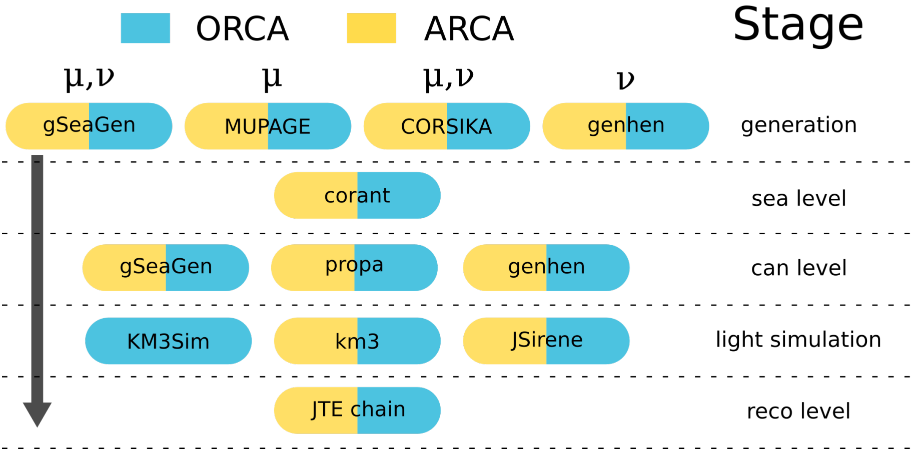
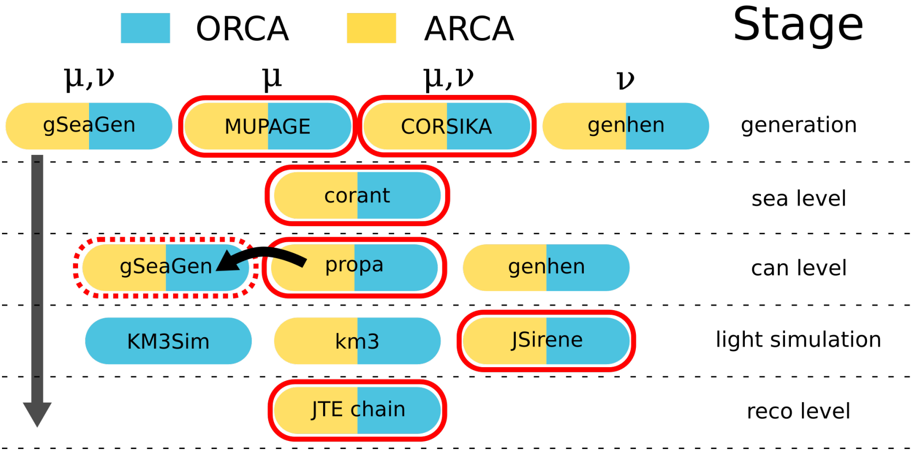
KM3NeT processing chain



can $\Longleftrightarrow$ cyllinder around the detector

KM3NeT processing chain (my branch)



can $\Longleftrightarrow$ cyllinder around the detector

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Statistics at reco level

Statistics (at reco level):

- ORCA:
  - $5 \times 5000 \times 1000 = 2.5 \cdot 10^7$ showers simulated
  - 331 k muon bundles
- ARCA:
  - $5 \times 3000 \times 1000 = 1.5 \cdot 10^7$ showers simulated
  - 205 k muon bundles

Warning: CORSIKA error bars ONLY statistical, no systematics
(e.g. hadronic model uncertainties)

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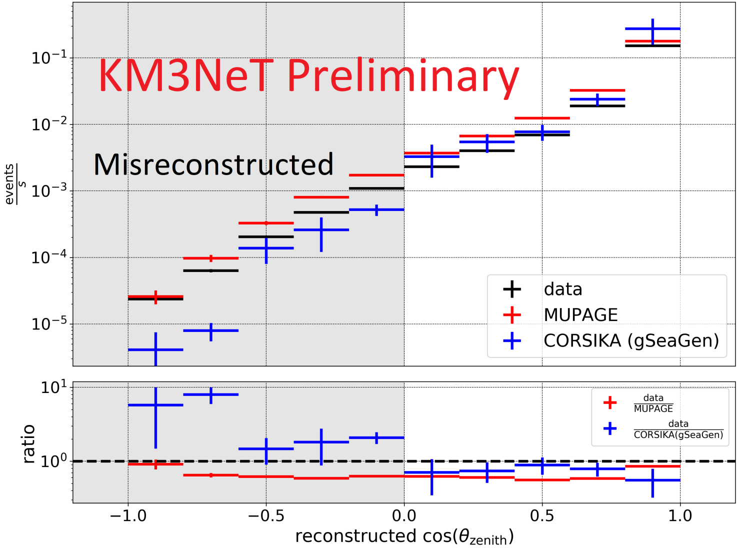
Zenith distributions



detector
ARCA2

generator
CORSIKA
mupage

MC
muon bundles

stage
reco level

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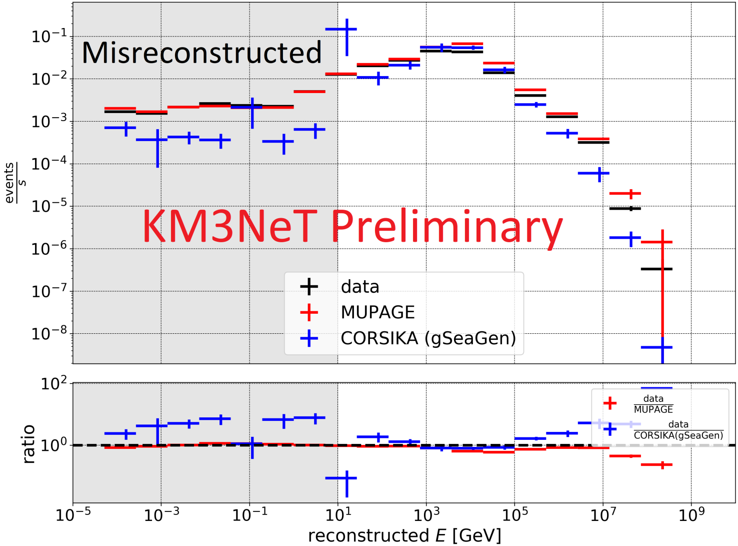
$t_{live}^{data} \approx 72.75$ days $\quad t_{live}^{MUPAGE} \approx 8.07$ days

Energy distributions



detector
ARCA2

generator
CORSIKA mupage

MC
muon bundles

stage
reco level

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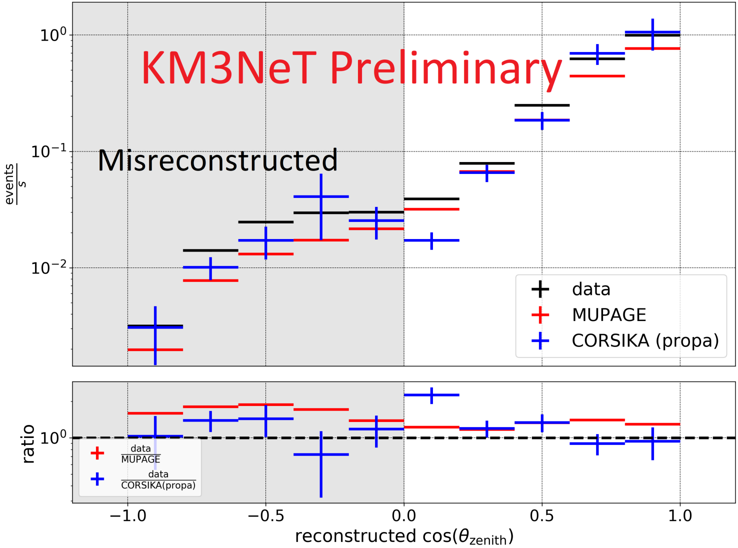
$t_{\text{live}}^{\text{data}} \approx 72.75$ days $\quad t_{\text{live}}^{\text{MUPAGE}} \approx 8.07$ days

Zenith distributions



detector
ORCA1

generator
CORSIKA mupage

MC
muon bundles

stage
reco level

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$t_{\text{live}}^{\text{data}} \approx 1.37$ days $\quad t_{\text{live}}^{\text{MUPAGE}} \approx 3.59$ days

Outline

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All the productions so far

We added new productions to increase low-E_{primary} statistics.

Generated statistics:

- $\gamma = -1$: $5 \times 5000 \times 1000 = 2.5 \cdot 10^7$ showers
- $\gamma = -2$: $5 \times 10 \times 1000000 = 5 \cdot 10^7$ showers
- $\gamma = -3$: $5 \times 100 \times 1000000 = 5 \cdot 10^8$ showers
  $(n_{\text{primaries}} \cdot n_{\text{files}} \cdot n_{\text{showers per file}})$

γ – generation spectral index
(we generate a $E^{\gamma}_{\text{primary}}$ spectrum)

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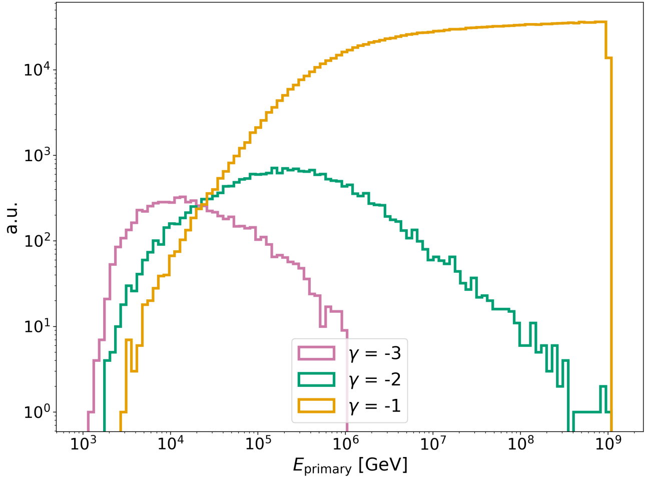
Unweighted Primary spectra



detector
ARCA2

generator
CORSIKA

MC
primaries

stage
can level

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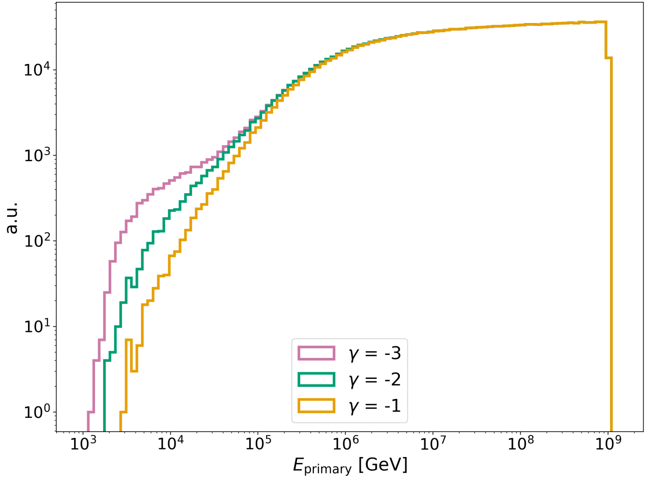
Reminder: small $E_{\mathrm{primary}} \iff$ big weight!

Unweighted Primary spectra (stacked)



detector
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stage
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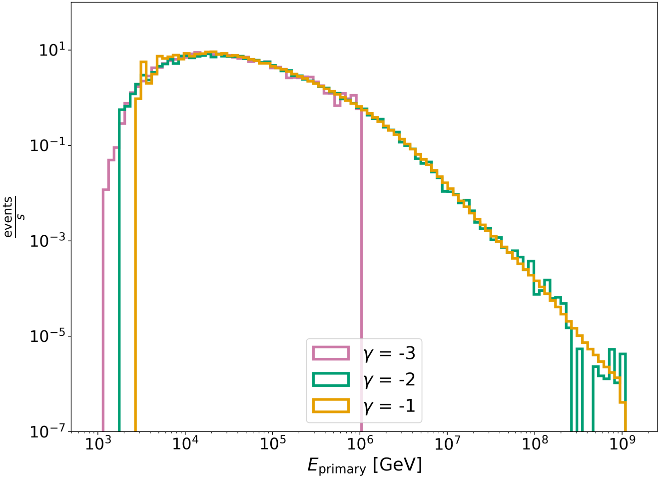
Reminder: small E_{primary} $\Longleftrightarrow$ big weight!

Weighted Primary spectra



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Reminder: small $E_{\text{primary}} \Longleftrightarrow$ big weight!

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Summary

The main message:

- data vs CORSIKA starting to look good
- we could constrain different models
- potential major fix -> filling the missing E_{primary}
- software upgrades in progress

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Requests/ideas for CORSIKA 8

Things we'd like to see in CORSIKA 8:

- casting the CORSIKA output directly into predefined formats (.i3, .evt, .root, .h5, ...)
- built-in further propagation through water/ice/rock/...
- more particles & processes implemented (e.g. for τ production)
- E cuts on E_{tot}, not E per nucleon
- all primaries in 1 file
- more advanced particle selection
- faster code
- some livetime estimation?

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Thank you for your attention. Any questions?

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CORSIKA simulation settings

Settings used for simulations:

- HE hadronic interaction model: SIBYLL 2.3
- LE hadronic interaction model: GHEISHA 2002d (not so important in our case)
- Charmed particles handled explicitly
- $10^3 < \frac{E_{\text{primary}}}{\text{GeV}} < 10^9$ (actually for now $\frac{E_{\text{primary}}}{A}$, but working on it)

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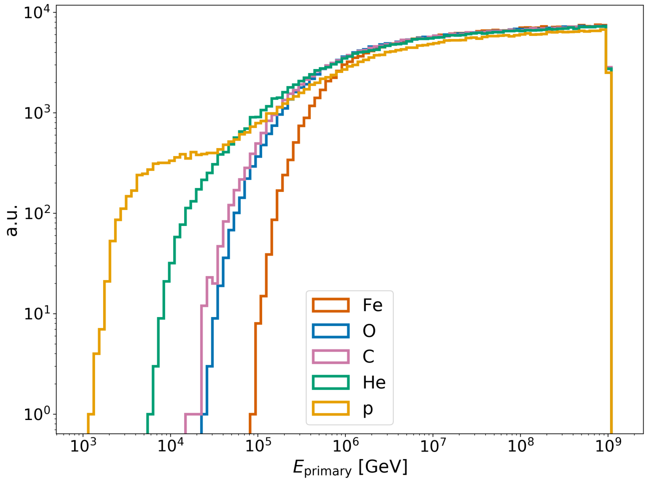
Outline

Unweighted all spectra combined



detector
ARCA2

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CORSIKA

MC
primaries

stage
can level

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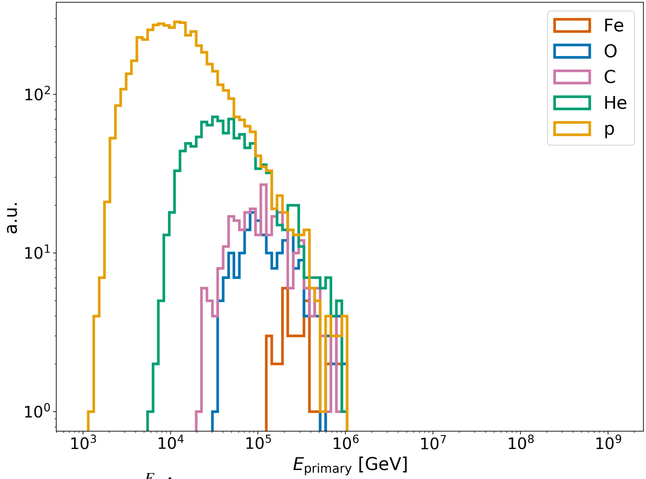
Unweighted $\gamma = -3$ spectra (primary contributions)



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CORSIKA cuts on $\frac{E_{\textbf{primary}}}{A}$ (E per nucleon) $\longrightarrow$ need different cut for each primary

Plus the effect of absporption of low-E showers

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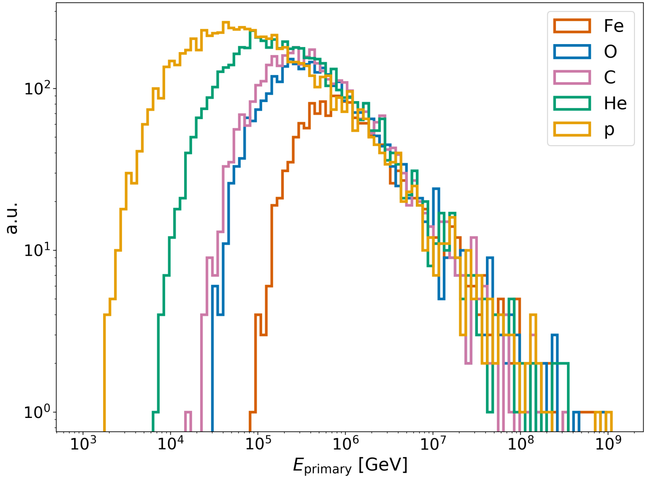
Unweighted $\gamma = -2$ spectra (primary contributions)



detector
ARCA2

generator
CORSIKA

MC
primaries

stage
can level

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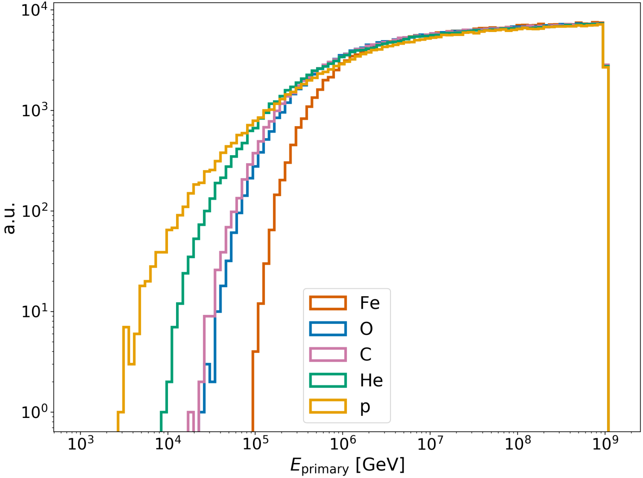
Unweighted $\gamma = -1$ spectra (primary contributions)



detector
ARCA2

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MC
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stage
can level

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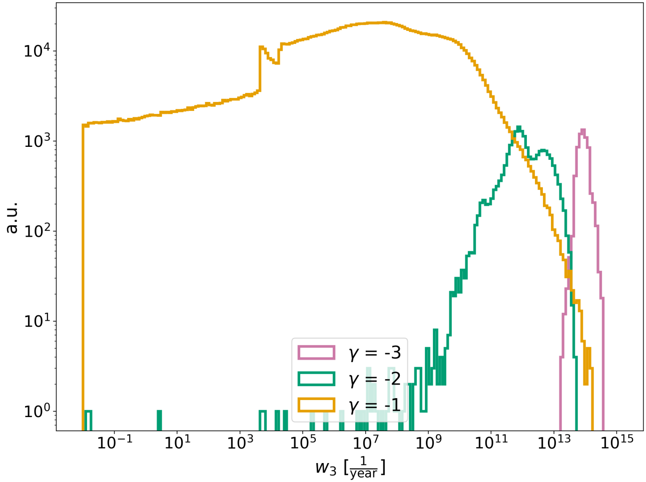
Outline

4 Primaries

5 Weights

Unweighted all primaries combined



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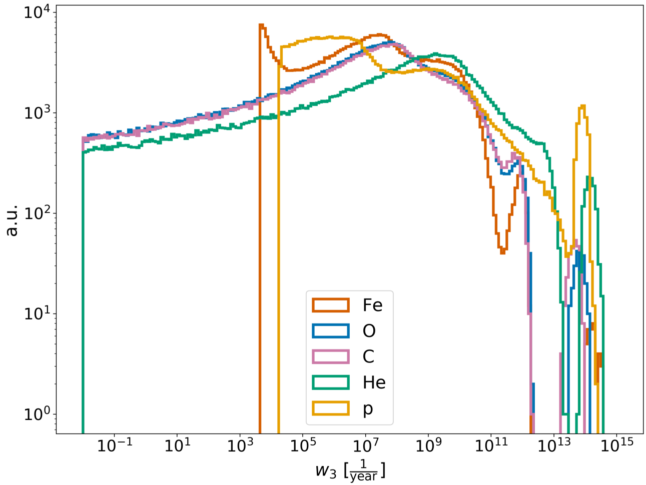
Unweighted all gammas combined



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Weights

Weights within KM3NeT (and ANTARES):

- w_1:
  - effective surface of the can[1] $w_1 = S$ [m^2] for surface drawing
  - can volume [2] $w_1 = V$ [m^3] for volume drawing
- w_2 – contain the generation weight [$\mathrm{GeV} \cdot \mathrm{m}^2 \cdot \mathrm{sr} \cdot \frac{\mathrm{s}}{\mathrm{year}}$] ; used to calculate A_{eff}
- w_3 – "global weight" [$\frac{1}{\mathrm{year}}$]

[1] can≡detector
[2] can≡detector

Weight formulae for volume drawing

The weights are calculated:

$$w_2 = \underbrace{V}_{w_1} \cdot I_\theta \cdot I_E \cdot E^\gamma \cdot \sigma(E) \cdot \rho \cdot N_\mathrm{A} \cdot P_\mathrm{Earth}(E,\theta) \cdot F \quad (1)$$

$$w_3 = w_2 \cdot \phi \quad (2)$$

where:

$I_\theta = 2\pi\left[\cos(\theta_\mathrm{max}) - \cos(\theta_\mathrm{min})\right]$ [sr] – angular phase space factor

γ – generated spectral index

$I_E = \begin{cases} \frac{E_\mathrm{max}^{1-\gamma} - E_\mathrm{min}^{1-\gamma}}{1-\gamma} & \text{if} \quad \gamma \neq 1 \\ \ln\left(\frac{E_\mathrm{max}}{E_\mathrm{min}}\right) & \text{if} \quad \gamma = 1 \end{cases}$ – energy phase space factor

$\sigma(E)$ $[\mathrm{m}^2]$ – total cross-section

$\rho \cdot N_\mathrm{A}$ $[\frac{1}{\mathrm{m}^3}]$ – number density of target nucleons

$P_\mathrm{Earth}(E,\theta)$ – probability to penetrate the Earth

F – number of seconds per year $(3600 \cdot 24 \cdot 365.2422)$

ϕ – expected flux $[\frac{1}{\mathrm{GeV} \cdot \mathrm{m}^2 \cdot \mathrm{sr} \cdot \mathrm{s}}]$

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Weight formulae for area drawing (used for CORSIKA)

The weights are calculated:

$$w_2 = \underbrace{S}_{w_1} \cdot I_\theta \cdot I_E \cdot E^\gamma \cdot F \tag{3}$$

$$w_3 = w_2 \cdot \phi \tag{4}$$

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Weights formulae for rate plots

This is how we weight events:

- CORSIKA:

$$w = \frac{w_3}{\underbrace{1000}_{\text{events per file}} \cdot n_{\text{files}} \cdot \underbrace{3600. \cdot 24. \cdot 365.2422}_{\text{seconds in a year}}} \frac{1}{\mathrm{s}} \tag{5}$$

- mupage/data:

$$w = \frac{1}{t_{\text{live}}} \tag{6}$$

with:

n_{files} – number of files (separately for each primary)
w_3 – weights giving us the rate (see next slide)
t_{live} – livetime

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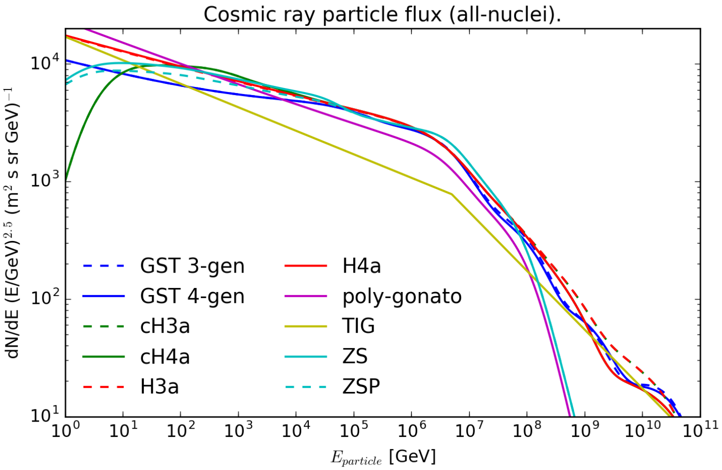
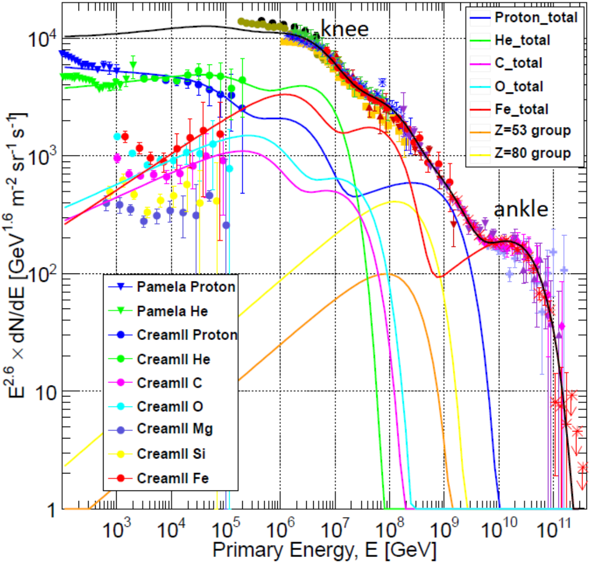
GST3 model vs other models

GST3 – Gaisser-Stanev-Tilav model with 3 primary populations[3]



[3] minimal assumption if the transition to extra-galactic CRs occurs at the ankle

Gaisser model



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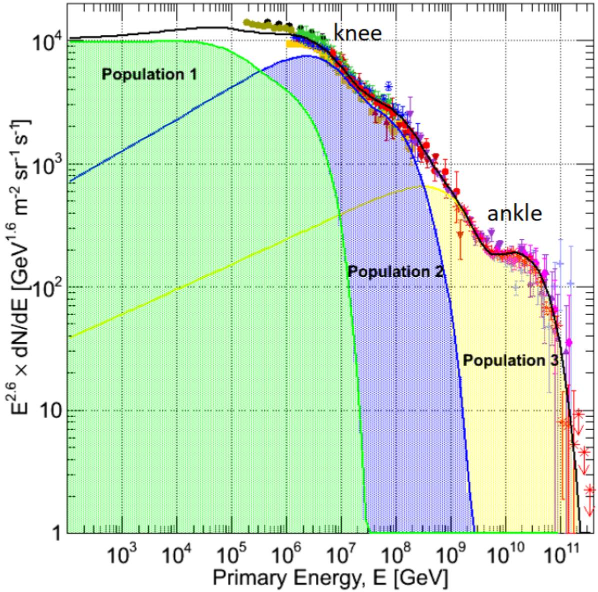
Gaisser model



GST3 flux formula

Mathematically, the flux formula:

$$\phi_i\left(E\right) = \sum_{j=1}^{3} a_{i,j} E^{-\gamma_{i,j}} \cdot e^{-\frac{E}{Z_i \cdot R_{i,j}}}, \tag{7}$$

with the parameter values:

	p	He	C	O	Fe	$50 < Z < 56$	$78 < Z < 82$
Pop. 1:	7000	3200	100	130	60		
$R_c = 120$ TV	1.66 1	1.58	1.4	1.4	1.3		
Pop. 2:	150	65	6	7	2.3	0.1	0.4
$R_c = 4$ PV	1.4	1.3	1.3	1.3	1.2	1.2	1.2
Pop. 3:	14				0.025		
$R_c = 1.3$ EV	1.4				1.2		
Pop. 2*:	150	65	6	7	2.1	0.1	0.53
$R_c = 4$ PV	1.4	1.3	1.3	1.3	1.2	1.2	1.2
Pop. 3*:	12				0.011		
$R_c = 1.5$ EV	1.4				1.2		
Pop. 4*:	1.2						
$R_c = 40$ EV	1.4						

TABLE III: Global Fit results for the cutoffs, normalization constants ($a_{i,j}$) and integral spectral indexes ($\gamma_{i,j}$) for Eq. 3. In the bottom part of the table(*) populations 2 and 3 are slightly modified to accommodate a Population 4 of protons to bring $< \ln(A) >$ down to the observed level in Fig. 5.

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