# Fast Hybrid Air Shower Simulations with **CONEX**

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CORSIKA School 2010, Ooty, India

**One-dimensional Hybrid Approach to Extensive Air Shower Simulation**

Astropart.Phys.26:420-432,2007

T. Bergmann(1), R. Engel(1), D. Heck(1),
N.N. Kalmykov(2), S. Ostapchenko(1,2), T. Pierog(1),
T. Thouw(1), K. Werner(3)

ROOT-Interface:
M. Unger(1), R. Ulrich(1) and T. Pierog(1)

(1) Karlsruhe Institute of Technology, Germany
(2) Moscow State University, Russia
(3) SUBATECH, Universite de Nantes, France

Write to **tanguy.pierog@kit.edu** to obtain the code

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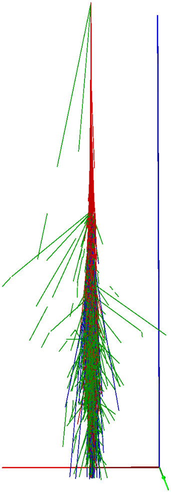
# Air Shower Simulations

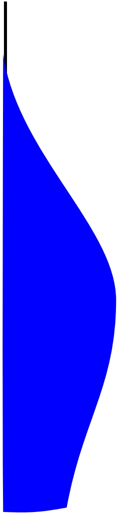


**Full Monte Carlo**

- Microscopic description
- Fluctuations
- Slow

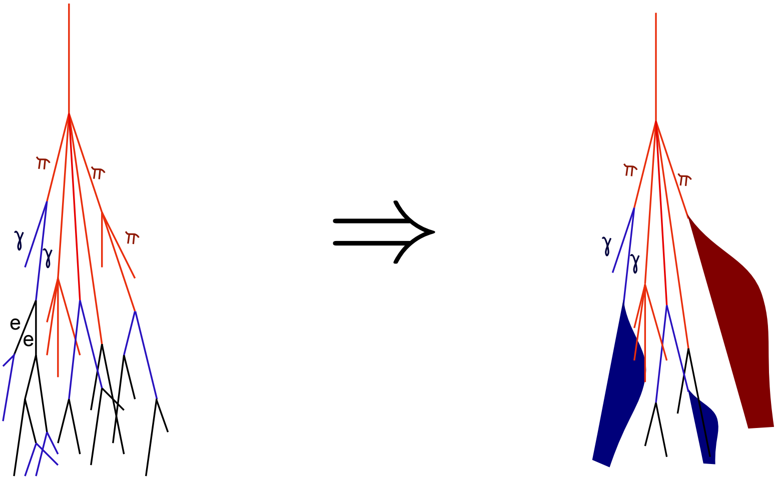
**Cascade Equations**

- Collective description
- Only average behavior
- Fast



**CONEX combines both: Fast and Fluctuations**

# Hybrid Approach




| | | |
|---|---|---|
| High Energies: | few particles, important fluctuations | ⇒ Monte Carlo |
| Lower Energies: | many particles, no relevant fluctuations | ⇒ Cascade Equations |

# Cascade Equations

$$\frac{\mathrm{d}n_i(E, X)}{\mathrm{d}X} =$$

For all particle types i=e, $\gamma$, p, n, $\pi$, K, ...

# Cascade Equations

$$\frac{\mathrm{d}n_i(E, X)}{\mathrm{d}X} = - \sigma_i \, n_i(E, X)$$

**Interactions**

For all particle types i=e, $\gamma$, p, n, $\pi$, K, ...

# Cascade Equations

$$\frac{\mathrm{d}n_i(E, X)}{\mathrm{d}X} = - \sigma_i \, n_i(E, X)$$

**Interactions**

$$+ \sum_j \int_E^{E_0} \sigma_{j\to i} \, n_j(E', X) \, P_{j\to i}(E', E) \, \mathrm{d}E'$$

**Production**

For all particle types i=e, $\gamma$, p, n, $\pi$, K, . . .

# Cascade Equations

$$\frac{\mathrm{d}n_i(E,X)}{\mathrm{d}X} = -\ \sigma_i\, n_i(E,X)$$

**Interactions**

$$+\ \sum_j \int_E^{E_0} \sigma_{j\to i}\, n_j(E',X)\, P_{j\to i}(E',E)\, \mathrm{d}E'$$

**Production**

$$-\ \alpha_i \frac{\partial n_i(E,X)}{\partial E}$$

**Ionization**

For all particle types i=e, $\gamma$, p, n, $\pi$, K, ...

# Cascade Equations

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**Production**

$$-\ \alpha_i \frac{\partial n_i(E,X)}{\partial E}$$

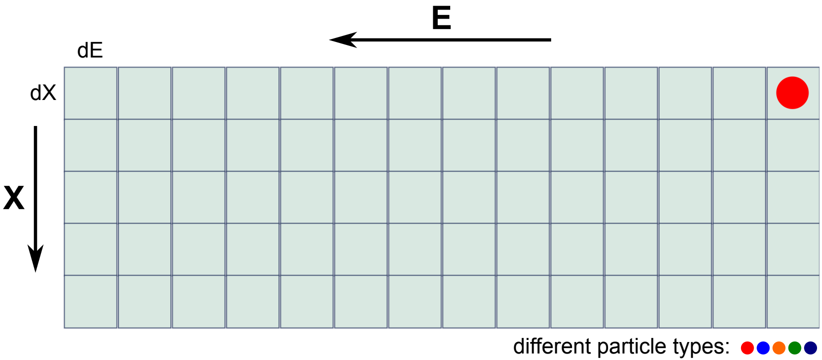
**Ionization**

For all particle types i=e, $\gamma$, p, n, $\pi$, K, . . .

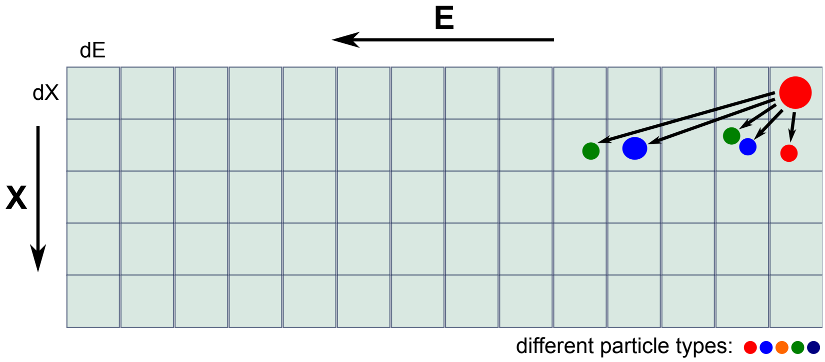
**Analytic solution:**
approximately possible for purely electromagnetic cascades.
Not possible for hadrons.

$\Longrightarrow$ **Numerical solution**

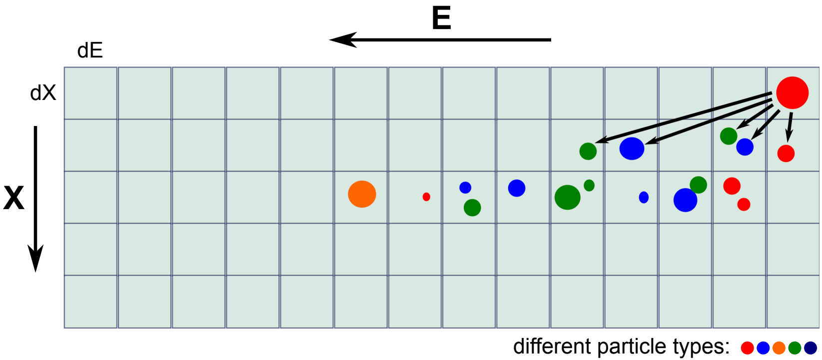
# Cascade Equations



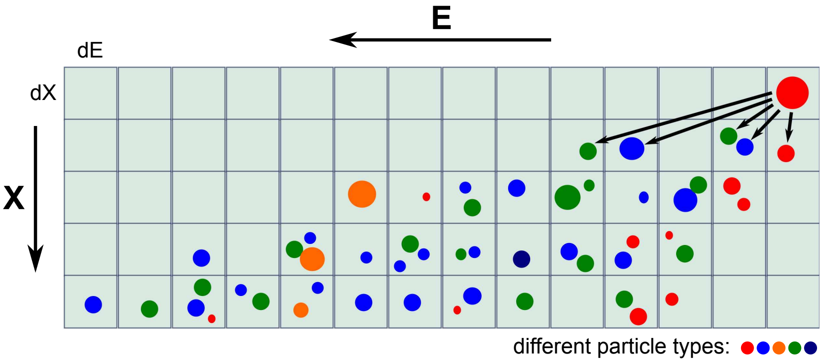
# Cascade Equations



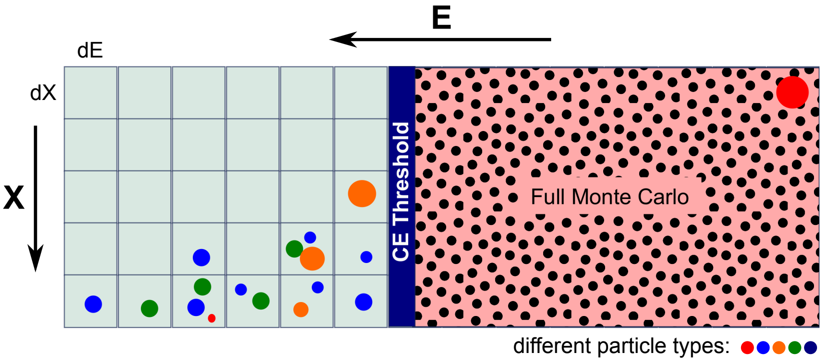
# Cascade Equations



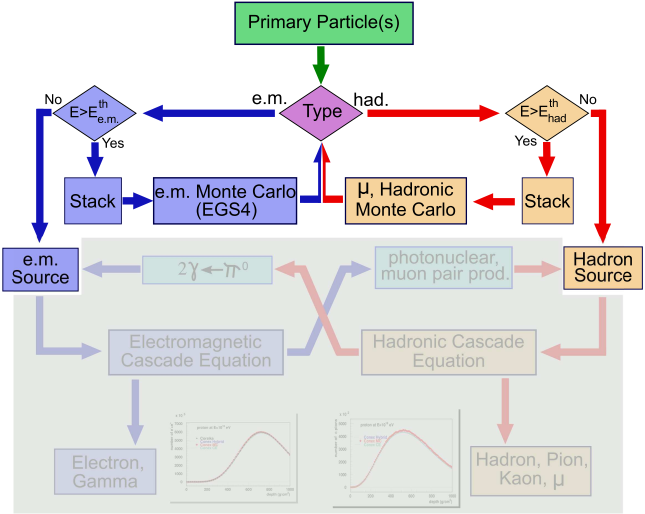
# Cascade Equations



# Cascade Equations in the Hybrid Approach



# Implementation



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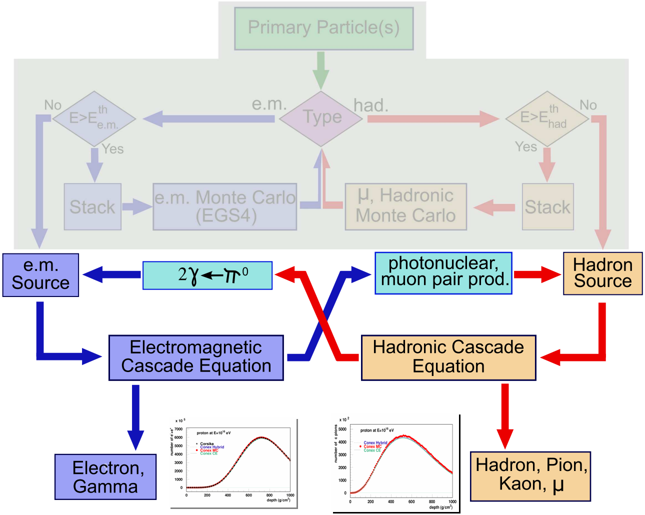
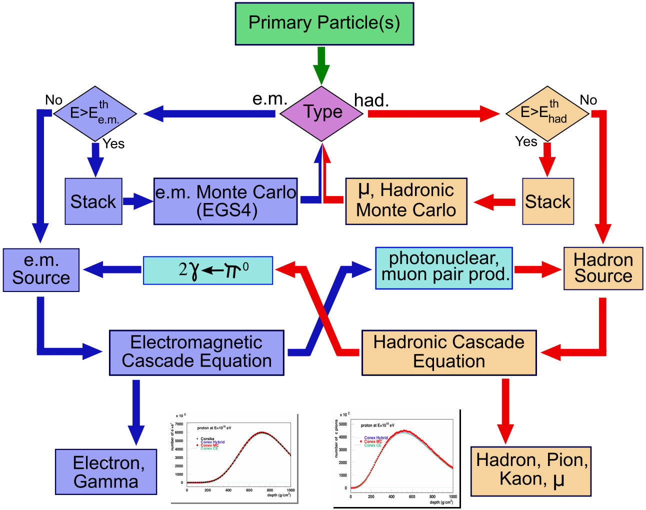
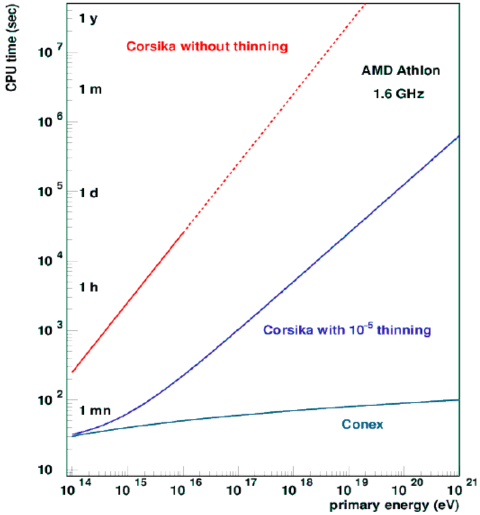


# Implementation






**CORSIKA**

$\propto$ Energy

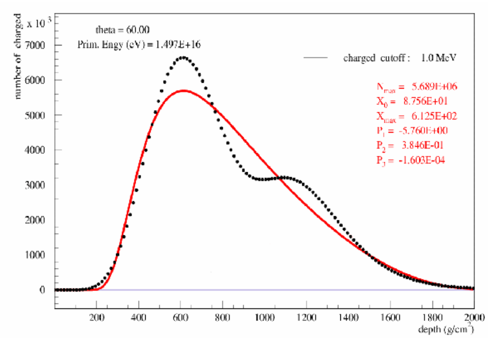
**CONEX**

$\propto$ log(Energy)

$\sim$ 1 min / shower

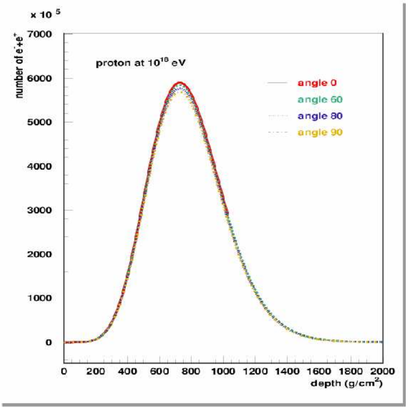
no thinning fluctuations

# Extreme Fluctuations of Longitudinal Development

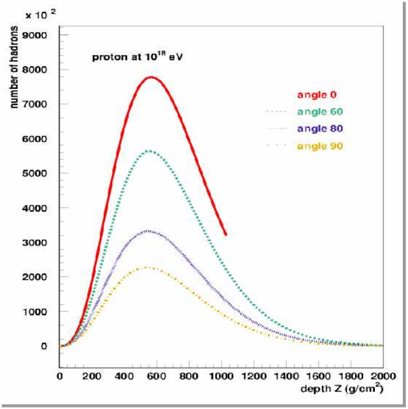



$\rightarrow$ difficult to study with e.g. CORSIKA

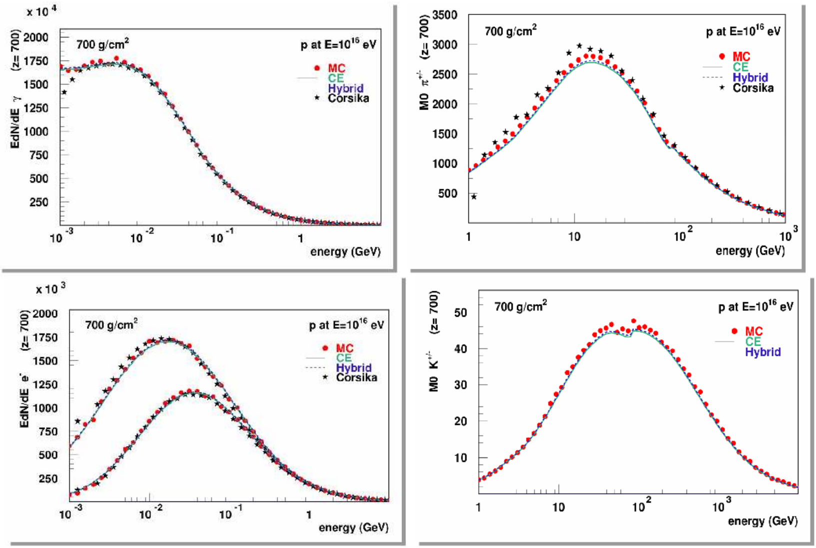
## Electromagnetic



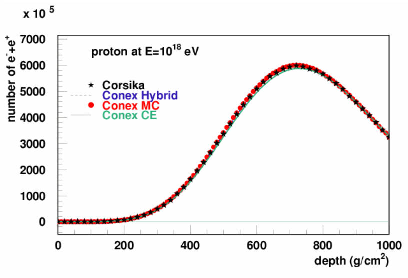

## Hadrons/Muons



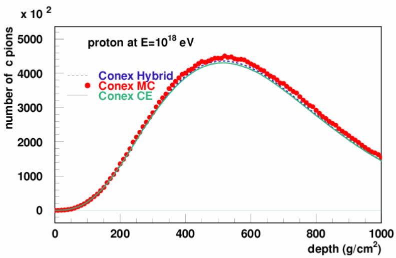
# Energy Distributions



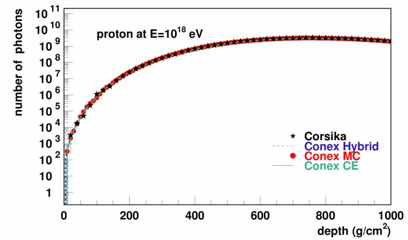
# Profiles



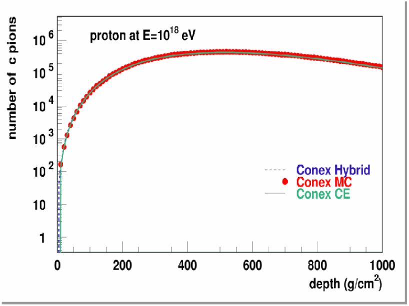
x 10^5
number of e-+e+
proton at E=10^18 eV
Corsika
Conex Hybrid
Conex MC
Conex CE
depth (g/cm^2)

x 10^2
number of c pions
proton at E=10^18 eV
Conex Hybrid
Conex MC
Conex CE
depth (g/cm^2)

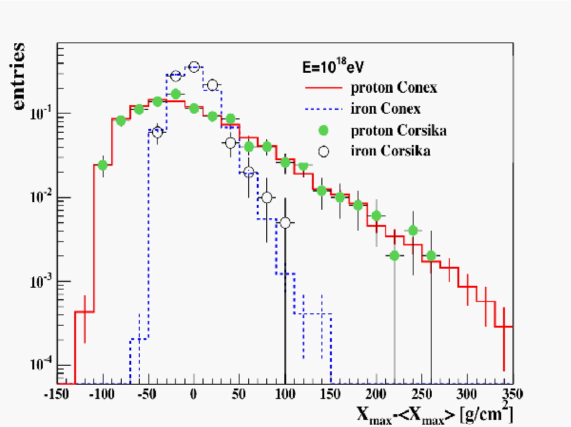



number of photons
proton at E=10^18 eV
Corsika
Conex Hybrid
Conex MC
Conex CE
depth (g/cm^2)

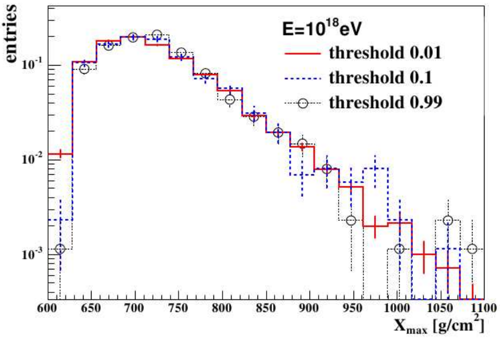



number of c pions
proton at E=10^18 eV
Conex Hybrid
Conex MC
Conex CE
depth (g/cm^2)

# Shower Fluctuations

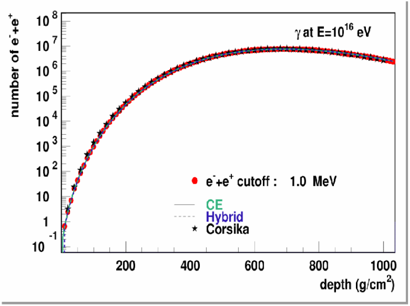


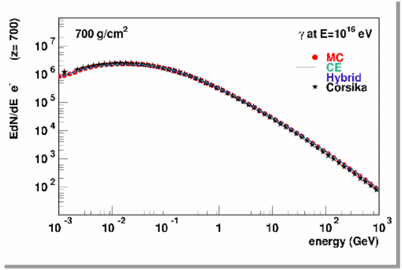
# Cascade Equation Threshold Energy

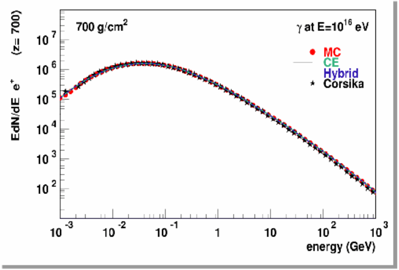



⇒ Shower fluctuations are dominated by the first interaction

# Photon Induced Showers



# Features

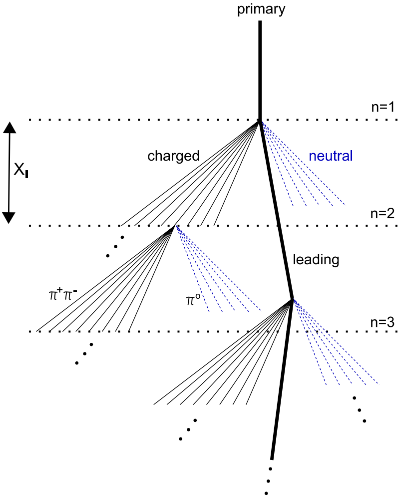
Main application: one dimensional hybrid air shower profile simulations

- Interactions in full Monte-Carlo
  - EPOS1.99
  - SIBYLL2.1
  - QGSJet01
  - QGSJetII.3
  - NEXUS3.97
  - GHEISHA (below 100 GeV)
  - EGS4 (for electromagnetic particles)
- Lower energy interactions: Cascade Equations
- No thinning
- Variable atmosphere and full 3D geometry implemented

  $\rightarrow$ Also upward going ($\theta \sim 90^\circ$) showers
- Extensive comparison to CORSIKA
- Typical simulation time: 1 min / shower
- Photon Pre-Shower available

  (Homola et al. Comp.Phys.Comm.173 (2005) 71)
- Output in ROOT format

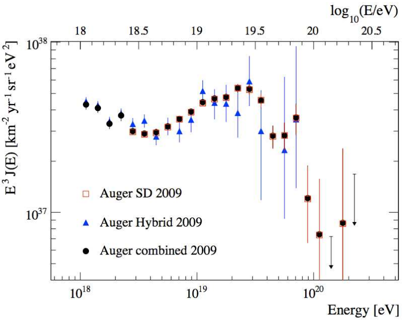
# Leading Interactions




- CONEX allows recording of the leading particle interactions and their secondary products
- Works only during the Monte Carlo part of CONEX
- Output in ROOT file

# Some Physics Results Obtained with the Use of CONEX

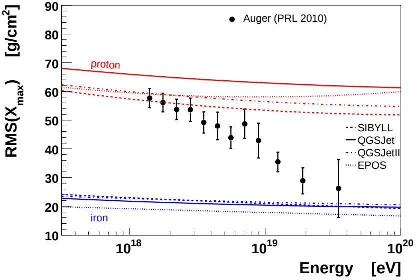
**Auger hybrid exposure/spectrum**




Phys.Lett.B685:239-246,2010

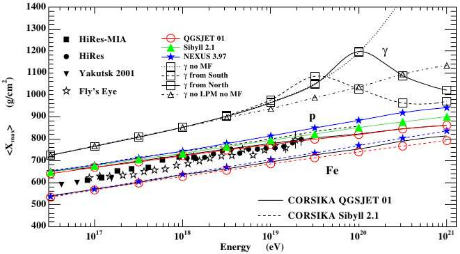
arXiv:1010.6162 [astro-ph.HE],
accepted by Astropart.Phys.

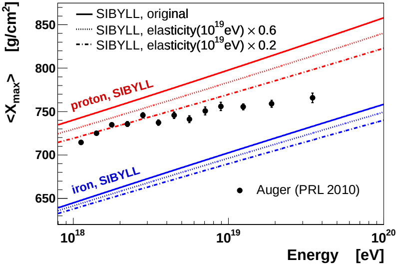
**Auger $X_{max}$**

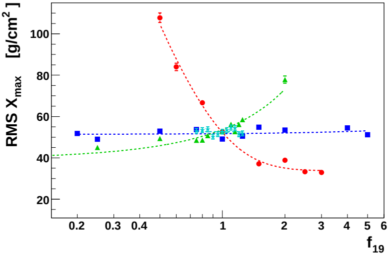



Phys.Rev.Lett.104:091101,2010

**Some examples:**




(e.g. Ulrich et al., arXiv:1010.4310 [hep-ph], submitted)

# Summary

- Extremely fast air shower simulations
- Cascade Equations, no thinning
- Will be available in CORSIKA as option to replace thinning

- Ideal for phenomenological studies
  - Air shower development
  - Hadronic interactions in air showers
- Suited for longitudinal observations (fluorescence, microwave, ...)
- No particle timing, no detailed ground particle output, not suited for surface arrays

  $\rightarrow$ Not so useful for air shower arrays (KASCADE/Grande, Grapes, etc.)