Astroparticle and particle physics with HiSCORE

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Roma, RICAP 2011

Physics motivations
Principle of the array
Status & outlook
Acronyms

**SCORE**

*Study for a Cosmic ORigin Explorer ~ 10 km²*

**HiSCORE**

*Hundred*<sup>i</sup> *Square-km Cosmic ORigin Explorer ~ 100+ km²*
HiSCORE aims

Cosmic-rays:
\[100 \text{ TeV} < E_{CR} < 1 \text{ EeV}\]

Gamma-rays:
\[E_{\gamma} > 10 \text{ TeV}\]

Large area: 10-100 km²

Large Field of view: \(~ 0.6 \text{ sr}\)

ASPERA recognizes the importance of

“development of ground-based wide-angle gamma-ray detectors”

We propose HiSCORE!
Astroparticle Physics @ E > 10 TeV

**Gamma-ray Astronomy**
- VHE spectra: where do they stop?
- Origin of cosmic rays: pevatrons
- Absorption in IRF & CMB
- Diffuse emission:
  - Galactic plane
  - Local supercluster

**Particle physics beyond LHC**
- Axion / photon conversion
- Hidden photon / photon oscillations
- Lorentz invariance violation
- pp cross-section measurements
- Quark-gluon plasma

**Charged cosmic ray physics**
- Composition / anisotropies
- Sub-knee to pre-ankle
Gamma-Ray Sky, $E>100\text{GeV}$
Gamma-Ray Sky, E>10TeV
Gamma-Ray Sky, $E>100\text{TeV}$

UHE Gamma-Ray Sky ($S > 5\sigma$, $E > 100\text{ TeV}$), September 2009

No detections yet – but why?
Gamma-Ray Sky, E>100TeV
Gamma-Ray Sky, $E>100\text{TeV}$

- Knee-energies: $E_{CR} \sim \text{PeV}$
- $E_{\gamma} \sim 100\text{ TeV}$
Gamma-Ray Sky, E>100 TeV

Knee-energies: $E_{\gamma} \sim 100$ TeV

Pevatrons must exist!
Need better sensitivity @100 TeV
UHE Gamma-rays

![Graph showing integral flux sensitivity vs. log(energy/TeV) for various sources and sensitivity goals.]
UHE Gamma-rays

The graph shows the integral flux sensitivity in erg cm\(^{-2}\) s\(^{-1}\) as a function of log(energy/TeV). The graph includes various lines representing different survey sensitivities and point-source sensitivities from H.E.S.S., Milagro, CTA, and HAWC, as well as the sensitivity goal. The highlighted region indicates a poorly covered energy range.
UHE Gamma-rays

Extend energy range to multi-PeV
Need a large area!

Poorly covered energy range
UHE Gamma-rays

Extend energy range to multi-PeV
Need a large area!
Bonus: unambiguous signal!
No hard IC emission beyond 100 TeV
(Klein-Nishina regime)

Poorly covered energy range
UHE Gamma-rays

Extend energy range to multi-PeV
Need a large area!

Bonus: unambiguous signal!
No hard IC emission beyond 100 TeV
(Klein-Nishina regime)

E~100TeV: absorption in ISRF relevant
E~1PeV: strong CMB absorption
→ use cutoff feature for distance measurement?

Absorption by e+e- pair production
Moskalenko et al. 2006
Cosmic rays

Adapted from Donato et al. 2001


Abbasi et al., http://arxiv.org/abs/1005.2960

Adapted from [Blümer et al. 2009]

HiSCORE, 10 yrs
Cosmic rays

Particle physics

Adapted from [Blümer et al. 2009]

Score

Shower maximum
Cover wide energy range w/ Score

Adapted from [Shibata et al. 2010]

Score

Average mass

Further particle physics topics:
- Axion search: photon/axion conversion & reconversion → absorption-free propagation
- Hidden sector
- Heavy dark matter
The detector

Goals:
Energy range goal: 10 TeV – 1 EeV
Area goal: 10 – 100+ km²
Sensitivity goal: better than $10^{-12}$ erg / cm² s

Concept:
Very large effective area, wide field of view
Non-imaging atmospheric Cherenkov technique
Lateral Cherenkov Photon Distribution

![Graph showing the lateral Cherenkov photon distribution for 10 TeV and 100 TeV gamma rays. The graph plots the Cherenkov photon density (m^-2) against the distance from the shower core (m). The graph shows two curves: one for 10 TeV gamma rays (red) and one for 100 TeV gamma rays (blue). The density decreases as the distance increases, with the 100 TeV curve being higher than the 10 TeV curve.](image_url)
Lateral Cherenkov Photon Distribution

~4 stations inner light pool
Large area: ~150 m spacing

Distance from shower core [m]

Cherenkov photon density [m⁻²]

10 TeV γ

100 TeV γ
Lateral Cherenkov Photon Distribution

Low photon density: Need large collector area → 0.5 m² per station

~4 stations inner light pool
Large area: ~150 m spacing
The HiSCORE principle

Ultra-High energy regime: **need large effective area**!

Imaging ACTs: > 10000 channels / km²

**Non-imaging Cherenkov light-front sampling**
SCORE: ~300 channels / km²

Array of detector stations

100-200 m
The HiSCORE principle

Ultra-High energy regime: need large effective area!

Imaging ACTs: > 10000 channels / km²

Non-imaging Cherenkov light-front sampling – record light amplitude and timing

SCORE: ~300 channels / km²
The HiSCORE principle

HiSCORE detector station concept

Total light-capturing area: 0.5 sqm

- 400mm Winston cone
- PMT ~ 206mm

HV divider

R/O DRS 4

Clock

USB

PlugPC

Central DAQ

Time sync.

Ethernet

Power distribution

Low gain – dyn 5

High gain – anode

Arduino

Slow control

Low voltage: 0.5V

On/off & monitor

12V
The HiSCORE principle

HiSCORE detector station concept

- Total light-collecting area: 0.5 sqm
- 400mm Winston cone
- PMT ~ 206mm
- HV divider
- R/O DRS 4
- clock
- USB
- clip
- Clipping
- Summing
- Discriminator threshold
- DRS 4 READOUT

Arduino
- Low gain – dyn 5
- High gain – anode
- Slow control
- Power distribution

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The HiSCORE principle

The HiSCORE detector station concept

Total light-collecting area: 0.5 sqm

- 400mm Winston cone
- PMT ~ 206mm

HV divider

- 0.5V
- 0.25kV
- on/off & moni
- anode - dyn 5

High gain - dyn 5

Power-distribution

R/O DRS 4

1024 cells

Clock

CLIPPING

SUMMING

Discriminator

DRS 4 READOUT

One station signal DRS 4
Simulation, E = 1PeV
The HiSCORE principle

HiSCORE detector station concept

- Total light-collecting area: 0.5 sqm
- PMT ~ 206mm
- HV divider
- 400mm
- Winston cone

One station signal DRS 4

Simulation, E = 1PeV

750 TeV gamma ray

Depth = 495 g/cm²
Depth = 718 g/cm²

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Air-shower simulation CORSIKA 6735 [1]:


• Gamma, H, He, N, Fe
• 1/E powerlaw from 10 TeV (H: 5 TeV) to 5 PeV
• New production using Fluka planned
Full detector simulation – sim_score [5]:

- Using iact package I/O routines, provided by [3]
- Winston cone acceptance included by ray-tracing simulation
- PMT quantum efficiency (Electron Tubes 8" PMT, data sheet)
- Electron collection efficiency
- PMT signal pulse-shape parameterization [4]
- Afterpulsing simulated w/ $P = 10^{-4}$ at 4 p.e.
- Local trigger: sum of 4 clipped channels
- Night-sky background (including pulse shaping), added to signals
- Array trigger: 1-station or 2-station NN (1µs coincidence window)
An event example

187 TeV gamma-ray
An event example

187 TeV gamma-ray

depth = 495 g/cm$^2$
depth = 718 g/cm$^2$
Effective CR trigger area

150 m station spacing
Local station trigger-threshold: 180 p.e.
Array trigger: 1 single-station trigger
No grading, no cells
Effective CR trigger area

150 m station spacing
Local station trigger threshold: 180 p.e.
Array trigger: 1 single-station trigger
No grading, no cells

- Gamma-rays
- Protons
- Helium
- Nitrogen
- Iron
Trigger rates summary

![Graph showing trigger rates summary. The x-axis represents station threshold in photoelectrons (p.e.), and the y-axis represents trigger rate in Hz. The graph includes data points for NSB photons, cosmic rays, and uncorrelated muons.](image)
Shower core reconstruction

- Nstations < 5: weighted center of gravity
- Nstations >= 5: Fit to LDF

\[
LDF(r) = \begin{cases} 
    P \exp(dr) & \text{for } r < c_{LDF} \approx 120 \text{ m} \\
    Q r^k & \text{for } r > c_{LDF}
\end{cases}
\]

\[
r = r(x, y) = \sqrt{x^2 + y^2}
\]

\[
Q = \frac{P \exp(d c_{LDF})}{(c_{LDF})^k}
\]

- Free parameters P, d, k, (x,y). Nstations >= 6: c_{LDF} free parameter
- To come: use width for outside showers
Shower core resolution

![Graph showing core position resolution against energy in TeV. The graph includes data points for the centre of gravity, LDF fit without transformation, and LDF fit with transformation.](image-url)
Angular resolution

with 2 ns jitter
with 1 ns jitter
ideal synchronisation

Angular resolution [deg]

Energy [TeV]

0
0.1
0.2
0.3
0.4
0.5
0.6
0.7

$10^2$

$10^3$

$10^4$
Energy reconstruction

- Smallest impact of shower depth on photon density at 220m
Shower depth reconstruction

- **Ds:** Depth from LDF slope, \( Q_{50}/Q_{220} \)

- **Dw:** Depth from signal width

- signal-stacking: add signals with same core-distance

- effective at core-distance > 150m

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**Graphs:**

1. **Core distance [m]**
   - X-axis: Core distance in meters
   - Y-axis: Signal intensity [p.e.]
   - Data points for two depths: 495 g/cm² and 718 g/cm²

2. **Core distance [m]**
   - X-axis: Core distance in meters
   - Y-axis: Signal width [ns]
   - Data points for two depths: 495 g/cm² and 718 g/cm²
Shower depth reconstruction

- **Ds:** Depth from LDF slope: \( \frac{Q50}{Q220} \)
- **Dw:** Depth from signal width
- **signal-stacking:** add signals with same core-distance

\[ \text{depth} = 495 \text{ g/cm}^2 \]
\[ \text{depth} = 718 \text{ g/cm}^2 \]
Shower depth resolution

Combination of LDF and width methods

Shower depth resolution (1 sigma) [g/cm²]

Energy [TeV]

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Particle identification

• Gamma-hadron separation
• Cosmic ray composition

1) Shower depth depends on particle type
2) The signal width also depends on particle type
   → Systematic shift of depth estimate $D_w$
   → Separator: $D_w/D_q$

Combination of 1) and 2) → gamma-ness parameter
Particle identification

![Histogram showing the distribution of Gamma, Proton, and Iron events.](image)
Effective area @ reconstruction level

Zenith<25 deg
After reconstruction & gamma-hadron separation

Reconstruction cuts:
- $\geq 3$ triggered stations
- Contained reconstructed core impact position
- Separator $\geq 400$
SCORE Sensitivity

- H.E.S.S. survey sensitivity 6 yrs
- Milagro, 5 yrs (North)
- Pevatron fit to MGROJ2019+37
- Weak Pevatron

KASKADE U.L.

- 50 $\gamma$-rays on 1 km$^2$ in 1000 h
- 10 km$^2$, 5 years
- 100 km$^2$, 5 years
- CTA pointed 50h
- LHAASO 10 evts
- HiSCORE, 50 evts

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Hardware status

- **Central PC**: GUI-client
- **WLAN router**: TK-LINK
- **WLAN or eth-cable**
- **Motor**
- **Power supply**: 12V / 220V?
- **12V OR 220V**
- **Microcontroller**: Arduino
- **Slow ctrl board**: UHH
- **HV Supply/Div. Signals ISEG**
- **PMT**
- **Detector**: sensors
- **+ box**
- **DRS 4 Eval. board**
- **USB**
- **Trigger**
- **t-synch.**
- **PC GuruPlug**: server
- **USB**

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Mechanics
Status & current activities

ET 9352, 8” PMT

First PMT test-bench results
ET9352 + preamp + DRS4 r/o

Winston cone prototype:
“Barrel-mounting” method
Plan: use UP4300 refl. foil
Available components
Available components

Clipped sum

Trigger Simulation
## Available components summary

<table>
<thead>
<tr>
<th>component</th>
<th>status</th>
<th>plan</th>
</tr>
</thead>
<tbody>
<tr>
<td>PMT</td>
<td>Available / tested</td>
<td>Await further delivery Test Hamamatsu PMTs</td>
</tr>
<tr>
<td>DRS4 R/O</td>
<td>Available / tested</td>
<td></td>
</tr>
<tr>
<td>HV sup/div</td>
<td>Available / tested</td>
<td></td>
</tr>
<tr>
<td>PlugPC</td>
<td>Available / tested</td>
<td></td>
</tr>
<tr>
<td>Microcontroller</td>
<td>Available / tested</td>
<td></td>
</tr>
<tr>
<td>SlowCtrl board</td>
<td>Developed / partly tested</td>
<td>Await full board this week</td>
</tr>
<tr>
<td>Sensors</td>
<td>Available / tested</td>
<td></td>
</tr>
<tr>
<td>Trigger</td>
<td>Concept ready To be developed</td>
<td>Fall-back: internal DRS4 trigger</td>
</tr>
<tr>
<td>GUI-client / server connection</td>
<td>Available / partly tested</td>
<td>Further development Full test with all station components @ UHH</td>
</tr>
</tbody>
</table>
HiSCORE prototype at TUNKA

- Deployment of 1 prototype station in 2011
- 2+ in 2012
- Cross-calibration with TUNKA Cherenkov
- Potential of joint operation with muon detectors
- Synergies with radio detectors
- 2011: use TUNKA trigger / DAQ
- 2012: HiSCORE local trigger
- 2012+: start deployment of engineering array for proof of principle and first physics
- New CORSIKA+sim_score production for TUNKA site, including FLUKA usage
Alternatives / Extensions

- Improvements of layout:
  - **4-channel-cells, 7m X 7m:** Operate each channel independently
    2-by-2 sub-arrays for better low-energy reconstruction
  - **Graded array:** decreasing station density towards array edge
    maximizes area for large energies
  - **Daytime-measurements** with scintillator material in lid:
    100% duty cycle
  - **Muon detector:** much better g/h separation

- Combination with imaging technique:
  - provide core-reconstruction for low-density telescope grid
    (even monoscopic ?)
  - Instrumentation of larger area for highest energies

- Combination / cross-calibration with radio detection technique?
Combination with IACTs

SCORE Detector stations — really not to scale!
Combination with IACTs

- Sharing site infrastructure
- Use SCORE stations for **shower impact reconstruction**
  - **improvement for large stereo angles**
  - **monoscopic telescopes** distributed on **larger area**. E.g. CTA: same number of small telescopes but larger distances giving **higher Aeff / channel ratio**!

- Caveat: observations constrained to station viewcone – might be overcome by using timing stereo at large zenith angles.
- Working on ... testing this in simulation
Plans

HiSCORE 1st prototype at TUNKA 2011
HiSCORE prototype at AUGER ~2012
PhD position from Helmholtz alliance, HAP

Engineering array at TUNKA:
start deployment ~2012

Site search: south, clear, dark, (low?), flat
HiSCORE: 10—100 km² in 2015?
Summary

- Many physics cases beyond 10 TeV primary energy
  The sensitivity goal is already reached by 10km² stage
- Detector fully simulated
- R&D advanced
  80% of components developed
- Cooperation with TUNKA started
- Further ideas:
  Combination with radio / scintil. / imaging technique under stud
References


Backup
HiSCORE prototype at TUNKA

Close to center of cluster \( \sim 2 \text{ m} \)

HiSCORE prototype diagram:
- HiSCORE Station
- Cluster 5, trigger box
- Optical wire
- Tunka DAQ
- 85m distance

HiSCORE "cluster" trigger box
Expected night-sky background trigger rate

Separate NSB simulation, 4-channel station:

- NSB-rate from measurement in Australia [Hampf et al. 2010]
- Arrays of Photon times: equally distributed random numbers
- Pulse shaping + afterpulsing
- 4-channel coincidence trg:
  → channel-amplitude-clipping
  → analog sum of 4 clipped signals
  → discriminate sum
- Resulting **noise file**: 2s in 1ns bins
- Noise added segment-wise from file to simulated air-shower signal
Winston cone acceptance
PMT simulation

- Wavelength-dependent QE simulated
- Photomultiplier response including afterpulses

$$2 \times 10^{-4} \exp\left(-\frac{x}{5}\right) + \exp\left(-\left(x-1\right)^2/(2 \times 0.6 \times 0.6)\right)$$
Direction reconstruction

- >3 stations: model fit adapted from Stamatescu et al. 2008, Parametrization of time-delay $dt$ at detector position

\[
dt(k, z) = \frac{1}{c} \left( \sqrt{k} - \frac{z}{\cos(\theta)} + \frac{8.0}{z} \sqrt{k} \eta_0 \left( 1 - \exp \left( \frac{-z}{8.0} \right) \right) \right)
\]

\[
k(r, z) = r^2 + z^2 \frac{1}{\cos(\theta)^2} + 2 rz \tan(\theta) \cos(\delta)
\]

\[
\delta = \phi + \text{atan2} \left((x_{Det} - x_{core}), (y_{Det} - y_{core})\right)
\]
Direction reconstruction

- >3 stations: model fit adapted from Stamatescu et al. 2008, Parametrization of time-delay $dt$ at detector position

$r$: Distance from shower core to detector

Shower height in km

$$dt(k, z) = \frac{1}{c} \left( \sqrt{k} - \frac{z}{\cos(\theta)} + \frac{8.0}{z} \sqrt{z} \eta_0 \left( 1 - \exp \left( \frac{-z}{8.0} \right) \right) \right)$$

$$k(r, z) = r^2 + z^2 \frac{1}{\cos(\theta)^2} + 2r z \tan(\theta) \cos(\delta)$$

$$\delta = \phi + \text{atan2} \left( (x_{Det} - x_{core}), (y_{Det} - y_{core}) \right)$$

Slope of atmospheric refractive index

Zenith angle
Direction reconstruction

- >3 stations: model fit adapted from Stamatescu et al. 2008, Parametrization of time-delay $dt$ at detector position

$r$: Distance from shower core to detector

Shower height in km

$$dt(k, z) = \frac{1}{c} \left( \sqrt{k} - \frac{z}{\cos(\theta)} + \frac{8.0}{z} \sqrt{\kappa} \eta_0 \left( 1 - \exp \left( \frac{-z}{8.0} \right) \right) \right)$$

$$k(r, z) = r^2 + z^2 \frac{1}{\cos(\theta)^2} + 2rz \tan(\theta) \cos(\delta)$$

Free parameters: height & direction

Results in good angular reconstruction
And rough 1$^{st}$ order shower max. estimation

Zenith angle

Slope of atmospheric refractive index
H.E.S.S. survey sensitivity

S. Hoppe, PhD thesis
Expected pevatron signal

Assuming MGRO 2019+37 is a pevatron (1deg extension, $3.49 \times 10^{-12}$ TeV cm$^{-2}$ s$^{-1}$ @ 12 TeV)

$$dN/dE = 4.26 \times 10^{-12} (E/\text{TeV})^{-2} e^{-\sqrt{x/300 \text{TeV}}} [\text{TeV}^{-1} \text{cm}^{-2} \text{s}^{-1}]$$

Fold $dN/dE$ and Hörandel w/ post-reconstruction area

Integral event numbers

<table>
<thead>
<tr>
<th>Energy</th>
<th>gammas</th>
<th>hadrons</th>
<th>Signific.</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt;50 TeV</td>
<td>7000</td>
<td>1050000</td>
<td>6.8</td>
</tr>
<tr>
<td>&gt;100 TeV</td>
<td>4000</td>
<td>450000</td>
<td>5.9</td>
</tr>
<tr>
<td>&gt;1PeV</td>
<td>100</td>
<td>20000</td>
<td>0.7</td>
</tr>
</tbody>
</table>

M. Tluczykont, 2009
Signal and noise
Expected night-sky background trigger rate
Hadron parametrization

Hoerandel 2003: polygonato model
Station hadron trigger rate

- Simulated average number of stations per bin
- Folding with polygonato model
- ~13Hz single station hadron trigger rate
Array hadron trigger rates

Trigger rates for $E > 10$ TeV, before reconstruction cuts
Detector layout: simple grid, 10 km$^2$ (SCORE)
Trigger condition: single station trigger

<table>
<thead>
<tr>
<th>Particle</th>
<th>Rate (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proton</td>
<td>774 Hz</td>
</tr>
<tr>
<td>He</td>
<td>436 Hz</td>
</tr>
<tr>
<td>N</td>
<td>257 Hz</td>
</tr>
<tr>
<td>Fe</td>
<td>90 Hz</td>
</tr>
<tr>
<td>Array rate, all particles</td>
<td>~ 2 kHz</td>
</tr>
<tr>
<td>Single station rate</td>
<td>~ 13 Hz</td>
</tr>
<tr>
<td>NSB per station</td>
<td>&lt; 300 Hz</td>
</tr>
</tbody>
</table>
Pevatron emission from Cygnus?

MGROJ2019+37 & Berkeley 87?

Composite Milagro signal
Diffuse + unresolved

HEGRA upper limit (converted for extension)

HE signal associated to pulsar?
Fermi: J2020.8+3649
EGRET: 3EG J2021+3716

Milagro signal might be dominated by extended pevatron emission!

SCORE: resolve emission from 10 TeV – 1 PeV
**p-p cross-section**

Correlation shower depth / first interaction
→ measure interaction length in air $\sigma(p-p)$

SCORE: $1.7 < E_{CM} < 170$ TeV

Particle physics-origin of knee?

Overlap:
- LHC
- CR experiments
Propagation: Galactic Absorption & CMB

e$^+$$e^-$ pair production: Interstellar radiation field (ISRF) and CMB

estimate ISRF density

CMB well known: **distance estimate?**

Weakening of absorption by:

**Photon / axion conversion** in Galactic Magnetic field

**Photon / hidden photon oscillation**

**Lorentz invariance violation** (modification of e$^+$$e^-$ threshold)

Moskalenko et al. 2006
Expected night-sky background trigger rate

Further suppression via 2-station coincidence possible
Hardware Prototyping / Testing

4300UP relative reflectivity measurement @ Uni HH

And... thanks Eckart, this was a good tip!
Time Synchronization

Need < 5ns timestamp accuracy

GPS is no option: 10 ns

Optical fibers: expensive

Alternative: **Lightsource synchronization**:

- Isotropic lightsource at central array readout
- Need short rise time of light-pulse (~1ns)
- Small mirrors on each cone: deflect light on PMT