Theoretical Summary

Angela V. Olinto
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13 contributions + imbedded discussion
Theorists deeply connected to experiments &/or observatories + v.v.
Theory Addressing:

What is the origin of Cosmic Rays?
- at the knee?
- at UHEs?

How do particles interact?
- at VHEs?
- at UHEs?

Any Signatures of New Physics?
3. 'Poin)ng' UHECRs E ~ 100s TeV CM

Engel '10

10 to 300 TeV CM

knee

ankle

Engel ‘10
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Any Signatures of New Physics?
dark matter cares about topological superstrings

$$\chi^0 \chi^0 \text{s-wave annihilation into gauge bosons}$$

$$\mathcal{L}_{\text{eff}} = 3g_s^3 N M_s^{-3} \tilde{F}^{(0,3)} (\text{Tr}WW)(\text{Tr}WW)|_{\theta\theta} + \text{h.c}$$

Gamma-ray Flux from annihilation in GC

H.E.S.S and Galactic Center

Line @ $m_{\chi}$!!!!
Antiprotons

Ralph Engel

Exotic models for knee: change of hadronic interaction characteristics above 2 TeV c.m.s.

Ruled OUT!

Primordial Black Holes

John Mitchell
Theory Addressing:

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Any Signatures of New Physics?
Cosmic Rays: Status Report

Concave spectrum suggestive of non-linear diffusive shock acceleration

Anchor EAS to direct measurements

Ptuskin, Zirakashvili, & Seo ‘10
Hillas: Galactic components A & B?
B needed if transition at ankle

“B” power \( \sim 2 \times 10^{39} \text{ erg/s} \)

Re-acceleration in Galactic wind shock? (Jokipii)

Sources may be nearby?

Many sources with relatively low \( E_{\text{max}} \), fewer with higher \( E_{\text{max}} \)
Summary comment - III

Remember the Hillas plot:

- Acceleration to $10^{20}$ eV is marginal
- “Cutoff” observed by HiRes, Auger could be a real cutoff at $E_{\text{max}}$ of accelerator and not the GZK suppression
- This scenario more likely if Auger heavy composition is correct
Cosmic magnetic fields and HE particle interactions

Philipp Kronberg
Are signatures of ultrahigh energy cosmic rays detectable in gamma rays?

Kumiko Kotera

- average type of sources not observable by current and upcoming instruments (2 orders of magnitude)
- powerful sources:
  \[ L_{19} = 10^{44} \text{ erg s}^{-1} \text{ at 100 Mpc at limit of observed CR spectrum, would produce a detectable } \gamma \text{ halo of } \sim 2^\circ \]
  \[ L_{19} = 10^{46} \text{ erg s}^{-1} \text{ at 1 Gpc produce 10% of observed CR spectrum, and a detectable } \gamma \text{ halo of } \sim 1^\circ \]
  Note: halo = clear signature of UHECR
- close-by sources: Cen A
  synchrotron radiation due to injection of UHECR in lobes not observable
  UHE emission potentially observable with Auger if Cen A is responsible for 10% of the \(6 \times 10^{19}\) eV flux
Periodicity in terrestrial biodiversity

Energy Deposition per Altitude

Ozone Depletion
Serious Suntan!!!
Theory Addressing:

What is the origin of Cosmic Rays?
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How do particles interact?
- at VHEs?
- at UHEs?

Any Signatures of New Physics?
2.a Crucial moment for Particle Physics and accelerators.

2.b Very exciting moment for Cosmic Ray science and High Energy Astrophysics

3. Possibility [in fact need] for communication
AUGER
Fluctuations result.
Sufficient
[after experimental confirmation]
to establish
That the highest particle Mass is close to iron?

But then also in
This case one should change the interaction model.

In the “opposite direction”:
Longer showers

Protons are preferred [....? ....]
Accelerator Data & HECRs

AUGER
Fluctuations result.
Sufficient
[after experimental confirmation]
to establish
That the highest particle Mass is close to iron?

Possibility of determining the beam astrophysically!!!

Protons are preferred [...? ...]
Saturating the Froissart Bound: $\sigma_{pp}$ and $\sigma_{p\bar{p}} \log^2(\nu/m)$ fits, with world’s supply of data

At the LHC, $\sigma_{tot} = 107.3 \pm 1.2$ mb, $\rho = 0.132\pm0.001$

Phenomenological approach to multiple particle production

A. Ohsawa*, E.H. Shibuya** and M. Tamada***

A model to describe (pseudo-) rapidity density distributions and transverse momentum distributions
Behaviour of the EAS Age parameter in the knee region

Relation between $s(r)$, $s$ (long), and $s$ (lat)
$s$ (long) = 1.25 $s$ (lat) in 1st approximation

More accurately $s$ (lat) = $\int s(r) rdr / \int rdr$ with integration on the shower disk taking into account the grid interval, the size of the detectors and the conditions of trigger.

After suitable corrections of bias introduced by the NKG global fitt to the lateral distribution, $s$ behaviour versus size is a good indicator of intrinsic cascading and mass composition.

- Local age parameter behavior at fixed primary energy (larger near axis, a minimum near 40-50m and a clear increase at large distance)
- It can explain the experimental behavior of $S$(lat) versus energy, with an apparent minimum in knee region and followed by a kind of bump by pure phenomenological effects, remaining in agreement with a mixed composition.
- Next simulations with EGS and also above 50 PeV are in progress, as well as interpretation of Kascade Grande data.
Modeling Hadronic Multiparticle Production at High Energy

Excellent Review of Hadronetic Interaction Models

Ralph Engel
Comparison to first LHC data

Pseudorapidity Distribution of Charged Particles
Sybill 2.1 & QGSjet 01 better

NO “PERFECT” MODEL YET –
great data period is beginning - to help improve Hadronic Interaction models
**Eun-Joo (Sein) Anh**

- New to 2.2c:
  1. Charm quark added
  2. Smoother diffraction - non-diffraction transition
     - increase phase-space ("fireball") decay range
     - non-sharp distribution of diffracted particle's energy
  3. Minor bugfix
     - better \( p_T \), higher multiplicity
  4. Increased \( s \) quark fraction

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*Overall structure*

- hadron-target
- nucleus-target
- semi-superposition model
- non-diffractive / diffractive
- hard / soft
- decay
- minijets, strings
- strings
- Fragment
- decay unstable Sibyll particles
New Developments of EPOS 2

EPOS first designed to be used for particle physics experiment analysis (SPS, RHIC, LHC)

\(<p_t> vs multiplicity ap-p@1.8 TeV : EPOS 2\)

- Using small flux tube size
  - Very good description of CDF data
  - No additional parameter
  - Hadron mass dependence

Hydro in EPOS 2

Hydro+hadronic cascade

No collective effects

Graphs showing mean \(p_t\) for different pseudorapidity and charged multiplicity.
New Developments of EPOS 2

On-going developments: EPOS 2

- Real hydrodynamical evolution
- Hard scattering (PDF and Jets) correctly described
- First test with LHC data
  - Good in average
  - Inconsistency pt/multiplicity: more checks needed
- No dramatic change for air shower development
  - $\sim 10$ gr/cm$^2$
Relation of Interaction Characteristics at Ultra-High Energies to Extensive Air Shower Observables

![Graph showing the relation between energy and maximum range for different observables: Auger, Fly’s Eye, HiRes, MIA, and proton and iron lines.](image)

Ralph Ulrich
\langle X_{\text{max}} \rangle \text{ can be shifted significantly}

Auger and HiRes data are suggesting

- Large cross section for a proton dominated composition
- Small cross section for an iron dominated composition
- Or: intermediate mass, mixed composition

\text{RMS}(X_{\text{max}}) \text{ mostly impacted by cross section, and elasticity}

Iron induced showers very robust

Auger data only marginally compatible with protons in a high cross section scenario
Hadronic Interactions
Parameters

Scaling factor at $10^{19}$ eV

(Rolf Ulrich, 16-Oct-2008)
WISH LISTS...
Accelerators vs. Cosmic Rays
Tanguy’s wish list:

**Direct measurements**

1. Cross section measurements: TOTEM
2. $\pi^0$ & n forward spectra ($x_f > 0.3$): LHCf
   
   3 o.o.m improvement in energy constraints on meson & baryon forward spectra. VERY important for air shower development (scaling, inelasticity); which change both $X_{\text{max}}$ & $N_\mu$, 
   
   if very good precision (systematics?)

**Indirect measurements**

1. forward calorimeter CASTOR: no particle ID, but observes energy flow and inelasticity. Better if associated to TOTEM trackers.
2. LHCb not as forward but does particle ID: anti-proton & strange particle yields @ 10 energy - important for $N_\mu$. Will help understand baryon production – crucial for $N_\mu$.
3. ALICE, ATLAS or CMS: no leading particle (like in air showers) but important to test models: measure inelasticity ($X_{\text{max}}$), $N_{\text{baryons}}$ ($N_\mu$ and LDF) and the average $p_t$ (LDF). Help understand the dynamic of the collision & the underlaying physics.
Wish List II

Cross Sections:
preferentially p-air (which means p-C), but also π-C, and K-C at high energy (π interact before decay).

Feynman-\(x\) distributions of the production cross section for:
- \(\pi\)'s, K's, p, n, pbar, nbar
- charm particles (\(\Lambda_c\) and \(D_c\)) – neutrino detectors

Transverse momentum distribution at low energy (< 250 GeV)
- to understand low-E interactions at large angles for muon production in Auger. (MIPP would help a lot here!)

NEEDS workshop: http://www-ik.fzk.de/~needs/
My wish list...

1st wish – not granted!!!!!
My 2\textsuperscript{nd} wish: MUCH MUCH HIGHER STATISTICS of UHECRs!!!!!
The highest-energy cosmic rays may be iron nuclei

Or perhaps, at energies far beyond what terrestrial accelerators can produce, protons just look fat.

Figure 1. Mean value$ of the shower maximum—the penetration length$ X_{\text{max}}$ into the atmosphere at which a cosmic-ray shower reaches its maximum development. Given as an atmospheric column density,$ (X_{\text{max}})$ is plotted against the energy$ E$ of the primary particle that initiated the shower. Each data point is labeled with the number of showers recorded by fluorescence telescopes at the Pierre Auger Observatory in each energy bin. The highest bin includes events up to$ (X_{\text{max}})$ 814 events seen in stereo by both of the facility’s fluorescence telescopes. Truncated Gaussian fluctuation widths$ \sigma$ are plotted as a function of the cosmic-ray primary’s energy and compared with Monte Carlo simulations of what the stereo data should look like for pure proton and iron fluxes. (Adapted from ref. 3.)

Figure 2. Comparing Auger shower-maximum data with a range of Monte Carlo simulations (yellow swaths) for showers initiated by protons or iron nuclei. (a) The mean-shower-maximum$ (X_{\text{max}})$ data of figure 1, shown here without error bars. (b) Root-mean-square fluctuation of the penetration length$ X_{\text{max}}$ from event to event at a given primary energy and the Auger data. (Adapted from ref. 1.)

Figure 3. The HiRes collaboration’s data on the event-by-event fluctuation of its$ X_{\text{max}}$ data for 814 events seen in stereo by both of the facility’s fluorescence telescopes. Truncated Gaussian fluctuation widths$ \sigma$ are plotted as a function of the cosmic-ray primary’s energy and compared with Monte Carlo simulations of what the stereo data should look like for pure proton and iron fluxes. (Adapted from ref. 3.)
Shower Depths of Maximum $X_{\text{max}}$

Heavy nuclei?

Protons? - Higher Cross section and/or high multiplicity at high energy.
Above 60 EeV: Simpler Composition
either Protons or Iron-like
Pure Nuclei Injection

Propagation of pure nuclei in cosmic backgrounds
- spectra fit to observed
- abundances of secondaries

Allard, Busca, Decerprit, A.O., Parizot '08
Pure Nuclei Injection

CNO in: H out

Fe in: Fe out

Allard, et al '08
Puzzling Composition

Unexpected Astrophysics:
Sources are very Iron rich: 4x Fe Galactic CRs! and have low $E_{\text{max}}$ (protons)

Allard, et al ‘08
If Correlated with sources
< $10^\circ$ $\rightarrow$ protons

Galactic & ExtraGalactic Magnetic Fields make iron deviate many $10^\circ$'s from source position

If Astrophysically shown to be protons then hadronic models can be tested knowing the primary composition.

For example, assume current data is protons $\rightarrow$ change the cross section...
Cross Section Uncertainties

Ulrich’s talk
Puzzling Composition*

Unexpected Astrophysics:
Sources are very Iron rich and have low $E_{\text{max}}$

Very Bad News for Neutrino Detectors

Interesting Particle Physics:
Hadronic Models do not represent well UHE interactions

Higher Cross Sections or Multiplicities

*based on Xmax up to 40 EeV
Chris Williams talk

MIDAS

IceCube80

Auger

ANITAII

JEM–EUSO

super Auger N

log E [GeV]
Auger North in SE Colorado
Black – 2MASS catalog $z<0.02$
Blue – Auger North simul Data – energy proportional to circle size
Red – Auger South Data
Nadir (2 yrs)
35° tilt (3 yrs)
2015 launch
$E_{\text{th}} > 10^{20}$ eV

Fluorescence from Above

J. Adams
NEED MUCH HIGHER STATISTICS!!!!

The poorest, but the most energetic!

THANKS!!!
Composition & Spectrum

$E^3 J(E) \text{ [km}^2 \text{ yr}^{-1} \text{ sr}^{-1} \text{ eV}^2]$ vs $E$.

- Black dots: Auger combined
- Black line: Fit
- Red dashed line: Proton, $\beta=2.6$, $m=0$
- Red dashed line: Proton, $\beta=2.3$, $m=5$
- Blue dotted line: Iron, $\beta=2.4$, $m=0$

$\sigma_{sys}(E)=22\%$

$\log(E/\text{eV})$ vs Energy [eV]
Modification of interaction characteristics?

(see talk by R. Ulrich)

- Variables influence differently mean and RMS
- Cross section most important