Plan of the talk:
• UHECR Cosmic Ray Physics
• Multi-Messenger Astroparticle Physics
• Particle Physics Connection
The puzzle of UHECR

Need accelerator of size of Mercury orbit to reach $10^{20}$ eV with LHC technology

- Source of cosmic rays
- Acceleration mechanisms of cosmic rays
- Propagation processes of cosmic rays
- Interaction physics and cross-sections at $\sqrt{s_{pp}} > 100$ TeV

Hillas plot (1984)
Ultra-High Energy Cosmic Rays

Equivalent c.m. energy $\sqrt{s_{pp}}$ (GeV)

Scaled flux $E^{2.5} J(E)$ (m$^2$ s$^{-1}$ sr$^{-1}$ eV$^{1.5}$)

- HERA ($\gamma$-p)
- RHIC (p-p)
- Tevatron (p-p)
- 7 TeV LHC (p-p)
- 13 TeV LHC (p-p)
- 100 TeV FCC (p-p)

R. Engel et al., ARNPS 61, 2011, 467
Ultra-High Energy Cosmic Rays

R. Engel et al., ARNPS 61, 2011, 467
UHECR: \( >10^{15} \text{ eV} \); Air-Shower Measurements

First, high energy interaction: LHC
+ multiparameter measurements EAS

Secondary interactions: Fix target experiments
+ multiparameter measurements EAS

EAS measurement and reconstruction:
• energy ?
• mass ?
• arrival directions ?
• interaction mechanism ?
Measurement Techniques of Air Showers

- First interaction (usually several 10 km high)
- Air shower evolves (particles are created and most of them later stop or decay)
- Some of the particles reach the ground
- Measurement of Cherenkov light with telescopes or wide angle pmts
- Measurement with scintillation counters
- Measurement of low energy muons with scintillation or tracking detectors
- Measurement of high energy muons deep underground
- Measurement of fluorescence light
Galactic Cosmic Rays: standard picture (charge dependent knees)

Acceleration of cosmic rays in supernova remnants

Propagation through galaxy $(B \approx 3 \mu G?)$

Direct or indirect measurement

Affirmation by H.E.S.S. Nature 531, 476 (2016)
KASCADE: energy spectra of single mass groups

Searched:
E and A of the Cosmic Ray Particles

Given:
N_e and N_μ for each single event

⇒ solve the inverse problem

\[
\frac{dJ}{d \lg N_e \, d \lg N_\mu} = \sum_A \int_{-\infty}^{+\infty} \frac{dJ_A}{d \lg E} \, p_A(\lg N_e, \lg N_\mu \mid \lg E) \, d \lg E
\]

- kernel function obtained by Monte Carlo simulations (CORSIKA)
- contains: shower fluctuations, efficiencies, reconstruction resolution

KASCADE collaboration, Astroparticle Physics 24 (2005) 1-25
KASCADE-Grande: transition to extragalactic origin

- steepening (knee) due to heavy primaries ($3.5\sigma$) ➔ charge dependent knees
- hardening (ankle) in light spectrum ($5.8\sigma$) ➔ onset of extragalactic CR?

Phys.Rev.D (R) 87 (2013) 081101
Dependence on Hadronic Interaction Models

- Spectra of heavy primary induced events based on different interaction models
- Relative abundances different for different high-energy hadronic interaction models

Protons: $E_{\text{lab}} = 8 \times 10^{18}$ eV

- Simulated pseudorapidity distributions for pp interactions
- Significant differences in models

Advances in Space Research 53 (2014) 1456

D‘Enterria, Pierog, JHEP 08 (2016) 170
Main Experiments $10^{16}$-$10^{18}$eV

KASCADE-Grande

IceTop (IceCube)

HEAT

TALE

Tunka
Measurement Techniques of Air Showers

KASCADE-Grande
IceTop
Tunka
HEAT/TALE

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Measurement of high energy muons deep underground

Measurement of particles with tracking detectors or calorimeters
- Structures of all-particle spectra similar (in the level of 15%)
- composition results are still uncertain
Light and Heavy Knees, Ankles, and Transition

Most probable rigidity dependent knees (A component)

(galactic) B-component needed to explain all-particle spectrum

Highest energy extragalactic (Auger) (mass dependent) Anisotropies in arrival direction?

⇒ One has to understand the transition region to understand the UHECR

Strategy:

Multi-component analyses = Combine data of various experiment to
• Validate \ improve hadronic interaction models
• Validate astrophysical models
Extragalactic Cosmic Rays

\[ p + \gamma_{2.7K} \rightarrow \Delta^+(1232) \]
\[ \rightarrow p + \pi^0 \rightarrow p\gamma\gamma \]
\[ \rightarrow n + \pi^+ \rightarrow pe^+\nu \]

GZK-Cutoff
\[ p + \gamma_{\text{CMB}} \rightarrow p + \pi^0 \ (>50\text{EeV}) \]
\[ \gamma_{3\text{K}} (400 \text{ cm}^{-3}) \]

Acceleration mechanism is unknown (strong extragalactic processes which happen very close are necessary)
Pierre Auger Observatory

Photo: Steven Saffi
Hybrid Events

$E \sim 2 \times 10^{19} \text{eV}$

$\theta = 63^\circ$
Telescope Array
**UHECR: Energy Spectrum**

- ankle feature with very high precision
- flux suppression
- very rare events above $10^{20}$ eV
- at highest energies difference in hemispheres?

R. Alves Batista et al., MIAPP 2019, 1903.06714
UHECR: Energy Spectrum Interpretation

A) p-dominated “dip” scenario

B) sources accelerate to maximum rigidity (“tired” sources)

C) (mostly) photo-disintegration, energies shifted down

⇒ Composition needed!
Composition: mean depth and rms of shower maximum

- Composition is getting heavier with energy
- Measurements only applicable up to 50 EeV due to statistics
- Absolut composition scale model dependent
Arrival Distribution: Anisotropies at different scales

- Indications for anisotropy
- Correlation with catalogues: best for Starburst-Galaxies


Dipole above 8 EeV with 5.2σ and an amplitude of 7%

⇒ Particles are indeed of extragalactic origin

Arrival Distribution: Dipole at E > 8 EeV

Deflection of UHECR in magnetic fields:

\[ \delta \approx 3^\circ \frac{B}{3 \mu G} \frac{L}{kpc} \frac{6 \times 10^{19} eV}{E/Z} \]

Arrival directions follow mass distribution of near-by galaxies (2MASS Redshift Survey)
Anisotropy at highest energies ($E > 6 \cdot 10^{19} \text{ eV}$)

- Hotspots found
- Distribution not directly correlated with matter distribution in close Universe
- Deflection in magnetic fields?

\[ E > 6 \times 10^{19} \text{ eV} \]

UHECR world data set

\[ \text{UHECR world data set} \]

- Virgo Cluster ($D=20\text{Mpc}$)
- Ursa Major Cluster ($D=20\text{Mpc}$)
- Perseus-Pisces Supercluster ($D=70\text{Mpc}$)
- Centaurus Supercluster ($D=60\text{Mpc}$)
- Eridanus Cluster ($D=30\text{Mpc}$)
- Fornax Cluster

Dots: 2MASS catalog Heliocentric velocity $<3000 \text{ km/s} \ (D<\sim 45\text{Mpc})$


Ogio et al. ISVHECRI 2018
Strategy: source identification by arrival distribution

- Assumption of sources
- Simulation of propagation
- Galactic magnetic field as spectrometer to fit GMF models

\[ \delta \approx 3^\circ \frac{B}{3 \mu G} \frac{L}{kpc} \frac{6 \times 10^{19} eV}{E/Z} \]

\( \Rightarrow \) composition and magnetic fields have to be known
(for composition determination the interaction physics have to be known)
Next: AugerPrime

- Scintillators (3.8 m²) and radio antenna on top of each array detector
- Composition measurement up to $10^{20}$ eV
- Composition selected anisotropy
- Particle physics with air showers

• Installation finished 2021
• Operation AugerPrime until 2030

⇒ Composition!

(AugerPrime design report 1604.03637)
• 500 new SDs with 2.08 km spacing and TA SDs cover 4×TA SD detection area (~3000 km²)
• 2 new Fluorescence Detector (FD) stations (4+8 HiRes Telescopes)
• First light was observed by north FD station
• Construction of south FD station is ongoing

• ➔ Statistics!!
200,000 km² arranged in ~10 independent arrays across the globe

Strong support from China; prototype until 2021 in China

Sensitive to Neutrinos and UHECR

→ Statistics!! + EHE Neutrinos
JEM-EUSO

International Space Station (ISS)

UV photon

Extensive Air Shower (EAS)

#Particles
EUSO-SPB2

→ Statistics!! + EHE Neutrinos
GCOS = Global COSmic ray observatory

p-astronomy with sources

- Global, few sites, N+S
- ca. 90,000 km² (x30 Auger)
- Optimal detector for composition sensitivity
UHECR: Exposure

.....higher statistics!!!  (we cannot change the luminosity...)

R. Alves Batista et al., MIAPP 2019, 1903.06714
Multi-Messenger Astroparticle Physics

The multi-messenger era:
- Cosmic rays, detected in 1912
- Gamma rays, detected in ~1950
- High-energy neutrinos, detected in 2013
- Gravitational waves, detected in 2015

Learn more about the High-Energy Universe by combining information from the different tracers

3000 authors / 70 observatories
Astrophys.J. 848 (2017) 2, L12
CR observatories are also Neutrino Detectors

the first EeV-neutrino should be ‘just around the corner’
The Dawn of Multi-Messenger Astroparticle Physics

Astrophys.J. 848 (2017) 2, L12
Multi-Messenger Astroparticle Physics

- Study the high-energy Universe
- Explore the correlation / connection between various tracers
Strategy:
● long-term operational observatories for ‘Shower-Measurements’
● synergies in detection technologies
● synergies in simulation and reconstruction of showers (Big Data Analytics)
● for MM-analyses common data format and access (Research Data Management)
● for Open Data common platforms (Data Curation)
Particle Physics

- Validity of hadronic interaction models
- Measuring cross sections
- Search for BSM physics

CORSIKA

CORSIKA: world-leading tool for air shower modeling
CORSIKA 8: global community effort to
- improve software
- improve shower simulations & hadronic event generators see talk Tanguy Pierog
- improve computational efficiency
- provide more flexibility for future experiments
- increase stability: debugging, testing facilities, automation
After exploiting pp collisions up to 13TeV it remains to study physics effects most relevant in EAS:

**Nuclear effects of light ions:**
Oxygen-proton, oxygen-oxygen collisions

Extrapolation from pp and PbPb systems to light ions is non-trivial and remains one of the large uncertainties in EAS simulations.

Planned in Run 3, see arXiv:1812.06772 [hep-ph]

**Pions (mesons) as projectile particles:**

By far most collisions in EAS are meson-air, the description of pion-air based on LHC pp data is the largest source of uncertainty in EAS simulations.

Tagging charge-exchange reactions where a O(0.1TeV) pion collides with a proton will be the most significant remaining help for CR physics.

Ralf Ulrich
Muon Deficit in Air Shower Simulations

\[ z = \frac{\ln(N_{\mu}^{\text{det}}) - \ln(N_{\mu p}^{\text{det}})}{\ln(N_{\mu \text{Fe}}^{\text{det}}) - \ln(N_{\mu p}^{\text{det}})} \]

- **AMIGA [Preliminary]**
- **IceCube [Preliminary]**
- **NEVOD-DECOR**
- **Pierre Auger**
- **SUGAR**
- **Yakutsk [Preliminary]**
- **EAS-MSU\(^a\)**
- **KASCADE-Grande\(^a\)**
- **Expected from \(X_{\text{max}}\)**
- **GSF**

\(^a\) not energy-scale corrected

Dembinski et al., arXiv:1902.08124
Nevod / Decor

< \Sigma_N_{ph.e.} / D > \times 10^{-3} \text{ph.e.m}^2

\eta = 55 - 65^\circ

60 \text{events}
Beyond Standard Model

....of Acceleration

Most models of UHECR from exotic sources are ruled out:
- topological defects
- monopoles
- cosmic strings
- cosmic necklaces
- HE neutrinos create Z-bursts in resonant interactions
- ...

The particle showers produced by an ultrarelativistic monopole with similar energy deposit than UHECR, but different profile.

Fluorescence measurements

Auger, PRED 94, 082002 (2016)

Hot topic: Plasma Wakefield Acceleration in the Lab and in the Universe?
Cross-section

Glauber model (multiple scattering approximation)

(Ulrich, Auger, ICRC 2017)
Interaction physics:
→ higher energies, forward direction
→ validation of models
→ beyond standard model physics
→ (proton-proton) cross-sections

Technology:
→ detector developments
→ readout electronics
→ Monte-Carlo software
→ handling large infrastructures
→ computing models
→ Big Data Analytics

Society:
→ ‘FAIR’ data life cycle
→ outreach
→ education / training

→ Sources of UHECR
→ Understanding the high-energy Universe
→ UHE particle physics