LHC and Cosmic Rays: the Chicken or the Egg?

Tanguy Pierog

Karlsruhe Institute of Technology, Institut für Kernphysik, Karlsruhe, Germany

KMI, Nagoya, Japan

September the 27th 2017
Introduction

Monte-carlo for Cosmic Ray analysis
  ➔ MC comparison to accelerator data

input from LHC
  ➔ Mass composition of primary cosmic rays

input from CR
  ➔ Electromagnetic (EM) signal in extended air showers
  ➔ Muon signal

LHC data reduced the model uncertainties and exclude old models for mass composition of cosmic rays. Good description of air showers improve model predictive power for the description of min.Bias LHC data and detector simulations.
History

- Victor Hess discovered in 1912 that natural radioactivity was increasing with height
  - radiation from space
- Pierre Auger discovered air showers in 1937
  - secondary particles produced by primary cosmic rays
- until ~1950 particle physics was studied thanks to cosmic rays
  - all unstable particles discovered in cosmic rays
    - muon, pion, strangeness ...
  - cosmic rays could not be used for astrophysics
- after first start of accelerators, things changed ... until now!
Astroparticles

- **Astronomy with high energy particles**
  - gamma (straight but limited energy due to absorption during propagation)
  - neutrino (straight but difficult to detect)
  - charged ions (effect of magnetic field)

- **Measurements of charged ions**
  - source position (only for light and high E)
  - energy spectrum (source mechanism)
  - mass composition (source type)
    - light = hydrogen (proton)
    - heavy = iron (A=56)
  - test of hadronic interactions in EAS via correlations between observables.

**mass measurements should be consistent and lying between proton and iron simulated showers if physics is correct**

From R. Ulrich (KIT)
Extensive Air Shower

Hadronic Models

- Extensive Air Shower
  - Cascade of particle in Earth's atmosphere
- hadronic physics
  - initial $\gamma$ from $\pi^0$ decay
    - $e^\pm \rightarrow e^\pm + \gamma$
    - $\gamma \rightarrow e^+ + e^-$
    - $\pi^\pm \rightarrow \mu^\pm + \nu_\mu/\bar{\nu}_\mu$

LHC for CR

- $A + air \rightarrow$ hadrons
- $p + air \rightarrow$ hadrons
- $\pi + air \rightarrow$ hadrons

CR for LHC or FCC

Introduction

- Hadronic Models
  - Extensive Air Shower
    - Number of particles at maximum:
      - $99.88\%$ of electromagnetic (EM) particles
      - $0.1\%$ of muons
      - $0.02\%$ hadrons
    - Energy:
      - from $100\%$ hadronic to $90\%$ in EM + $10\%$ in muons at ground (vertical)

From R. Ulrich (KIT)
Introduction

Hadronic Models

LHC for CR

CR for LHC or FCC

Extensive Air Shower Observables

- **Longitudinal Development**
  - number of particles vs depth
  - \( X = \int_{h}^{\infty} dz \ \rho(z) \)
  - Larger number of particles at \( X_{\text{max}} \)
  - For many showers
    - mean : \(<X_{\text{max}}\>
    - fluctuations : RMS \( X_{\text{max}} \)
    - depends on primary mass
    - depends on Hadr. Inter.

- **Lateral distribution function (LDF)**
  - particle density at ground vs distance to the impact point (core)
  - can be muons or electrons/gammas or a mixture of all.

- Others: Cherenkov emissions, Radio signal
Hybrid Detection

Pierre Auger Observatory / Telescope Array

Surface detector (SD)

Fluorescence detector (FD)

Various detection technique = energy scale independent of hadronic inter. models

\[ E_{\text{cal}} = \int dX \frac{dE}{dX} \]

\[ \sigma_{\Delta_{\text{sys}}} \approx 14 \% \]

\[ \sigma_{E/E} \approx 8 \% \]

\[ \sigma_{\chi_{\max}} < 20 \text{ g/cm}^2 \]

\[ \Delta_{\text{sys}} \approx 15 \text{ g/cm}^2 \]

**From R. Urich (KIT)**

**[Graph showing energy scale vs. atmospheric depth]**

**[Diagram showing detection techniques]**
Pierre Auger Observatory (PAO)
- Mendoza, Argentina
- Southern Hemisphere
- 3000 km²: 32000 km²/sr/yr

Telescope Array (TA)
- Utah, USA
- Northern Hemisphere
- 680 km²: 3700 km²/sr/yr
Energy Spectrum

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)

knee(s)

ankle

Telescope Array

Pierre Auger Obs.

ATIC

PROTON

KASCADE (SIBYLL 2.1)

KASCADE-Grande

Tibet ASg (SIBYLL 2.1)

IceTop

R. Engel (KIT)
Introduction

Sensitivity to Hadronic Interactions

- Air shower development dominated by few parameters
  - mass and energy of primary CR
  - cross-sections (p-Air and (π-K)-Air)
  - (in)elasticity
  - multiplicity
  - charge ratio and baryon production

- Change of primary = change of hadronic interaction parameters
  - cross-section, elasticity, mult. ...

With unknown mass composition hadronic interactions can only be tested using various observables which should give consistent mass results
Pre-LHC Composition

With pre-LHC models current CR data would be difficult to interpret

- Full (QGSJET): proton ("easy" and "old" astrophysical interpretation)
- Dashed (EPOS/SIBYLL): mixed composition

Roberto Aloiso UHECR (2015 PAO/TA working group)
Introduction

LHC for CR

CR for LHC or FCC

Hadronic Models

LHC acceptance

- p-p data mainly from “central” detectors
  - pseudorapidity $\eta = -\ln(\tan(\theta/2))$
  - $\theta = 0$ is midrapidity
  - $\theta >> 1$ is forward
  - $\theta << 1$ is backward

- Different phase space for LHC and air showers
  - most of the particles produced at midrapidity
    - important for models
  - most of the energy carried by forward (backward) particles
    - important for air showers
**Introduction**

**Hadronic Models**

**LHC for CR**

**CR for LHC or FCC**

---

**Hadronic Interaction Models for EAS**

**(HDPM)**

**(SIBYLL 2.1 QGSJET01 DPMJET 2.55 VENUS)** (<2001)

**Old generation:**

- All Glauber based

  But differences in hard, remnants, diffraction ...

**New (!) generation:**

- LHC tuned:
  - Motivation:
    - Hard Pomeron-Pomeron connexion
  - LHC inspired:
    - SIBYLL 2.3c
      - Motivation:
        - update with latest LHC results in simple model
    - QGSJET III (?)
      - Motivation:
        - Hard Pomeron-Pomeron connexion
    - DPMJET III
      - Motivation:
        - update with LHC results -fix high energy
    - EPOS 3
      - Motivation:
        - binary scaling in hard probes

---

**Motivation**

- Attempt to get everything described in a consistent way (energy sharing)
Introduction

Hadronic Models

LHC for CR

CR for LHC or FCC

Cross Section andMultiplicity in Models

Gribov-Regge and optical theorem

- Basis of all models (multiple scattering) but
  - Classical approach for QGSJET, SIBYLL
    and DPMJET (no energy conservation for cross section calculation)
  - Parton based Gribov-Regge theory for EPOS (energy conservation at amplitude level)

pQCD

- Minijets with cutoff in SIBYLL and DPMJET
- Same hard Pomeron (DGLAP convoluted with soft part: no cutoff) in QGSJET and EPOS but
  - Generalized enhanced diagram in QGSJET-II
  - Simplified non linear effect in EPOS
  - Phenomenological approach
Models used for EAS had better LHC predictions than HEP MC
LHC data well bracketed by models used for CR analysis: reliable simulations up to LHC energy: knee energy ...
Spectral shape not due to a change in hadronic interactions: change in the mass composition!
Post-LHC Models

- **Sibyll 2.1 to Sibyll 2.3c:**
  - $\rho^0$ forward production in pion interaction
  - re-tuning some parameters for LHC and lower energies
  - improved remnants and baryon production
  - charm production

- **DPMJETIII.06 to DPMJETIII.17-1**
  - improved treatment of very high energy
  - improved baryon distributions at low energy
Post-LHC Models

- **QGSJETII-03 to QGSJETII-04:**
  - Loop diagrams
  - $\rho^0$ forward production in pion interaction
  - Re-tuning some parameters for LHC and lower energies

- **EPOS 1.99 to EPOS LHC**
  - Tune cross section to TOTEM value
  - Change old flow (collective effect) calculation to a more realistic one
  - Introduce central diffraction
  - Keep compatibility with lower energies

No direct influence of collective effects on EAS simulations seen but important to compare to LHC and set parameters properly ($<pt>$, ...).
Cross Sections

- Same cross section prediction at pp level and low energy (data for tuning)

- Extrapolation to high energy looks settled
  - Different amplitude and scheme
  - Same extrapolations

**Pre - LHC**

**Post - LHC**

Graphs showing the dependence of cross section on energy for different models.
Introduction

Hadronic Models

LHC for CR

CR for LHC or FCC

Multiplicity

- Multiplicity fixed by data up to 900 GeV

- extrapolation to high energy is still model dependent?

Pre - LHC

Post - LHC

\[ N \]
\[ \sqrt{s} \text{ (GeV)} \]

\[ 10 \] \[ 10^2 \] \[ 10^3 \] \[ 10^4 \] \[ 10^5 \]

\[ 0 \] \[ 50 \] \[ 100 \] \[ 150 \] \[ 200 \] \[ 250 \] \[ 300 \]

\( p+(a)p \)

QGSJET01

SIBYLL 2.1

QGSJET II-03

EPOS 1.99

\( p+(a)p \)

EPOS LHC

QGSJETII-04

SIBYLL 2.3c

DPMJETIII.17-1
Multiplicity at mid-rapidity

Looking at particles produced perpendicular to the beam axis:
- multiplicity fixed by data up to 13 TeV
- extrapolation to high energy less model dependent after LHC
- QGSJET01 and QGSJETII-03 extrapolation excluded

Pre - LHC

Post - LHC
**Pseudorapidity**

- Difference between mid-rapidity and full multiplicity coming from the width of the pseudorapidity distributions
- From LHC data
  - DPMJETIII.17-1 and SIBYLL 2.3c too narrow
  - QGSJETII-04 ~ OK
  - EPOS LHC a bit too large

### Pre - LHC

\[ p + p \rightarrow \text{chrg at 7 TeV LHCb} \]

- EPOS 1.99
- QGSJETII-03
- QGSJET01
- SIBYLL 2.1

### Post - LHC

\[ p + p \rightarrow \text{chrg at 7 TeV LHCb} \]

- EPOS LHC
- QGSJETII-04
- DPMJETIII.17-1
- SIBYLL 2.3c
**Introduction**

- **LHC for CR**
- **CR for LHC or FCC**

**Test of Models vs Accelerator Data**

- From LHC data
  - All pre-LHC models extrapolation excluded
  - DPMJETIII.17-1 and SIBYLL 2.3c underestimate multiplicity
  - QGSJETII-04 and EPOS LHC \(\sim\) OK (and similar to Pythia 8)

**Pre - LHC**

- **p + p \rightarrow\text{chrg} 13\text{ TeV ATLAS}**
  - \(N>1\) \(p_t>0.1\text{ GeV}\)

**Post - LHC**

- **p + p \rightarrow\text{chrg} 13\text{ TeV}**
  - \(N>1\) \(p_t>0.1\text{ GeV}\)

**Graphs:**

- **Pre - LHC**
  - **EPOS 1.99**
  - **QGSJET II-03**
  - **SIBYLL 2.1**

- **Post - LHC**
  - **EPOS LHC**
  - **QGSJETII-04**
  - **SIBYLL 2.3c**
  - **DPMJETIII-17.1**
Ultra-High Energy Hadronic Model Predictions $p$-Air

- **p+p**
  - Inelastic cross section (mb) vs. $\sqrt{s}$ (GeV)
  - Multiplicity vs. $\sqrt{s}$ (GeV)
  - Elasticity vs. $\sqrt{s}$ (GeV)

- **p+Air**
  - Inelastic cross section (mb) vs. $\sqrt{s}$ (GeV)
  - Multiplicity vs. $\sqrt{s}$ (GeV)
  - Elasticity vs. $\sqrt{s}$ (GeV)

Models compared:
- QGSJETII-04
- EPOS LHC
- SIBYLL 2.3c
- DPMJETIII.17-1
Ultra-High Energy Hadronic Model Predictions $\pi$-Air
Introduction

LHC for CR

CR for LHC or FCC

Ultra-High Energy Hadronic Model Predictions A-Air

Nucleus+Air

- EPOS
- QGSJETII
- SIBYLL

Inelastic cross section (mb)

- Charged particles

- EM part. with x > 0.01

- Multiplicity

- Mean E_{EM}/E_{kin} per part.
Introduction

EAS with Old CR Models: $X_{\text{max}}$

- HiRes-MIA
- HiRes (2005)
- Yakutsk 2001
- Fly's Eye
- Yakutsk 1993
- Auger (2017)

Energy (eV)

- EPOS 1.99
- SIBYLL 2.1
- QGSJETII-03
- QGSJET01

$X_{\text{max}}$ vs. Energy plot with data points and fitted curves for different models and experiments.
**EAS with Re-tuned CR Models**: $X_{\text{max}}$

- **Hadronic Models**
- **EAS with Re-tuned CR Models**: $X_{\text{max}}$

**Graph**:
- **Energy** (eV) on the x-axis
- **$X_{\text{max}}$ (g/cm$^2$)** on the y-axis
- Data points and lines for different models:
  - HiRes-MIA
  - HiRes (2005)
  - Yakutsk 2001
  - Fly’s Eye
  - Yakutsk 1993
  - Auger (2017)

**Legend**:
- EPOS LHC
- SIBYLL 2.3c
- QGSJETII-04
- DPMJETIII.17-1

**Points**:
- **25gr/cm$^2$** and **40gr/cm$^2$** are marked on the graph.
With post-LHC models there is no doubt about **mixed composition**
Introduction

LHC for CR

Fluorescence Detector (FD)

- Most direct measurement
  - dominated by first interaction
- Reference mass for other analysis
  - \(<\ln A>\) from \(<X_{\text{max}}\rangle\) and RMS
- Possibility to use the tail of \(X_{\text{max}}\) distribution to measure p-Air inelastic cross-section.
  - require no contamination from photon induced showers (independent check)
  - correction to “invisible” cross-section using hadronic models
  - conversion to p-p cross-section using Glauber model.
Model Consistency using Electromagnetic Component

Study by Pierre Auger Collaboration (ICRC 2017)

- std deviation of lnA allows to test model consistency.

Positive (physical) variance only if $X_{\text{max}}$ fluctuations are compatible with $\langle X_{\text{max}} \rangle$ for a given model.

Tensions if $\langle X_{\text{max}} \rangle$ too small

QGSJETII-04 is a lower limit for $X_{\text{max}}$
**p-Air Production Cross Section @ 39 and 55 TeV**

**Introduction**

LHC for CR

CR for LHC or FCC

**Hadronic Models**

**p-Air Production Cross Section @ 39 and 55 TeV**

### Results, $\sigma_{p\text{-air}}$ in mb

- **Lower energy point**
  - $457.5 \pm 17.8$ (stat) $+19/-25$ (syst)

- **Higher energy point**
  - $485.8 \pm 15.8$ (stat) $+19/-25$ (syst)
**Introduction**

**LHC for CR**

**p-p Inelastic Cross Section @ 39 and 55 TeV**

Conversion using Glauber model:

\[ \text{Glauber}(\sigma_{pp}^{tot}, B_{el}, \lambda, \ldots) \rightarrow \sigma_{p-\text{air}} \]

- Extended Glauber conversion with inelastic screening
- Propagation of modeling uncertainties
- Model uncertainties may be underestimated, since there are other theoretical models available for the conversion

**Results, }\sigma_{pp}^{\text{inel}} \text{ in mb**

Lower energy point

\[ 76.95 \pm 5.4 \text{(stat)} + 5.2/-7.2 \text{(syst)} \pm 7 \text{(glauber)} \]

at \[ \sqrt{s_{pp}} = 38.7 \pm 2.5 \text{ TeV} \]

Higher energy point

\[ 85.62 \pm 5 \text{(stat)} + 5.5/-7.4 \text{(syst)} \pm 7.1 \text{(glauber)} \]

at \[ \sqrt{s_{pp}} = 55.5 \pm 3.6 \text{ TeV} \]
**Hybrid Analysis**

- **Analysis based on 411 Golden Hybrid Events**
  - find simulated showers reproducing each FD profile for all possible models and primary masses (p, He, N, Fe),
  - decompose ground signal into pure electromagnetic ($S_{EM}$) and muon dependent signal ($S_{\mu}$),
  - rescale both component separately ($R_E$ and $R_\mu$) to reproduce SD signal for each showers,
  
  \[ S_{\text{ResC}}(R_E, R_\mu)_{i,j} \equiv R_E S_{EM,i,j} + R_E^\alpha R_\mu S_{\mu,i,j} \]
  - for mixed composition, give weight according to $X_{\text{max}}$ distribution.
Simulations don't reproduce FD and SD signal consistently

\[ R = \frac{S_{1000}^{\text{observed}}}{S_{1000}^{\text{predicted}}} \text{ increase with zenith angle} \]

EPOS-LHC Iron could be (almost) compatible with data, but \( X_{\text{max}} \) data are NOT pure Iron (but mixed).

To reproduce data simulations have to be rescaled

for mixed composition, only muon component has to be changed

correct energy scale

30% muon deficit for EPOS-LHC and 59% for QGSJETII-04.

Introduction

Hadronic Models

Surface Detector (SD)

- SD detector sensitive to
  - electromagnetic particles (EM)
  - muons

- Particles at ground produced after many generations of hadronic interactions
  - most of EM particles from pure EM (universal) shower (depend on high (first) energy hadronic interactions)
  - muons produced at the end of hadronic cascade (depend on low energy hadronic interactions)
  - small fraction of EM (at large r) produced by last hadronic generation

- EM and muons give different signal in Cherenkov detector.
  - property of time traces
Old showers contain only muon component

- direct muon counting with very inclined showers (>60°) by comparing to simulated muon maps (geometry and geomagnetic field effects)
- EM halo accounted for
- correction between true muon number and reconstructed one from map by MC (<5%)

\[ \frac{R_{\mu}}{E_{FD}} \text{ in energy bins} \]

Ratio to preLHC QGSJETII-03

\[
\begin{align*}
R_{\mu}(E/10^{19} \text{ eV}) \\
\log_{10}(E/\text{eV})
\end{align*}
\]

\[
\begin{align*}
E = 10^{19} \text{ eV}, \theta = 67^\circ \\
\langle X_{\text{max}} \rangle / \text{g cm}^{-2}
\end{align*}
\]
Independent SD mass composition measurement

- geometric delay of arriving muons

\[ c \cdot t_g = l - (z - \Delta) \]
\[ = \sqrt{r^2 + (z - \Delta)^2} - (z - \Delta) \]

- mapped to muon production distance

\[ z = \frac{1}{2} \left( \frac{r^2}{ct_g} - ct_g \right) + \Delta \]

- decent resolution and no bias

Inclined events to avoid EM contamination:

\[ \theta = 59.06 \pm 0.08^\circ \]
\[ E = 92 \pm 3 \text{ EeV} \]
2 independent mass composition measurements

- both results should be between p and Fe
- both results should give the same mean logarithmic mass for the same model
- problem with EPOS appears after corrections motivated by LHC data (low mass diffraction) and model consistency (forward baryon production at high energy): direct constraint on hadronic interactions.
**Introduction**

**LHC for CR**

**MPD and Diffraction**

Inelasticity linked to diffraction (cross-section and mass distribution)

- weak influence on EM $X_{\text{max}}$ since only 1st interaction really matters
- cumulative effect for $X_{\mu\text{max}}$ since muons produced at the end of hadr. subcasc.
- rapidity-gap in p-p @ LHC not compatible with measured MPD
- harder mass spectrum for pions reduce $X_{\mu\text{max}}$ and increase muon number!

**different diffractive mass distribution for mesons and baryons!**

---

**Graphs**

- **ATLAS** $\sqrt{s} = 7$ TeV $p_t > 200$ MeV
- **QGSJETII-03**
- **EPOS 1.99**
- **EPOS LHC**
- **QGSJETII-04**
- **ATLAS**

---

**Graphs**

- **p**
- **Fe**

- **EPOS LHC small y-gap**
- **EPOS LHC SMALL Y-GAP $\pi$**

- **EPOS 1.99**
- **EPOS LHC**

---

**KMI – Sept 2017**

T. Pierog, KIT - 41/47
<X^\mu_{\text{max}} \rangle$ with modified EPOS LHC

**Introduction**

**Hadronic Models**

$\langle X^\mu_{\text{max}} \rangle$ with modified EPOS LHC

**LHC for CR**

**CR for LHC or FCC**

Same than in mixed models

- softer meson spectra (lower elasticity) : lower $X^\mu_{\text{max}}$

- less forward baryons: lower $X^\mu_{\text{max}}$

-25 g/cm$^2$ for diff

-20 g/cm$^2$ for baryons

MPDs sensitive to baryon (less generation) and meson spectra in pion interactions

Introduction

LHC for CR

Hadronic Models

\( \langle X_{\text{max}} \rangle \) with Modified EPOS

Same than in mixed models

- softer meson spectra: lower \( X_{\text{max}} \)
- forward baryons: small effect

-10 g/cm² for diff

\( \sim 0 \) g/cm² for baryons

\( X_{\text{max}} \) less sensitive to baryon spectra than to pion spectra in pion interactions
Number of muons depends on the same parameters

- softer meson spectra: larger $N_\mu$
- forward baryons: lower $N_\mu$ but could be compensated by $\rho^0$ (keep energy to produce muons but doesn't change the number of generations: lower MPD)

$N_\mu$ sensitive to baryon (less generation) and meson spectra in pion interactions

+5% for diff
-15% without forward baryons
Muons at Ground

- Muon production depends on all int. energies
- Muon production dominated by pion interactions (LHC indirectly important)
- Resonance and baryon production important
- Post-LHC Models ~ agrees on numbers but with different production height and spectra
Hadronic interaction models very important to interpret cosmic ray data

- mass composition
- LHC data used to tune and complete the models

Central particle production at LHC reduced model uncertainties in slope of $X_{\text{max}}$

- same energy evolution in models important for mass of primary cosmic rays
- all pre-LHC models in contradiction with LHC data (central and forward prod.)
- using latest model version reduce uncertainties and avoid unphysical behavior

Remaining 20 gr/cm$^2$ difference for $X_{\text{max}}$ predictions

- linked to forward physics (photon spectra and diffraction measured at LHC) not yet taken into account in models used for EAS simulation (coming...)
- effect of extrapolation to p-Air interaction
  - p-O beam necessary to check that p-p properly extrapolated
  - p-Pb measurements can be used but need change in most models (only EPOS reproduces p-Pb data for the moment)
Auger data (and other low energy cosmic ray experiments) not consistently described by hadronic interaction models (even post LHC)

- $<X_{\text{max}}>$ and fluctuations, number of muons and muon production depth …

- but it has never been so good! only 1 to 2 sigma difference in most of the cases

Comparison of $\langle \ln A \rangle$ from $X_{\text{max}}$ from FD and $X_{\text{max}}^\mu$ from SD allows direct test of hadronic interaction models (and Physics behind!)

- test small effects amplified by cascade effect

- test energy, phase space (forward) and projectile (mesons) difficult to reach with accelerators

Hadronic models used for cosmic ray analysis very important for LHC

- constraints from CR on hadronic models improve their predictive power (better energy dependence than HEP models)

- CR models compared to minimum bias data (best description from EPOS LHC)

- EPOS used in detector simulations (correction, reconstruction …)

- more reliable predictions for the Future Circular Collider (100 TeV)
LHC data reduced the model uncertainties and exclude old models for mass composition of cosmic rays. Good description of air showers improve model predictive power for the description of min. Bias LHC data and detector simulations.

Thank you!
Correlation between $X_{\text{max}}^{*}$ and $S^{*}(1000)$

- In data correlation is significantly negative
  \[ r_G = -0.125 \pm 0.024 \]

- $r_G(X_{\text{max}}^{*}, S^{*}(1000))$ for p
  - EPOS-LHC : 0.00 (5σ to data)
  - QGSJetII-04 : +0.08 (8σ to data)
  - Sibyll 2.1 : +0.07 (7.5σ to data)

- Difference is larger for other pure beams

- Primary composition near the `ankle' is mixed

- Test of “exotic” models fails

$r_G$ - rank correlation coefficient introduced in R. Gideon, R. Hollister, JASA 82 (1987) 656
Dispersion of Masses in Data

Epos-LHC

\[ r_G (X^*_\text{max}, S^*(1000)) \]

\[ r_G = -0.125 \pm 0.024 \]
\[ \text{lg}(E/eV) = 18.5 - 19.0 \]

Auger 2015, preliminary

\[ \text{data are compatible with } 1.0 \leq \sigma(\ln A) \leq 1.7 \]
Comparison with LHCf

- LHCf favor not too soft photon spectra (EPOS LHC, SIBYLL 2.3) : deep $X_{\text{max}}$
- No model compatible with all LHCf measurements : room for improvements!
- Can p-Pb data be used to mimic light ion (Air) interactions?

T. Sako for the LHCf collaboration
Baryons in Pion-Carbon

- Very few data for baryon production from meson projectile, but for all:
  - strong baryon acceleration (probability ~20% per string end)
  - proton/antiproton asymmetry (valence quark effect)
  - target mass dependence

- New data set from NA49 (G. Veres' PhD)
  - test $\pi^+$ and $\pi^-$ interactions and productions at 158 GeV with C and Pb target
  - confirm large forward proton production in $\pi^+$ and $\pi^-$ interactions but not for anti-protons
    - forward protons in pion interactions are due to strong baryon stopping
      (nucleons from the target are accelerated in projectile direction)
    - strong effect only at low energy

- EPOS overestimate forward baryon production at high energy
**Diffraction measurements**

- TOTEM and CMS diffraction measurement not fully consistent
- Tests by S. Ostapchenko using QGSJETII-04 (PRD89 (2014) no.7, 074009)
  - SD+ option compatible with CMS
  - SD- option compatible with TOTEM

<table>
<thead>
<tr>
<th>$M_X$ range</th>
<th>$&lt; 3.4$ GeV</th>
<th>$3.4 - 1100$ GeV</th>
<th>$3.4 - 7$ GeV</th>
<th>$7 - 350$ GeV</th>
<th>$350 - 1100$ GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>TOTEM [13, 24]</td>
<td>$2.62 \pm 2.17$</td>
<td>$6.5 \pm 1.3$</td>
<td>$\simeq 1.8$</td>
<td>$\simeq 3.3$</td>
<td>$\simeq 1.4$</td>
</tr>
<tr>
<td>QGSJET-II-04</td>
<td>$3.9$</td>
<td>$7.2$</td>
<td>$1.9$</td>
<td>$3.9$</td>
<td>$1.5$</td>
</tr>
<tr>
<td>option SD+</td>
<td>$3.2$</td>
<td>$8.2$</td>
<td>$1.8$</td>
<td>$4.7$</td>
<td>$1.7$</td>
</tr>
<tr>
<td>option SD-</td>
<td>$2.6$</td>
<td>$7.2$</td>
<td>$1.6$</td>
<td>$3.9$</td>
<td>$1.7$</td>
</tr>
</tbody>
</table>

- Difference of $\sim 10$ gr/cm$^2$ between the 2 options
### Simplified Shower Development

Using generalized Heitler model and superposition model:

\[
X_{\text{max}} \sim \lambda_e \ln \left( (1 - k) \cdot \frac{E_0}{2N_{\text{tot}} \cdot A} \right) + \lambda_{\text{ine}}
\]

- **Model independent parameters**: 
  - $E_0$ = primary energy 
  - $A$ = primary mass 
  - $\lambda_e$ = electromagnetic mean free path 
- **Model dependent parameters**: 
  - $k$ = elasticity 
  - $N_{\text{tot}}$ = total multiplicity 
  - $\lambda_{\text{ine}}$ = hadronic mean free path (cross section)

---

**Toy Model for Hadronic Cascade**

Primary particle: hadron

*Muons produced after many hadron generations*

\[ N_{\text{had}}^n \text{ particles} \]

- can produce muons after \( n \) interactions

\[ E(n) = E_0 / N_{\text{tot}}^n \]

Assumption: particle decay to muon when \( E = E_{\text{dec}} \) (critical energy) after \( n_{\text{max}} \) generations

\[ E_{\text{dec}} = E_0 / N_{\text{tot}}^{n_{\text{max}}} \]

\[ n_{\text{max}} = \frac{\ln(E_0 / E_{\text{dec}})}{\ln(N_{\text{tot}})} \]

\[ \ln(N_\mu) = \ln(N(n_{\text{max}})) = n_{\text{max}} \ln(N_{\text{had}}) \]
**Introduction**

**LHC for CR**

**CR for LHC or FCC**

---

**MPD and Models**

- **Data set**: 01/2004 – 12/2012
- **E > 1e19.3 eV**
- **Zenith angles** [55°, 65°]
- **Core distances**: [1700 m, 4000 m] (more muons/event)
- **481 events after quality cuts**
- **Syst**: 17 g/cm²
- **Event by event resolution**:
  - 100 (80) g/cm² at $10^{19.3}$ eV for p (Fe)
  - 50 g/cm² at $10^{20}$ eV

---

**Large discrepancies between models**:

- **EPOS LHC predictions for MPD excluded by data** (outside p-Fe range)
- **High sensitivity of MPD to some details of hadronic interactions**
Introduction

Hadronic Models

LHC for CR

CR for LHC or FCC

**Nuclear Interactions**

- **Sibyll**
  - Glauber for pA
  - with inelastic screening for diffraction in new Sibyll 2.3 (only nuclear effect)
  - superposition model for AA (A x pA)

- **QGSJETII**
  - Pomeron configuration based on A projectiles and A targets
  - Nuclear effect due to multi-leg Pomerons

- **EPOS**
  - Pomeron configuration based on A projectiles and A targets
  - screening corrections depend on nuclei
  - final state interactions (core-corona approach and collective hadronization with flow for core)
Light Ion Data

Very few data to compare with all CR models:

- strong limitations in Sibyll (projectile up to Fe only and target up to O !)
- no final state interactions exclude heavy nuclei for QGSJETII
- no light ion data at high energy
Tests using hydrogen atmosphere

- Work done with David D'Enterria (CERN) and Sun Guanhao
  - test of Pythia event generator

- Modified air shower simulations with air target replaced by hydrogen
  - for interactions only (no change in density)
  - no nuclear effect