LHC (mostly CMS) data and UHECR physics

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D. d'E, T. Pierog, G. Sun, arXiv:1809.06406
Ultra High Energy Cosmic-Rays via EAS

- CR energy & identity for $E_{CR} = 10^{15} - 10^{21}$ eV determined using earth atmosphere as a "calorimeter" & comparing shower to hadronic MCs:

- CR+Air collisions: QCD interactions at c.m. energies up to $\sqrt{s_{GZK}} \sim 400$ TeV
Hadrons are extended composite objects: even at asymptotically large c.m. energies, only ~60% of x-section is “computable” within pQCD. For modeling high-energy p-p collisions, we can consider two types of interactions:

1. **Perturbative parton-parton collisions**
   - ~60%

2. **Diffractive + elastic**
   - ~40%
   - 1 or 2 protons intact.
   - 1 or 2 rapidity gaps:
     - No colour flux.
     - Colourless exchange with vacuum $J^{PC}=0^{++}$ quantum-numbers:
       - |Pomeron = 2-gluons in colour-singlet state.

pQCD (~60 mb) + diffractive (~15 mb) + elastic (~25 mb) ~ 100 mb at the LHC.
Hadronic Monte Carlos for UHECR

- Primary hadronic collisions (p-p, p-A) = Complex QCD interactions:

  - String hadronization.
  - Beam-remnants.

- Theoretical basis:
  - Reggeon Field Theory: soft, diffraction, eikonal (multi)parton ladders (pA, AA)
  - pQCD LO: “(cut) hard Pomerons”
  - Parton saturation in PDFs.

- Non-pQCD modeling:
  - String hadronization.
  - Beam-remnants.

- Model parameters:
  - O(20-100) parameters tuned to multiple accelerator/collider data.
Hadronic Monte Carlos for LHC collisions

Proton-proton collisions in PYTHIA, HERWIG,...

Theoretical basis:
- Perturbative QCD (LO + K-factor): PDFs, matrix-elements.
- Leading-log parton shower.
- Multiparton interactions.
- Saturation-based infrared $p_T$ cut-off

Non-pQCD modeling:
- String fragmentation (Lund model).
- Beam-remnants.
- Diffraction.

Model parameters:
- $O(100)$ parameters
- Multiples tunes to many collider measurements.

No p-A, A-A available (yet). But PYTHIA comparable to EPOS/QGSJET e.g. via:
- Constructing a CONEX hydrogen atmosphere with same density as air.
- Running PYTHIA-6 proton-hydrogen with varying MC tunes to LHC data.
Hadronic MCs tuning with (pre-LHC) collider data

Pre-LHC models
tuned here

\[ \sqrt{s} = \sqrt{m_{\text{proj}}^2 + m_{\text{targ}}^2 + 2 \cdot E_{\text{proj}} \cdot m_{\text{proj}}} \approx \sqrt{2 \cdot 10^9 \cdot E_{\text{proj}}(\text{eV})} \]

**\( \sqrt{s_{\text{GZK}} \approx 400 \text{ TeV} \)**

**\( \times 200 \text{ extrapolation} \)**
The LHC provides a significant lever-arm in providing constraints for hadronic Monte Carlos for UHECR
Key MC parameters for EAS development

- Average shower max. depth \( (X_{\text{max}}) \) & its fluctuations \( (\text{RMS} - X_{\text{max}}) \) are key observables to determine primary CR energy & identity (p, Fe).
- Chiefly depend on the p-p inel. cross section, multiplicity, elasticity in the MC:

  \[ \text{p-Air at } E_{\text{lab}} = 10^{19} \text{eV} \]

  \[ \text{Fe-Air at } E_{\text{lab}} = 10^{19} \text{eV} \]

LHC experiments: $(p_T, \eta)$ acceptance

- Particle production in $p$-$p$, $p$-$A$, $A$-$A$ up to $\Delta \eta \sim 2 \times \ln(\sqrt{s})/m_p \sim 20$ units
- Dedicated detectors at forward rapidities: CASTOR, TOTEM, LHCf, Alfa,..
- All phase-space virtually covered: 1st time in a collider!
Cosmic-ray MCs (pre-LHC) vs. LHC data

Hadronic inelastic cross-section

**Forward particle production**

**Average transverse momentum**

**Hadron multiplicity**

- **p+p | η| < 2.5**

- LHC

- EPOS 1.6

- QGSJET01

- SIBYLL 2.1

- QGSJETII

- NEXUS 3.96
Cosmic-ray MCs vs. LHC data (I)

**Hadronic inelastic cross-section**

![Graph showing hadronic inelastic cross-section](image)

**Forward particle production**

![Graph showing forward particle production](image)

**Average transverse momentum**

![Graph showing average transverse momentum](image)
Total & (in)elastic p-p cross sections (pre-LHC)

- Non-computable from QCD Lagrangian (maybe lattice?), but constrained by fundamental QM relations: Froisart bound, optical theorem, dispersion relations.

- LHC p-p total x-section predictions:
  \[ \sigma_{\text{tot}}(\text{LHC}) = 90–120 \text{ mb} \pm 10\% \]

- Pre-LHC \( \sigma(\text{inel}) \) uncertainties driven by E710–CDF 2.6\( \sigma \) disagreement

- p-Air x-sections even more uncertain (Glauber model):

R. Ulrich, eConf C0906083 (2009)
Many measurements (TOTEM, ALFA, CMS, ATLAS, ALICE, LHCb):

At $\sqrt{s}=13$ TeV: $\sigma_{\text{tot}} = 110.6 \pm 3.4$ mb ($\sigma_{\text{inel}} \sim 72\%$, $\sigma_{\text{el}} \sim 28\%$).

Inelastic cross section mostly overestimated by MCs.

Most MCs over- (under)estimate high- (low-)mass diffraction.
Inelastic p-p, p-Pb cross sections (LHC)

- All retuned MCs predictions are now ~consistent up to GZK cutoff.
- Measured $\sigma(p-Pb)$ at 5.16 TeV confirms Glauber-scaling of $\sigma(p-p)$ to $\sigma(p-Air)$
- Measured $\sigma(p-p)$ at LHC, slightly below pre-LHC MC predictions, leads to reduced $\sigma(p-Air)$: Deeper shower $X_{\text{max}}$ position.

Cosmic-ray MCs vs. LHC data (II)

**Hadronic inelastic cross-section**

- Cross-section (proton-air) vs. Energy (eV)
  - QGSJET01c
  - EPOS 1.61
  - NEXUS 3.96
  - SIBYLL 2.1
  - QGSJETII.3

**Forward particle production**

- \( \frac{dN}{d\chi_{\text{lab}}} \) at \( E_{\text{lab}} = 10^{17} \text{ eV} \)
- Most energetic baryon

**Average transverse momentum**

- \( \langle p_T \rangle \) (GeV/c)
- DPMJET II.55
- nEXUS 2
- QGSJET01
- SIBYLL 2.1

**P-p collisions, NSD**

- \( E_{\text{cm}} = 10^{5} \text{ GeV} \)

**Hadron multiplicity**

- \( p+p | \eta| < 2.5 \)
  - QGSJET II
  - EPOS 1.6
  - QGSJET01
  - SIBYLL 2.1
Particle production from multi-gluon collisions

- Most (~70%) of hadrons from gluon fragmentation in multiple low-x scatterings with typical exchanged momenta 1–4 GeV:
  - $x = p_t/\sqrt{s}$:
  - $<p_t>$: $10^{-2}$ ~1.2 GeV, $10^{-3.5}$ ~2 GeV, $10^{-5}$ ~4 GeV

- Steeply rising ($x^{-0.3} \approx Q^{0.15}$) gluon density:
  - At GZK multi g-g collisions at $x<10^{-5}$
  - Note very large gluon PDF uncertainties

[Graph and diagram showing particle production rates and gluon density]
Central particle production: Data vs. pre-LHC MCs

- First LHC pseudorapidity distributions data vs. CR models:
  - 0.9 TeV
  - 2.36 TeV
  - 7.0 TeV

900-GeV data well reproduced (MCs were tuned to SppS, Tevatron).

Particle multiplicity less well predicted at 7.0 TeV but all CR models "bracket" the experimental distributions.

[Dd'E et al., Astr.Phys. 35 (2011) 98]
Central particle production: Data vs. pre-LHC MCs

- Power-law $s^\varepsilon$, $\varepsilon \approx 0.15$ controlled by soft-hard $p_T$-cutoff (sat. scale) evolution

- Very large differences predicted at $\sqrt{s}_{\text{GZK}} \approx 400$ TeV!

  QGSJET-II ($\sim 40$) > QGSJET01 ($\sim 20$) > SIBYLL 2.1, EPOS 1.99 ($\sim 8$)

- EPOS (1.99→LHC), QGSJETII-04, SIBYLL (2.1→2.3) retuned based on these (and other) data. $dN_{\text{ch}}/d\eta \approx 15\pm5$ at GZK now.
Central particle production: Data vs. post-LHC MCs

- Charged particle pseudorapidity density & multiplicity distributions:
  - particle density: Data vs. post-LHC MCs
  - Central particle production: Data vs. post-LHC MCs

- Retuned UHECR hadronic MCs “bracket” well all p-p, p-A distributions up to 13 TeV.
- Improvements needed in tails of distributions (but small impact on UHECR).

Pre-LHC
- pp → h^0, ALICE (Inel=0), |η| < 1
  - √s = 7 TeV (x 10^3)
  - √s = 2.36 TeV (x 10^3)
  - √s = 900 GeV

Post-LHC
- pp (13 TeV)
  - Nch ≥ 1 in |η| < 2.4
  - pT > 0.5 GeV

Data
- Systematic uncertainties
  - PYTHIA8 CUETM1
  - PYTHIA8 MBR 4C
  - EPOS LHC
  - EPOS 1.99

MC/Data
- Data
  - Systematic uncertainties
  - PYTHIA8 CUETM1
  - PYTHIA8 MBR 4C
  - EPOS LHC
  - EPOS 1.99
Central charged particle multiplicity vs. CR energy:

- Pre-LHC MCs: Factors of ~2 differences on predicted LHC particle multiplicities.

- Post-LHC MCs:

- Much better agreement among LHC-retuned models compared to pre-LHC versions up to $E_{CR} \approx 10^{18.5}$ eV.

- $dN_{ch}/d\eta \approx 15 \pm 5$ with ~30% differences at GZK-cutoff among EPOS, QGSJET-II, PYTHIA 6.
Cosmic-ray MCs vs. LHC data (III)

Hadronic inelastic cross-section

Hadron multiplicity

Forward particle production

Average transverse momentum
Very forward particle production

- The inelasticity $K = \frac{1 - E_{\text{lead}}}{E_{\text{CR}}}$ (fraction of primary particle energy transferred to secondary particles after removing the most energetic “leading” hadron emitted at very forward rapidities) has an important influence on cosmic-ray EAS development.

- EPOS, QGSJET have an increased inelasticity with increasing CR energy, but SIBYLL (and PYTHIA) show a flatter behaviour:

  - Less energy goes to very forward particle production. (Faster shower development: Smaller $X_{\text{max}}$)
  - More energy goes to very forward particle production. (Slower shower development: Larger $X_{\text{max}}$)

[Graph showing inelasticity $K$ vs. CR energy $E_{\text{CR}}$.]

Forward particle production: $|\eta| \sim 5.–7.$

- Forward energy flow in pp at LHC *moderately controlled* theoretically (but CR MCs better than collider MCs).
- Sensitive to *multiparton interactions* and beam-remnants.

- Some *forward particle retuning* needed by all MCs.
Very forward photons (LHCf): $|\eta| \sim 8.-11.$

- Leading baryon (inelasticity) & had-to-e.m. energy transfer ($\pi^0 \rightarrow \gamma\gamma$) moderately controlled theoretically (but CR MCs better than collider MCs).

- Some forward particle retuning needed by all MCs.
Cosmic-ray MCs vs. LHC data (IV)

Hadronic inelastic cross-section

- Cross section (proton-air) vs. Energy (eV)

Forward particle production

- pp collisions at $E_{lab} = 10^{17}$ eV
- Most energetic baryon

Hadron multiplicity

- $p+p$, $|\eta| < 2.5$
- Comparisons: QGSJET II, EPOS 1.6, QGSJET01, SIBYLL 2.1

Average transverse momentum

- $p+\bar{p}$ collisions, NSD
- Comparisons: DPMJET II.55, nXus 2, QGSJET01, SIBYLL 2.1, UA1/UA5
**Mean \( p_T \) driven by minijet saturation dynamics**

- Low-\( x \) gluons start to overlap at “saturation scale” \( Q_{sat} \)

- Saturation effects enhanced in nuclear interactions (p-Air): Larger number of partons per unit transverse area. \( Q_{sat} \) increases by \( A^{1/6} \sim 1.5 \) (for oxygen, nitrogen).

- pQCD minijet x-section peaks at running \( p_T \approx Q_{sat} \approx s^{0.15} \sim 1–4 \) GeV

- Less soft minijets. Harder pQCD activity.
<p><strong>Mean $p_T$ vs. energy: Data vs. pre-LHC MCs</strong></p>

- **$<p_T>$** is sensitive to pQCD x-sections & gluon-saturation.
- **$<p_T>$** should follow power-law saturation scale evolution: $Q_{\text{sat}} \sim S^{0.15}$

### CRs MCs predict very slow $<p_T>$ increase (but EPOS, due to collective flow)

At GZK: $<p_T> \sim 0.6-1.0$ GeV (PYTHIA: $<p_T> \sim 0.7-1.5$ GeV)

[Dd'E et al., Astr.Phys. 35 (2011) 98]
In general, CR MCs have softer tails than data & pQCD-based MCs (PYTHIA).

CR MCs need to improve pQCD minijets evolution (also for muons, see later)

EPOS with final-state collective flow reaches good agreement with density- and species-dependent $\langle p_T \rangle$ activity.
Mean $p_T$ vs. energy: Data vs. MCs

- **Average transverse momentum vs. collision energy:**

  ![Graph showing transverse momentum vs. collision energy with different lines representing various models (DPMJET, JET, QGSJET01, SIBYLL, UA1/UA5).]

  Pre-LHC MCs:
  - Soft particle production.
  - $\langle p_T \rangle$ at GZK only around 0.6 GeV

  Post-LHC MCs:

  - EPOS with final-state collective flow leads to faster $\langle p_T \rangle$ evolution.
  - But still below PYTHIA 6 with $\langle p_T \rangle \sim 1$ GeV at GZK-cutoff.

- Harder activity needed in CR MCs.
Impact on UHECR after LHC MC retuning

- Reduced p-Air (less so for Fe-Air) uncertainties w/ LHC-retuned Mcs.

- All models consistent now with increasing CR-mass approaching GZK.

(Pre-LHC)

(Plots by Ralf Ulrich (KIT))

(post-LHC)
Impact on UHECR after LHC MC retuning

Mean depth of shower maximum:

Number of muons on ground:

Overall $X_{\text{max}}$ increase. Improved MC agreement (but still ~40 gcm$^{-2}$ inter-MC differences)

$N_\mu$ increase but still ~30% deficit compared to data (heavy-quarks?)
Solving the “muon anomaly” with a collider MC?

- UHECR show $\mu$ excess (esp. at large axis distance) than predicted by MC:
  - Due to missing pQCD processes? Hard $\pi,k \rightarrow \mu$ or $D,B \rightarrow \mu$ decays?
  - Impact of heavy-Q & pQCD minijet production on the $\mu$ excess studied with PYTHIA-6 (tuned to LHC data) in proton-H CONEX atmosphere.

<table>
<thead>
<tr>
<th>PYTHIA 6.428 Perugia tune</th>
<th>PDF</th>
<th>$Q_0$ cutoff at $\sqrt{s_0} = 7$ TeV</th>
<th>$Q_0$ scaling power $\epsilon$</th>
<th>ISR/FSR scale $\alpha_s(k \cdot p_T)$</th>
<th>Hadronization</th>
</tr>
</thead>
<tbody>
<tr>
<td>PYTUNES number (main features)</td>
<td></td>
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<td></td>
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<tr>
<td>350 (central tune 2011)</td>
<td>CTEQ5L1</td>
<td>2.93 GeV</td>
<td>0.265</td>
<td>$k = 1$</td>
<td>$s\bar{s},\eta,\eta'$ suppr. = 95,63,12%</td>
</tr>
<tr>
<td>350, noHQ (central 2011; no c-,b-quarks)</td>
<td>CTEQ5L1</td>
<td>2.93 GeV</td>
<td>0.265</td>
<td>$k = 1$</td>
<td>$s\bar{s},\eta,\eta'$ suppr. = 95,63,12%</td>
</tr>
<tr>
<td>371 (var. 2012, high rad.)</td>
<td>CTEQ6L1</td>
<td>2.72 GeV</td>
<td>0.25</td>
<td>$k = 1/2$</td>
<td>$s\bar{s},\eta,\eta'$ suppr. = 92,70,13.5%; softer baryons</td>
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<tr>
<td>372 (var. 2012, low rad.)</td>
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<td>2.60 GeV</td>
<td>0.23</td>
<td>$k = 2$</td>
<td>$s\bar{s},\eta,\eta'$ suppr. = 92,70,13.5%; softer baryons</td>
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<td>380 (var. 2012, $gg$ only at low-$p_T$)</td>
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<td>0.245</td>
<td>$k = 1$</td>
<td>$s\bar{s},\eta,\eta'$ suppr. = 92,70,13.5%; softer baryons</td>
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<td>381 (var. 2012, higher UE)</td>
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<td>2.46 GeV</td>
<td>0.23</td>
<td>$k = 1$</td>
<td>$s\bar{s},\eta,\eta'$ suppr. = 92,70,13.5%; softer baryons</td>
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<tr>
<td>382 (var. 2012, lower UE)</td>
<td>CTEQ6L1</td>
<td>2.92 GeV</td>
<td>0.26</td>
<td>$k = 1$</td>
<td>$s\bar{s},\eta,\eta'$ suppr. = 92,70,13.5%; softer baryons</td>
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</table>
Proton EAS properties: PYTHIA-6 vs. UHECR MCs

PYTHIA-6 tuned to LHC data shows similar EAS as std. UHECR MCs

Proton EAS properties: PYTHIA-6 vs. UHECR MCs

- PYTHIA-6 tuned to LHC data shows similar EAS as std. UHECR MCs

- PYTHIA-6 (esp. without heavy-Q) produces more \( \mu \)'s (at larger axis distances) than UHECR MCs. However, EPOS–QGSJET p-H, p-Air differences point to nuclear effects.
Summary: UHECR MCs vs. LHC data

- Reasonable agreement of all pre-LHC MCs and Run-1 LHC. They “bracelet” data, though no model reproduced consistently all results:

<table>
<thead>
<tr>
<th></th>
<th>SIBYLL 2.1</th>
<th>QGSJET01</th>
<th>QGSJETII</th>
<th>EPOS 1.99</th>
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<tr>
<td>$\sigma_{incl}$</td>
<td>✓</td>
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<td>✓</td>
<td>✓</td>
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<tr>
<td>$dN_{ch}/d\eta</td>
<td>\eta=0$</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>$P(N_{ch} &lt; 5)$</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
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<tr>
<td>$P(N_{ch} &gt; 30)$</td>
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<td>✓</td>
<td>✓</td>
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<tr>
<td>$\langle p_{\perp} \rangle$</td>
<td>✓</td>
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</tbody>
</table>

- No significant change of multiparticle production at the LHC ($\sim 10^{16}$ eV): "CR knee" at $\sim 10^{15.5}$ eV NOT due to new (unobserved) particles.

- EPOS-LHC, QGSJET-II-4, SIBYLL2.3 updates: Retuning of diffraction, multiparton colls., saturation, proton-nucleus effects (based on p-Pb at 5 TeV, 2015). Improved reproduction of newest LHC data.

- Still further improvements needed in:
  - Very forward particle production.
  - Semi-hard MPFs. Perturbative QCD dynamics (harder minijets).

- Solution of UHECR $\mu$ deficit requires pQCD minijet + nuclear effects combined (not missing heavy-quark production). Enough or new physics?
Backup slides
Total & elastic p-p cross sections

- Non-computable from QCD Lagrangian, but constrained by fundamental QM relations: Froisart bound, optical theorem, dispersion relations.

- p-Air x-sections even more uncertain (Glauber model):

R.Ulrich, eConf C0906083 (2009)
LHC low multiplicity probabilities

- Models ~OK with average multiplicity/event, may miss the event-by-event multiplicity probability at low $N_{ch}$ in the data:

**PYTHIA, PHOJET:**

0.9 TeV

2.36 TeV

7.0 TeV

**CRs MCs:**

- Improvement of diffractive interactions needed.
LHC large multiplicity probabilities

- Models ~OK with average multiplicity/event, may miss the event-by-event multiplicity probability at high $N_{ch}$ in the data:

- Improvement of multi-parton interactions modeling needed.
Impact of LHC data on UHE CRs (Auger)

Mean depth of shower maximum:

Auger 2010

Fluctuations of shower max:

Auger 2010

Data prefer average p-Fe composition, w/ reduced model uncertainties.
UHECR at GZK-cutoff: p or Fe-ions? (pre-LHC)

- Auger shower-max position & fluctuations favour **heavy-ions** for $>10^{19}$ eV

- **Hadronic MC uncertainties** propagate to CR mass.

  - QGSJET-II, SIBYLL: favour **protons**
  - EPOS: favours **mixture protons+Fe-ions**

Auger: PRL 104 (2010) 091101
UHECRs energy & identification

- Position & fluctuations of shower maximum:
  Depth: $\gamma > p > A$
  $X_{\text{max}}(p) \sim X_{\text{max}}(\text{Fe}) + 150 \text{ g/cm}^2$
  Shower-to-shower fluctuations: smaller for ions than proton.

- Number of $e^\pm$ & muons:

\[ \langle \ln A \rangle \sim \log\left(\frac{N_e}{N_\mu}\right) \]