Impact of Minijet & Heavy-quark Production on the Muon Anomaly in Atmospheric Showers from Ultrahigh Energy Cosmic Rays

QCD at Cosmic energies VII

Chalkida, 19th May 2016

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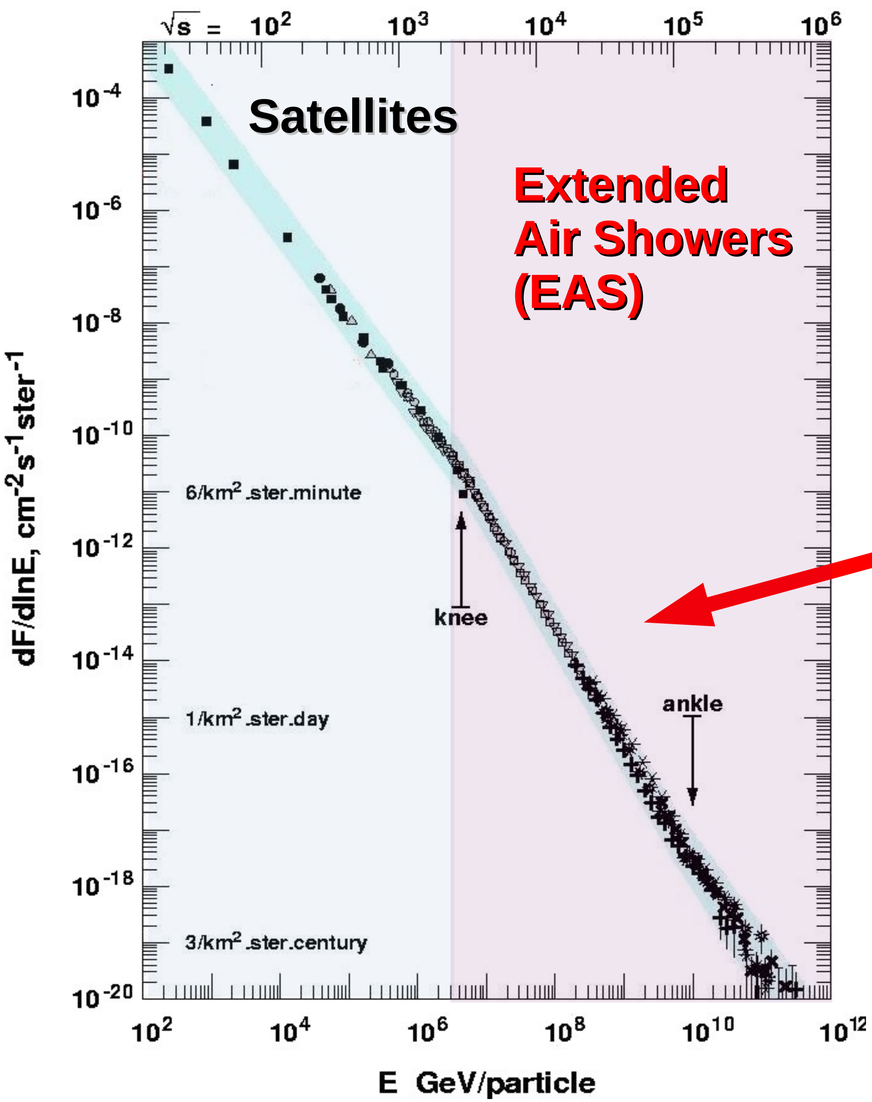
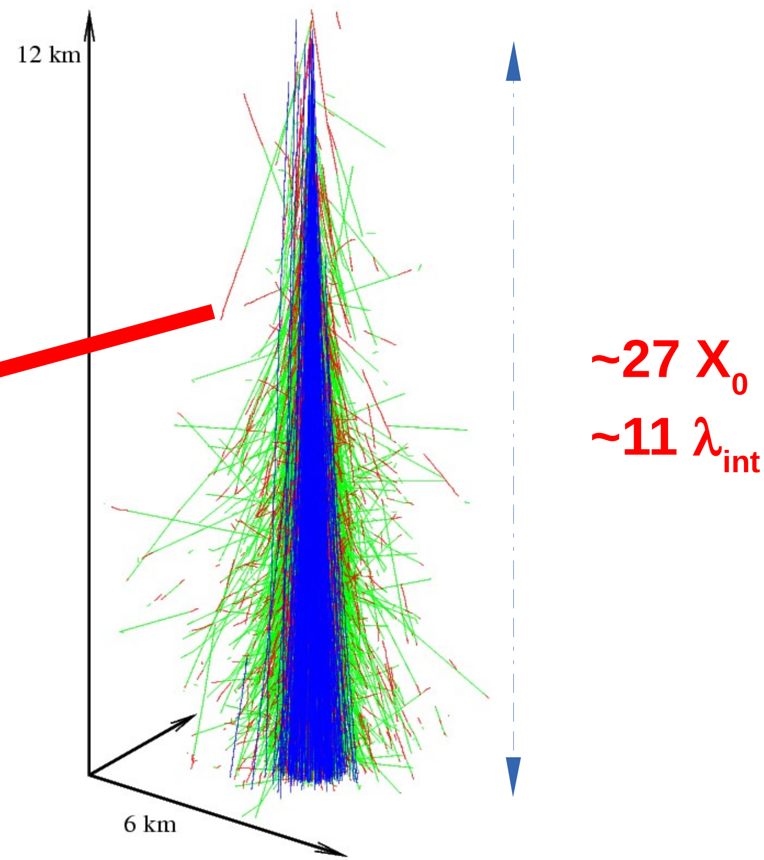
Introduction

- Cosmic-ray flux as a function of energy: power-law E^{-n}.
  For $E_{lab} > 10^{15}$ eV flux too low for satellites/balloons (1 CR per m^2-year):



- Indirect measurements using the atmosphere as a “calorimeter”:



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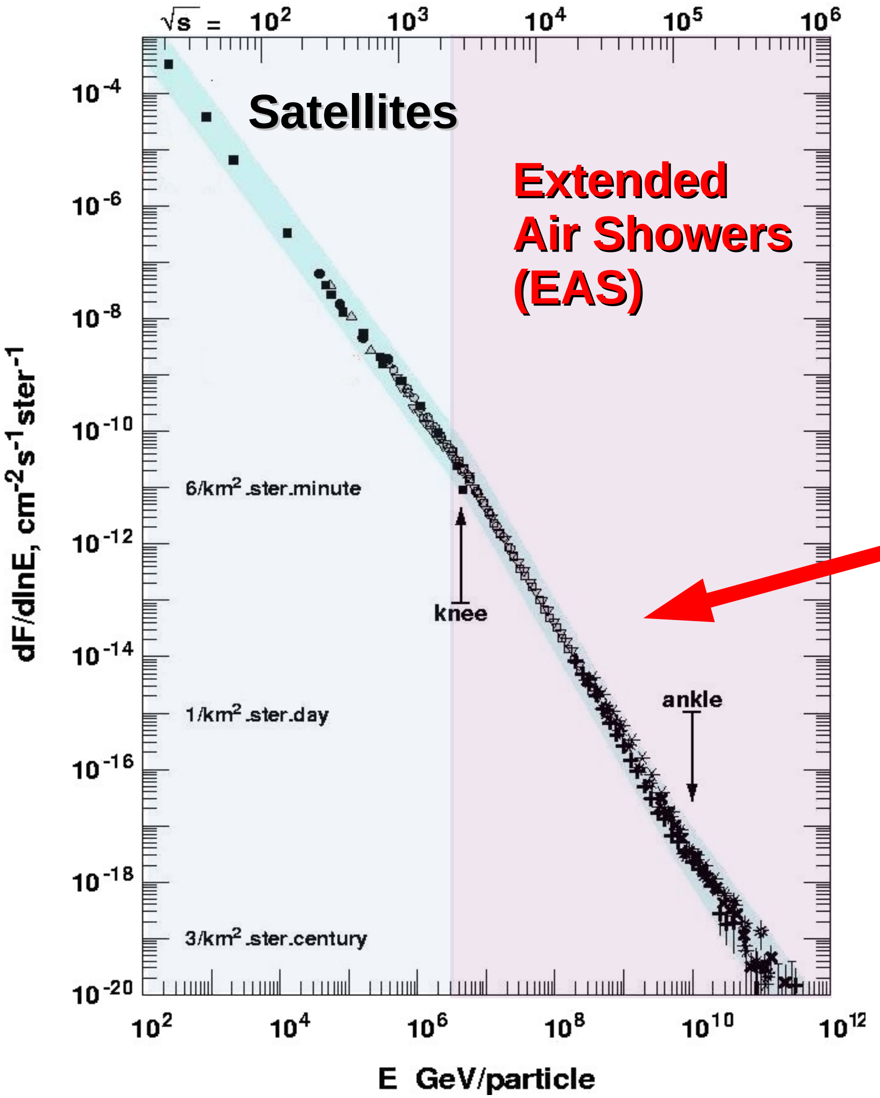
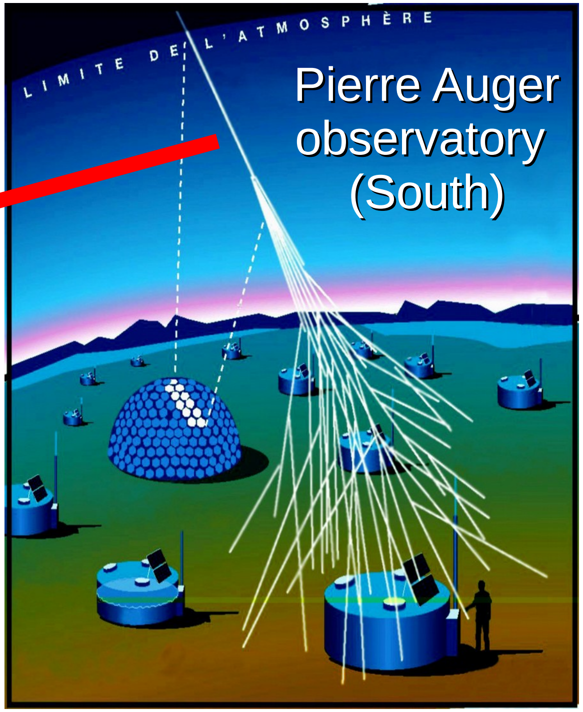


- Indirect measurements using the atmosphere as a "calorimeter":
  - UV fluorescence light in air (N*)
  - Cherenkov-light from $e^{\pm},\mu^{\pm}$ at ground



HiRes/TA
observatory
(North)

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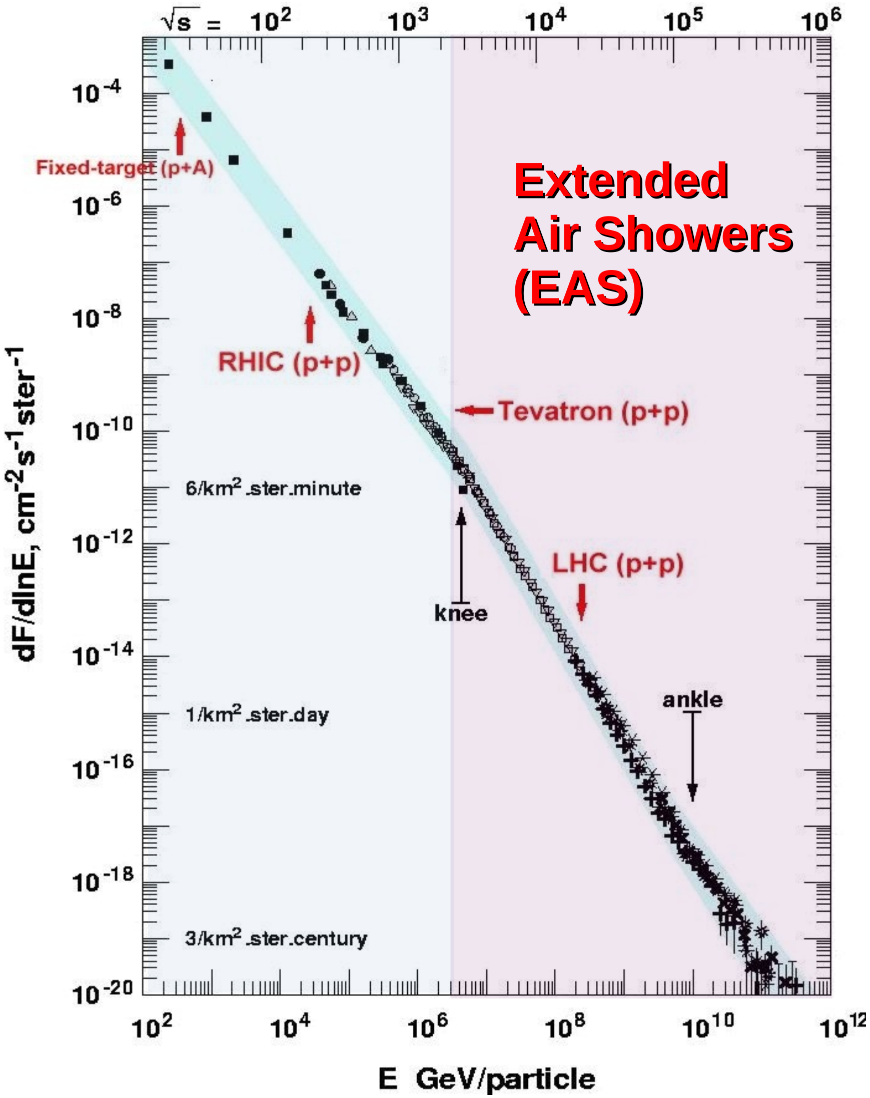
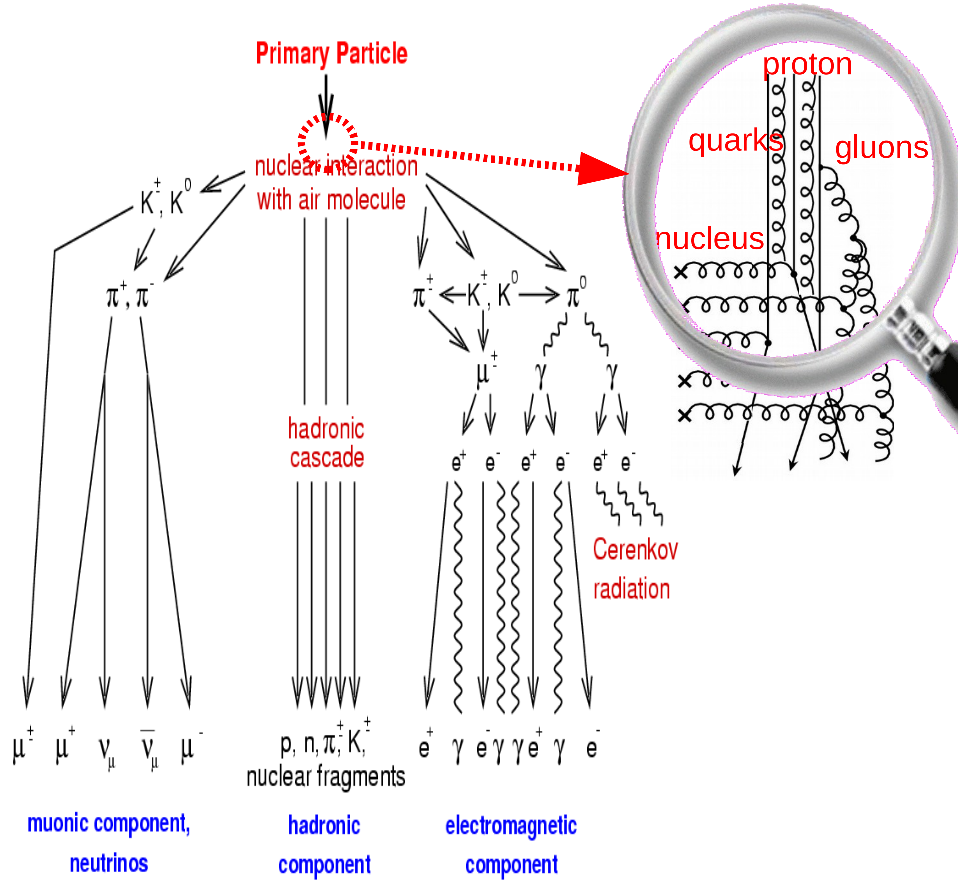
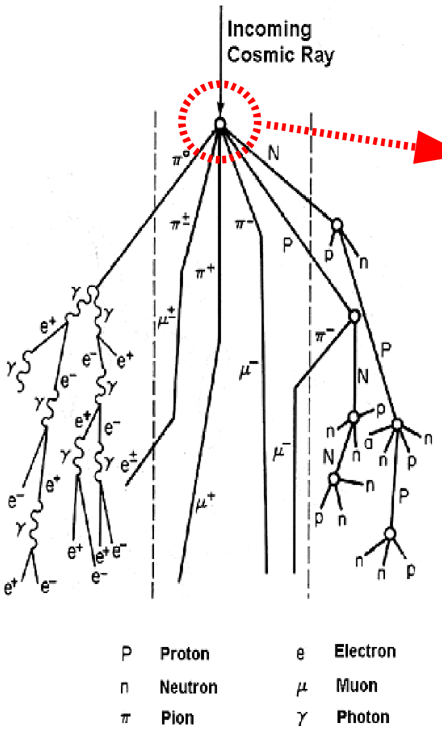


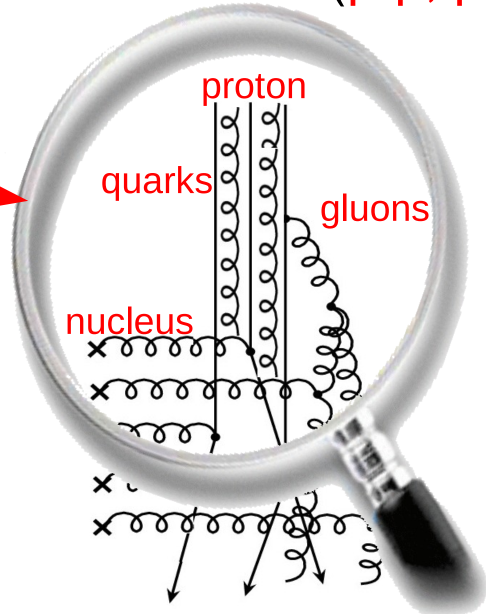
- Comparison of X_{max},N_{μ}... to predictions for p,Fe+Air collisions up to $\sqrt{s_{GZK}}$~300 TeV



Hadronic Monte Carlos for UHECR

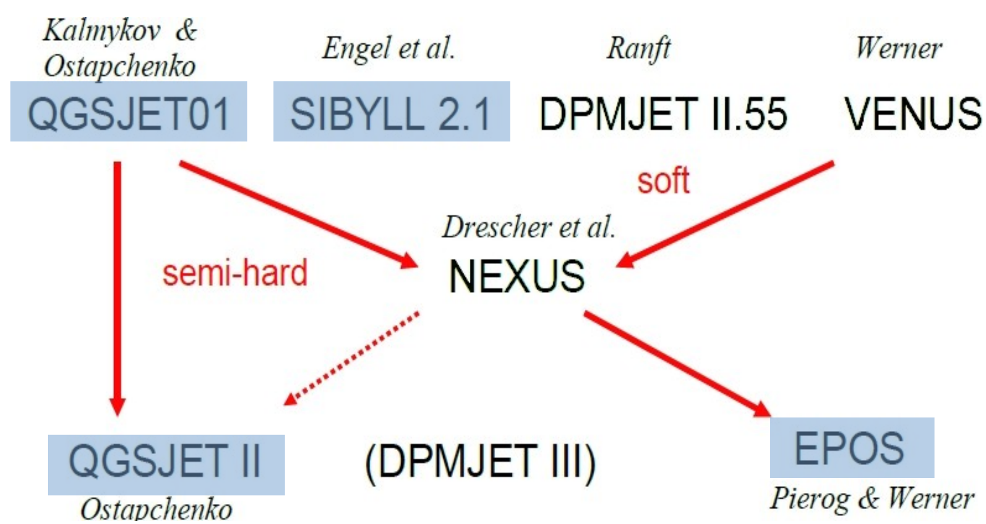
■ Primary hadronic collisions (p-p, p-A) = Complex QCD interactions:





■ Theoretical ingredients:

- Gribov-Regge: soft, diffraction, Multiparton scattering.
- pQCD: hard scatterings.
- Parton saturation in PDFs.
- Parton fragmentation (Lund)
- Beam-remnants
- ...



■ Hadronic CR Monte Carlos:

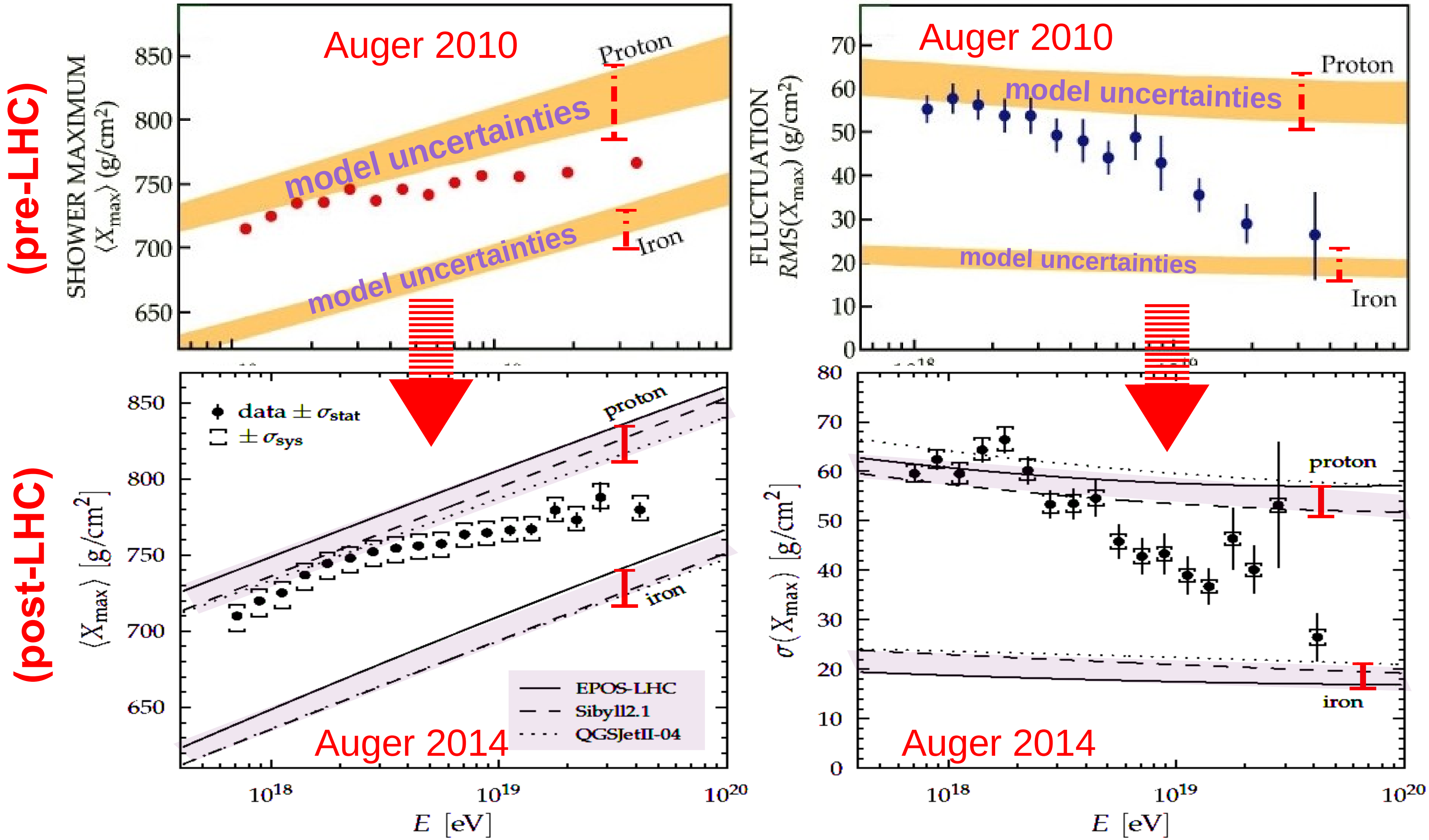
Tuned with accelerator data.

Large √s extrapolations involved:

√s(LHC)=14 TeV → √s(GZK)~300 TeV

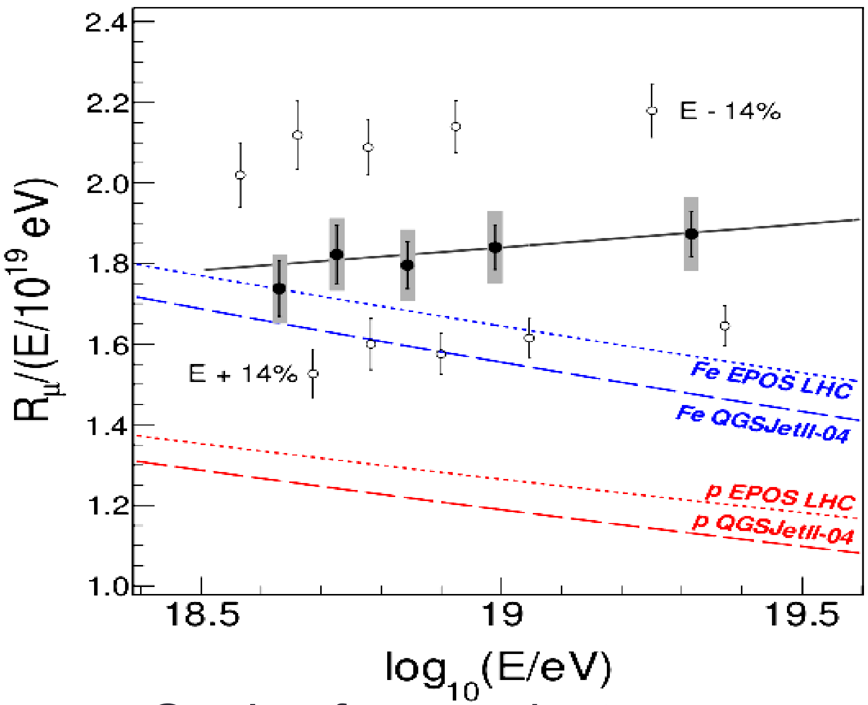
Nature of ultra-high energy cosmic-rays

Mean depth of shower maximum: Fluctuations of shower max:



- Reduced model uncertainties after retuning of MCs with LHC data
- Data prefer average composition between p and Fe.

Muon anomaly in UHECRs



- MCs predict 30% less muons at E_{CR}~19 GeV than measured in data. μ's driven by charged-hadron shower (while $\pi^0 \to \gamma\gamma$ feed e.m. air-shower).
- Is this due to lack of heavy-quark (c,b) production (+decay) in the CR MCs?
- PYTHIA includes heavy-Q production, but does not run with nuclear targets...
- Goals of our project:

→ Employ a fast-simulation (CONEX) model of Earth atmosphere changing N,O atoms by Hydrogen ("Jupiter"-like atmosphere with air density), so that we can run with PYTHIA p-p collisions (1.000 air-showers per E_{CR}).

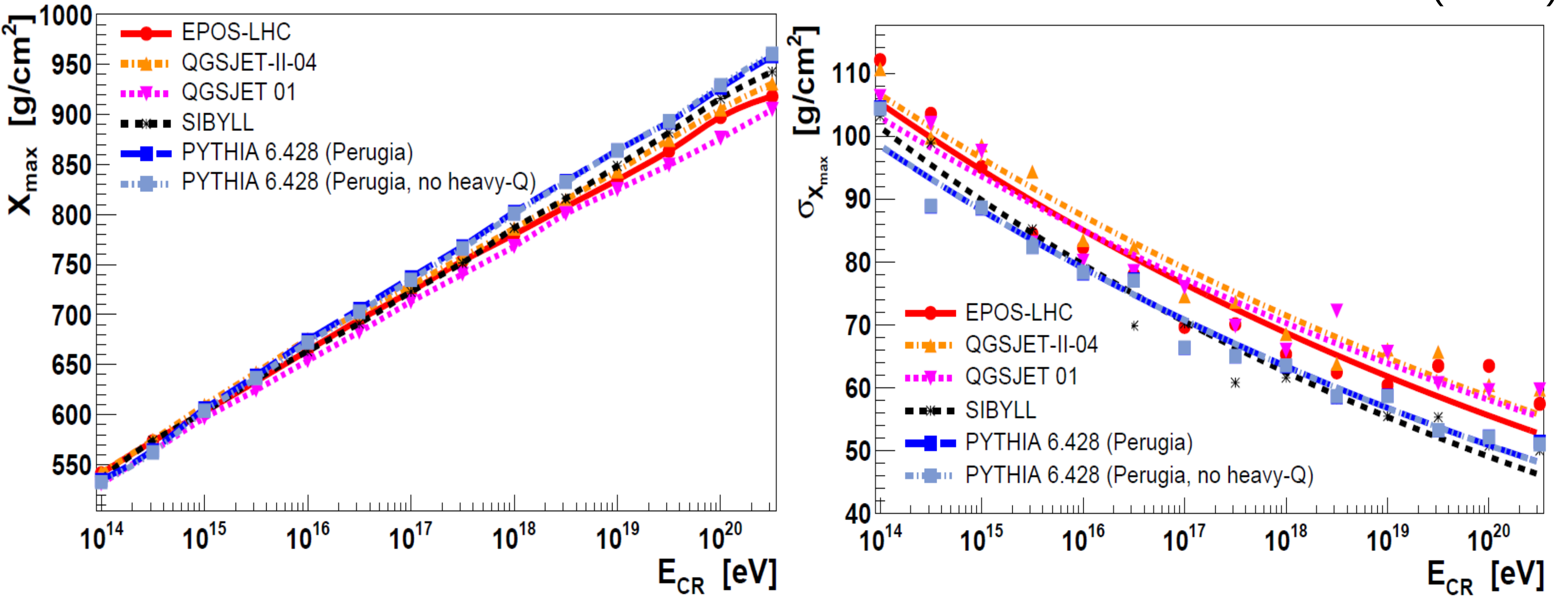
→ Compare air-shower features, especially $\mu^\pm$ production, among PYTHIA6 (different tunes: 350, 371, 372, 380, 381, 382, -350[without heavy quark]) with: EPOS-LHC, QGSJET-II, QGSJET-1, SIBYLL.

Comparison of <u>generic</u> shower features:

PYTHIA6 vs. CR Mcs

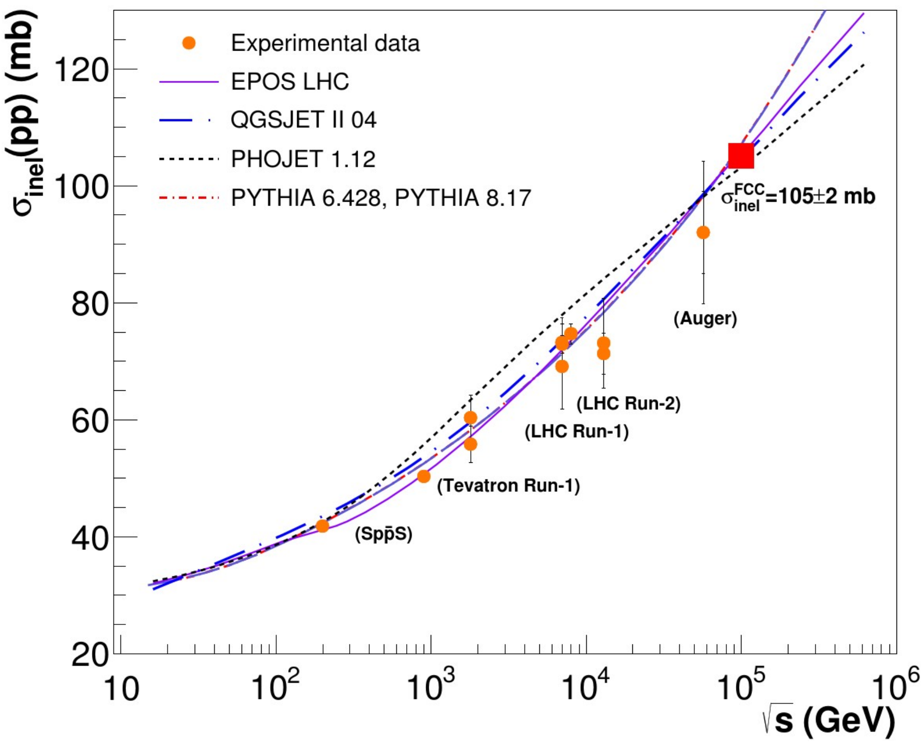
Altitude (mean X_{max} & width σ_{max}) of shower max

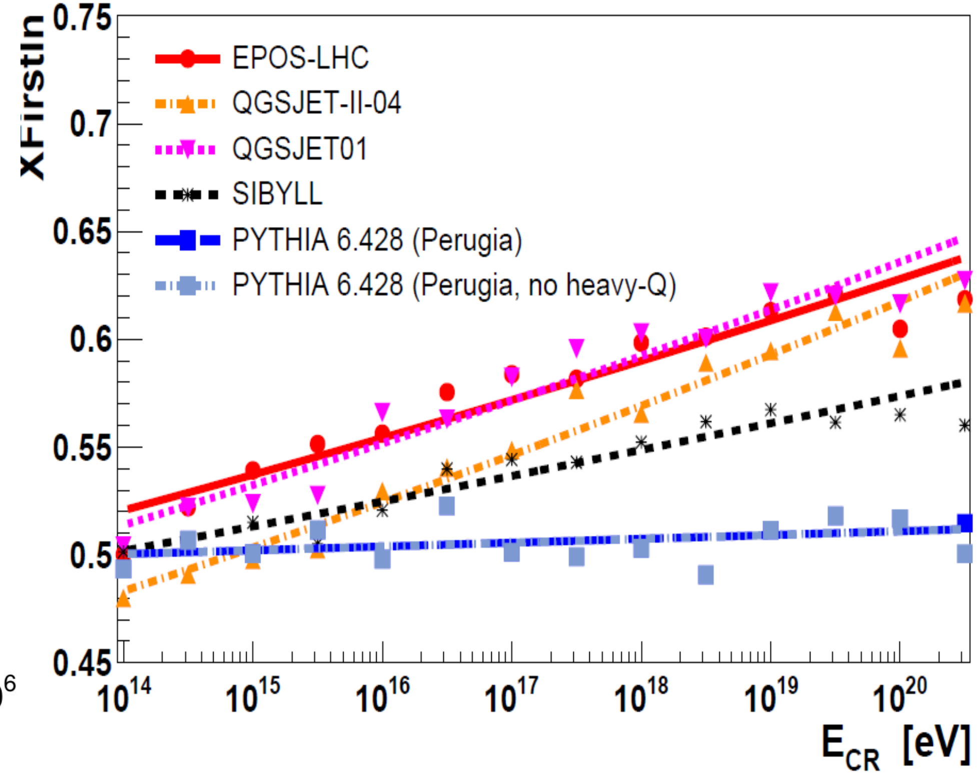
Inclined showers (θ=60°)



- PYTHIA6 (all tunes indistinguishably) features largest X_{max} (more penetration in atmosphere) & lowest σ_{Xmax} (less fluctuations in altitude).
- X_{max} & width are mostly driven by p-p inelastic cross section & inelasticity. PYTHIA6 features similar σ_{inel}(pp), but smaller inelasticities than CR MCs. (see next slide).

p-p inelastic x-section & inelasticity

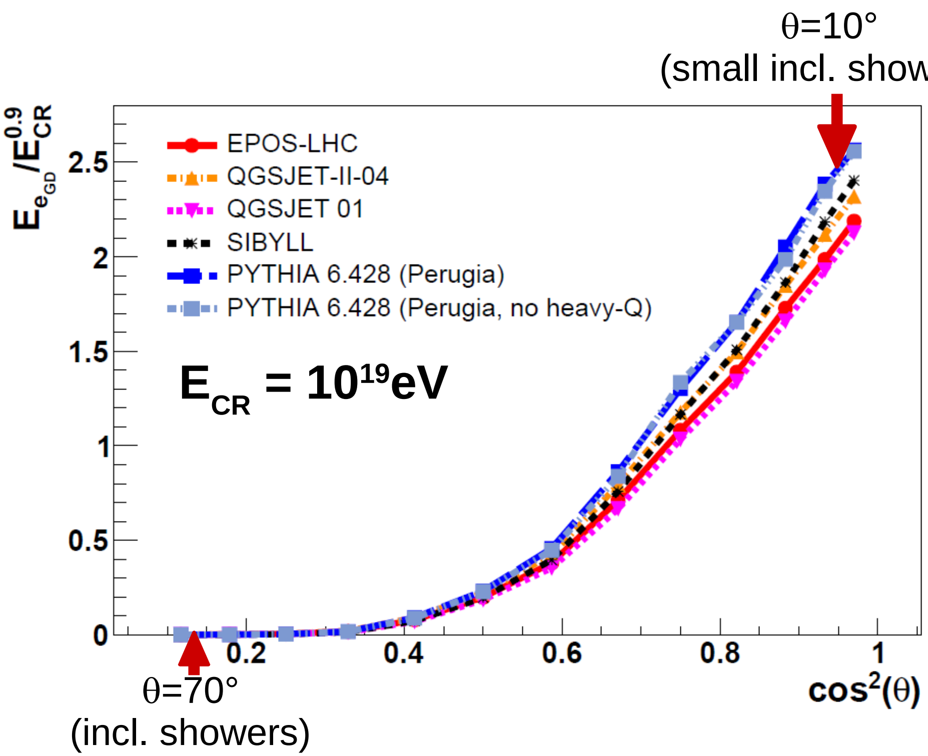


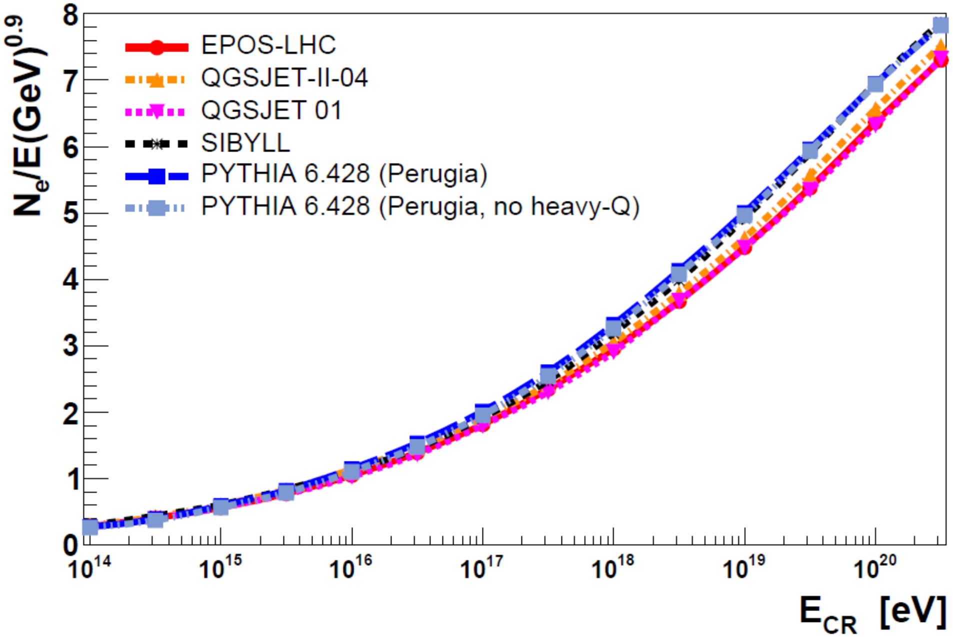


- PYTHIA & CR MCs feature quite similar inelastic x-sections up to √s~100 TeV (E_{CR}~10^{19} eV)

- XFirstIn = 1-(fraction of primary energy carried by the leading particle in each collision).
- PYTHIA6 has smaller XFirstIn value, which leads to larger X_{max}.

Ground E(e$^\pm$) vs. zenith angle, Ground N(e$^\pm$) vs. E_{CR}

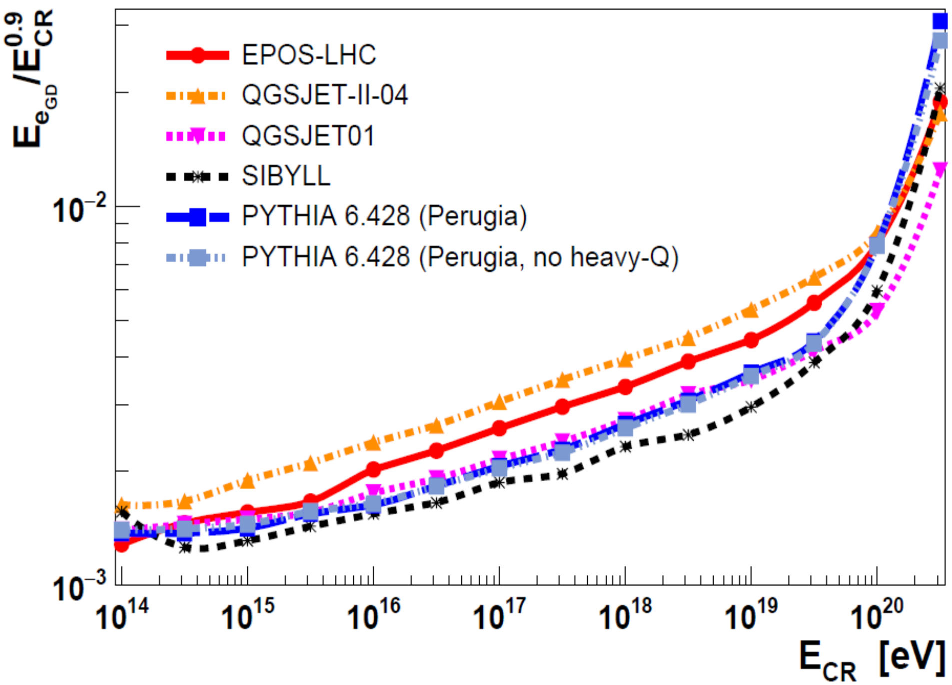


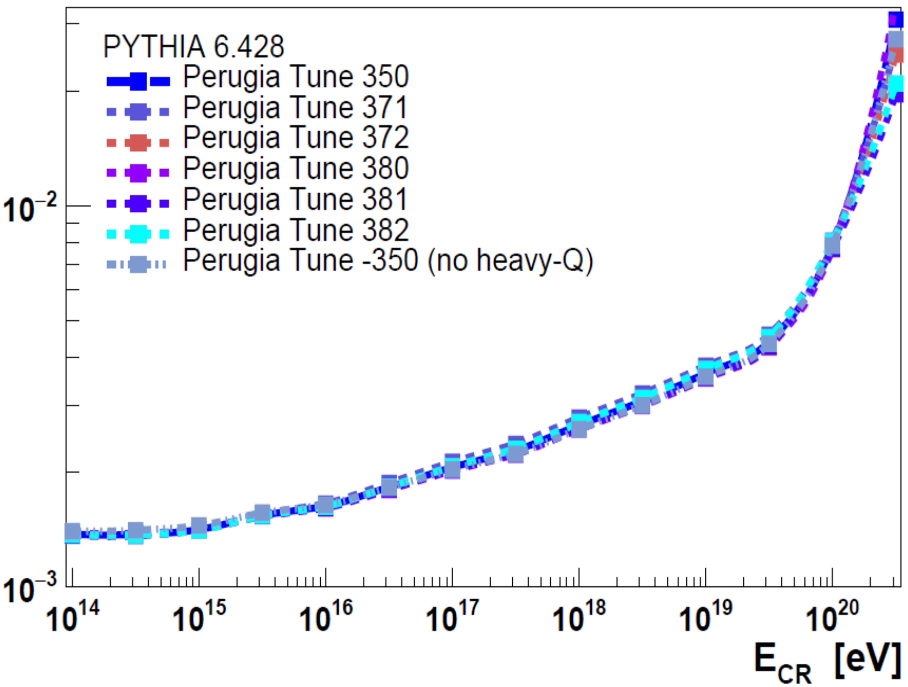


- Fraction of shower energy carried by electrons at ground increases with decreasing CR incident angle in atmosphere:
  More vertical shower = Ground closer to X_{max}(max. of EM particles)
- PYTHIA6 features more ground energy of electrons for more vertical showers (simply due to higher X_{max}).
- PYTHIA6 generally produces more e$^\pm$ vs. zenith angle & at ground

Ground energy for electrons

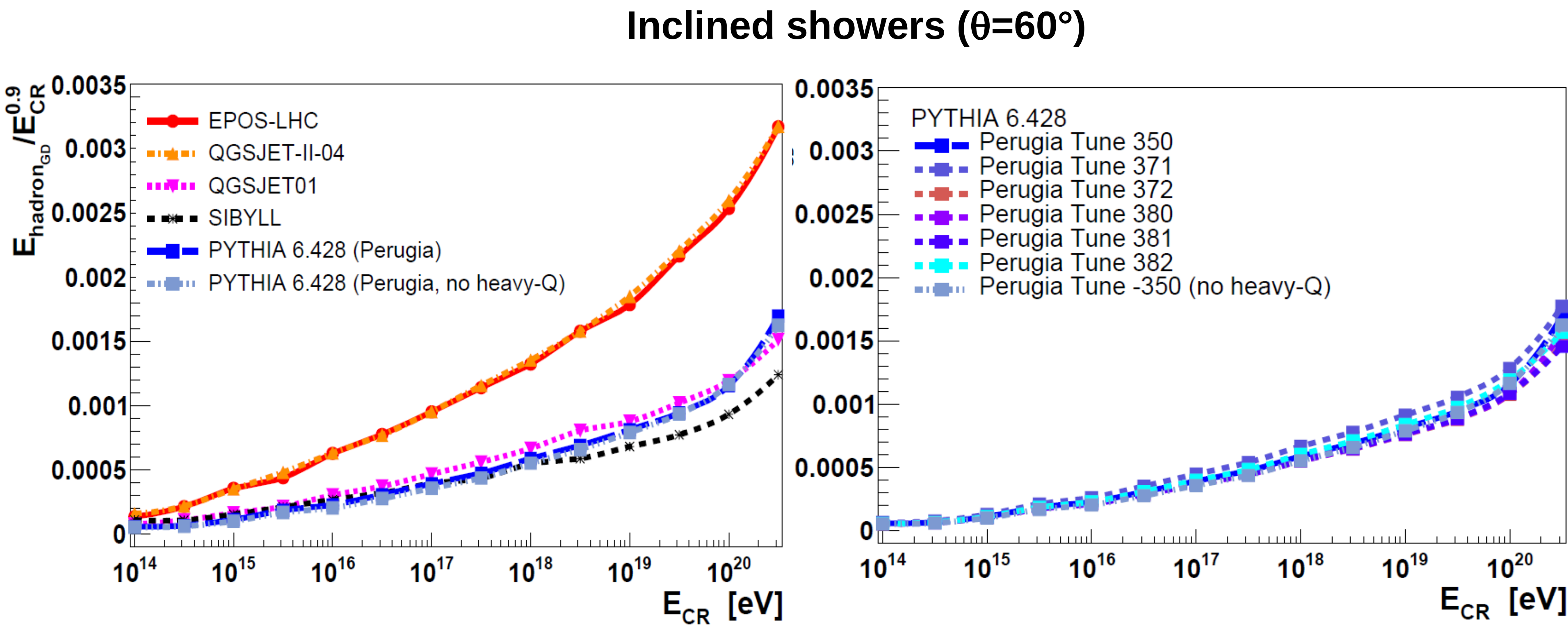
Inclined showers (θ=60°)





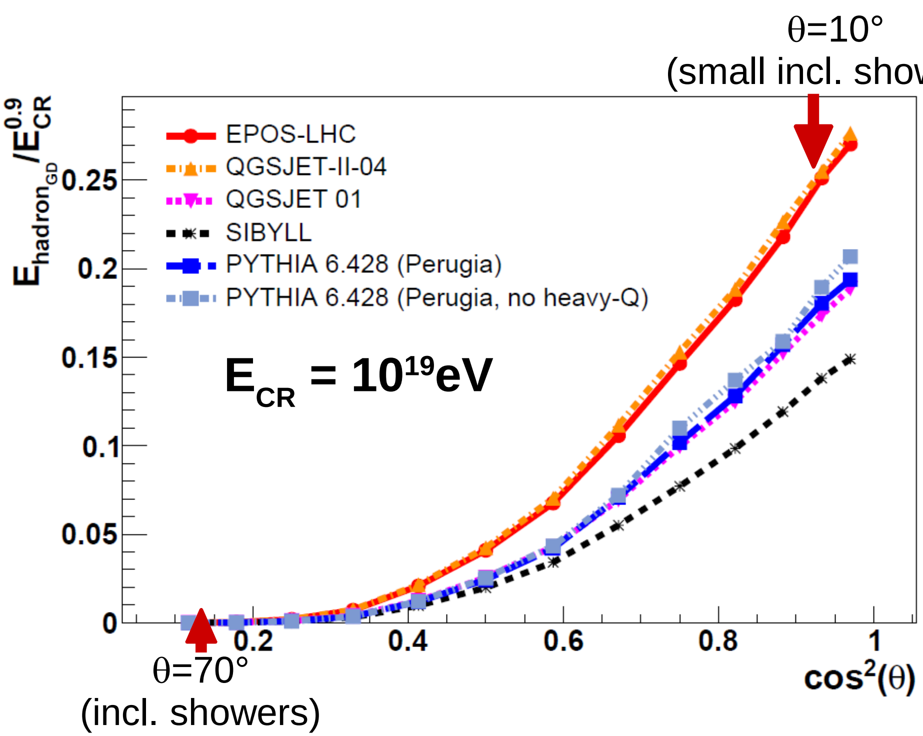
- The electromagnetic part of the shower is the best theoretically-controlled one. Relatively small differences among models. PYTHIA6 shows an average behaviour among MCs.
- Beyond 10^{20} eV the ground is closer to shower maximum: Since PYTHIA has more penetration (shower develops more slowly), its EM component peaks also more strongly than others
- Minimum difference among PYTHIA tunes.

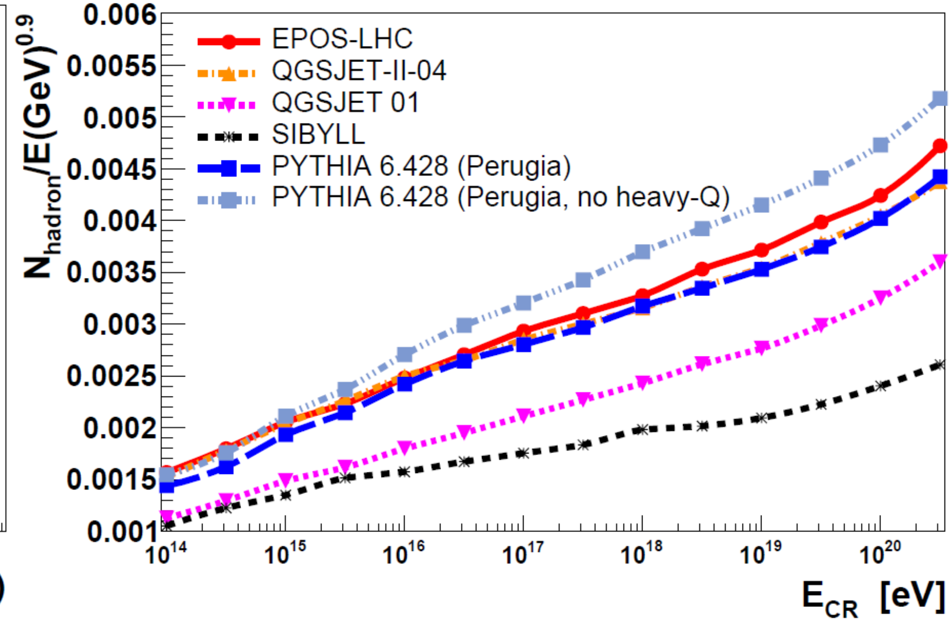
Ground energy for charged hadrons



- EPOS & QGSJET-II ground hadrons have twice more energy than PYTHIA6, SIBYLL, & QGSJET01 predictions.
- When heavy-quark production is turned off in PYTHIA, charged hadron energy does not change evidently.
- The underlying mechanisms need further investigation.

Ground E(h±) vs. zenith angle, Ground N(h±) vs. E_{CR}



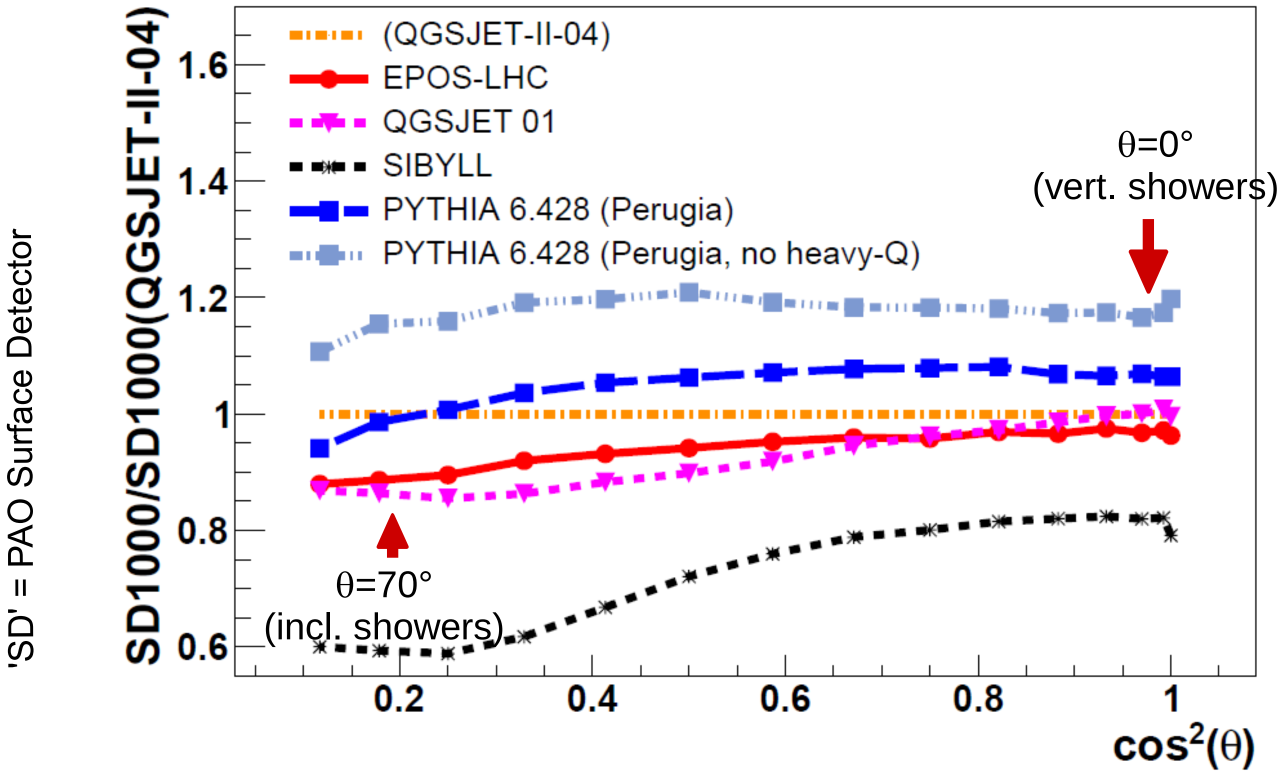


- Fraction of shower energy carried by hadrons at ground increases with decreasing CR incident angle in atmosphere:
  More vertical shower = Ground closer to X_{max} (more HAD particles)

- EPOS-LHC & QGSJET-II feature higher hadron energies for all angles though PYTHIA produces similar number of hadrons. Switching off heavy-quarks in PYTHIA leads to higher number of ch. hadrons – in contrast with previous plot (further investigations needed).

Cherenkov light from all part. (1.000m from shower axis)

- Cherenkov signal from all particles at 1-km from shower axis (PAO measurable) as a function of $\cos^2(\theta_{zenith})$:

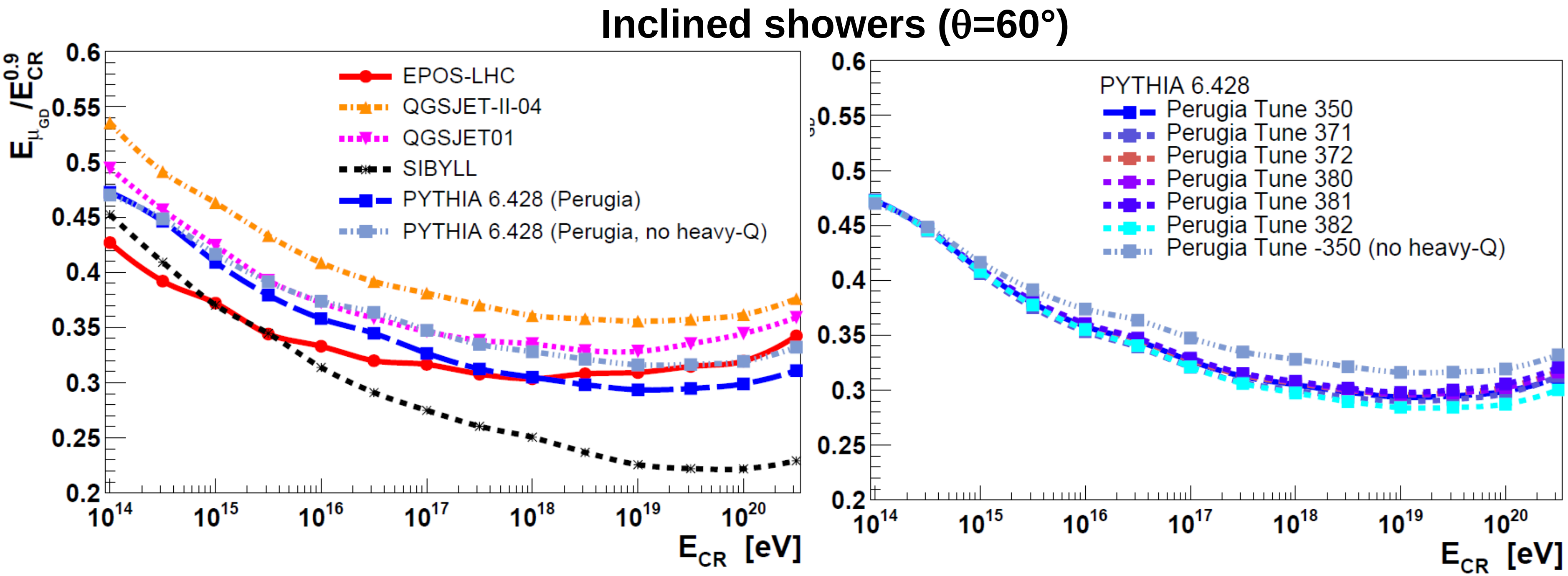


- PYTHIA6 produces ~10-30% more Cherenkov light at 1-km from shower core than all other MCs, except for QGSJET-II-04 at large angle
- PYTHIA6 produces more particles further away from shower axis than all the other CR models: More production at higher p_T's.

Comparison of <u>muon</u> shower features:

PYTHIA6 vs. CR Mcs

Ground energy for muons

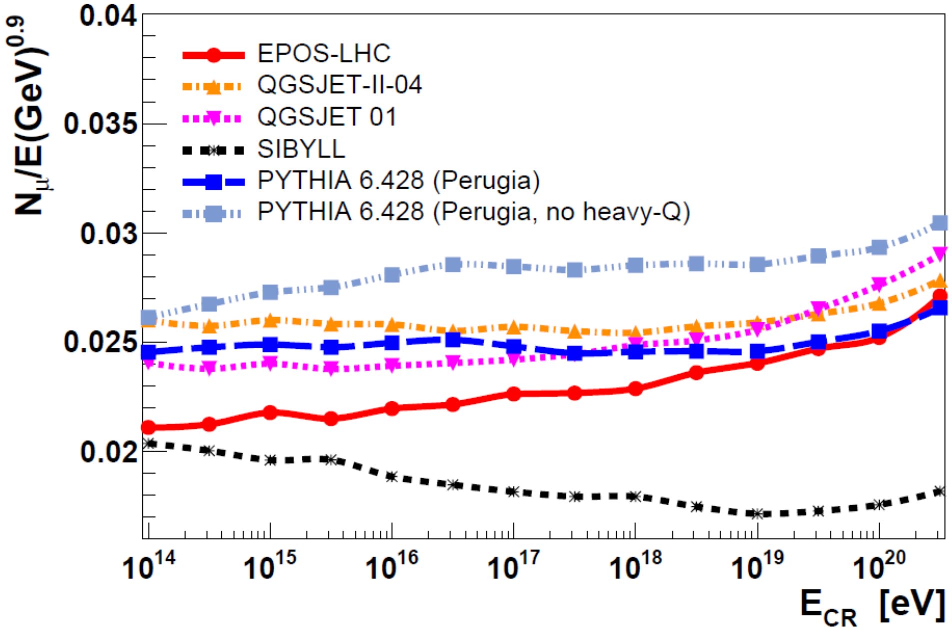


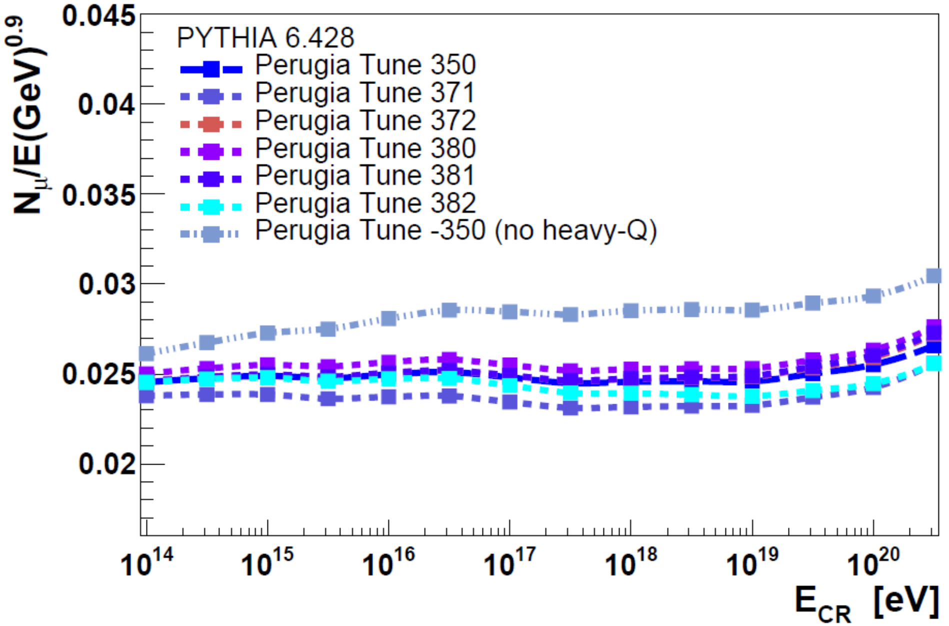
- PYTHIA6 predict ~20% less muon energy at ground than QGSJET-II & QGSJET01 (PYTHIA6 E(μ) a bit larger than EPOS).
- Small differences among PYTHIA tunes. (Surprisingly) slightly more muon energy for tune -350 (without heavy quarks). When energy is “spared” not producing charm & bottom, the final muon energy from p,K decays is larger ?
  Further investigations needed...

Number of muons at Pierre Auger Obs.

Inclined showers (θ=60°)

Bin101 in CONEX corresponds to Pierre Auger Observatory: 1500m.



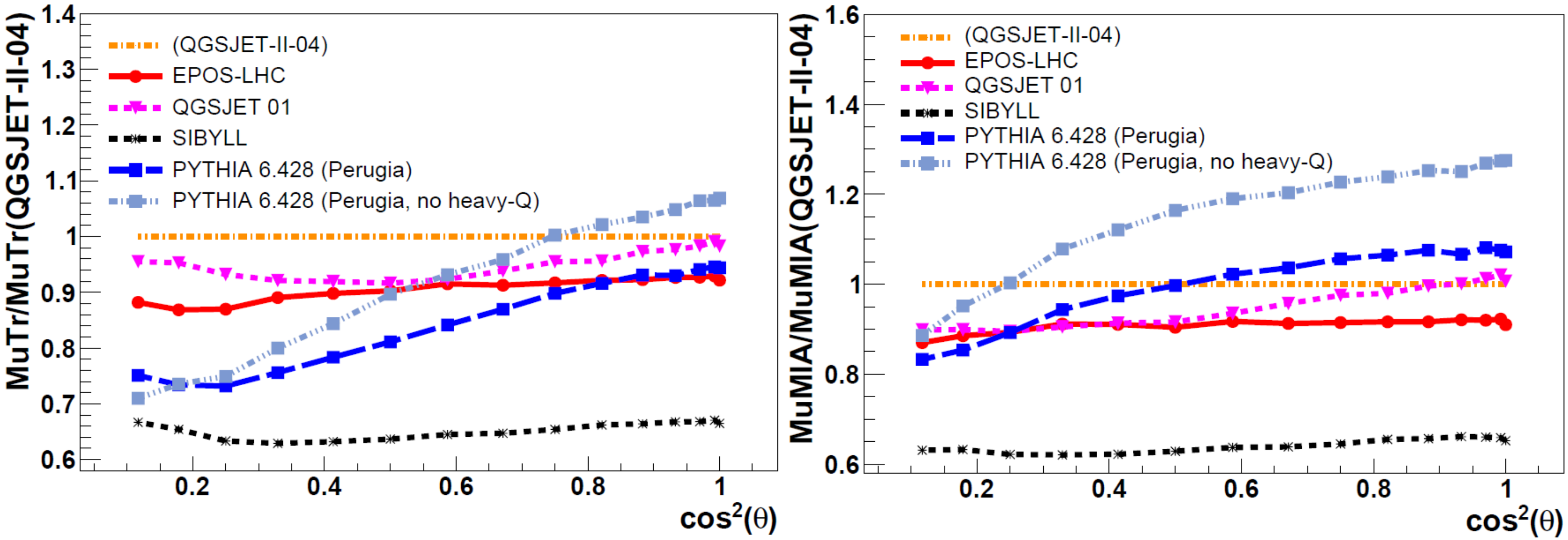


- PY6 produces more μ's than EPOS,SIBYLL but a bit less than QGSJET. Different tunes shows ±5% more/less muon yields.
- However: EPOS produces more muons than QGSJET for normal air showers. Extra nuclear effects, that are absent in the case of running with hydrogen atmosphere, play a role in muon production.
- For tune -350 (no heavy quarks), muon number is higher: Heavy-quark production surprisingly suppresses final muon number.

Muon density ($E_{CR}=10^{19}$ eV) vs. zenith & altitude

MuTr = μ density between 40-200m   MuMIA = μ lateral density at 600m

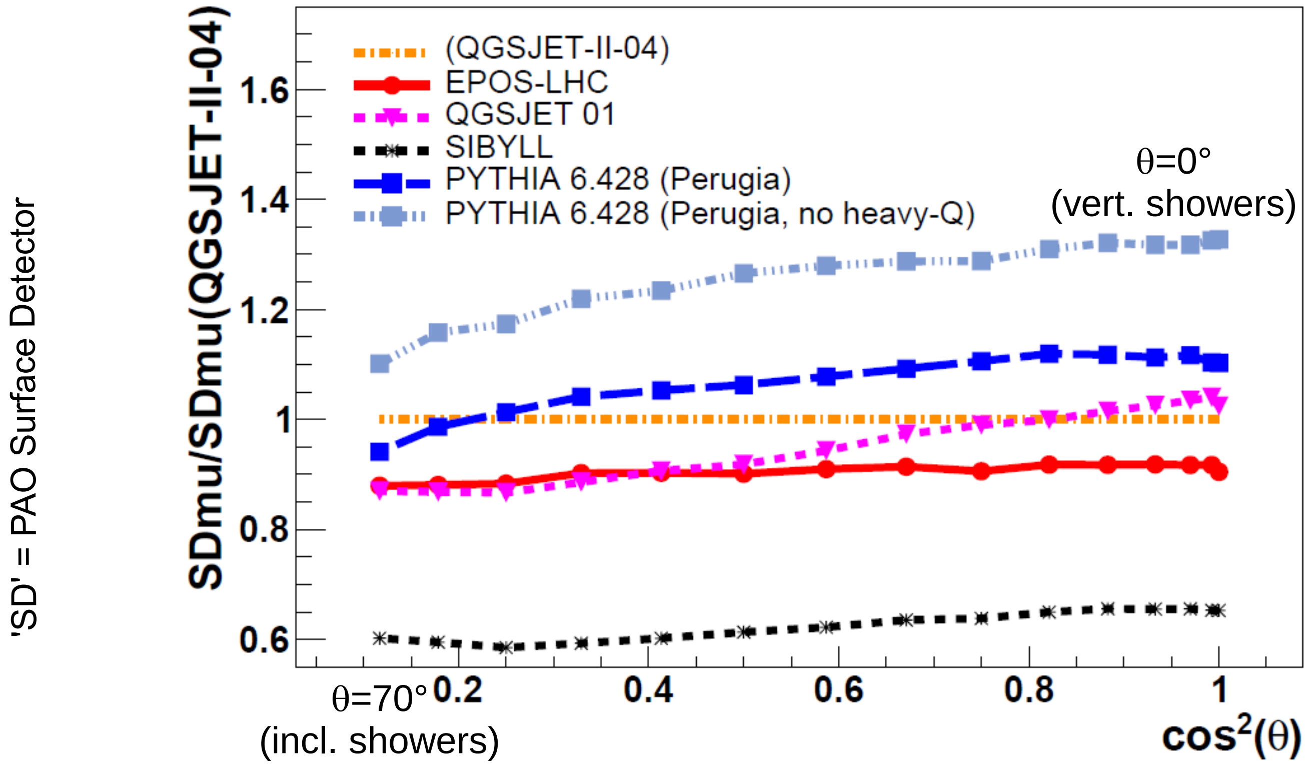
with respect to QGSJET-II prediction as a function of zenith angle



- PYTHIA6 has less muons than other MCs closer to the core shower (40-200m), but more at a distance of 600 m from shower axis. This is especially evident for PYTHIA without heavy quark.
- PYTHIA6 has a much harder muon lateral distribution than CR MCs. Higher transverse momentum muons.

Cherenkov light from μ's (1.000m from shower axis)

- Muon Cherenkov signal at 1-km from shower axis (PAO measurement) as a function of zenith angle:



- PYTHIA6 produces ~10-30% more Cherenkov light at 1-km from shower core than all other MCs, except for QGSJET-II-04 at large angle. Tune -350 has an even higher value (~40%).

- Confirms PYTHIA6 has harder lateral μ± distribution than other MCs

Conclusions

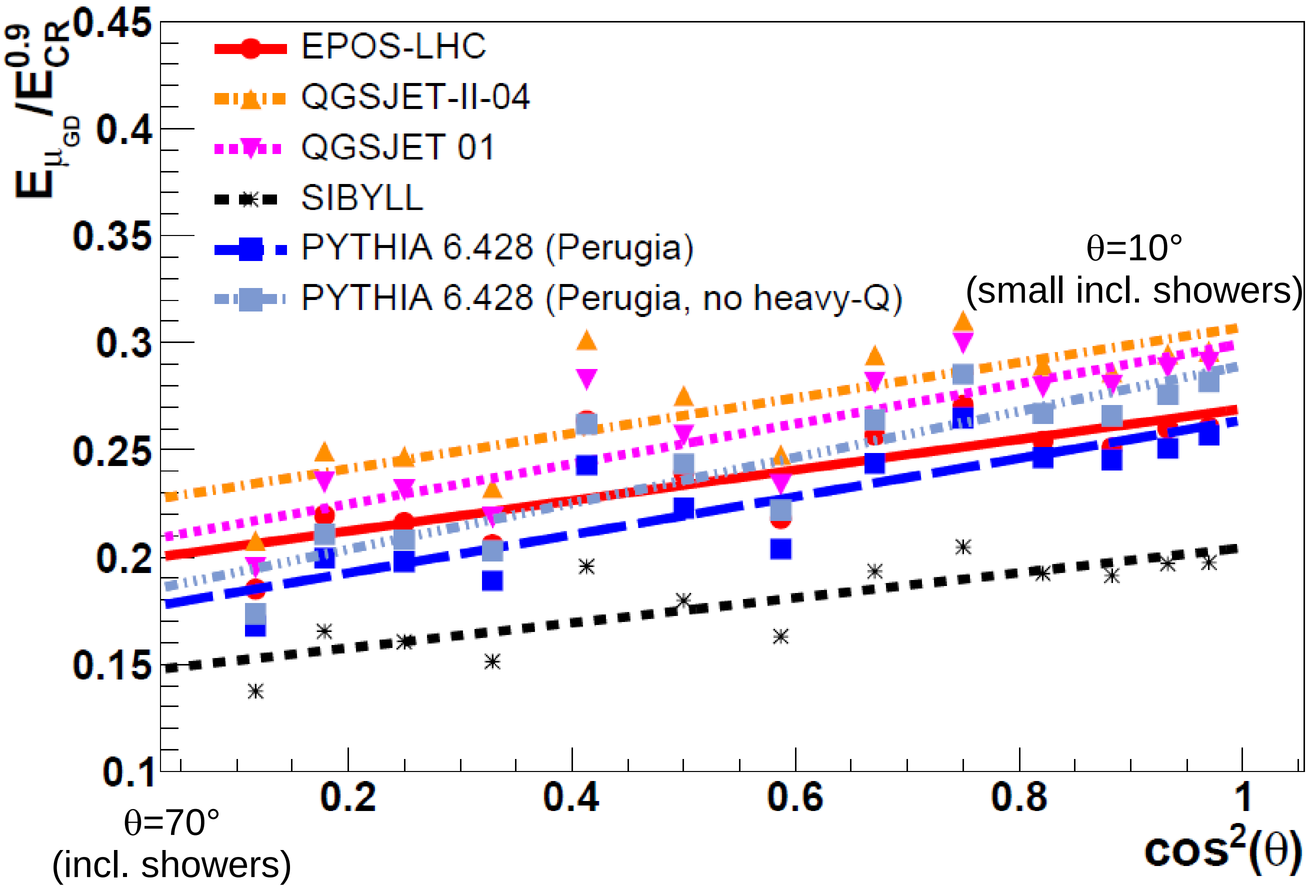
- Properties of PYTHIA generic showers (in "Jupiter-like" atmospheres):
  - PYTHIA6 gives quite similar results to showers from standard CR models: 1st time ever that this has been tested!
  - Lower p-p inelasticity leads to deeper penetration (i.e. higher shower max position X_{max}) & smallest X_{max} fluctuations.
  - Its electromagnetic shower is in between that of other MCs.
  - Its charged-hadron shower is less energetic than EPOS & QGSJET-II, and more similar to SIBYLL & QGSJET01. However, transverse activity (Cherenkov light) at 1-km from axis is 10-30% larger: Higher p_T hadrons

- Properties of PYTHIA muon component (in "Jupiter-like" atmospheres):
  - PYTHIA6 predicts a total muon production in between other MCs: More than EPOS but bit less than QGSJET-II. But,
    (i) Tune-dependent; heavy quark production seems to suppress (not enhance!?) the energy and number of muons at ground.
    (ii) For normal air-showers the situation is reversed: EPOS produces more μ than QGSJET-II: Extra nuclear effects important.
  - PYTHIA6 average μ energy at ground is similar to EPOS but ~20% less than for QGSJET-II.
  - PYTHIA6 has a much harder μ lateral distribution: less μ's close to core, 10-30% more at 600-m and 1-km from core axis.

Thank You!

BACKUP SLIDES

Ground E(μ±) for $E_{CR}=10^{19}$ eV at different zenith angles



- Ground energy of muons rises slowly with decreasing angle
- PYTHIA6 features less muon energies at ground than EPOS-LHC, QGSJET01, QGSJET-II for all angles.