Recent results from Auger and KASCADE-Grande, and introduction to the CORSIKA air shower simulation code

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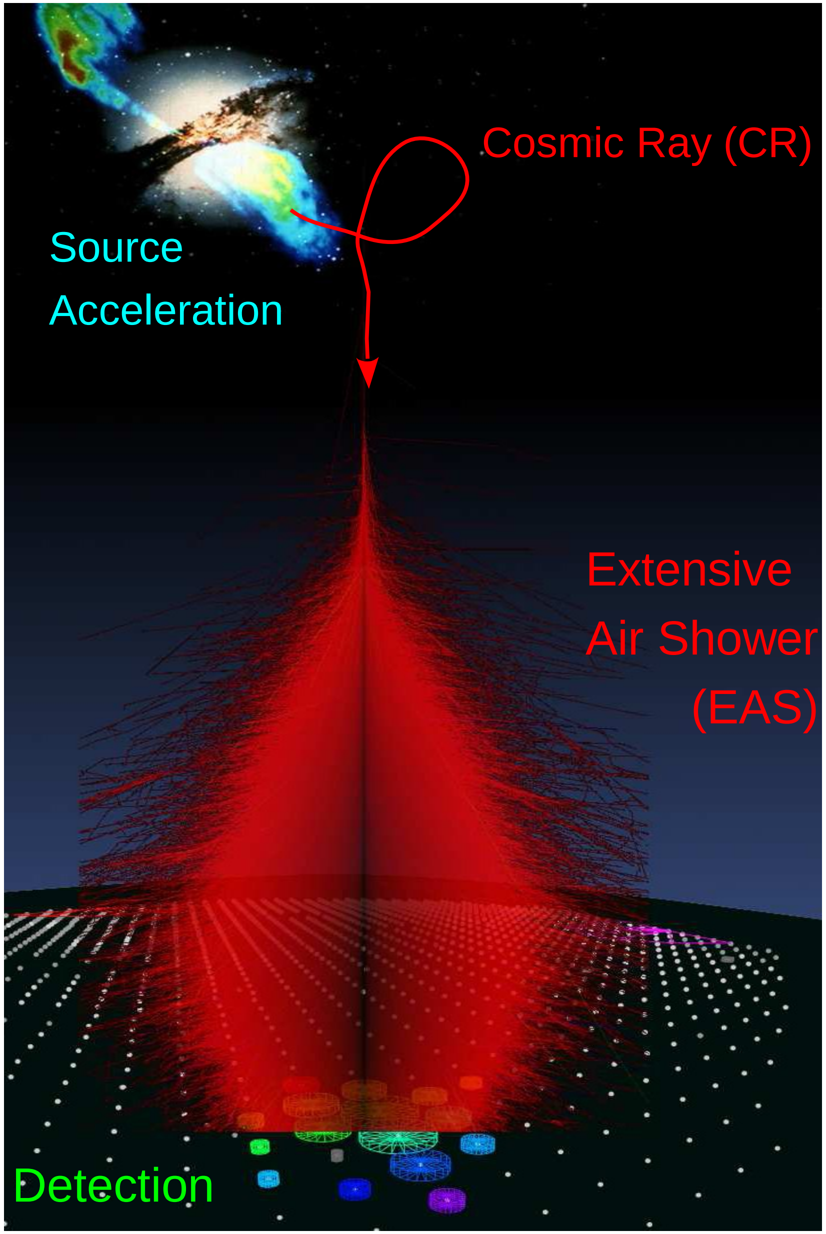
Outline

Modern simulation tools constrained by LHC data allowed a big step forward in the interpretation of charged cosmic ray (CR) data towards an unexpected mixed composition of extra-galactic cosmic rays.

- **Extensive Air Shower (EAS) simulations**
  - CORSIKA
  - CONEX
- **Hadronic Interactions and EAS**
- **Latest results from KASCADE-Grande and Pierre Auger Observatory**
  - new CR interpretations
- **Muons in EAS**
  - open problems

Preamble

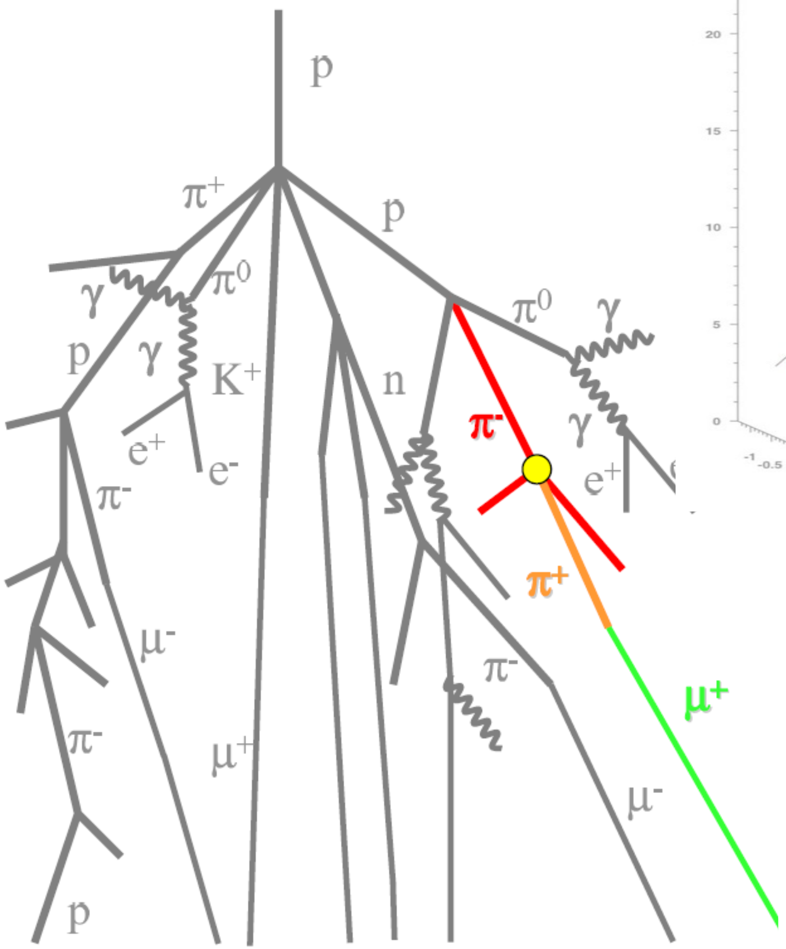


From R. Ulrich (KIT)

- **Goal of Astroparticle Physics :**
  - astronomy with high energy particles
    - source study
- **How to test hadronic interactions ?**
  - if the source mechanism is well understood we could have a known beam at ultra-high energy (10^{10} GeV and more)
    - unlikely situation
  - reasonable minimum limits from CR abundance :
    - low = hydrogen (proton)
    - high = iron (A=56)
  - test of hadronic interactions in EAS via correlations between observables.

mass measurements should be consistent and between proton and iron simulated showers !

Extensive Air Shower



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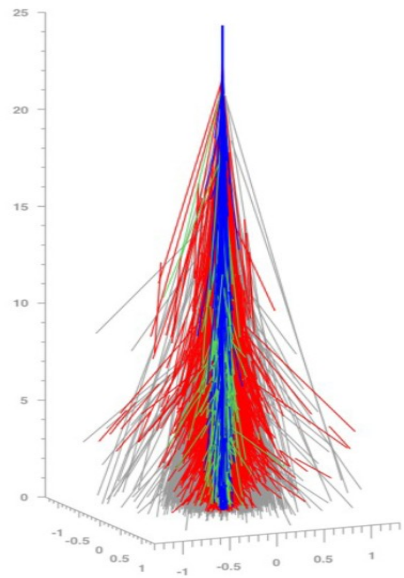


$A + air \rightarrow$ hadrons
$p + air \rightarrow$ hadrons
$\pi + air \rightarrow$ hadrons

hadronic physics

initial γ from π^0 decay

$e^{\pm} \rightarrow e^{\pm} + \gamma$
$\gamma \rightarrow e^{+} + e^{-}$

well known QED

$\pi^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}/\bar{\nu_{\mu}}$

Cascade of particle in Earth's atmosphere

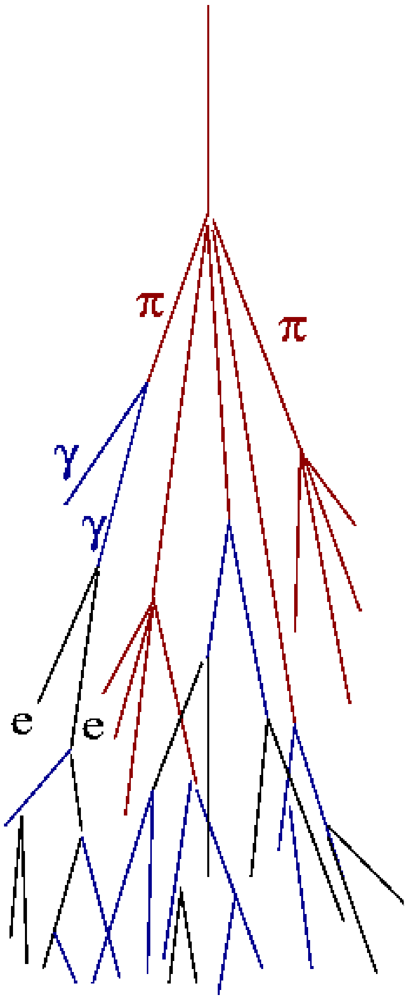
Number of particles at maximum

- 99,88% of electromagnetic (EM) particles
- 0.1% of muons
- 0.02% hadrons

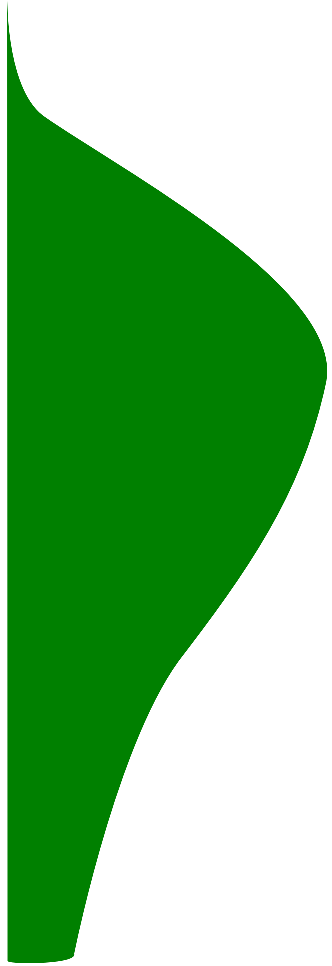
Energy

- from 100% hadronic to 90% in EM + 10% in muons at ground (vertical)

Air Shower Simulations



- **Air shower simulations, 2 main methods**
  - Full MC simulations: CORSIKA
    - realistic
    - flexible
    - fluctuations
    - slow
  - Cascade Equations
    - fast
    - mean behavior
    - no fluctuations
    - limited to analytic formula ?



- **Mix of both:** CONEX hybrid simulations

CORSIKA

Monte carlo simulations of EAS

- Reminder :

  COsmic Ray SImulations for KASCADE

- 1989 : original design optimized for vertical showers on a flat array detector using monte-carlo technique
- 1994< : extension to different type of experiments
  - Cherenkov, fluorescence light, inclined showers, ...
- 2010< : extension to new type of simulations
  - cascade equations, parallelization, different media …
- About 1000 users from 50 different countries for about 60 experiments !

Monte Carlo Simulations of EAS

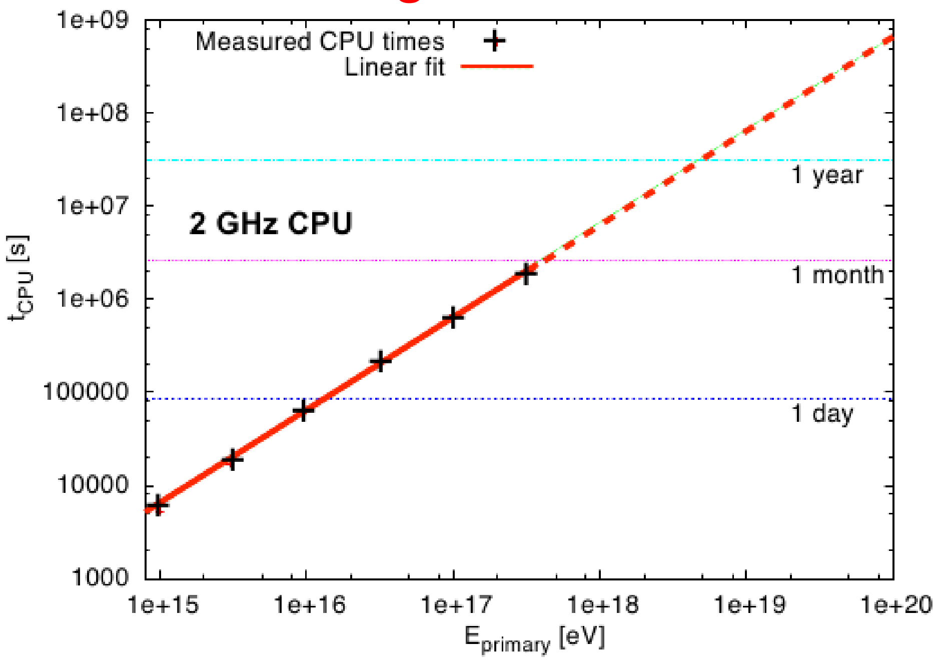
- **Random Numbers**
- **Environment:**
  - atmosphere (composition, density $\propto e^{-h/c}$)
  - Earth magnetic field (strength, orientation)
- **Particles:**
  - type, energy, position, direction, time
- **Range estimation:**
  - cross section σ
  - life time τ
- **Particle transport:**
  - ionization energy loss dE/dx
  - multiple scattering (for leptons and muons)
  - deflection in Earth magnetic field
  - particle reaches detector or cut
- **Interaction / decay with production of secondaries:**
  - high-energy hadronic interaction model
  - low-energy hadronic interaction model
  - particle decay (branching ratio > 1 %)
  - electromagnetic interaction (EGS4)
- **Secondary particles:**
  - store particles on stack

Limitations of Air Shower Simulations

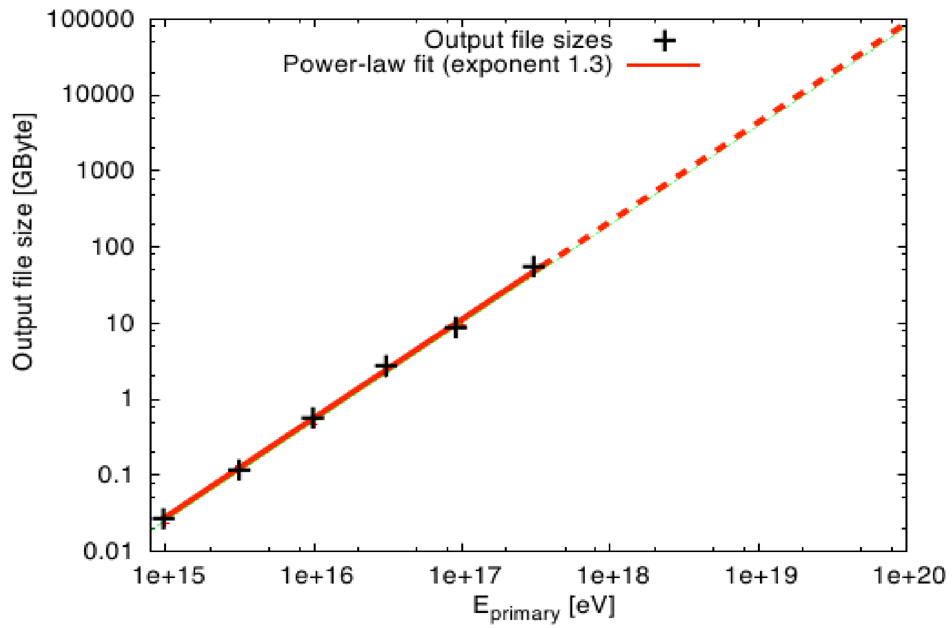
Analysis based on air shower simulations affected by 2 main problems :

- limited statistic due to :

Large CPU time



Large disk space

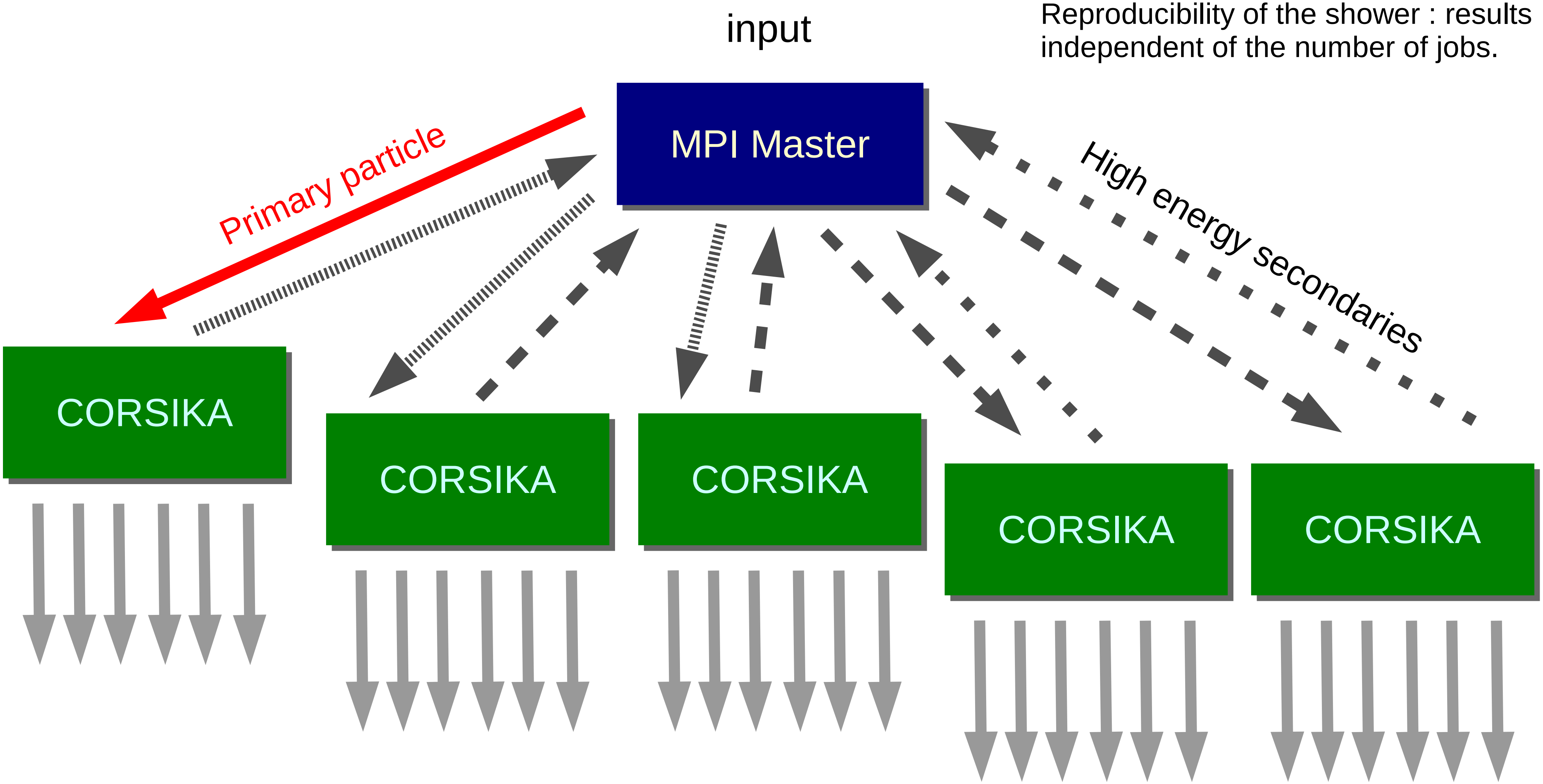


- problems with fluctuations created by thinning

- uncertainties due to hadronic interactions

Parallelization of CORSIKA with MPI

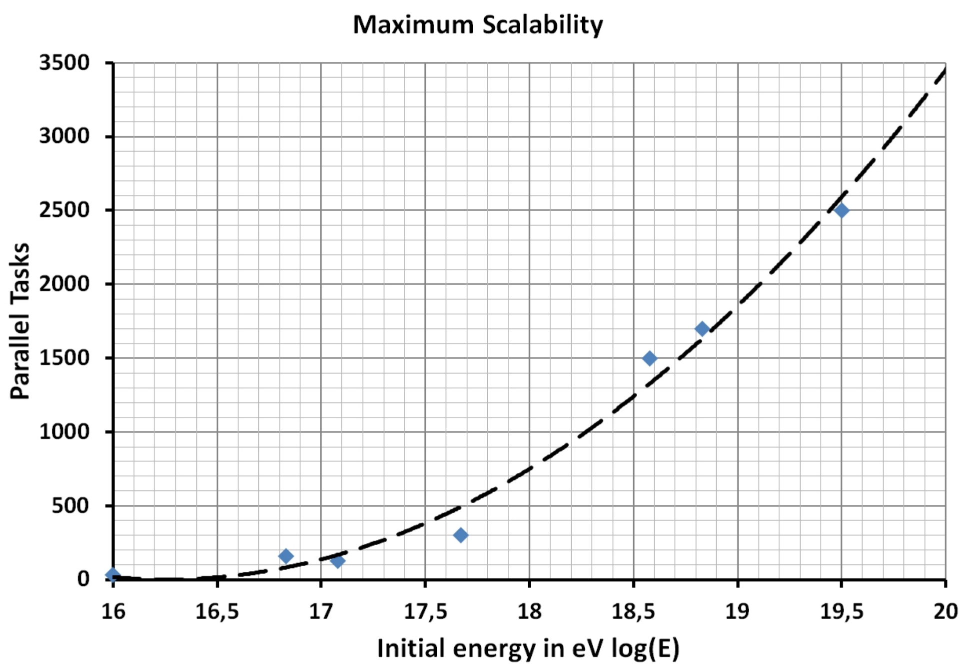
Reproducibility of the shower : results independent of the number of jobs.

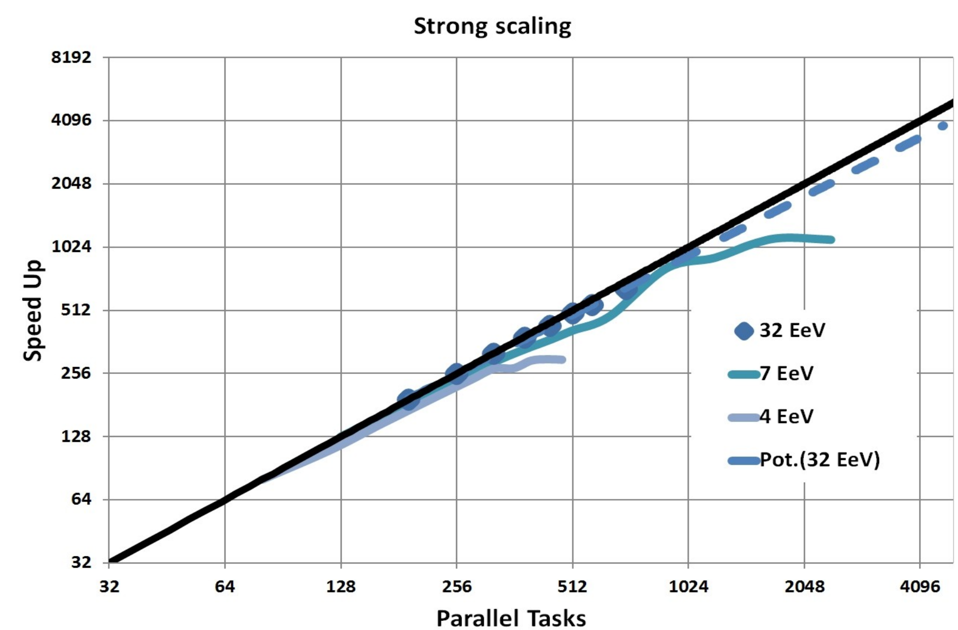


Low energy secondaries down to observation level

Parallelization of CORSIKA

- **Each shower is simulated on a large number of CPU**
  - Simulation time reduction limited by the number of machines
  - Disk space problem solved by saving particles in detectors only
    - possible only if simulation time is short
- **solution at high energy : unthinned simulations for each real events**





Parallel version tested on HP XC3000 (2.53 GHz CPUs, InfiniBand 4X QDR)

New Developments

- **Parallel option already available**
  - simulation shower-by-shower (high energy)
  - system dependent, please contact us in case of problem
- **On-going developments**
  - data merging to limit the number of final files
  - automatic multi-shower management
    - mix low/high energy by user : master job decide if a shower should be treated on a single node or many
    - high statistic of low and high energy unthinned showers from a single job on giant CPU clusters (billions of CPU hours available)
- **Project**
  - Use of GPU for Cerenkov photon calculation

Cascade Equations

- **Can be CE as flexible than MC ?**
  - electron cascade equations: analytical solution for each X step

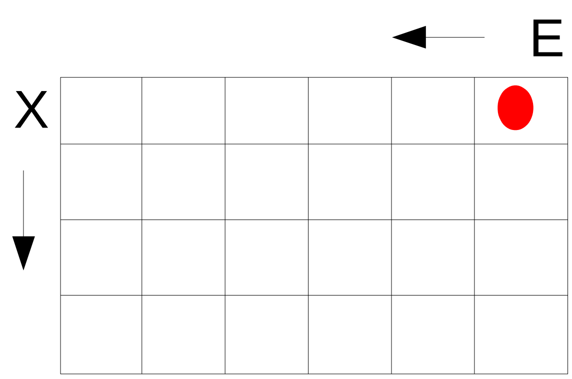
production terms

$$\frac{d\,\phi_e(E)}{dX} = -\sigma_e \phi_e(E) + \boxed{\begin{aligned}&\int_E^{E_0} \sigma_e \phi_e(\tilde{E})\; P_{e\rightarrow e}(\tilde{E}, E)\, d\tilde{E} \\ +&\int_E^{E_0} \sigma_\gamma \phi_\gamma(\tilde{E})\; P_{\gamma\rightarrow e}(\tilde{E}, E)\, d\tilde{E}\end{aligned}} - \alpha \frac{\partial \phi_e(E)}{\partial E}$$

interaction term

ionization loss term

- **analytical solution needs simplified distributions**
  - no analytical function for hadronic production
  - numerical solution more flexible



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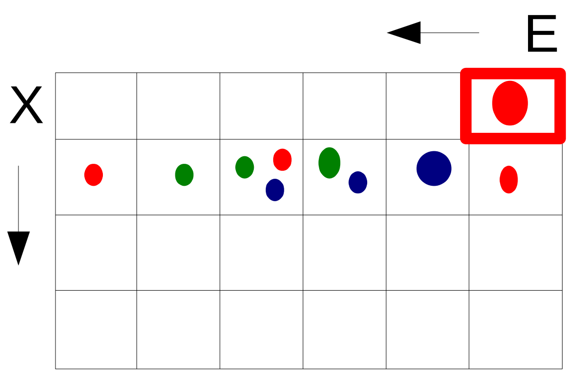

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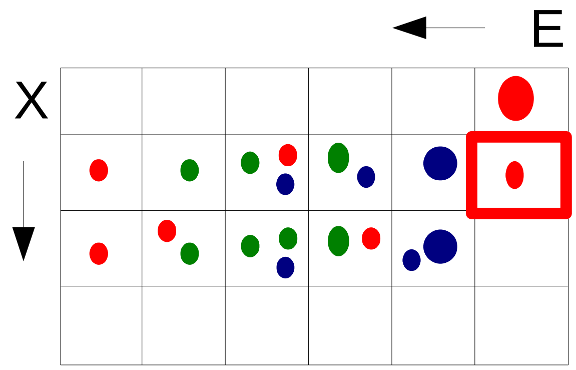

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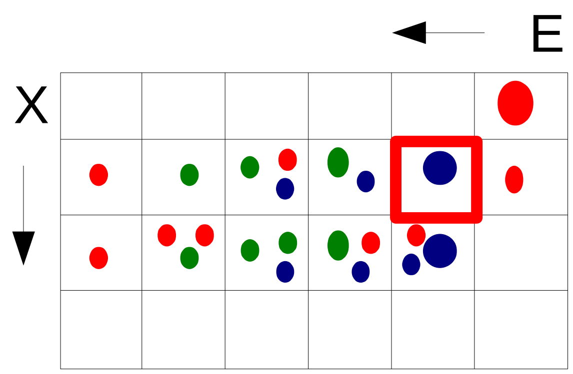
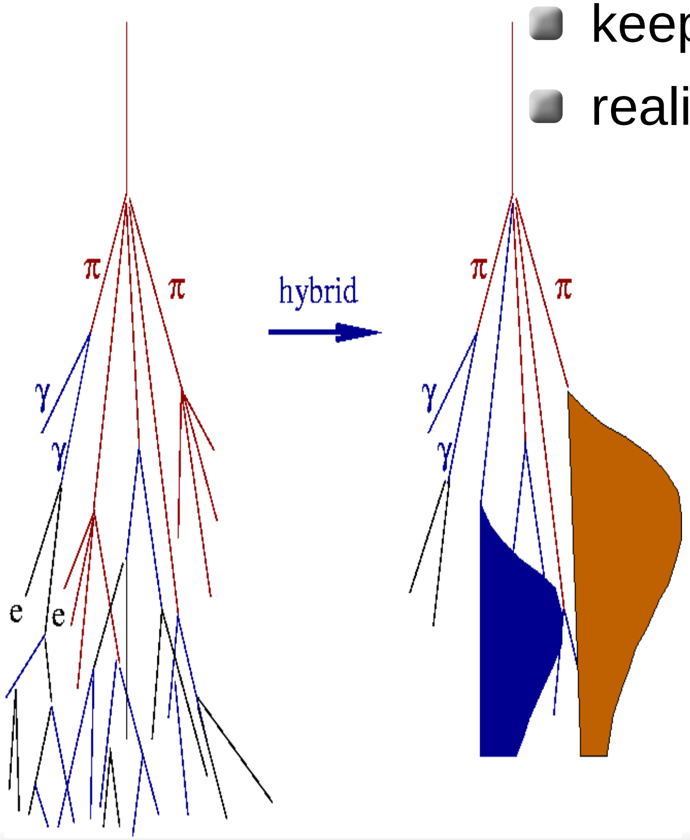


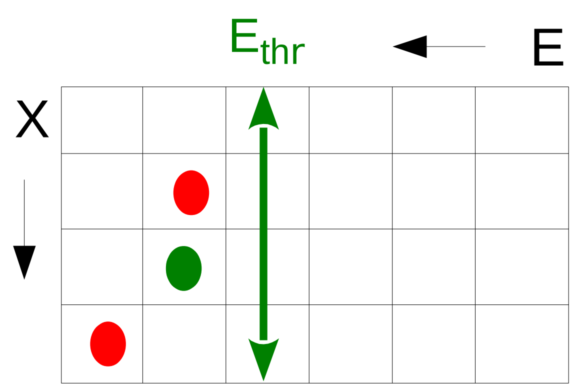
Hybrid Calculation

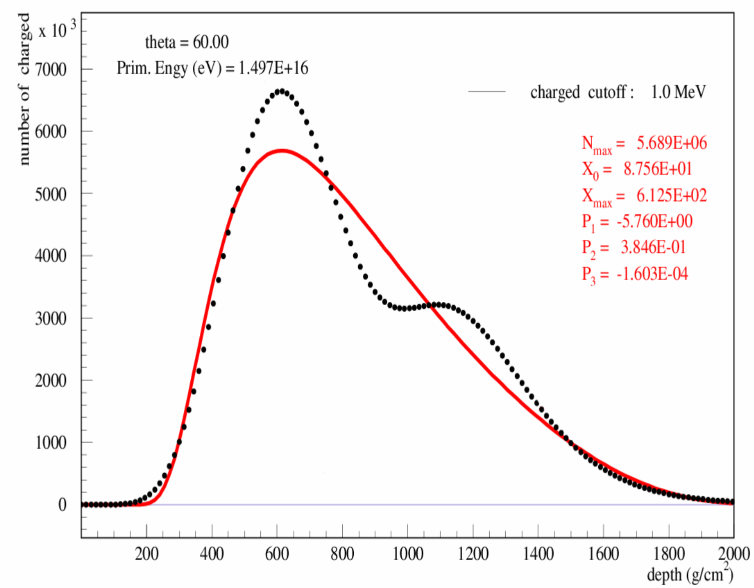
Numerical solution of cascade equations

- same cross-section, atmosphere, models for CE and MC
  - mixing possible : hybrid simulation
- CE replace MC when number of particles is large ($E<E_{th}r$)
  - save lot of time
  - keep fluctuations
  - realistic 1D simulations (longitudinal profiles)



MC fill the source function of the CE





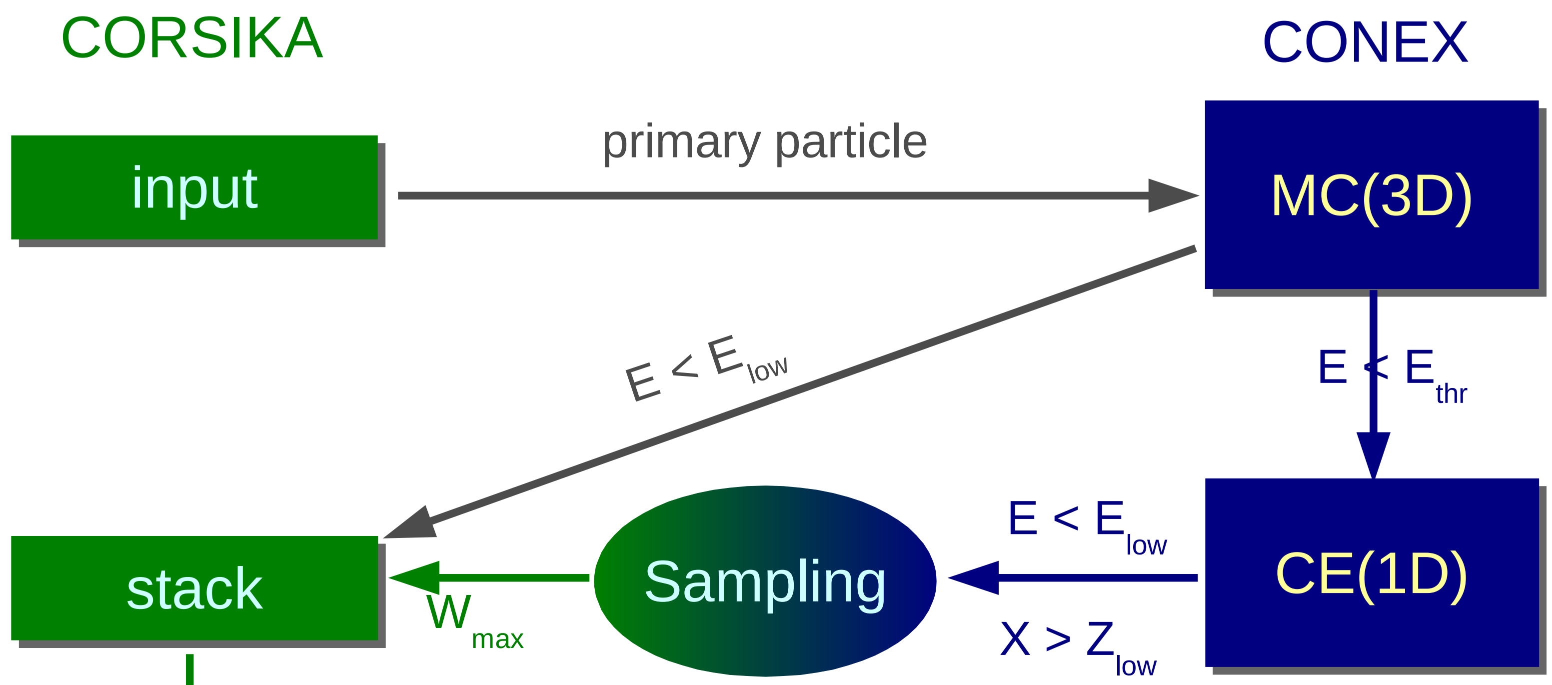
CONEX v4.37 in CORSIKA v7.4

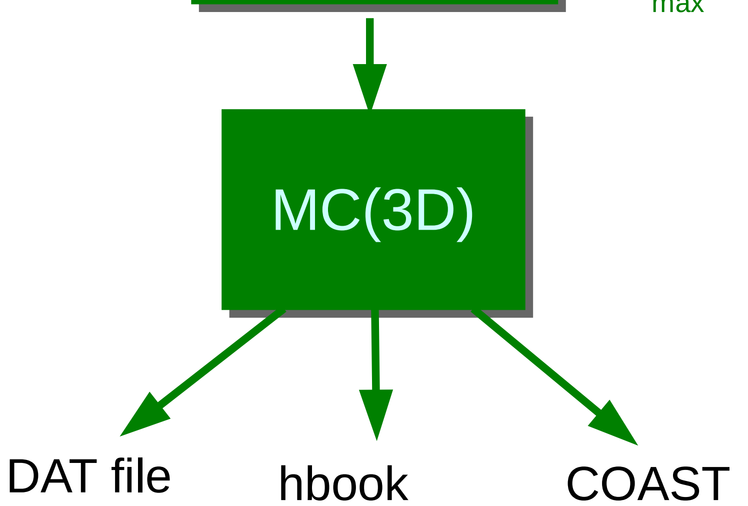
CONEX as an option in CORSIKA

- Hybrid 3D simulation (other model: SENECA by H.J. Drescher)
  - same seed = same shower (1D (fast) or 3D (slow))
- CORSIKA running script and installation
- CORSIKA input
  - one more line in steering file for CONEX parameters
- CORSIKA output
  - no new interface (MC compatible with COAST)
- CORSIKA low energy hadronic interactions models
- CONEX high energy hadronic interaction models
  - EPOS LHC, QGSJET01, QGSJETII-04, SIBYLL 2.1

CONEX (cascade equations (CE)) used as a new type of thinning in CORSIKA : transparent for users !

CORSIKA with CONEX



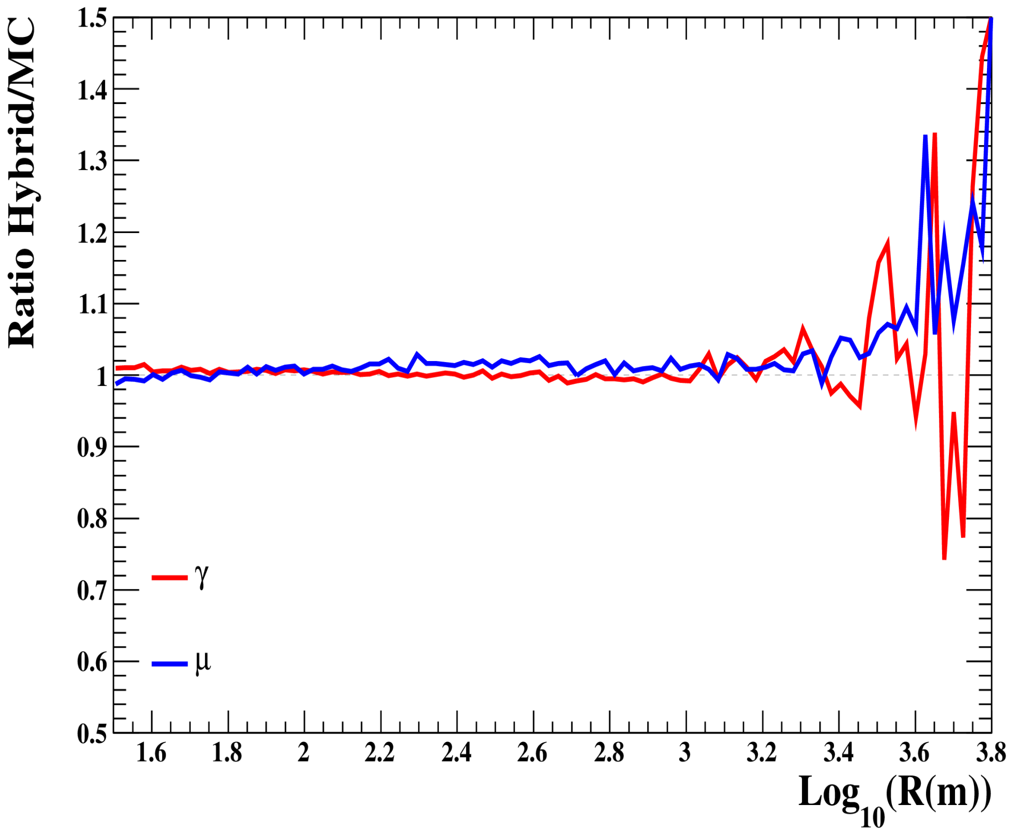


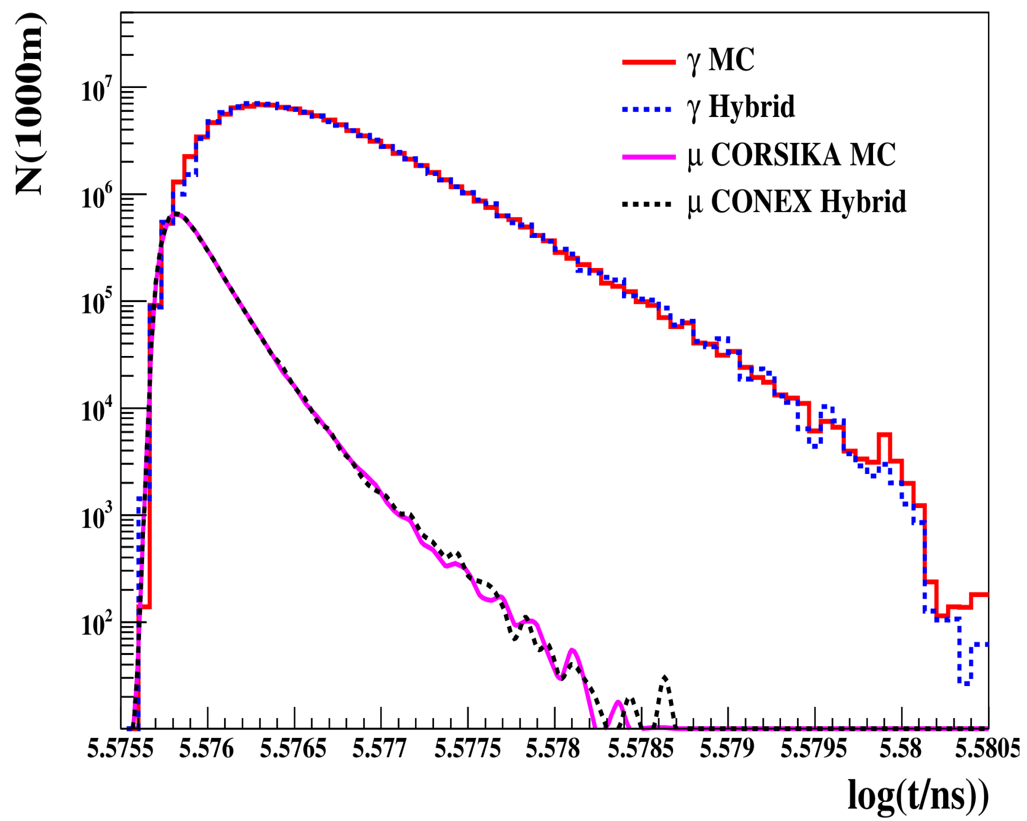
Parameters :

- E_{thr} : MC → CE (ha,μ,e/m)
- E_{low} : CE → MC (ha,μ,e/m)
- W_{max} : weight CE → MC (ha,μ,e/m)
- Z_{low} : minimum slant depth to ground for CE → MC (only e/m)

Example

- QGSJET01/GHEISHA Iron shower 10^{19} eV
  - MC : 49h (max weight = 1000(em)/100(had))
  - Hyb : 10h (max weight = 1000(em)/100(had))
- 1 shower (same seed) : X_{max}=670(MC) / 673(Hyb) g/cm^2



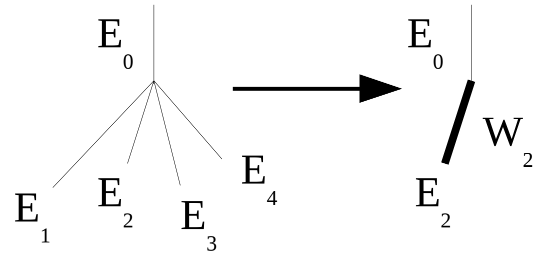


Cascade Equations vs Thinning

Both save computation time by reducing the number of particles :

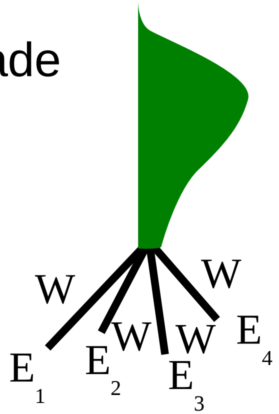
a weight is introduced

- thinning : randomly selected particle carry the weight of all particles produced at the same time to conserve energy
  - large spread of weight = large artificial fluctuations !



$$W_2 = \frac{E_0}{E_2}$$

- cascade equations : same weight for all particles sampled from the cascade equations :
  - unique weight = no artificial fluctuations !
  - less fluctuations = larger weight can be used
  - larger weight = less particles
  - less particles = less time

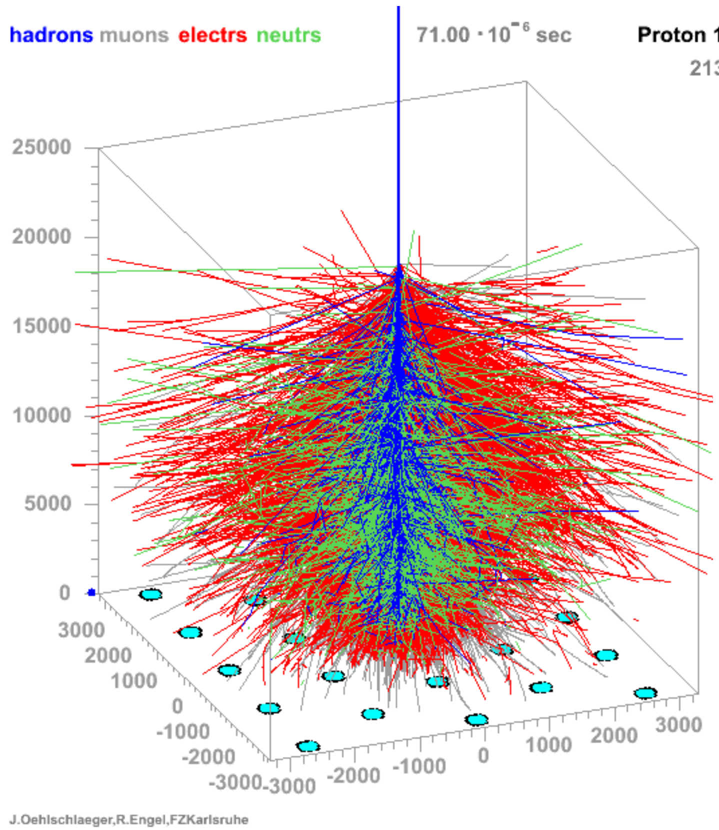


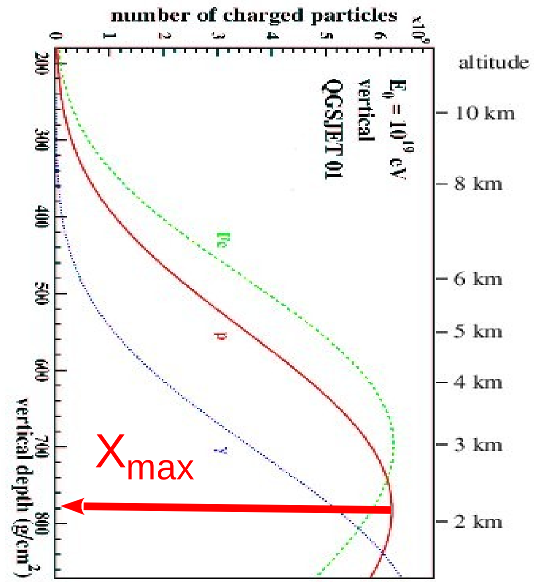
More time saved with cascade equations and less artificial fluctuations !

Properties

- **CORSIKA replace part of the CE**
  - First interactions in CONEX independent from E_{low}
    - Event-by-event simulations using first 1D only and then 3D with exactly the same shower (top-down reconstruction :Golden Hybrid, radio)
- **CE replace part of the thinning in CORSIKA**
  - No thinned high energy gammas (stay in CE)
    - No muons from EM particles with very large weight
  - Very narrow weight distributions : less artificial fluctuations
  - No thinning for very inclined shower
    - Only muons and corresponding EM sub-showers in MC
- **CONEX and CORSIKA are independent**
  - Different media might be used
- **Mean showers can be simulated directly** **(no high energy MC)**
- **Not tested for Cherenkov photons yet …**
- **Parallel+CONEX not yet possible ...**

Extensive Air Shower Observables



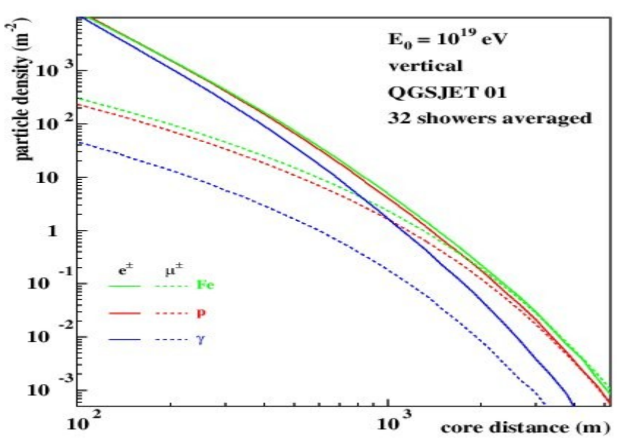


- **Longitudinal Development**
  - ➔ number of particles vs depth

    $$X = \int_h^\infty dz\ \rho(z)$$

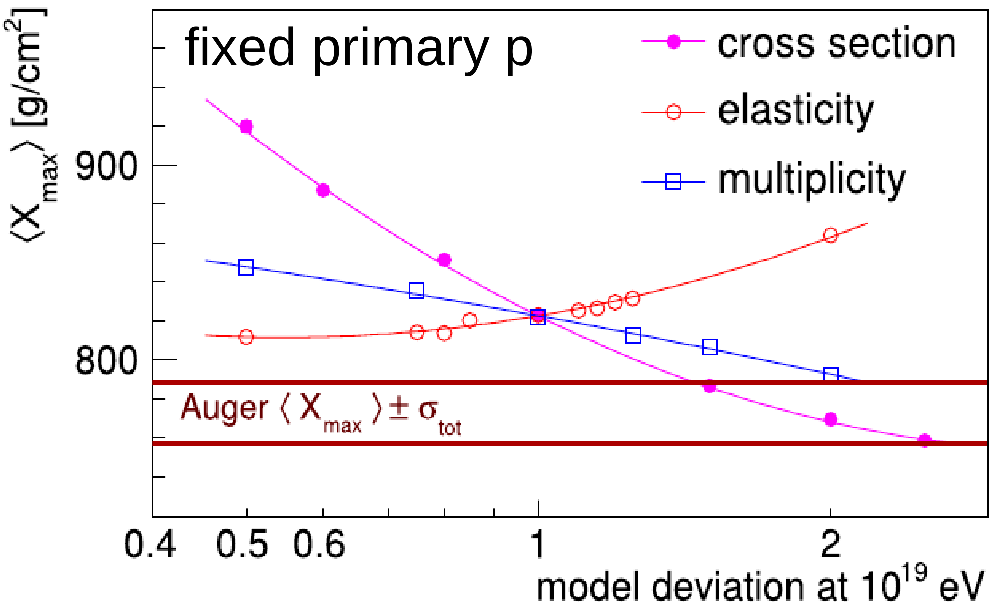
  - ➔ Larger number of particles at X_{max}

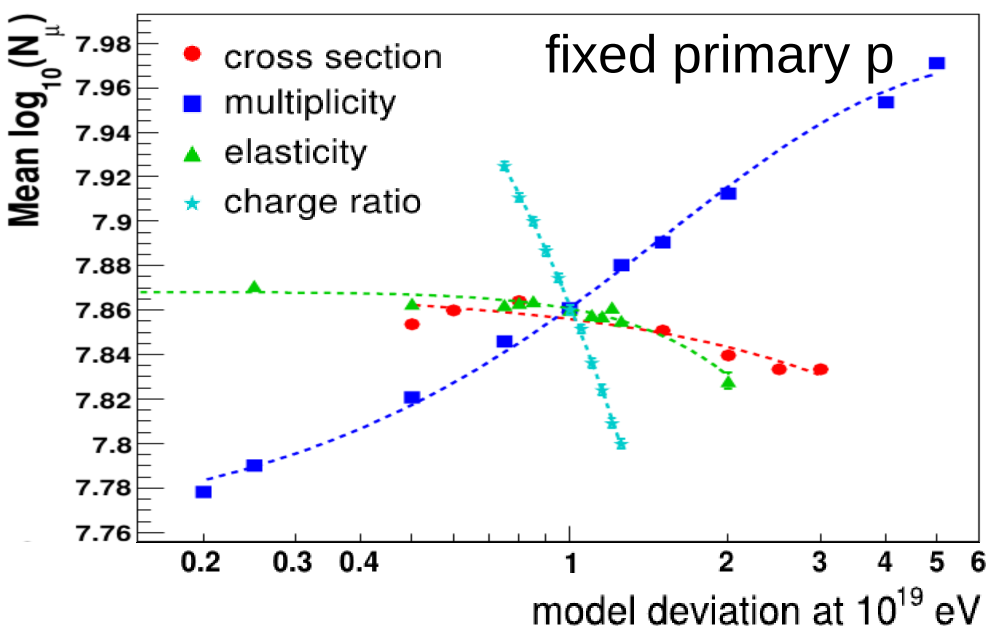
    For many showers
    - mean : $<X_{max}>$
    - fluctuations : RMS X_{max}



- **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.

Sensitivity to Hadronic Interactions





From R. Ulrich (KIT)

- **Air shower development dominated by few parameters**
  - ➡ mass and energy of 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

Hadronic Interaction Models in CORSIKA

(HDPM)

Old generation : SIBYLL 2.1 (QGSJET01 DPMJET 2.55 VENUS) (<1999)

All Glauber based

But differences in hard, remnants, diffraction …

semi-hard

soft

NEXUS 3.97

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

New generation : (QGSJET II-03) (DPMJET III) (EPOS 1.99) (2005-2012)

LHC tuned : QGSJET II-04 EPOS LHC (2013-)

LHC inspired : SIBYLL 2.3 QGSJET III EPOS 3 (2015-)

Motivation :

- **update with LHC results**
- **charm production**

Motivation :

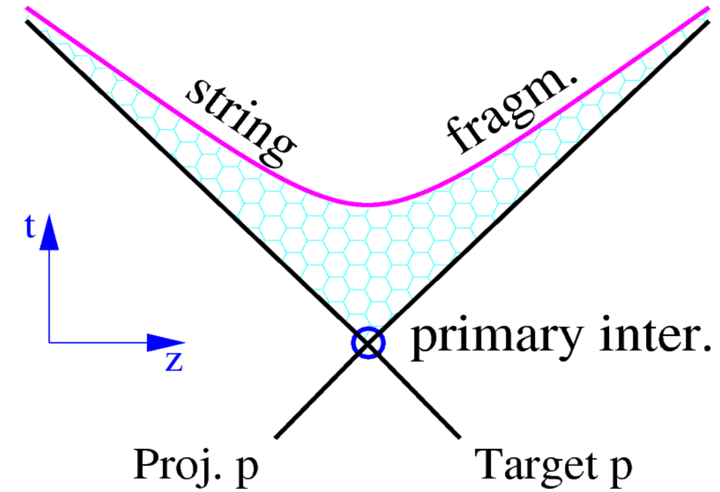
- **Hard Pomeron-Pomeron connexion**

Motivation :

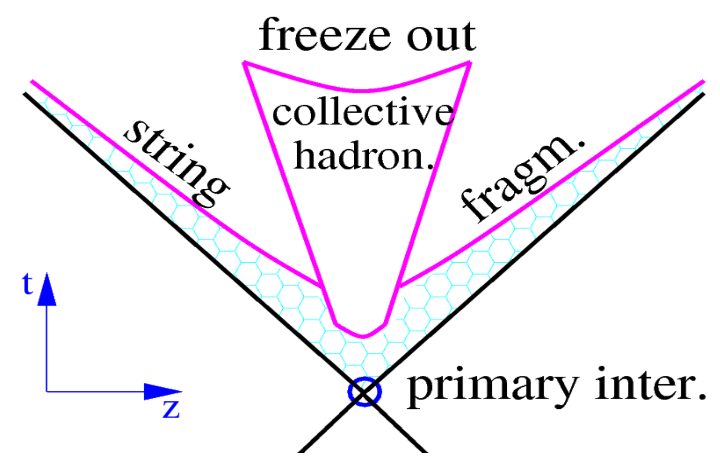
- **binary scaling in hard probes**
- **heavy flavors**

Post-LHC Models

- **QGSJETII-03 to QGSJETII-04 :**
  - loop diagrams
  - rho0 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

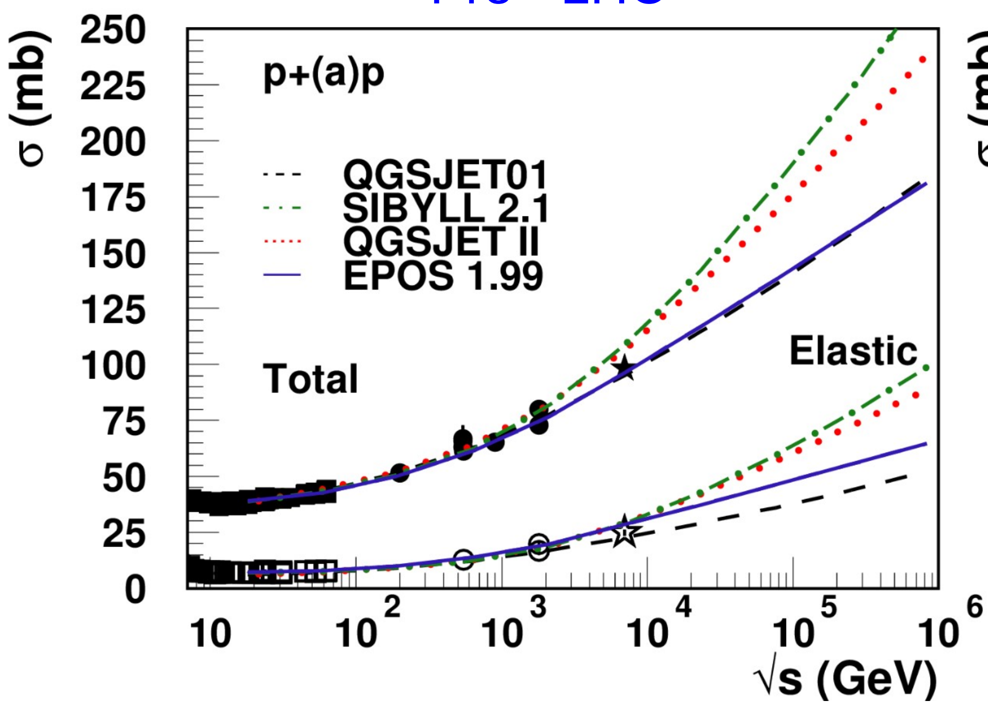


No direct influence of collective effects on EAS simulations seen but important to compare to LHC and set parameters properly (<pt>, ...).

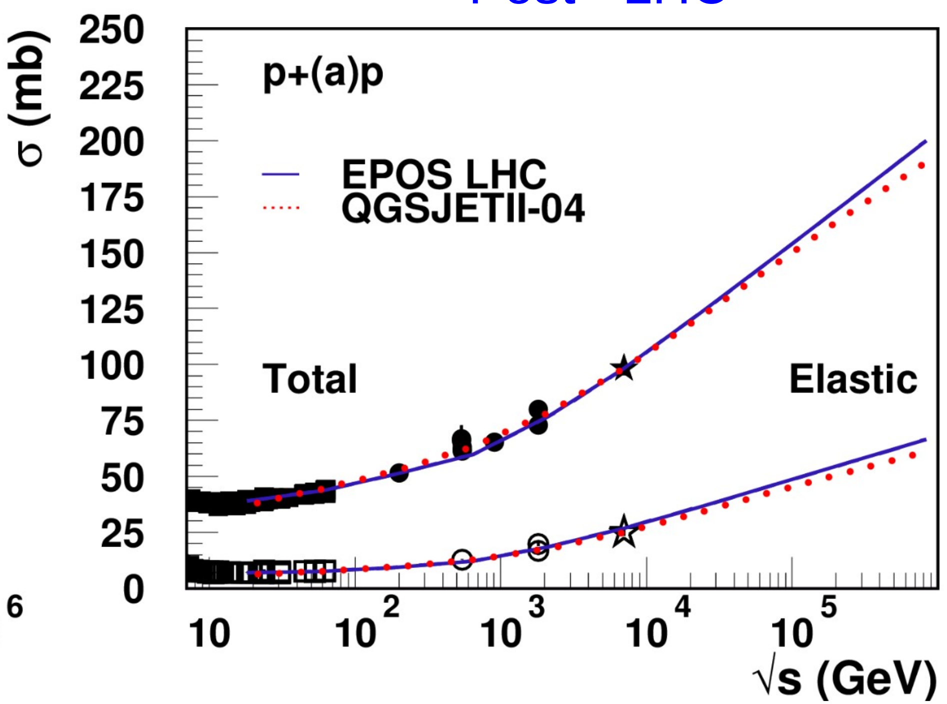
Cross Sections

- Same cross section at pp level and low energy for models (data for tuning)
- extrapolation to pA or to high energy (model dependent)
  - different amplitude and scheme
    - different extrapolations

Pre - LHC



Post - LHC



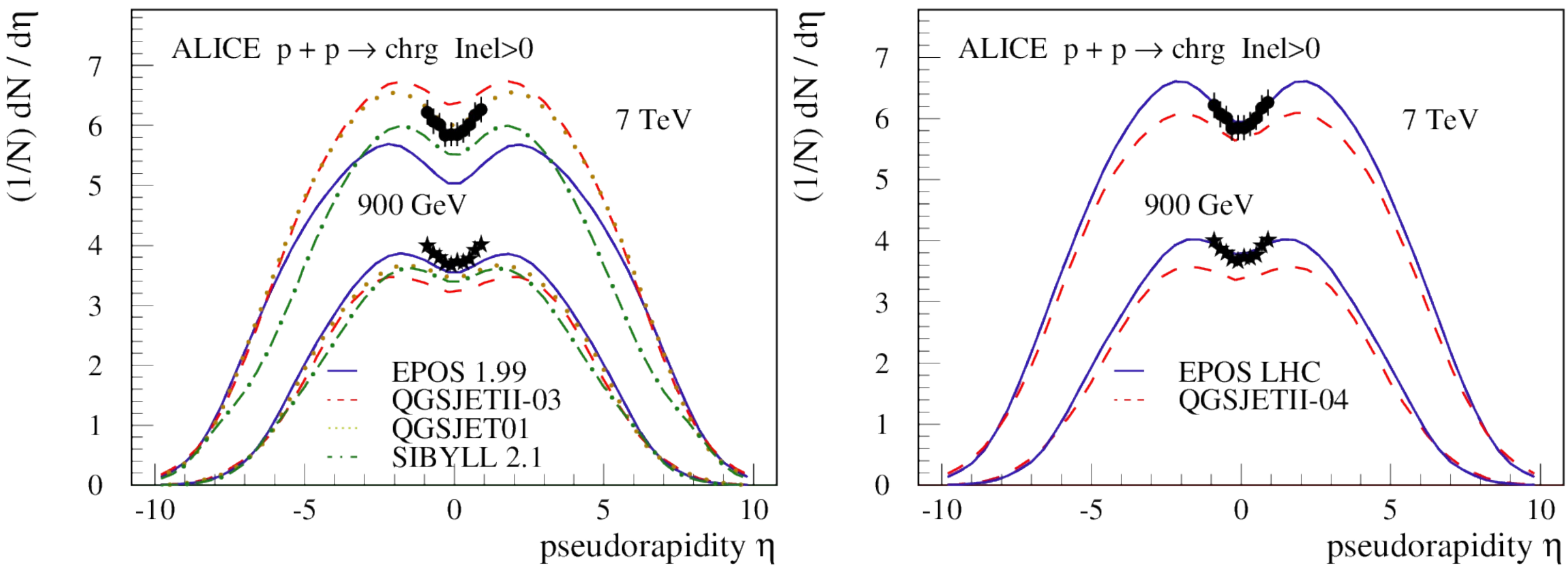
Pseudorapidity

Consistent results

- Better mean after corrections
  - difference remains in shape
    - model property

Pre - LHC

Post - LHC



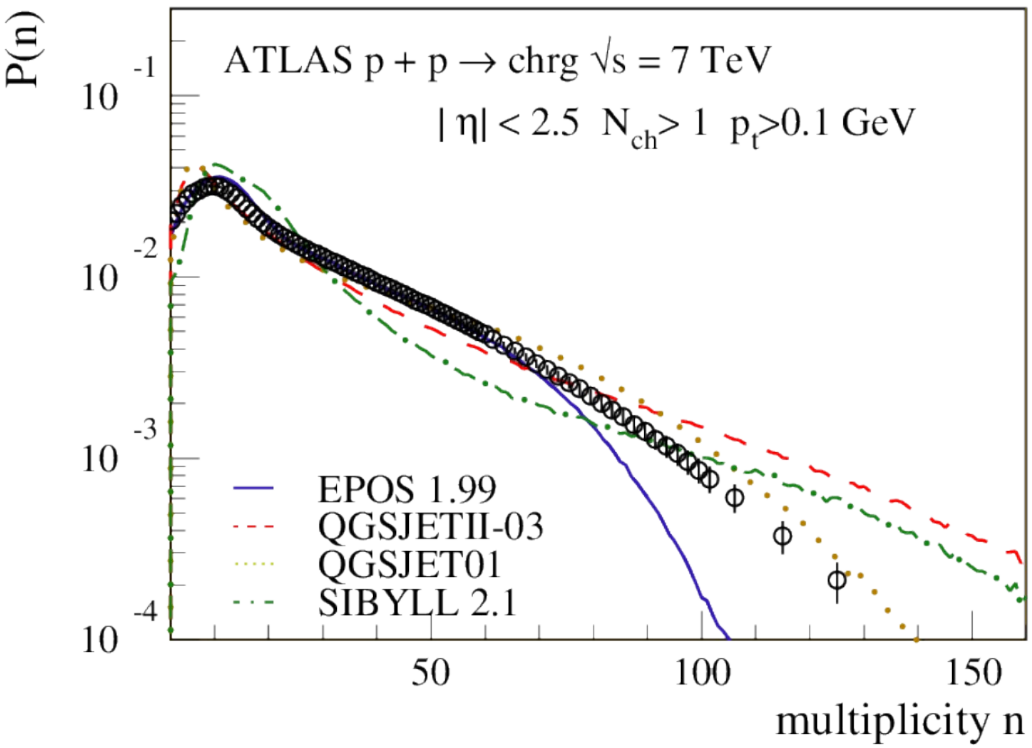
Multiplicity Distribution

Consistent results

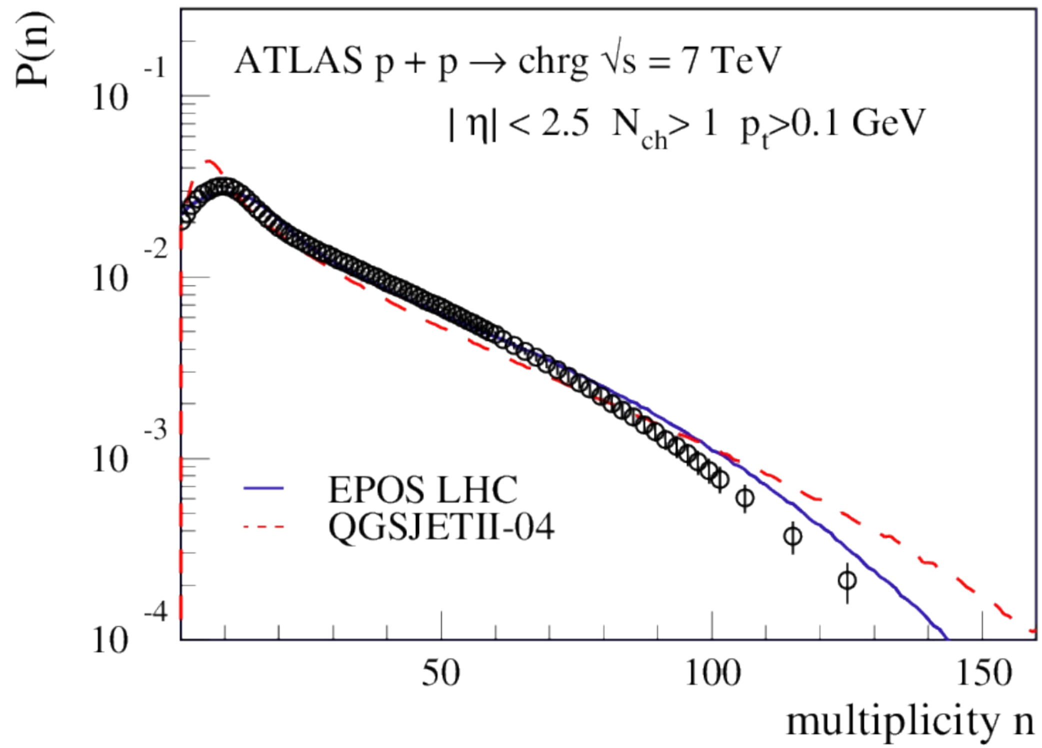
- Better mean after corrections
  - difference remains in shape
- Better tail of multiplicity distributions
  - corrections in EPOS LHC (flow) and QGSJETII-04 (minimum string size)

LHC data in the range defined by Pre-LHC models : no unexpected results in basic distributions

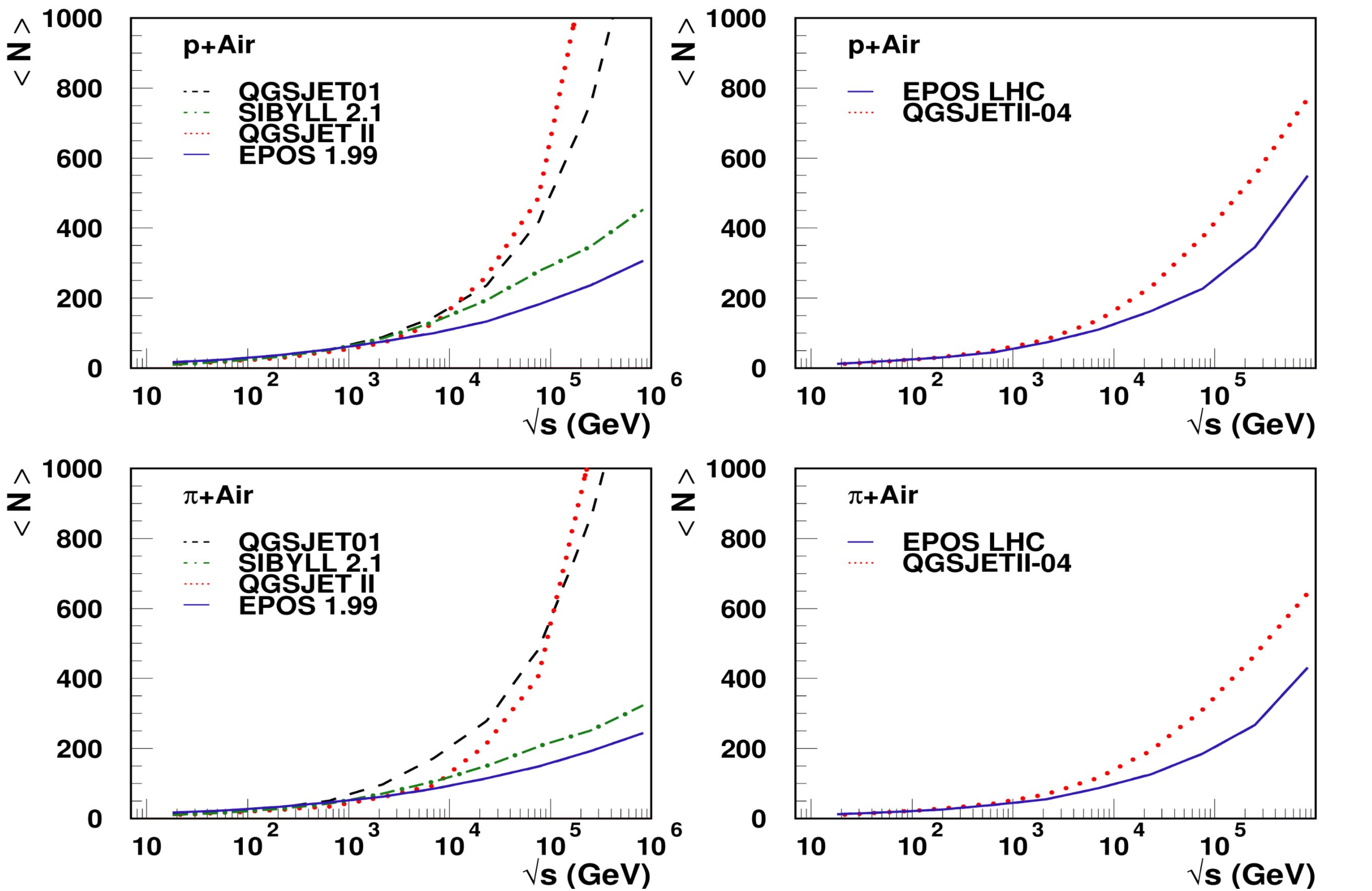
Pre - LHC



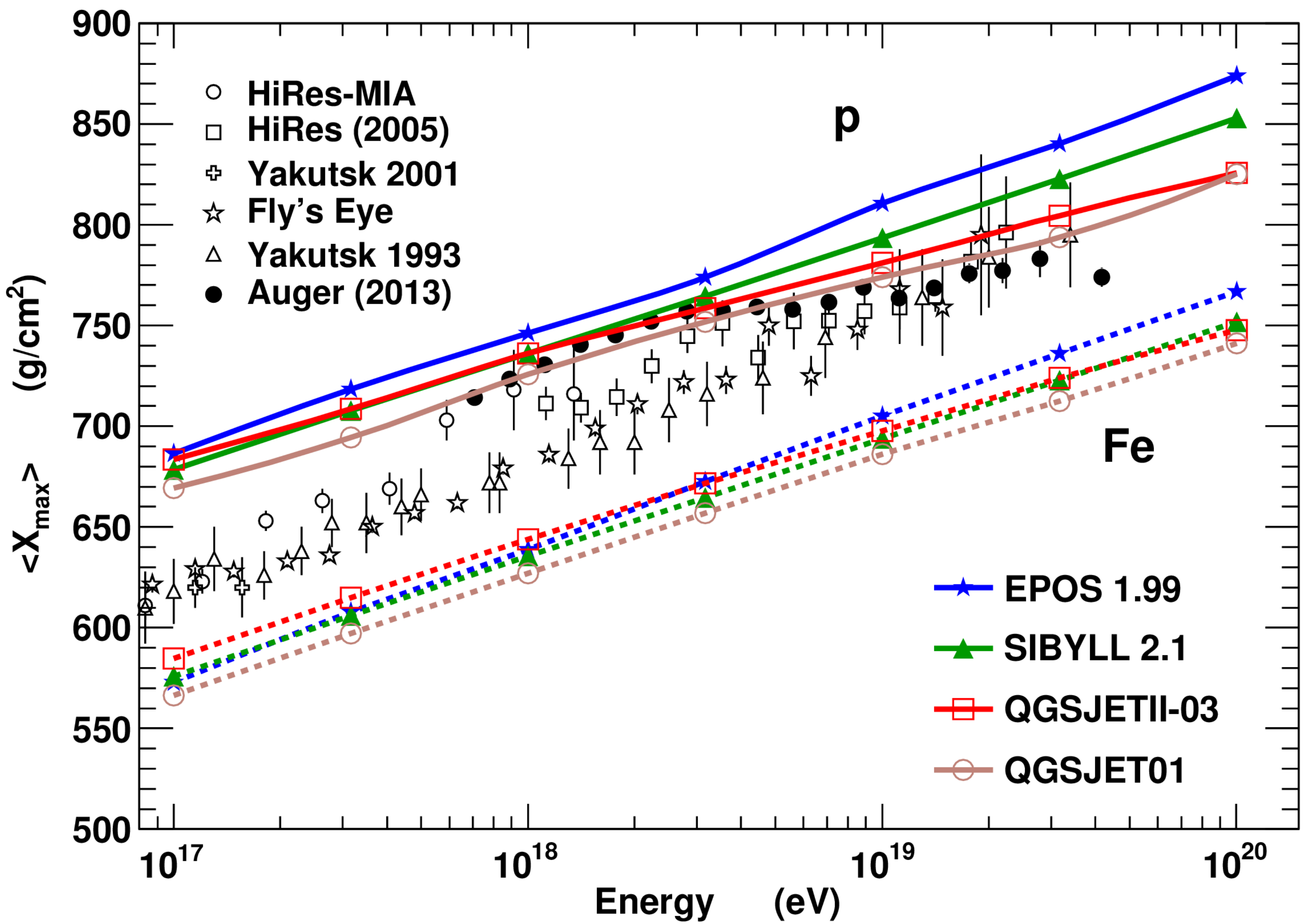
Post - LHC



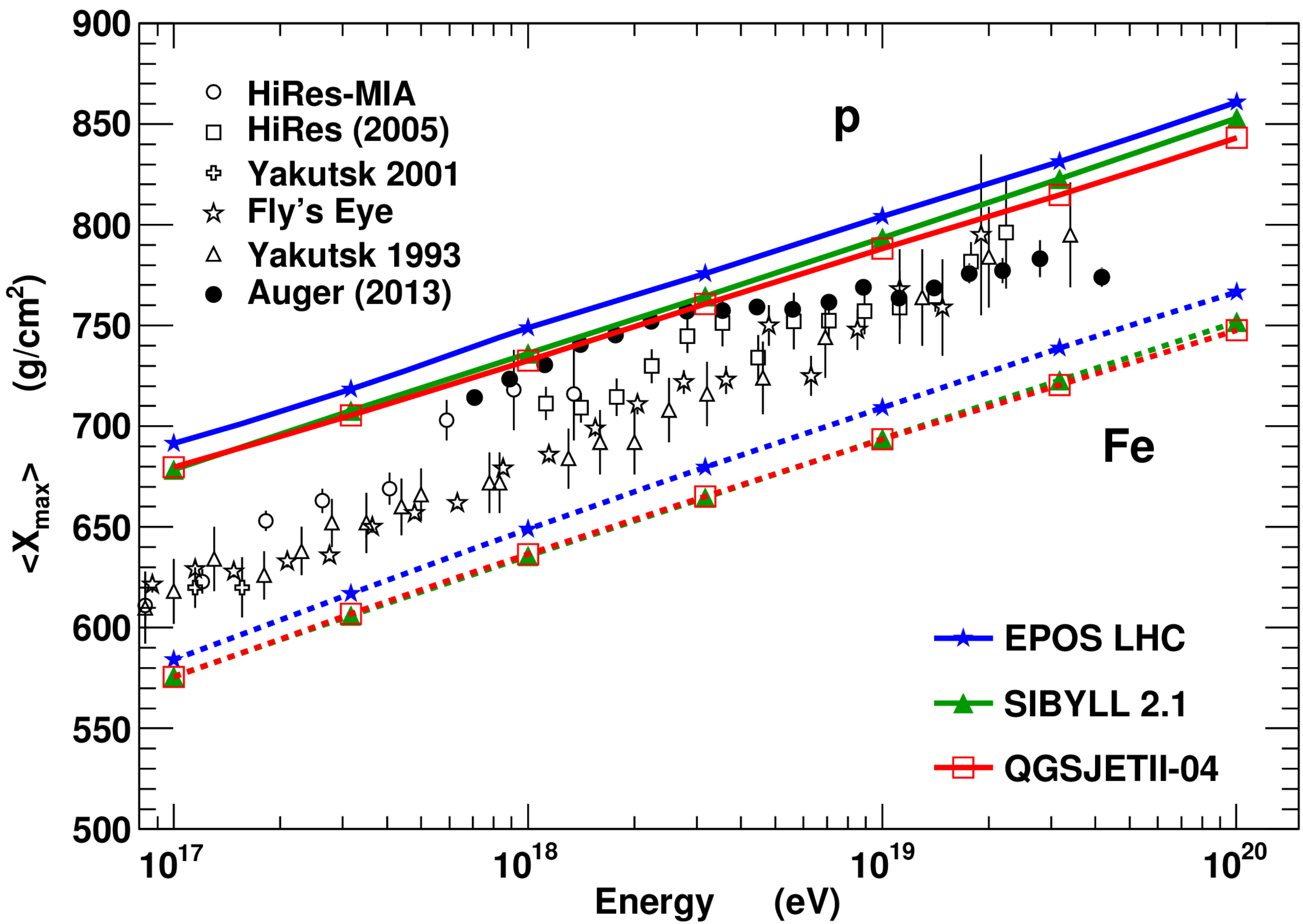
Ultra-High Energy Hadronic Model Predictions



EAS with Old CR Models : X_{max}

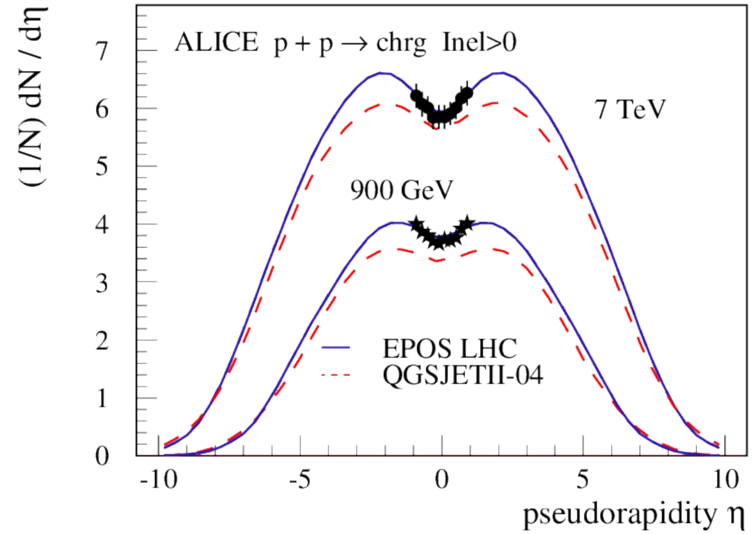


EAS with Re-tuned CR Models : X_{max}

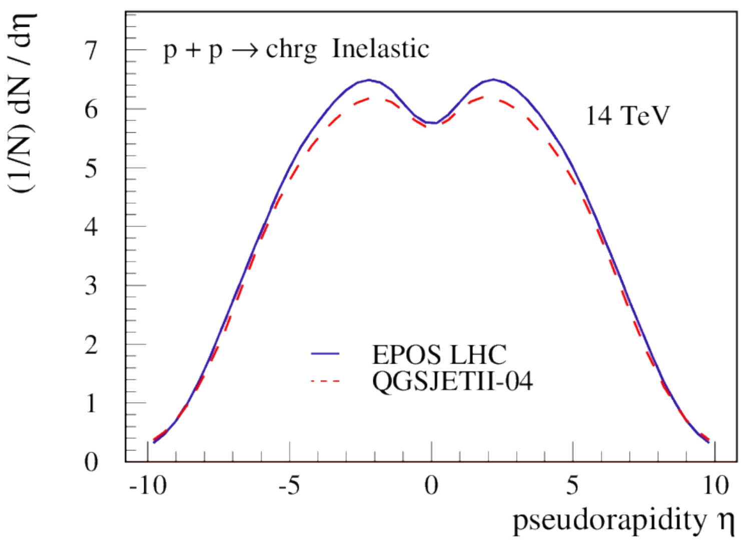


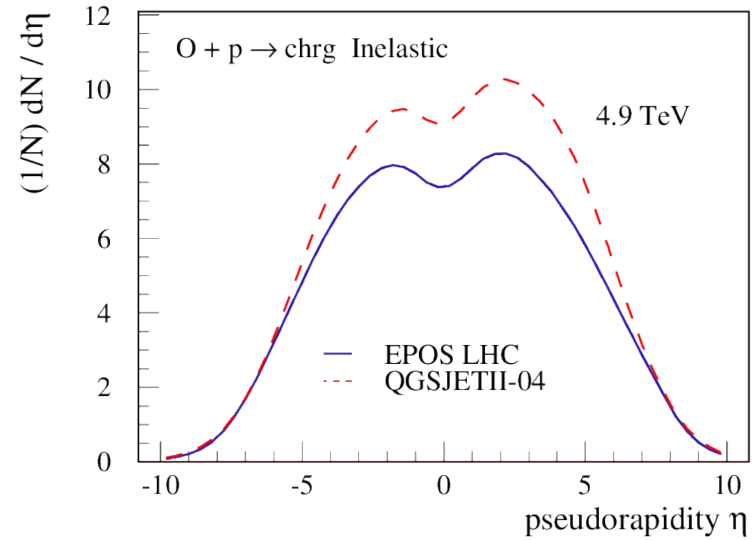
Extrapolation and LHC Results

- **Source of uncertainties : extrapolation**
  - to higher energies
    - strong constraints by current LHC data
  - from p-p to p-Air and pi-Air
    - current main source of uncertainty
- **Needs to better take into account last LHC results :**



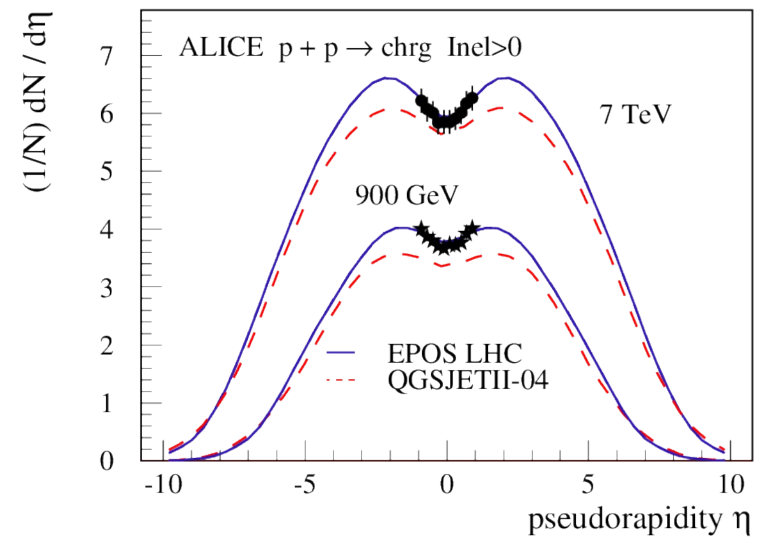
- hard scale saturation
- collective effects in small system
- detailed diffractive measurements
- particle correlations
  - EPOS 3
  - QGSJETxxx





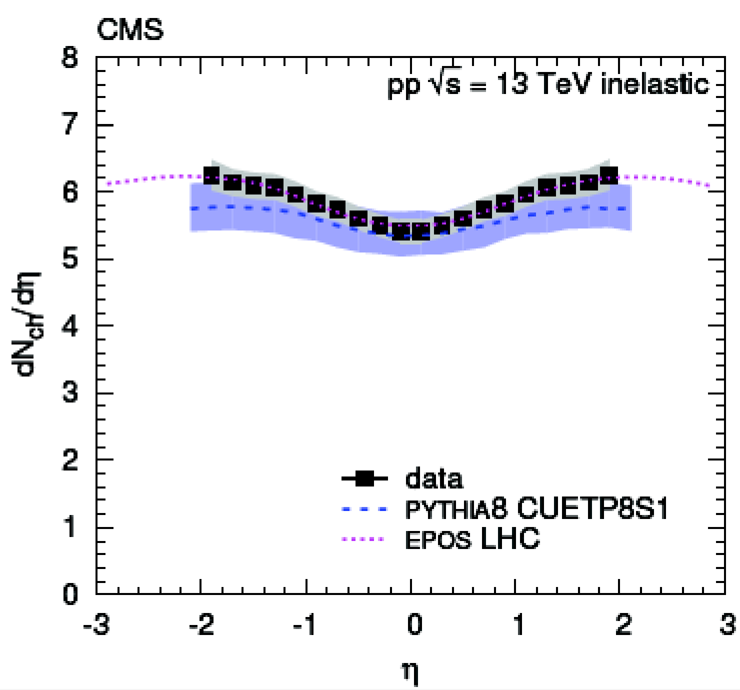
Extrapolation and LHC Results

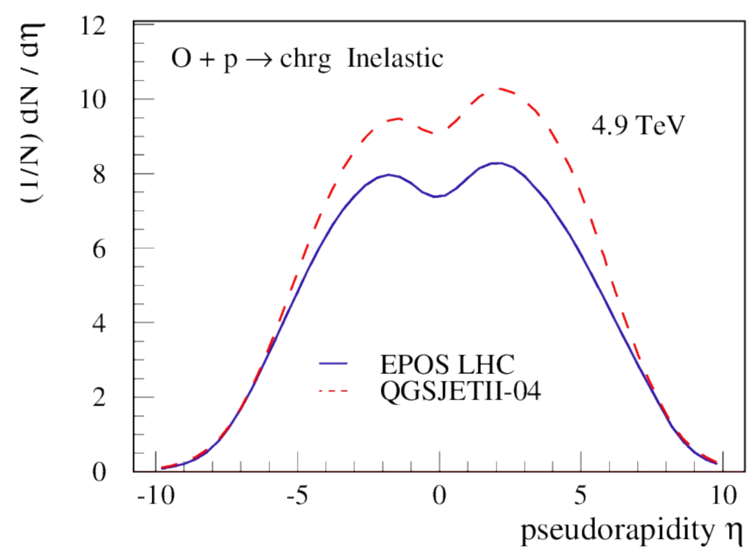
- **Source of uncertainties : extrapolation**
  - to higher energies
    - strong constraints by current LHC data
  - from p-p to p-Air and pi-Air
    - current main source of uncertainty
- **Needs to better take into account last LHC results :**



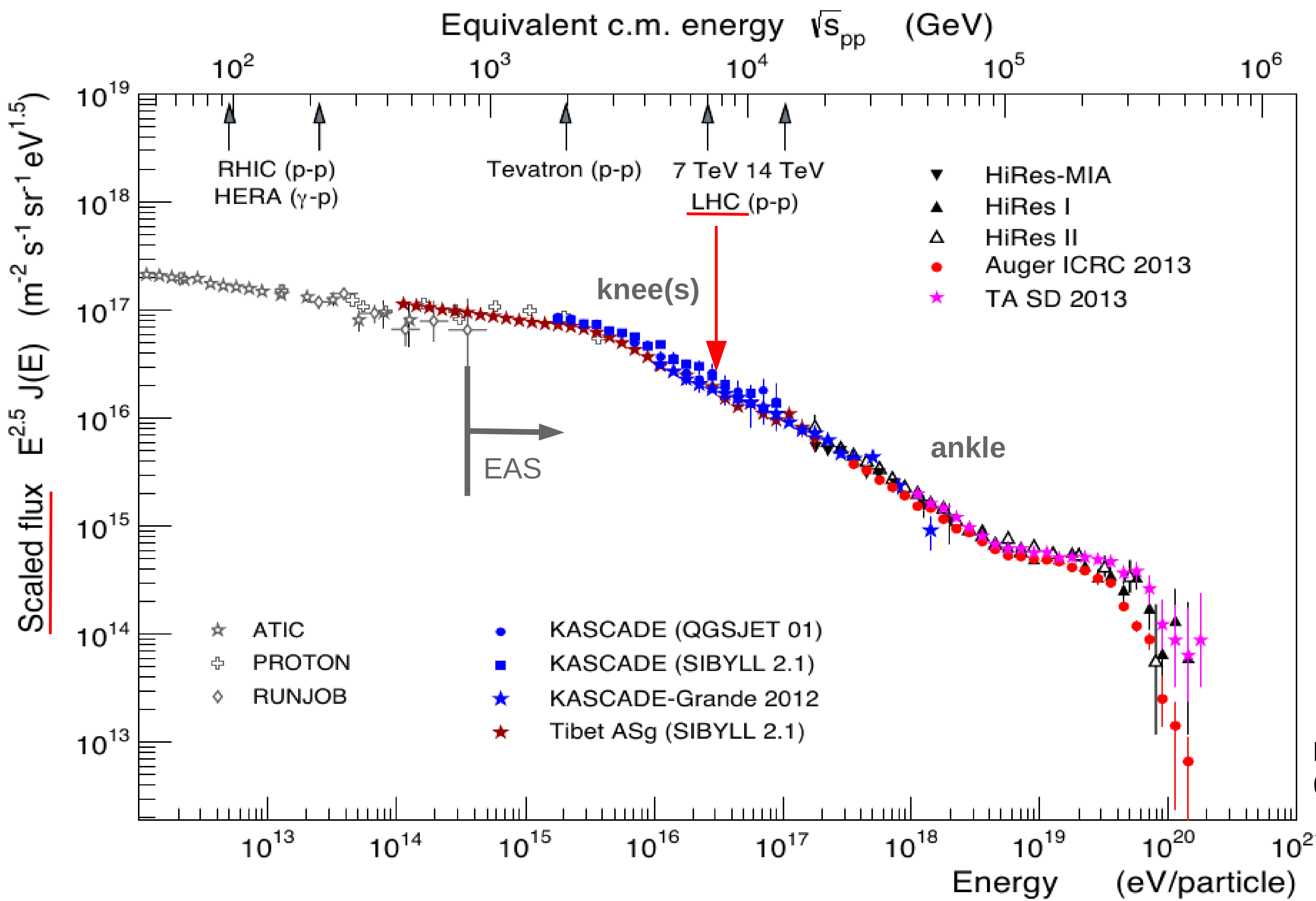
(CMS, 1507.05915)

- hard scale saturation
- collective effects in small system
- detailed diffractive measurements
- particle correlations
  - EPOS 3
  - QGSJETxxx





Spectrum



R. Engel (KIT)

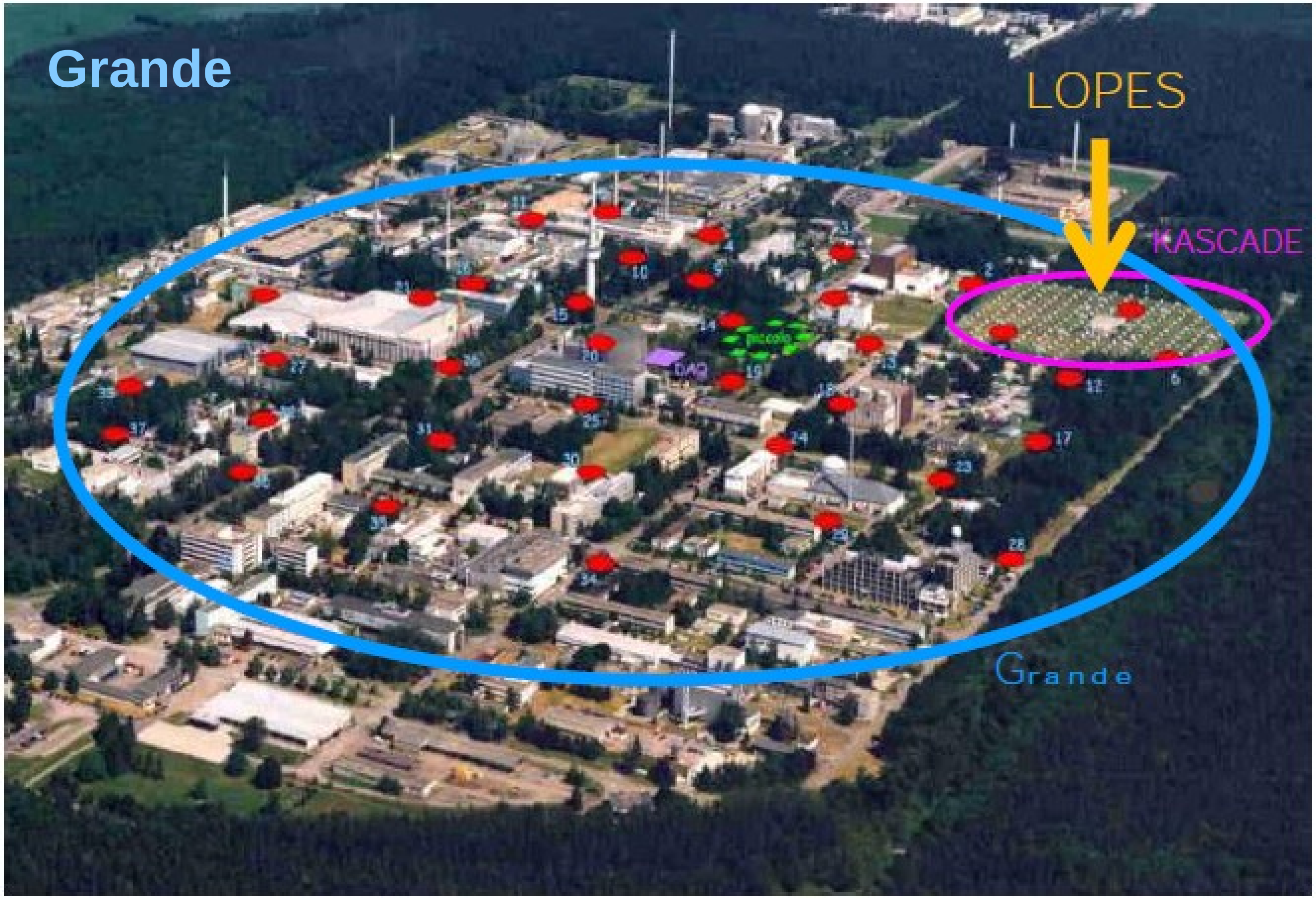
KASCADE-Grande

KASCADE facility (1988-2016)

- KASCADE data taking 1996-2012
- KASCADE-Grande data taking 2003-2012

Energy range: 100TeV –1EeV
Area: 0.5 km2
Grande: 37x10 m^2 plastic scint. det.
N_{ch}+ total muon number

- LOPES (2004-2012) MHz radio and CROME (2012) GHz radio
- CORSIKA (air shower simulation) and KCDC (web interface to data)

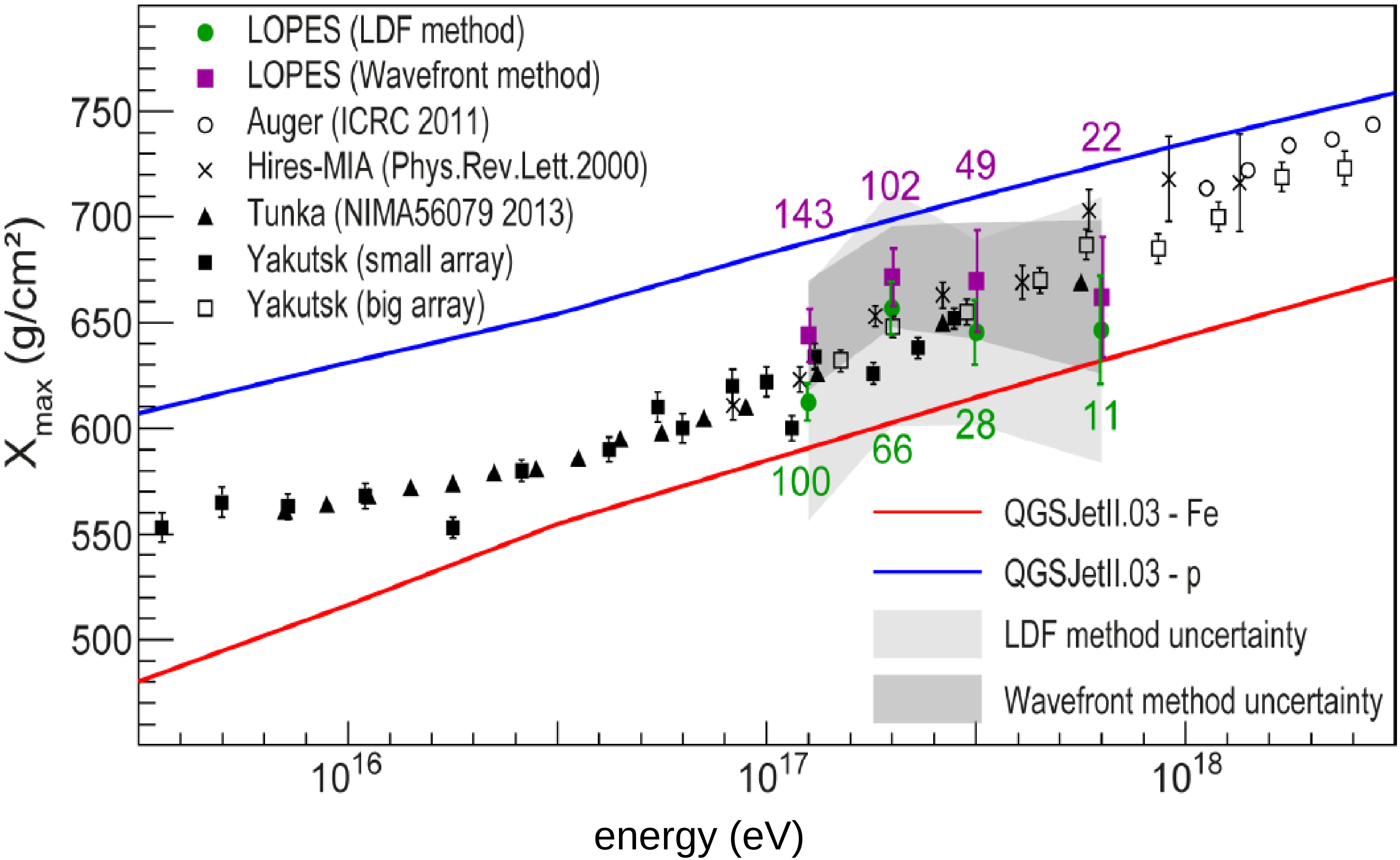


LOPES Results

Radio measurement at KASCADE

➡ first composition measurement from radio EAS detection

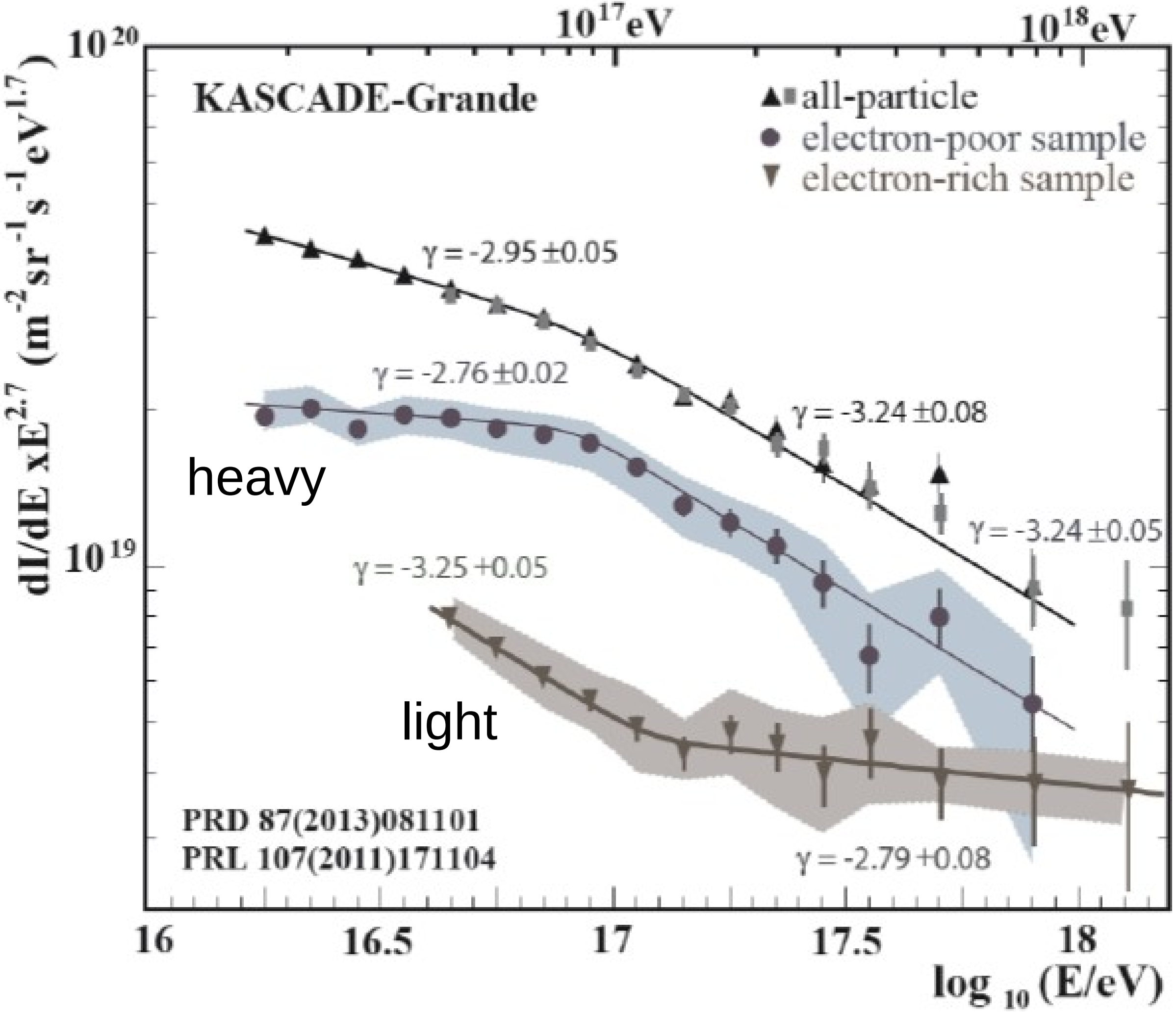
K. Link, ICRC 2015



KASCADE-Grande Results

KASCADE-Grande spectrum

- separation between 2 mass group
- steepening due to heavy primaries (3.5σ)
- hardening at $10^{17.08}$ eV (5.8σ) in light spectrum
- slope change from $\gamma = -3.25$ to $\gamma = -2.79$
- relative abundance is hadronic model dependent but similar behavior observed for all models



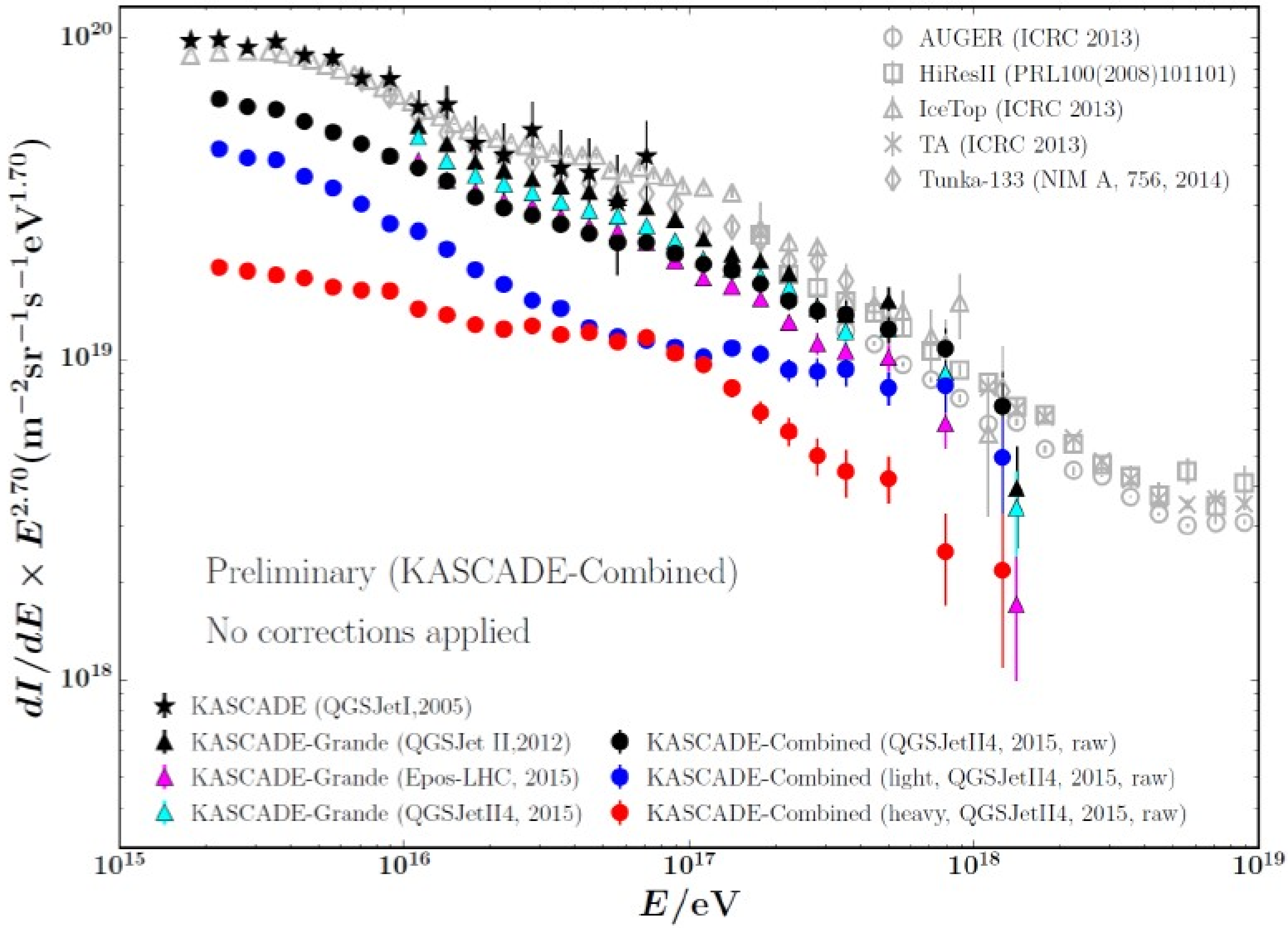
H. Haungs, ICRC 2015

Knee due to heavy component observed around 100 PeV and ankle like feature seen in light component at about the same energy: absolute flux (hadr. mod. dep.) important to understand transition galactic/extra-galactic...

KASCADE/Grande combined analysis

Use KASCADE and KASCADE-Grande as a unique experiment

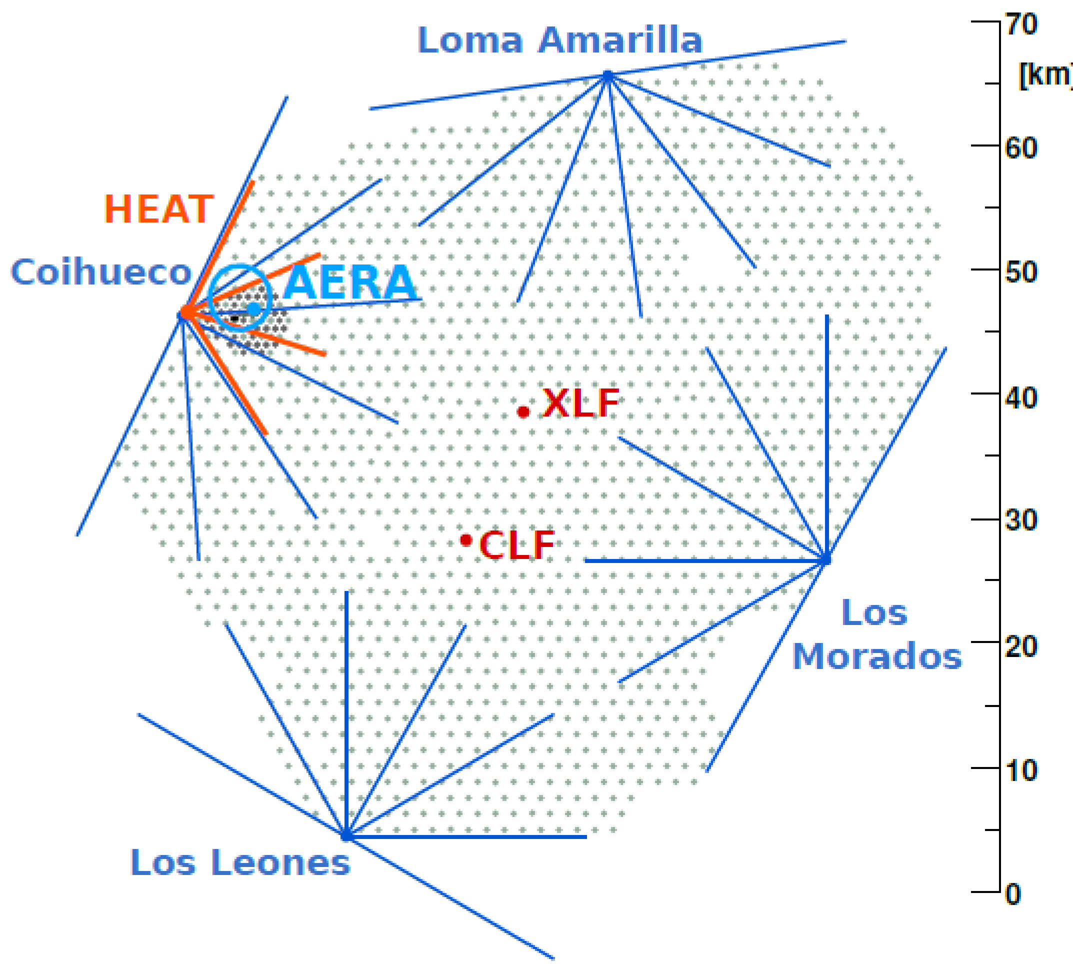
➡ larger energy range and use latest model for low energy analysis



S. Schoo, ICRC 2015

Pierre Auger Observatory (PAO)

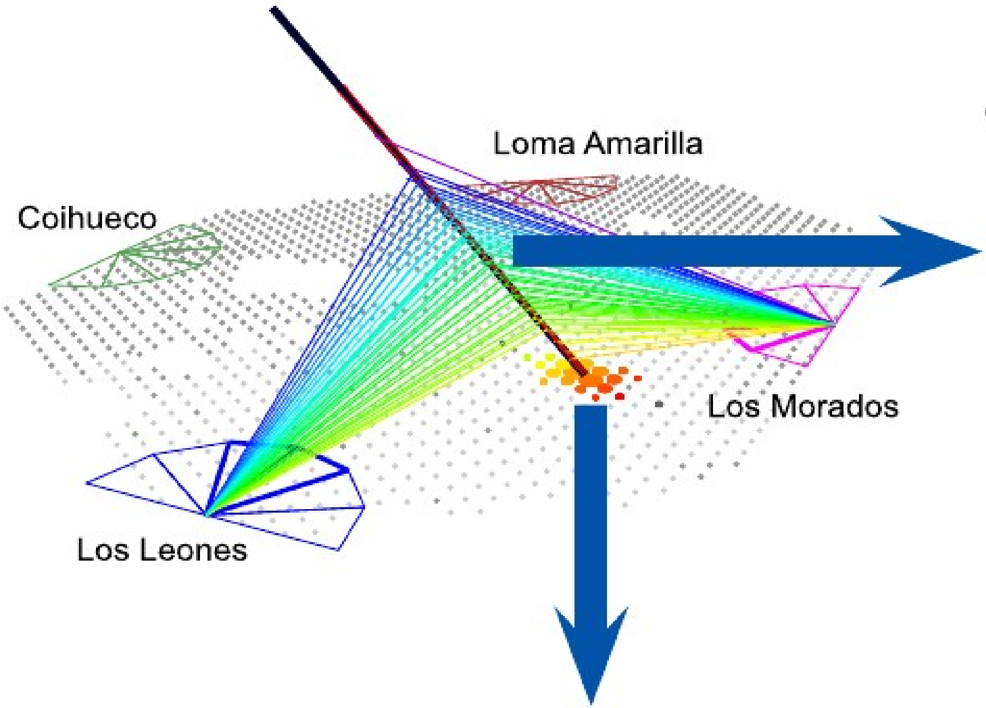
- **Fluorescence detector (FD)**
  (longitudinal profile)
  - 24 + 3 (HEAT) Fluorescence telescopes at 4 locations
  - duty cycle 15%
  (day, moon, clouds, ...)
- **Surface detector (SD)**
  (lateral distribution)
  - area of 3000 km^2
  - 1660 water-Cherenkov stations at 1500 m spacing
  - duty cycle 100%
- **AMIGA**
  - low energy infill and muon detectors
- **Radio detector AERA (RD)**

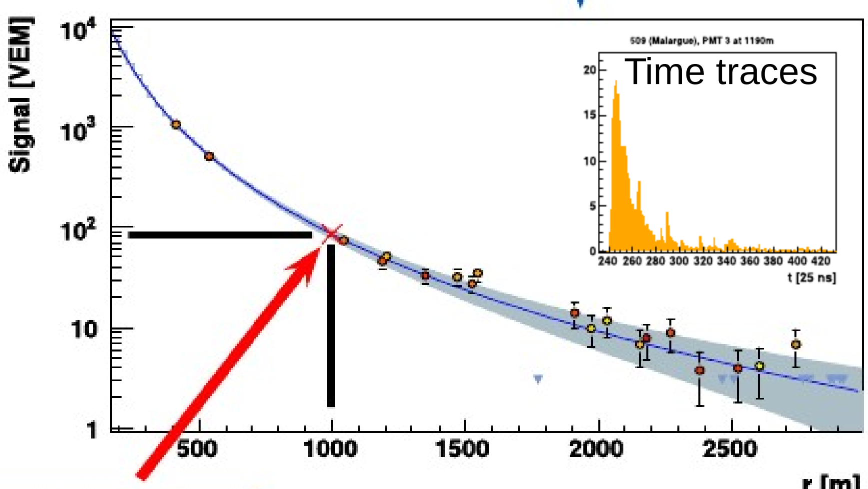


Mendoza province, Argentina

Nucl. Instrum. Meth. A798 (2015) 172

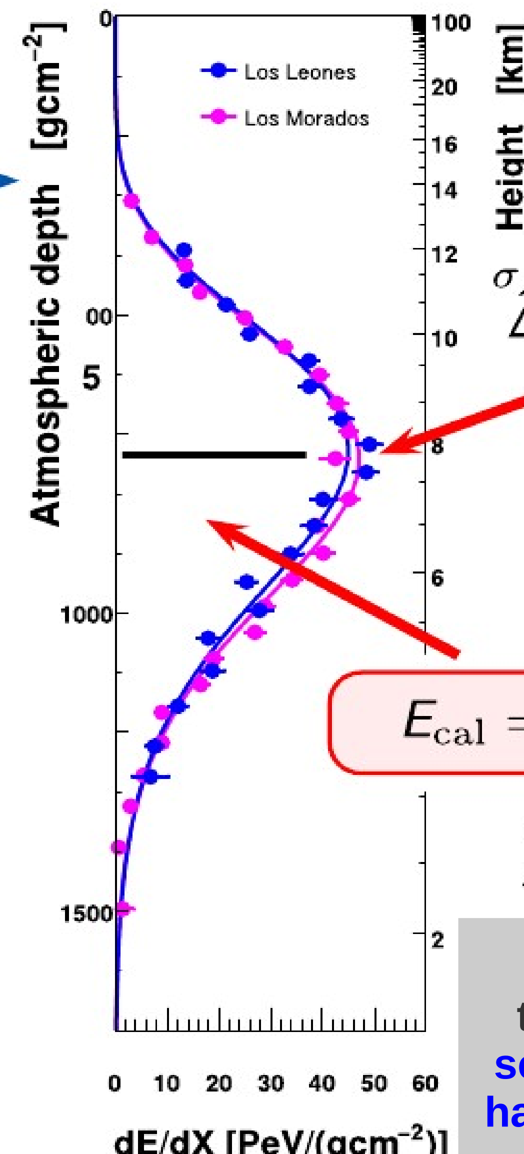
Hybrid Detection





S_{1000}

$E_{\mathrm{surface}} = f(S_{1000},\, \theta)$



$\sigma X_{\mathrm{max}} < 20\,\mathrm{g/cm^2}$
$\Delta_{\mathrm{sys}} \approx 15\,\mathrm{g/cm^2}$

X_{max}

$E_{\mathrm{cal}} = \int \mathrm{d}X\ \frac{\mathrm{d}E}{\mathrm{d}X}$

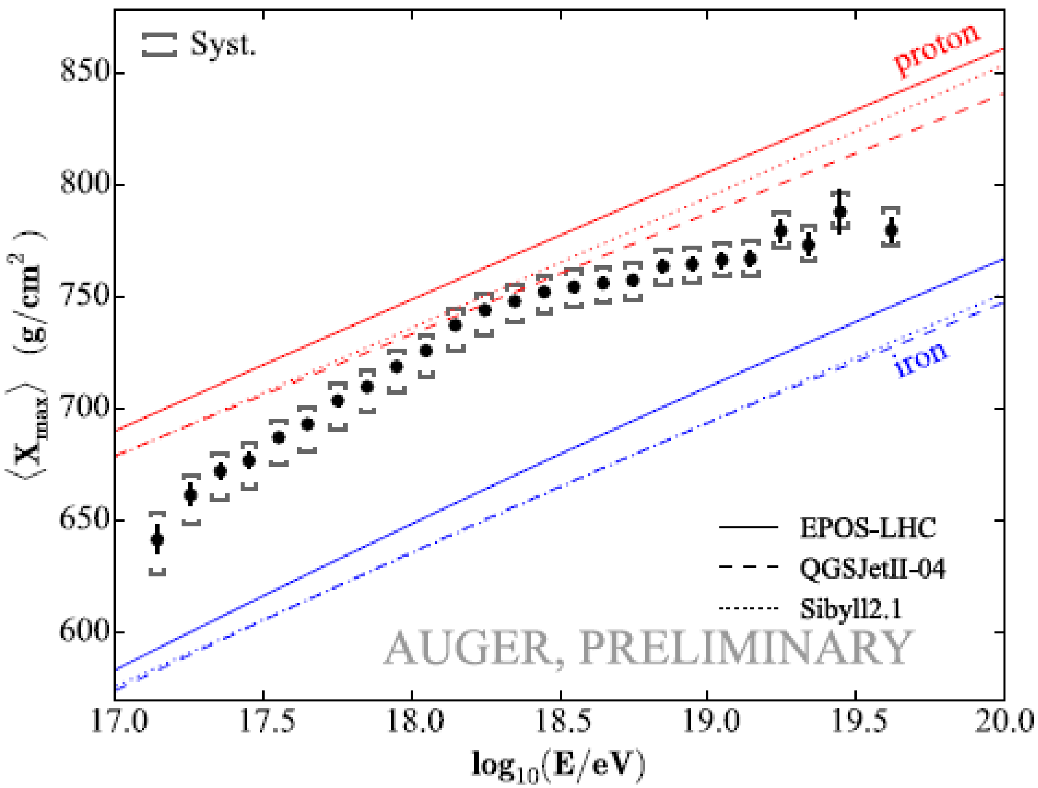
$\sigma_E/E \sim 8\,\%$
$\Delta_{\mathrm{sys}} \approx 14\,\%$

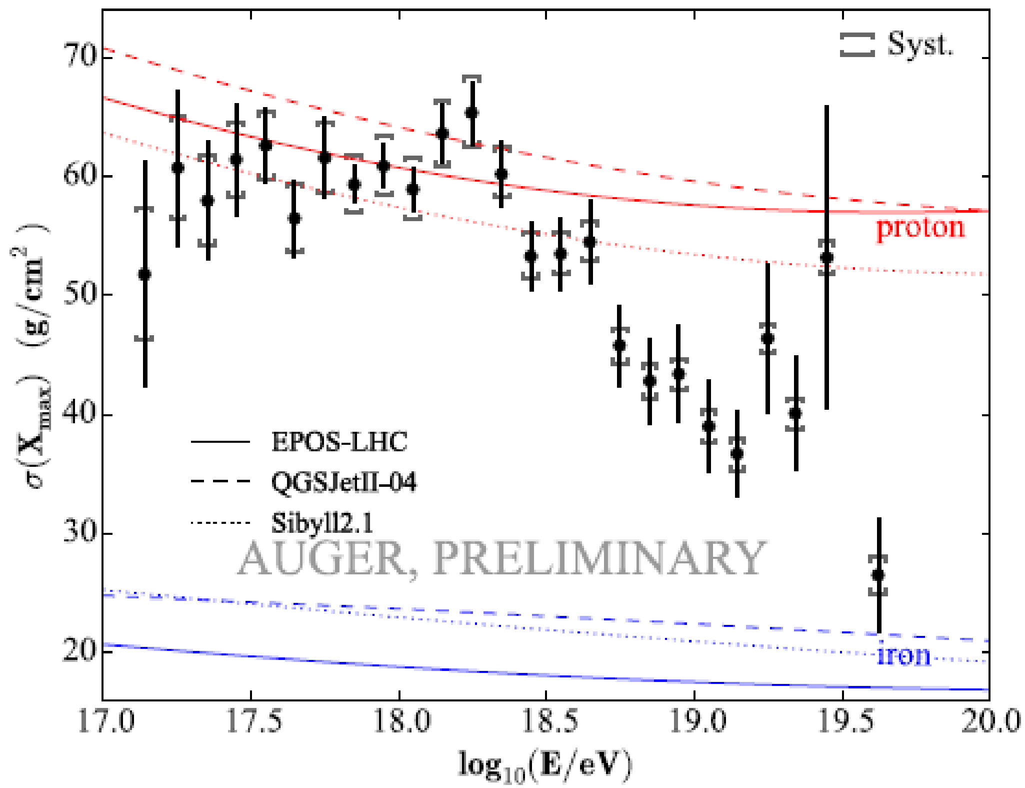
Various detection technique = **energy scale independent of hadronic inter. models**

From R. Ulrich (KIT)

Xmax Measurements

- One of the most reliable mass indicators
  - uncertainties due to models << difference proton-iron
- update for E < $10^{17.8}$ eV presented at the ICRC 2015 (The Hague)
- Composition is getting lighter below E_0~2 EeV (consistent with KASCADE-Grande ?) and heavier afterwards



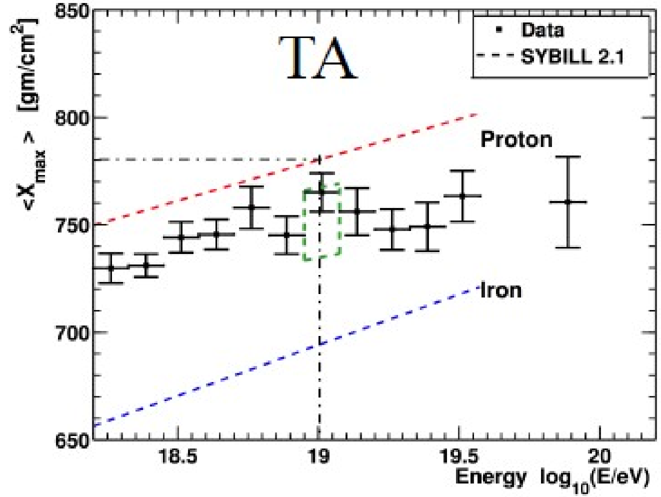


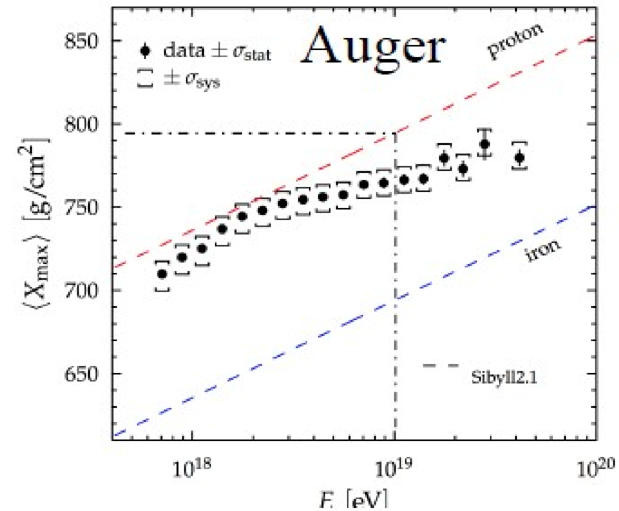
A. Yushkov (HESZ 2015) and A. Porcelli (ICRC 2015)

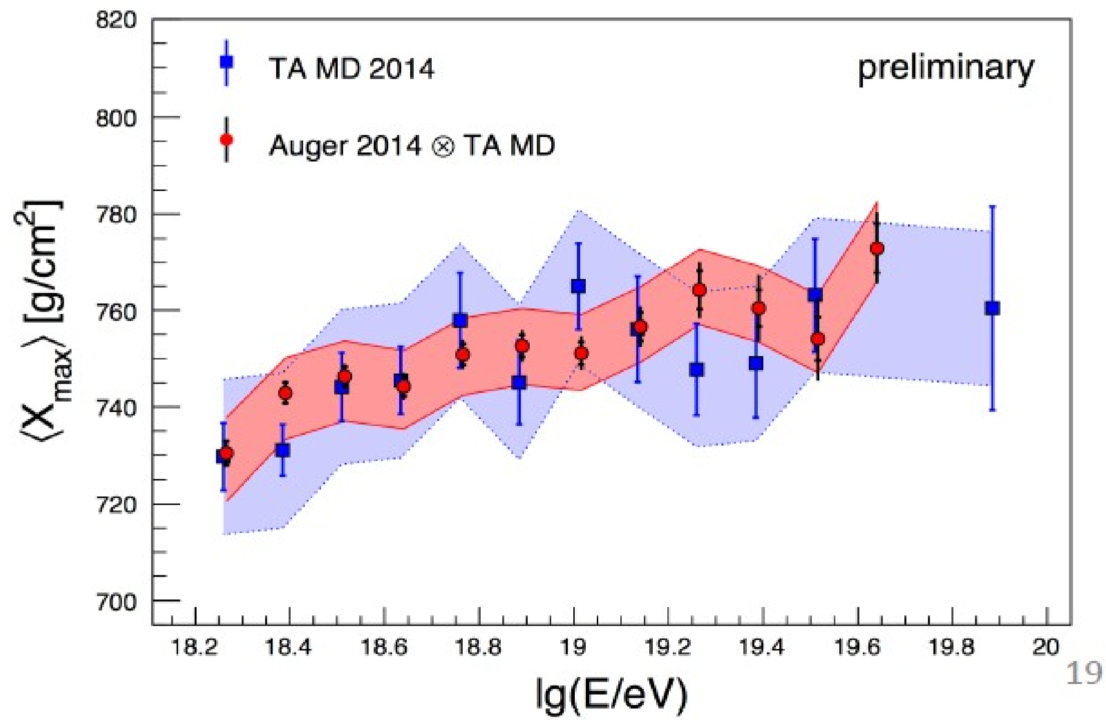
High Energy CR Composition

- **Hadronic models**
  - ➜ similar elongation rate (slope)
  - ➜ SIBYLL2.1 predictions confirmed by EPOS LHC and QGSJETII-04
  - ➜ QGSJET01 and QGSJETII-03 (old reference) disfavored
- **CR experiments**
  - ➜ more statistic
  - ➜ common analysis
  - ➜ experimental results fully compatible

Using the same reference model compatible with post-LHC results, PAO and TA observe the same MIXED composition at high energy

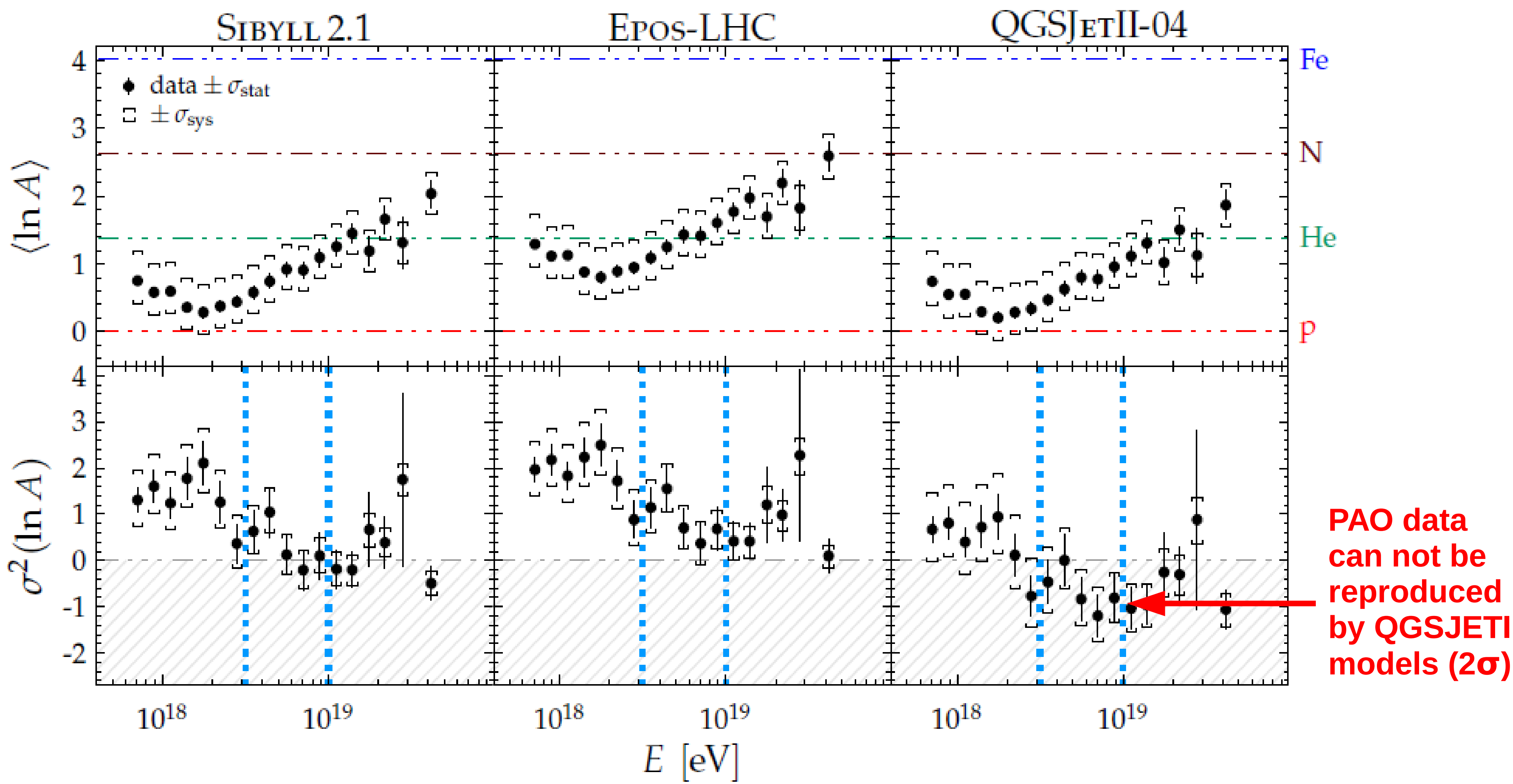






Mass Estimation

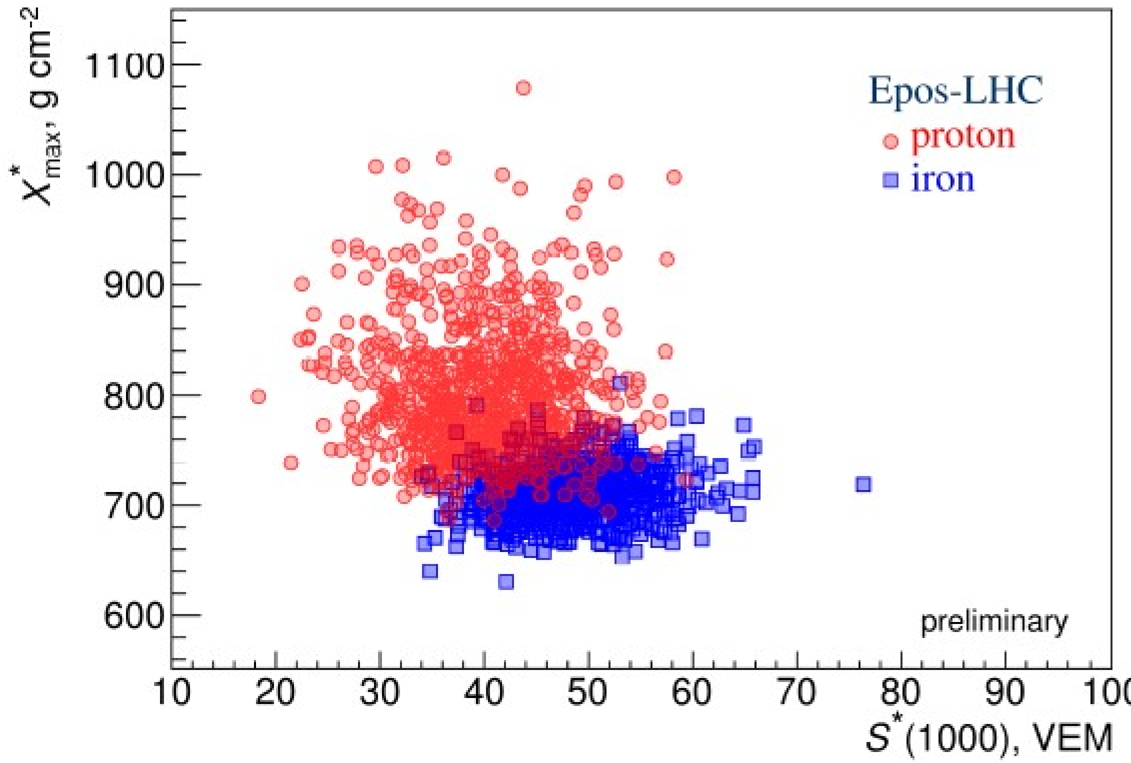
- **Mass evolution**
  - <lnA> = average (log) mass and σ²(lnA) is the variation of the mass (0=constant mass)
  - test consistency of hadronic models



Correlation between X^*_{max} and $S^*(1000)$

- **Heavier nuclei produce shallower showers with larger signal (more muons)**
  - ➜ general characteristics of air showers / minor model dependence

- **Correlation (Xmax, S(1000)) EPOS-LHC**
  - ➜ pure beams
    - 0.00 for proton
    - +0.08 for iron
  - ➜ max mixing
    - -0.37 for 0.5 p - 0.5 Fe



A. Yushkov (ICRC 2015)

More negative correlation ⇒ more mixed composition

$S^*(1000)$: SD signal at 1000 m from the core scaled to 10 EeV, 38°

X^*_{max}: X_{max} scaled to 10 EeV

Correlation between X^*_{max} and $S^*(1000)$

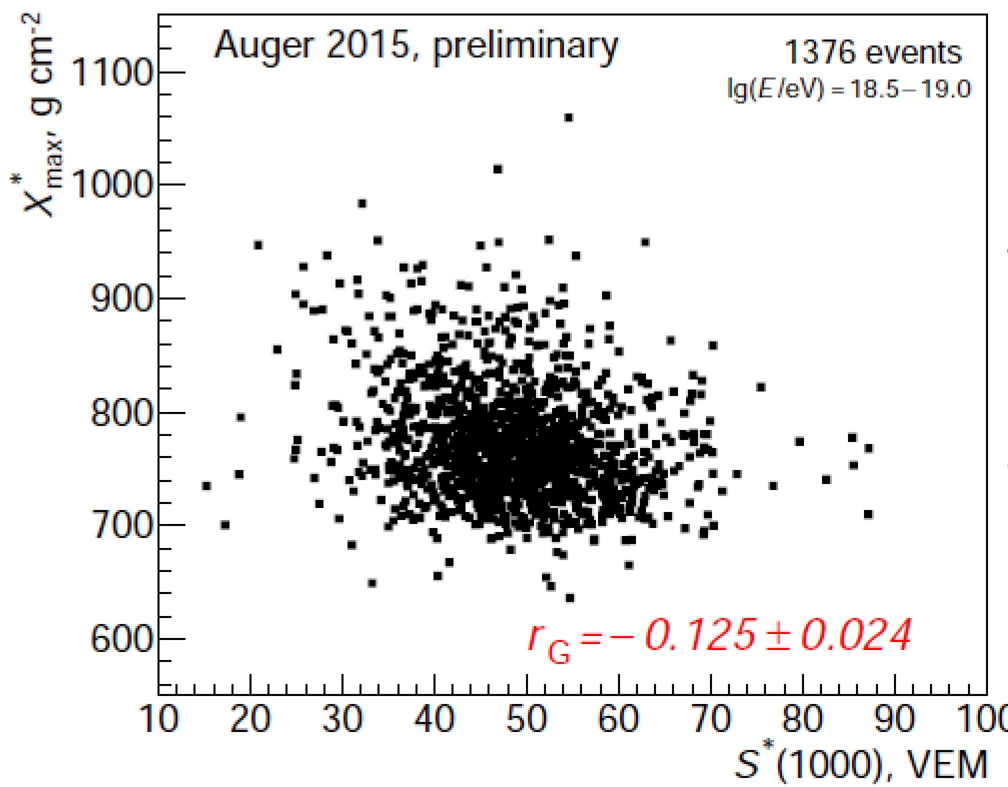
- **in data correlation is significantly negative**

  ➜ $r_G = -0.125 \pm 0.024$

- **$r_G(X^*_{max}, S^*(1000))$ 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

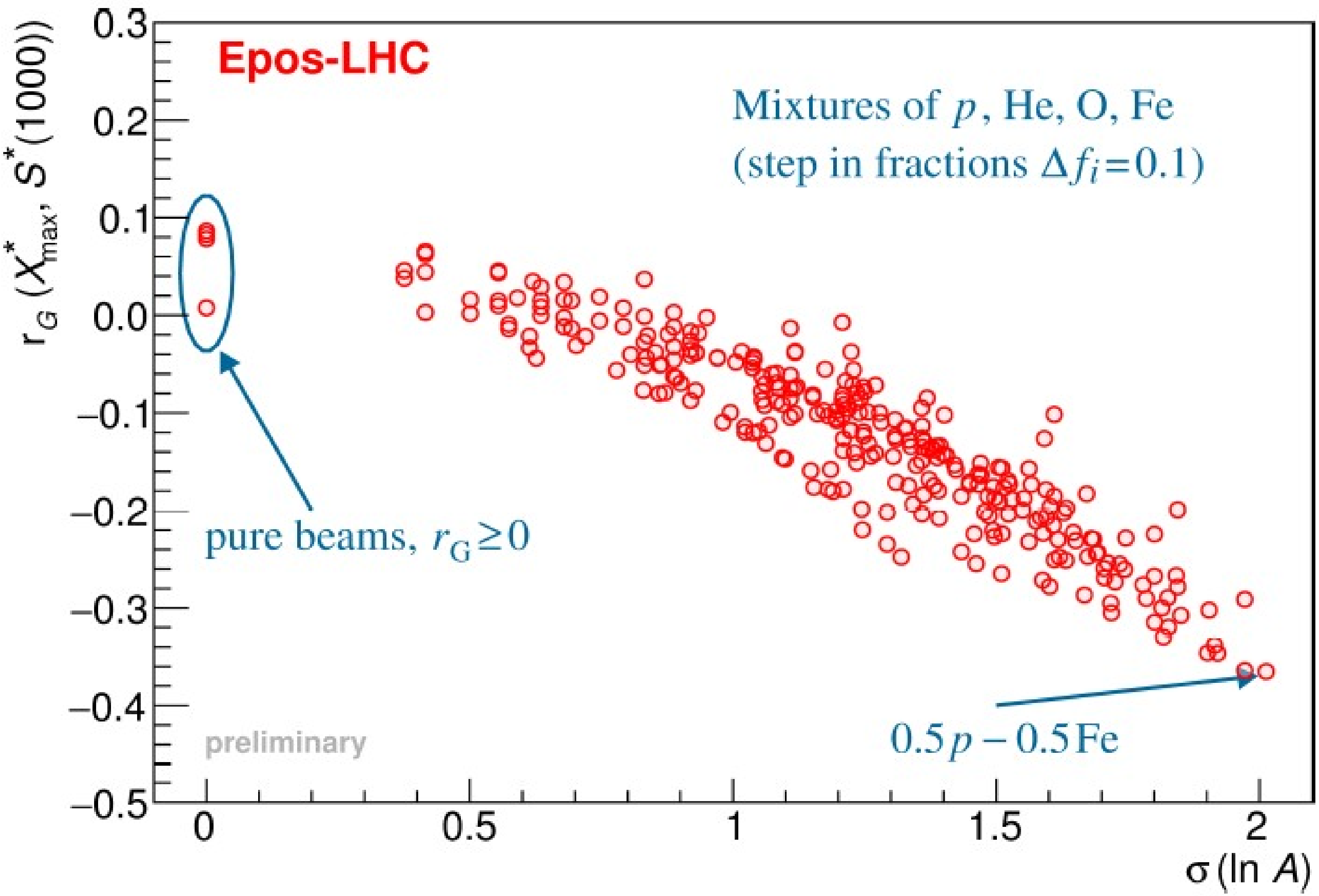
- **test of "exotic" models fails**



A. Yushkov (ICRC 2015)

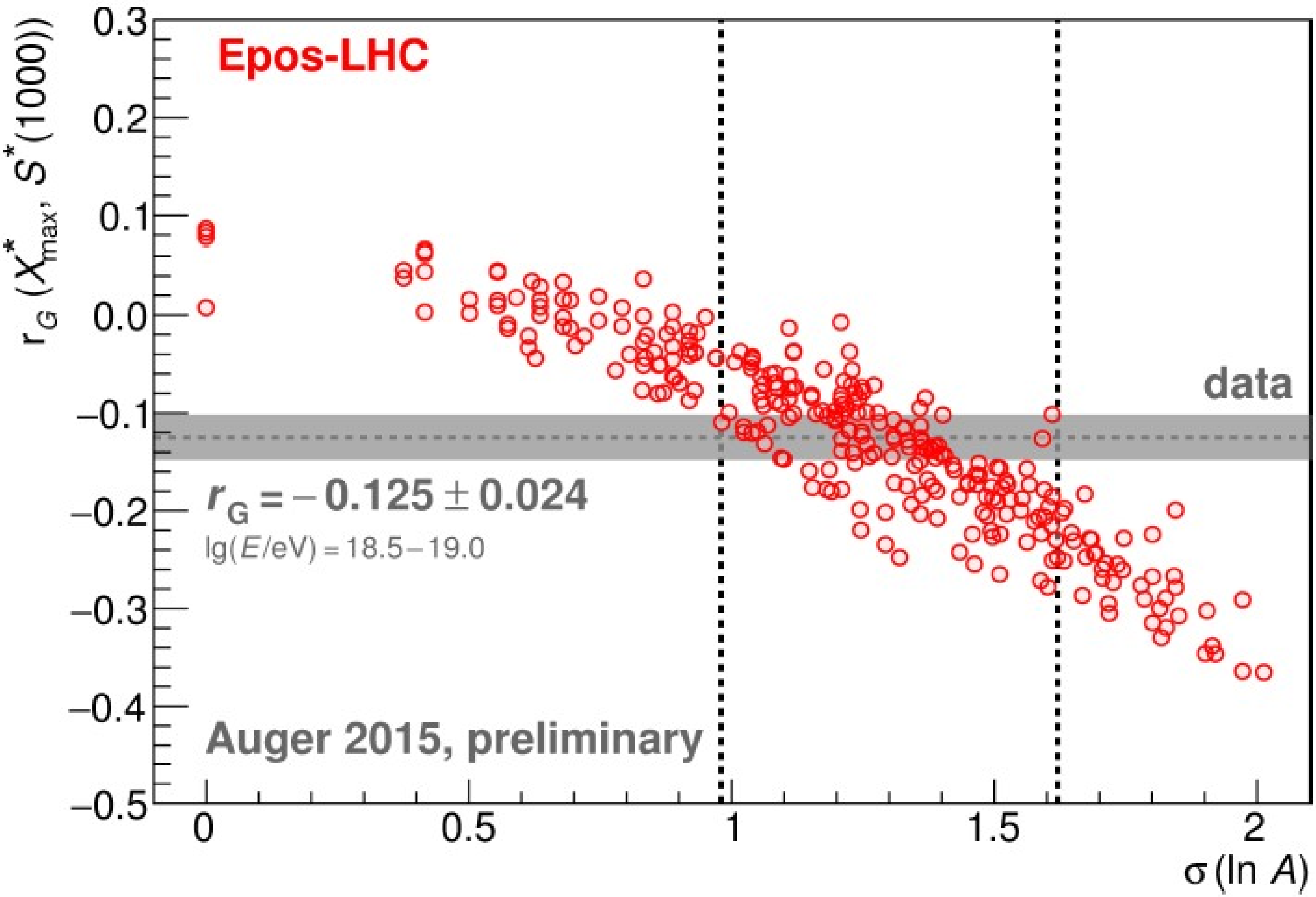
r_G - rank correlation coefficient introduced in R. Gideon, R. Hollister, JASA 82 (1987) 656

Dispersion of Masses in Data



A. Yushkov (ICRC 2015)

Dispersion of Masses in Data



A. Yushkov (ICRC 2015)

data are compatible with 1.0 $\lesssim$ σ(ln A) $\lesssim$ 1.7

Muon Production Depth

- **Independent SD mass composition measurement**
  - ➡ geometric delay of arriving muons

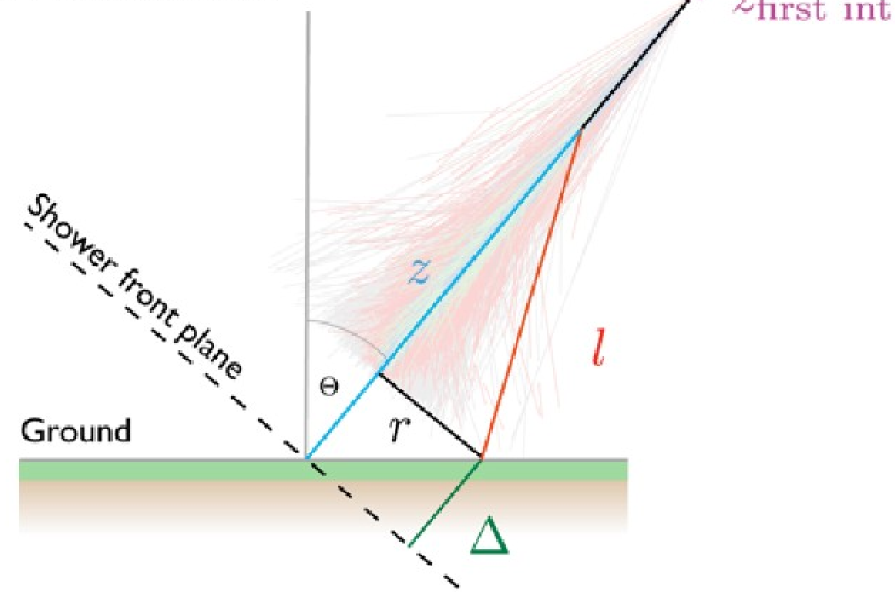
$$c \cdot t_g = l - (z - \Delta)$$
$$= \sqrt{r^2 + (z-\Delta)^2} - (z - \Delta)$$

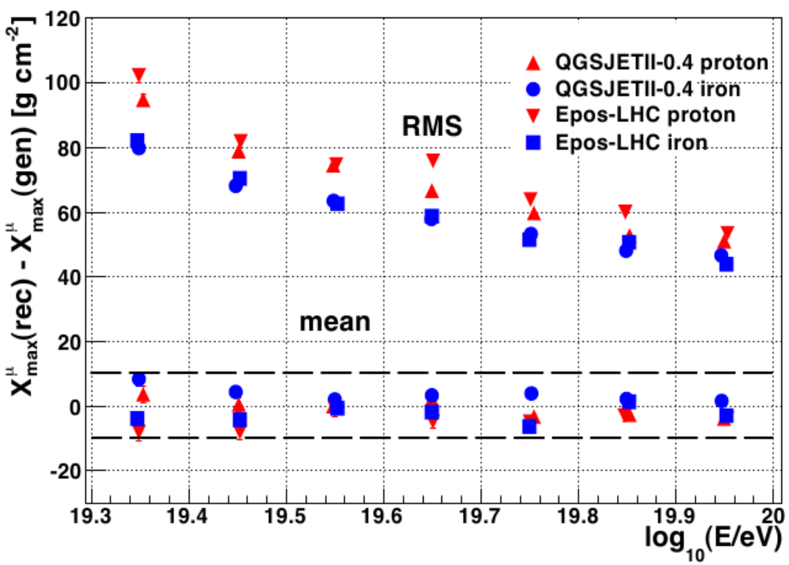
  - ➡ mapped to muon production distance

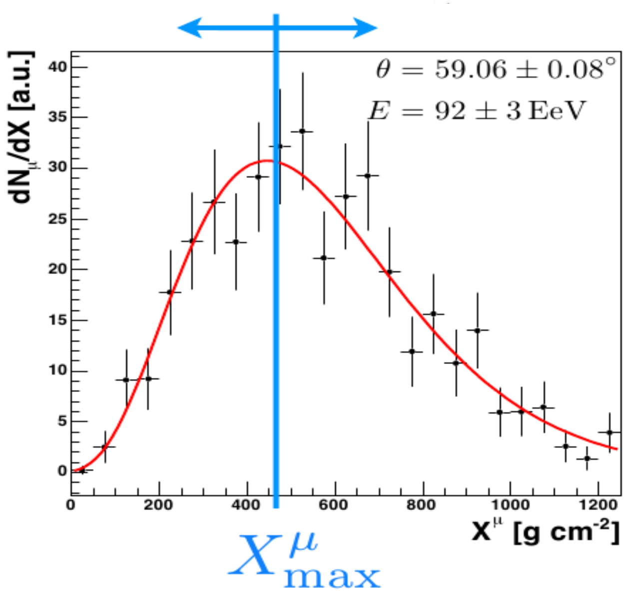
$$z = \frac{1}{2}\left(\frac{r^2}{ct_g} - ct_g\right) + \Delta$$

  - ➡ decent resolution and no bias

Inclined events to avoid EM contamination:

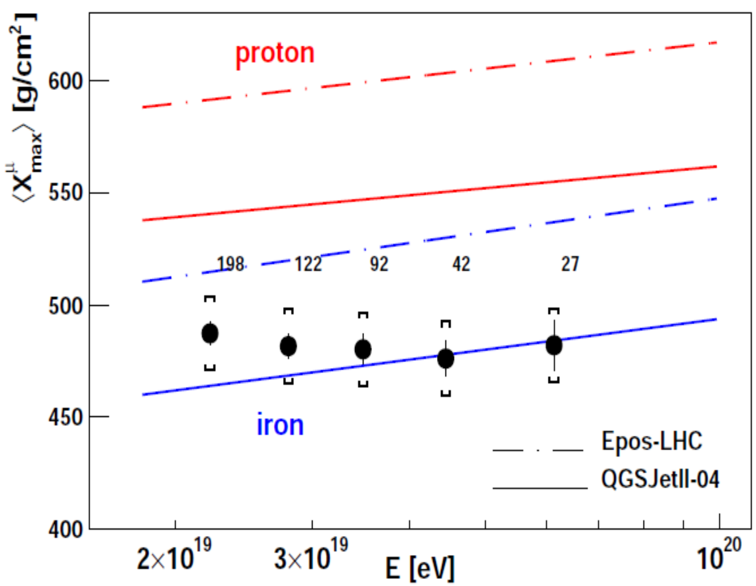


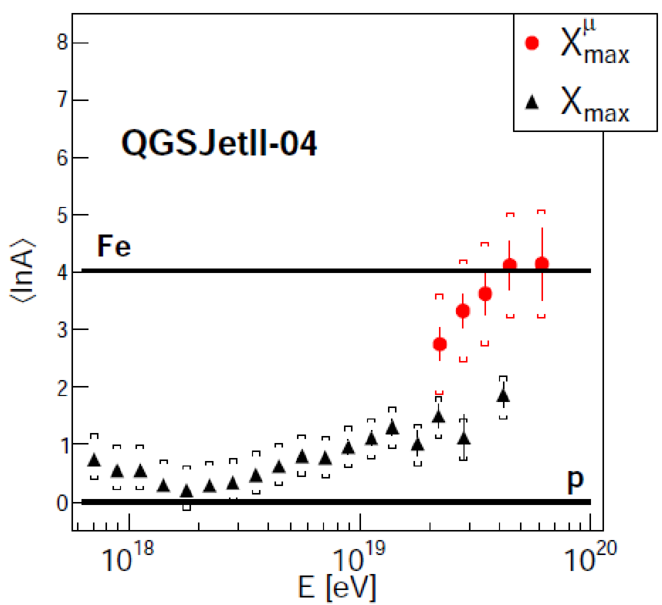


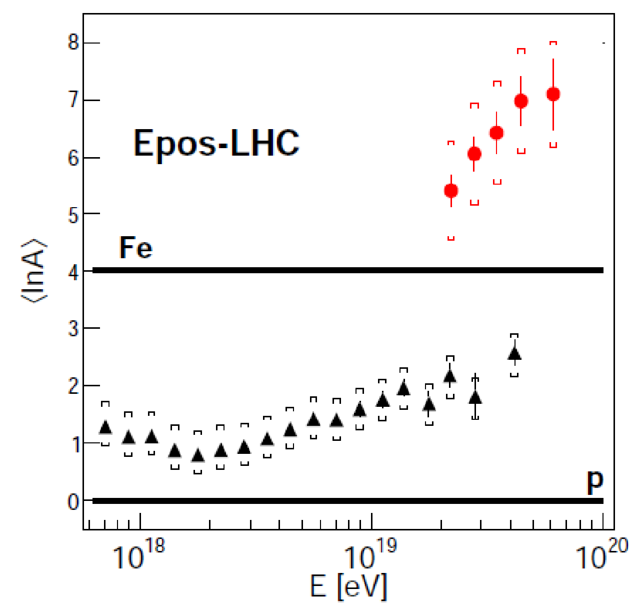


MPD and Models

- **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
    - lower diffractive mass motivated by rapidity gap cross-section !
    - strong influence of pion diffraction on muon production evolution
    - additional data needed to improve pion diffraction (neutron exchange at LHC ?)



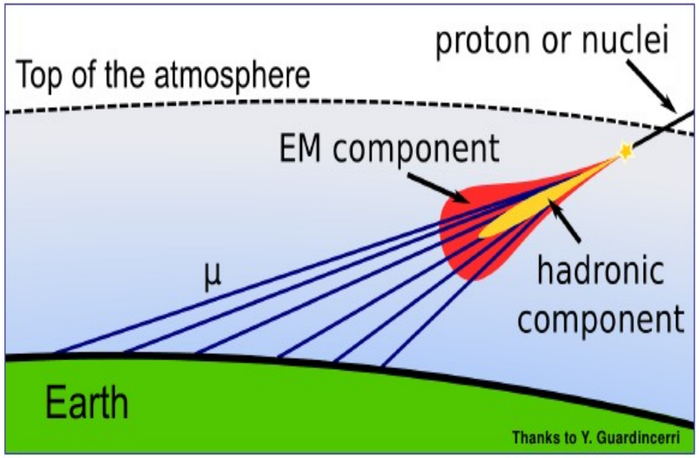




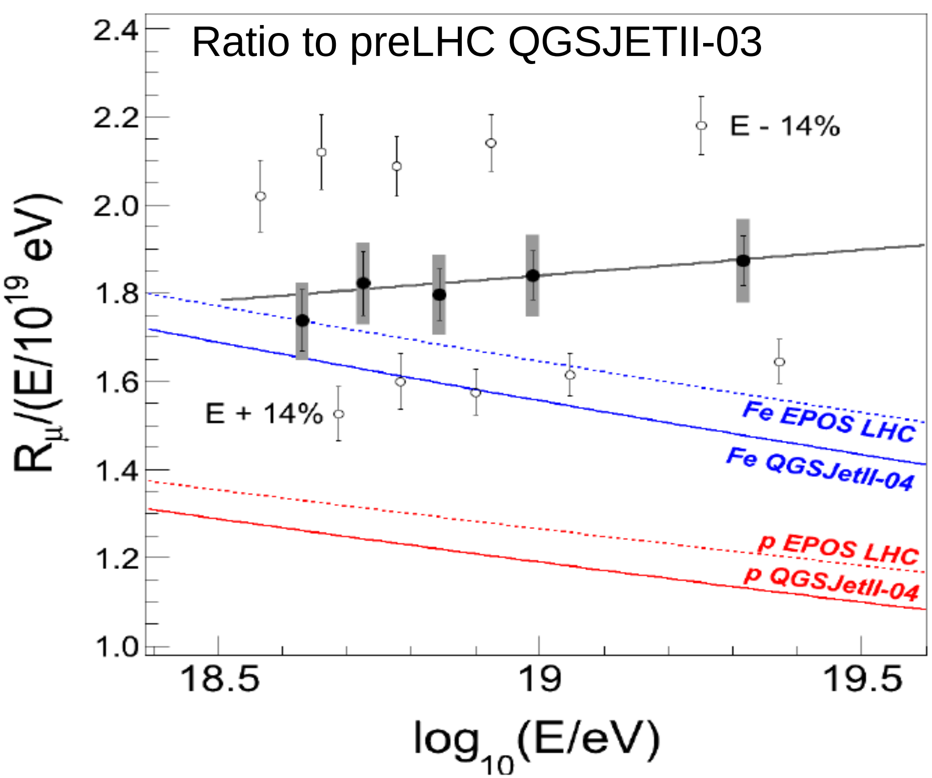
PAO, ICRC 2015

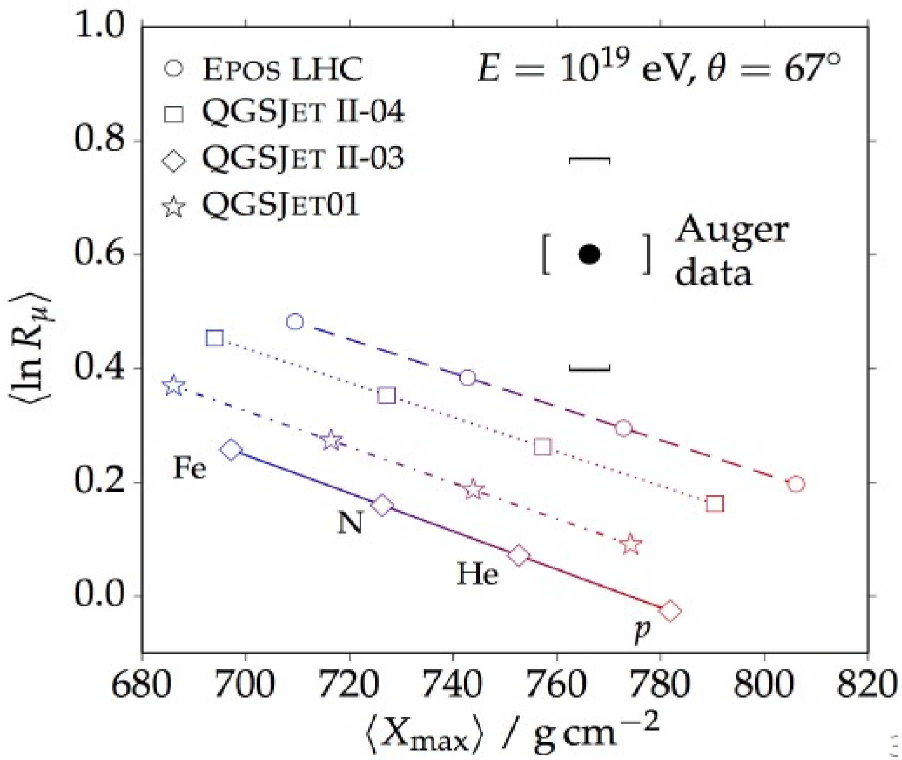
Direct Muon Measurement

- **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%)



R_μ/E_{FD} *in energy bins*

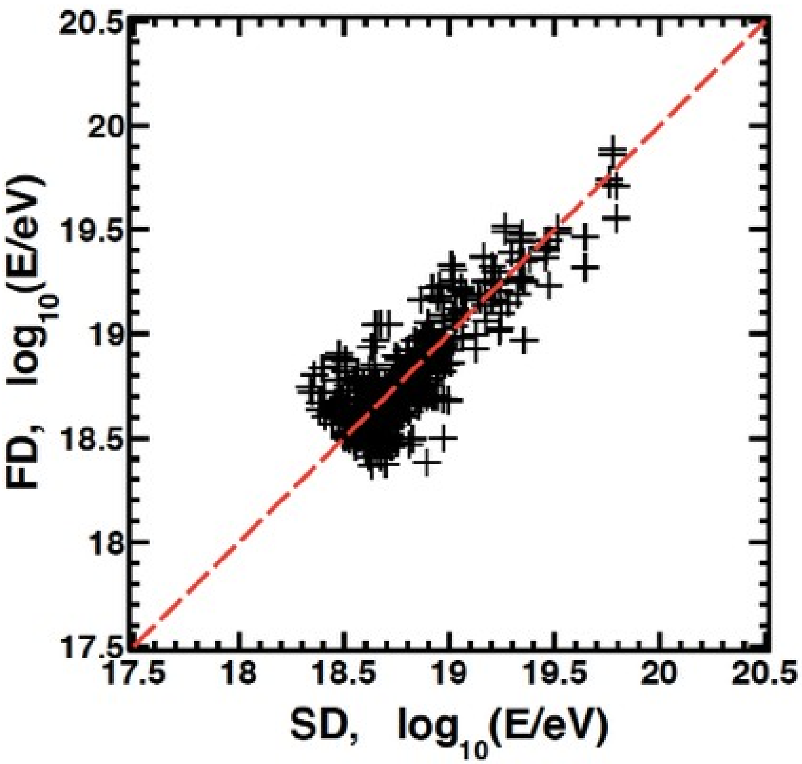


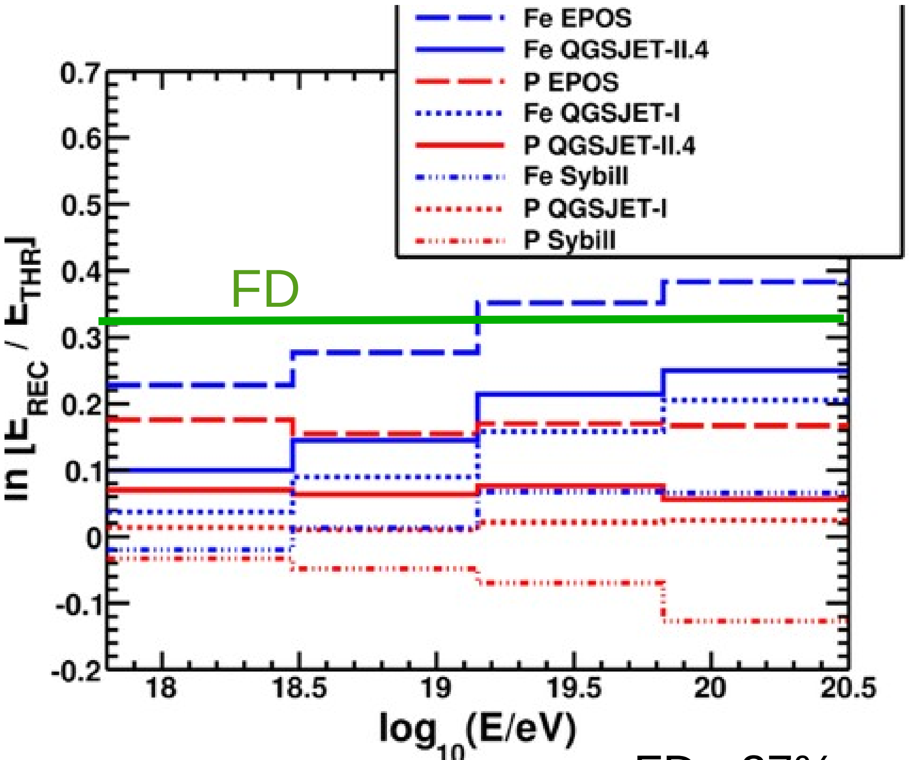


Telescope Array Energy Scale

- General behavior of data a ground well reproduced by QGSJETII-03 proton but energy scale have to be shifted by 27% to match FD hybrid measurements

J. Gonzalez, Hadronic Int. WG, UHECR 2014





FD: -27%

QGSJet II.04: -5%

EPOS: -20%

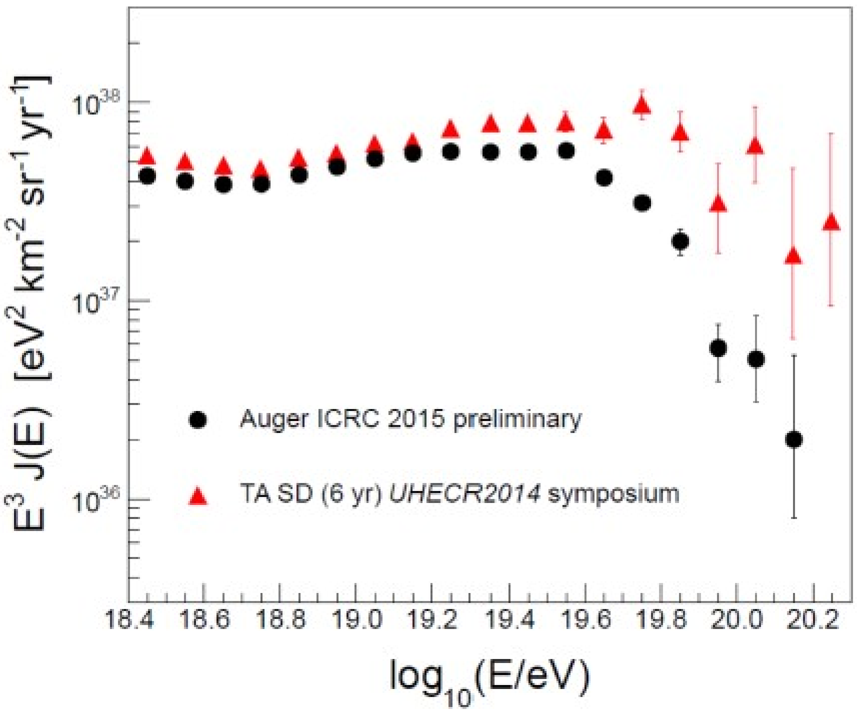
Sibyll: +5-1-%

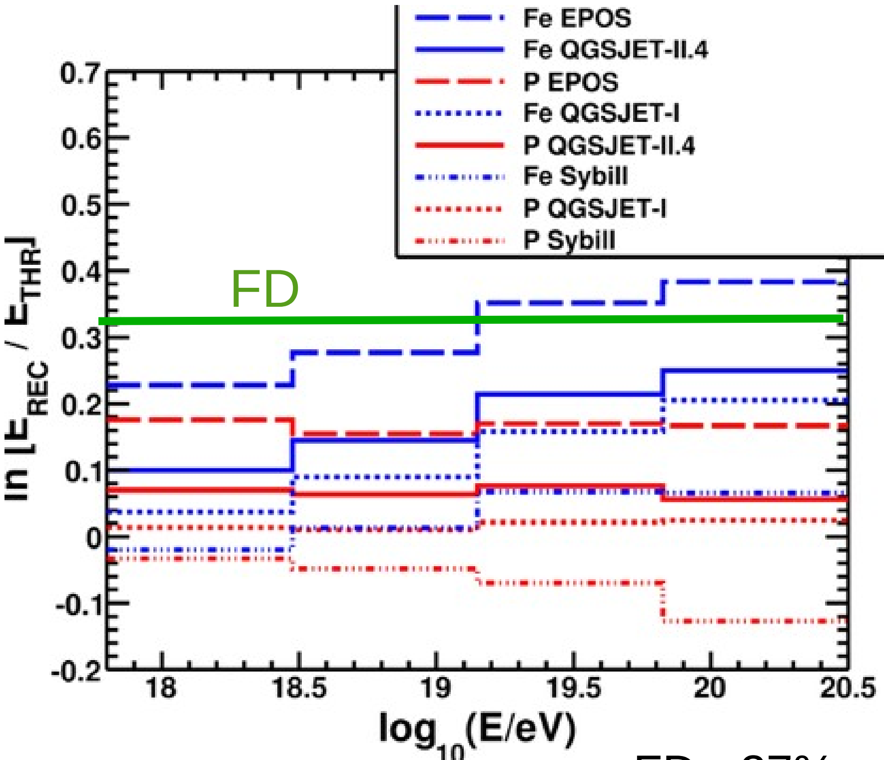
Could be explain by the same muon deficit observed in PAO (vs QGSJETII-03 proton !)

Telescope Array Energy Scale

- General behavior of data a ground well reproduced by QGSJETII-03 proton but energy scale have to be shifted by 27% to match FD hybrid measurements

Energy/mass dependence of mismatch (spectrum) ?





FD: -27%

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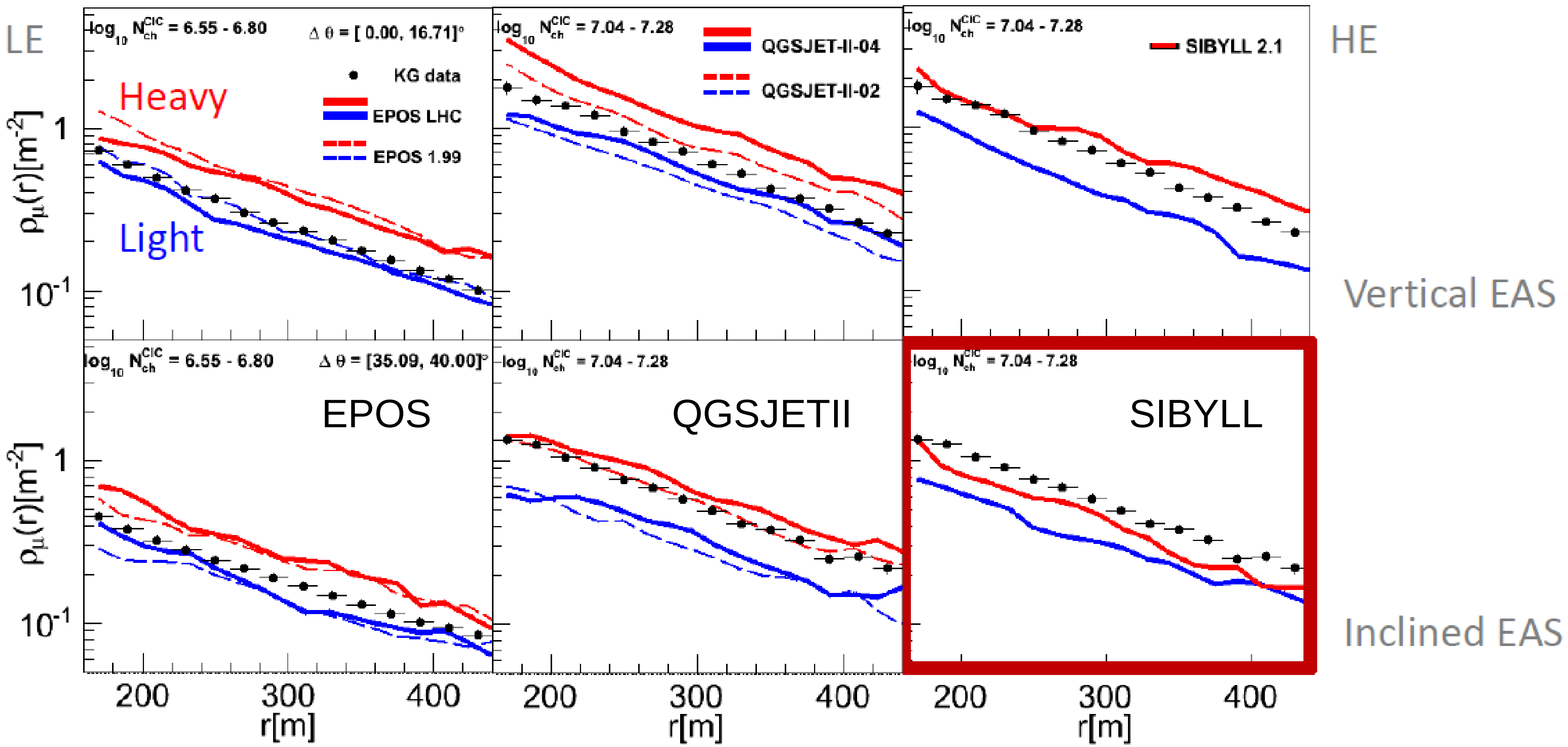
Could be explain by the same muon deficit observed in PAO (vs QGSJETII-03 proton !)

KASCADE-Grande

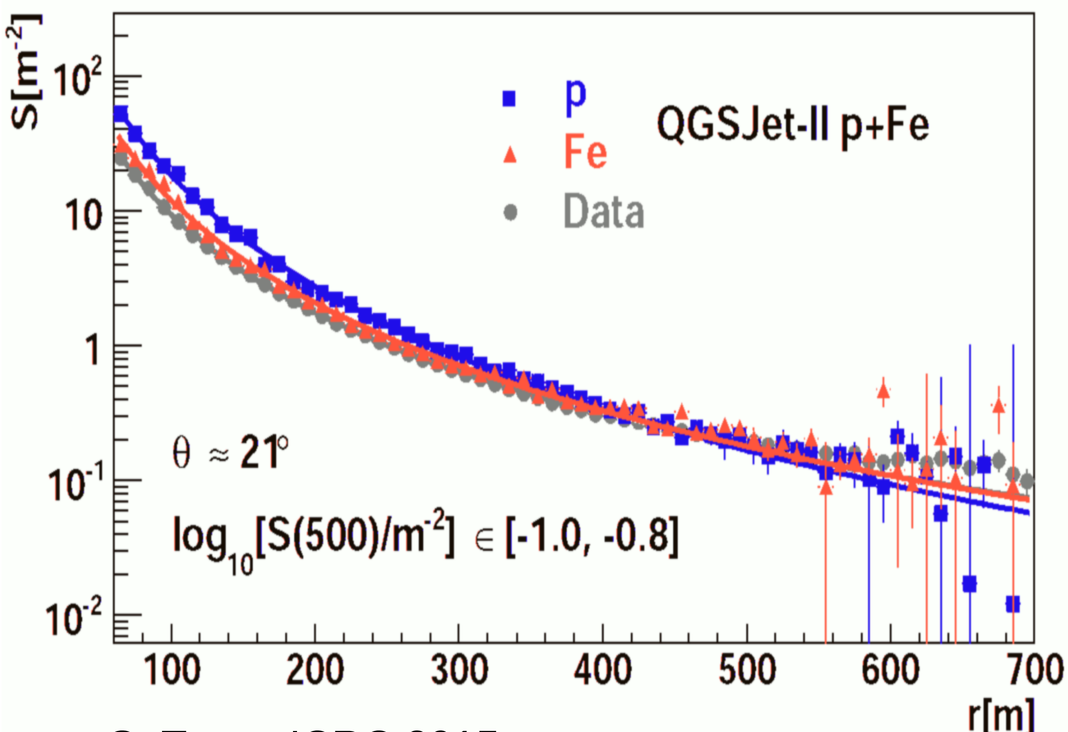
- Muon density indicates a high number of muon
  - ➡ pre-LHC not consistent with data
  - ➡ post-LHC between p and Fe but composition not consistent



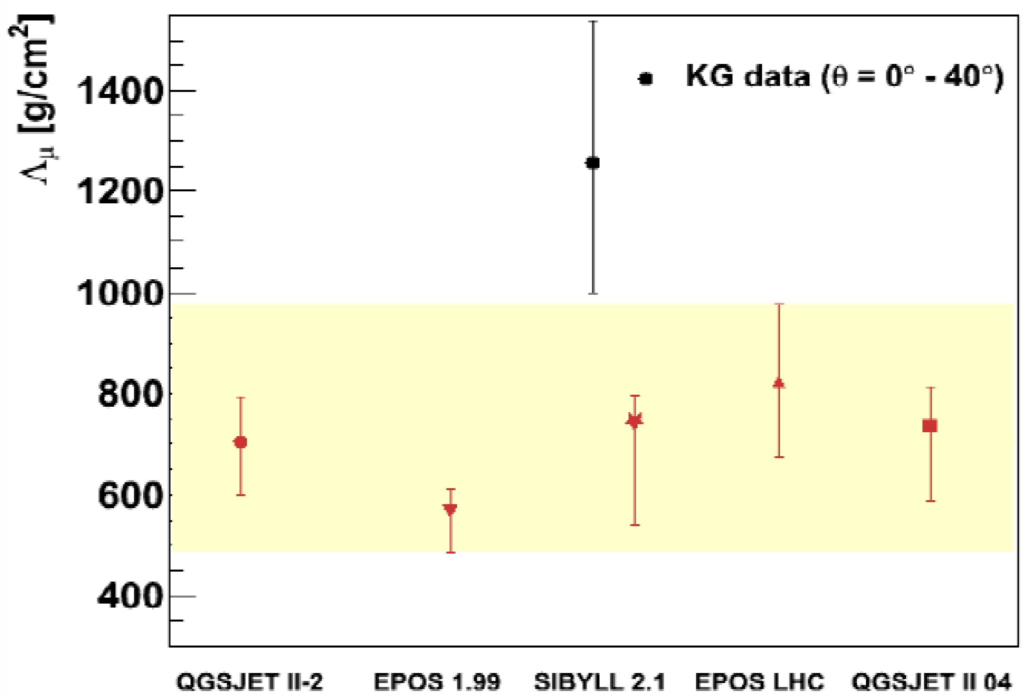
J.C. Arteaga, ICRC 2015

KASCADE-Grande

- Muon density indicates a high number of muon
  - ➡ pre-LHC not consistent with data
  - ➡ post-LHC between p and Fe but composition not consistent
- Shape of LDF for charged particles seems to indicate the same
- Problem with muon attenuation length
- Other KASCADE data on direct test with hadronic calorimeter



G. Toma, ICRC 2015

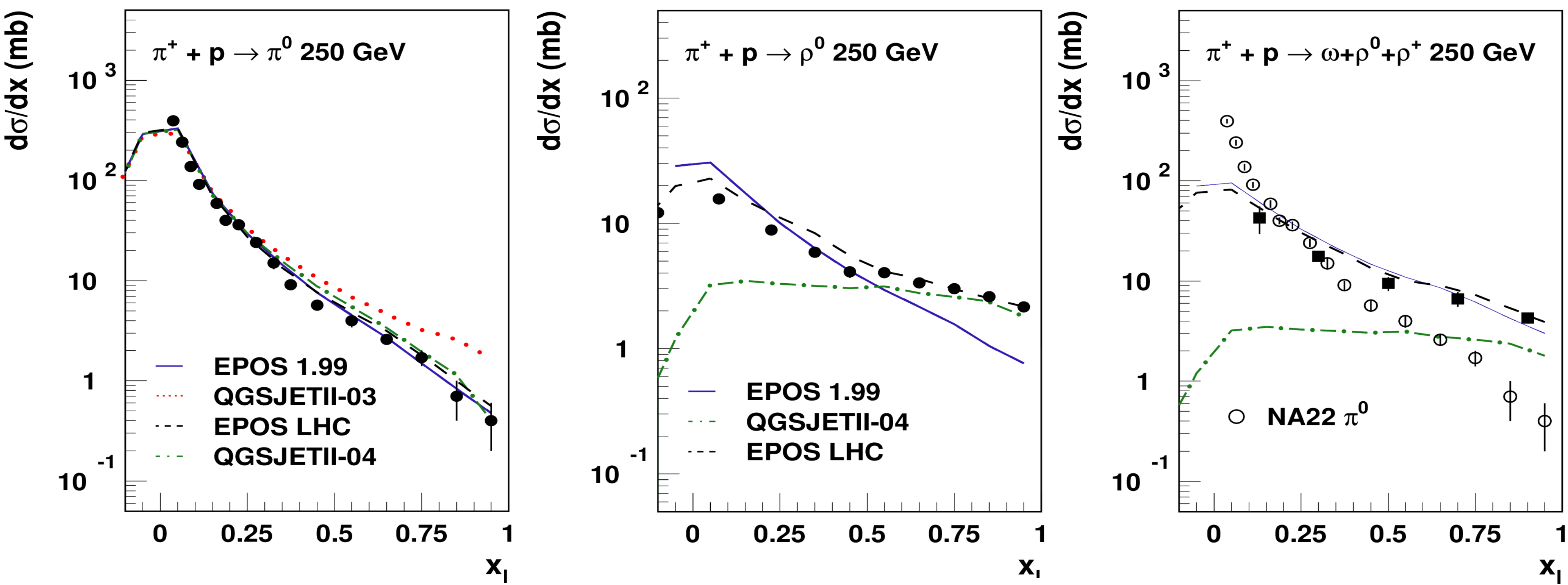


J.C. Arteaga, ICRC 2015

Pion Leading Particle Effect

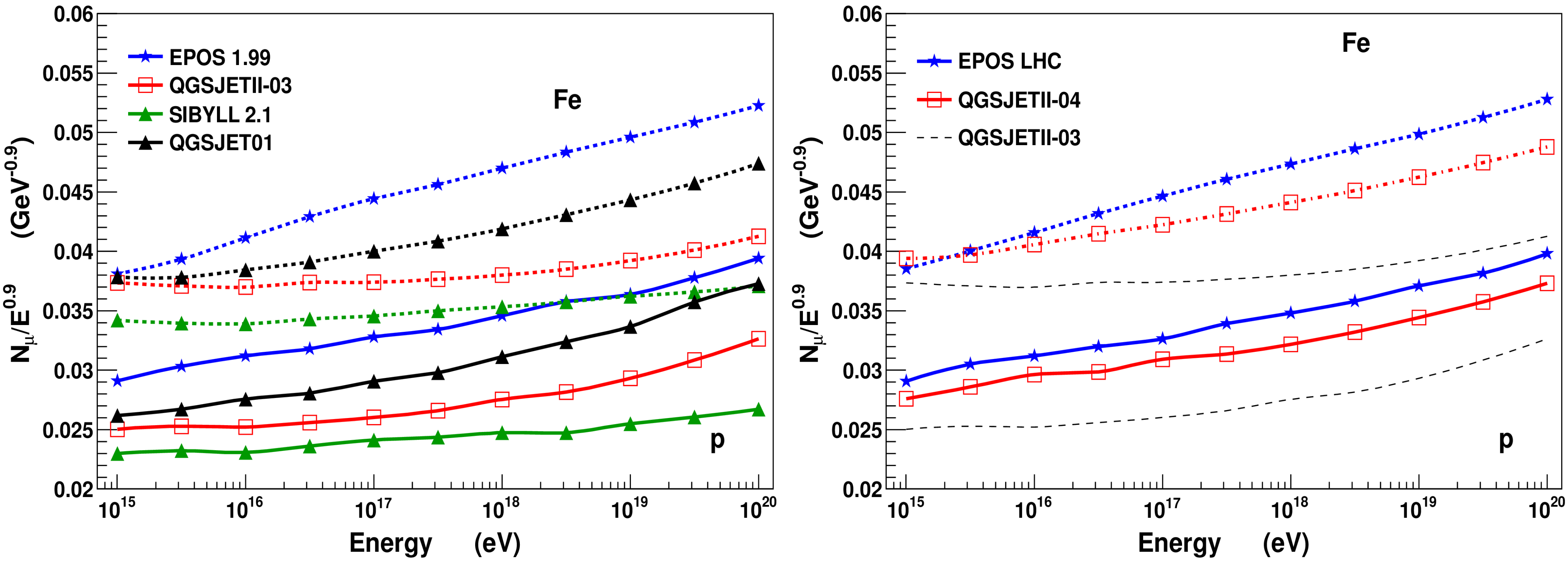
- Rho meson production added in QGSJETII to take into account leading particle effect in pion-Air interaction
  - ➜ same effect as baryon production : forward π^0 replaced by charged pions (reduced leading π^0)
  - ➜ increase muon production

Not only Rho0 should be taken into account !



EAS with Re-tuned CR Models : Muons

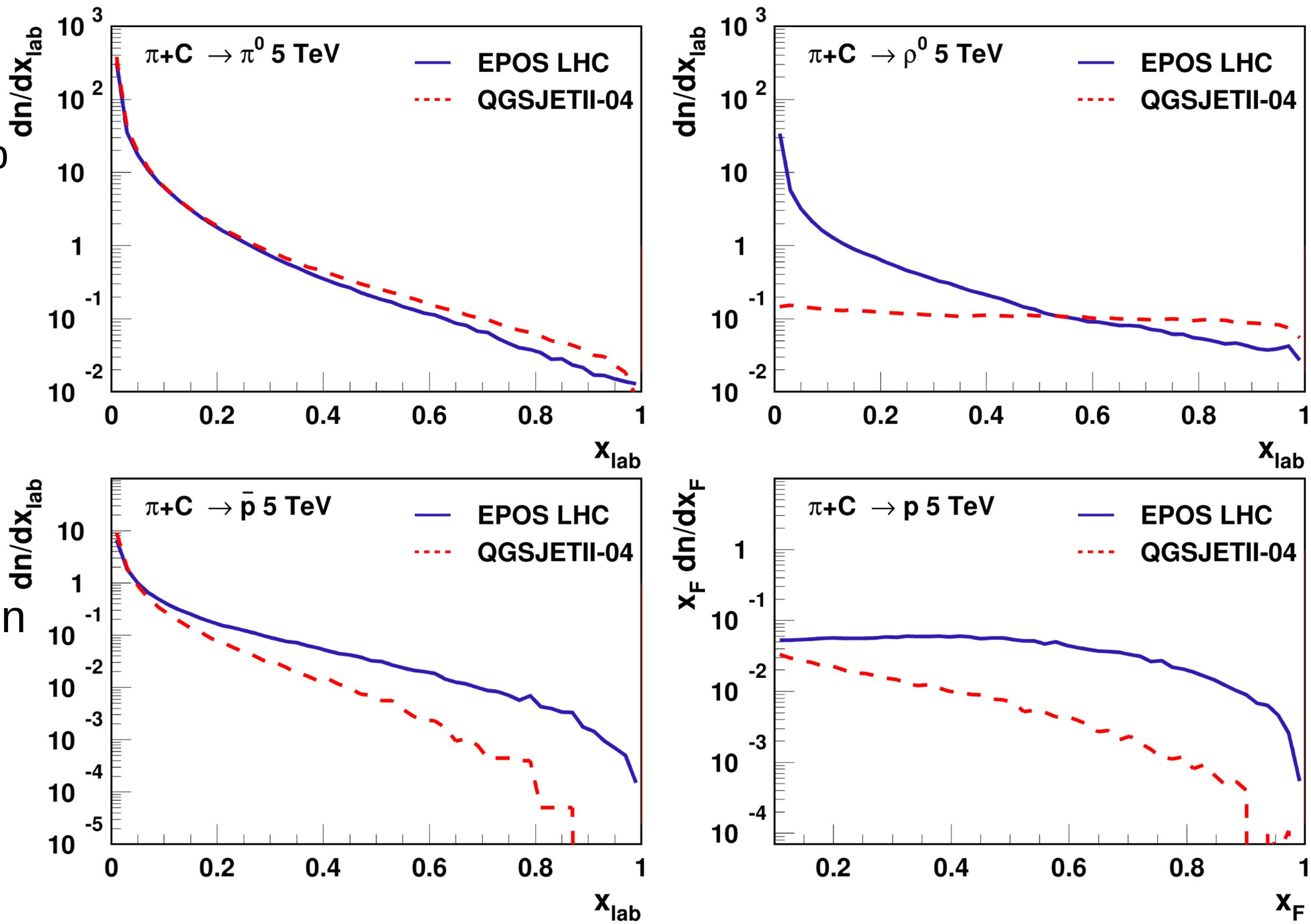
- Effect of LHC hidden by other changes
  - Corrections only at mid-rapidity for EPOS
  - Changes in QGSJET motivated by pion induced data
  - EPOS LHC ~ EPOS 1.99 and only -7% for QGSJETII-04 vs EPOS LHC
  - different energy spectra (more low energy muons in EPOS LHC)
- Deficit still observed in data (+MPD problem)



Momentum Fraction π+C

- Harder spectra in QGSJETII-04

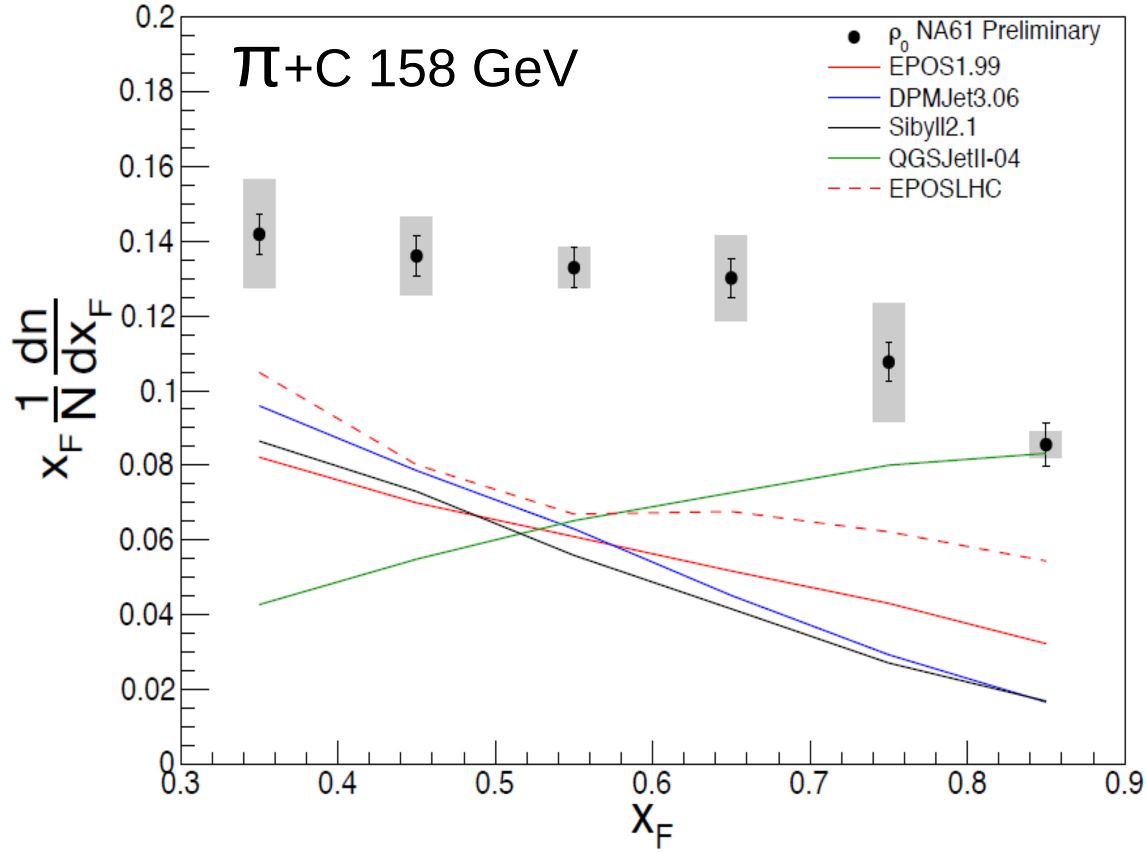
- low and Intermediate energies (5 TeV lab here)
- important for muon production in EAS
- still very different behavior in π interactions
- large difference for forward baryon production



Momentum Fraction π+C

- **Harder spectra in QGSJETII-04**

- low and Intermediate energies (5 TeV lab here)
- important for muon production in EAS
- still very different behavior π interactions
- large difference for forward baryon production
- large discrepancy for ρ^0 production in π-A



(NA61, Herve, ICRC 2015)

Room for improvement on muon production. NA61 data on baryon prod. and midrapidity prod. needed to fix models.

Summary

- **New developments to have faster reliable EAS simulations**
- **Direct effect of LHC data on CR analysis**
  - ➡ explanation of the knee in CR spectrum as a change in hadronic interactions is now excluded
- **Indirect effect of LHC data on CR analysis: reduced uncertainties in hadronic models**
  - ➡ common behavior of <Xmax>
  - ➡ mixed composition observed above the ankle for both TA and PAO with more confidence
- **Still open problems with muon production**
  - ➡ data not consistently reproduced even by post-LHC models (both PAO and KASCADE)
  - ➡ more LHC data to be taken into account
  - ➡ NA61 data to reduce differences between models and with data
  - ➡ cross-check at high energy using pion exchange at LHC (LHCf+ATLAS) ?

Modern simulation tools constrained by LHC data allowed a big step forward in the interpretation of charged cosmic ray (CR) data towards an unexpected mixed composition of extra-galactic cosmic rays.