

LHC and Cosmic Rays : the Chicken or the Egg ?

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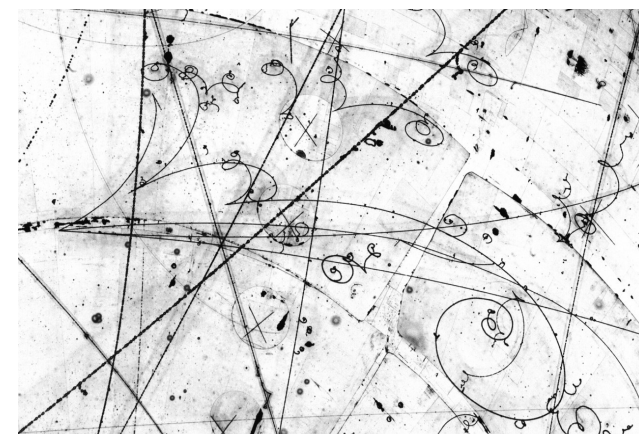
Outline

- 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

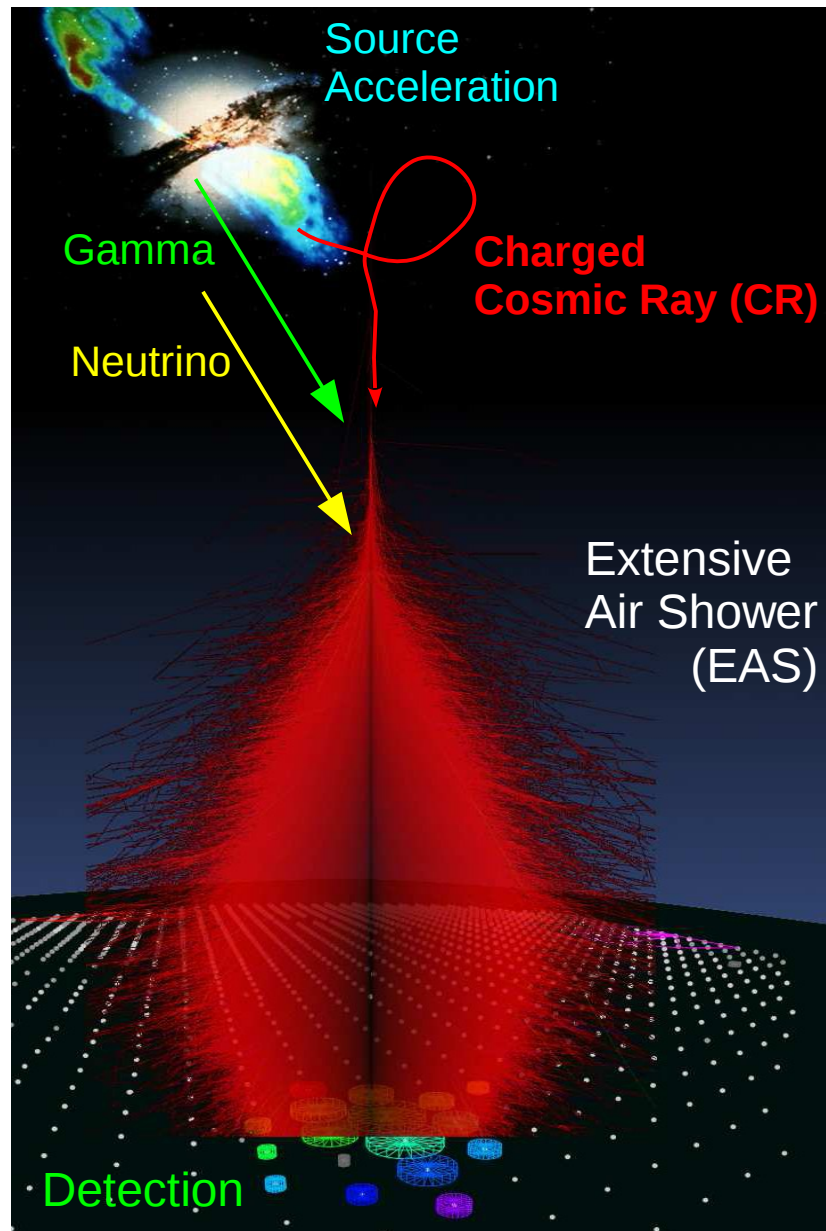
LHC data reduced the model uncertainties and **exclude old models** for mass composition of cosmic rays. Good description of air showers improve model **predictive power** for the description of min.Bias LHC data and detector simulations.

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

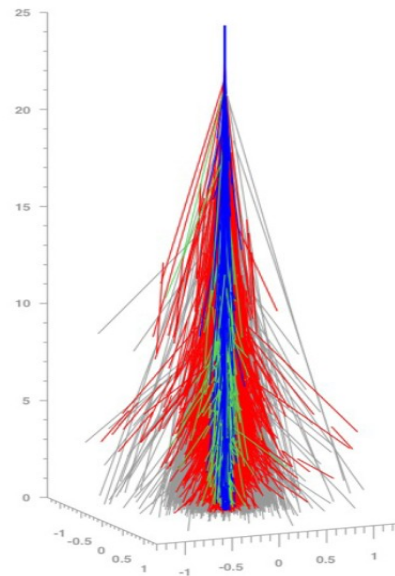
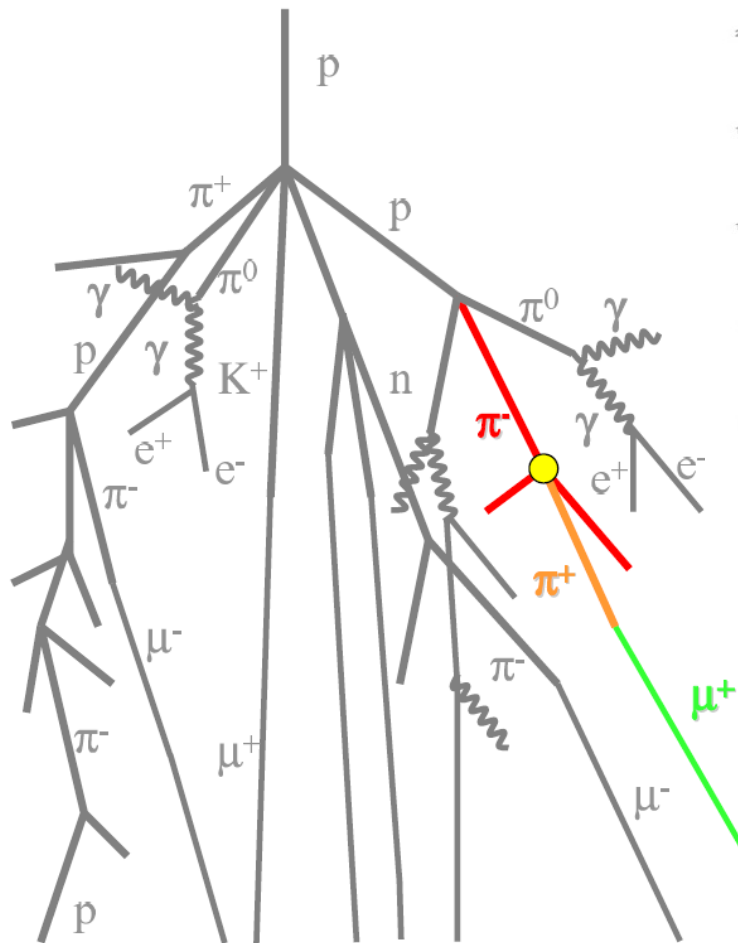


From R. Ulrich (KIT)

- **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

Extensive Air Shower



$A + air \rightarrow \text{hadrons}$

$p + air \rightarrow \text{hadrons}$

$\pi + air \rightarrow \text{hadrons}$

hadronic physics

initial γ from π^0 decay

$e^\pm \rightarrow e^\pm + \gamma$

well known

$\gamma \rightarrow e^+ + e^-$

QED

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

Cascade of particle in Earth's atmosphere

Number of particles at maximum

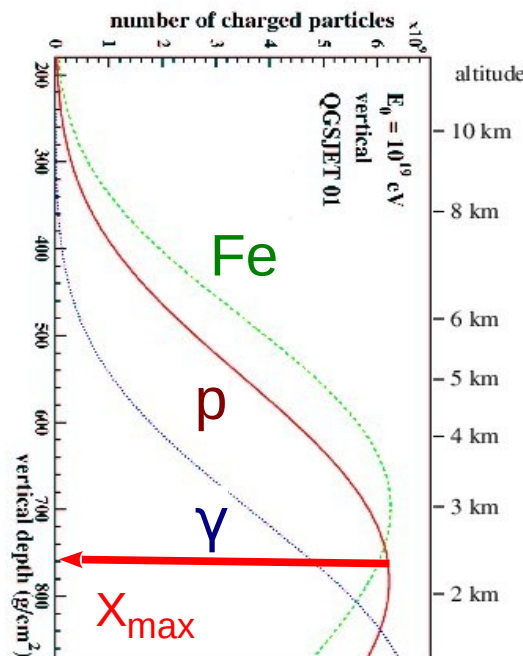
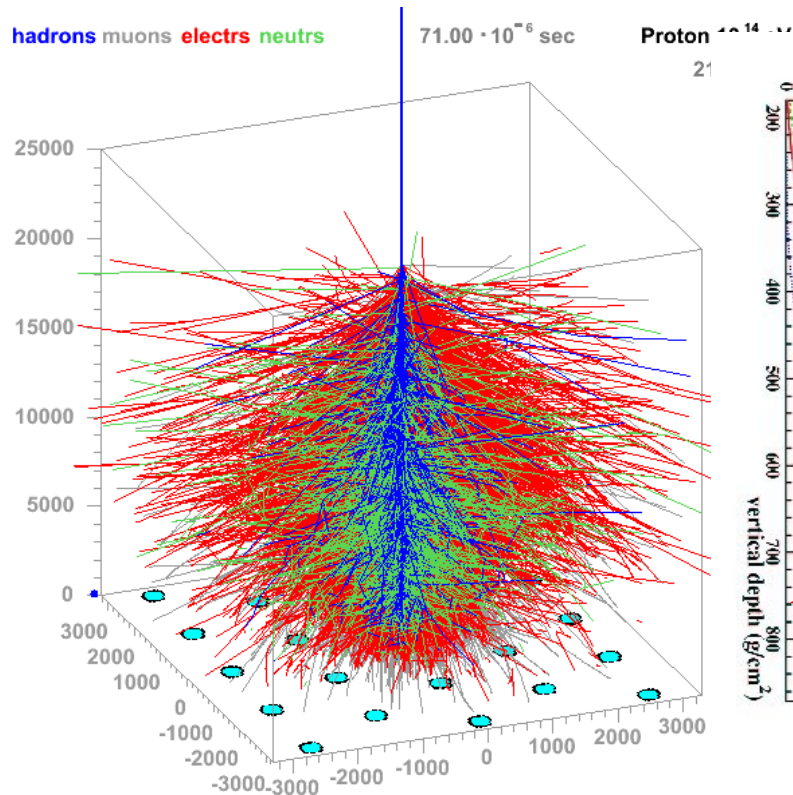
- ➔ 99,88% of electromagnetic (EM) particles
- ➔ 0.1% of muons
- ➔ 0.02% hadrons

Energy

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

From R. Ulrich (KIT)

Extensive Air Shower Observables



● Longitudinal Development

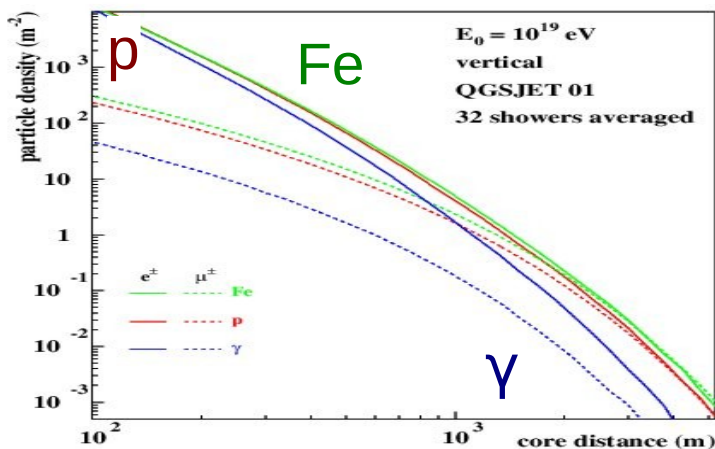
→ number of particles vs depth

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

→ Larger number of particles at X_{max}

For many showers

- ◆ mean : $\langle X_{\max} \rangle$
- ◆ fluctuations : RMS X_{max}
- ◆ depends on primary mass
- ◆ depends on Hadr. Inter.



● Lateral distribution function (LDF)

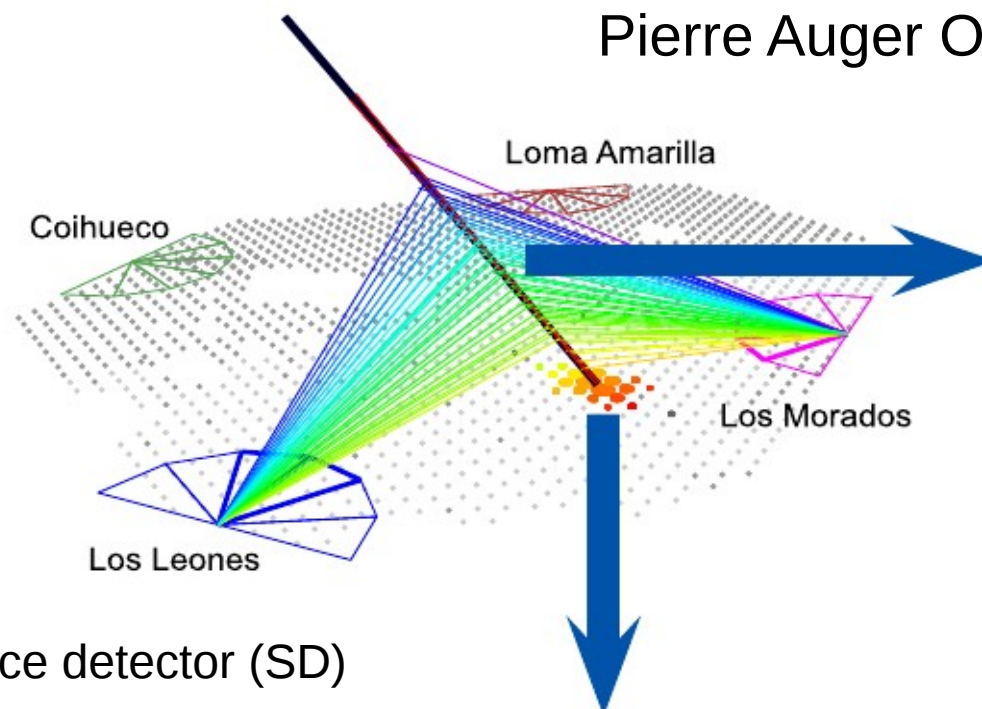
→ particle density at ground vs distance to the impact point (core)

→ can be muons or electrons/gammas or a mixture of all.

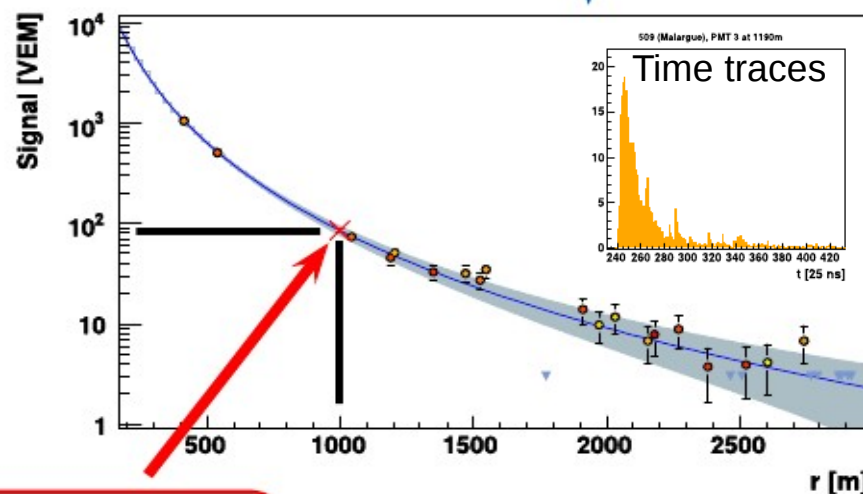
● Others: Cherenkov emissions, Radio signal

Hybrid Detection

Pierre Auger Observatory / Telescope Array

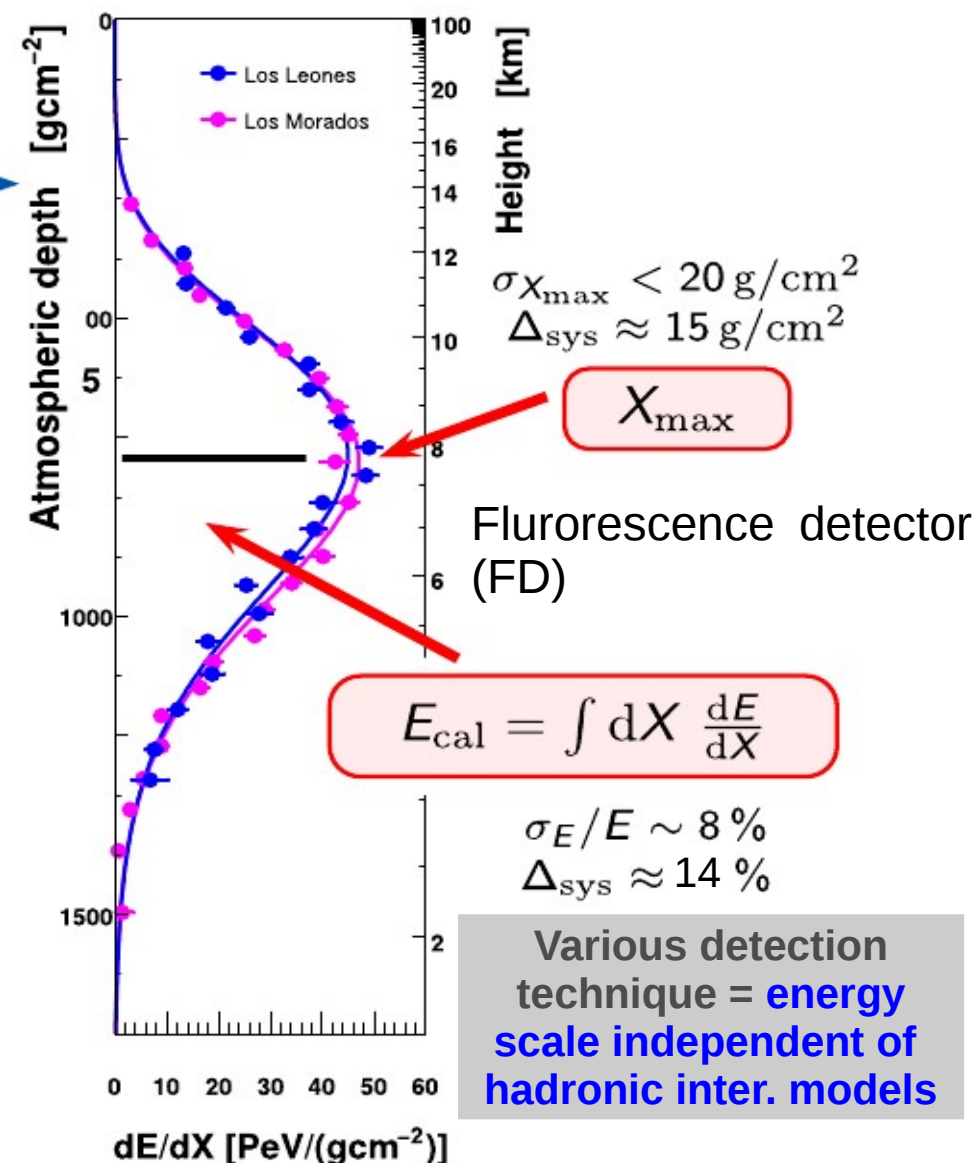


Surface detector (SD)



S_{1000}

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



Fluorescence detector (FD)

$$E_{\text{cal}} = \int dX \frac{dE}{dX}$$

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

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

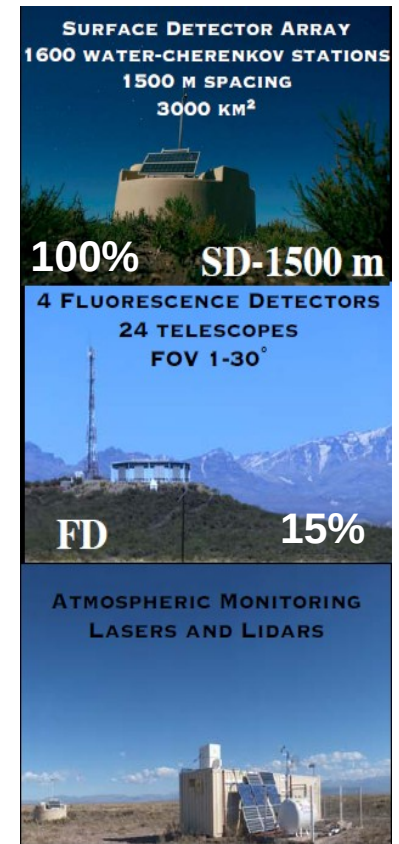
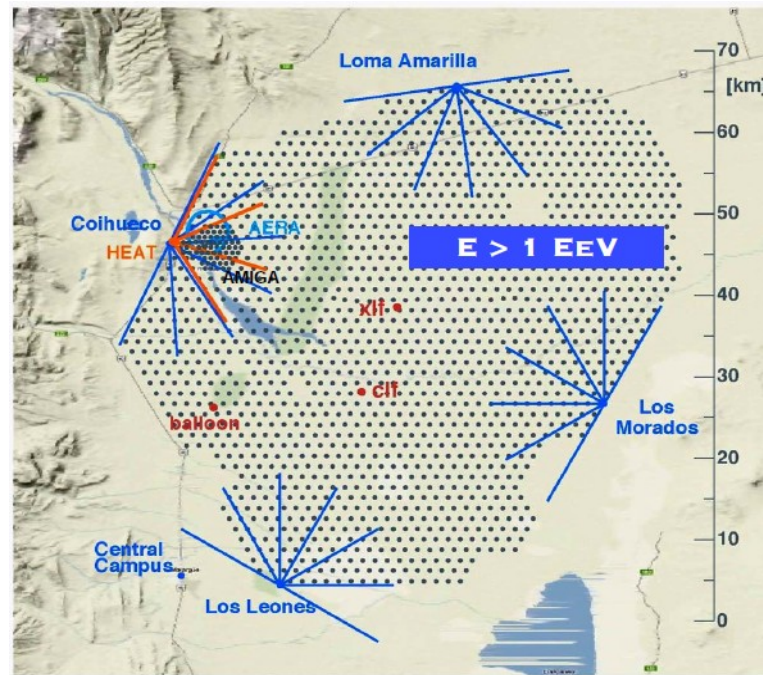
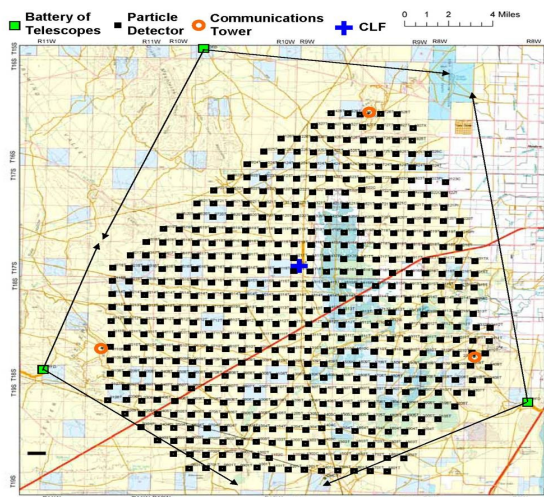
PAO/TA

● Pierre Auger Observatory (PAO)

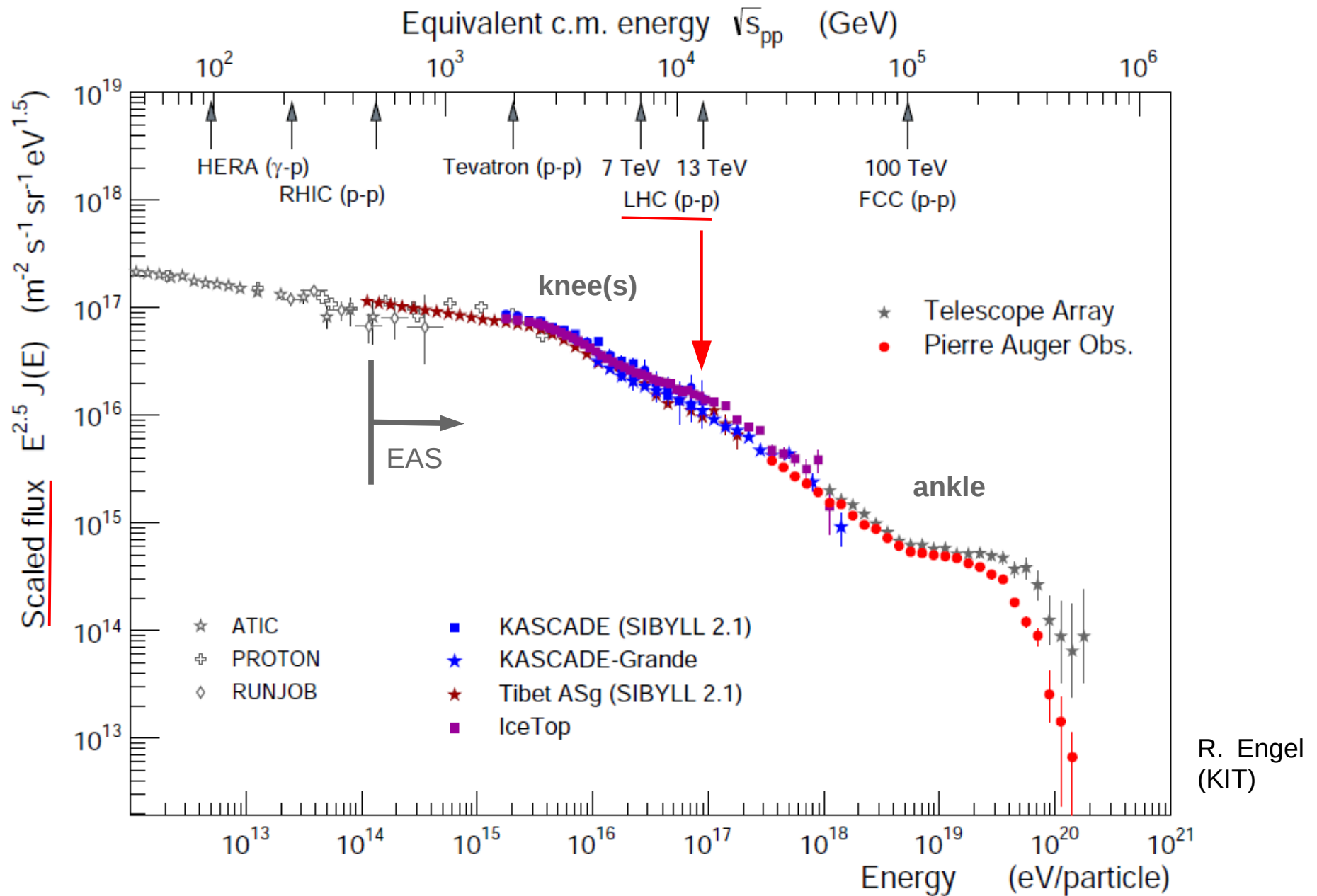
- ➔ Mendoza, Argentina
- ➔ Southern Hemisphere
- ➔ 3000 km^2 : $32000 \text{ km}^2/\text{sr/yr}$

● Telescope Array (TA)

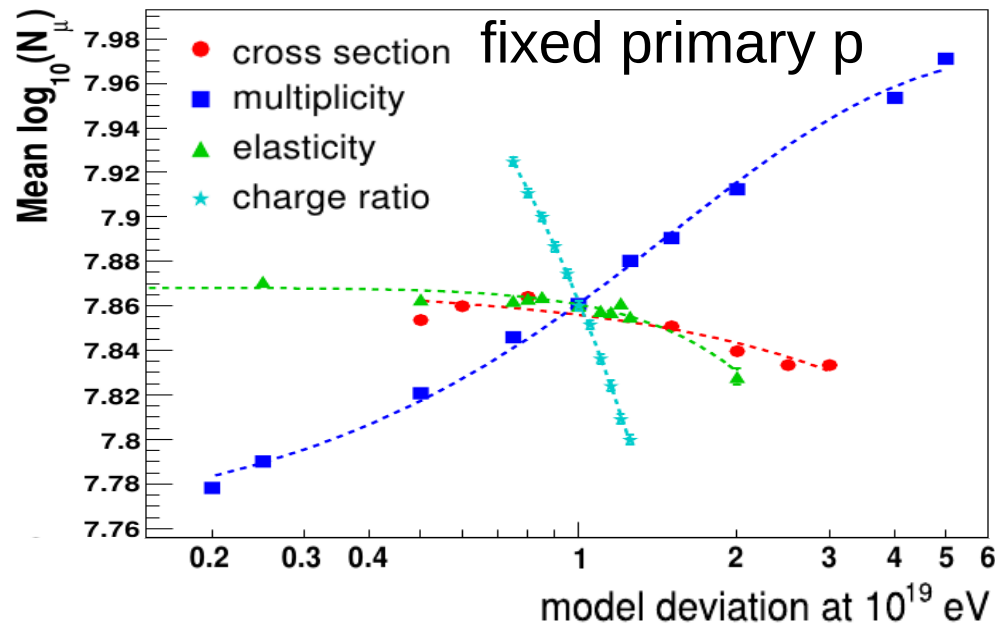
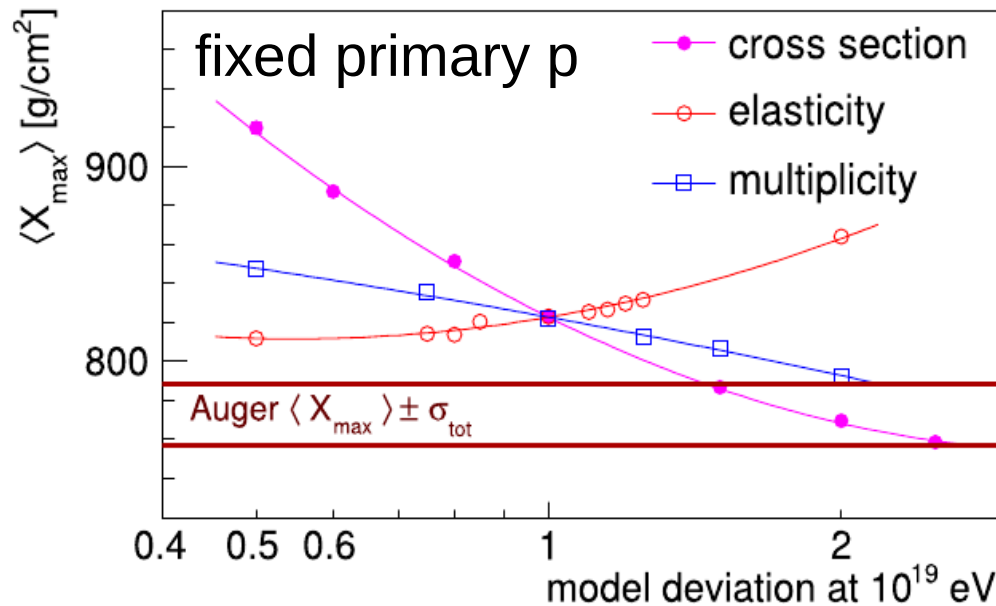
- ➔ Utah, USA
- ➔ Northern Hemisphere
- ➔ 680 km^2 : $3700 \text{ km}^2/\text{sr/yr}$



Energy Spectrum



Sensitivity to Hadronic Interactions



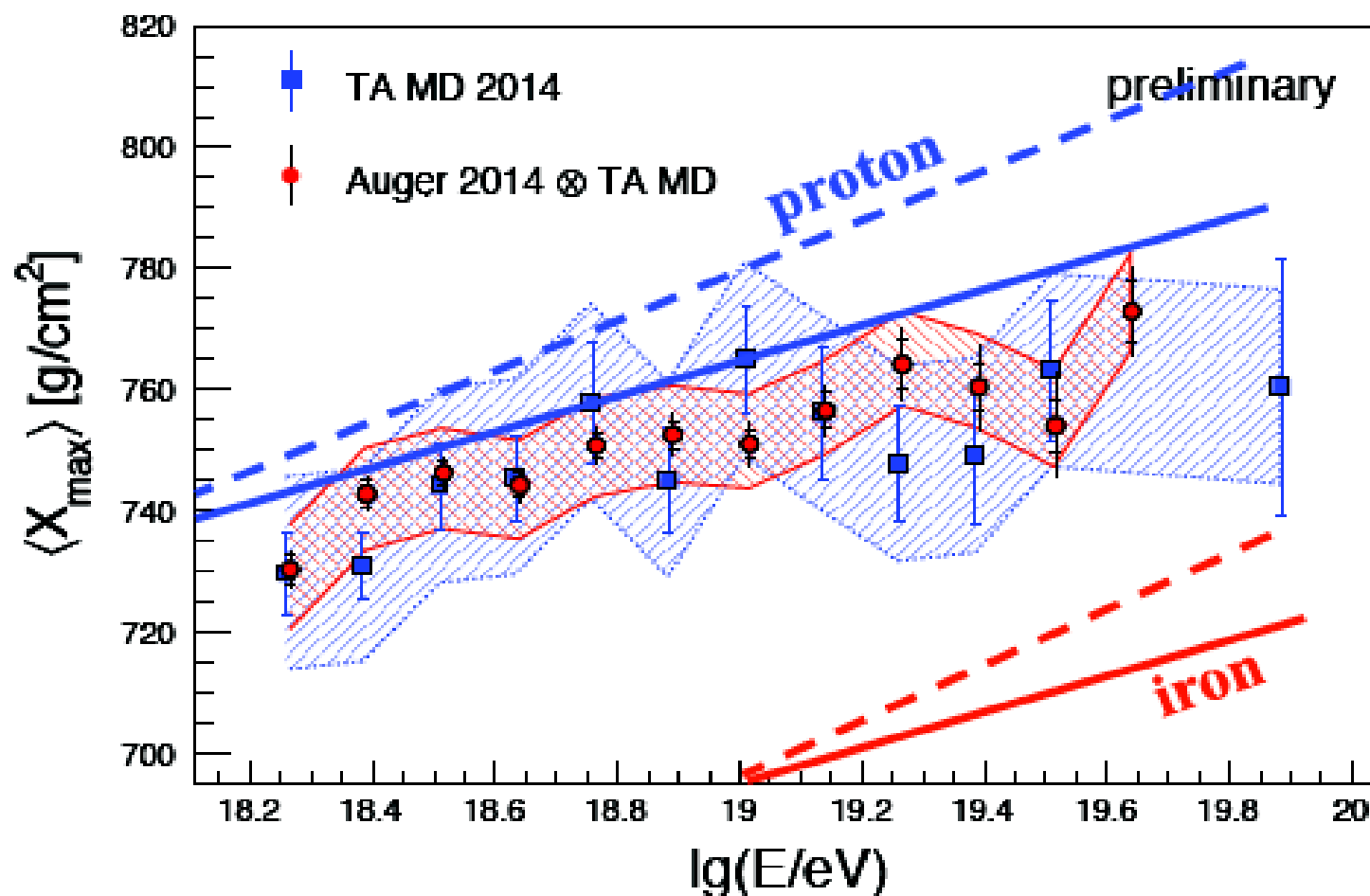
- Air shower development dominated by few parameters
 - ➔ mass and energy of primary CR
 - ➔ cross-sections (p-Air and (π-K)-Air)
 - ➔ (in)elasticity
 - ➔ multiplicity
 - ➔ charge ratio and baryon production
- Change of primary = change of hadronic interaction parameters
 - ➔ cross-section, elasticity, mult. ...

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

Pre-LHC Composition

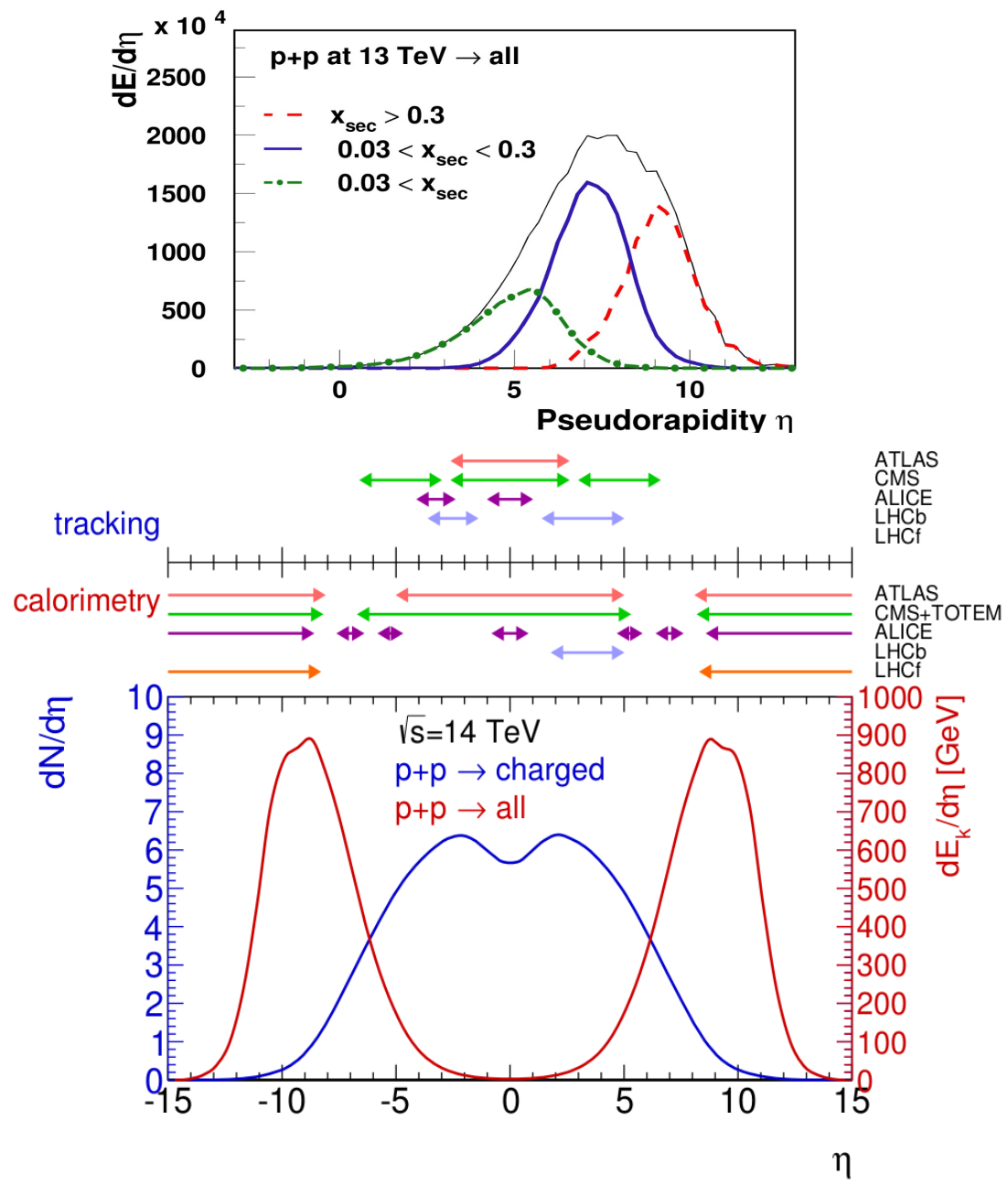
With pre-LHC models current CR data would be difficult to interpret

- ➔ Full (QGSJET) : **proton** (“easy” and “old” astrophysical interpretation)
- ➔ Dashed (EPOS/SIBYLL) : **mixed composition**



Roberto Aloiso UHECR (2015 PAO/TA working group)

LHC acceptance



● p-p data mainly from “central” detectors

- ➔ pseudorapidity $\eta = -\ln(\tan(\theta/2))$
- ➔ $\theta=0$ is midrapidity
- ➔ $\theta \gg 1$ is forward
- ➔ $\theta \ll 1$ 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

Hadronic Interaction Models for EAS

(HDPM)

Old generation : (SIBYLL 2.1 QGSJET01 DPMJET 2.55 VENUS) (<2001)

All Glauber based

But differences in hard, remnants, diffraction ...

New (!) generation :

LHC tuned :

LHC inspired : SIBYLL 2.3c QGSJET III (?) DPMJET III EPOS 3 (2017-)

Motivation :

- update with latest LHC results in simple model

Motivation :

- Hard Pomeron-Pomeron connexion

Motivation :

- update with LHC results
- fix high energy

Motivation :

- binary scaling in hard probes

Engel et al.

semi-hard

soft

NEXUS 3.97

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

(QGSJET II-03)

(EPOS 1.99) (2005-2012)

QGSJET II-04

Ostapchenko

EPOS LHC

(2013-)

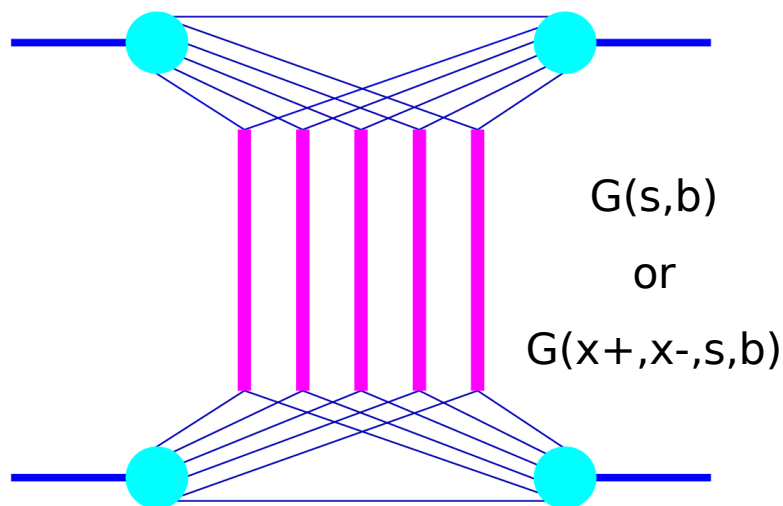
Pierog & Werner

Riehn & Engel

Fedinitch & Engel

(2017-)

Cross Section and Multiplicity 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**)

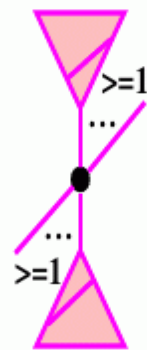
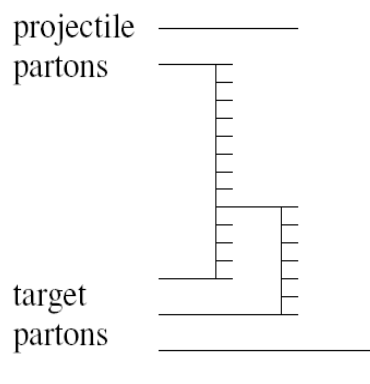
● pQCD

- ➔ 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

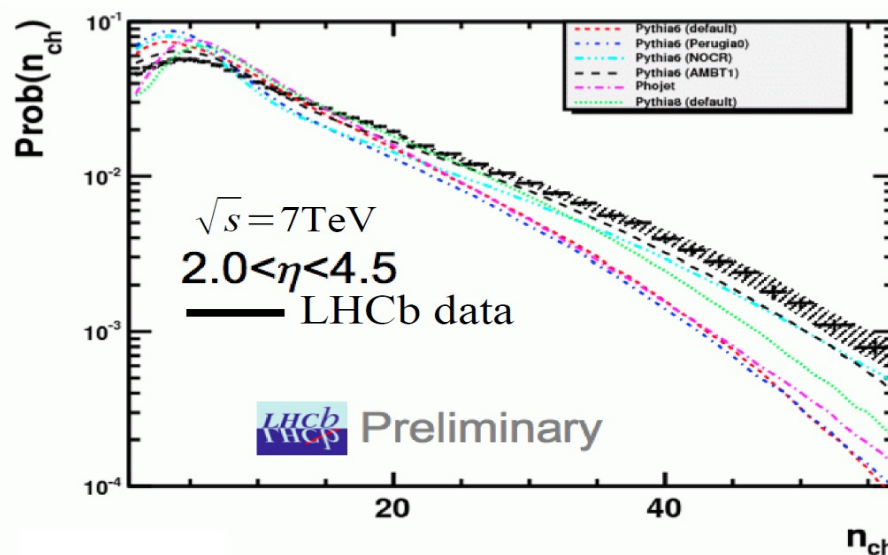
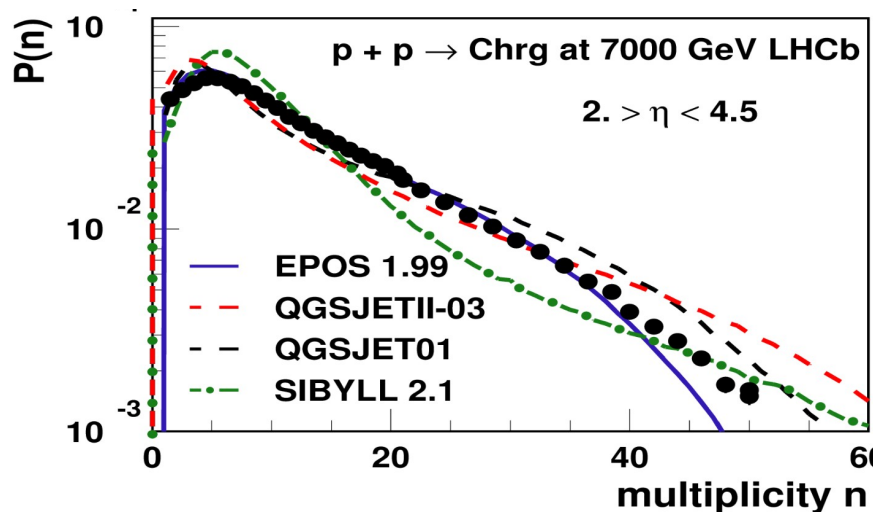
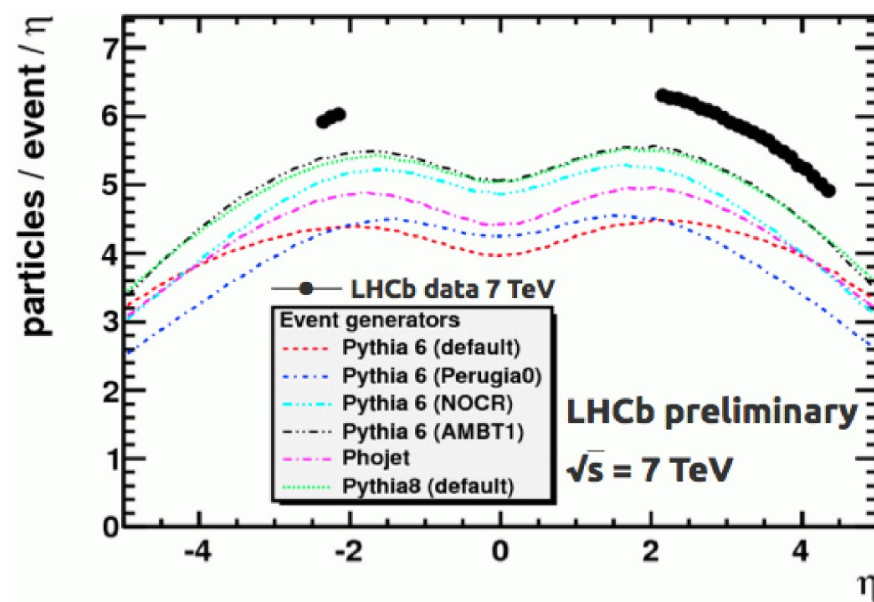
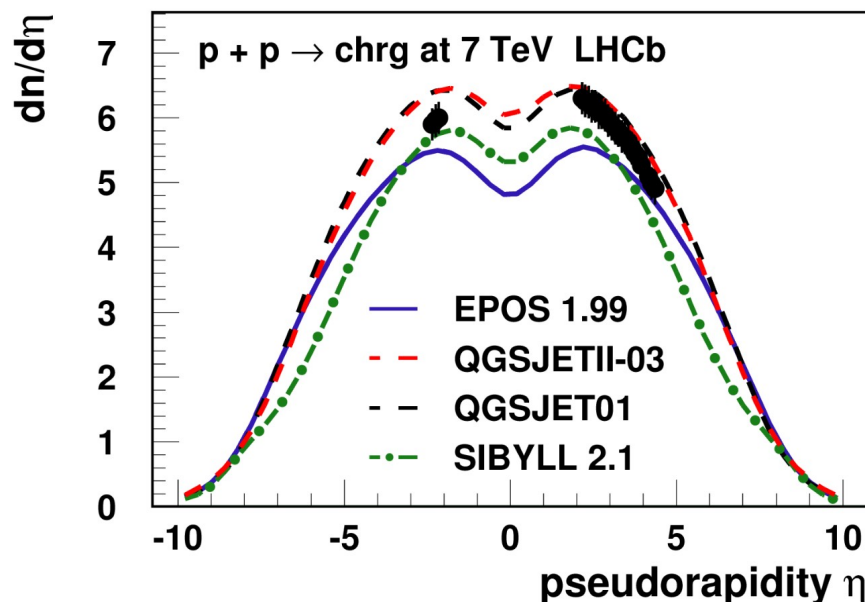
EPOS

QGSJET II



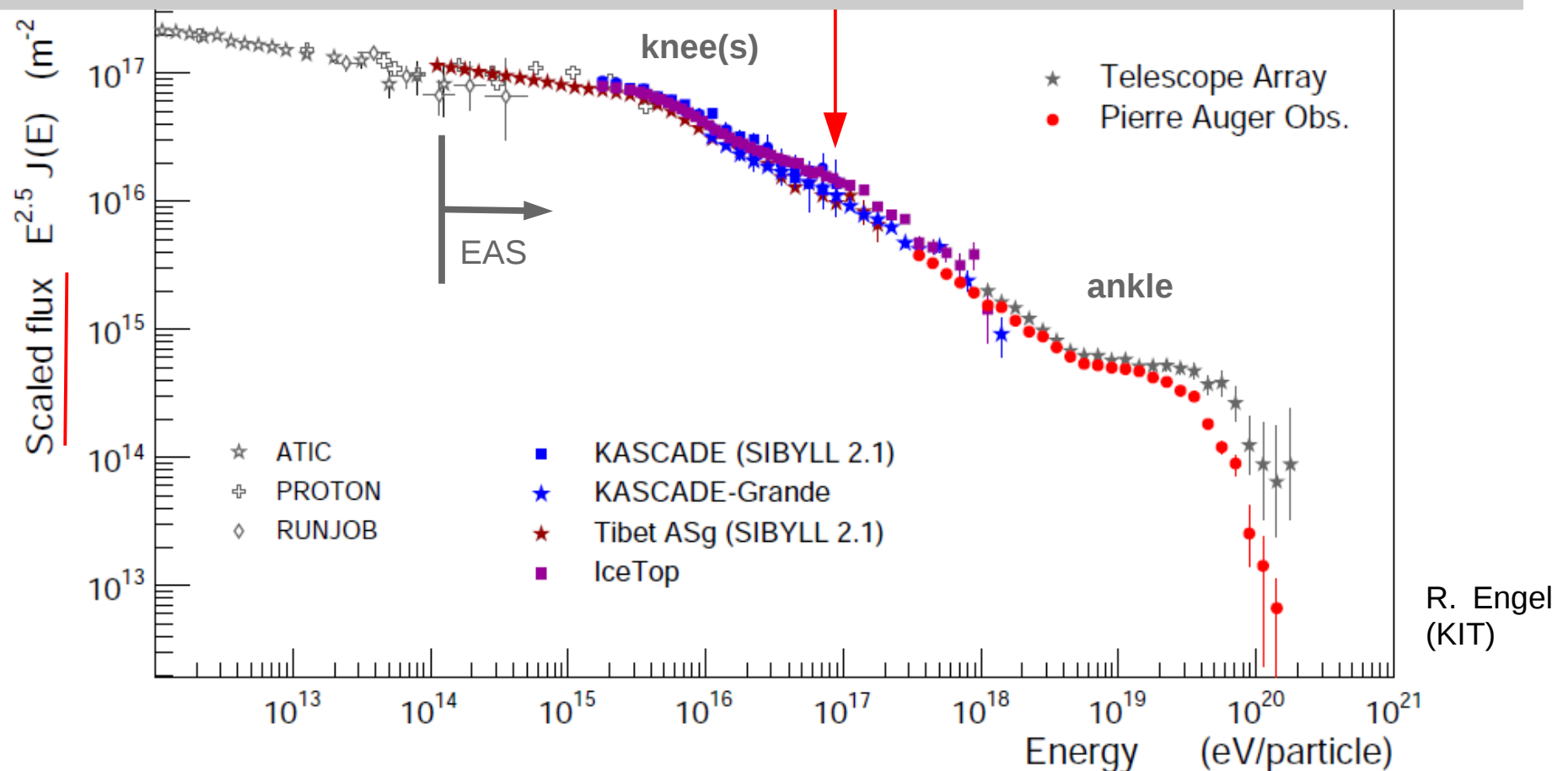
Cosmic Ray vs High Energy Physics

Models used for EAS had better LHC predictions than HEP MC



Energy Spectrum

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 !



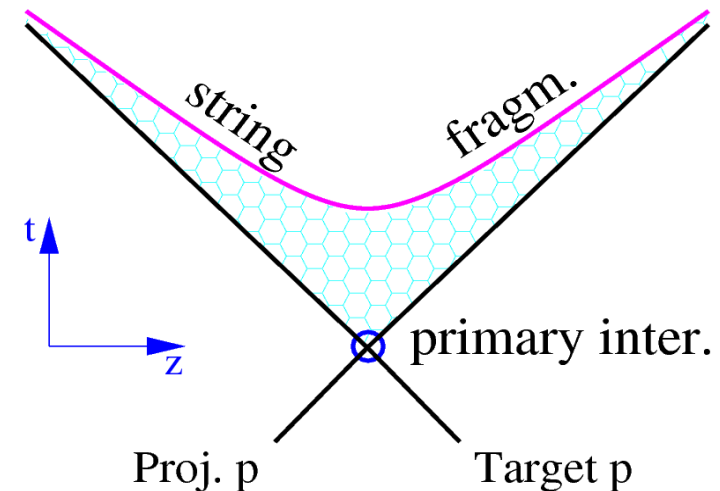
Post-LHC Models

● Sibyll 2.1 to Sibyll 2.3c :

- ➔ ρ^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



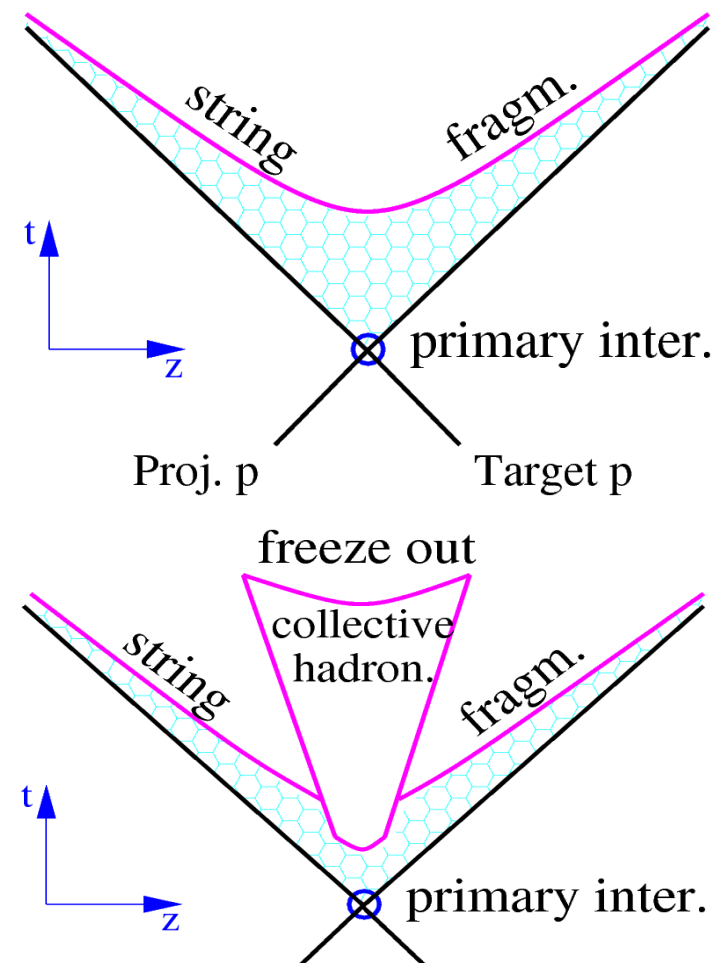
Post-LHC Models

● QGSJETII-03 to QGSJETII-04 :

- ➔ loop diagrams
- ➔ ρ^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

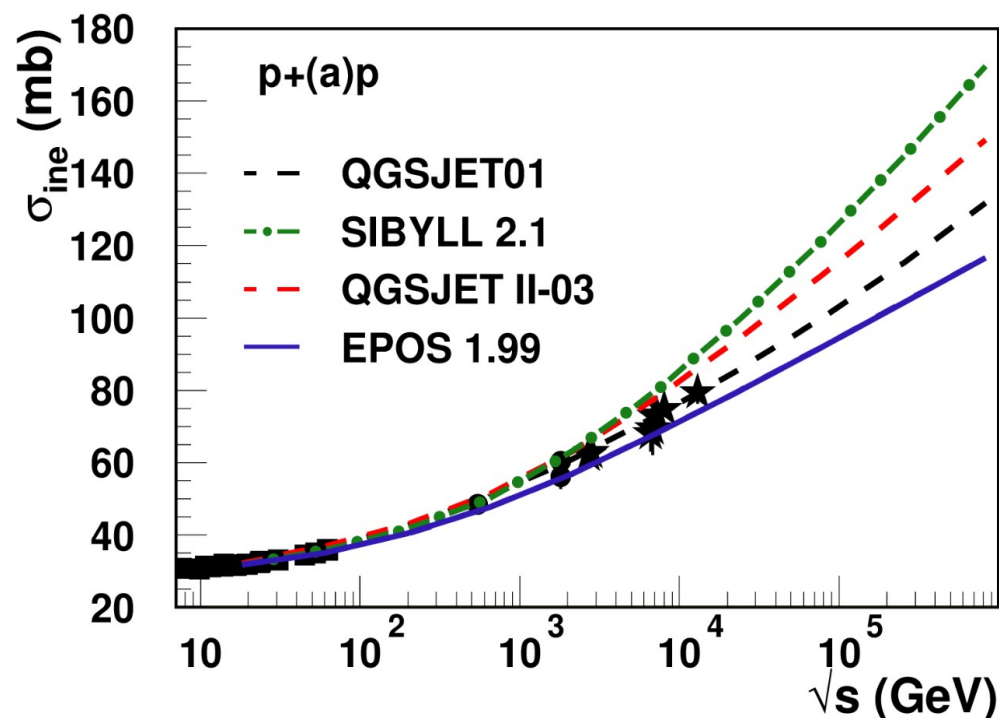


No direct influence of collective effects on EAS simulations seen but important to compare to LHC and set parameters properly ($\langle p_t \rangle$, ...).

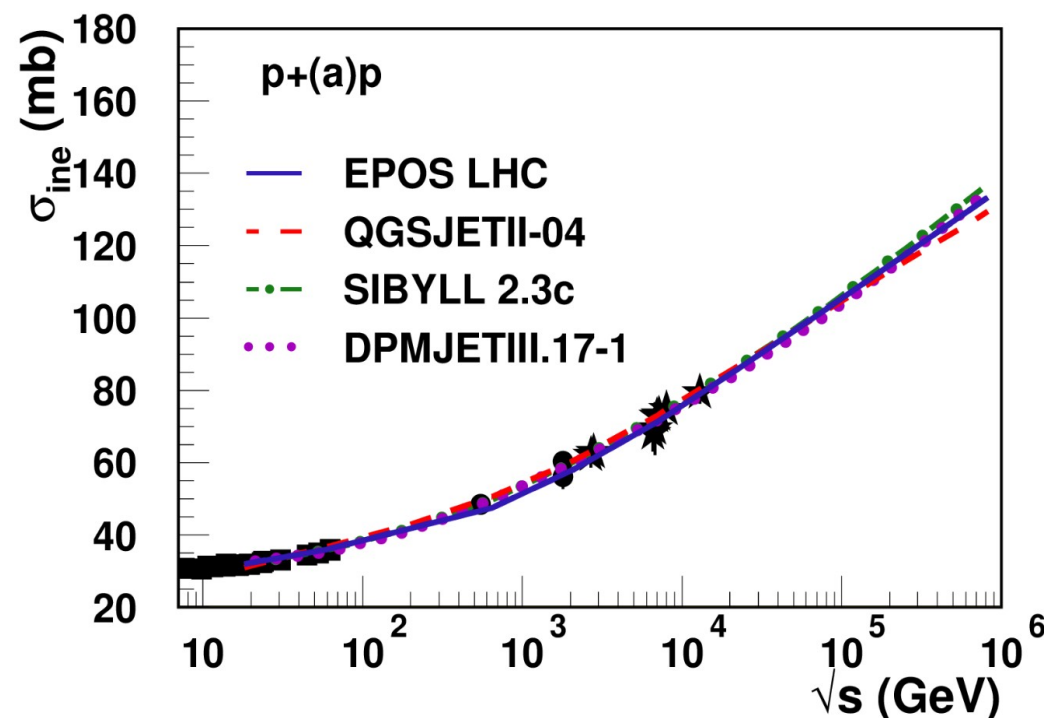
Cross Sections

- ➔ 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



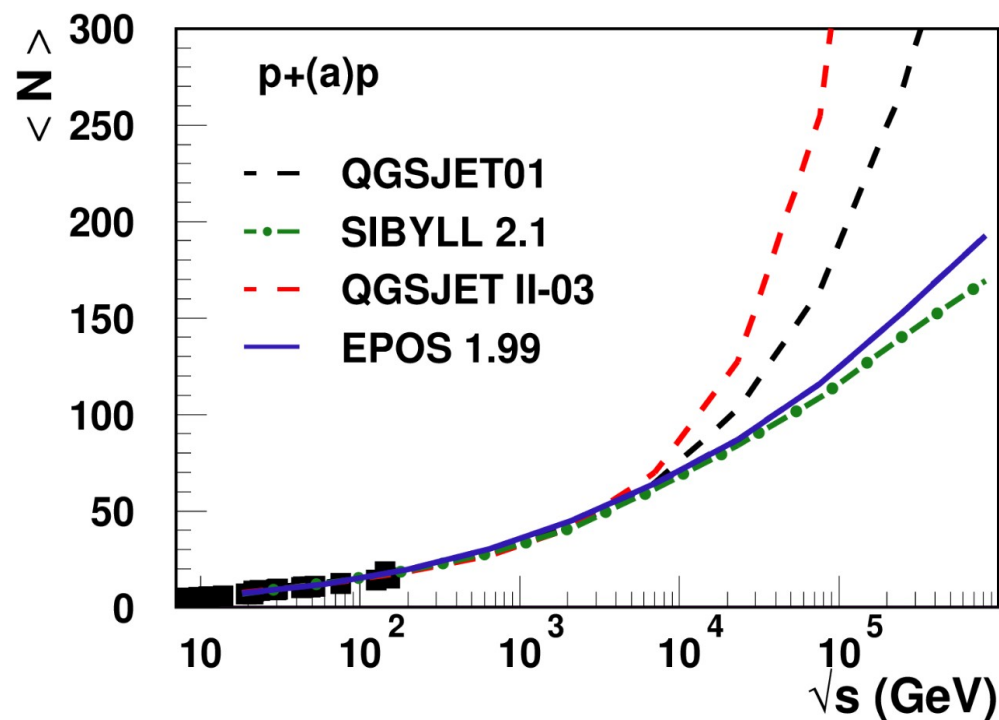
Post - LHC



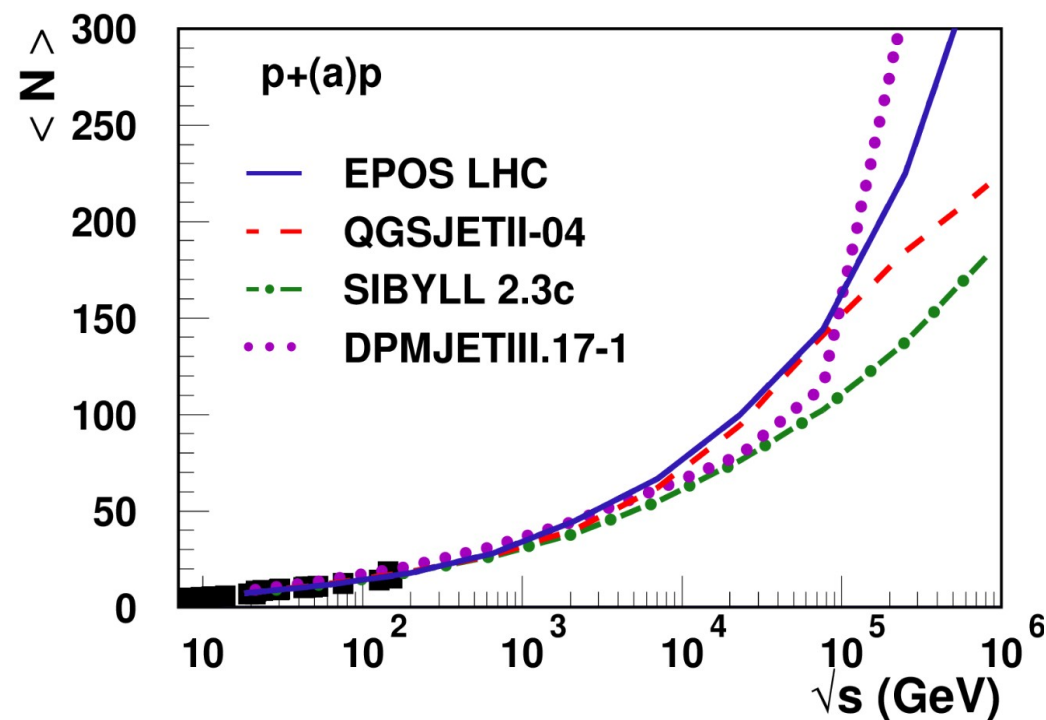
Multiplicity

- Multiplicity fixed by data up to 900 GeV
- extrapolation to high energy is still model dependent ?

Pre - LHC



Post - LHC

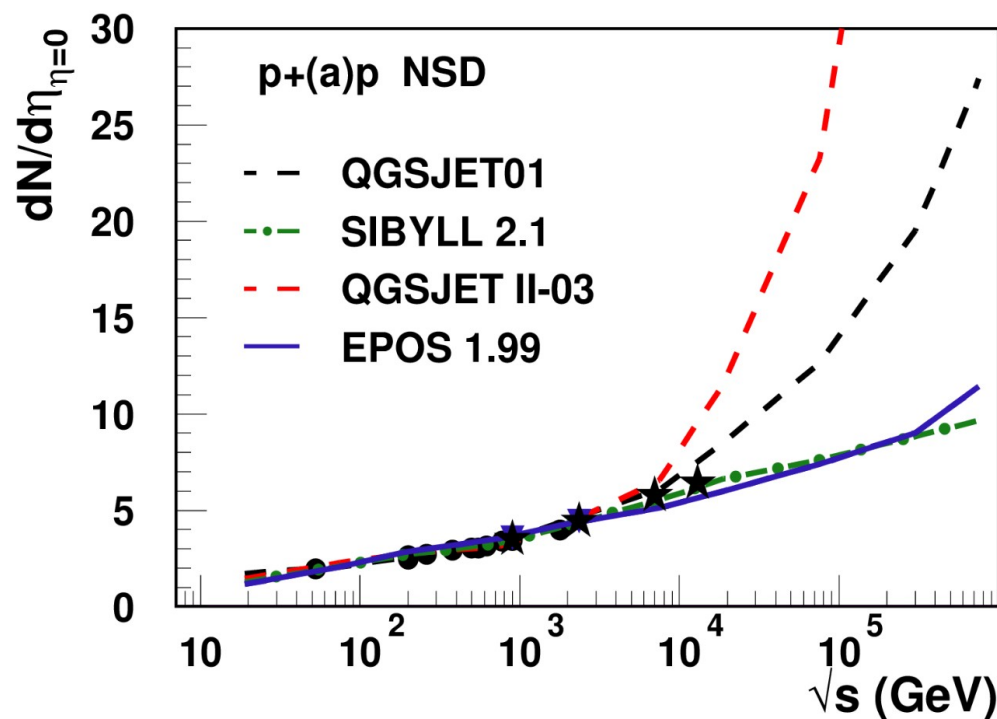


Multiplicity at mid-rapidity

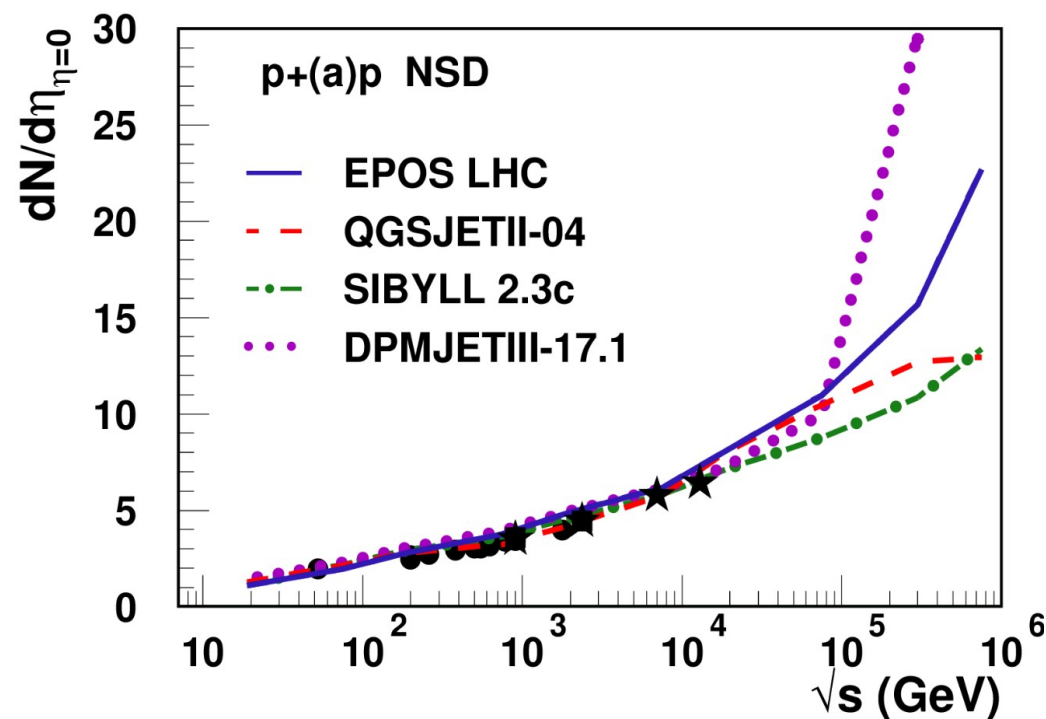
Looking at particles produced perpendicular to the beam axis :

- ➡ 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



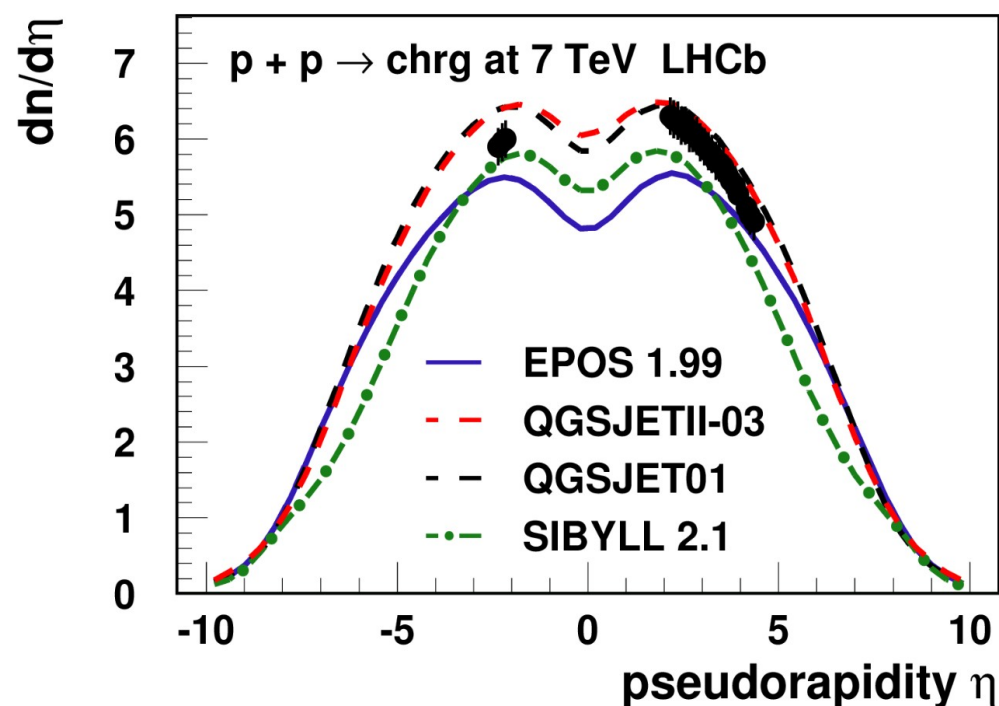
Post - LHC



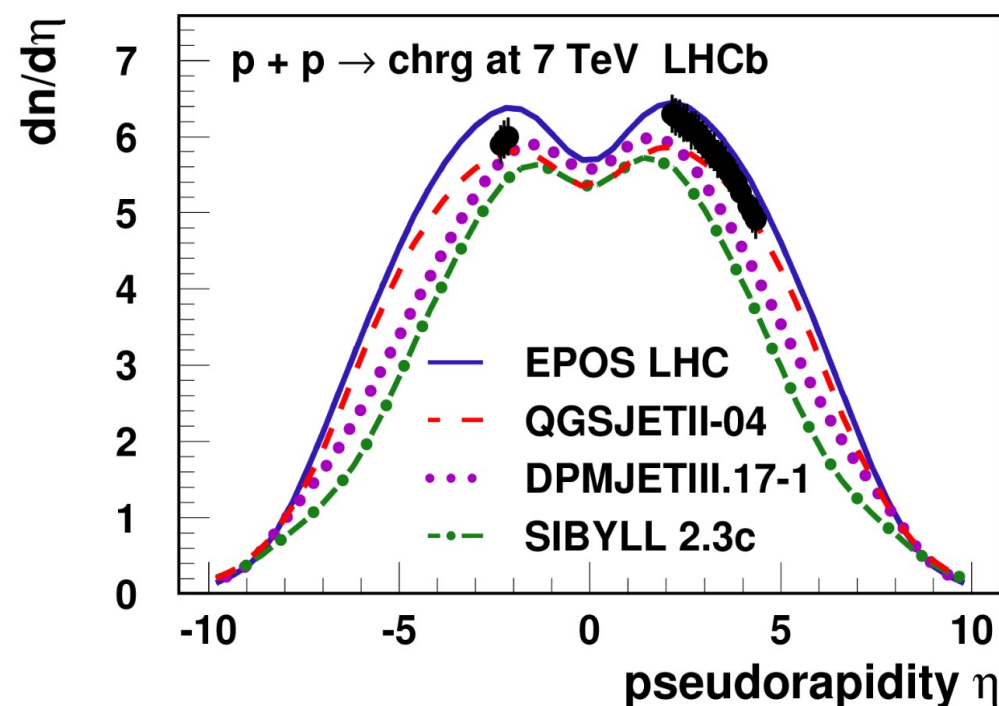
Pseudorapidity

- ➔ 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



Post - LHC



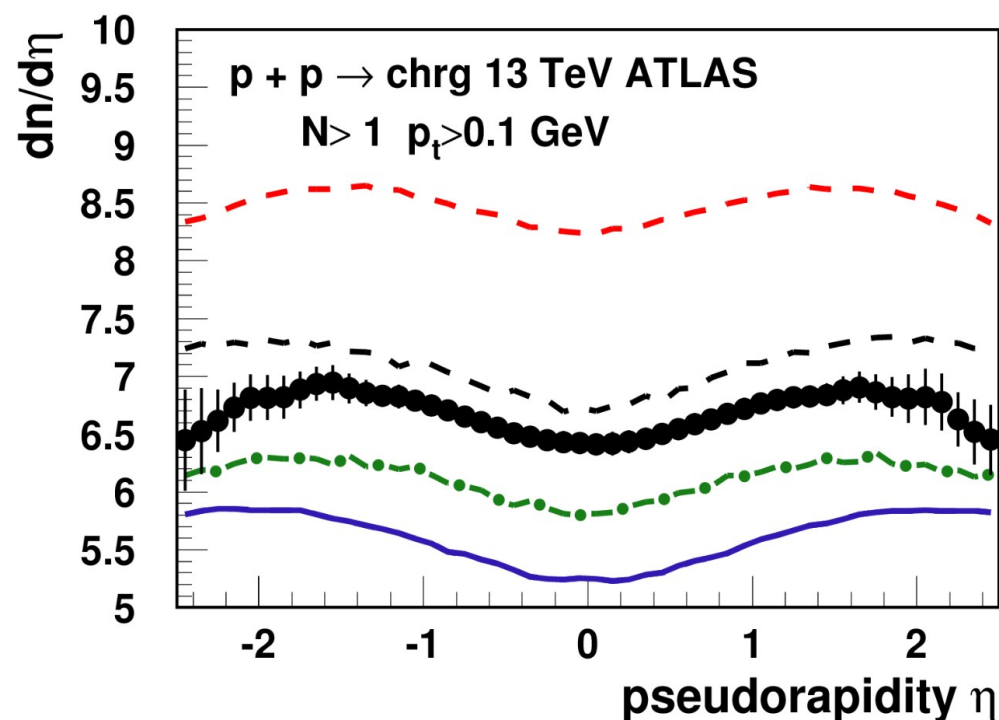
Test of Models vs Accelerator Data

➔ From LHC data

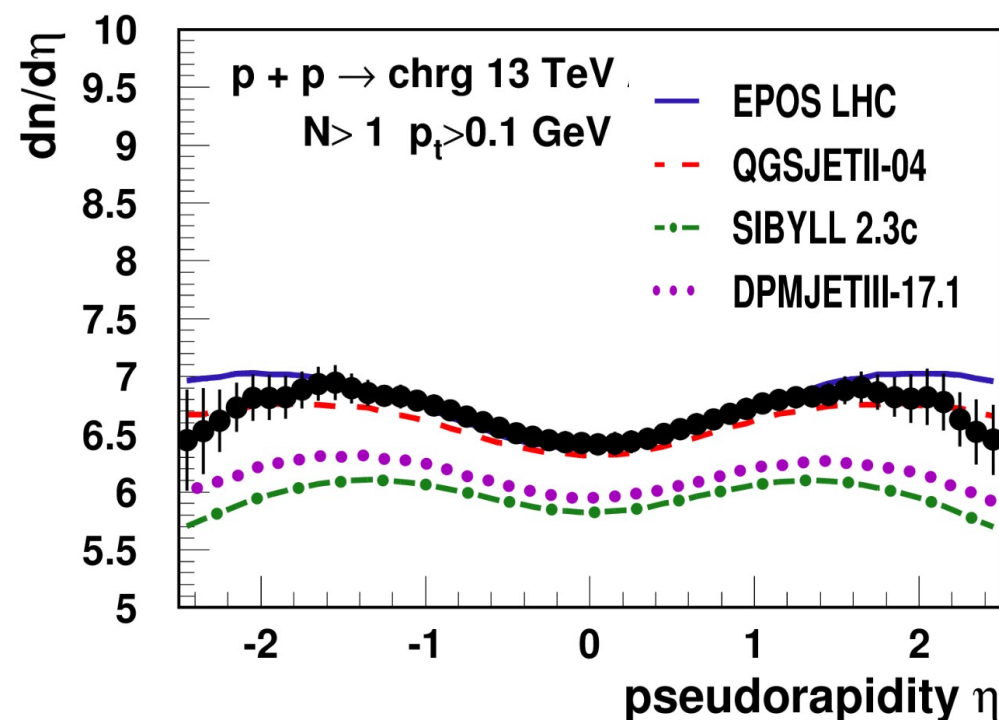
■ All pre-LHC models extrapolation excluded

- - QGSJET01
- - SIBYLL 2.1
- - QGSJET II-03
- - EPOS 1.99
- DPMJETIII.17-1 and SIBYLL 2.3c underestimate multiplicity
- QGSJETII-04 and EPOS LHC ~ OK (and similar to Pythia 8)

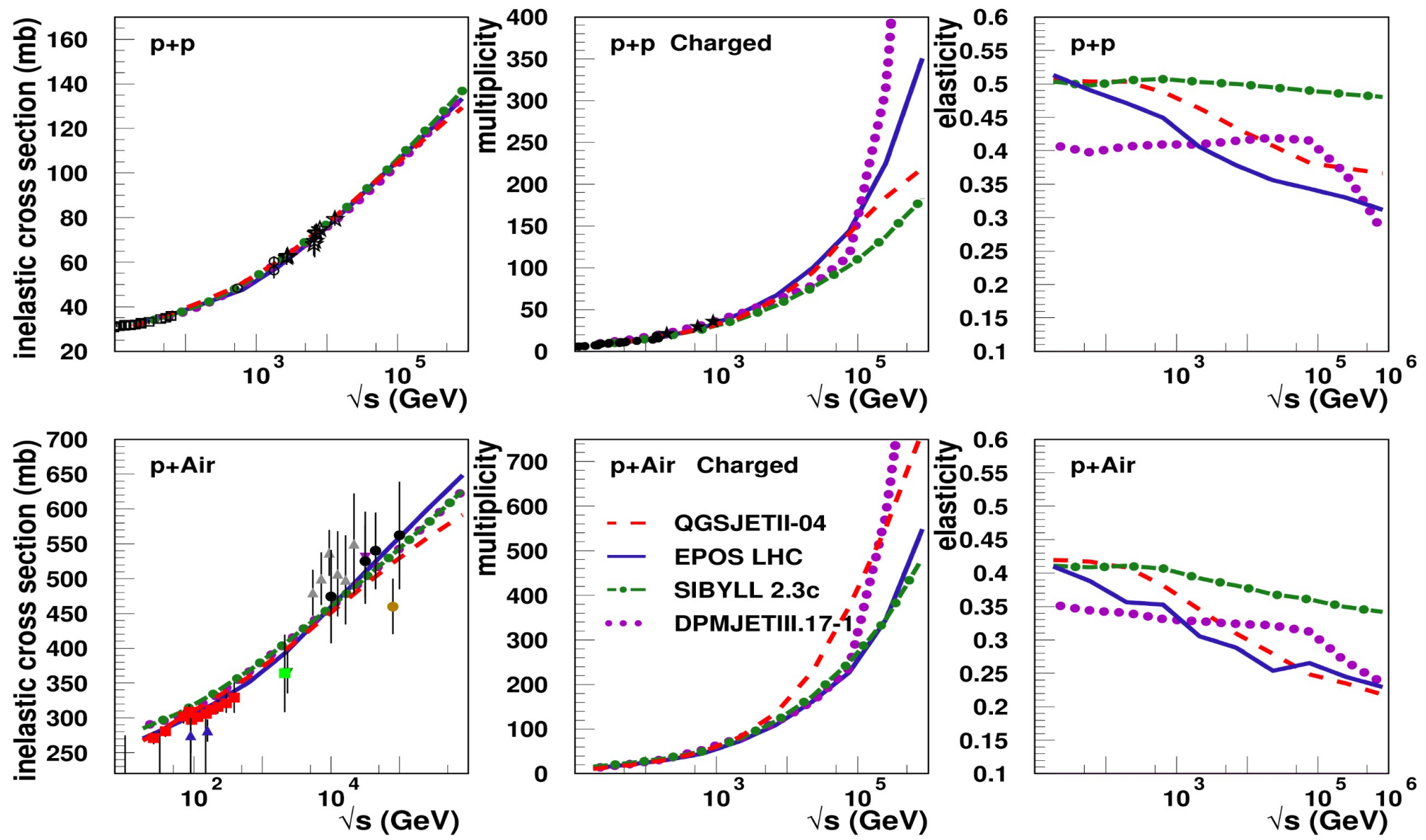
Pre - LHC



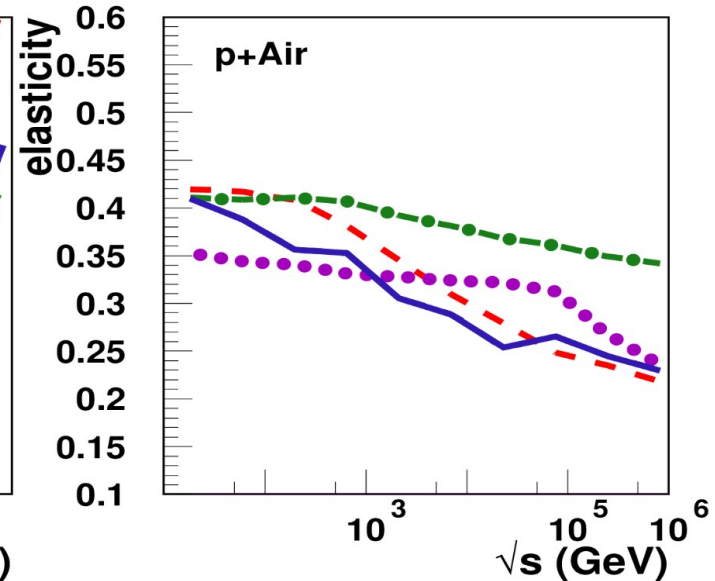
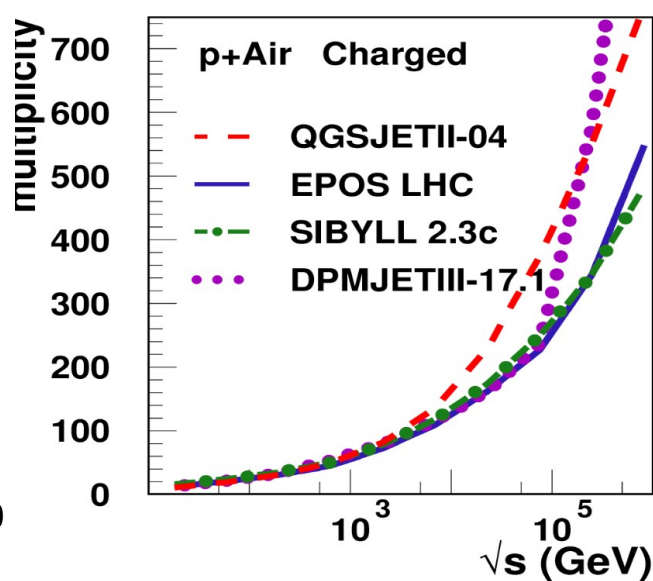
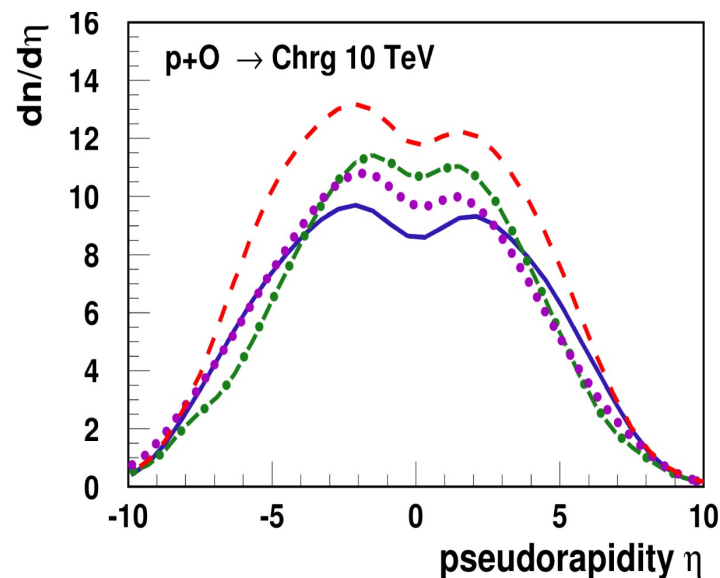
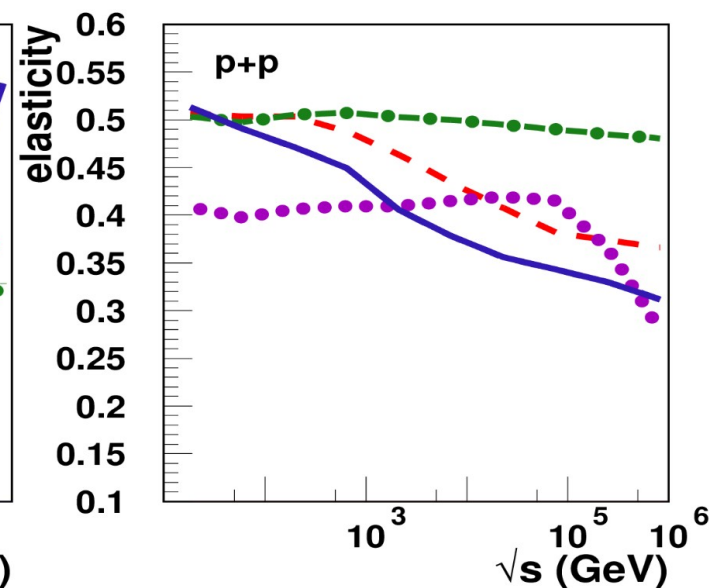
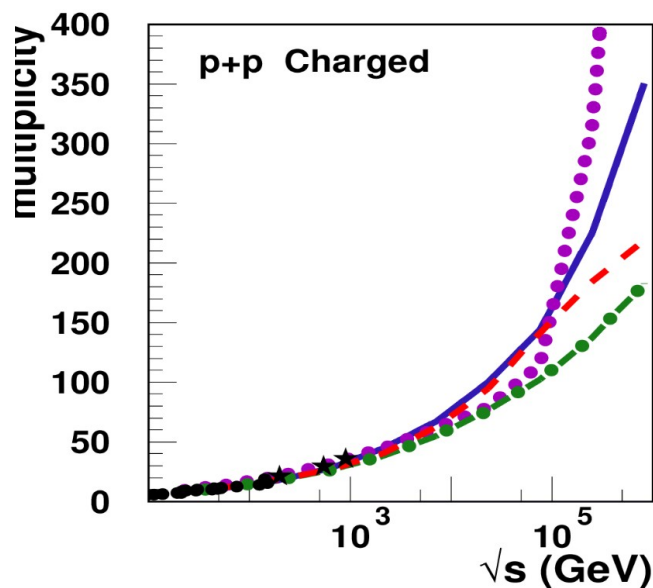
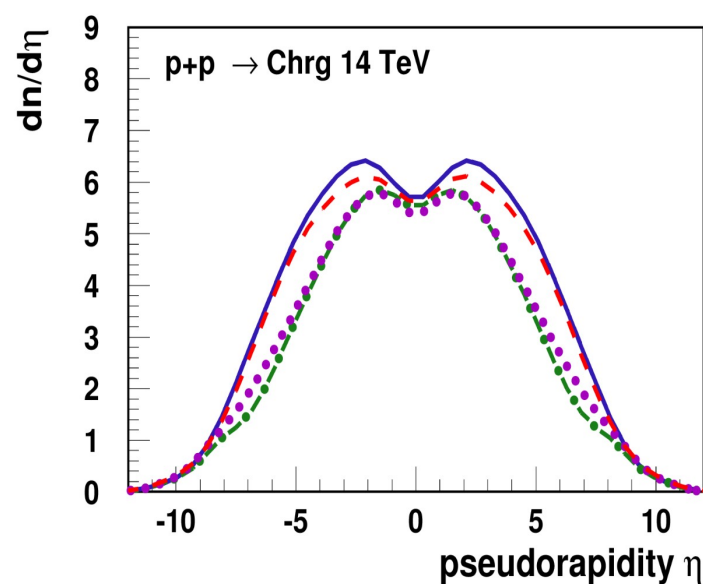
Post - LHC



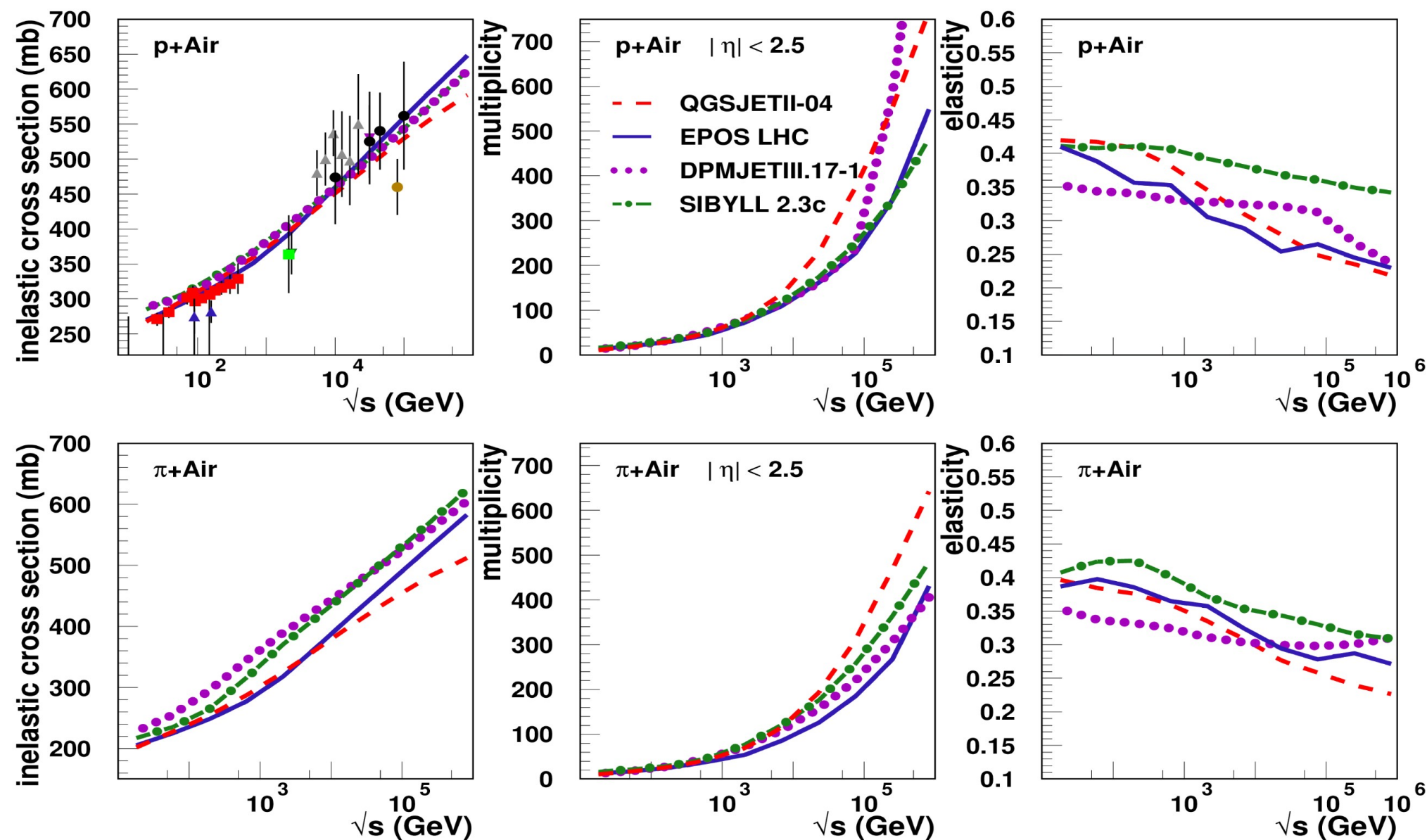
Ultra-High Energy Hadronic Model Predictions p-Air



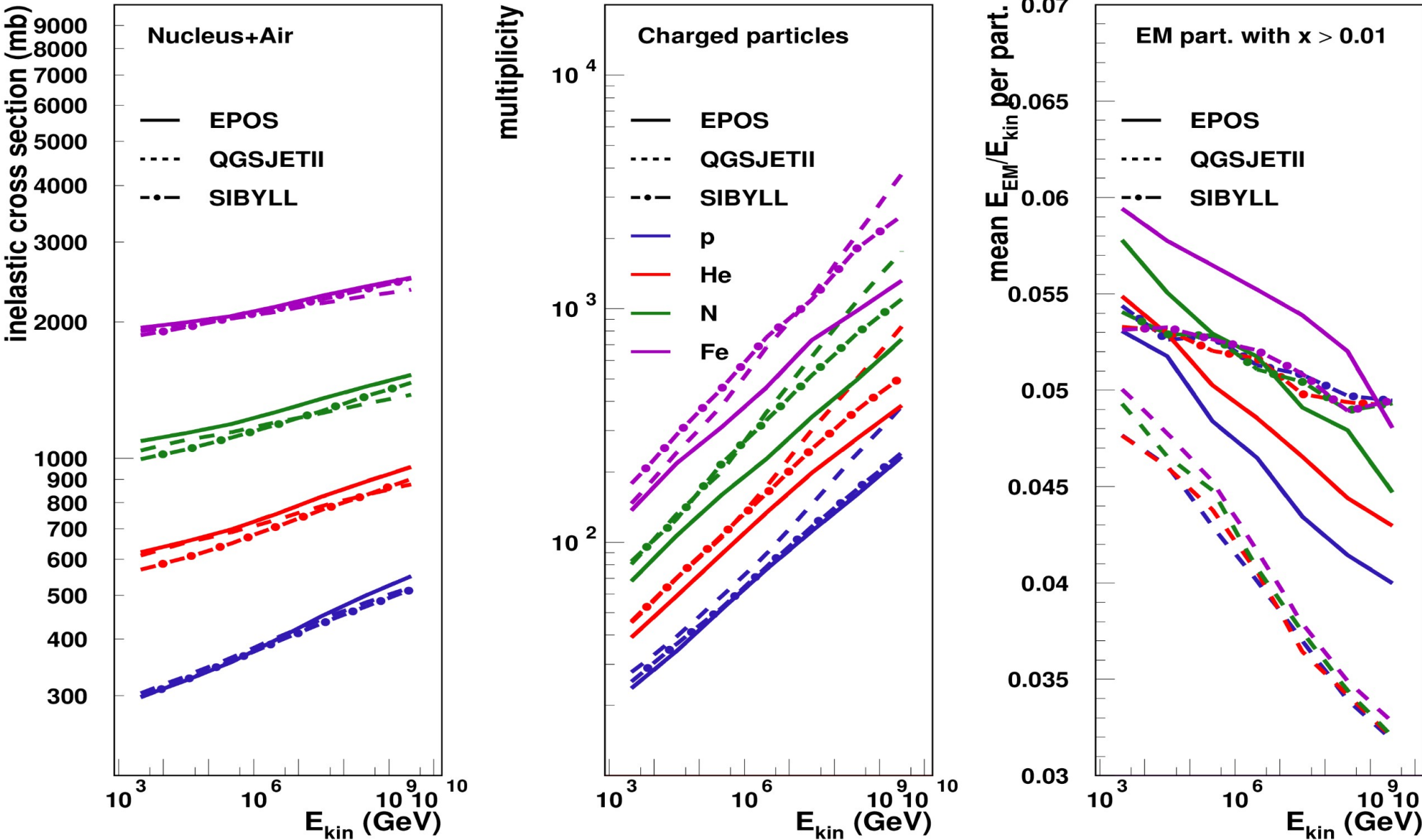
Ultra-High Energy Hadronic Model Predictions p-Air



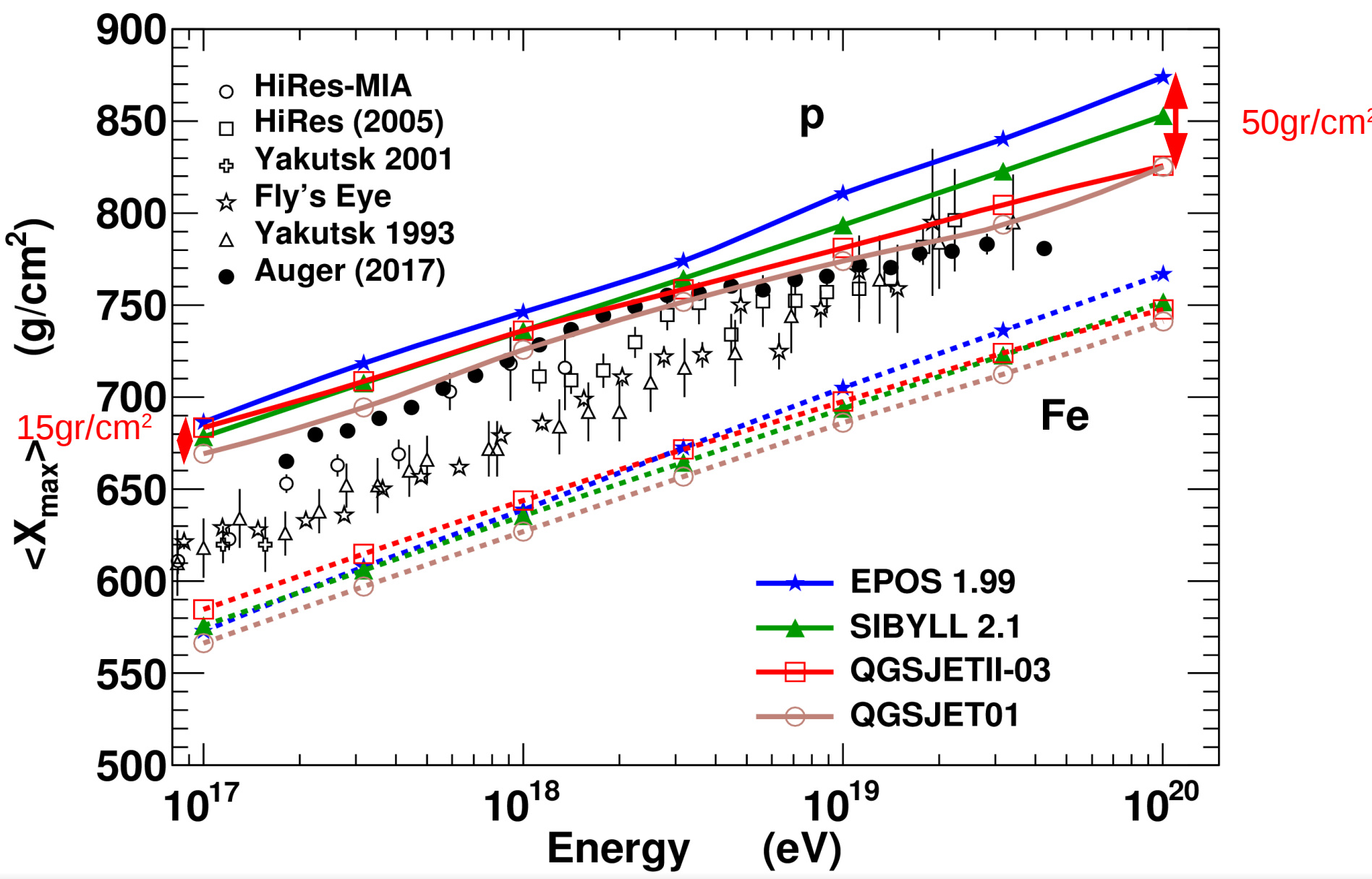
Ultra-High Energy Hadronic Model Predictions π -Air



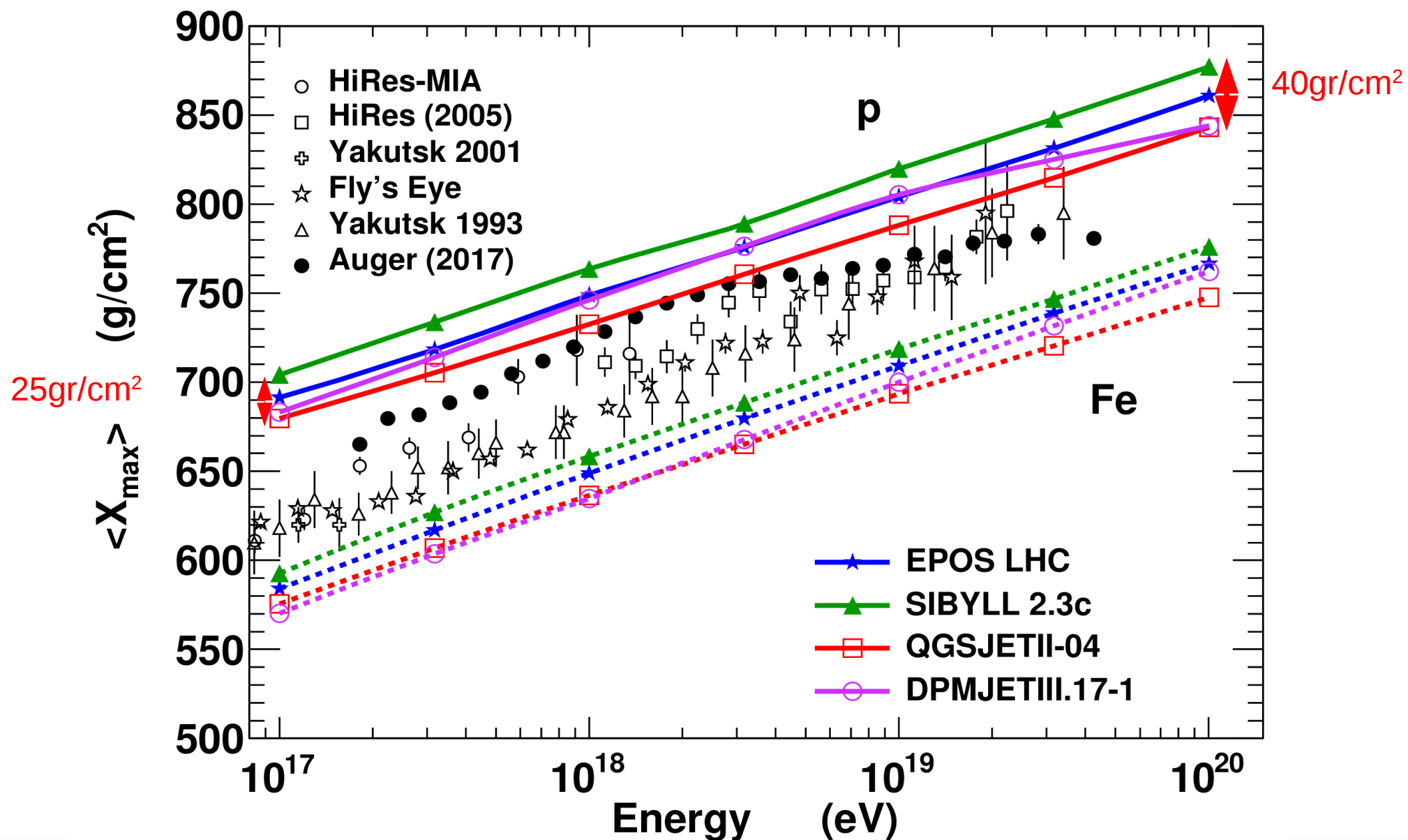
Ultra-High Energy Hadronic Model Predictions A-Air



EAS with Old CR Models : X_{max}

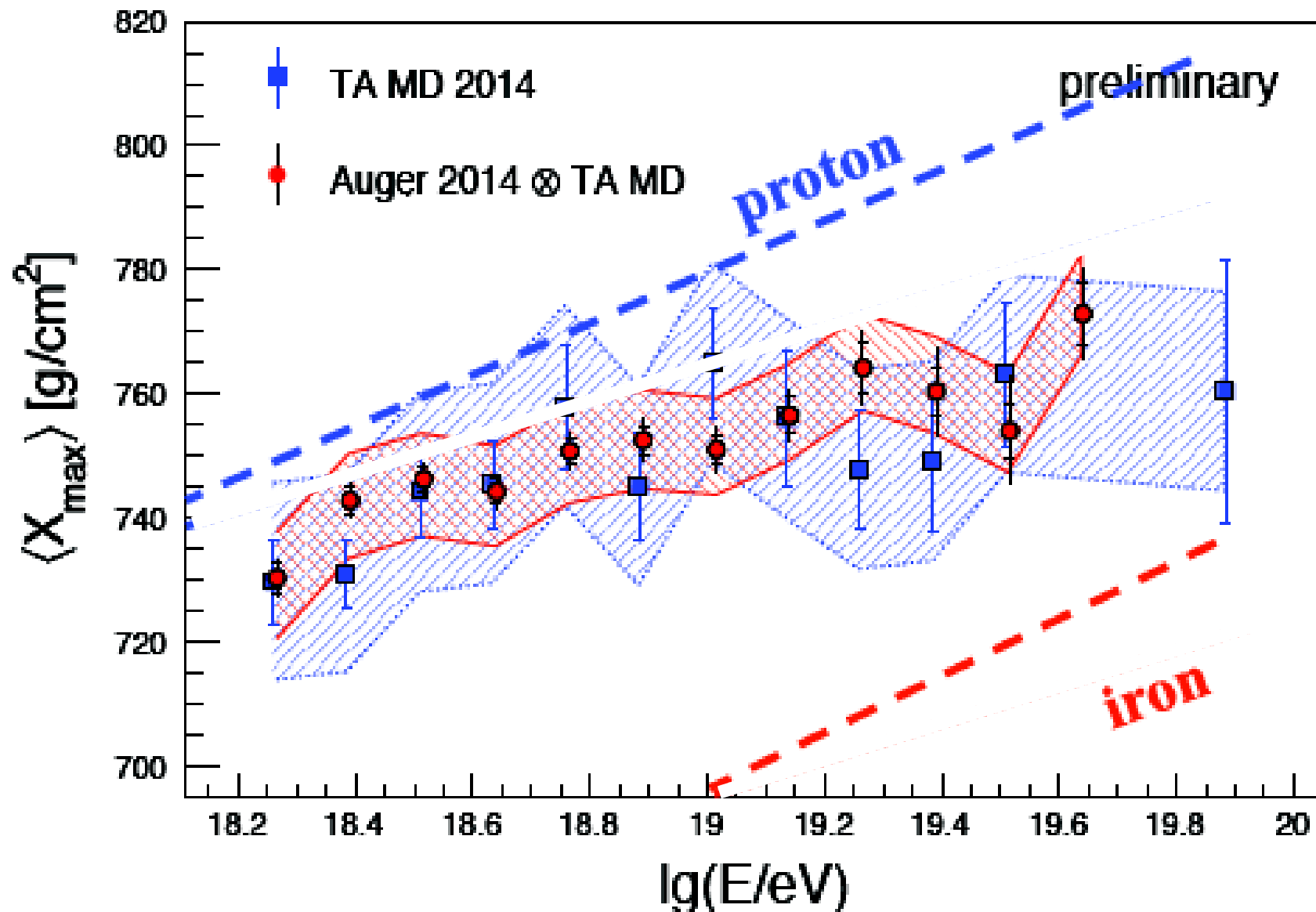


EAS with Re-tuned CR Models : X_{\max}



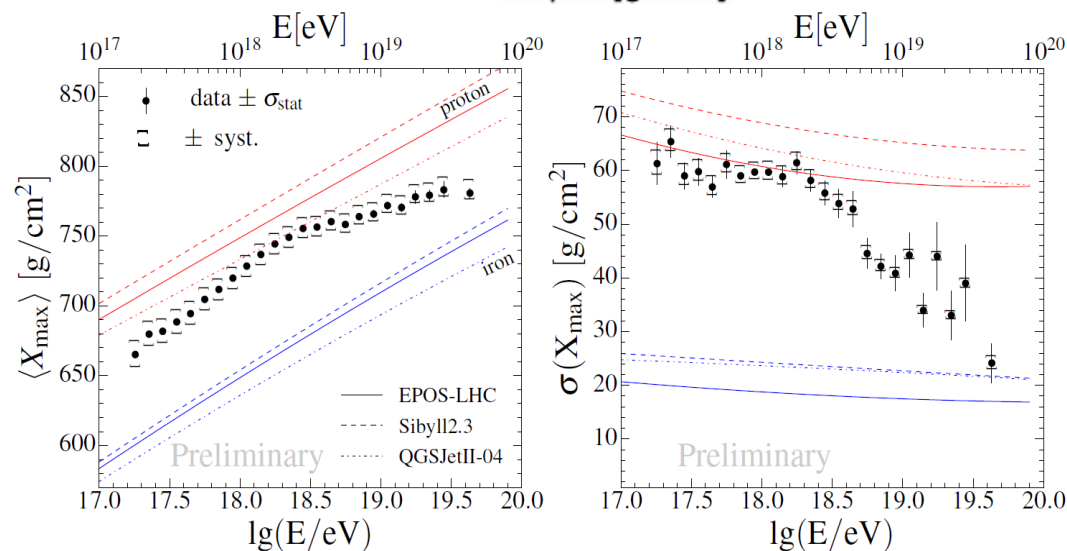
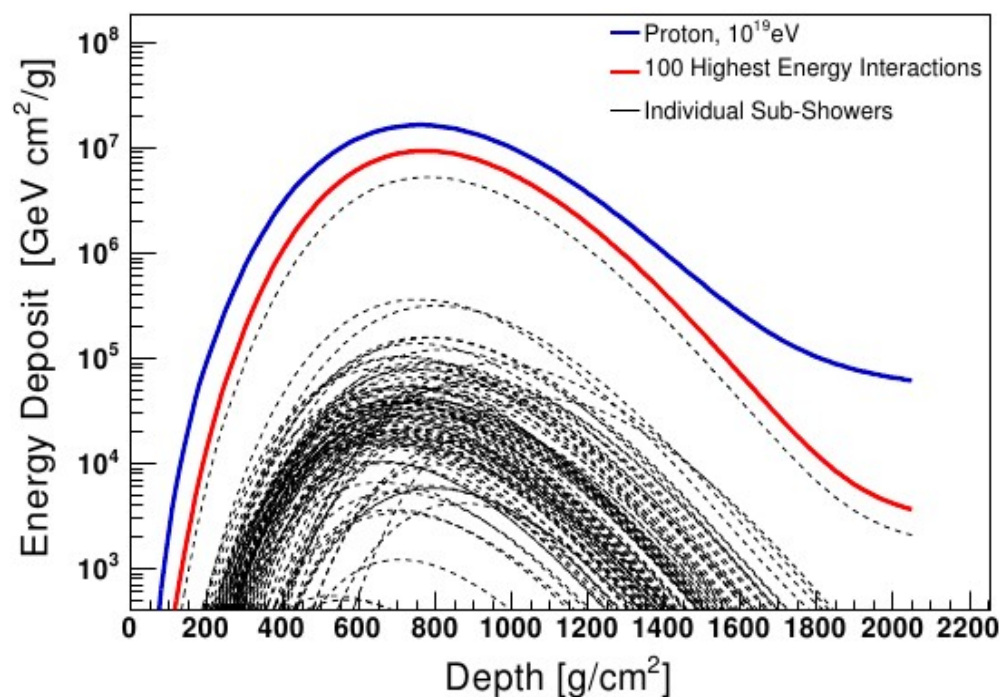
Post-LHC Composition

With post-LHC models there is no doubt about **mixed composition**



Fluorescence Detector (FD)

From R. Ulrich (KIT)

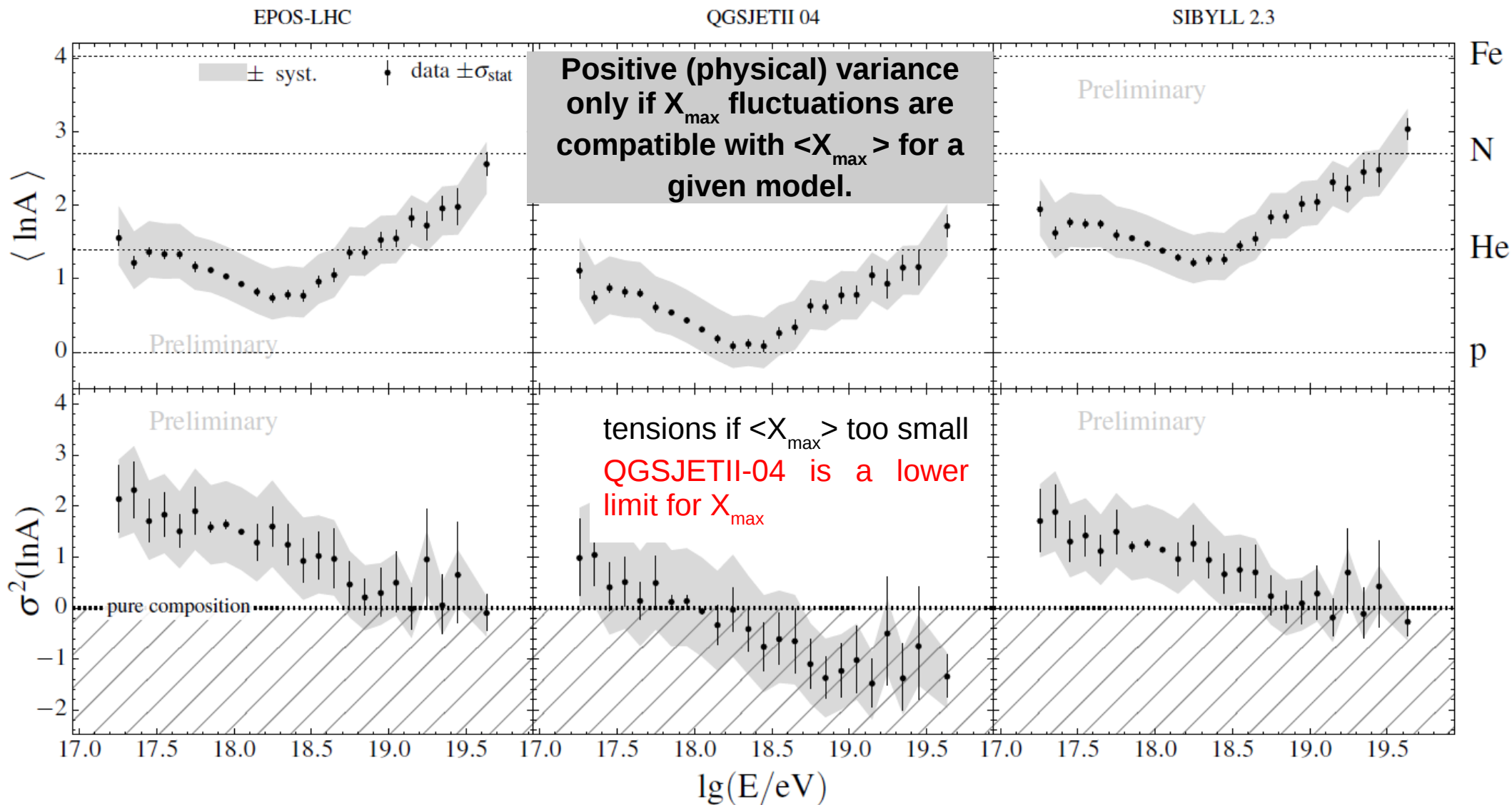


- **Most direct measurement**
 - ➔ dominated by first interaction
- **Reference mass for other analysis**
 - ➔ $\langle \ln A \rangle$ from $\langle X_{\max} \rangle$ and RMS
- **Possibility to use the tail of X_{\max} distribution to measure p-Air inelastic cross-section.**
 - ➔ require no contamination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

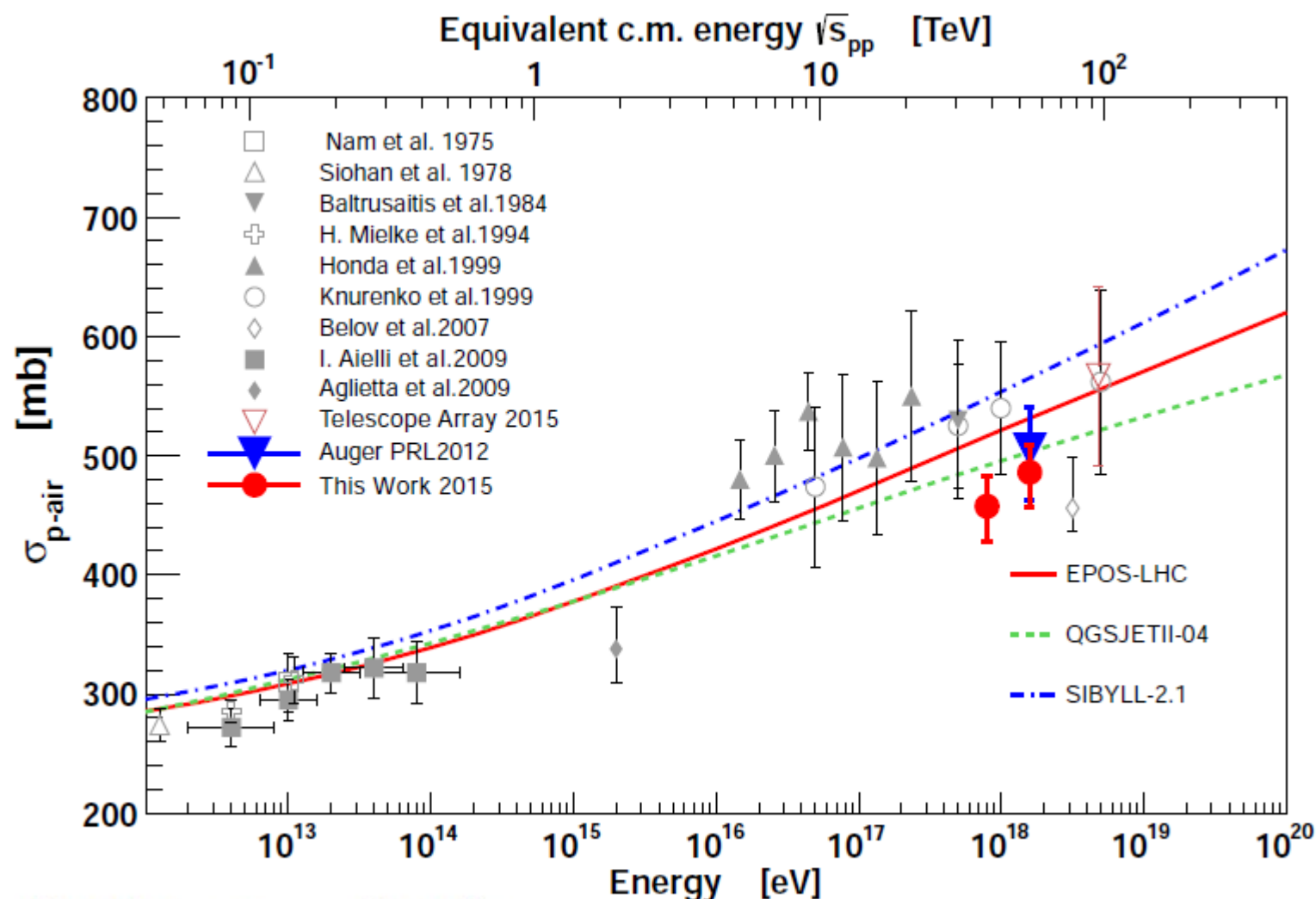
Model Consistency using Electromagnetic Component

Study by Pierre Auger Collaboration (ICRC 2017)

➔ std deviation of $\ln A$ allows to test model consistency.



p-Air Production Cross Section @ 39 and 55 TeV



Results, σ_{p-air} in mb

Lower energy point

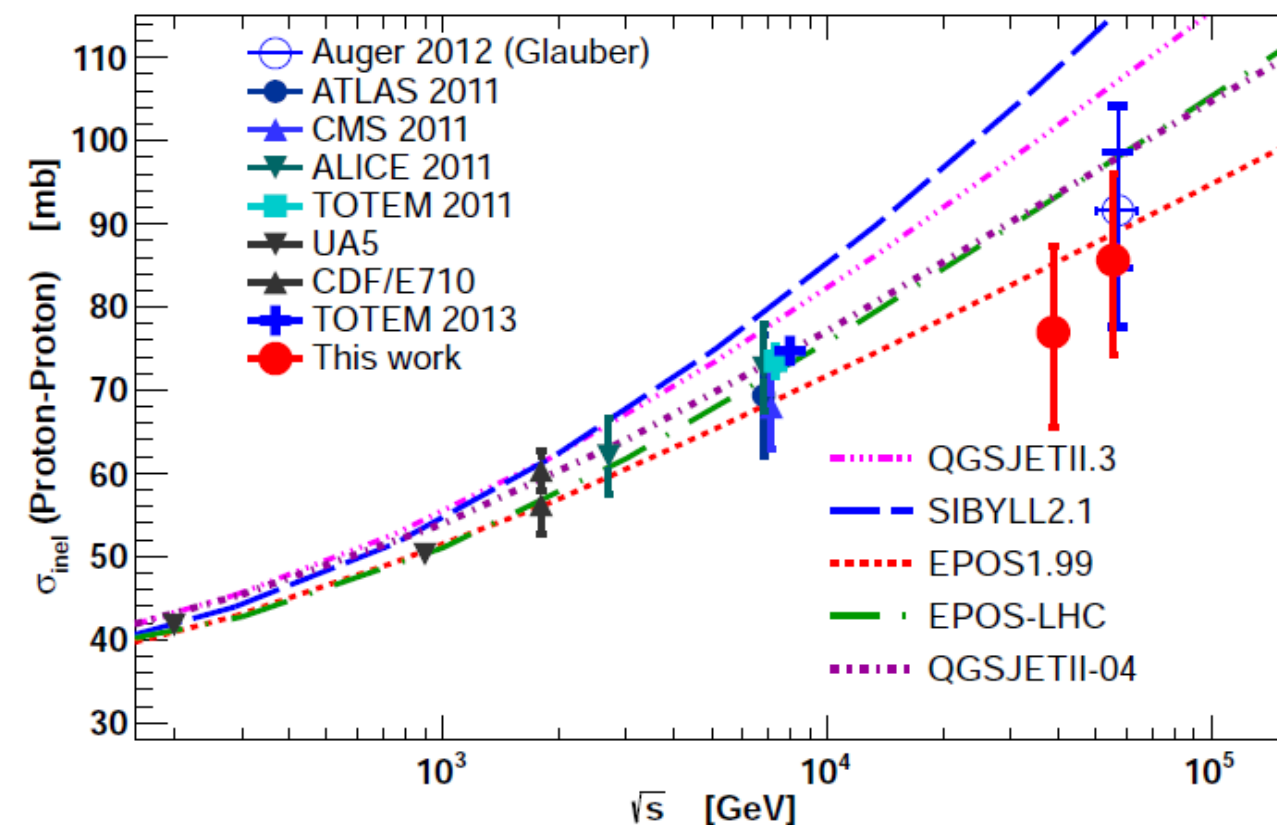
$457.5 \pm 17.8(\text{stat}) + 19/-25(\text{syst})$

Higher energy point

$485.8 \pm 15.8(\text{stat}) + 19/-25(\text{syst})$

p-p Inelastic Cross Section @ 39 and 55 TeV

Conversion using Glauber model: $\text{Glauber}(\sigma_{pp}^{\text{tot}}, B_{\text{el}}, \lambda, \dots) \rightarrow \sigma_{p-\text{air}}$



→ 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, $\sigma_{pp}^{\text{inel}}$ in mb

Lower energy point

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

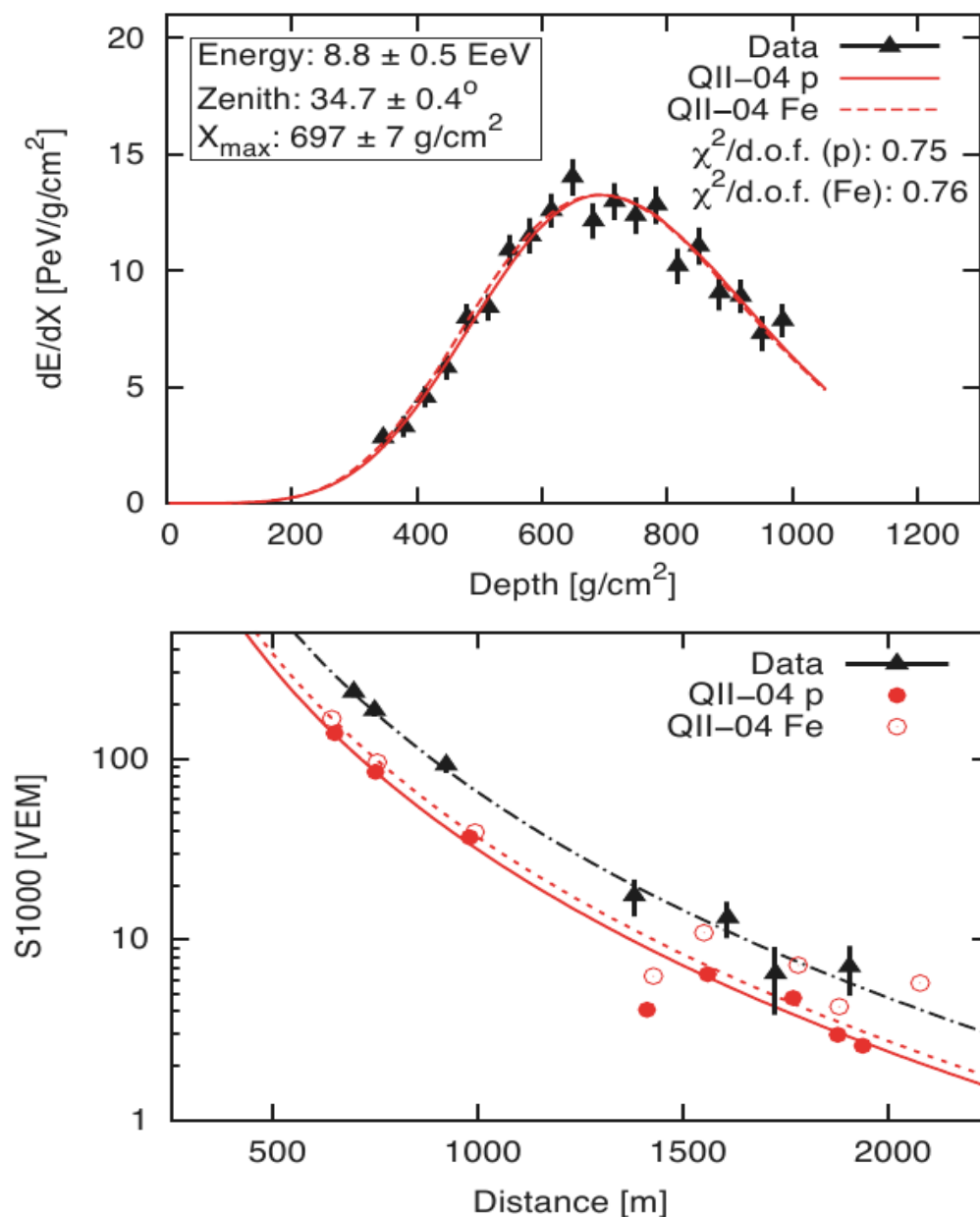
at $\sqrt{s_{pp}} = 38.7 \pm 2.5 \text{ TeV}$

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_μ),
 - ➔ rescale both component separately (R_E and R_μ to reproduce SD signal for each showers,
- $$S_{\text{resc}}(R_E, R_\mu)_{i,j} \equiv R_E S_{\text{EM},i,j} + R_E^\alpha R_\mu S_{\mu,i,j}$$
- ➔ for mixed composition, give weight according to X_{max} distribution.

Muon Rescaling

- Simulations don't reproduce FD and SD signal consistently

➔ $R = S_{1000}^{\text{observed}} / S_{1000}^{\text{predicted}}$ increase with zenith angle

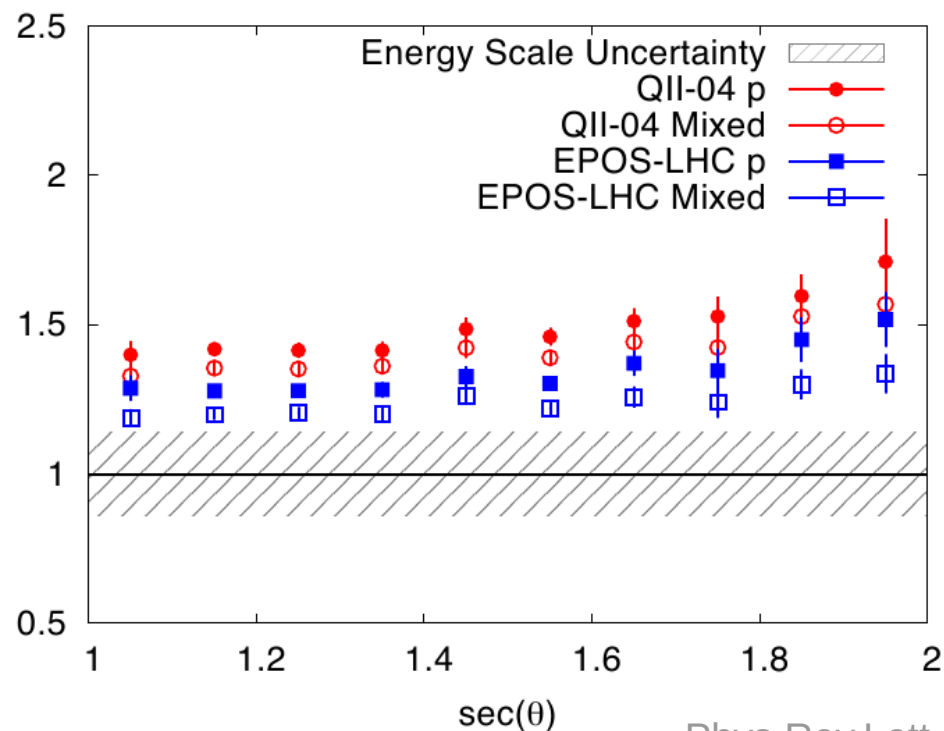
➔ EPOS-LHC Iron could be (almost) compatible with data, but X_{max} data are NOT pure Iron (but mixed).

- To reproduce data simulations have to be rescaled

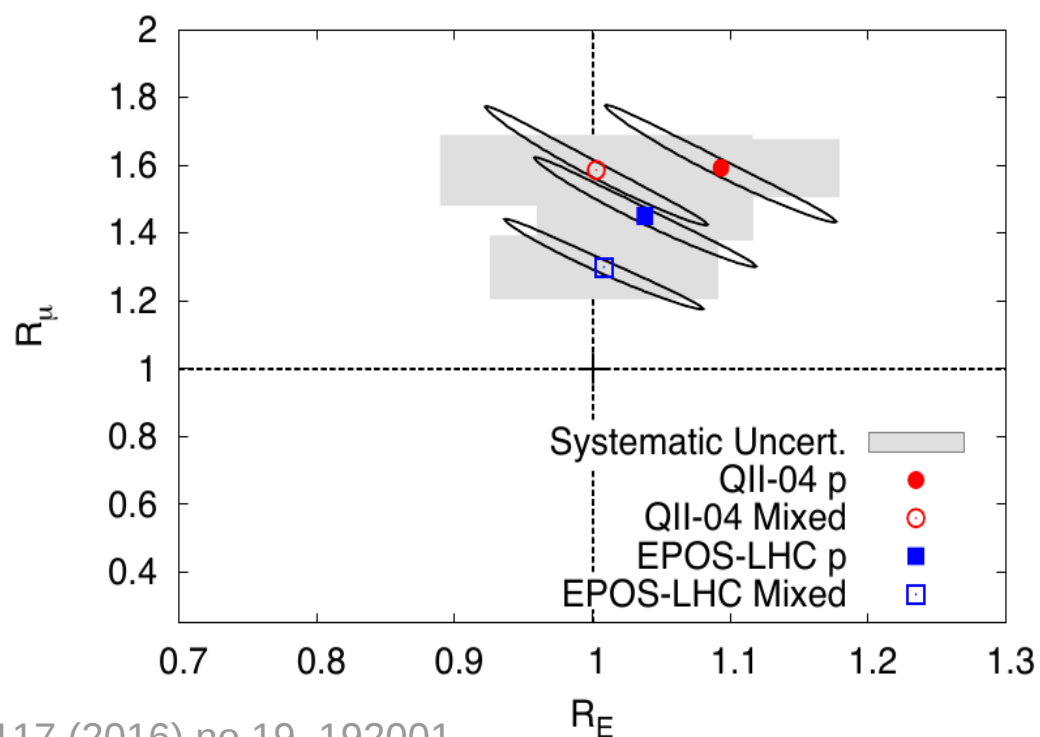
➔ for mixed composition, only muon component has to be changed

➔ correct energy scale

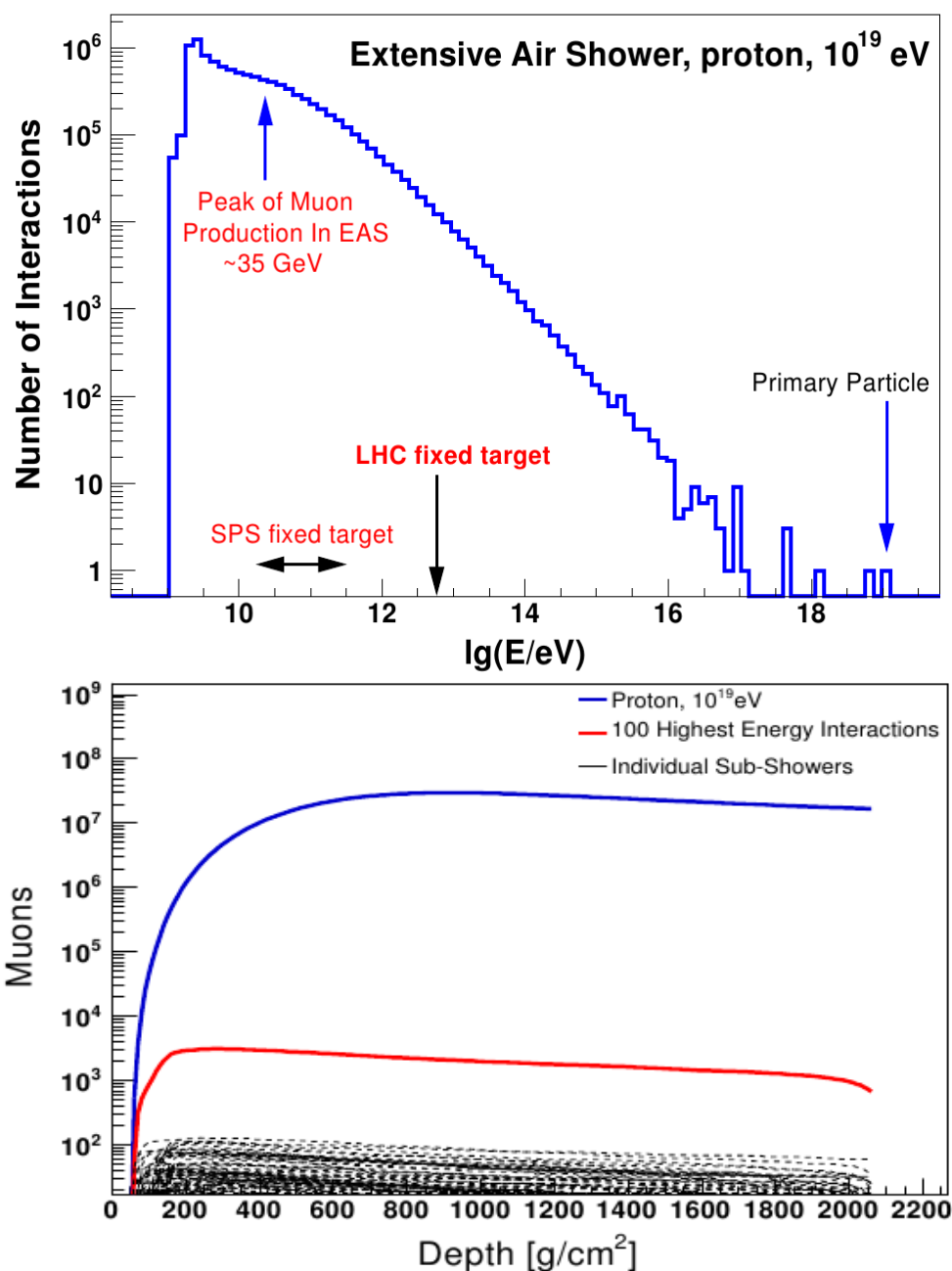
➔ 30% muon deficit for EPOS-LHC and 59% for QGSJETII-04.



Phys.Rev.Lett. 117 (2016) no.19, 192001



Surface Detector (SD)

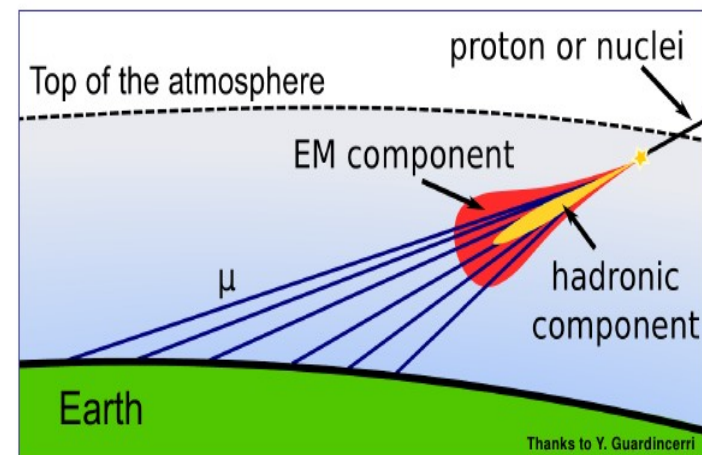


- **SD detector sensitive to**
 - ➔ electromagnetic particles (EM)
 - ➔ muons
- **Particles at ground produced after many generations of hadronic interactions**
 - ➔ most of EM particles from pure EM (universal) shower (depend on high (first) energy hadronic interactions)
 - ➔ muons produced at the end 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

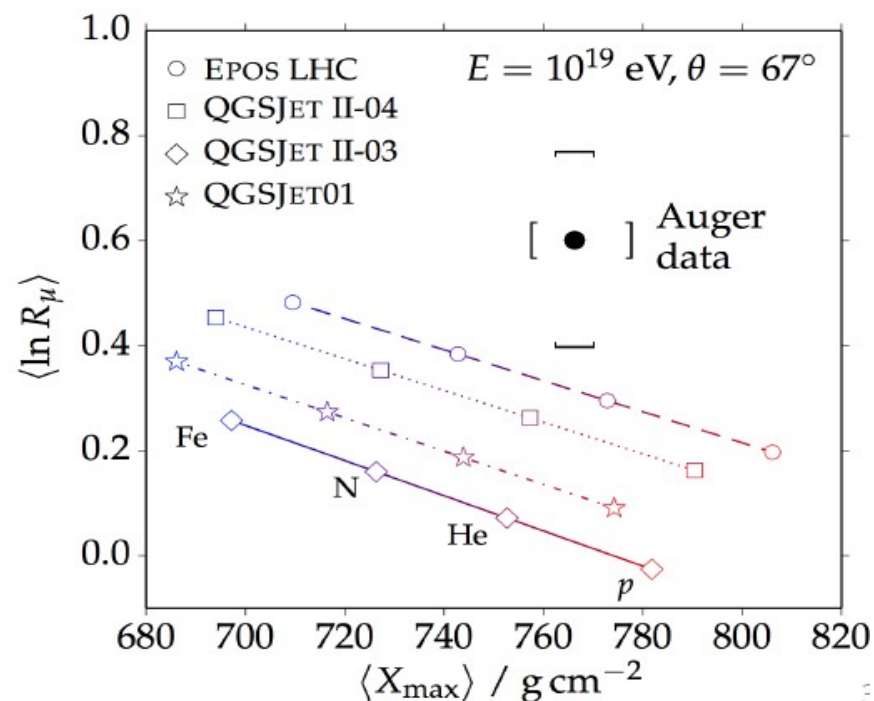
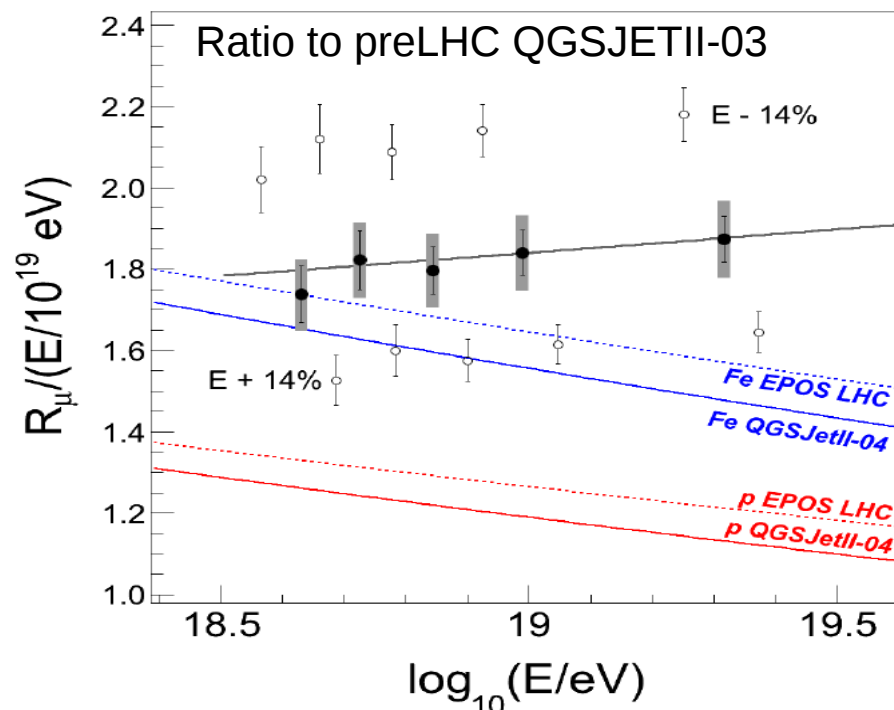
Direct Muon Measurement

● Old showers contain only muon component

- ➔ direct muon counting with very inclined showers ($>60^\circ$) 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



Muon Production Depth

Independent SD mass composition measurement

➔ geometric delay of arriving muons

$$c \cdot t_g = l - (z - \Delta)$$

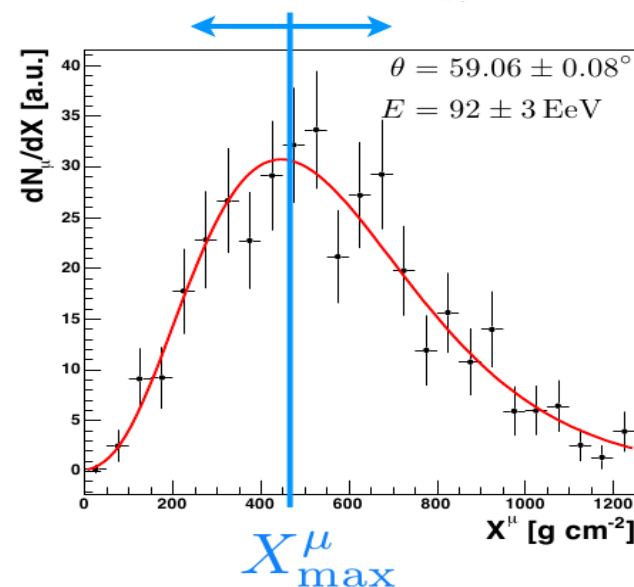
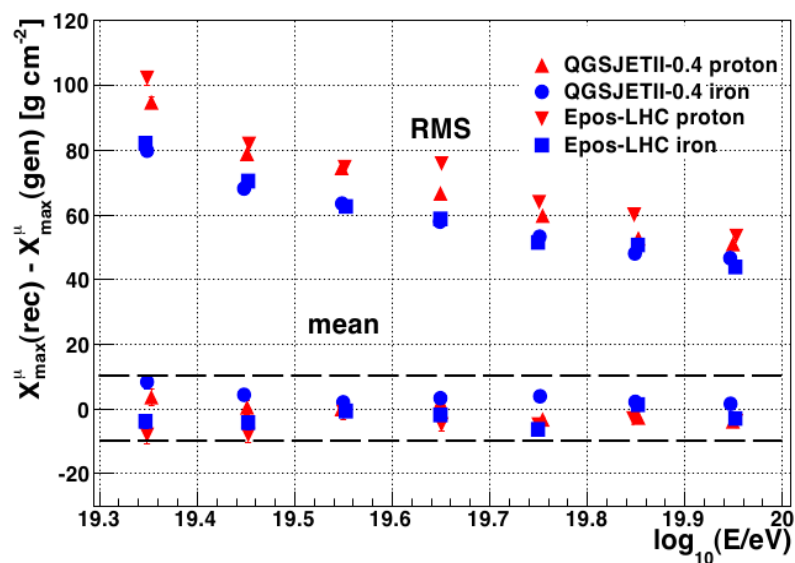
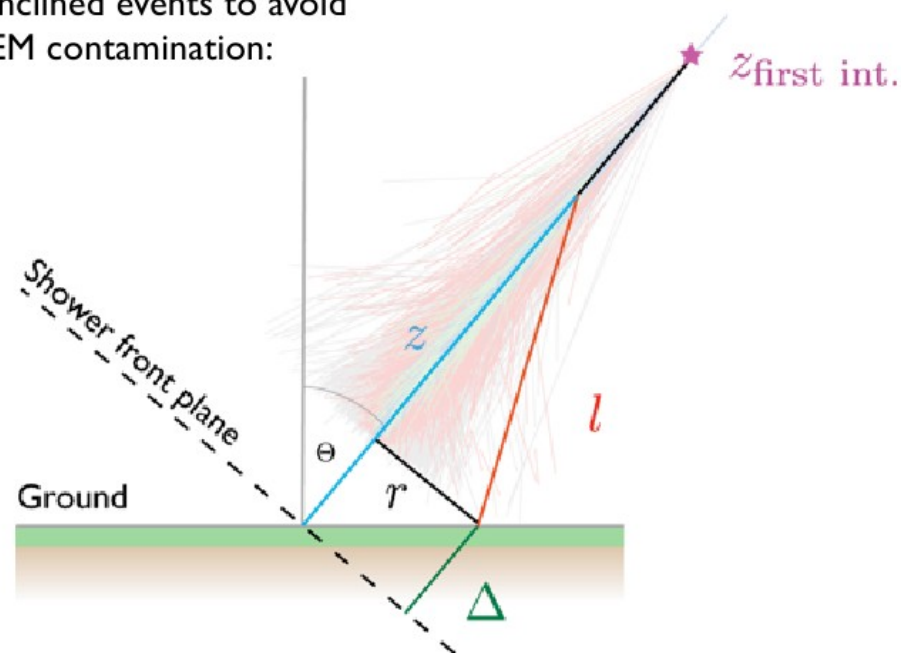
$$= \sqrt{r^2 + (z - \Delta)^2} - (z - \Delta)$$

➔ mapped to muon production distance

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

➔ decent resolution and no bias

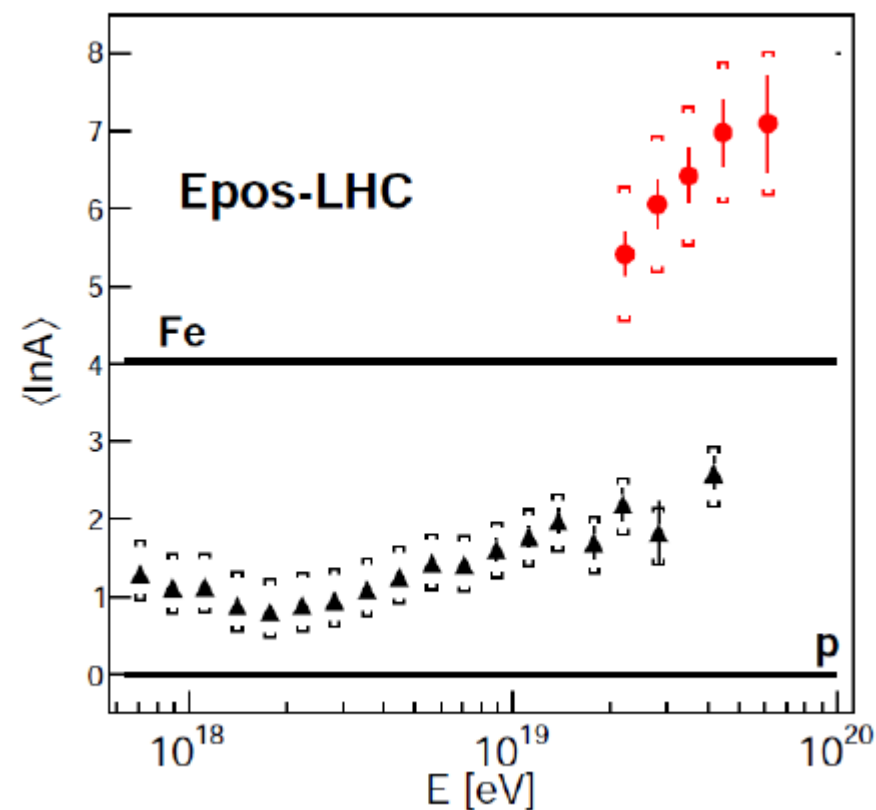
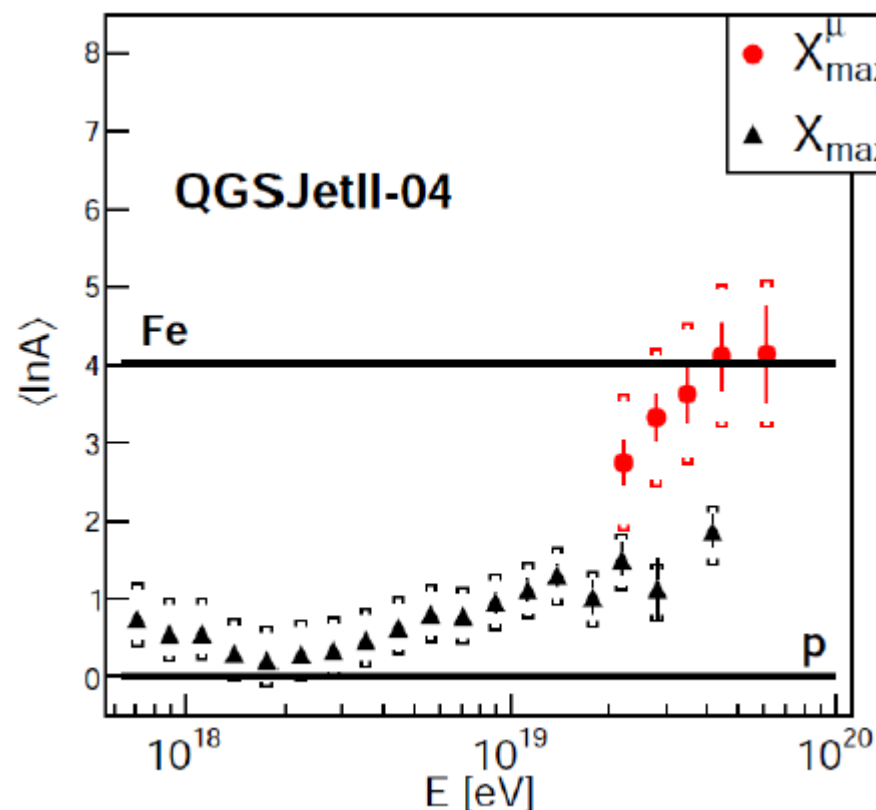
Inclined events to avoid EM contamination:



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 (low mass diffraction) and model consistency (forward baryon production at high energy): direct constraint on hadronic interactions.

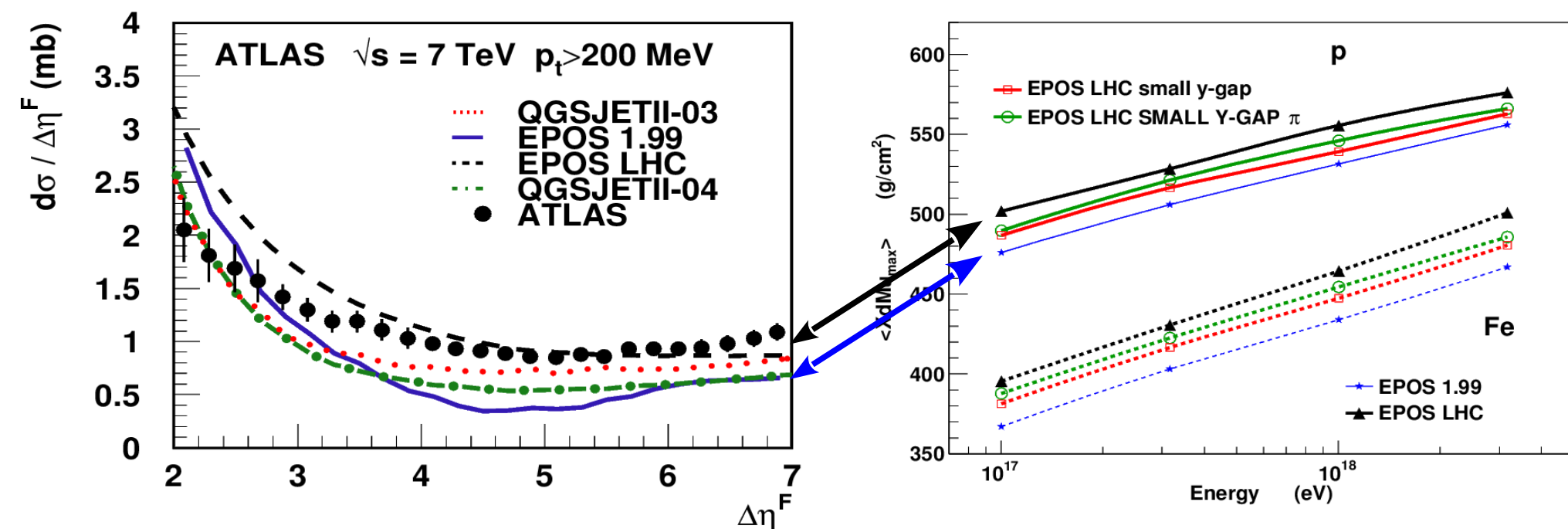


MPD and Diffraction

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

- ➔ weak influence on EM X_{\max} since only 1st interaction really matters
- ➔ cumulative effect for X_{\max}^{μ} 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_{\max}^{μ} and increase muon number !

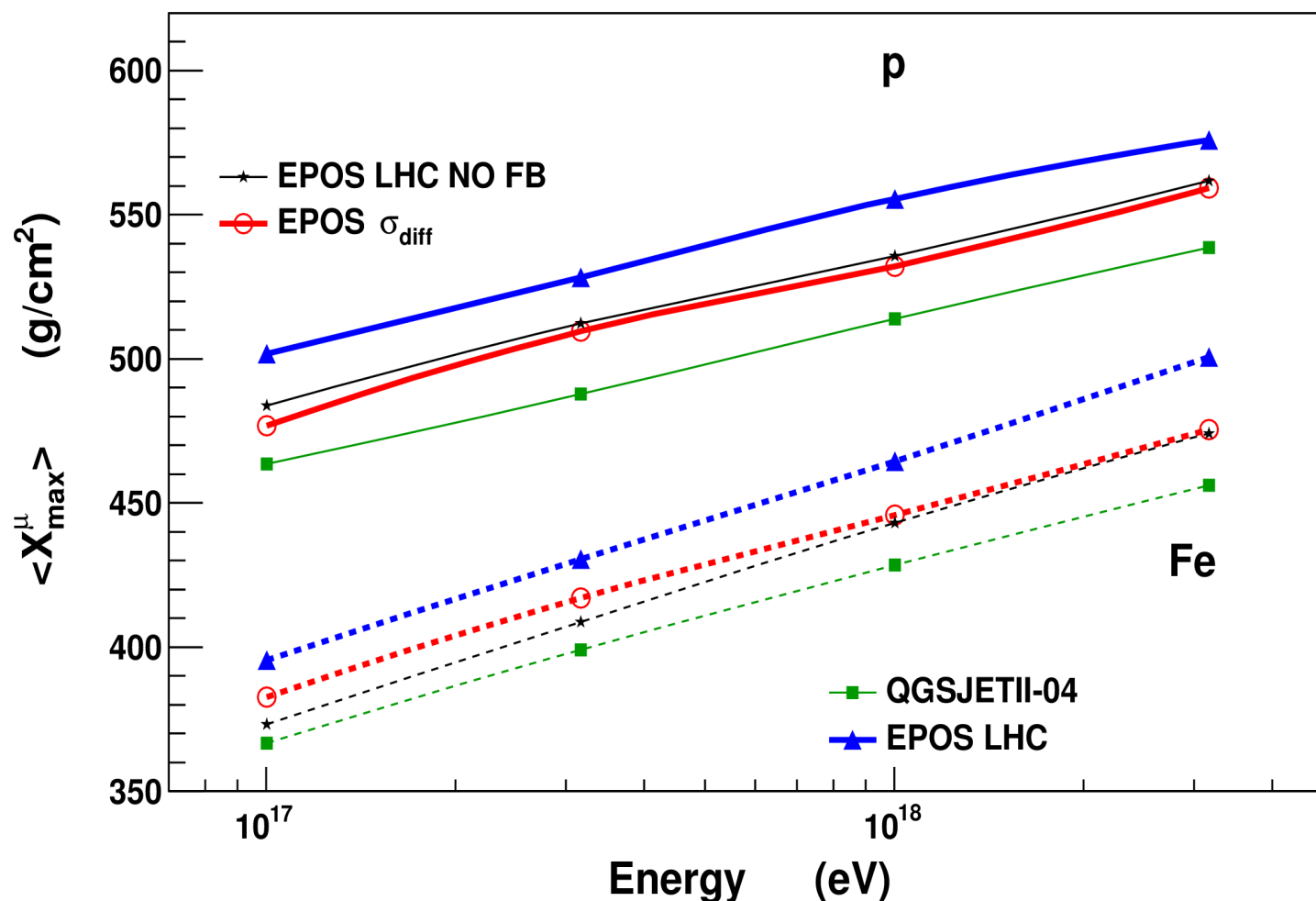
different diffractive mass distribution for mesons and baryons !



$\langle X_{\max}^{\mu} \rangle$ with modified EPOS LHC

Same than in mixed models

- ➔ softer meson spectra (lower elasticity) : lower X_{\max}^{μ}
- ➔ less forward baryons: lower X_{\max}^{μ}



-25 g/cm² for diff

-20 g/cm² for baryons

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

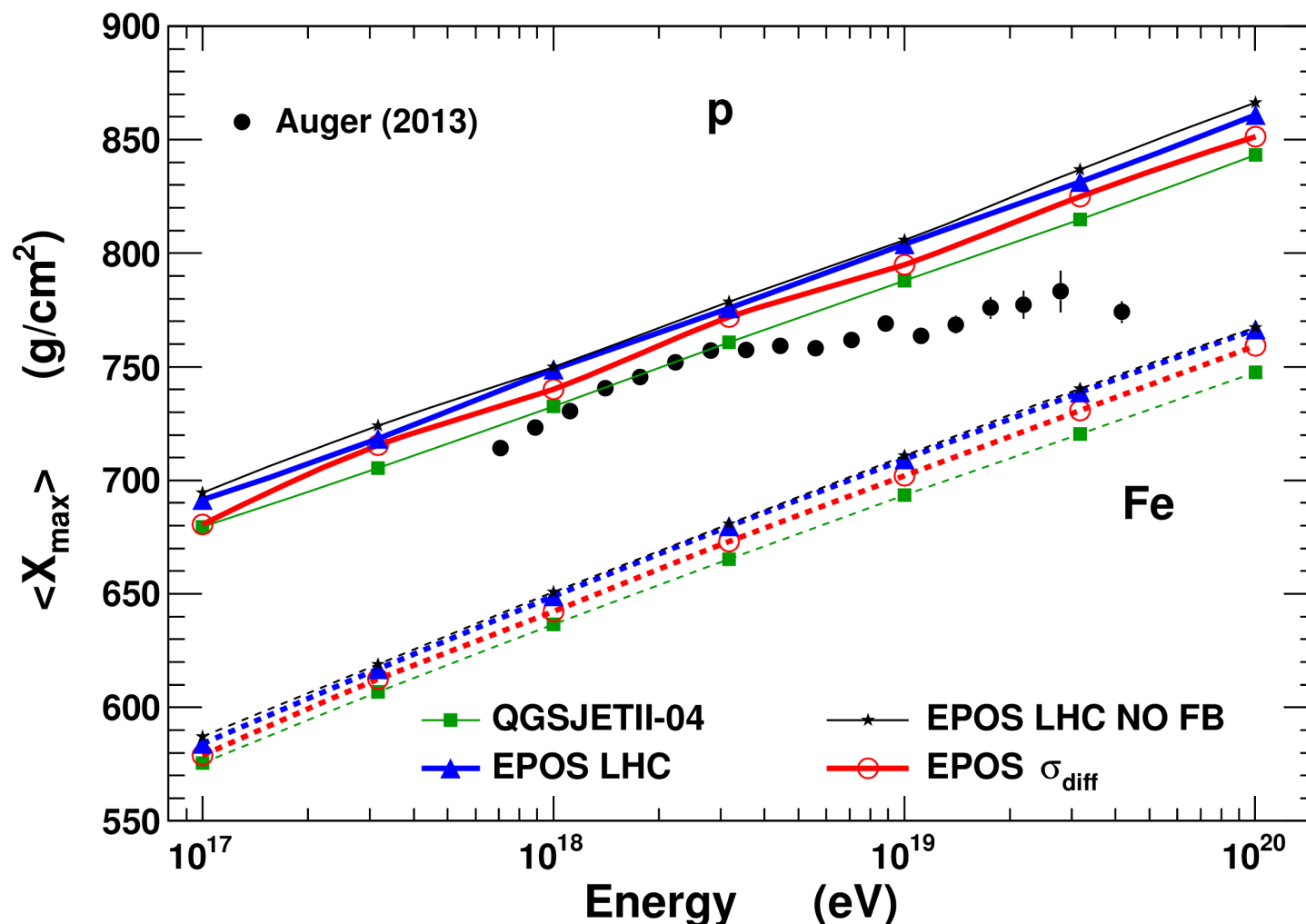
Ostapchenko et al.
Phys.Rev. D93 (2016)
no.5, 051501

$\langle X_{\max} \rangle$ with Modified EPOS

Same than in mixed models

→ softer meson spectra: lower X_{\max}

→ forward baryons: small effect



-10 g/cm² for diff

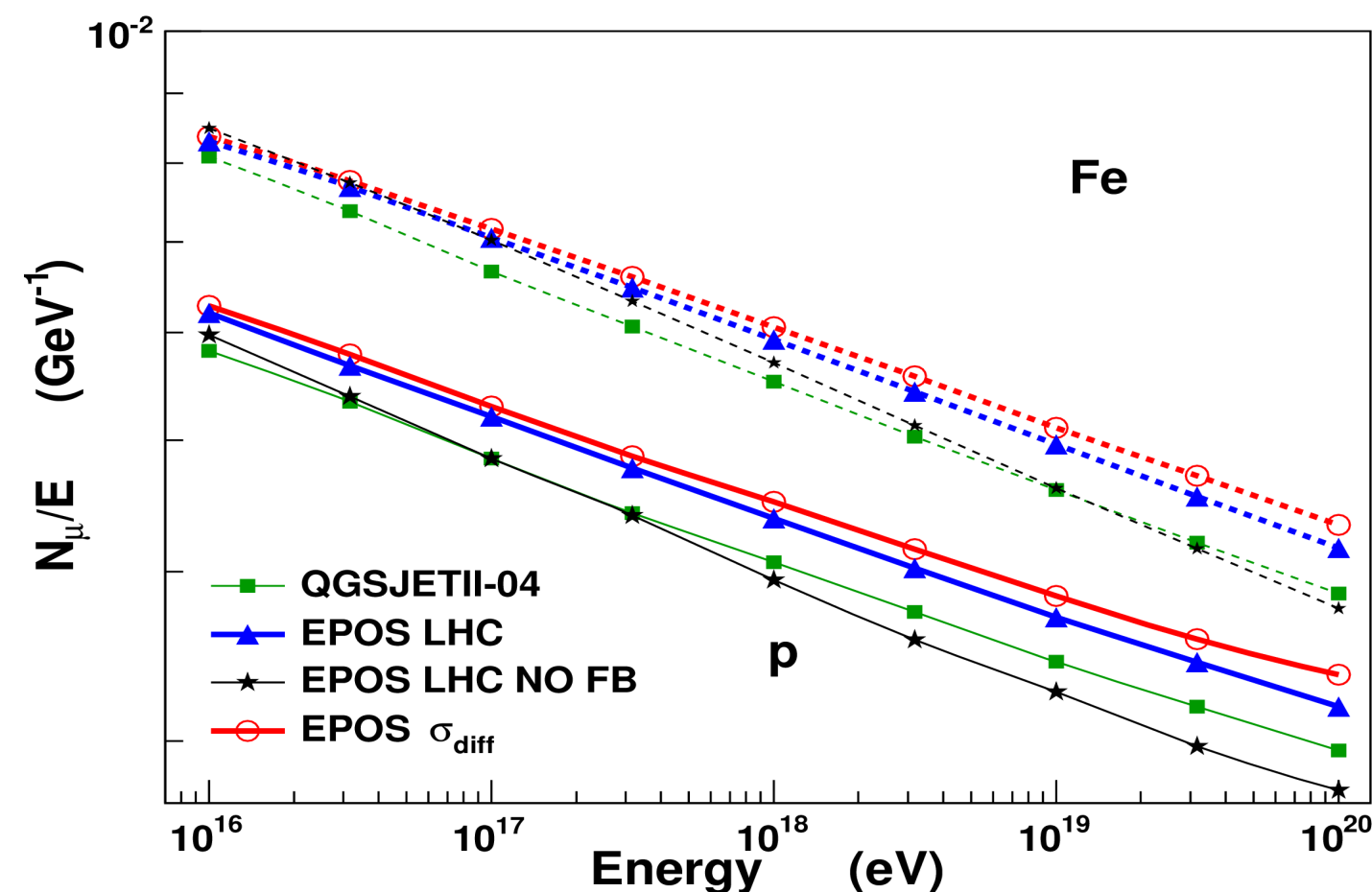
~0 g/cm² for baryons

X_{\max} less sensitive to baryon spectra than to pion spectra in pion interactions

N_μ with Modified EPOS

Number of muons depends on the same parameters

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

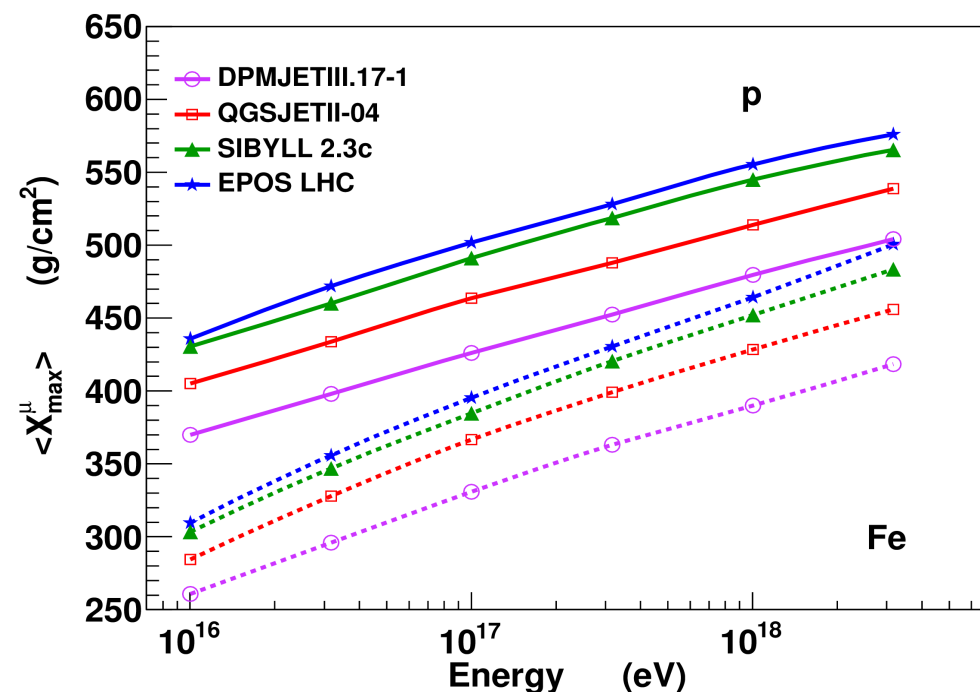
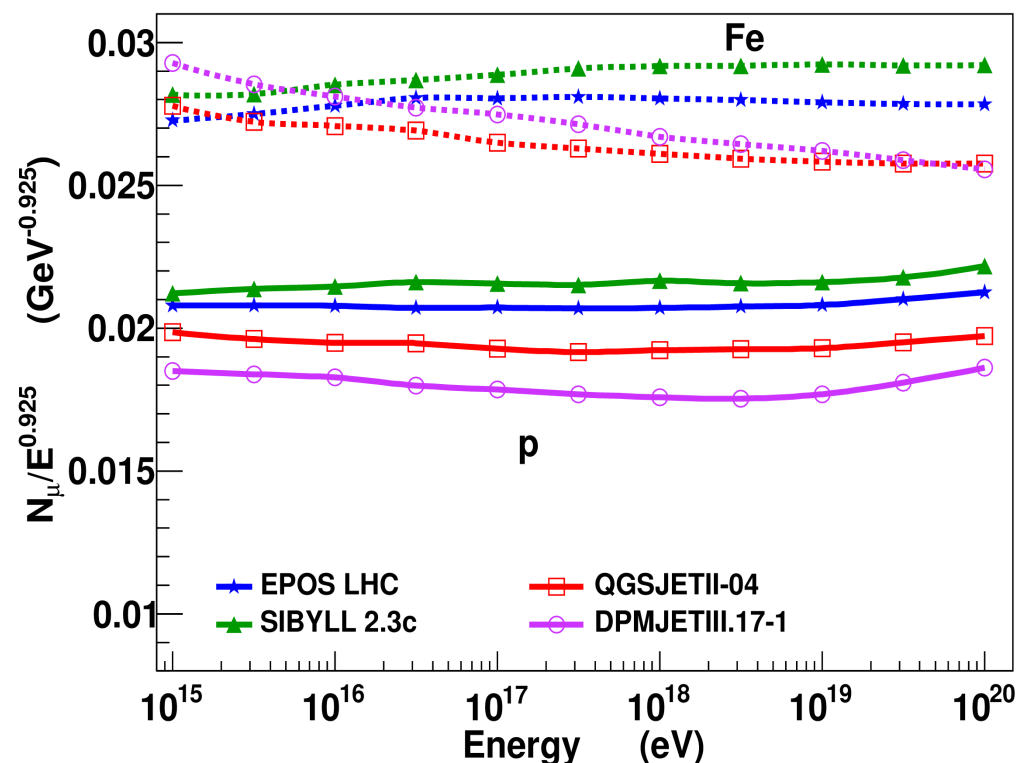
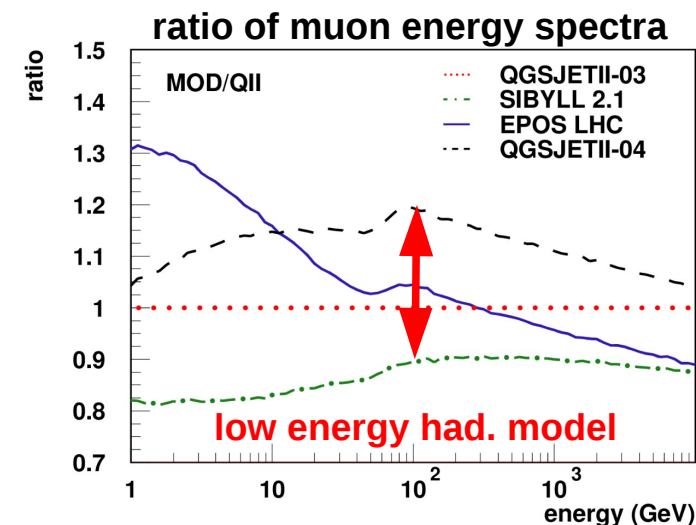


N_μ sensitive to
baryon (less
generation) and
meson spectra in
pion interactions

+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



The chicken ...

- **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_{\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/cm² difference for X_{\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)

... or the egg

- Auger data (and other low energy cosmic ray experiments) not consistently described by hadronic interaction models (even post LHC)
 - ◆ $\langle X_{\max} \rangle$ 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_{\max} from FD and X_{\max}^{μ} 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_{\max}^* and $S^*(1000)$

- in data correlation is significantly negative

$$\rightarrow r_G = -0.125 \pm 0.024$$

- $r_G(X_{\max}^*, S^*(1000))$ for p

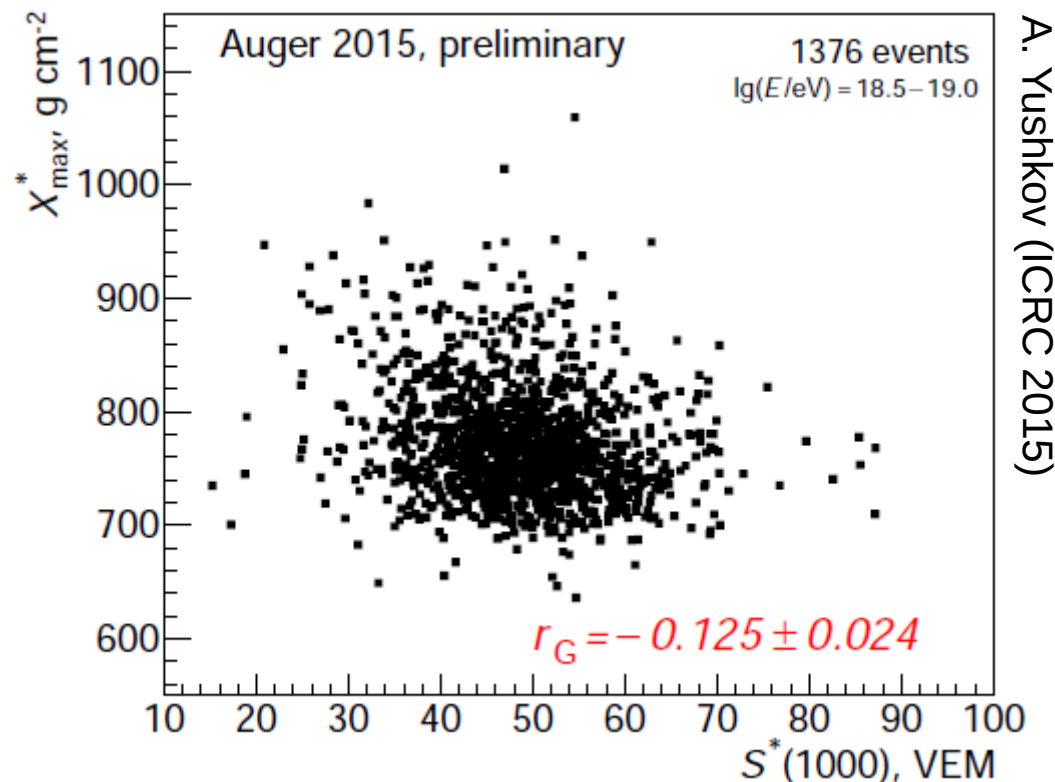
→ EPOS-LHC : 0.00 (5σ to data)

→ QGSJetII-04 : +0.08 (8σ to data)

→ Sibyll 2.1 : +0.07 (7.5σ to data)

- difference is larger for other pure beams

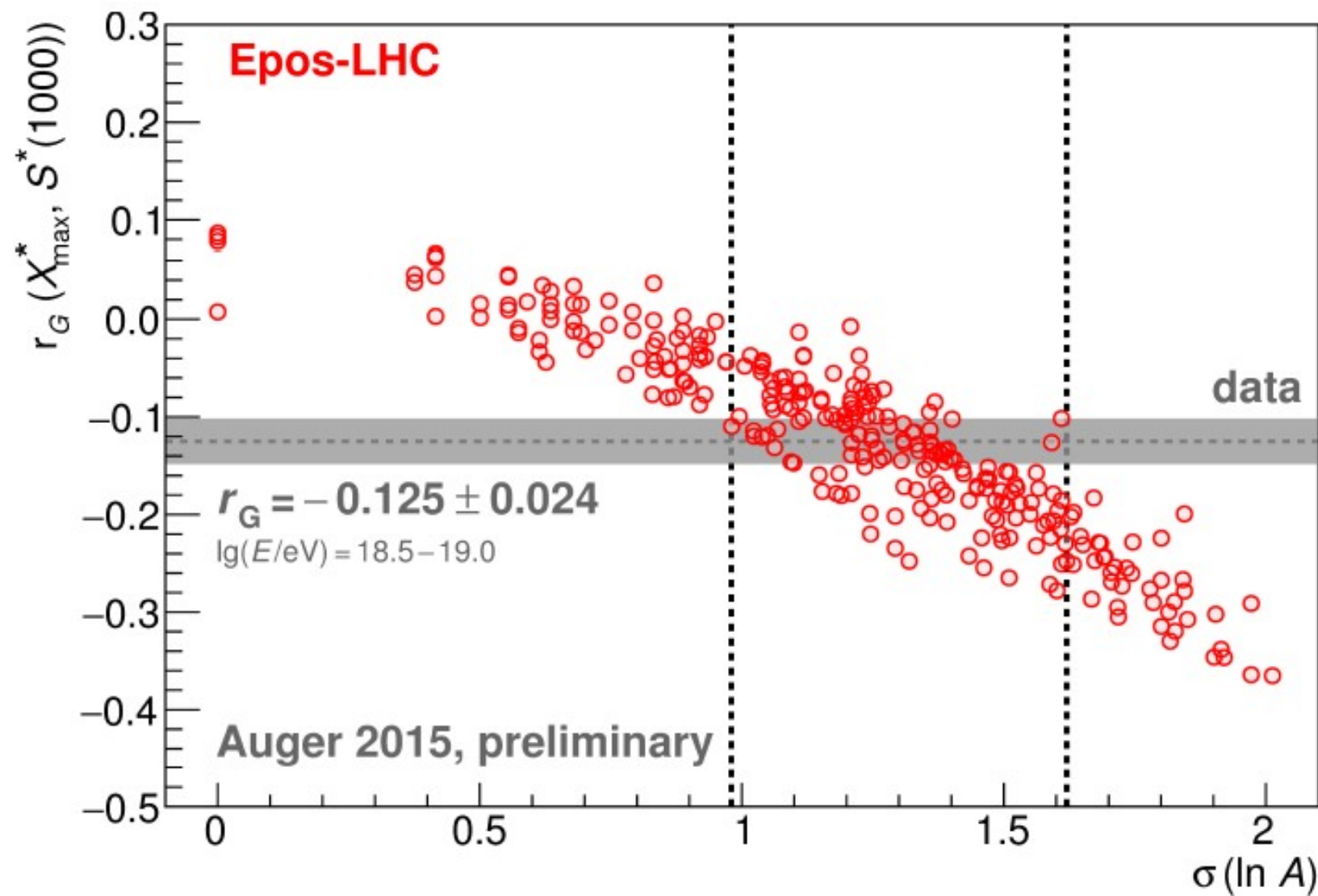
**primary composition
near the 'ankle' is
mixed**



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

- test of “exotic” models fails

Dispersion of Masses in Data



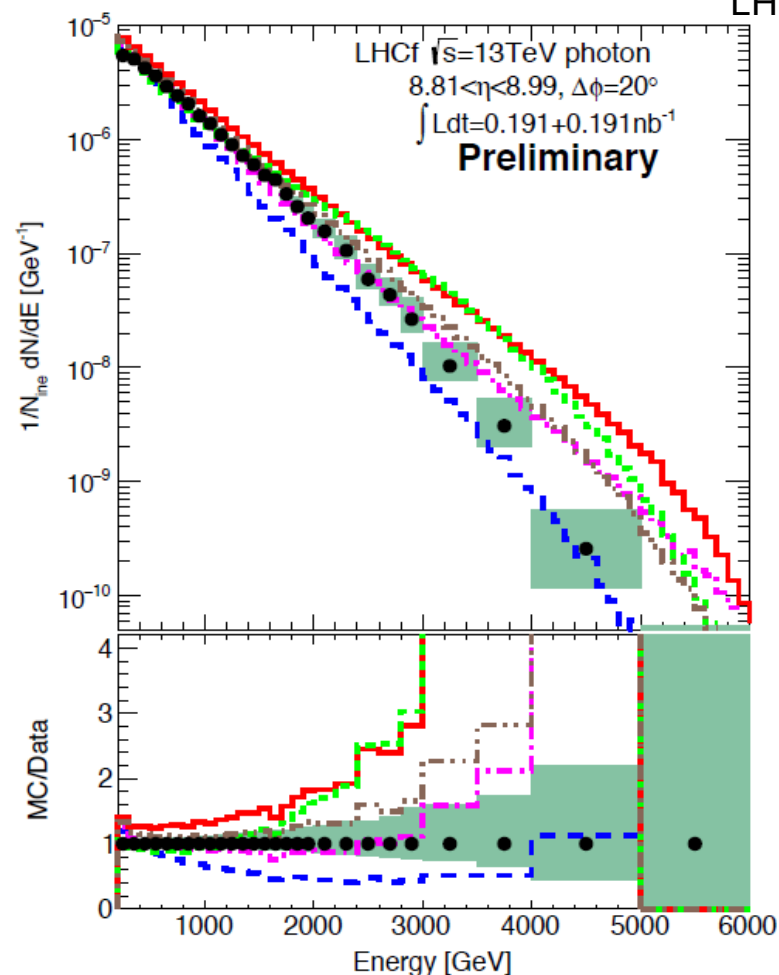
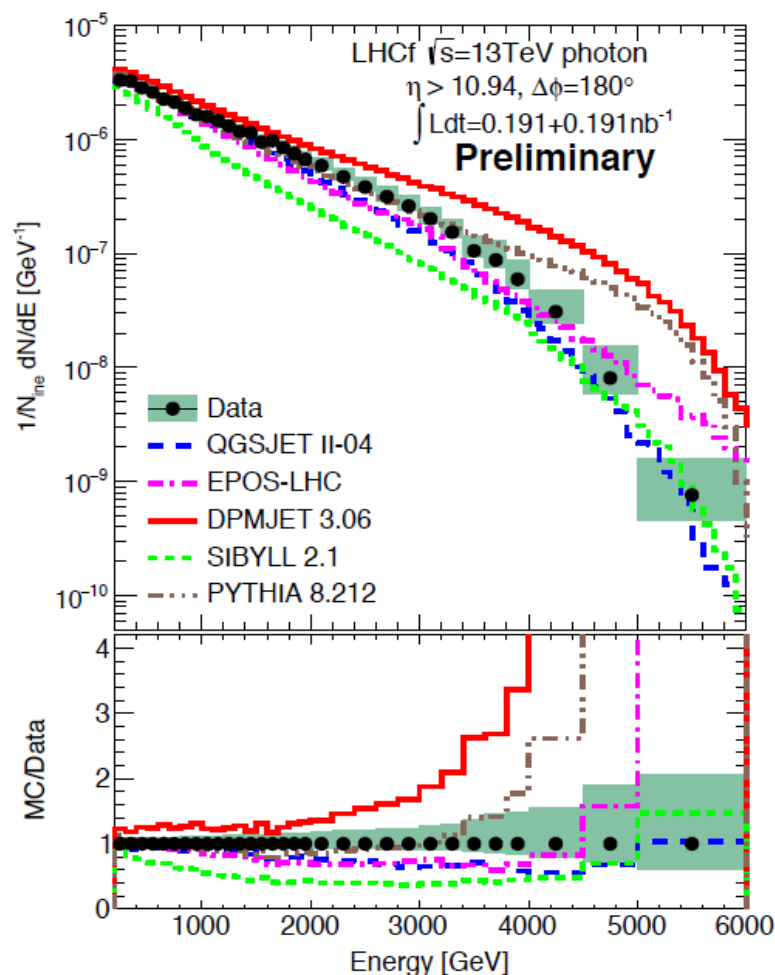
A. Yushkov (ICRC 2015)

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

Comparison with LHCf

- ➔ LHCf favor not too soft photon spectra (EPOS LHC, SIBYLL 2.3) : deep X_{\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

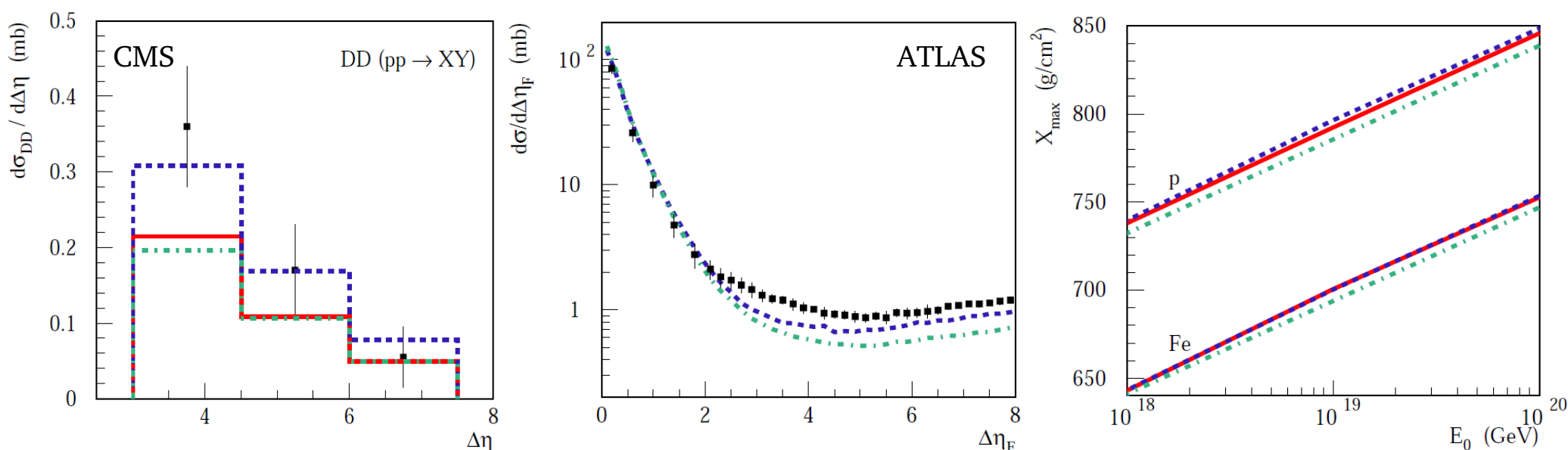
- **Very few data for baryon production from meson projectile, but for all :**
 - ➔ strong baryon acceleration (probability $\sim 20\%$ per string end)
 - ➔ proton/antiproton asymmetry (valence quark effect)
 - ➔ target mass dependence
 - **New data set from NA49 (G. Veres' PhD)**
 - ➔ test π^+ and π^- interactions and productions at 158 GeV with C and Pb target
 - ➔ confirm large forward proton production in π^+ and π^- 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

M_X range	< 3.4 GeV	$3.4 - 1100$ GeV	$3.4 - 7$ GeV	$7 - 350$ GeV	$350 - 1100$ GeV
TOTEM [13, 24]	2.62 ± 2.17	6.5 ± 1.3	$\simeq 1.8$	$\simeq 3.3$	$\simeq 1.4$
QGSJET-II-04	3.9	7.2	1.9	3.9	1.5
option SD+	3.2	8.2	1.8	4.7	1.7
option SD-	2.6	7.2	1.6	3.9	1.7

➔ difference of ~ 10 gr/cm² between the 2 options



Simplified Shower Development

Using generalized Heitler model and superposition model :

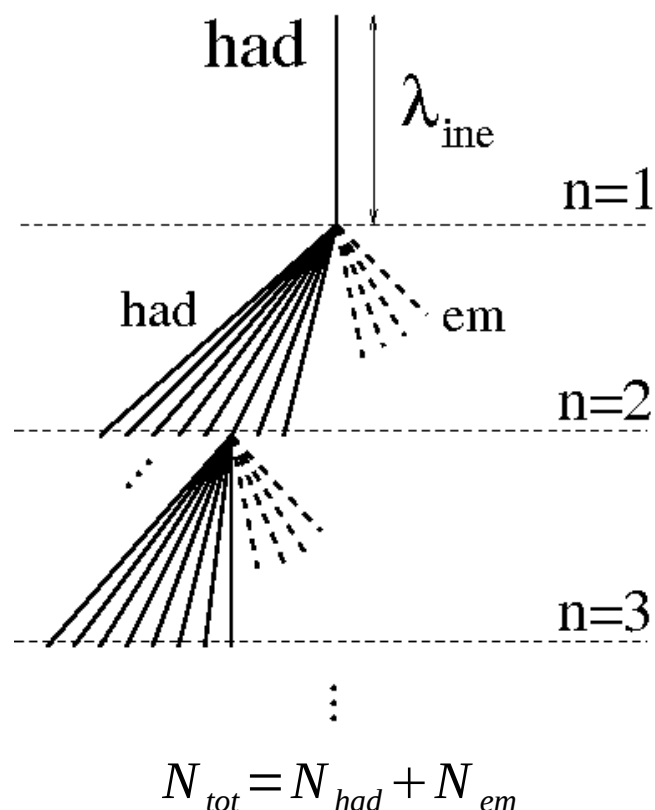
$$X_{max} \sim \lambda_e \ln \left((1-k) \cdot E_0 / (2 \cdot N_{tot} \cdot A) \right) + \lambda_{ine}$$

➔ Model independent parameters :

- E_0 = primary energy
- A = primary mass
- λ_e = electromagnetic mean free path

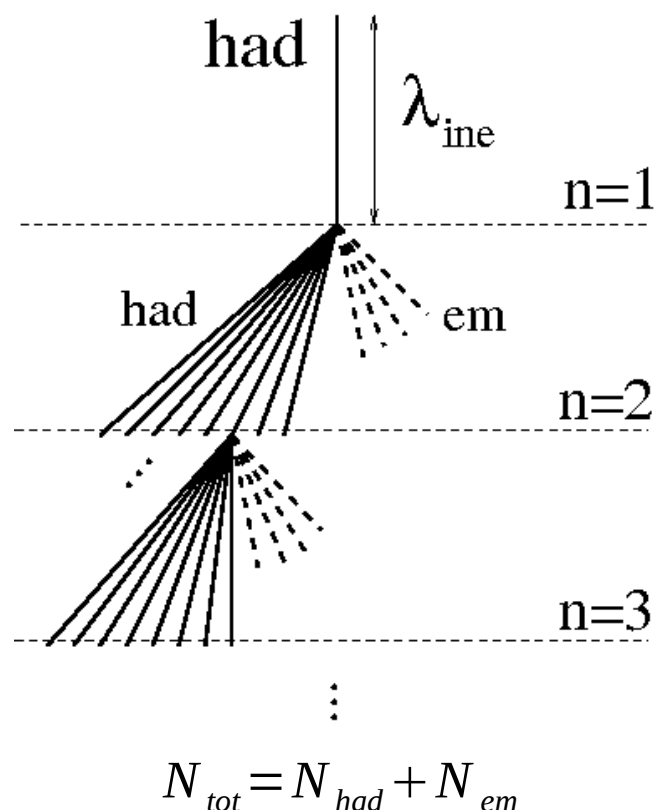
➔ Model dependent parameters :

- k = elasticity
- N_{tot} = total multiplicity
- λ_{ine} = hadronic mean free path (cross section)



J. Matthews, Astropart.Phys. 22
(2005) 387-397

Toy Model for Hadronic Cascade



Primary particle : hadron

Muons produced after many had. generations

N_{had}^n particles
can produce
muons after n
interactions

$$N(n) = N_{had}^n$$

N_{tot}^n particles
share E_0 after n
interactions

$$E(n) = E_0 / N_{tot}^n$$

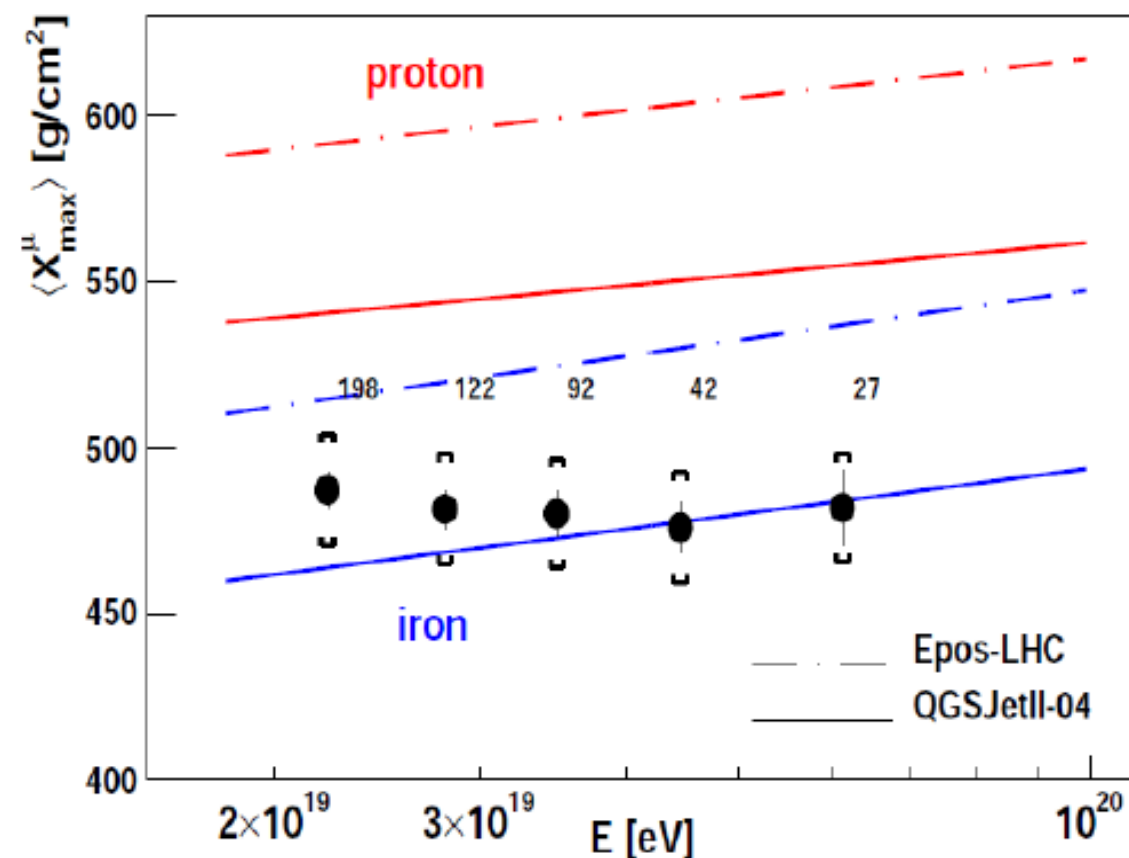
Assumption: particle decay to muon when $E = E_{dec}$ (critical energy) after n_{max} generations

$$E_{dec} = E_0 / N_{tot}^{n_{max}}$$

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

$$\ln(N_\mu) = \ln(N(n_{max})) = n_{max} \ln(N_{had})$$

MPD and Models

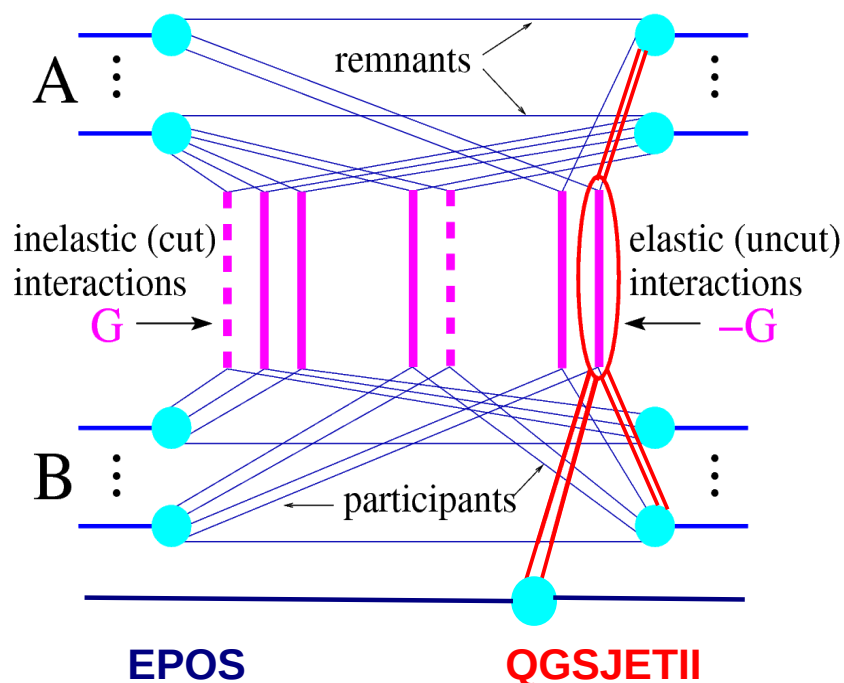
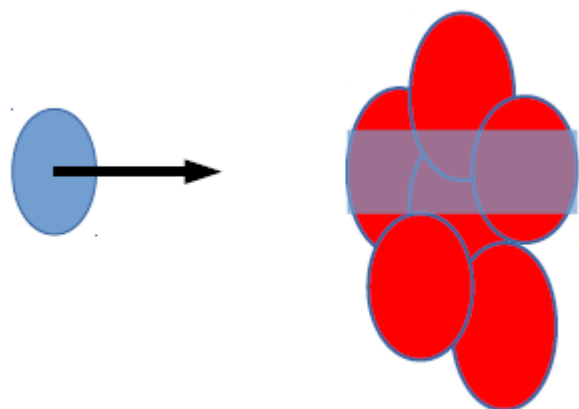


- ➔ data set: 01/2004 – 12/2012
- ➔ $E > 10^{19.3}$ eV
- ➔ zenith angles $[55^\circ, 65^\circ]$
- ➔ Core distances [1700 m, 4000 m]
(more muons/event)
- ➔ 481 events after quality cuts
- ➔ syst: 17 g/cm^2
- ➔ Event by event resolution:
 - 100 (80) g/cm^2 at $10^{19.3}$ eV for p (Fe)
 - 50 g/cm^2 at 10^{20} 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

Nuclear Interactions



● Sibyll

➔ Glauber for pA

■ with inelastic screening for diffraction in new Sibyll 2.3 (only nuclear effect)

➔ superposition model for AA ($A \times pA$)

● 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

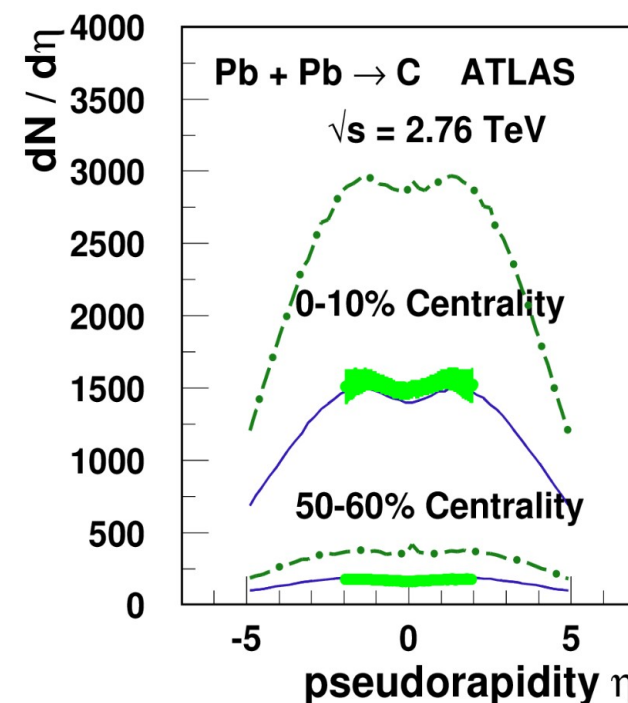
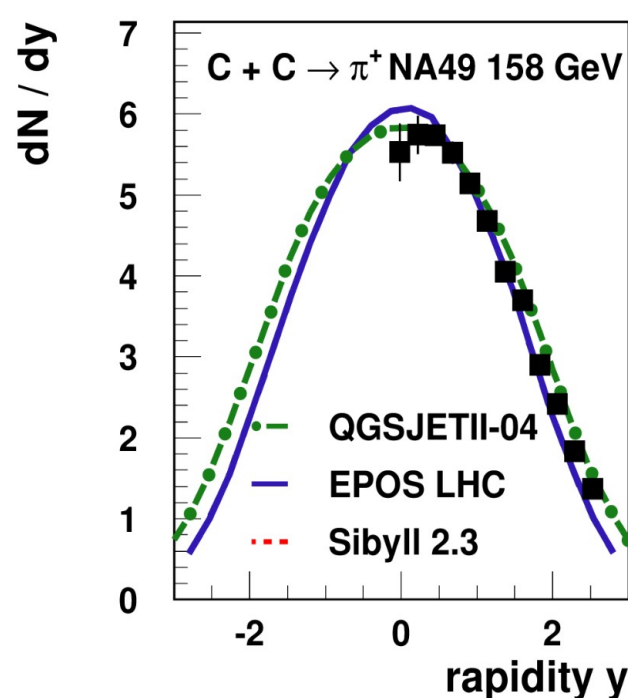
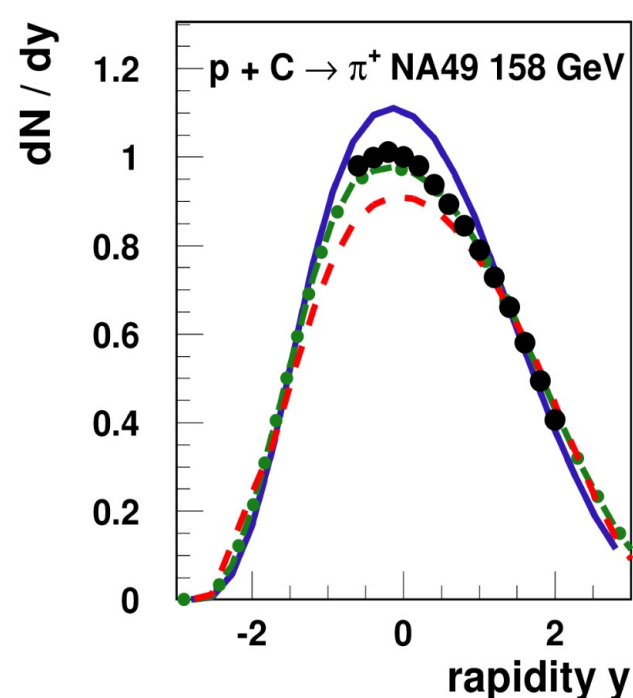
➔ screening corrections depend on nuclei

➔ 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

