The *p*-air inelastic cross section at √s ≈ 2 TeV

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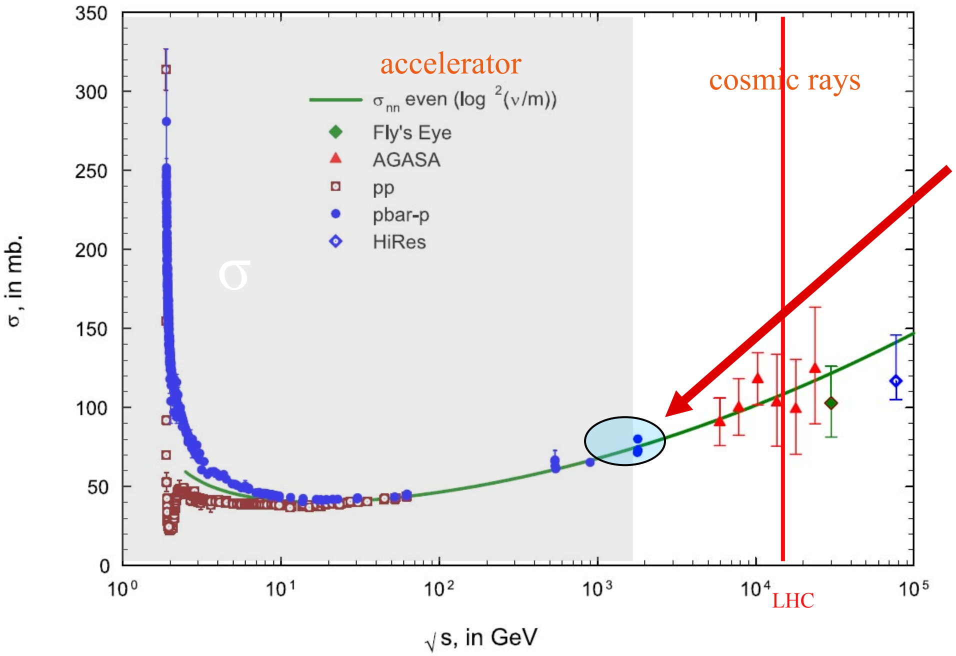
XVI International Symposium on Very High Energy Cosmic Rays Interactions

Introduction



Accelerator data up to $\sqrt{s}$=1.8 TeV
Available results differ of ≈10% exceeding the statistical uncertainties of the individual measurements

- PRD 50 (1994),5550
- PLB 445(1999),419

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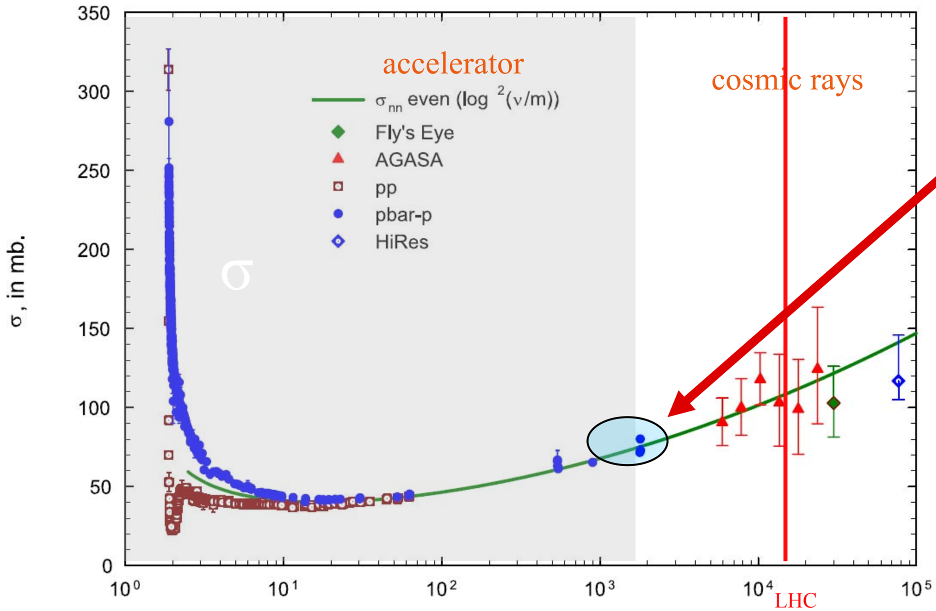

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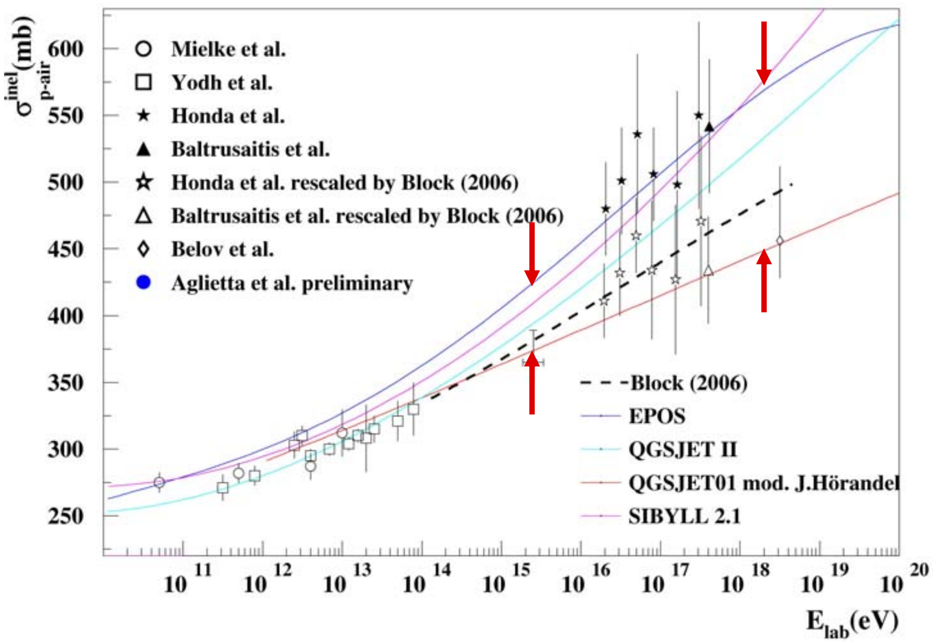

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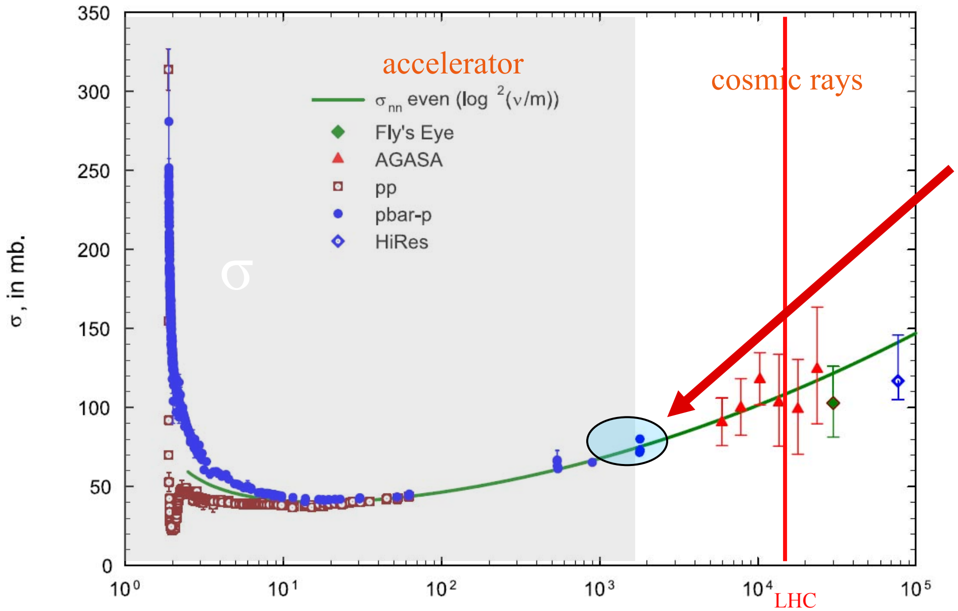

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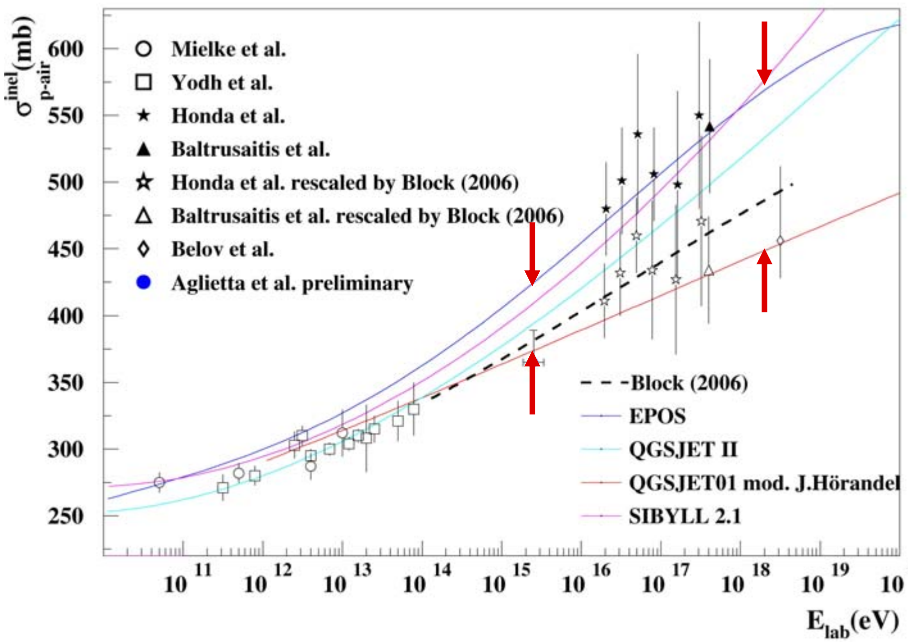
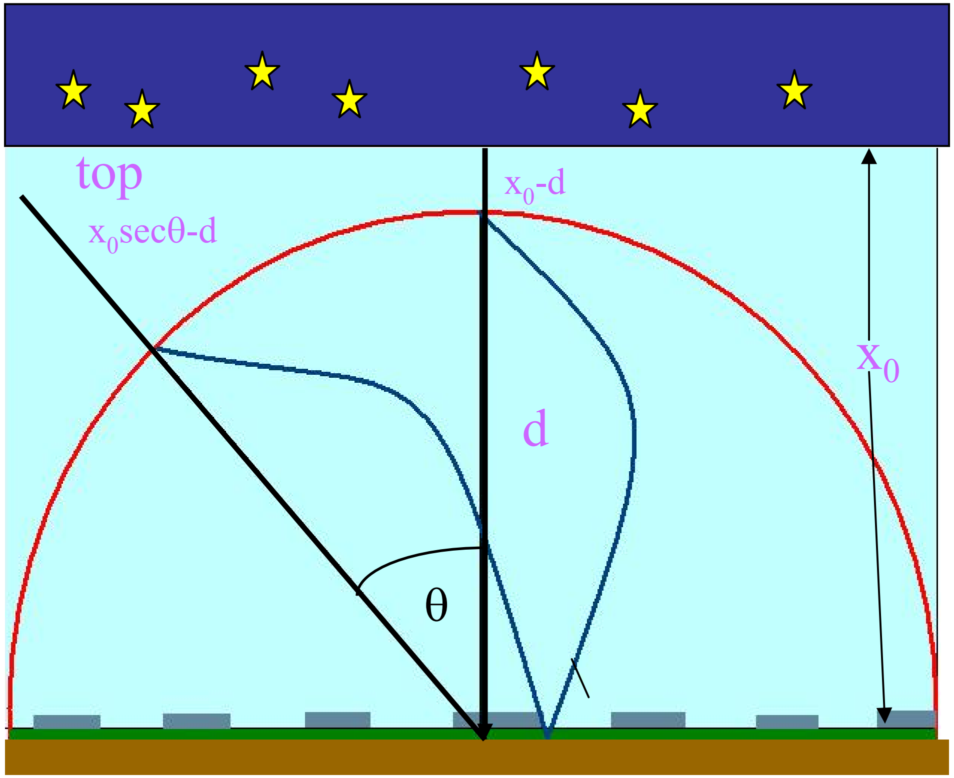


The interpretation of EAS measurements rely on simulation based on Hadronic Interaction Models which exhibit large differences at the highest energies

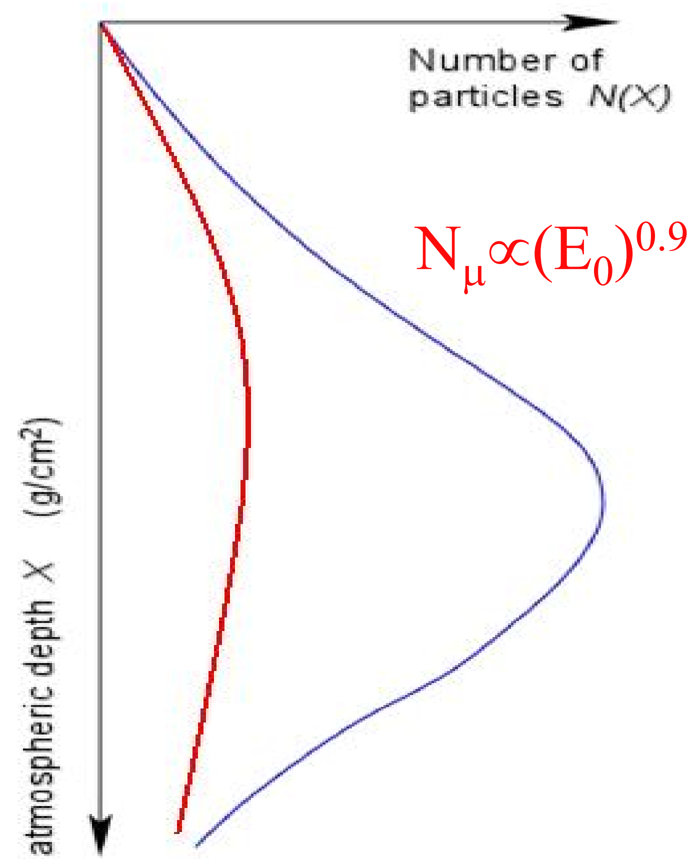
$\sigma^{in}_{p\text{-}air}$ and σ^{tot}_{pp} are related (Glauber)
Result of different calculations differing ≈20% around √s=2 TeV

Frequency Attenuation: Constant N_e-N_μ cuts



Primary Energy E_0 selected using muon number

$E_1 < E_0 < E_2 \Rightarrow N_{\mu,1} < N_\mu < N_{\mu,2}$



PRL 50 (1983) 2058
PRL 70 (1993) 525

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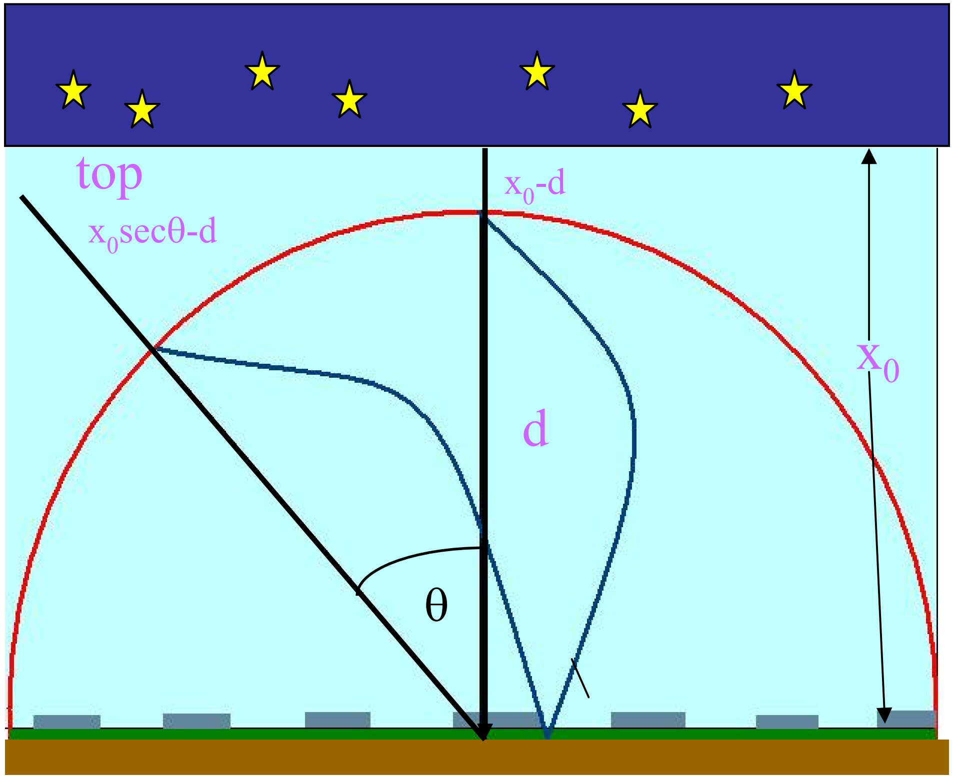

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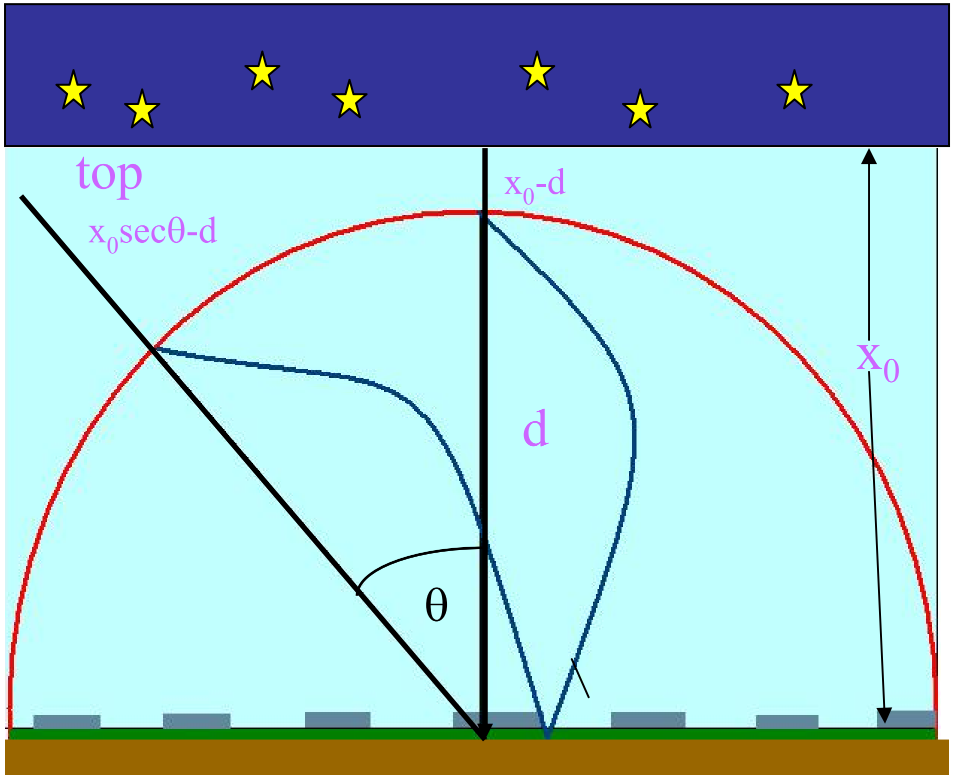

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$$\Phi(\theta) = \Phi_0 \exp[- (x_0 \sec\theta - d)/\lambda_{p\text{-}air}]$$

$$\Phi(\theta) / \Phi(0) = \exp[- (x_0 \sec\theta - 1) / \lambda_{p\text{-}air}]$$

X_{max} Distribution

Fly's Eye PRL 52 (1984) 1380

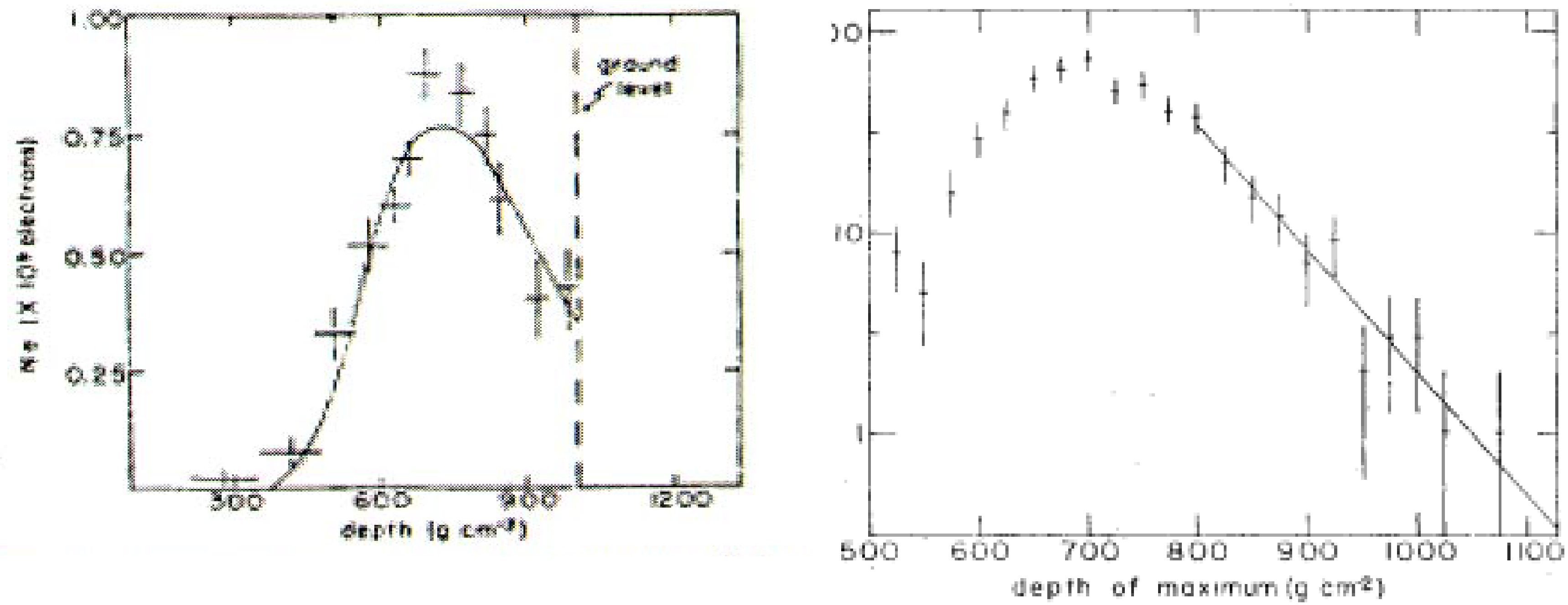


Fig. 1 An extensive air shower that survives all data cuts. The curve is a GaisserHillas shower-development function: shower parameters E=1.3 EeV and X_{max} =727 ± 33 g cm^{-2} give the best fit.

Fluctuations: *k* parameter

The observed absorption length is affected by fluctuations in the longitudinal development of cascades and in the detector response. The *k* parameter is obtained from simulation and accounts for all fluctuations:

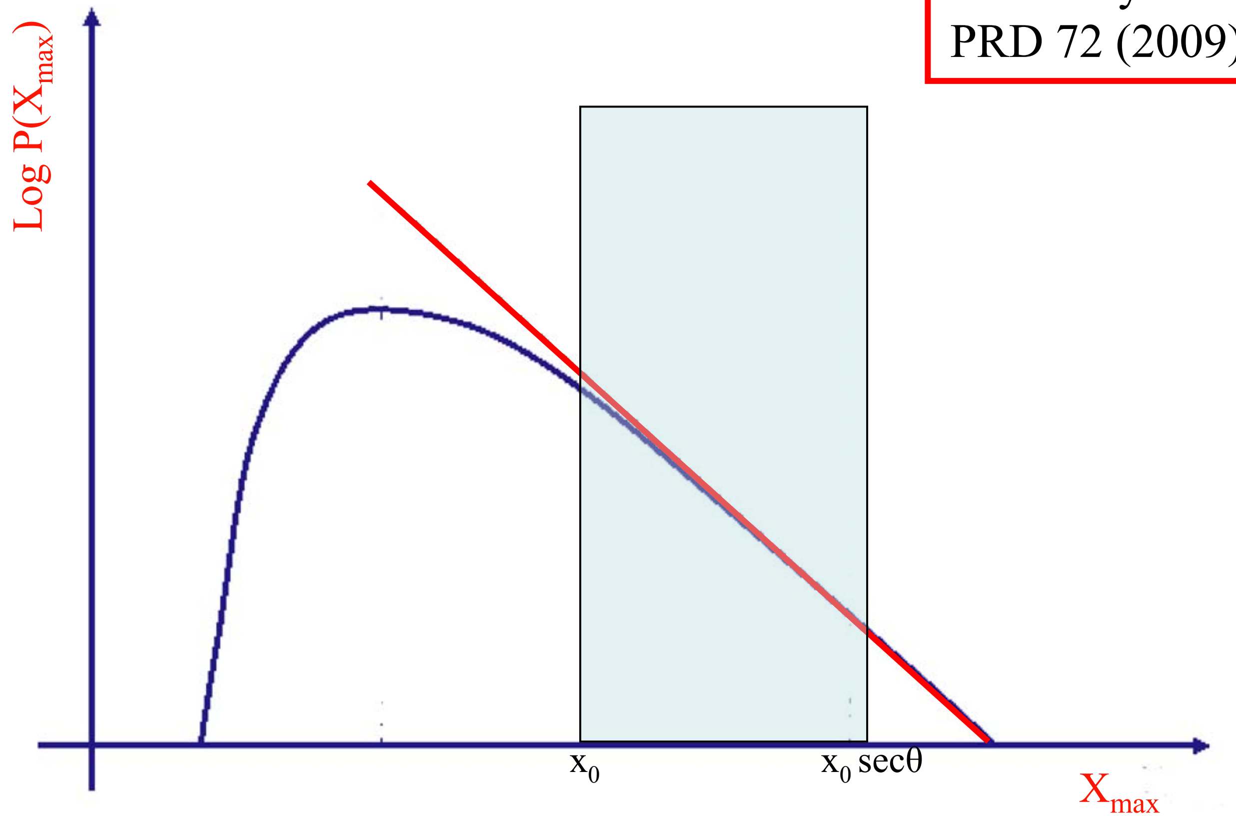
$$k = \lambda_{sim}^{obs} \Big/ \lambda_{sim}^{p-air}$$

$$\lambda_{p\text{-air}}^{\exp} = \lambda_{obs}^{\exp} \Big/ k$$

$$\sigma_{p\text{-}air}^{inel} = k \cdot (14.5) / N \cdot \lambda_{obs} = 2.411 \cdot 10^4 / \lambda_{p\text{-air}} \quad [mb]$$

EAS-TOP: Ne-Nμ cuts + Xmax Distribution

Nucl. Phys. B 75 (1999) 222
PRD 72 (2009) 032004



✓Fluctuation are lower if showers at maximum development are selected

✓This technique cannot always be applied .

✓Once the primary CR energy (i.e. X_{max}), observation level (x_0) and angular acceptance are defined, also the accessible part of the tail of X_{max} distribution is determined.

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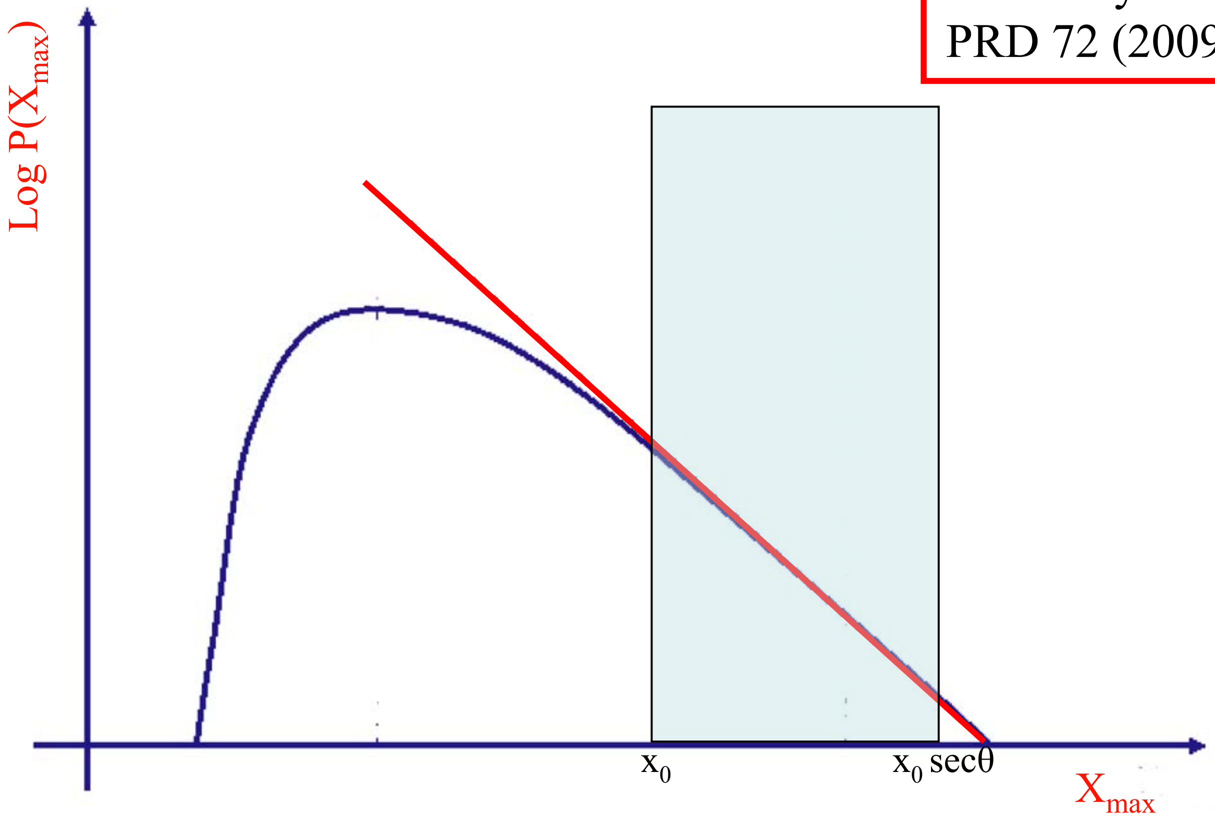

✓Fluctuation are lower if showers at maximum development are selected
✓This technique cannot always be applied .
✓Once the primary CR energy (i.e. X_{max}), observation level (x_0) and angular range are defined, also the part of the X_{max} distribution that can be used is fixed.

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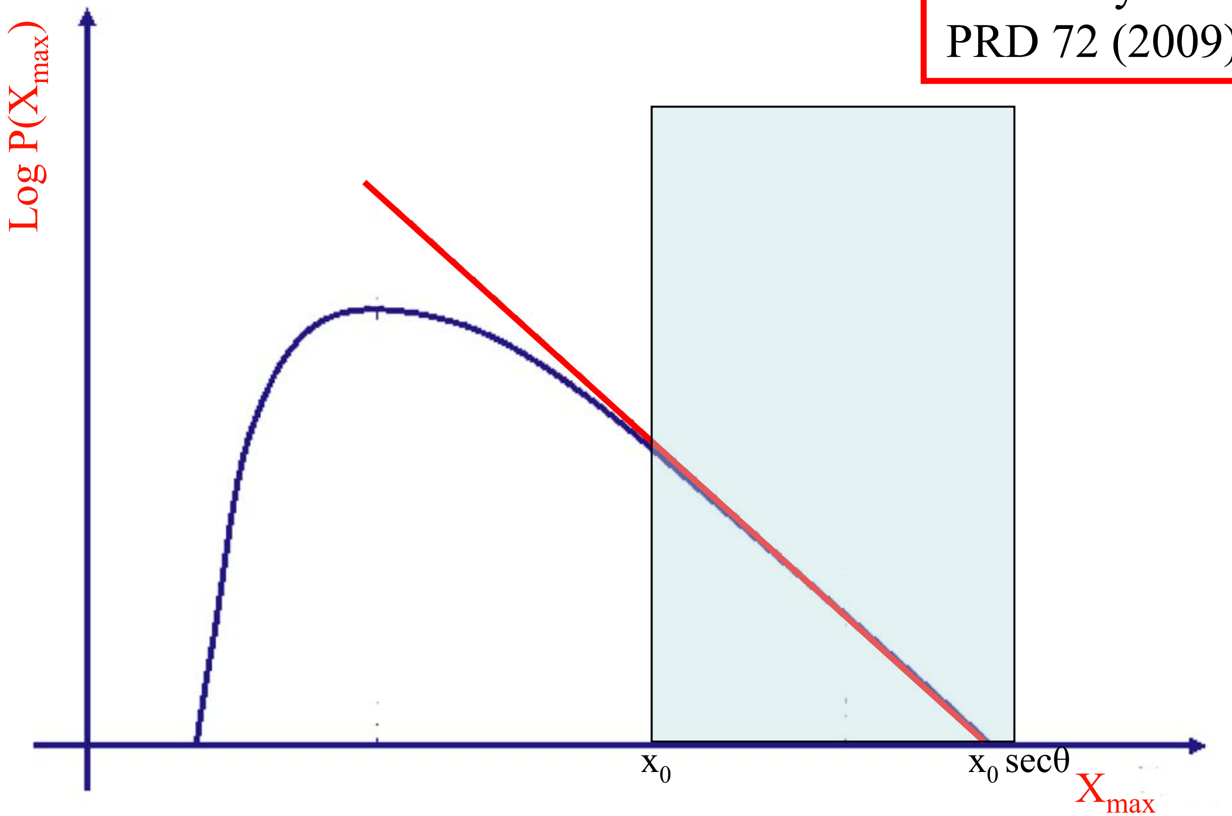

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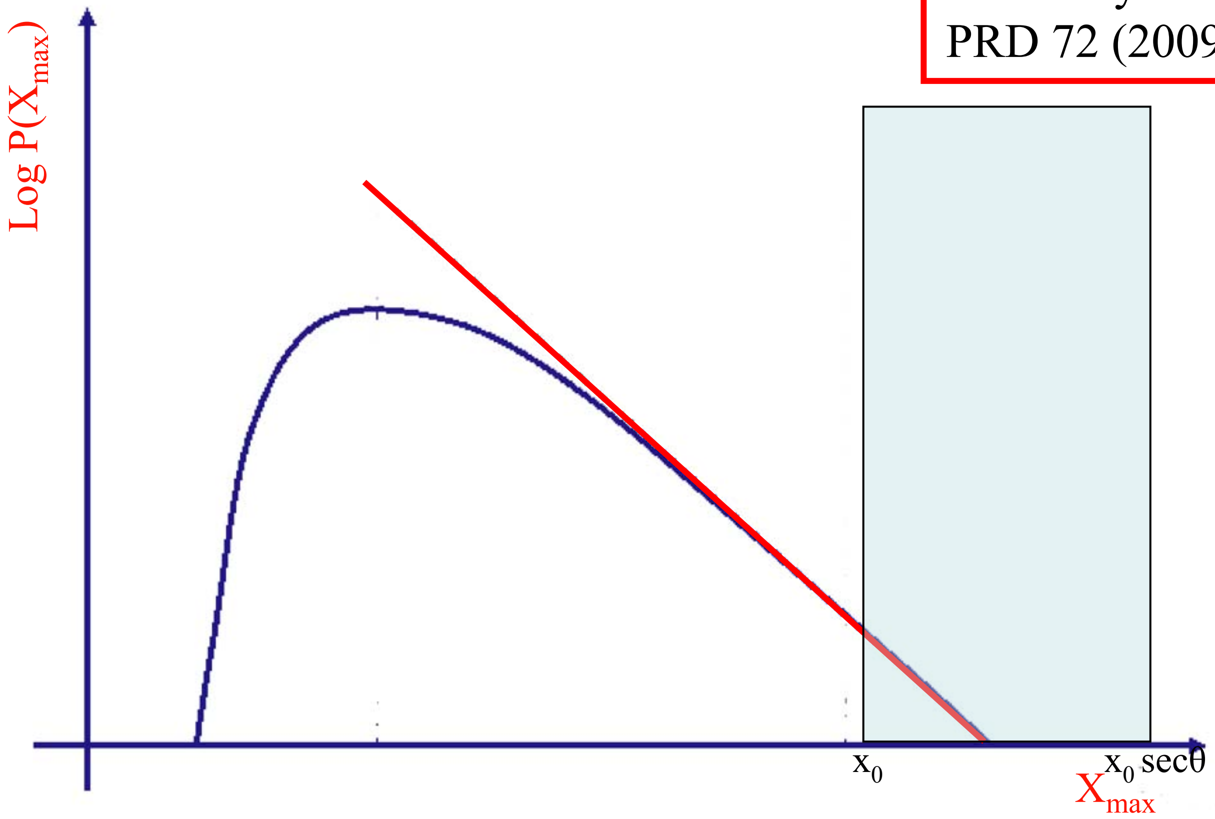

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EAS-TOP 1989-2000

Campo Imperatore

2000 m a.s.l. 820 $g \cdot cm^{-2}$

$10^{14} < E0 < 10^{16}$

- Hadrons
- E.M.
- Low Energy μ ($E_\mu > 1$ GeV)
- Atmospheric Čerenkov Imaging
- H.E. μ ($E > 1.3$ TeV) (MACRO & LVD)

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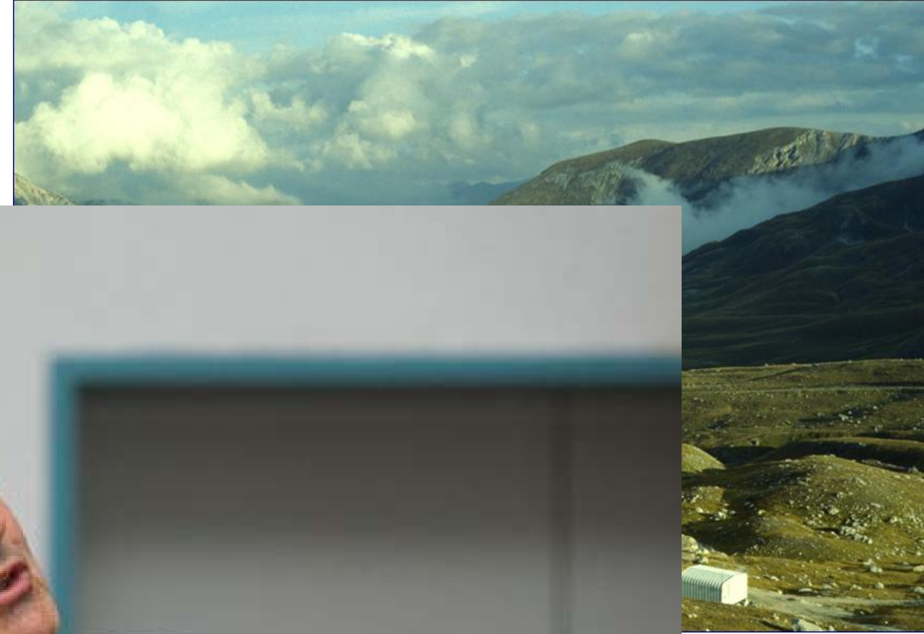

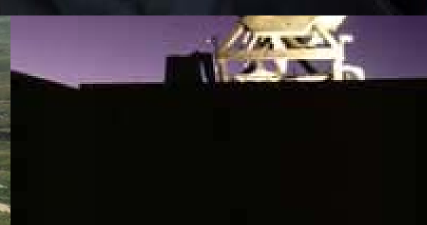

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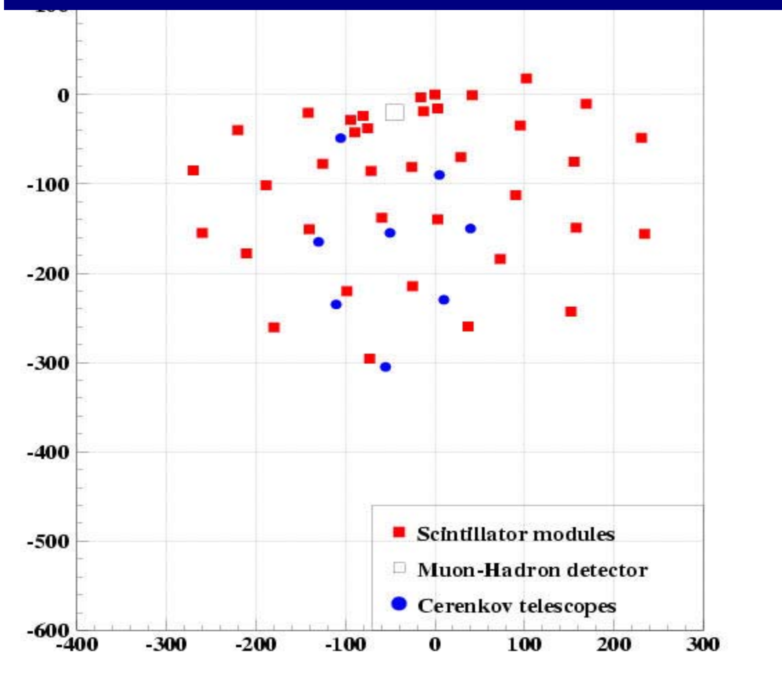
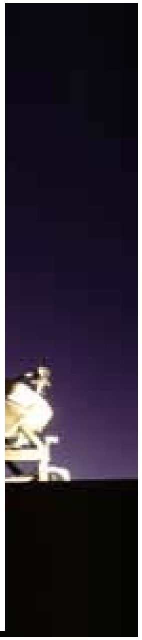
For Ne>$2\cdot10^5$

$\sigma_{Ne}/N_e \cong 0.1$

$\sigma_{Xc} = \sigma_{Yc} = 5$ m

$\sigma_\theta \cong 0.9°$





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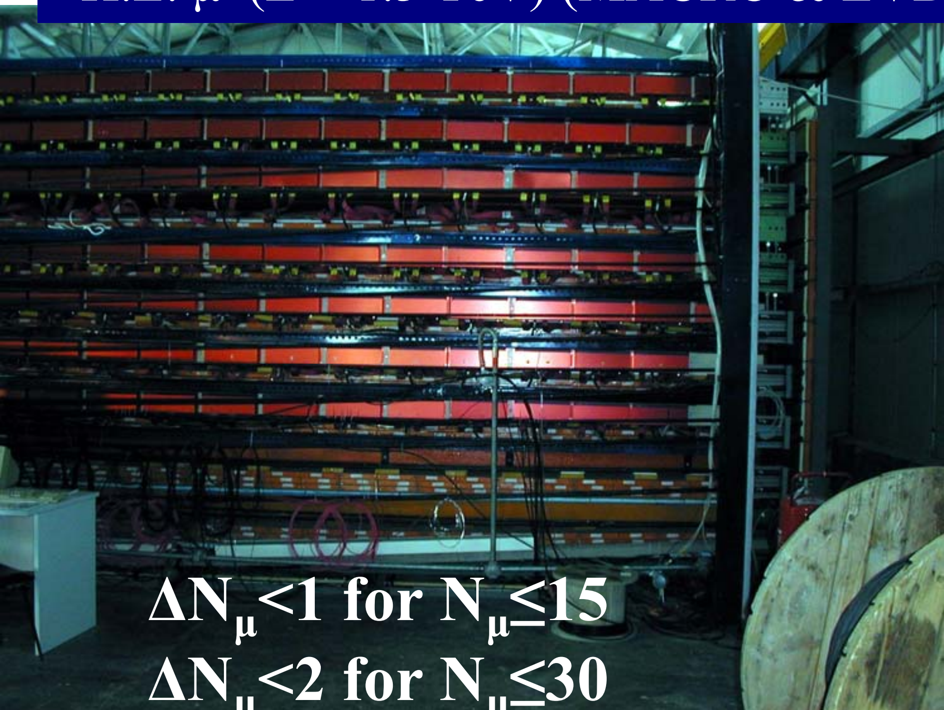


$\Delta N_{\mu} < 1$ for $N_{\mu} \leq 15$

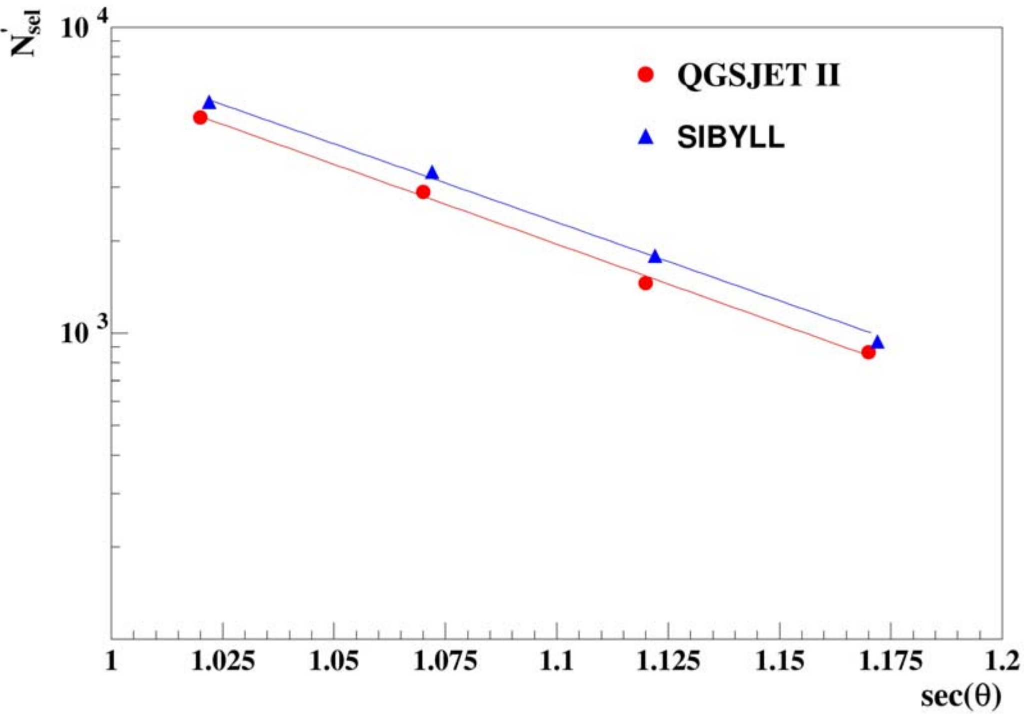
$\Delta N_{\mu} < 2$ for $N_{\mu} \leq 30$

8 x 13 cm Fe layers

9x144 m^2 streamer tubes

k parameter

$$N'_{sel}(\theta) = N_{sel}(\theta, N_1 < N_{\mu,x} < N_2, 6.01 < \mathrm{Log}(N_e) < 6.17) \cdot \Gamma_1(\theta)$$



Average depth of 1st interaction

$1.5\cdot10^6 < E_0 < 2.5\cdot10^6$ GeV

QGSJET II: $\lambda_{p\text{-}air} = 60.3 \pm 0.1$ g/cm^2
SIBYLL: $\lambda_{p\text{-}air} = 59.4 \pm 0.1$ g/cm^2

QGSJET II

$\lambda_{obs}^{sim} = 68.5 \pm 1.4$ g/cm^2

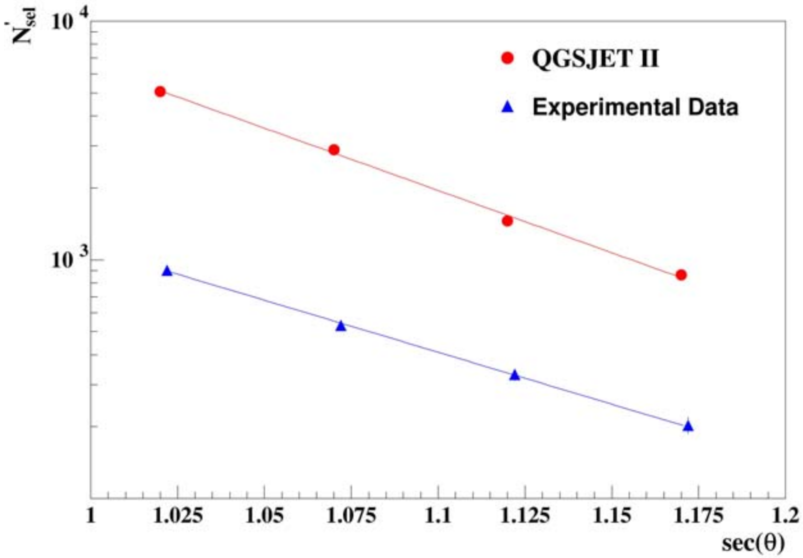
SIBYLL 2.1

$\lambda_{obs}^{sim} = 69.9 \pm 1.4$ g/cm^2

QGSJET II $k = \lambda_{obs}^{sim} / \lambda_{p\text{-}air}^{sim} = 1.14 \pm 0.02$

SIBYLL 2.1 $k = \lambda_{obs}^{sim} / \lambda_{p\text{-}air}^{sim} = 1.18 \pm 0.02$

Experimental data

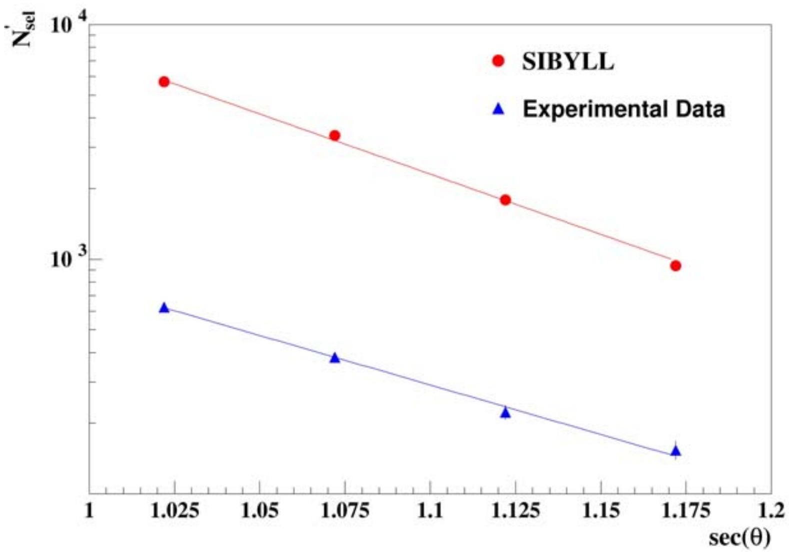


$$\lambda_{obs}^{exp} = 80.2 \pm 4.3 \text{ g/cm}^2$$

$$\lambda_{p\text{-air}}^{exp} = \lambda_{obs}^{exp} / k$$

$$\lambda_{p\text{-air}}^{exp} = 71\ .0 \pm 4.1 \text{ g/cm}^2$$

$$\sigma_{p\text{-air}}^{inel} = 2{,}41*10^4 / \lambda_{p\text{-air}}^{exp} = 341 \pm 20 \text{ mb}$$



$$\lambda_{obs}^{exp} = 84.7 \pm 5.0 \text{g/cm}^2$$

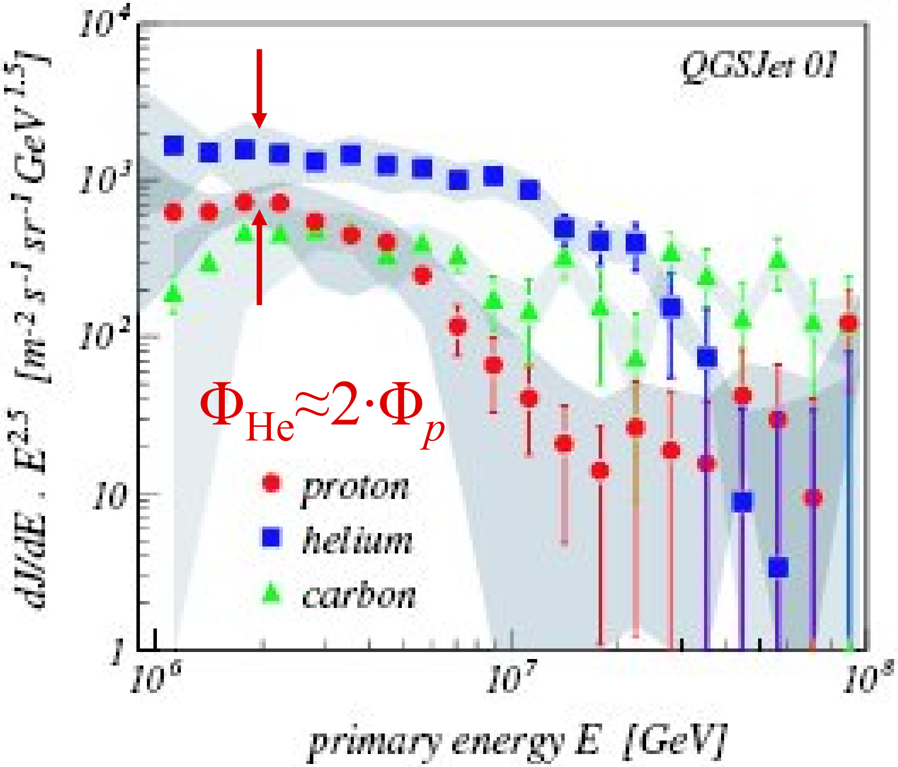
$$\lambda_{p\text{-air}}^{exp} = \lambda_{obs}^{exp} / k$$

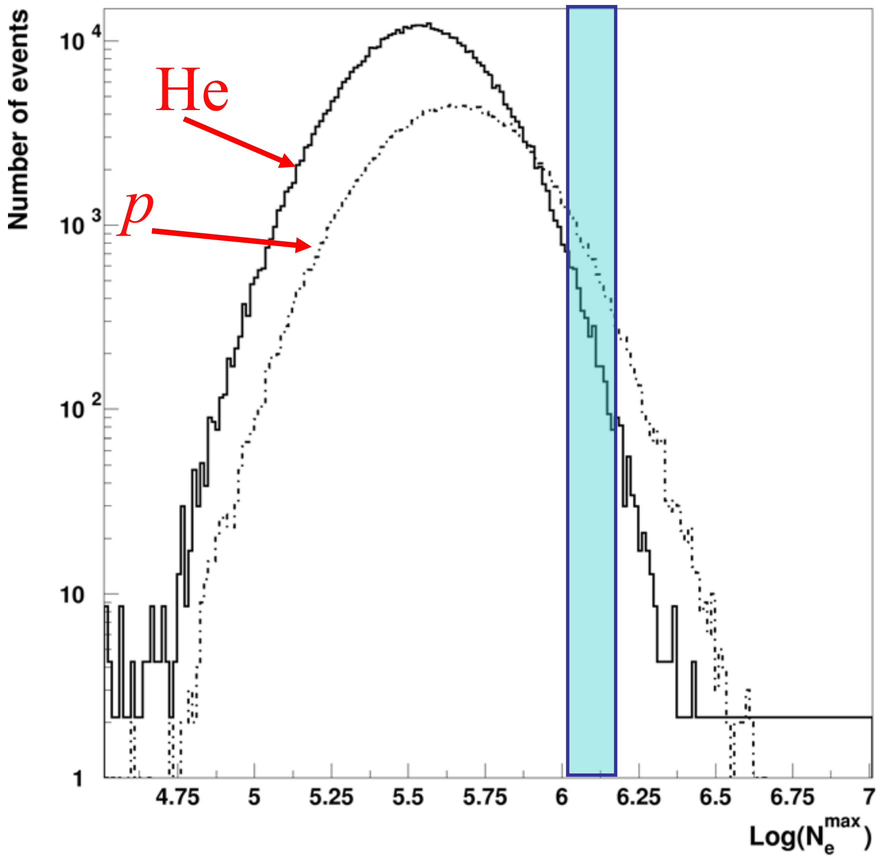
$$\lambda_{p\text{-air}}^{exp} = 72.2 \pm 4.2 \text{ g/cm}^2$$

$$\sigma_{p\text{-air}}^{inel} = 2{,}41*10^4 / \lambda_{p\text{-air}}^{exp} = 335 \pm 21 \text{ mb}$$

Heavier Primaries

Helium QGSJET II





systematic uncertainty: σ_{sys}(He)= -29 mb

Systematic Uncertainties

In order to determine the systematic uncertainties due to the analysis procedure (e.g. HE interaction model), the cross section is reconstructed with a model that differs from the one used to produce the simulated datasets

Experiment	SIBYLL 2.1 $\sigma_{p\text{-air}}^{\text{inel}} = 406 \pm 1$ mb		QGSJET II $\sigma_{p\text{-air}}^{\text{inel}} = 400 \pm 1$ mb		QGSJET II_{HDPM} $\sigma_{p\text{-air}}^{\text{inel}} = 367 \pm 1$ mb	
Analysis	$\sigma_{p\text{-air}}^{\text{inel}}$ [mb]	$\Delta\sigma_{p\text{-air}}^{\text{inel}}$ [mb]	$\sigma_{p\text{-air}}^{\text{inel}}$ [mb]	$\Delta\sigma_{p\text{-air}}^{\text{inel}}$) [mb]	$\sigma_{p\text{-air}}^{\text{inel}}$ [mb]	$\Delta\sigma_{p\text{-air}}^{\text{inel}}$ [mb]
SIBYLL 2.1	...	...	419 ± 12	$+19 \pm 12$	372 ± 13	$+5 \pm 13$
QGSJET II	393 ± 11	-13 ± 11	...	...	361 ± 12	-6 ± 12

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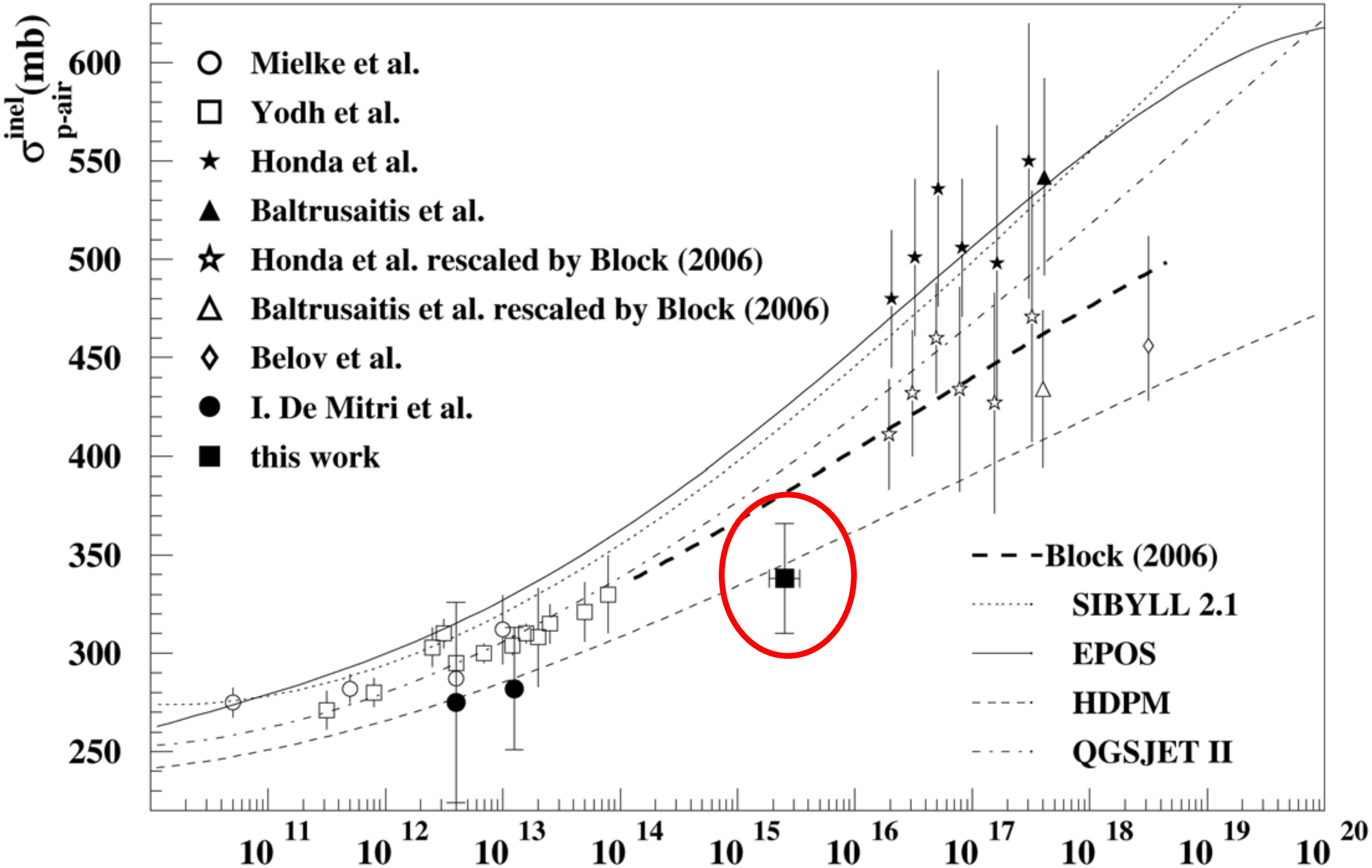
$\sigma_{syst} = 19$ mb (99%)

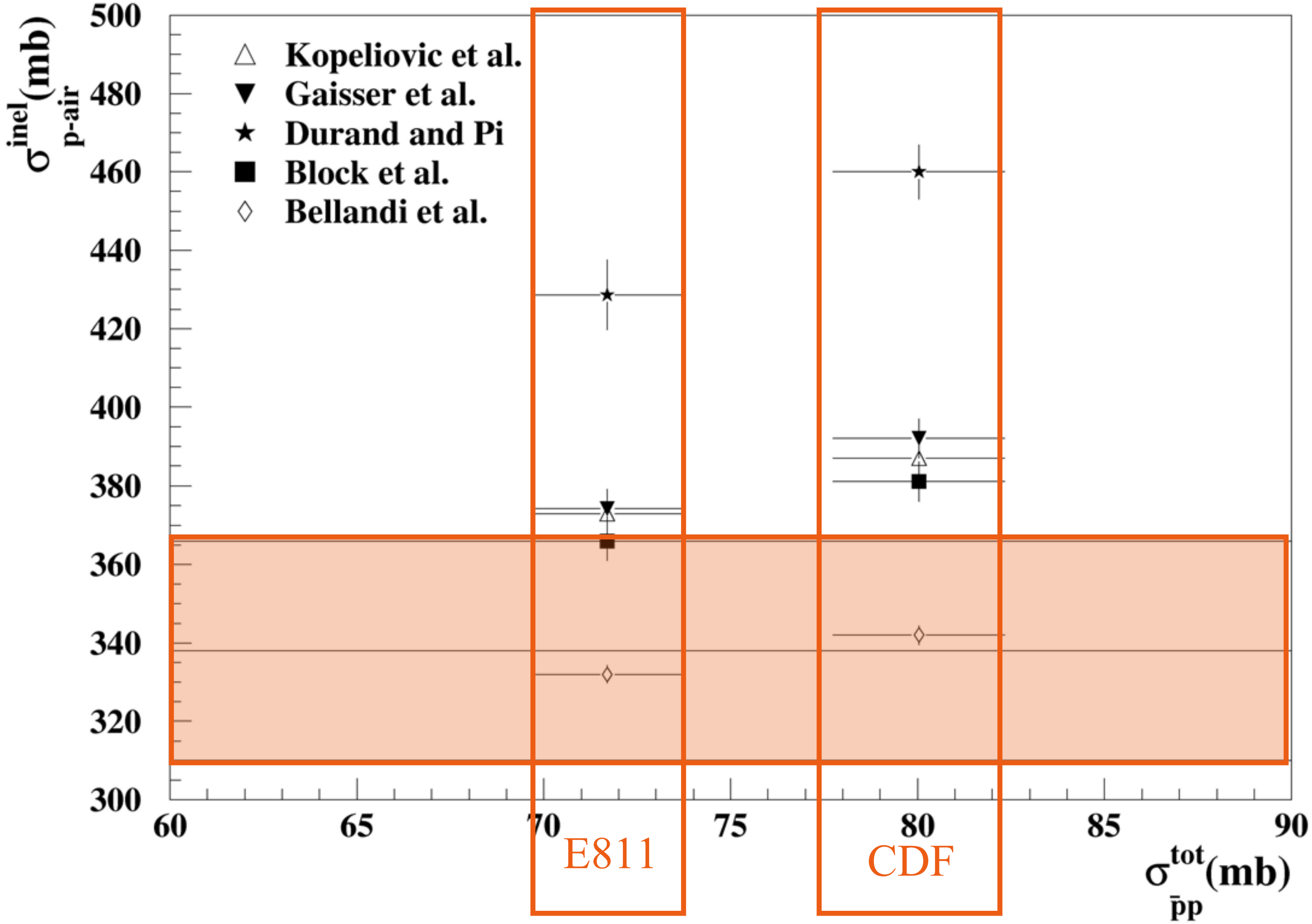
EAS-TOP *p*-air cross section at $\sqrt{s} \approx 2$ TeV



$$\sigma^{inel}_{p\text{-air}} = 338 \pm 21_{stat} \pm 19_{syst} - 29_{syst(\mathrm{He})}\ \mathrm{mb}$$

PRD 72 (2009) 032004

EAS-TOP: p-air ⟷ pp at $\sqrt{s} \approx 2$ TeV



PRD 72 (2009) 032004

Summary

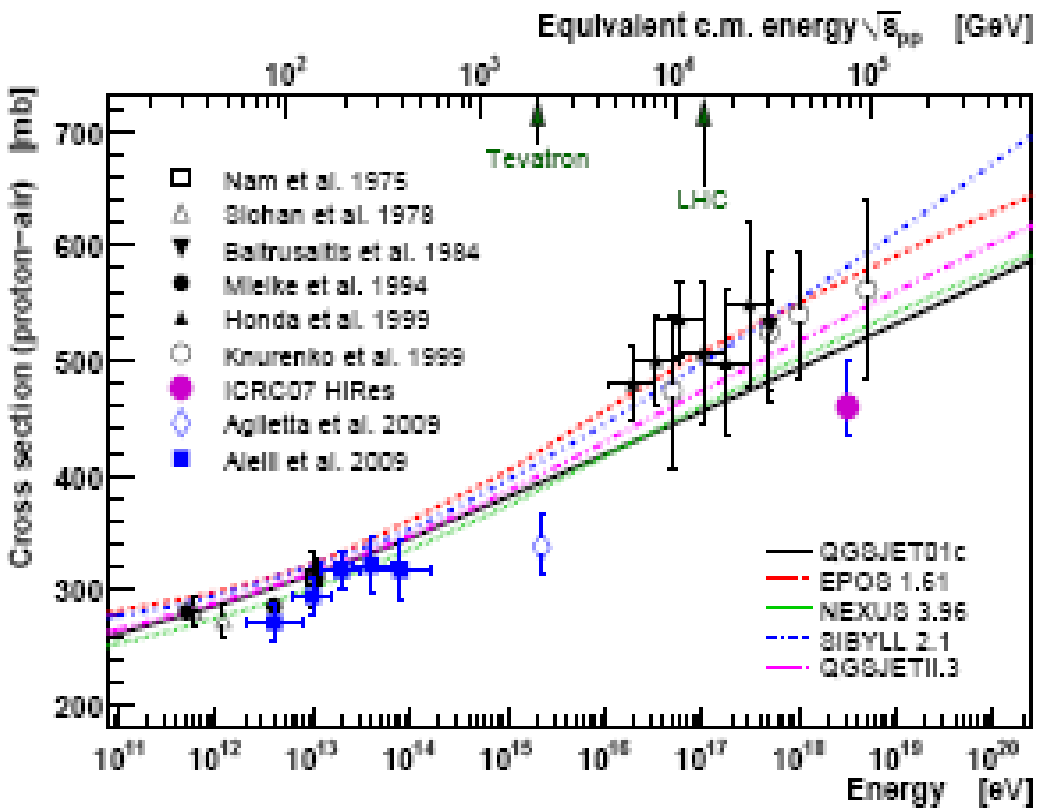
- The absorption length of cosmic ray proton showers at maximum development in the energy range $E_0 = (1.5 \div 2.5) \cdot 10^{15}$ eV (i.e. at $\sqrt{s} \approx 2$ TeV) is measured at the atmospheric depth of 820 g/cm^2

$$\sigma^{inel}_{p\text{-air}} = 338 \pm 21_{stat} \pm 19_{syst} - 29_{syst(\mathrm{He})}\ \mathrm{mb}$$

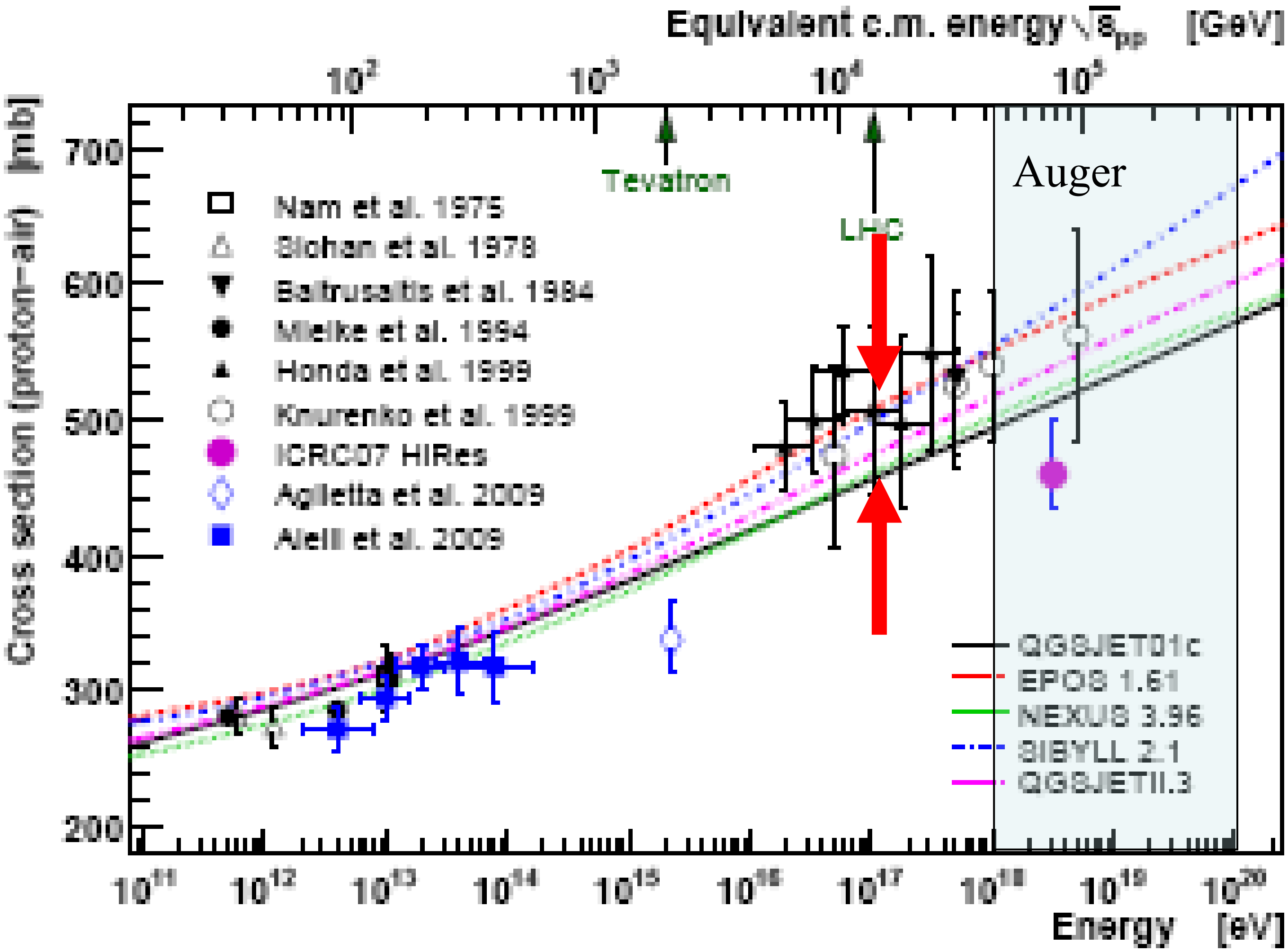
- This value is about 20% smaller than the values in use within most used hadronic interaction models

- Deeper shower penetration in the atmosphere with respect to the predictions of the interaction models

- $\lambda^{sim}_{obs} < \lambda^{exp}_{obs}$

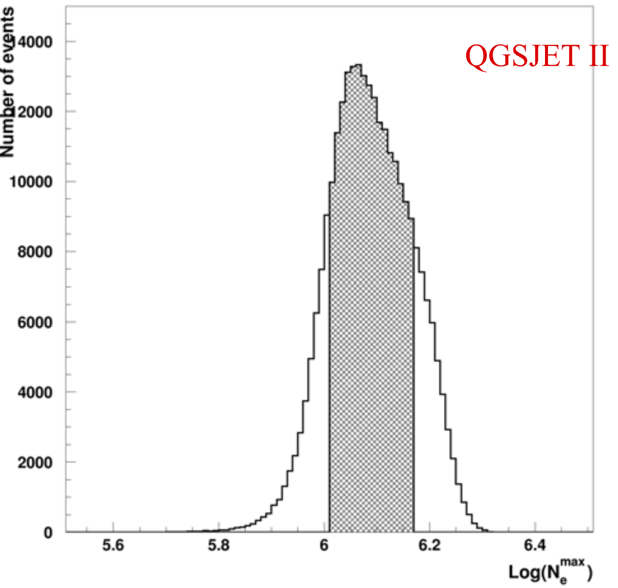


Outlook



Equivalent c.m. energy $\sqrt{s_{pp}}$ [GeV]
10^2
10^3
10^4
10^5
Cross section (proton−air) [mb]
700
600
500
400
300
200
Tevatron
LHC
Auger
Nam et al. 1975
Siohan et al. 1978
Baltrusaitis et al. 1984
Mielke et al. 1994
Honda et al. 1999
Knurenko et al. 1999
ICRC07 HiRes
Aglietta et al. 2009
Aielli et al. 2009
QGSJET01c
EPOS 1.61
NEXUS 3.96
SIBYLL 2.1
QGSJETII.3
10^{11}
10^{12}
10^{13}
10^{14}
10^{15}
10^{16}
10^{17}
10^{18}
10^{19}
10^{20}
Energy [eV]

Shower Max Selection



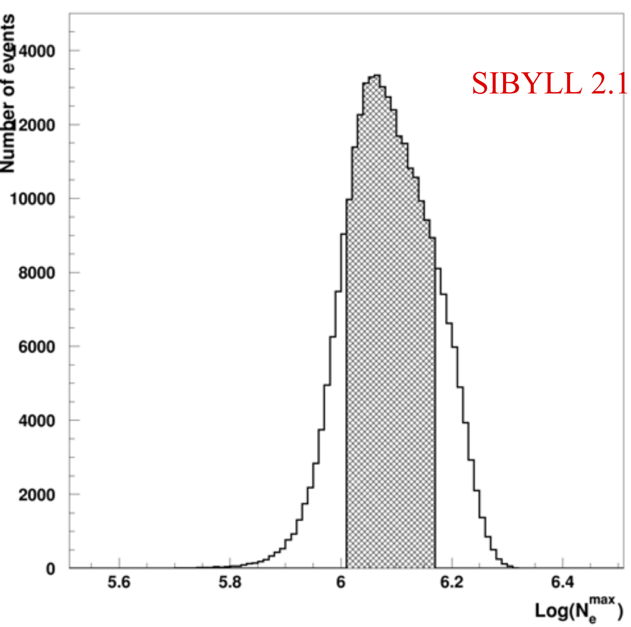
Ne @ max of *p* Showers with primary energy in the range $1.5 \cdot 10^6$ GeV $< E_0 < 2.5 \cdot 10^6$ GeV

$\mathrm{Log}(N_e) = \langle \mathrm{Log}(N_e^{max}) \rangle \pm 1$ s.d.

$6.01 < \mathrm{Log}(N_e) < 6.17$

(<5% of the ev. selected with $N_{\mu,x}$.)

$E_{median} = 2.49 \cdot 10^{15}$ eV with r.m.s. $0.78 \cdot 10^{15}$ eV

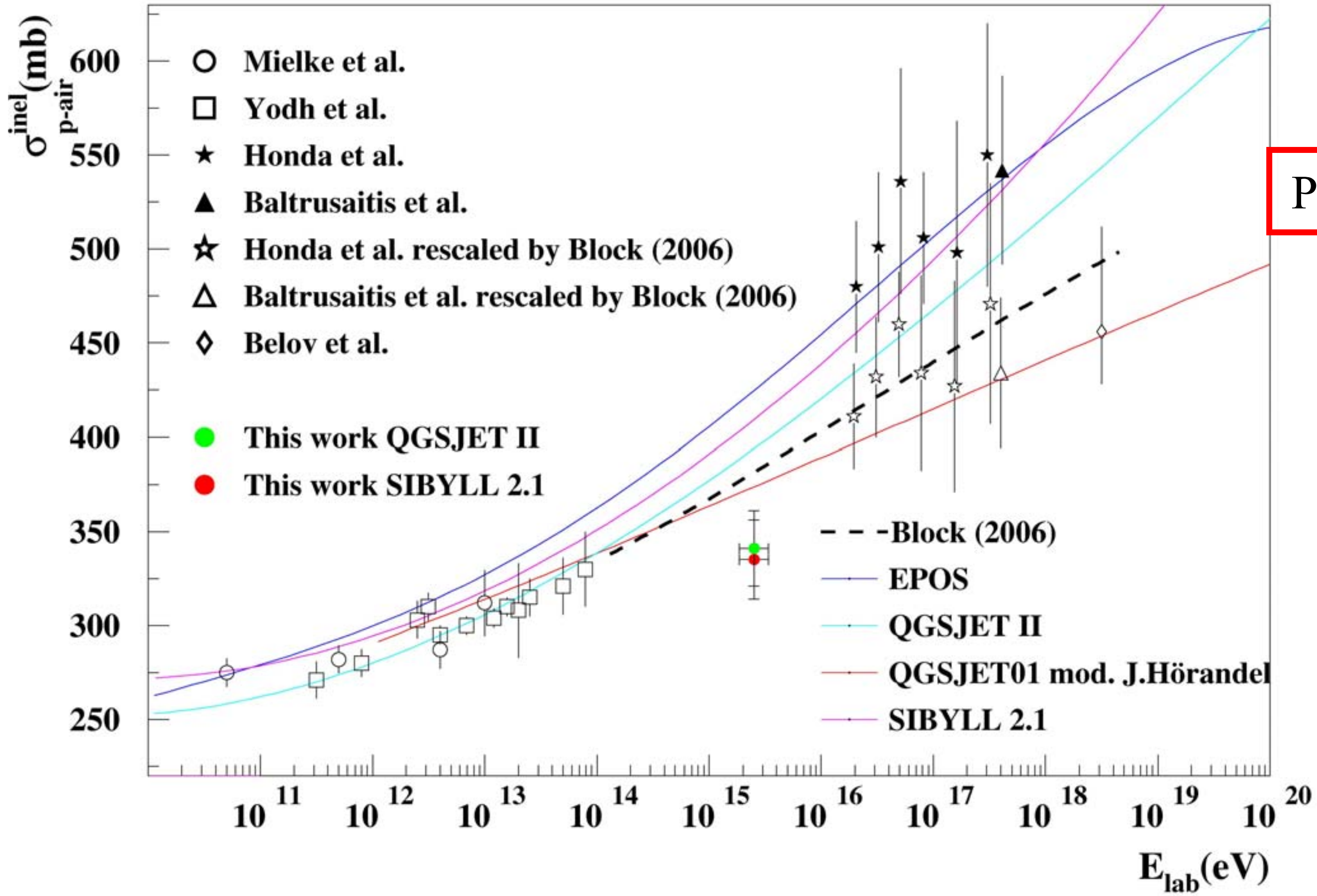


$6.01 < \mathrm{Log}(N_e) < 6.17$

(<5% of the ev. selected with $N_{\mu,x}$.)

$E_{median} = 2.50 \cdot 10^{15}$ eV with r.m.s. $0.80 \cdot 10^{15}$ eV

EAS-TOP *p*-air cross section at $\sqrt{s} \approx 2$ TeV



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High energy hadronic interaction model	λ^{sim}_{int} [g/cm^2]	λ^{sim}_{obs} [g/cm^2]	k	λ^{exp}_{obs} [g/cm^2]	λ^{exp}_{int} [g/cm^2]	σ^{inel}_{p-air} [mb]
SIBYLL 2.1	59.4 ± 0.1	69.9 ± 1.4	1.18 ± 0.02	84.7 ± 5.0	71.8 ± 4.5	336 ± 21
QGSJET II	60.3 ± 0.1	68.5 ± 1.4	1.14 ± 0.02	80.2 ± 4.3	70.7 ± 4.2	341 ± 20

Electron Size N_e Cuts (Stability)

$$R(\vartheta_1,\vartheta_2)=\frac{f(N_\mu,N_{e,}\vartheta_1)}{f(N_\mu,N_{e,}\vartheta_2)}=\exp\left[-\frac{X_v}{\Lambda_{obs}}(\sec\vartheta_1-\sec\vartheta_2)\right]$$

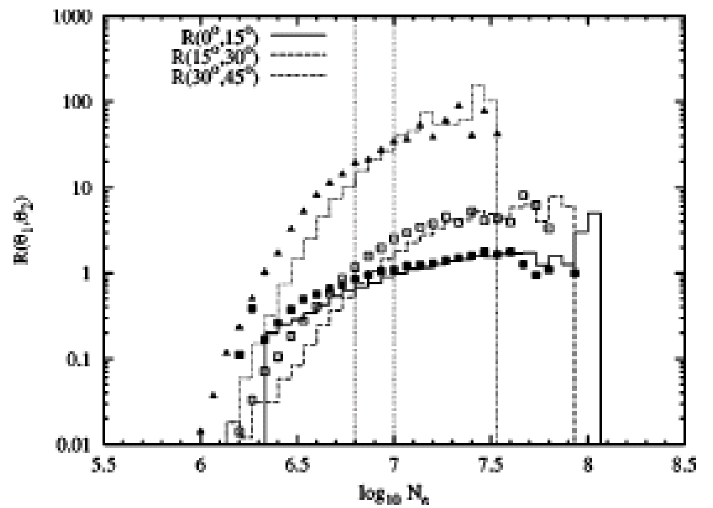
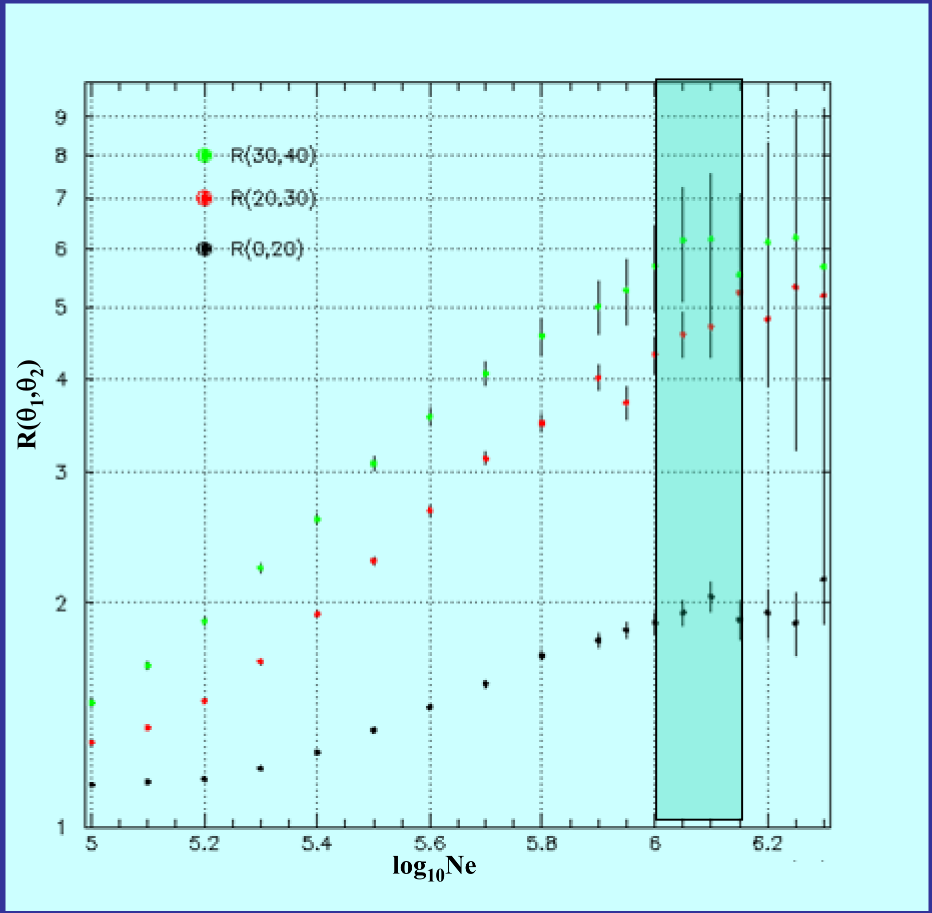


FIG. 5. Ratios of number of proton-initiated showers having between $10^{5.25}$ and $10^{5.45}$ muons and electron size N_e at 920 g/cm^2 as a function of N_e. Histograms correspond to showers simulated using SIBYLL 2.1, and points to showers simulated with QGSJET98.



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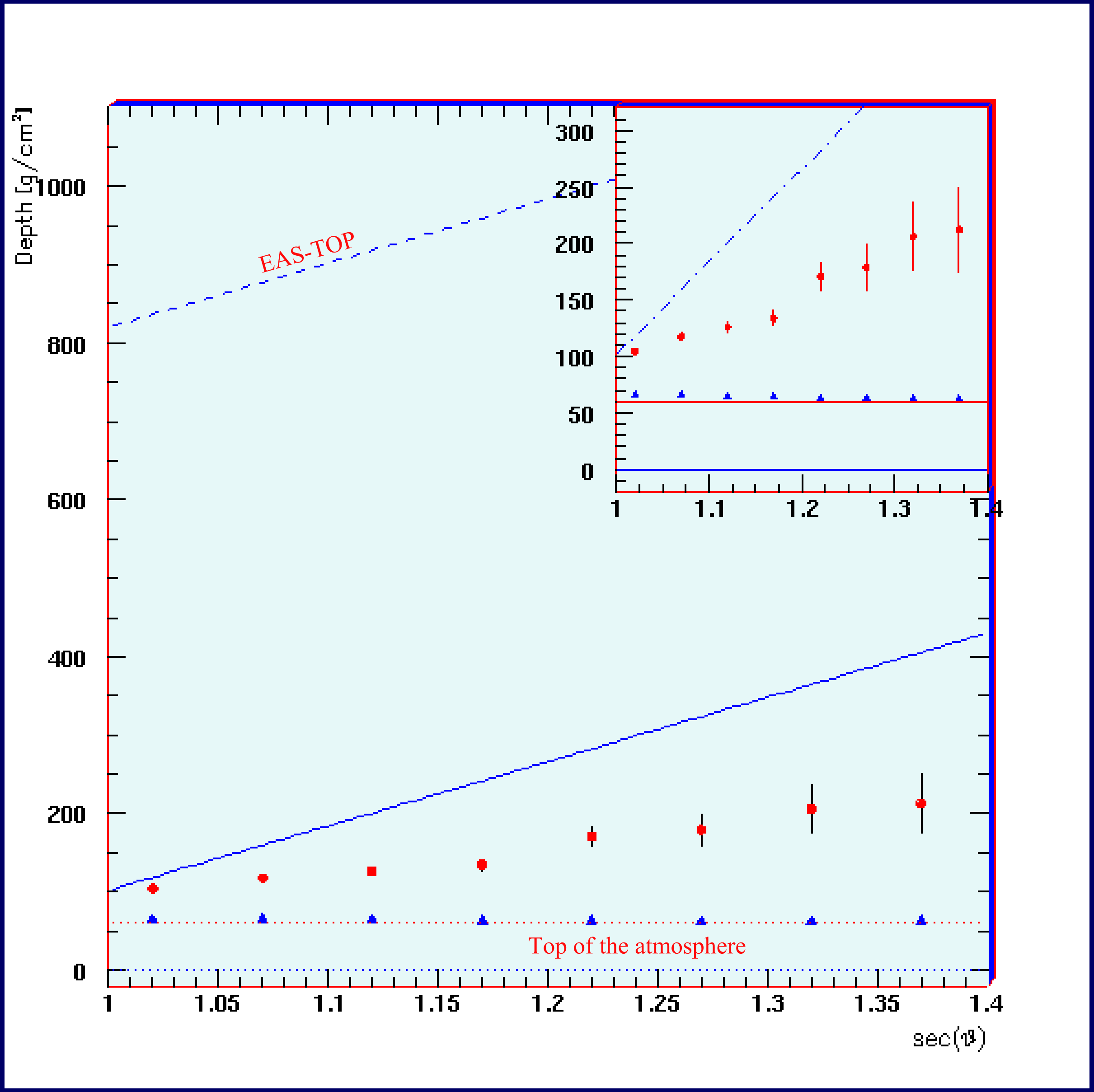
Event Selection

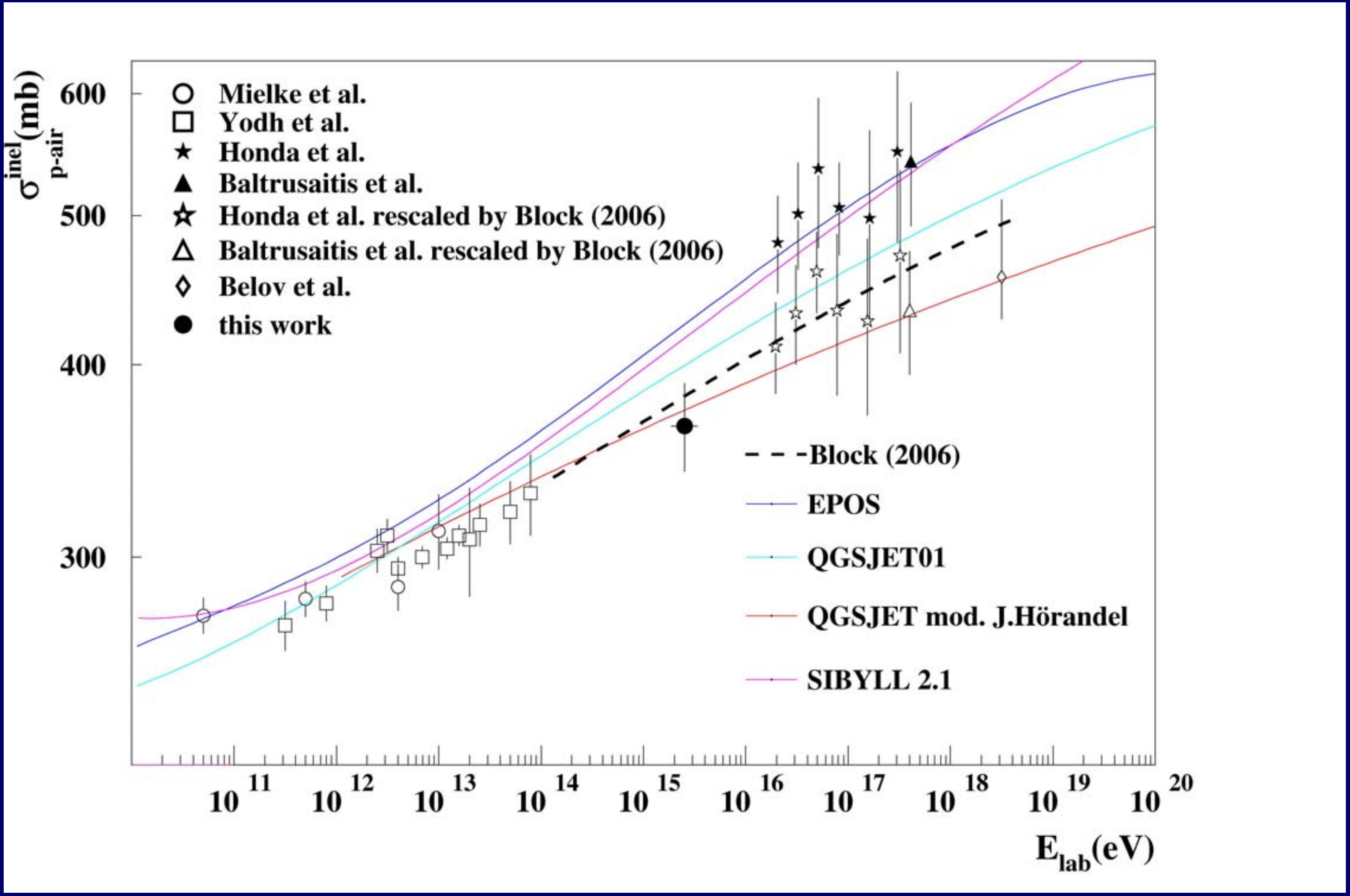


QGSJet01
Perfect selection

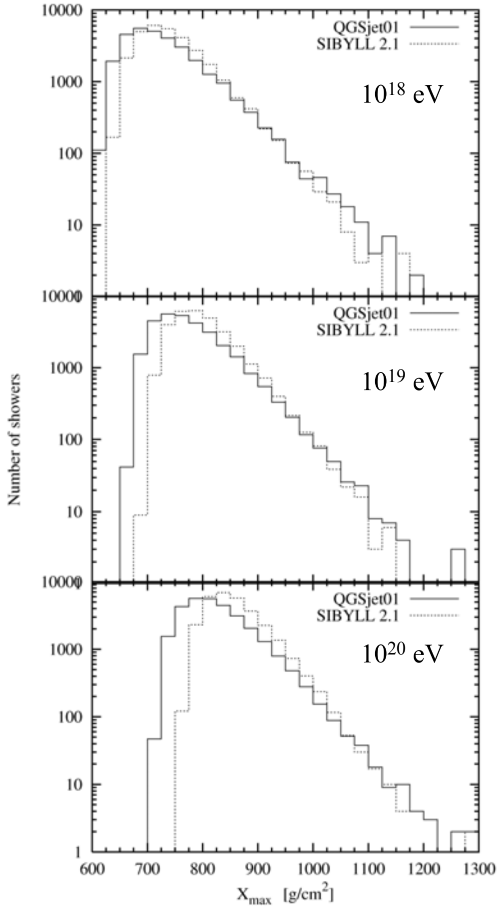
Selection criteria provide events with deeper interaction in the atmosphere with increasing zenith angle

E_0 selection (using muon number) does not modify the average depth of first interaction

p-air cross section at $\sqrt{s} \approx 2$ TeV



$$\sigma^{inel}_{p\text{-air}} = 365 \pm 24(\text{stat}) - 28(\text{sys})\ \text{mb}$$


10000
1000
100
10
QGSjet01
SIBYLL 2.1
10^{18} eV
10^{19} eV
10^{20} eV
Number of showers
1
600
700
800
900
1000
1100
1200
1300
X_{max} [g/cm^2]