Measurements of the proton-air cross section with high energy cosmic ray experiments.

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International Symposium OF MULTIPARTICLE DYNAMICS

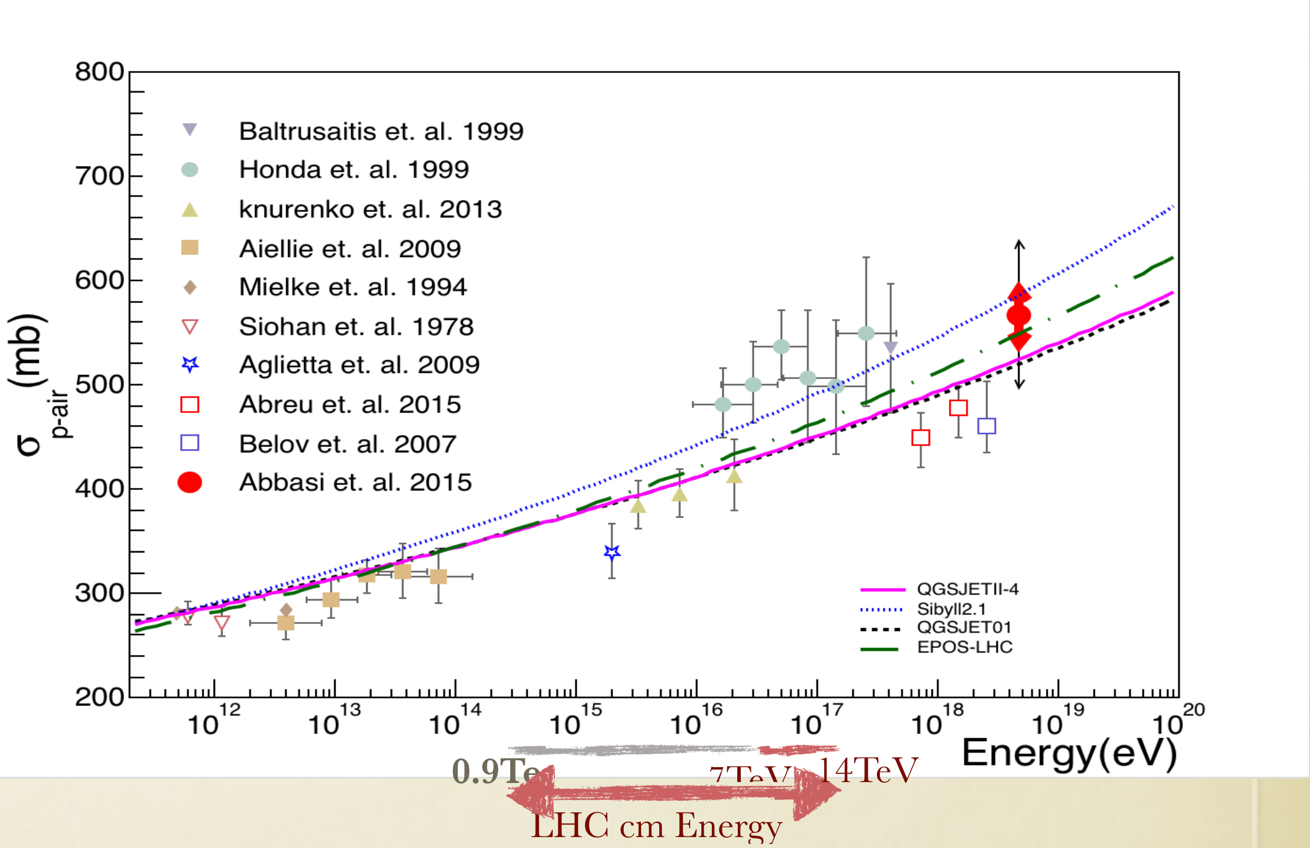
Oct. 6th 2015

Outline

- Motivation
- Experimental Methods
- Experimental Results
- Conclusion

Motivation

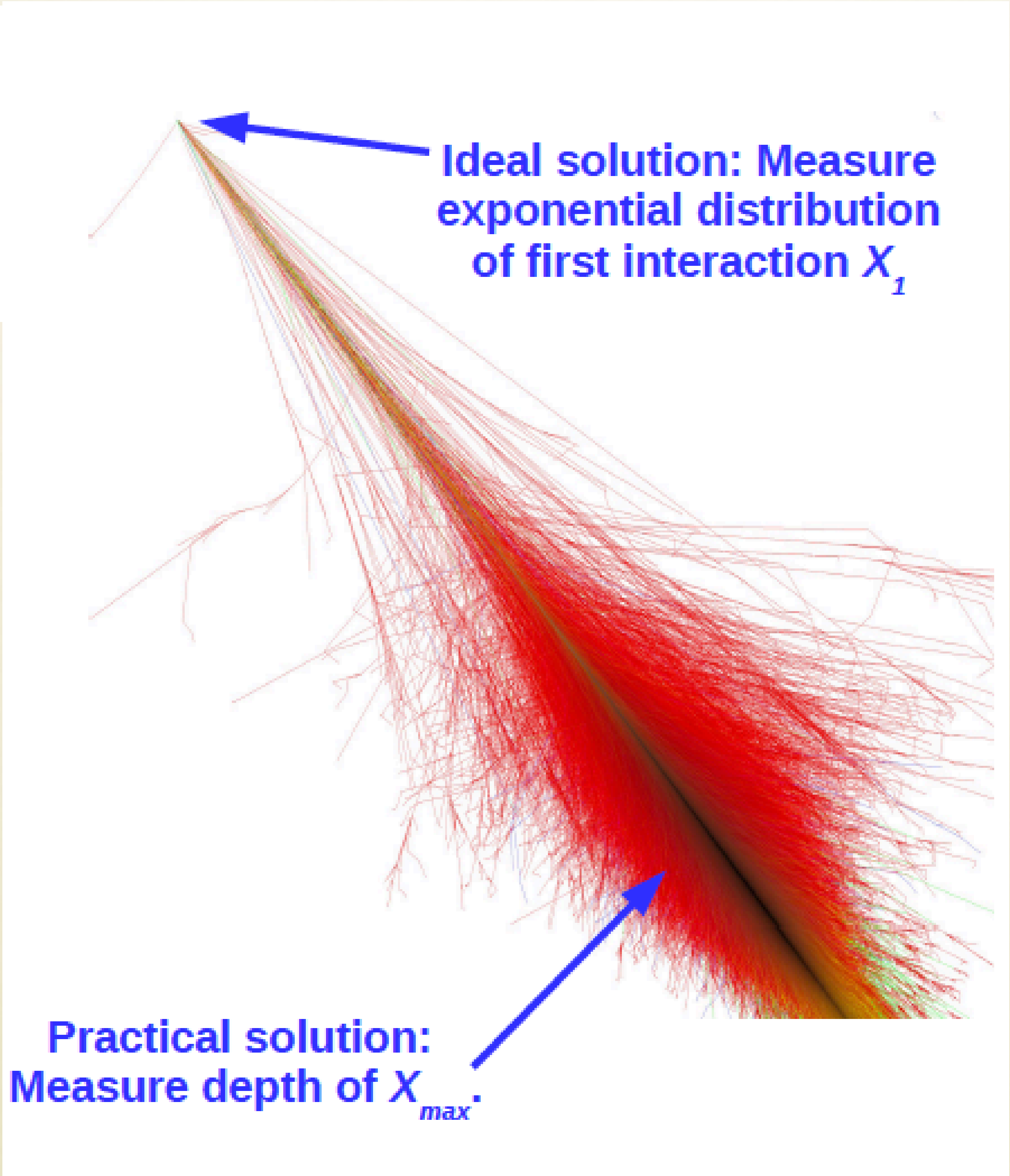
- $\sigma_{p\text{-}p}$ beyond the lhc
- constrain the high energy models prediction of hadronic interaction $\sigma_{p\text{-}air}$ in the atmosphere.



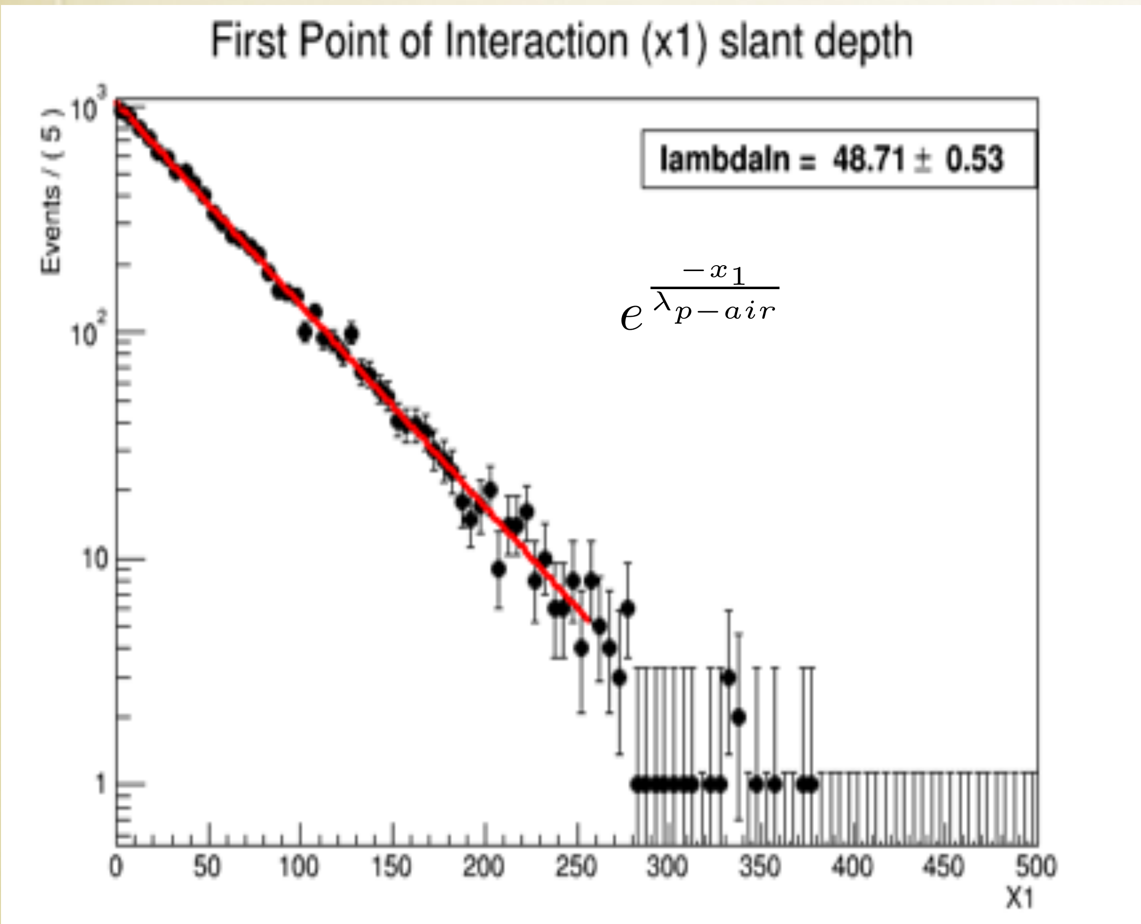
Access beyond the LHC

Experimental methods

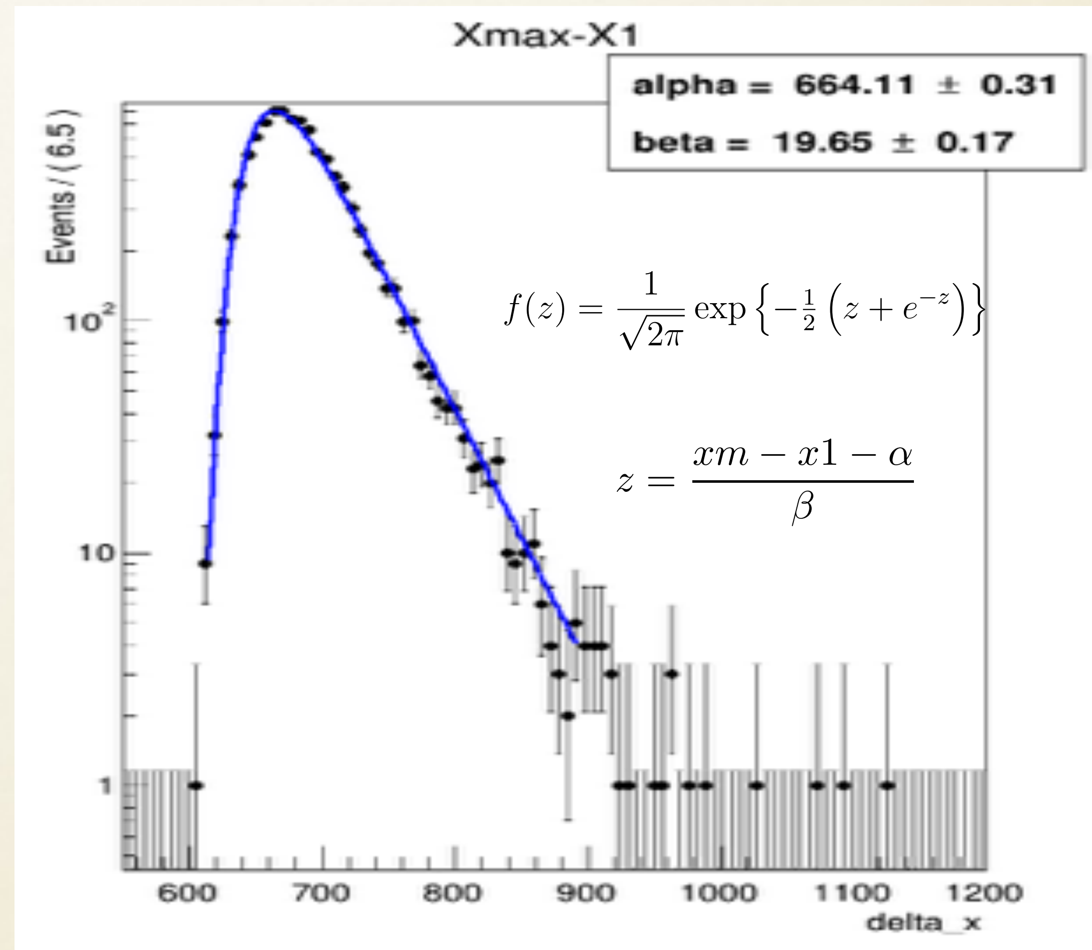
$\sigma_{p\text{-}air}$ from the extensive air shower



Convolution Method



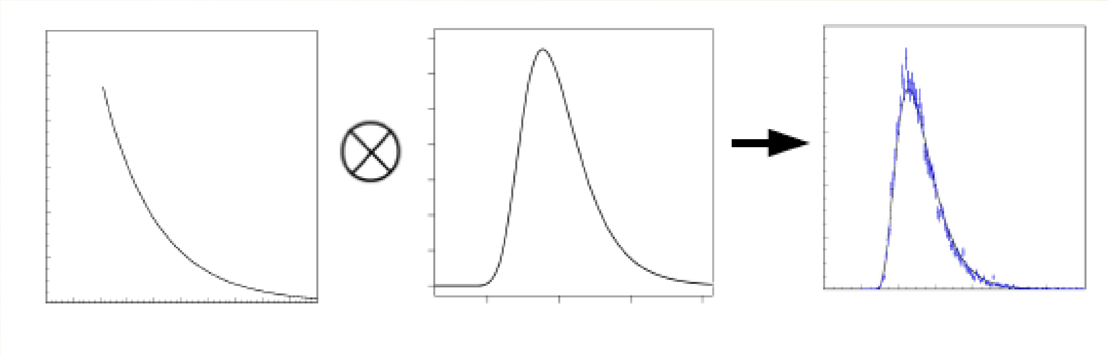
$\bigotimes$

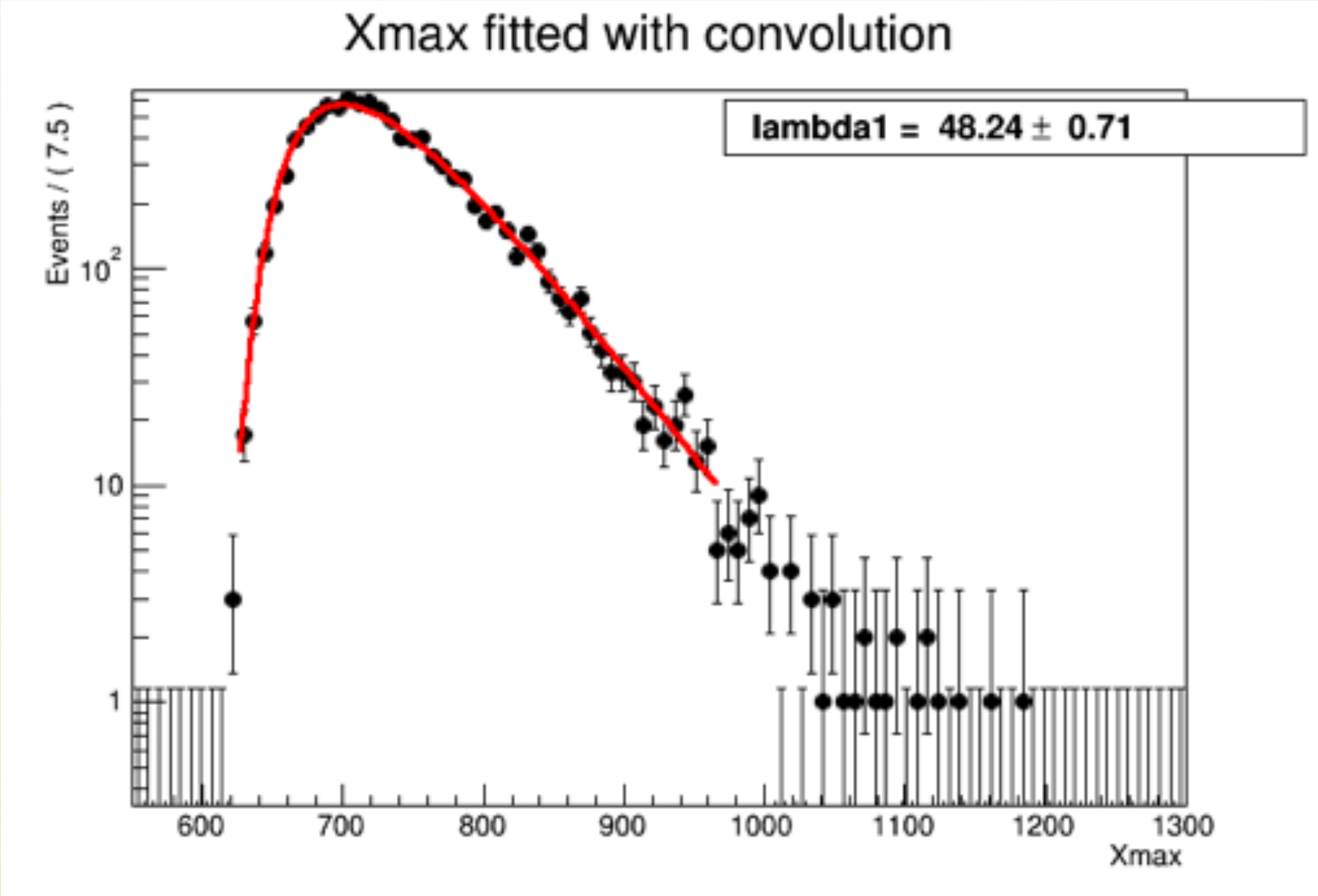


$$\frac{1}{\beta\sqrt{2\pi}} \int_0^{x_m} \frac{1}{\lambda_{p-air}} e^{-x_1/\lambda_{p-air}} e^{\frac{1}{2}[\frac{x_m - x_1 - \alpha}{\beta} + e^{-[\frac{x_m - x_1 - \alpha}{\beta}]}]} dx_1$$

Extract lambda from the Xmax distribution

- Xmax distribution is convolution of X1 and Landau like distribution
- Get lambda by deconvolution
- Advantage: fit to the whole Xmax distribution.



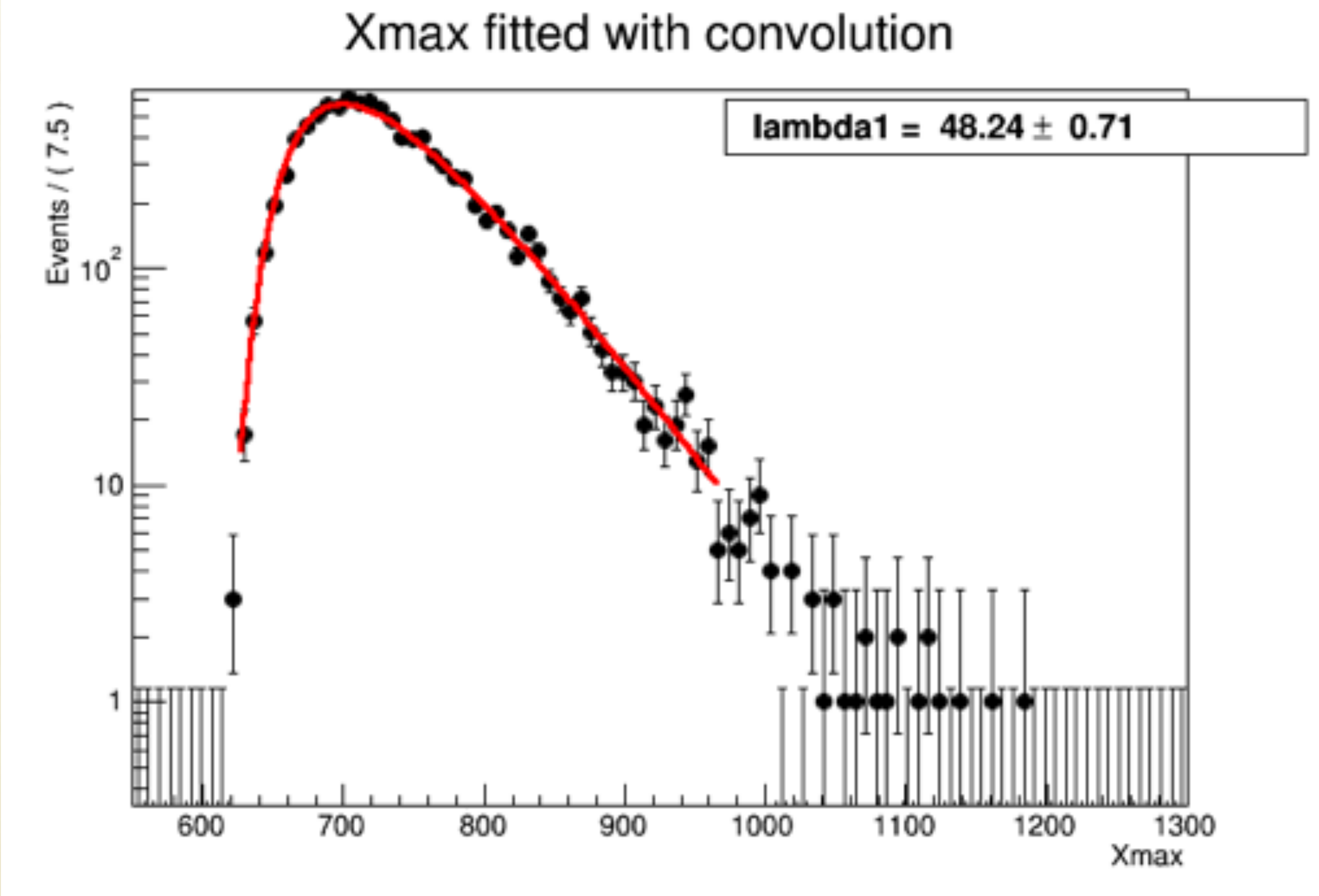


$$\frac{1}{\beta\sqrt{2\pi}}\int_0^{x_m}\frac{1}{\lambda_{p-air}}e^{-x_1/\lambda_{p-air}}e^{\frac{1}{2}[\frac{x_m-x_1-\alpha}{\beta}+e^{-[\frac{x_m-x_1-\alpha}{\beta}]}]}dx_1$$

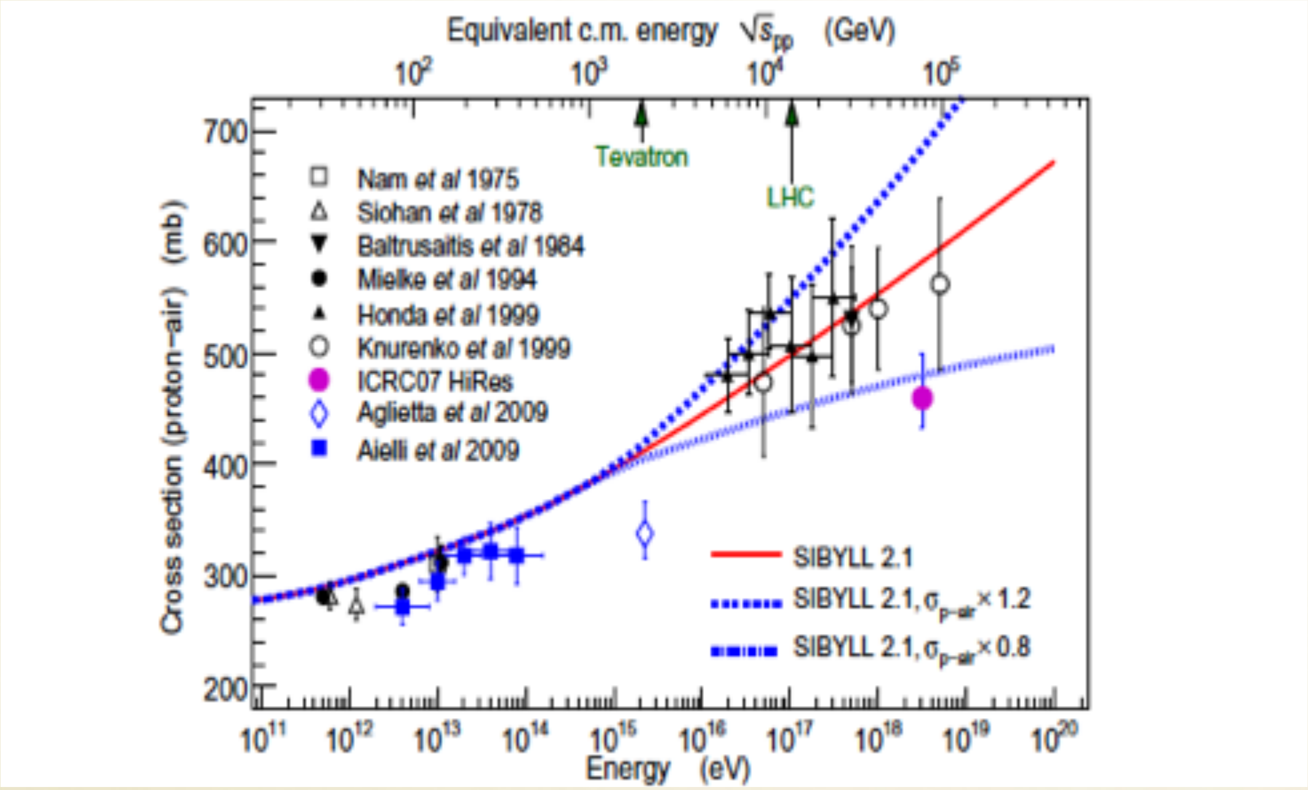
Convolution Method

$$\frac{1}{\beta\sqrt{2\pi}}\int_0^{x_m}\frac{1}{\lambda_{p-air}}e^{-x_1/\lambda_{p-air}}e^{\frac{1}{2}[\frac{x_m-x_1-\alpha}{\beta}+e^{-[\frac{x_m-x_1-\alpha}{\beta}]}]}dx_1$$

- Disadvantage: Highly dependent on the mean Xmax value —>Highly model dependence.



Modified cross section Method



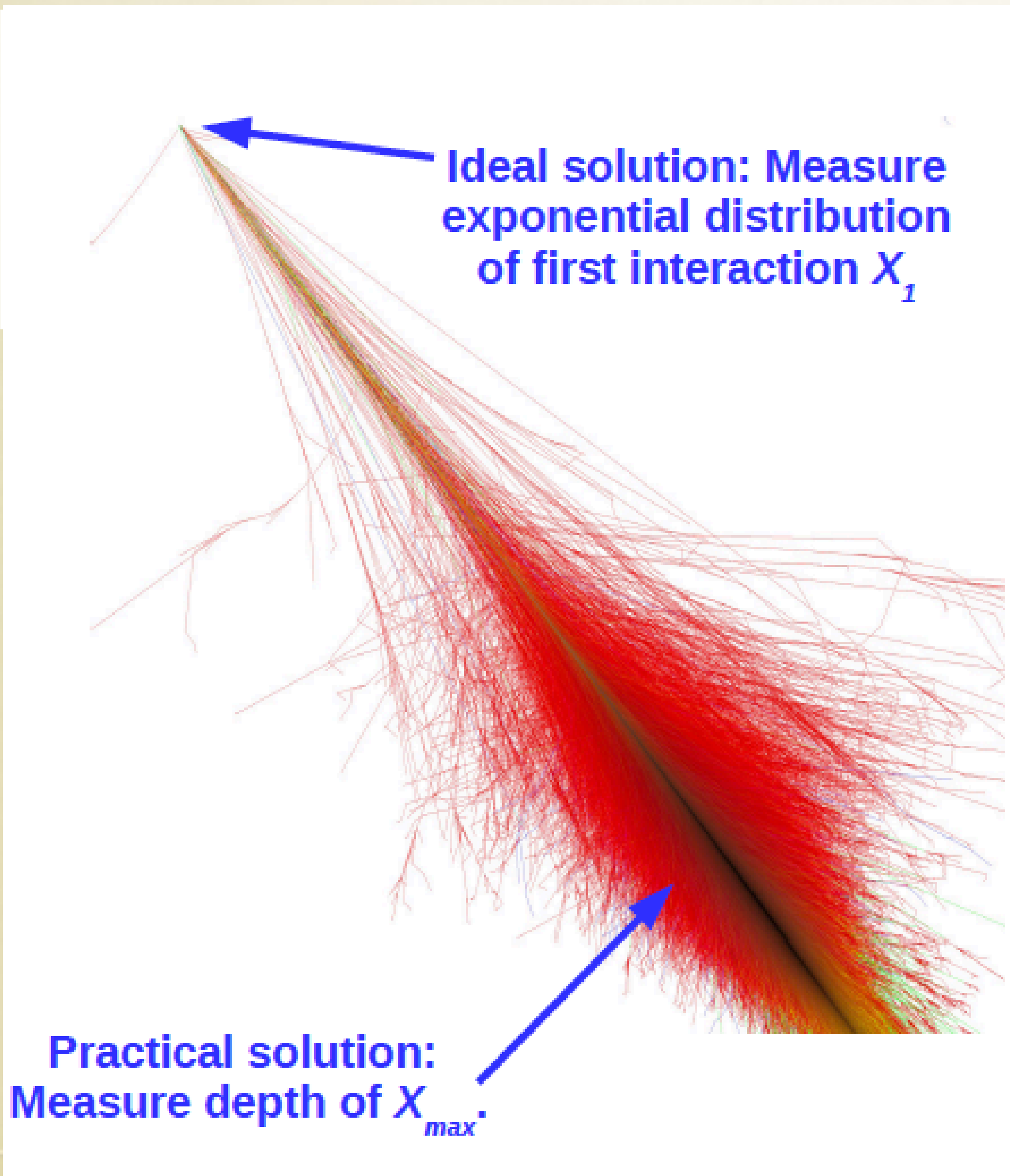
$$\sigma^{modified} = \sigma^{E-model}(E).\left(1 + (f19 - 1)\frac{log_{10}(E/1PeV)}{log_{10}(10EeV/1PeV)}\right)$$

E: Shower energy

f19: factor by which show is modified at 10^{19}eV

- Modifying the energy dependence cross section of the p-air and the hadronic cross sections in the shower
- Modifying multiplicity, *elasticity*, pion to charge ratio.

K factor Method

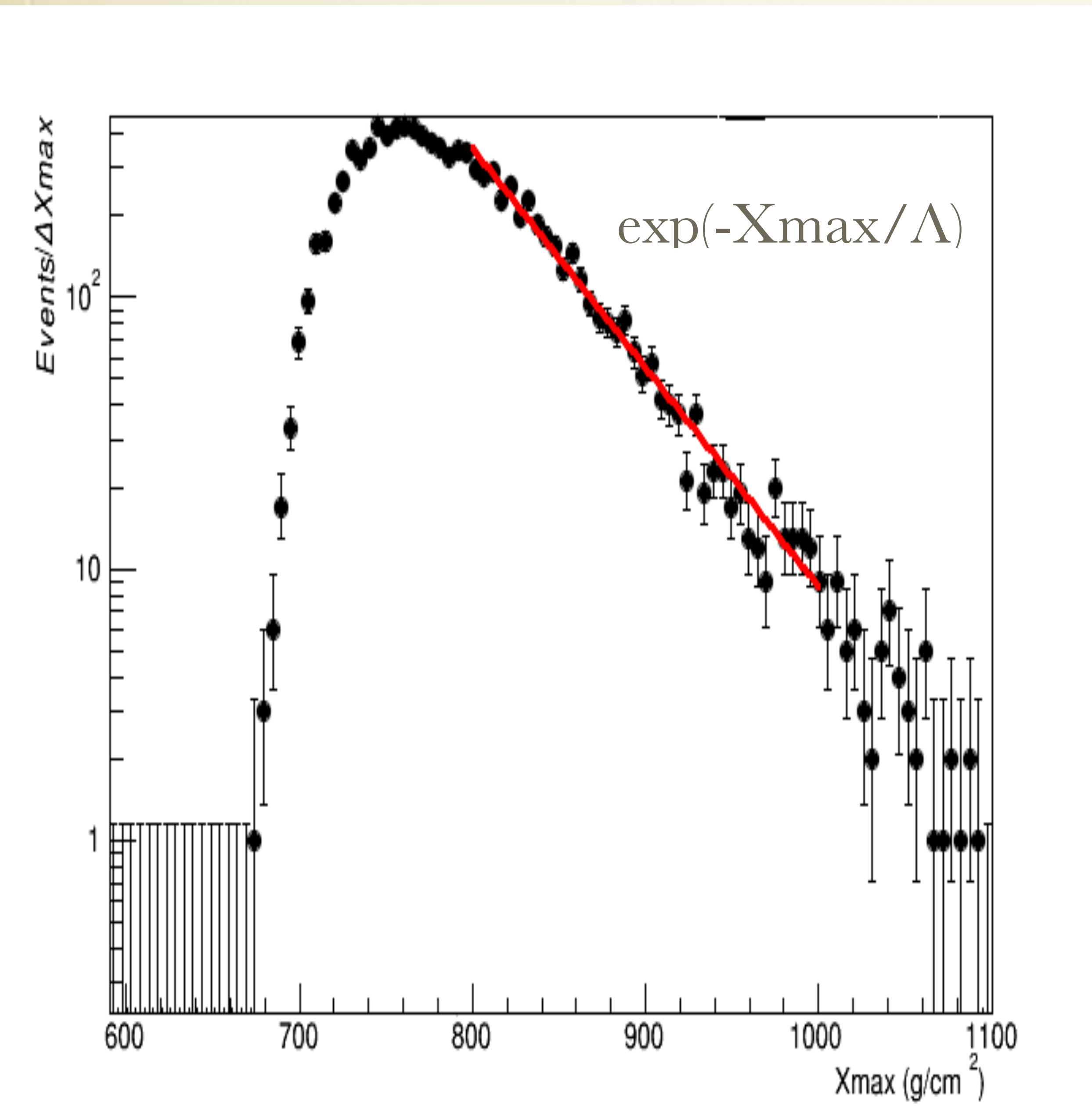


- Beam of N protons will be attenuated by $dN/dX = -N/\lambda$

  λ: proton mean free path $\lambda = m_{pair}/\sigma_{pair}$

  $= 14.45 \times m_p/\sigma_{pair}$

K-Factor Method



- Using deeply penetrating particles. the tail of the Xmax distribution
- Attenuation length in proportion to the propagation length.

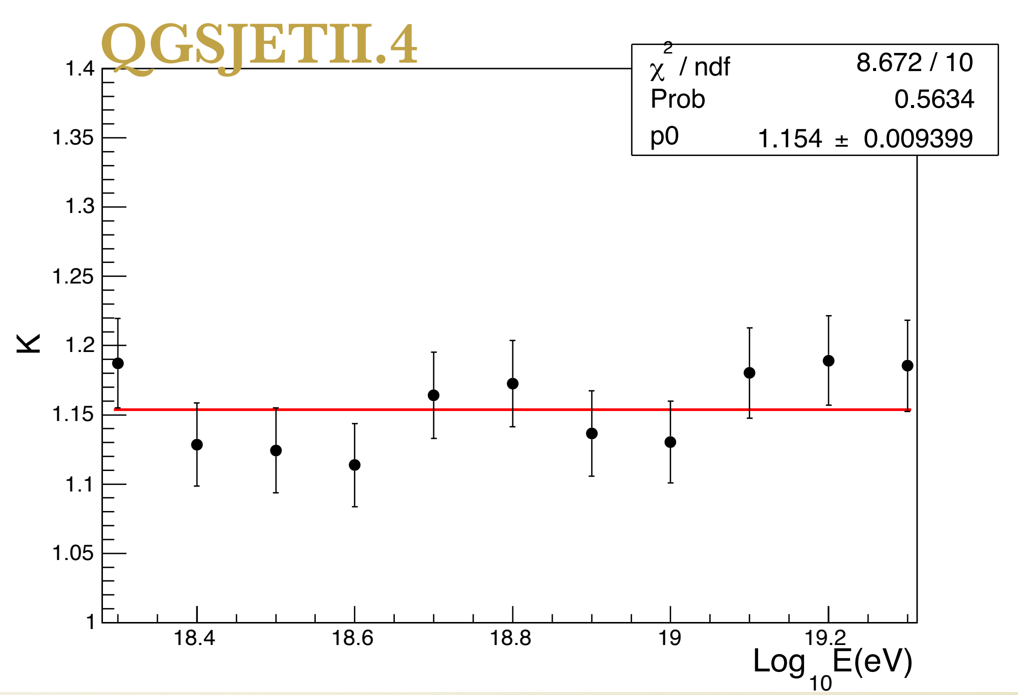
$$\Lambda = k\lambda_{p-air}$$

- Determine the inelastic proton-sir cross section

$$k\lambda_{p\text{-air}} = k\frac{14.5m_p}{\sigma_{p\text{-air}}^{\text{inel}}}$$

K VALUE

- Determined from high energy shower models.
- Simulate 10000 events for each 0.1 step in $Log_{10}E(eV)$ [Conex*]
- Calculate the attenuation length from the slope of the Xmax distribution decrement
- determine the interaction length λ_{pair} from the model first point of the pair interaction slant depth X_1.



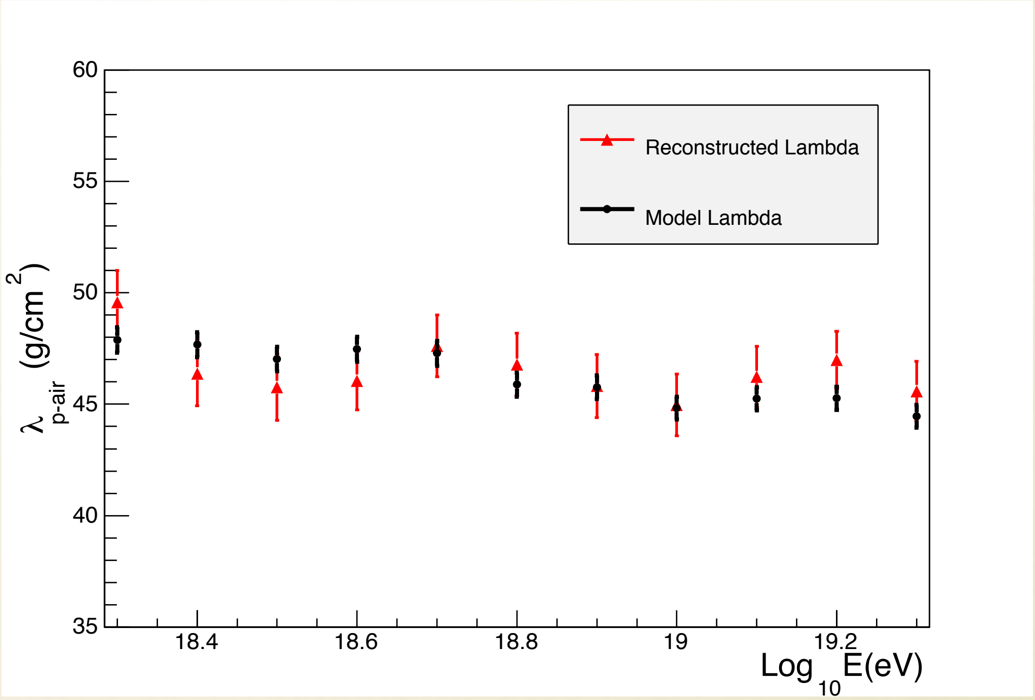
Model	K
QGSJETII.4	1.15±0.01
QGSJET01	1.22±0.01
SIBYLL	1.18±0.01
EPOS-LHC	1.19±0.01

* T. Bergmann et al., Astropart.Phys. 26, 420 (2007)

K value development and this work

- Fly's Eye K value 1.6 (theoretical model)
- by 2001(Pryke) K from the full model simulations~7%*
- Models evolving and LHC data
- K model dependence 3%

Weekly model dependence



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QGSJETII.4	1.15±0.01
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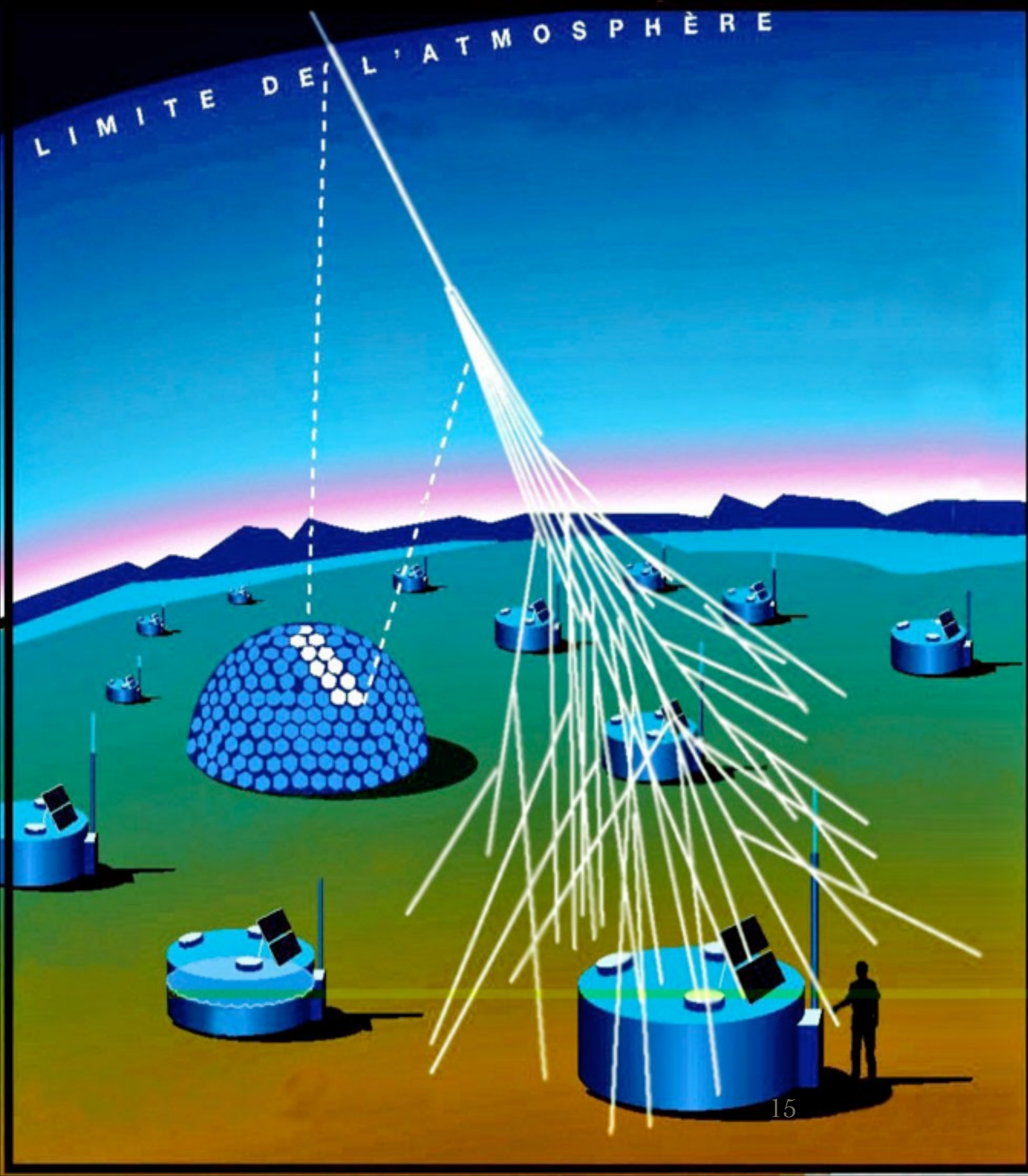
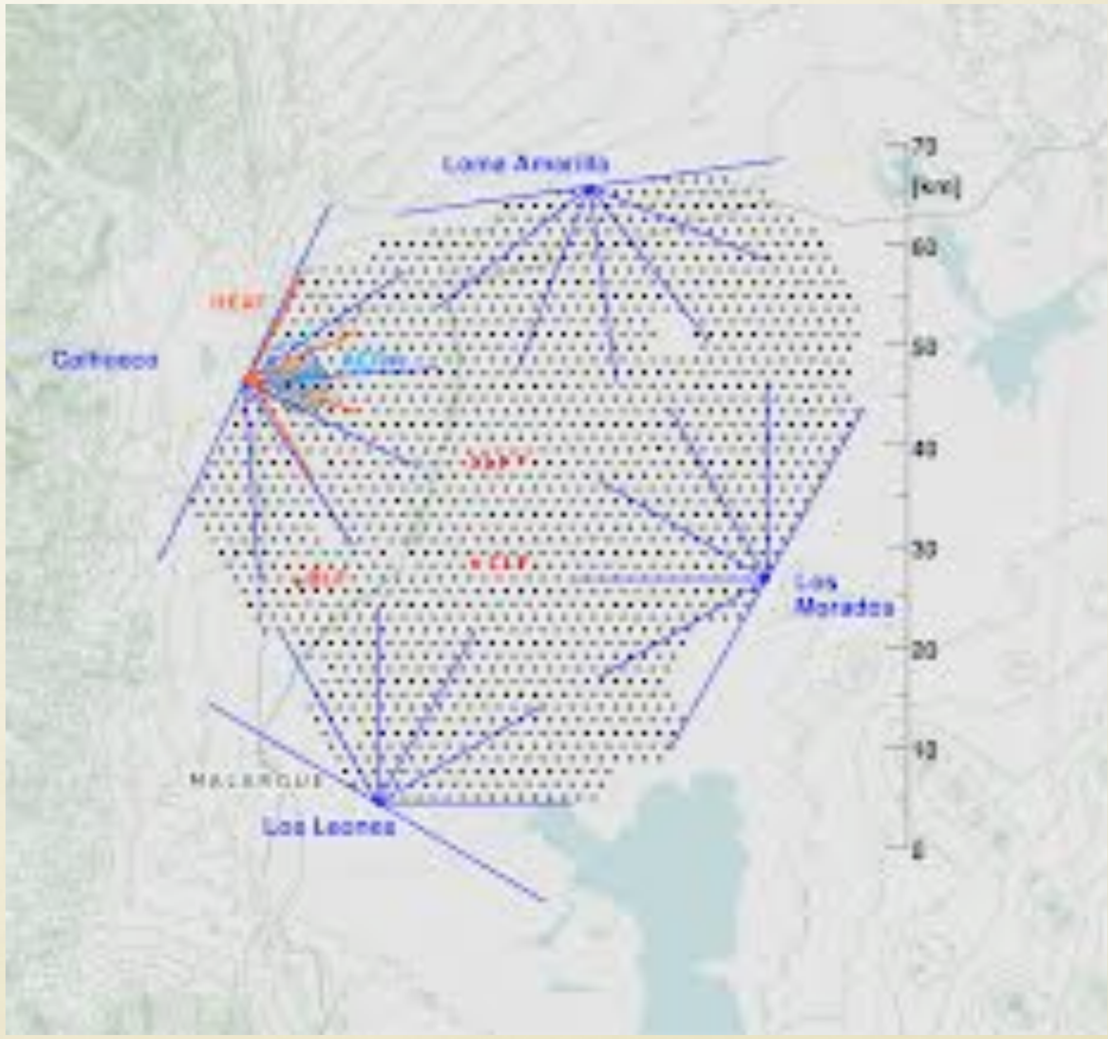
Experimental Results



PIERRE AUGER OBSERVATORY

The Auger Detector

- Malargue, Argentina
- 1660 water Cherenkov stations [3000 km^2]
- four Fluorescence Detectors
- 39360 hybrid events
- 2004-2012
- Energy Range $10^{17.8}$-10^{18}-$10^{18.5}$ eV



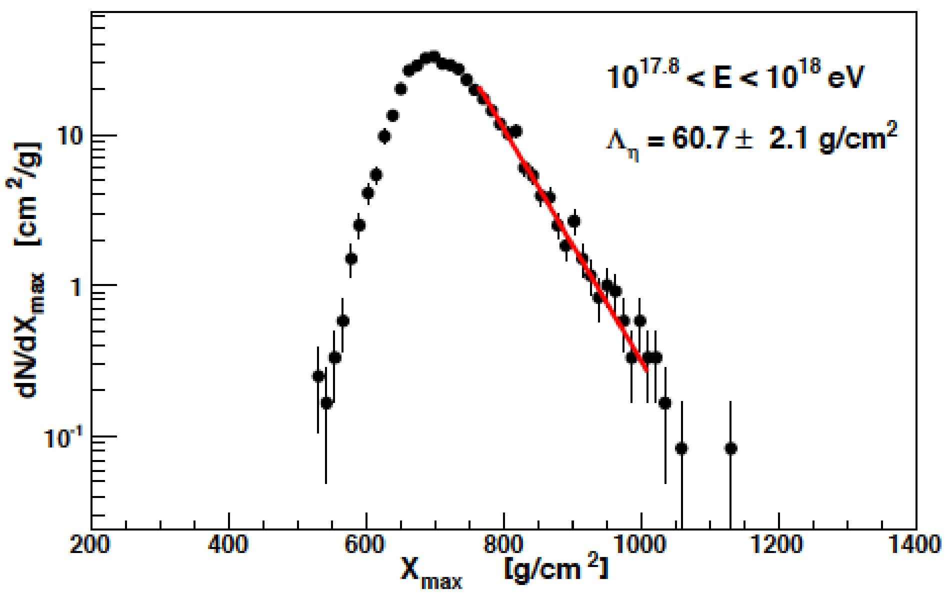
Auger Collaboration PRL 104,091101 (2010)

Data selection

- Quality cuts. Fiducial selection.
- Tight cuts to remove acceptance, reconstructed biases.
- compare simulation at generator level
- Xmax resolution of < 25 g/cm2,   E above EeV

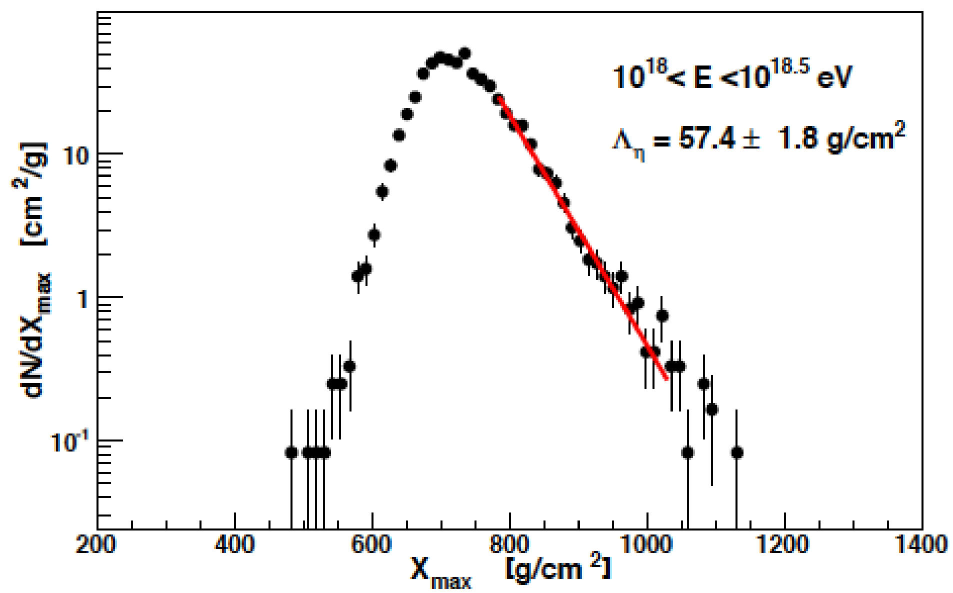
Auger Collaboration PRL 104,091101 (2010)

Attenuation Length



$\langle E \rangle = 10^{17.90}$ eV

$\Lambda_\eta = 60.7 \pm 2.1(\text{stat}) \pm 1.6(\text{syst})\,\text{g/cm}^2$



$\langle E \rangle = 10^{18.22}$ eV

$\Lambda_\eta = 57.4 \pm 1.8(\text{stat}) \pm 1.6(\text{syst})\,\text{g/cm}^2$

conversion of Λ to $\sigma_{p\text{-air}}^{inel}$ using modified cross section method

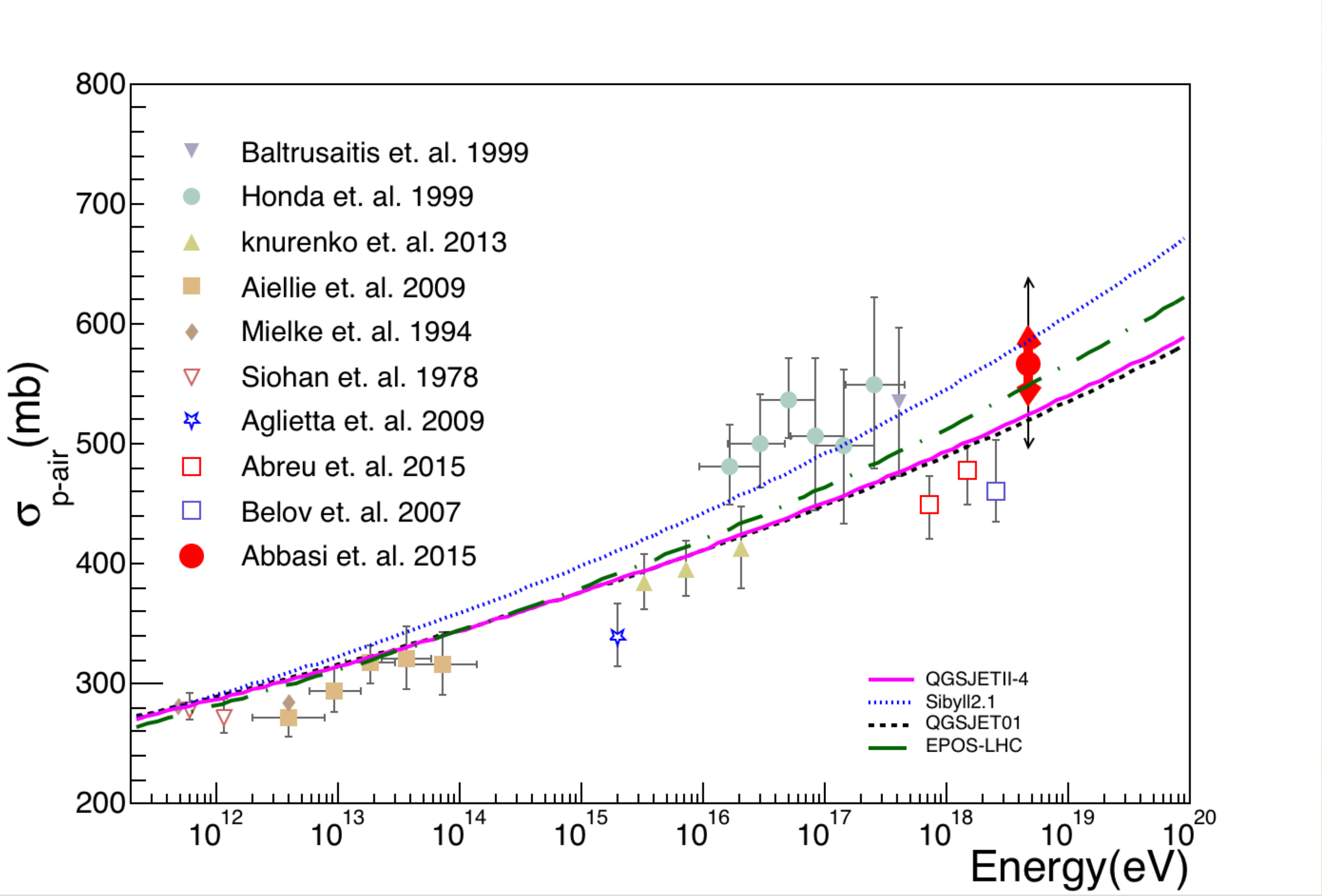
Auger Collaboration ICRC2015

Systematic uncertainties

	$10^{17.8} - 10^{18}$ eV	$10^{18} - 10^{18.5}$ eV
Λ_η, systematic uncertainties (mb)	13.5	14.1
Hadronic interaction models (mb)	10	10
Energy scale uncertainty, $\Delta E/E = 14\%$ (mb)	2.1	1.3
Conversion of Λ_η to $\sigma_{\mathrm{p-air}}$ (mb)	7	7
Photons (mb)	+4.7	+4.2
Helium, 25% (mb)	-17.2	-15.8
Total systematic uncertainty on $\sigma_{\mathrm{p-air}}$ (mb)	+19/-25	+19/-25

Auger Collaboration ICRC2015

Proton-Air cross section

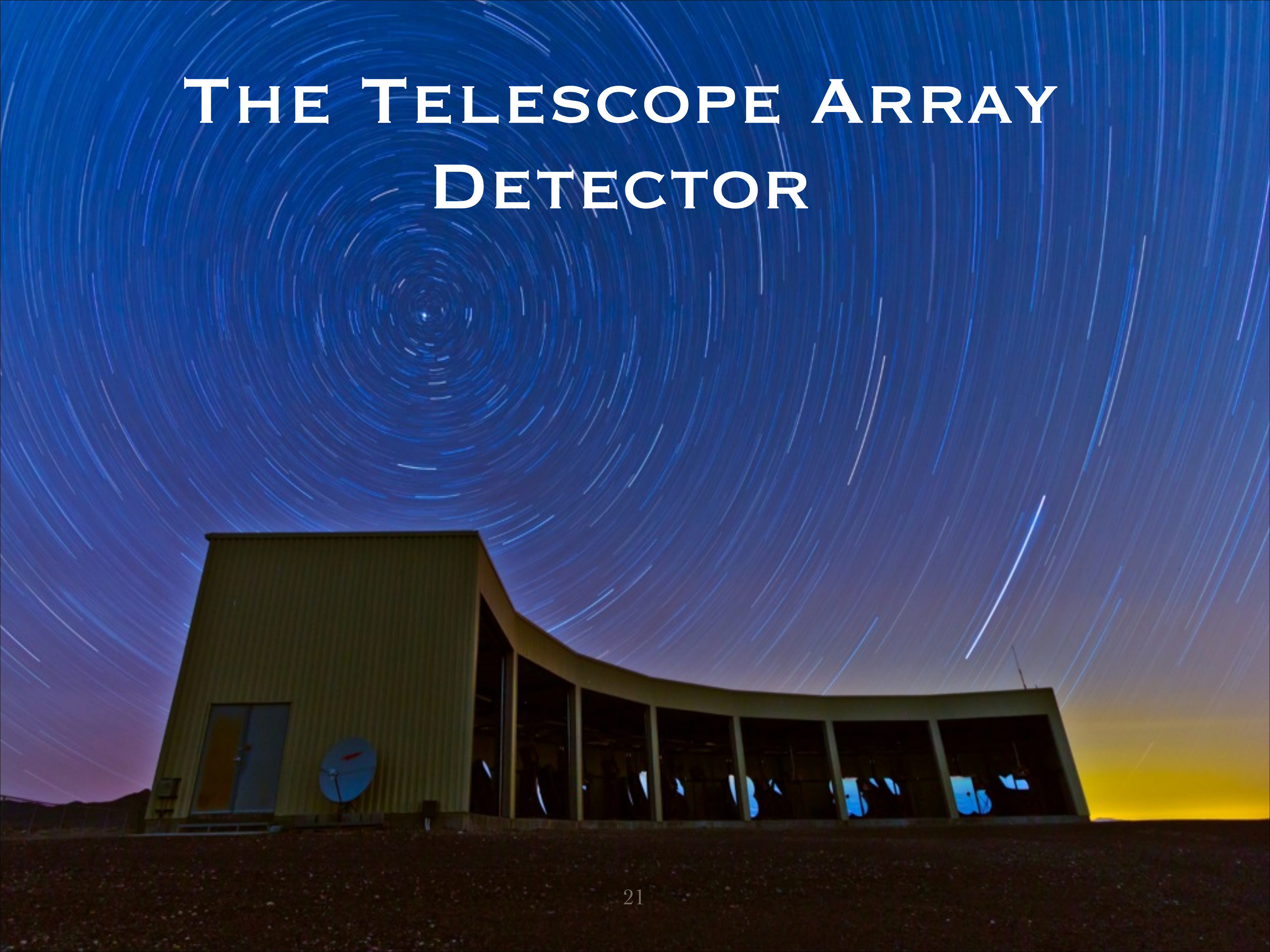


Results, $\sigma_{\mathrm{p-air}}$ in mb

- Lower energy point
  457.5±17.8(stat)+19/-25(syst)
- Higher energy point
  485.8±15.8(stat)+19/-25(syst)

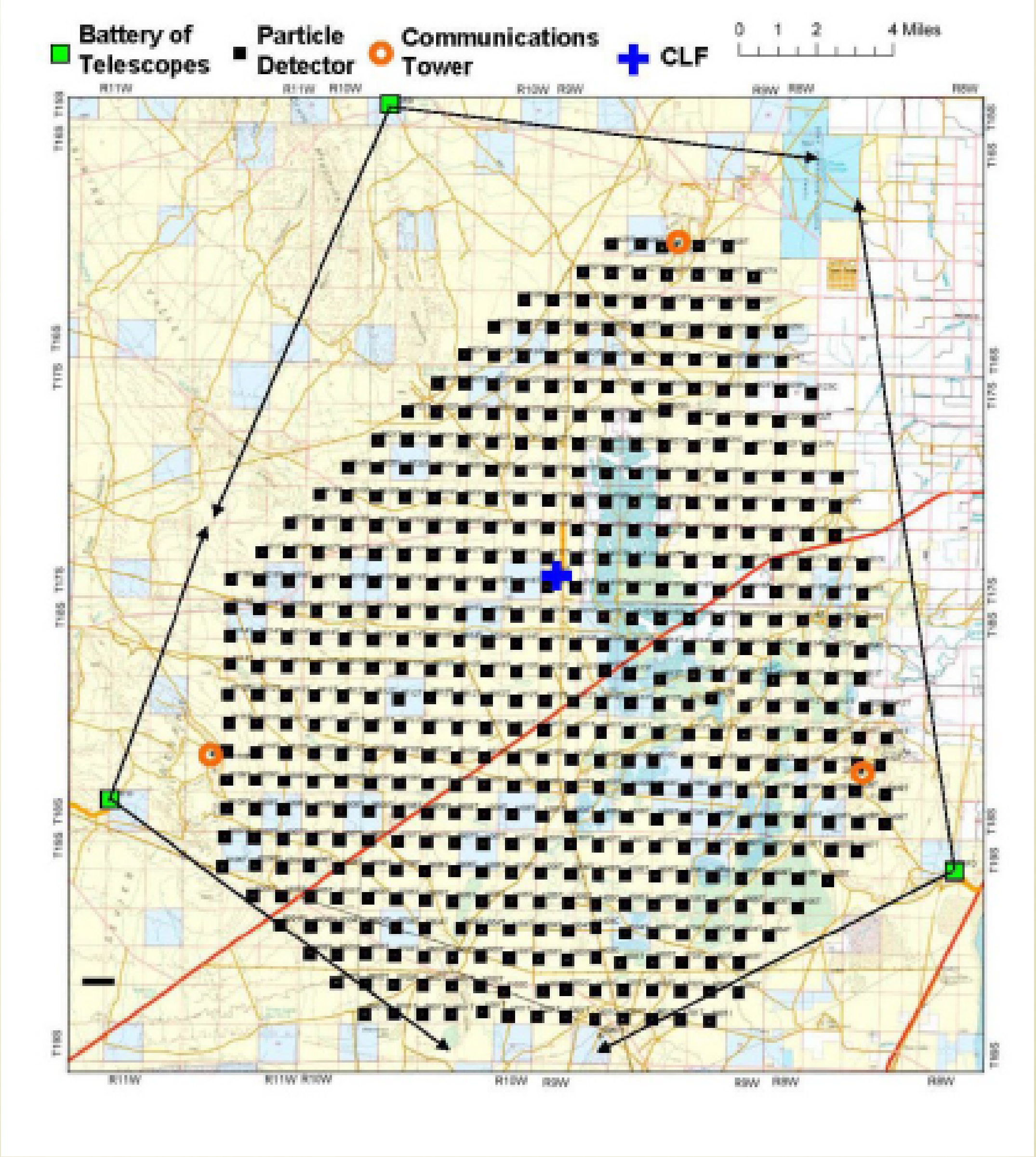
Auger Collaboration ICRC2015

The Telescope Array Detector



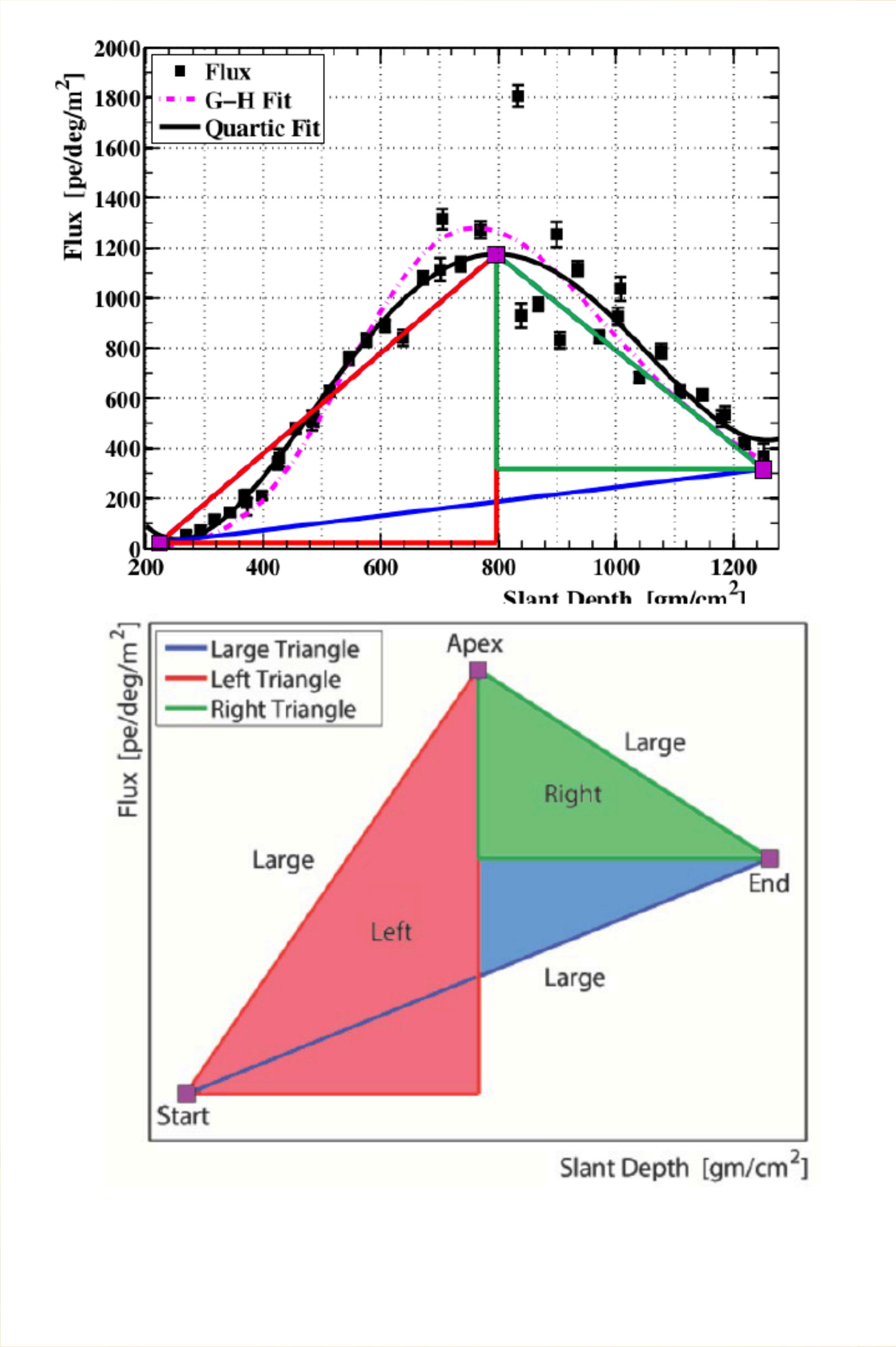
Data Collection

- Delta, Utah
- 507 scintillation surface detector [700 km^2]
- three Fluorescence Detectors
- 439 hybrid events 1 fluoresce detector and surface detector array
- 2008-2013
- Energy Range $10^{18.3}$-$10^{19.3}$ eV



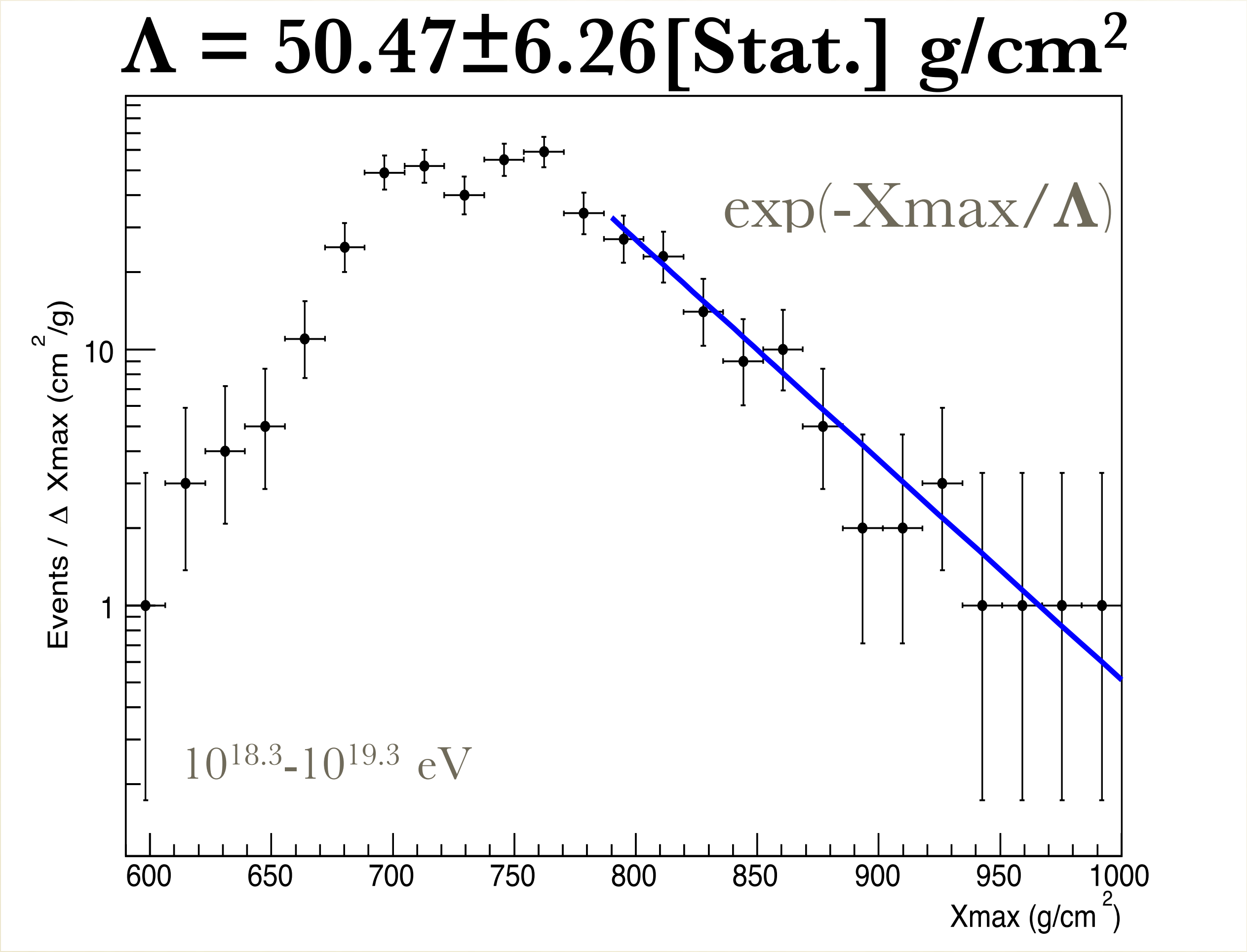
Data Selection

- Pattern recognition cuts.
- compare to simulation including detector and reconstruction effect.
- Xmax resolution of ~ 23 g/cm^2, E above EeV.



*R. Abbasi et al., Astropart.Phys. 64, 49 (2014),

Attenuation Length

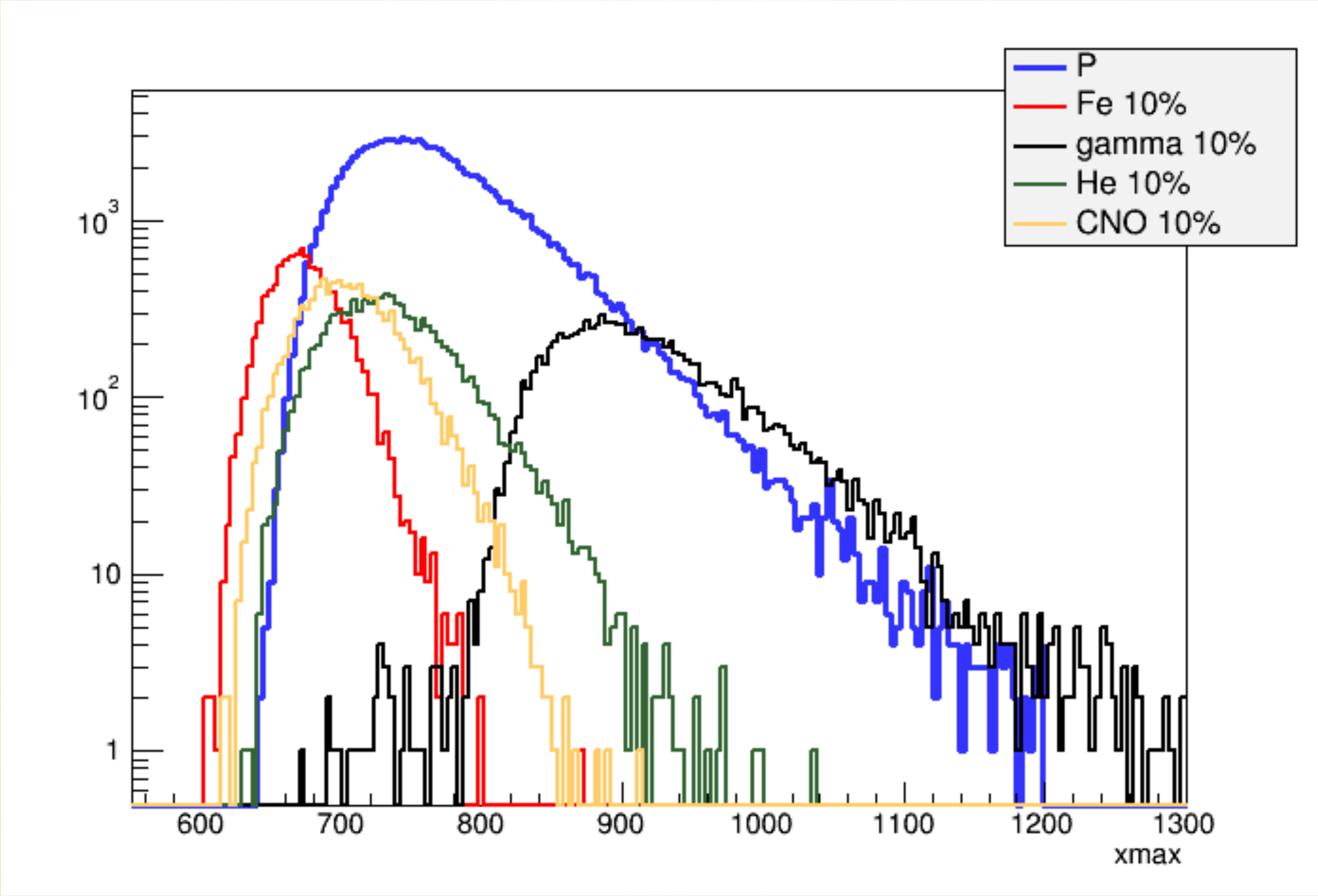


conversion of Λ to $\sigma_{p\text{-}air}^{inel}$ using the k-factor method

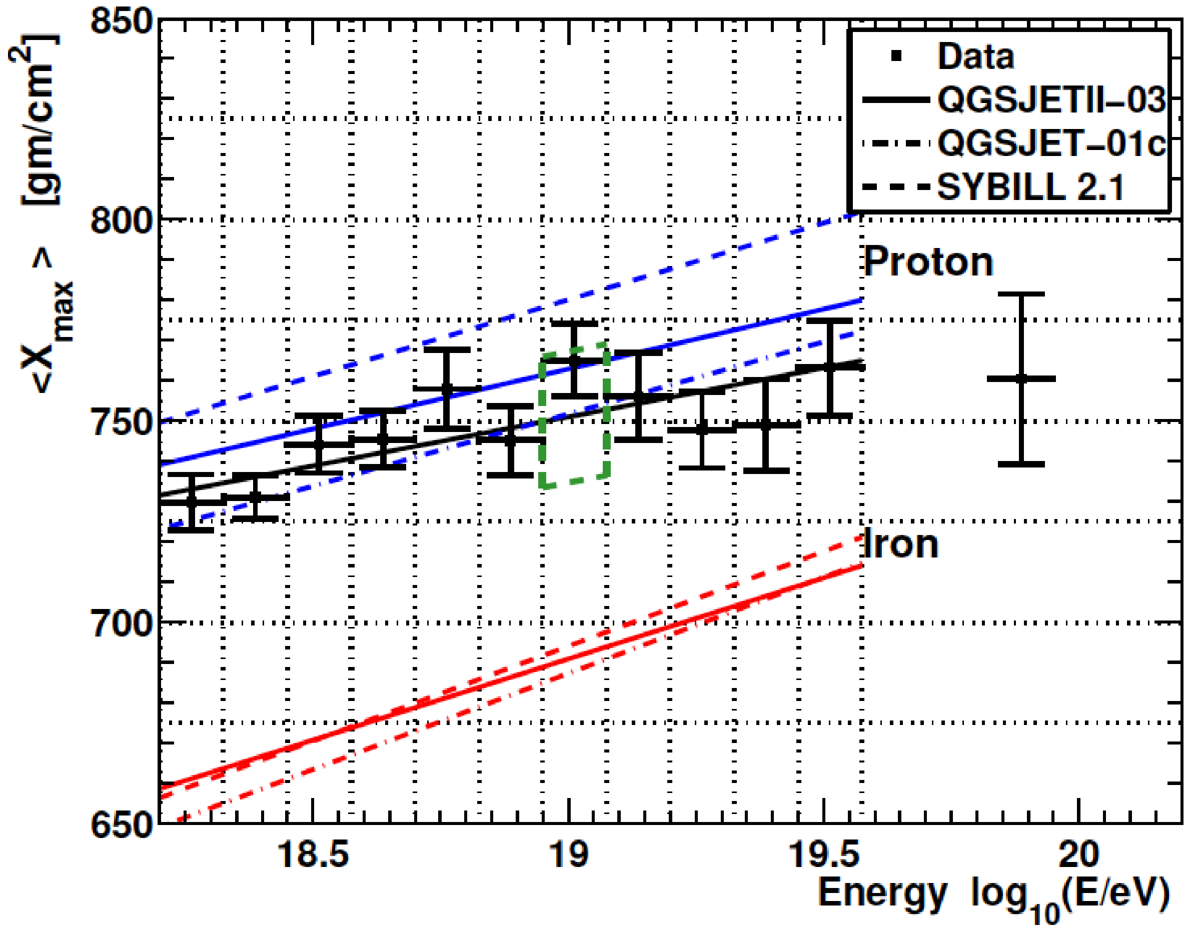
R. Abbasi et al., PRD 92 032007 (2015)

Systematics Uncertainties

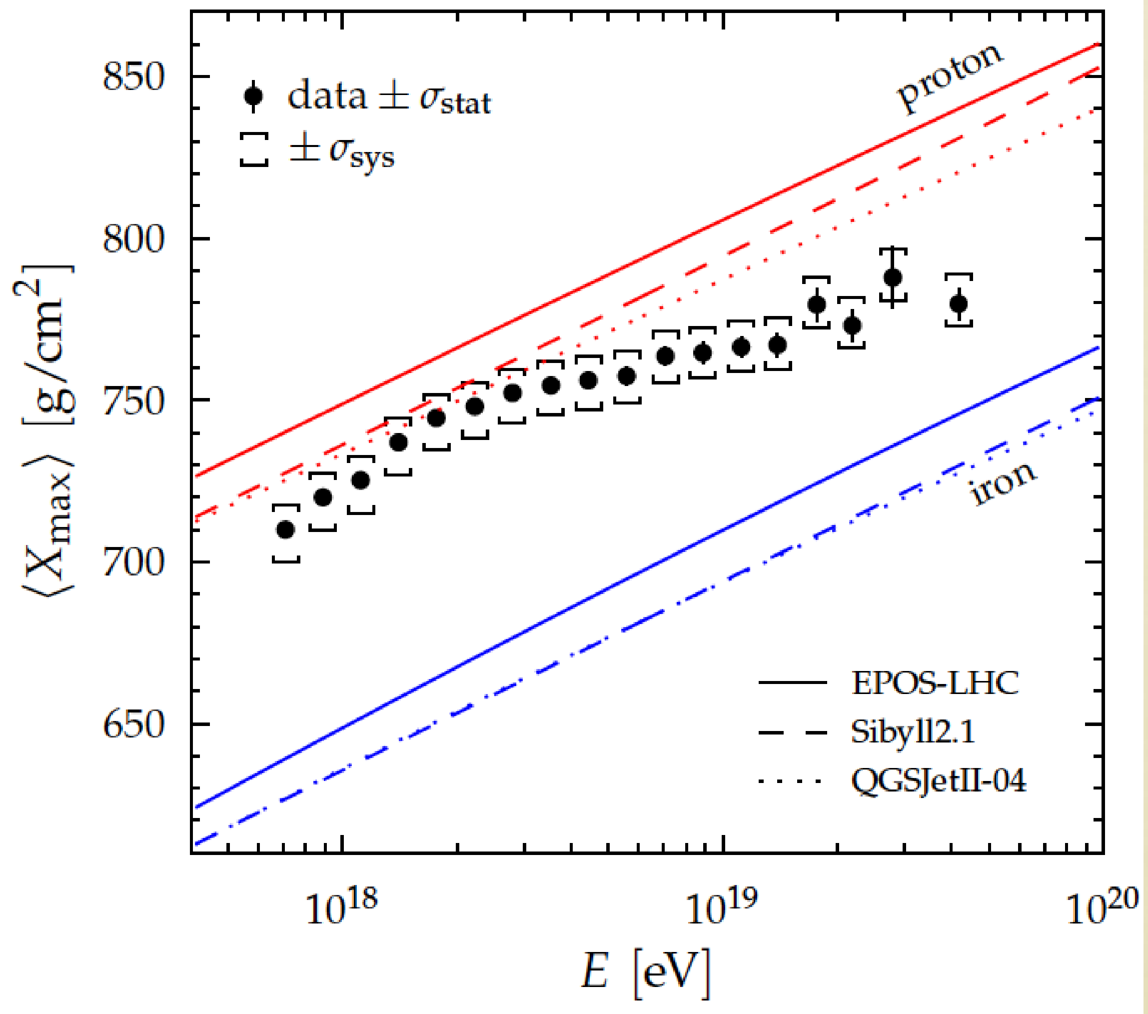
Largest Systematics Uncertainties: Unknown contamination



Composition from Average Shower <Xmax>

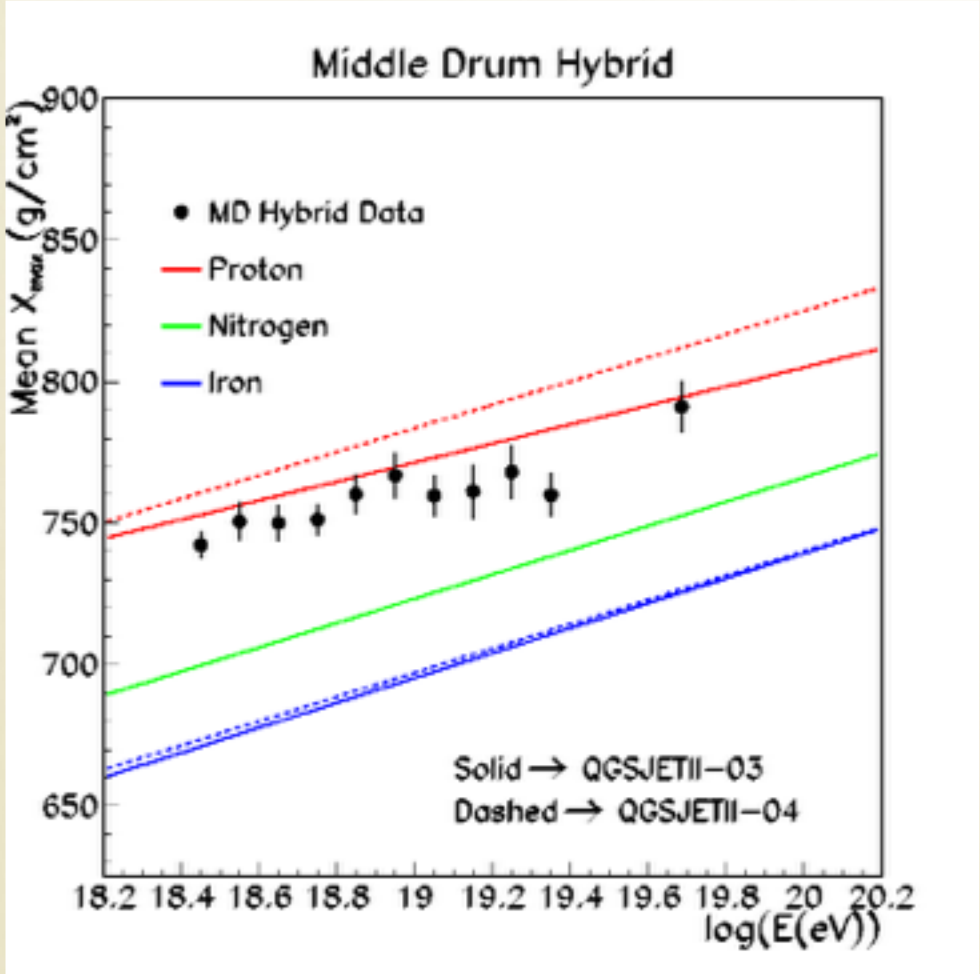


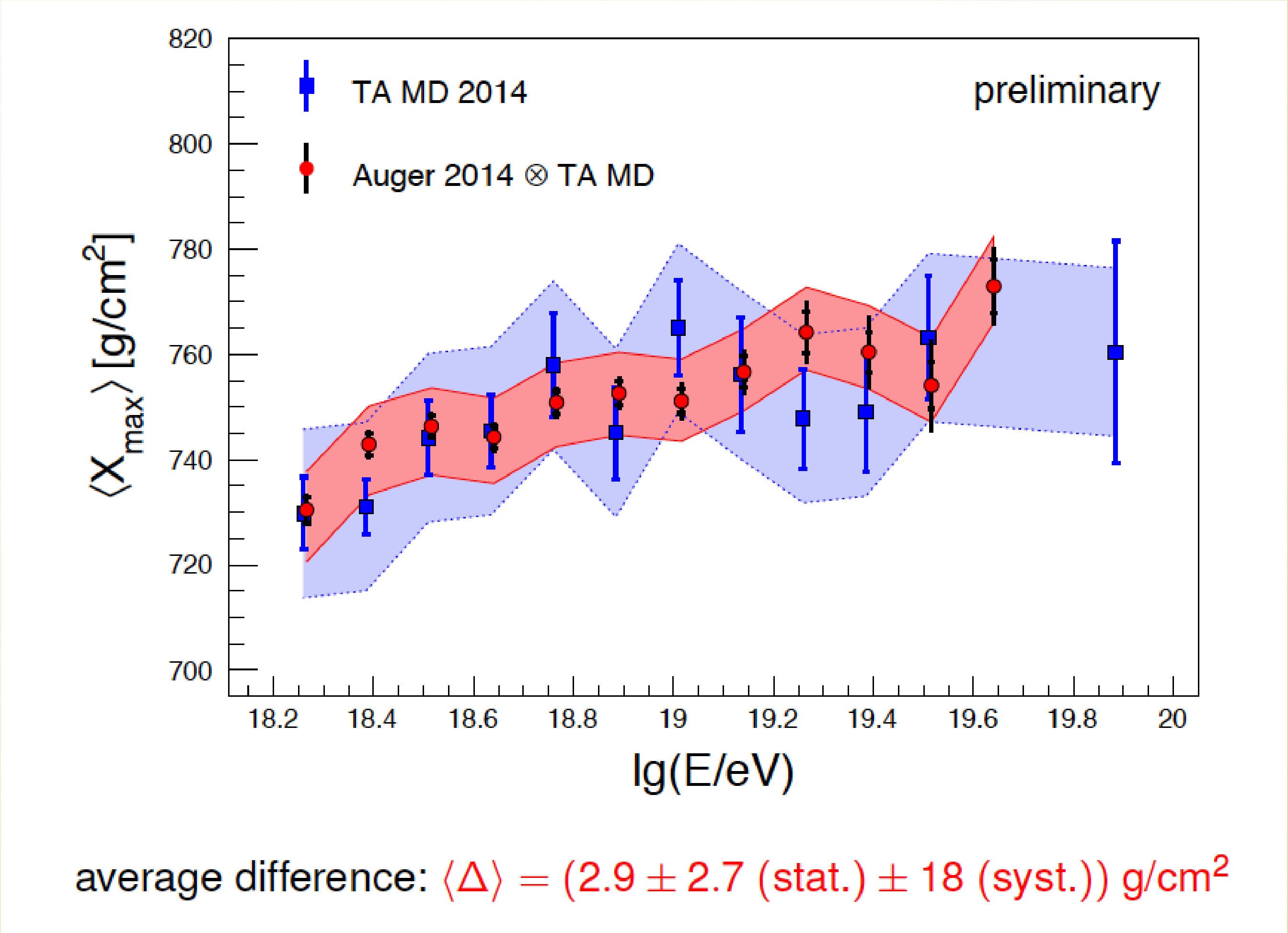
Telescope Array Collaboration, APP **64** (2014) 49



Pierre Auger Collaboration, PRD **90** (2014) 12, 122005

TA/AUGER COMPOSITION WORKING GROUP



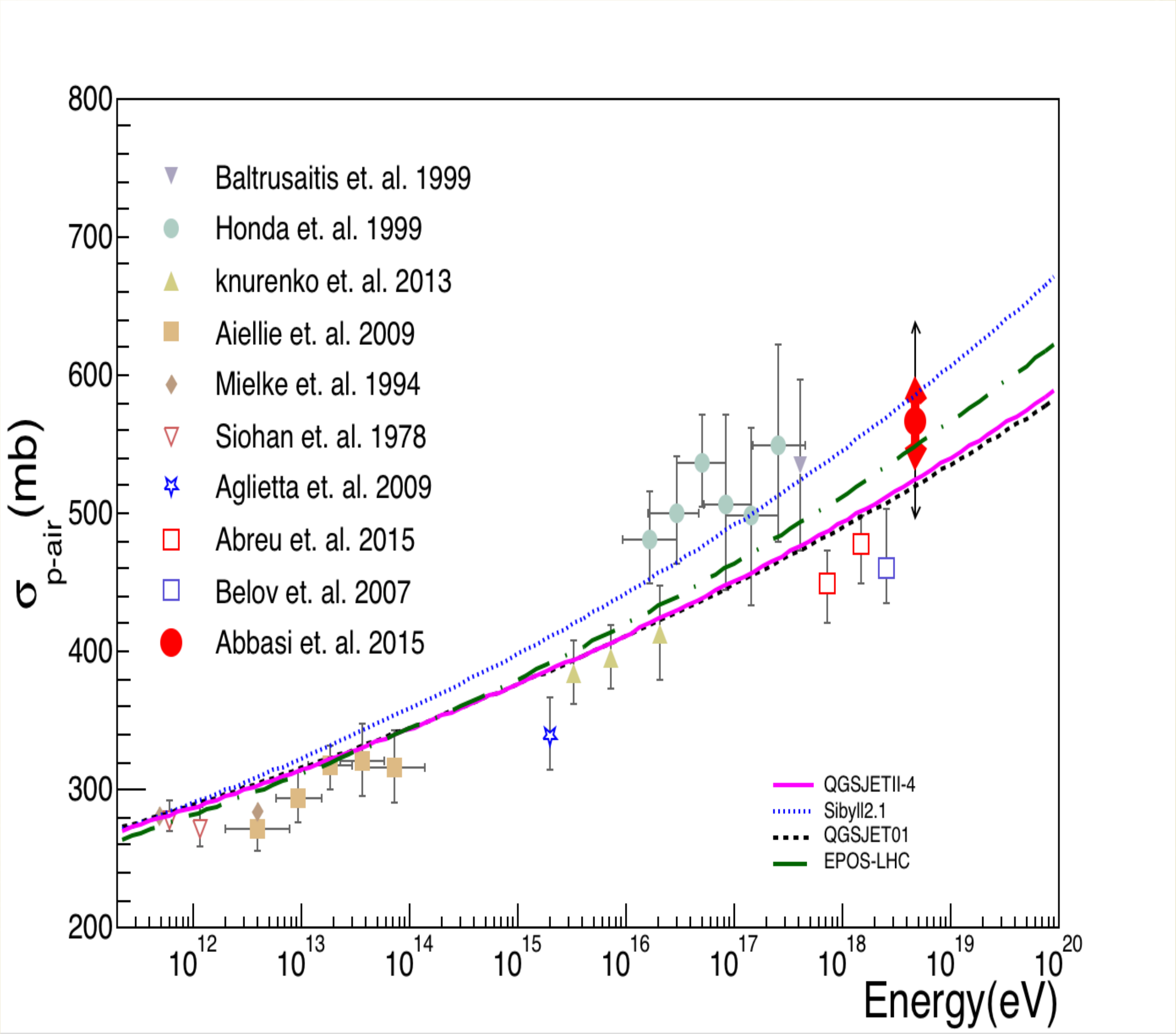


The Average Xmax of the two observatories are in good agreement.

ICRC2015, arXiv:1503.07540

P-Air cross section Systematics summary

- Model dependence (±17 mb)
- Attenuation length
- Energy dependence bias in the Xmax distribution (Negligible)
- Detector Bias(Negligible):
- Helium contamination(10,20,50)% (-9,-18,-42)mb
- Gamma(<1%) 23mb.



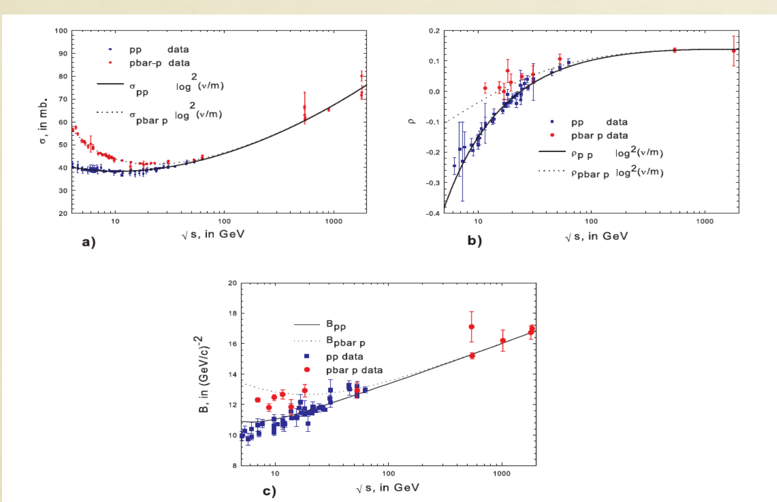
$$\sigma_{p\text{-}air}^{inel} = 567.0 \pm 70.5[\text{Stat.}]\ (+25,-29)[\text{Sys.}]\ \text{mb}$$

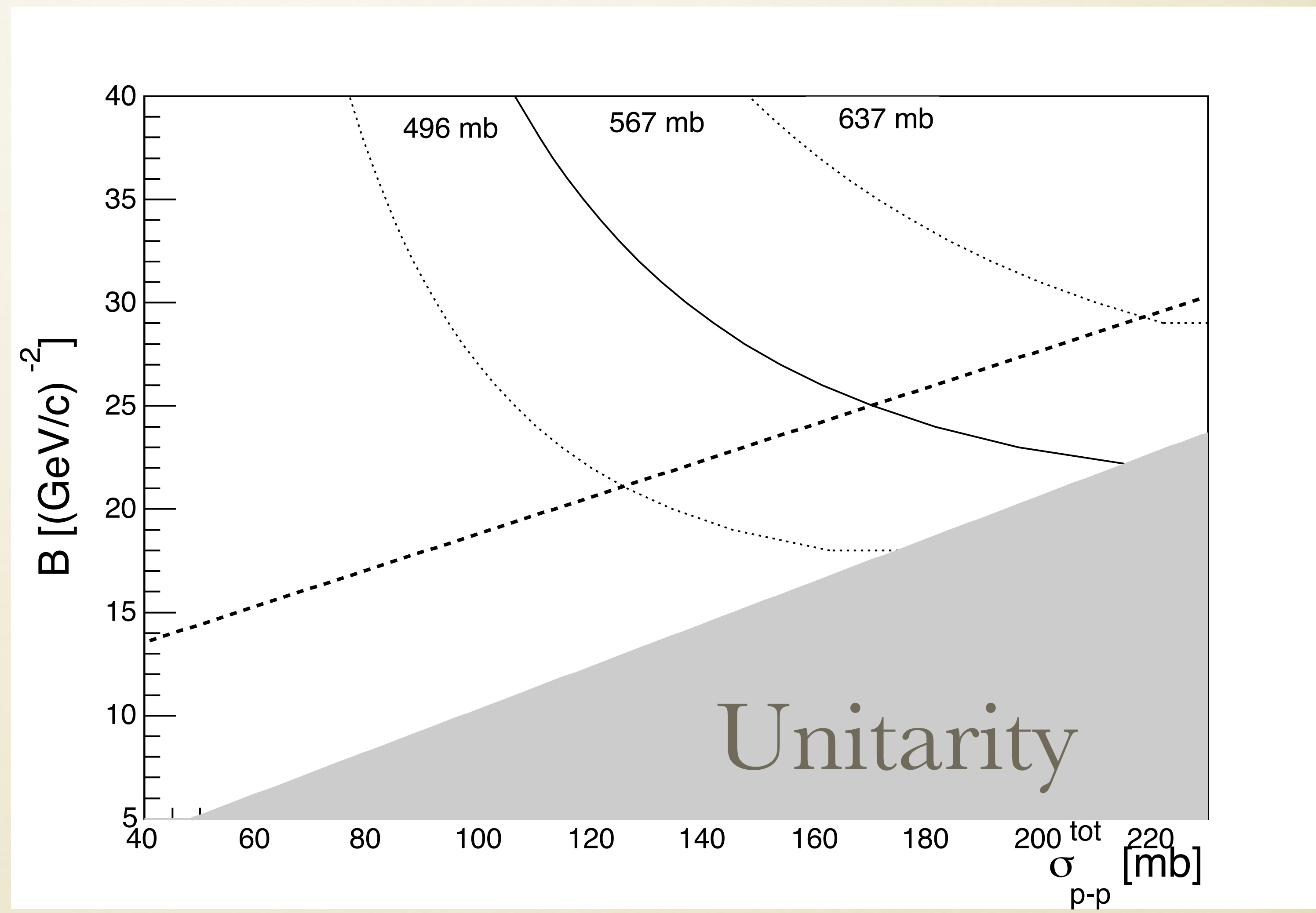
R. Abbasi et al., PRD 92 032007 (2015)

Conversion to Proton-Proton cross section

P-Air cross section
Proton-Proton cross section

- Glauber Formalism*
  - nuclear geometry
  - multiple interactions
  - opacity profile of nucleons
  - ….
- Block, Halzen, and Stanev. **



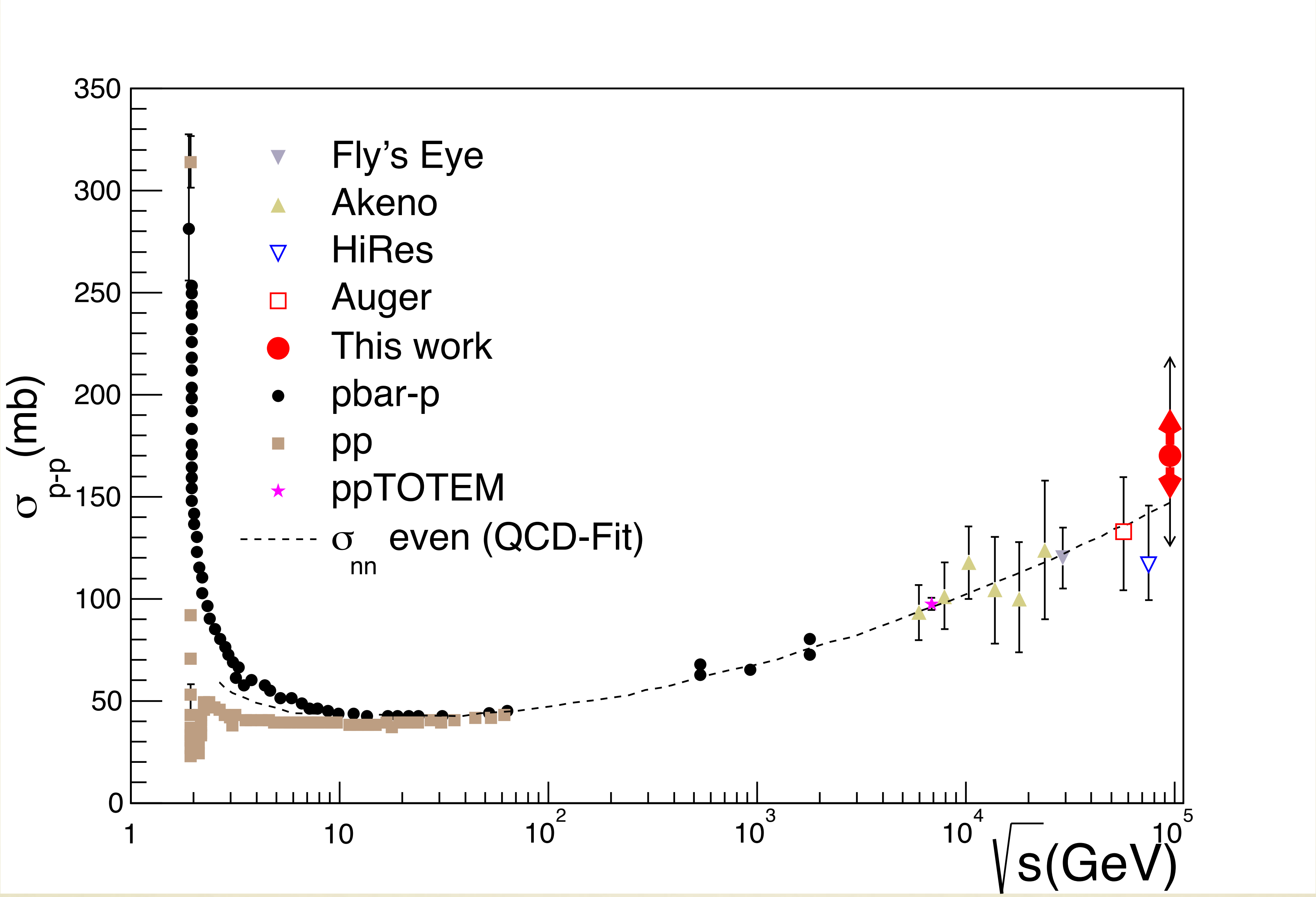


** PHYSICAL REVIEW D 76, 111503(R) (2007).

*R. Glauber and G. Matthiae, Nucl.Phys. B21, 135 (1970)
**M. Block and F. Halzen, Phys.Rev. D72, 036006 (2005).

** Block, Phys.Rev. D84, 091501 (2011).

P-Air cross section
Proton-Proton cross section at CME 97 TeV



$\sigma_{p\text{-}p}^{total}$ = 170 (+48,-44)[Stat.] (+17,-19)[Sys.] mb

R. Abbasi et al., PRD 92 032007 (2015)

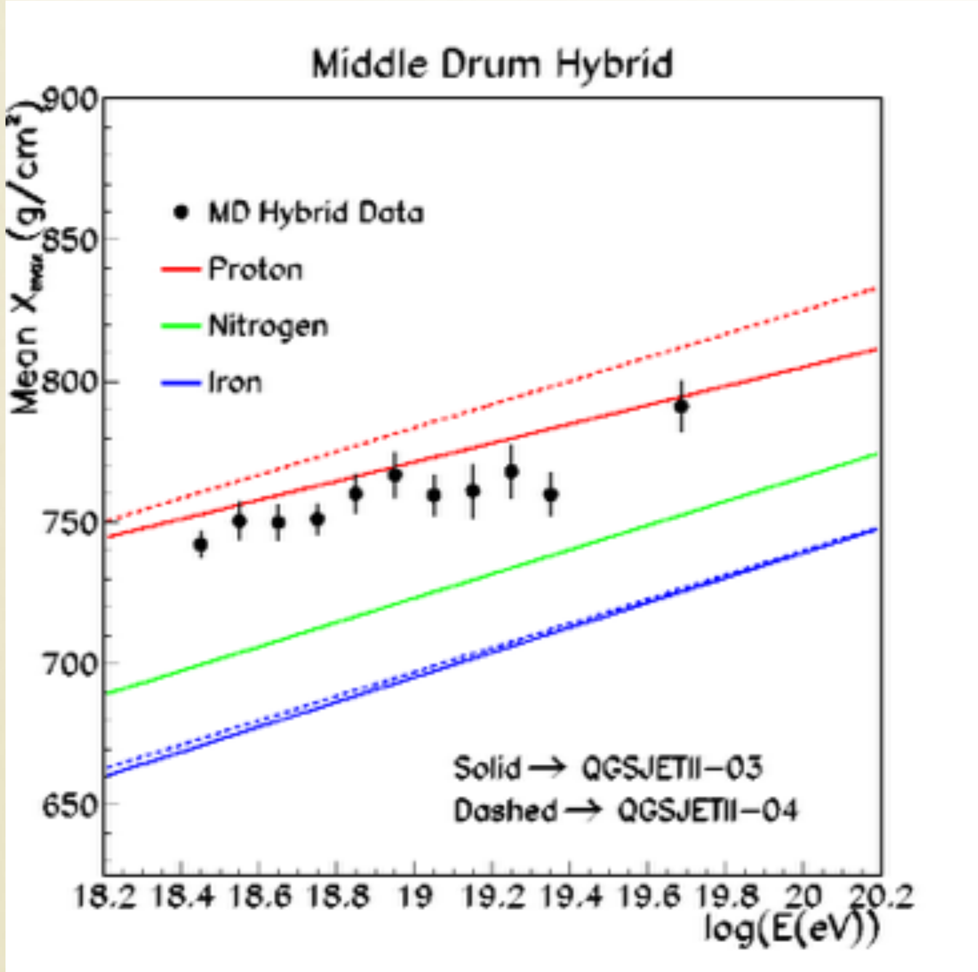
Conclusion and outlook

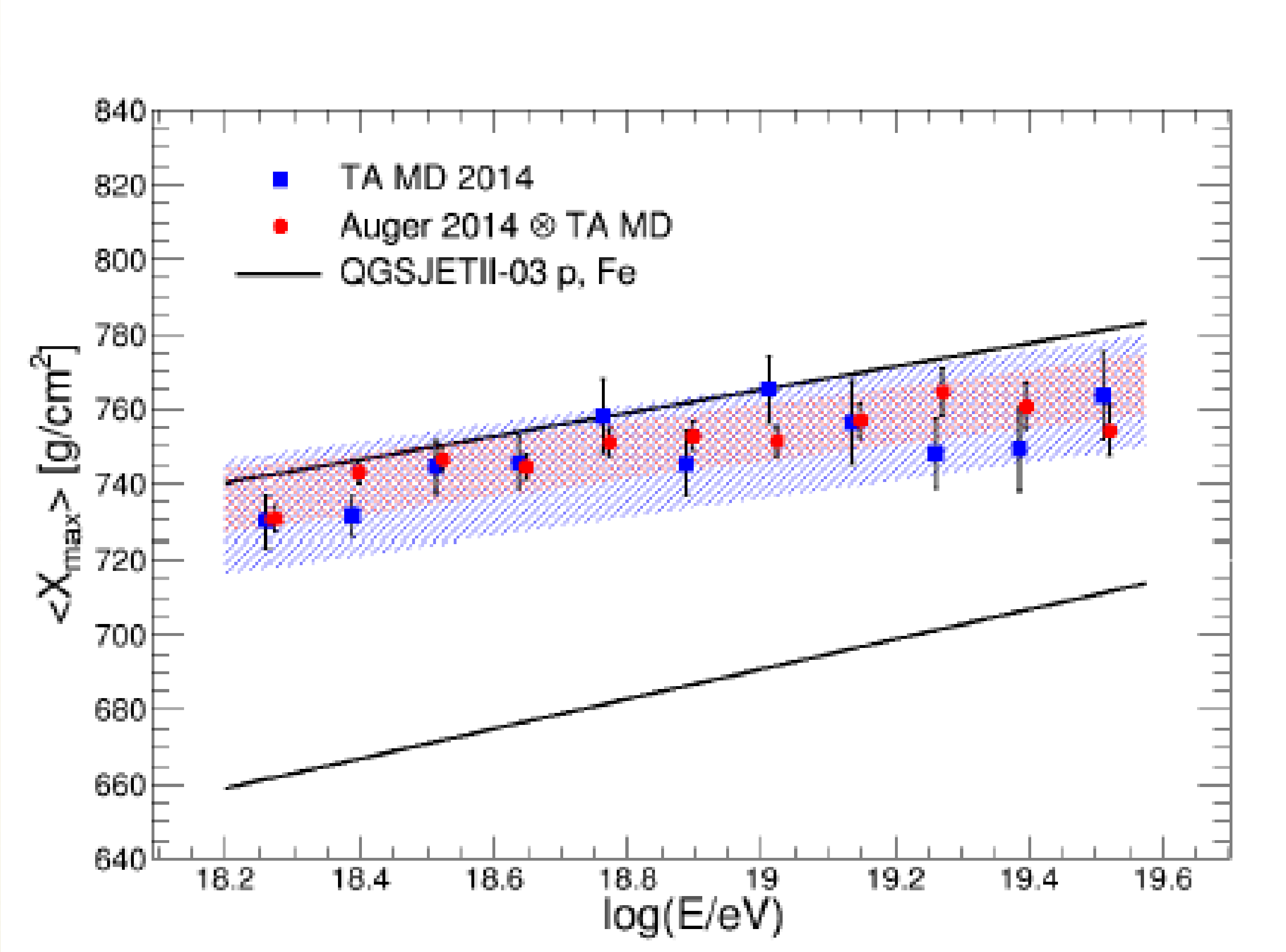
- Continuously further improved experimental results on the $\sigma_{p\text{-}air}^{inel}$ measurement from cosmic ray detectors $E_{UHECR} >> E_{LHC}$.
- Latest updates:
  - Auger ICRC 2015
  - TA R. Abbasi et al., PRD 92 032007 (2015)
  - Future measurements with the full TA detector.

Thank You!

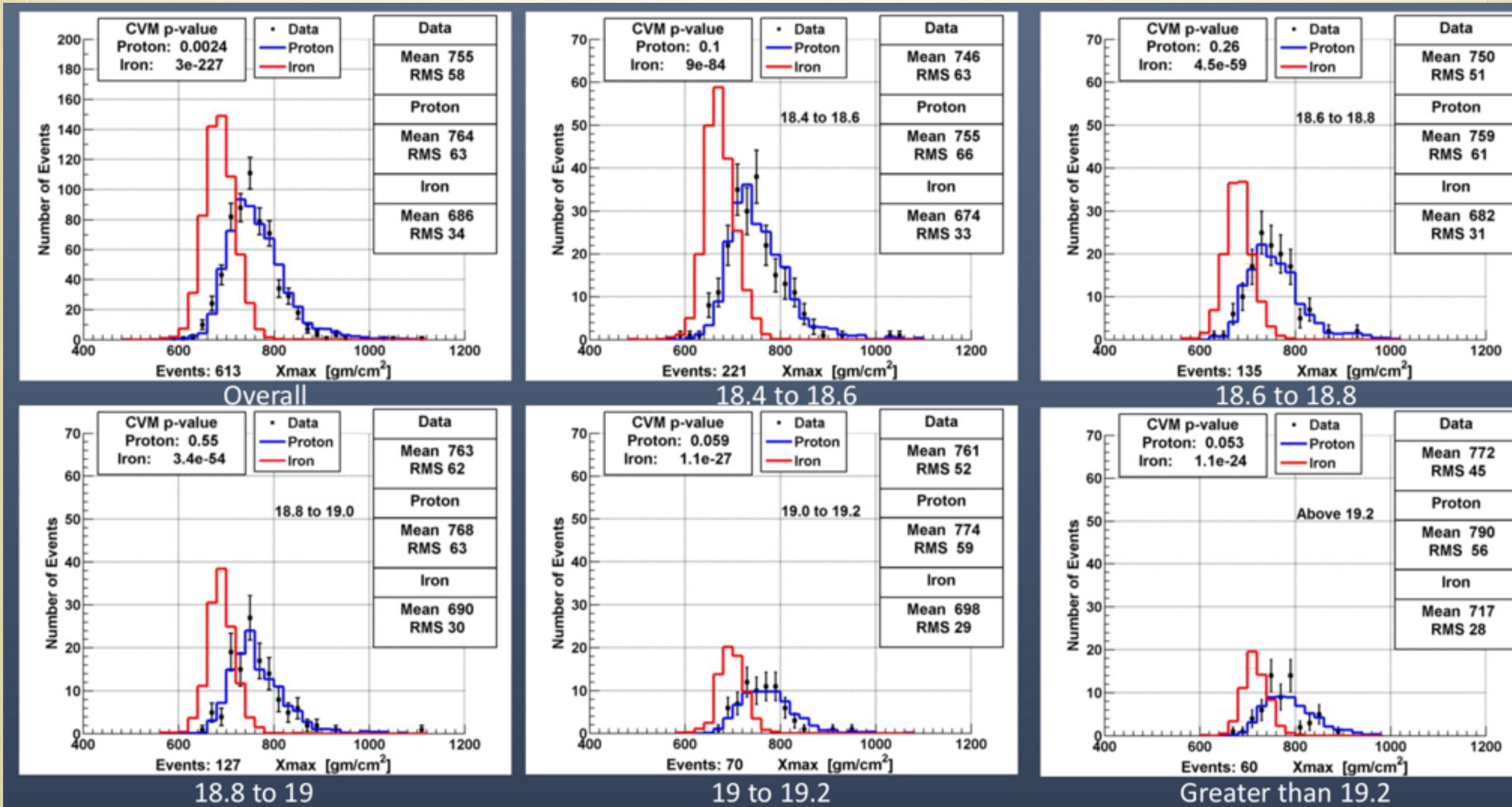
Backup slides

TA/AUGER COMPOSITION WORKING GROUP

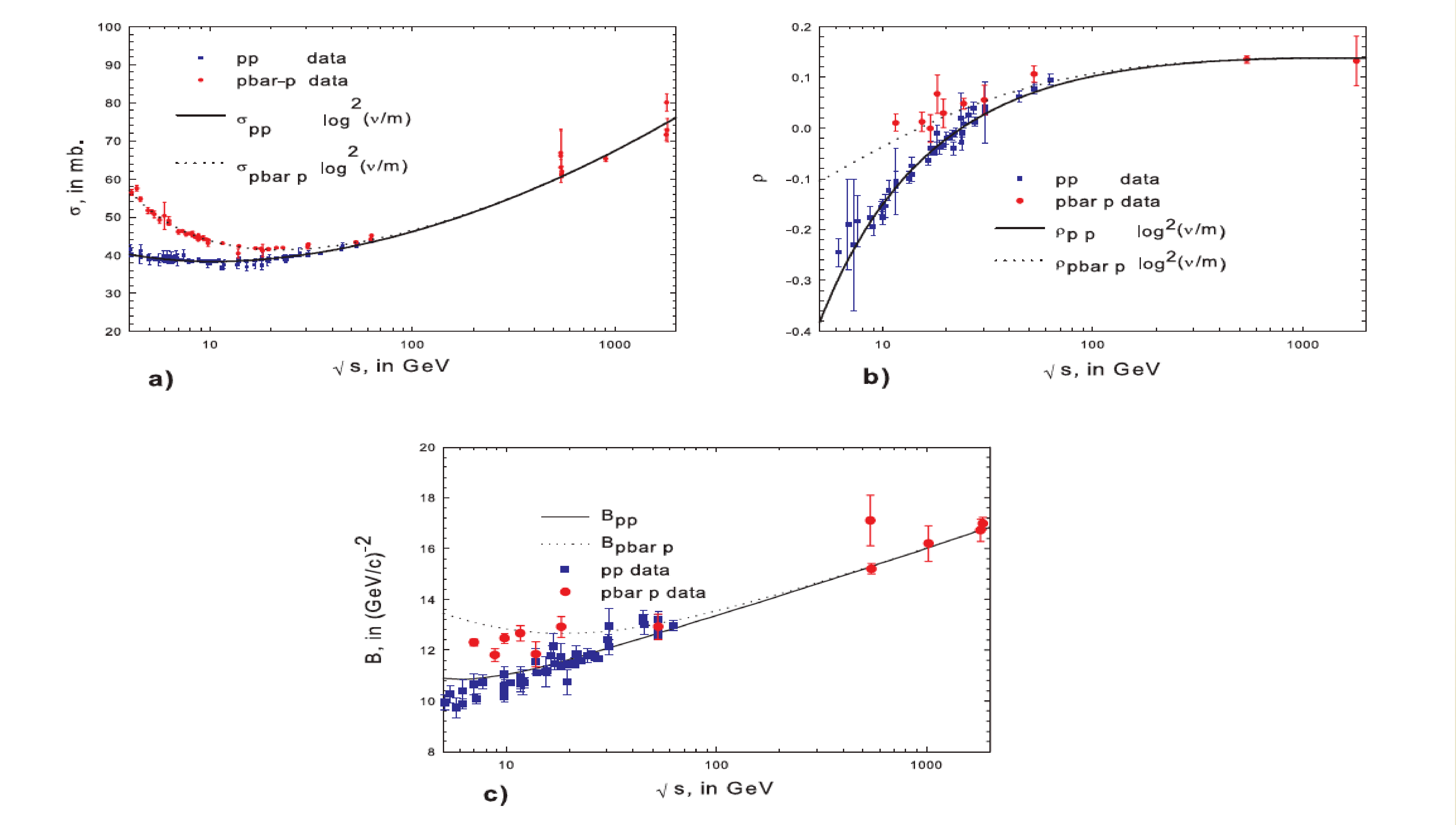




TA Comparison of Xmax distribution QGSJETII3

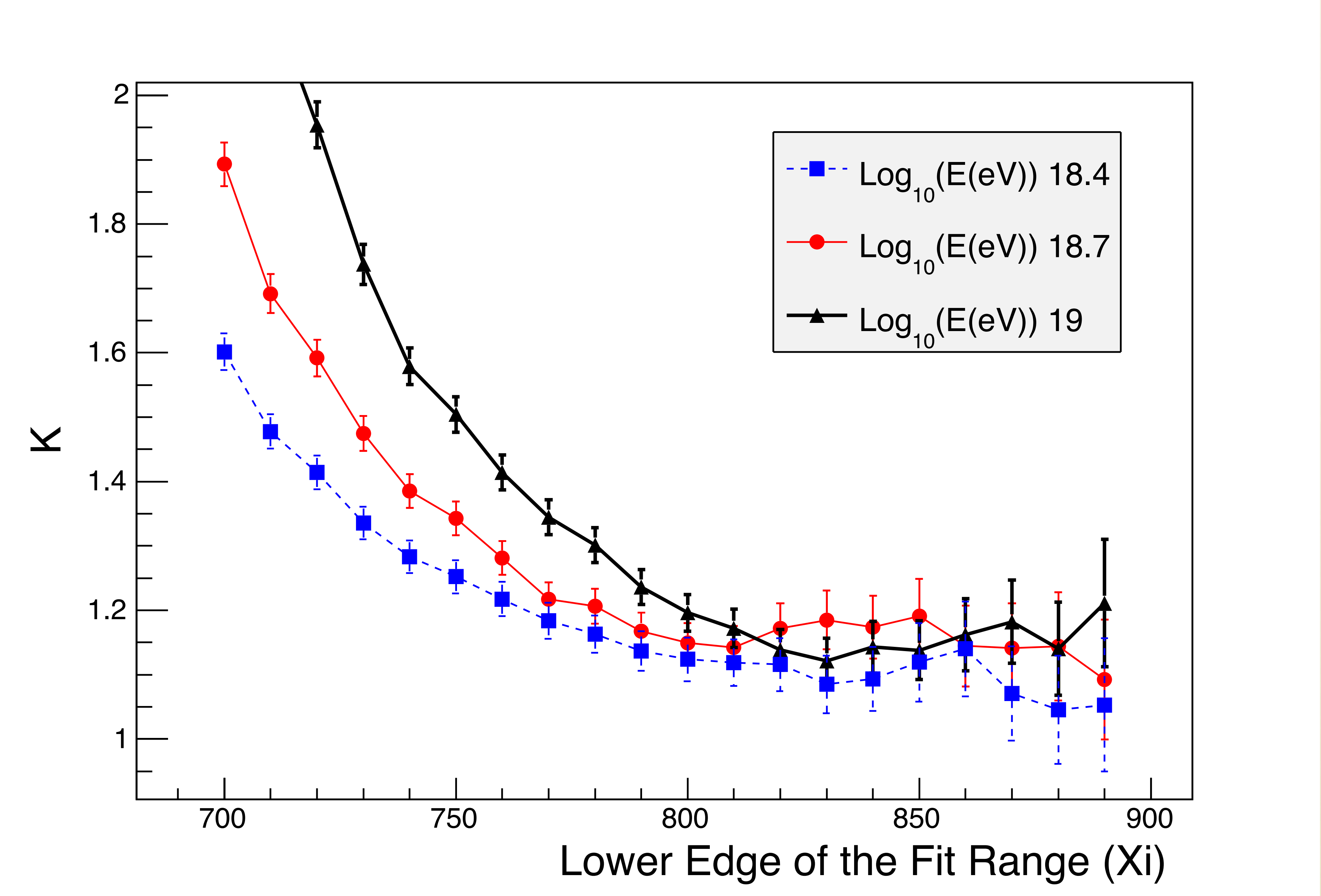


Block Halzen and Stanev



** PHYSICAL REVIEW D 76, 111503(R) (2007).

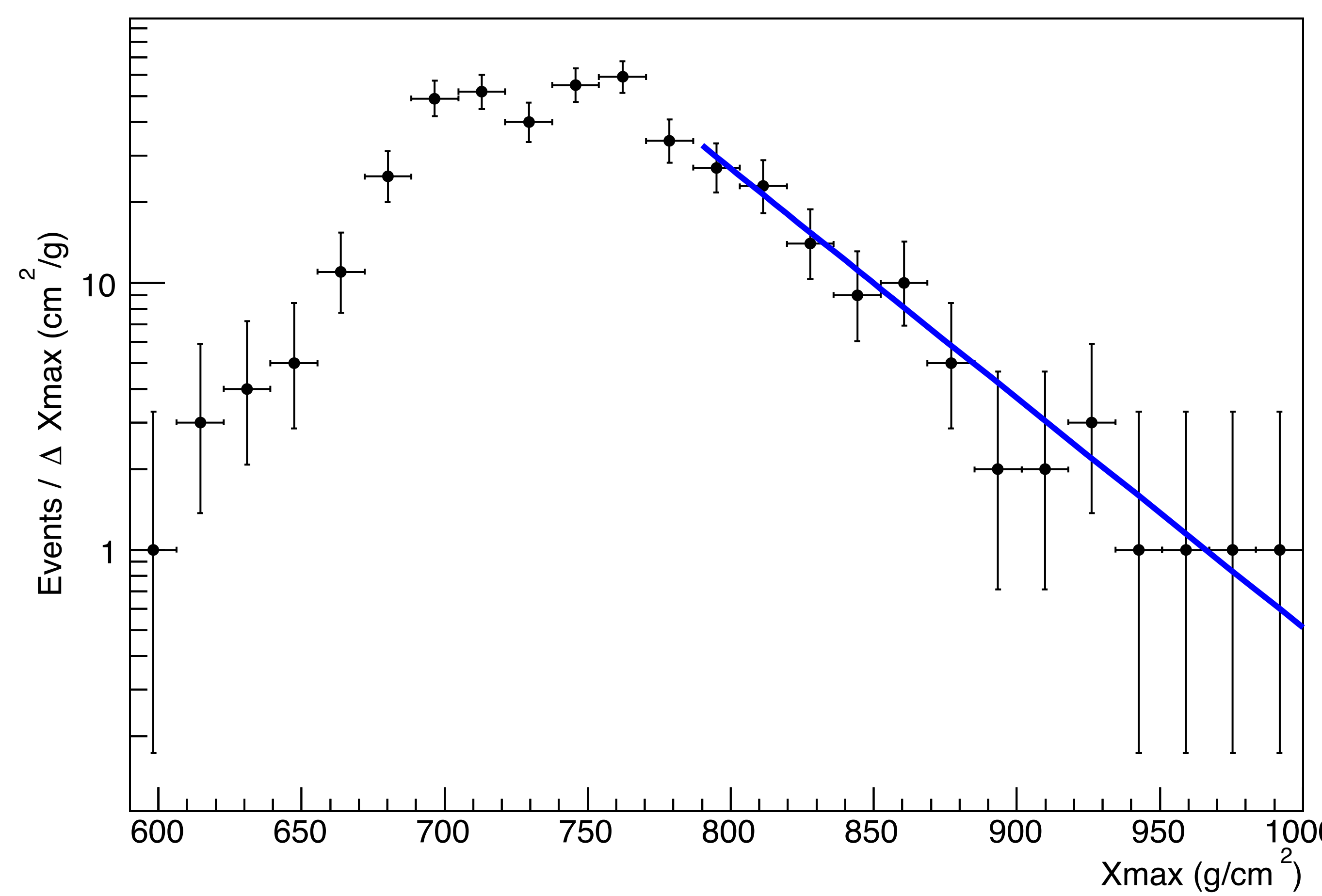
K value dependence



Decrement of the slope systematics

$\Lambda = 50.47 \pm 6.26[\text{stat.}]\ g/cm^2$

- Data divided in halves based on:
  - Zenith angle
  - Distance of Shower (Rp)
  - Energy of events



Energy (eV)	Λ [g/cm^2]
$E > 10^{18.63}$	55.7±10.1
$E < 10^{18.63}$	45.5±7.7

Attenuation lengths are consistent within the statistical fluctuations.

Decrement of the slope systematics

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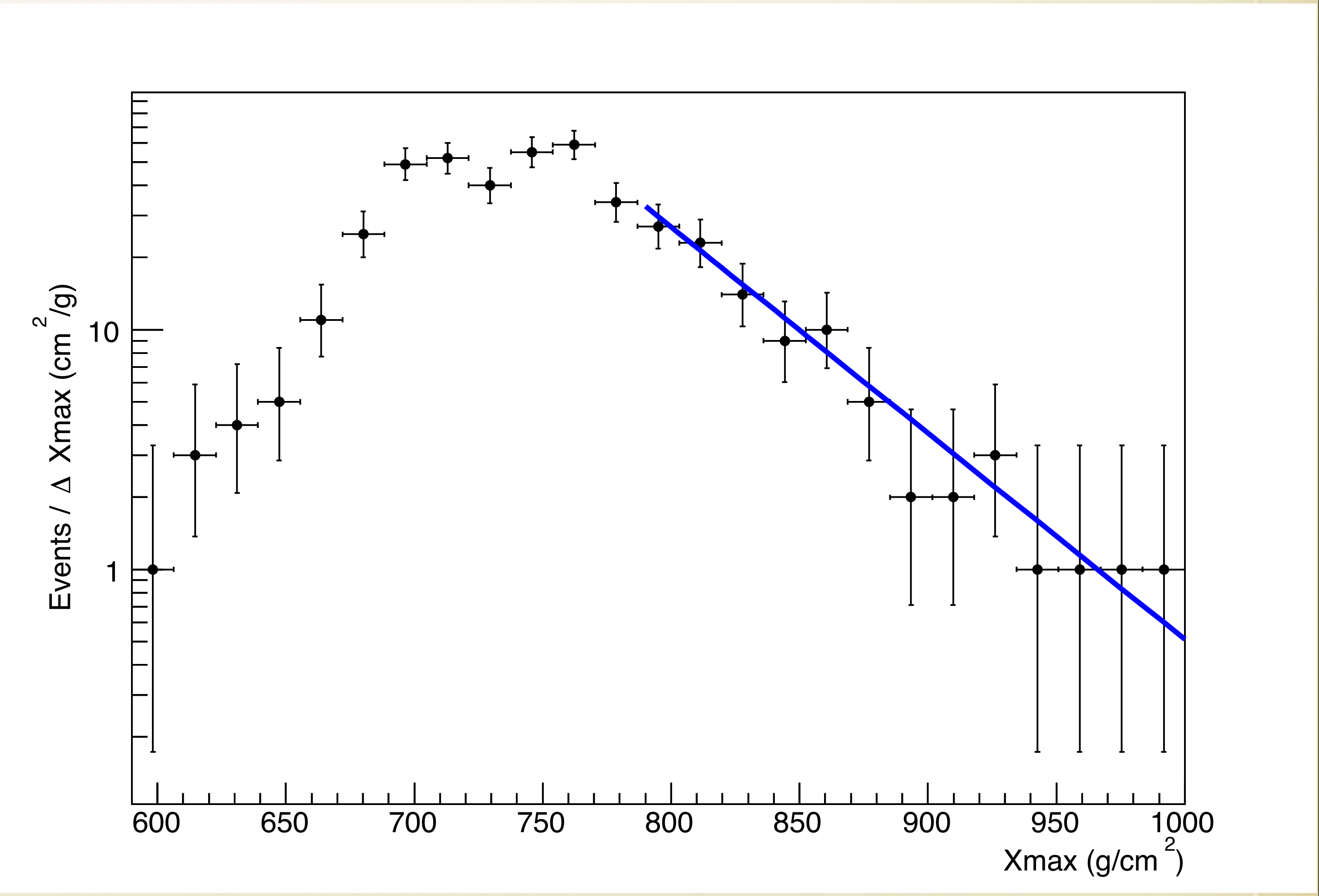

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P-Air cross section

Model	K
QGSJETII.4	1.15±0.01
QGSJET01	1.22±0.01
SIBYLL	1.18±0.01
EPOS-LHC	1.19±0.01

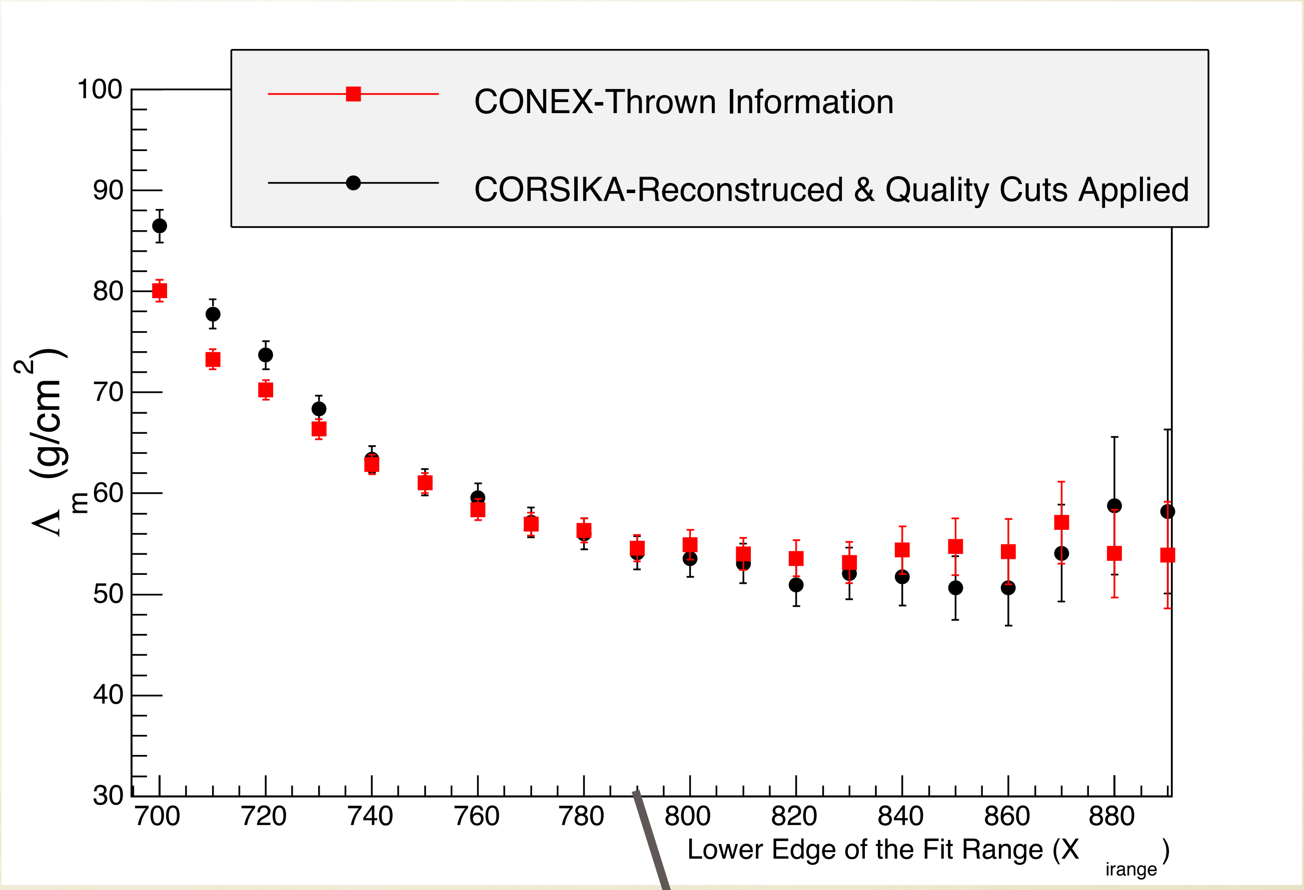
$\longrightarrow$

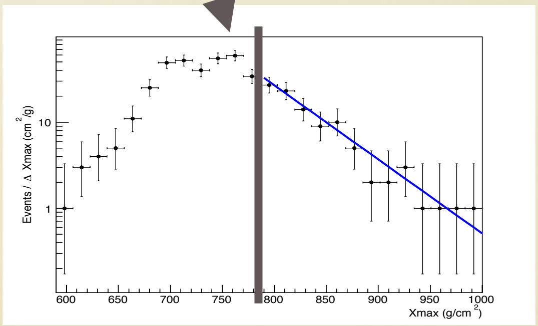
Model	$\sigma_{p\text{-}air}^{inel}$ [mb]
QGSJETII.4	550.3±68.5
QGSJET01	583.7±72.6
SIBYLL	564.6±70.2
EPOS-LHC	569.4±70.8

$\sigma_{p\text{-}air}^{inel} = 567.0 \pm 70.5$[Stat.] mb

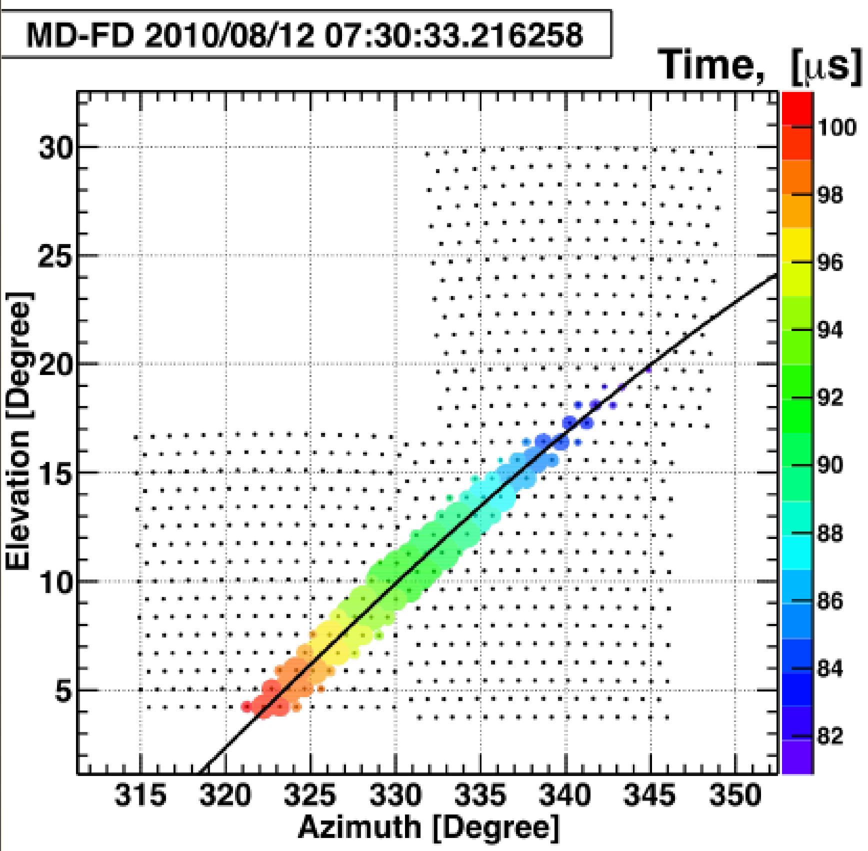
P-Air cross section Systematics

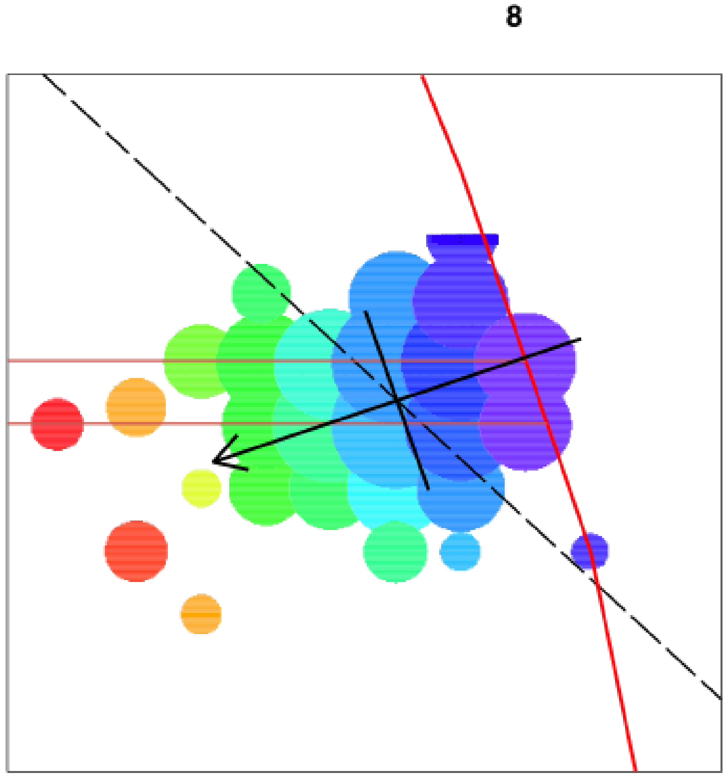
- Energy dependence bias in the Xmax distribution (Negligible): Shift Xmax by elongation rate.
- Detector Bias(Negligible): Event detection, reconstruction, cuts.

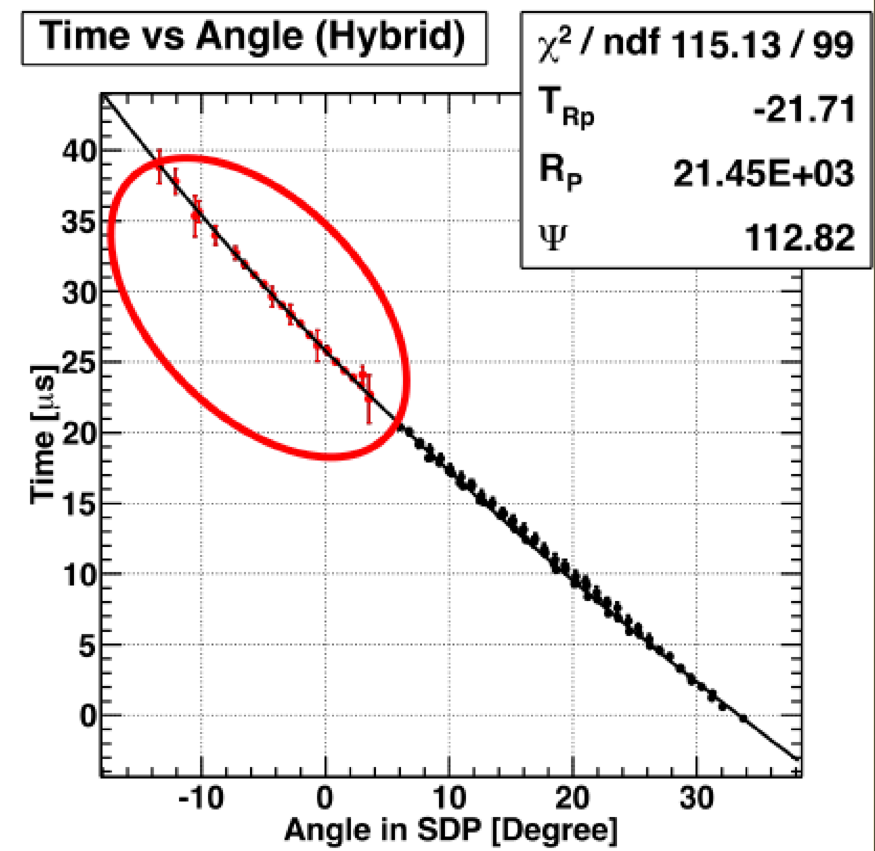


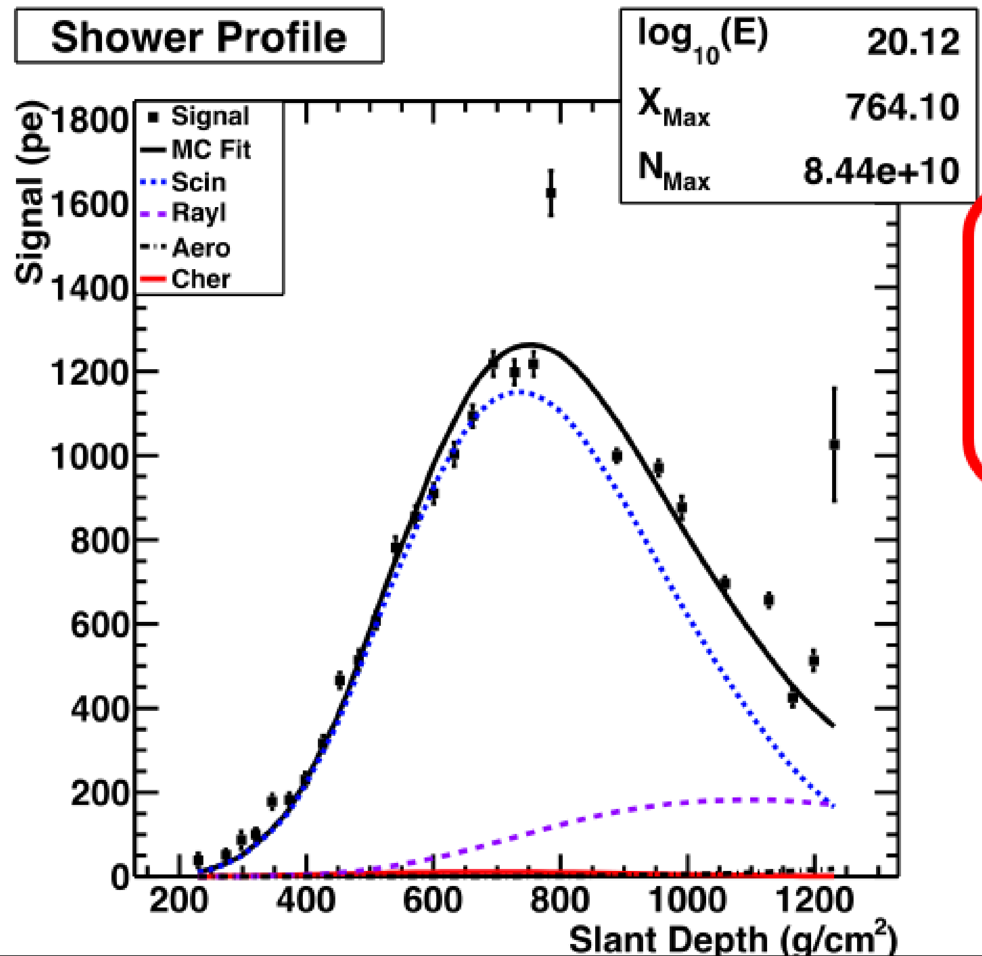


High Energy Hybrid Event









Energy: 1.3×10^{20} eV

Zenith Angle: 55.7°

Surface array constrains geometry fit via extra timing & core information