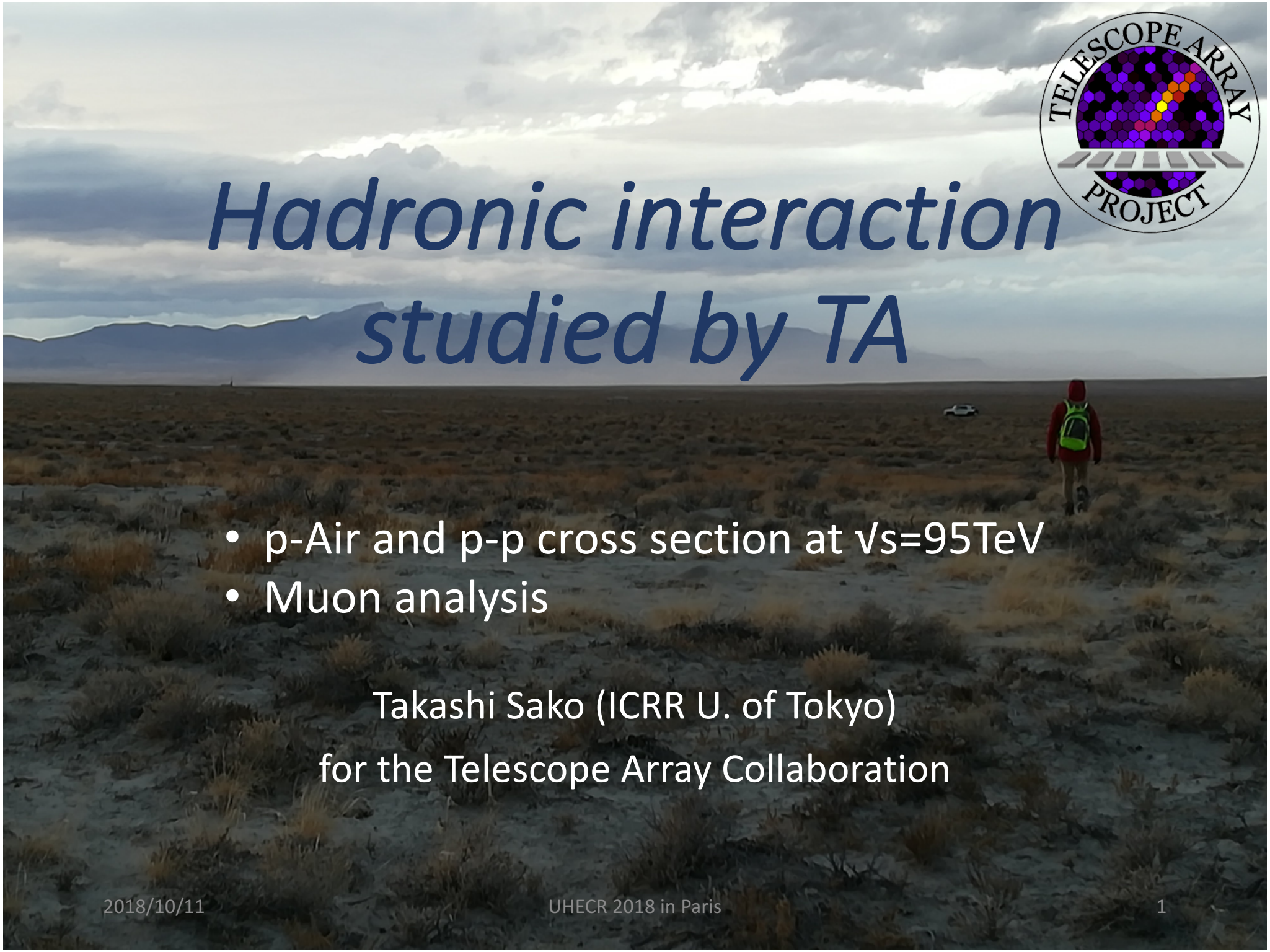


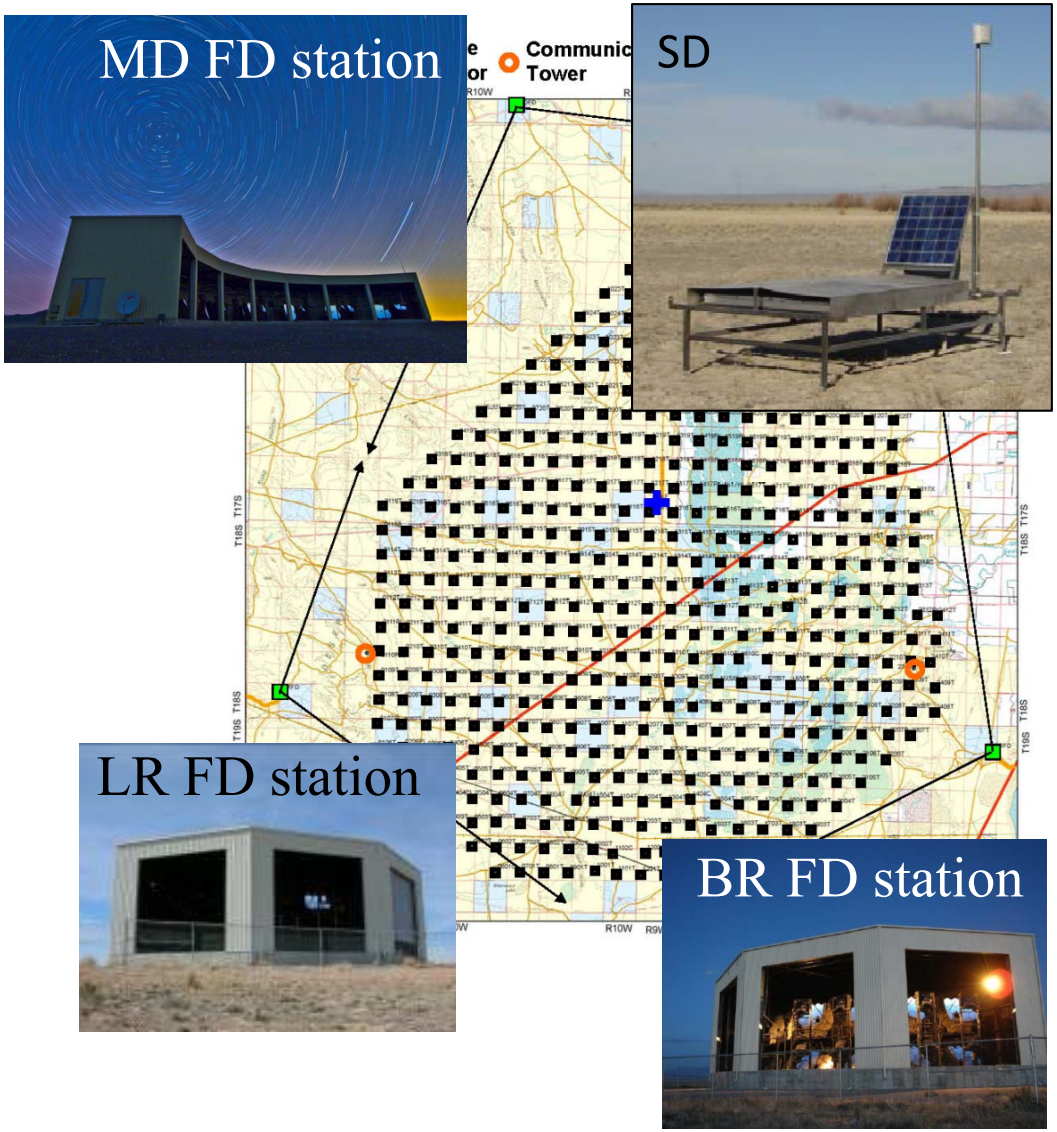
Hadronic interaction studied by TA

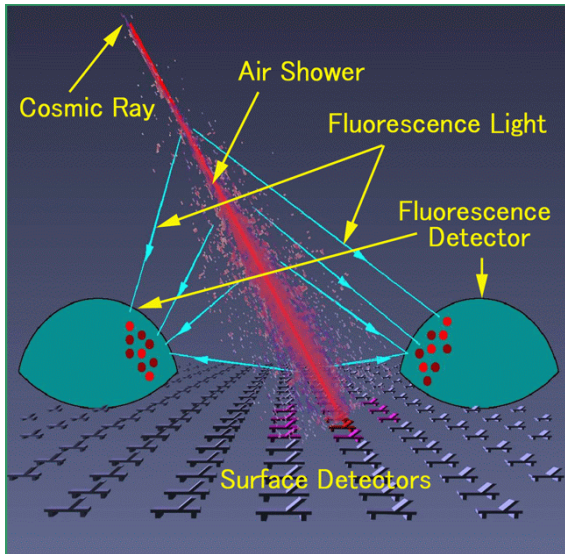
- p-Air and p-p cross section at √s=95TeV
- Muon analysis

Takashi Sako (ICRR U. of Tokyo)

for the Telescope Array Collaboration

Brief reminder of TA





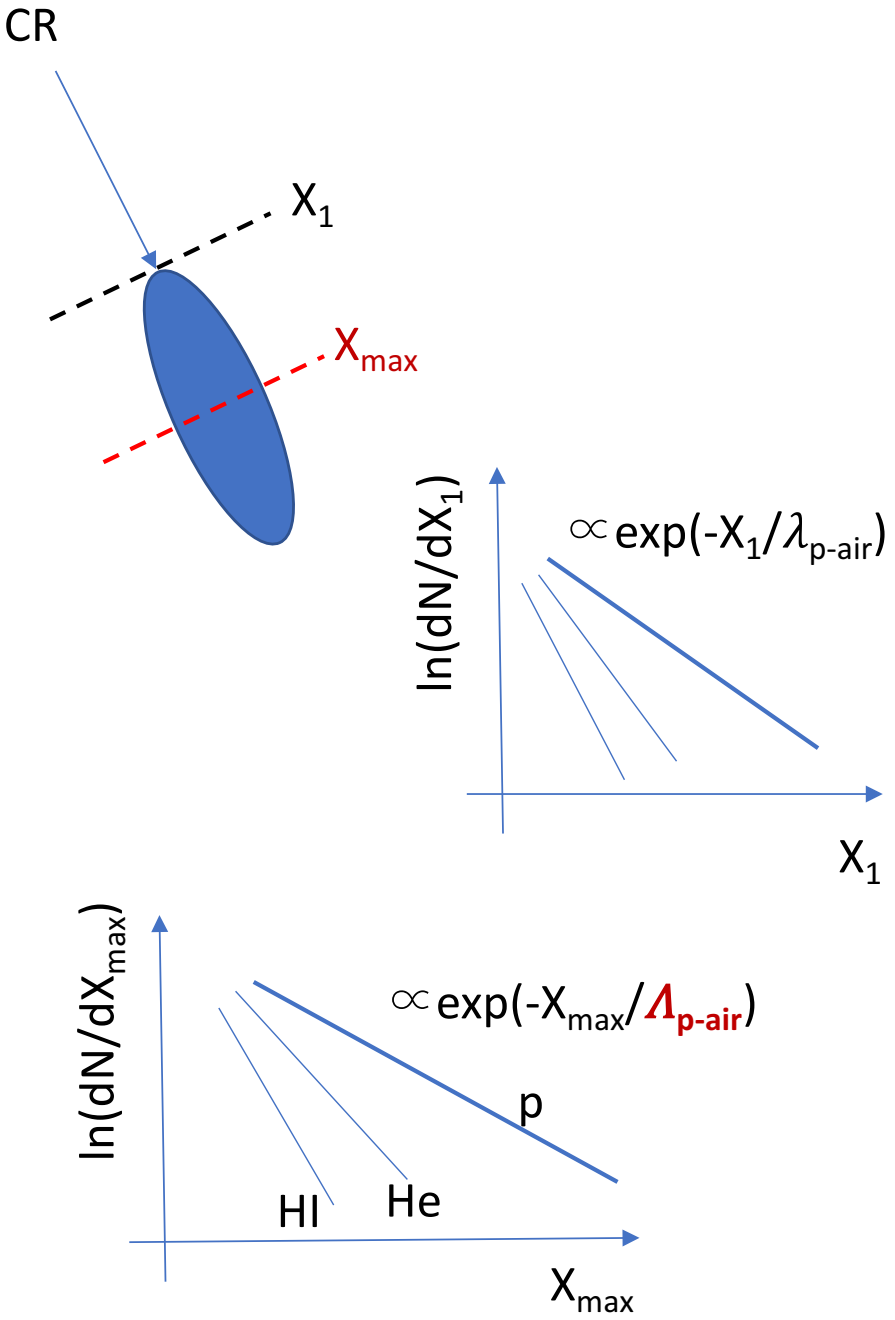
- Detectors
  - 507 SDs cover 700km^2
  - 3 FD stations
- Full operation since May 2008 (10th anniversary!!)
- SD-FD Hybrid trigger and Hybrid analyses improve the geometry reconstruction
- Dataset used in this talk
  - Cross section : 5 years MD FD (hybrid)
  - Muon : 7 years SD

Cross section

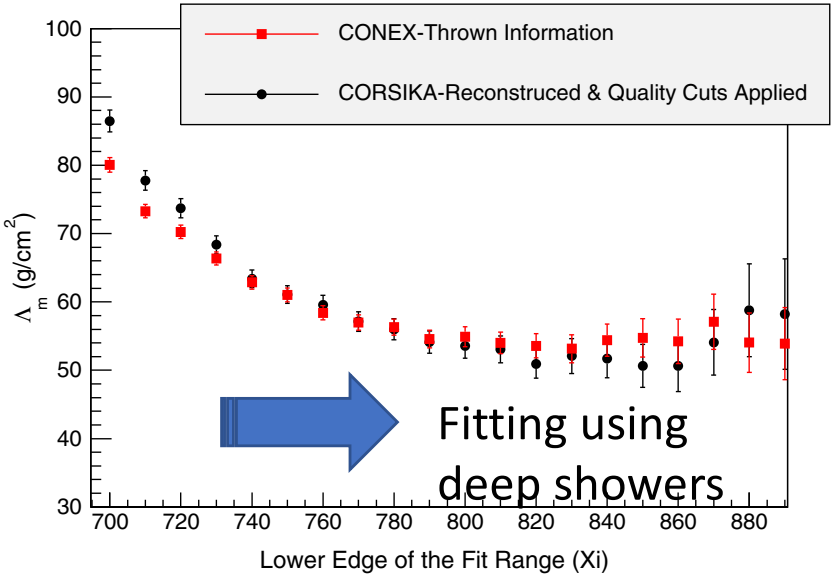
Phys. Rev. D92, 032007 (2015)

Outline

- **$\sigma_{\text{p-air}}$ at the highest energy**
- Ideally, measurement of 1st interaction point X_1, then determine $\lambda_{\text{p-air}}$
  - Difficult to observe
  - Mass composition
- Instead, distribution of of X_{max}
  - Well known observable
  - X_{max} tail => $\Lambda_{\text{p-air}}$ => $\lambda_{\text{p-air}}$ => $\sigma_{\text{p-air}}$
  - Tail represents proton
- "K-factor" method : $\Lambda_{\text{p-air}} = K\,\lambda_{\text{p-air}}$
- $\sigma_{\text{p-air}}$ => $\sigma_{\text{p-p}}$ through Glauber + BHS QCD inspired fit



K-factor method



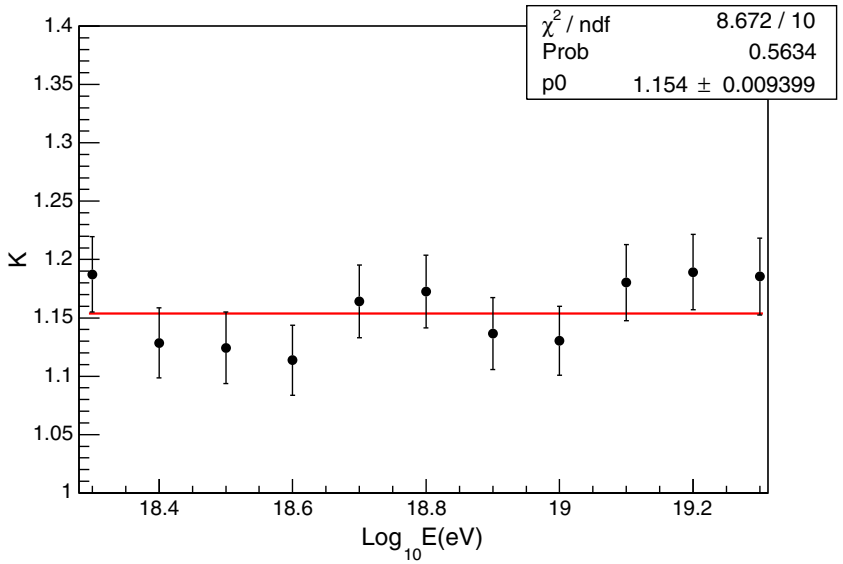
Given by experiment

Mean mass number of air

$$\Lambda_m = K\lambda_{p-\mathrm{air}} = K\frac{14.45 m_p}{\sigma^{\mathrm{inel}}_{p-\mathrm{air}}}$$

K-factor (CONEX MC)

- CORSIKA-CONEX comparison
  - CONEX : only 1-D shower
  - CORSIKA : 3-D shower + detector simulation + reconstruction
- Fitting deep X_{max} data, result is stable and consistent between CONEX and CORSIKA

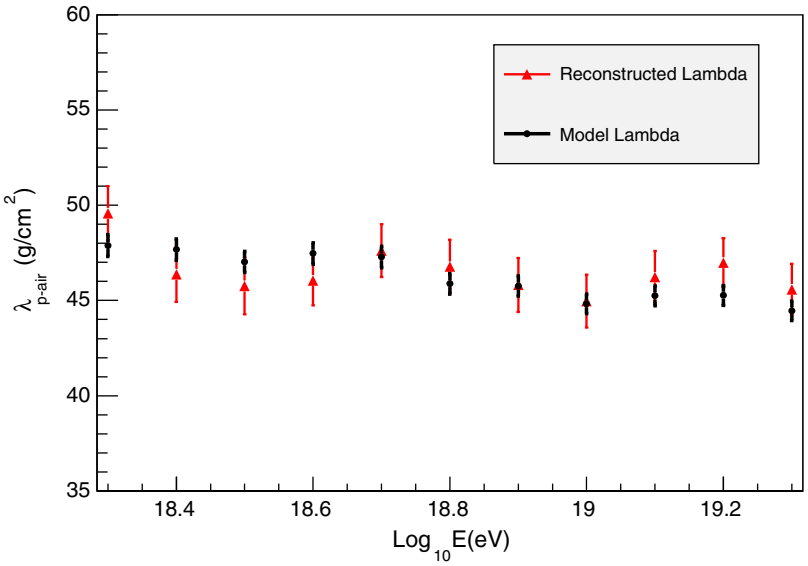


Using QGSJET II-04 :
No energy dependence in K-factor

K-factor (continued)

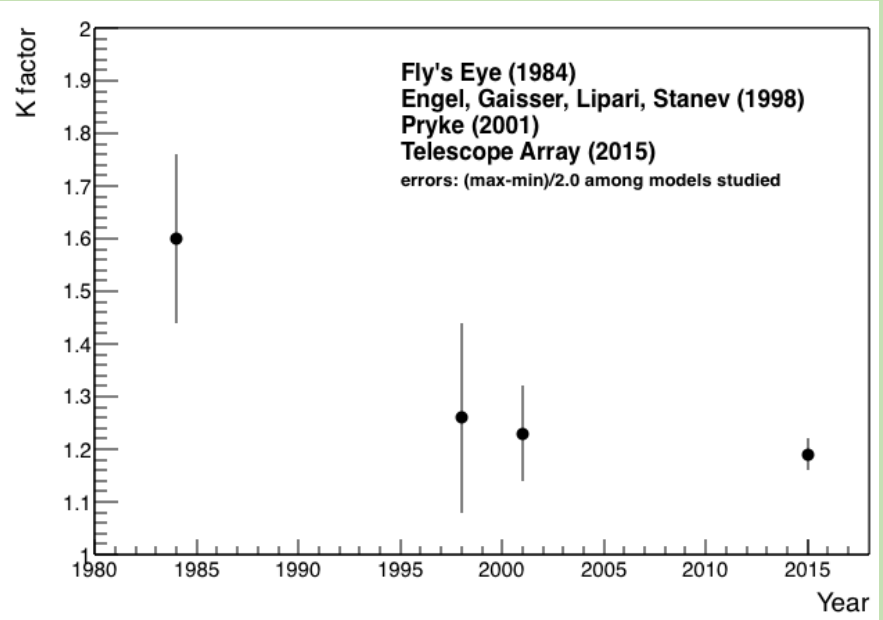
Model	K
QGSJETII.4	1.15 ± 0.01
QGSJET01	1.22 ± 0.01
SIBYLL	1.18 ± 0.01
EPOS-LHC	1.19 ± 0.01

Small model dependence
(max-min)/mean = 0.06 => $\pm$ 3%



True λ vs. reconstructed λ through K-factor
No reconstruction bias

K-value in history (not in TA paper)



Old data can be revised with new MC
Error: (max-min)/2 in each paper

Dataset used in TA analysis

- MD FD -SD hybrid (independent trigger, offline matching) => X_{max} resolution : ~23g/cm^2
- May 2008 –May 2013 (5 years)
- 439 events
- E=$10^{18.3}$-$10^{19.3}$ eV, <E>=$10^{18.68}$ eV $\sqrt{s_{NN}}$=95TeV

NOTE: Analysis using BR/LR FDs hybrid events on going (x5.7 events)

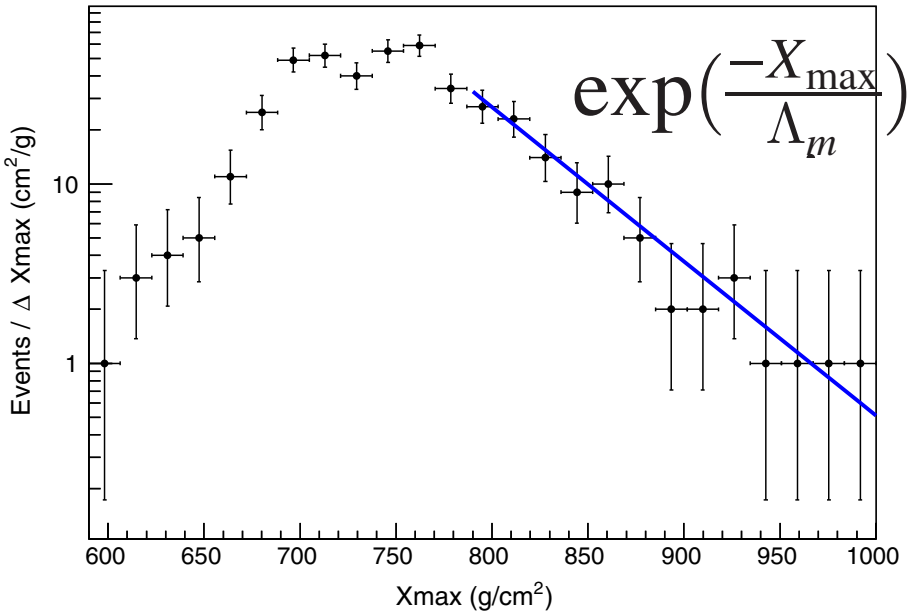
Results

$$\Lambda_m = (50.47 \pm 6.26[stat])\, g/cm^2$$

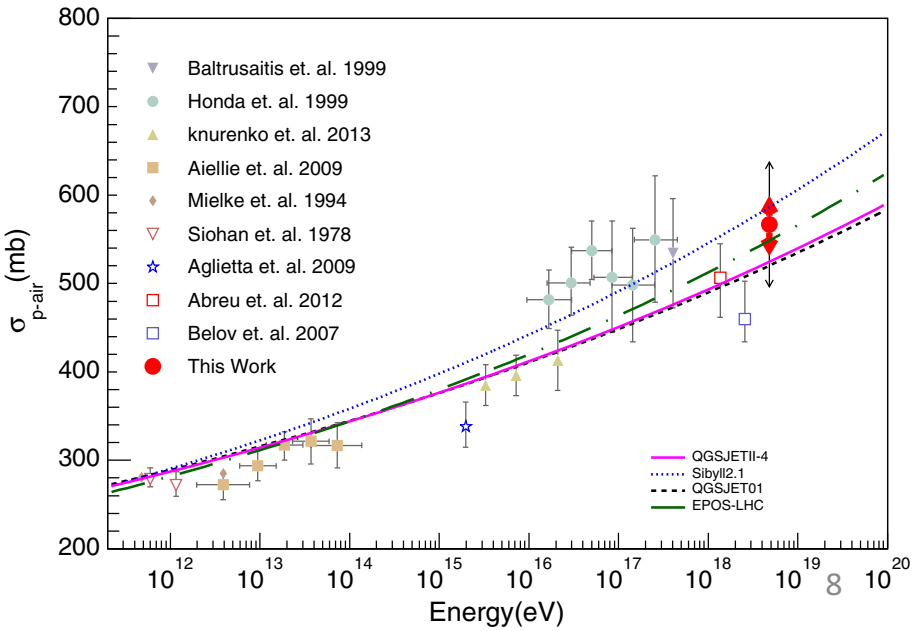
$$\Lambda_m = K\lambda_{p-\mathrm{air}} = K\frac{14.45 m_p}{\sigma^{\mathrm{inel}}_{p-\mathrm{air}}}$$

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

Mean $\pm$ 3%



$$\sigma^{inel}_{p-air} = \left(567.0 \pm 70.5[stat]^{+29}_{-25}[sys]\right) mb$$

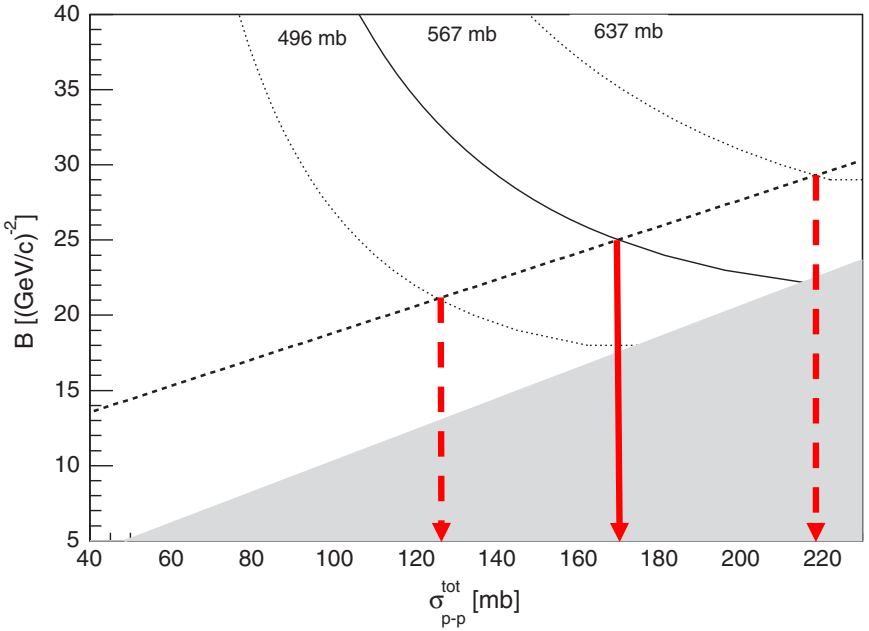


<E>=$10^{18.68}$ eV $\sqrt{s_{NN}}$=95TeV

Systematic error contains

- Hadronic model dependence ($\pm$ 17mb)
- 1% photon contamination (+23mb)
- 20% He contamination (-18mb)

σ^{inel}_{p-air} to σ^{tot}_{p-p}



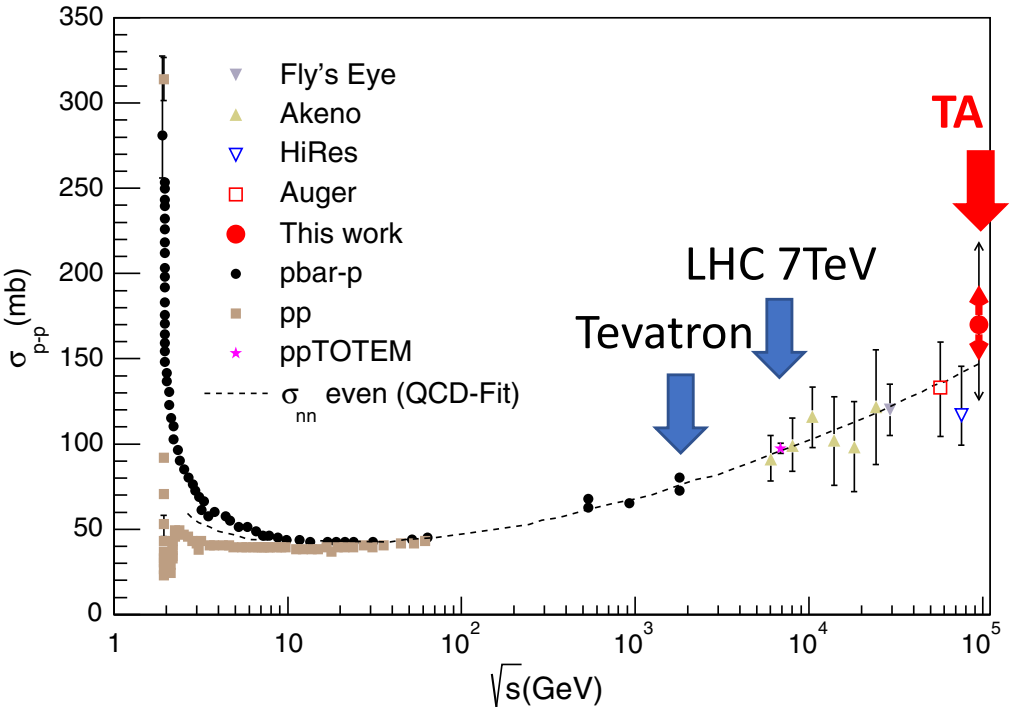
Glauber calculation for nuclear effect

$$\sigma^{inel}_{p-air}\left(\sigma^{tot}_{p-p}, B\right)$$

(B: elastic slope in p-p collision)

- σ^{inel}_{p-air} given by TA
- $\sigma^{tot}_{p-p} - B$ relation based on a model (BHS QCD inspired fit)

$$\sigma^{tot}_{p-p} = 170^{+48}_{-44}[stat]^{+19}_{-17}[sys]mb$$



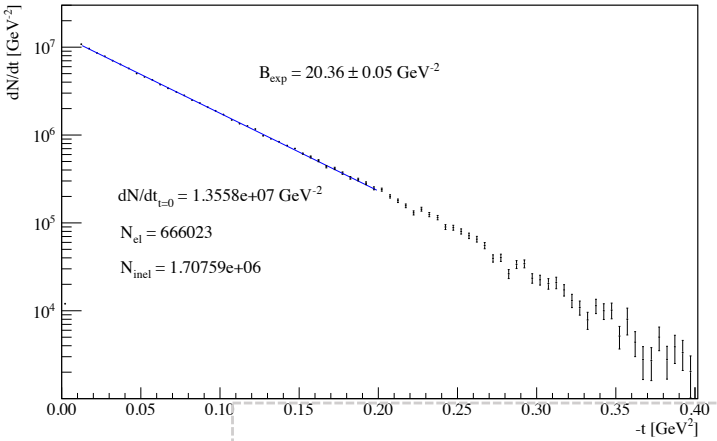
"OK, on the extrapolation from low energy"

Only that?

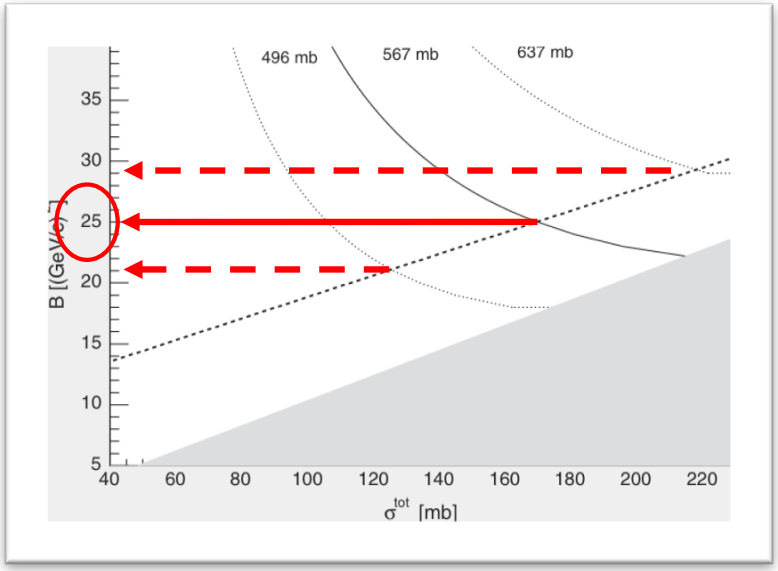
σ-B : TA and LHC

(not in TA paper)

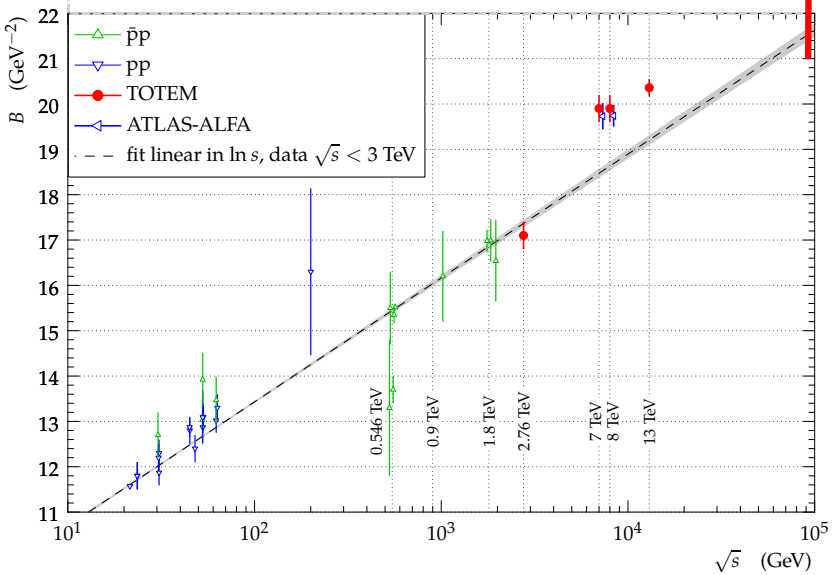
CERN-EP-2017-321



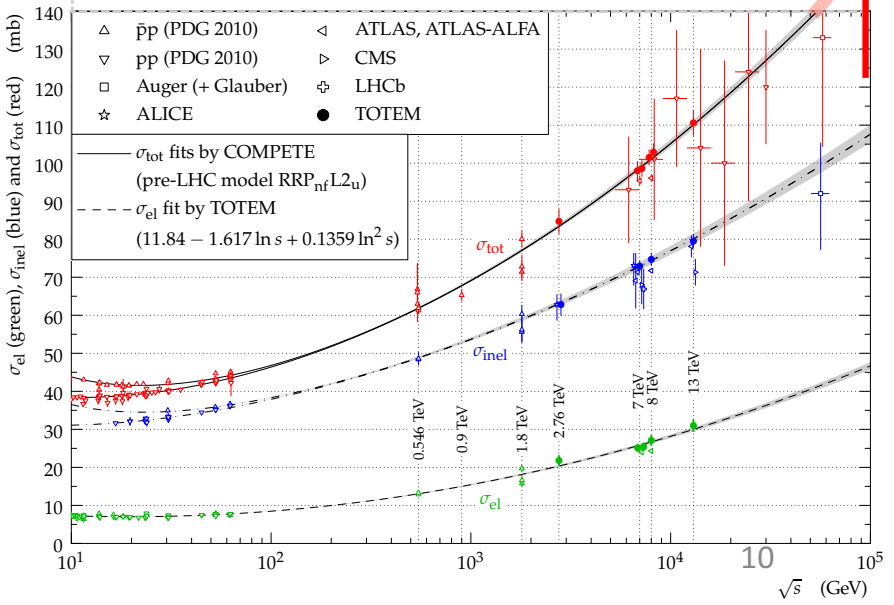
σ-B relation used in TA analysis



Read from TA (2015)



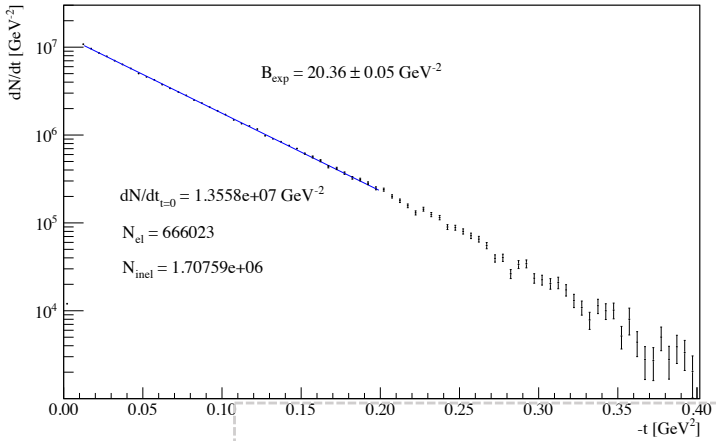
TA (2015)



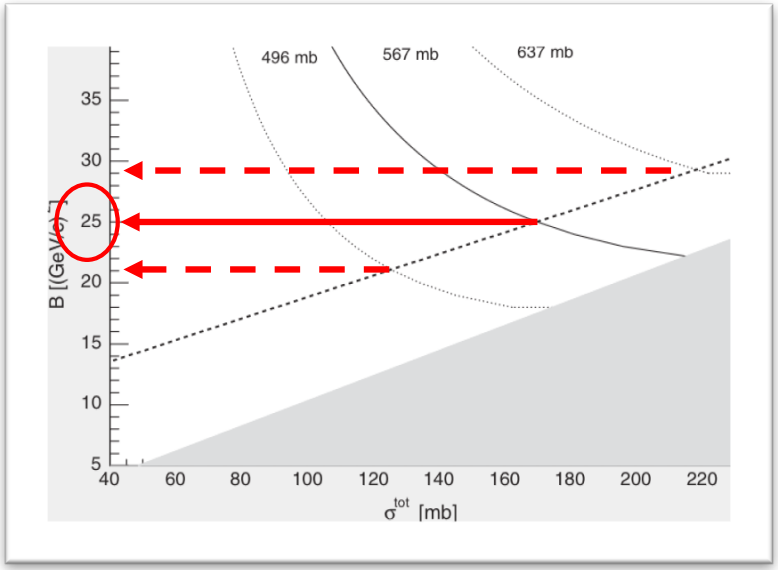
σ-B : TA and LHC

(not in TA paper)

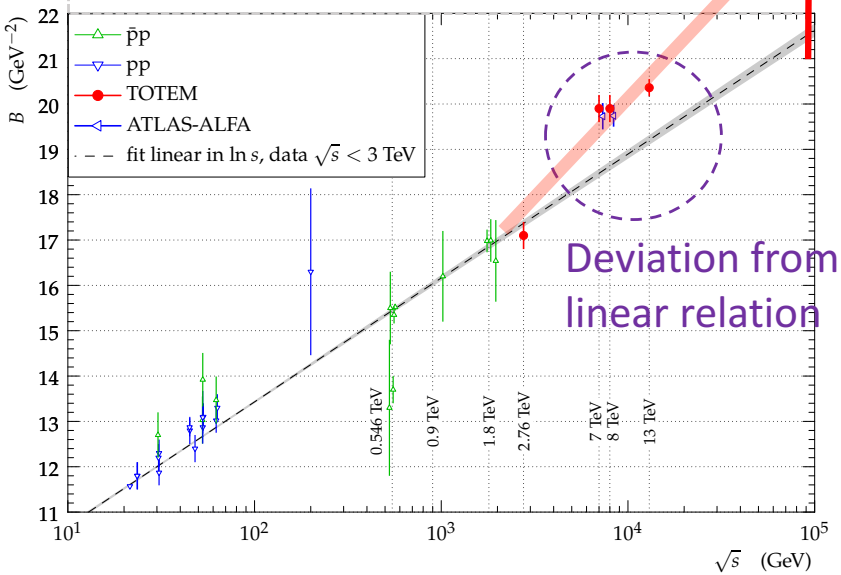
CERN-EP-2017-321



σ-B relation used in TA analysis

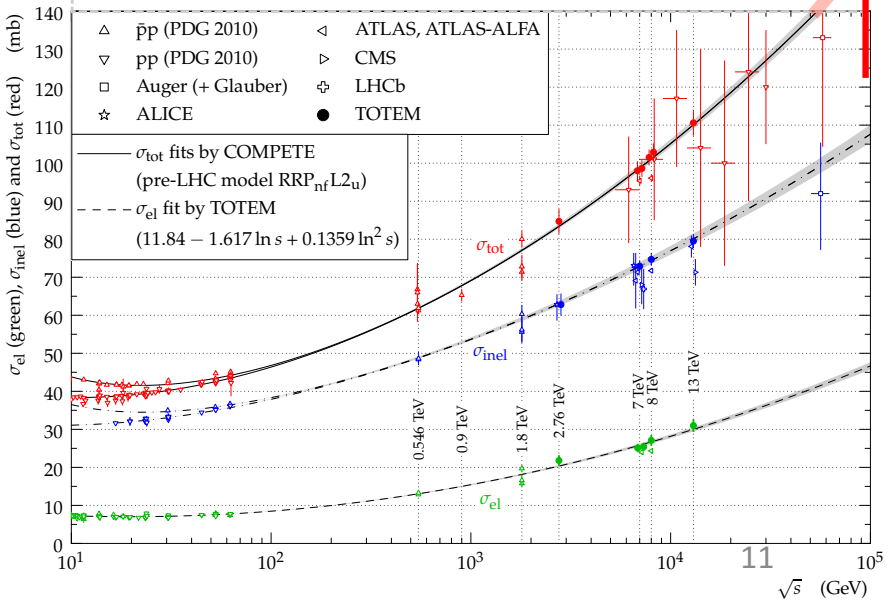


Read from TA (2015)



Deviation from linear relation

TA (2015)

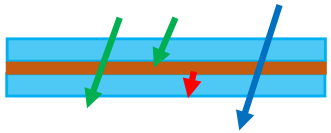


Muons

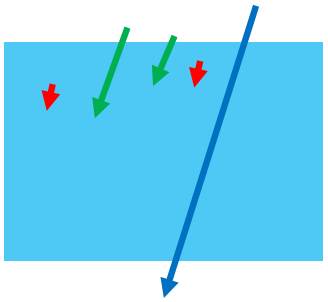
Phys. Rev. D 98, 022002 (2018)
Detail in poster by R. Takeishi

Muon problem

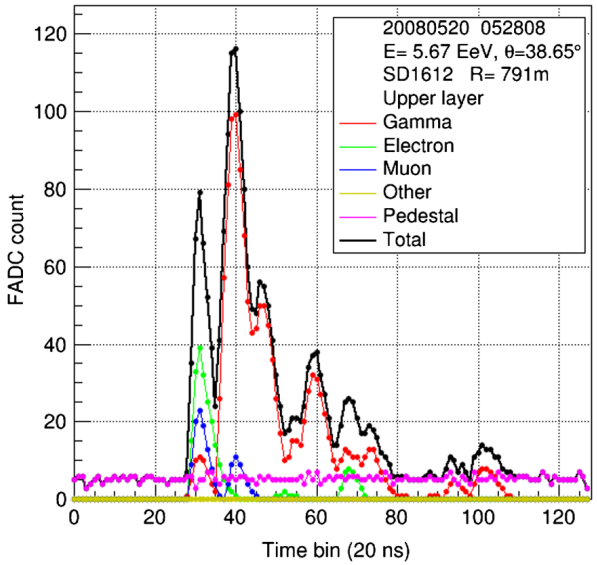
- Excess of number of muons compared to MC predictions (deficit in MC)
- Review in the next talk by Hans Dembinski
- Different sensitivities of TA SD and Auger tank to muon and EM

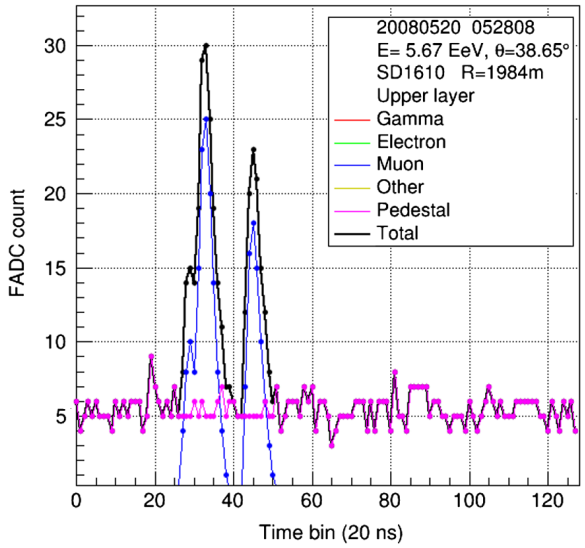


Thin scintillators
(TA type)



Thick water Cherenkov
detector
(Auger type)





TA detector simulation
Signal size of MIP is same in
muon and **electron**

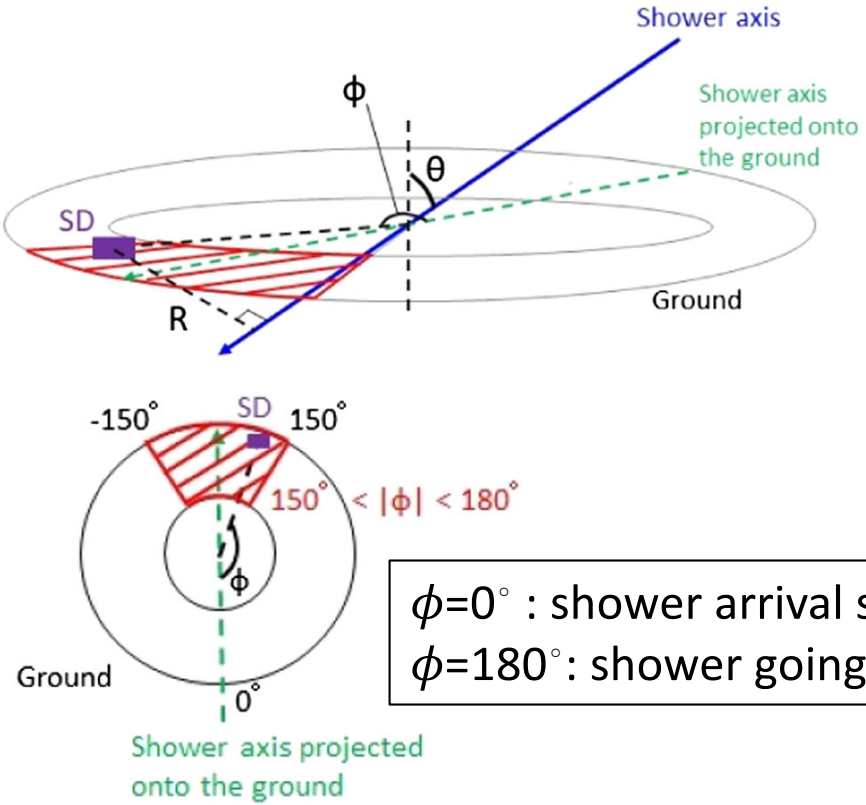
Method in TA analysis : muon purity

- Muon purity P

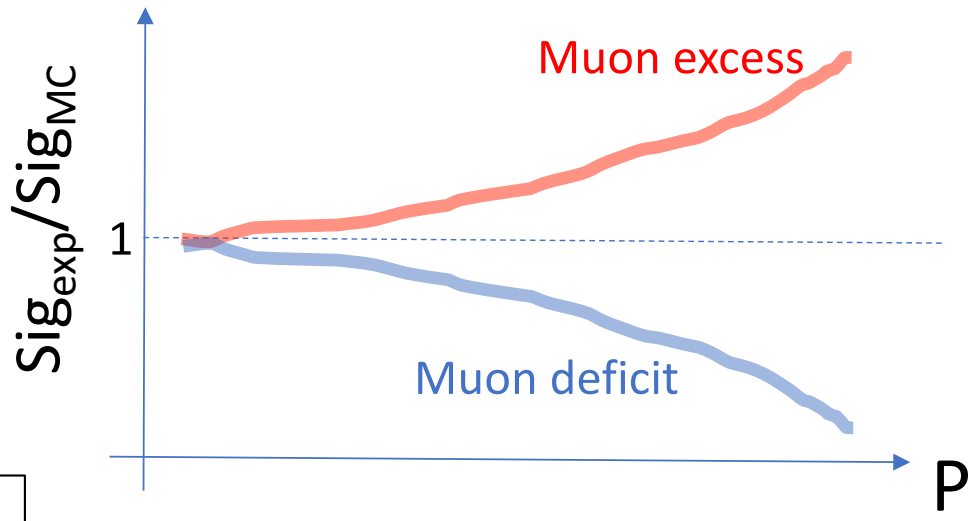
$$P = \frac{E_\mu}{E_{all}} = f(\theta, \phi, R)$$

is defined by MC but only a function of geometrical parameters

- Large P with large θ, ϕ, R



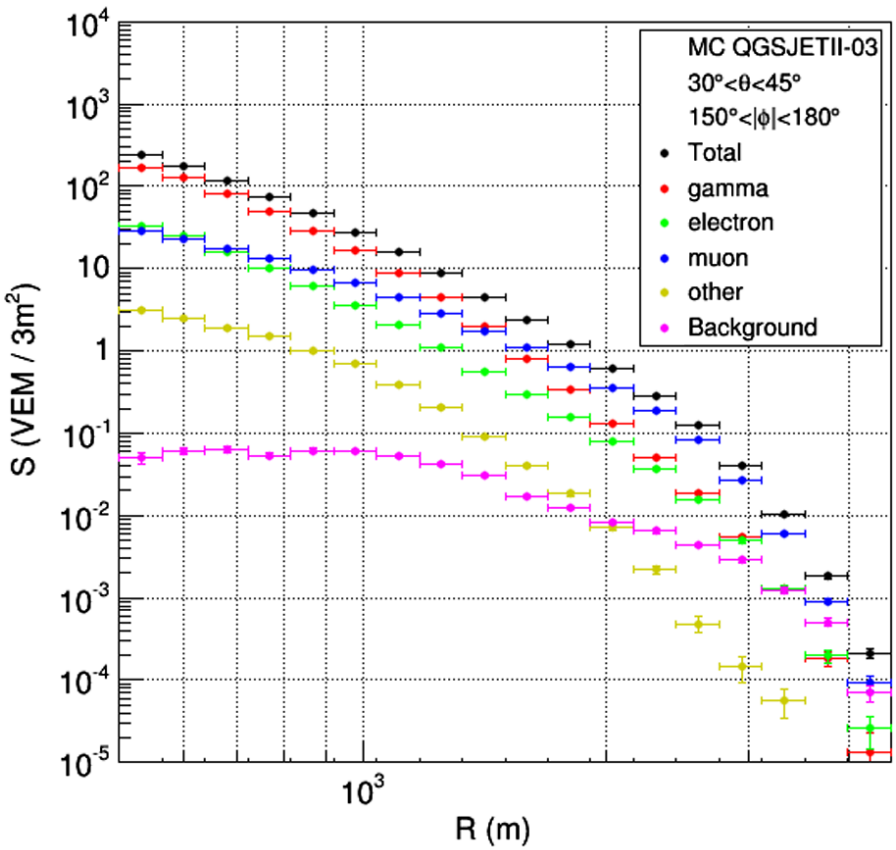
ϕ=0° : shower arrival side
ϕ=180°: shower going side

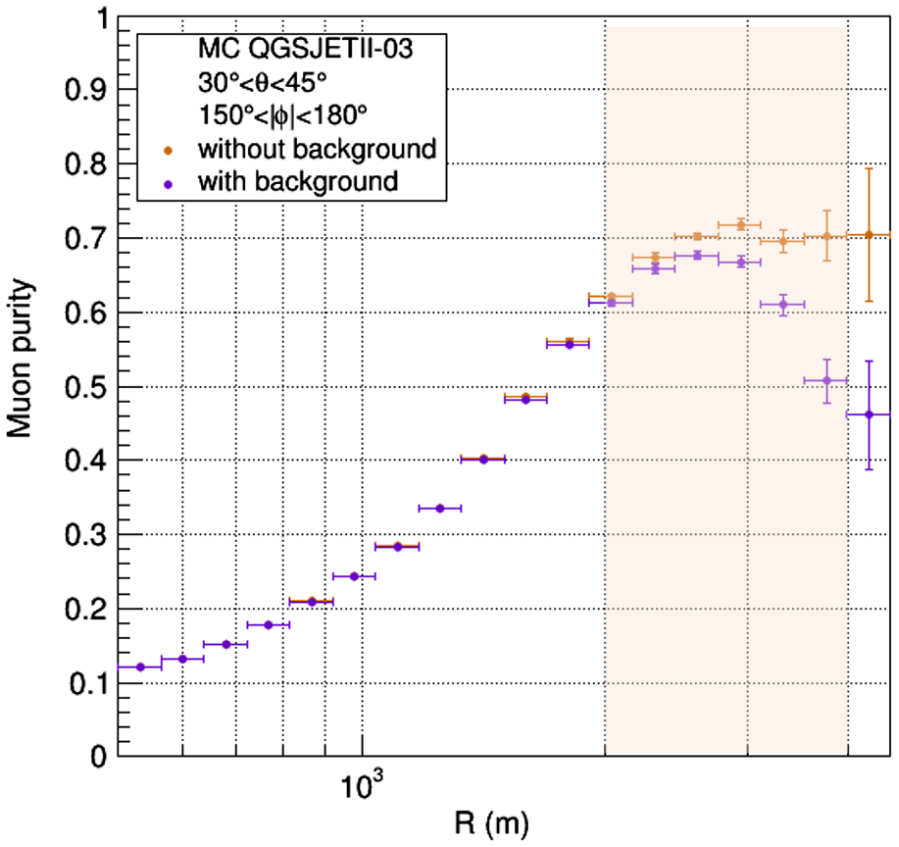


Dataset and MC

- Dataset
  - May 11, 2008 – May 11, 2015 (7 years)
  - $18.8 < \log_{10}(E_{FD}/eV) < 19.2$
  - $E_{FD} = E_{SD}/1.27$
- MC
  - E : thrown (true) energy
  - Reference : QGSJET II-03 proton
  - MC : CORSIKA 6.960 (FLUKA2008.3C+EGS4), thinning + dethinning
  - Detector : GEANT4
  - $16.55 < \log_{10}(E/eV) < 20.55$
  - $0^\circ < \theta < 60^\circ$
  - 0.05 accidental muons / station / $\pm 32\mu s$

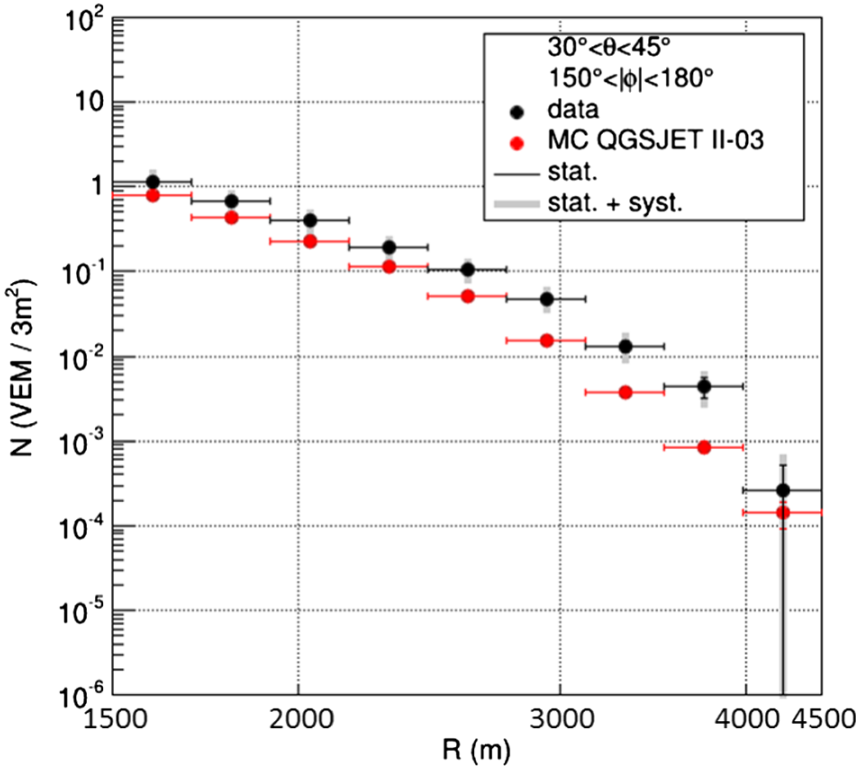
Purity vs. R (MC: QGSJET II-03)

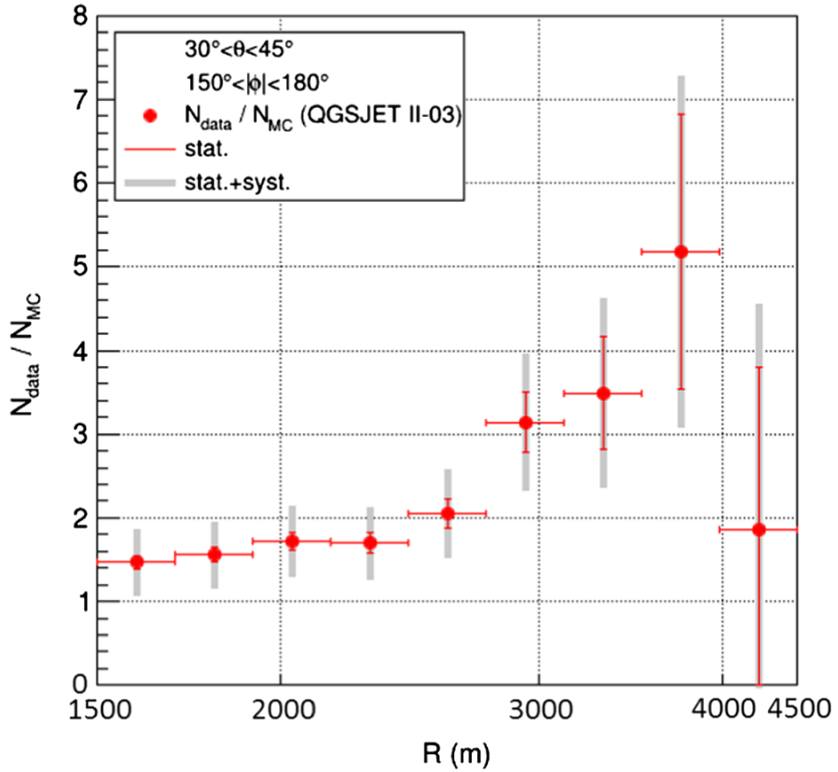




- $30^\circ<\theta<45^\circ$, $150^\circ<\phi<180^\circ$
- 2000m<R<4000m : high muon purity sample

Result 1 (data/MC vs. R)

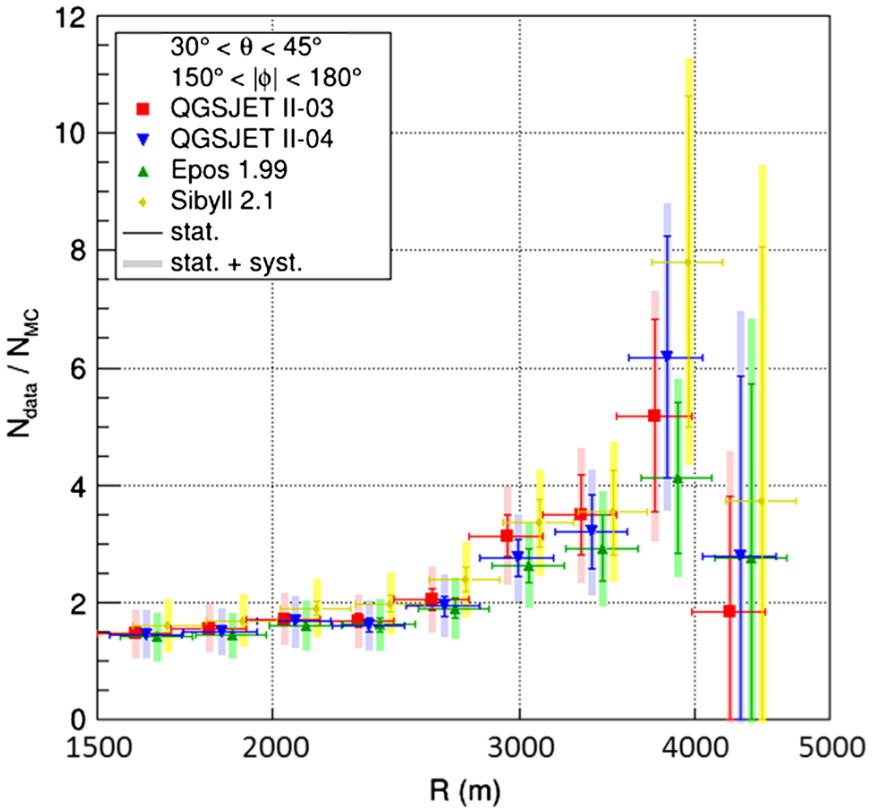


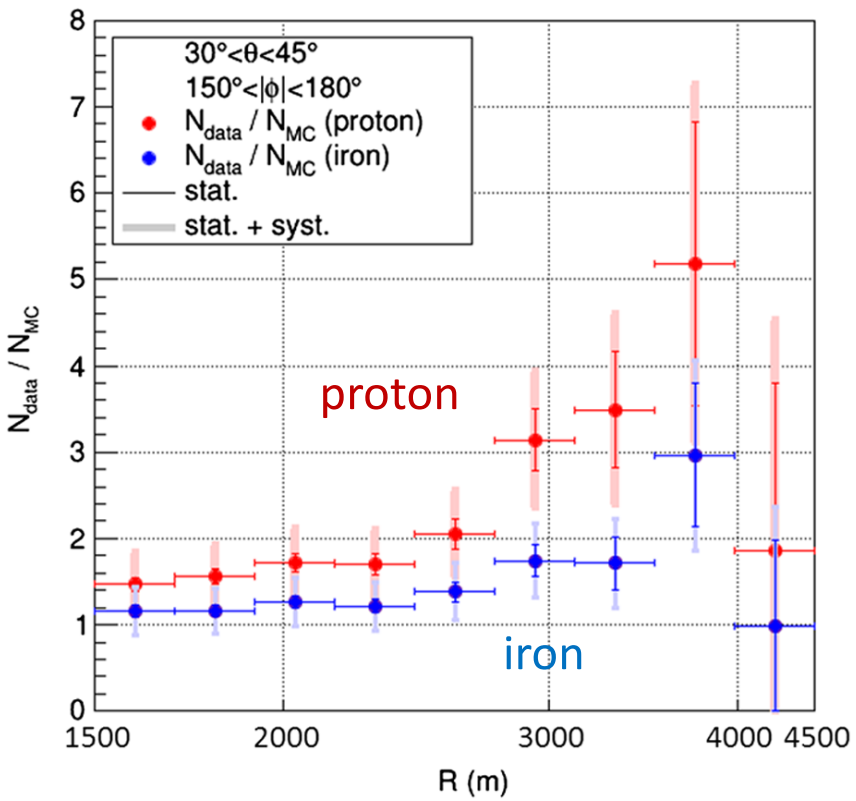


Source	Systematic error
FD energy determination	±21%
1 MIP calibration	±1.2%
Atmospheric muon cut	±1%
Poisson distribution assumption	±(<4%)
Event reconstruction	±(4–13%)
SDs not working properly	±(<1%)
Total	±(22–24%)

- N_{data}/N_{MC} >1 and increases with R
- N_{data}/N_{MC} => 1 @ R>4000m because BG dominates

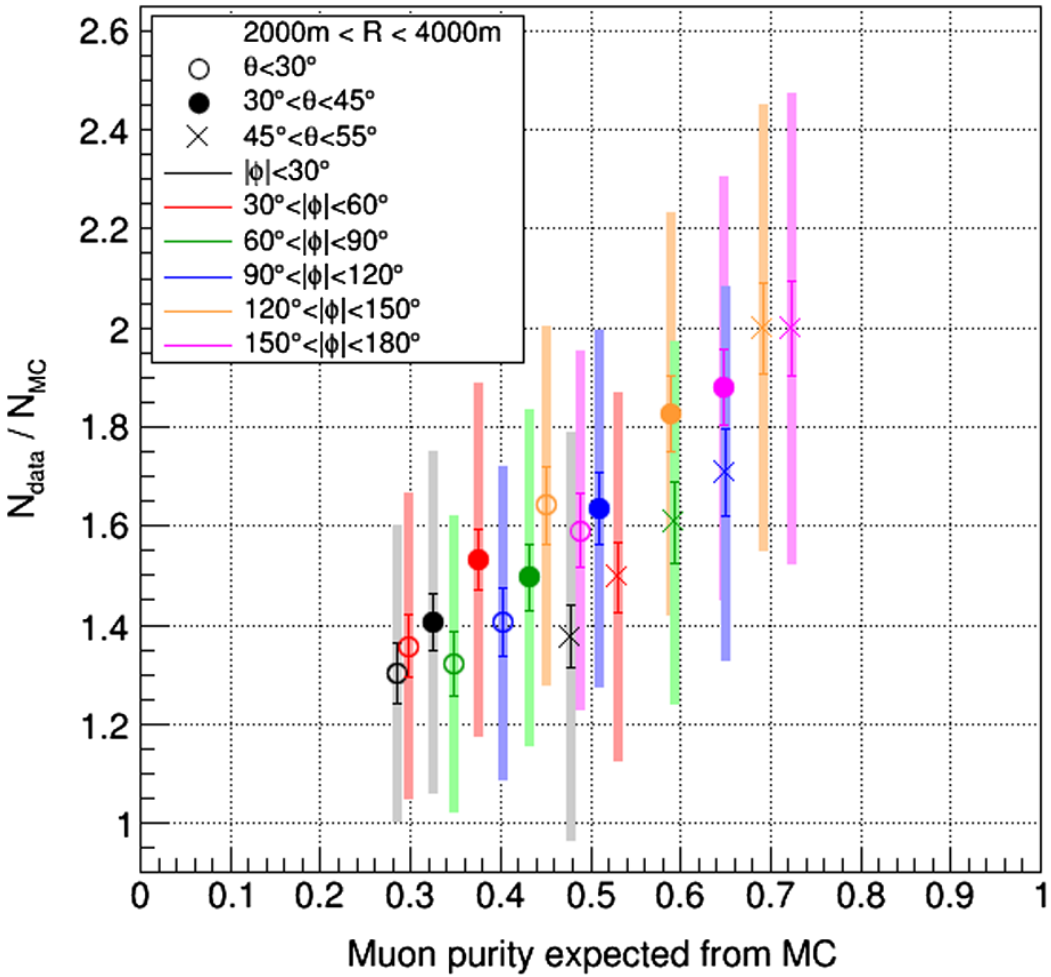
Result 2
(model and mass dependences)





- Same trend with all models
- Same trend with Fe primary, but less excess

Result 3
(P dependence with various θ, ϕ)

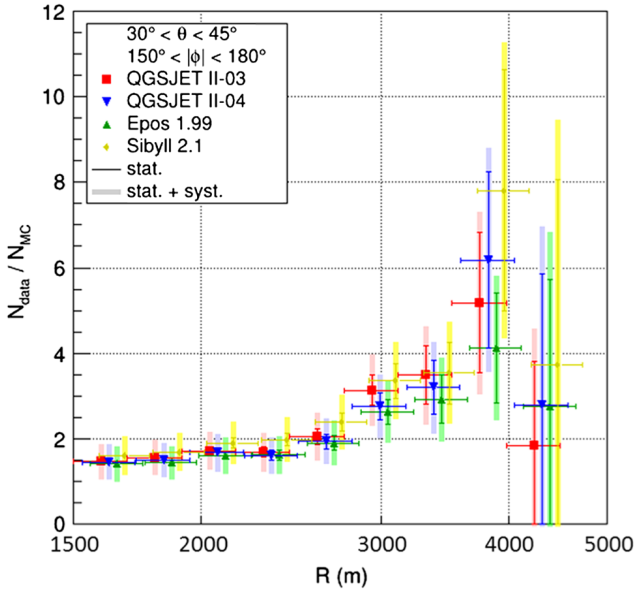


- Large N_{data}/N_{MC} in the large P sample
- Energy scale uncertainty dominates the systematic. This error is correlated between data points.

Summary

- Cross section measurement
  - $\sigma_{p-air}^{inel} = \left(567.0 \pm 70.5[stat]^{+29}_{-25}[sys]\right)mb$ is determined using MD station FD data
  - $\sigma_{p-p}^{tot} = 170^{+48}_{-44}[stat]^{+19}_{-17}[sys]mb$ is obtained using Glauber calculation and QCD model of $\sigma_{p-p}^{tot} - B$ relation
  - Cross section and B are consistent with the most recent extrapolation from low energy
  - Ongoing analysis increases statistics x5.7
- Muon analysis
  - Signal excess w.r.t. MC is observed in high muon purity samples

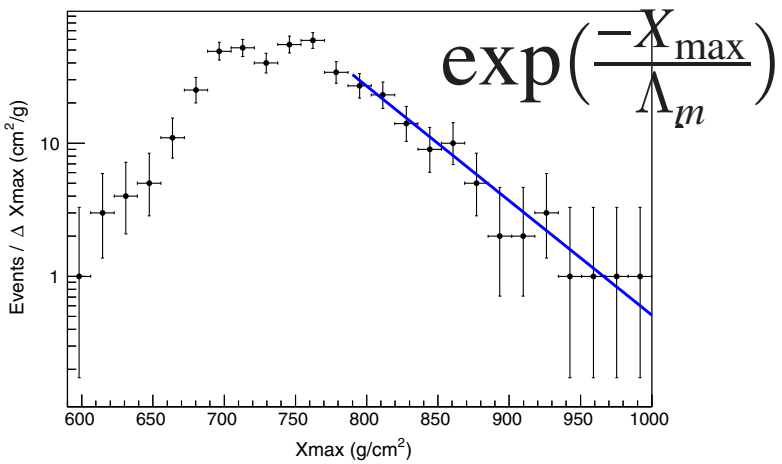
    => indicating muon excess
  - In other words, observed lateral distribution is not reproduced by MC simulations



TA is powerful to test hadronic interaction beyond LHC energy

Backup

K-factor method

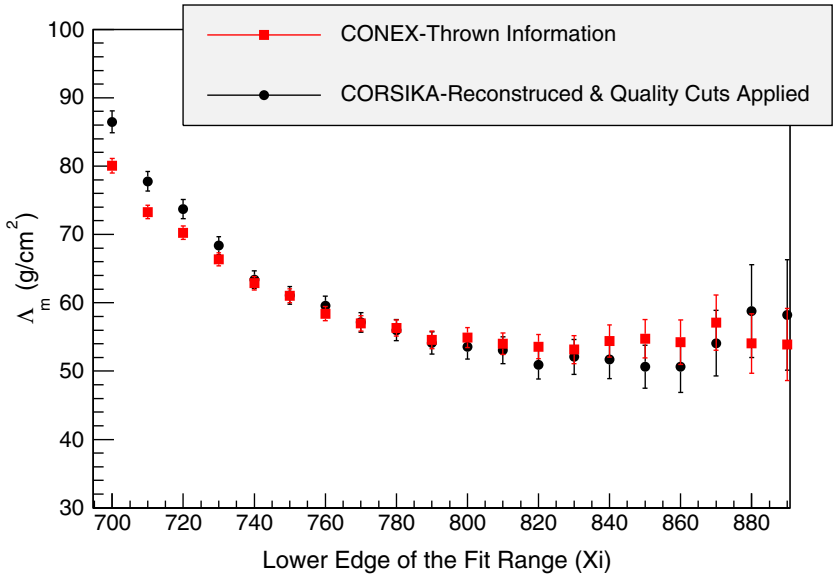


Mean mass number of air

$$\Lambda_m = K\lambda_{p-\text{air}} = K\frac{14.45 m_p}{\sigma^{\text{inel}}_{p-\text{air}}}$$

K-factor

- Experiment (Λ_m) and MC (K) are decoupled
- K is Model dependent
- K is determined by using CONEX



- CORSIKA-CONEX comparison
  - CONEX : only 1-D shower
  - CORSIKA : 3-D shower + detector simulation + reconstruction
- Fitting deep X_{max} data, result is stable and consistent between CONEX and CORSIKA

Glauber calculation

- Superposition of p-p amplitude (function of σ^{tot}_{pp} and elastic slope B)
- Nucleon distribution function in a nucleus