Muons in Air Showers at the Pierre Auger Observatory

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http://www.auger.org/archive/authors_2014_09.html

Outline

published:

PHYSICAL REVIEW D **90,** 012012 (2014)

Muons in air showers at the Pierre Auger Observatory: Measurement of atmospheric production depth

accepted by PRD (selected for Editors' Suggestion):

Muons in air showers at the Pierre Auger Observatory: Mean number in highly inclined events

preliminary analyses (ICRC13):

Measurement of the muon signal using the temporal and spectral structure of the signals in surface detectors of the Pierre Auger Observatory

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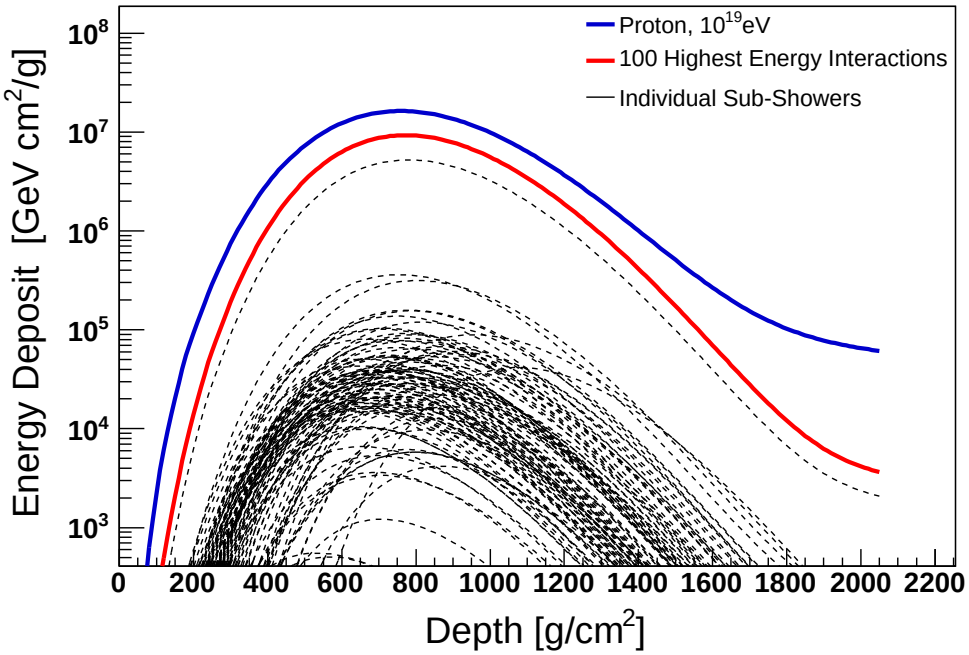
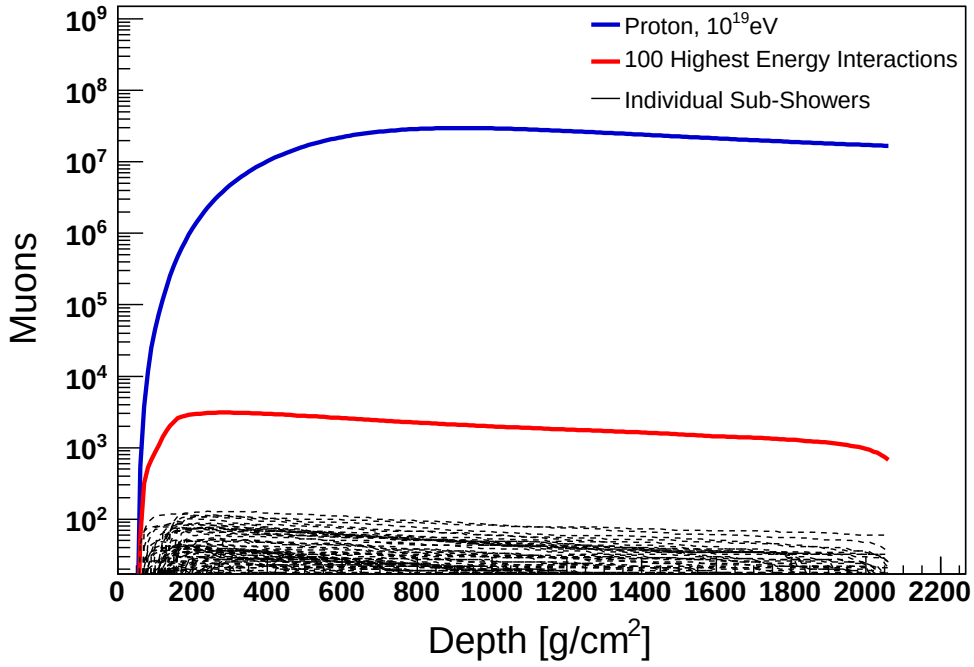
The muon content of hybrid events recorded at the Pierre Auger Observatory

GLENNYS R. FARRAR[1] FOR THE PIERRE AUGER COLLABORATION[2]

Muons in air showers



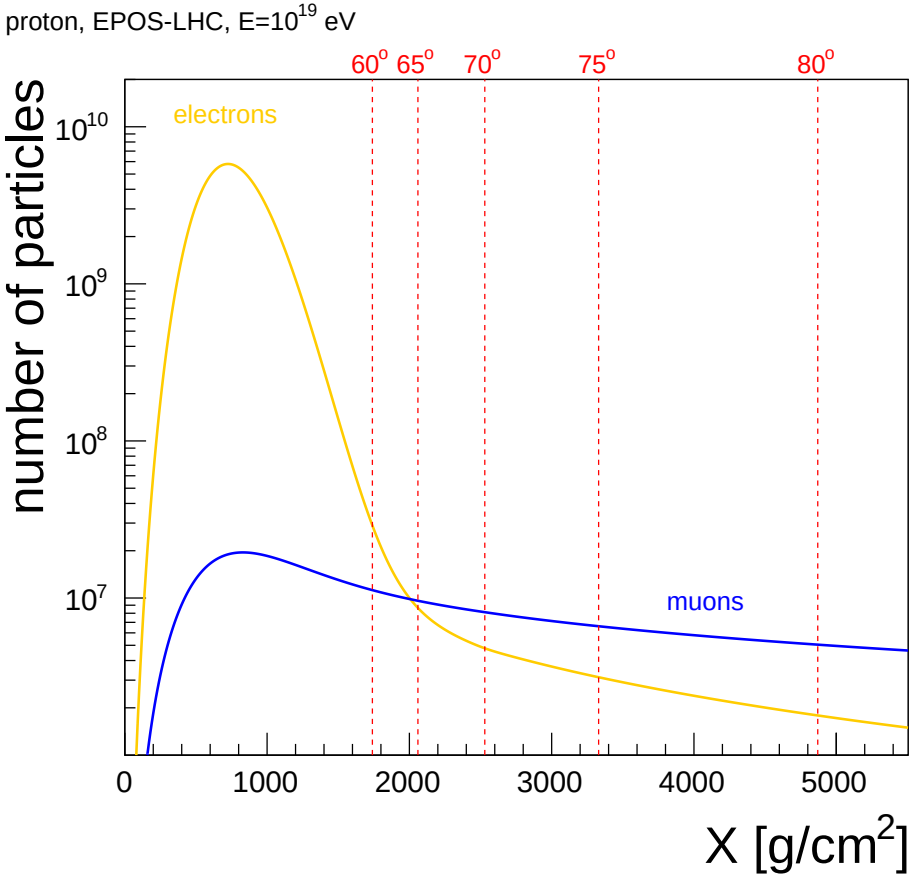


R. Ulrich, APS 2010

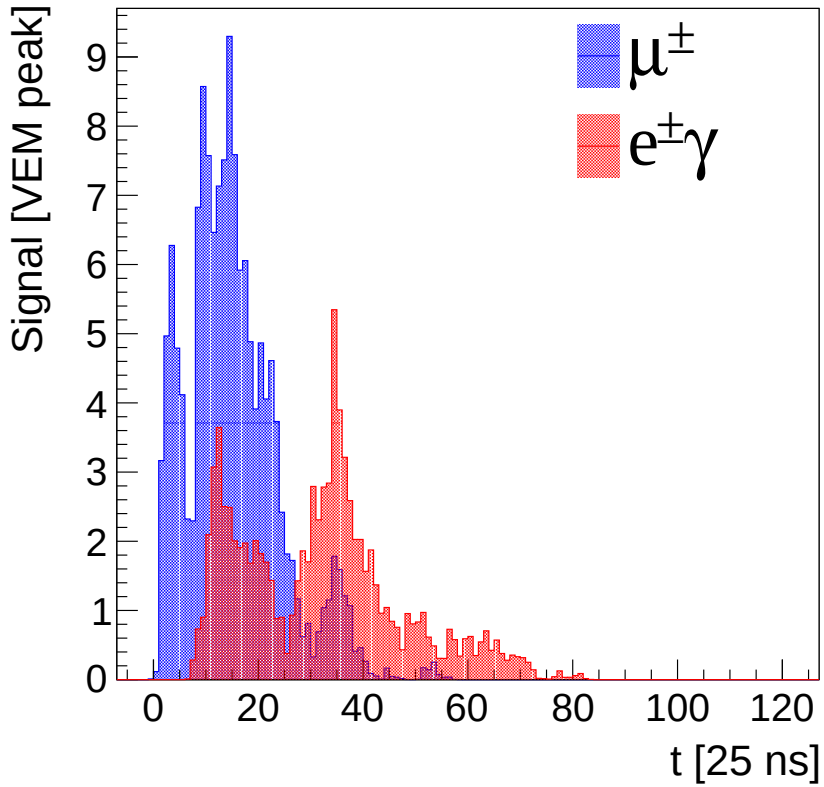
- muons are produced late in the shower cascade
  $\rightarrow$ number of generations $\sim$ 6 at 10^{19} eV
  $\rightarrow$ amplified sensitivity to hadronic interactions
- X_{max} is dominated by first interaction
- disentangle particle physics and composition using hybrid events?

Measuring muons with the Auger SD

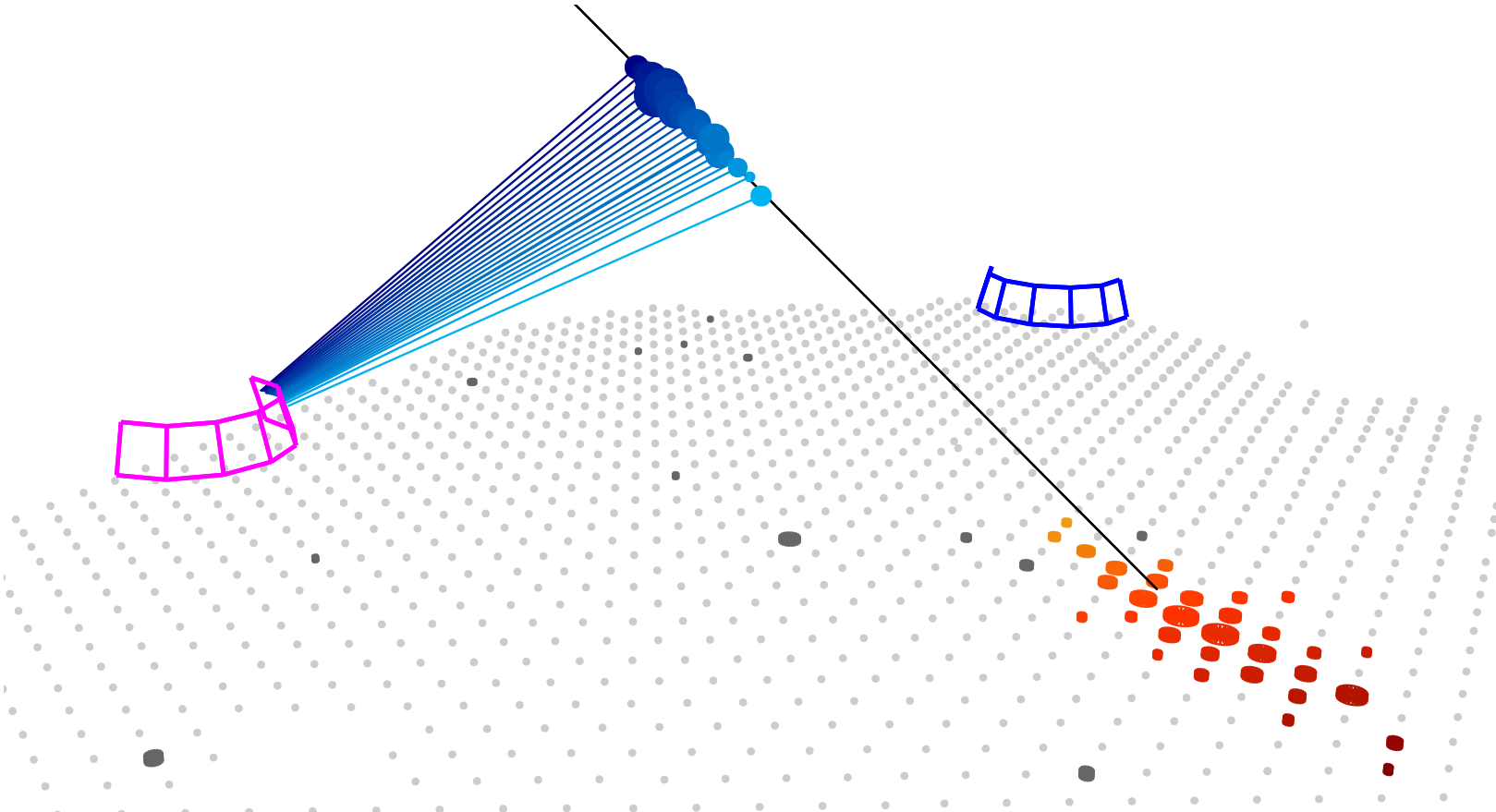
a) shielding of EM component:



b) time structure:



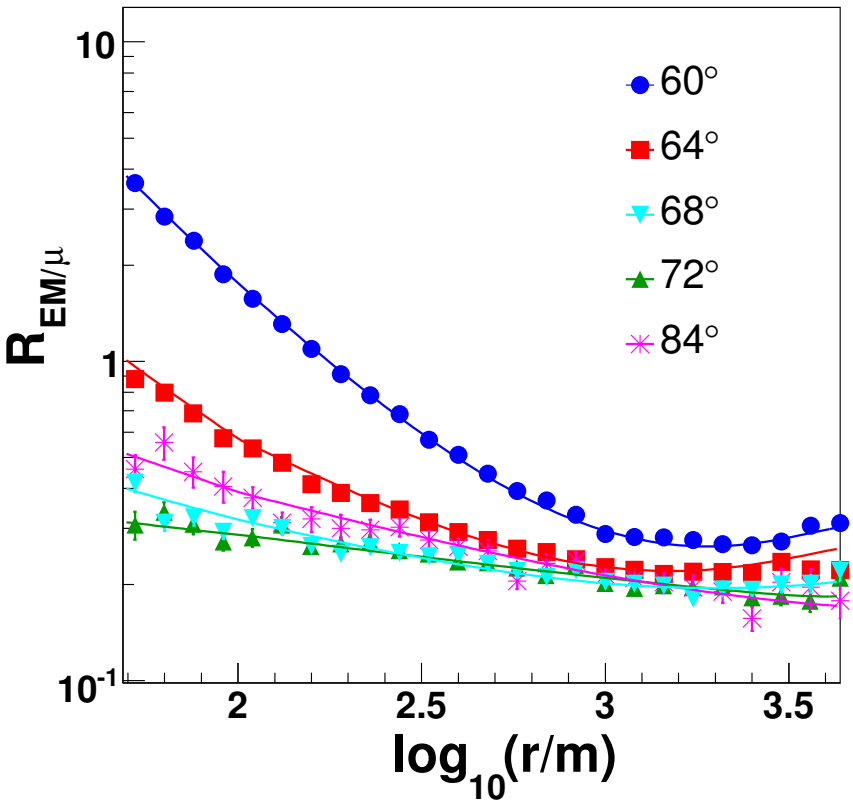
Muon studies with inclined hybrid events (62°-80°)



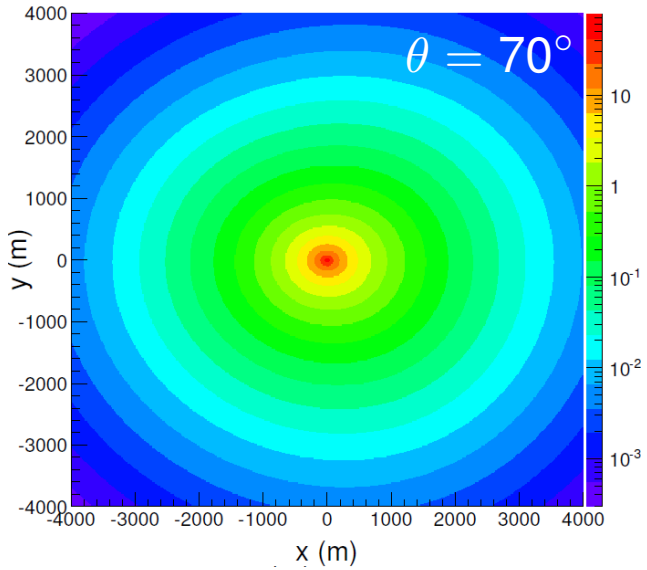
event 201114505353, $\theta = 75.6°$, $E = 15.5$ EeV

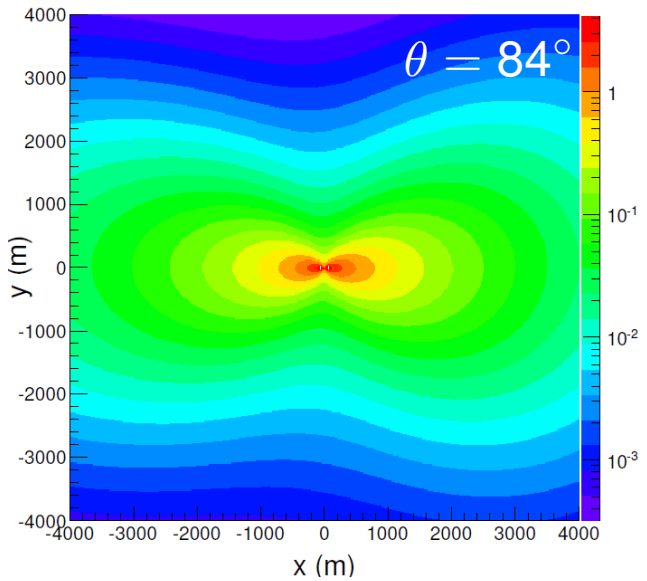
Reconstruction of inclined events (62°-80°)

contribution from $\gamma, e^{\pm}$:



muon density templates:





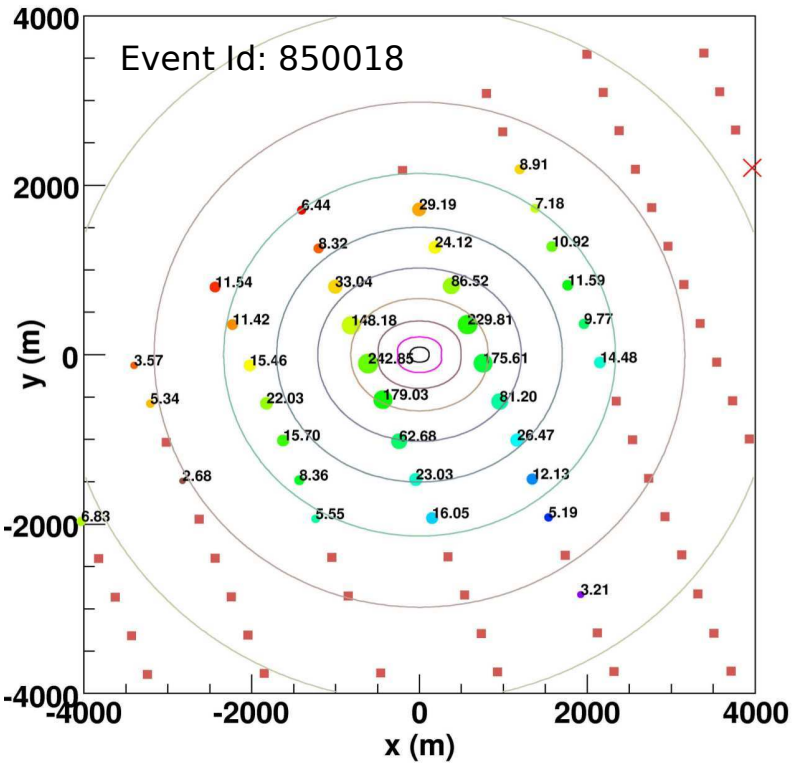
Pierre Auger Coll., JCAP **1408** (2014) 019

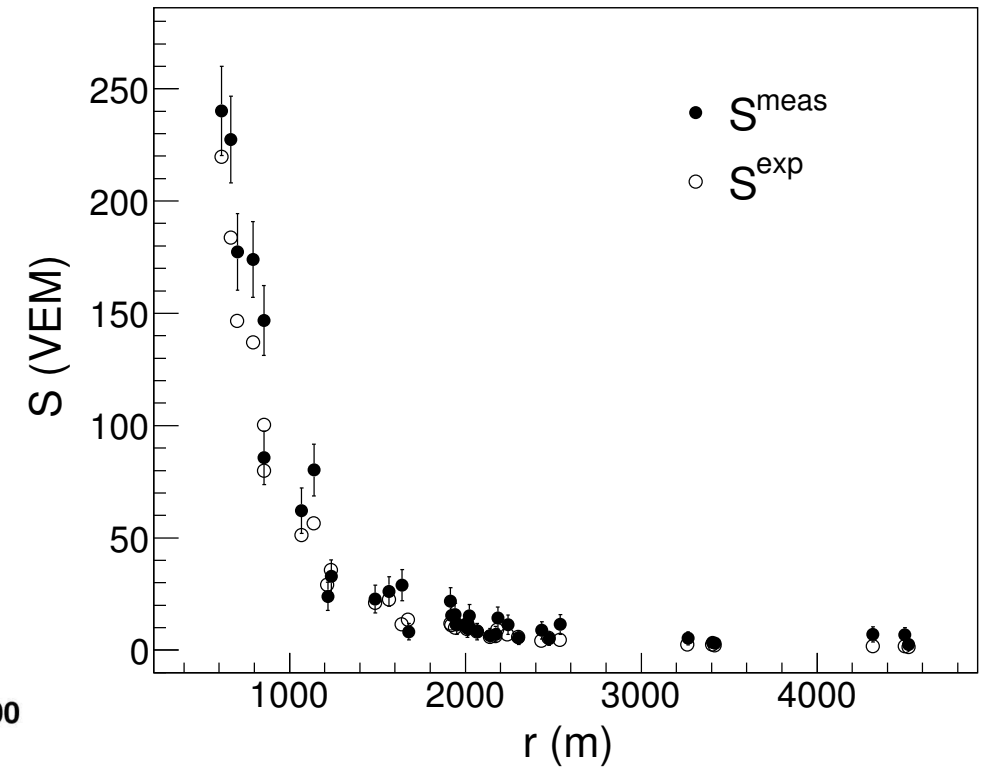
Reconstruction of inclined events (62°-80°)

Rescaling of density-template to match data:

$$\rho_\mu(\text{data}) = N_{19} \cdot \rho_\mu(\text{QGSJETII-03}, p, E = 10^{19}\ \text{eV}, \theta)$$

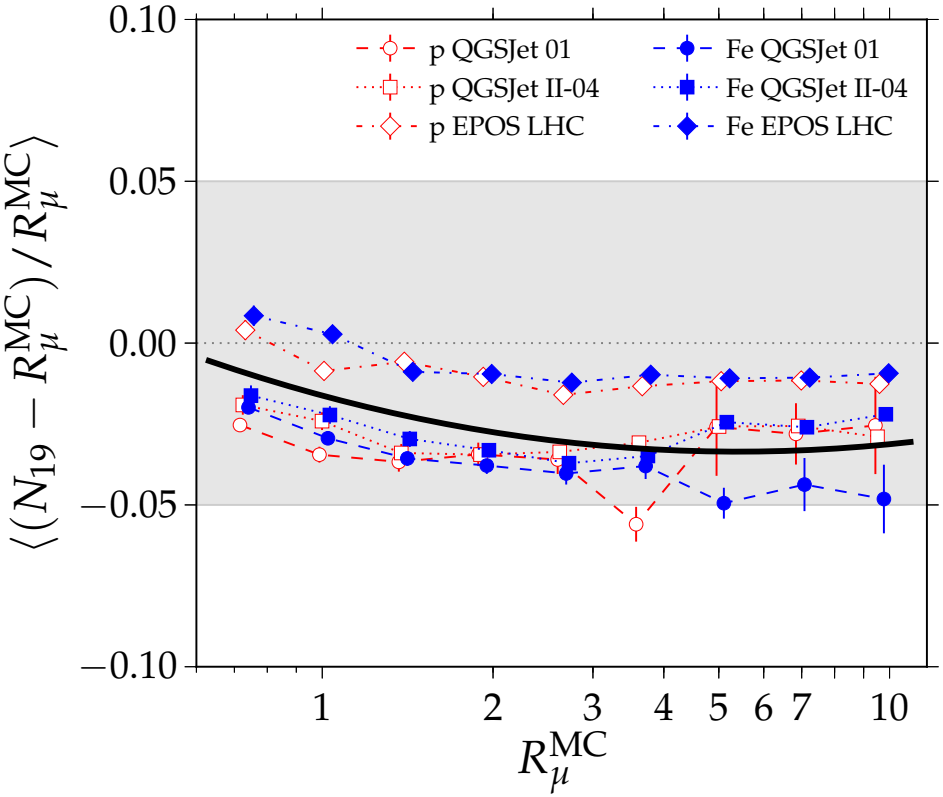
Example: $\theta = 71°$, $E = 54.6$ EeV, $N_{19} = 9.2$



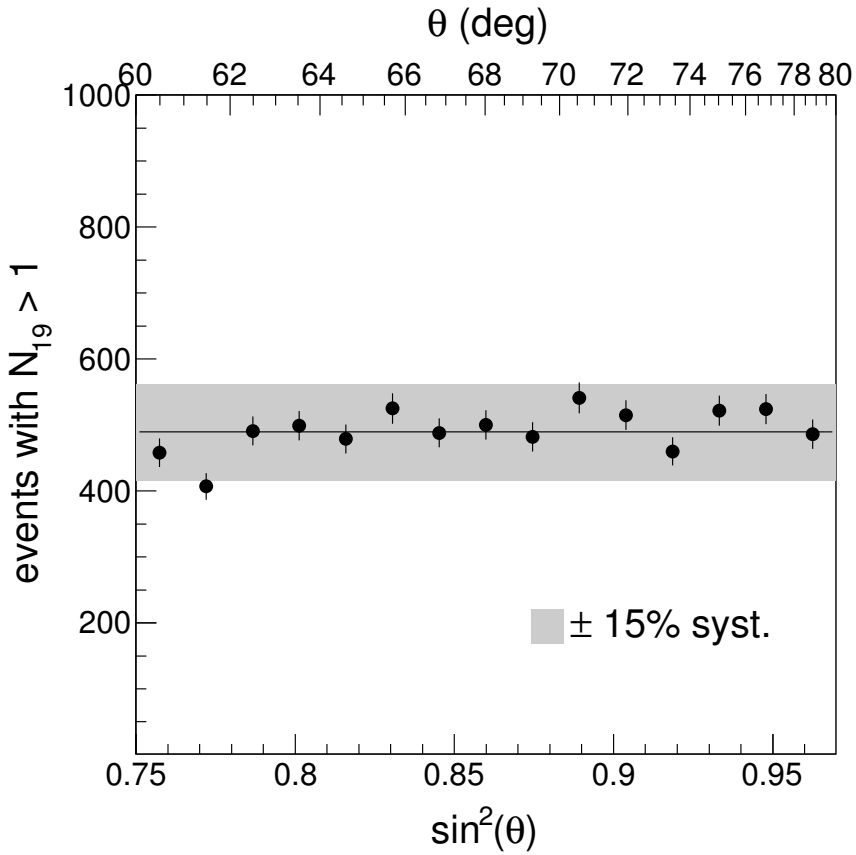


Cross-checks of reconstruction

reconstruction bias:

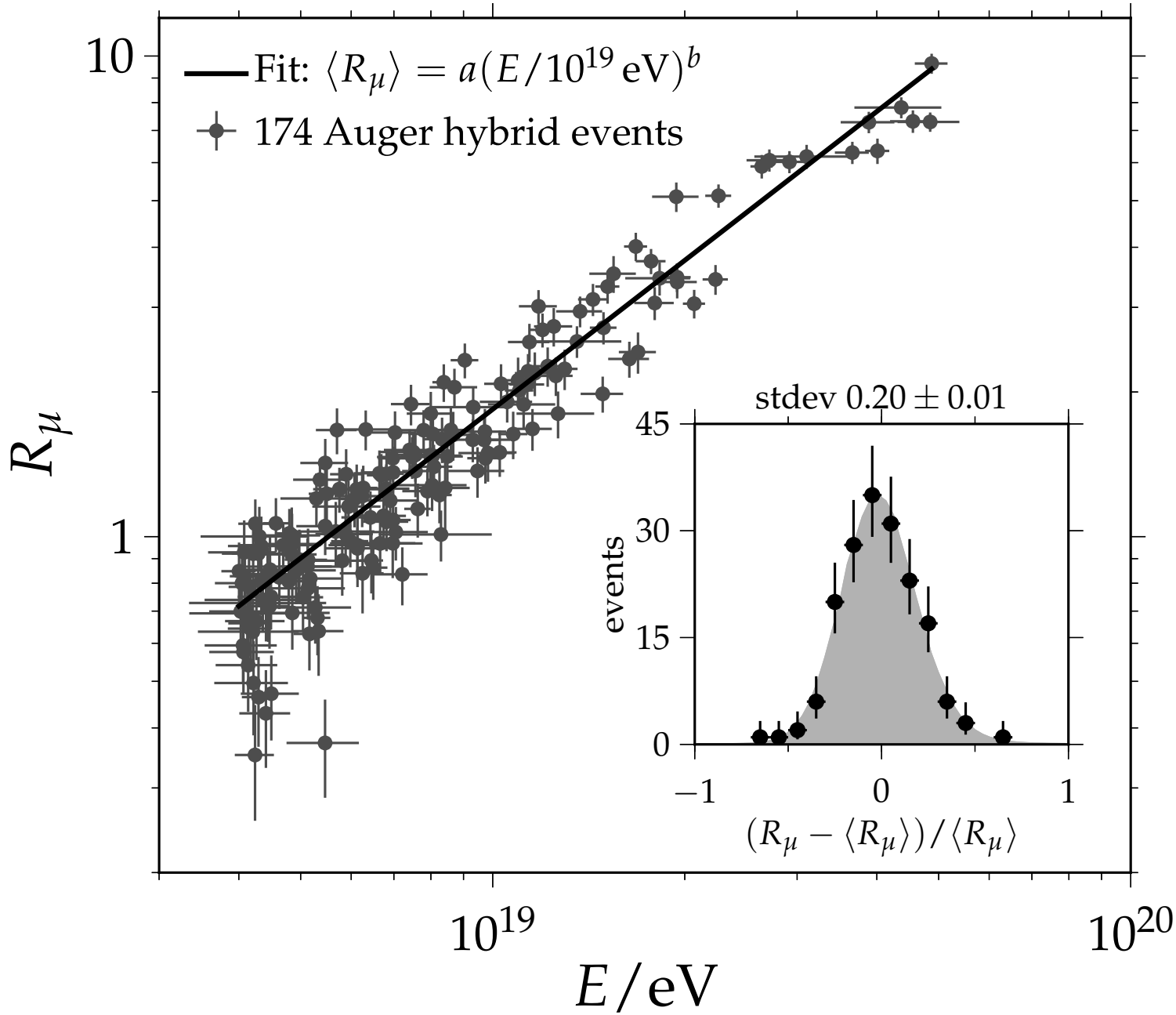


constant intensity?

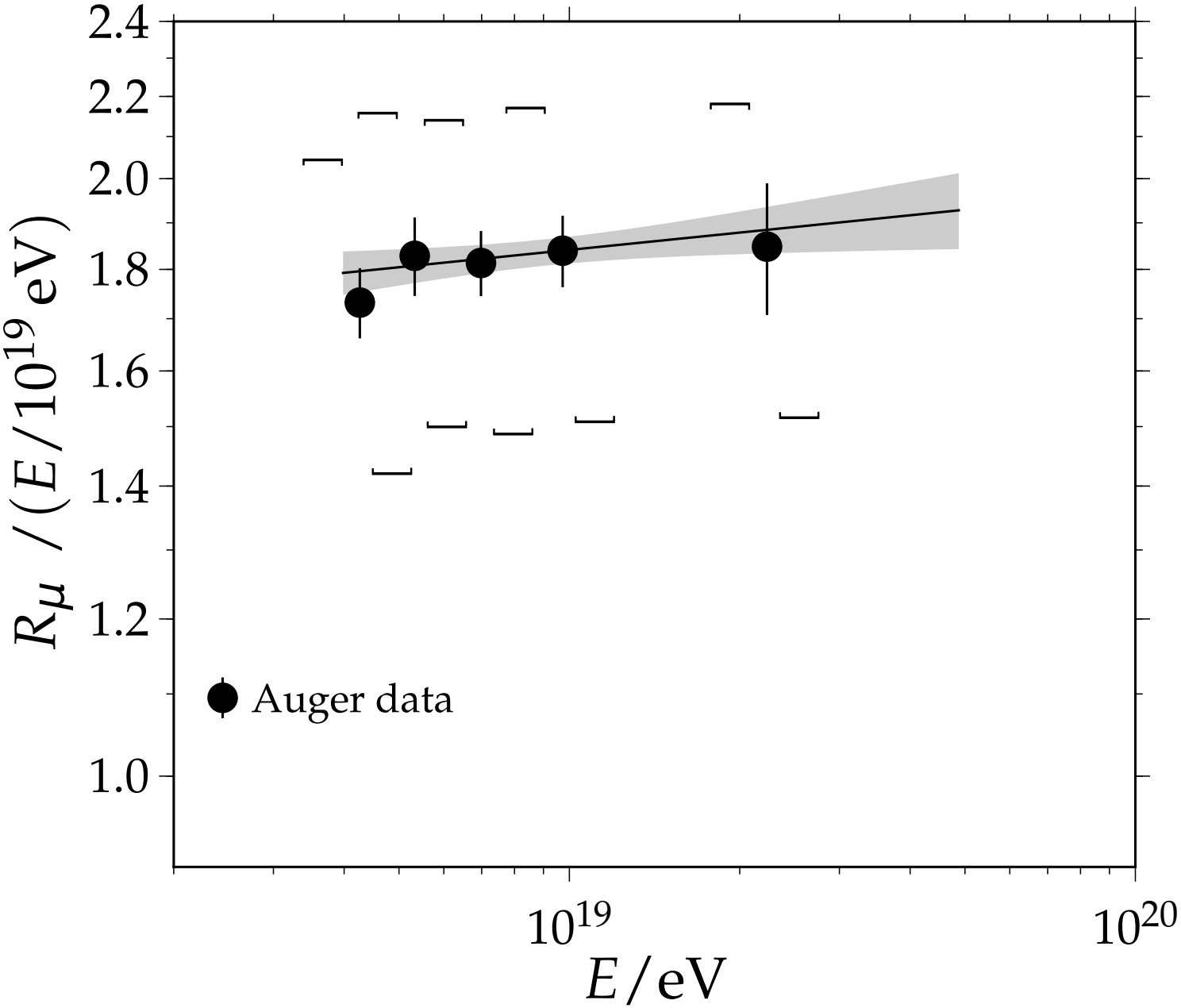


correct average bias: $N_{19} \rightarrow R_\mu$

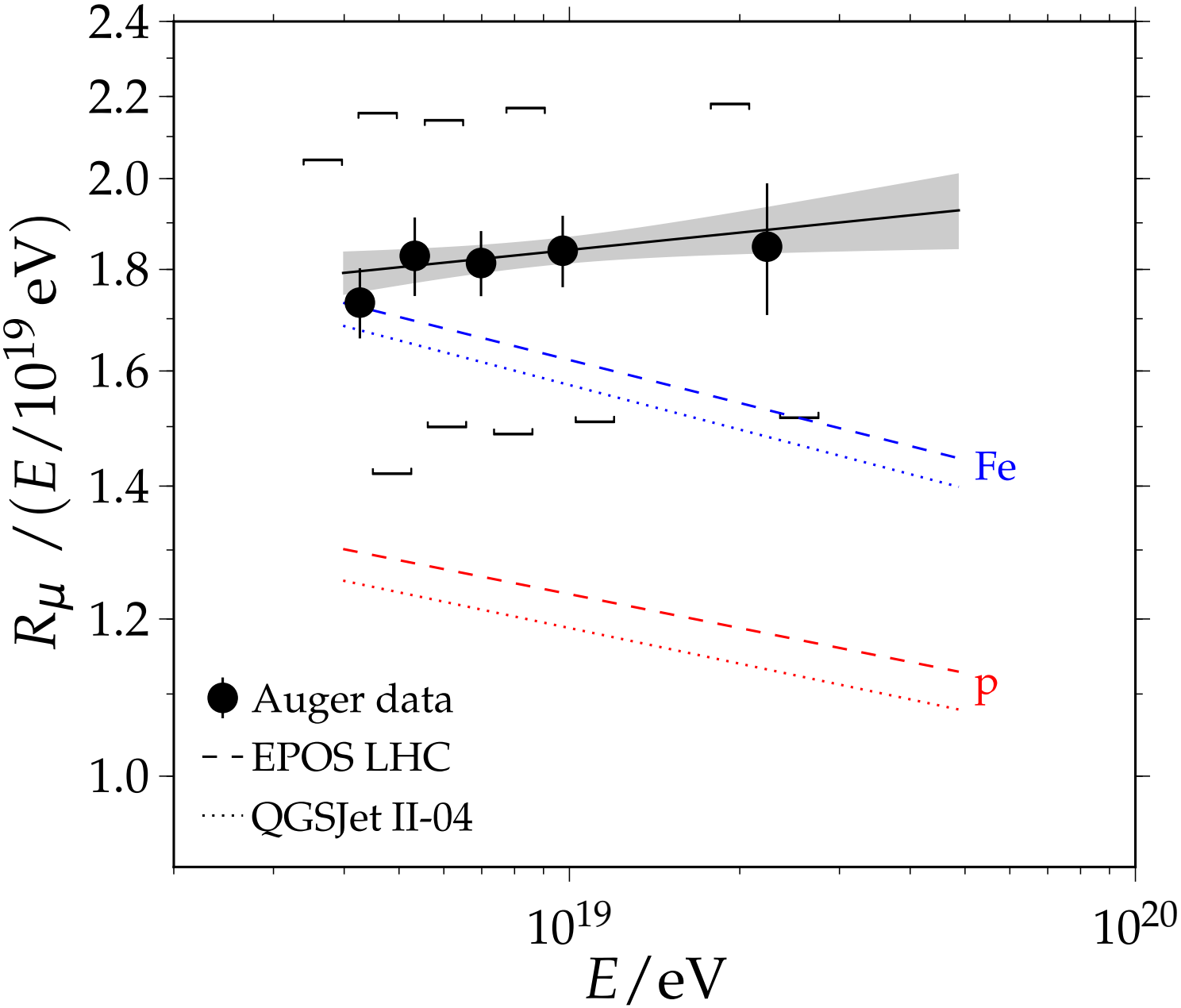
R_μ vs. E_{FD}



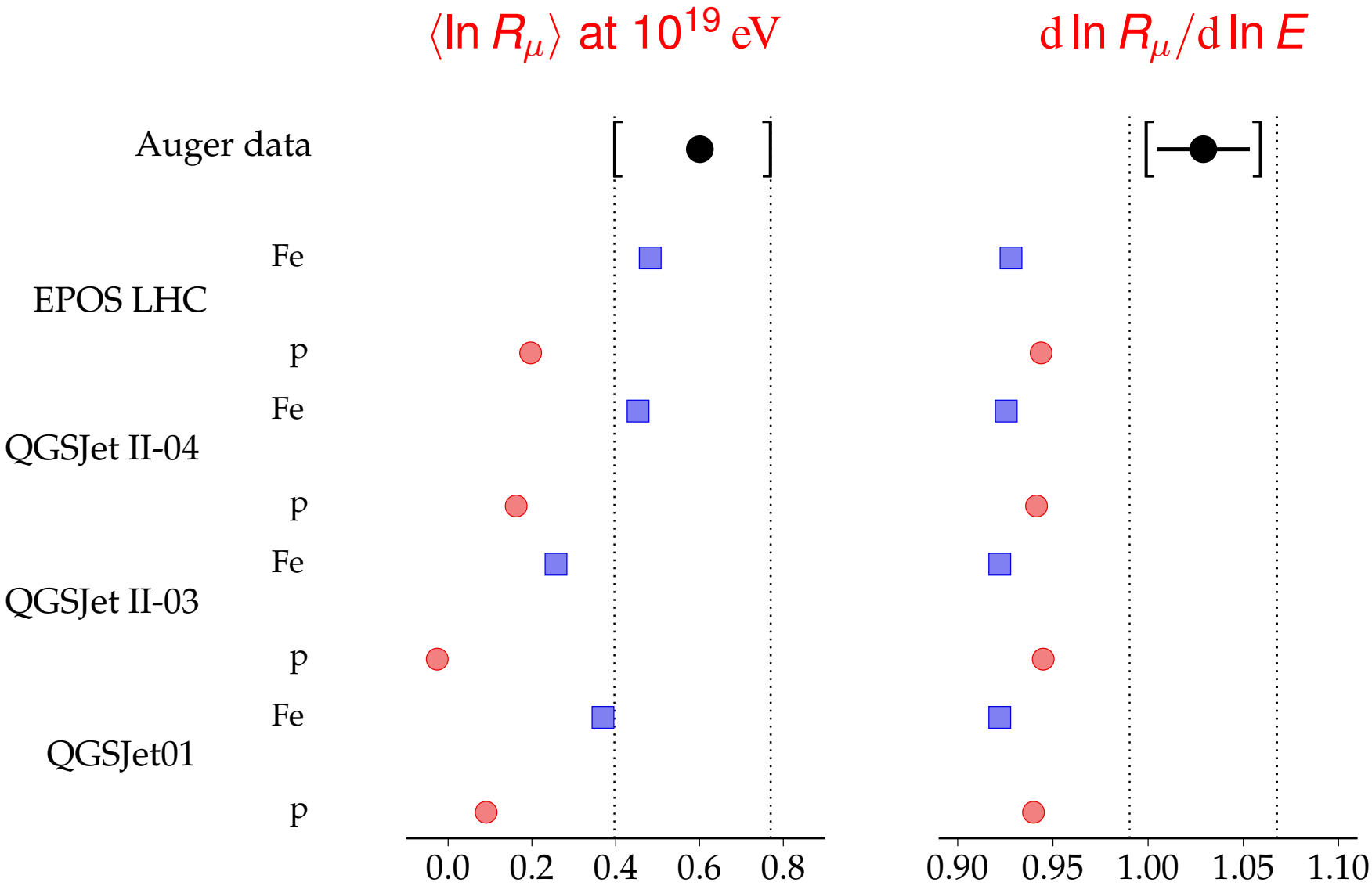
$\langle R_\mu \rangle / E_{\mathrm{FD}}$ vs. E_{FD}



$\langle R_\mu \rangle / E_{\mathrm{FD}}$ vs. E_{FD}

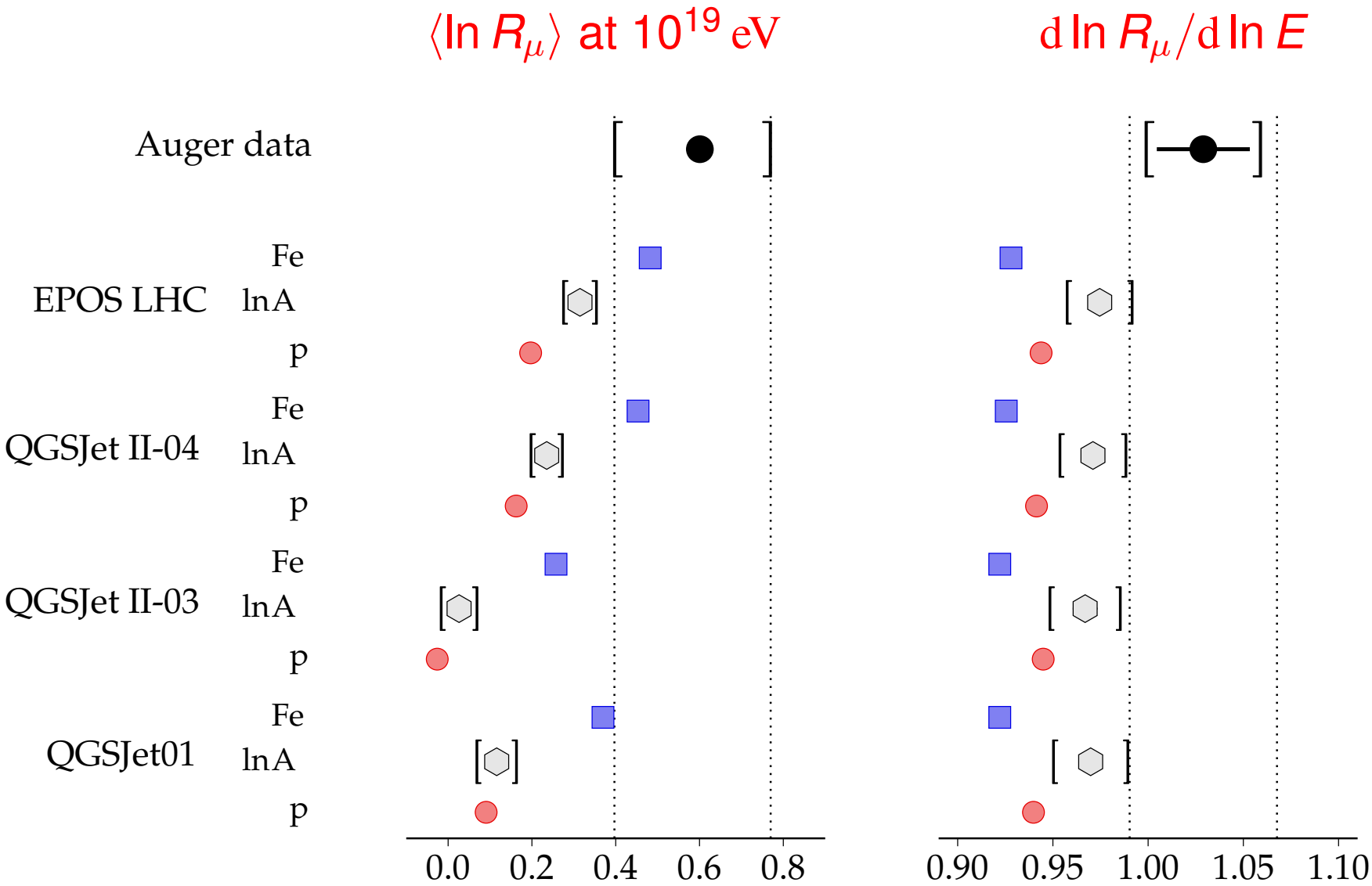


Muon “elongation rate” vs. p/Fe



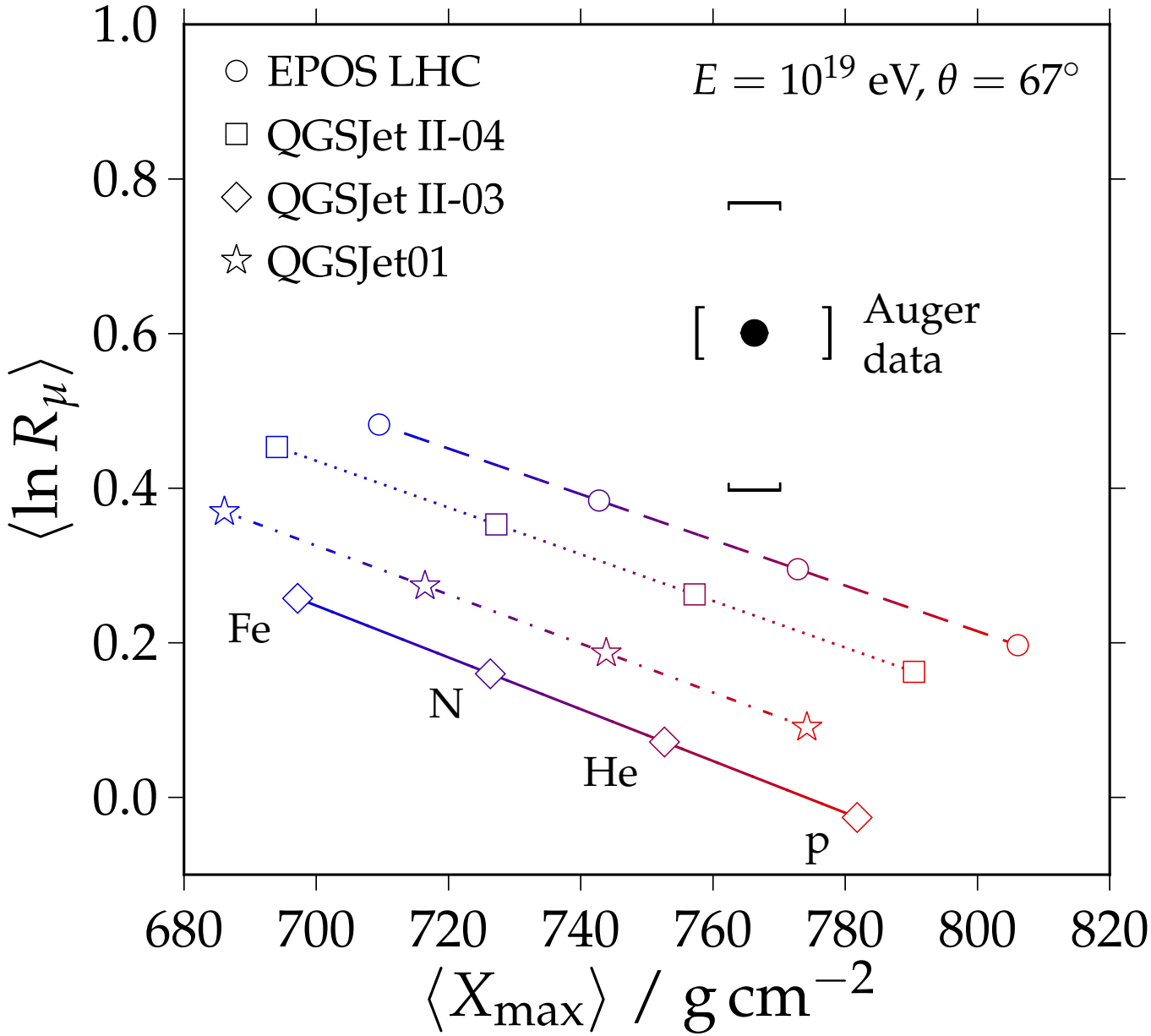
N.B.: $R_\mu = 1 \leftrightarrow N_\mu = 1.455 \times 10^7$

Muon "elongation rate" vs. p/Fe and ln$A$ (FD)

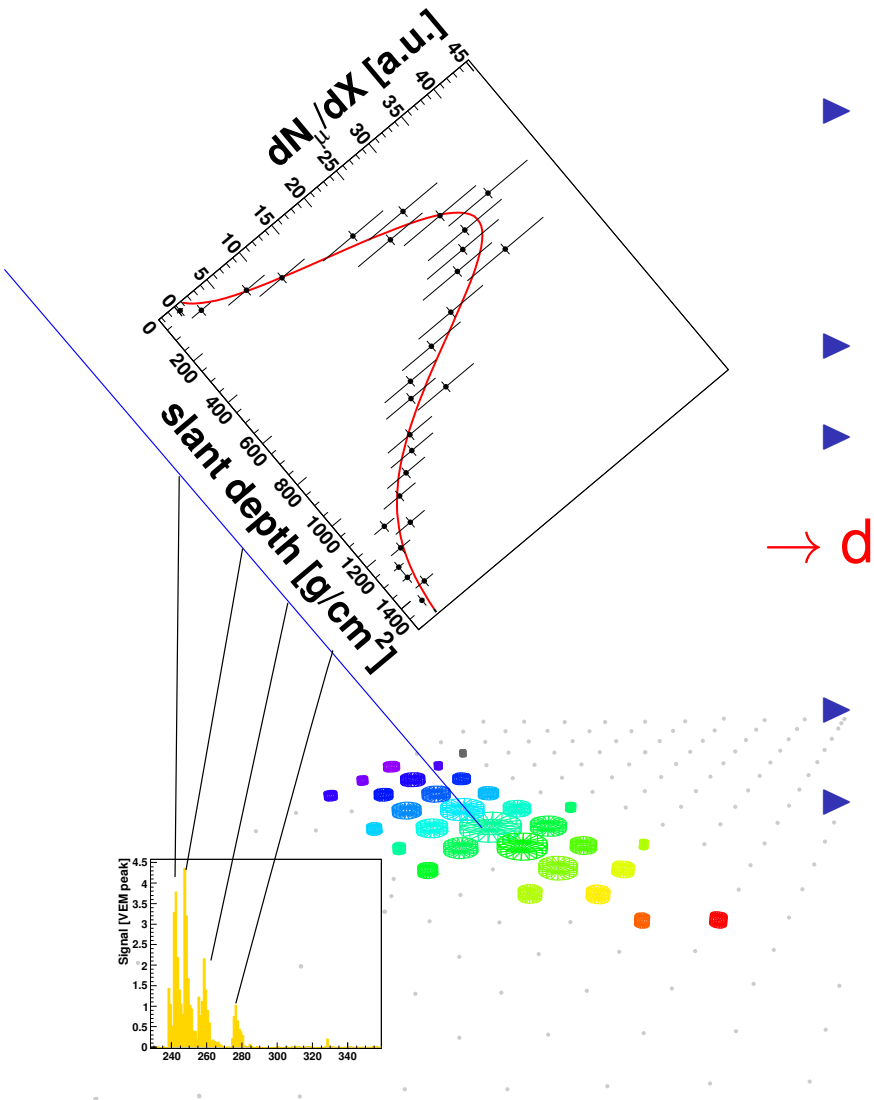


N.B.: $R_\mu = 1 \leftrightarrow N_\mu = 1.455 \times 10^7$

Muon scale vs. $X_{\max}$ (FD)



Muon production depth: Reconstruction



- muon-rich stations:
  - events with zenith angle 55-65 deg.
  - stations with core distance $>$1.7 km
- projection of signal time traces to axis
- sum up stations

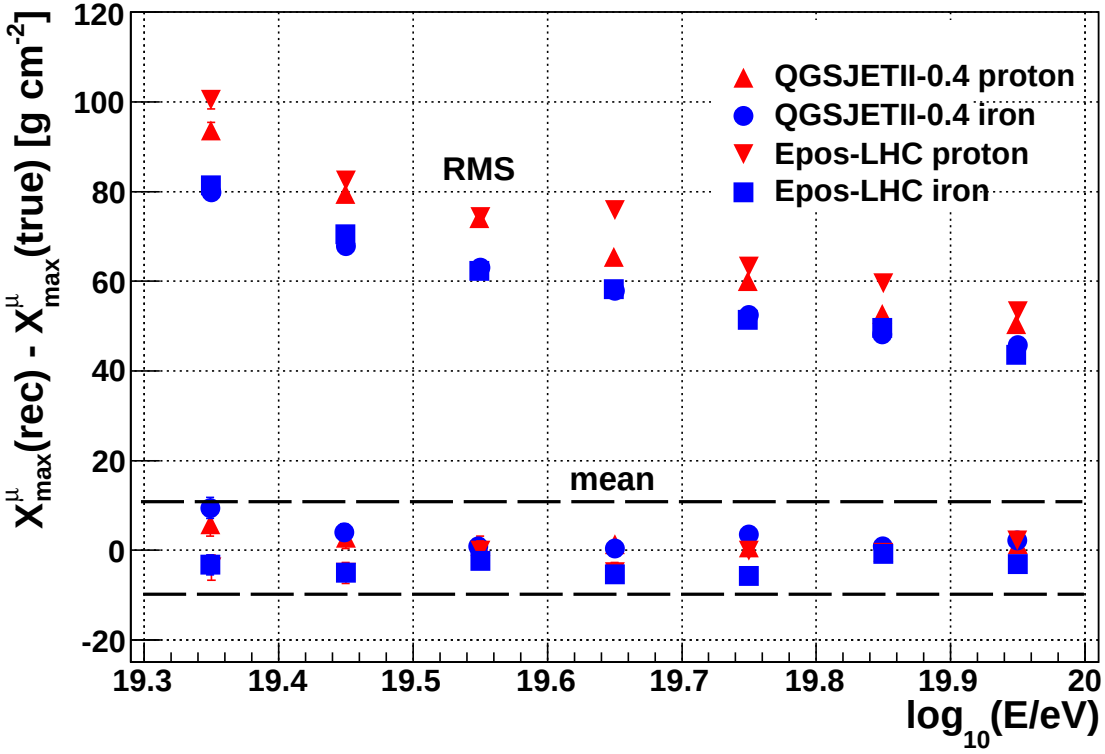
$\rightarrow$ distribution of muon production heights

- distance to slant depth conversion
- fit with Gaisser-Hillas

  $\rightarrow$ maximum at X^{μ}_{max}

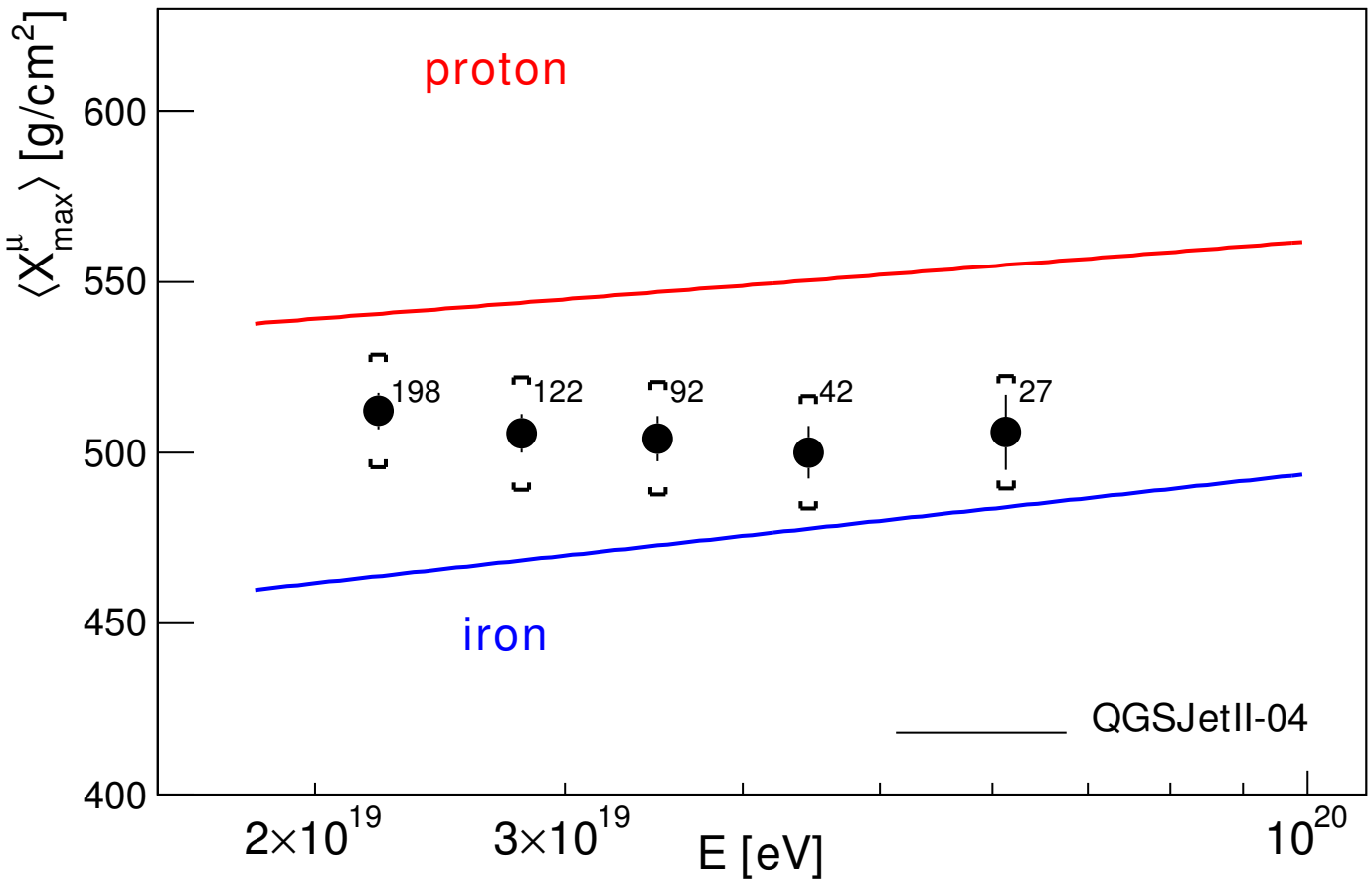
L. Cazon et al., APP21 (2004), 71

Muon production depth: Performance



Source	Sys. uncertainty [$\mathrm{g/cm^2}$]
Reconstruction, hadronic model and primary	10
Seasonal effect	12
Time variance model	5
Total	**17**

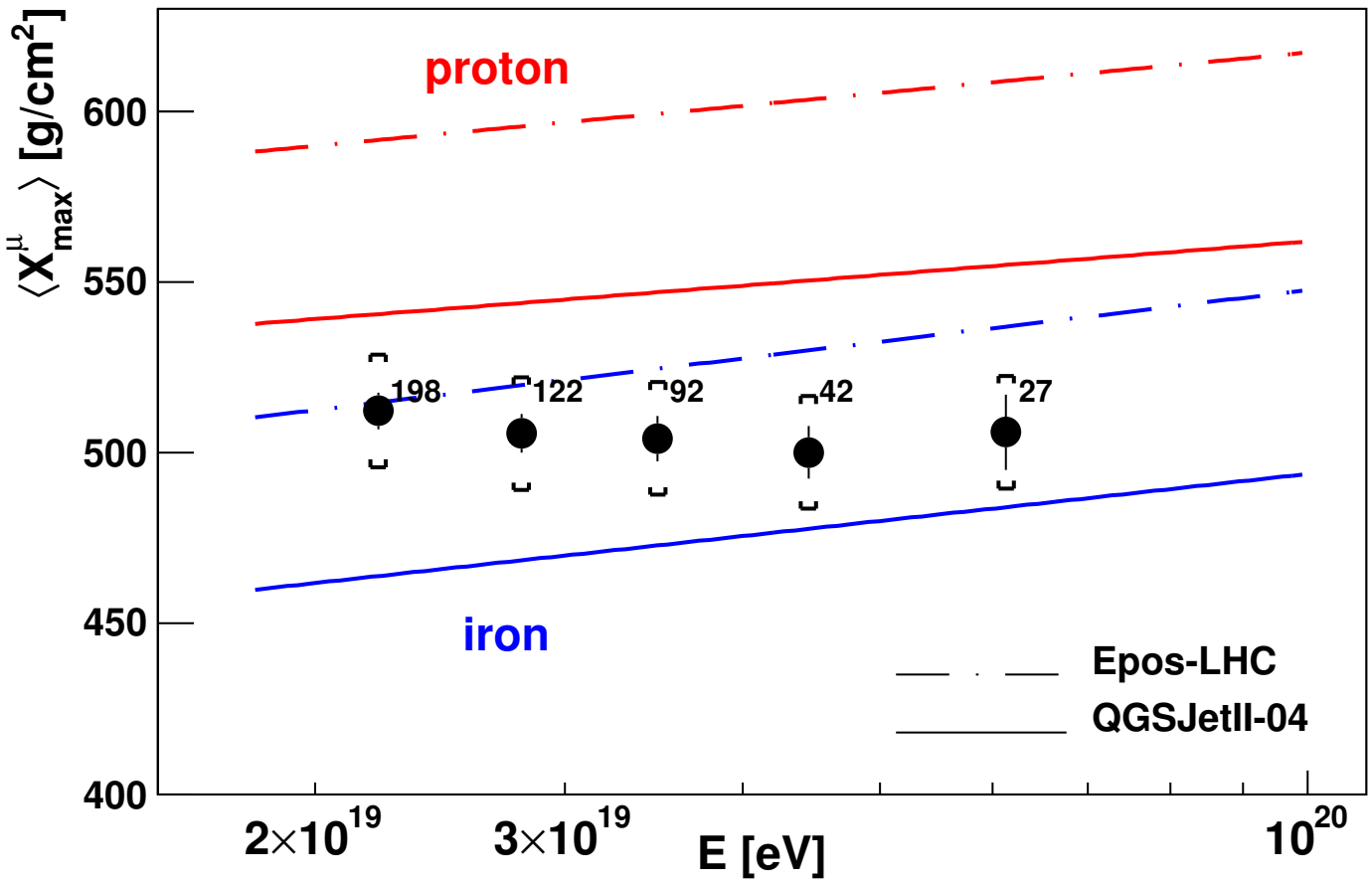
$X^{\mu}_{\max}$ vs. energy



$$\mathrm{d}\langle X^{\mu}_{\max}\rangle/\mathrm{d}\lg E = -25 \pm 22\,(\mathrm{stat.}) \pm 21\,(\mathrm{syst.})\,\mathrm{g/cm^2/decade}$$

proton: 35.9 ± 1.2, iron: $48.0 \pm 1.2\,\mathrm{g/cm^2/decade}$

$X^{\mu}_{\max}$ vs. energy



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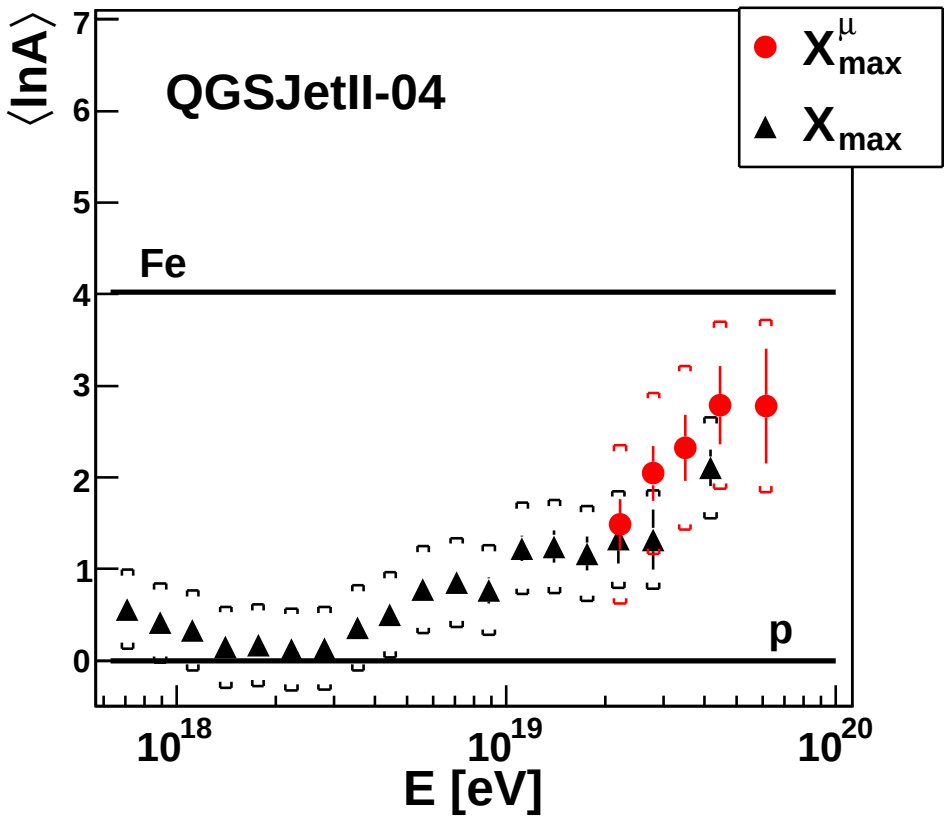
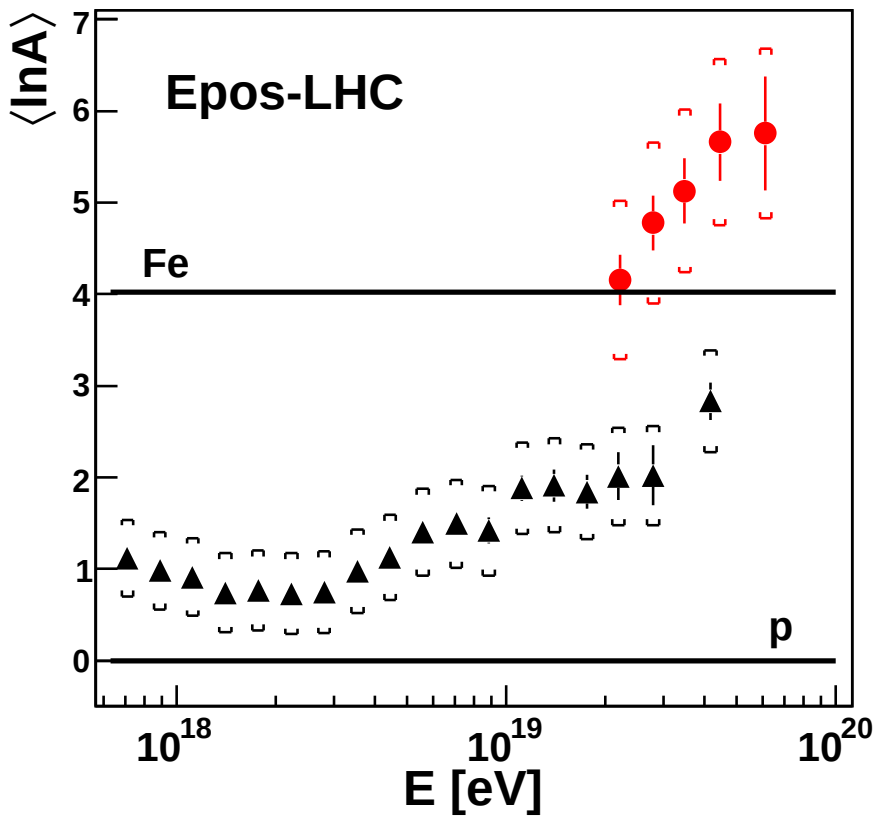
proton: 35.9 ± 1.2, iron: $48.0 \pm 1.2\,\mathrm{g/cm^2/decade}$

Comparison of ln$A$ from $X^{\mu}_{\max}$ and $X_{\max}$

ln$A$ (FD) from JCAP 1302 (2013) 026

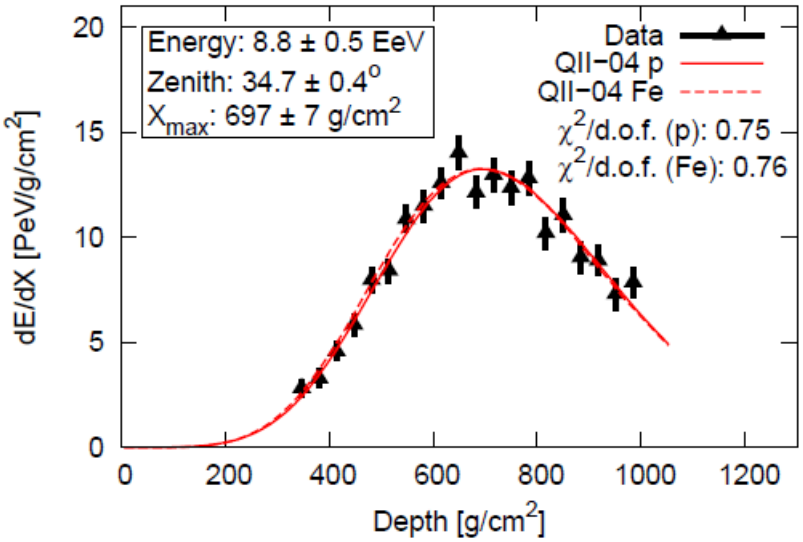


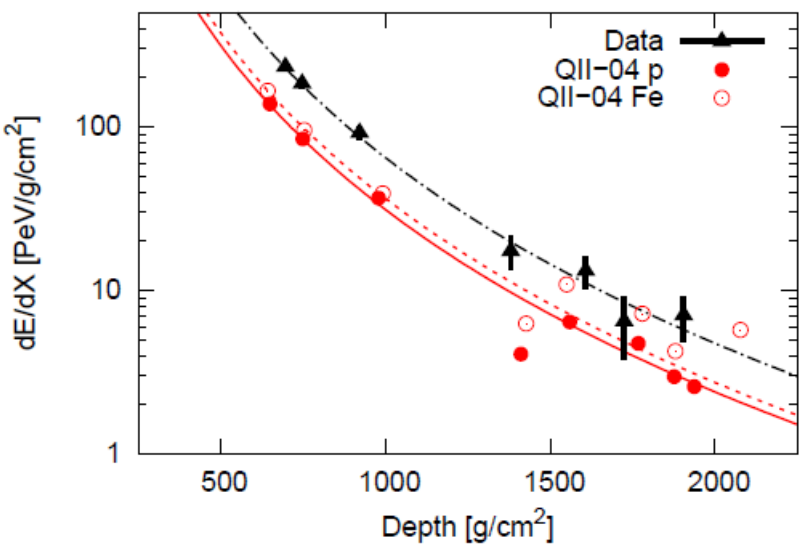


Retune of EPOS-LHC possible within uncertainty of π + air interactions (not measured at LHC!) (see talk by R.Engel)

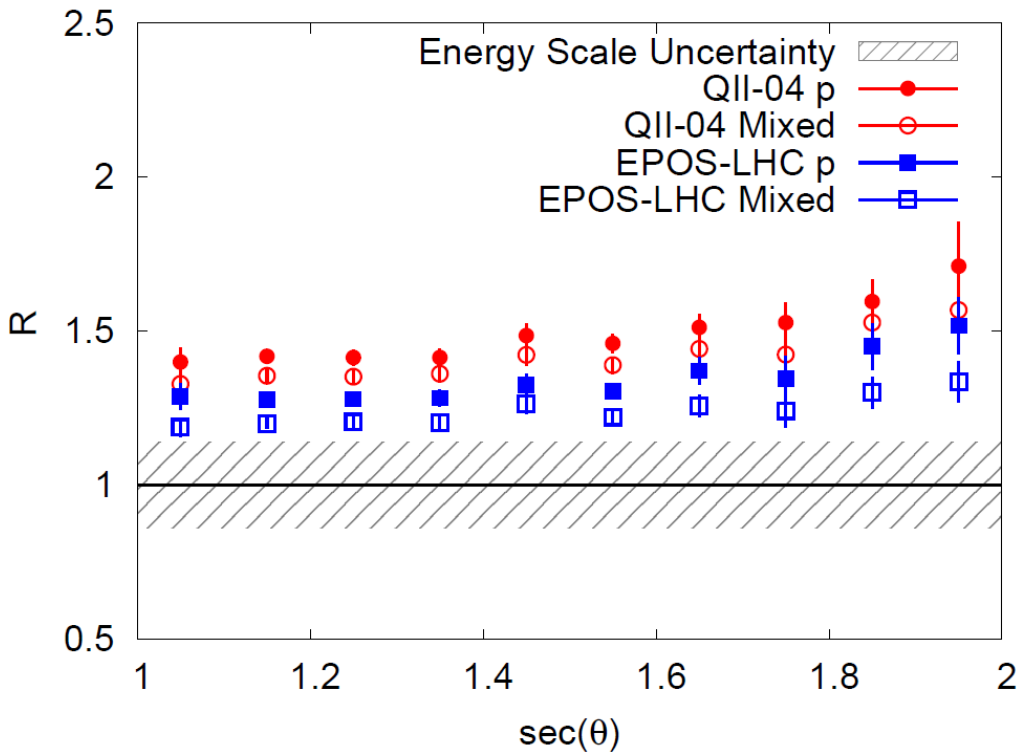
Hybrid events, data vs. simulation

example:



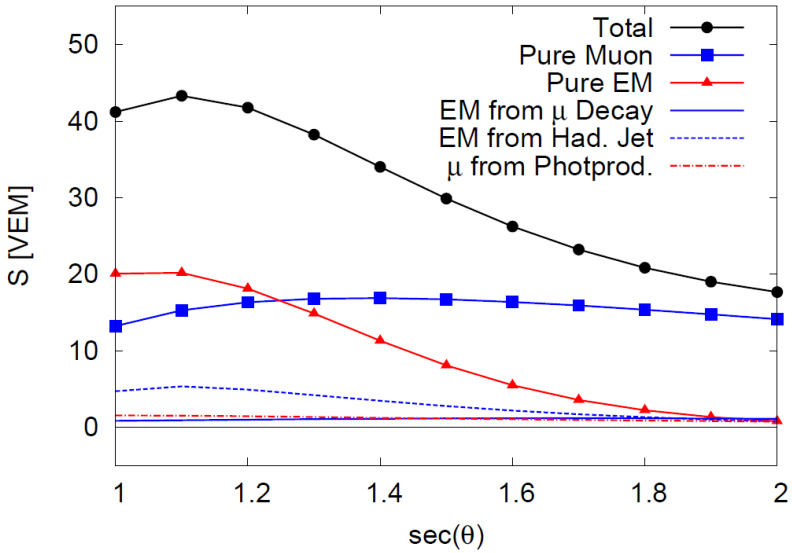


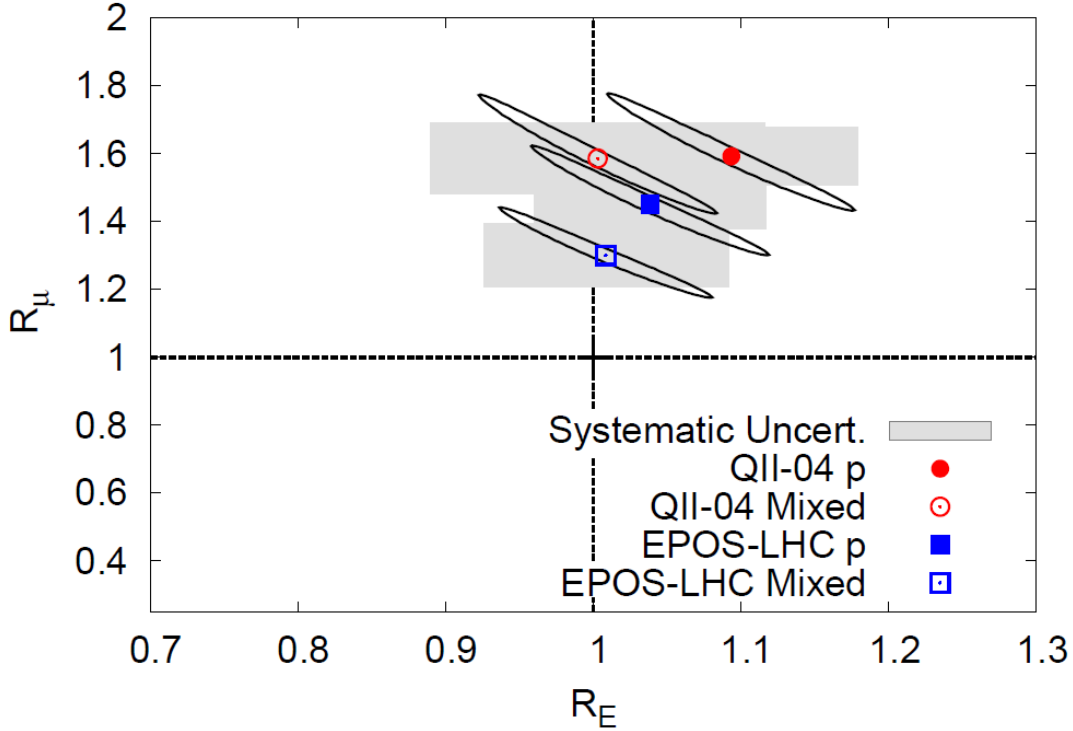
ratio of $S(1000)$ data/MC:



Hybrid events, data vs. simulation, prelim. results

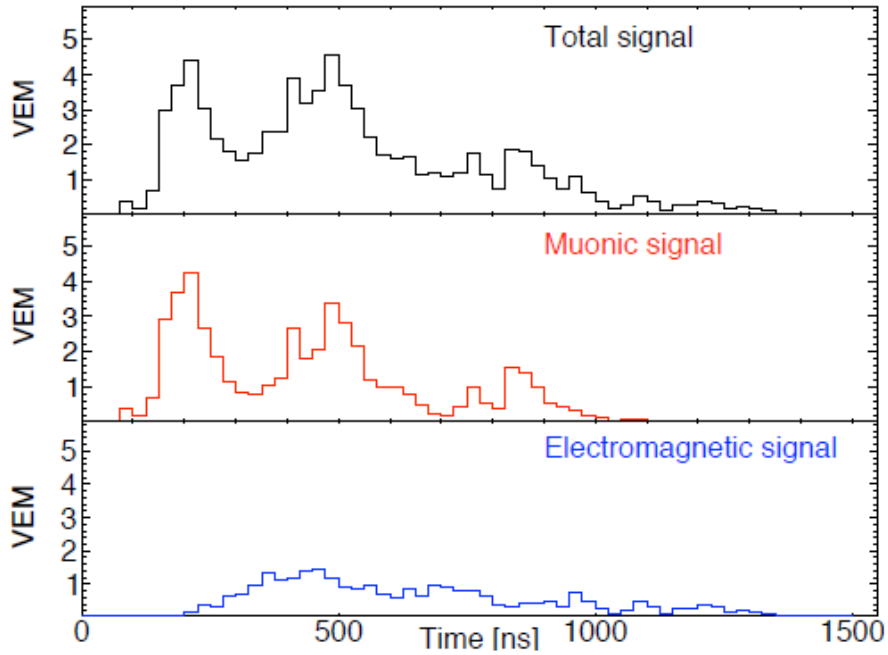
Combined fit of energy scale R_E and muon rescaling R_μ





model	R_E	R_μ
QGSJETII-04, p	$1.09 \pm 0.08 \pm 0.09$	$1.59 \pm 0.17 \pm 0.09$
QGSJETII-04, mixed	$1.00 \pm 0.08 \pm 0.11$	$1.59 \pm 0.18 \pm 0.11$
EPOS-LHC, p	$1.04 \pm 0.08 \pm 0.08$	$1.45 \pm 0.16 \pm 0.08$
EPOS-LHC, mixed	$1.01 \pm 0.07 \pm 0.08$	$1.30 \pm 0.13 \pm 0.09$

Analysis of SD time traces

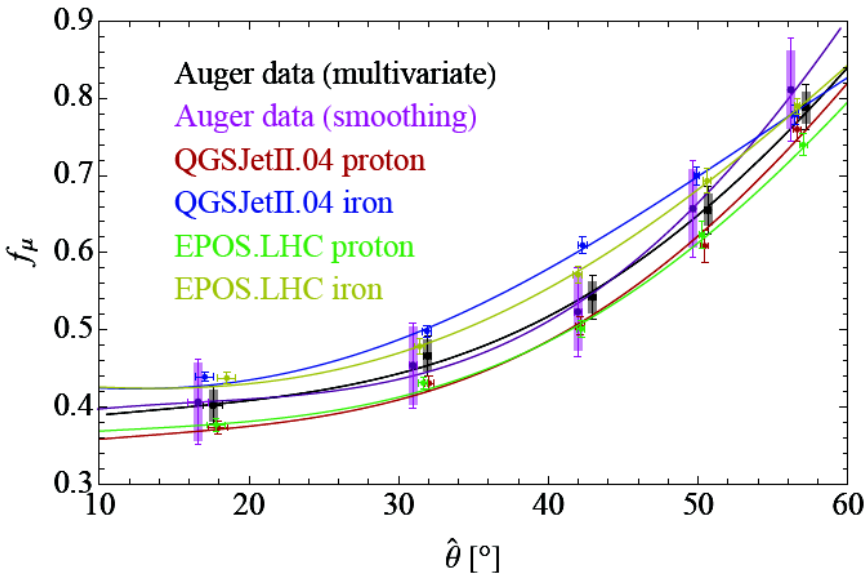


use different features to estimate muon fraction

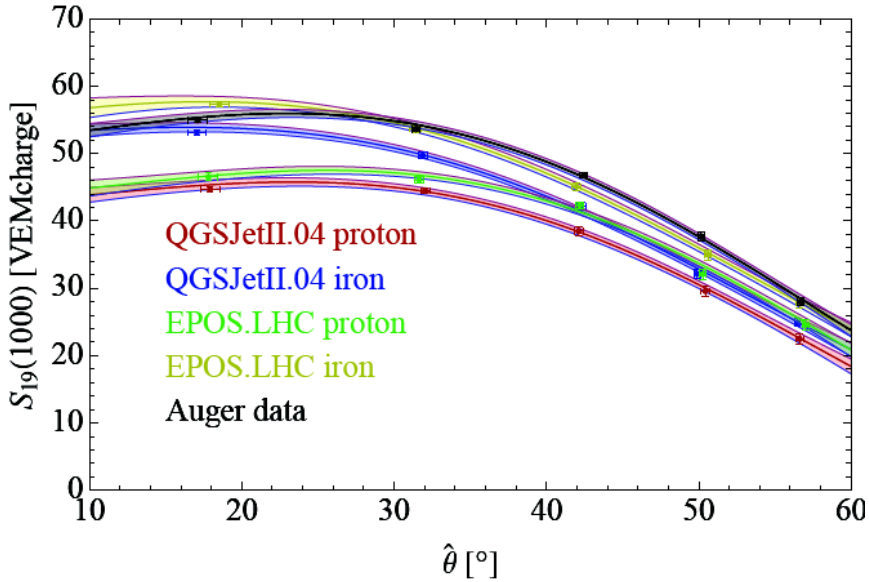
	μ	$e^{\pm}$, γ
arrival:	early	late
signal:	large	small
structure:	peaky	smooth

- smoothing method (low-pass filter)
- multivariate method ('spike fraction', moment ratio)

Analysis of SD time traces, preliminary results



X



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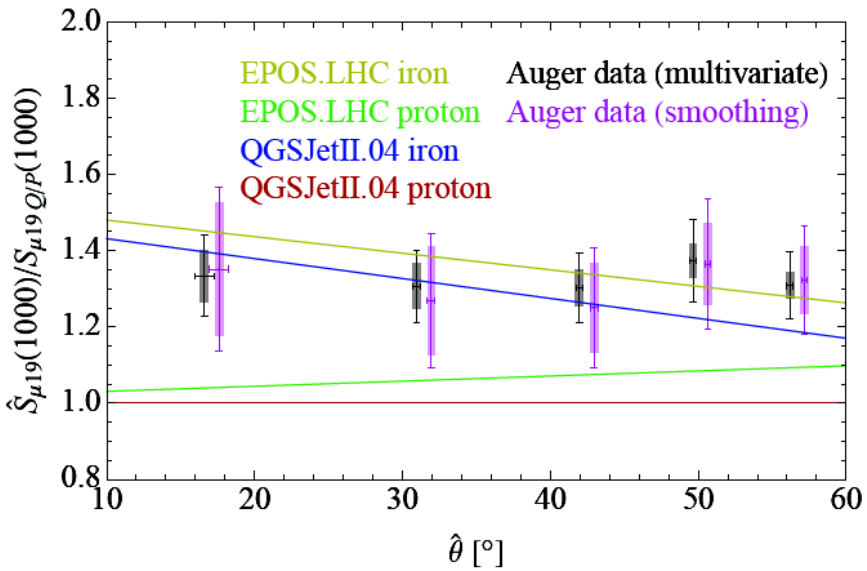

Summary

- measurements of muons in air shower with the Auger surface detector
- use $X_{\max}$ measurement for tests of hadronic interactions beyond "observable between proton and iron?"
- each of the finalized studies is individually in marginal agreement with some model
- the ensemble of results in greater tension with current models because no model is in marginal agreement with *all* studies

	EPOS-LHC	QGSJETII-04
$\langle \ln R_\mu \rangle$ vs. $\langle X_{\max} \rangle$	-1.4 σ	-1.8 σ
elongation rate ($\ln R_\mu$ vs. $\langle X_{\max} \rangle$)	-1.3 σ	-1.4 σ
$X^{\mu}_{\max}$ vs. $\langle X_{\max} \rangle$	incompatible	compatible
$\langle X_{\max} \rangle$ vs. $\sigma(X_{\max})^{\dagger}$	ok	2 σ

(note: σ dominated by systematics)

- analyses in progress will provide additional discriminating power
- improved muon measurements with upgraded detector!

† see talk by V. de Souza