UHECR 2014
Springdale - Utah

PIERRE AUGER OBSERVATORY

Measurement of the depth of maximum of air-shower profiles and its composition implications

The Pierre Auger Collaboration

Av. San Martin Norte 304, 5613 Malargüe, Argentina

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

Presenter: Vitor de Souza (University of Sao Paulo-Brazil)

background

Depth of Maximum of Air-Shower Profiles at the Pierre Auger Observatory: Measurements at Energies above $10^{17.8}$ eV

arXiv:1409.4809

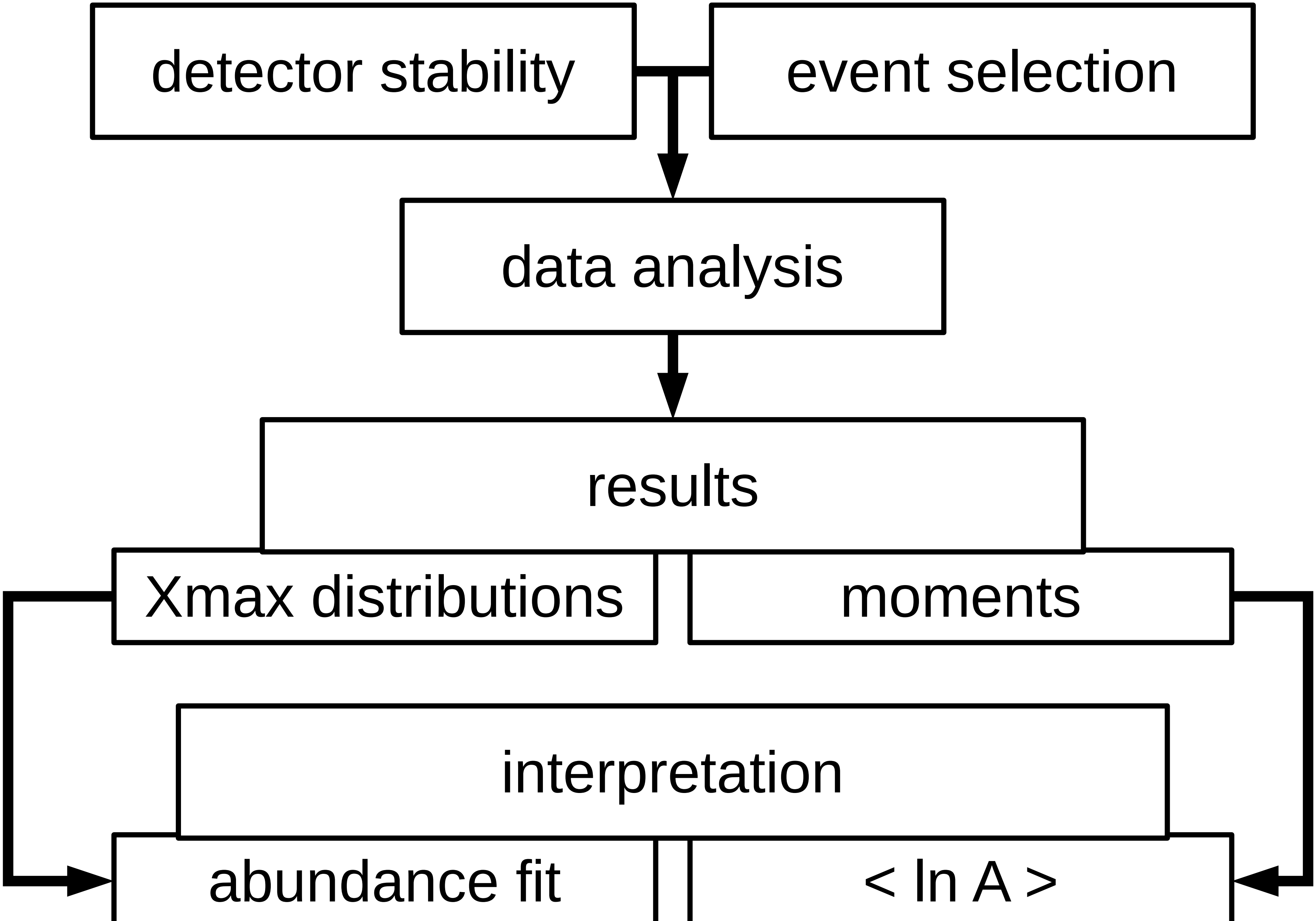
submitted to Physical Review D

Depth of Maximum of Air-Shower Profiles at the Pierre Auger Observatory: Composition Implications

arXiv:1409.5083

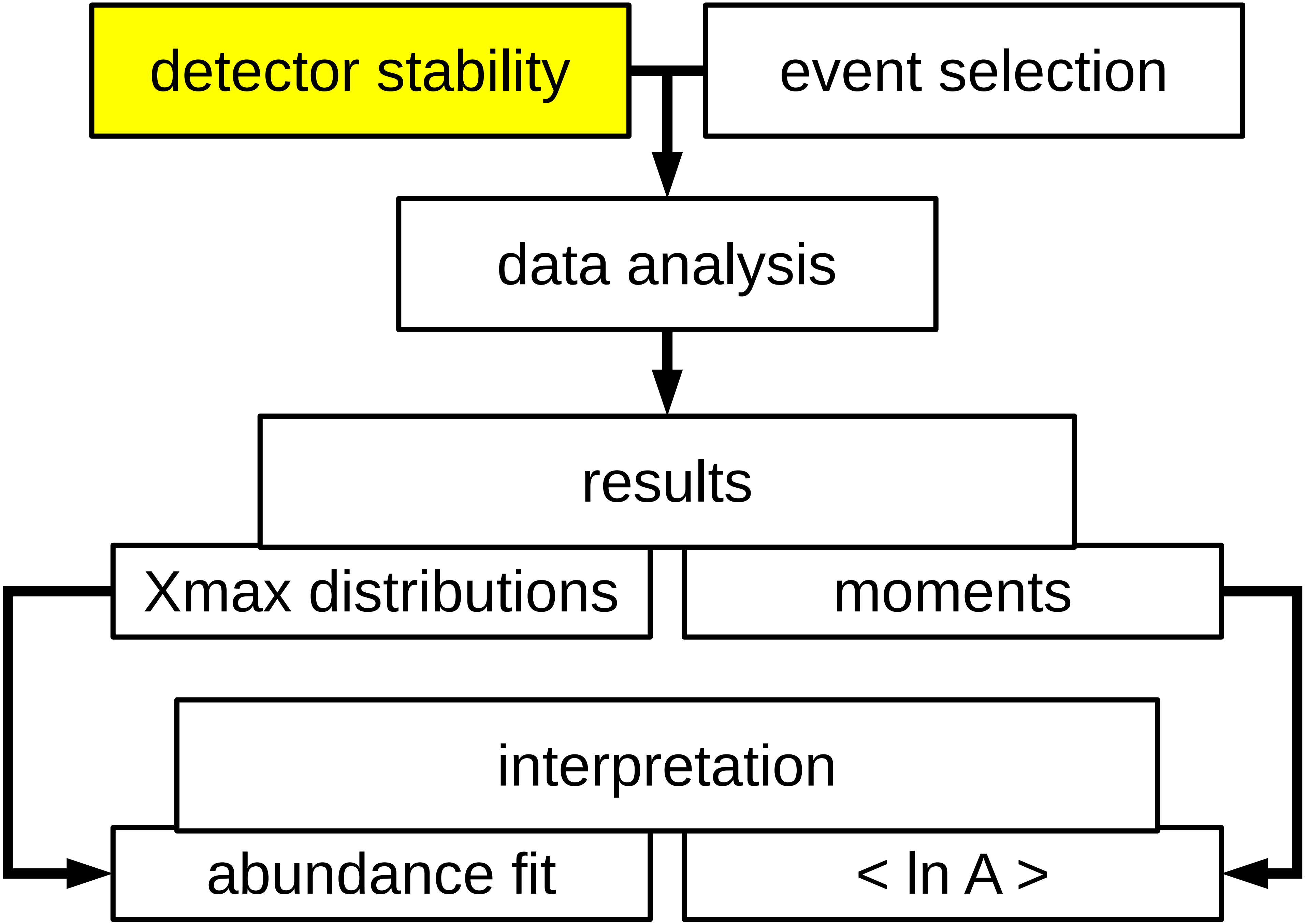
accepted by Physical Review D

outline



detector stability
event selection
data analysis
results
Xmax distributions
moments
interpretation
abundance fit
< ln A >

outline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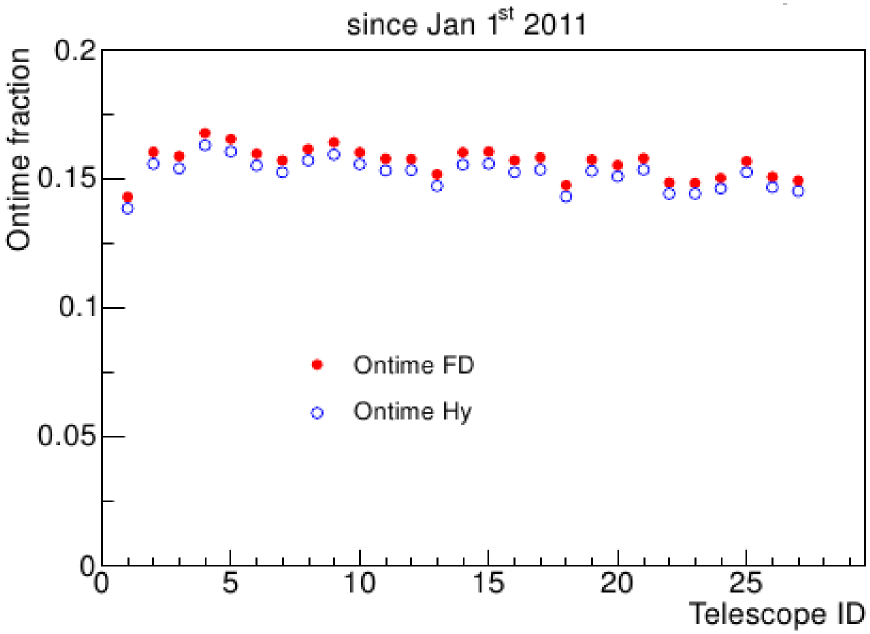
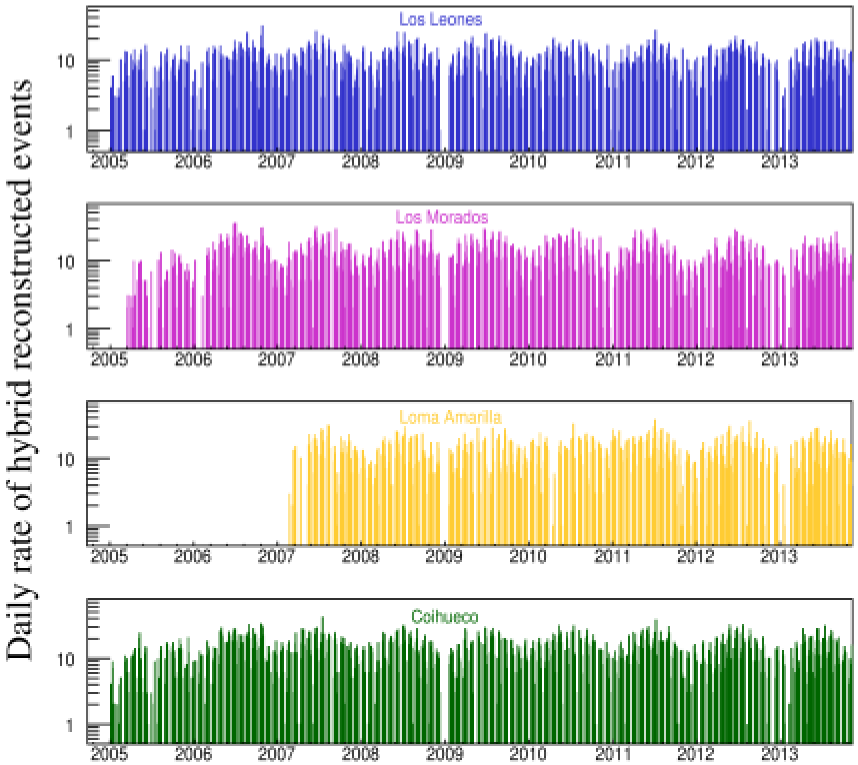
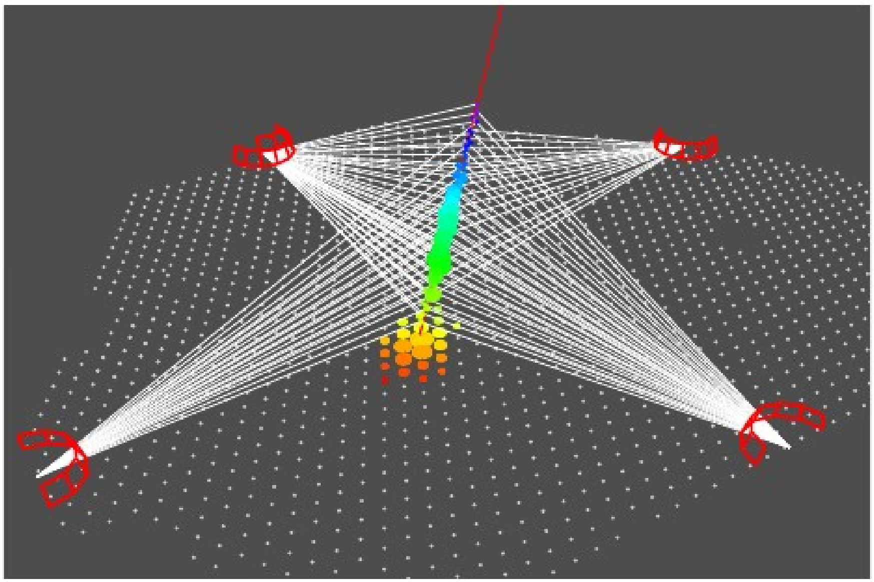
< ln A >

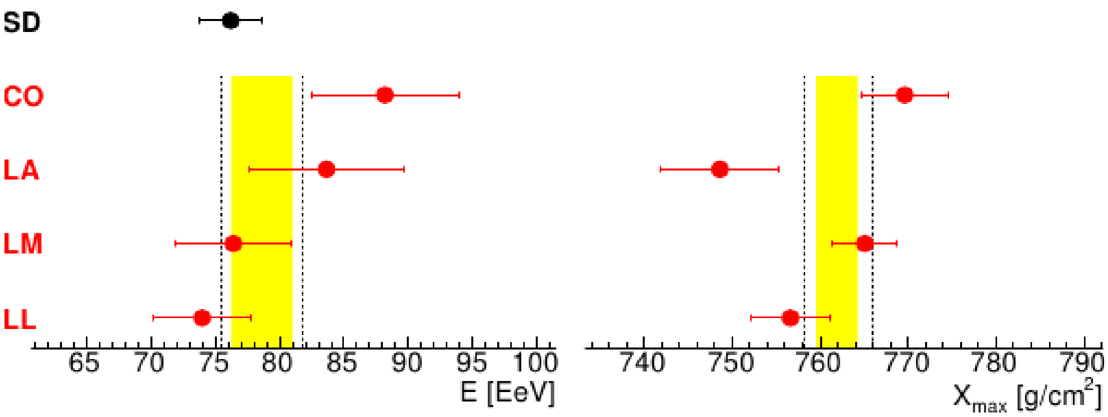
detector stability

8 years of data: 12/2004 – 12/2012

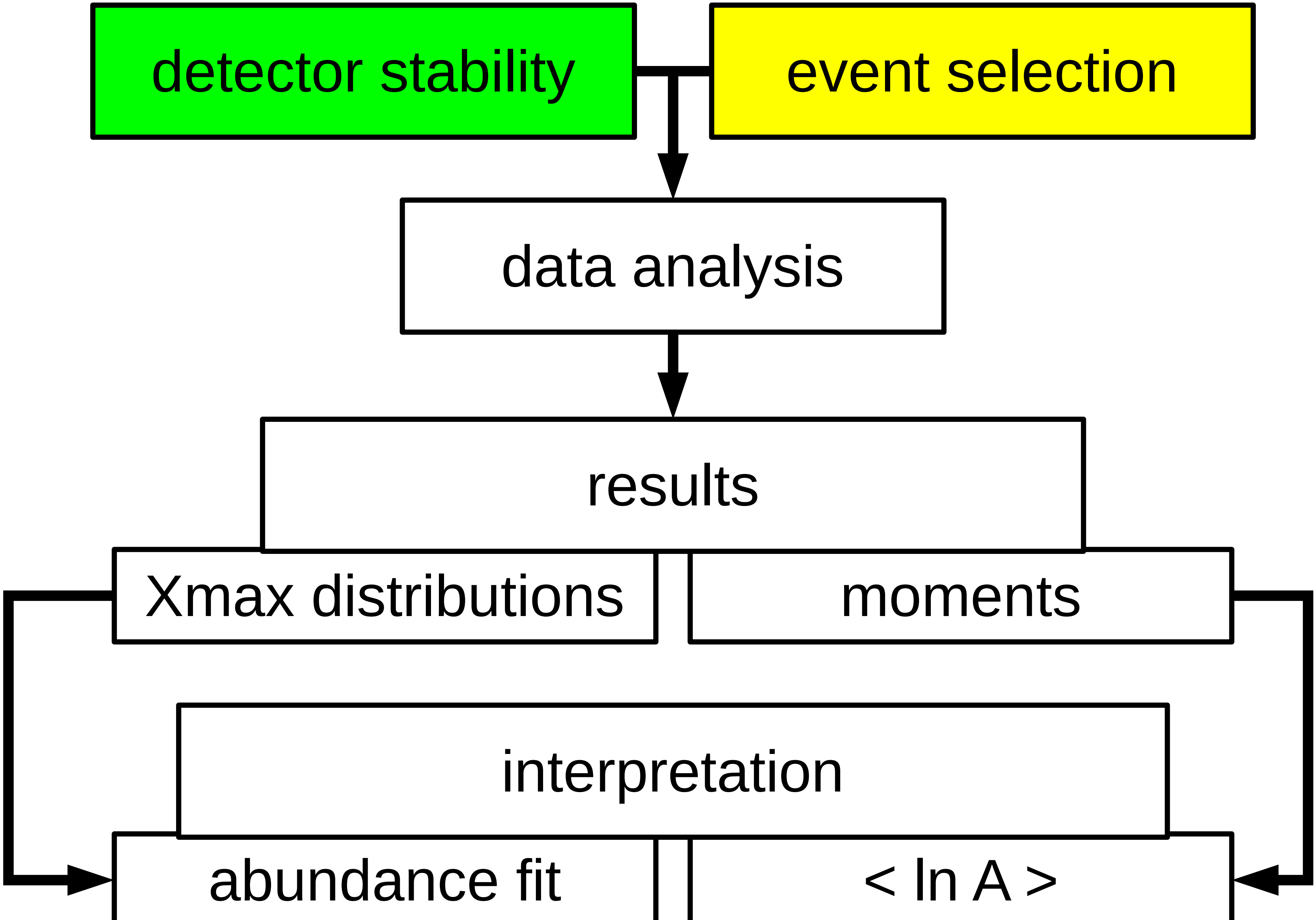








outline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cut	events	ε [%]
pre-selection:		
air-shower candidates	2573713	-
hardware status	1920584	74.6
aerosols	1569645	81.7
hybrid geometry	564324	35.9
profile reconstruction	539960	95.6
clouds	432312	80.1
$E > 10^{17.8}$ eV	111194	25.7
quality and fiducial selection:		
P(hybrid)	105749	95.1
$X_{\max}$ observed	73361	69.4
quality cuts	58305	79.5
fiducial field of view	21125	36.2
profile cuts	19947	94.4

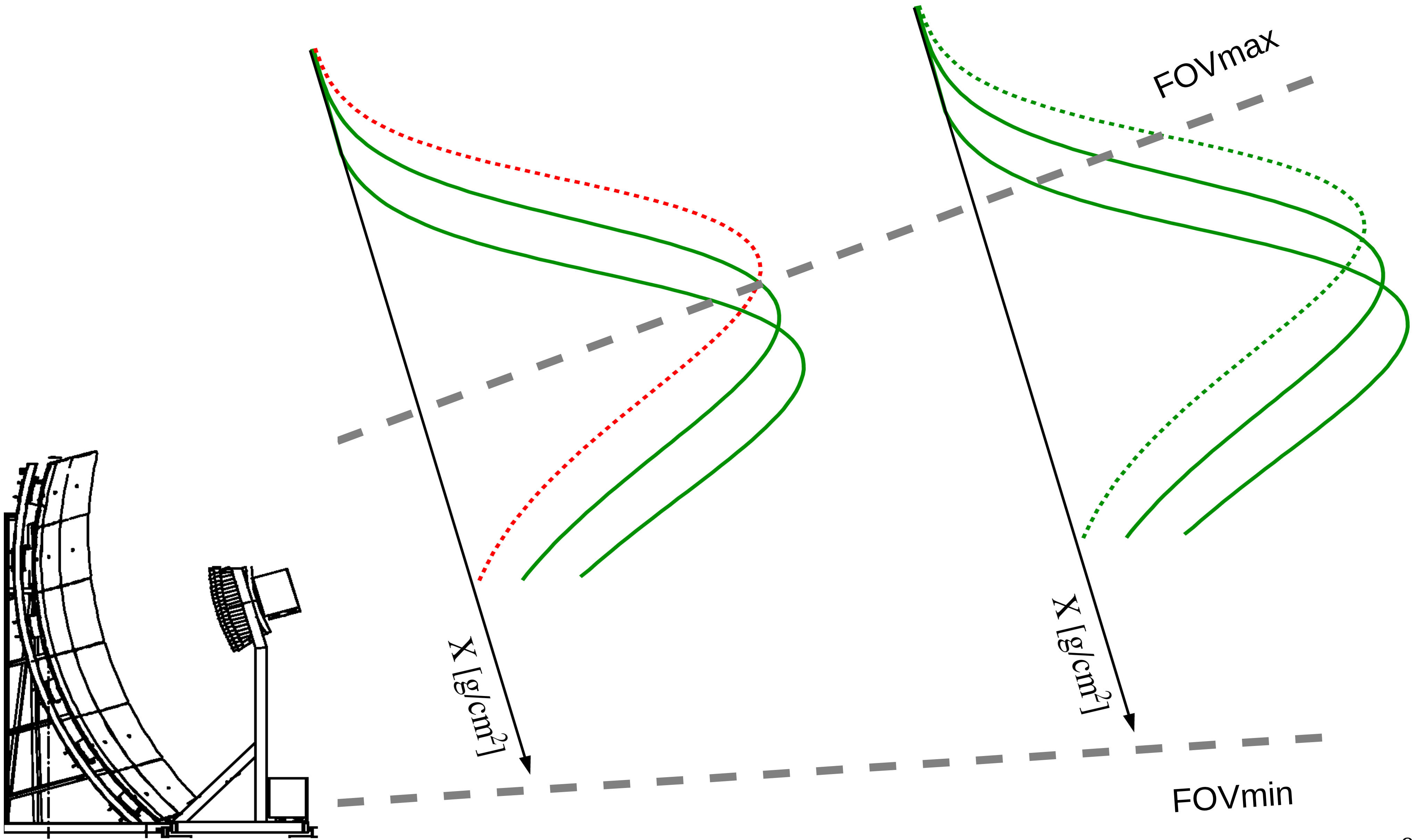
quality cuts

- Xmax resolution in the smaller than 40 g/cm^2
- Viewing angle larger than 20º

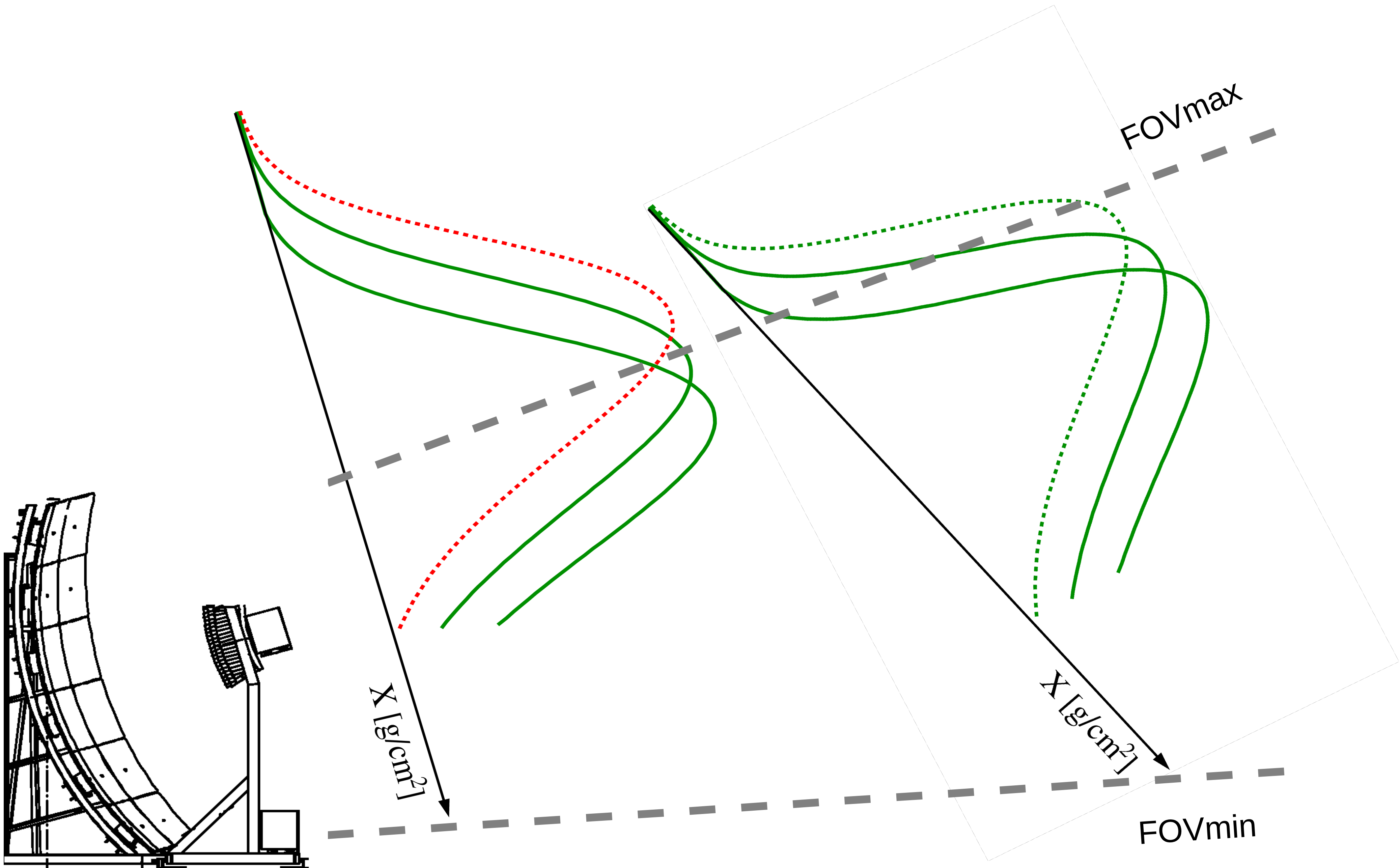
profile cuts

- No gaps in the profile larger than 20% of the total length
- Gaisser-Hillas χ^2 smaller than 2.25 sigma
- Minimum track length of 300 g/cm^2

fiducial field of view



fiducial field of view

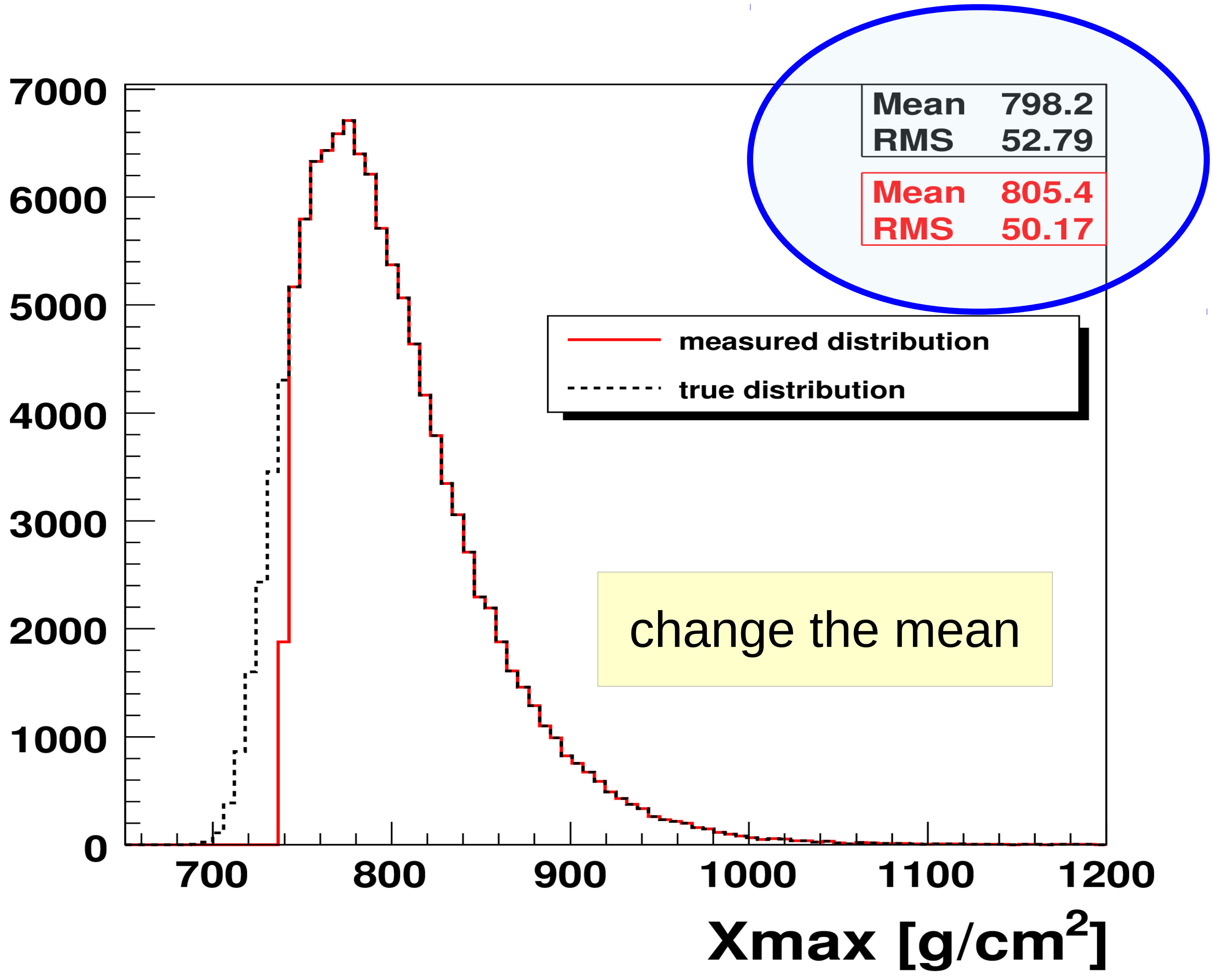


What are the geometries

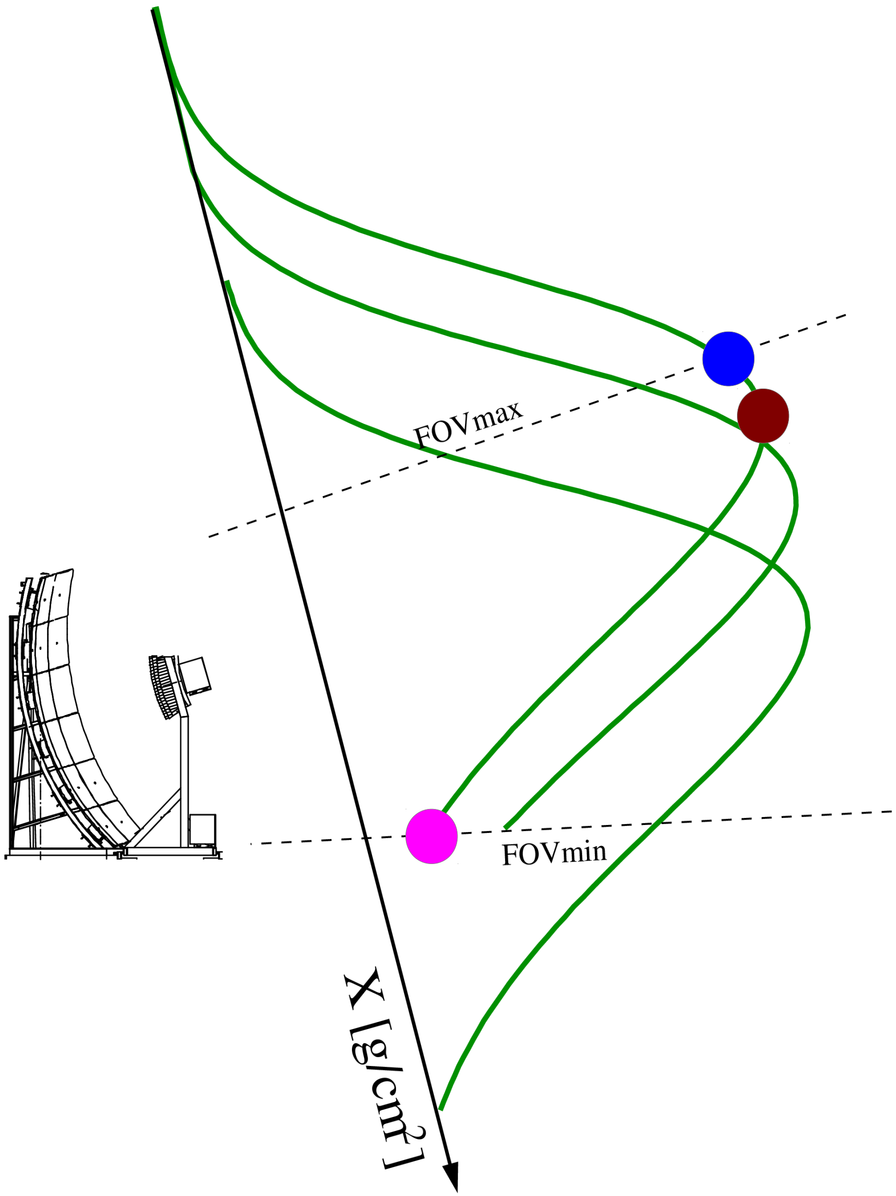
that allows the measurement

of the entire Xmax distribution ?

valid geometries ?



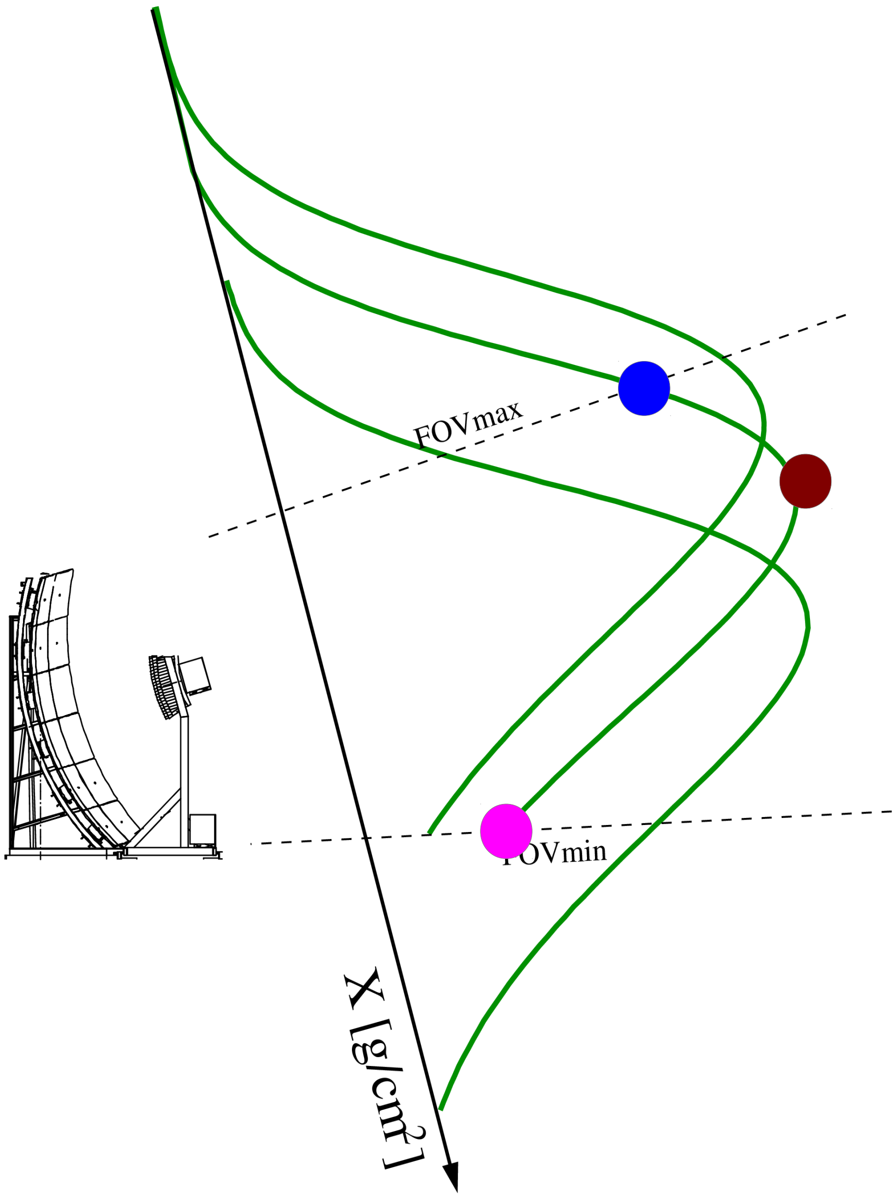
study how <Xmax> changes with FOV



From the data

Xmax	Xup	Xlow	Energy
780	750	970	$1x10^{18}$

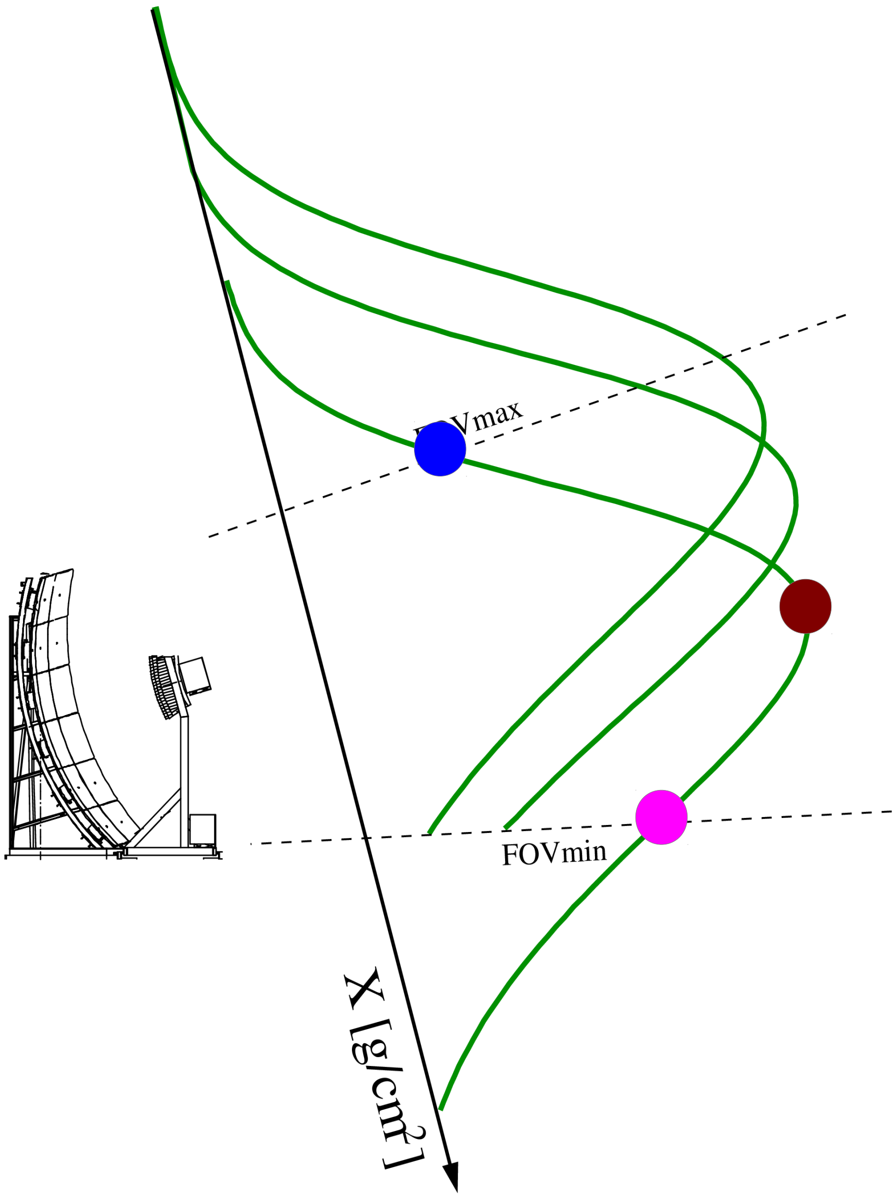
study how <Xmax> changes with FOV



From the data

Xmax	Xup	Xlow	Energy
780	750	970	7.0×10^{18}
760	740	990	1.2×10^{19}

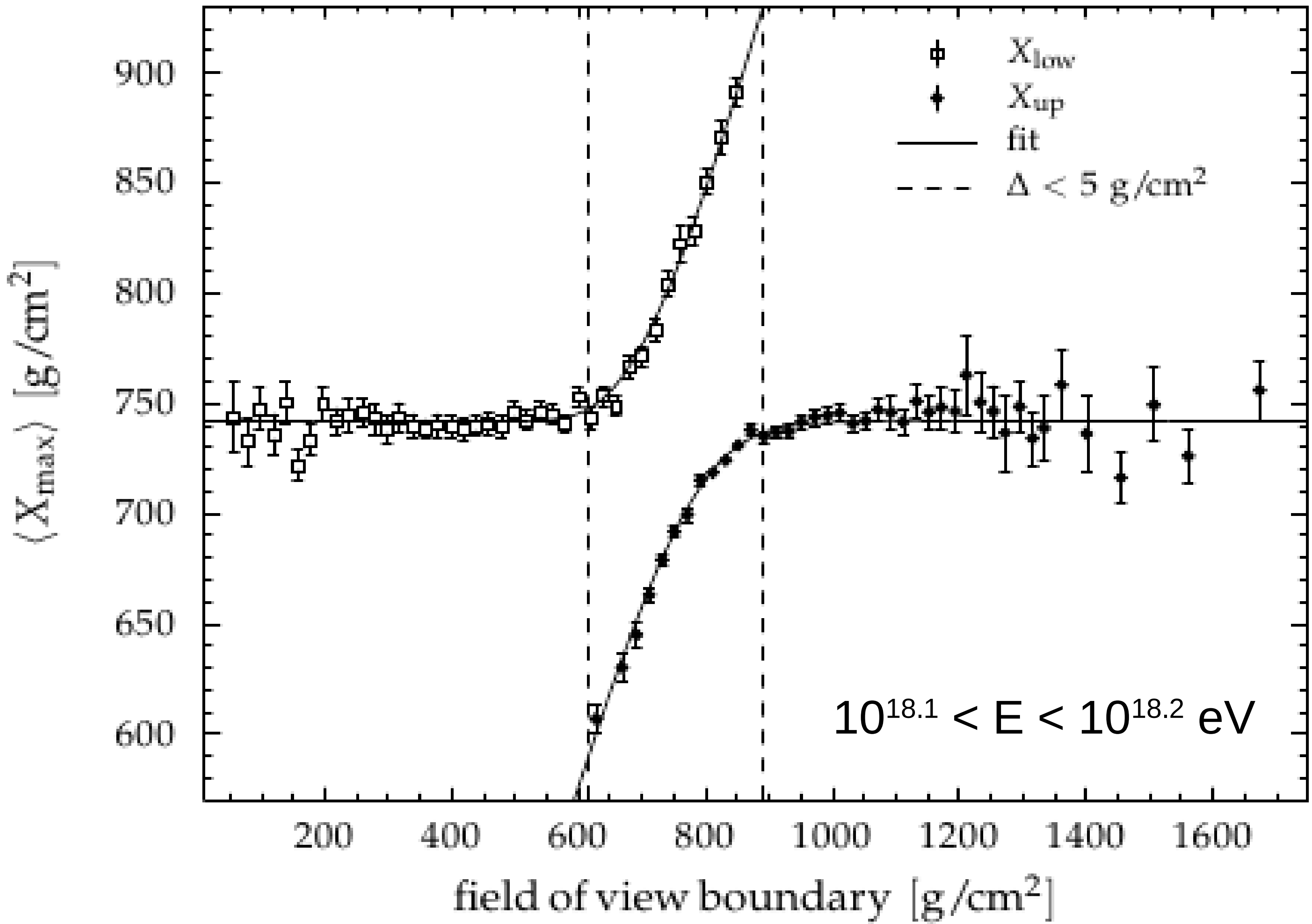
study how <Xmax> changes with FOV



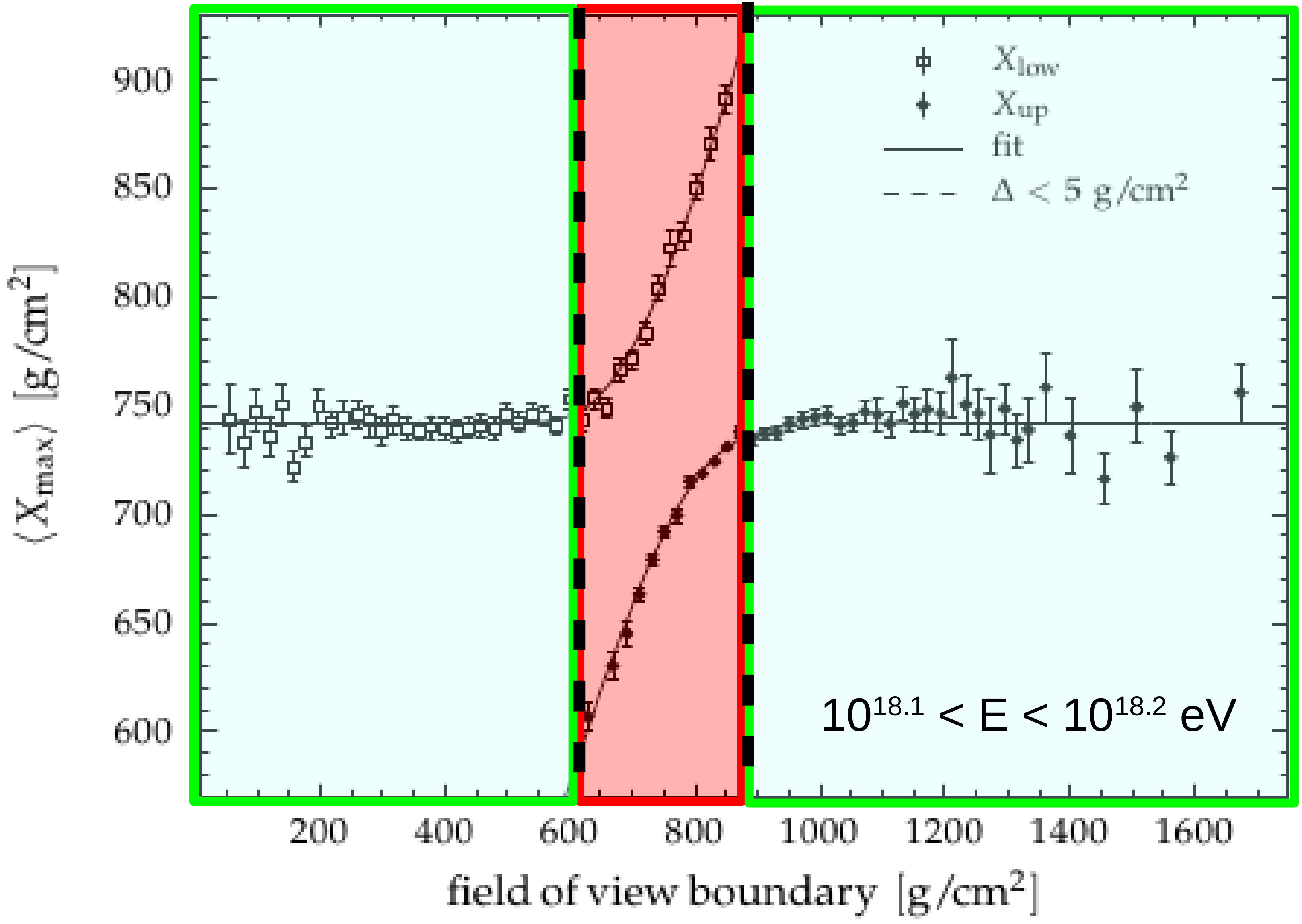
From the data

Xmax	Xup	Xlow	Energy
780	750	970	7.0×10^{18}
760	740	990	1.2×10^{19}
•	•	•	•
•	•	•	•
•	•	•	•
•	•	•	•
•	•	•	•
•	•	•	•

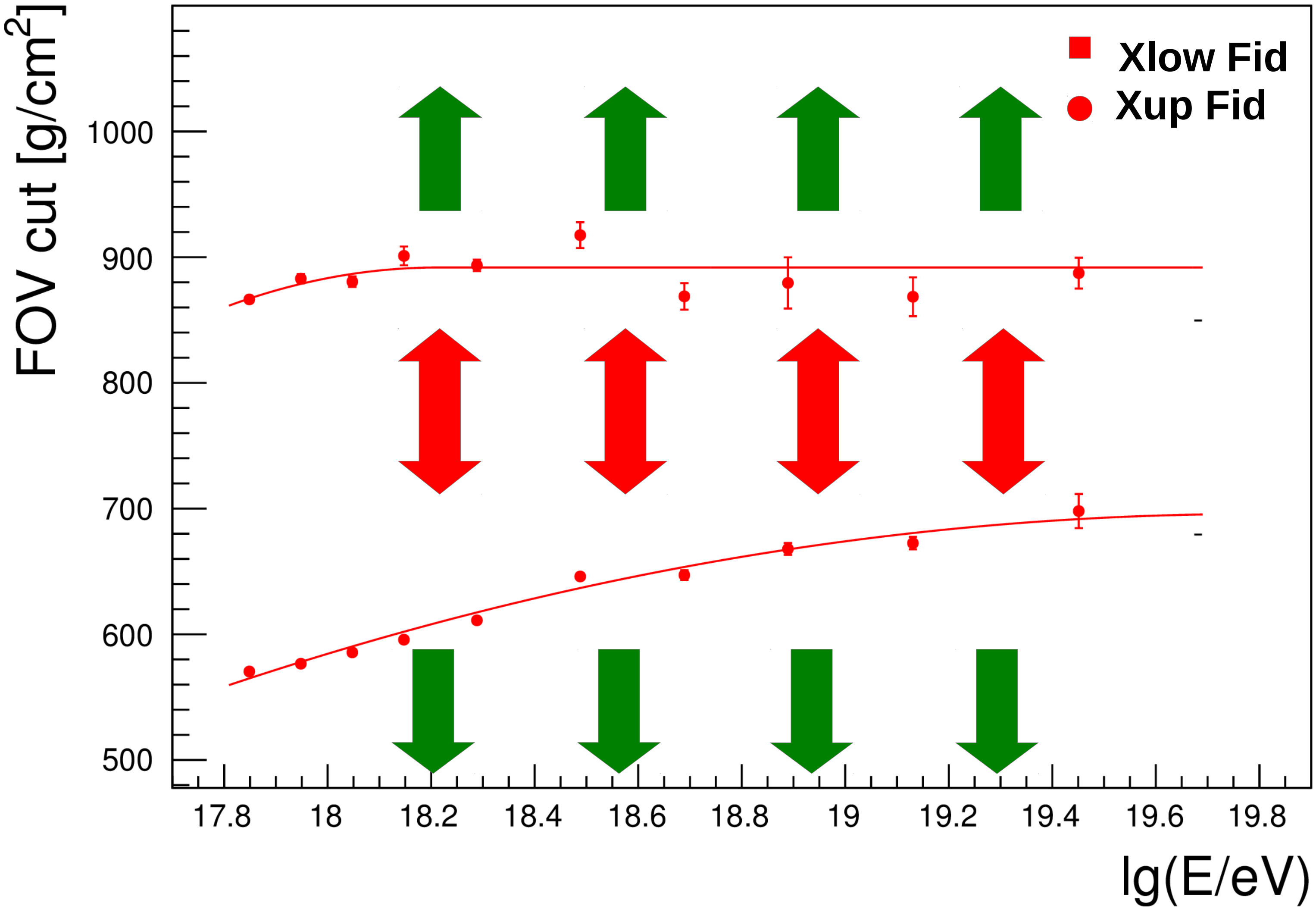
valid geometries ?



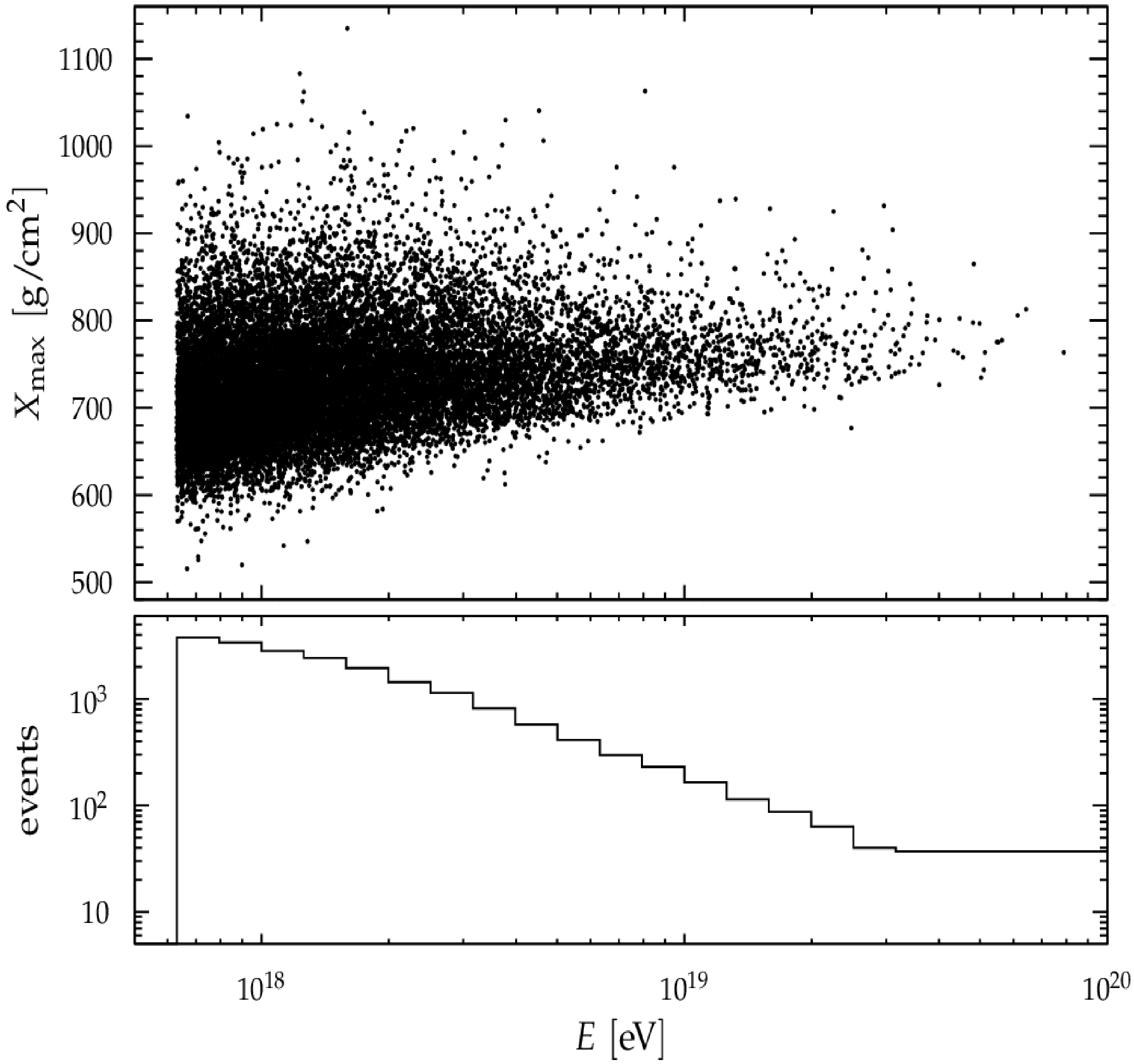
valid geometries ?



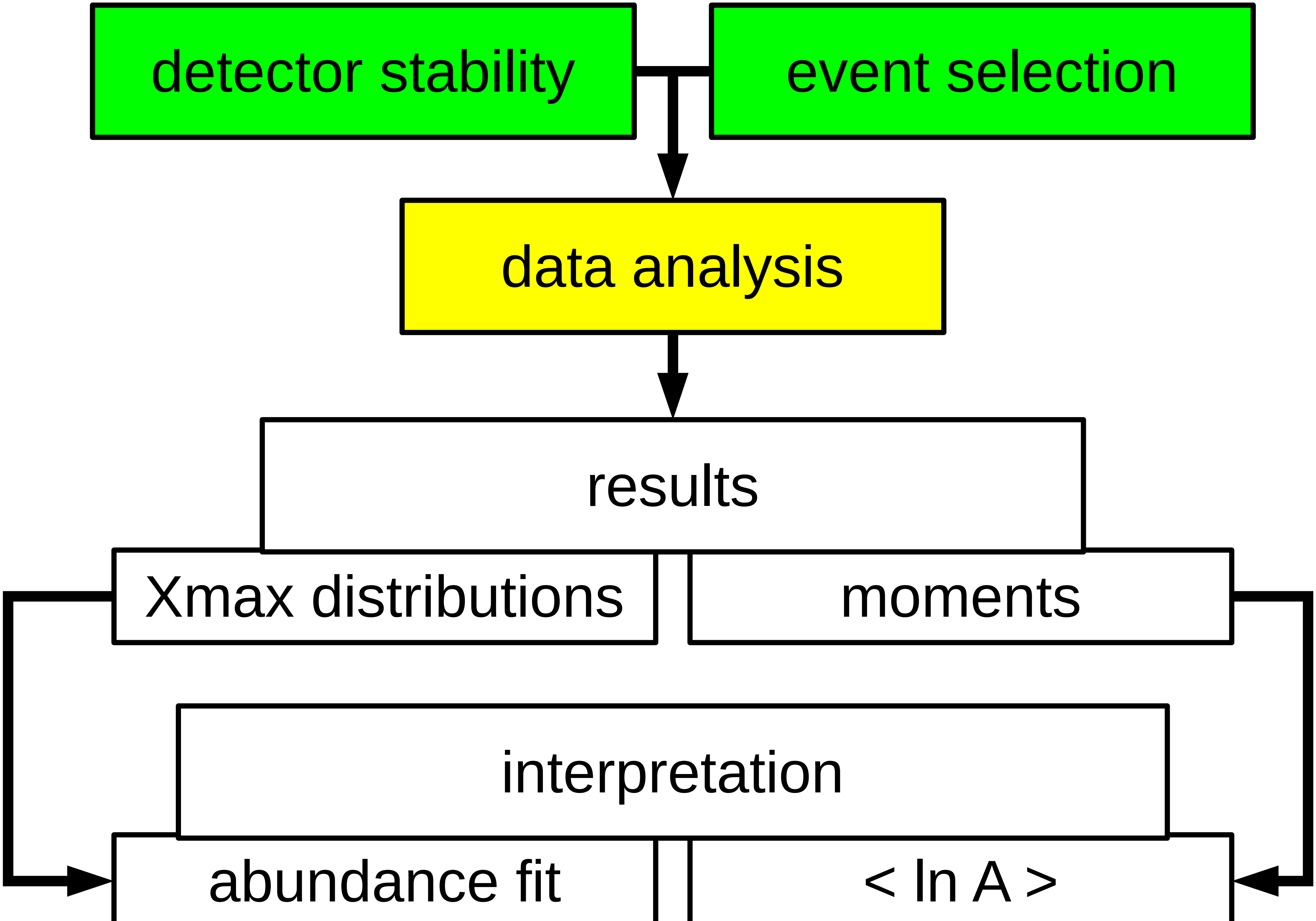
this is the valid geometry that assures unbiased Xmax distributions



events to be analyzed



outline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< ln A >

Target: analyze the set of selected events in order to guarantee:

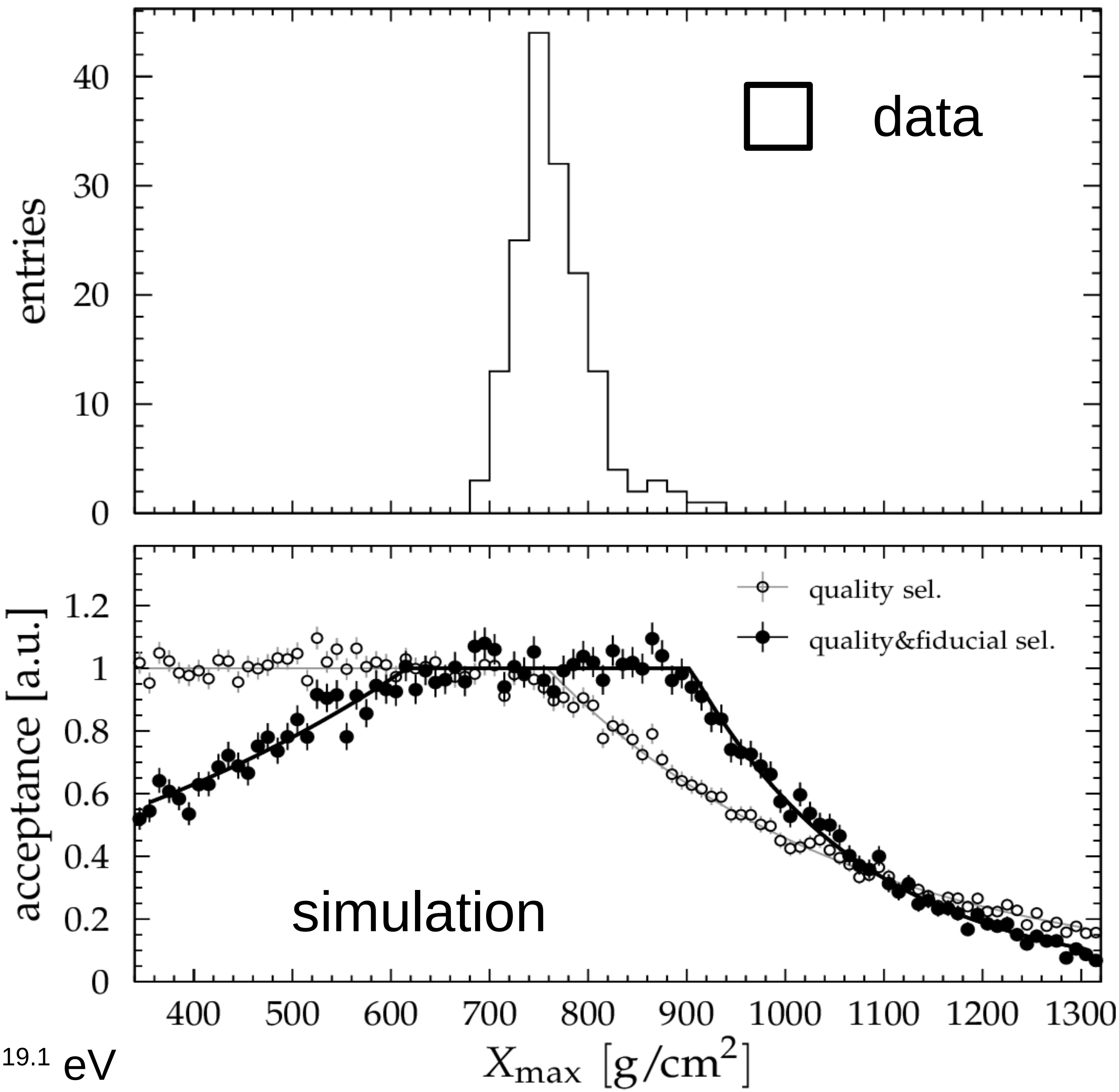
minimum bias

maximum statistical significance

control over systematic uncertainties

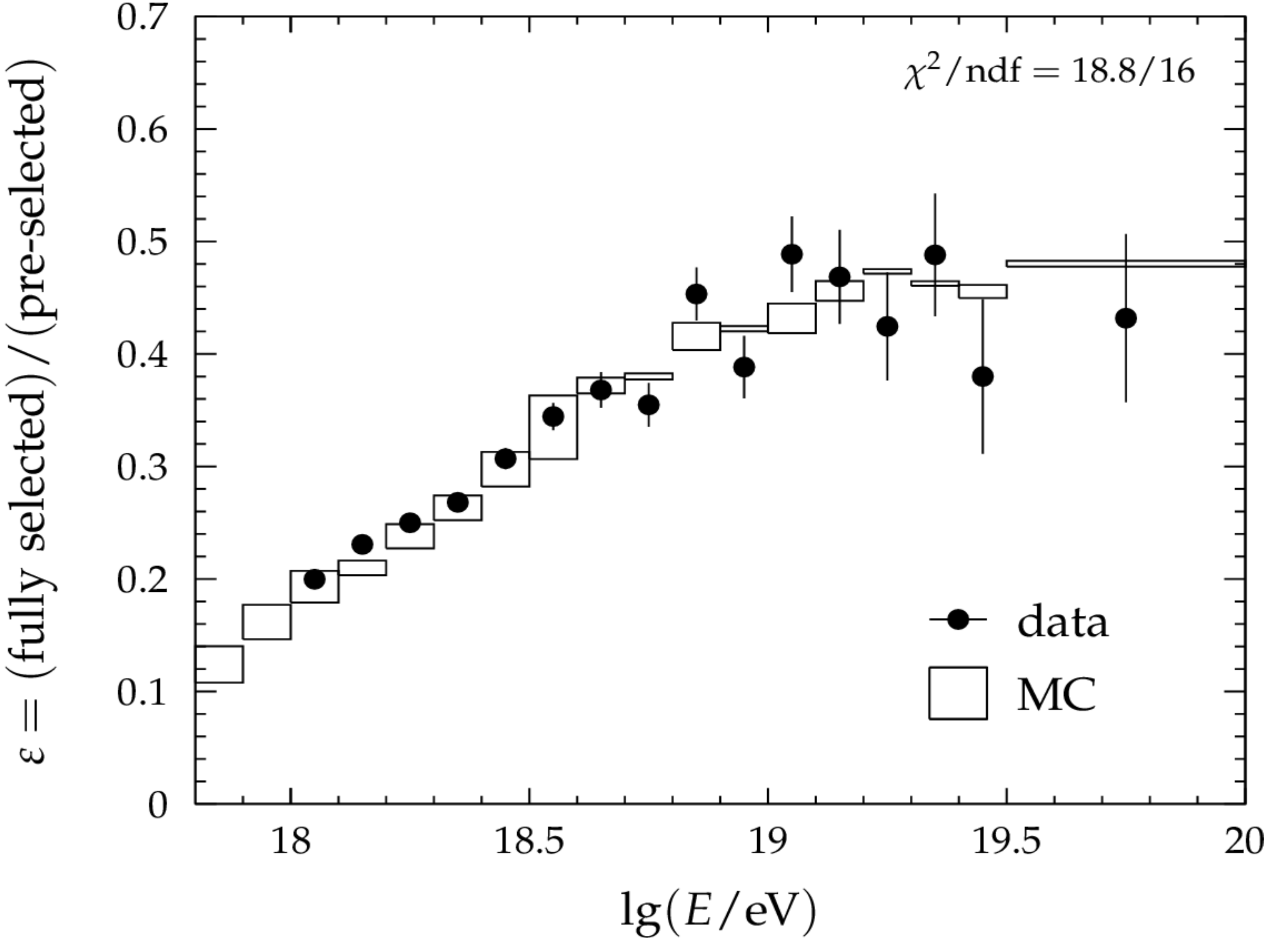
verification / cross-checks

acceptance



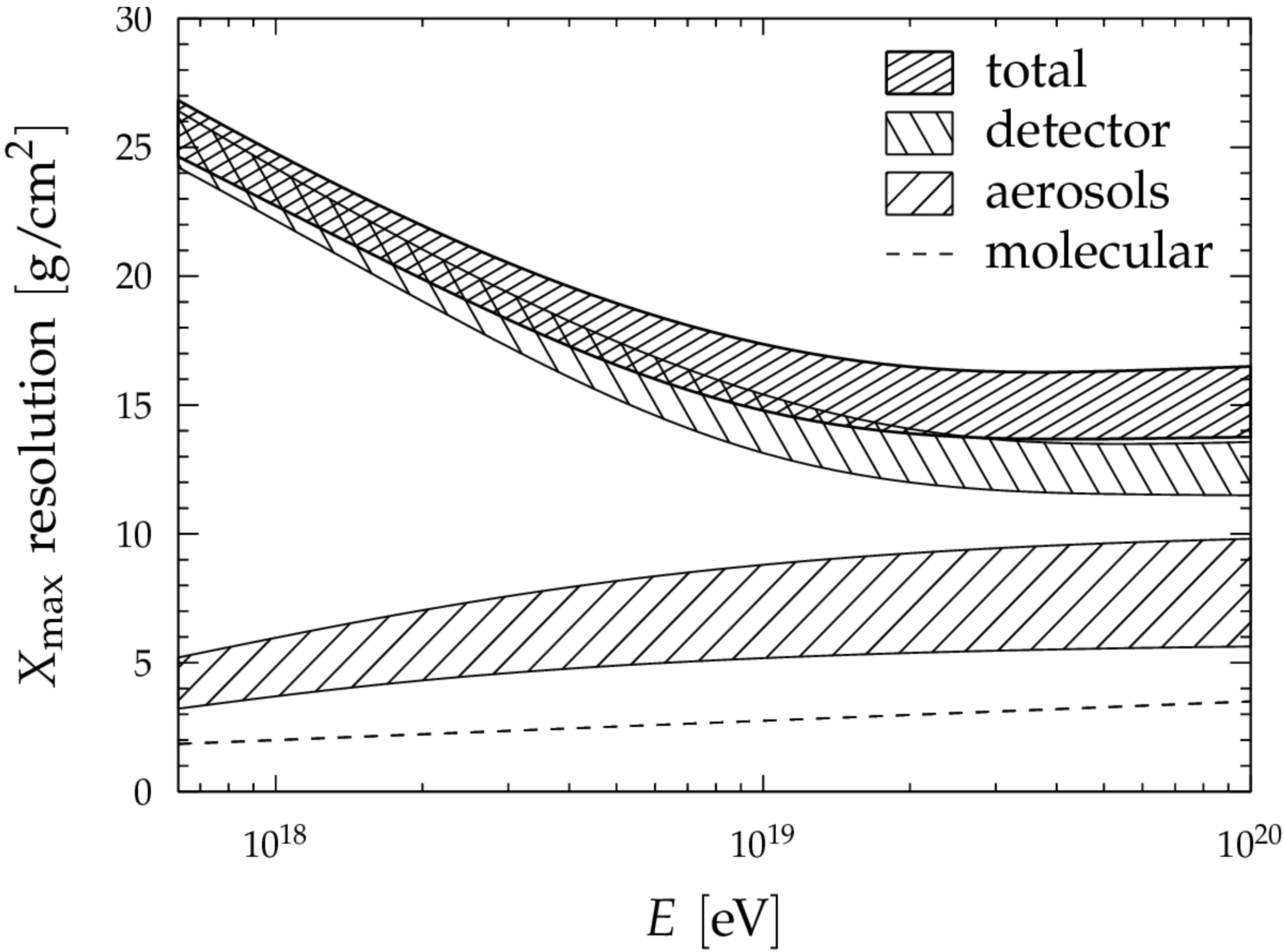
$10^{19.0} < E < 10^{19.1}$ eV

cross-check



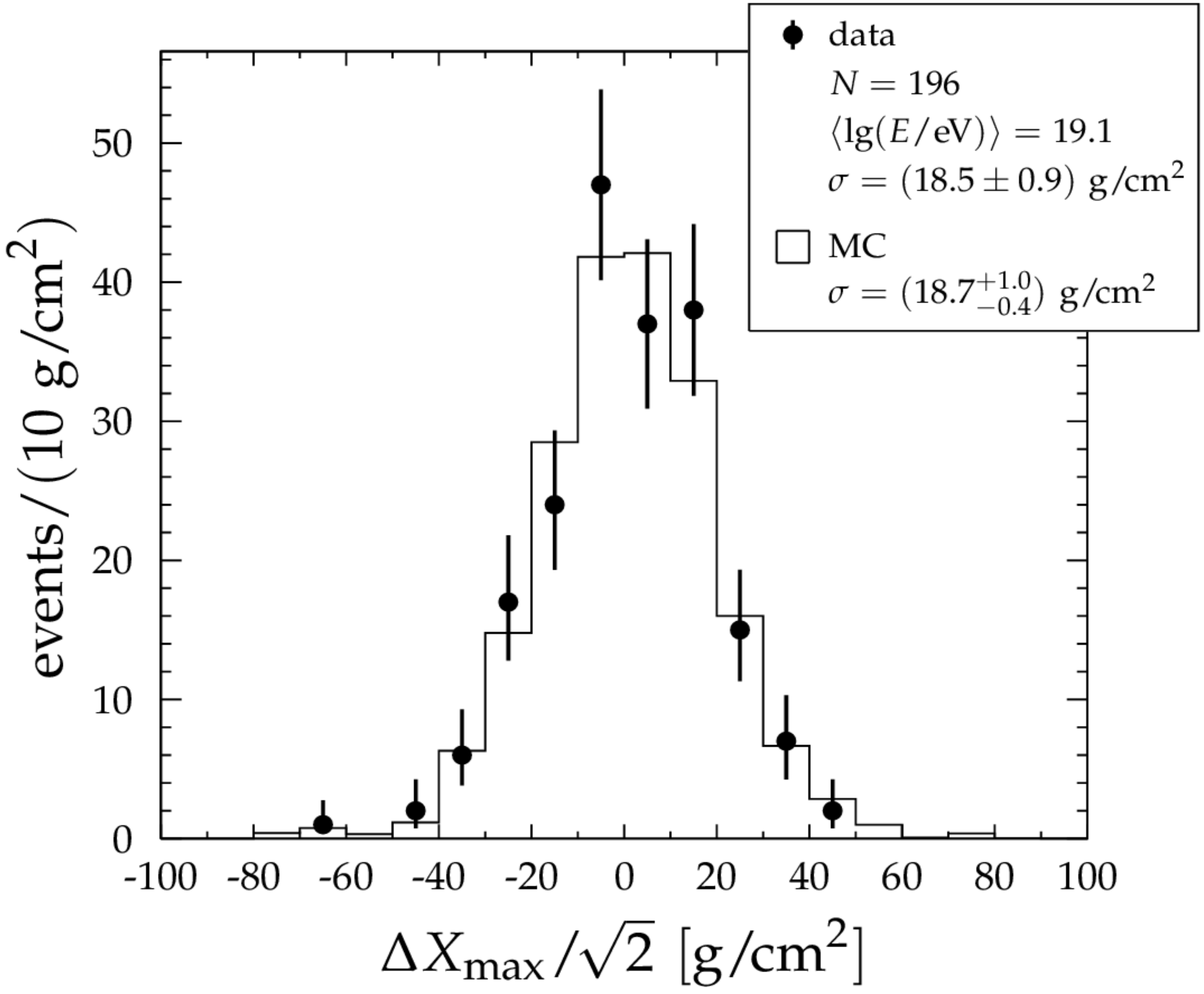
$\chi^2/\text{ndf} = 18.8/16$
data
MC
$\varepsilon = (\text{fully selected})/(\text{pre-selected})$
$\lg(E/\text{eV})$
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
18
18.5
19
19.5
20

resolution

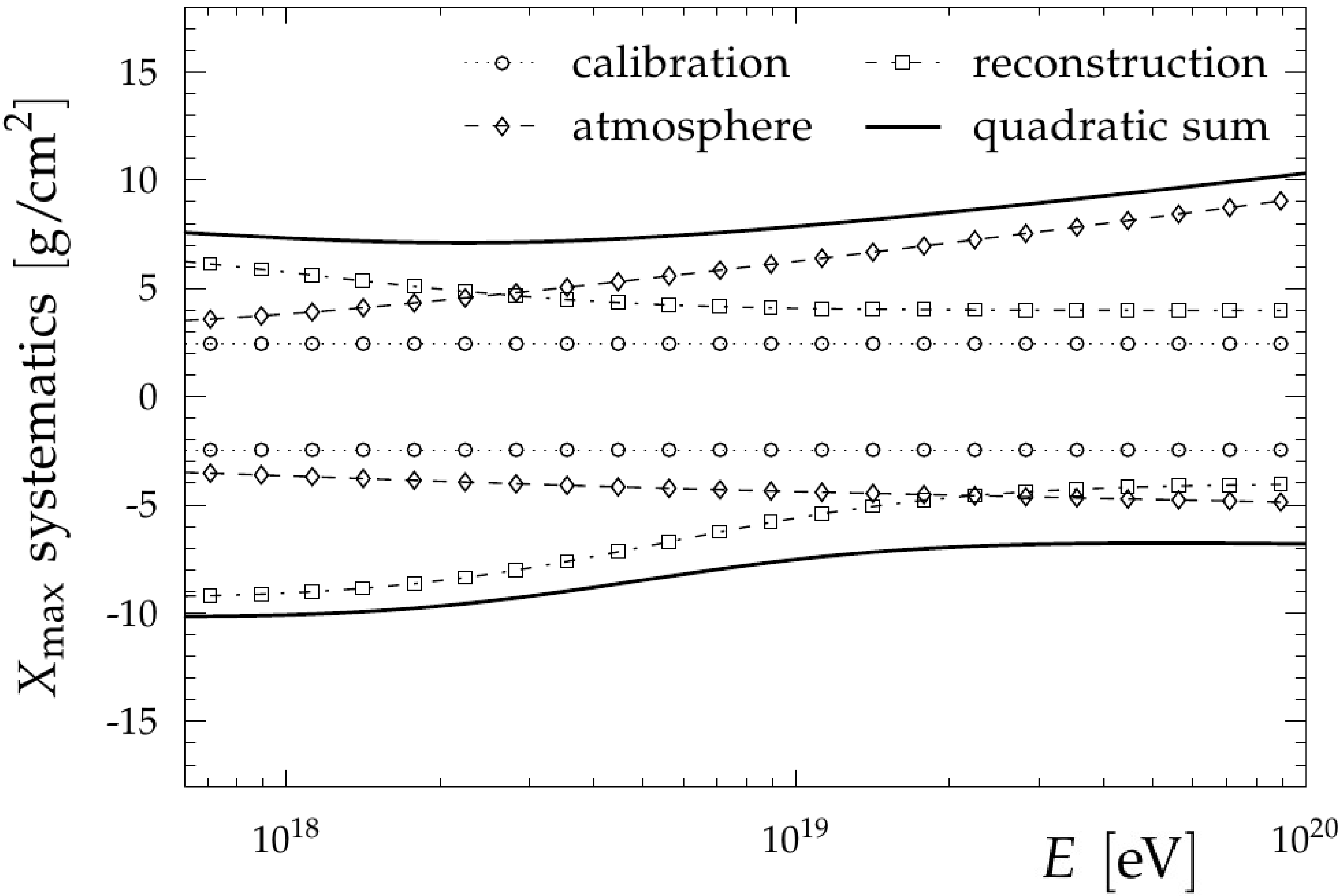


total
detector
aerosols
molecular
X_{max} resolution [g/cm^2]
30
25
20
15
10
5
0
10^{18}
10^{19}
10^{20}
E [eV]

cross-check: stereo events



systematics



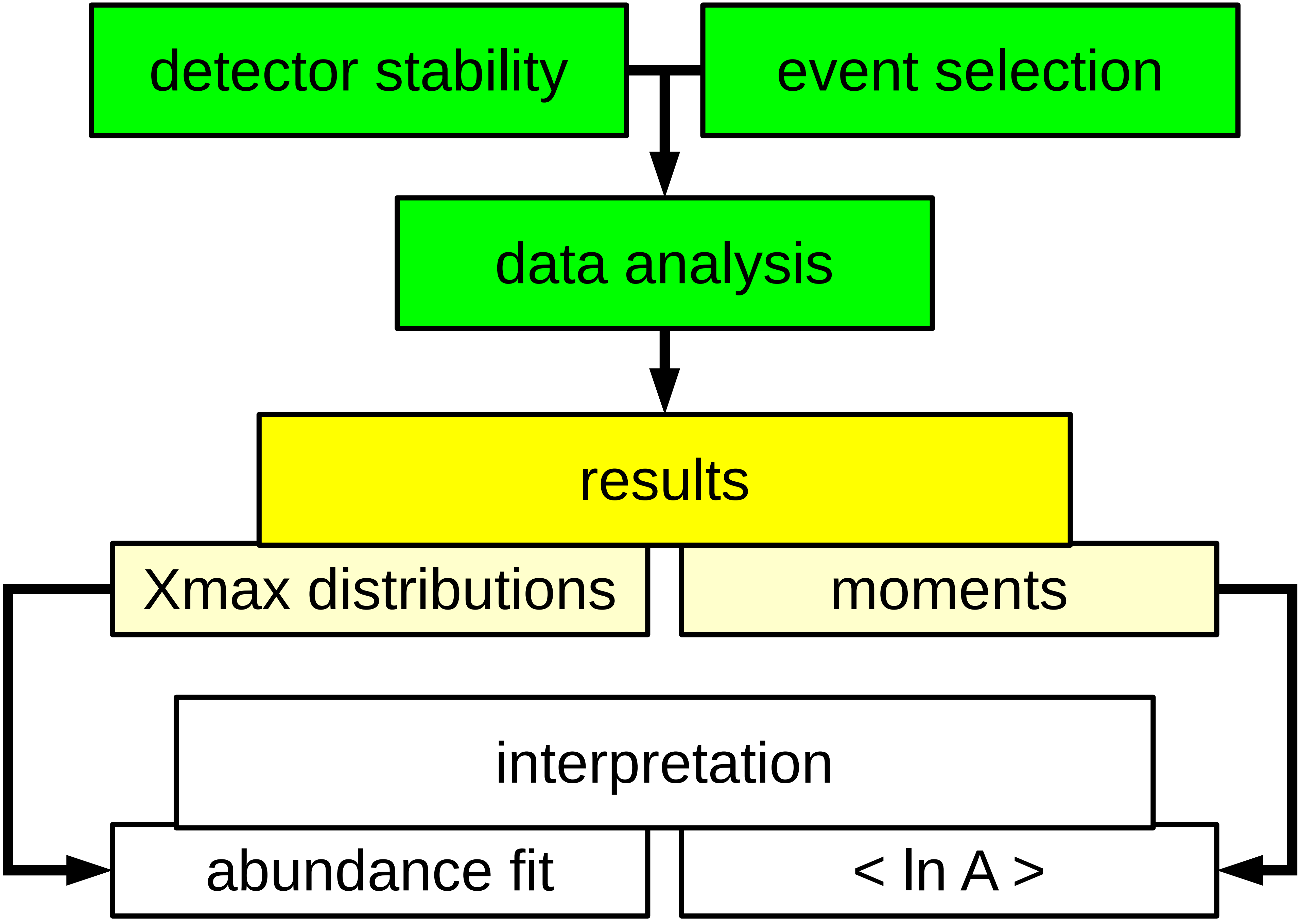
complete data analysis

- acceptance
- resolution
- systematics

everything published

everybody can use Auger data
for comparison
to models and other measurements

outline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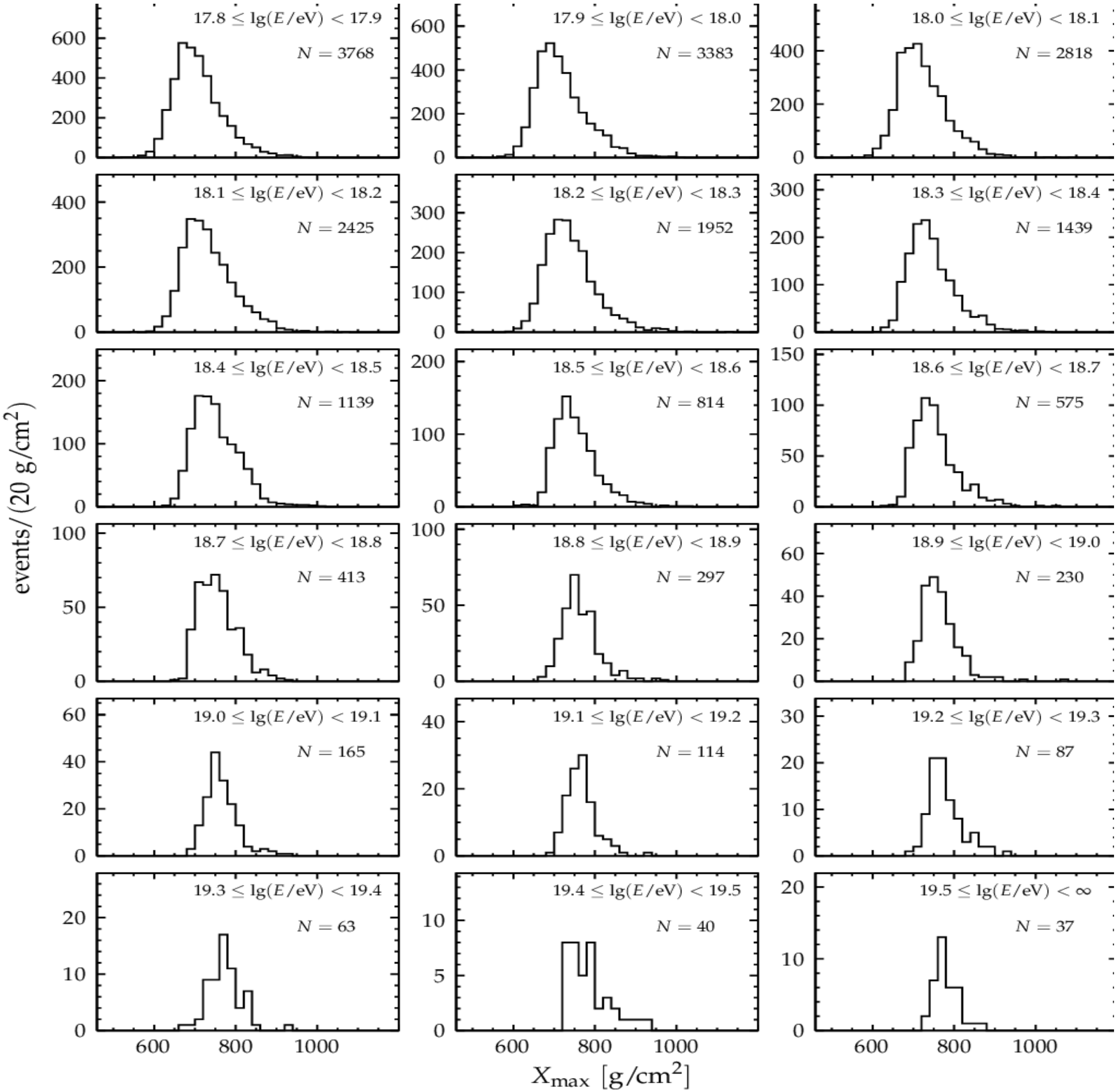


17.8 ≤ lg(E/eV) < 17.9
N = 3768
17.9 ≤ lg(E/eV) < 18.0
N = 3383
18.0 ≤ lg(E/eV) < 18.1
N = 2818
18.1 ≤ lg(E/eV) < 18.2
N = 2425
18.2 ≤ lg(E/eV) < 18.3
N = 1952
18.3 ≤ lg(E/eV) < 18.4
N = 1439
18.4 ≤ lg(E/eV) < 18.5
N = 1139
18.5 ≤ lg(E/eV) < 18.6
N = 814
18.6 ≤ lg(E/eV) < 18.7
N = 575
18.7 ≤ lg(E/eV) < 18.8
N = 413
18.8 ≤ lg(E/eV) < 18.9
N = 297
18.9 ≤ lg(E/eV) < 19.0
N = 230
19.0 ≤ lg(E/eV) < 19.1
N = 165
19.1 ≤ lg(E/eV) < 19.2
N = 114
19.2 ≤ lg(E/eV) < 19.3
N = 87
19.3 ≤ lg(E/eV) < 19.4
N = 63
19.4 ≤ lg(E/eV) < 19.5
N = 40
19.5 ≤ lg(E/eV) < ∞
N = 37
events/(20 g/cm²)
X_max [g/cm²]
600
800
1000

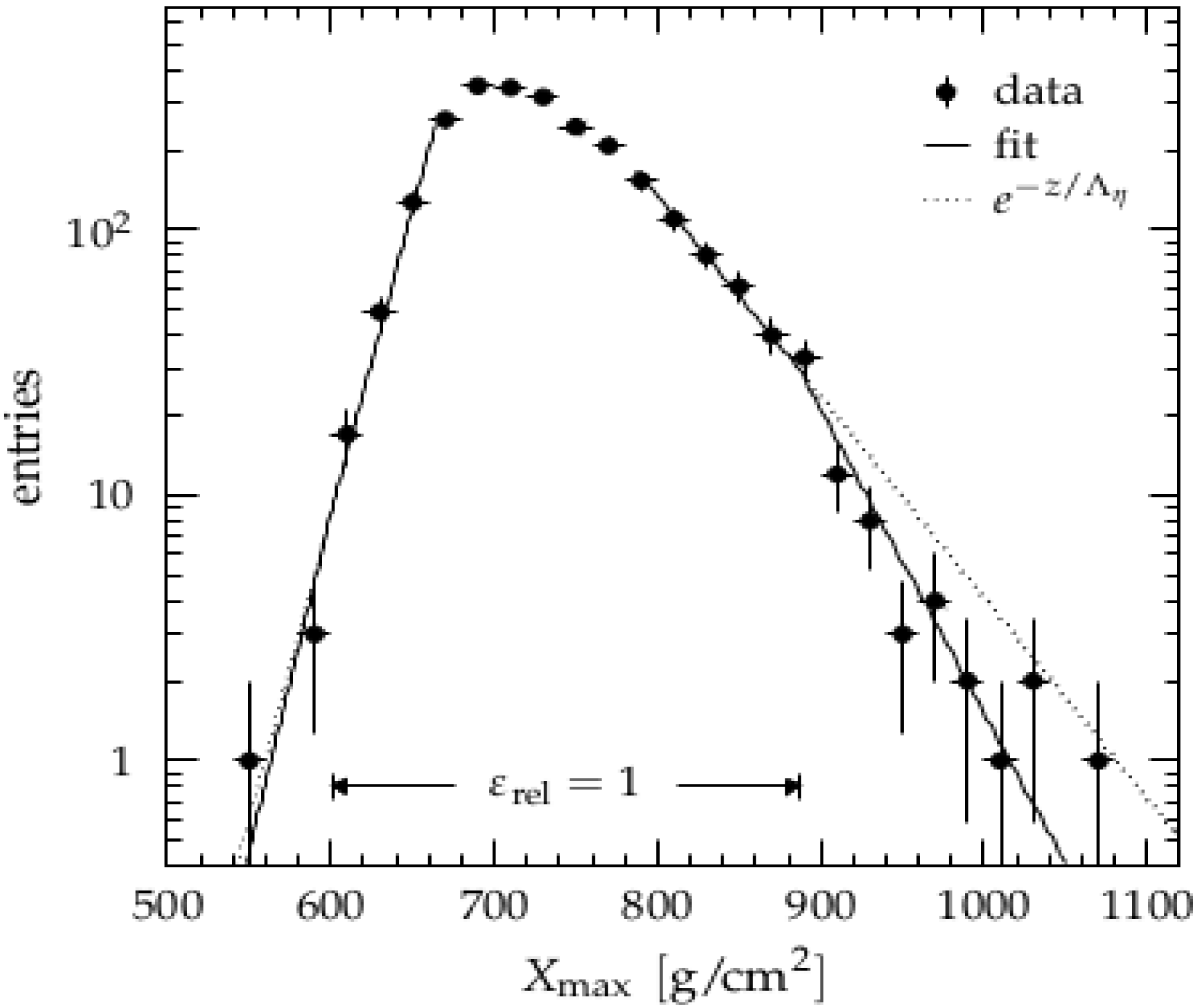
three independent ways to extract the moments

1) Λ_η **method**: an exponential is fit to the tail of the Xmax distribution

2) **event weighting:** events receive a weight given by the parametrization of the acceptance

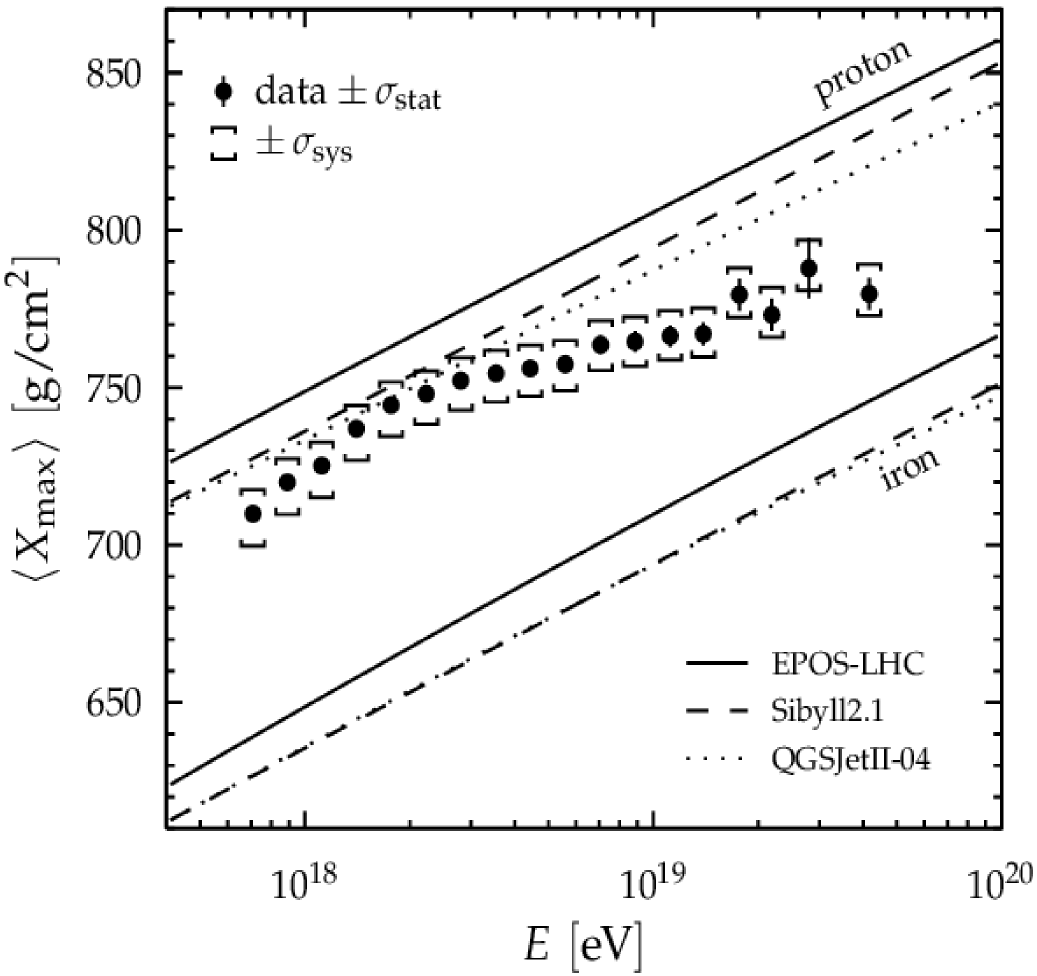
3) **unfolding:** mathematical determination of the true distribution using migration matrix

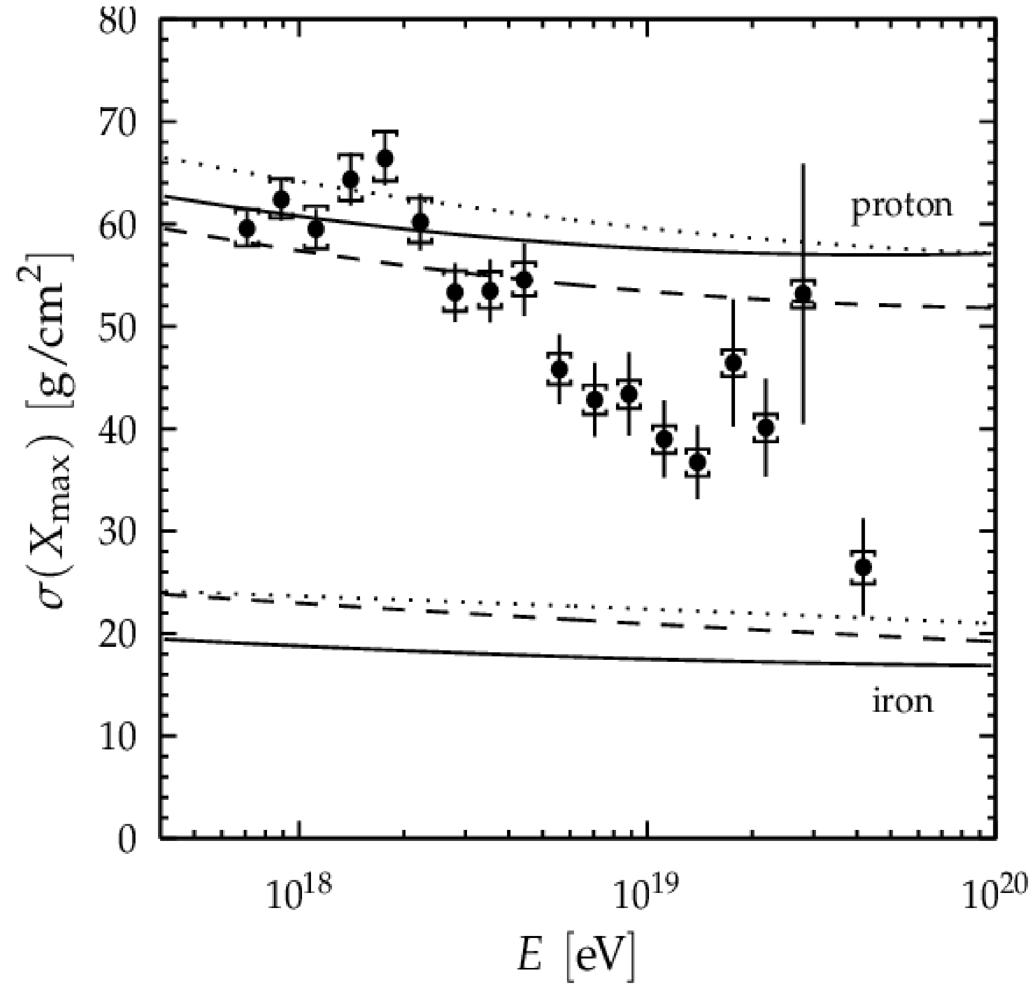
Λ_η method



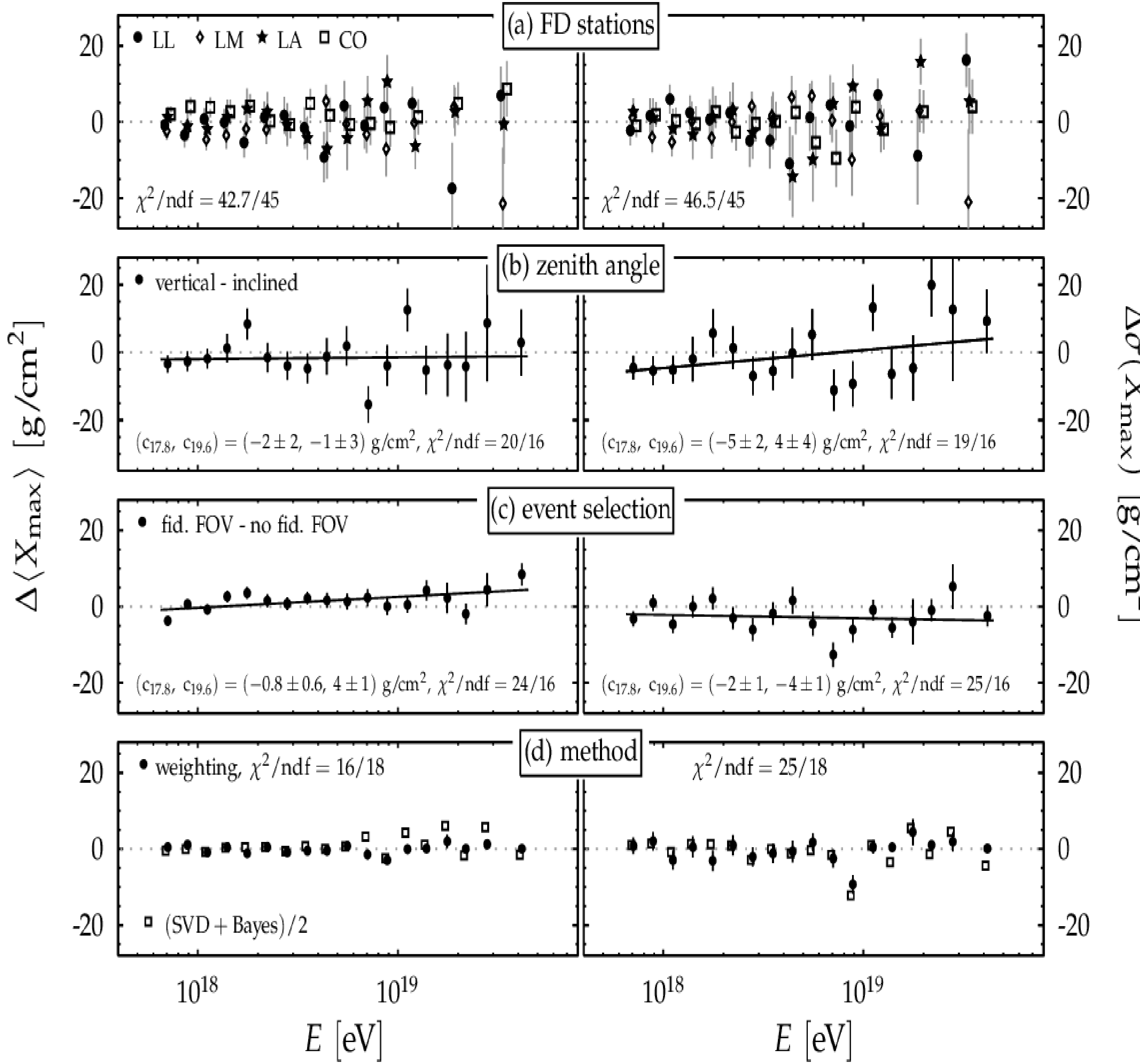
$10^{18.1} < E < 10^{18.2}$ eV

moments

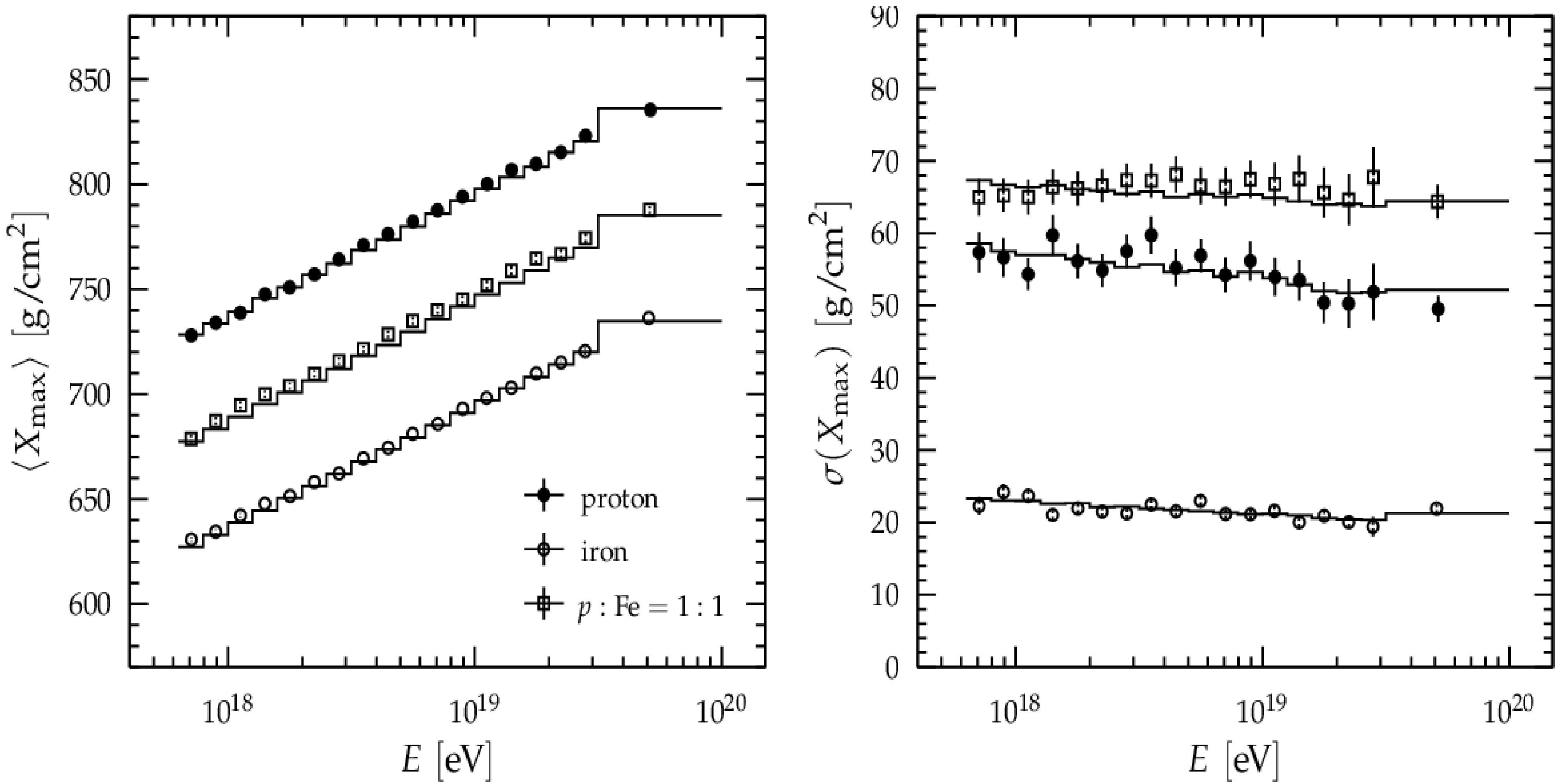




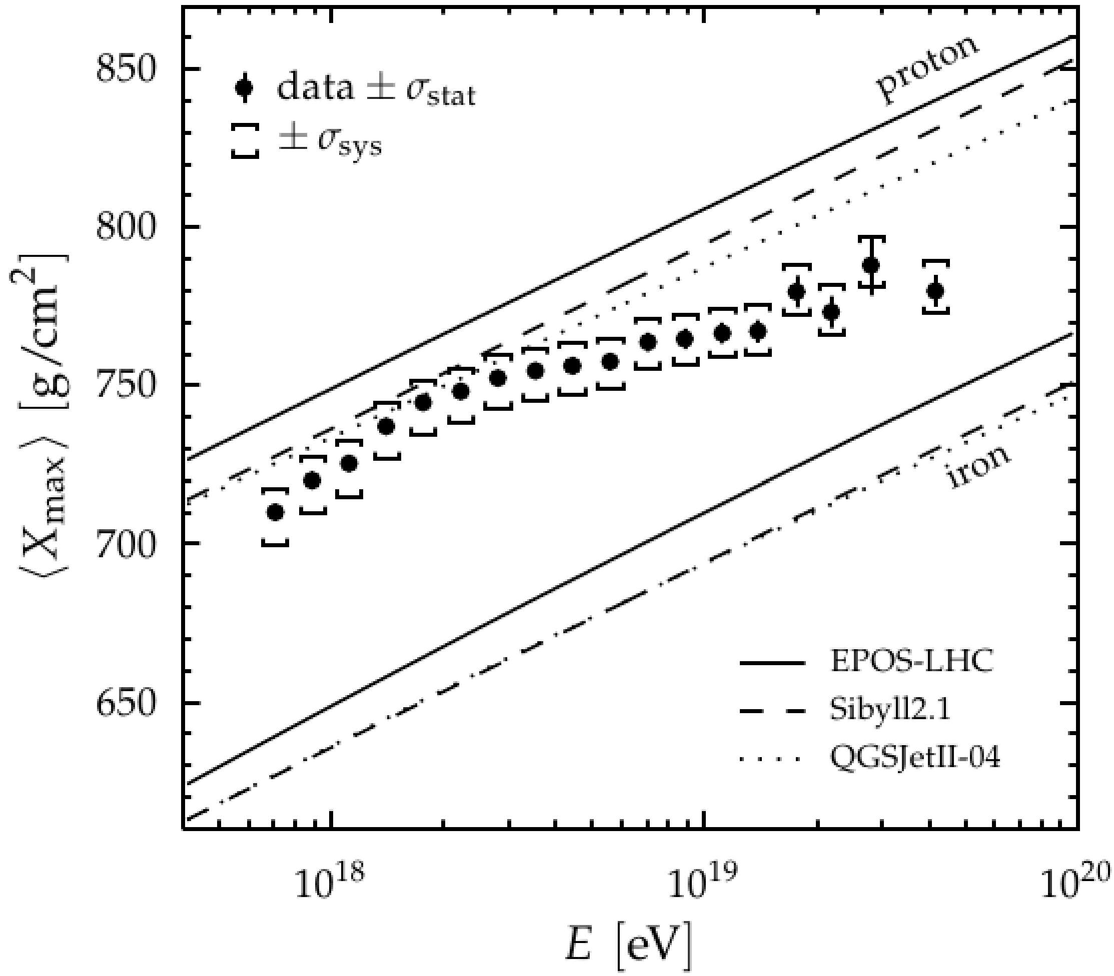
Λ_η method


(a) FD stations
LL LM LA CO
χ^2/ndf = 42.7/45
χ^2/ndf = 46.5/45
(b) zenith angle
vertical - inclined
$(c_{17.8}, c_{19.6}) = (-2 \pm 2, -1 \pm 3)$ g/cm^2, χ^2/ndf = 20/16
$(c_{17.8}, c_{19.6}) = (-5 \pm 2, 4 \pm 4)$ g/cm^2, χ^2/ndf = 19/16
(c) event selection
fid. FOV - no fid. FOV
$(c_{17.8}, c_{19.6}) = (-0.8 \pm 0.6, 4 \pm 1)$ g/cm^2, χ^2/ndf = 24/16
$(c_{17.8}, c_{19.6}) = (-2 \pm 1, -4 \pm 1)$ g/cm^2, χ^2/ndf = 25/16
(d) method
weighting, χ^2/ndf = 16/18
χ^2/ndf = 25/18
(SVD + Bayes)/2
$\Delta\langle X_{max}\rangle$ [g/cm^2]
$\Delta\sigma(X_{max})$ [g/cm^2]
E [eV]
E [eV]

cross check: simulation



same analysis used for data



linear fit:

χ^2/ndf = 138.4/16

two lines with a break fit:

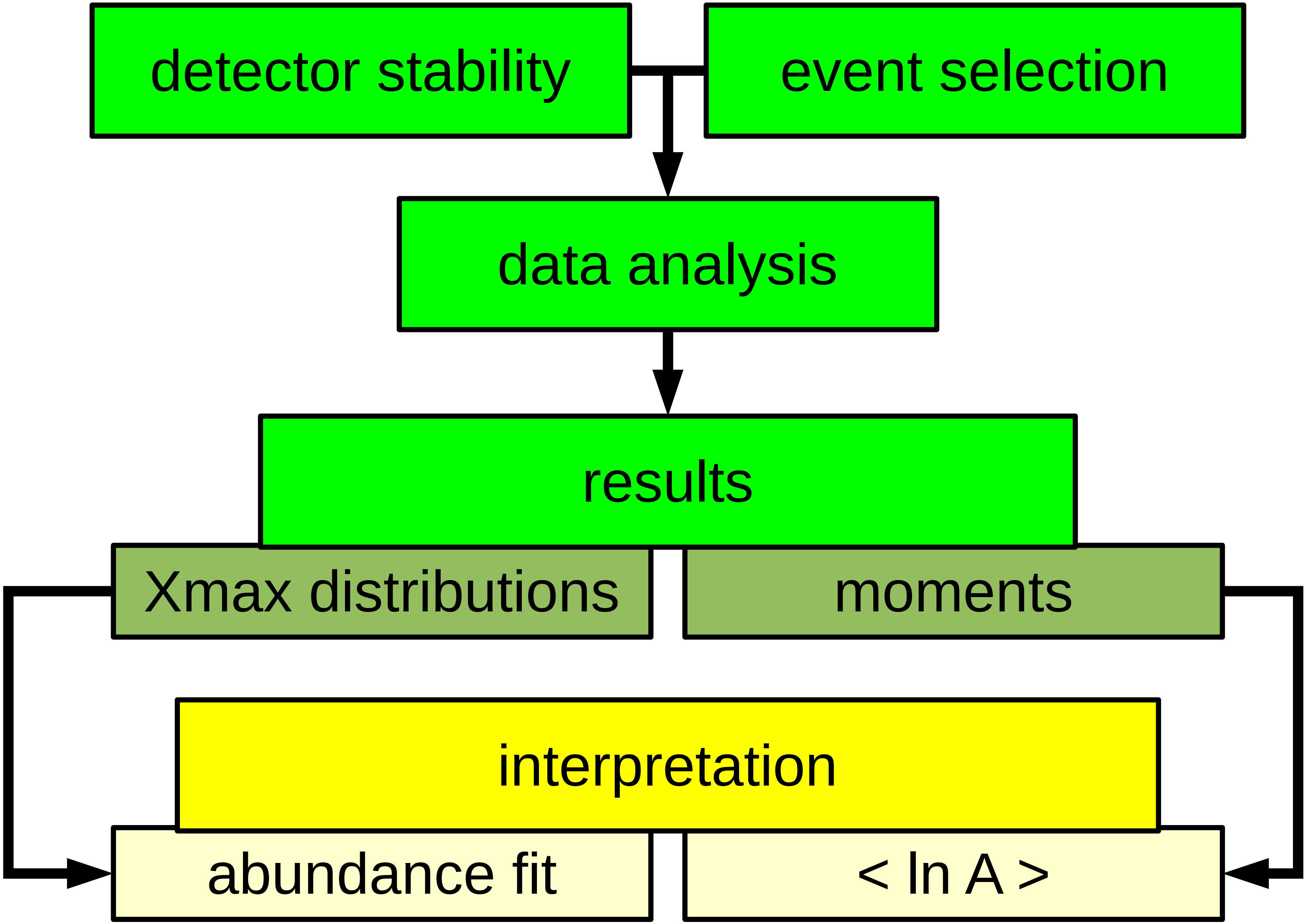
χ^2/ndf = 8.2/14

$$D_{10} = 86.4 \pm 5.0\,(\text{stat.})\,^{+3.8}_{-3.2}\,(\text{sys.})\,\text{g/cm}^2/\text{decade}$$

$$\lg(E_0/\,\text{eV}) = 18.27 \pm 0.04\,(\text{stat.})\,^{+0.06}_{-0.07}\,(\text{sys.})$$

$$D_{10} = 26.4 \pm 2.5\,(\text{stat.})\,^{+7.0}_{-1.9}\,(\text{sys.})\,\text{g/cm}^2/\text{decade}$$

outline



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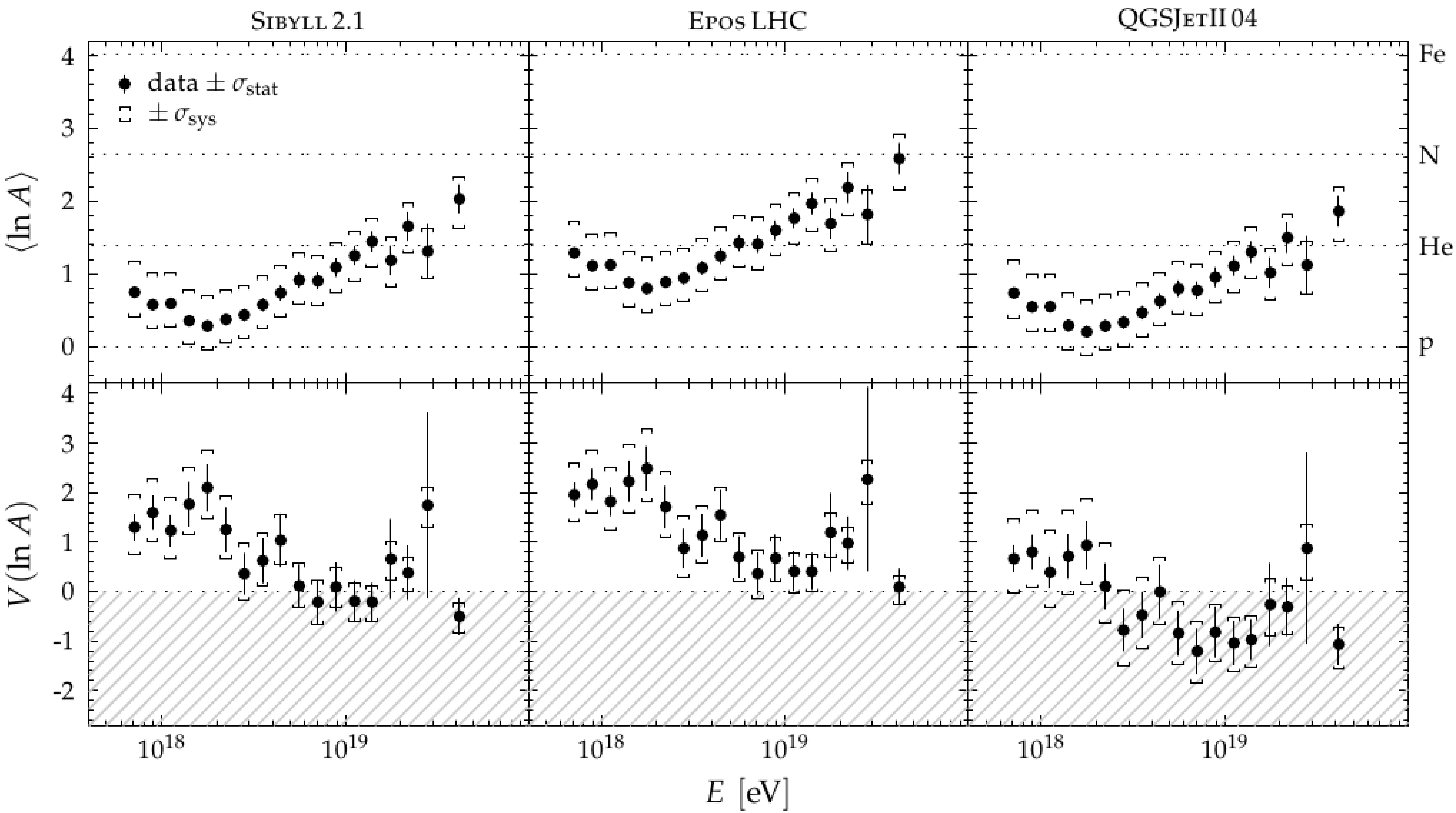
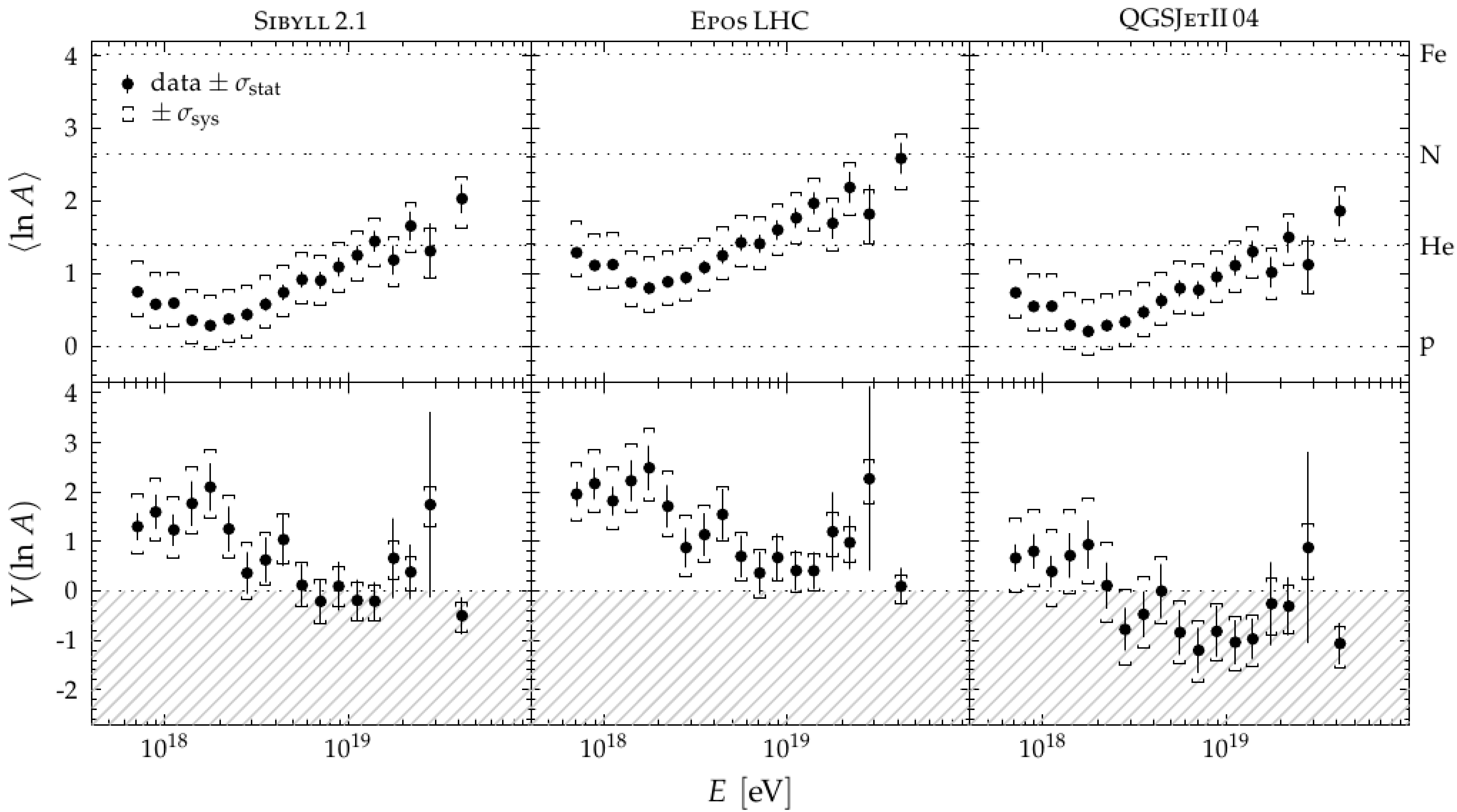
Warning

In the following slides the interpretation presented depends on hadronic interaction models

CONEX v4r37 : EPOS-LHC QGSJetII-04 Sibyll 2.1



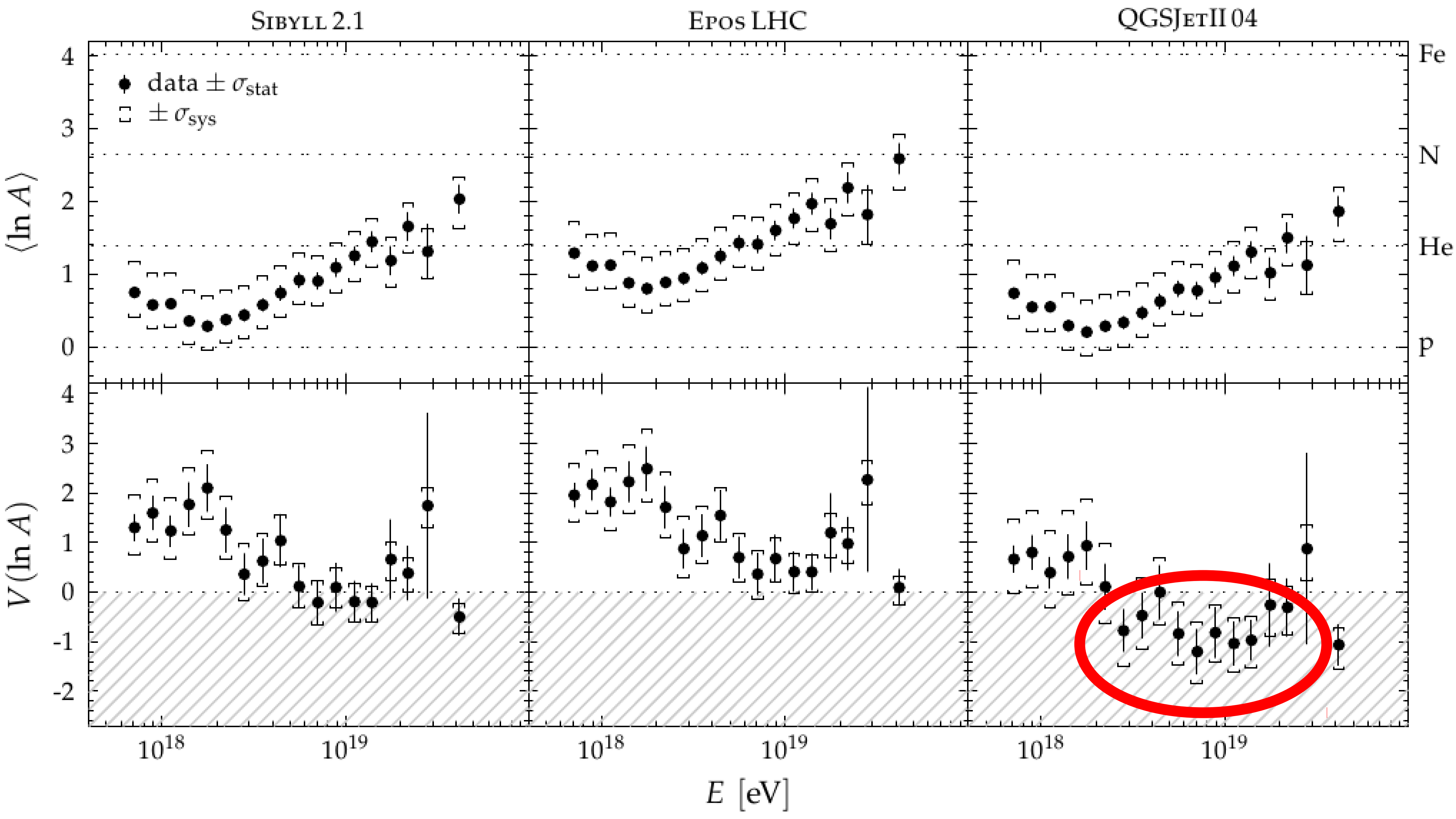
Sibyll 2.1
Epos LHC
QGSJetII 04
data $\pm \sigma_{stat}$
$\pm \sigma_{sys}$
$\langle \ln A \rangle$
$V(\ln A)$
Fe
N
He
p
10^{18}
10^{19}
E [eV]



V (ln A) measures the purity of the sample:

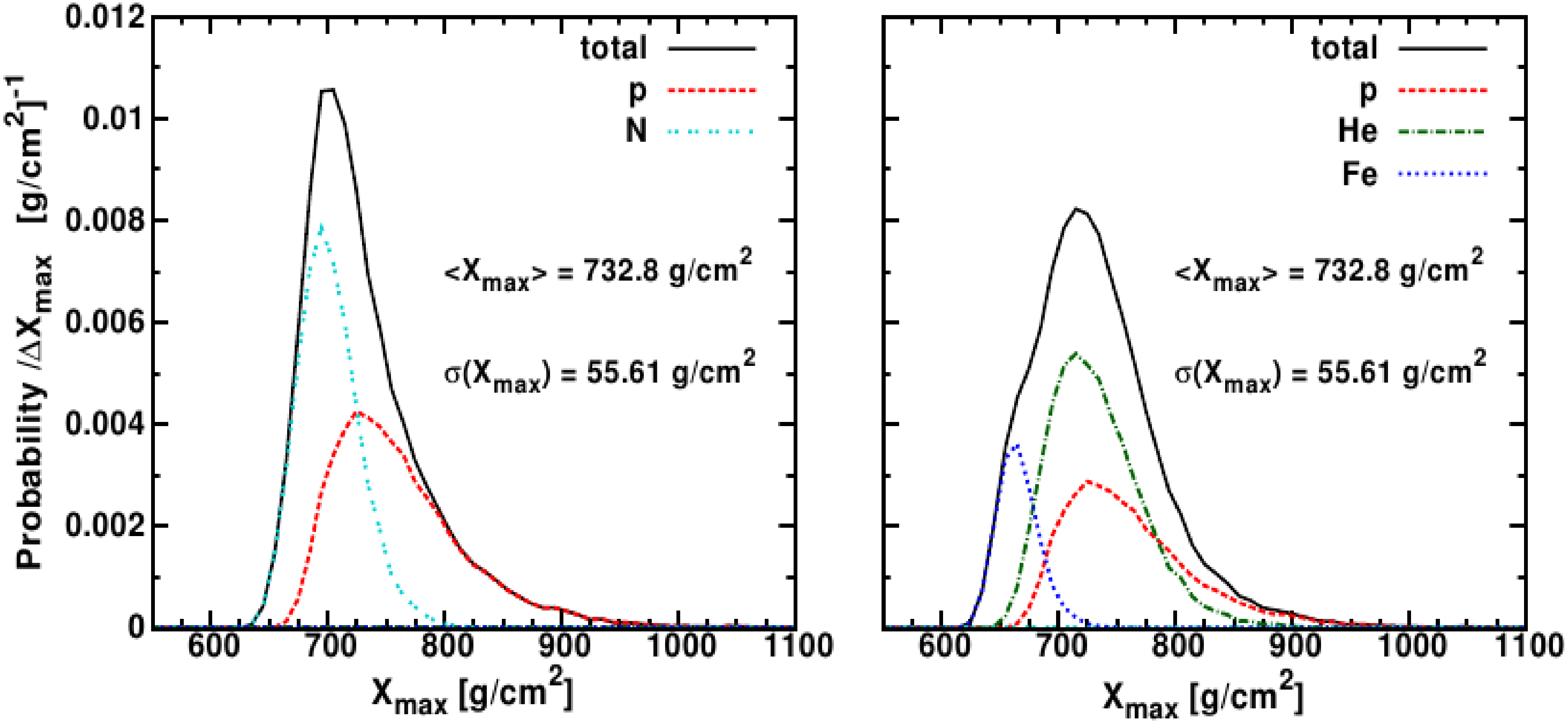
- pure Pr or pure Fe or pure anything → *V(ln A)* = 0
- 50:50 Pr:Fe → *V(ln A)* ≈ 4

J. Lisley, ICRC 1985



SIBYLL 2.1
EPOS LHC
QGSJETII 04
data ± σ_{stat}
± σ_{sys}
Fe
N
He
p
⟨ln A⟩
V(ln A)
4
3
2
1
0
-1
-2
10^{18}
10^{19}
E [eV]

from moments to full distribution



example of different distributions with the same moments

fitting abundances

simulated air shower including the detector response

2×10^4 showers
per energy bin

Proton
Helium
Nitrogen
Iron

s

Pr + Fe

Pr + N + Fe

Pr + He + N + Fe

In each bin of energy
Log Likelihood fit

$$L = \prod_j \left[\frac{e^{-C_j} C_j^{n_j}}{n_j!} \right]$$

fraction of
each species

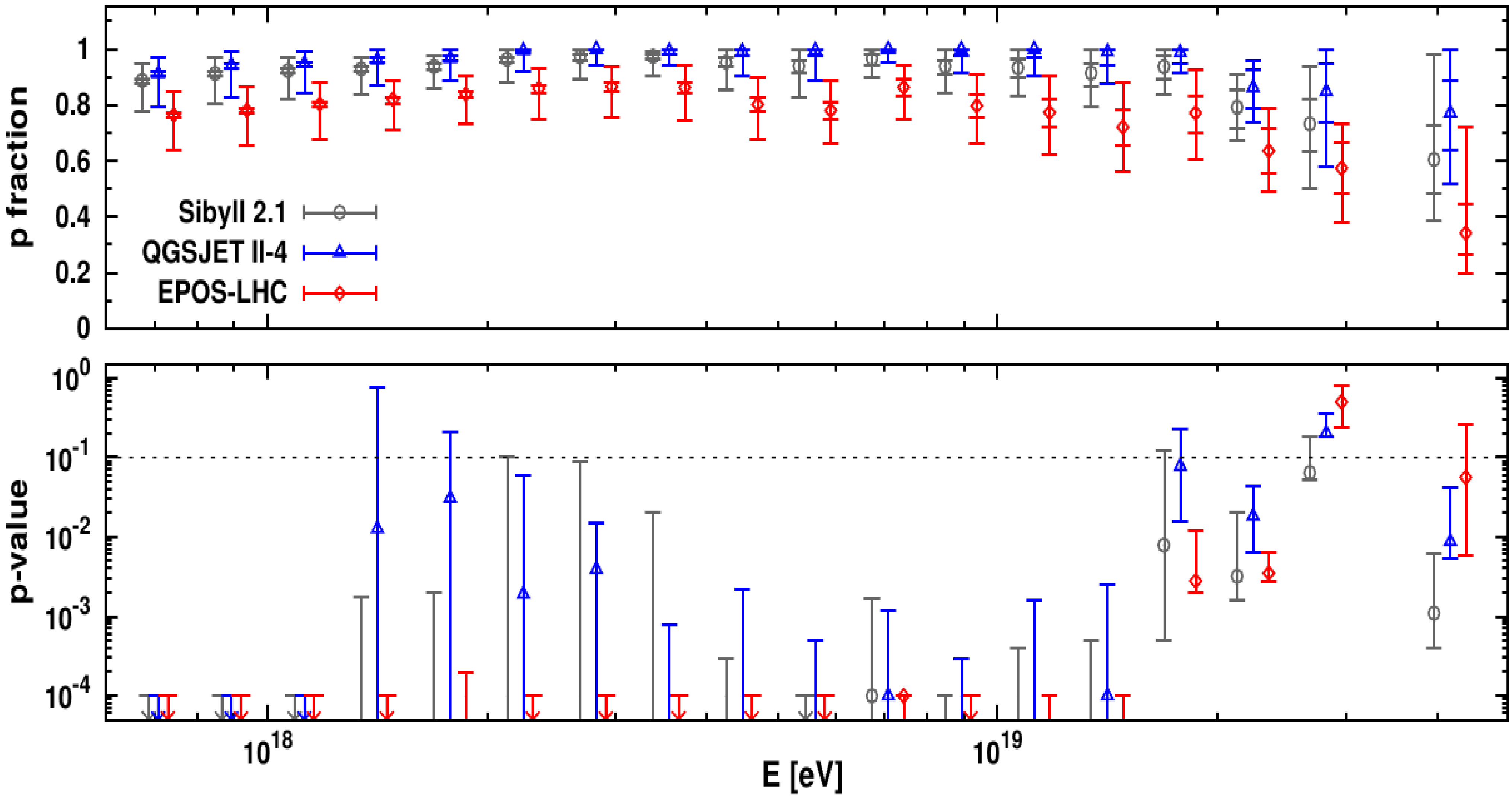
$$C_j = \frac{N_{data}}{N} \sum_s f_s X^{\mathrm{m}}_{s,j}$$

j = index of Xmax bin

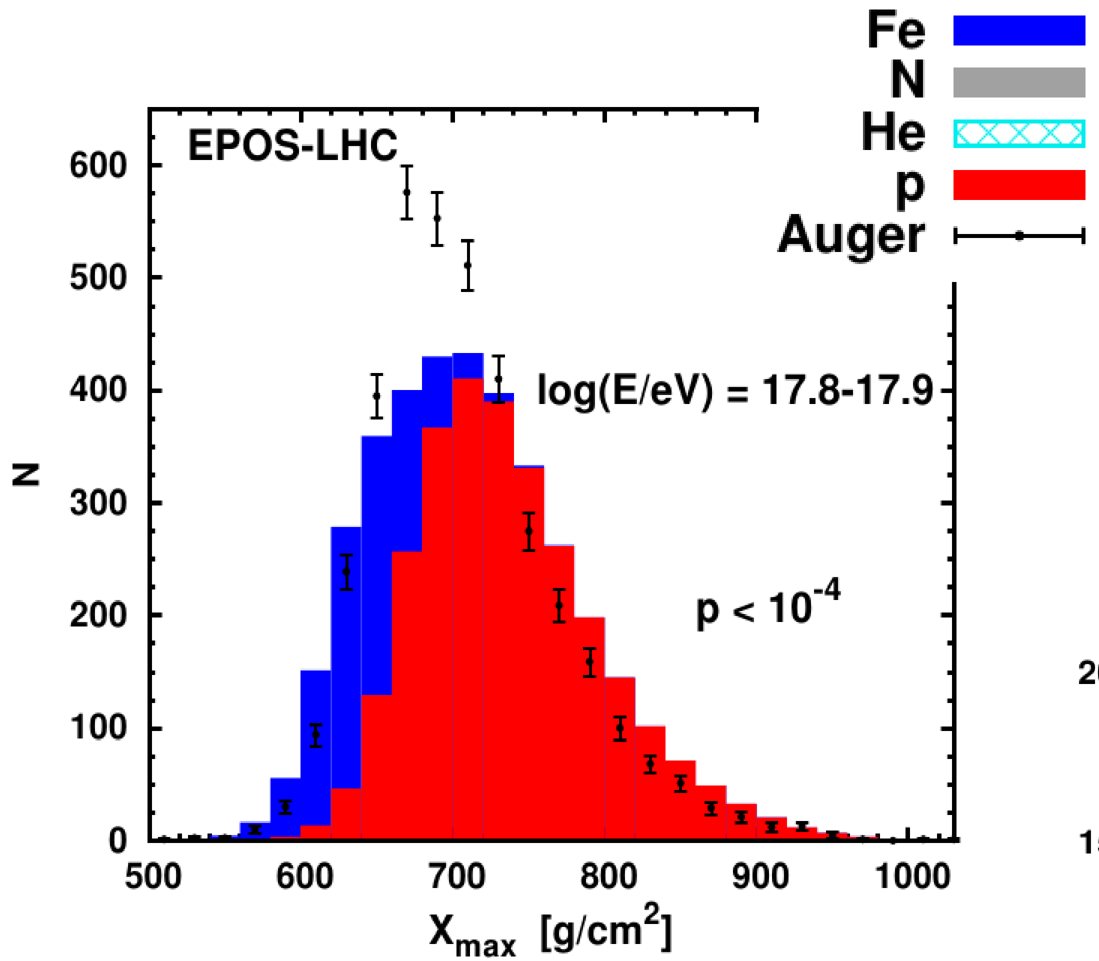
n_j = measured number of shower

C_j = Simulation prediction

proton + iron



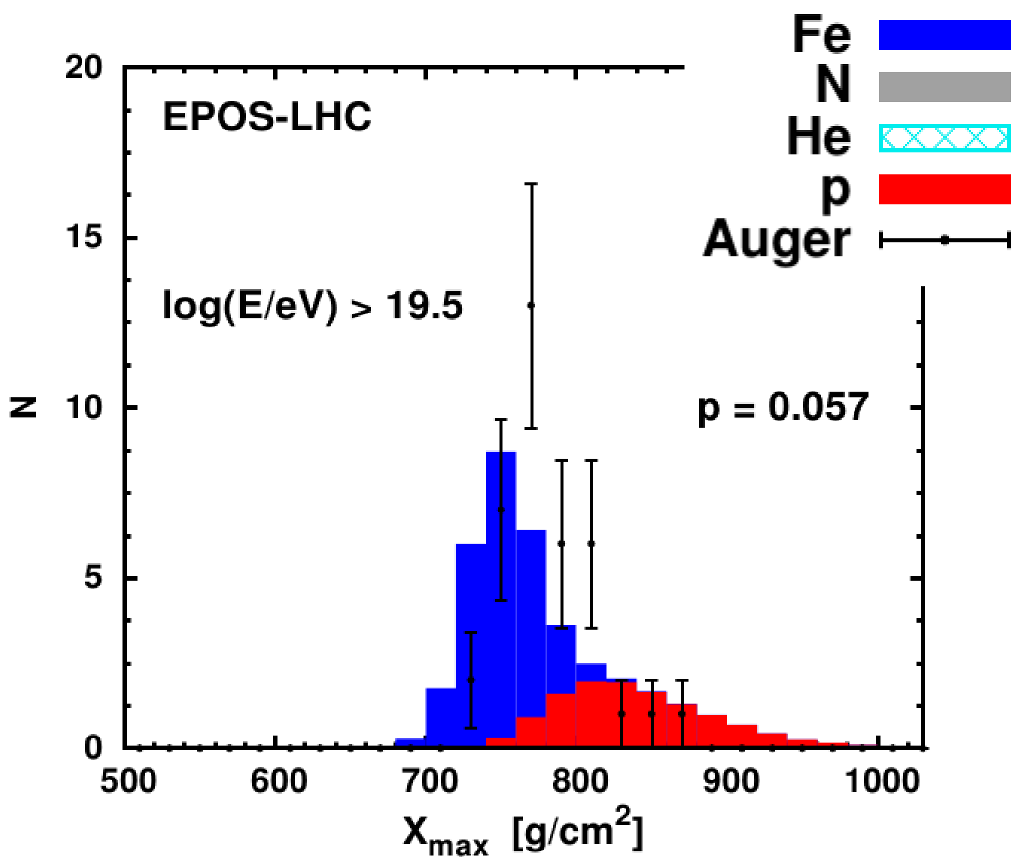
Very poor agreement with the data



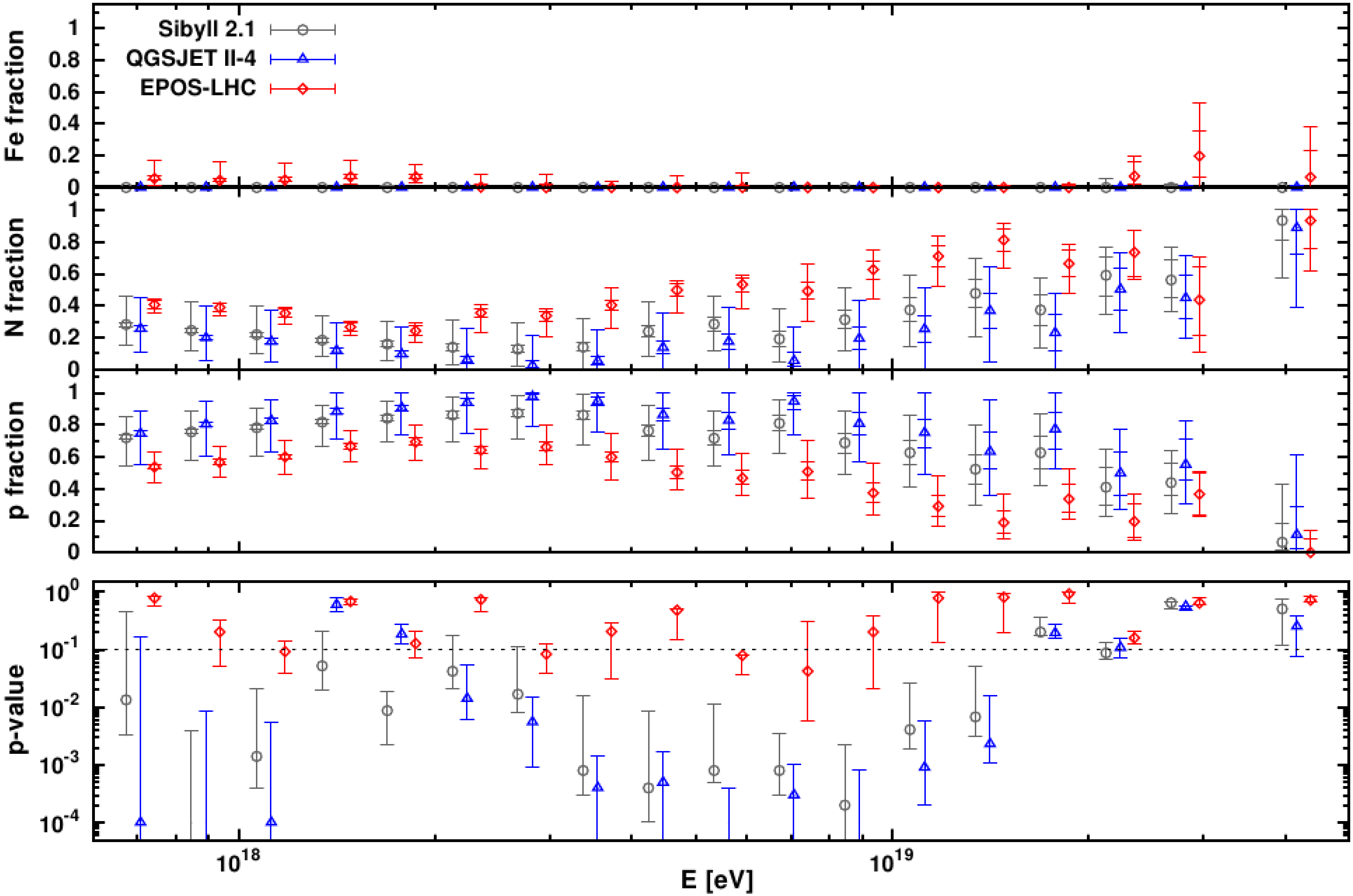
proton + iron

Similar picture for all hadronic interaction models

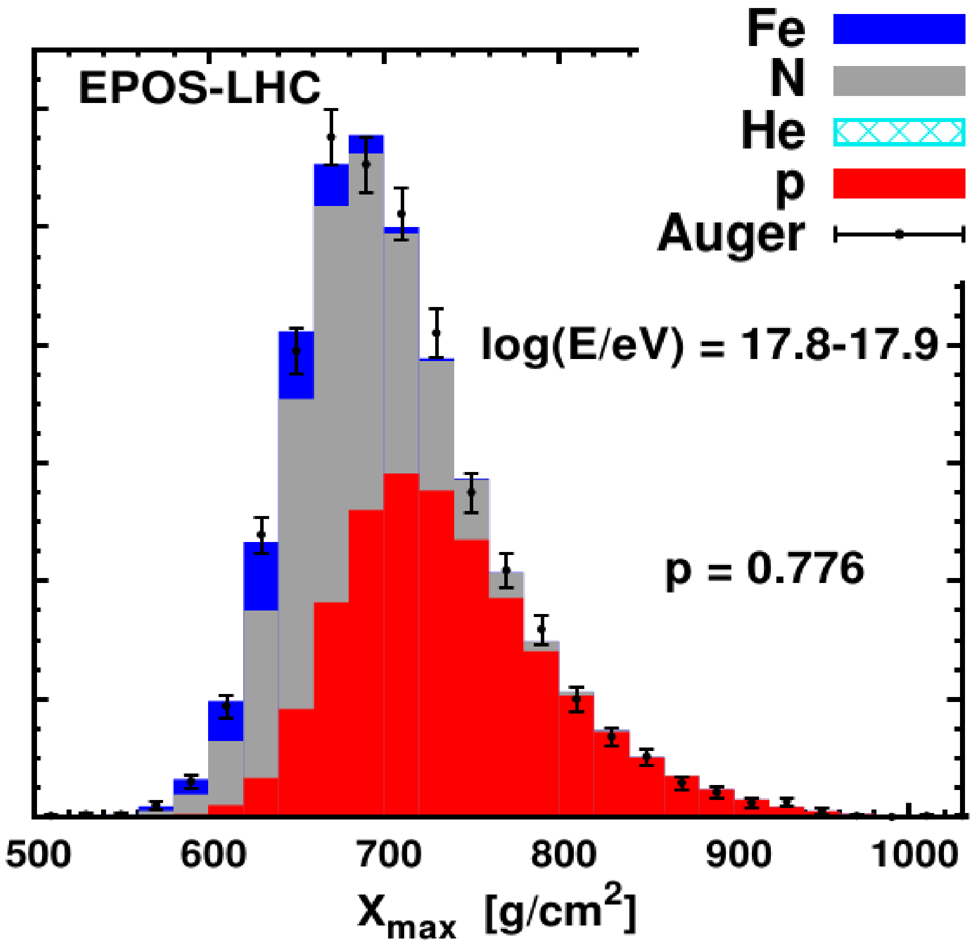
Very poor agreement with the data for most energy bins



proton + nitrogen + iron

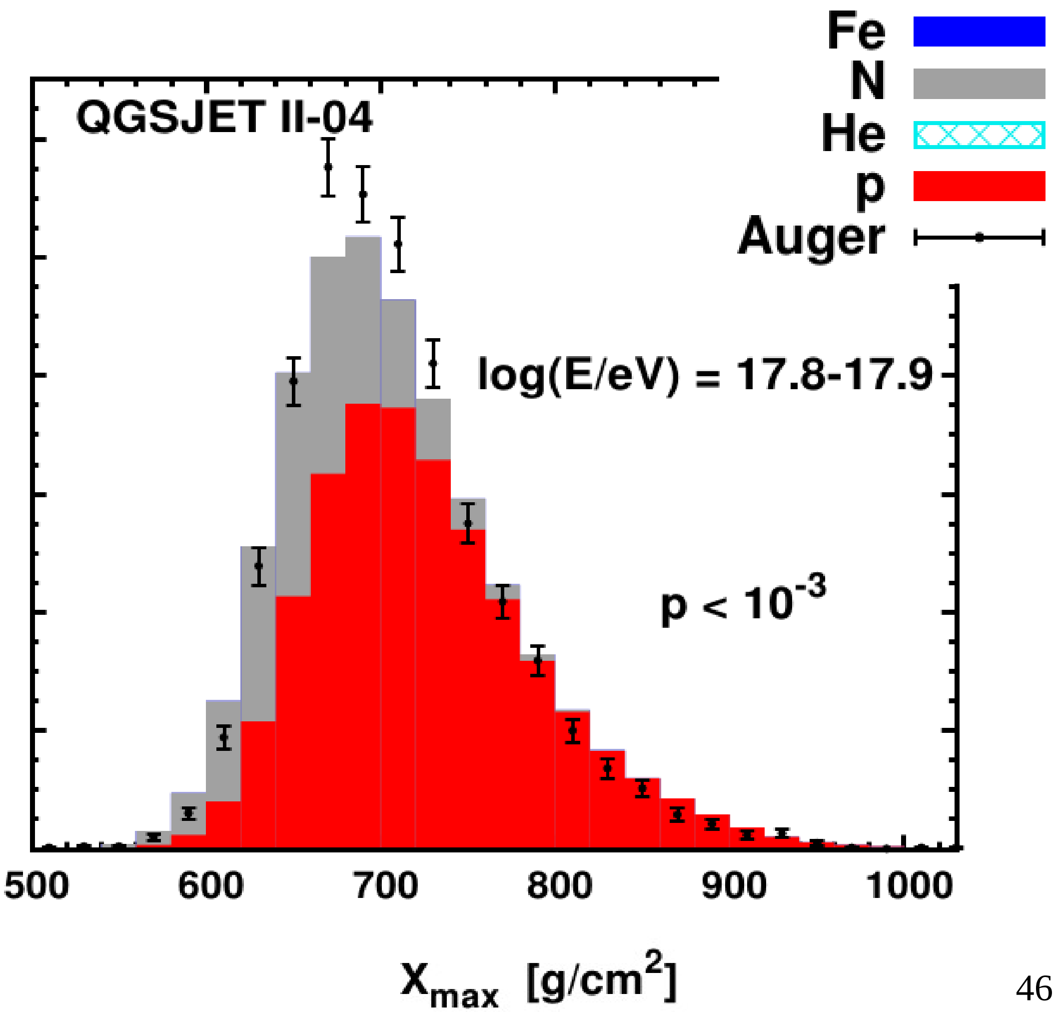


acceptable /poor agreement with the data



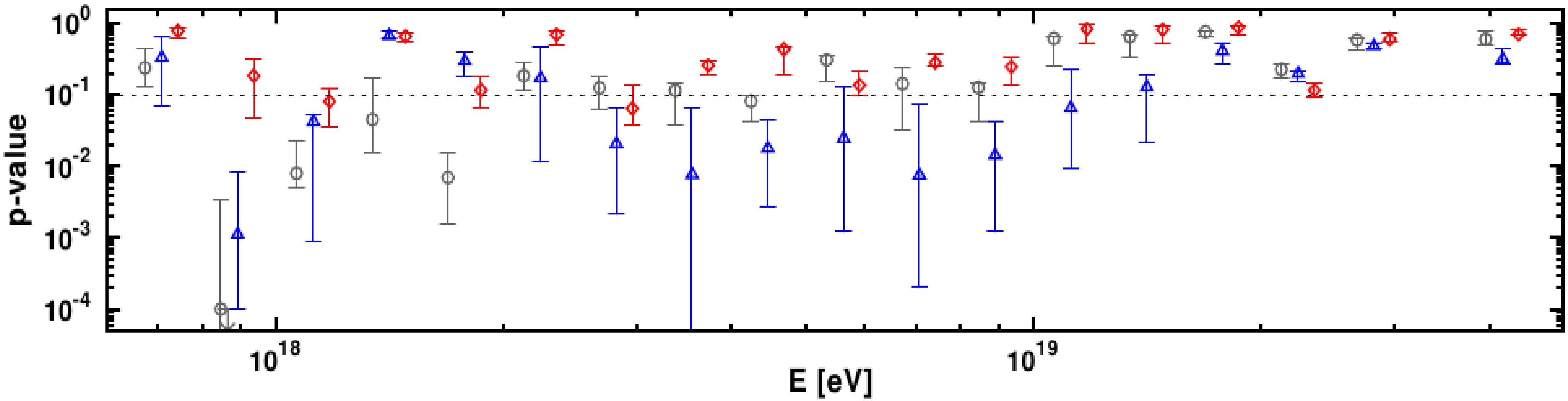
proton + nitrogen + iron

EPOS-LHC describes
the data best



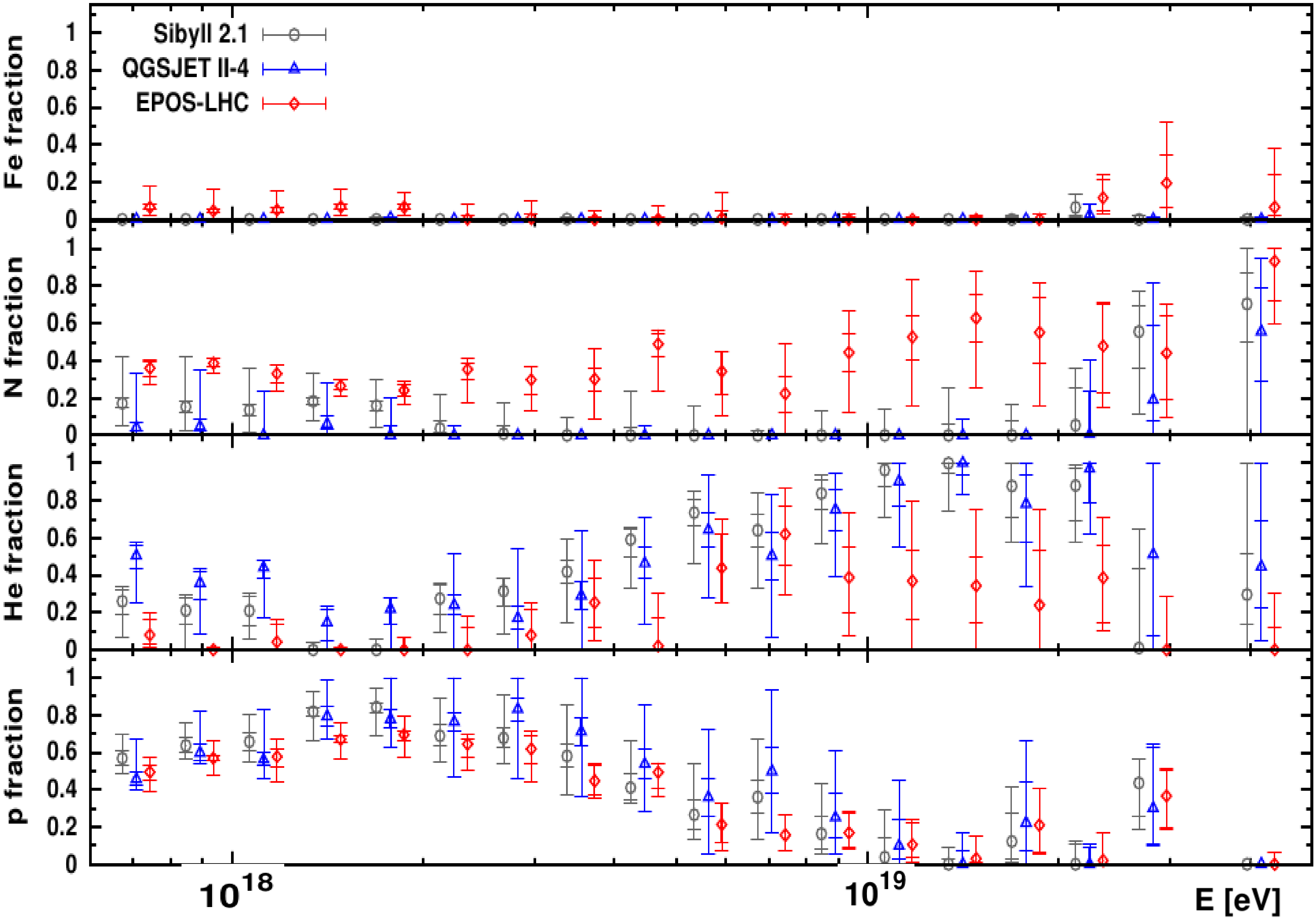
acceptable/poor
agreement with
the data

proton + helium + nitrogen + iron

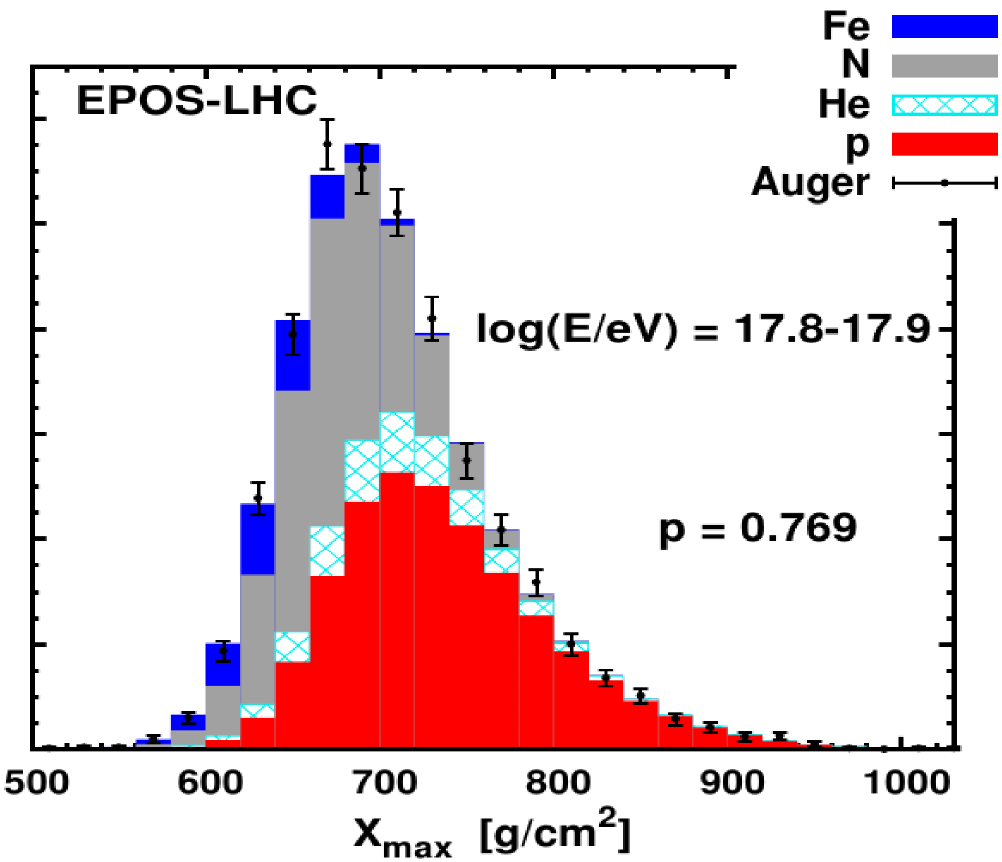


acceptable/good agreement with the data

proton + helium + nitrogen + iron

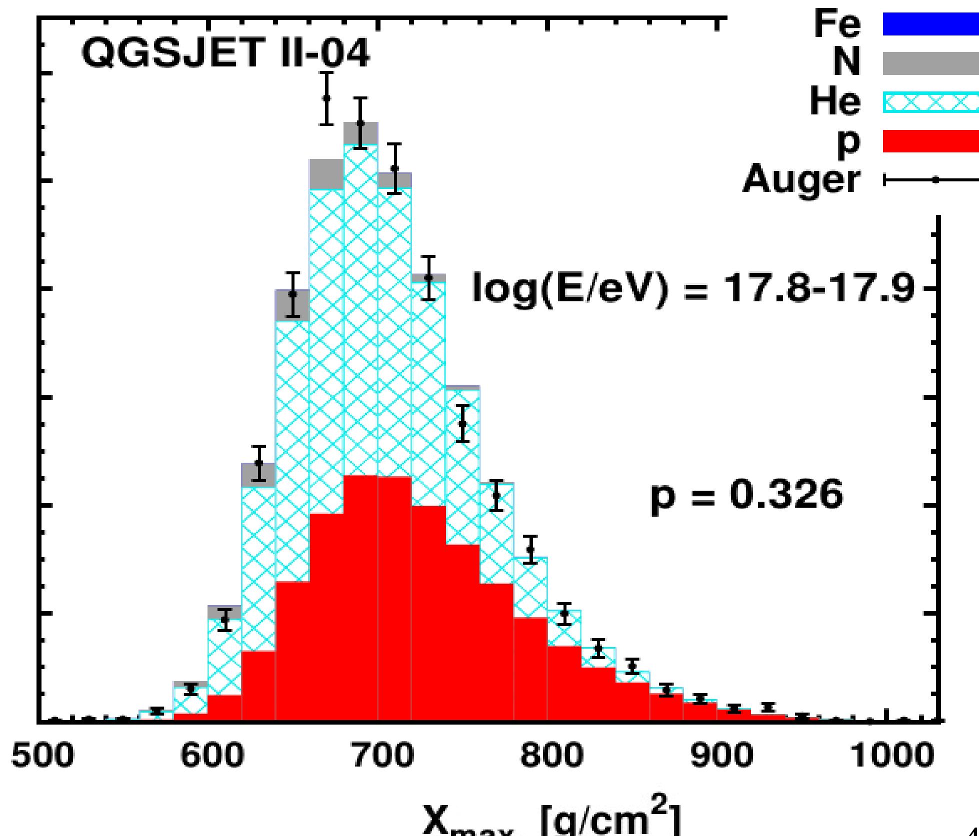


proton + helium + nitrogen + iron



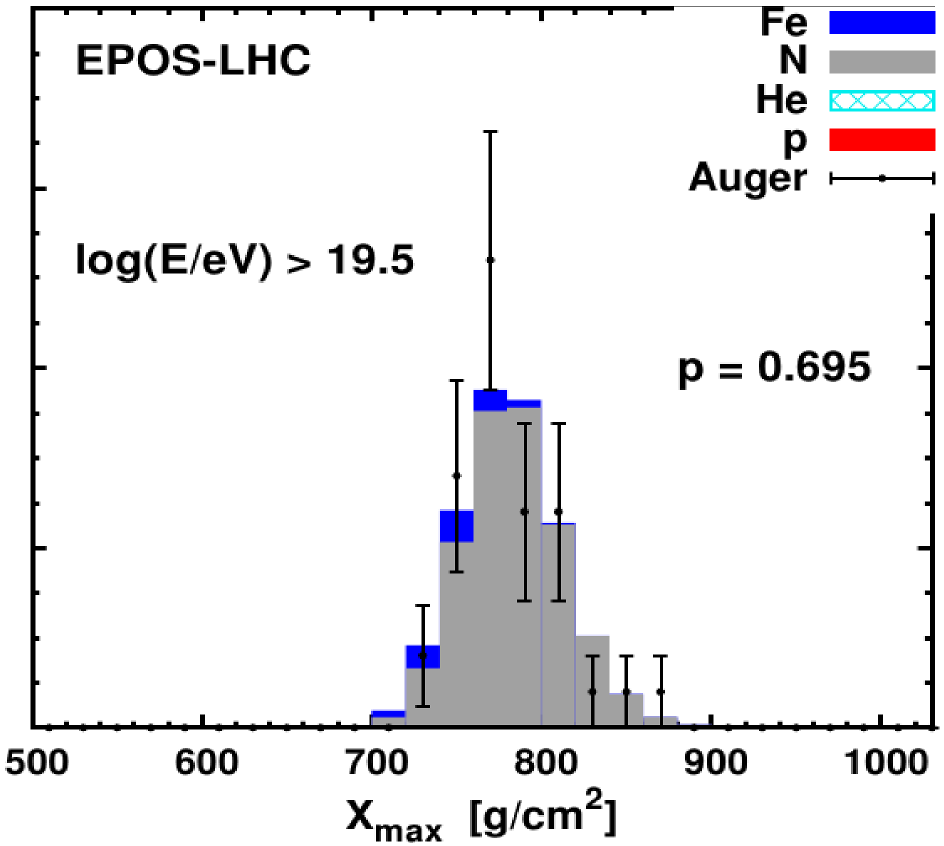
EPOS-LHC describes the data best

QGSJet II-04 describes the data worst



acceptable/good agreement with the data

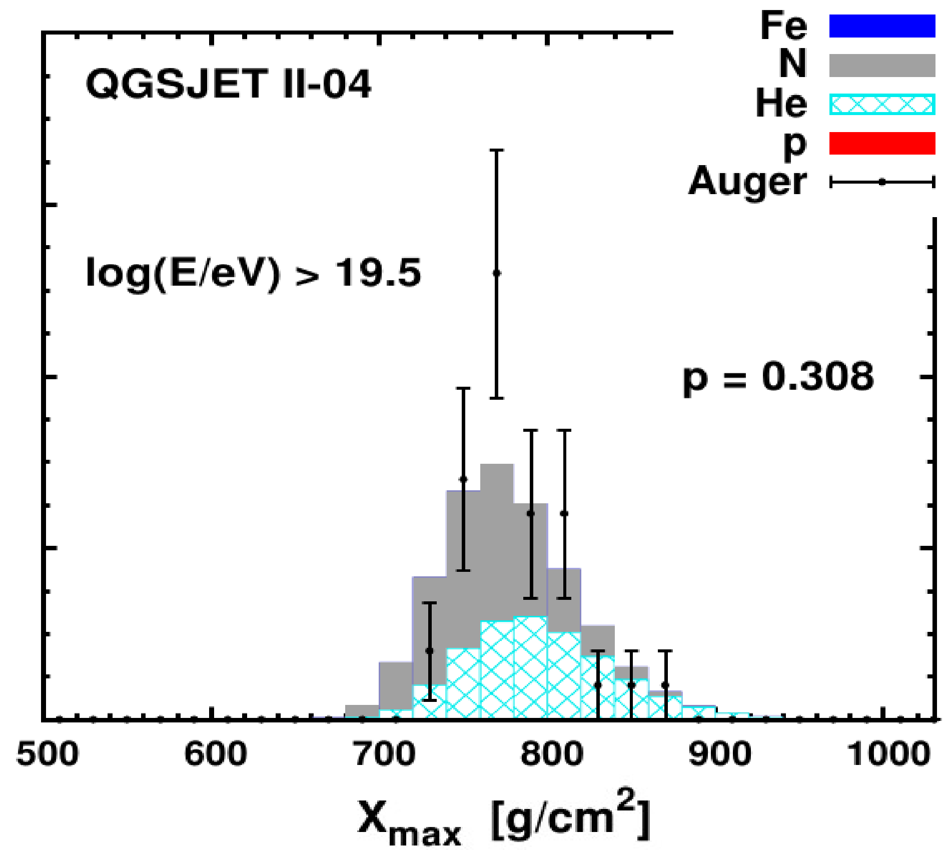
proton + helium + nitrogen + iron



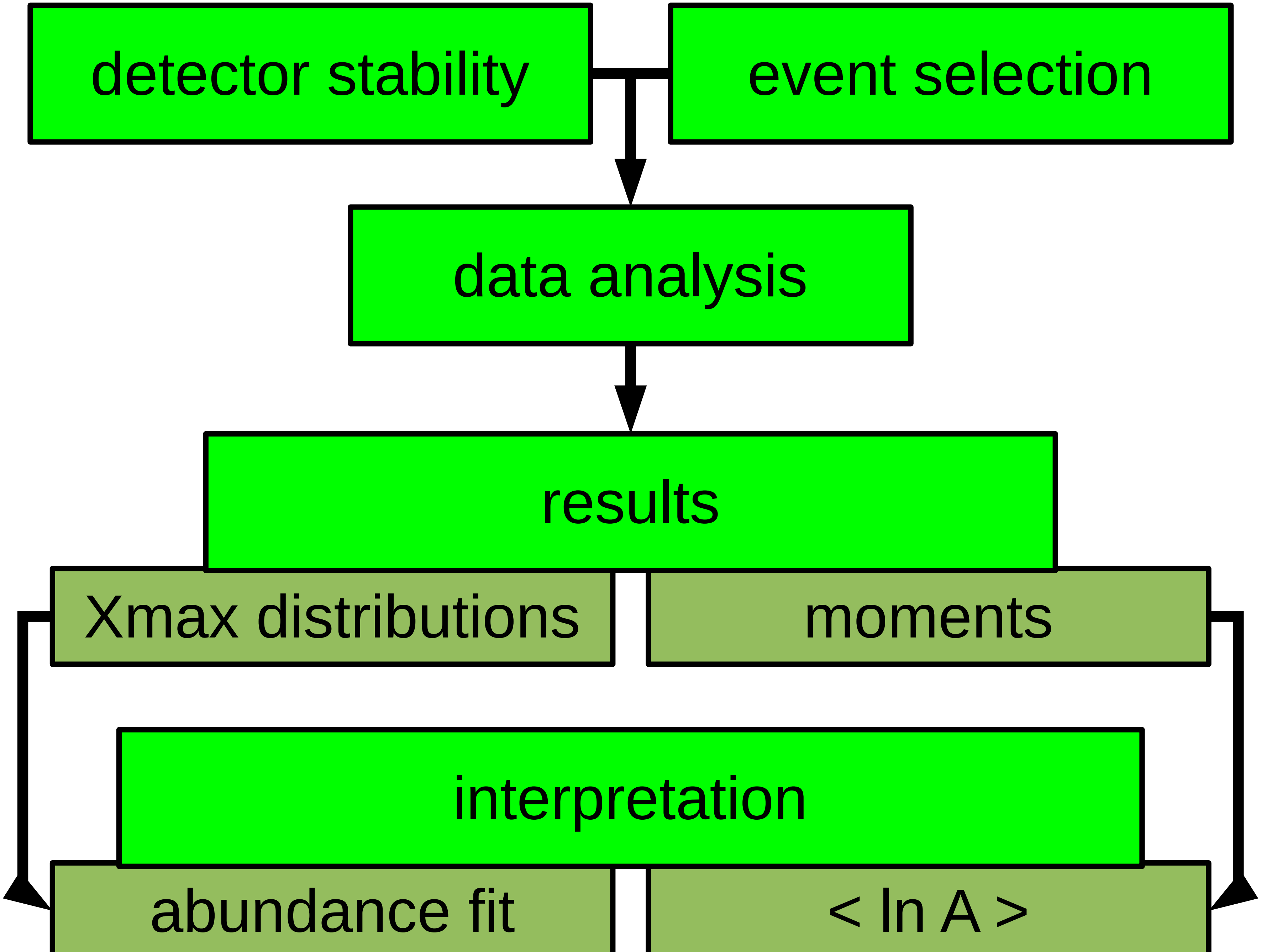
EPOS-LHC describes the data best

QGSJet II-04 describes the data worst

acceptable/good agreement with the data



outline


detector stability
event selection
data analysis
results
Xmax distributions
moments
interpretation
abundance fit
< ln A >

final remarks

- data
  - all information is public: distributions, resolution, systematics and acceptance
  - largest statistics with controlled systematics
- Xmax moments
  - confirms previous findings
  - improved cross-checks
  - showers with $E > 10^{18.27}$ eV are shallower and fluctuate less than proton simulations

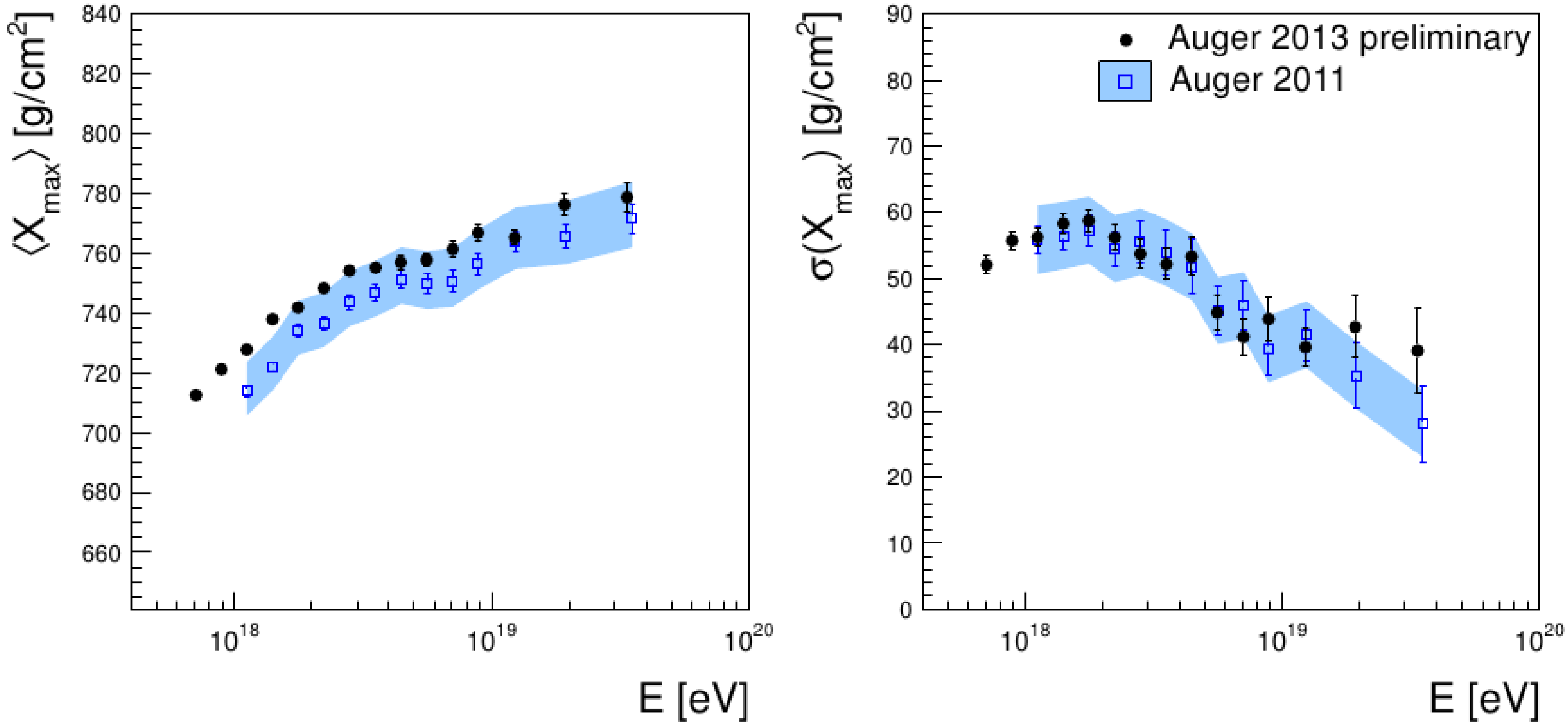
final remarks

- $< \ln A >$ – EPOS-LHC, QGSJet II-04 and Sibyll 2.1
  - E < $10^{18.3}$ eV: $< \ln A >$ decreases with increasing energy
  - E > $10^{18.3}$ eV: $< \ln A >$ increases with increasing energy
  - V (ln A) rather pure composition around 10^{19} eV
  - V (ln A) < 0 for QGSJet II-04 (within 2 sigma)

- abundance fit – EPOS-LHC, QGSJet II-04 and Sibyll 2.1
  - mixed flux: light + intermediate + heavy is favored
  - proton flux decreases with increasing energy
  - no significant amount of iron nuclei is detected
  - EPOS-LHC describes the data best
  - QGSJet II-04 describes the data worst

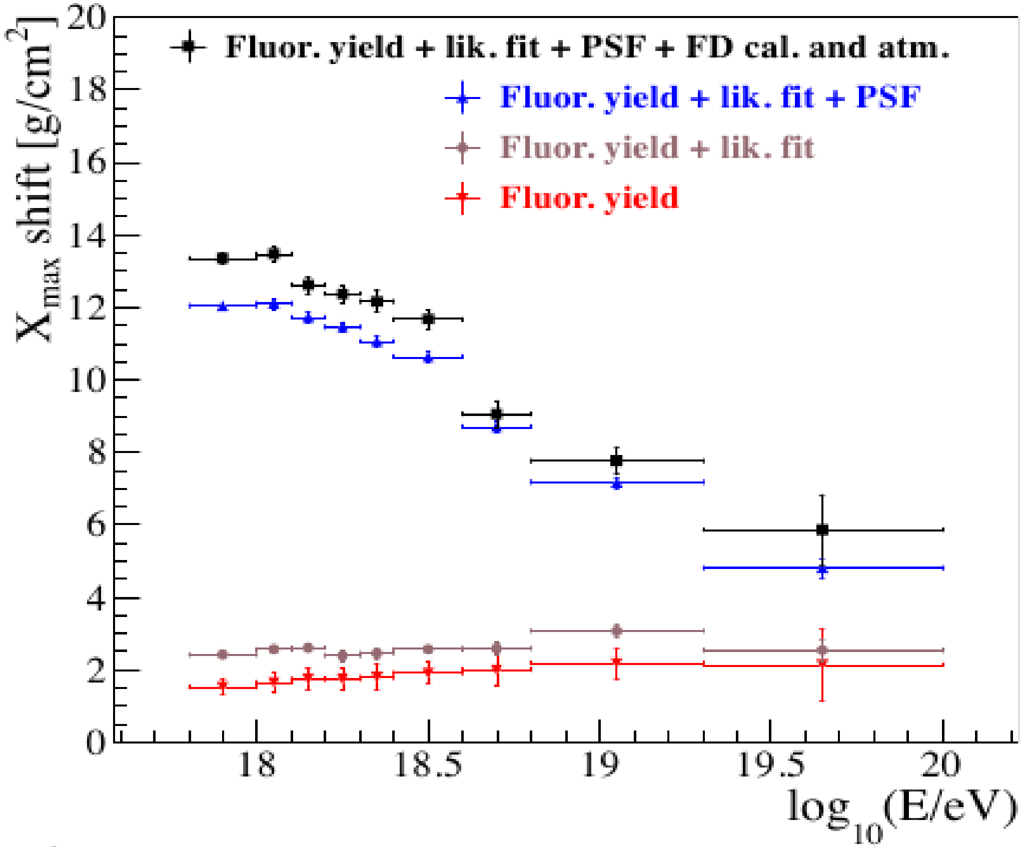
extras

comparison to previous results



Update of X_{max} Results

accumulated effect of **improved reconstruction and calibration**†:



most important change:

convolution of point spread function‡ with lateral shower width

$\rightarrow \Delta X_{max} \sim +10$ g/cm^2 at low energies

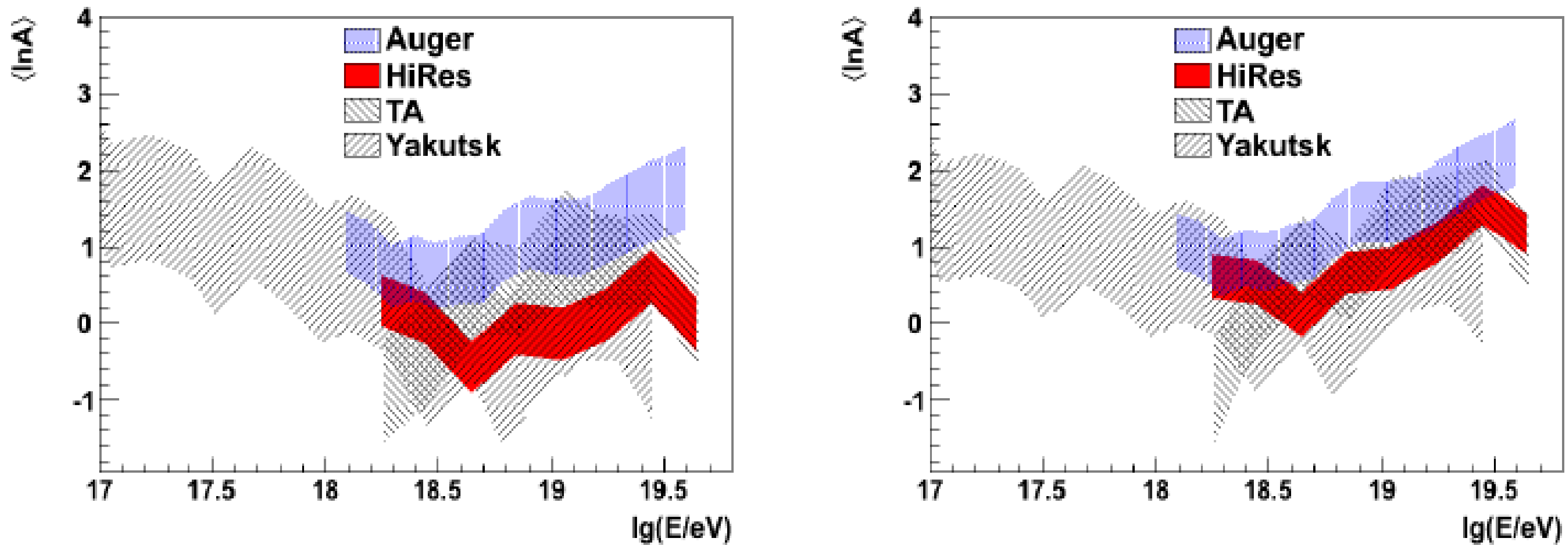
† V. Verzi for the Auger Collab., ICRC #0928, ‡ J. Bäuml for the Auger Collab., ICRC #0806

Slide by M. Unger for the Pierre Auger Collaboration - ICRC2013

Mass Composition Working Group Report

E. Barcikowski[1], J. Bellido[2a], J. Belz[1], Y. Egorov[3], S. Knurenko[3], V. de Souza[4], Y. Tsunesada[5], and M. Unger[6] for the HiRes, Pierre Auger, Telescope Array and Yakutsk Collaborations

UHECR2012: International Symposium on Future Directions in UHECR Physics

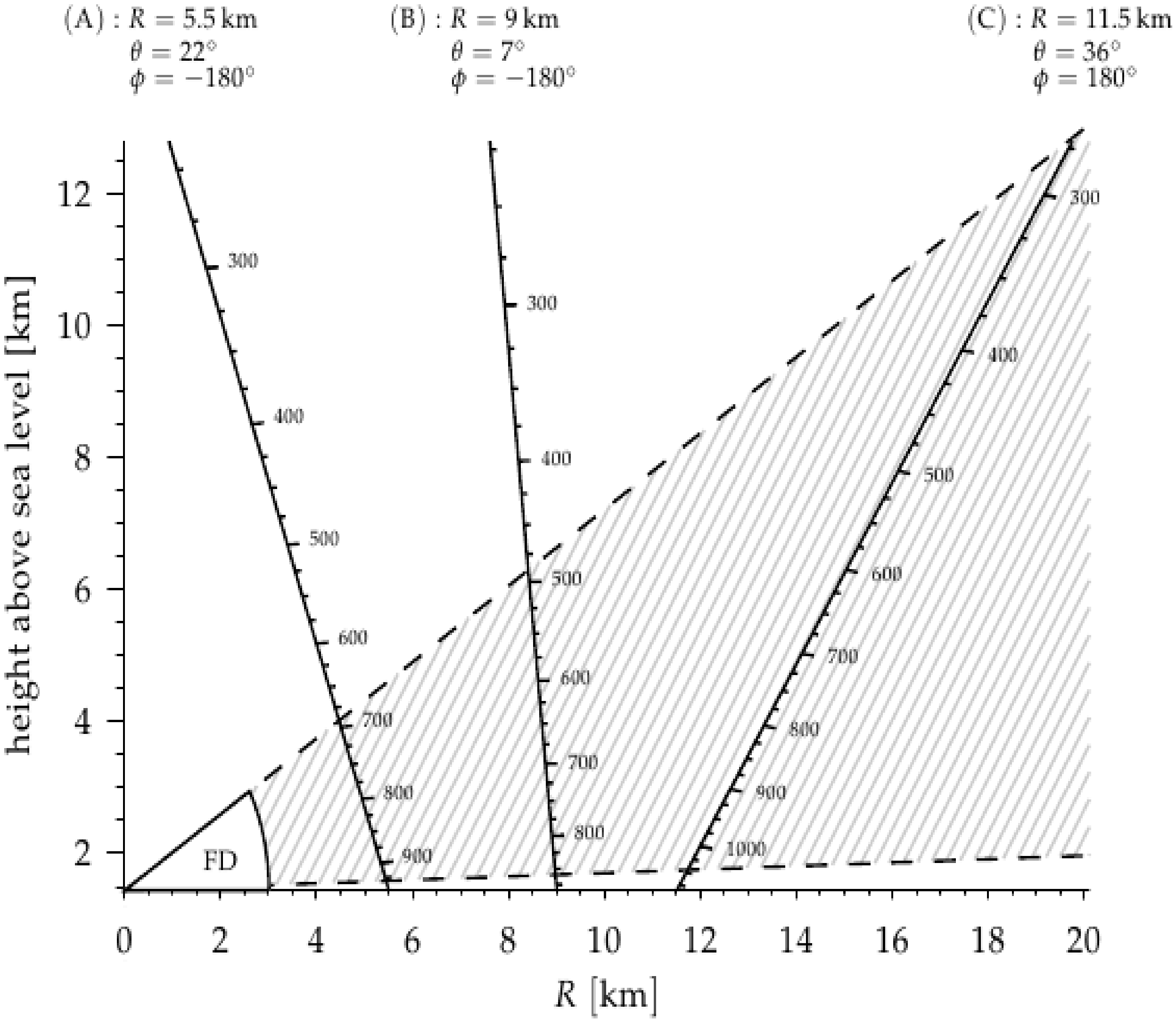


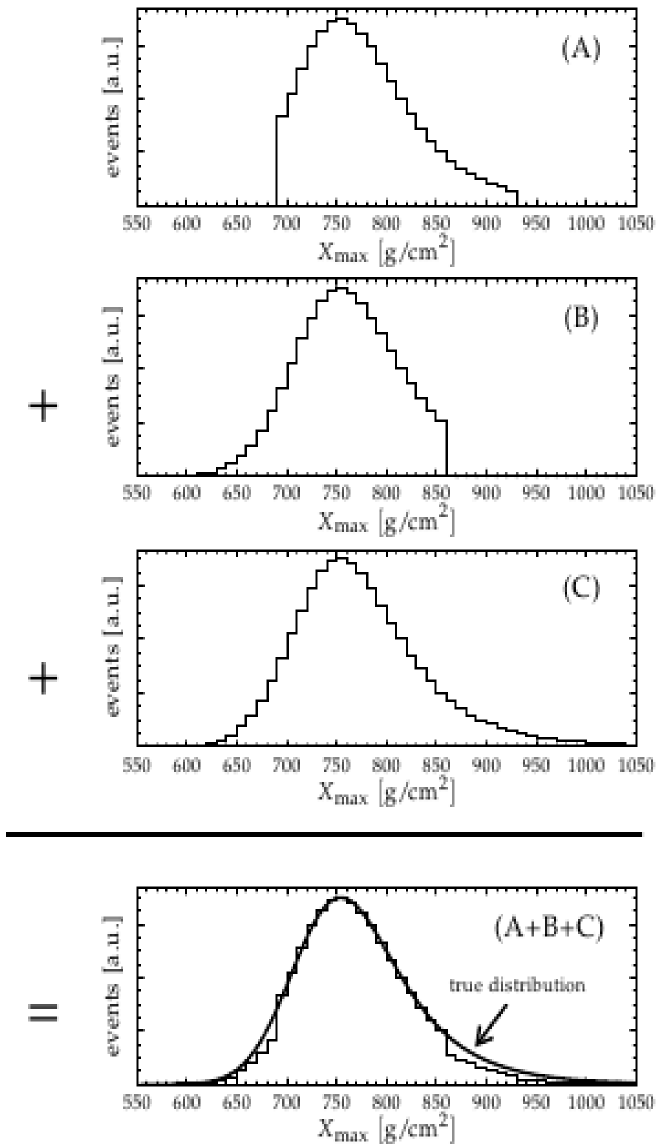
(a) using QGSJet-II model.

(b) using SIBYLL model.

Fig. 11. Comparing the average composition (⟨lnA⟩) estimated using Auger, HiRes , TA and Yakutsk data. The shaded regions correspond to the systematic uncertainty ranges. To infer the average composition from $\langle X_{\max} \rangle$, QGSJet-II and SIBYLL models have been used.

fiducial field of view

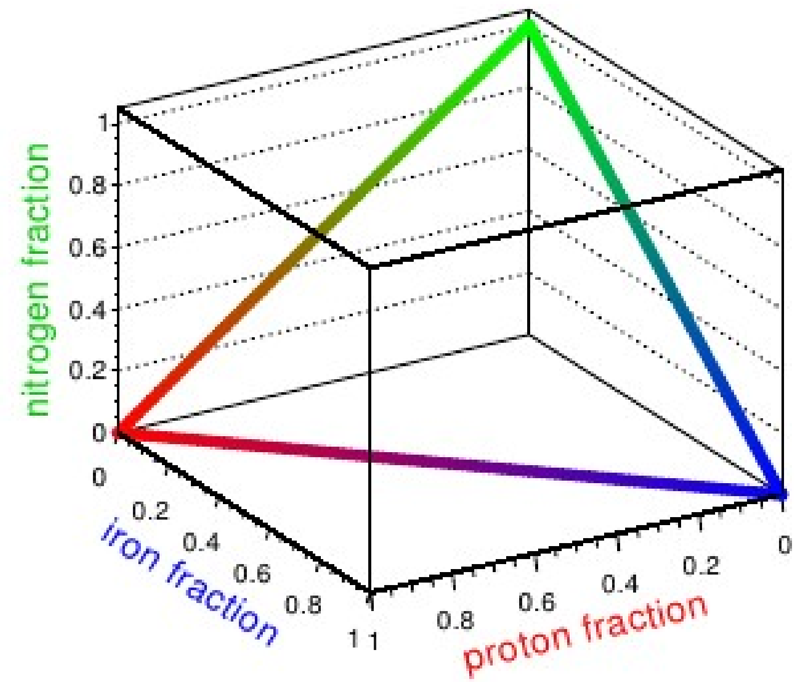


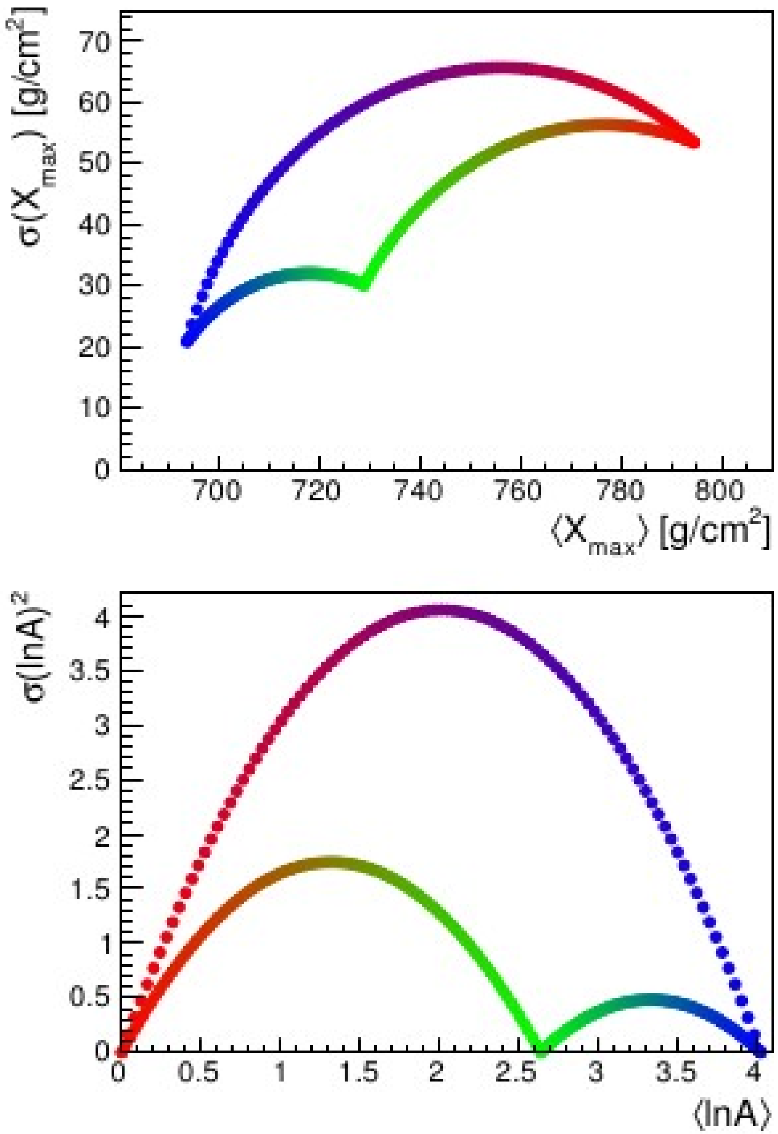


$\langle \ln A \rangle$ vs. $\sigma^2_{\ln A}$

transition:

- p → Fe
- p → N
- N → Fe





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