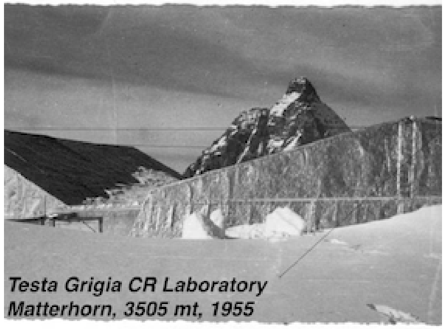


XXV ECRS 2016
Torino - Italy

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

PIERRE AUGER OBSERVATORY

The Pierre Auger Collaboration

Av. San Martin Norte 304, 5613 Malargüe, Argentina

http://www.auger.org/archive/authors_2016_08.html

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

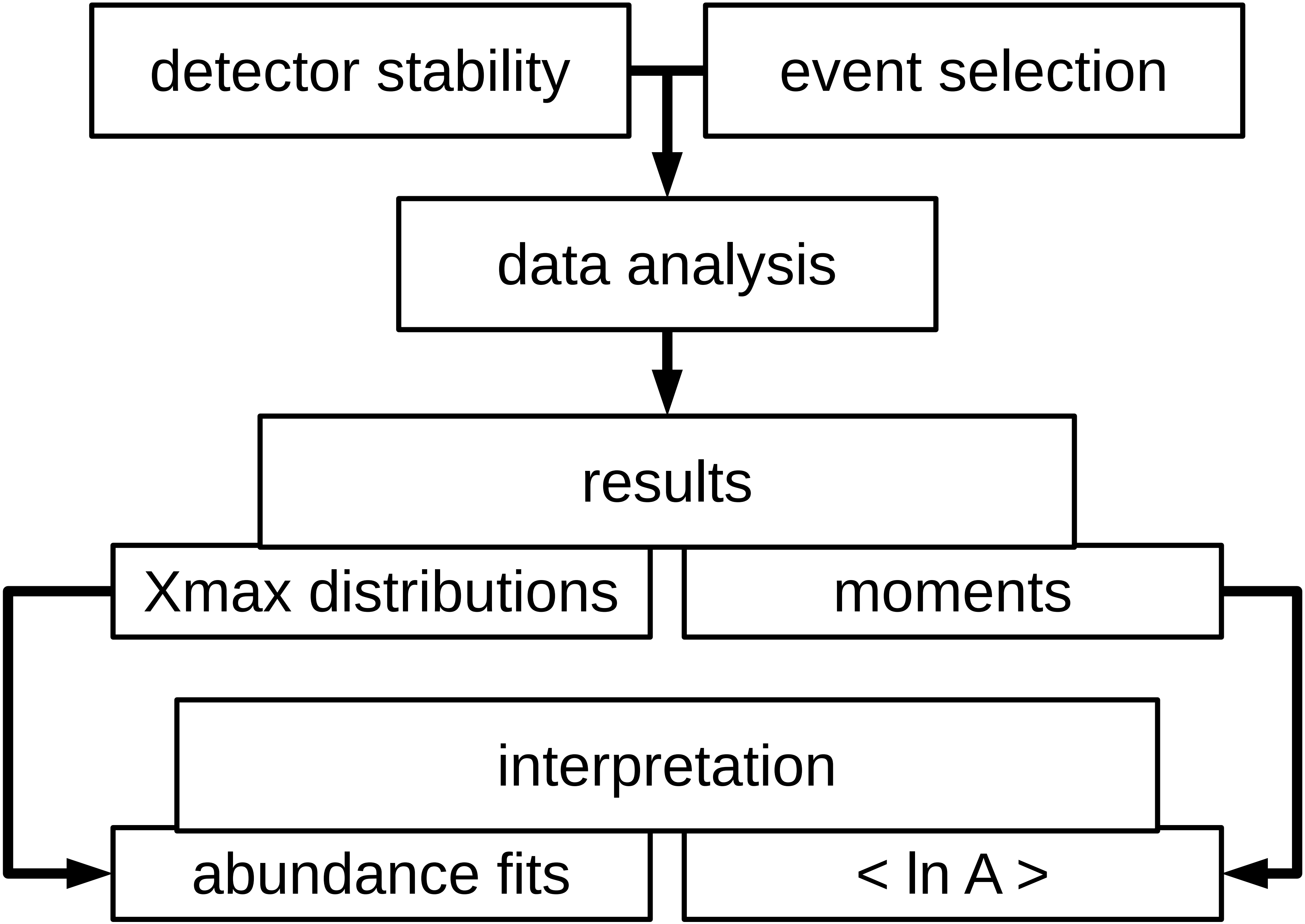
background

Depth of Maximum of Air-Shower Profiles at the Pierre Auger Observatory. I. Measurements at Energies above $10^{17.8}$ eV
arXiv:1409.4809
PHYSICAL REVIEW D 90, 122005 (2014)

Depth of Maximum of Air-Shower Profiles at the Pierre Auger Observatory. II. Composition Implications
arXiv:1409.5083
PHYSICAL REVIEW D 90, 122006 (2014)

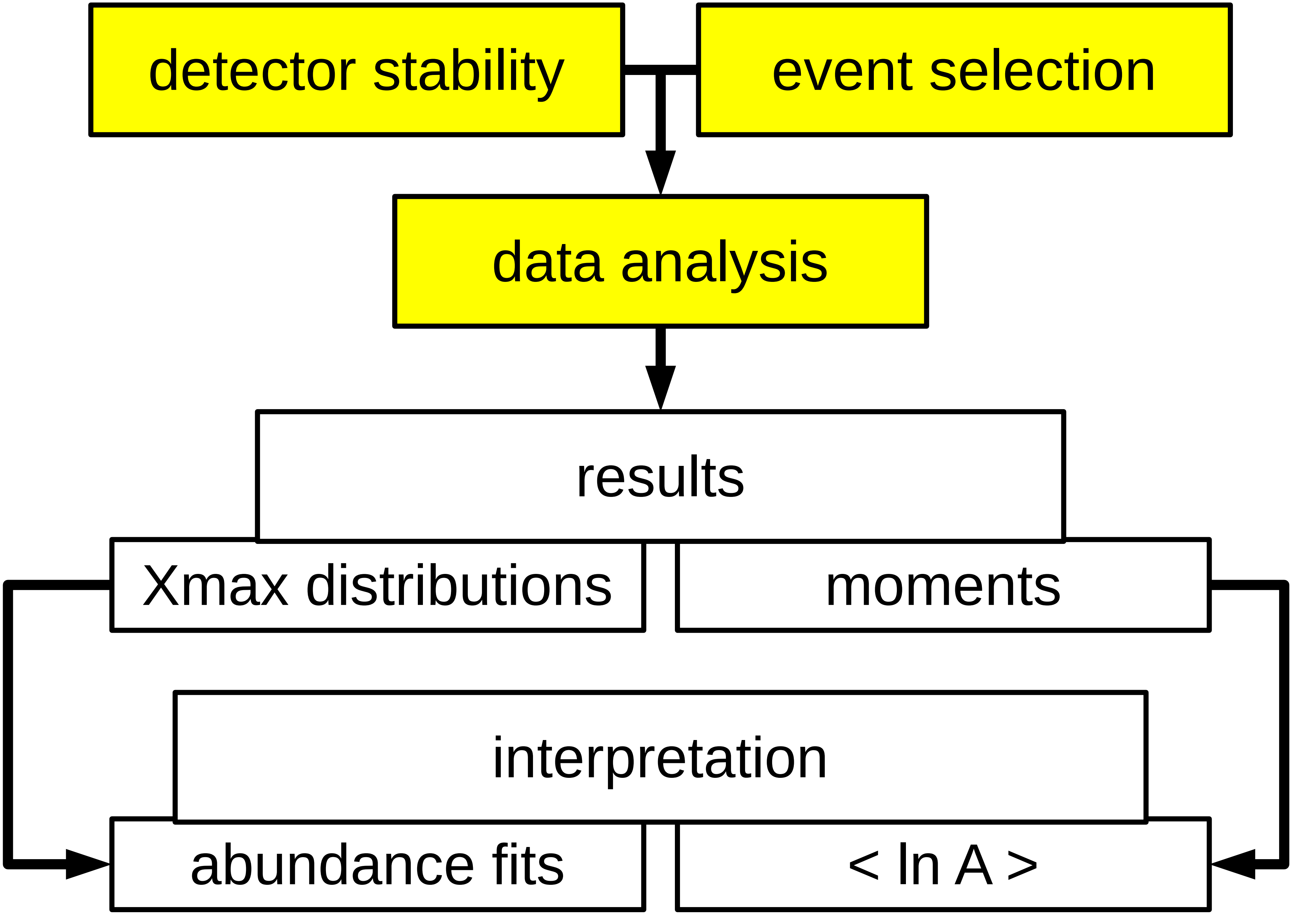
ICRC 2015: **arXiv: 1509.03732**
Speakers: I. Valiño, A. Porcelli, A. Yushkov, A. di Mateo

outline



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

outline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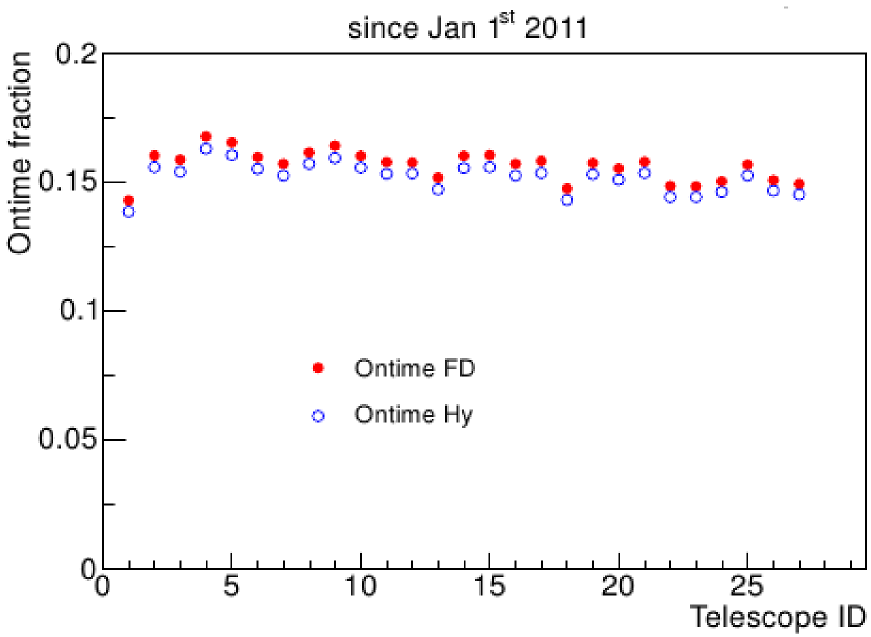
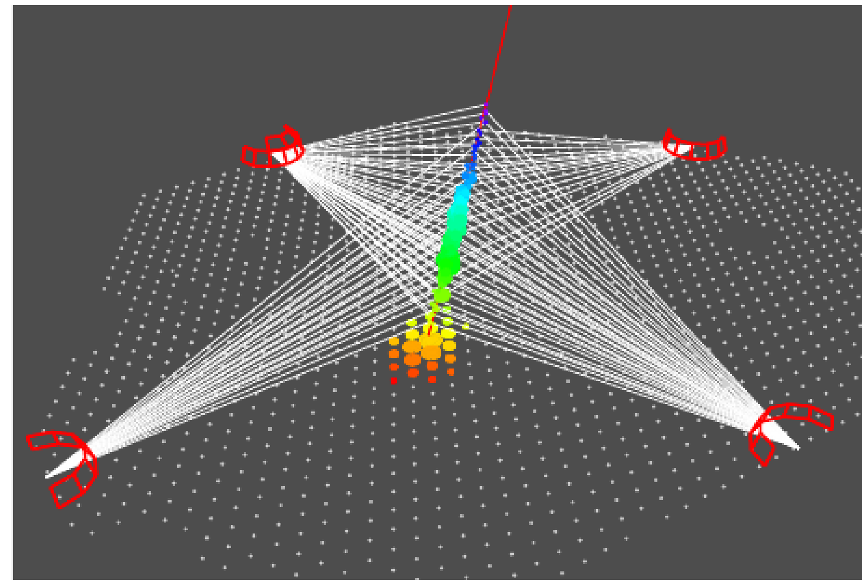
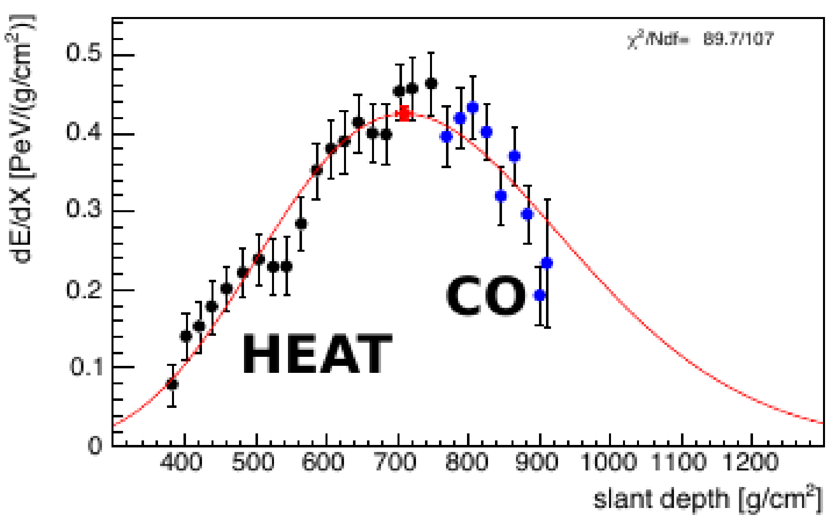
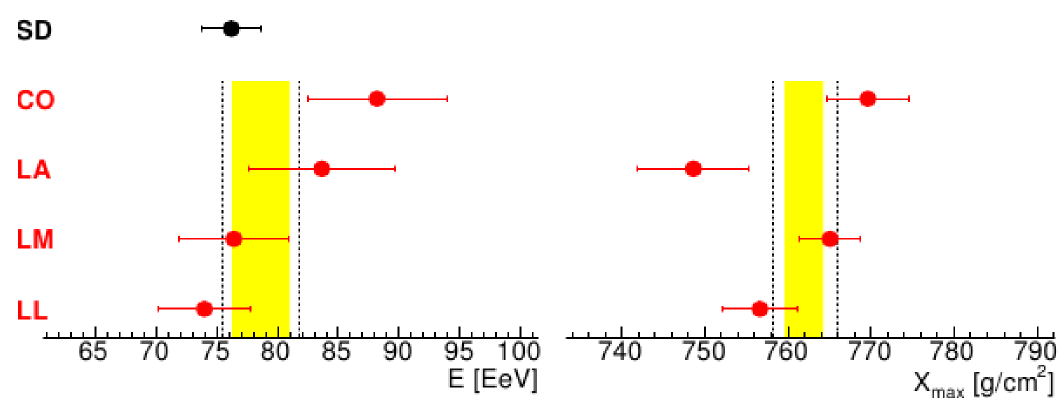
detector stability



24 FD (0-30 deg): 12/04 – 12/12
3 HEAT (30-60 deg): 06/10 – 08/12







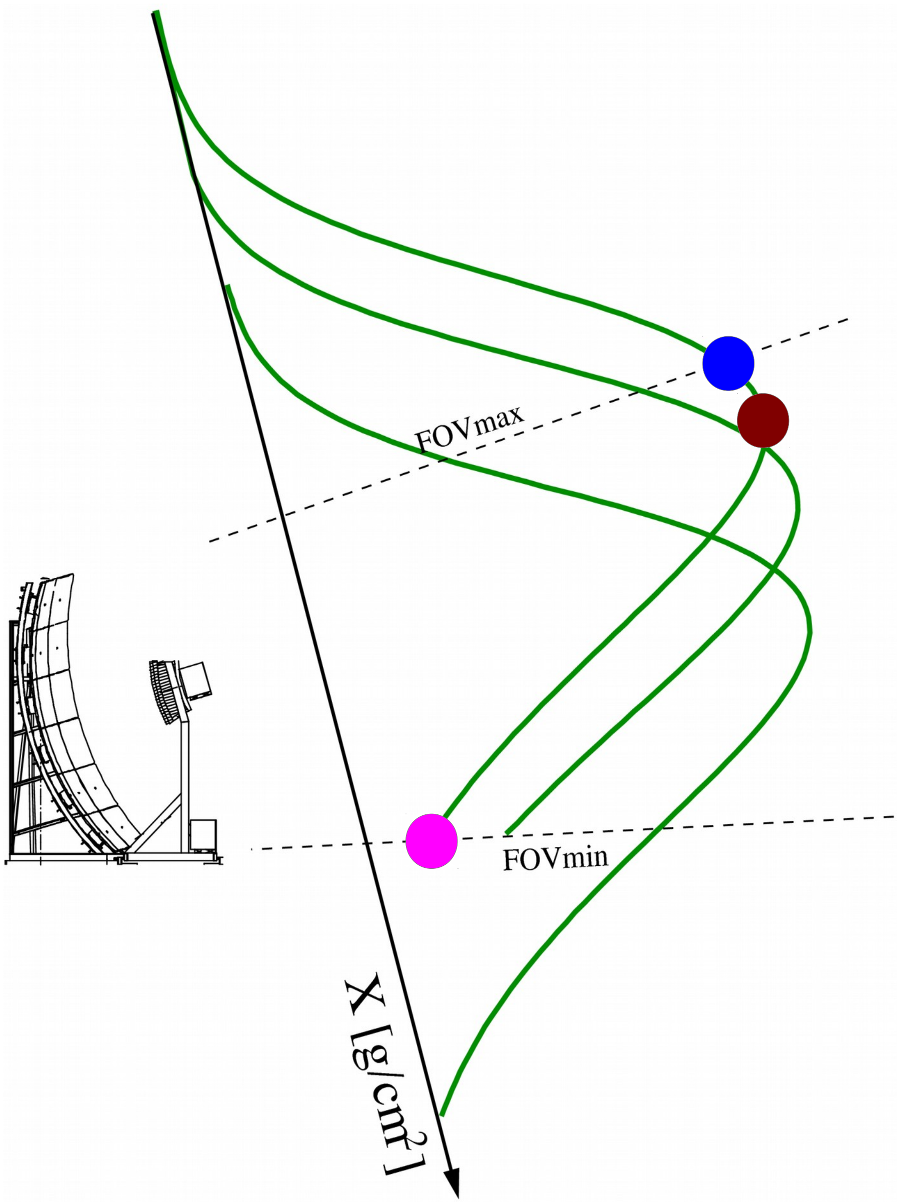
cut	$E > 10^{18}$ eV	events	ε [%]
pre-selection:			
air-shower candidates		2573713	-
hardware status		1920584	74.6
aerosols		1569645	81.7
hybrid geometry		564324	35.9
profile reconstruction		539960	95.6
clouds		432312	80.1
$E > 10^{17.8}$ eV		111194	25.7
quality and fiducial selection:			
P(hybrid)		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

What are the geometries

that allows the measurement

of the entire Xmax distribution ?

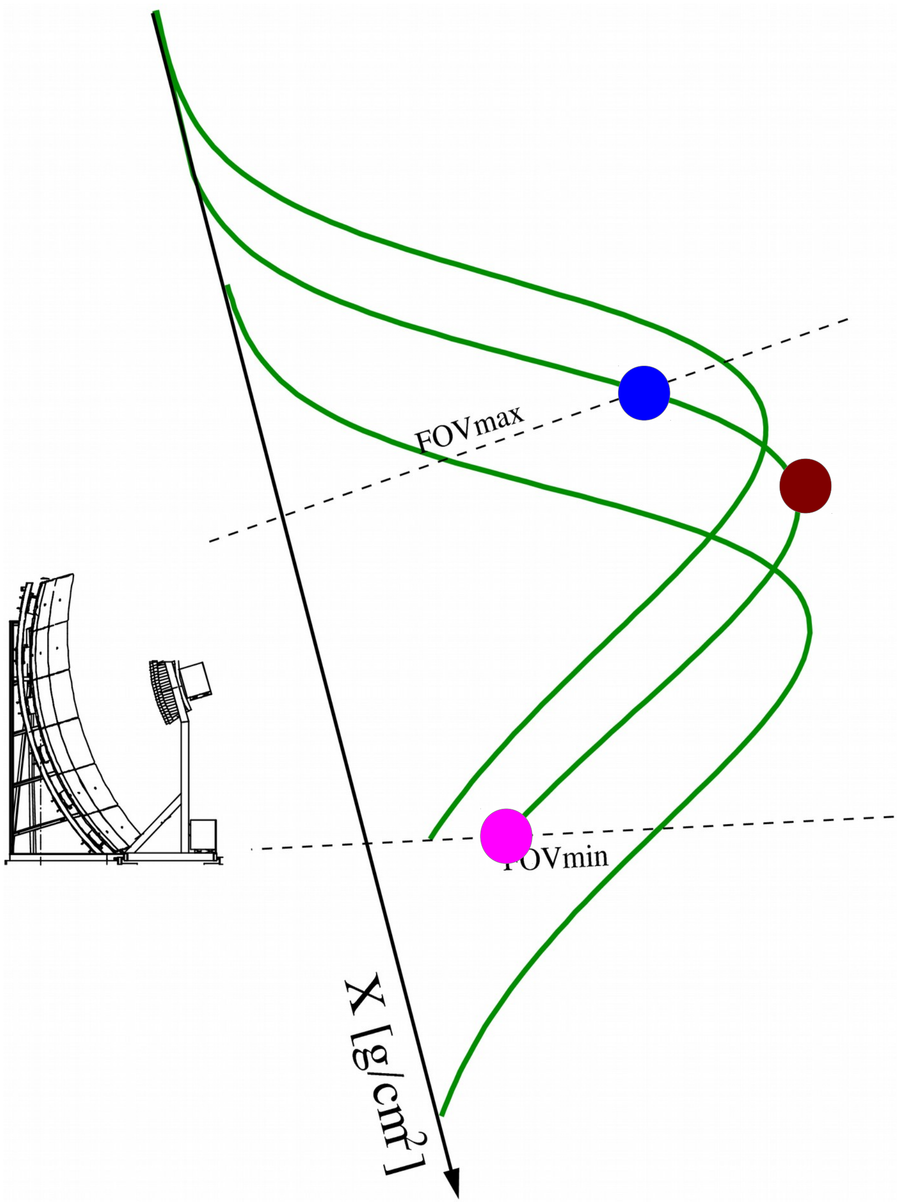
study how <Xmax> changes with FOV



<u>From the data</u>

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

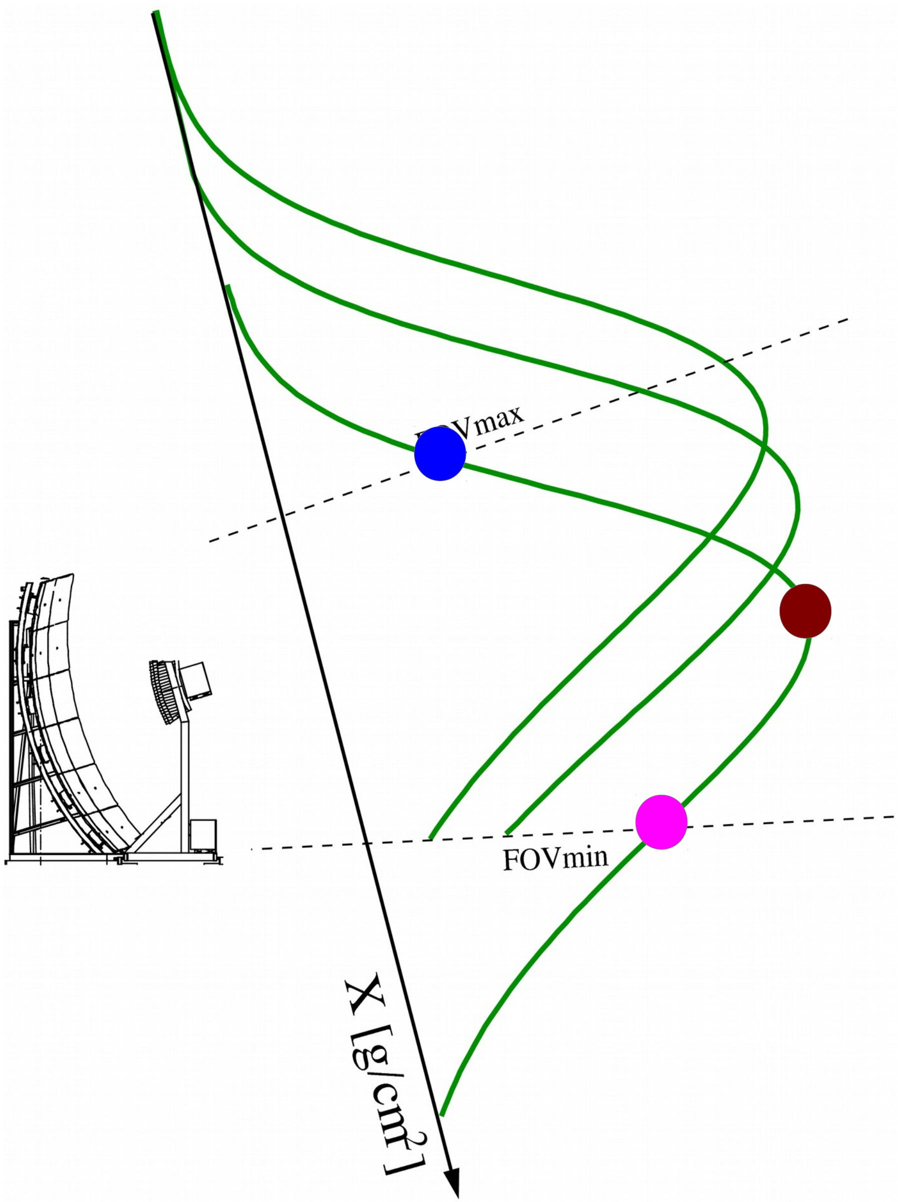
study how <Xmax> changes with FOV



From the data

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

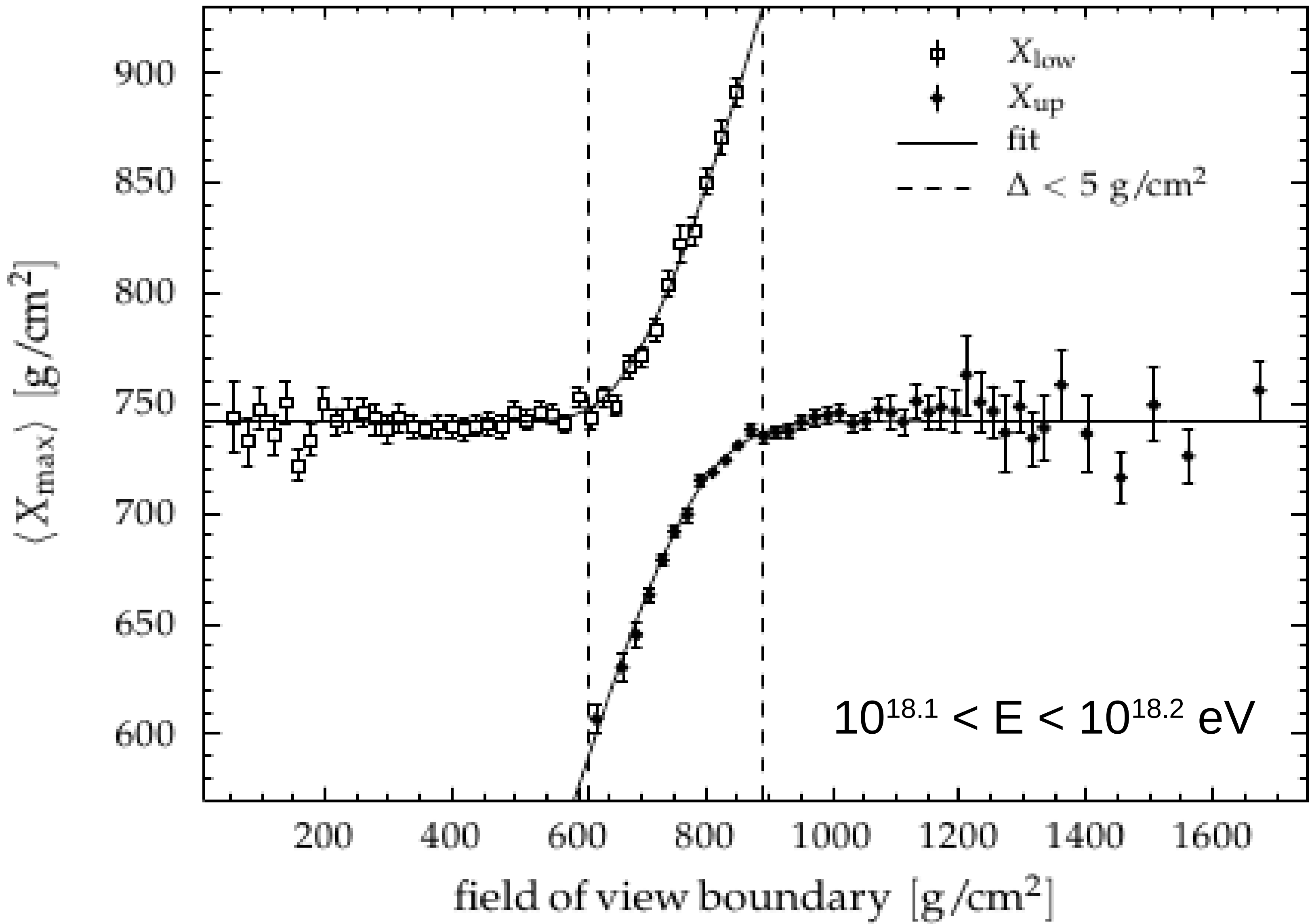
study how <Xmax> changes with FOV



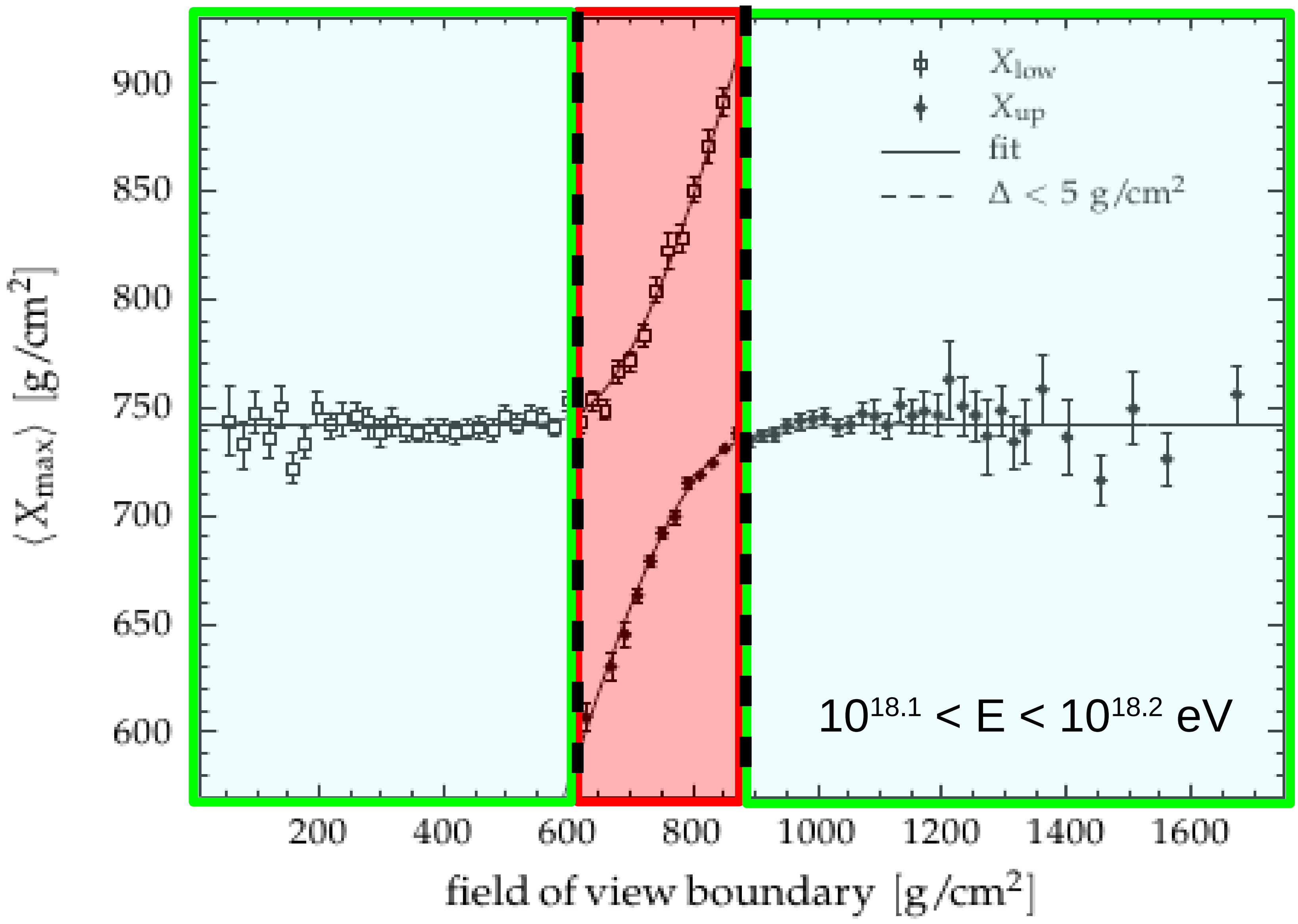
<u>From the data</u>

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

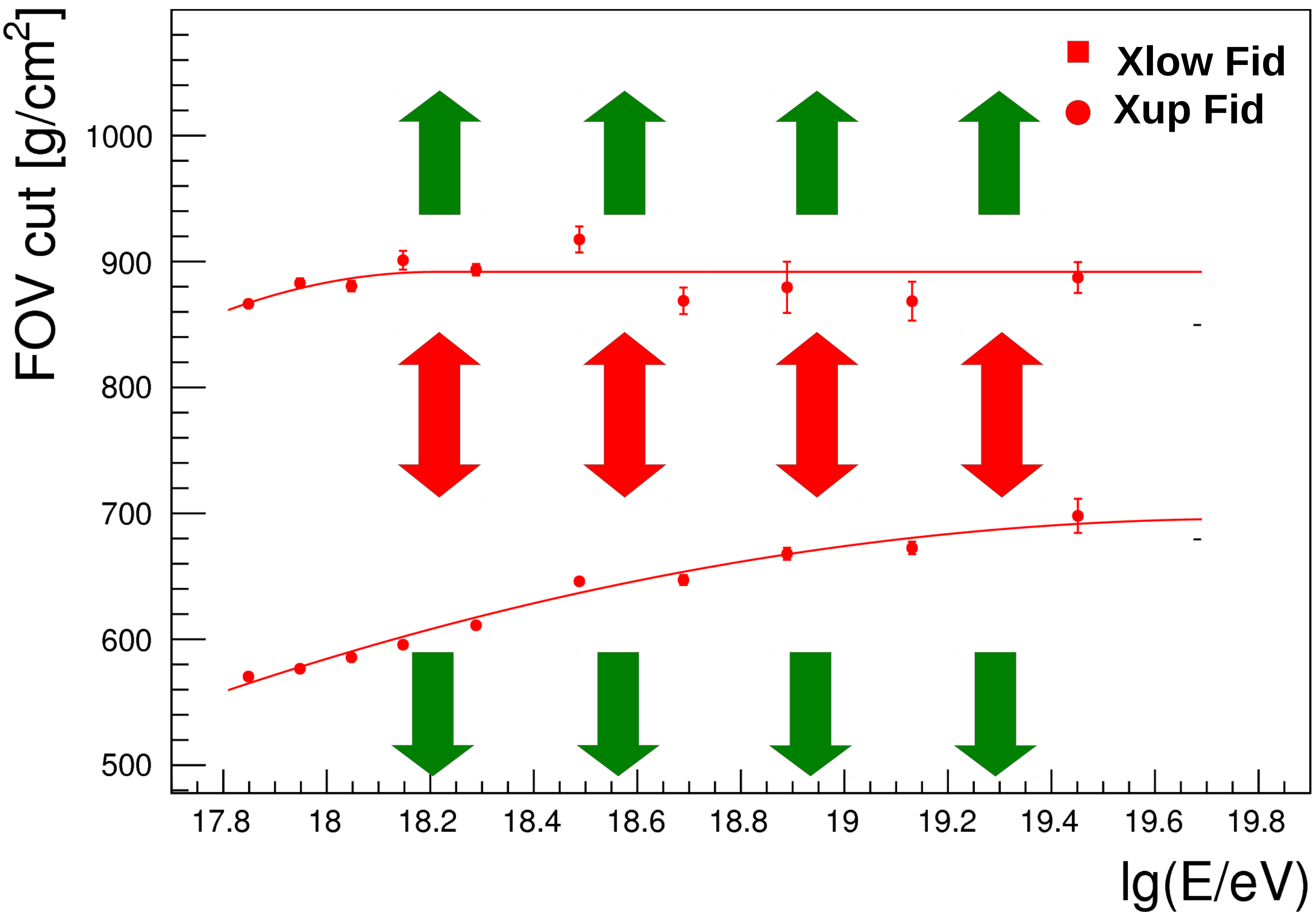
valid geometries ?



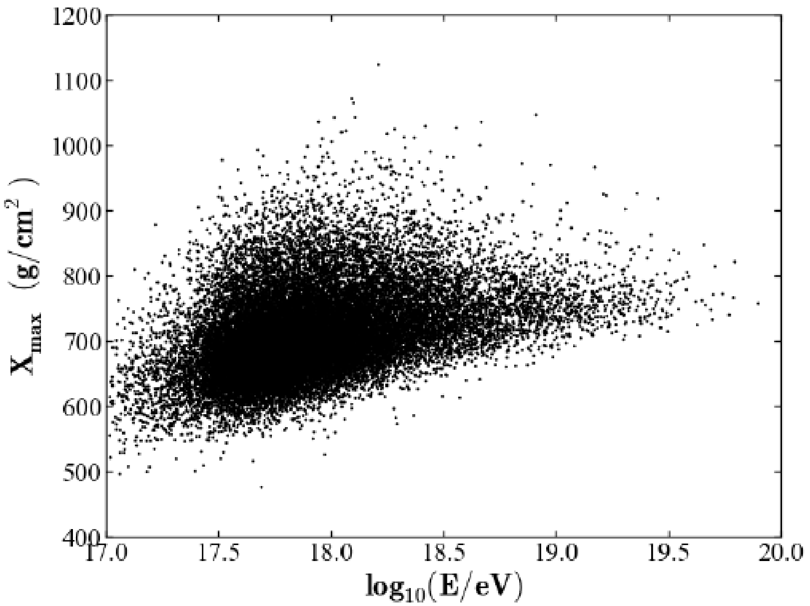
valid geometries ?

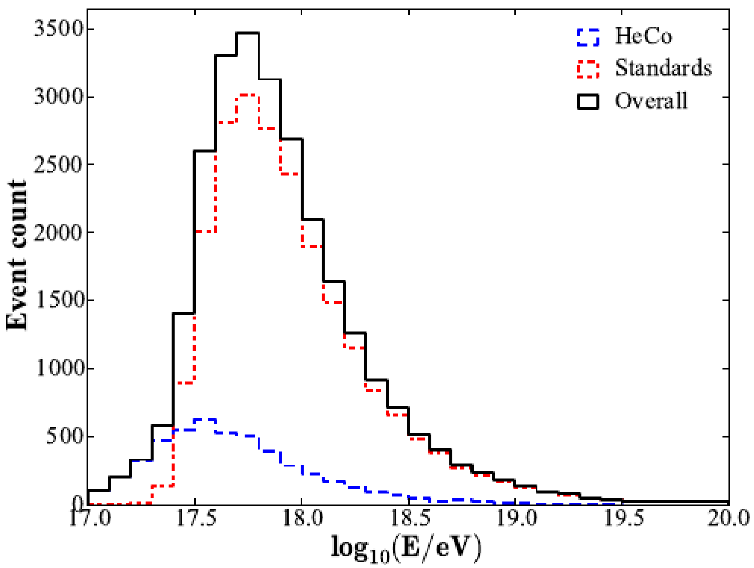


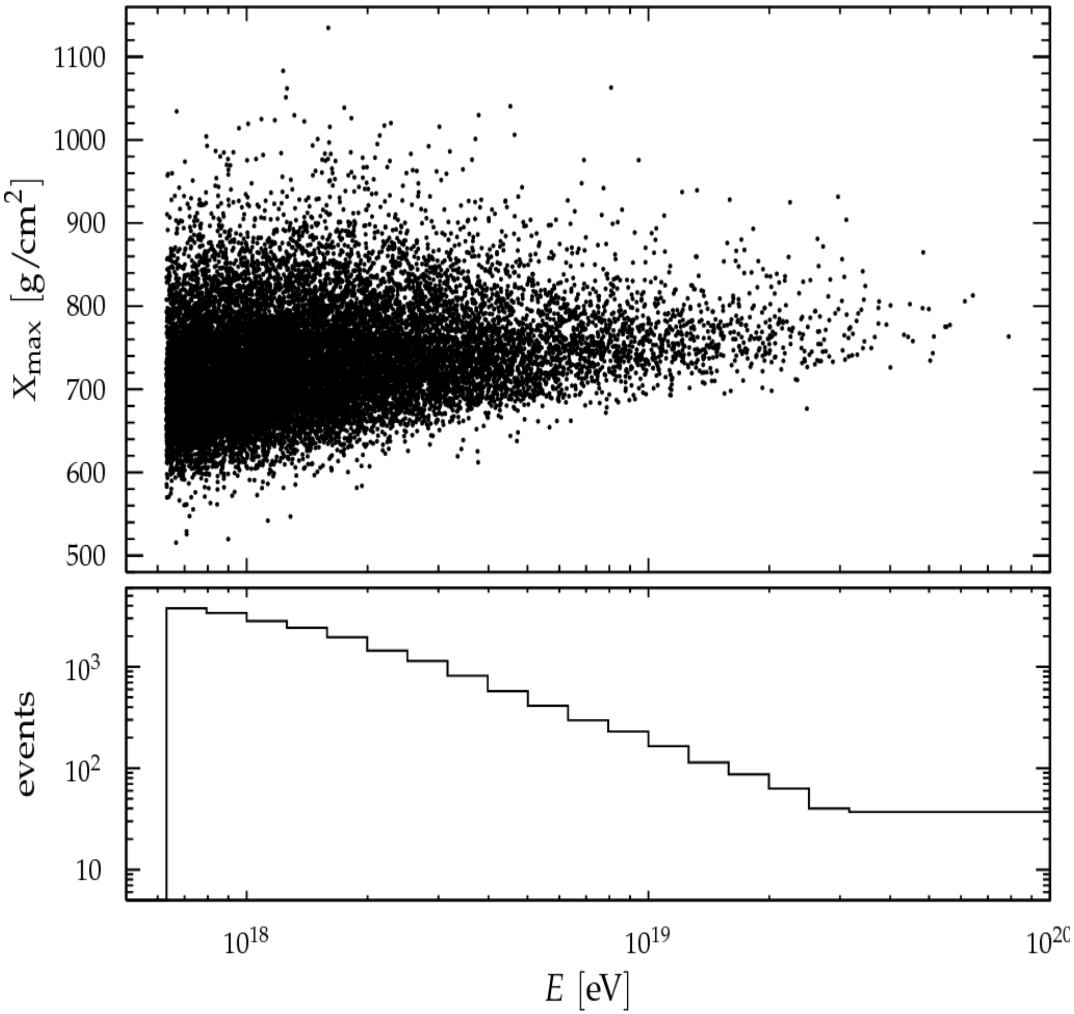
this is the valid geometry that assures unbiased Xmax distributions



events to be analyzed







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

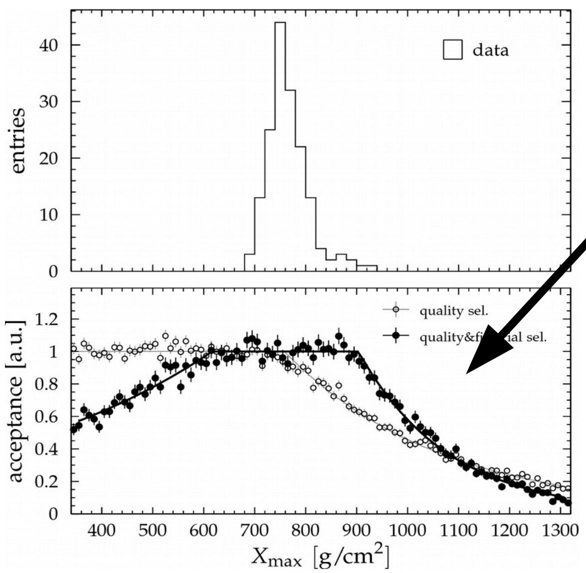
minimum bias

maximum statistical significance

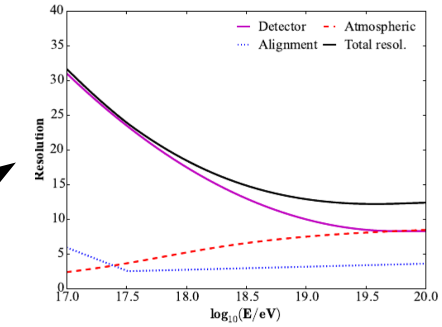
control over systematic uncertainties

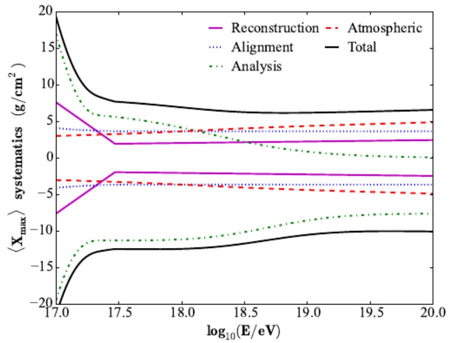
verification / cross-checks

complete data analysis



- acceptance
- resolution
- systematics

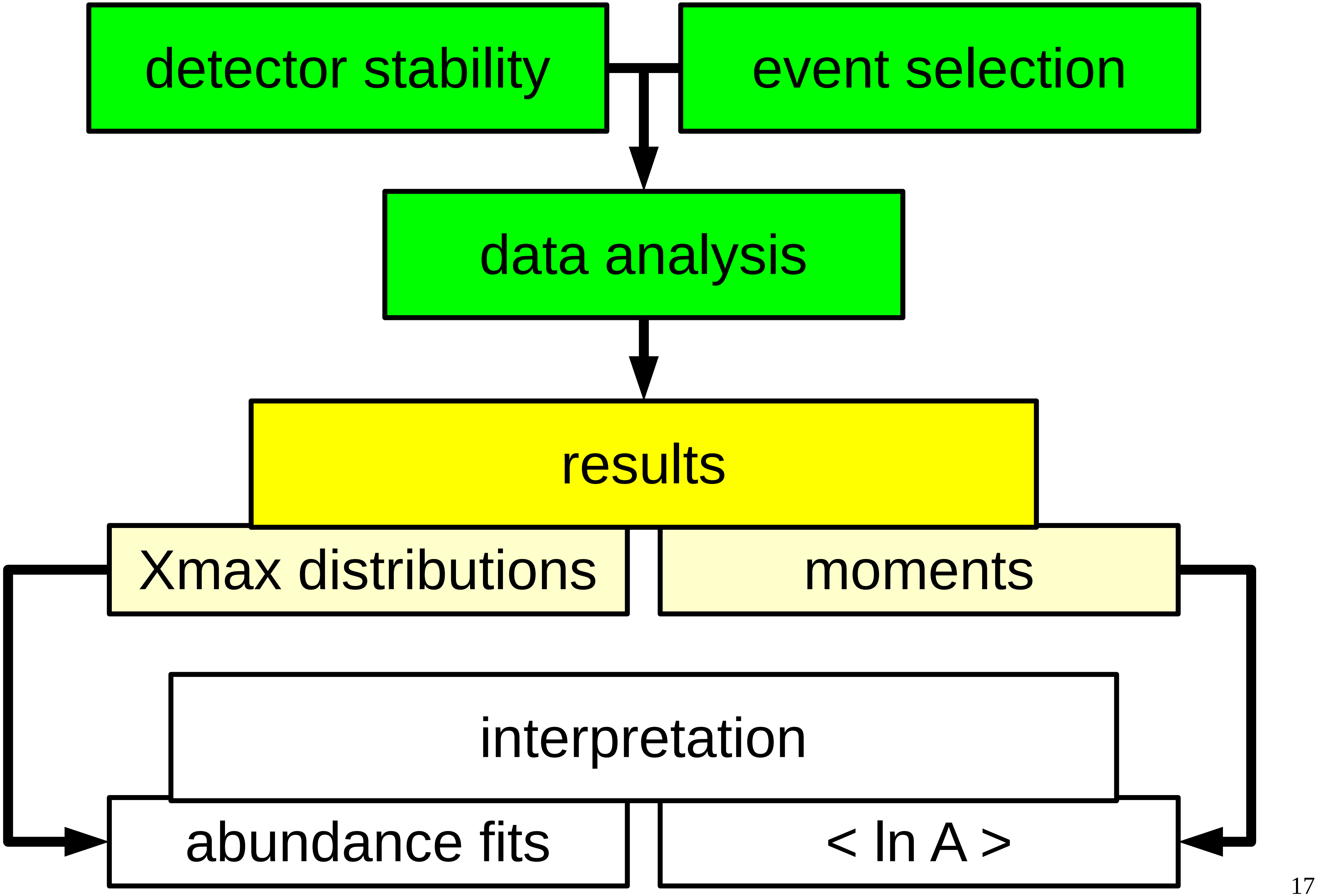




everything published

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

outline


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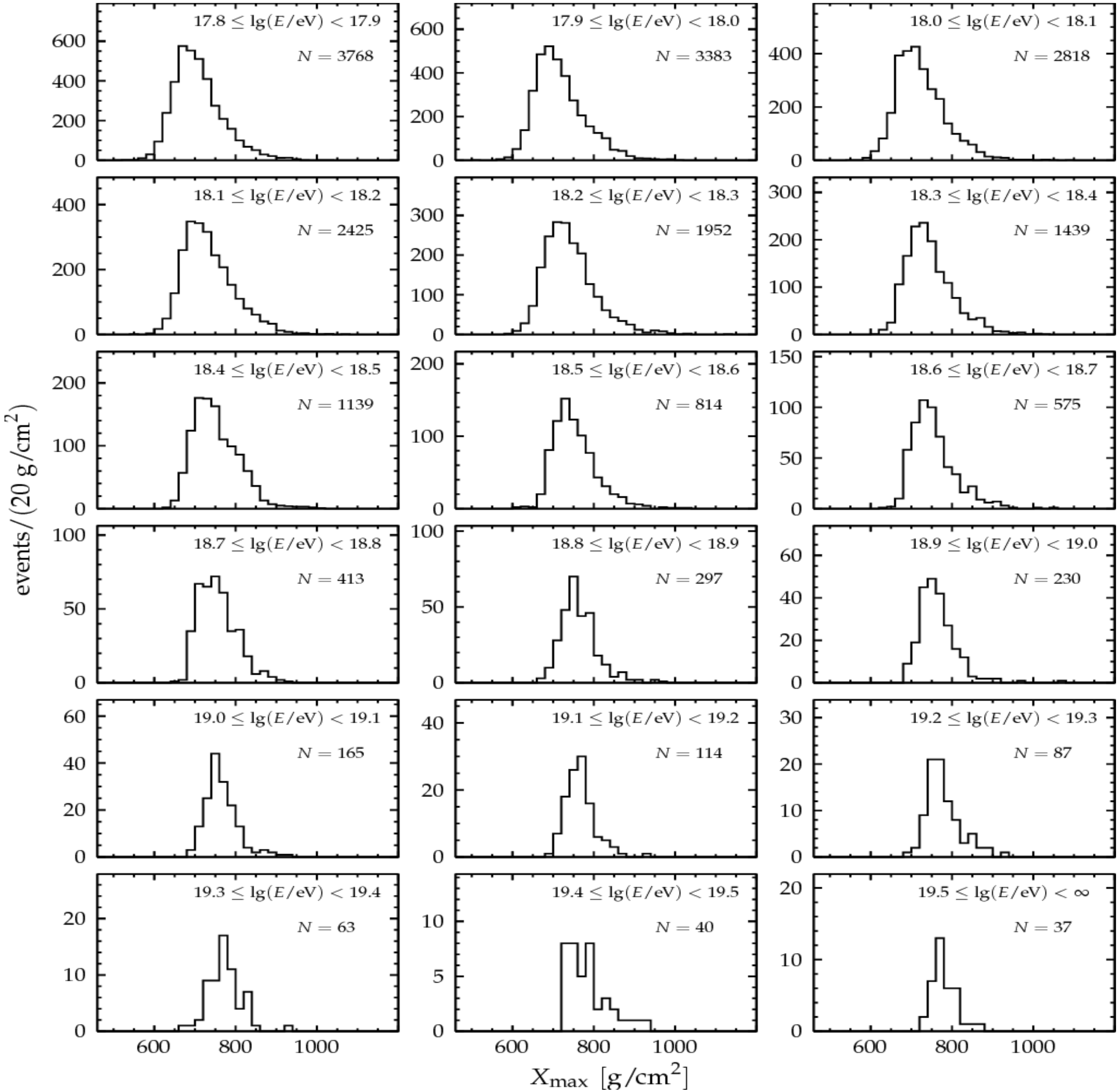
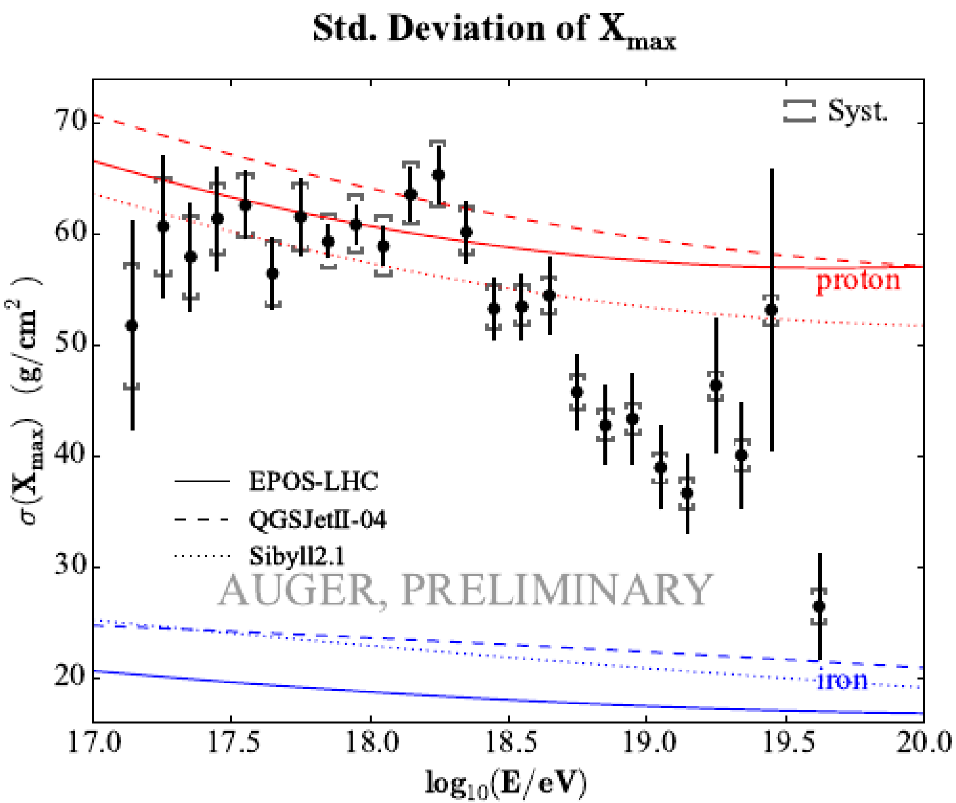
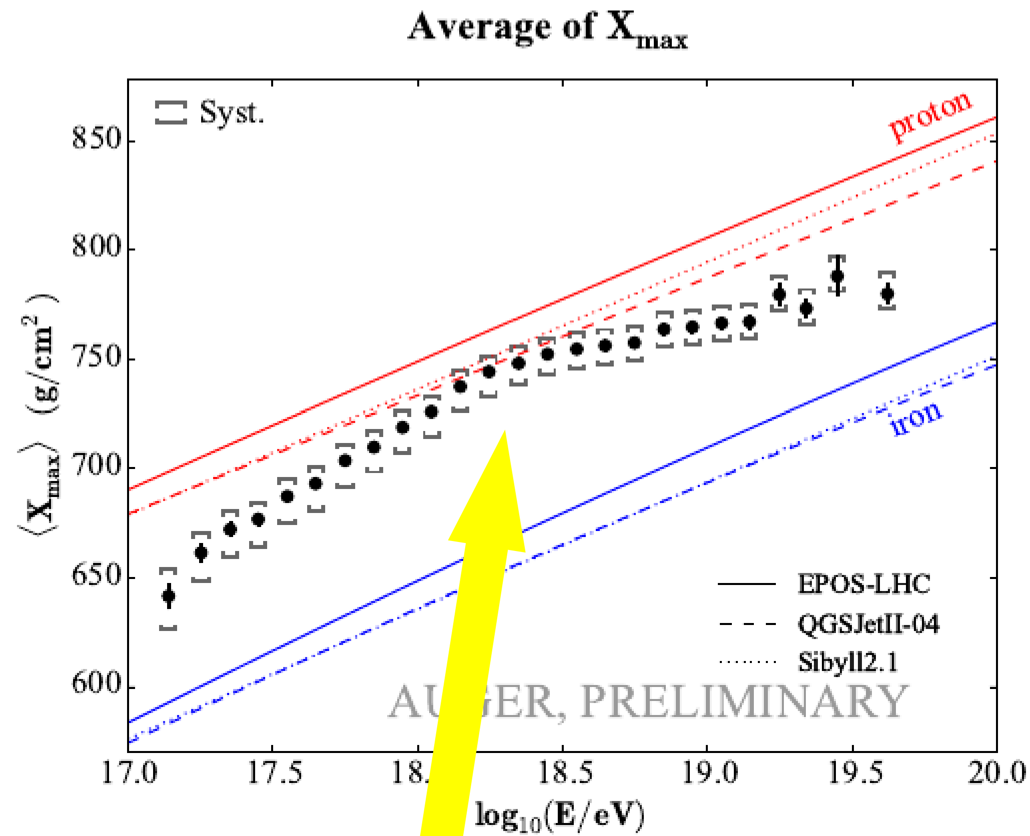
abundance fits
< ln A >


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)
Xmax [g/cm²]

moments

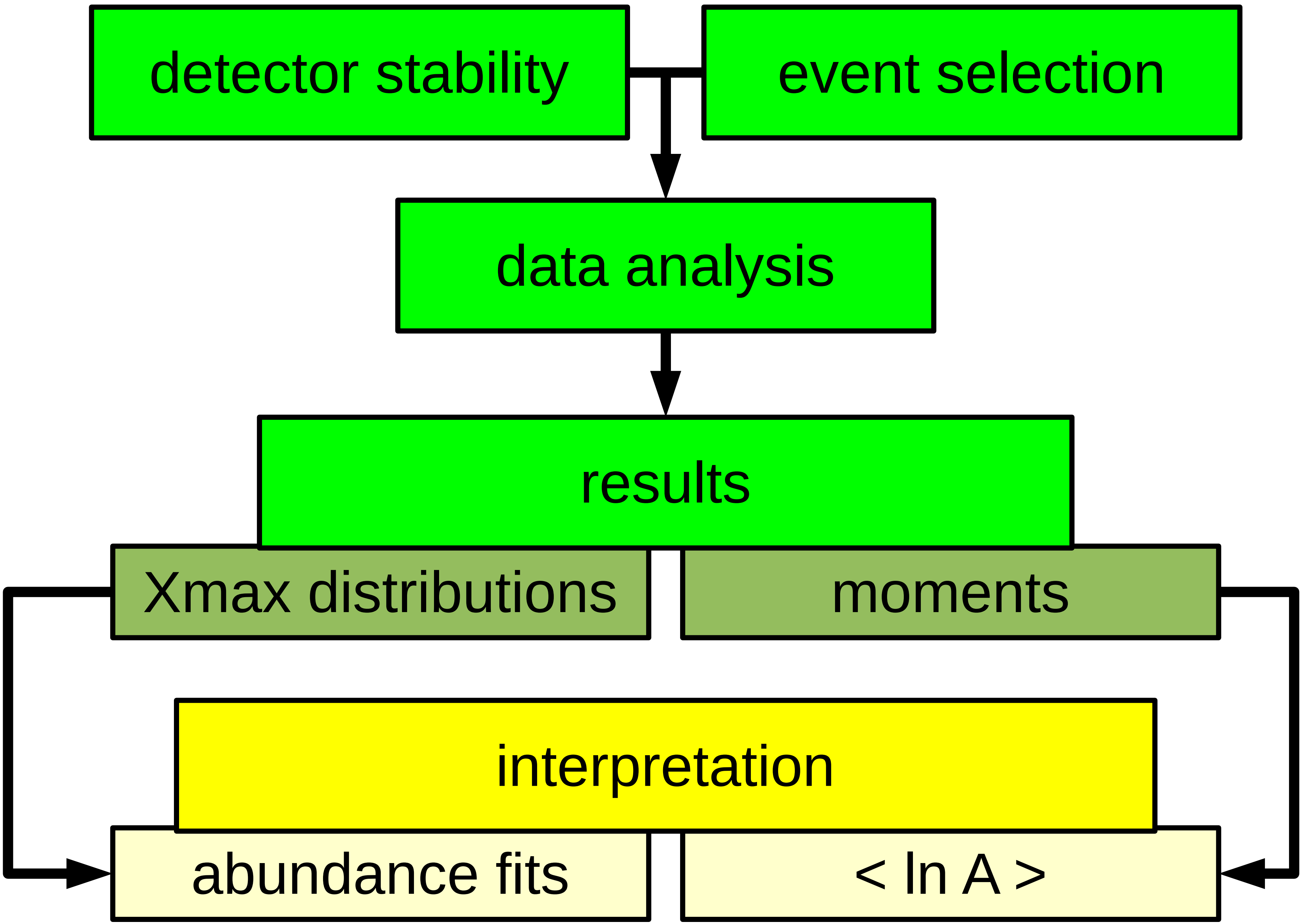




Clear break @

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

outline



detector stability
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abundance fits
< ln A >

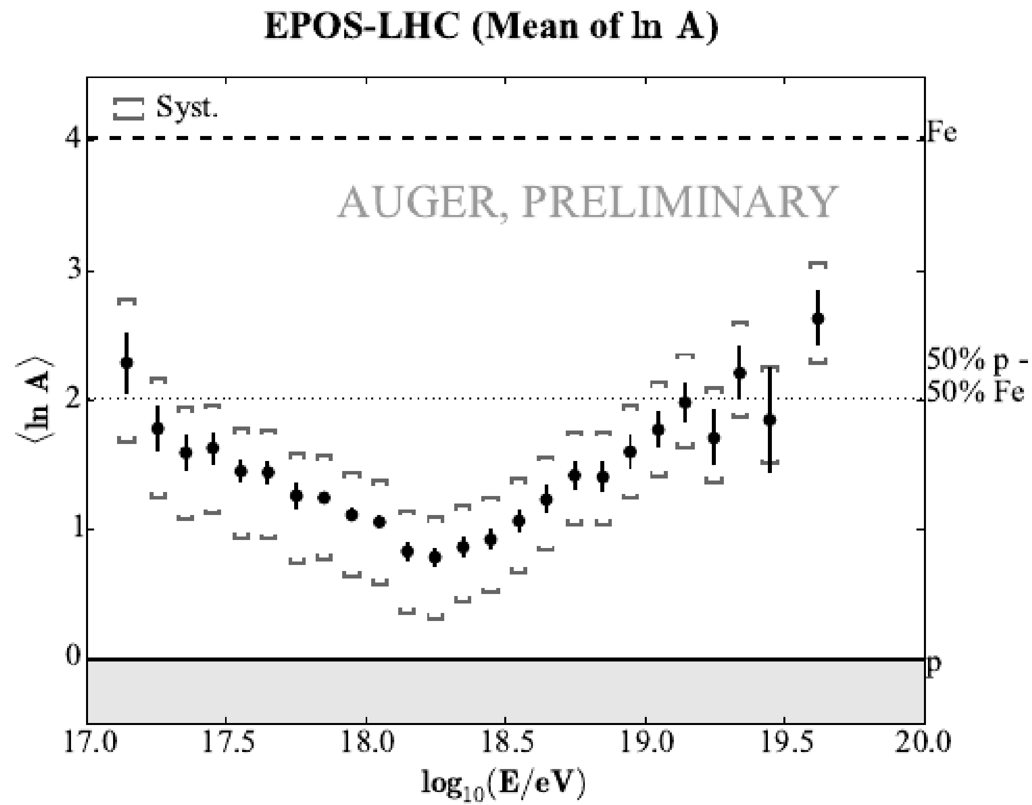
Warning

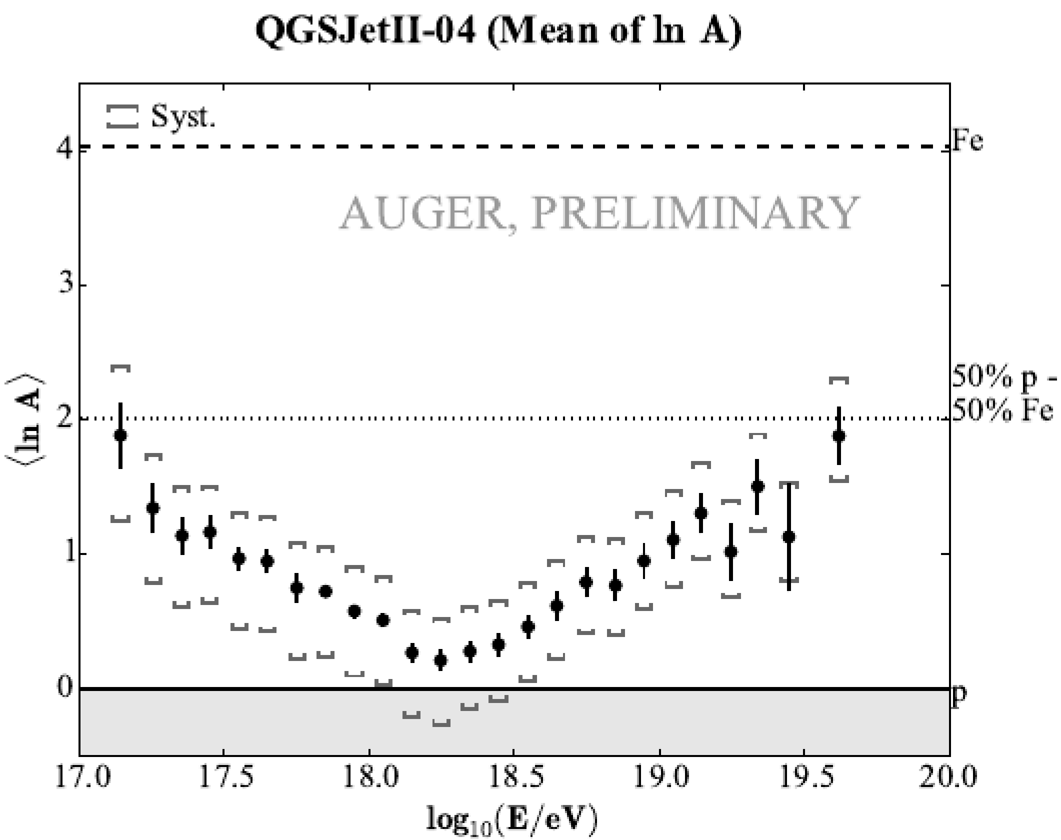
In the following slides the interpretation presented depends on hadronic interaction models

CONEX v4r37 : EPOS-LHC QGSJetII-04 Sibyll 2.1

SimProp or CRPropa: THALYS Geant4

Mean ln A





Clear trend:

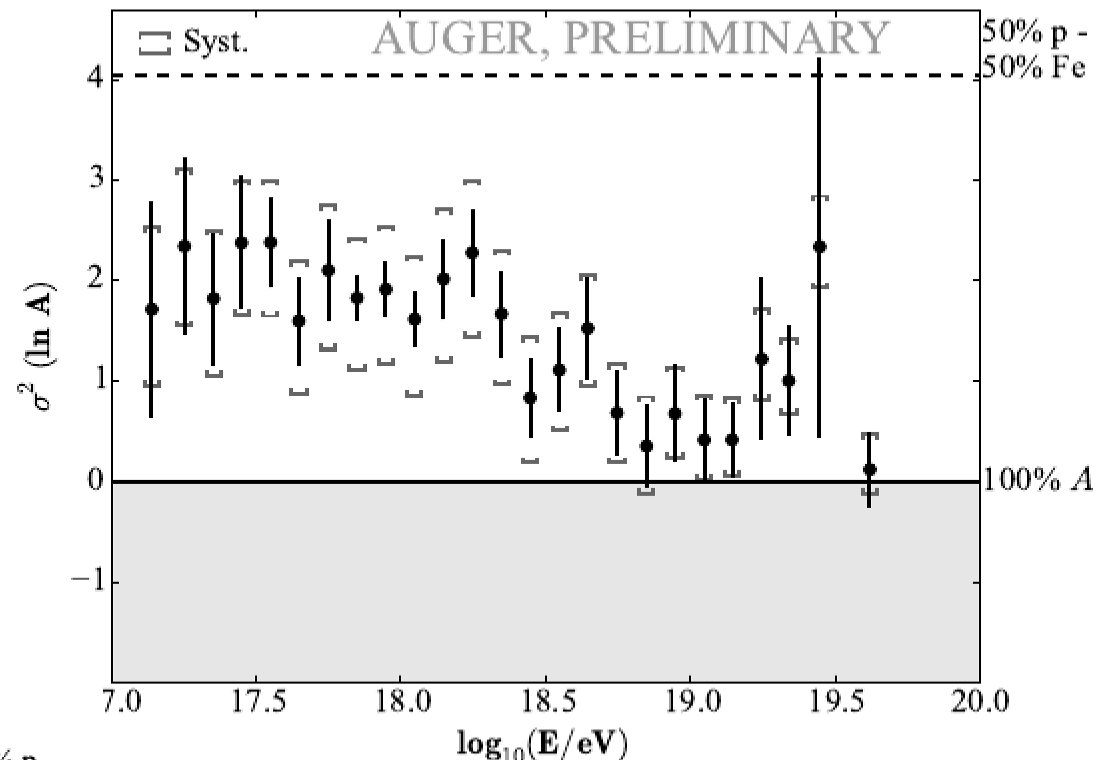
$10^{17} < E < 10^{18.27}$ eV: getting ligther

$E > 10^{18.27}$ eV: getting heavier

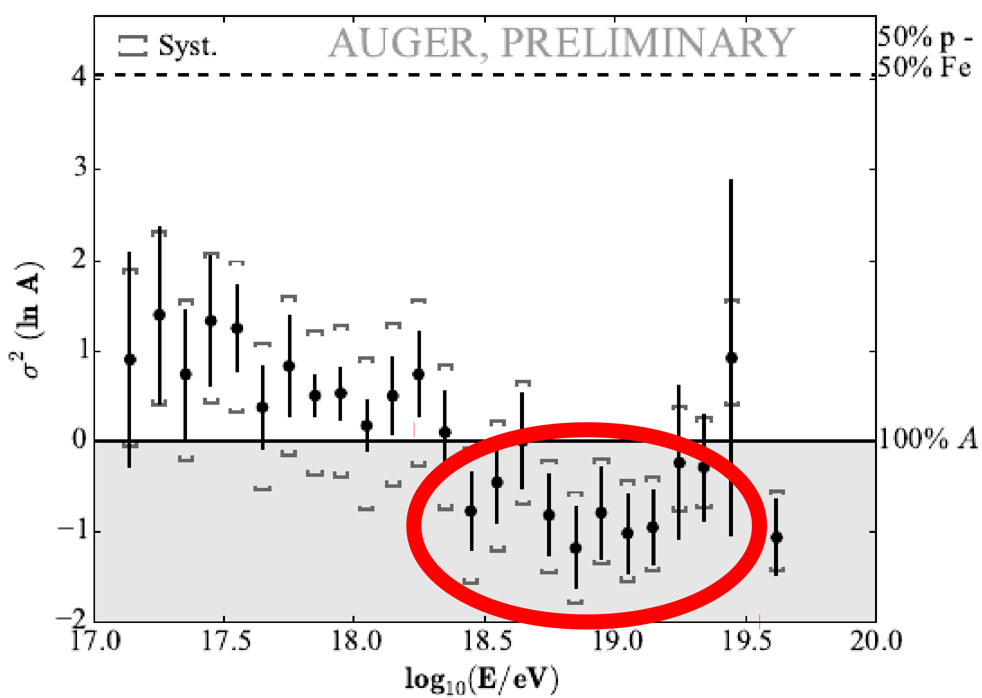
Variance of ln A

$\sigma^2(\ln A)$

EPOS-LHC (Variance of ln A)



QGSJetII-04 (Variance of ln A)



$\sigma^2(\ln A)$ measures the purity of the sample:

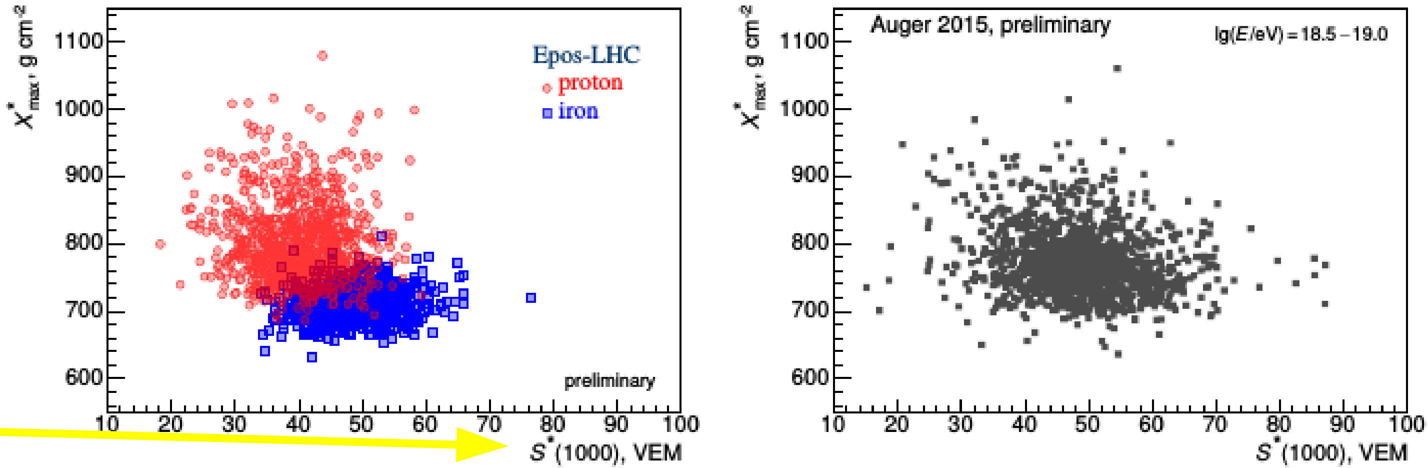
- pure A → $\sigma^2(\ln A) = 0$
- 50:50 Pr:Fe → $\sigma^2(\ln A) \approx 4$

J. Lisley, ICRC 1985

Fluorescence
EM Component

versus

Surface Detector
EM + Muon
Component

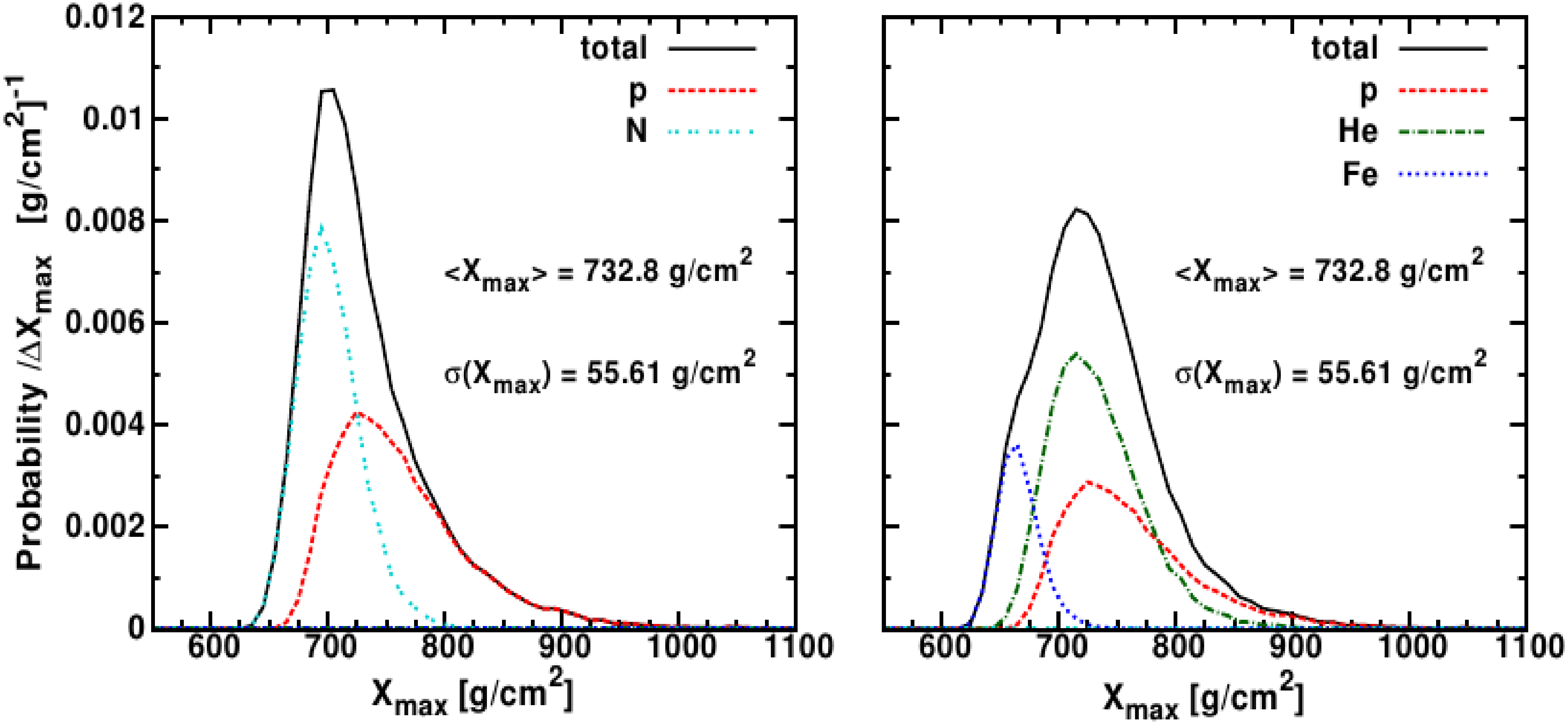


Purity of the sample

$10^{18.5} < E < 10^{19}$ eV

data	-0.125 ± 0.024 (stat)		
	Epos-LHC	QGSJetII-04	Sibyll 2.1
p	0.00	0.08	0.07
He	0.08	0.15	0.15
O	0.09	0.15	0.14
Fe	0.08	0.12	0.12

from moments to full distribution



example of different distributions with the same moments

fitting abundances: Only Xmax distributions

simulated air shower including the detector response

$2\text{x}10^4$ 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

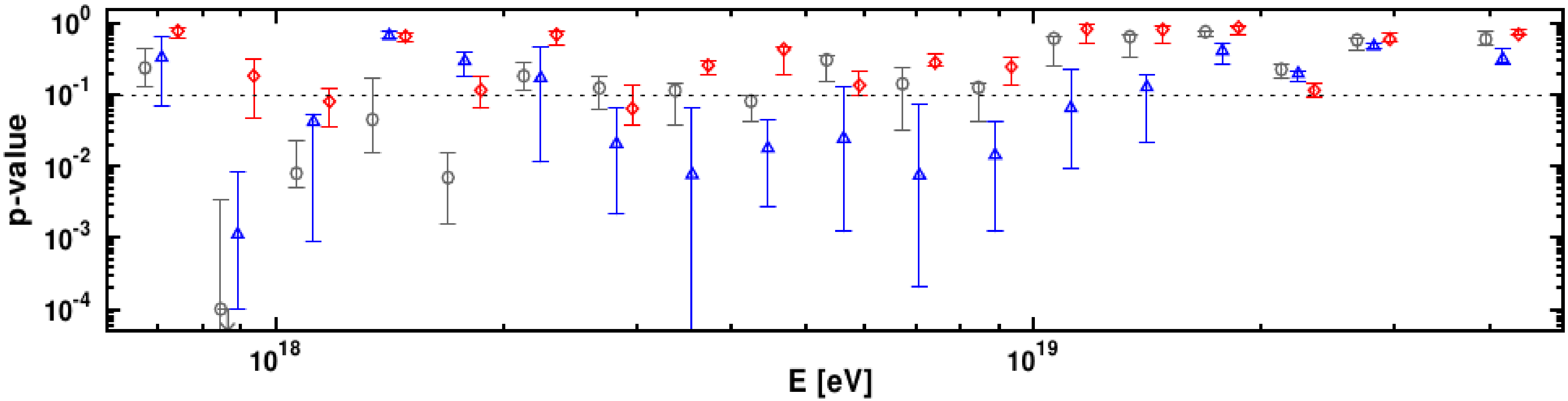
$$L = \prod_j \left[\frac{e^{-C_j} C_j^{n_j}}{n_j!} \right]$$

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

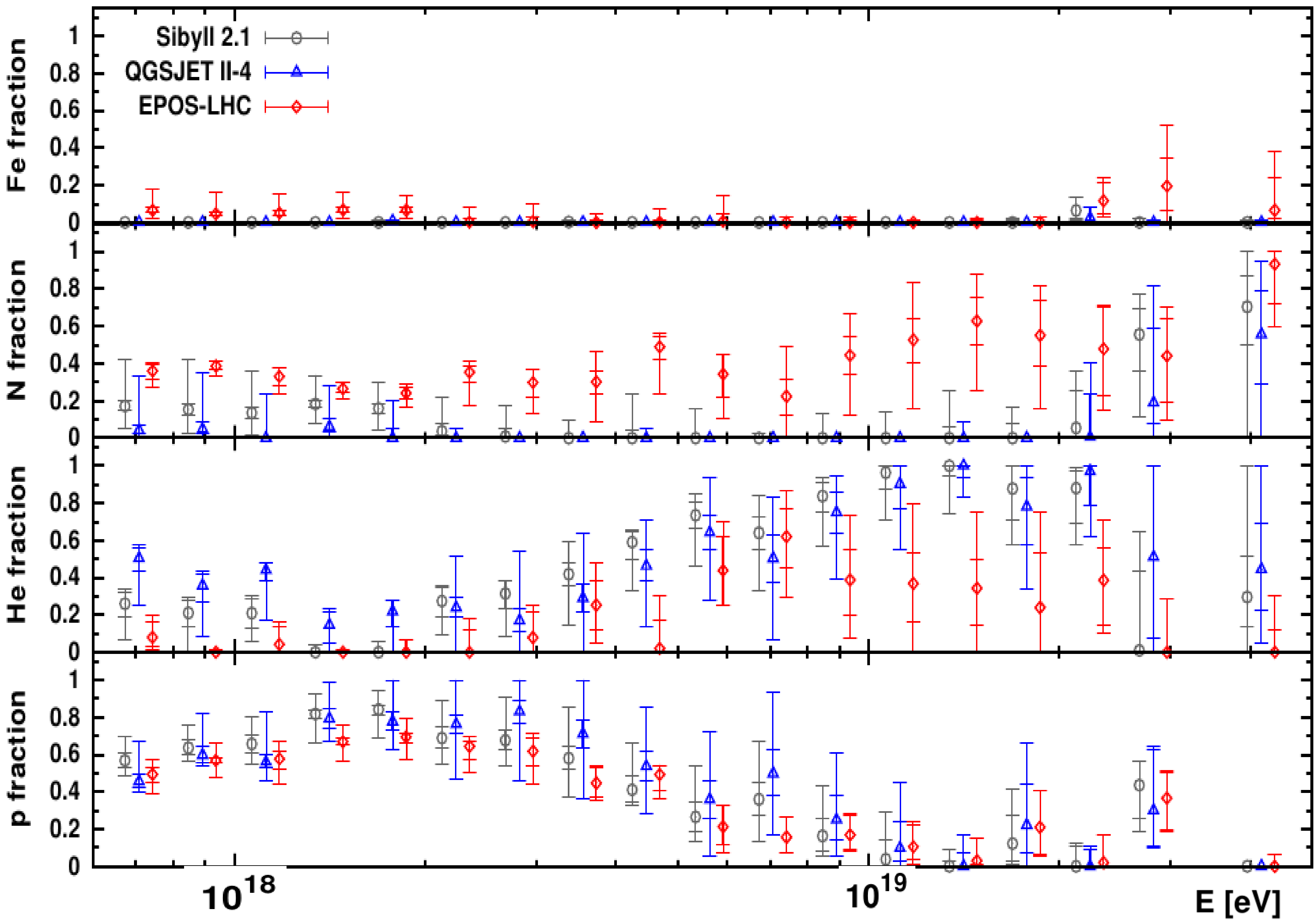
proton + helium + nitrogen + iron

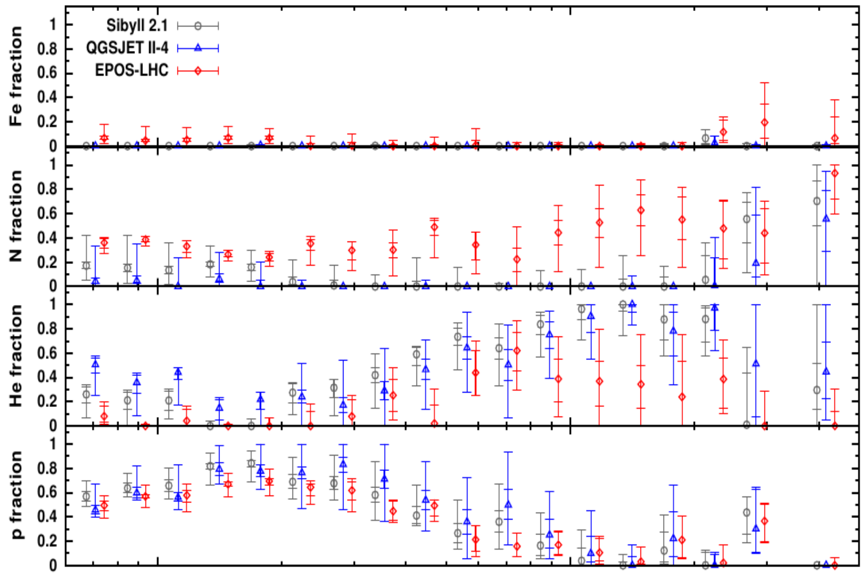


acceptable/good agreement with the data

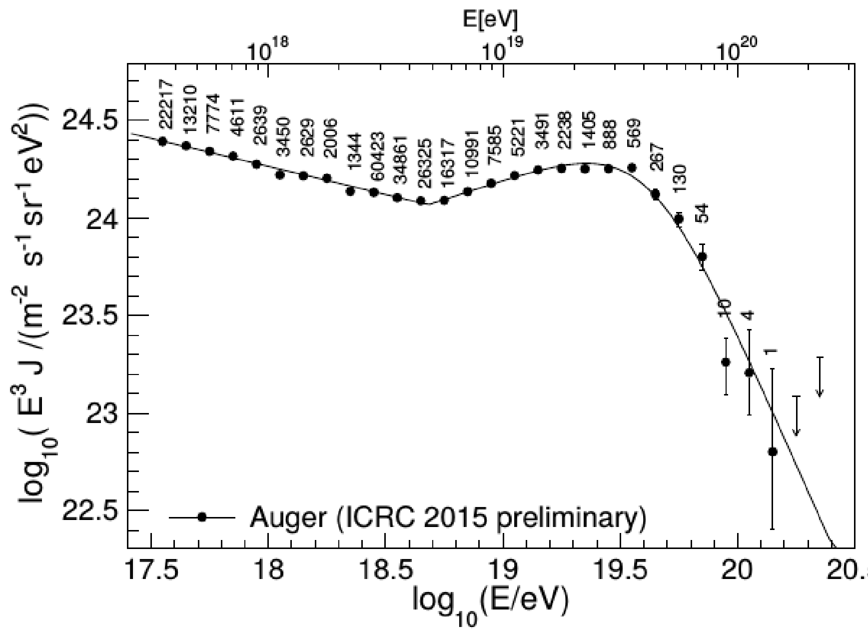
Sibyll 2.1
QGSJET II-4
EPOS-LHC

proton + helium + nitrogen + iron

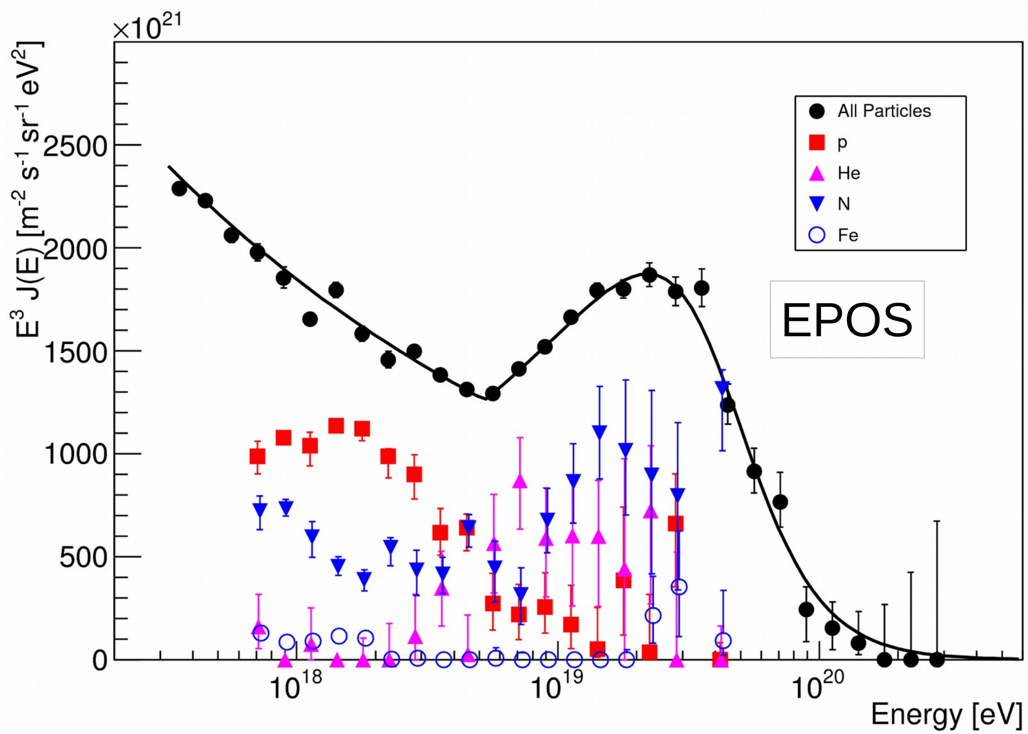



Sibyll 2.1
QGSJET II-4
EPOS-LHC
Fe fraction
N fraction
He fraction
p fraction

⊗


E[eV]
Auger (ICRC 2015 preliminary)
log10(E/eV)
log10(E^3 J /(m^-2 s^-1 sr^-1 eV^2))

=


All Particles
p
He
N
Fe
EPOS
Energy [eV]
E^3 J(E) [m^-2 s^-1 sr^-1 eV^2]

final remarks

- data
  - all information is public: distributions, resolution, systematics and acceptance
  - largest statistics with controlled systematics
- Xmax moments
  - clear break @ log (E/eV) = 18.27
  - 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
  - σ^2(ln A) and S1000 analysis: no pure composition from $10^{18.5}$ to 10^{19} eV

- abundance fits – 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