Results of the Pierre Auger Observatory after 10 years of operation

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Outline

Review of some of the latest results

- Energy spectrum
- Anisotropy
- Mass composition
- Photons and neutrinos

Future perspectives (see R. Smida's talk)

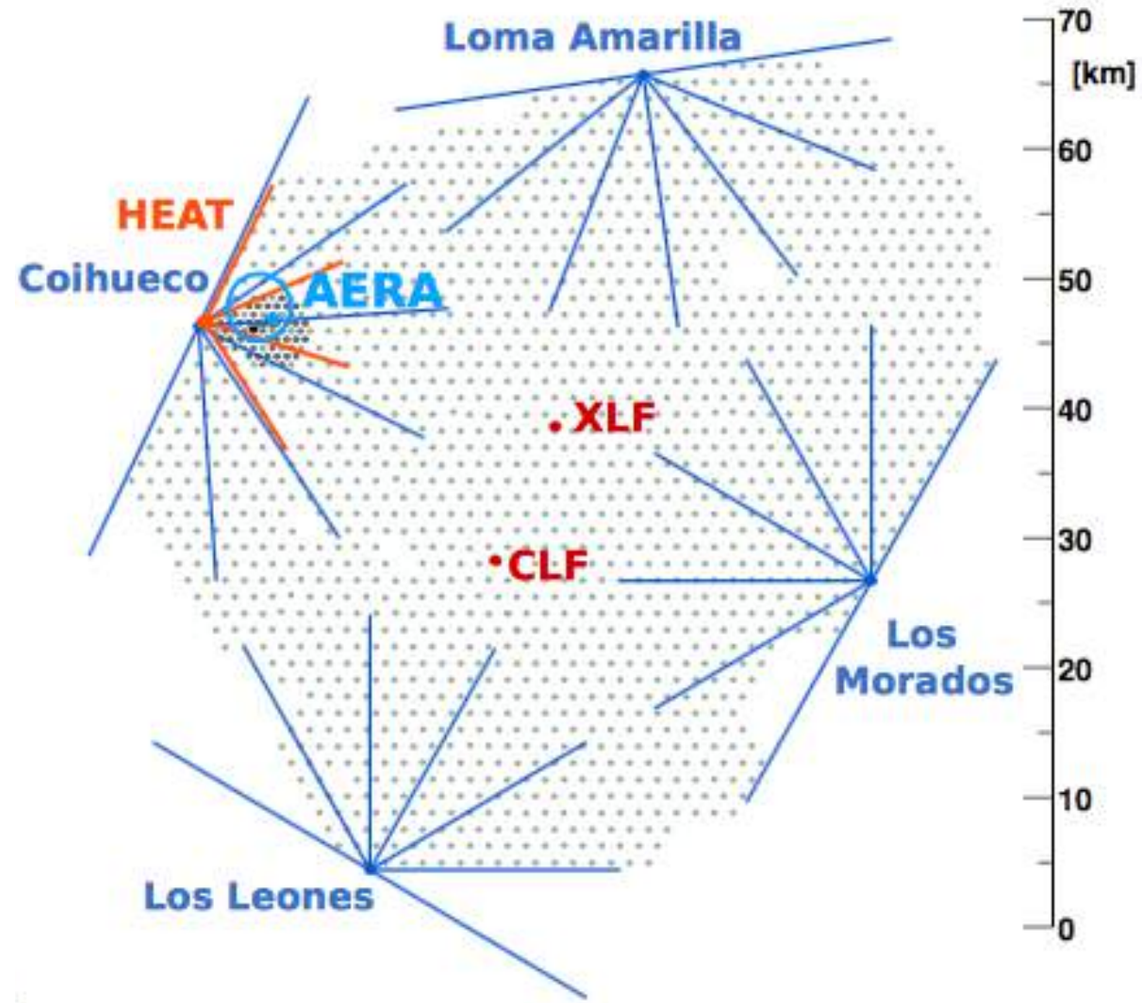
The Pierre Auger Observatory

Malargüe (Mendoza, Argentina), 1400 m s.l.

Fluorescence Detector (FD)
longitudinal profile
10-15% duty cycle

24 telescopes in 4 buildings,
FoV: 1- 30º in elevation

+ 3 High Elevation Auger Telescopes (HEAT)
FoV: 30- 60º in elevation
(in tilted mode)

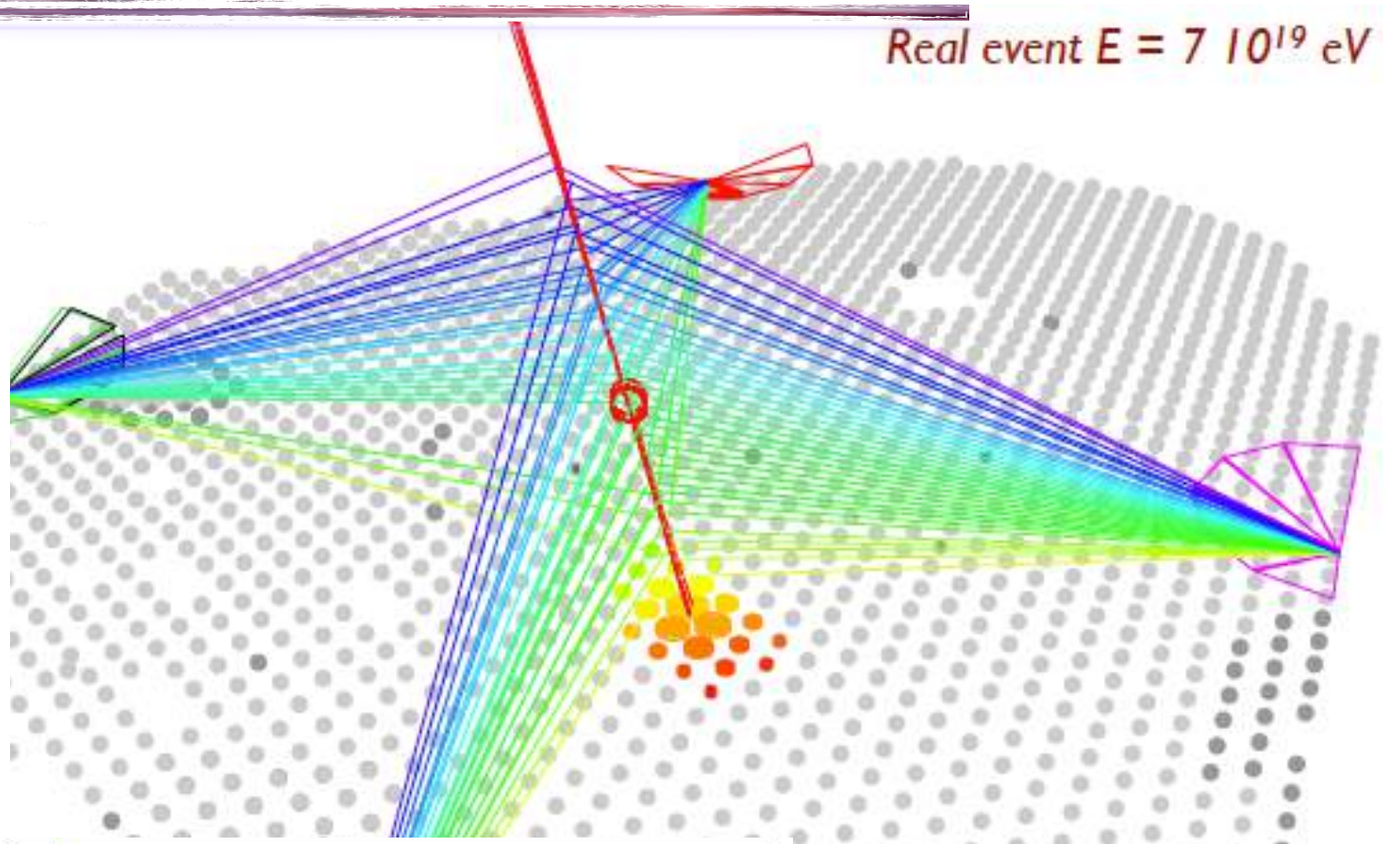


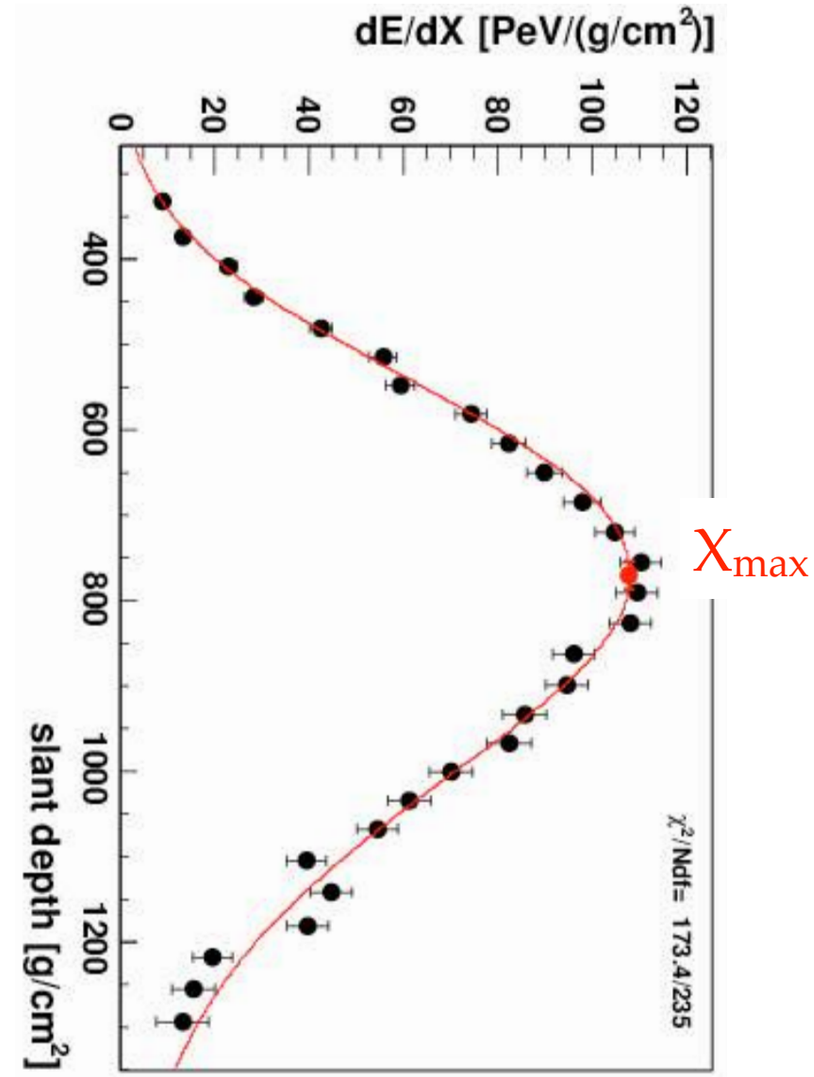
Surface Detector array (SD)
particle density at ground
1600 + 60 water Cherenkov stations, surface of 3000 km^2, 1.5 km spacing
100% duty cycle

Total surface: 3000 km^2
Taking data since 2004, completed in 2008

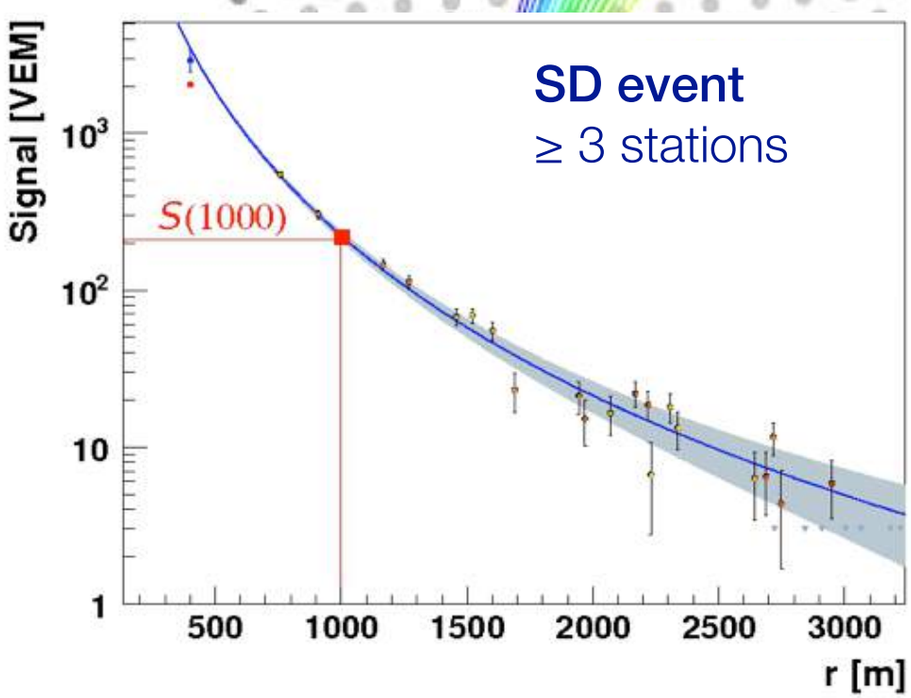
Hybrid events: at least 1FD + 1SD

The hybrid concept





FD: longitudinal development
calorimetric energy



SD: Lateral distribution of
secondary particles at ground

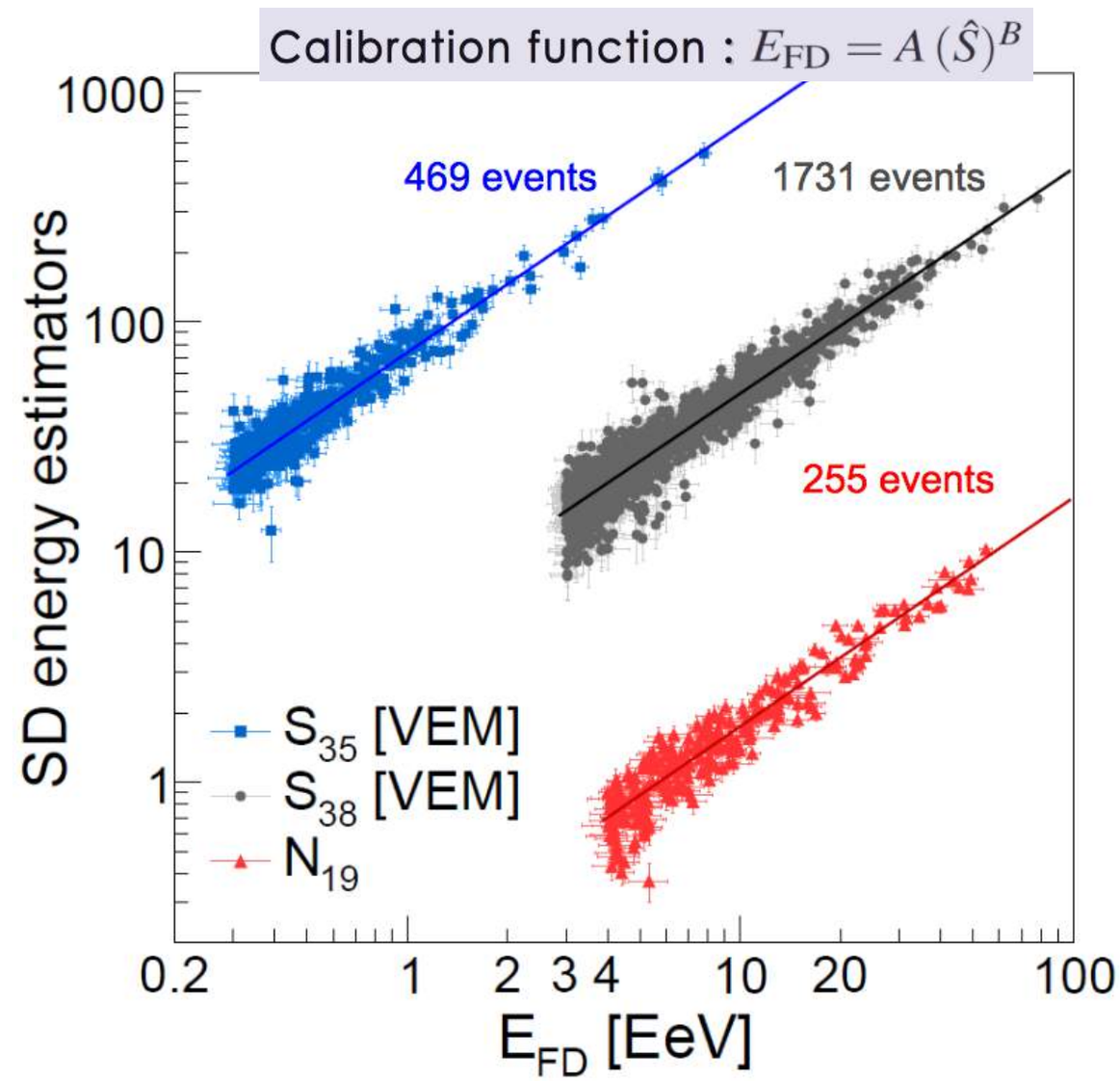
- signal at 1000 m **S(1000) ➔ energy**
- **energy calibration from FD in hybrid events**

The hybrid concept and the energy scale

- Wide energy range covered
  - **SD infill:** spacing 750 m (E > 10^{17} eV)
  - **SD:** spacing 1500 m (E>$10^{18.5}$ eV)
  - **horizontal** (zenith > 60º)
  - **Hybrid:** (E > 10^{18} eV): not shown in the plot

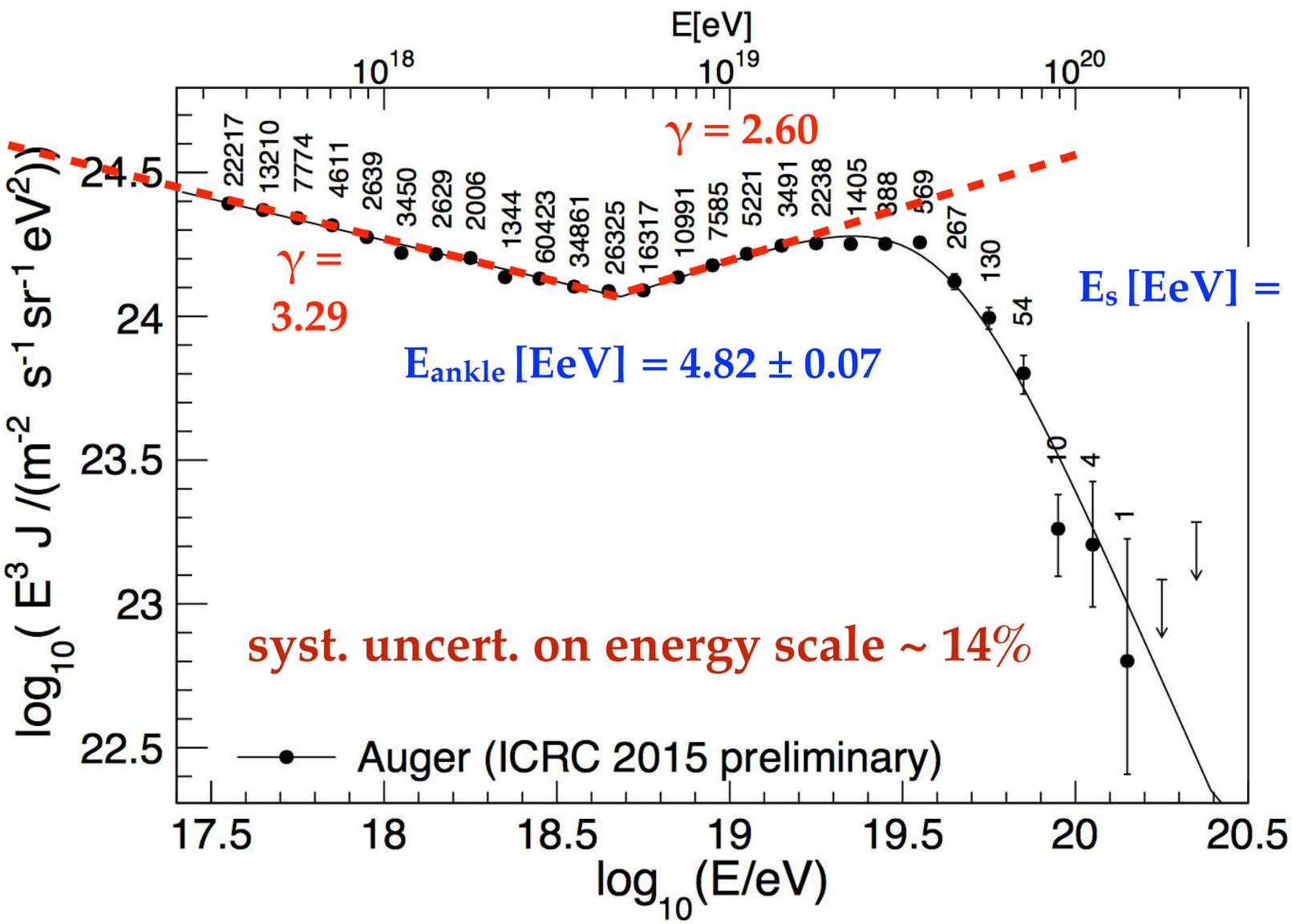
- Common energy scale (from FD)
  - **SD energy calibrated with hybrids**
  - **systematic uncertainties** on the energy scale: **14% at E > 10^{18}eV**

  - **Combined spectrum above 10^{17} eV**



- Exposure : ~ 50000 km^2 sr y

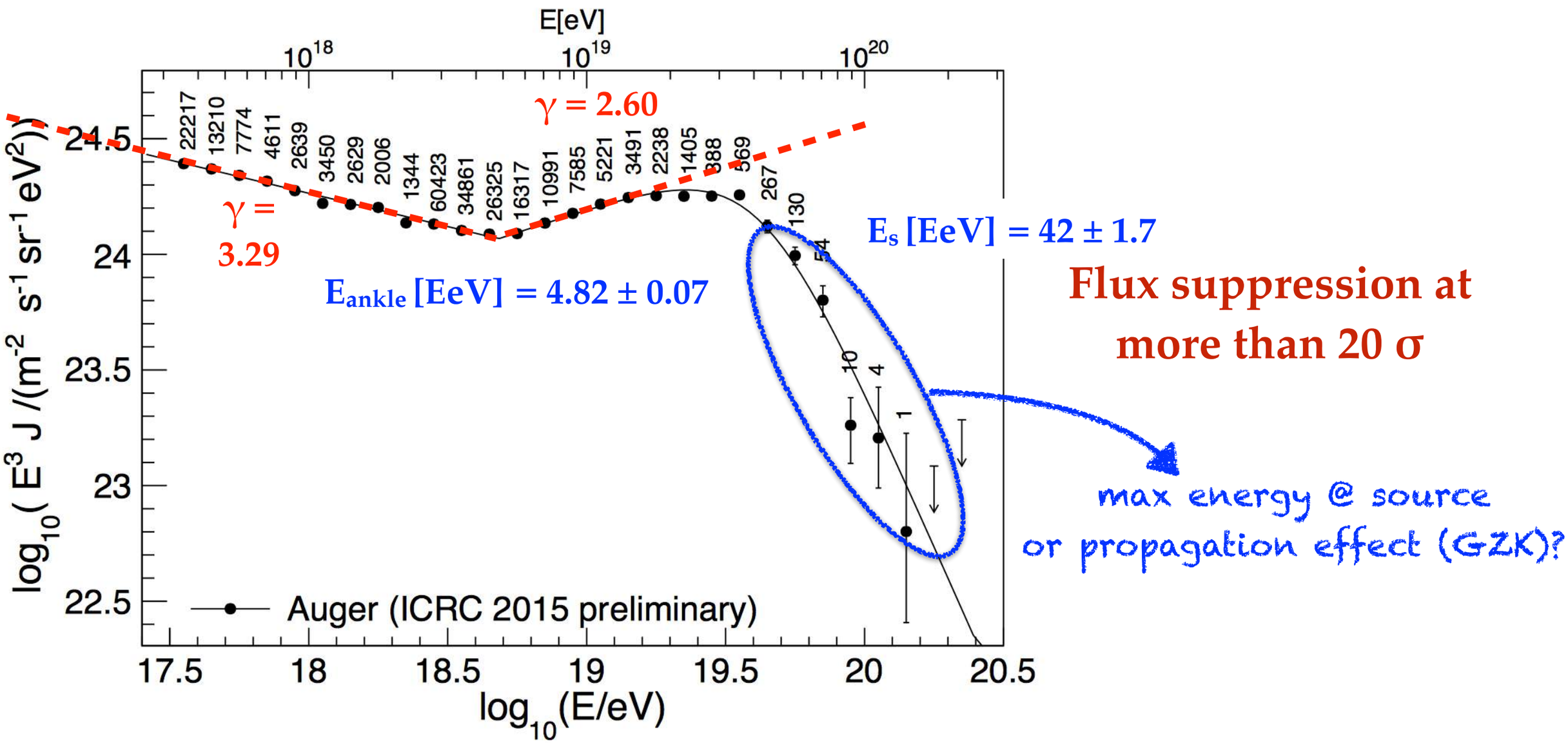
The energy spectrum



Flux suppression at more than 20 σ

I.Valino for the Pierre Auger Coll., ICRC2015

The energy spectrum

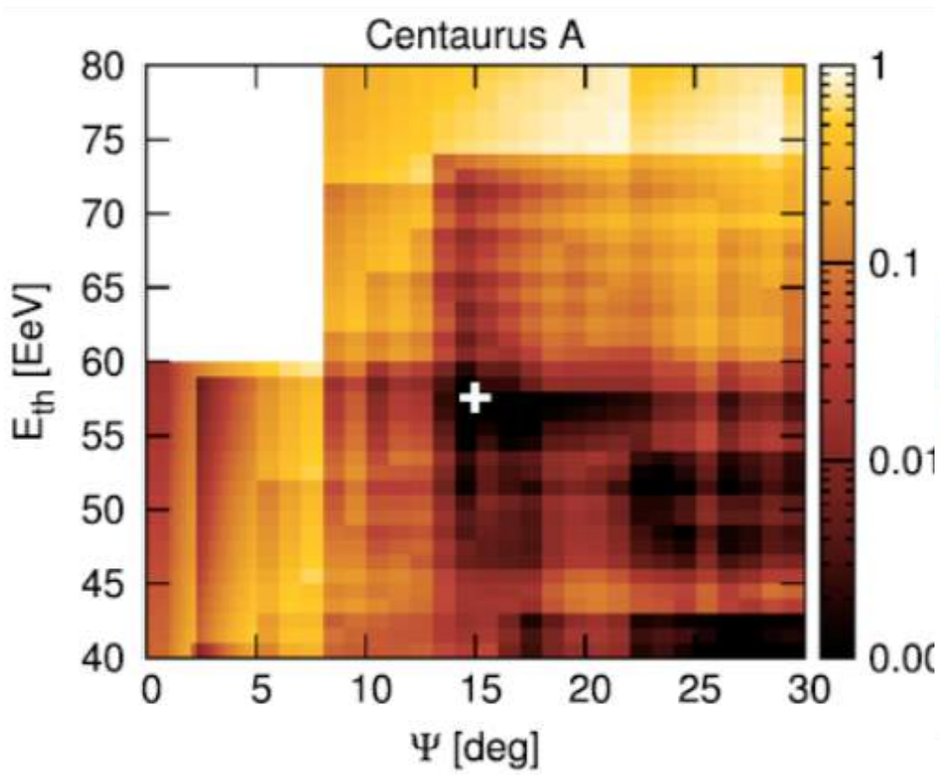


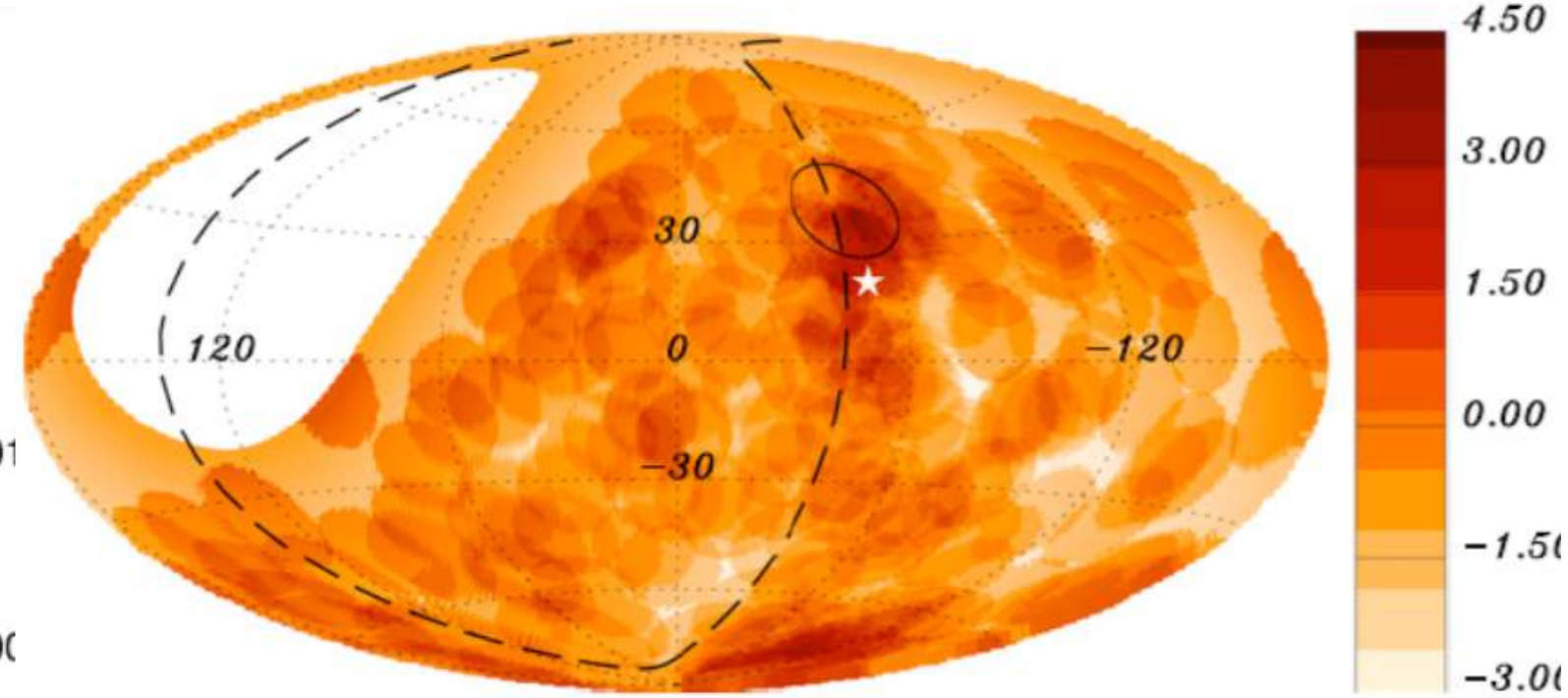
To discriminate between different scenarios:

- **mass composition** on event-by-event basis
- cosmogenic **photons** and **neutrino**

Arrival directions

Autocorrelation (search for pairs of events): look for excesses of "self clustering"
All-sky search: look for localized excesses of events





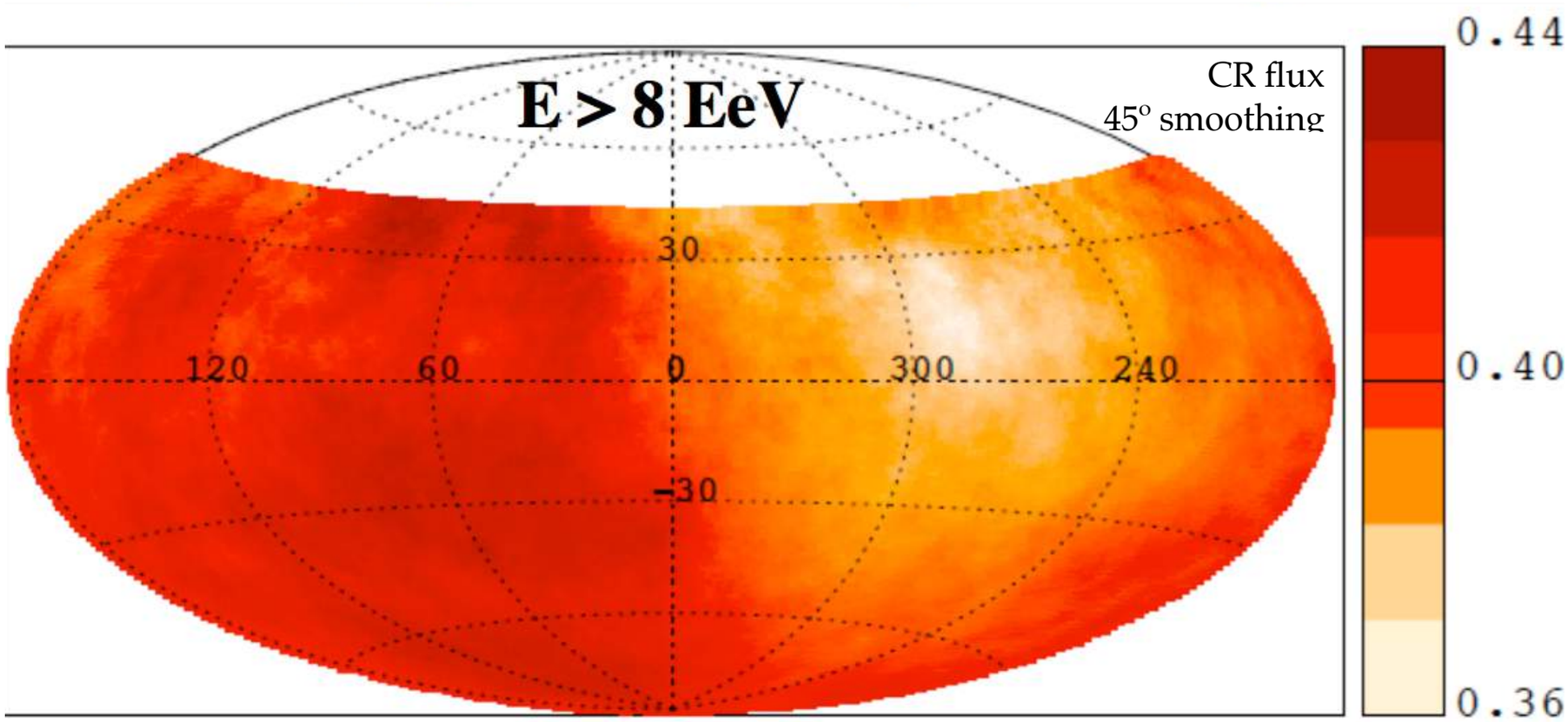
Minimum at 15° and E_{th} = 58 EeV
Post-trial probability: 1.3%

Largest excess (4.3 σ) E_{th} > 54 EeV, θ = 12deg, (18 deg from CenA)
Post-trial probability: 69%

- **High degree of isotropy challenging the original expectation of few sources and light primaries**
- **The most significant deviation from isotropy are at intermediate angular scales**

Large scale anisotropy

Harmonic analysis in right ascension and azimuth (declination sensitive)
~ 70k events with E > 4 EeV and θ < 80º. Two energy bins (4 < E < 8 EeV and E > 8 EeV)

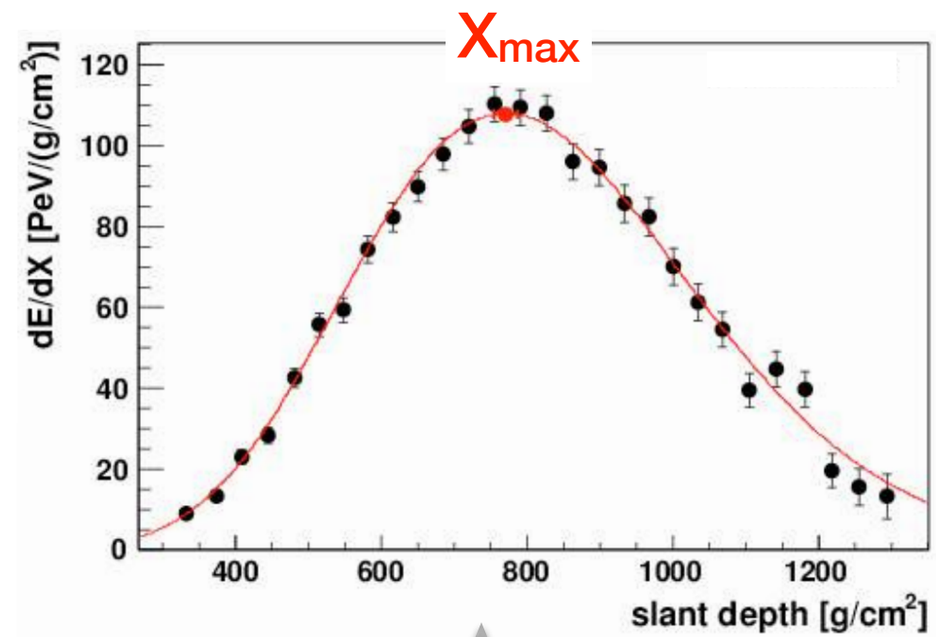


Dipole amplitude: 7.3 ± 1.5% , Pointing to (95º ± 13º, -39º ± 13º)

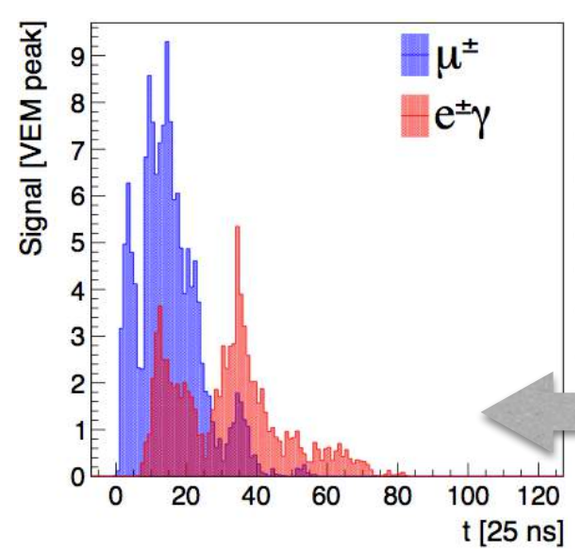
Indication of a dipole at E > 8 EeV
Challenging the original isotropy expectation at these energies

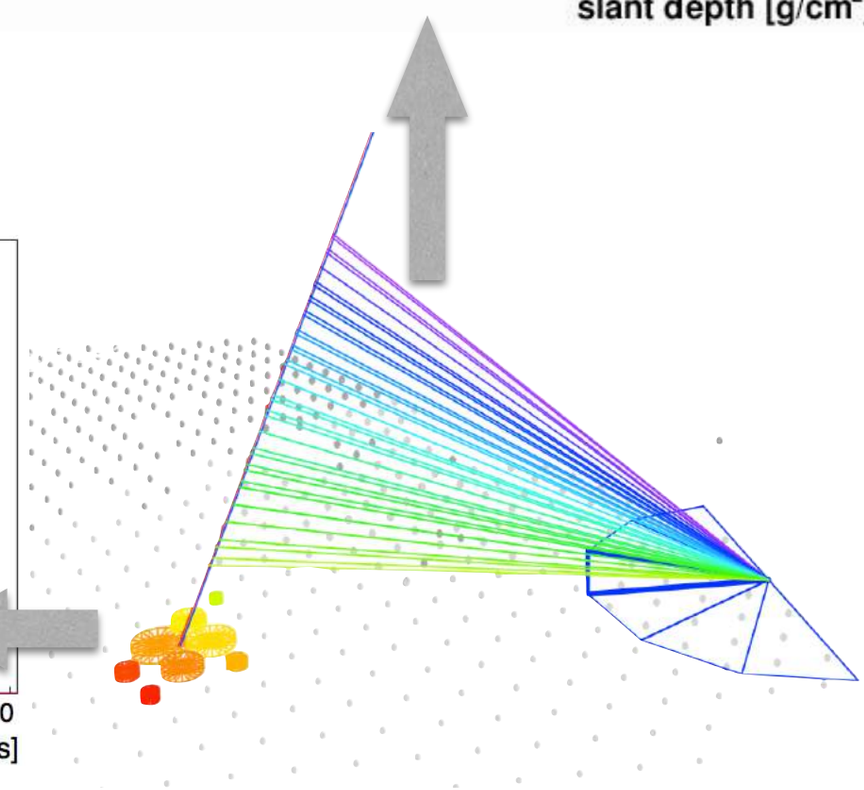
Complementary measurements

- **LONGITUDINAL PROFILE WITH THE FD**
  - direct observation of X_{max}
  - average composition from **1st and 2nd moments of the X_{max} distribution**
  - abundances of masses from **fit of the X_{max} distribution**



- **MUON COUNTING WITH THE SD**
  - Muon density at ground
  - Temporal structure
    SD traces



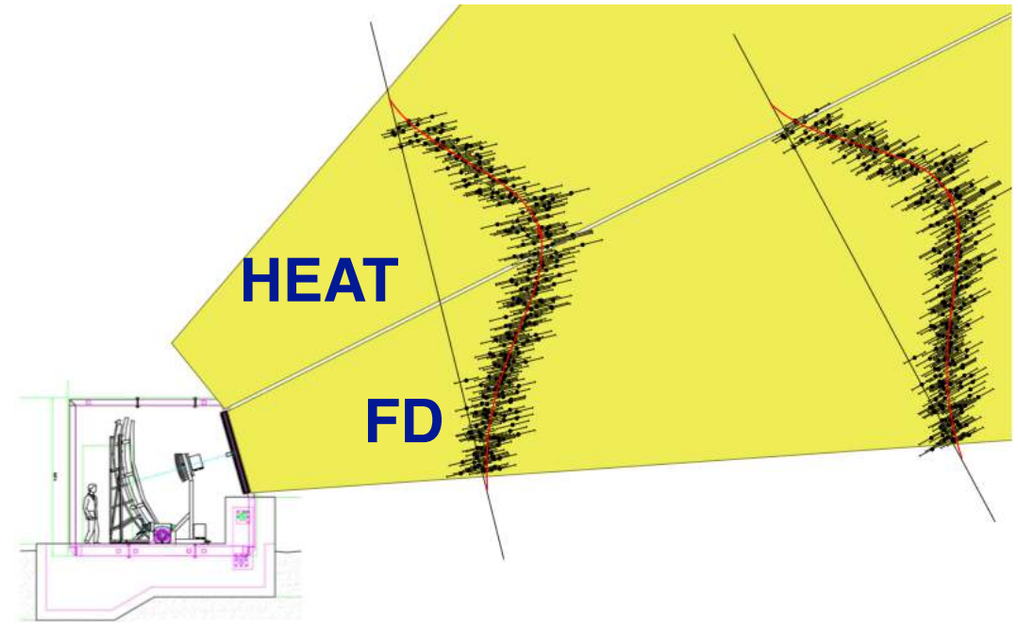


- **COMPLEMENTARITY**
  - constrain **hadronic interaction models**

Xmax measurement with the FD

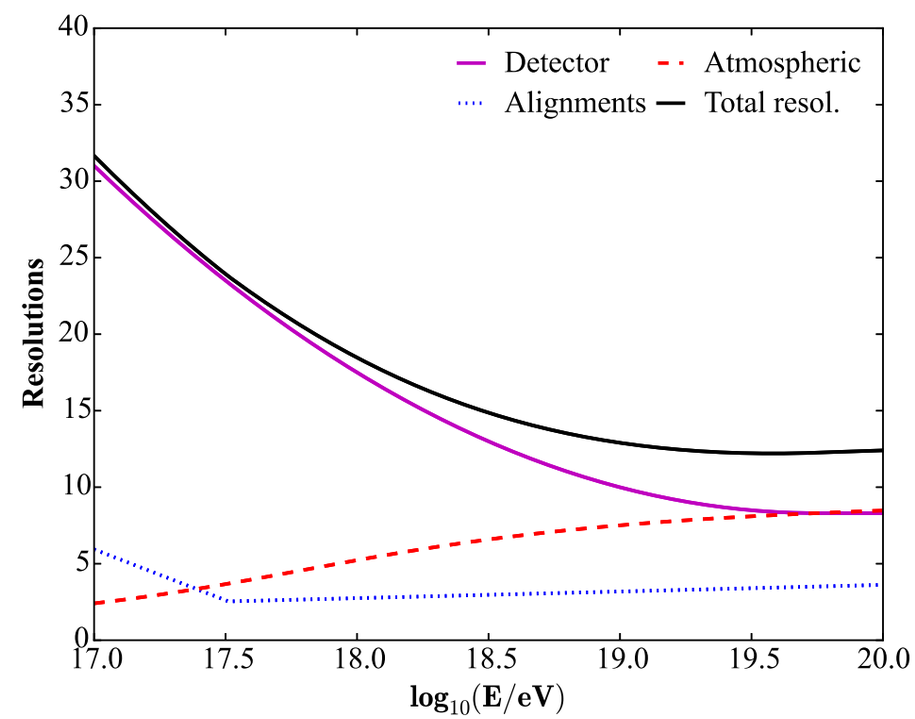
FD standard analysis ($E > 10^{17.8}$ eV)

- ~8 years of data (2004 - 2012)
- Good detector and atmospheric conditions
- Good profile reconstruction
- X_{max} observed in the field of view



Extension to low energies ($E > 10^{17}$ eV)

- 2010 - 2012: HEAT + 1 FD (Coihueco site)
  - X_{max} difference HEAT-FD compatible within systematics



Fiducial cuts

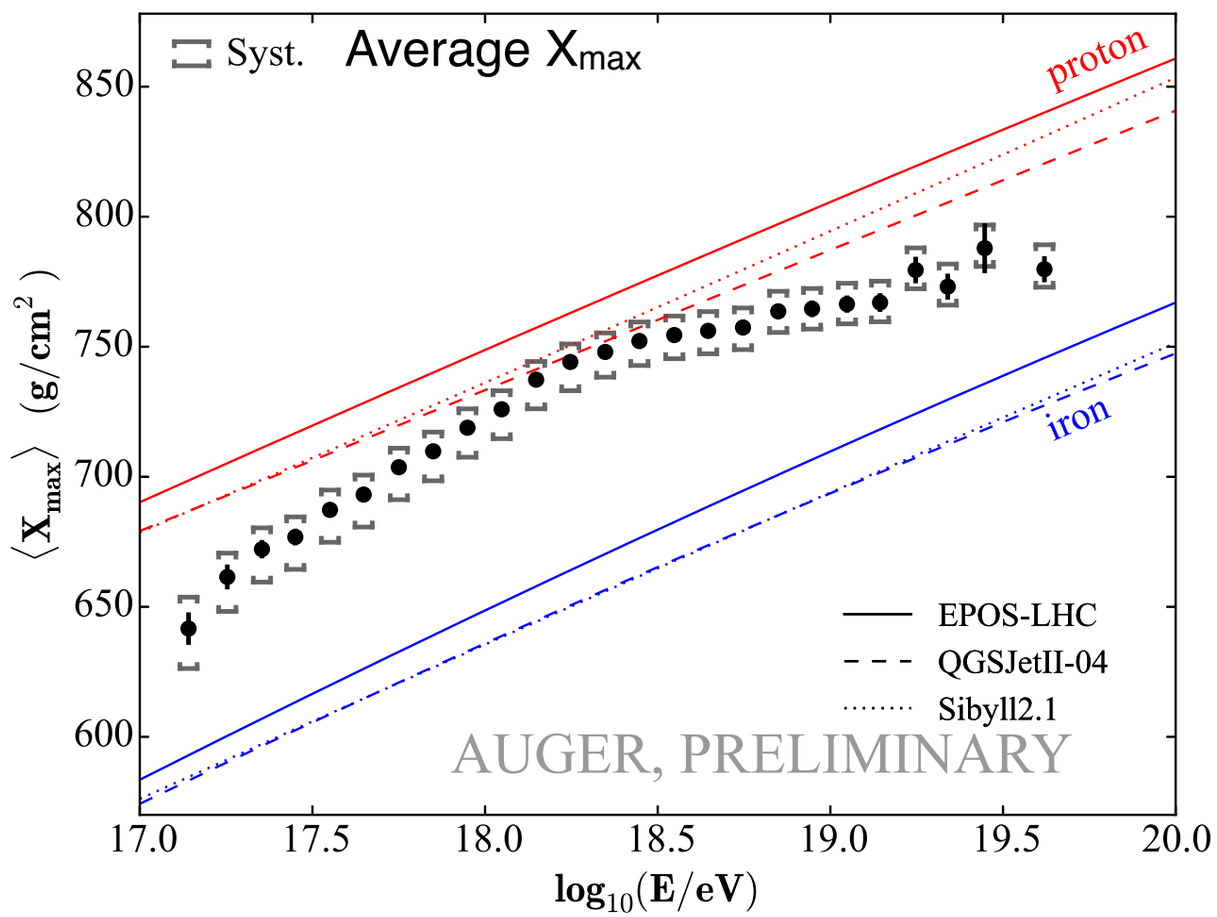
- Cut to avoid biases in the distribution of X_{max}
- Correction for FD acceptance

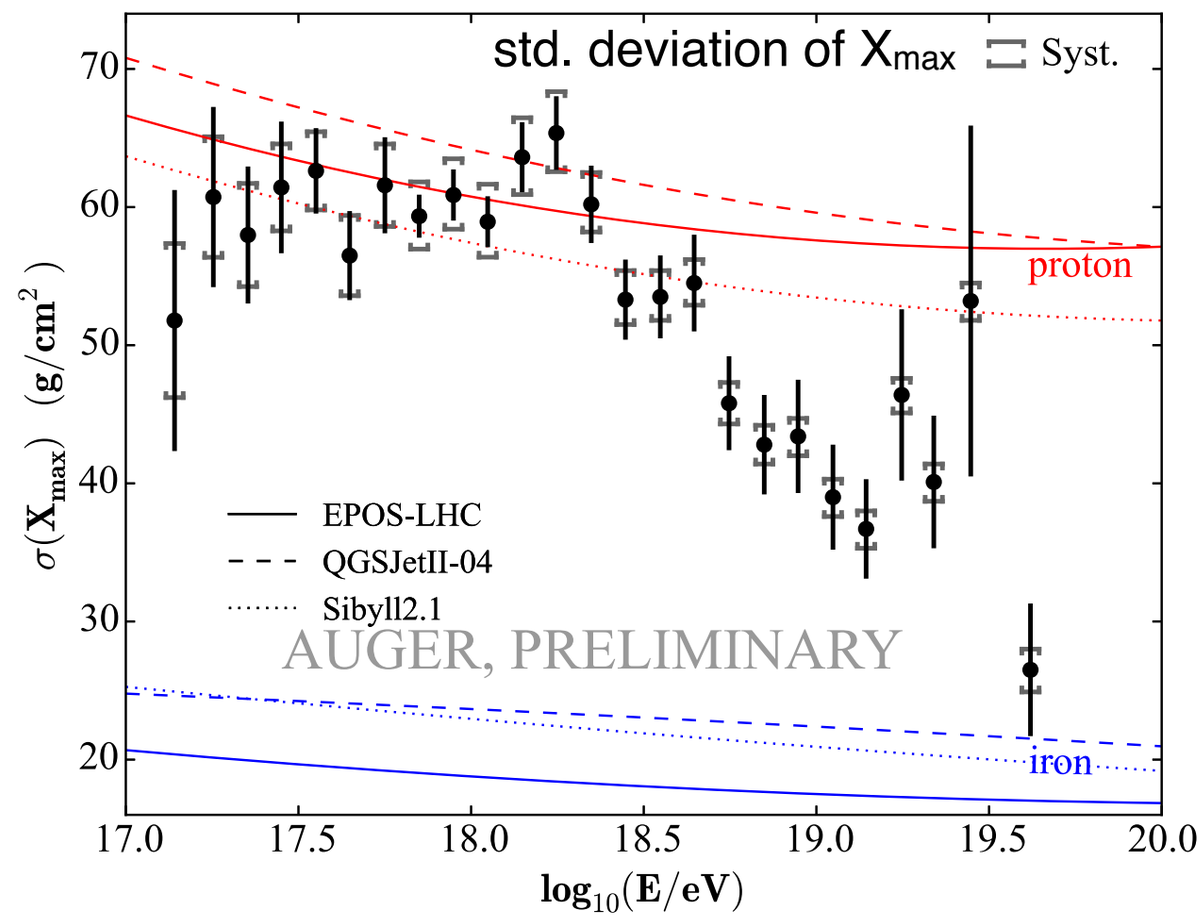
systematic uncertainties: ~ 15 g/cm^2

Xmax measurement with the FD

Depth of shower maximum (Xmax) proportional to the lnA.

Mass inferred from the first two moments of the Xmax distribution





Break-point @ E ~$10^{18.3}$ eV: Mass composition **from intermediate to light primaries at low energy** and **to intermediate/heavy at high energy**

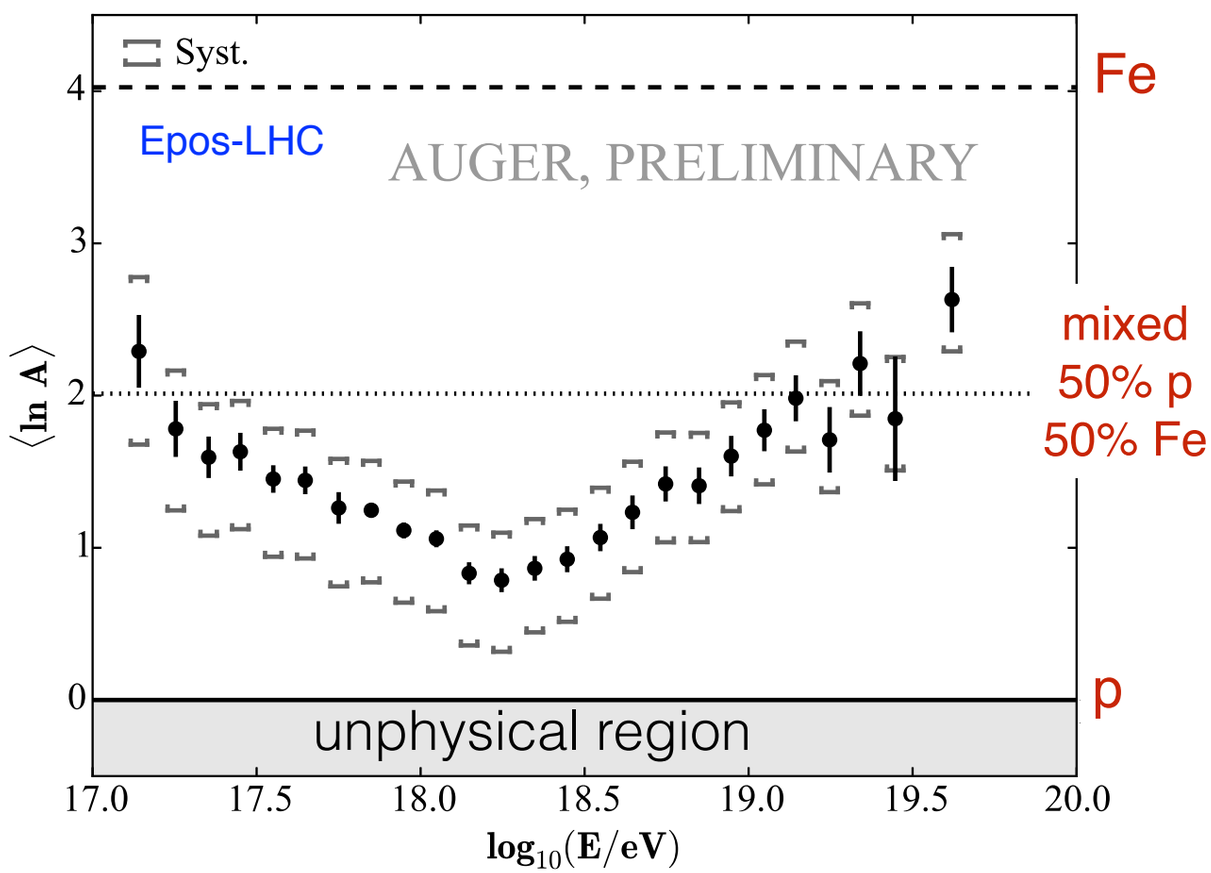
The Pierre Auger Coll., Phys. Rev. D 90, 122005 (2014)
A. Porcelli for the Pierre Auger Coll., ICRC 2015

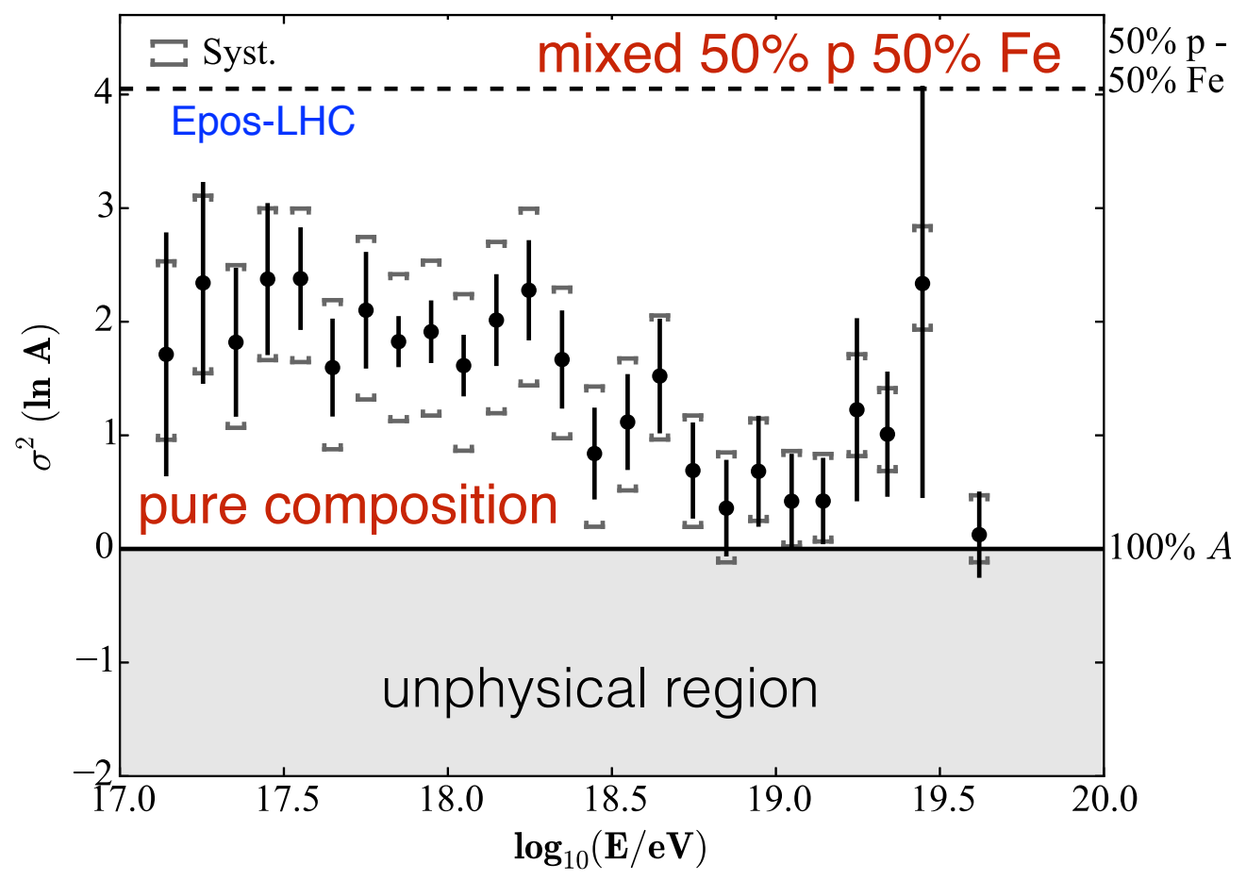
Interpretation of results: conversion to <lnA>

Epos-LHC

X_{max} converted to <lnA> based on simulations

Low energy	from intermediate to light	many components
High energy	from light to heavy	dominated by one/a few comp.



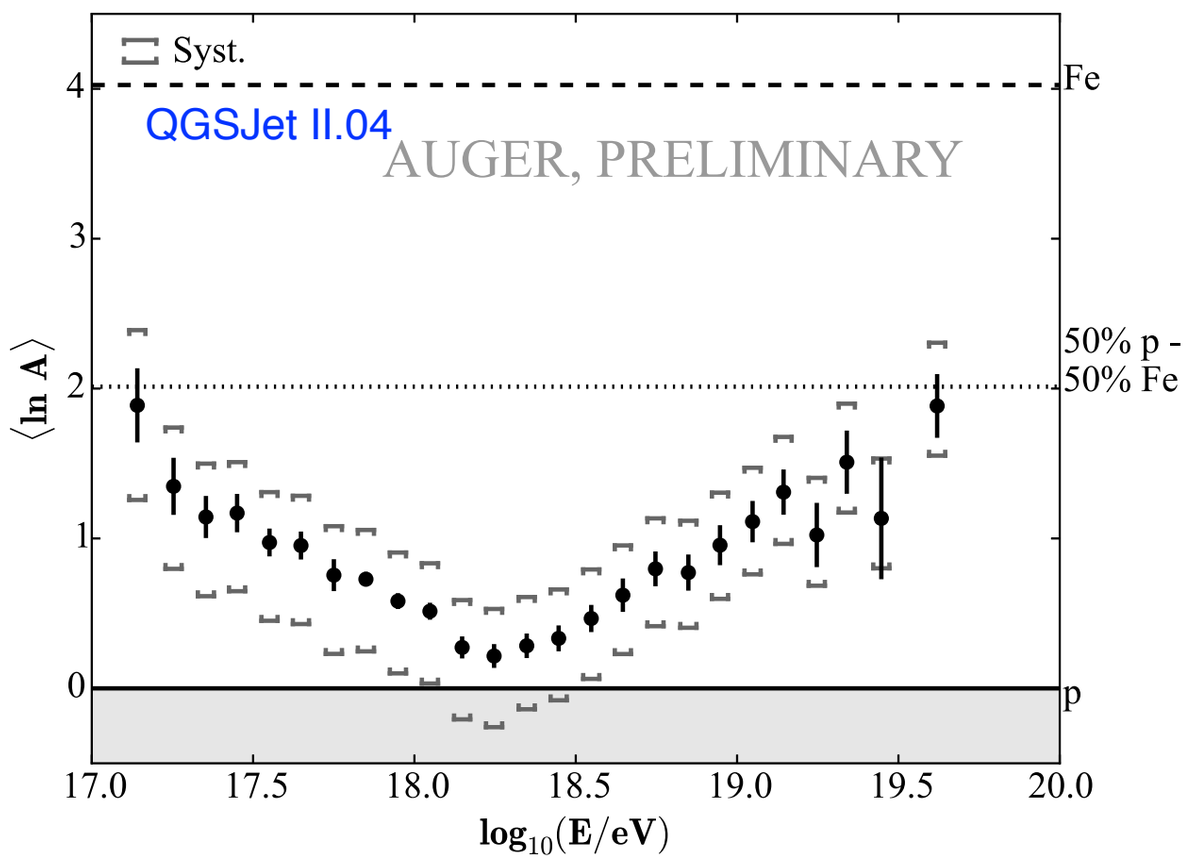


Interpretation of results: conversion to <lnA>

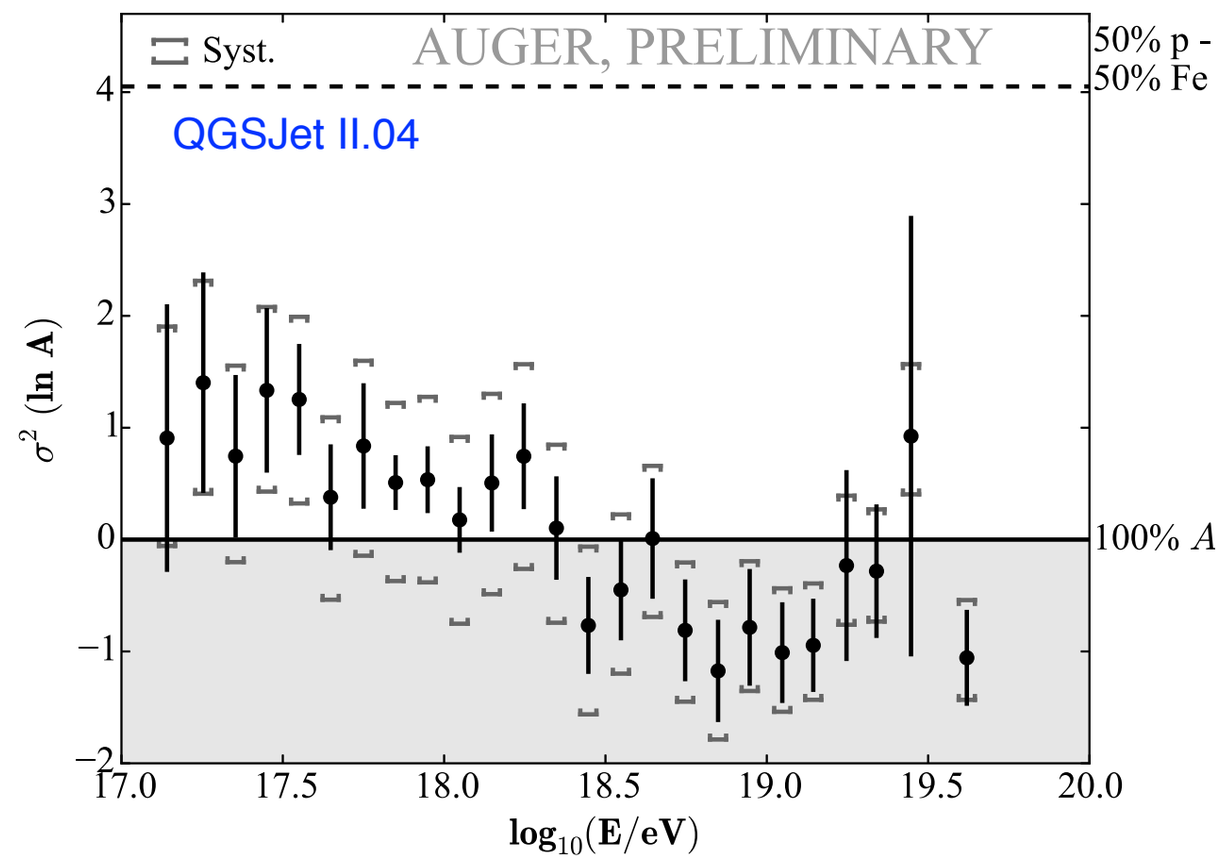
QGSJet II.04

X_{max} converted to <lnA> based on simulations

Low energy	from intermediate to light	many components
High energy	from light to heavy	dominated by one/a few comp.



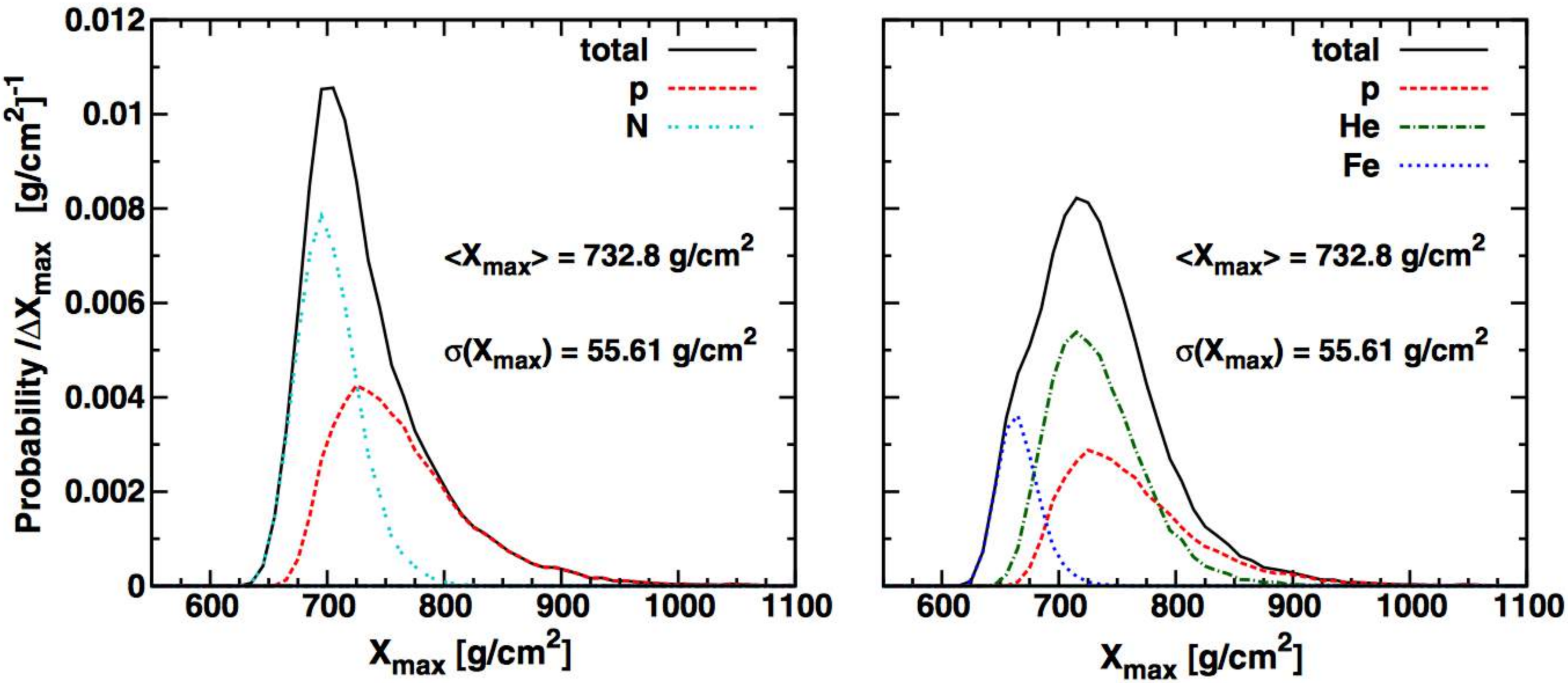
compatible results between QGSJet II.04 and Epos-LHC



unphysical results at high energy!
QGSJet-II.04 disfavored (even if still compatible within syst. uncert.)

Are the moments of Xmax distribution enough?

The Pierre Auger Coll., Phys. Rev. D 90, 122006 (2014)



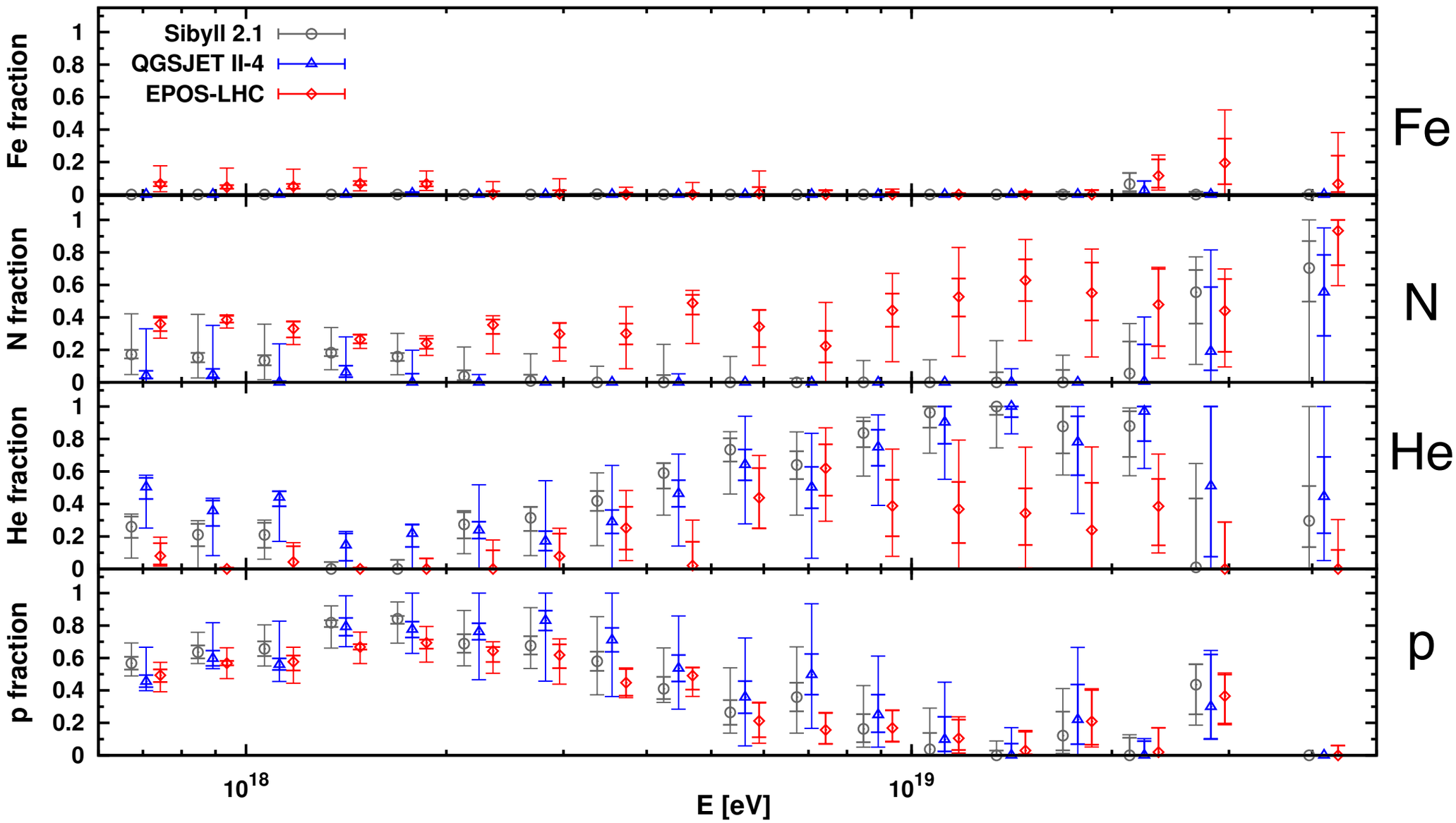
Same X_{max} and $\sigma(X_{max})$ but different mixtures

fit the X_{max} distribution with a *N-components model*

Mass composition (up to 40 EeV)

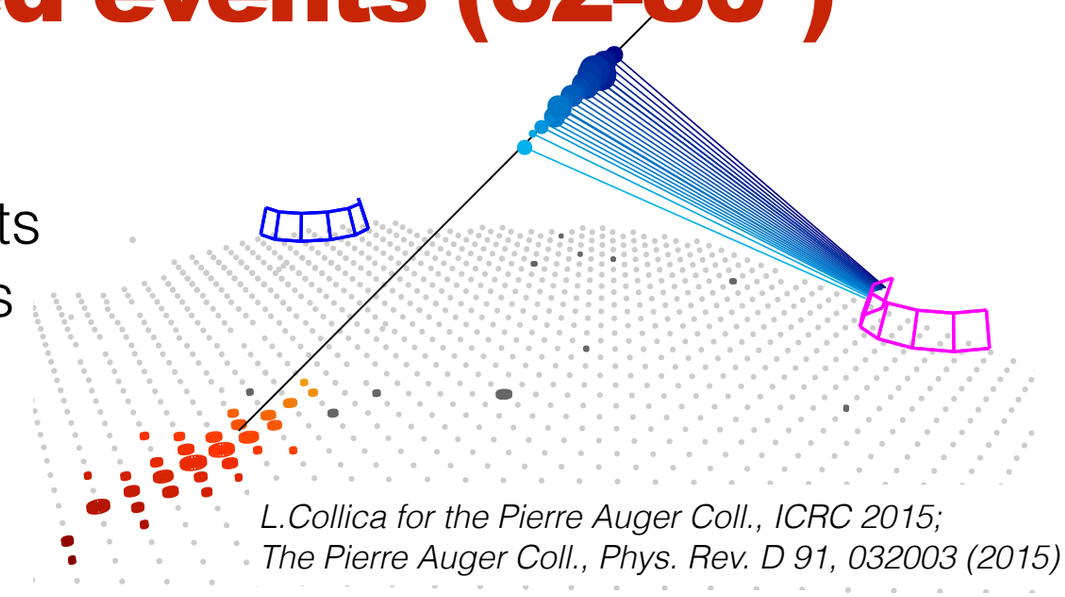
The Pierre Auger Coll., Phys. Rev. D 90, 122006 (2014)

Hybrid data (E $> 10^{17.8}$ eV)

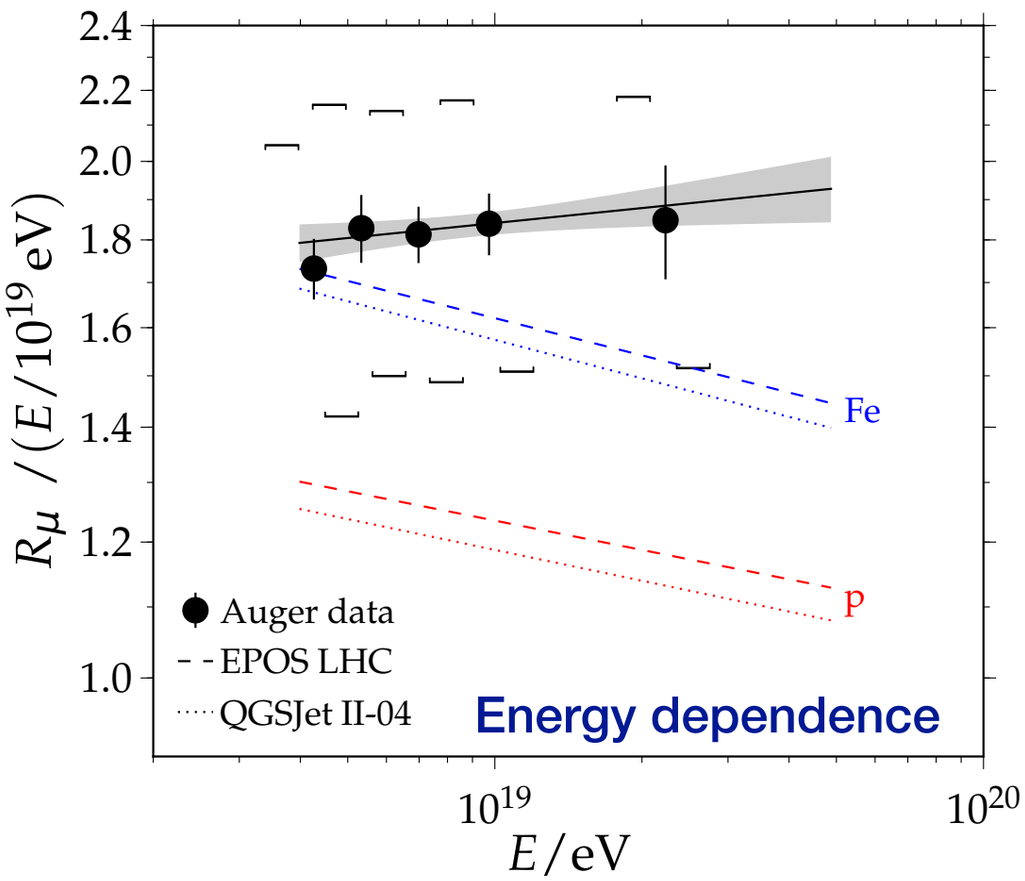


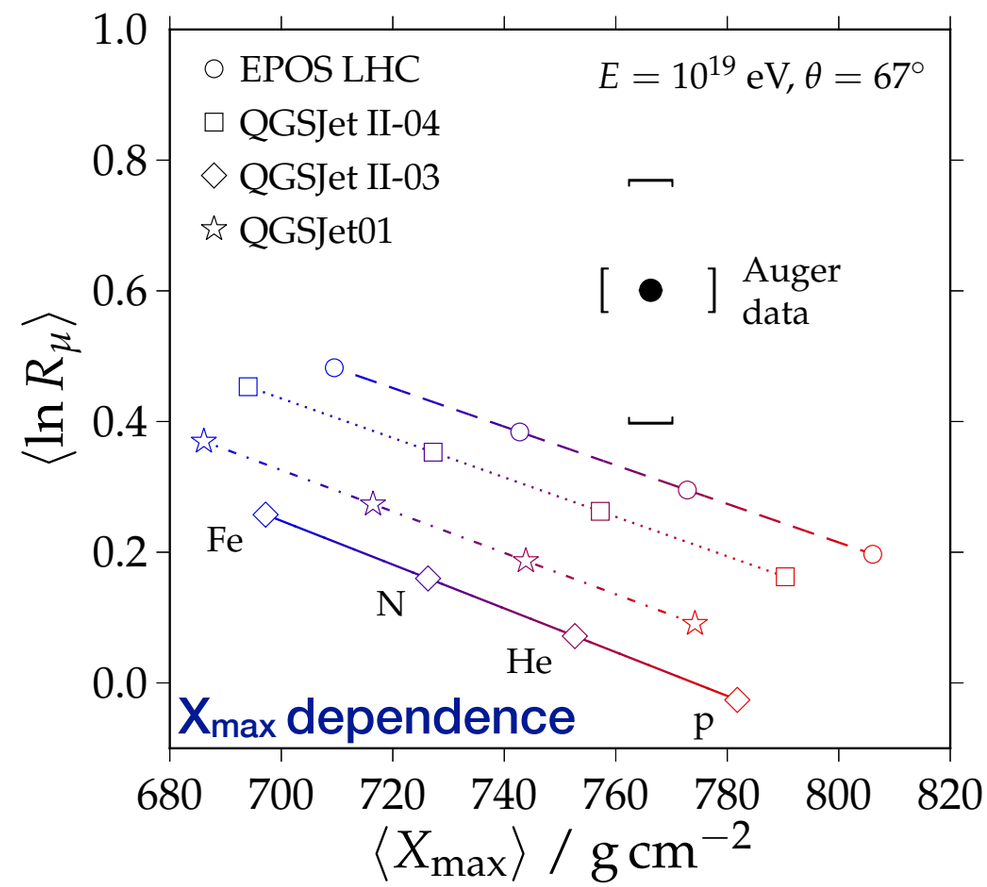
Muon counting with inclined events (62-80º)

- EM component mostly absorbed in inclined events
- Reconstruction based on muon density templates



Muon scale: $R_\mu = \frac{N_\mu^{data}}{N_{\mu,19}^{MC}}$



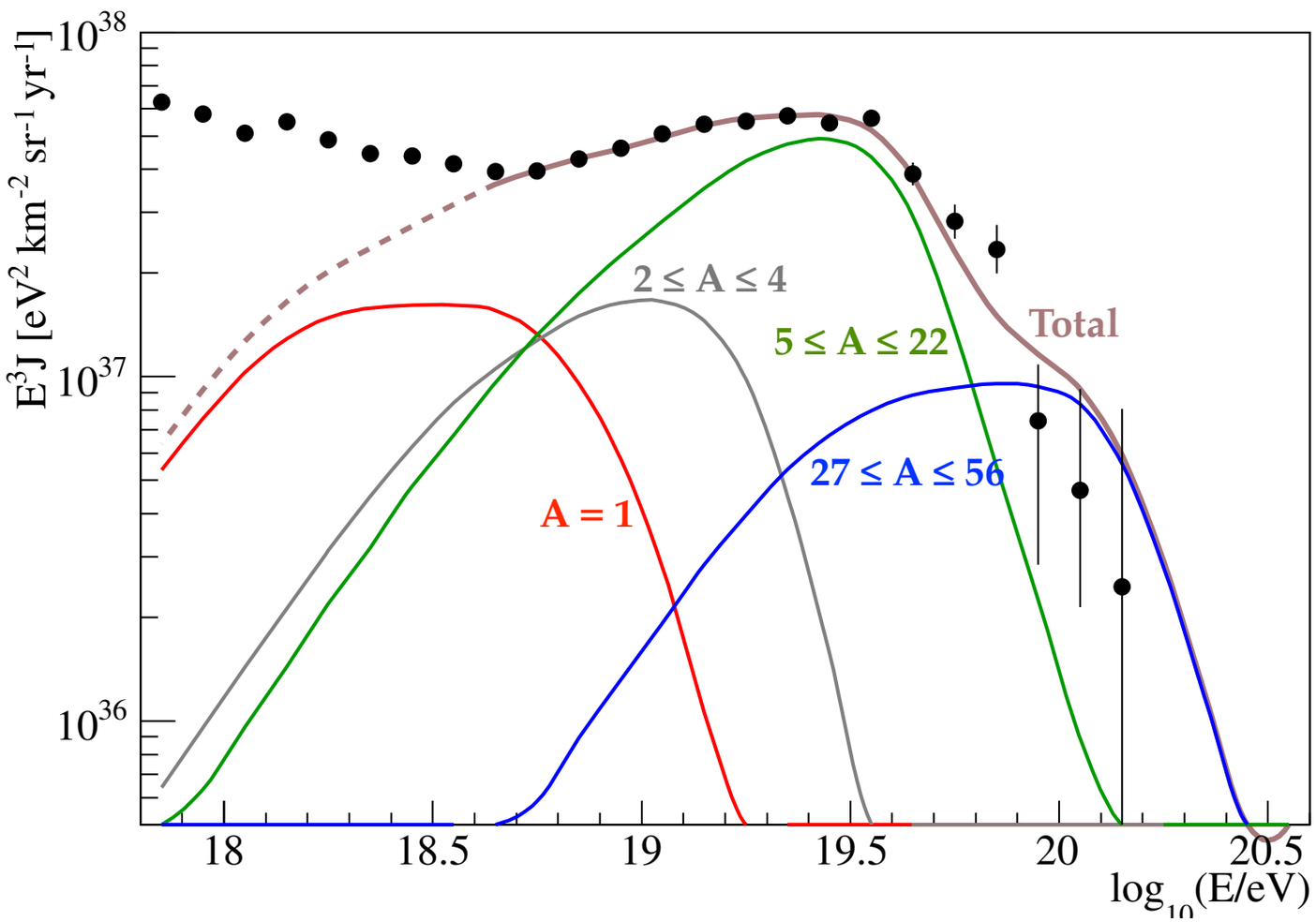


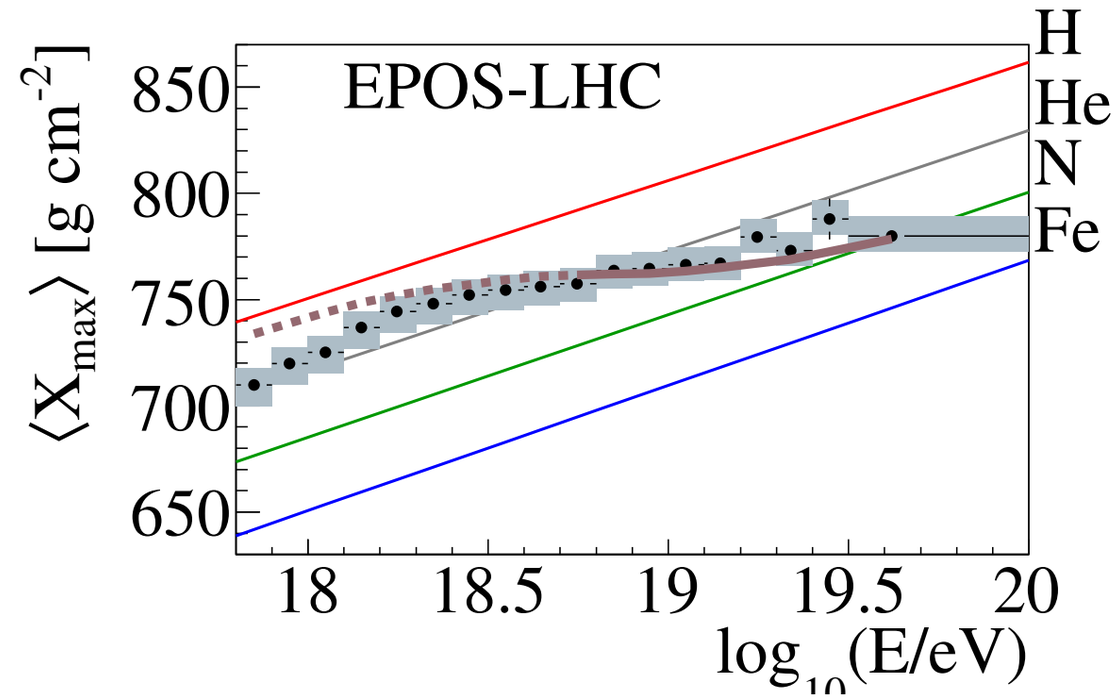
- Muon deficit in simulations (from 30% to 80% @ 10^{19} eV depending on models)
- Uncertainties too large to make conclusions on mass

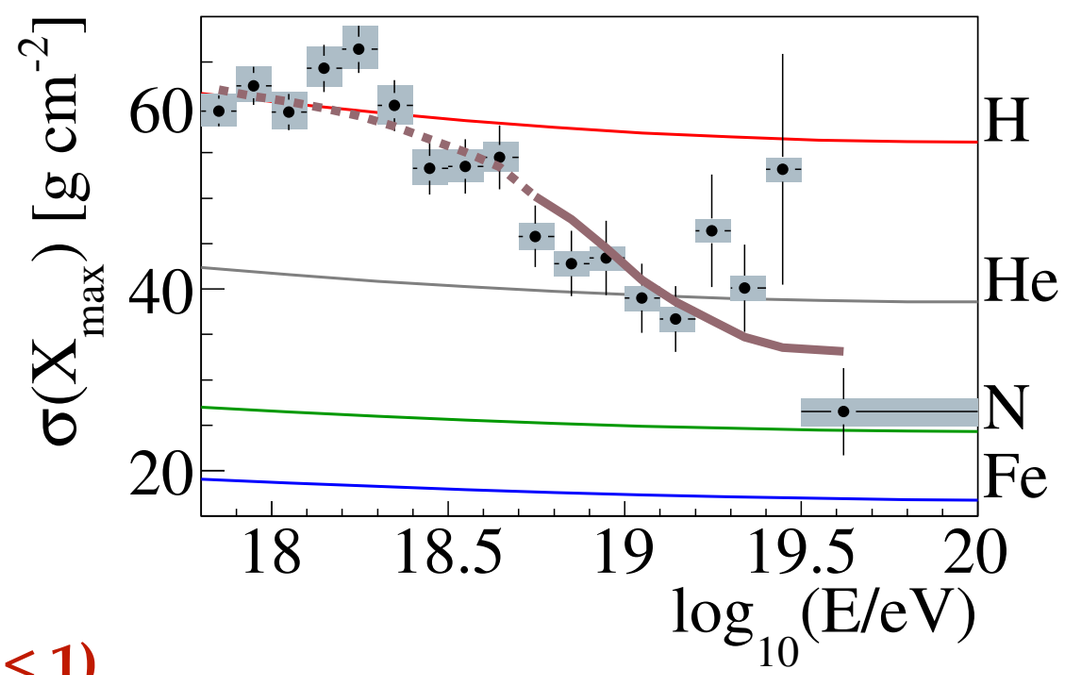
Combined fit: spectrum and mass composition

Model: identical sources (uniformly distributed) accelerating p, He, N, Fe

fit parameters: injection flux, spectral index, energy cut off, mass fractions



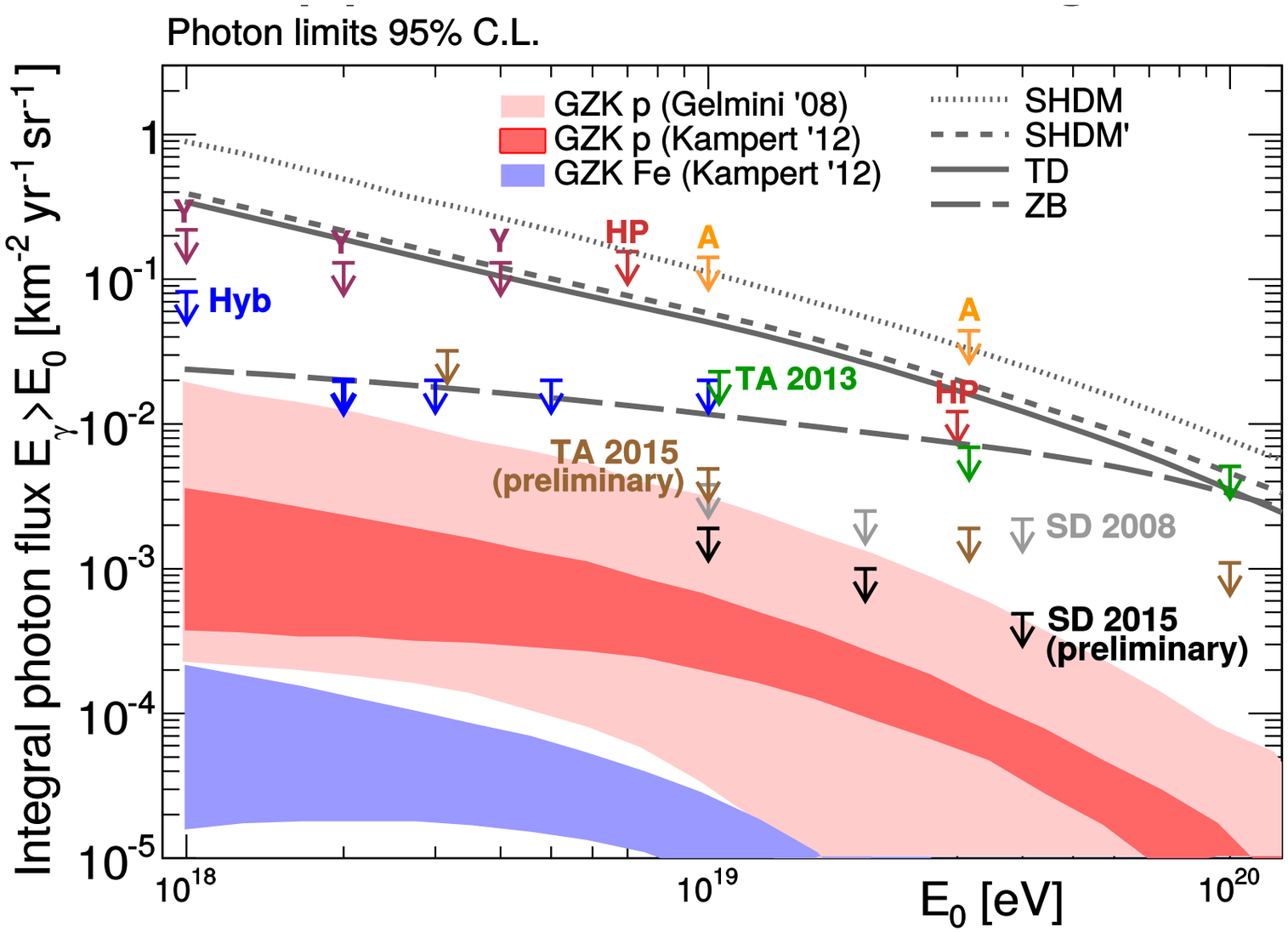




Best fit with very hard spectra ($\gamma \le 1$)

Prevailing intermediate mass at the source

UHE photons

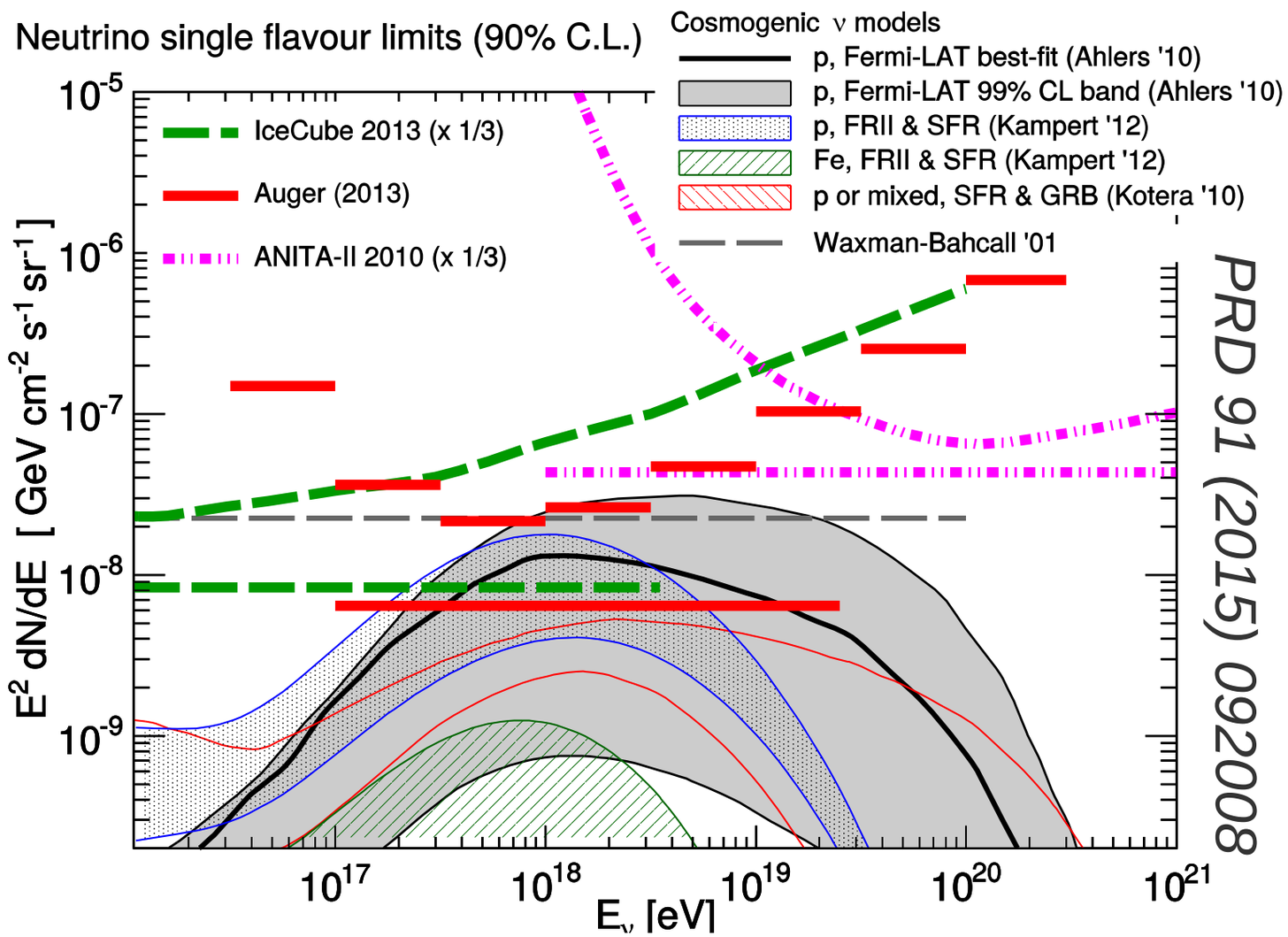


✓ top-down models disfavored

✓ GZK flux region within reach

UHE neutrinos search

ν selected as inclined showers with large em component (time spread of SD signals)



✓ Waxman-Bahcall landmark reached

✓cosmogenic model with pure p composition at the source and strong FRII evolution disfavored

Summary of results

After 10 years of operation, the Pierre Auger Observatory has answered to some long-standing questions and has opened new ones:

- **Ankle** position and **flux suppression** at high energy observed with high significance
- **mass composition** measured over a wide energy range:
  - predominantly mixed with a break around $10^{18.3}$ eV
- Data and air-shower models **discrepancies in the number of muons**
- Doing **astronomy with UHECRs** is becoming more and more challenging
- UHE **photons and neutrinos** disfavor exotic models and are reaching the sensitivity to test the GZK expected fluxes

AugerPrime: A needed step to proceed further

1. **Elucidate the origin of the flux suppression (energy-loss vs. maximum-energy scenarios)**
   - Fundamental constraints on UHECR sources
   - Galactic vs. extragalactic sources
   - Prediction of GZK neutrino and photon fluxes

2. **Search for a flux contribution of protons at ~10% level up to highest energies**
   - Prospects for future UHECR experiments
   - Proton astronomy and anisotropy searches

3. **Increase sensitivity to neutrino and photon detection**
   - Improved limits on exotic models
   - Discovery potential

4. **Study of extensive air showers and hadronic multiparticle production**
   - Particle physics beyond man-made accelerators
   - Search / constraints on new physics phenomena (LIV)

(see R.Smida's talk)

Backup slides

Fitting the Xmax distributions

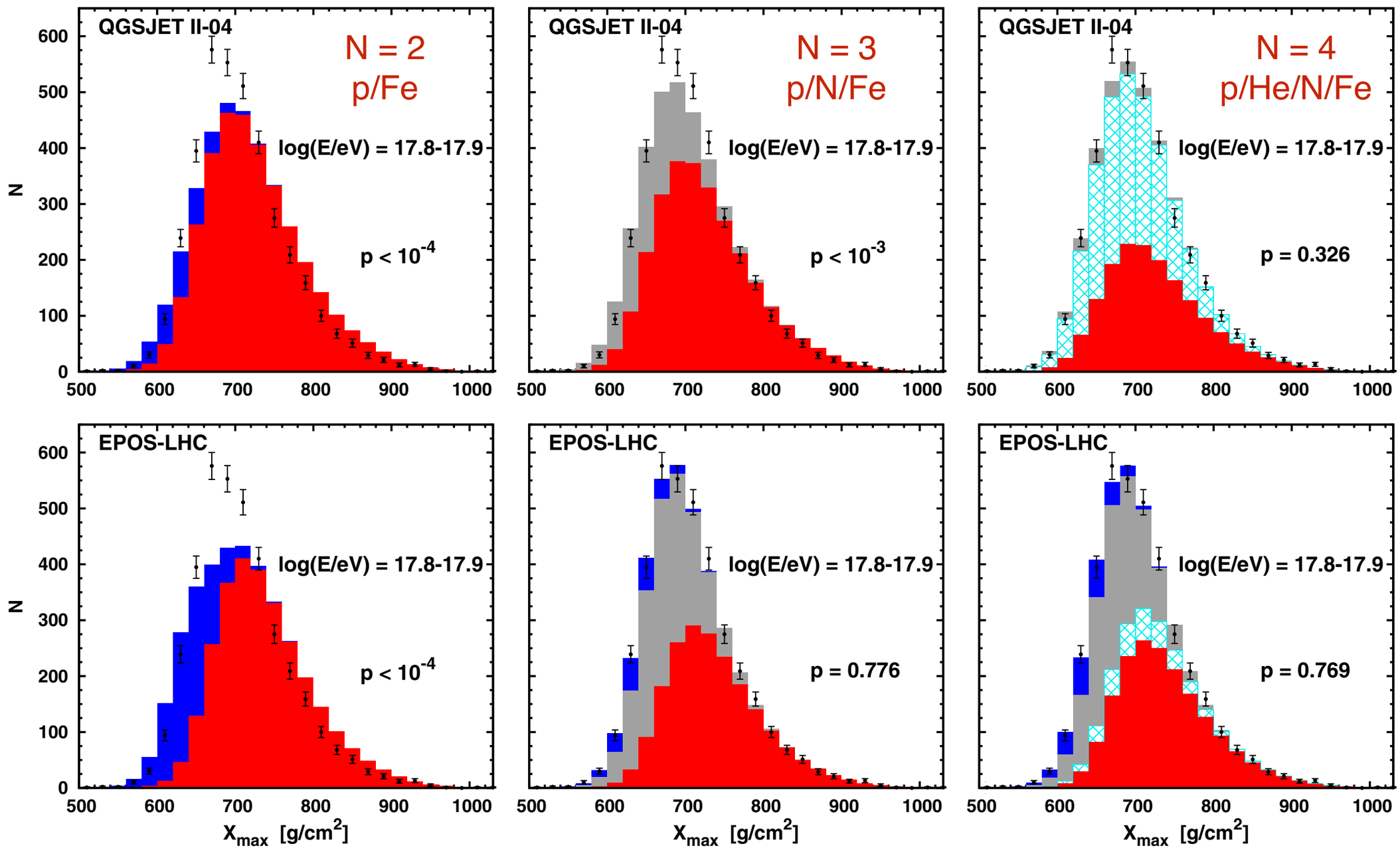
Hybrid data (E > $10^{17.8}$ eV)

fit the X_{max} distribution with a *N-components model*

simulation template

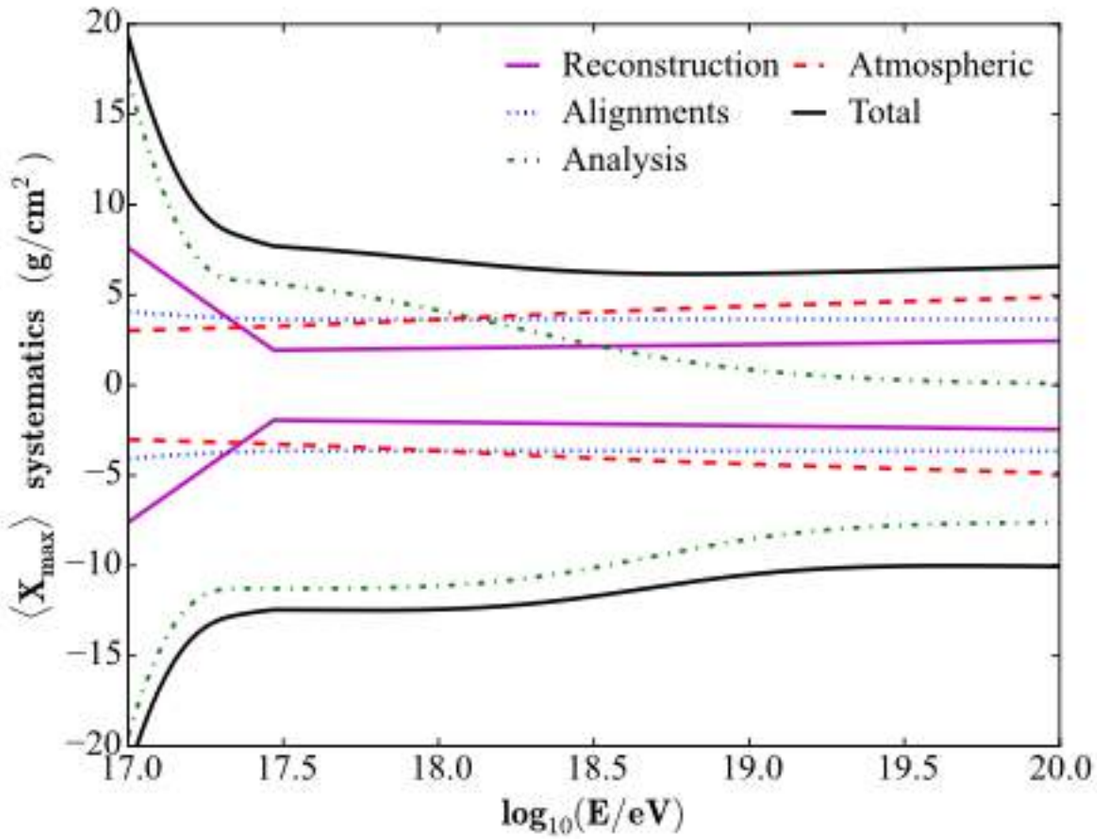
$$C_j = \frac{N_{\text{data}}}{N} \sum_s f_s X^{\text{m}}_{s,j},$$

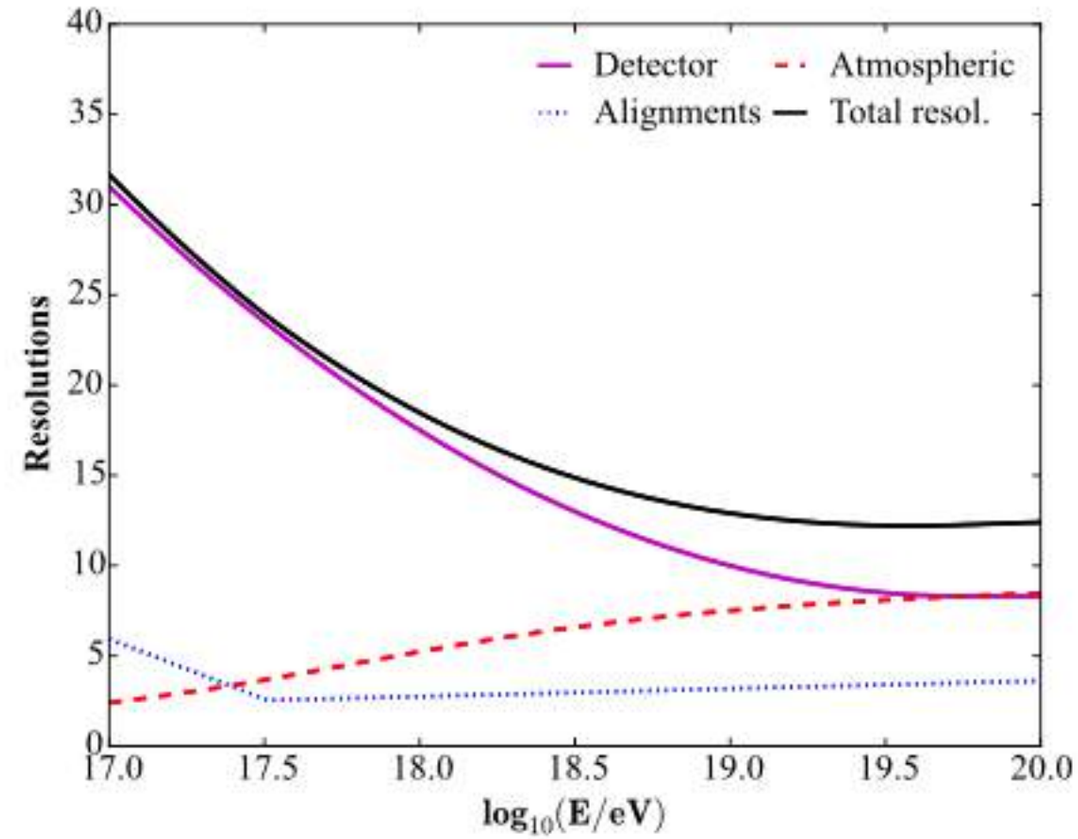
fraction of the specie *s*



Resolution and systematic uncertainties

A. Porcelli for the Pierre Auger Coll., ICRC 2015
The Pierre Auger Coll. , Phys. Rev. D90 12 (2014)





- reconstruction bias (only left) and detector resolution (right)
- offset in time between SD-FD, calibration and telescopes alignment
- analysis
- atmospheric uncertainty in the geometry reconstruction and fluorescence light yield

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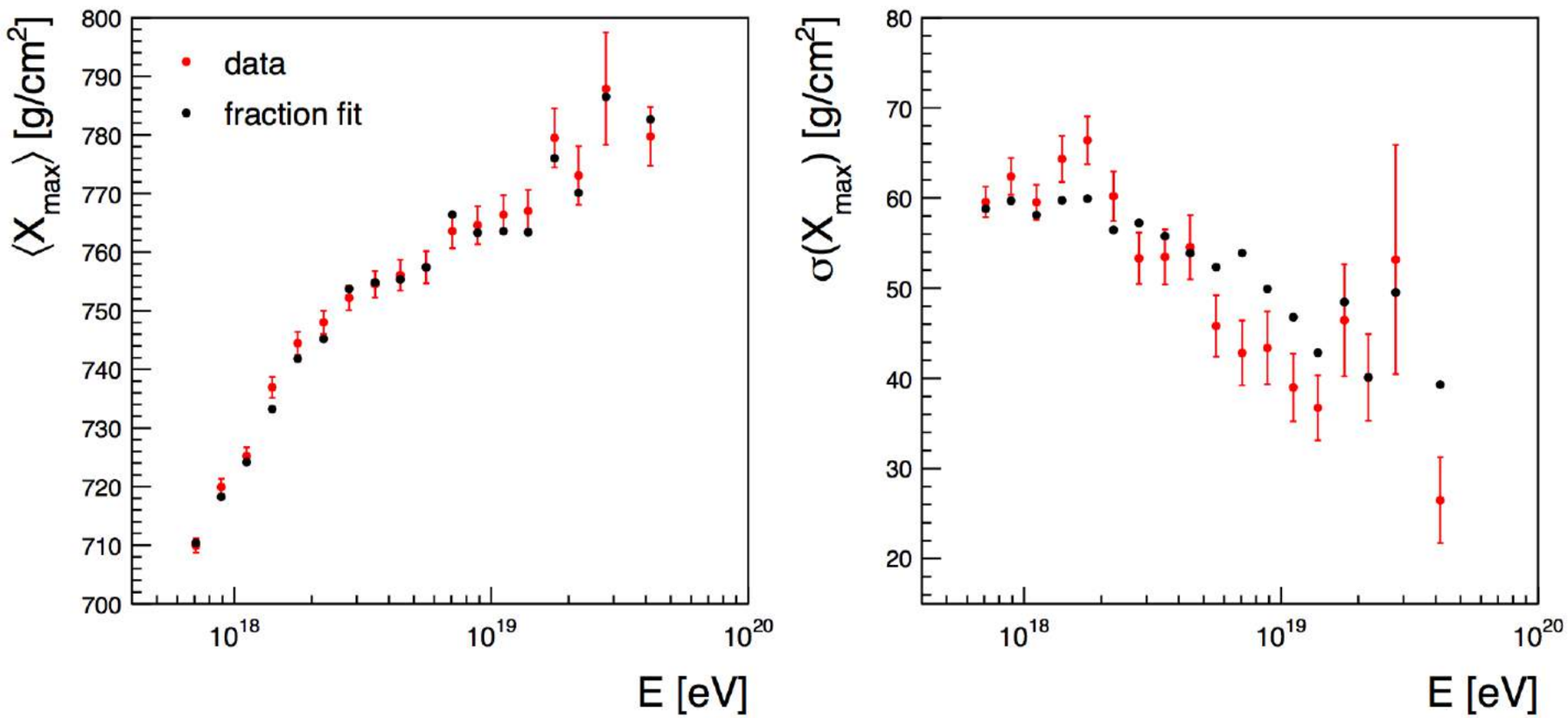
Comparing Auger and Telescope Array

1) **Construct a model of X_{max} distribution** describing the Auger data (based on the fit of X_{max} distributions)



2) Pass the ``Auger-like'' composition through the TA detector simulation and reconstruction/analysis chain

caveat: only QGSJet II.04 hadronic model used so far

Comparing Auger and Telescope Array

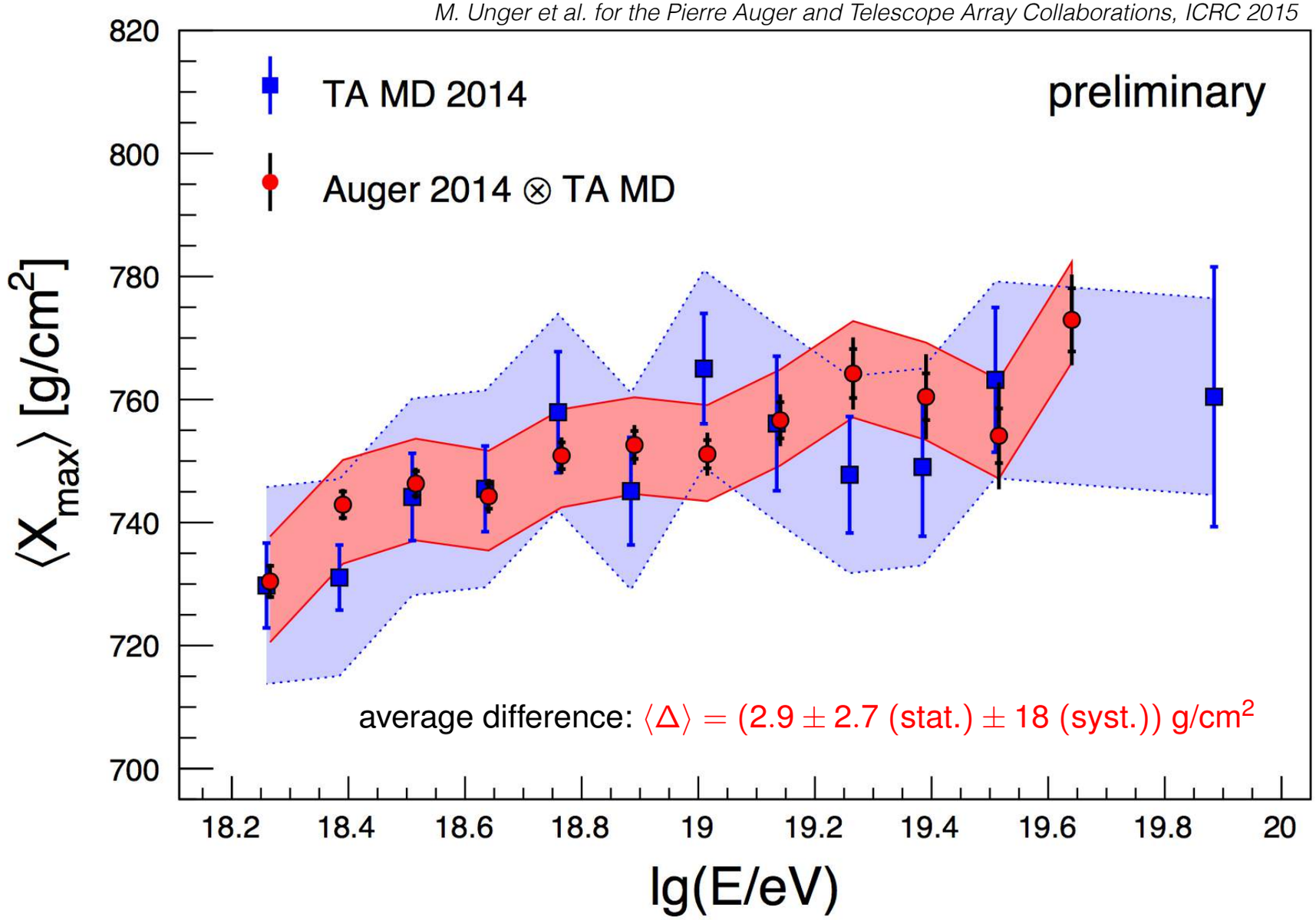
Auger:

- 8 years
- hybrid (at least one surface detector station)
- 24 telescopes
- PRD **90** (2014) 12, 122005

TA:

- 5-year hybrid data sample
- hybrid (at least three surface detector station)
- Middle Drum telescopes (MD)
- APP **64** (2014) 49

M. Unger et al. for the Pierre Auger and Telescope Array Collaborations, ICRC 2015



AugerPrime: timeline and exposure

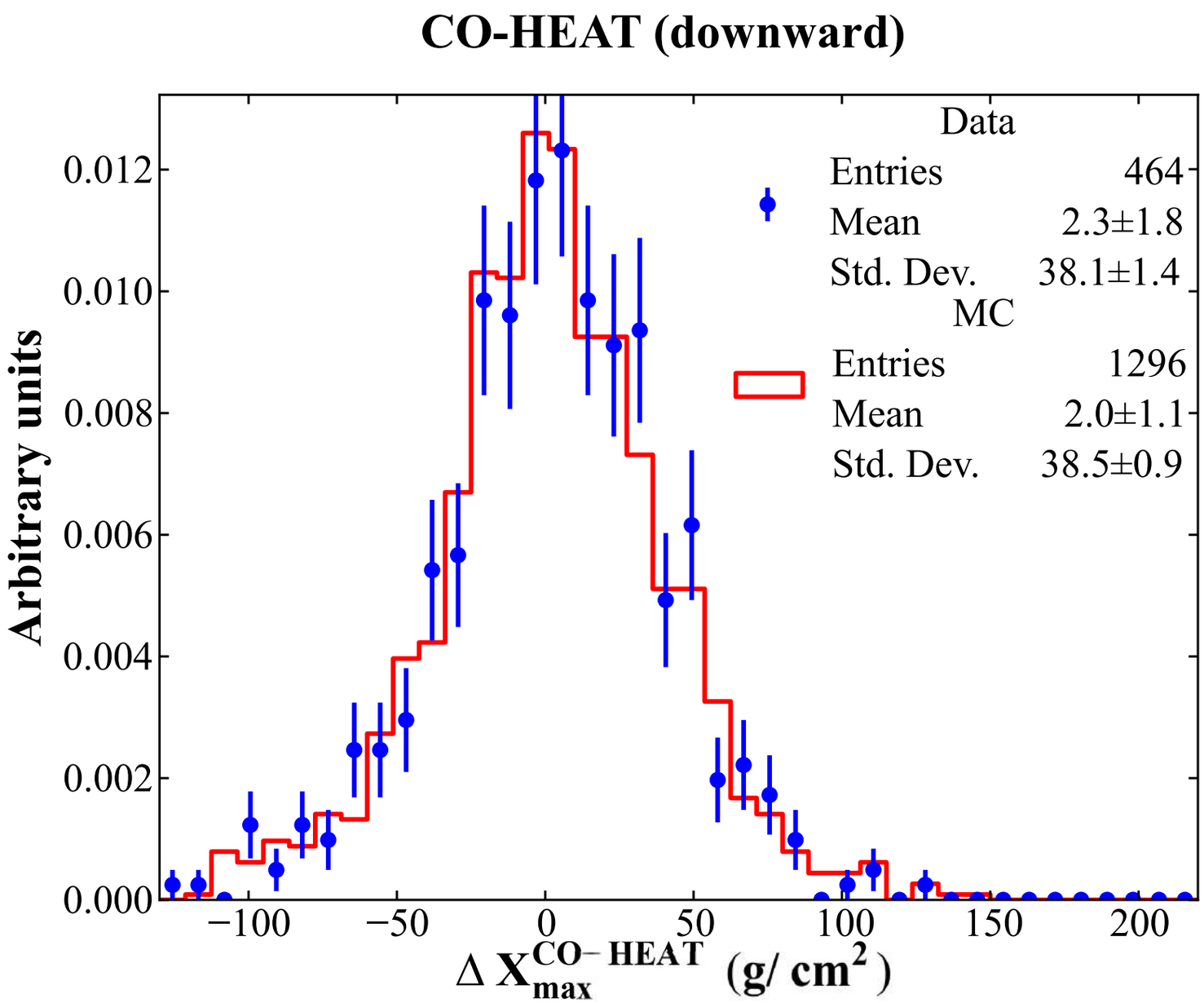
R. Engel, ICRC 2015

Timeline

April 2015: preliminary design report
March 2016: engineering array
2017-2018: deployment
2018 - 2024: data taking

$\log_{10}(E/\mathrm{eV})$	$\mathrm{d}N/\mathrm{d}t\|_{\mathrm{infill}}$ [yr^{-1}]	$\mathrm{d}N/\mathrm{d}t\|_{\mathrm{SD}}$ [yr^{-1}]	$N\|_{\mathrm{infill}}$ [2018-2024]	$N\|_{\mathrm{SD}}$ [2018-2024]
17.5	11500	-	80700	-
18.0	900	-	6400	-
18.5	80	12000	530	83200
19.0	8	1500	50	10200
19.5	~1	100	7	700
19.8	-	9	-	60
20.0	-	~1	-	~9

Cross-Checks HEAT - Coihueco



X_{max} difference between HEAT and FD (Coiheuco site)

- compatible within systematics

- good agreement data/MC

Muon counting with vertical events

Muons with zenith angles < 60°

Hybrid events used to test LHC-tuned hadronic models

Ground signal modified in MC to fit the one in the data

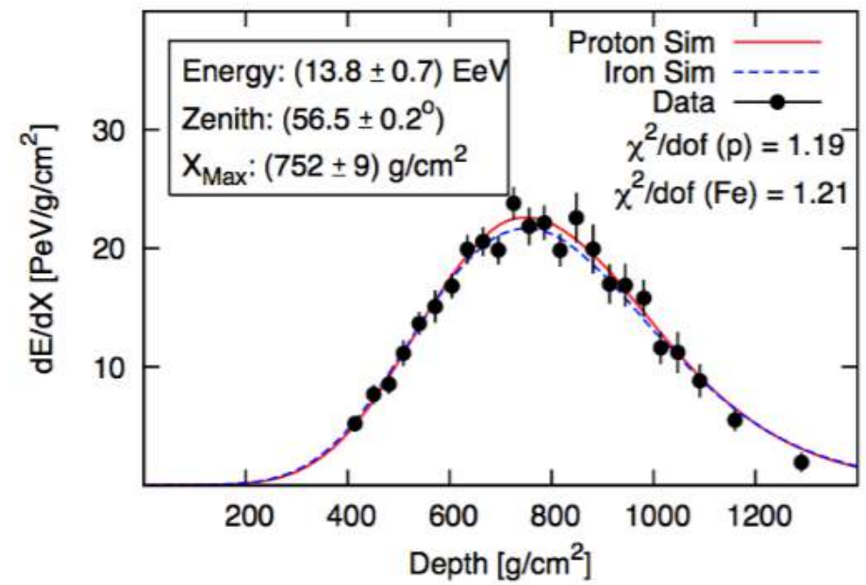
Rescaling factors:

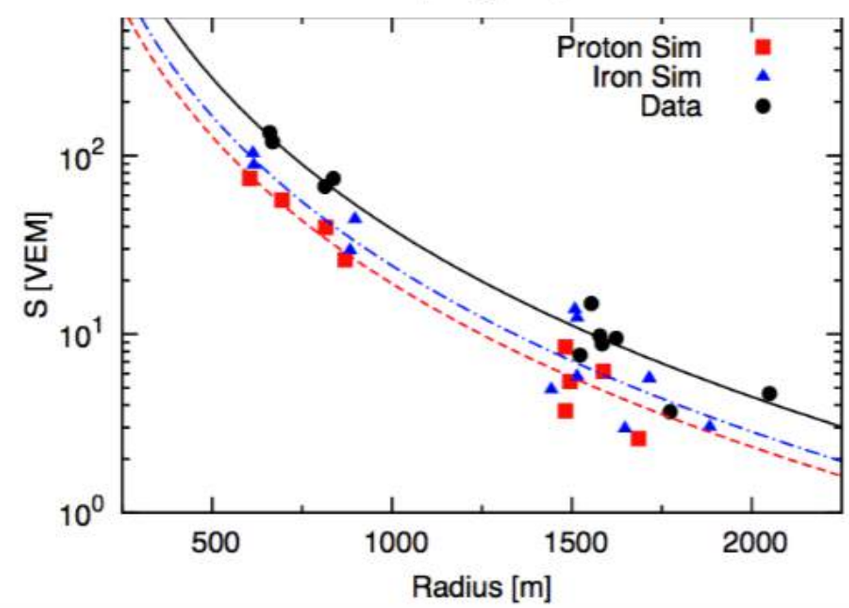
R_E ⟶ primary energy

R_{had} ⟶ hadronic contribution to the ground signal

Analysis details:

- data set: 01/2004 - 12/2012
- $E = 10^{18.8} - 10^{19.2}$ eV
- zenith angles [0°, 60°]
- 411 hybrid events after quality cuts
- Systematic Uncertainties on R_E and R_{had}: 10 %

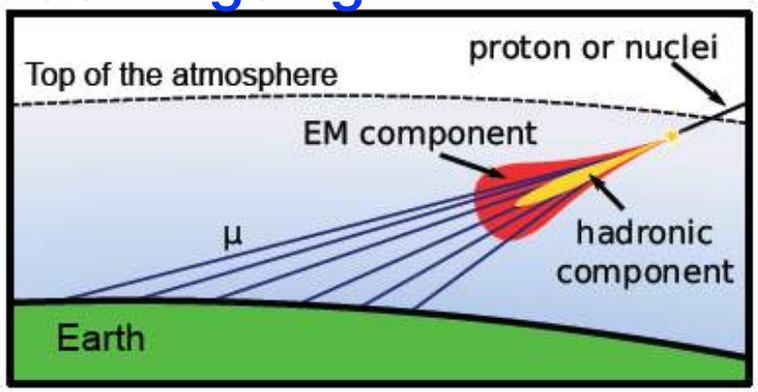


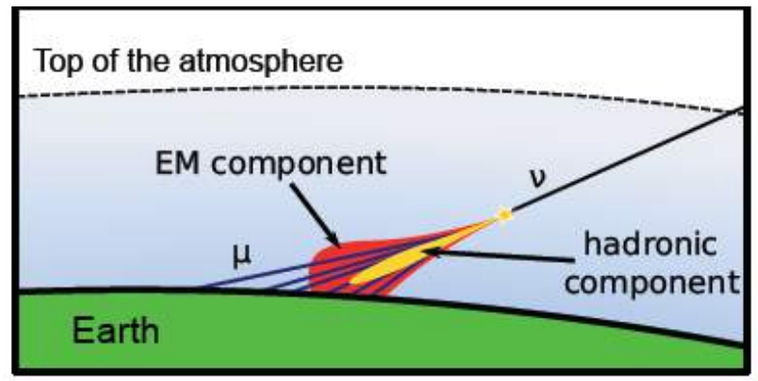


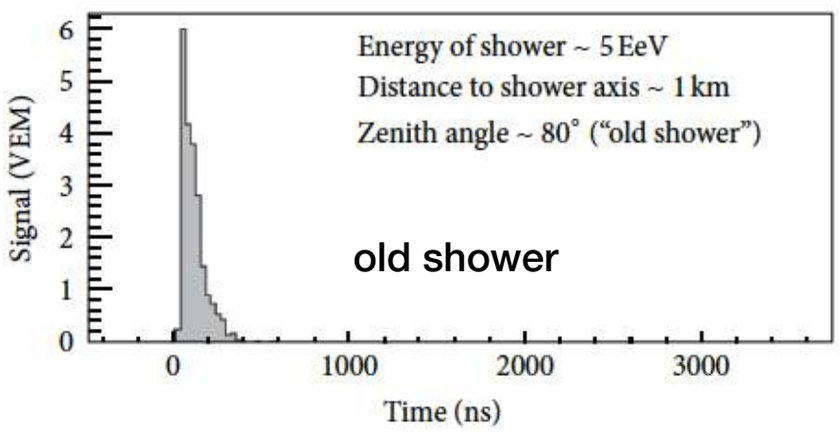
UHE neutrino

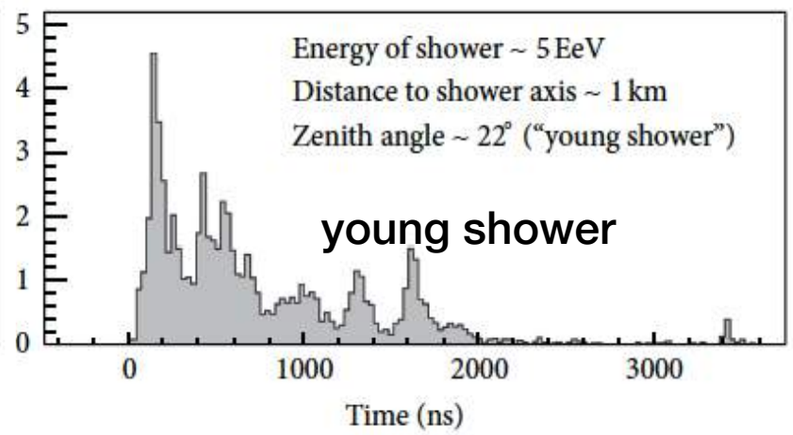
ν selected as inclined showers with large em component (time spread of SD signals)

- down-going





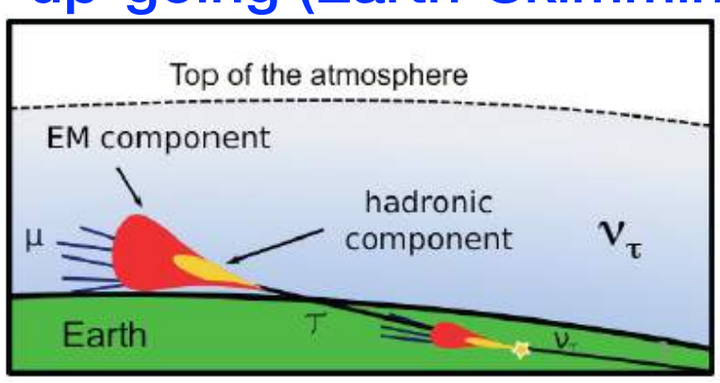




all ν flavor

Low zenith (65º,75º)
contrib. to total evt rate: **23%**
High zenith (75º,90º):
contrib. to total evt rate: 4%

- up-going (Earth-Skimming)



ν_τ **flavor**
Earth-Skimming (90º, 95º)
contrib. to total evt rate **73%**

ν identification applied "blindly" to data: 01/2004 - 12/2012

No candidates found!

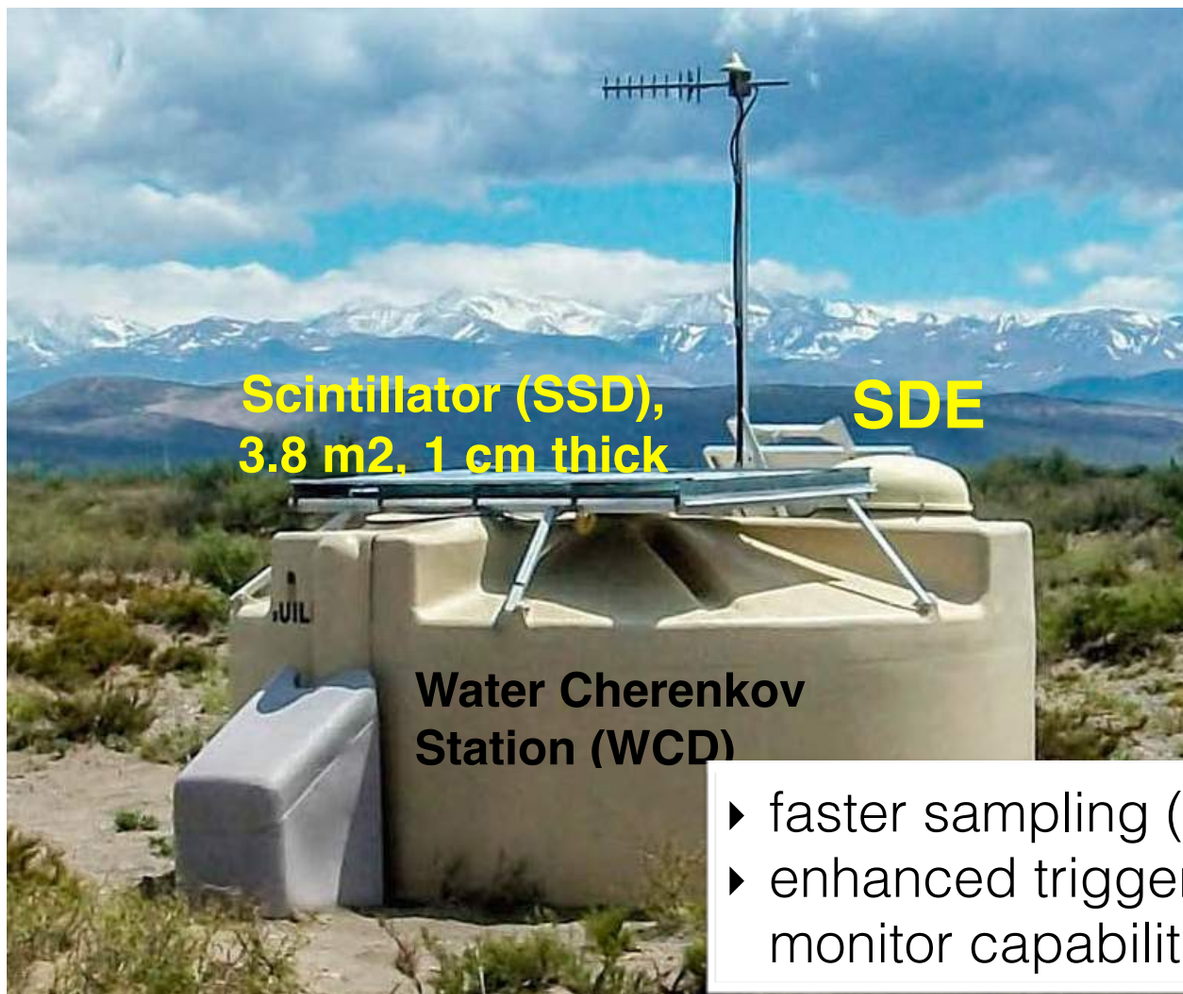
An international effort

Argentina
Australia
Brazil
Czech Republic
France
Germany
Italy
Mexico
Netherland
Poland
Portugal
Romania
Slovenia
Spain
UK
USA
Colombia (associated)
Boliva, Peru (Lol)

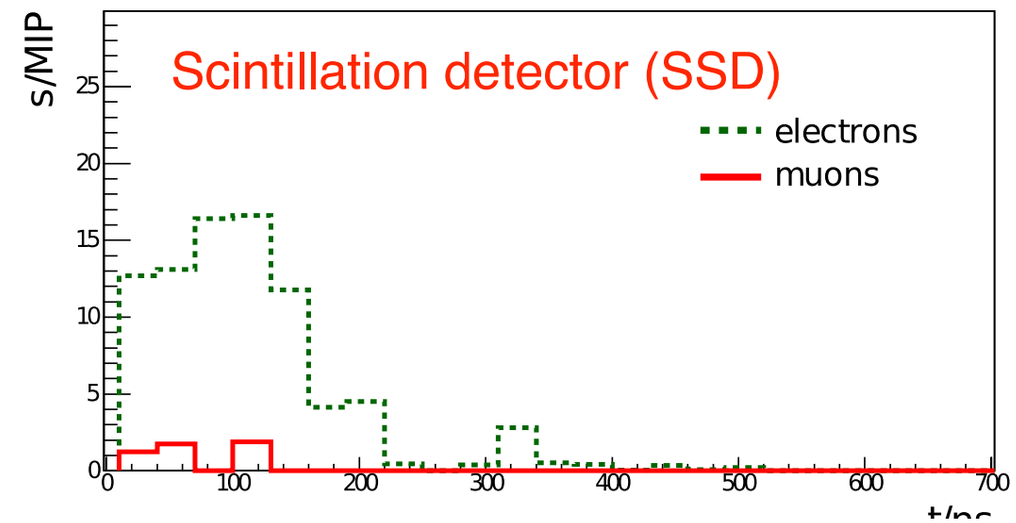
~ 500 Collaborators; 88 Institutions; 17 countries

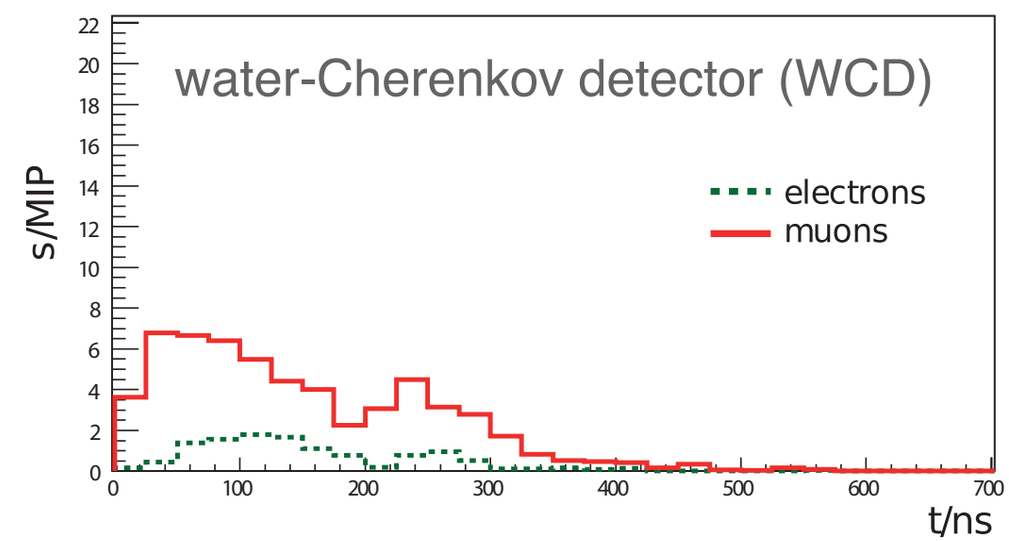
The Scintillator Surface Detector

- S_μ from WCD and SSD signals
- $\frac{\sigma[S_\mu(800)]}{\langle S_\mu(800)\rangle}$ ~ 15% (iron)-20% (proton)
- resolution X_{max} ~ 30 g/cm^2



- faster sampling (120 MHz)
- enhanced trigger and monitor capabilities





$$S_{\mu,\mathrm{WCD}} = a\,S_{\mathrm{WCD}} + b\,S_{\mathrm{SSD}}$$