Estimation of the composition of cosmic rays from radio measurements with AERA

PIERRE AUGER OBSERVATORY

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for the Pierre Auger Collaboration

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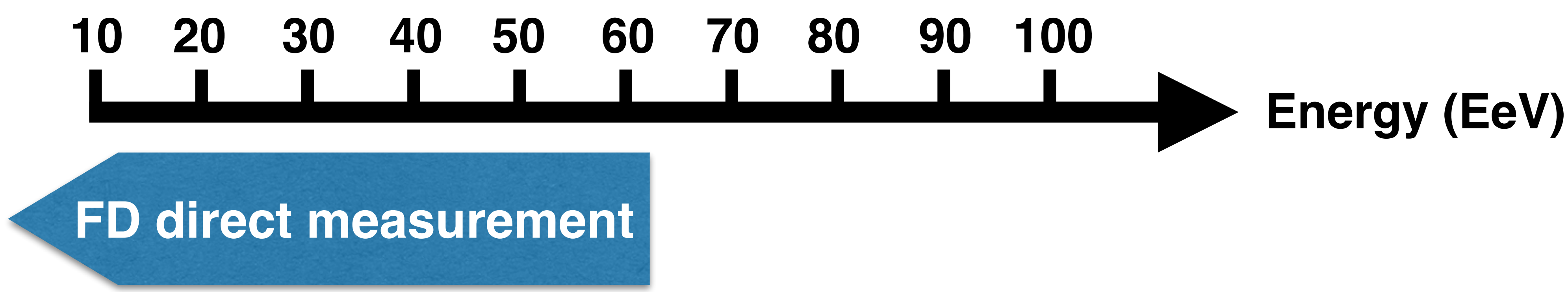
Auger Engineering Radio Array

Estimation of the composition of cosmic rays from radio measurements with AERA

- **Motivations**



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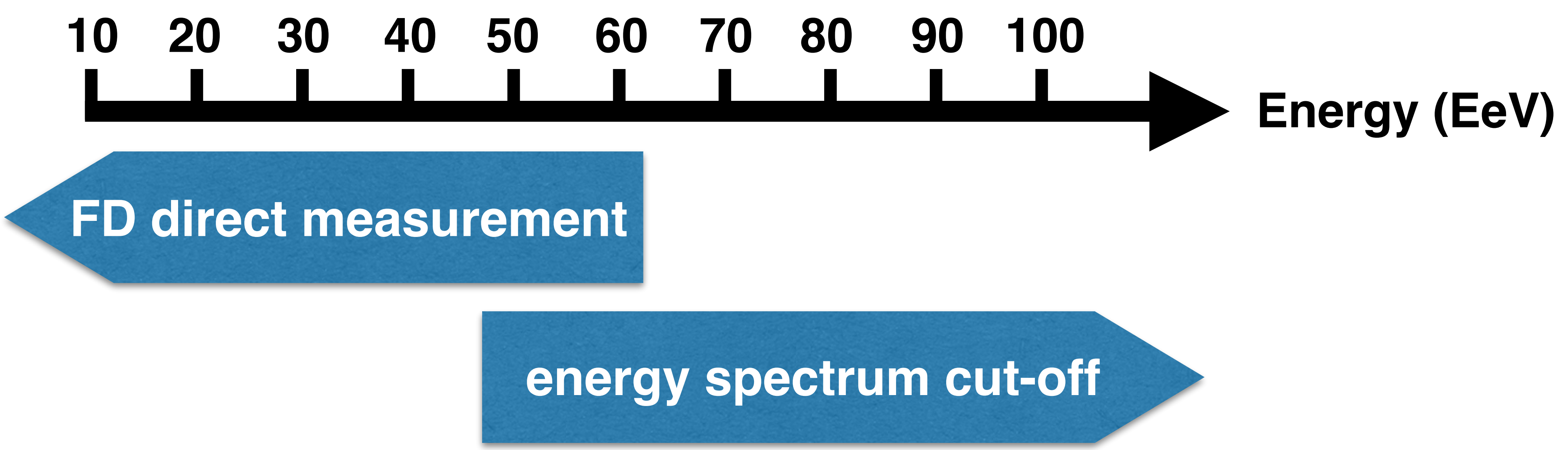

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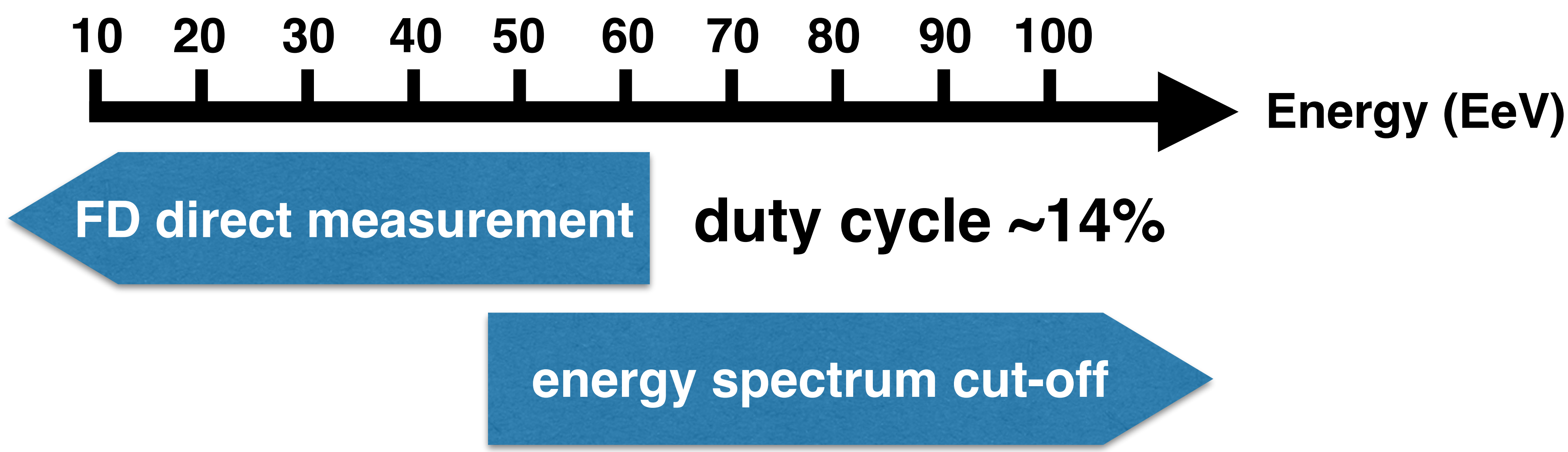

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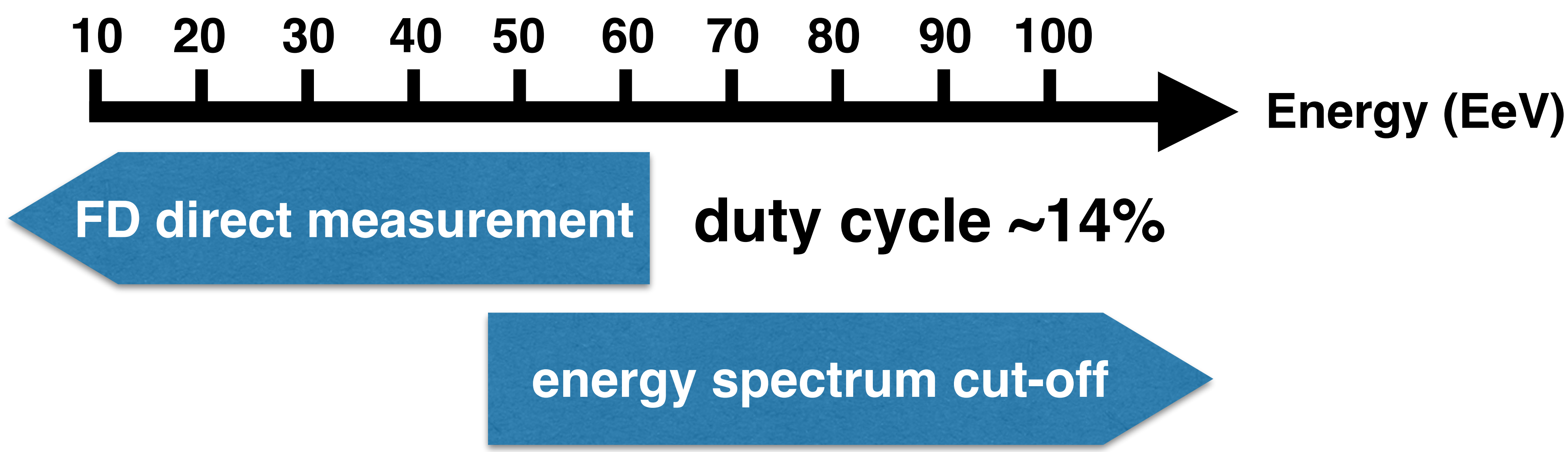

radio signal now well understood and antenna duty cycle ~100%

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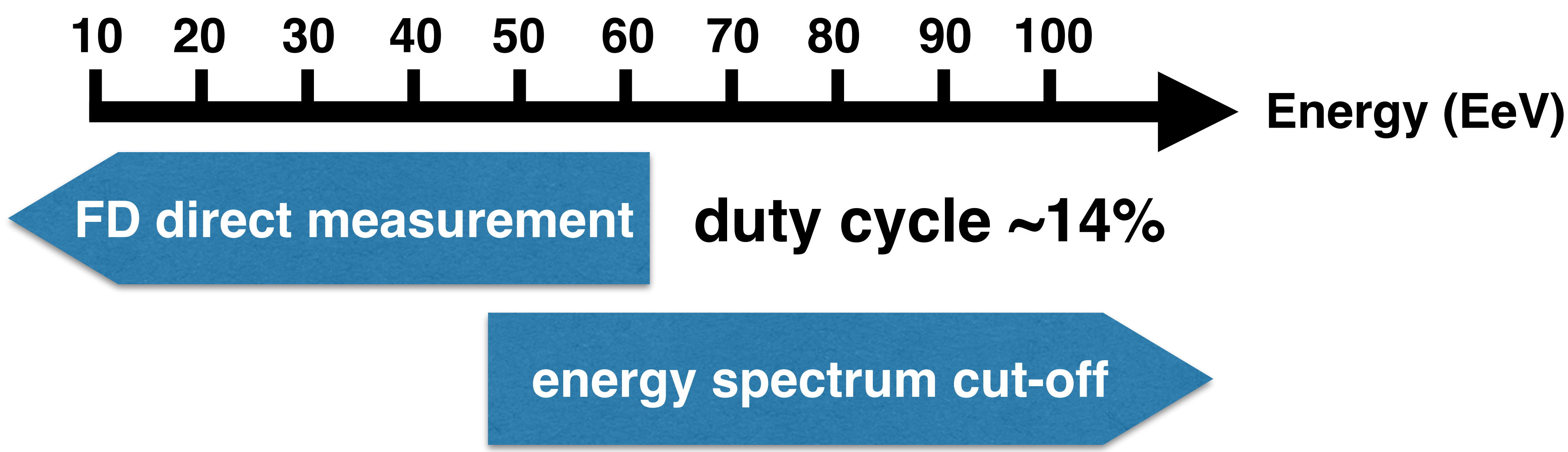

radio signal now well understood and antenna duty cycle ~100%

use the radio measurement to estimate the composition with a larger number of events

• Reconstruction of the depth of the shower maximum: Xmax

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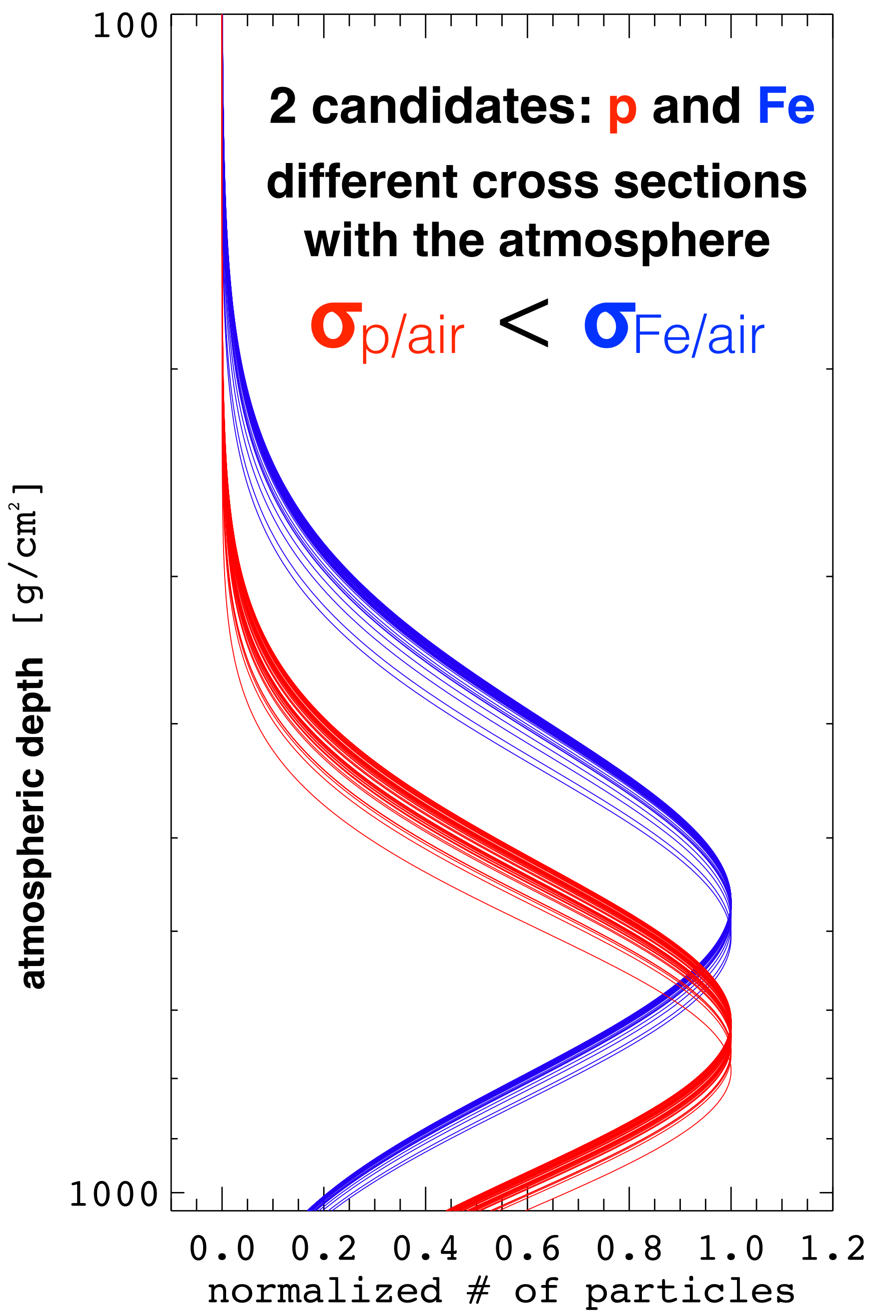

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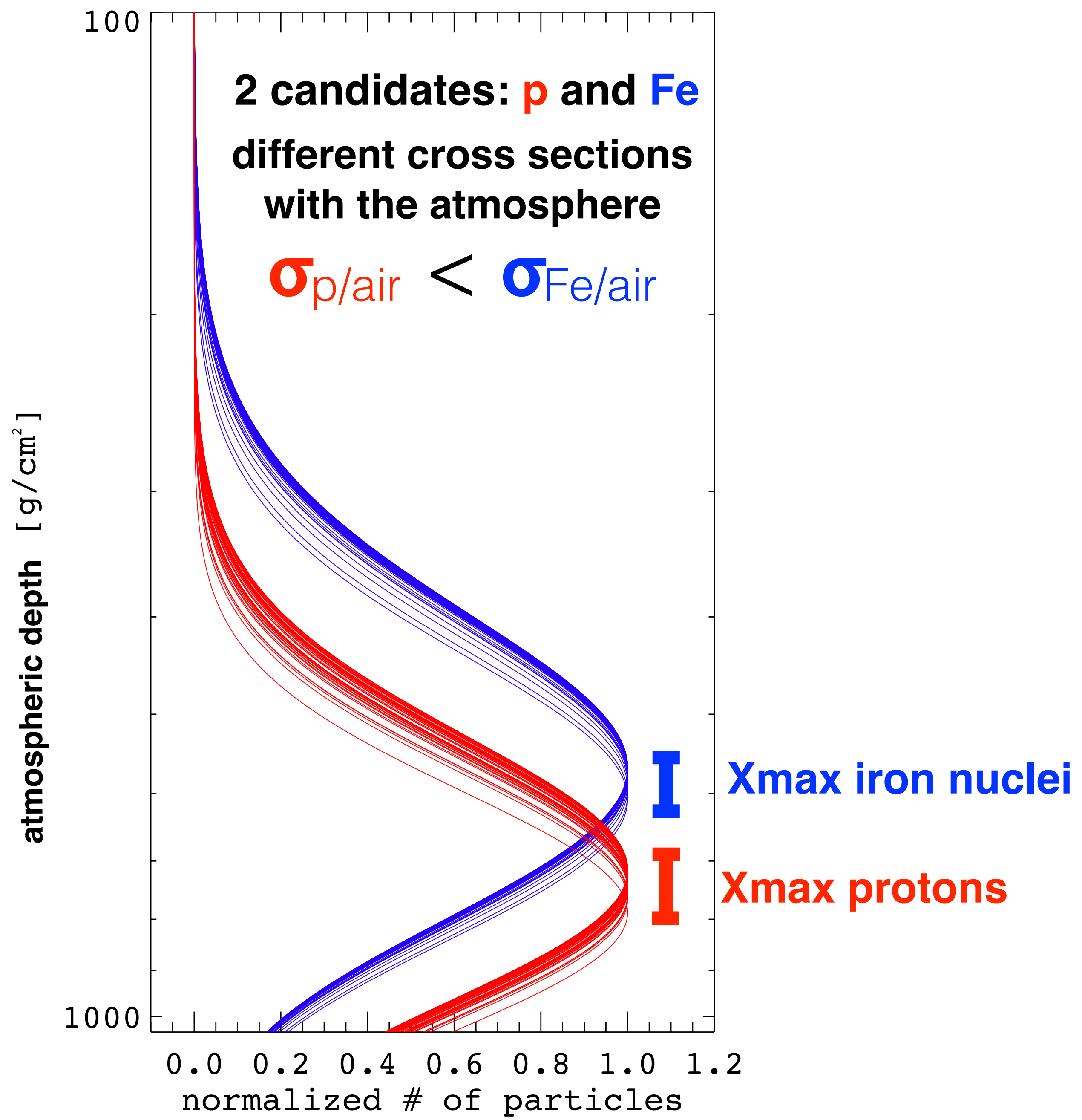

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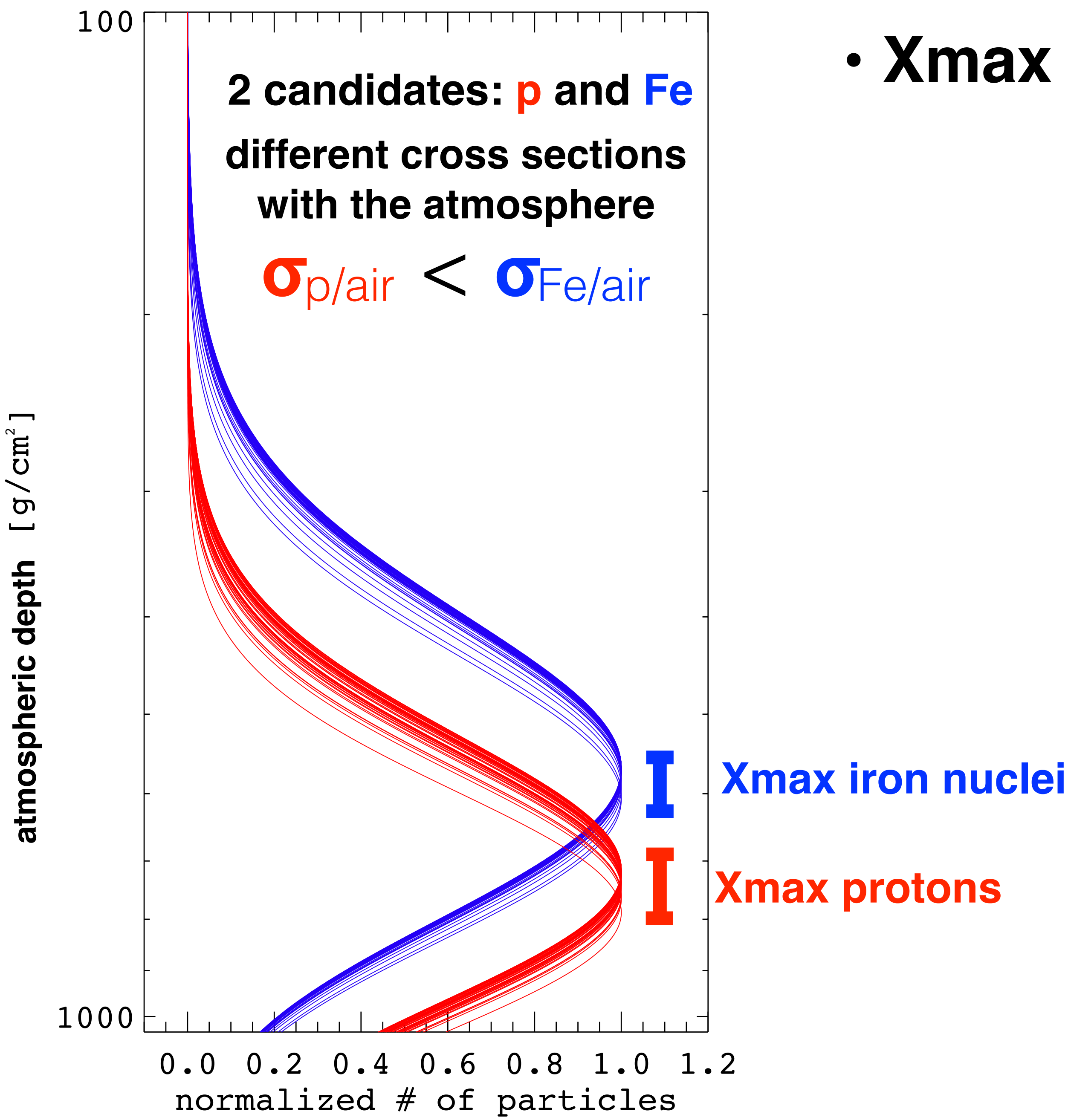

- **Xmax measurement = mass estimator**

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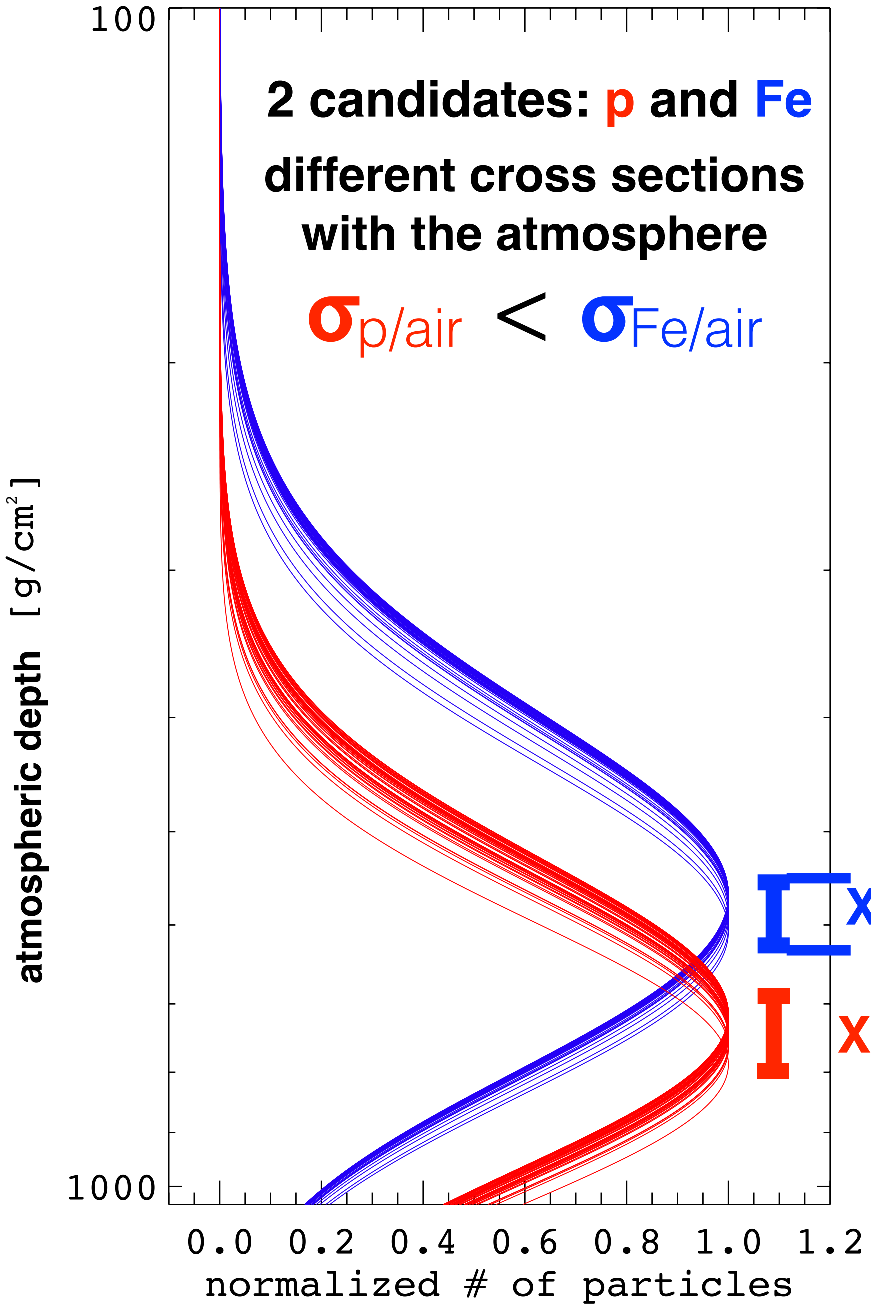

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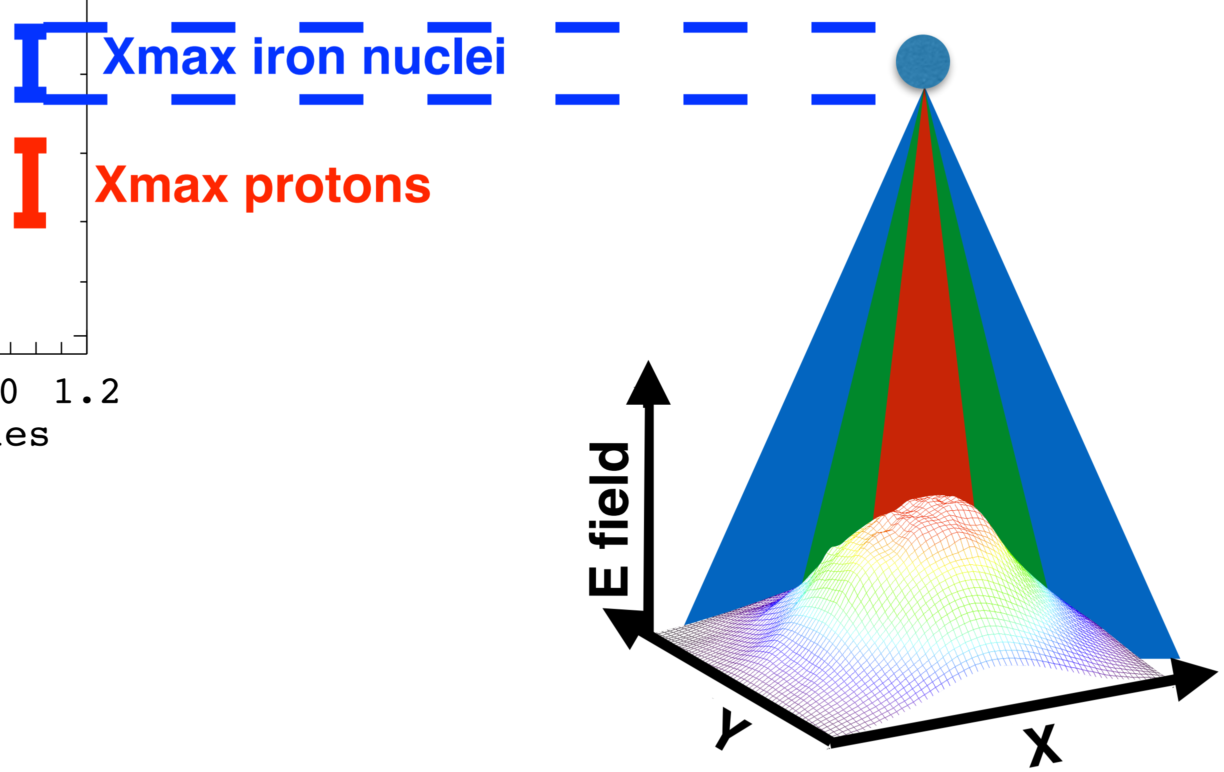

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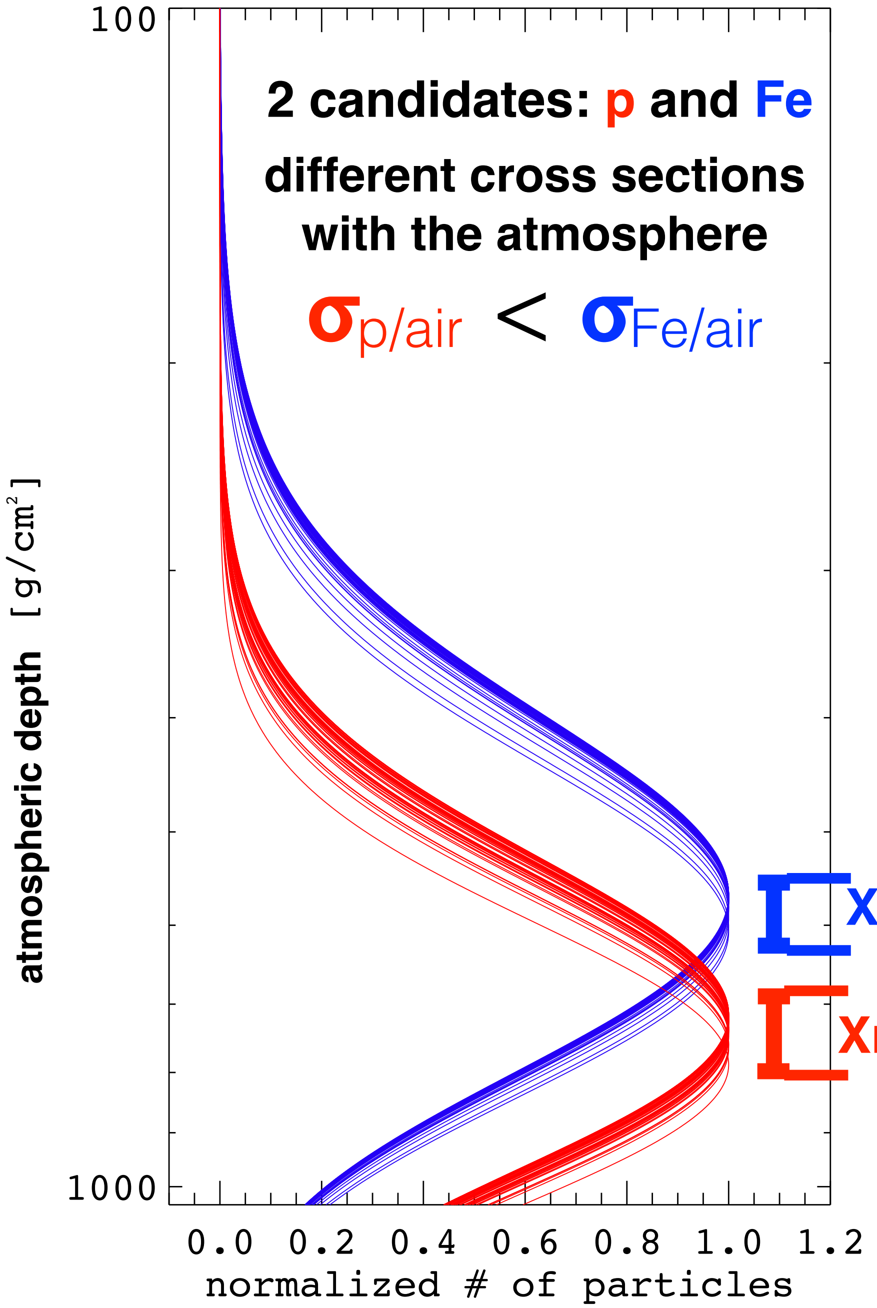

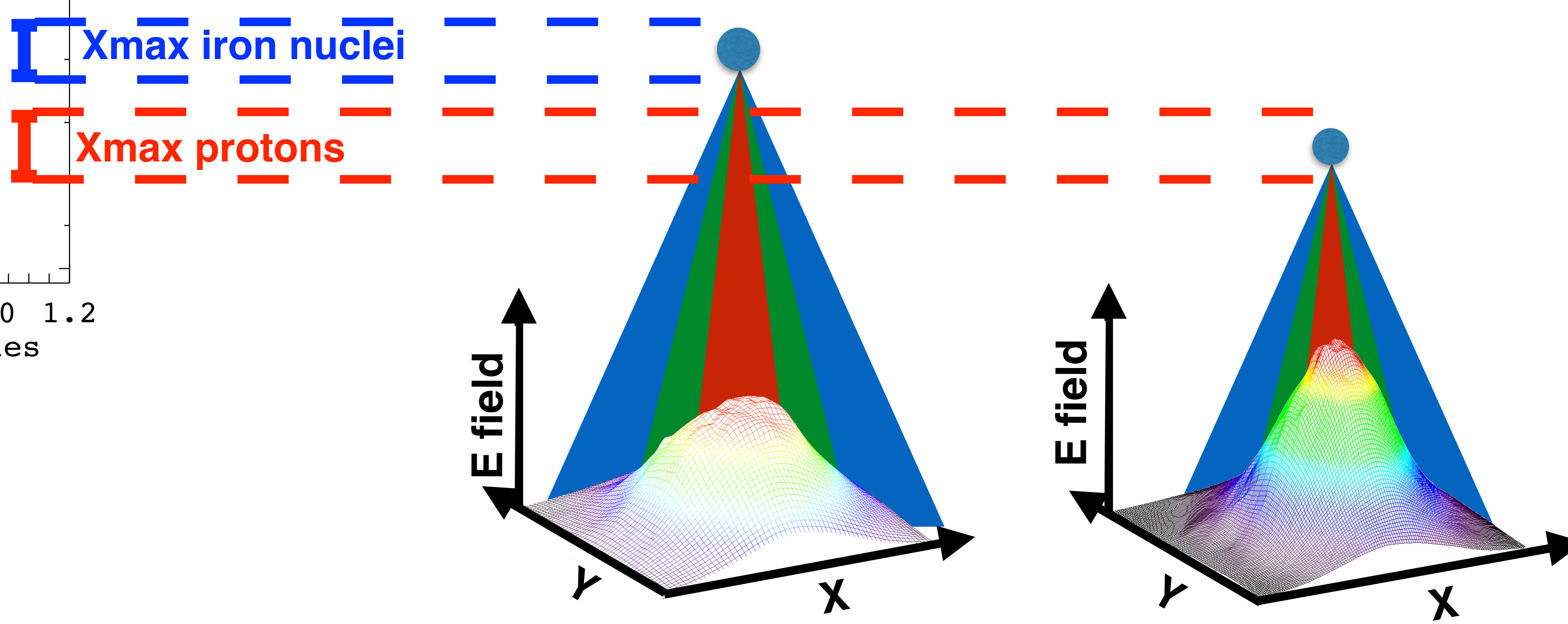

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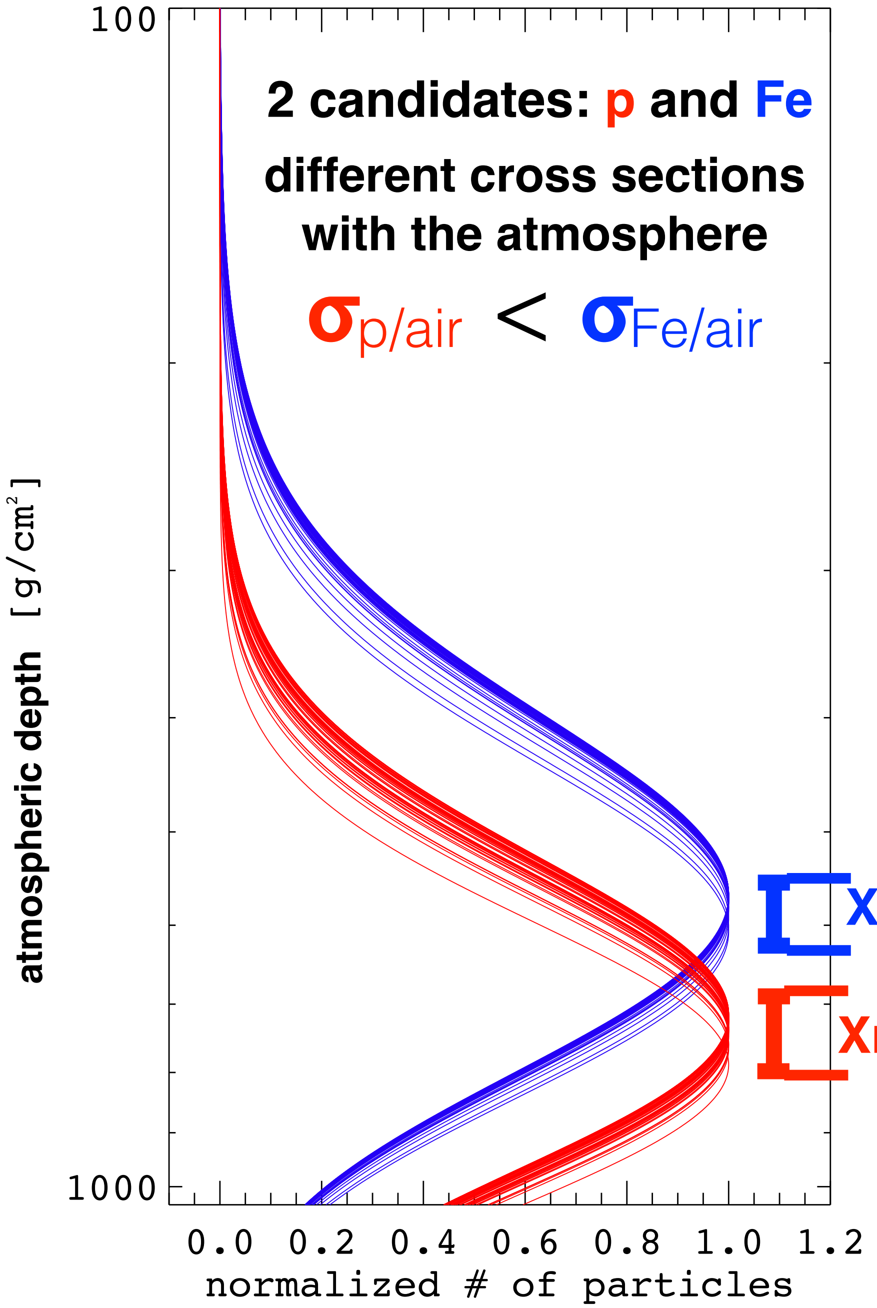
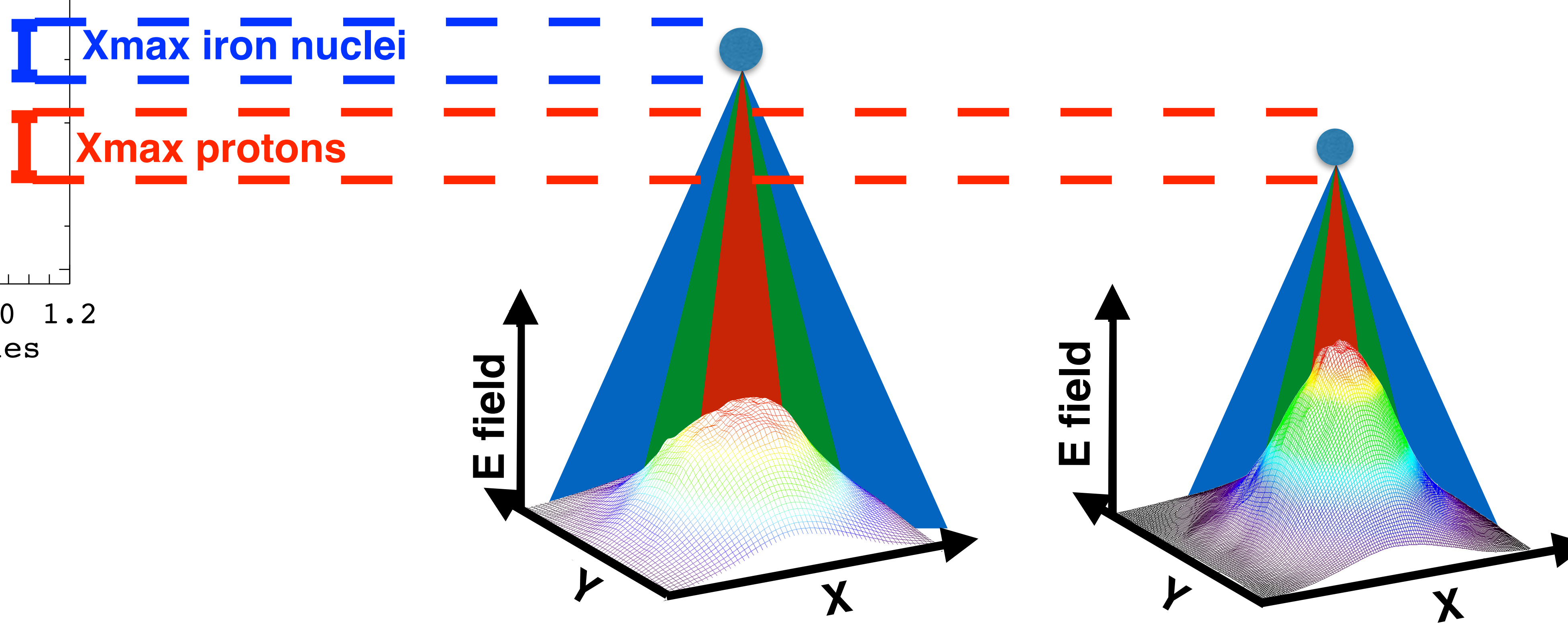


- Xmax measurement = mass estimator
- radio sensitivity to Xmax



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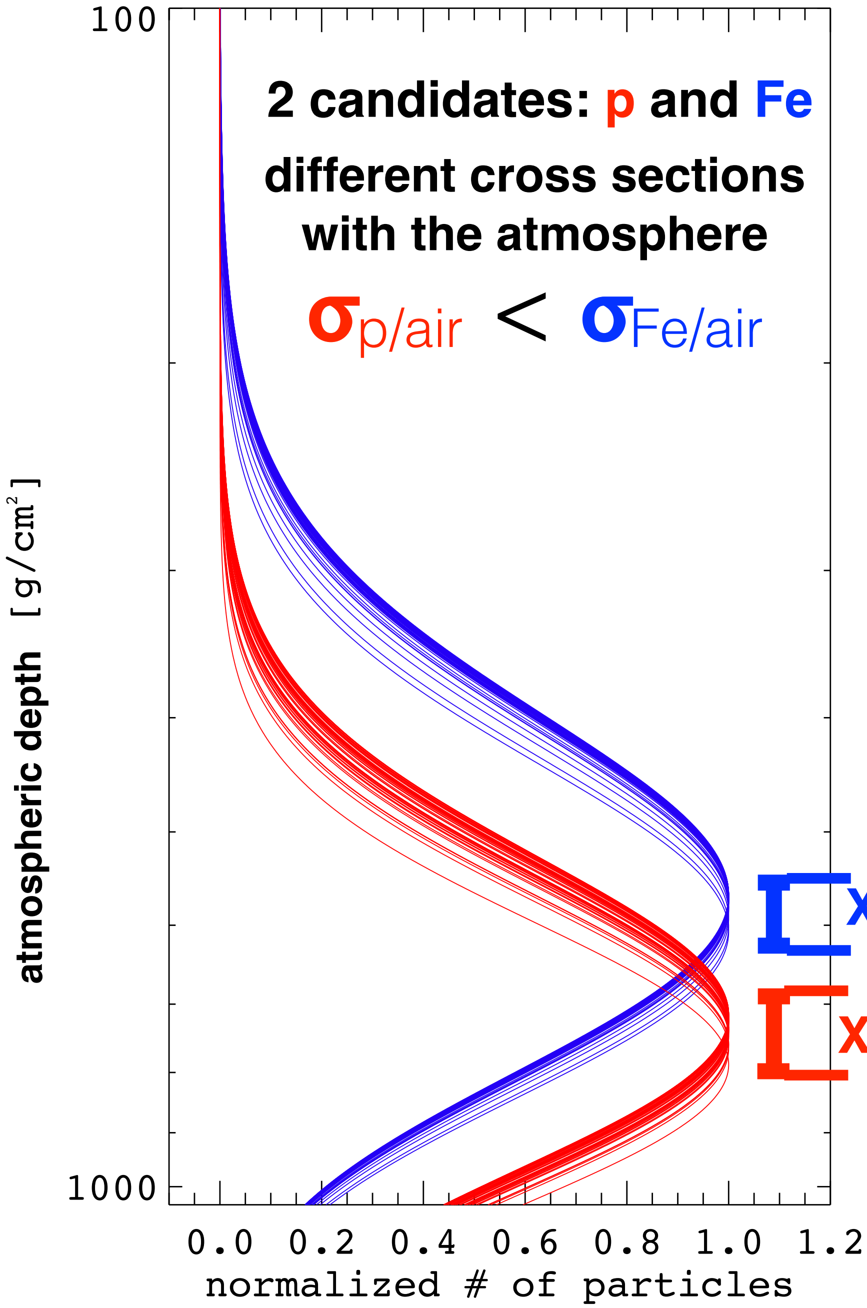

- Xmax measurement = mass estimator
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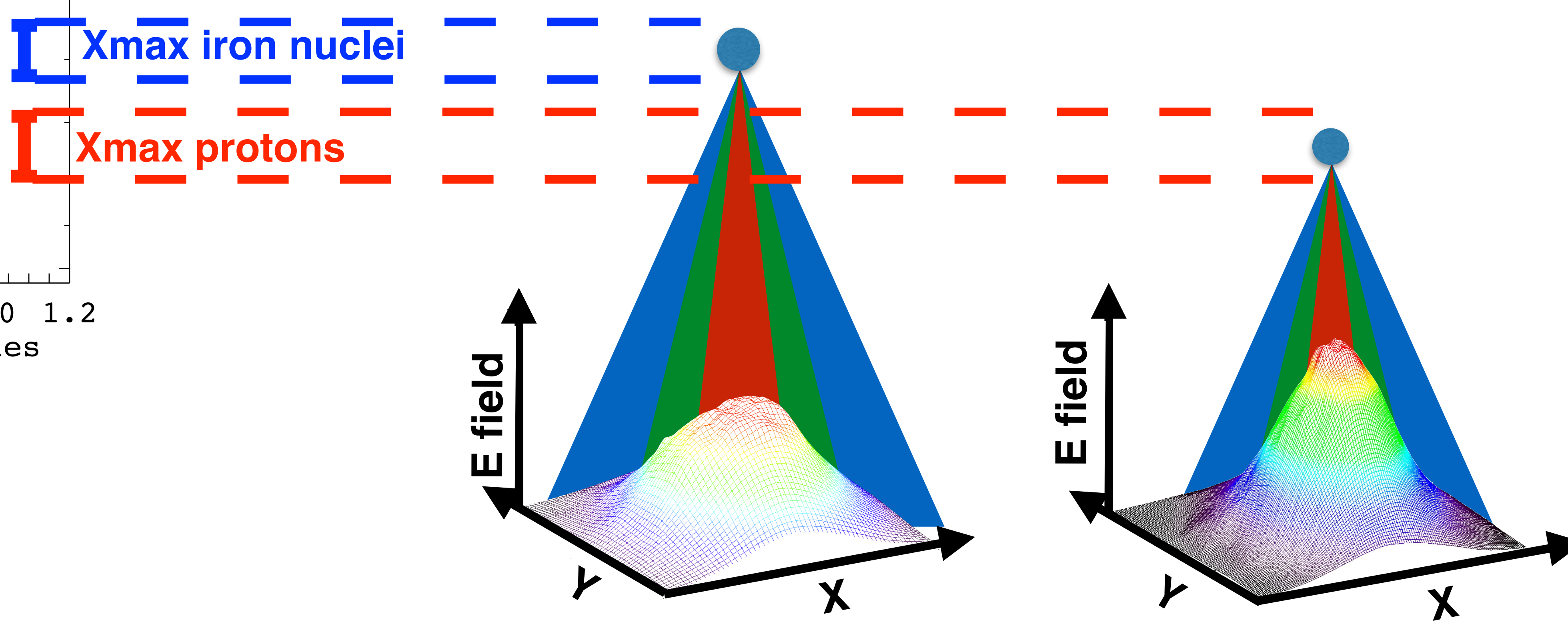
Xmax reconstruction from the amplitude of the electric field



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• Amplitude based methods

Comparison of simulated electric field to data

Method	A	B	C	D
model	**SELFAS** Astropart. Phys. 35 (2012) 733 – 741	**2D gaussian** Astropart. Phys. 60 (2015) 13	**CoREAS** AIP Conf. Proc. (2013) 128– 132	**ZHAireS** **horizontal components** Astropart. Phys. 59 (2014) 29
requirements	RD arrival direction	RD arrival direction	SD arrival direction SD energy	SD core (initialization) SD energy
# of simulations per event	40 p + 10 Fe	no simulation	20 p + 10 Fe	30 p + 30 Fe

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• Amplitude based methods

- Comparison of reconstructed Xmax with FD measurements.

  - Data set:

    at least 5 radio stations
    zenith angle < 55°

    + official FD cuts → 32 events

- But the total number of events varies slightly from one method to another.

  - Reasons are:

    event characteristics (Ep, A, Xmax) not reproducible (interaction model dependent)

    a method will produce degenerate Xmax solutions (simulation code / antennas pattern dependent)

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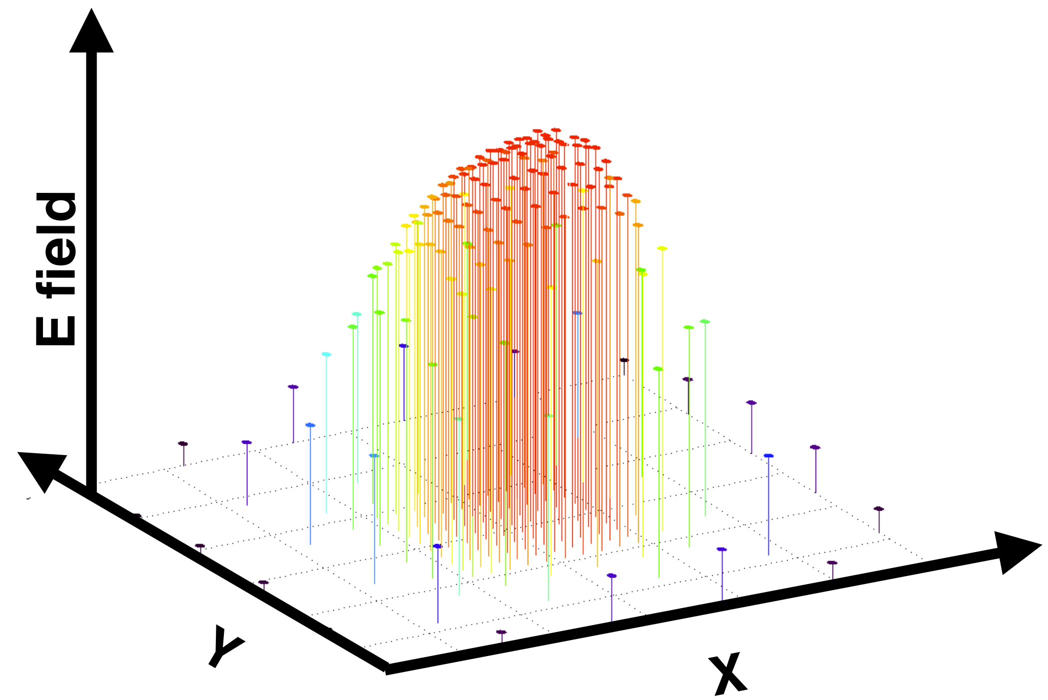
•SELFAS + interpolation

A
SELFAS Astropart. Phys. 35 (2012) 733 – 741
RD arrival direction Ep = 1EeV
40 p + 10 Fe

Simulation with dense fictive array



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SELFAS Astropart. Phys. 35 (2012) 733 – 741
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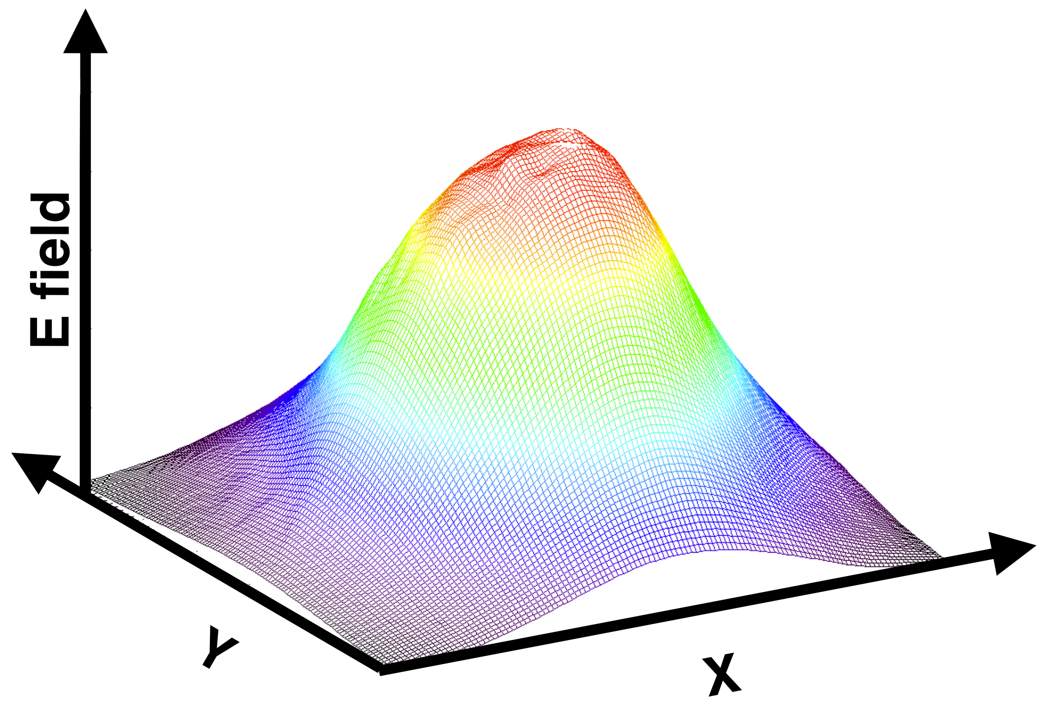
Interpolation:



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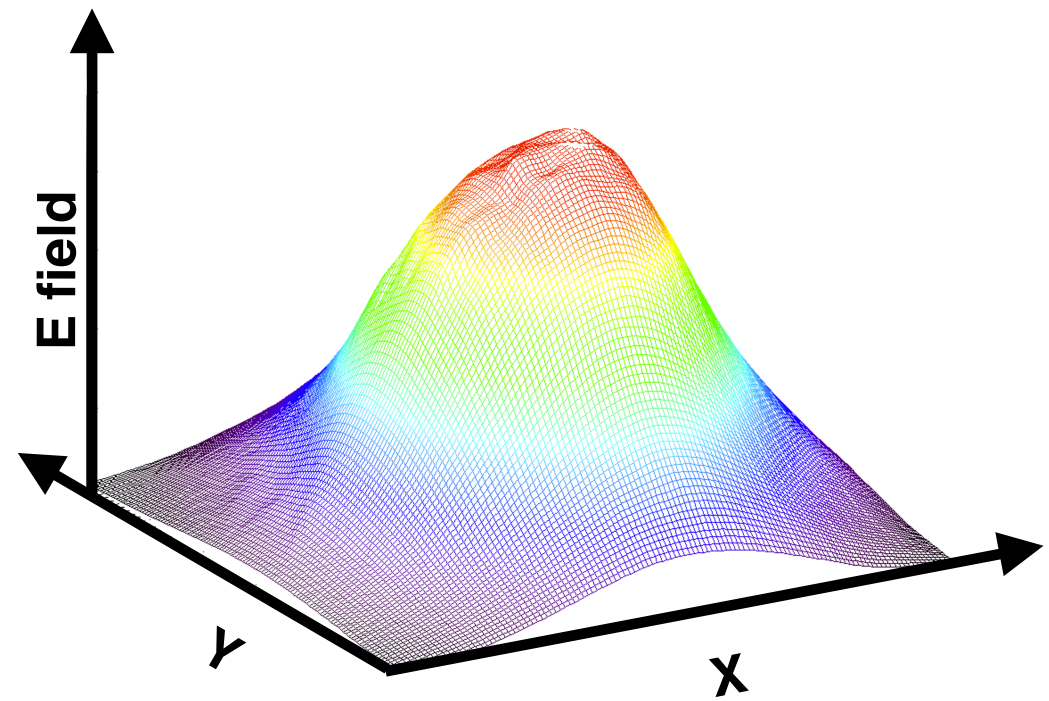
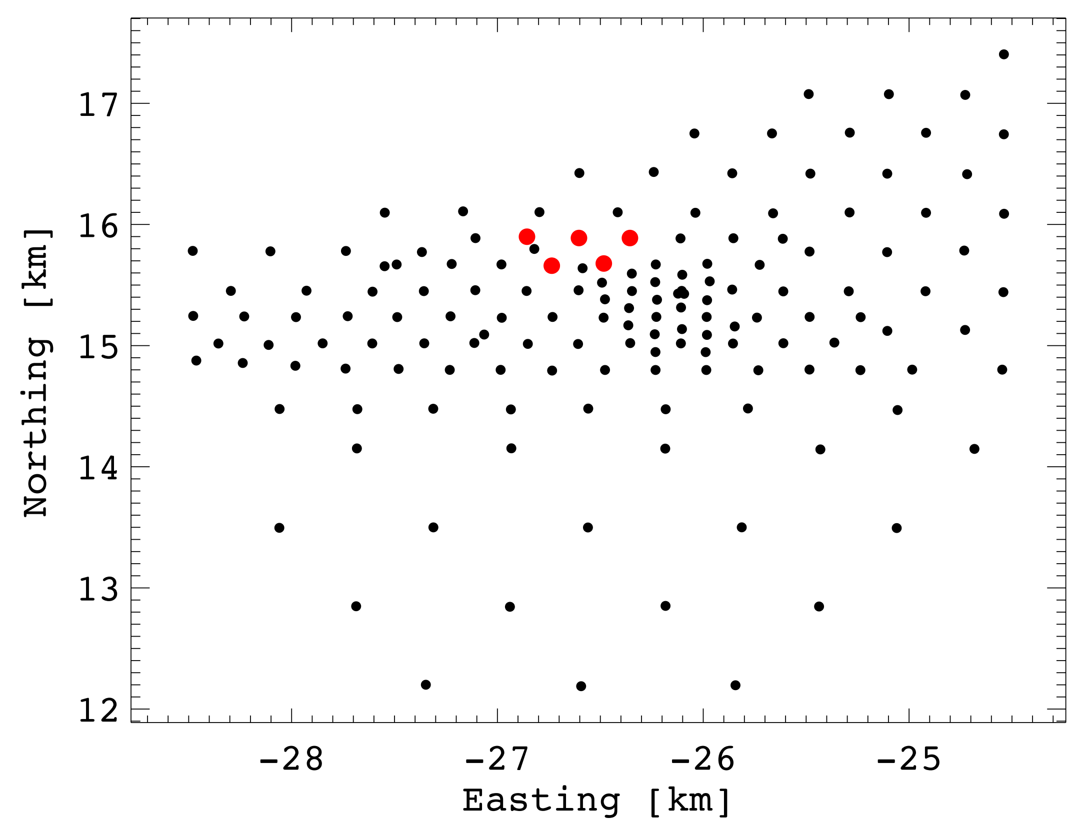


Search for core position:



$$\chi^2(x_i, y_j) = \frac{1}{n}\sum_{k=1}^{n}\left(\frac{C_{ij}E_{ijk}^{\mathrm{sim}} - E_k^{\mathrm{exp}}}{\sigma_k^{\mathrm{exp}}}\right)^2$$

Linear dependency of amplitude with Ep

•SELFAS + interpolation

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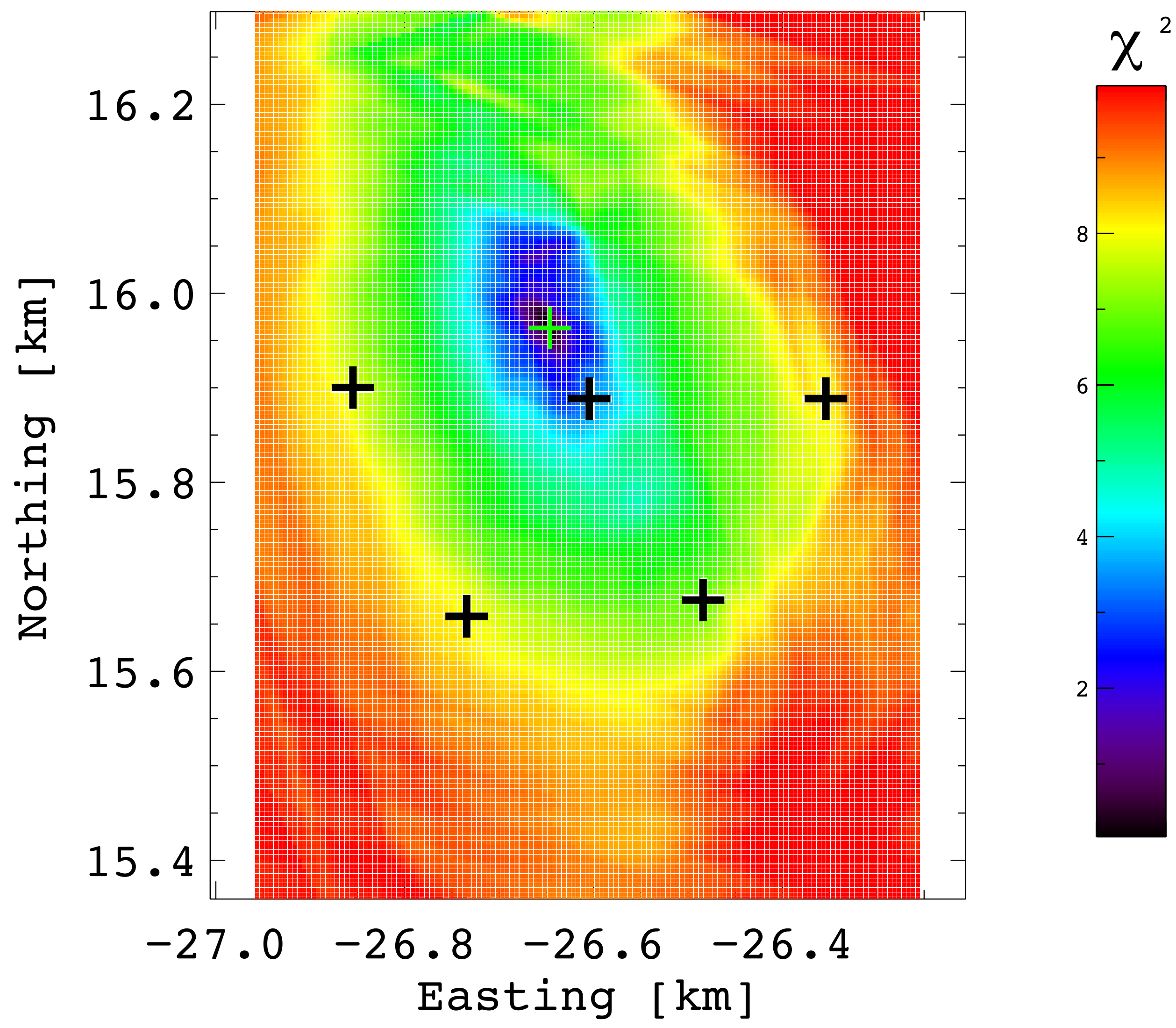
RD arrival direction **Ep = 1EeV**
40 p + 10 Fe

Core position:

$$\chi^2(x_i, y_j) = \frac{1}{n} \sum_{k=1}^{n} \left(\frac{C_{ij} E_{ijk}^{\mathrm{sim}} - E_k^{\mathrm{exp}}}{\sigma_k^{\mathrm{exp}}} \right)^2$$



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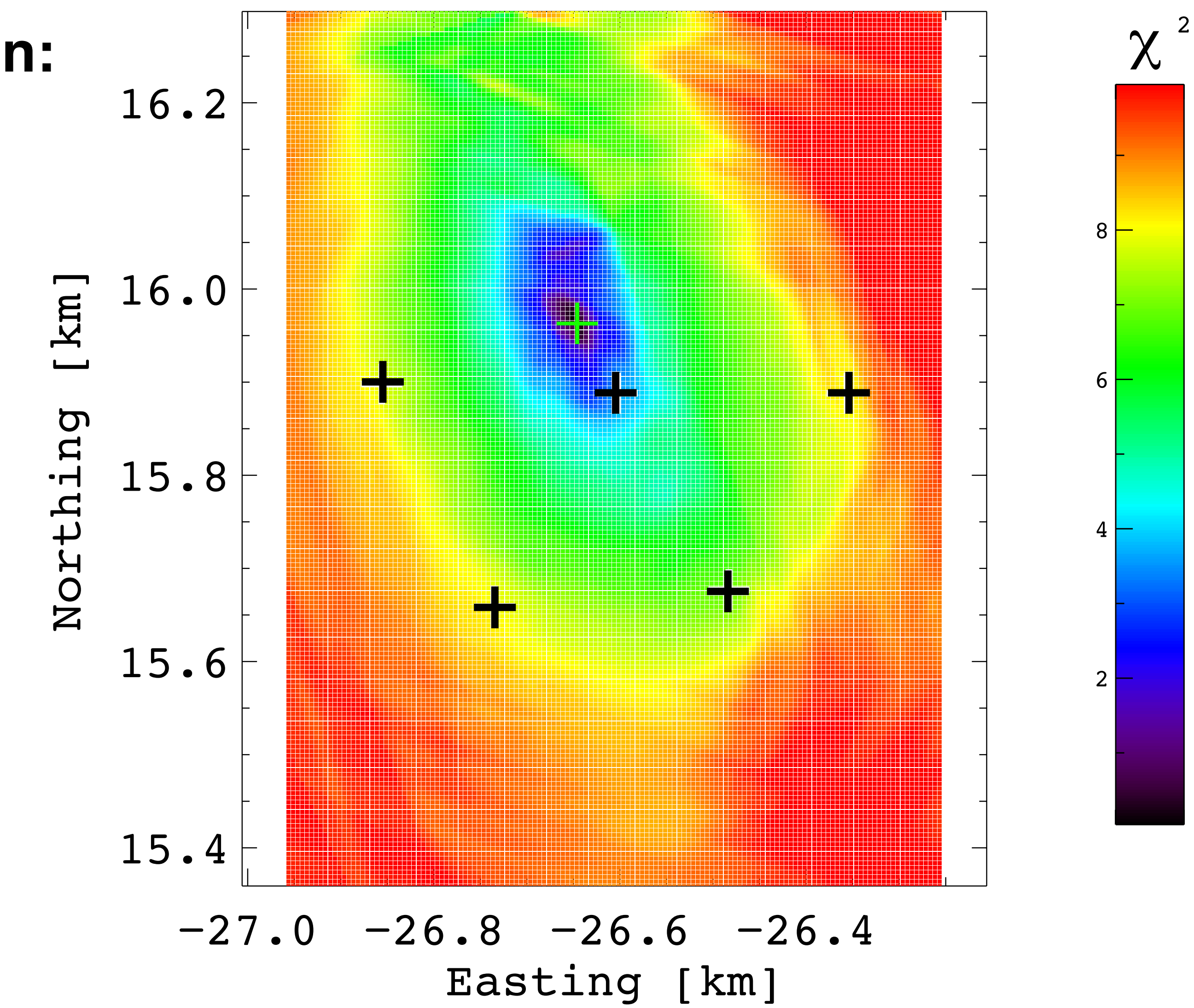
For each simulation:

↓

$$(\chi^2, X_{\text{max}})$$



•SELFAS + interpolation

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SELFAS Astropart. Phys. 35 (2012) 733 – 741
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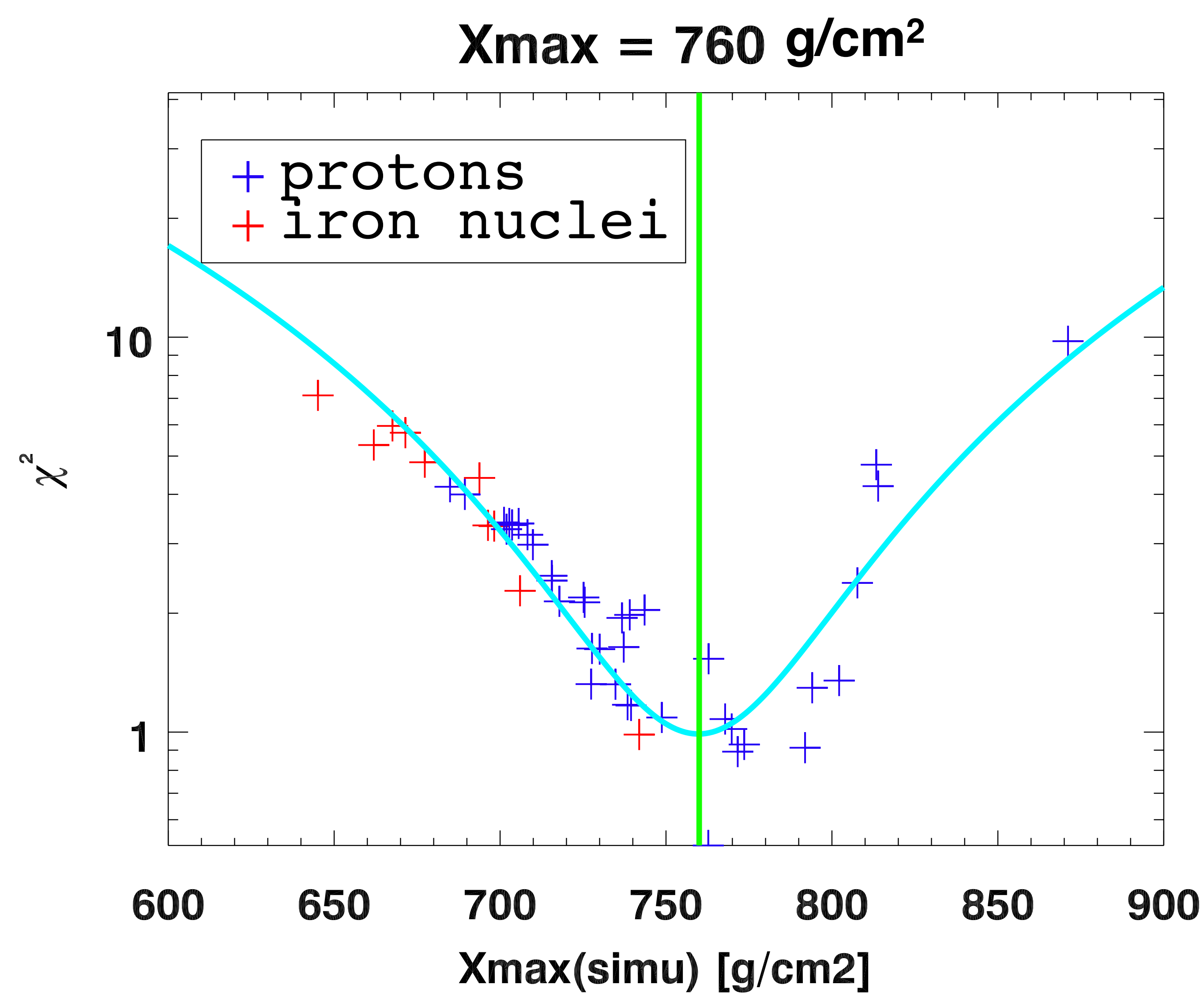
$(\chi^2, X_{\max})$ **of all simulations gives Xmax estimation**



•SELFAS + interpolation

A

SELFAS
Astropart. Phys. 35 (2012) 733 – 741

RD arrival direction
Ep = 1EeV

40 p + 10 Fe

Method applied on high quality RD - FD events

FD quality cuts:

- **Xmax in field of view**
- σ_{Xmax} **< 40 g/cm²**
- **reduced** χ^2 **for the Gaisser - Hillas fit below set value**

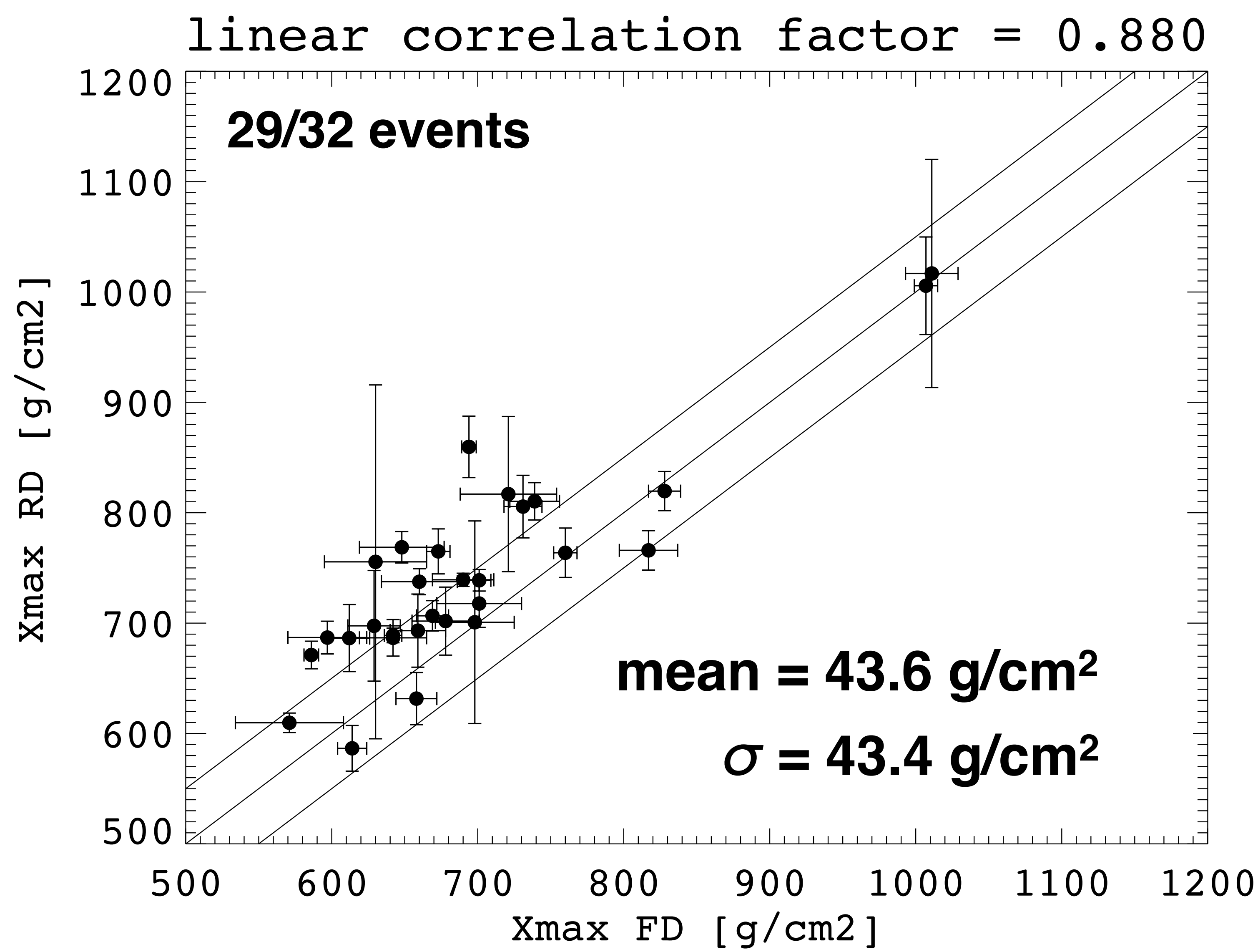
⋮

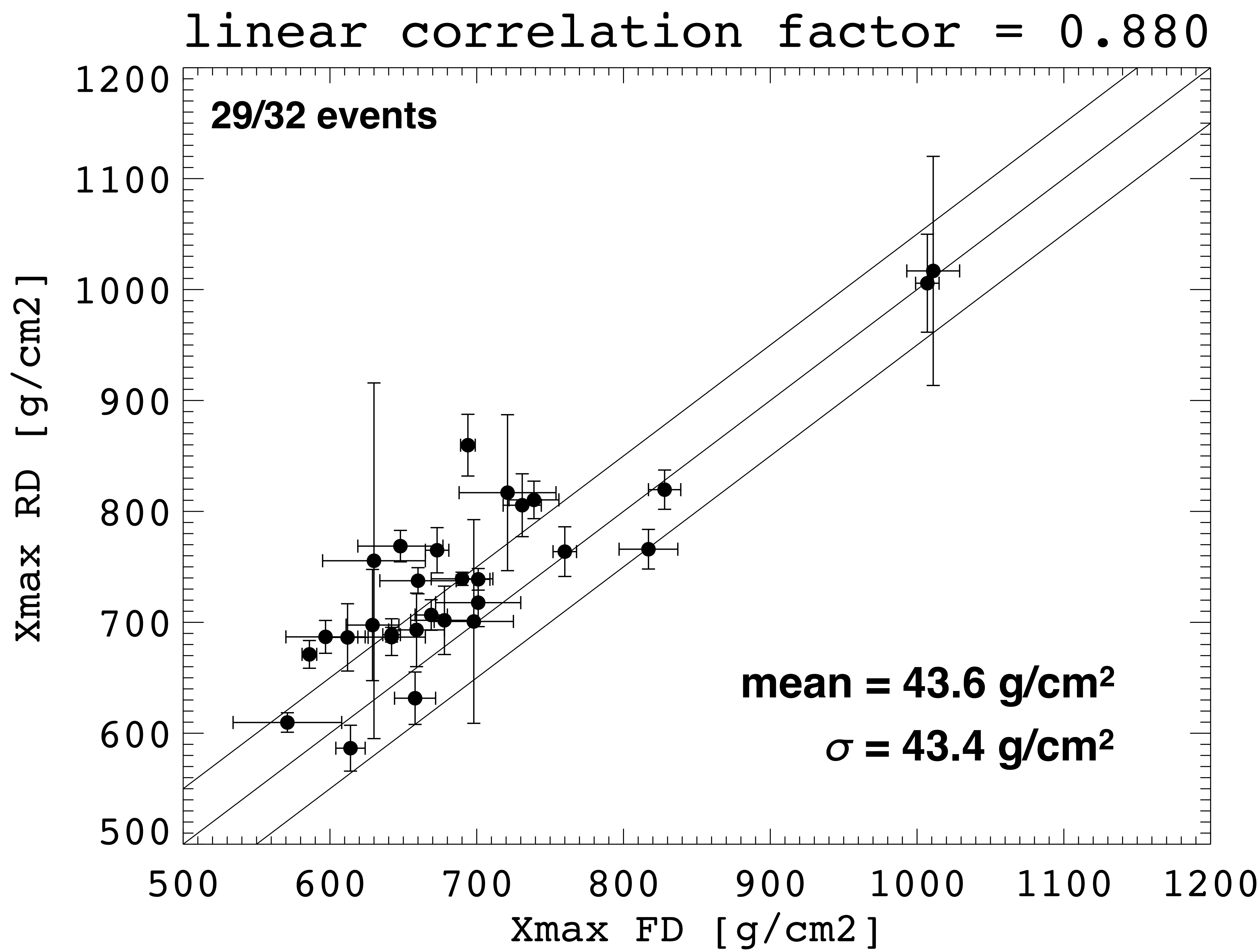
great confidence in FD Xmax measurements

• SELFAS + interpolation

A
SELFAS Astropart. Phys. 35 (2012) 733 – 741
RD arrival direction **Ep = 1EeV**
40 p + 10 Fe

Method applied on high quality Rd - Fd events




linear correlation factor = 0.880
29/32 events
mean = 43.6 g/cm²
σ = 43.4 g/cm²
Xmax RD [g/cm2]
Xmax FD [g/cm2]
500
600
700
800
900
1000
1100
1200

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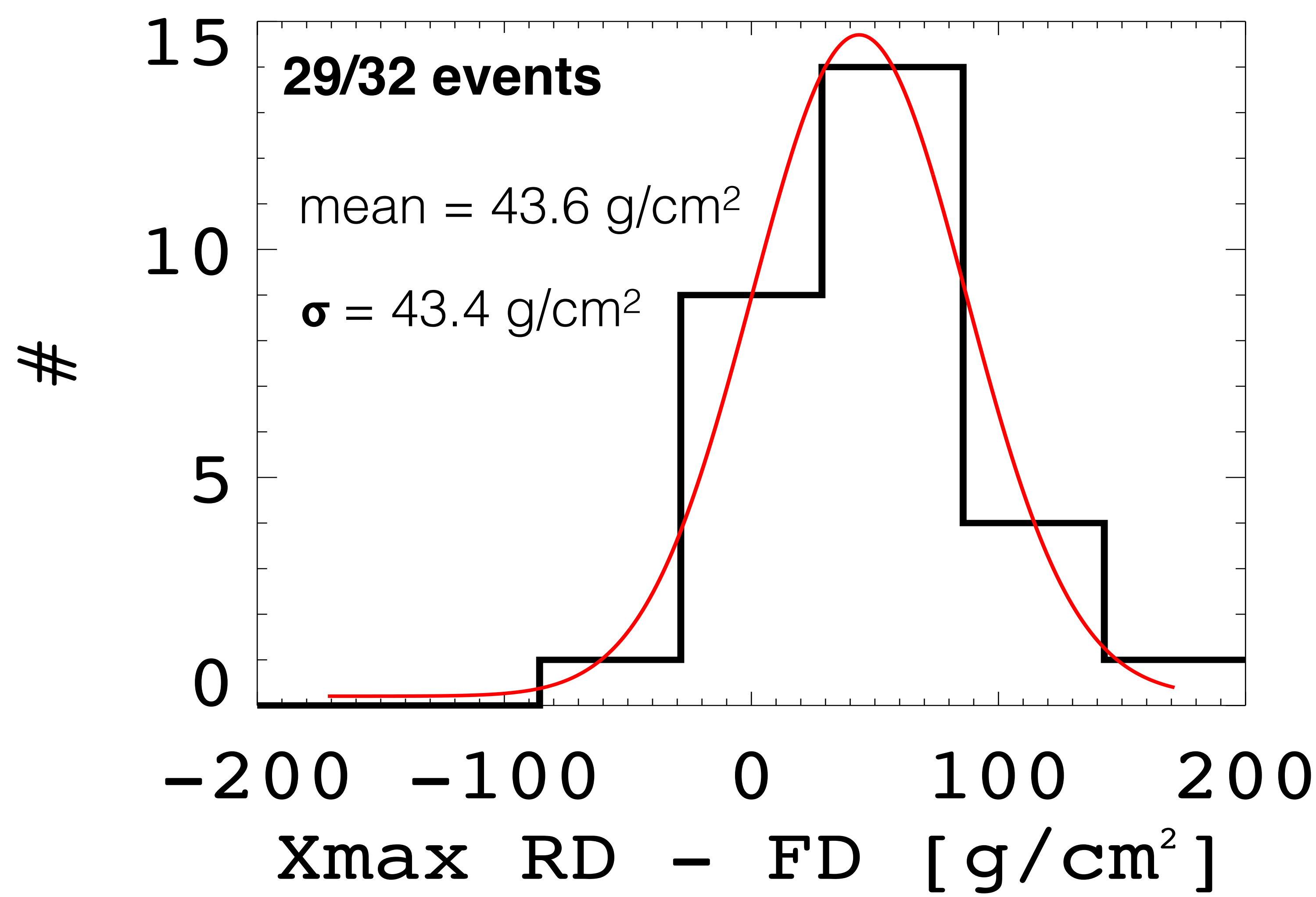


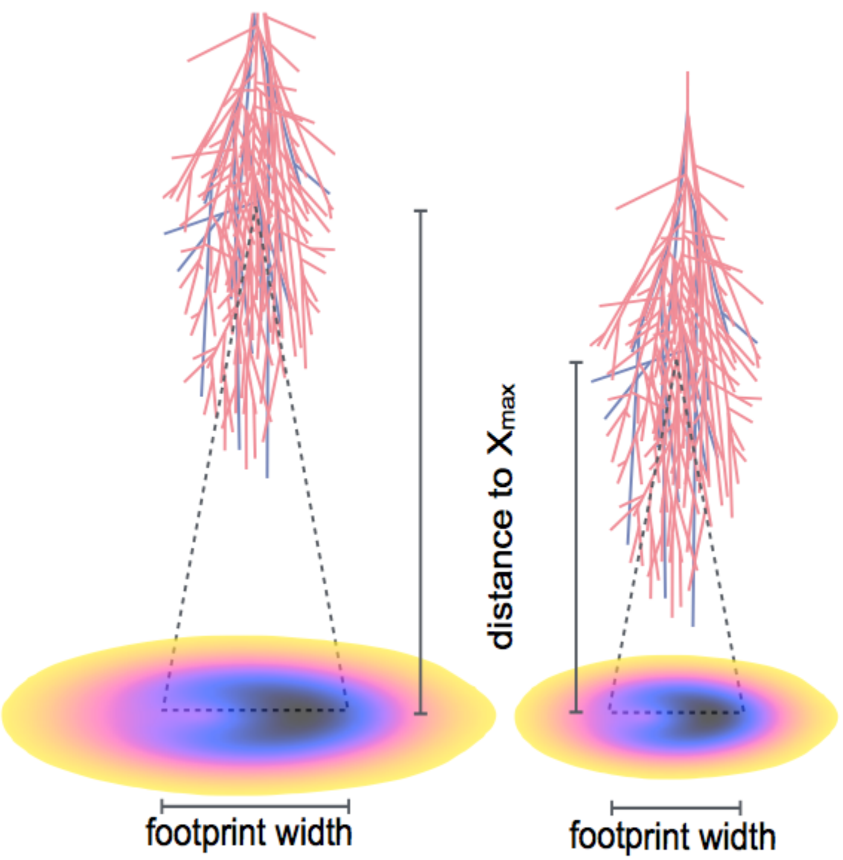
- pure radio
- good precision
- gives all parameters

- systematic shift

•2D gaussian parameterization

$$u(\vec{r}) = A\left[\exp\left(\frac{-(\vec{r}+C_1\vec{e}_{\vec{v}\times\vec{b}}-\vec{r}_{\rm core})}{\sigma^2}\right) - C_0\exp\left(\frac{-(\vec{r}+C_2\vec{e}_{\vec{v}\times\vec{b}}-\vec{r}_{\rm core})}{(C_3 e^{C_4\sigma})^2}\right)\right]$$

B
2D gaussian Astropart. Phys. 60 (2015) 13
RD arrival direction
no simulation



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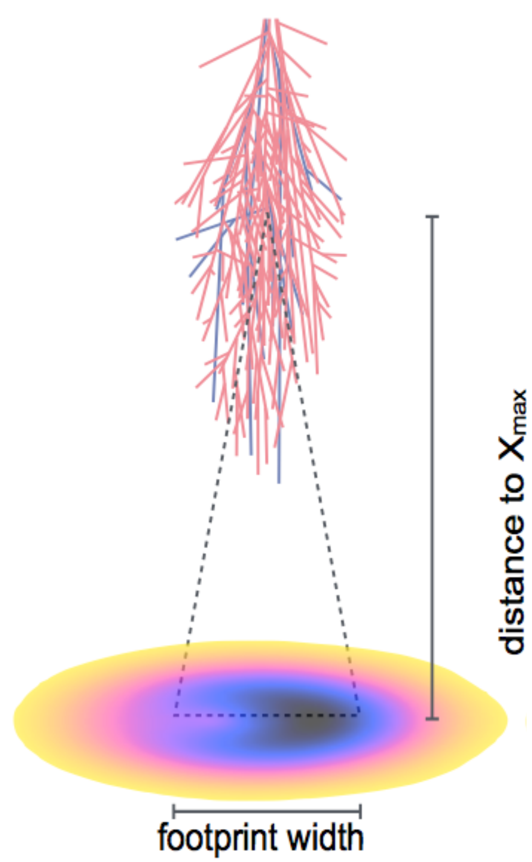

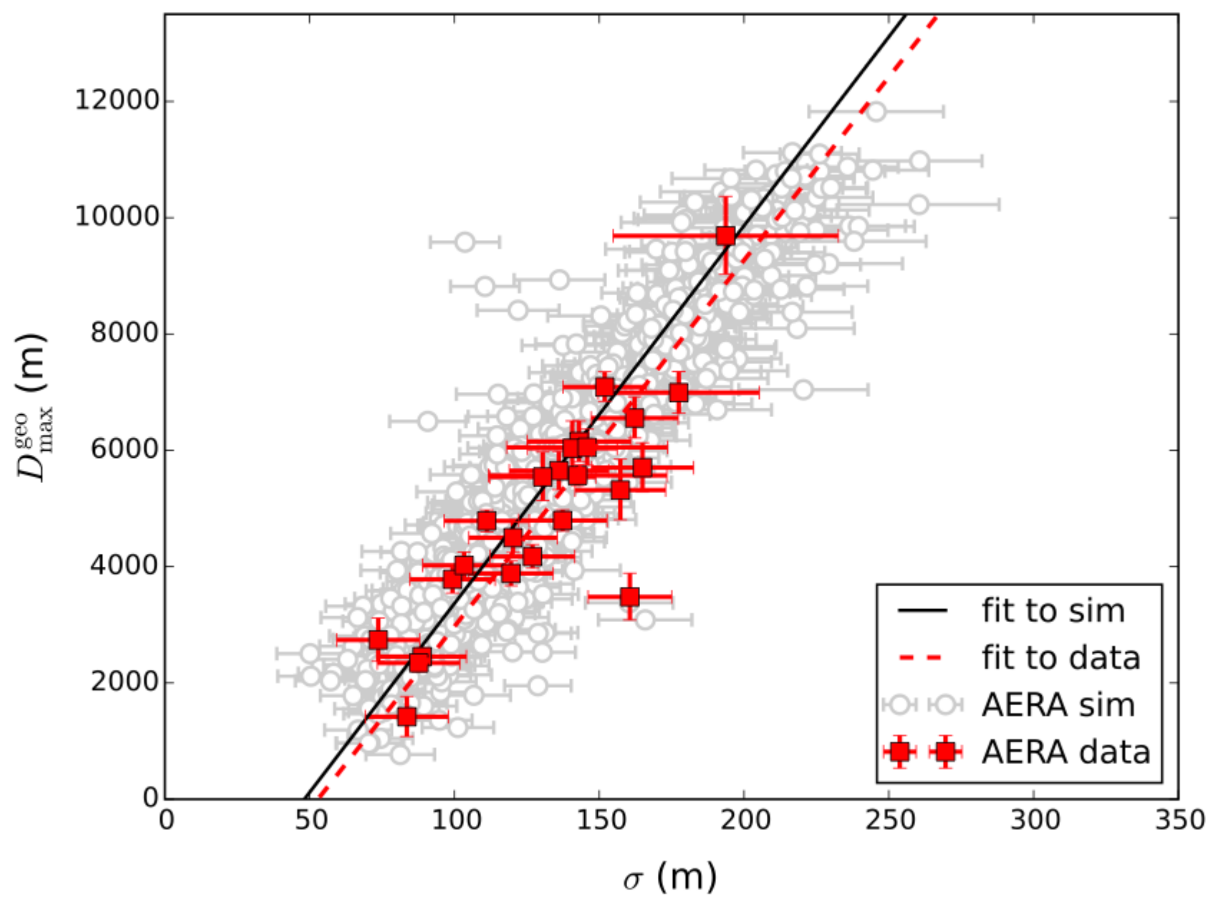

$$D^{\rm geo}_{\rm max}(X_{\rm max},\theta) = (h_{\rm GDAS}(X_{\rm max}/\cos\theta) - h_{\rm Auger})/\cos\theta$$

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• 2D gaussian parameterization

Method applied on high quality Rd - Fd events

$$u(\vec{r}) = A\left[\exp\left(\frac{-(\vec{r}+C_1\vec{e}_{\vec{v}\times\vec{b}}-\vec{r}_{\rm core})}{\sigma^2}\right) - C_0\exp\left(\frac{-(\vec{r}+C_2\vec{e}_{\vec{v}\times\vec{b}}-\vec{r}_{\rm core})}{(C_3e^{C_4\sigma})^2}\right)\right]$$

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2D gaussian Astropart. Phys. 60 (2015) 13
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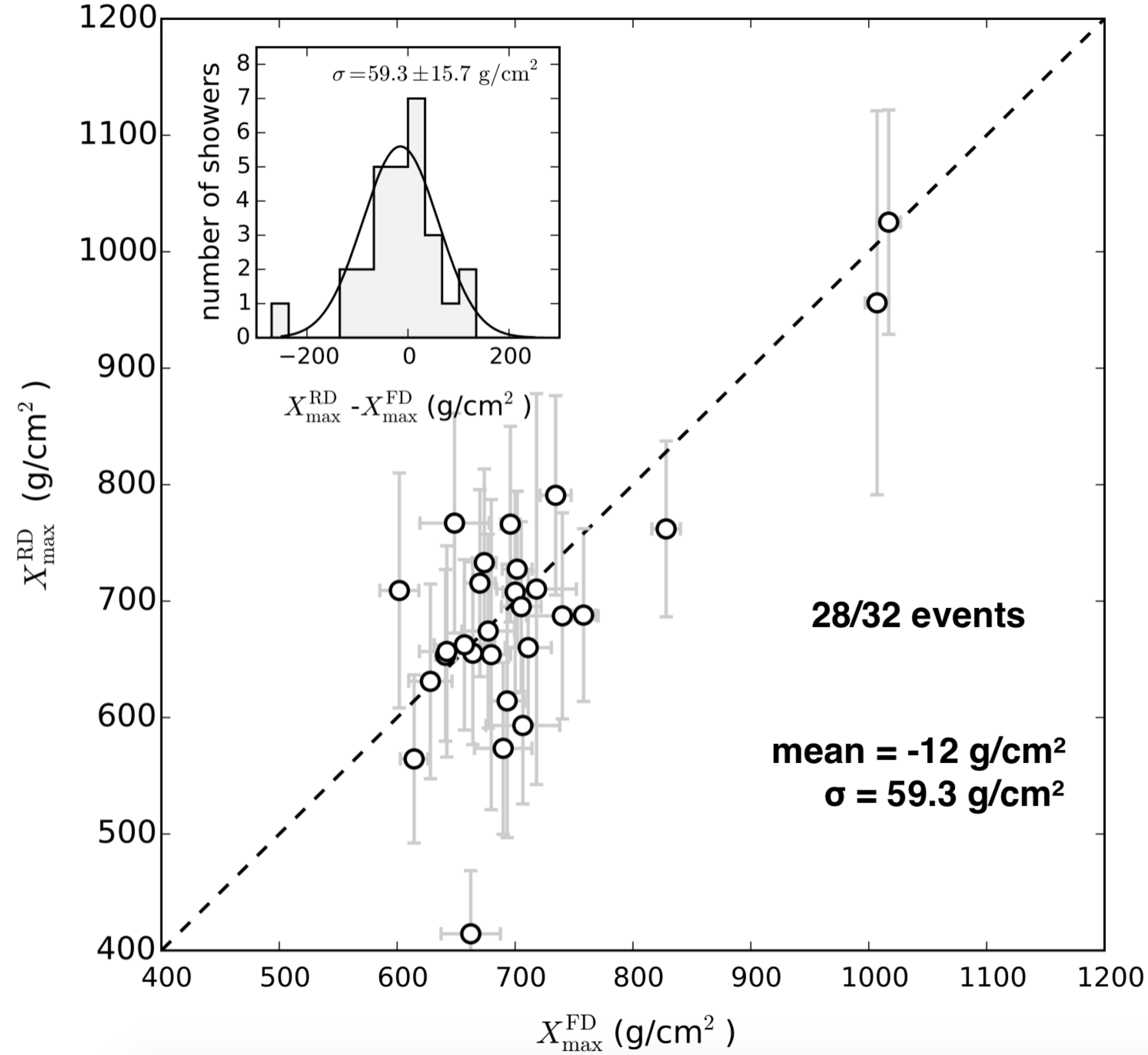
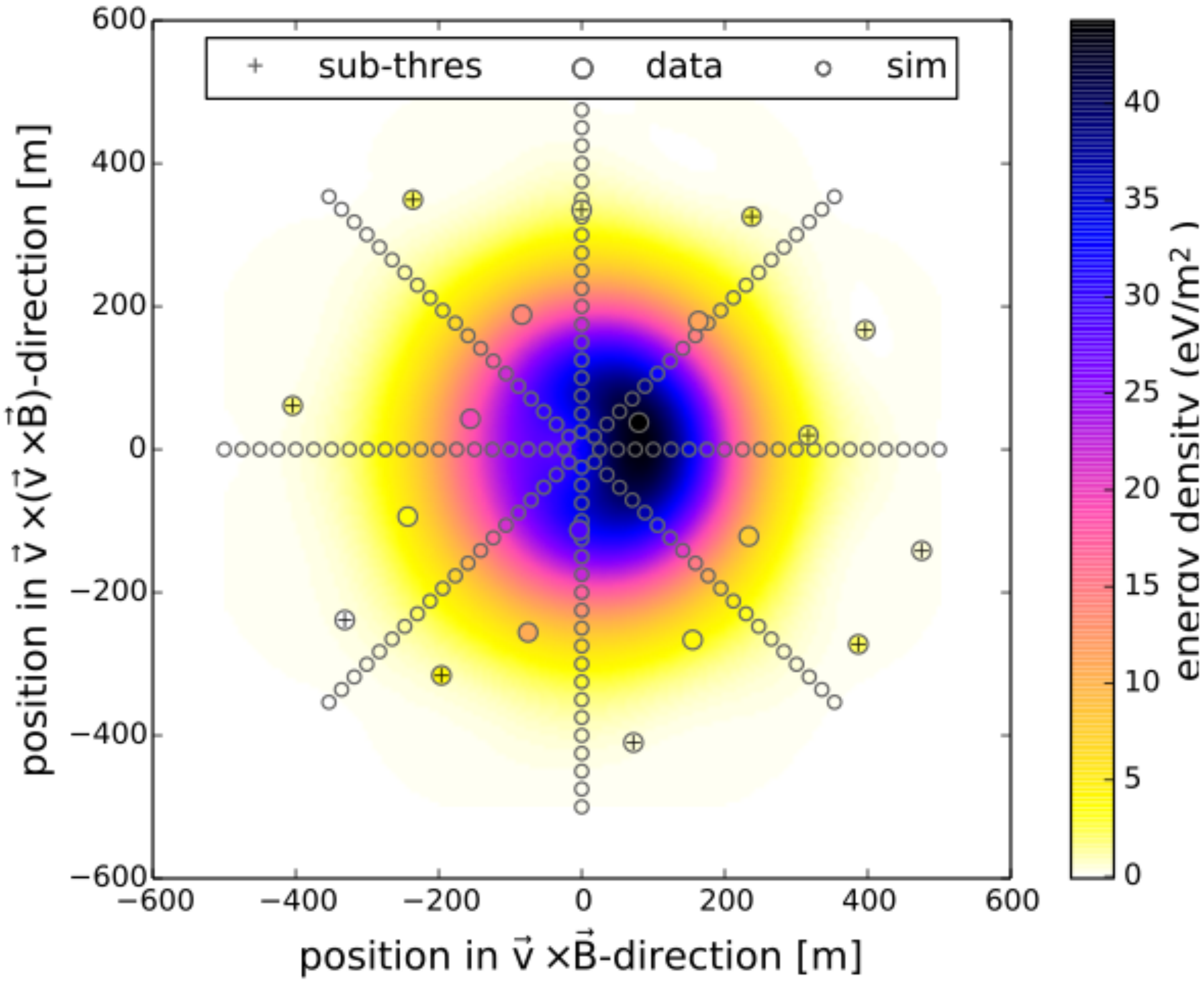


- pure radio
- gives all parameters

- poor precision

•CoREAS + energy density interpolation

C
CoREAS AIP Conf. Proc. (2013) 128– 132
SD arrival direction SD energy
20 p + 10 Fe



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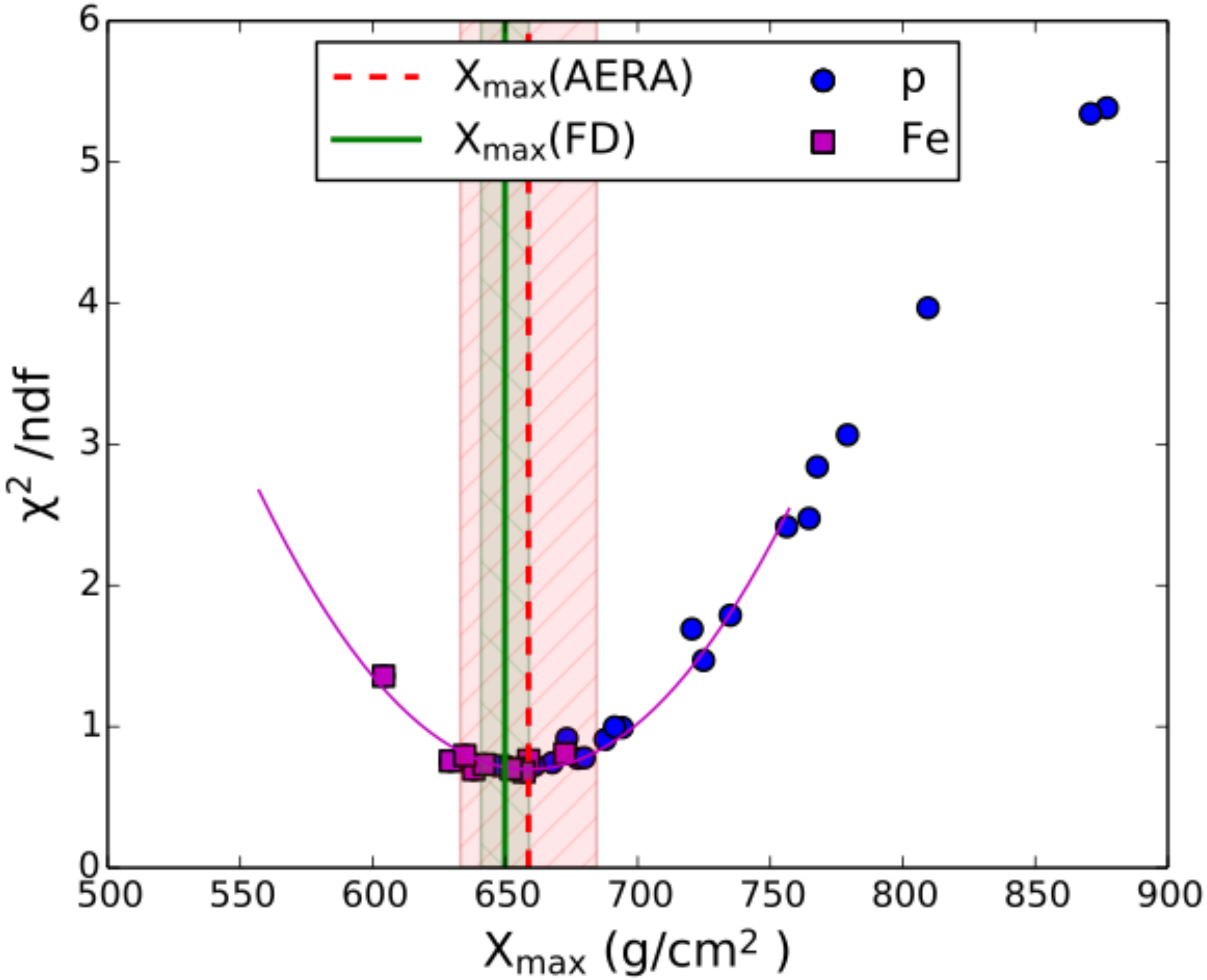

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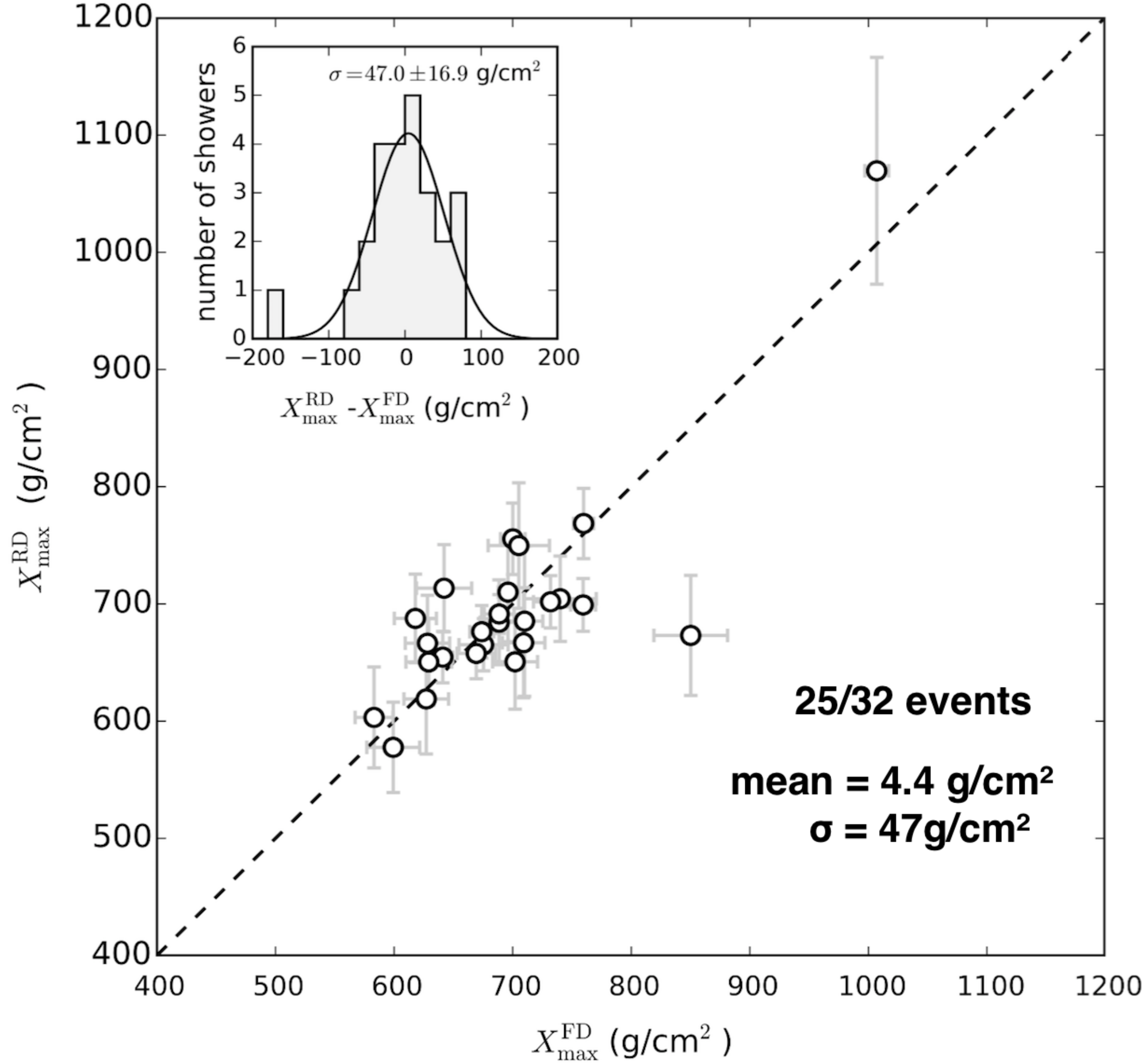

- very good agreement
- good precision

- needs SD information
- and a lot of time

•ZHAireS + superposition model

D
ZHAireS horizontal components Astropart. Phys. 59 (2014) 29
SD core (initialization) SD energy
30 p + 30 Fe

Only a few positions along a single direction w.r.t. the core: Very Fast!

Superposition model used instead of interpolation.

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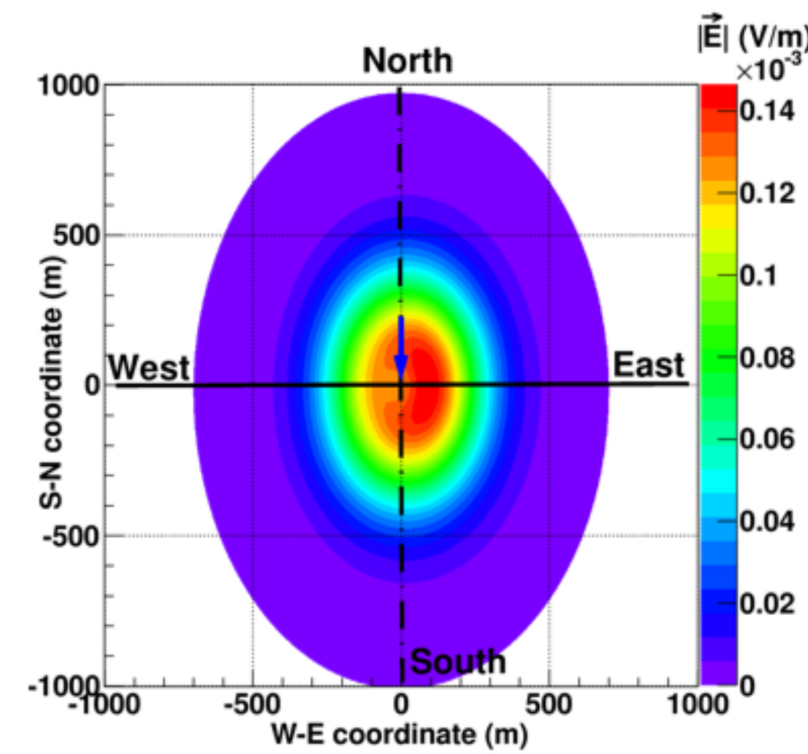
Astropar. Phys. **59**, 29, 2014

Superposition model:

Amplitudes of Askaryan & geomagnetic emissions are circularly symmetric in the transverse plan of the shower



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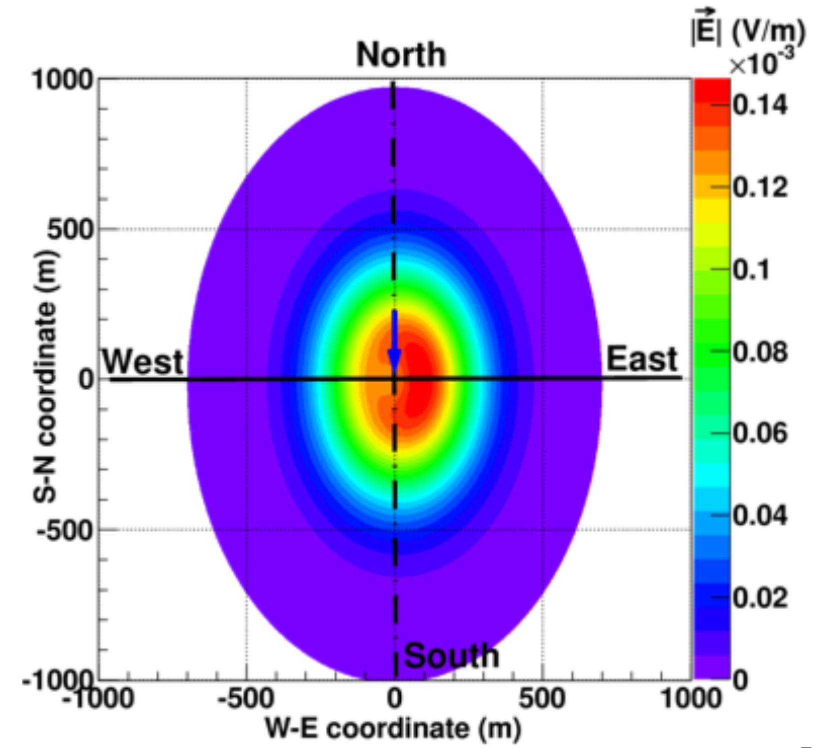

$$\sum_{\text{all antennas}} \left[|\vec{E}_{\text{ant}}| - f_s . |\vec{E}|(x_{\text{ant}} - x_{\text{core}}, y_{\text{ant}} - y_{\text{core}}) \right]^2$$

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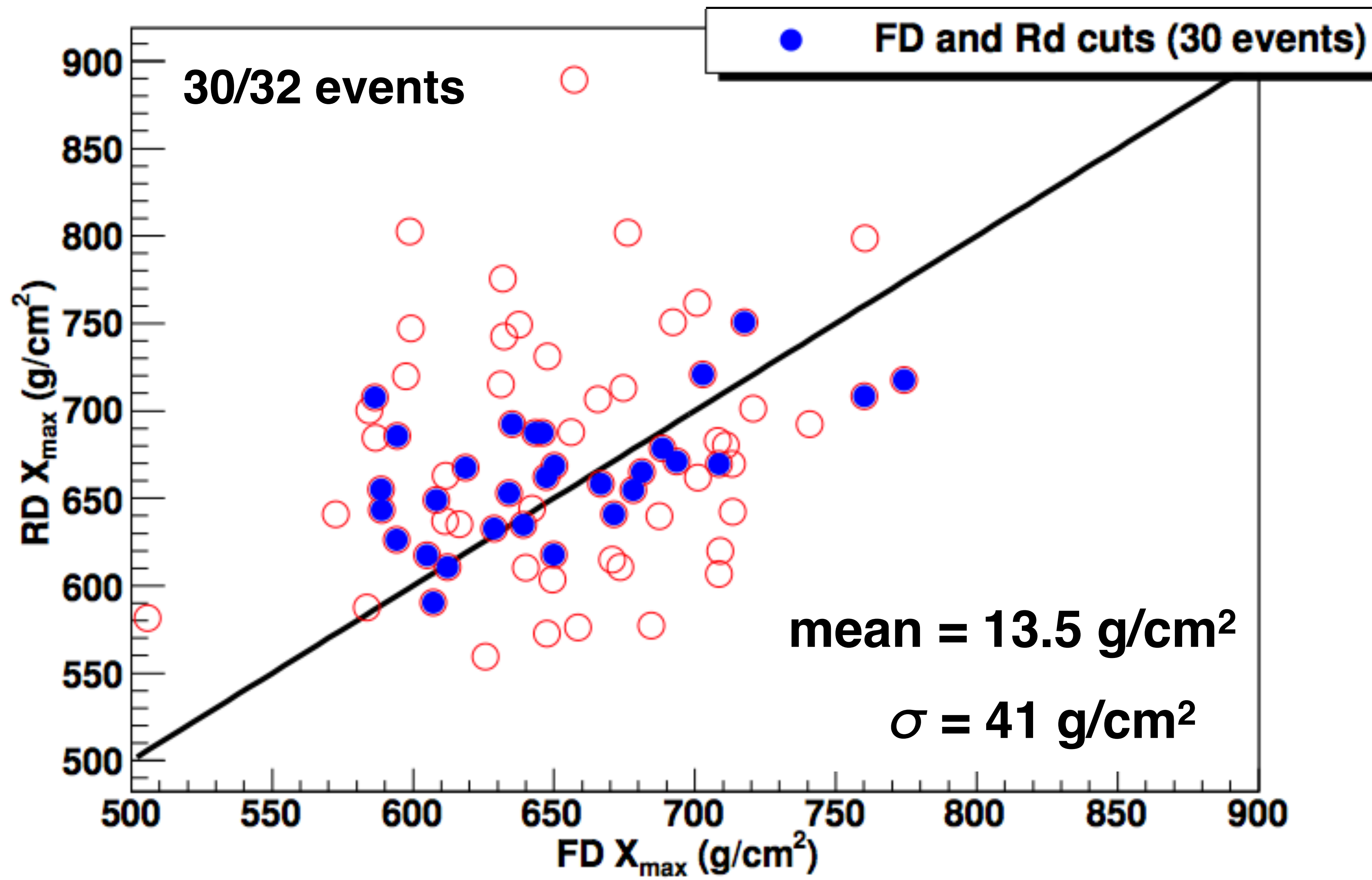

- good agreement
- good precision
- very fast

- needs SD information

•Conclusions

Method	A	B	C	D
model	SELFAS Astropart. Phys. 35 (2012) 733 – 741	2D gaussian Astropart. Phys. 60 (2015) 13	CoREAS AIP Conf. Proc. (2013) 128– 132	ZHAireS horizontal components Astropart. Phys. 59 (2014) 29
requirements	RD arrival direction	RD arrival direction	SD arrival direction SD energy	SD core (initialization) SD energy
Xmax Rd - Fd distribution	mean = 43.6 g/cm² σ = 43.4 g/cm²	mean = -12 g/cm² σ = 59.3 g/cm²	mean = 4.4 g/cm² σ = 47 g/cm²	mean = 13.4 g/cm² σ = 41.3 g/cm²
outputs	Core position Energy Xmax	Core position Energy Xmax	Core position Xmax	Core position Xmax
simulation duration	~ 8 hours	--	~ 1 week	~ 1 hour

Combine strengths:
- **Pure radio method (A, B)**
- **Fast (B, D)**
- **Good agreement (C)**
- **Good precision (A, C, D)**

•Conclusions

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simulation duration	~ 8 hours	--	~ 1 week	~ 1 hour

A good way to compare simulation codes,
ex: method A algorithm with CoREAS or ZHAireS

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•Conclusions

- The radio signal allows the estimation of the composition of cosmic rays
- The Pierre Auger Collaboration is working on determining the composition from radio signal with no bias
- Comparison with a larger set of FD + RD events is essential for the validation of the methods
- The air density and refractivity can explain systematic shifts
- Xmax estimation from radio signals will be a decisive asset for the estimation of the mass composition of cosmic rays due to the high duty cycle of the detectors

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Thank you for your attention!

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• FD quality cuts

- **hasMieDatabase**: selects events with aerosol measurements.
- **minLgEnergyFD**: selects events with FD energy greater than set value.
- **skipSaturated**: removes events with saturated pixels.
- **badFDPeriodRejection**: removes events missing calibration data.
- **maxVAOD**: removes events where VAOD measurements are larger than 0.1 at a distance 3 km from the telescopes.
- **minBackgroundRMS**: selects events with a minimum background RMS.
- **LidarCloudRemoval**: removes events in which too many clouds were present based on LIDAR measurement.
- **MinCloudDepthDistance**: selects events with cloud depth distance greater than minimum.

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• FD quality cuts

- **MaxCloudThickness**: selects events with cloud thickness below maximum.
- **badPixels**: removes events in which telescopes had one or more pixels with bad calibration constants.
- **xMaxObsInExpectedFOV**: selects events for which X_{max} is in the expected field of view.
- **xMaxError**: selects events with an error in X_{max} below set value.
- **energyTotError**: selects events with an error in energy below set value.
- **profileChi2Sigma**: selects events where reduced χ^2 for Gaisser-Hillas fit is below set value.
- **maxDepthHole**: removes events for which the hole in the longitudinal profile is greater than 20%.
- **maxCoreTankDist**: selects events for which the reconstructed FD core is less than 750 m away from an SD station.
- **FidFOVICRC13prel**: removes events which may induce a bias in the energy calibration.