New methods to reconstruct X_{max} and the energy of gamma-ray air showers with high accuracy in large wide-field observatories

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R. Conceição, L. Peres, M. Pimenta, B. Tomé

LIP

TÉCNICO LISBOA

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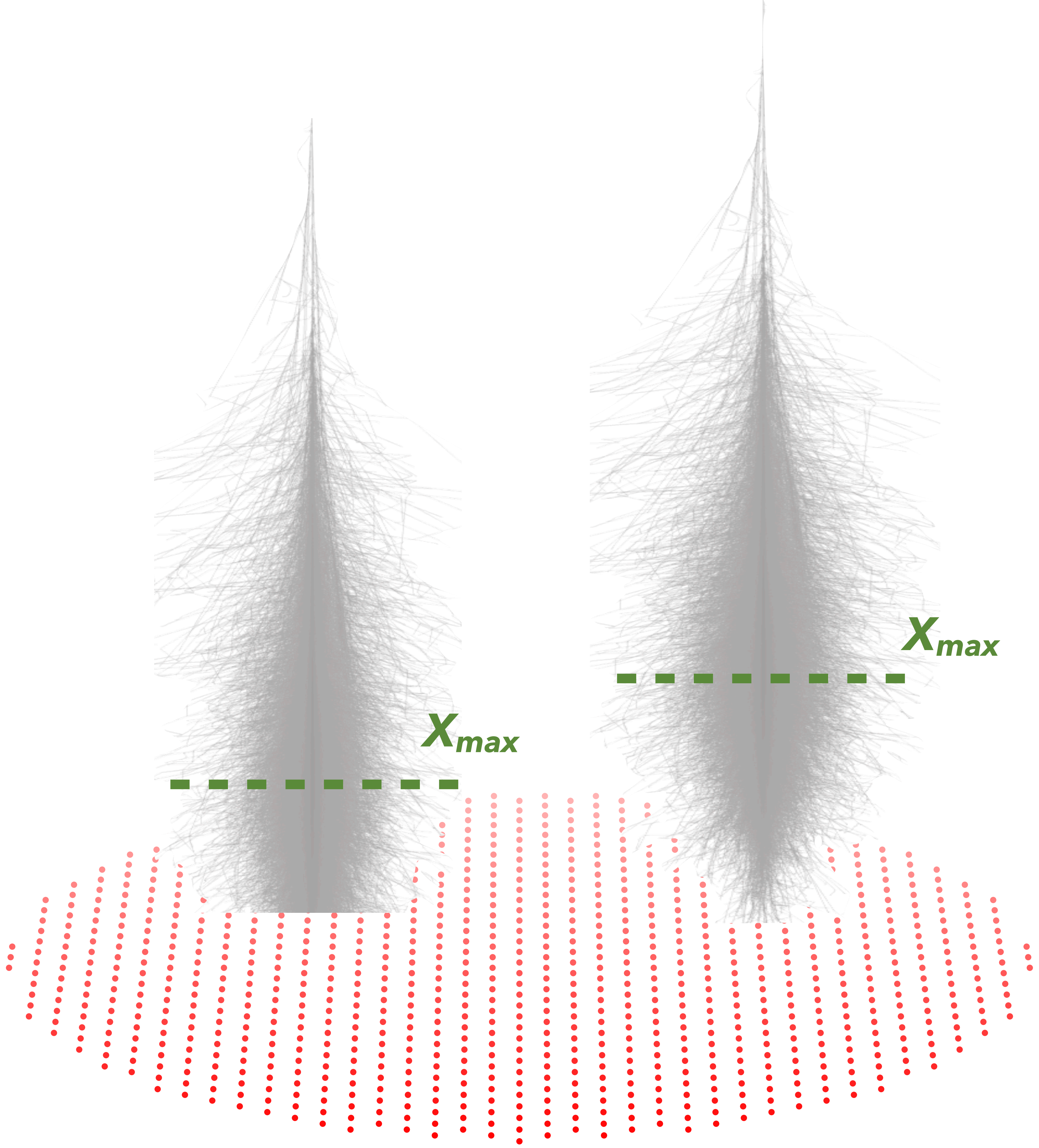
The problem

- In ground-arrays the energy of gamma-rays is estimated by sampling the particles at the ground
- The primary energy is proportional to the recorded signal at the ground
- The shower fluctuation induces large uncertainties on the energy determination even using MC template-based likelihood fits
  - At E = 10 TeV results found in the literature quote uncertainties of around 50%

Same energy gamma-rays



A new strategy

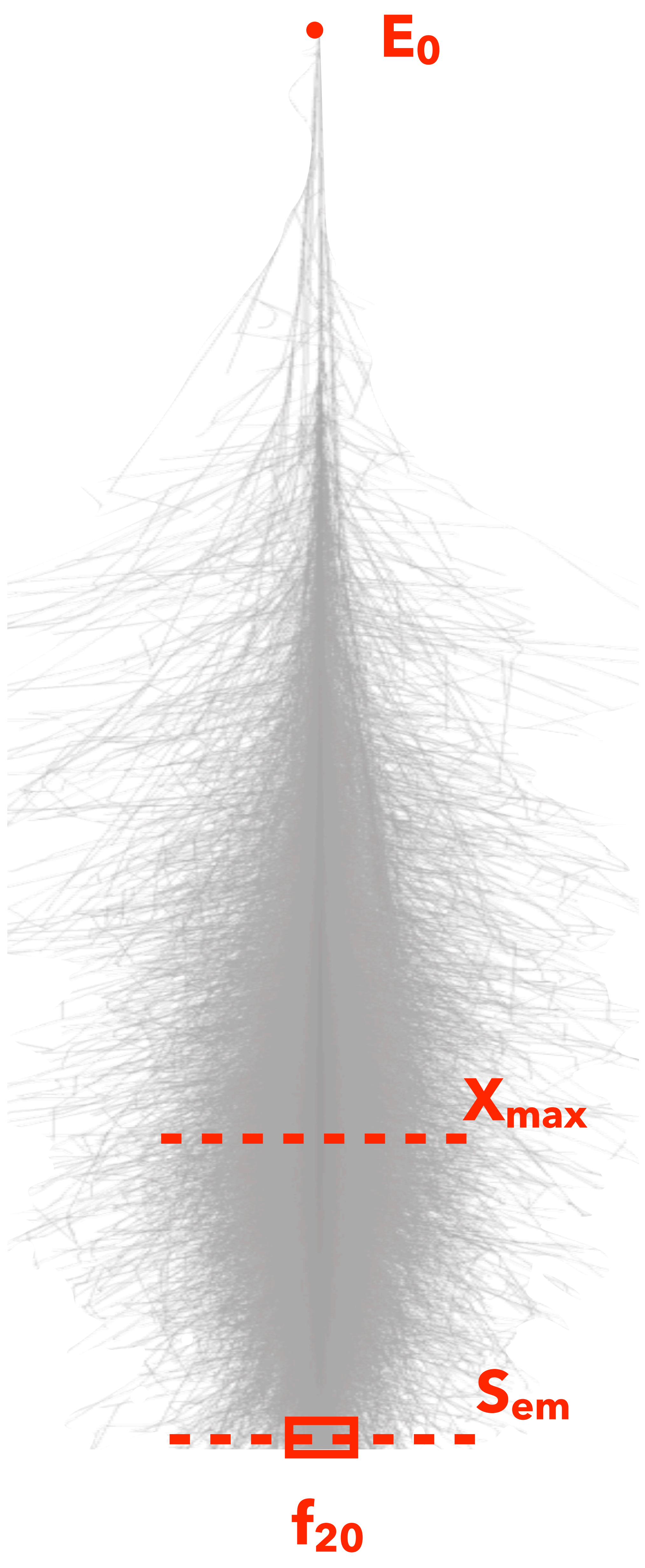
- Determine the shower stage and achieve a better determination of the primary energy through:

1. The energy at the ground (**S_{em}**) from the measured signal in the array

2. The shower stage (**X_{max}**) from the S_{em} or the shower front curvature

3. The primary energy (**E_0**) from the S_{em}, X_{max} and the energy fraction in the core region

    - **f_{20}** - energy fraction within 20 m from the shower core
      $f_{20} = F_{20} / S_{em}$

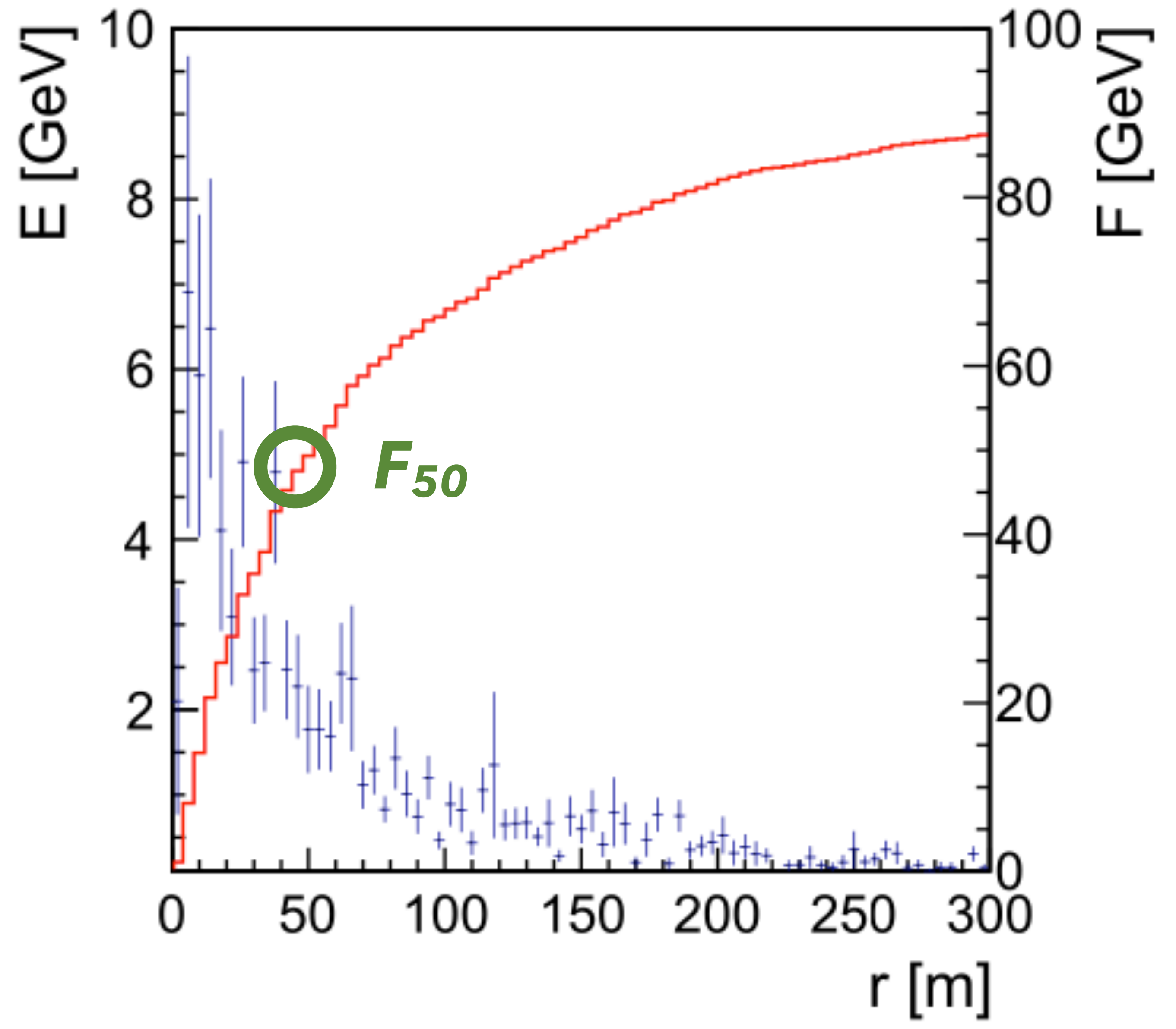


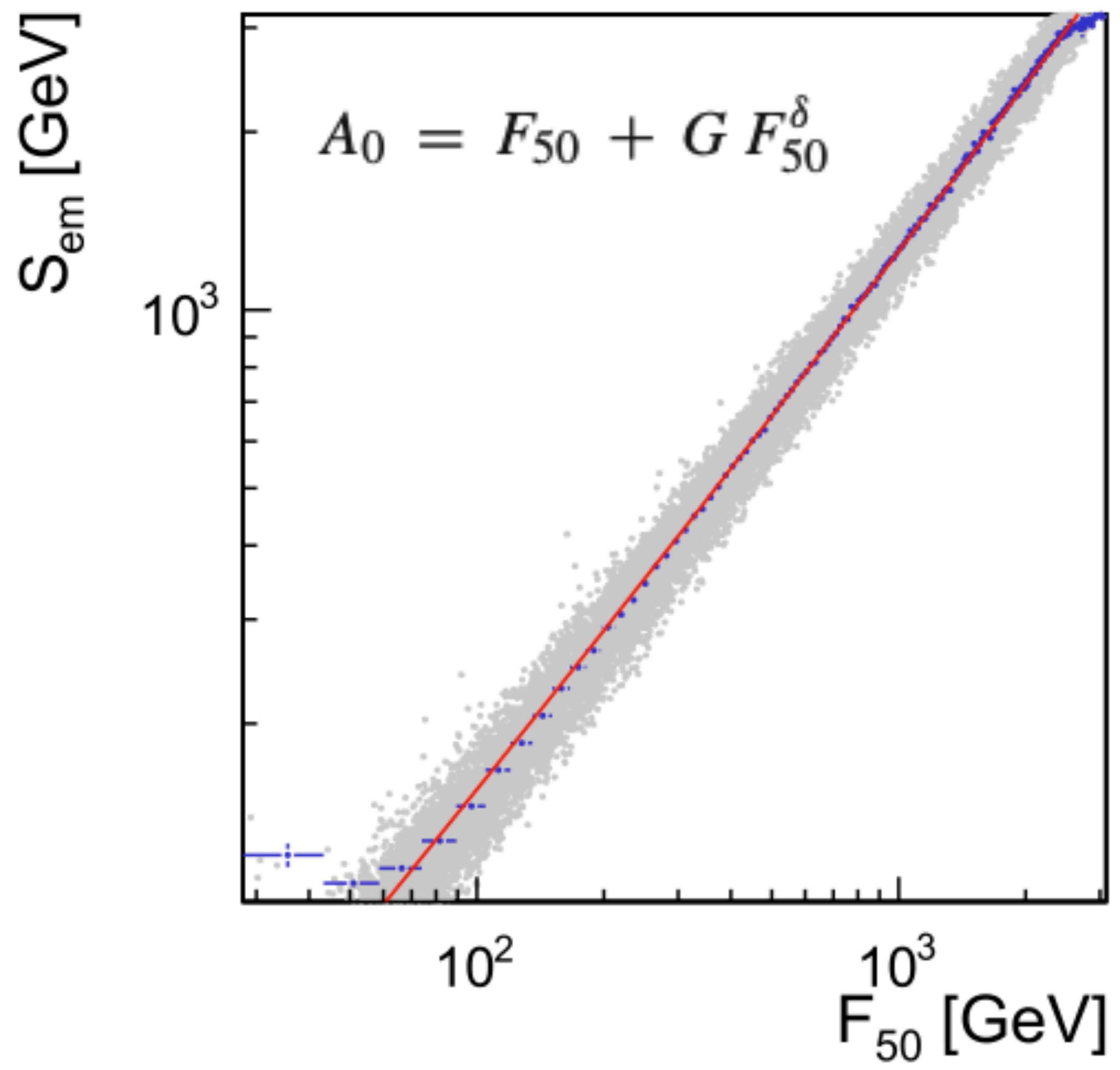
Simulations

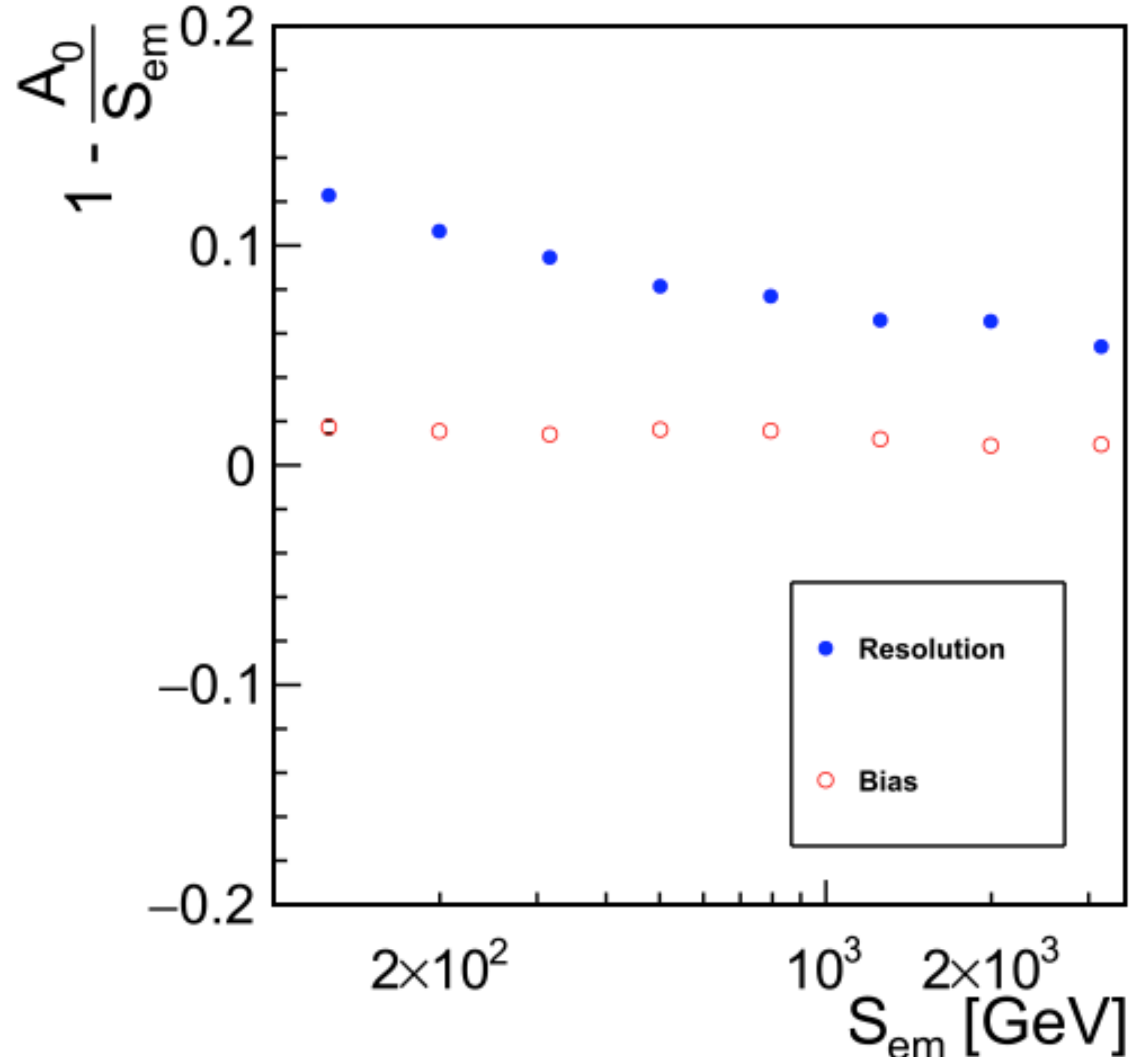
- Vertical gamma primaries with energies between 250 GeV and 15 TeV simulated with CORSIKA
- Observation level at 5200 m a.s.l.
- The total energy of electromagnetic shower particles was recorded at the observation level and histogrammed in radial bins of 4 meters
- The signal measured by a water Cherenkov detector is proportional to the energy carried by the electromagnetic shower particles hitting it
- Mimic a ground-based gamma-ray observatory such as LHAASO or the future SWGO

Energy at the ground (S_{em})

- ✧ Integrate energy (WCD signal) contained within 50 meters from the shower core (F_{50})
- ✧ A_0 is the estimator for S_{em}

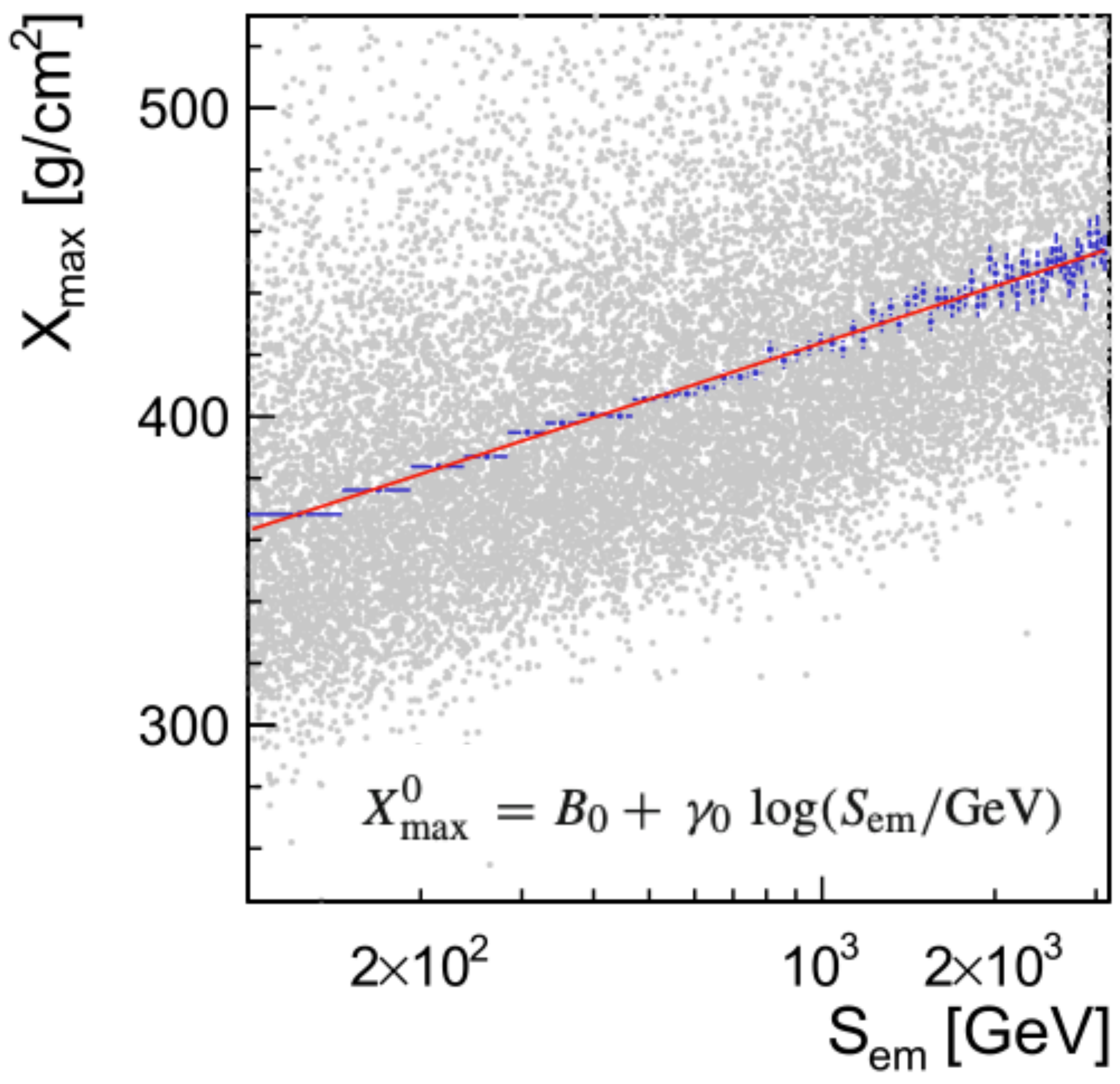




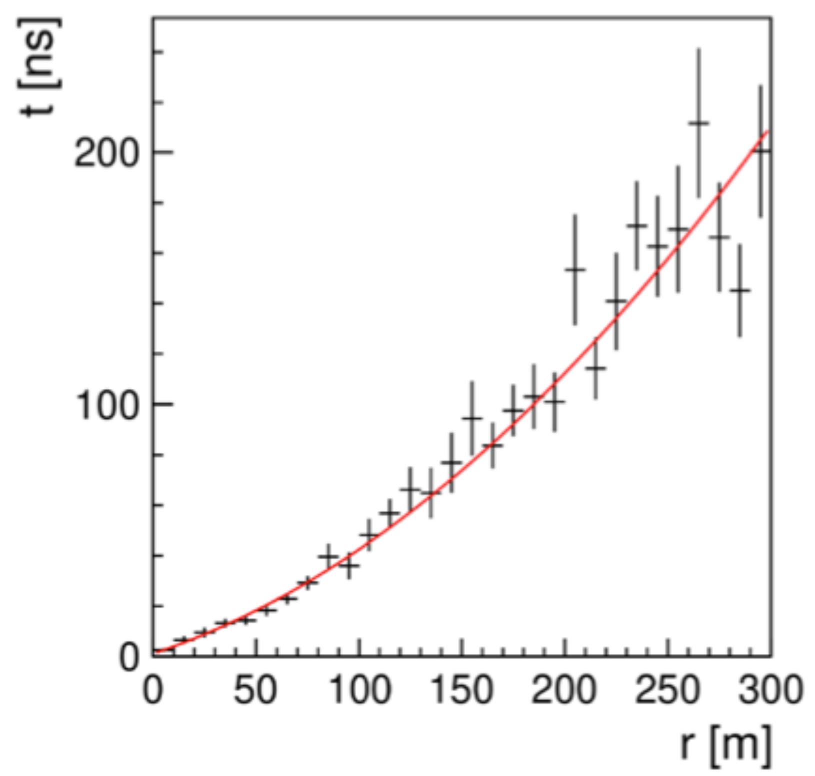


Depth of the Shower Maximum (X_{max})

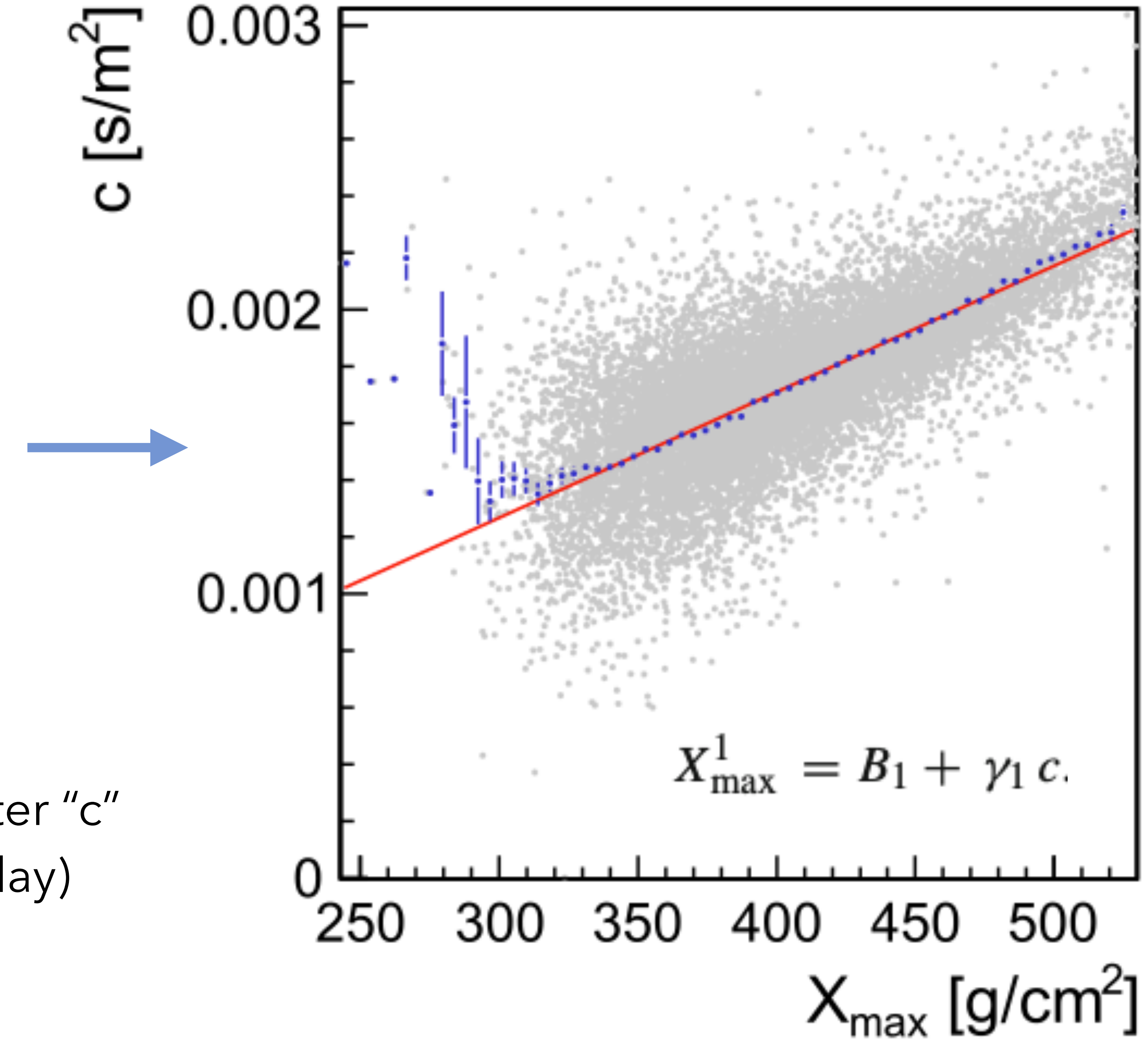
- From the S_{em}
  - X^0_{max}



- From the shower curvature
  - X^1_{max}



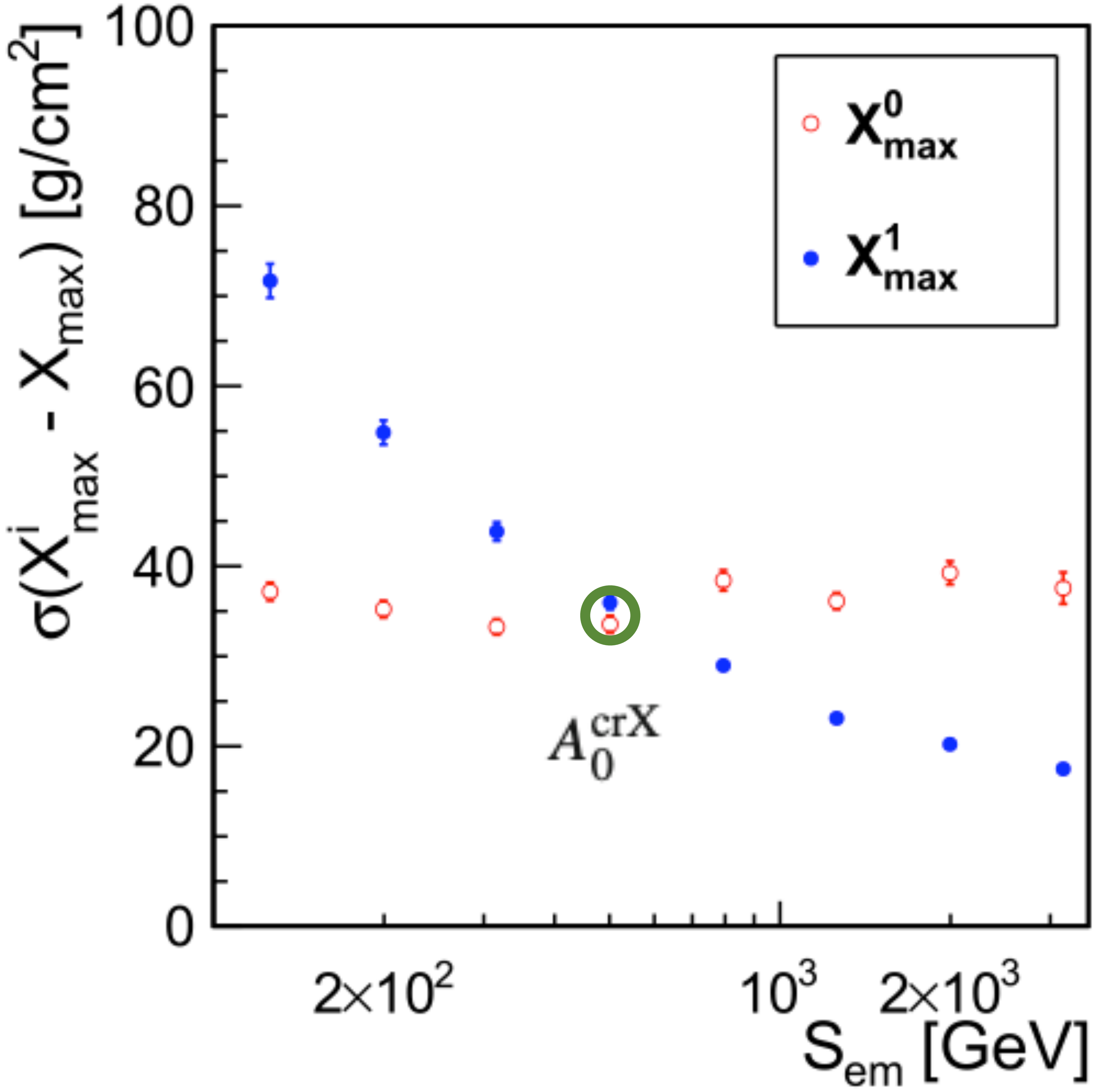
(get shower curvature parameter "c" from shower arrival time delay)



Depth of the Shower Maximum (X_{max})

- From the S_{em}
  - X^0_{max}
- From the shower curvature
  - X^1_{max}
- Neglibible bias
- Use shower curvature only for high energies

$$X^R_{max} = \begin{cases} X^1_{max} & \text{if } A_0 > A_0^{crX} \\ & \text{and } X^1_{max} > 300\,\mathrm{g\,cm^{-2}} \\ X^0_{max} & \text{otherwise} \end{cases}$$

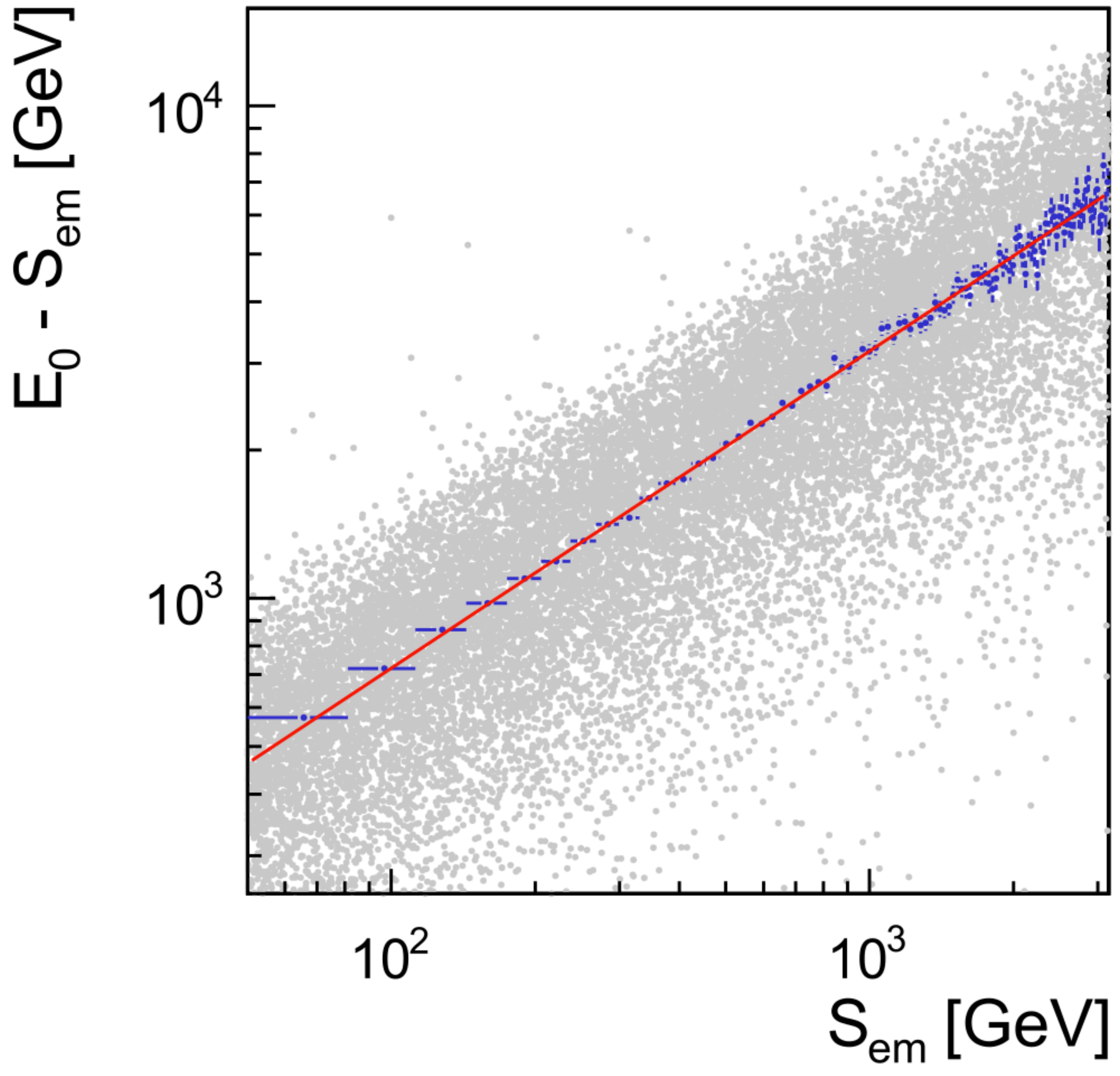


Measurement of primary energy (E_0)

Using only S_{em}

$$E_0^{(1)} = S_{\rm em} + C\,(S_{\rm em})^{\beta}$$

C - calibration constant



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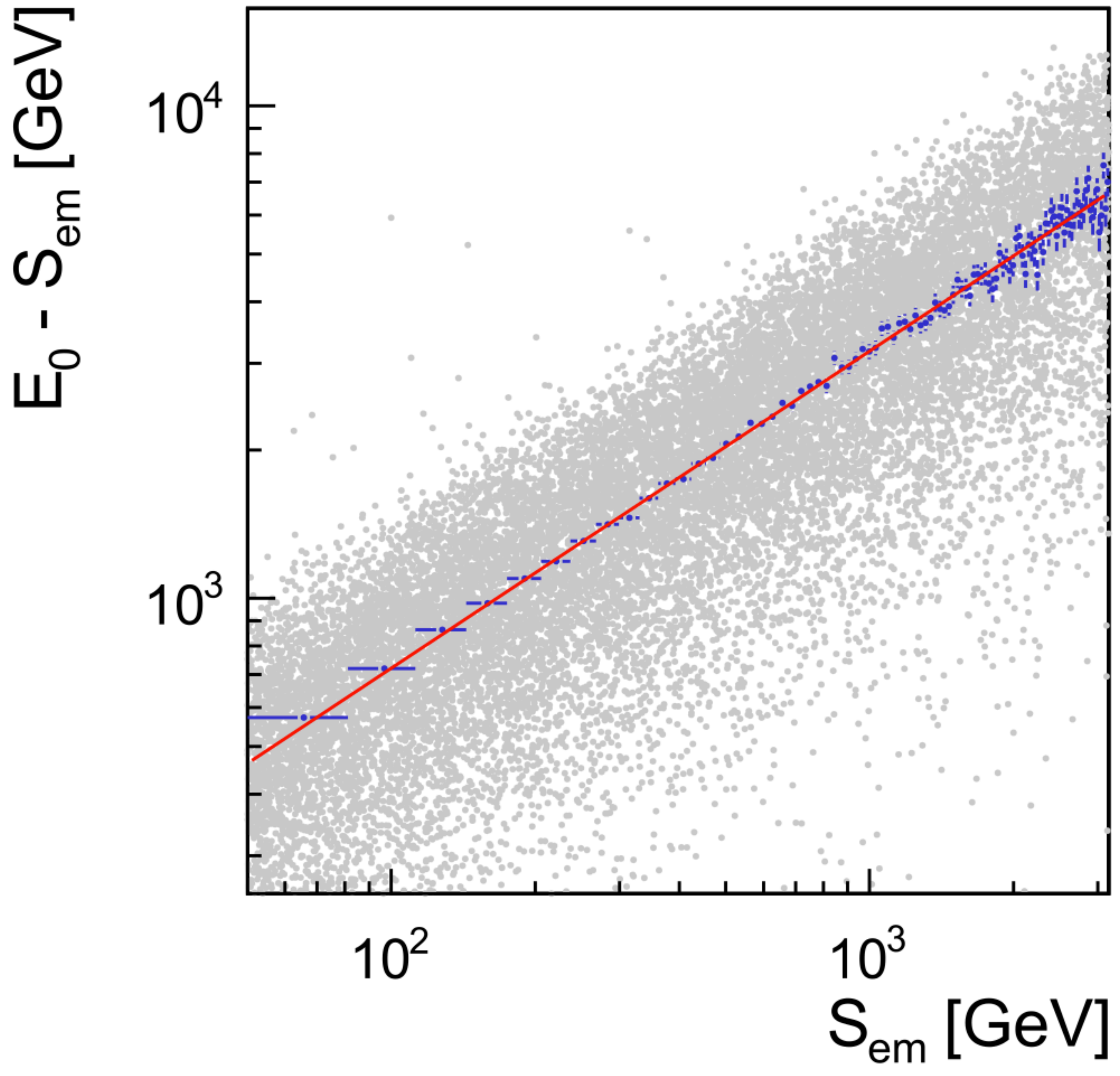
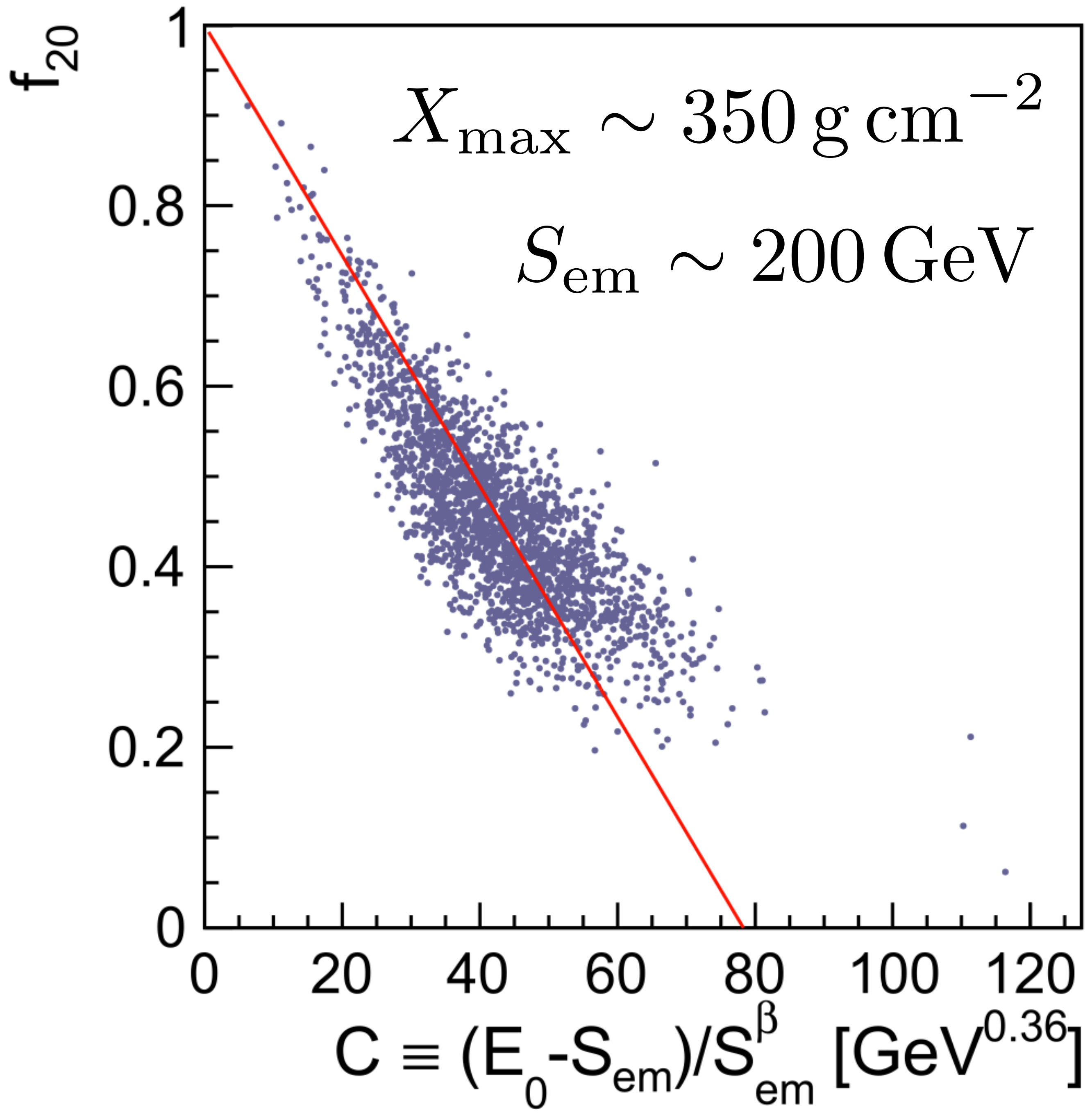


Using S_{em} , X_{max} , f_{20}

$$E_0^{(2)} = S_{\rm em} + C(f_{20}, X_{\rm max}, S_{\rm em})\,(S_{\rm em})^{\beta}$$

C - is a function of 3-measured shower observables

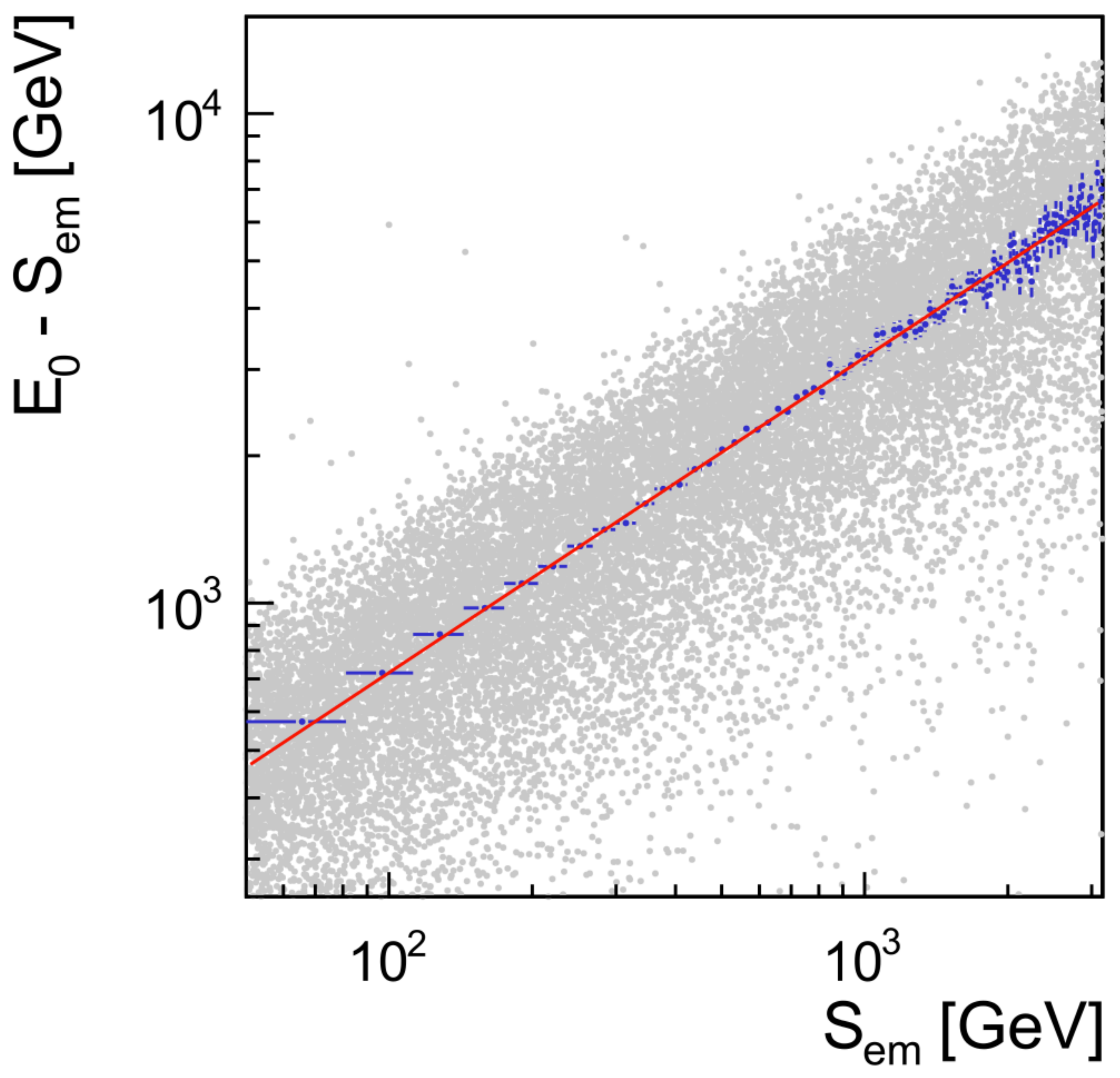


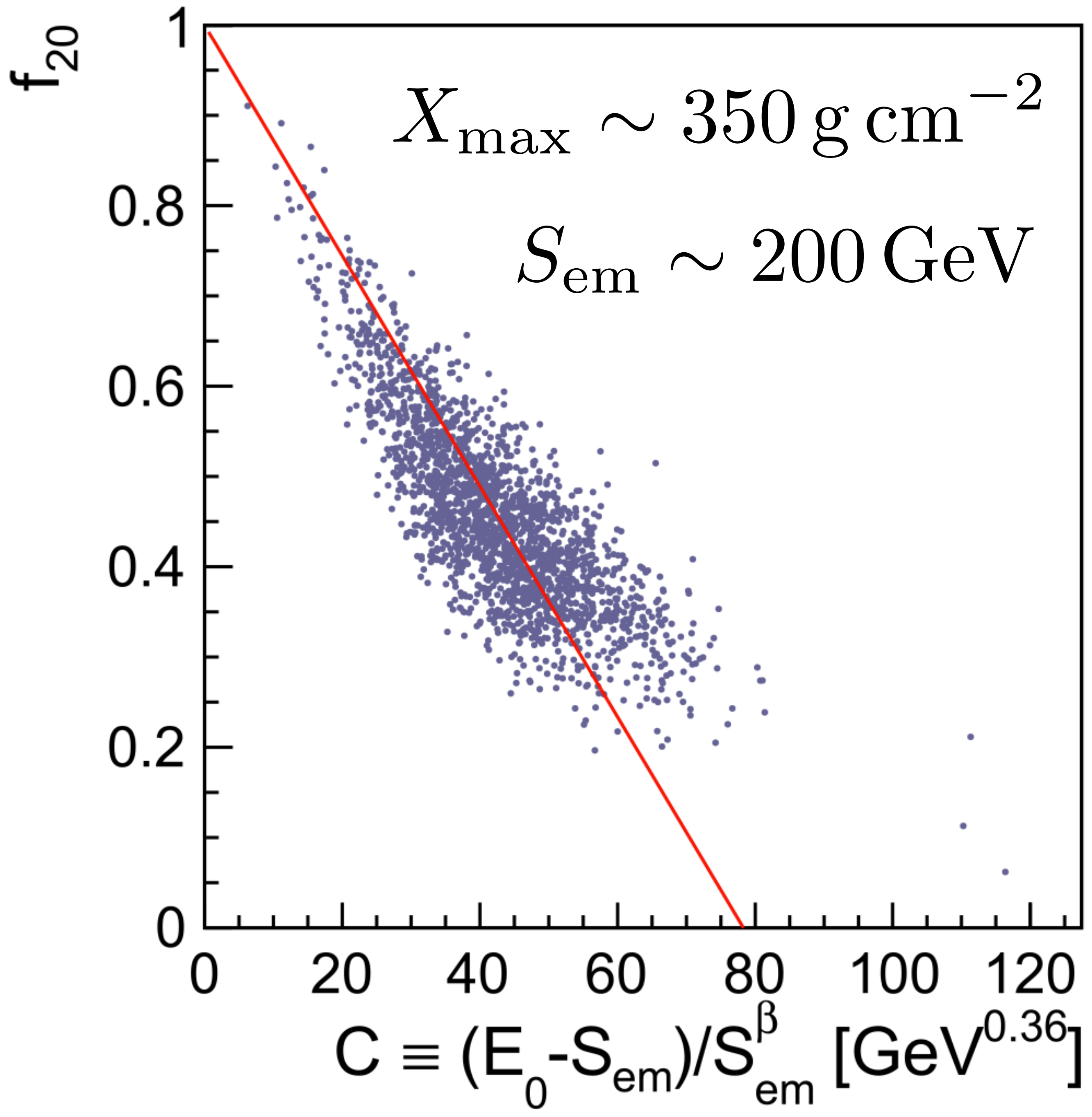
Ruben Conceição

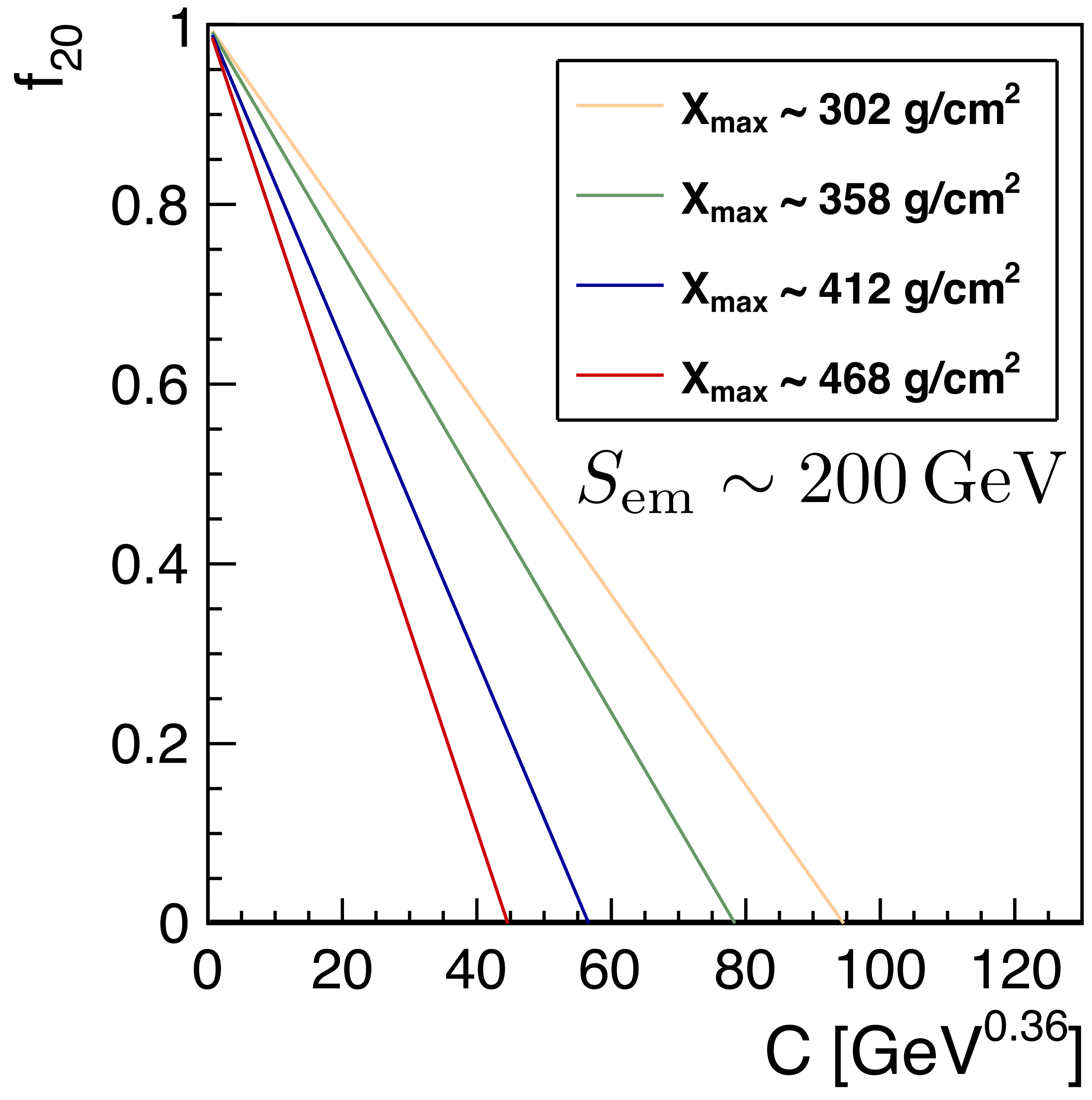
Even with the same X_{max} showers can have distinct developments leading to a different energy lateral distribution function at the ground

Measurement of primary energy (E_0)

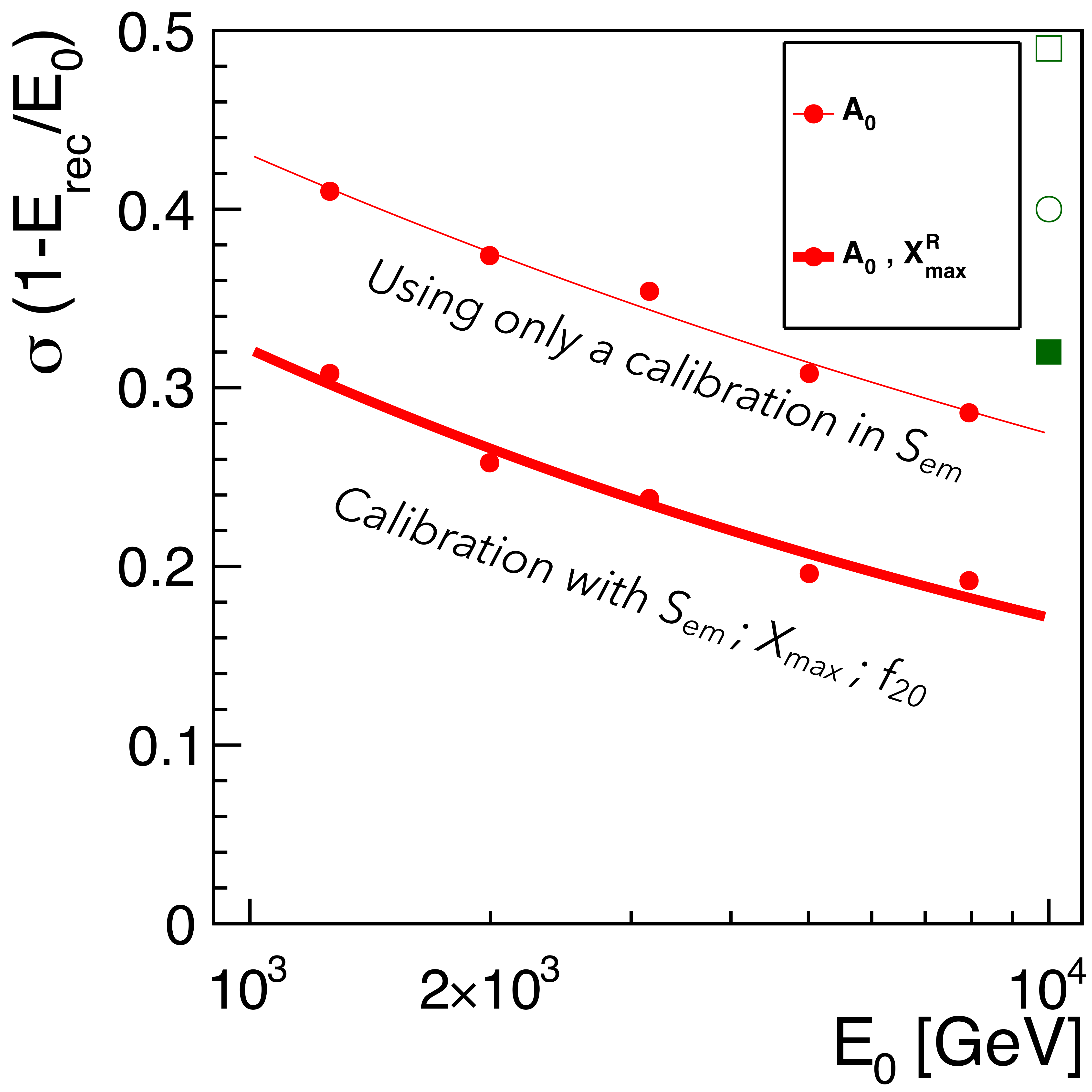
Using only S_{em}	**Using S_{em} , X_{max} , f_{20}**
$$E_0^{(1)} = S_{\rm em} + C\,(S_{\rm em})^{\beta}$$	$$E_0^{(2)} = S_{\rm em} + C(f_{20}, X_{\rm max}, S_{\rm em})\,(S_{\rm em})^{\beta}$$
C - calibration constant	C - is a function of 3-measured shower observables







The final result



MC template - θ < 45° (2019)

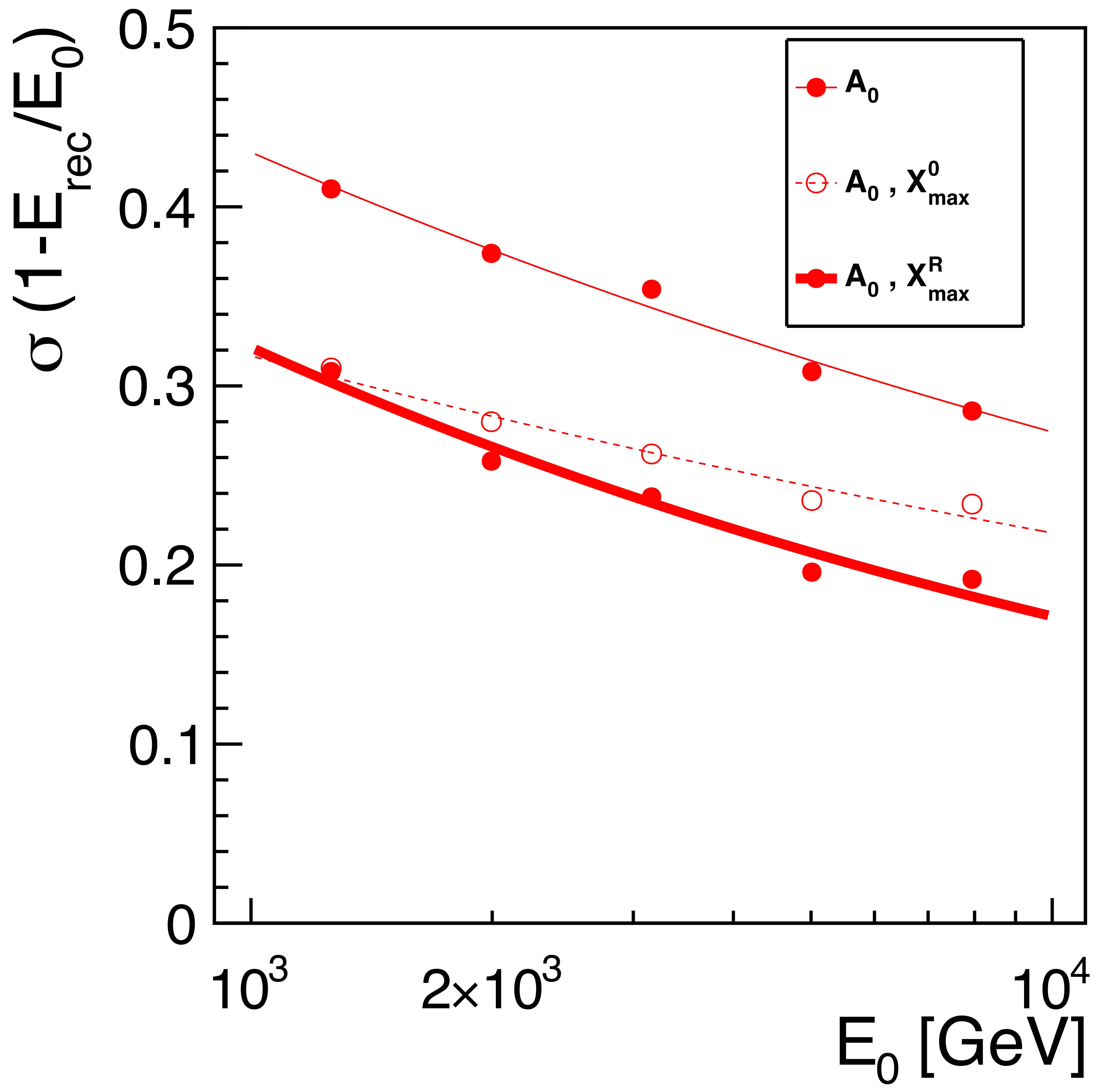
HAWC - θ < 45° (2019)

LHASSO - θ = 0° (2020)

Improvement of more than 10%

The final result

The measurement of X_{max} through the shower curvature has a noticeable effect at the highest energies

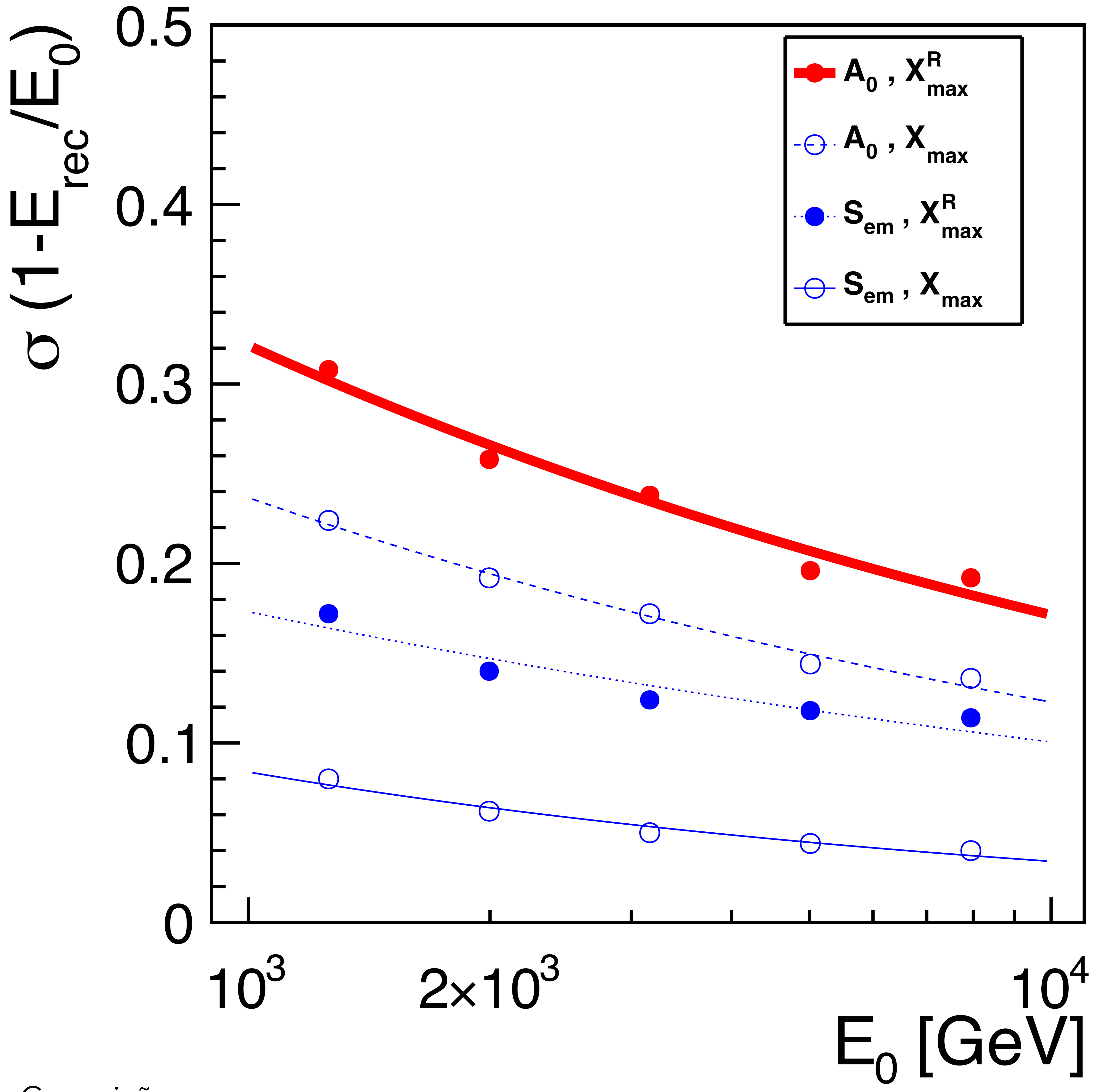


The final result

As expected the, the determination of the shower stage plays an important role on the energy reconstruction resolution

Knowing X_{max} the resolution on the determination of S_{em} becomes crucial

There is still space for improvement



Summary

- We present a method to improve the energy reconstruction of shower in ground-array gamma-ray observatories
  - *Eur. Phys. J. C (2021) 81:80 - arXiv:2010.11390 [hep-ph]*

- The energy reconstruction is improved through the determination of the shower development stage, which is achieved combining the following measurable shower quantities:
  - Energy (signal) collected at the ground, S_{em};
  - Estimation of the shower maximum depth, X_{max}, through the shower front plane curvature
  - Fraction of energy collected near the shower core, f_{20}.

Acknowledgements

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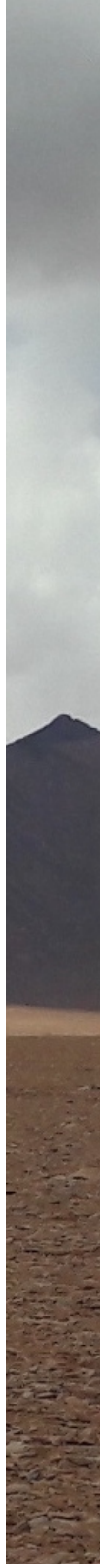
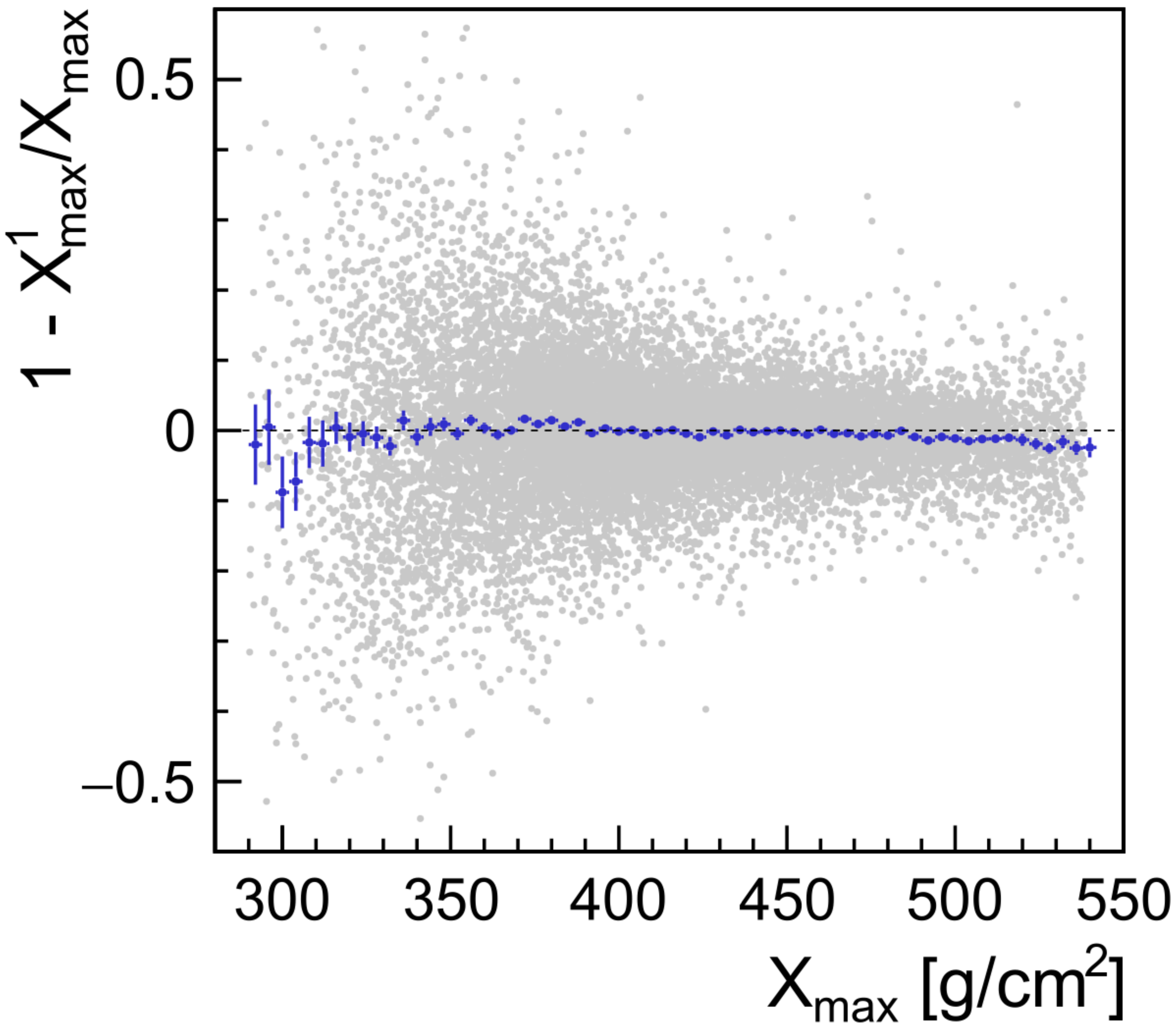
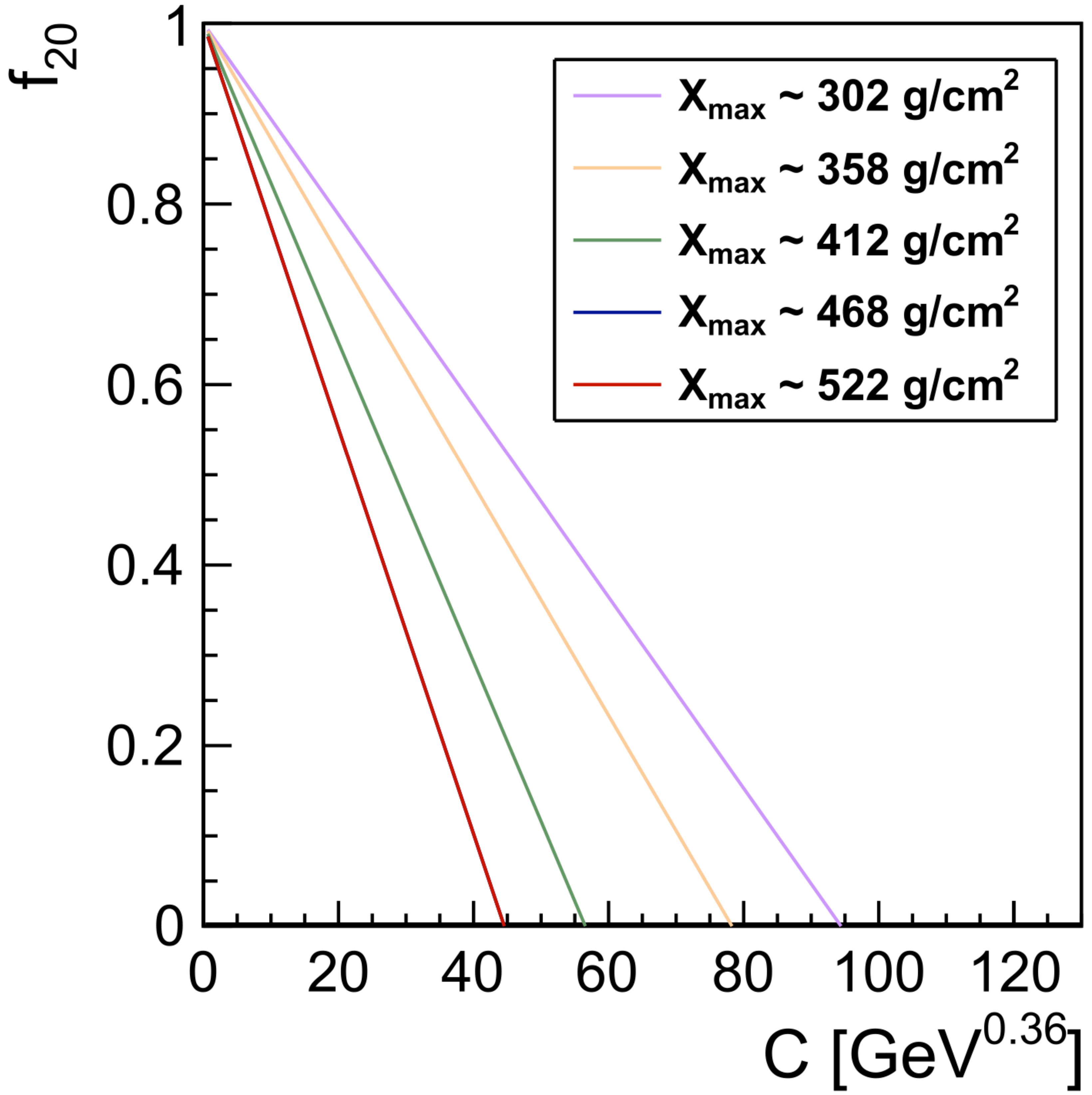
Backup Slides

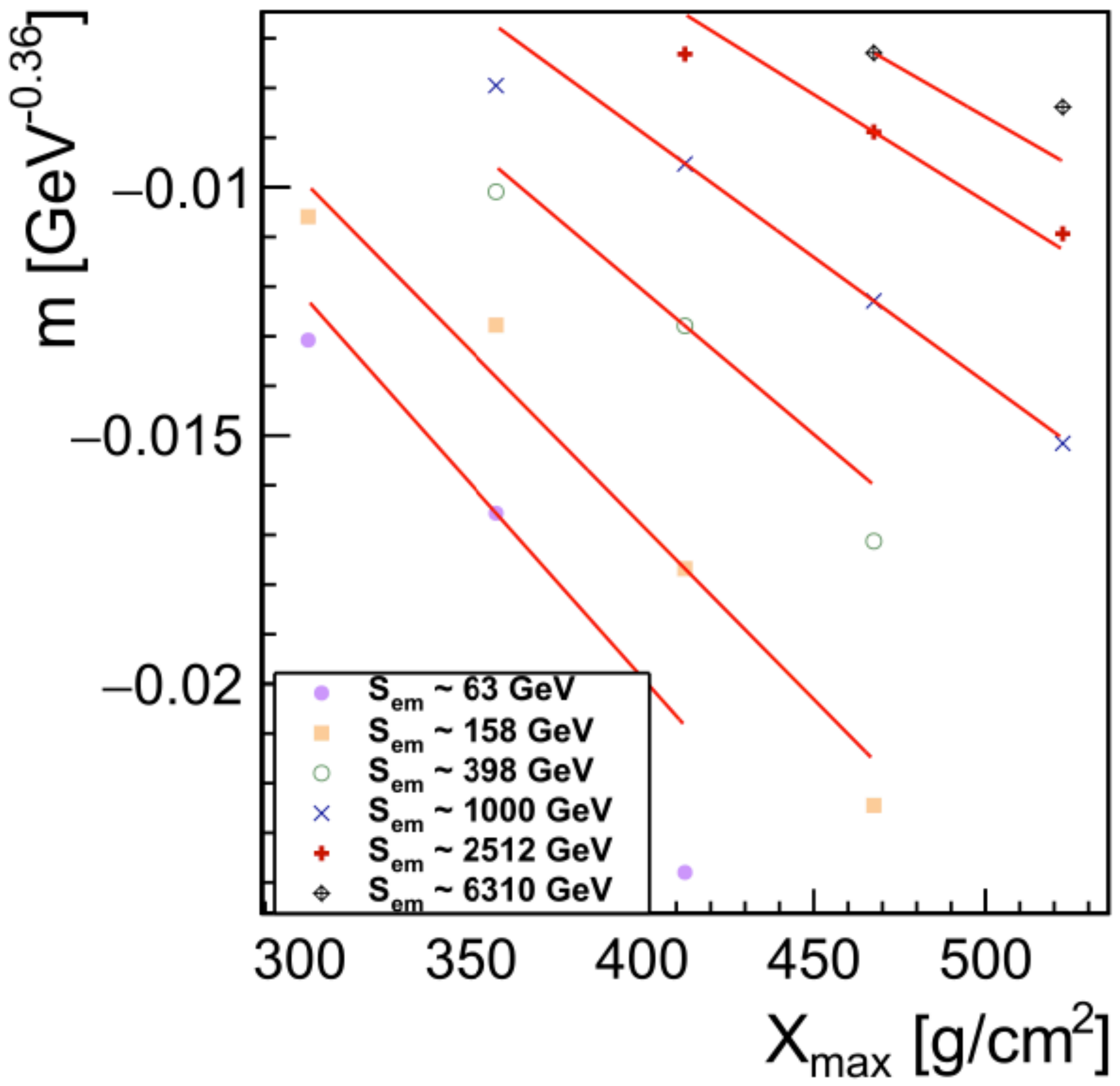


Bias on the determination of X_{max} using the shower curvature



f_{20} parametrization





$$f_{20} = 1 + m(X_{\max}, S_{\rm em})\, C(f_{20}, X_{\max}, S_{\rm em})$$

$$m(X_{\max}, S_{\rm em}) = b_m + [s_{m0} + s_{m1}\, \log(S_{\rm em}/{\rm GeV})]\, X_{\max}$$