KIT
Karlsruhe Institute of Technology

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# Study on the Combined Estimate of the Cosmic-Ray Composition and Particle Cross Sections at Ultrahigh Energies

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# Motivation

## What?

Combined estimate of the cosmic-ray composition and particle interaction cross sections.

## Why?

- Mass composition is one of the key observables to understand the nature of ultra-high energy cosmic rays;
- Study of hadronic interactions is a fundamental probe of elementary particle physics.

## How?

- Vary the proton-proton cross section
- Perform a standard composition fit

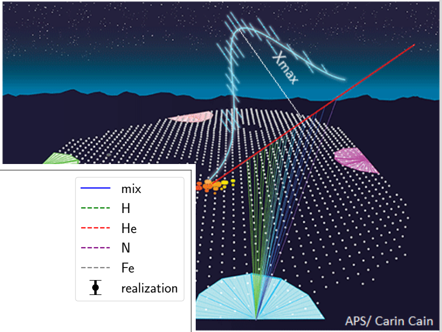
$\rightarrow$ estimation of the interaction cross sections and cosmic-ray primary composition ***without underlying assumptions***

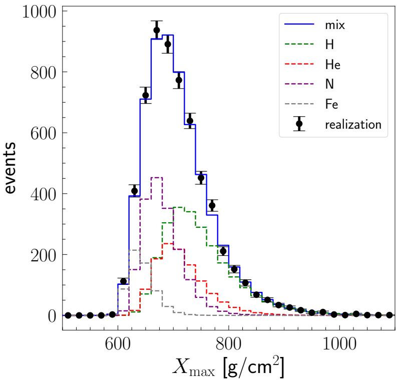
# Standard mass composition and cross section measurements

## Mass composition

1. Compare the measured $X_{\max}$ distributions to the predictions from air shower simulations.

- ***Assumption:*** the validity of the hadronic interaction models corresponding theoretical uncertainties dominate the uncertainty on the mass composition.



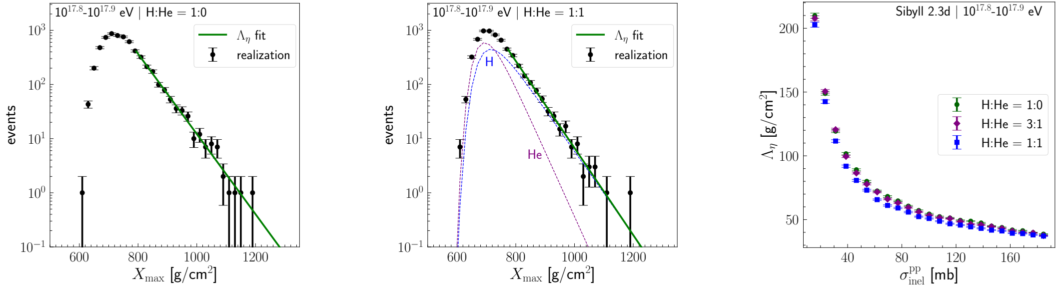
# Standard mass composition and cross section measurements

## Interaction cross sections

1. Measure attenuation length $\Lambda$ by fitting the tail of the $X_{\max}$ distribution;
2. Convert $\Lambda$ into $\sigma^{\mathrm{p-Air}}$.

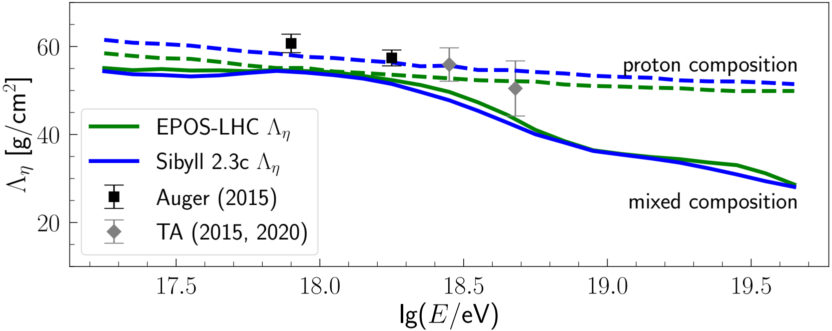
- ***Assumption:*** Proton-dominated $X_{\max}$ tail -> He-contamination = systematic uncertainty.

$\Lambda_\eta$ fit examples




* underscript $\eta$ corresponds to the fraction of deep-$X_{\max}$ events used for the fit; here $\eta$=0.2

# Attenuation length




- "Mixed composition" simulations are based on the fractions derived by the Pierre Auger Collaboration [1];
- In the analysis of the Pierre Auger Collaboration, $\eta$ is set to 0.2 [2];
- Telescope Array Collaboration reports the exponential slope fitted within the range of 790 to 1000 g/cm$^2$ [3,4].

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[1] J. Bellido for the Pierre Auger Collaboration, *PoS ICRC2017 (2017)* 506.
[2] R. Ulrich for the Pierre Auger Collaboration, *PoS ICRC2015 (2015)* 401.
[3] R.U. Abbasi et al. [Telescope Array Collaboration], *Phys. Rev. D* ***92*** *(2015)* 032007.
[4] R.U. Abbasi et al. [Telescope Array Collaboration], *Phys. Rev. D* ***102*** *(2020)* 062004.

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# $X_{\max}$ distributions for the modified cross sections

$f_{\lg E_1}$ → $\sigma^{\mathrm{pp}}_{\mathrm{mod}}$ → Glauber[5] → $\sigma^{\mathrm{p-Air}}_{\mathrm{mod}}$ → CONEX → $X_{\max}$ distr.

Rescale the proton-proton cross section:

$$\sigma^{\mathrm{pp}}_{\mathrm{mod}} = \sigma^{\mathrm{pp}}_{\mathrm{orig}} f(E, f^{\mathrm{pp}}_{19}), \quad (1)$$

with a linear scaling factor[6] $f(E)$ between the energy threshold $E_0$ and energy of interest $E$:

$$f(E) = 1 + H(E - E_0)(f_{\lg E_1} - 1)\frac{\lg(E/E_0)}{\lg(E_1/E_0)}, \quad (2)$$

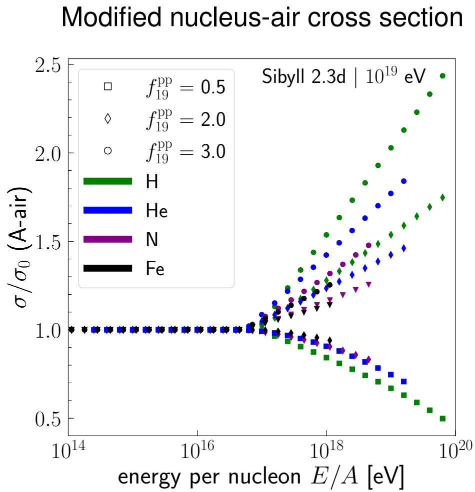
where $f_{\lg E_1}$ is the rescaling factor at $E = E_1$ and $H(x)$ denotes the Heaviside step function.

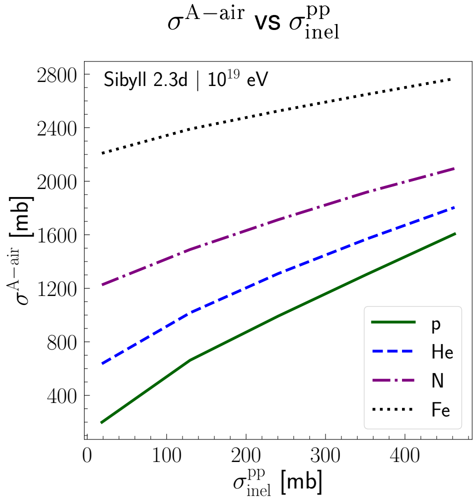
* Energy threshold $E_0 \approx 10^{16.95}$ eV is set by the lab energy equivalent to the LHC center of mass energy.
* Modified implementation of Sibyll hadronic interaction model.

[5] R.J. Glauber, G. Matthiae, *Nucl.Phys.B* **21** *(1970) 135.*

[6] R. Ulrich *et al*, *Phys. Rev. D* **83** *(2011)* 054026 .

# Nucleus-air interaction cross sections

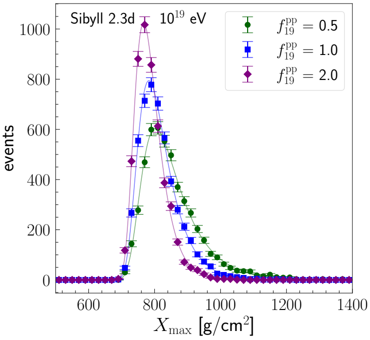


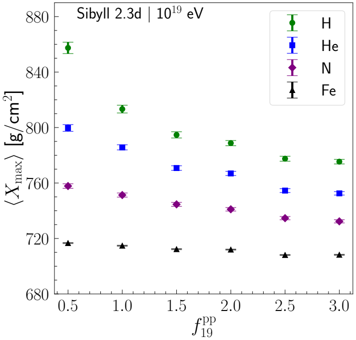

* Here $E = 10^{19}$ eV
* Hadronic interaction model: Sibyll 2.3d

# $X_{\max}$ distributions for the modified cross sections

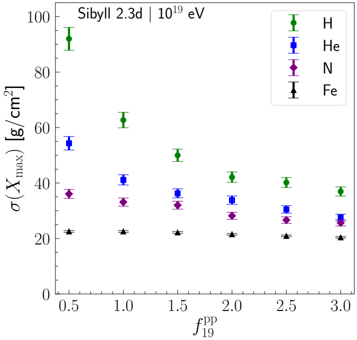
## $X_{\max}$ distribution (H)




## $\langle X_{\max} \rangle$




## $\sigma(X_{\max})$




- larger $f_{\lg E}^{pp}$ -> smaller $\langle X_{\max} \rangle$ & $\sigma(X_{\max})$;
- the heavier the element the less it is affected.

* Here $E = 10^{19}$ eV
* Hadronic interaction model: Sibyll 2.3d

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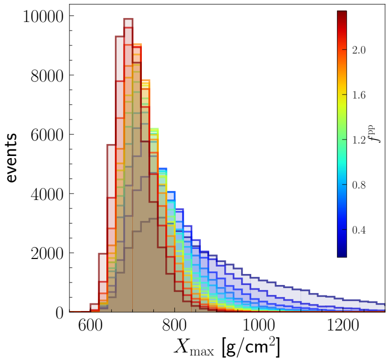
# Fitting algorithm

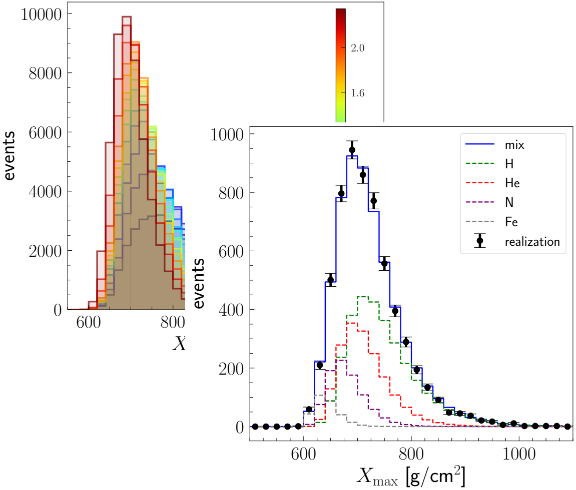
1. generate the $X_{\max}$ distributions for the discrete set of scaling factor values




* $X_{\max}$ distributions are simulated with the generalized Gumbel distribution parameterization as a function of the scaling factor.

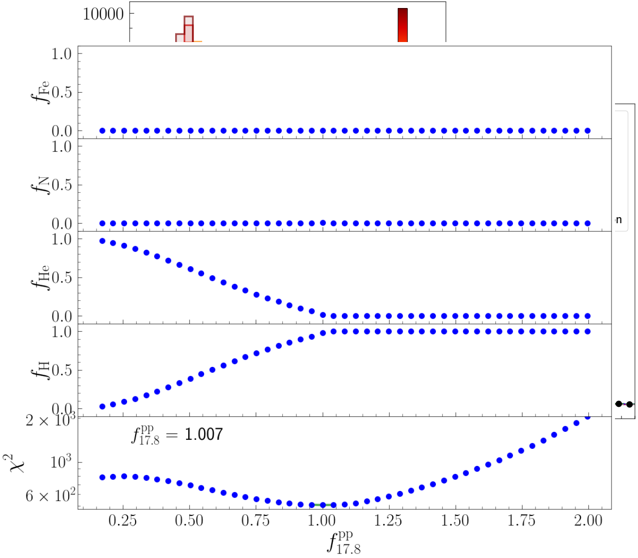
# Fitting algorithm

1. generate the $X_{\max}$ distributions for the discrete set of scaling factor values;
2. perform the 4-component binned maximum likelihood mass composition fit for each $f^{pp}_{\lg E}$



# Fitting algorithm

1. generate the $X_{\max}$ distributions for the discrete set of scaling factor values;
2. perform the 4-component binned maximum likelihood mass composition fit for each $f^{\mathrm{pp}}_{\lg E}$;
3. find the minimum $\chi^2$ and the corresponding $f^{\mathrm{pp}}_{\lg E}$ and composition fractions

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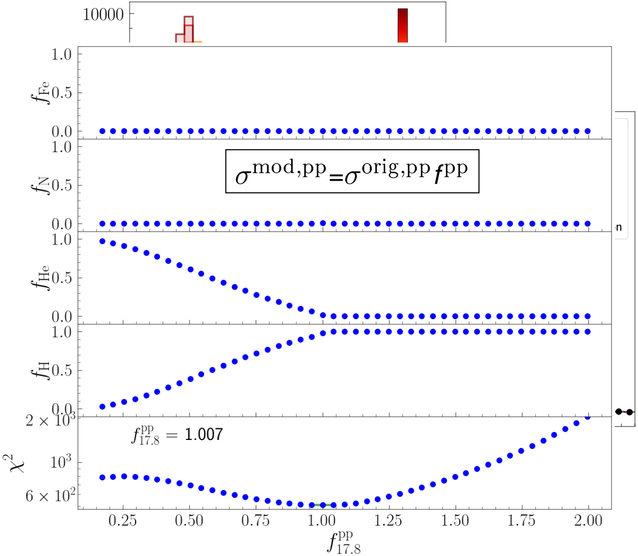
4. convert $f^{\mathrm{pp}}_{\lg E}$ into the $\sigma^{\mathrm{mod,pp}}$.

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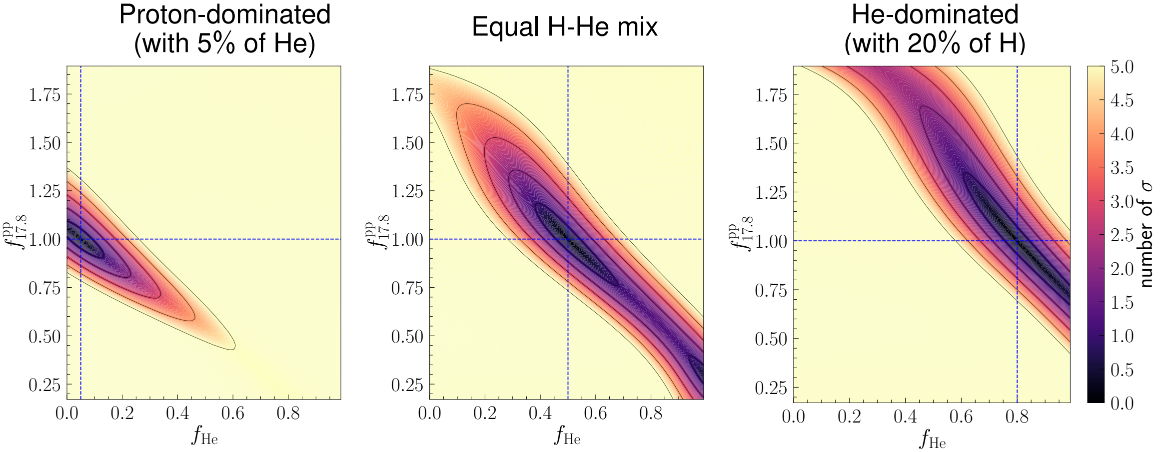
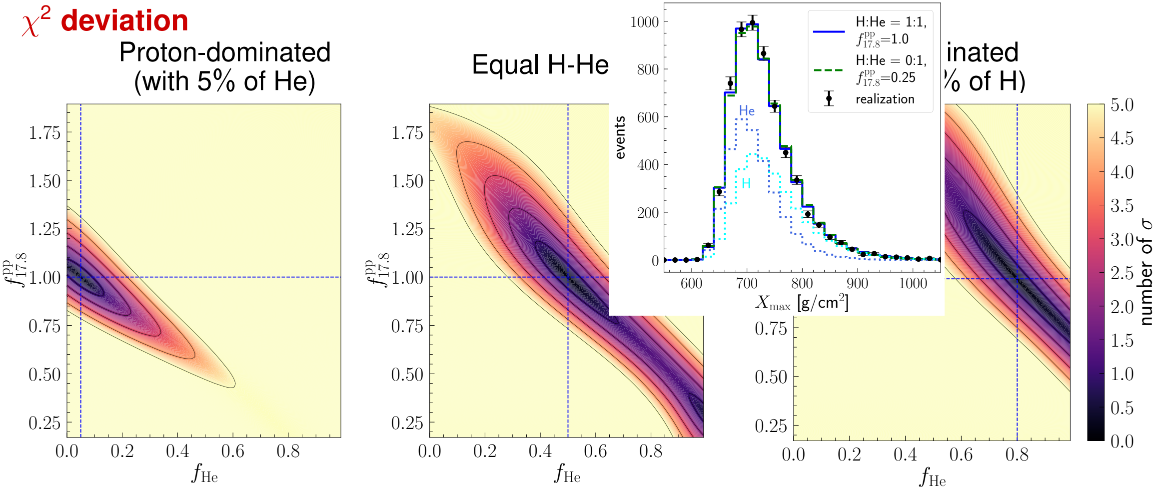
# $\chi^2$ deviation




- 6000 events per species in data
- lg(E/eV) = $10^{17.8}$-$10^{17.9}$ eV
- Model: Sibyll 2.3d

**blue dashed line* shows the simulated He fraction and scaling factor, and colorbar shows the $\chi^2$ deviation in units of sigma.

# $\chi^2$ deviation

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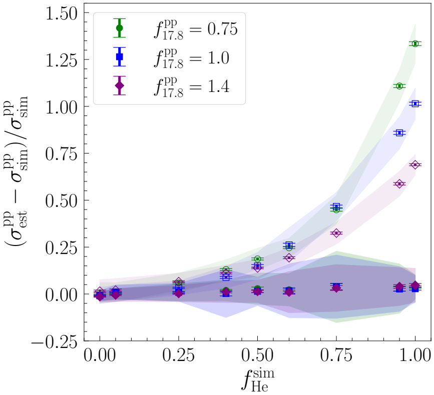
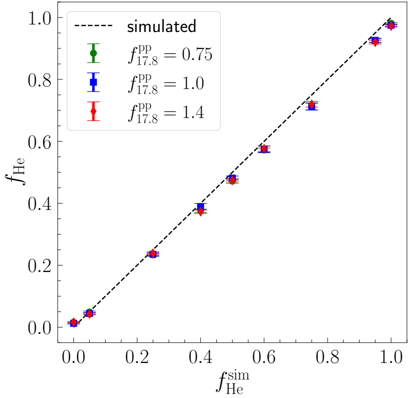
# Estimated mass composition and interaction cross sections

Relative cross section bias as a function of the simulated He fraction




Fitted He fraction as a function of the simulated He fraction



# Summary and Outlook

## Summary

- A method for the combined mass composition and cross section analysis is presented:
  - proton-proton cross section as a fit parameter -> self-consistent prediction of the corresponding nucleus-nucleus cross sections and air shower properties;
- The combined fit was applied to the simulated data with varied H-He ratio and proton-proton interaction cross sections:
  - is compatible with the standard approach for the proton-dominated composition;
  - can be used to obtain near-unbiased results at higher helium fractions.

## Next

- Performance in the case of a large fraction of intermediate-mass nuclei;
- Stability with respect to the $X_{\mathrm{max}}$ scale uncertainties, other properties of hadronic interactions and parameters of the Glauber calculation.

Thank you :)