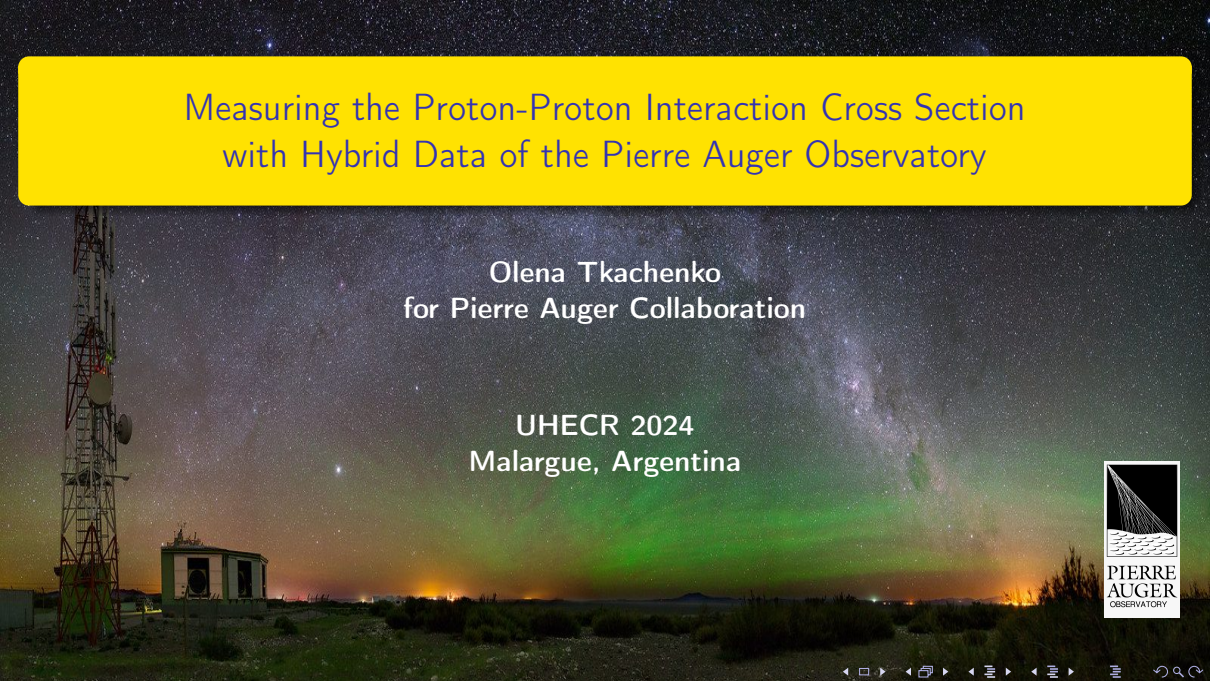
Measuring the Proton-Proton Interaction Cross Section with Hybrid Data of the Pierre Auger Observatory

Olena Tkachenko
for Pierre Auger Collaboration

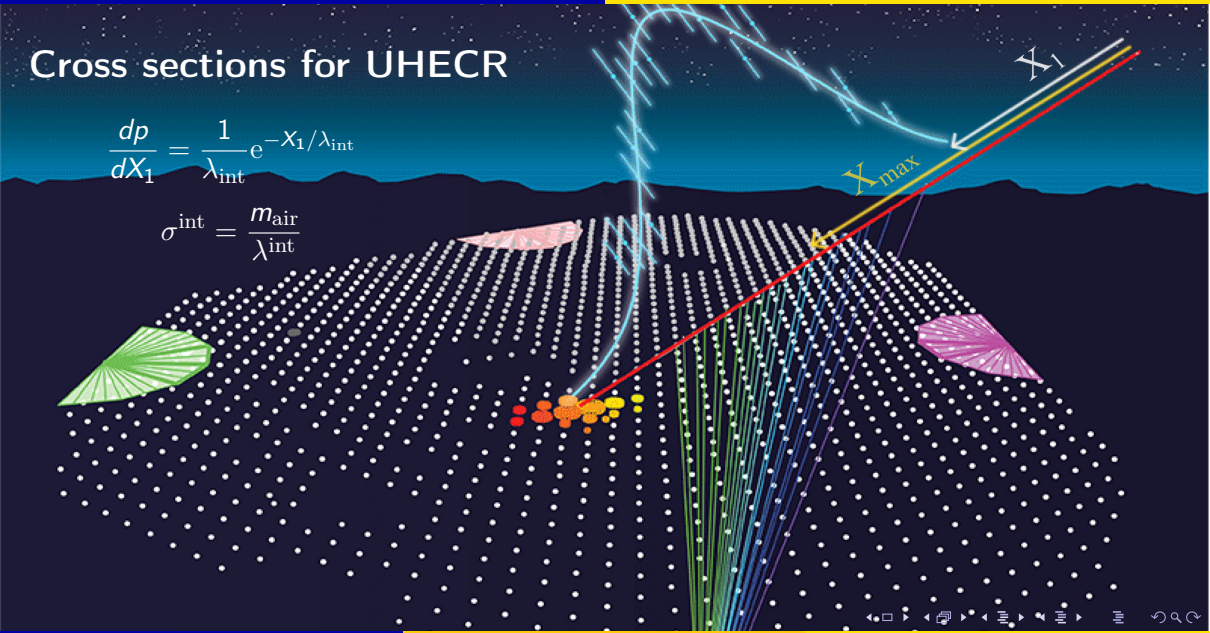
UHECR 2024
Malargue, Argentina



Cross sections for UHECR

$$\frac{dp}{dX_1} = \frac{1}{\lambda_{\rm int}} e^{-X_1/\lambda_{\rm int}}$$

$$\sigma^{\rm int} = \frac{m_{\rm air}}{\lambda^{\rm int}}$$



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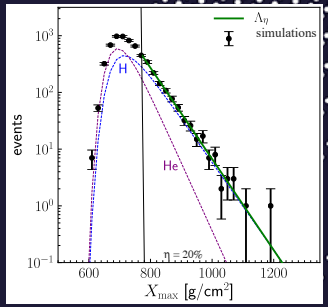
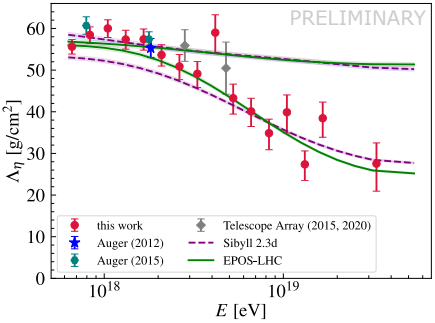


$X_{\rm max}$ distribution tail:

- $f(X_{\rm max}) \sim e^{-X_{\rm max}/\Lambda_\eta}$
- proton-dominated

Standard approach: proton-proton cross section from the tail fit



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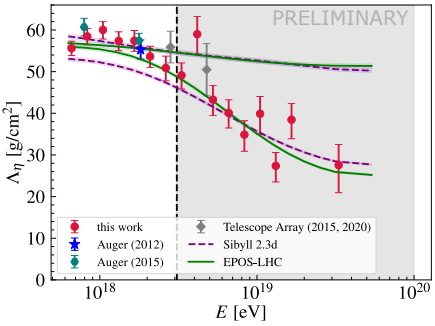

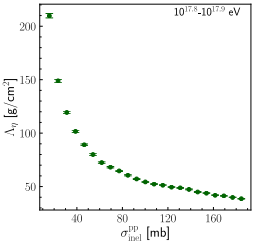

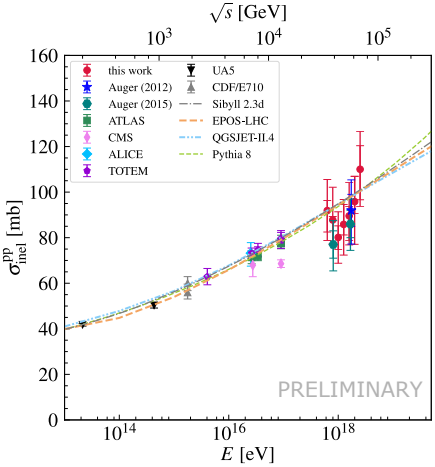

*In original analysis (Phys. Rev. Let. **109**, 2012) σ_{p-air} was evaluated first and then converted into σ_{pp}

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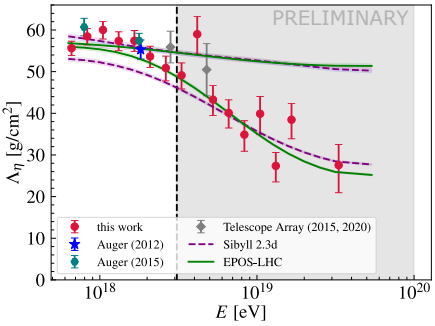
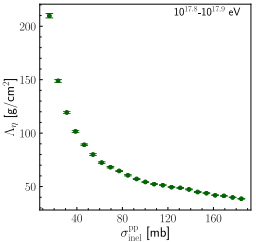
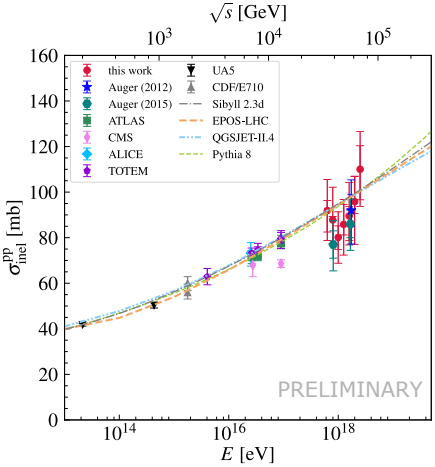




He contribution $\Rightarrow$
systematic uncertainty



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Simultaneous Mass Composition and Cross Section Measurement

Why?

Assumptions in the Standard Analyses:

- *Mass Composition:*
  Assumes validity of a specific interaction model.
- *Interaction Cross Section:*
  Relies on a proton-dominated tail of the $X_{\max}$ distribution.

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→ ***self-consistent*** estimation of the interaction cross sections and cosmic-ray primary composition

Rescaling of the interaction cross section

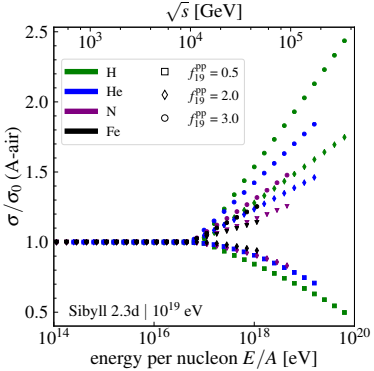
$f_{\mathrm{lg}\,E_1}$ → $\sigma^{\mathrm{pp}}_{\mathrm{mod}}$ → Glauber → $\sigma^{\mathrm{A-Air}}_{\mathrm{mod}}$ → air shower simulations → X_{max} distributions

Rescale the proton-proton cross section:

$$\sigma^{\mathrm{pp}}_{\mathrm{mod}} = \sigma^{\mathrm{pp}}_{\mathrm{orig}} f^{\mathrm{pp}}(E_0, E),$$

with a linear scaling factor $f^{\mathrm{pp}}(E_0, E)$:

$$f^{\mathrm{pp}}(E_0, E) = 1 + H(E - E_0)(f^{\mathrm{pp}}_{\mathrm{lg}\,E_1} - 1)\frac{\lg(E/E_0)}{\lg(E_1/E_0)}.$$



Same approach for cross section modification as in original analysis[1,2] but instead of $\sigma_{\mathrm{p-air}}$ we directly modify σ_{pp}

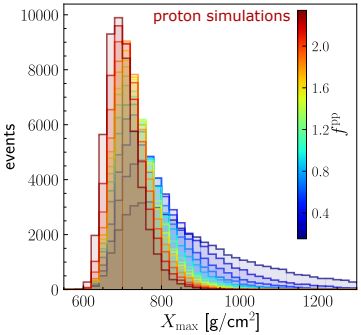
* H is a Heaviside function;
* f_{lgE1} is the rescaling factor at $E = E_1$ (here $E_1 = 10^{19}$ eV);

* Threshold E_0 sets an energy above which cross sections are modified;
* Modified implementation of Sibyll 2.3d hadronic interaction model.

[1] *Phys. Rev. Let. 109 (2012) 062002.* [2] R. Ulrich *et al*, *Phys. Rev. D 83 (2011)* 054026 .

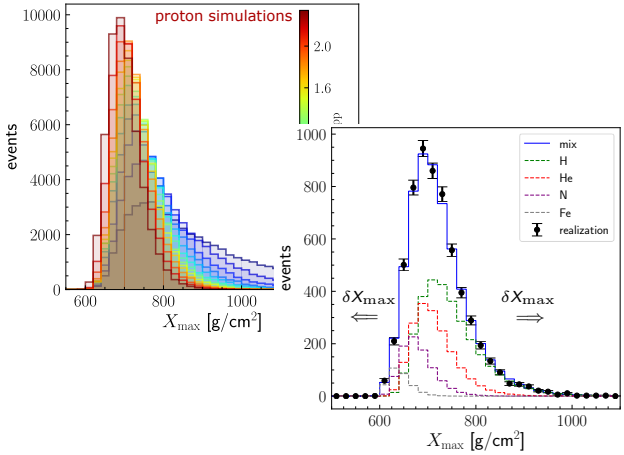
Algorithm: fitting procedure

1. get the $X_{\max}$ distributions for the discrete set of $f_{\lg E}^{\mathrm{pp}}$ values;



Algorithm: fitting procedure

1. get the $X_{\max}$ distributions for the discrete set of $f_{\lg E}^{\mathrm{pp}}$ values;
2. perform the 4-component binned maximum likelihood mass composition with for varied:
   - rescaling factor $f_{\lg E}^{\mathrm{pp}}$ [0.2, 3.0]
   - shift in the $X_{\max}$ [-50, 40] g/cm^2



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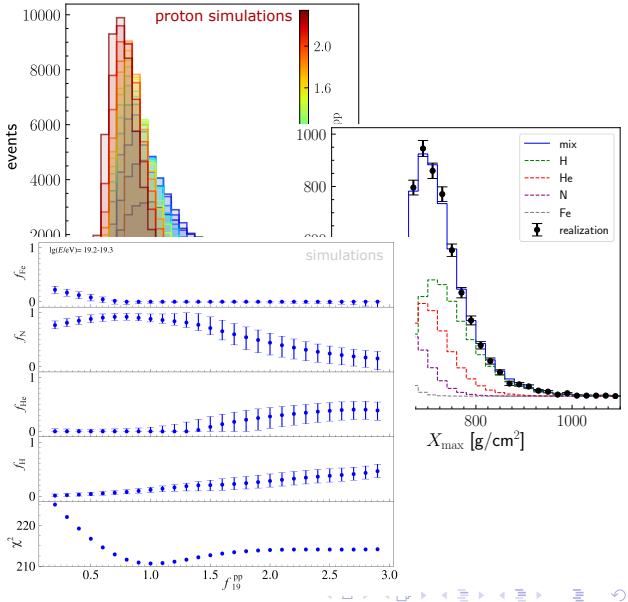

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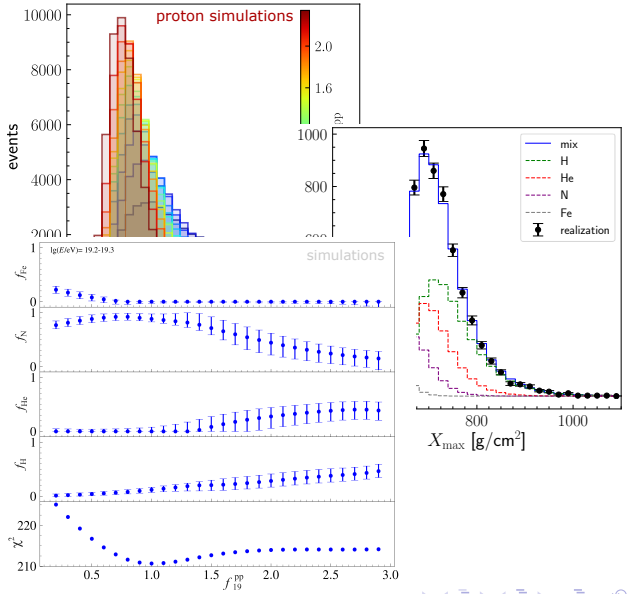

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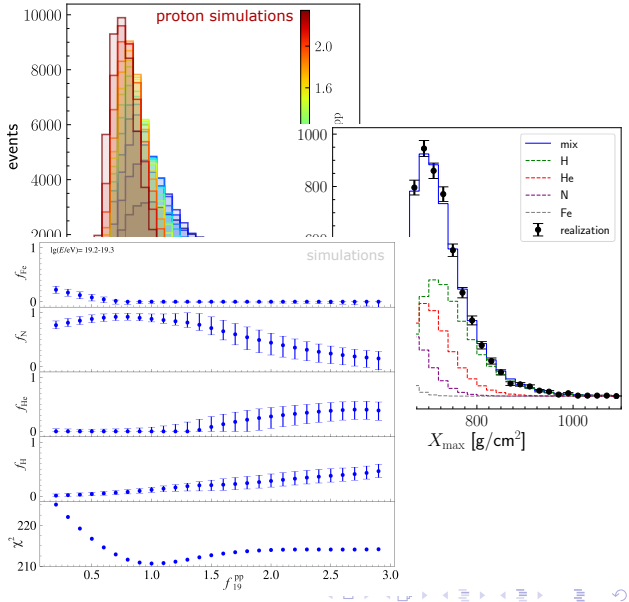
4. find the best-fit χ^2 and get the corresponding cross section σ_{pp}, shift $\delta X_{\max}$, and composition.



Systematic uncertainties

Origin	Impact on σ_{pp}, %	Impact on δX_{max}, g/cm^2
Energy scale	-3.1	$^{+6}_{-4}$
Detector effects	$^{+7}_{-12}$	$\pm$ 1
E-dependent X_{max} syst.	$\pm$ 2	$\pm$ 7
Composition	$^{+3}_{-7}$	+5
Elasticity	$^{+15}_{-17}$	$^{+1}_{-3}$
Multiplicity	+9	$^{+1}_{-8}$

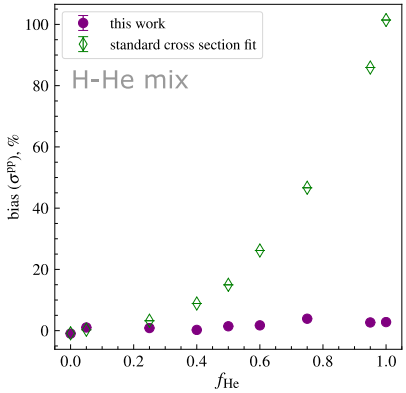
Under evaluation: mass-dependent shift in X_{max}

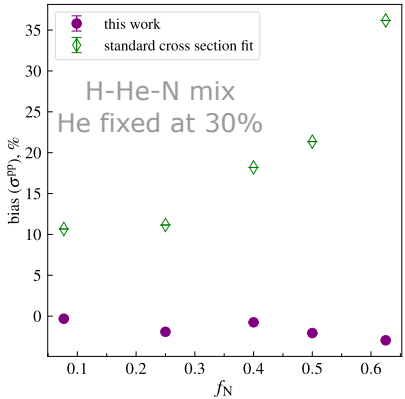
Decrease in uncertainty compared to standard analyses:

- up to 25% He-fraction bias;
- X_{max} scale systematics.

Composition-related bias

Simulations for $10^{17.8}$-$10^{17.9}$ eV energy bin





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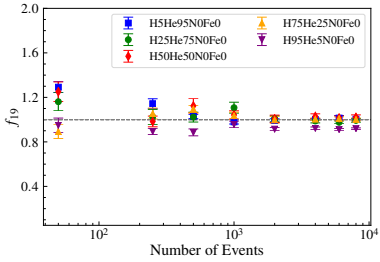
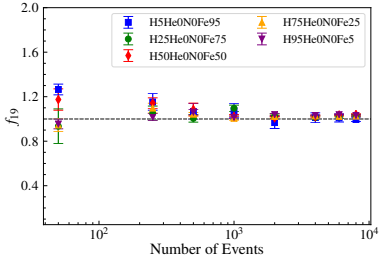
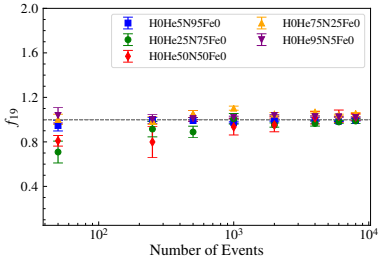
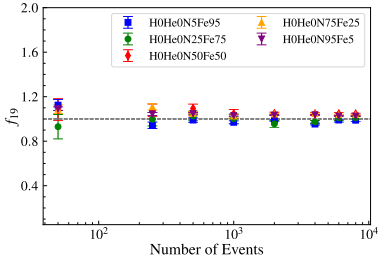




- Lowest E: $N \to 10^4$
- Highest E: $N \to 50$
- Considering the χ^2 sum over all energies compensates for the possible bias contribution from the highest energies

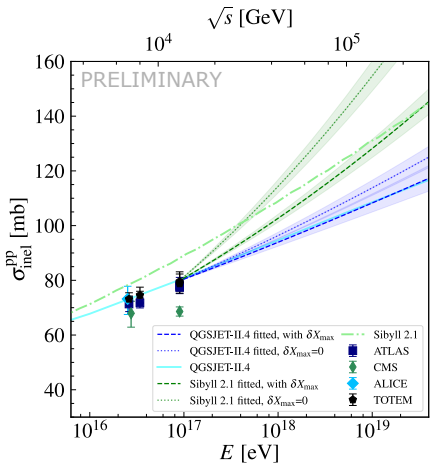


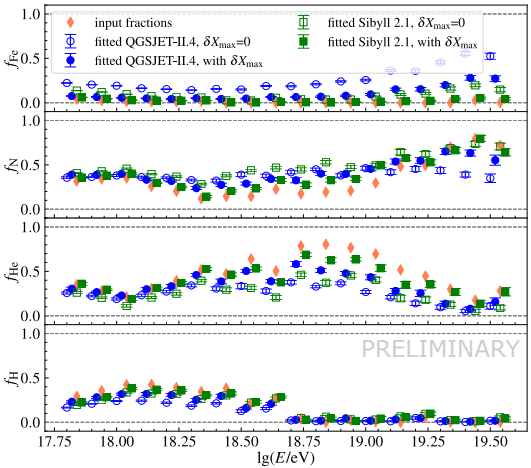


*fits are shown for one energy bin

Why fitting a shift in $X_{\max}$ matter

Fit with the modified Sibyll 2.3d to QGSJETII.4 and Sibyll 2.1 simulations





*The fittted $X_{\max}$ scales are close to the differences between the models

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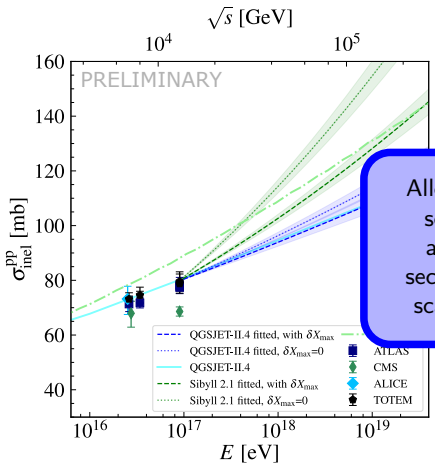

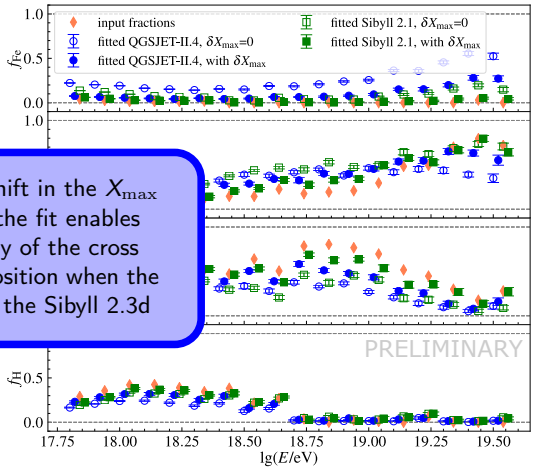

Allowing for the shift in the $X_{\max}$ scale to vary in the fit enables accurate recovery of the cross section and composition when the scale differs from the Sibyll 2.3d

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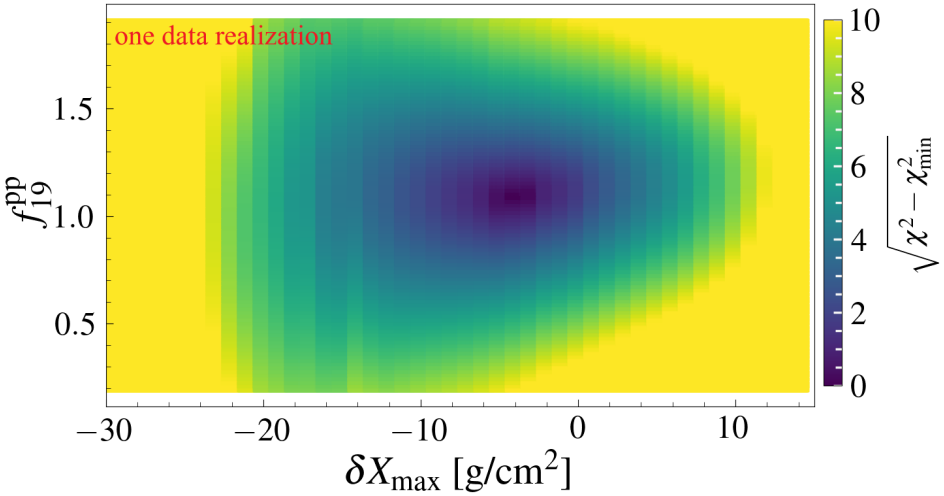
Analysis Results

assuming the Auger-like data in simulations



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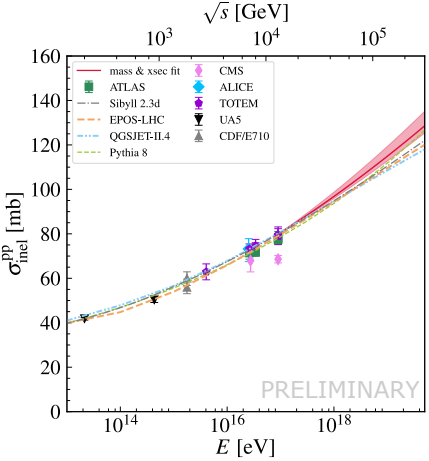
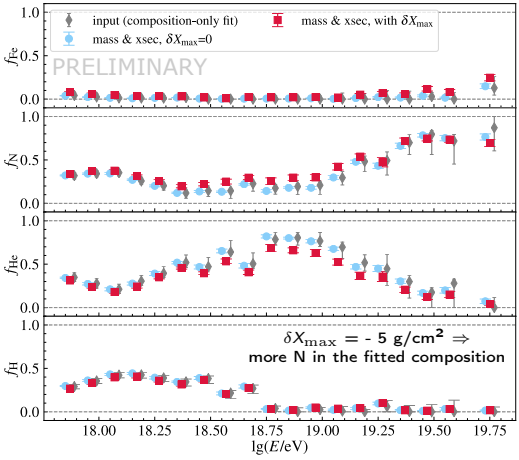
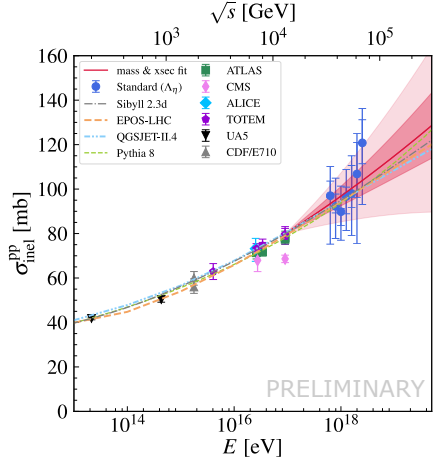


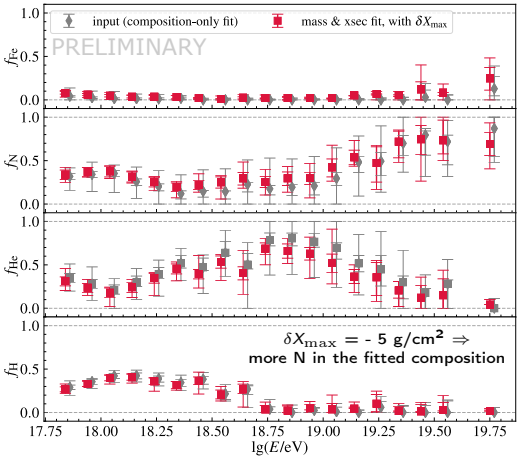


*statistical uncertainty on the mass & xsec fit is from averaging the 100 sim. data realizations

Analysis Results

assuming the Auger-like data in simulations, including possible systematics





*statistical/systematical uncertainties correspond to one sim. data realization

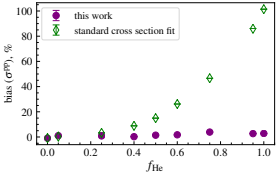
Summary

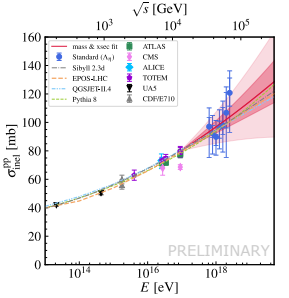
Simultaneous estimation of the cosmic-ray mass composition and proton-proton interaction cross section:

- Remove degeneracy from previous analyses:
  - independent on the underlying composition;
  - independent on the underlying cross section;
- Improvement in the statistical/systematic uncertainty compared to standard analyses:
  - supressed He fraction-related systematics
  - supressed $X_{\max}$ scale systematics
- Higher confidence in the estimation;

Future plans

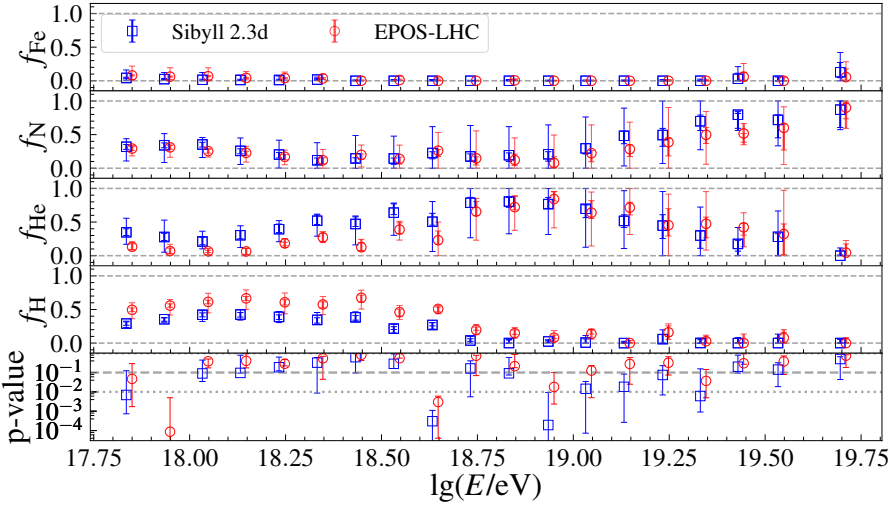
- Careful evaluation of the potenital biases and systematics
- Apply to the full Phase I Auger data





Back-up

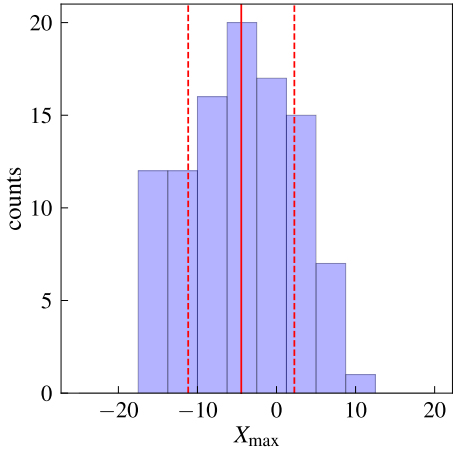
Mass composition from data

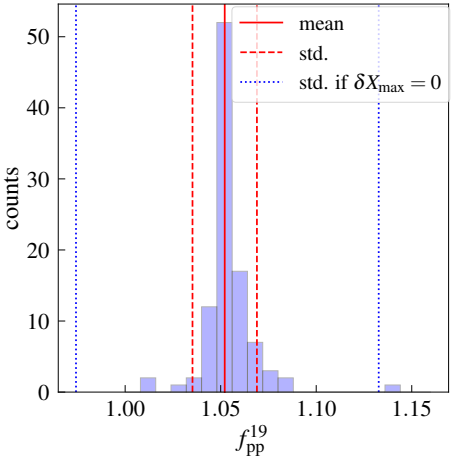


*default cross section and $X_{\max}$ scale

Energy-dependent $X_{\max}$ systematics

Distribution of fit results assuming the energy-dependent shifts in $X_{\max}$ scale





**100 simulated data realizations*

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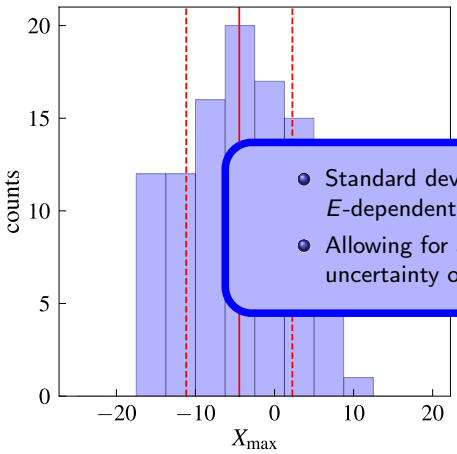
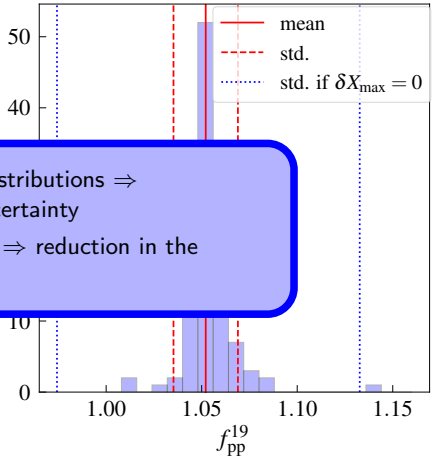
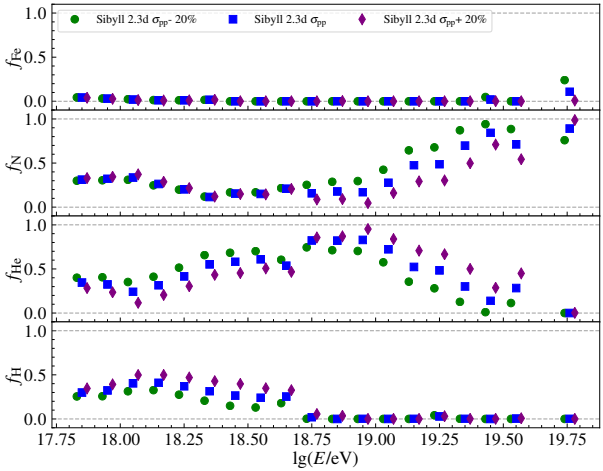


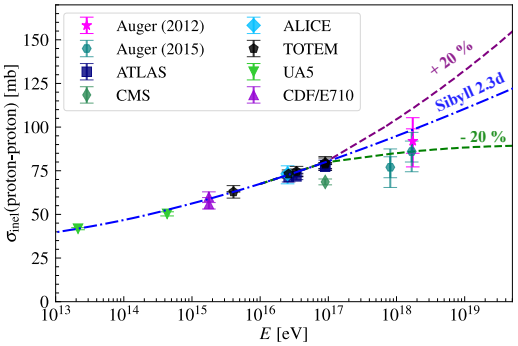


- Standard deviation of the distributions ⇒ *E*-dependent systematic uncertainty
- Allowing for a shift in $X_{\max}$ ⇒ reduction in the uncertainty on cross section

**100 simulated data realizations*

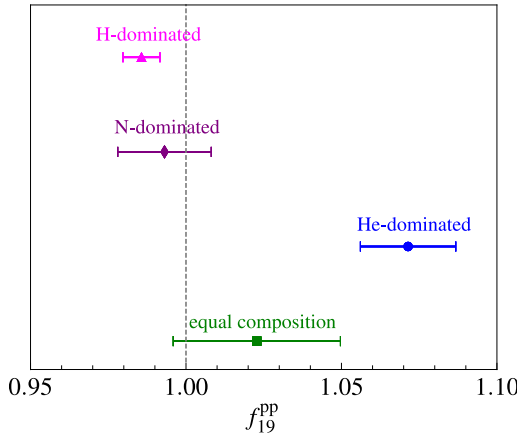
Mass composition measurements: effect of cross section rescaling

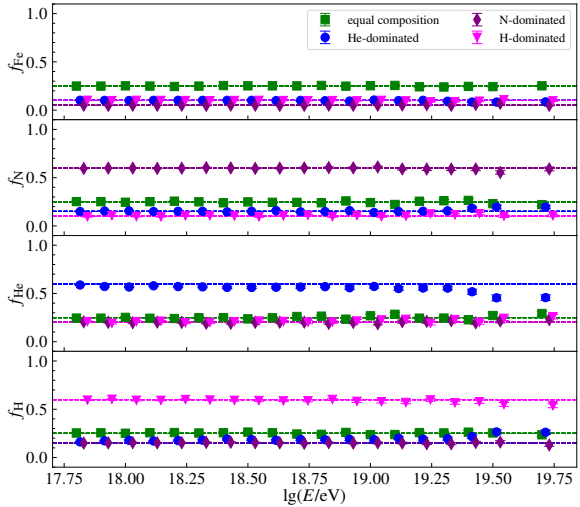




Rescaling by $\pm$ 20% at 10^{19} eV

Fit results for the different composition scenarios





*Contstant composition over the considered energy range
*Number of events in each energy bin the same as in Auger data