# Avenues to New Physics Searches in Cosmic Ray Air Showers

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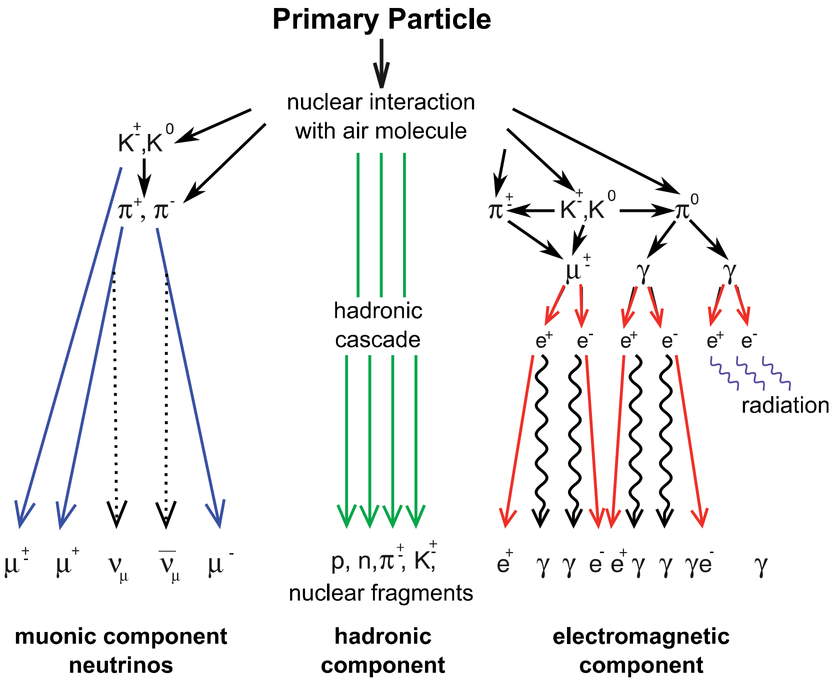
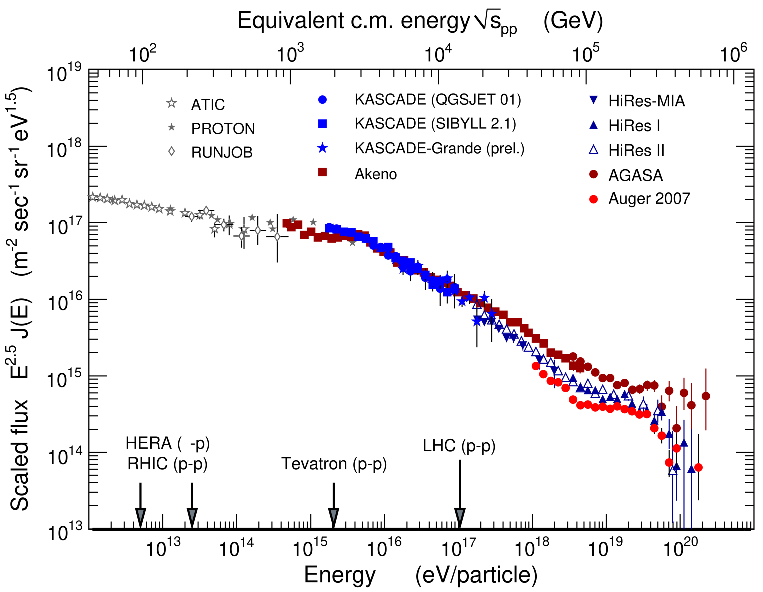
# Contents

- How much luminosity do cosmic rays and extensive air showers provide (compared to LHC)?
- What's the imprint of *Higgsplosion* events on EAS?

# Introduction

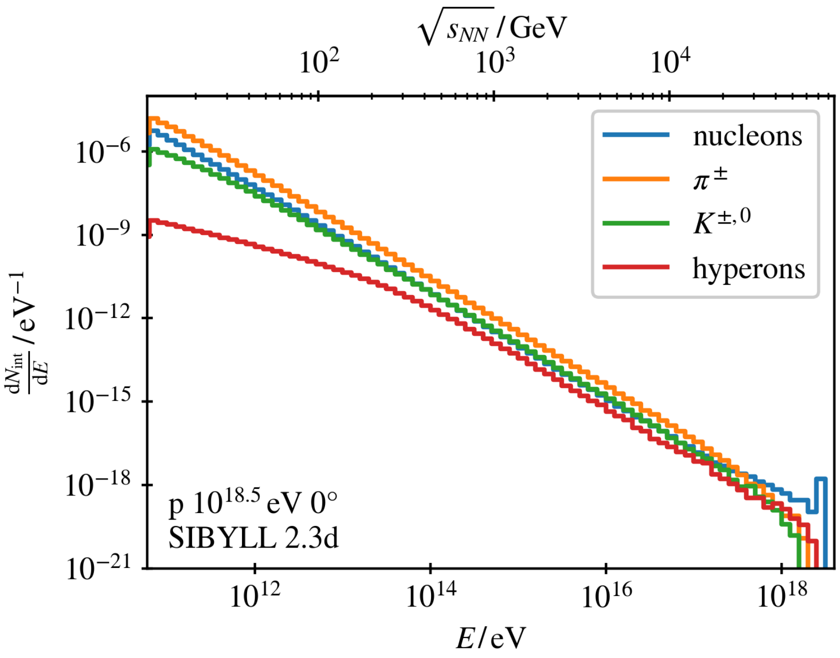
- c.m. energies up to 400 TeV in CR-air collisions
- small fluxes
- composition uncertain
- primary interaction not accessible, only indirect measurement of the *extensive air shower*



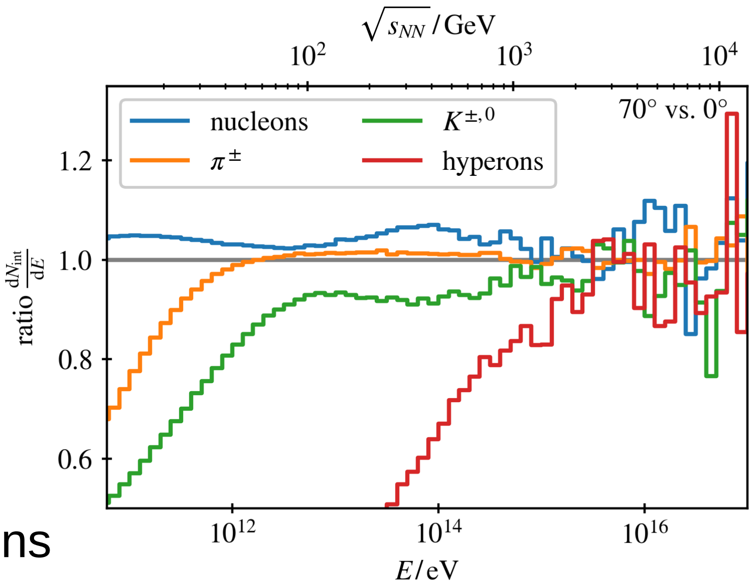

*d'Enterria, Engel, McCauley, Pierog, 0806.0944*

# Counting interactions in EAS




for **single showers of fixed energy**:

- very close to primary energy dominated by nucleons (→ leading baryon effect)
- pions take over at ~ $E_0$ / 10
- power law with index α ≈ -2



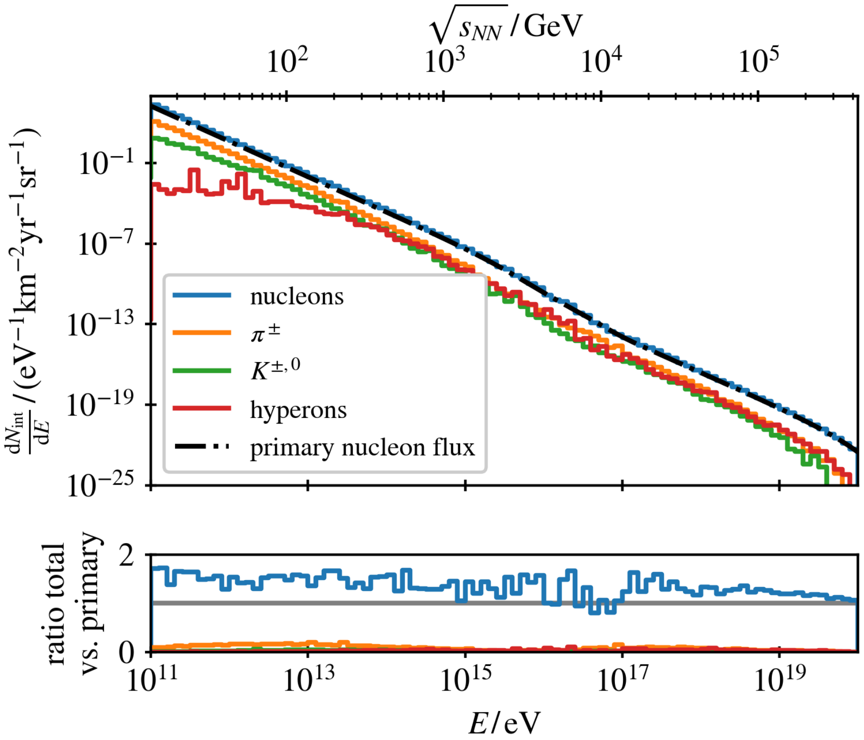

**zenith angle dependence:** compare 70° vs. 0°

- < 20 % change above 1 TeV (lab) for long-lived mesons
- due to shift of critical energy

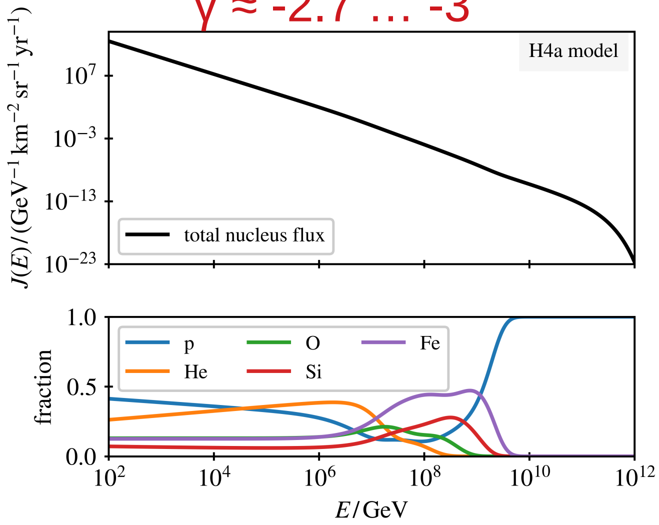
# *Inclusive* spectra

fold with CR spectrum:

$$\frac{\mathrm{d}N_{\mathrm{int}}}{\mathrm{d}E} = \int \mathrm{d}E_0 \frac{\mathrm{d}N_{\mathrm{int}}}{\mathrm{d}E}(E|E_0) J(E_0)$$

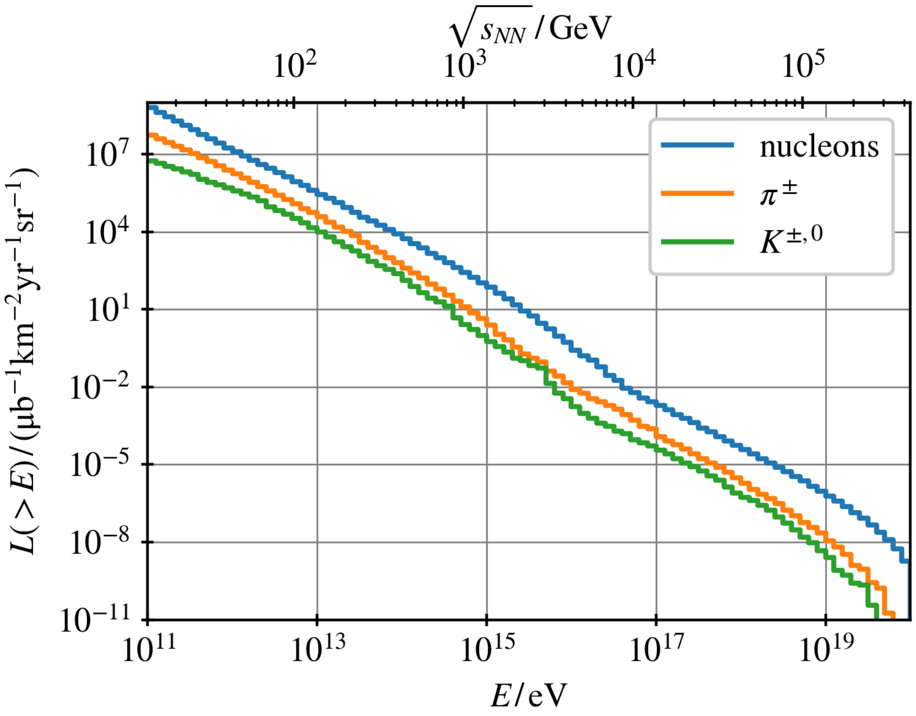



spectral index
γ ≈ -2.7 … -3




- CR spectrum steeper than $dN_{int}/dE$
- dominated by nucleons
- secondary nucleon flux ≲ 80 % greater than primary

# Luminosity




$$L = \frac{1}{\sigma}\frac{\mathrm{d}N_{\mathrm{int}}}{\mathrm{d}t}$$

instantaneous lumi of monoenergetic beam

here:

$$L(>E_0) = \int_{E_0}^{\infty} \mathrm{d}E \frac{1}{\sigma(E)} \frac{\mathrm{d}N_{\mathrm{int}}}{\mathrm{d}E\mathrm{d}t\mathrm{d}\Omega\mathrm{d}A}$$

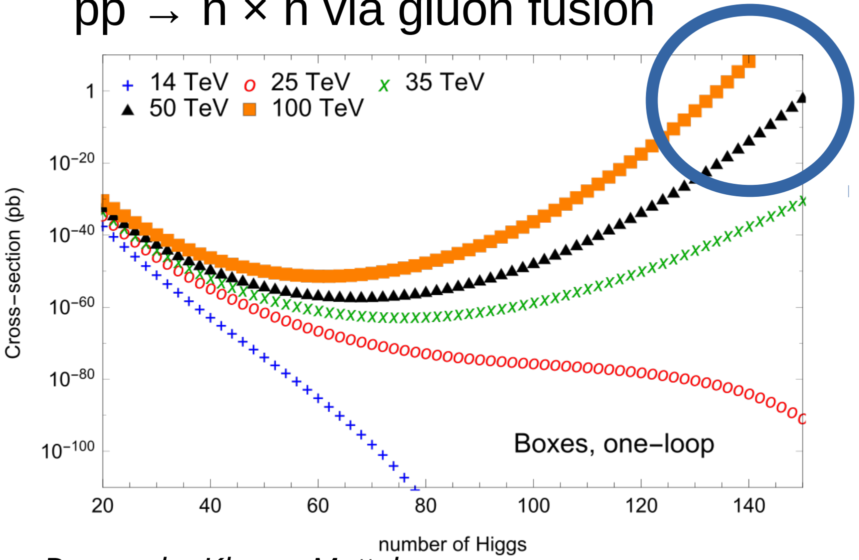
integrate over whole Earth surface (5 x $10^8$ km$^2$)
e.g. **$L_{nucl}$(>10 TeV c.m.) ~ 30 pb$^{-1}$ yr$^{-1}$**

for comparison:
LHC run 2: 50 fb$^{-1}$ yr$^{-1}$
planned p-O run: 200 μb$^{-1}$ in 1 week

# Part II: "Higgsplosion" in EAS

$h^*(p^2 \gg m_\mathrm{h}^2) \to n \times h$ transition rate growing with ***n!***

pp → n × h via gluon fusion




*Degrande, Khoze, Mattelaer*
*PRD 94, 085031 (2016)*

energy fraction converted to Higgs:

$$\frac{n \times m_\mathrm{h}}{\sqrt{s}} \gtrsim 0.20$$

- ≳ 100 mb cross-sections reachable?!
- observable impact on EAS?

n.b.: theoretical foundations of the mechanism still under discussion:
*Monin, 1808.05810*
*Khoze, Spannowsky, 1809.11141*
*Dine, Patel, Ulbricht, 2002.12449*

# Implementation in CORSIKA 8

$$\sqrt{\hat{s}} = f\sqrt{s_{NN}} = f\sqrt{\frac{s}{14.5}}$$

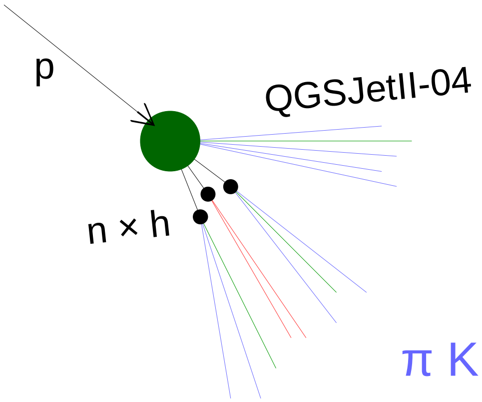
energy fraction
for Higgs production

$$n_{\mathrm{h}} = \frac{\sqrt{\hat{s}}}{m_{\mathrm{h}}(1+\varepsilon)}$$

fractional kinetic energy, ≲ ~ few

$$(1-f)\sqrt{s}$$

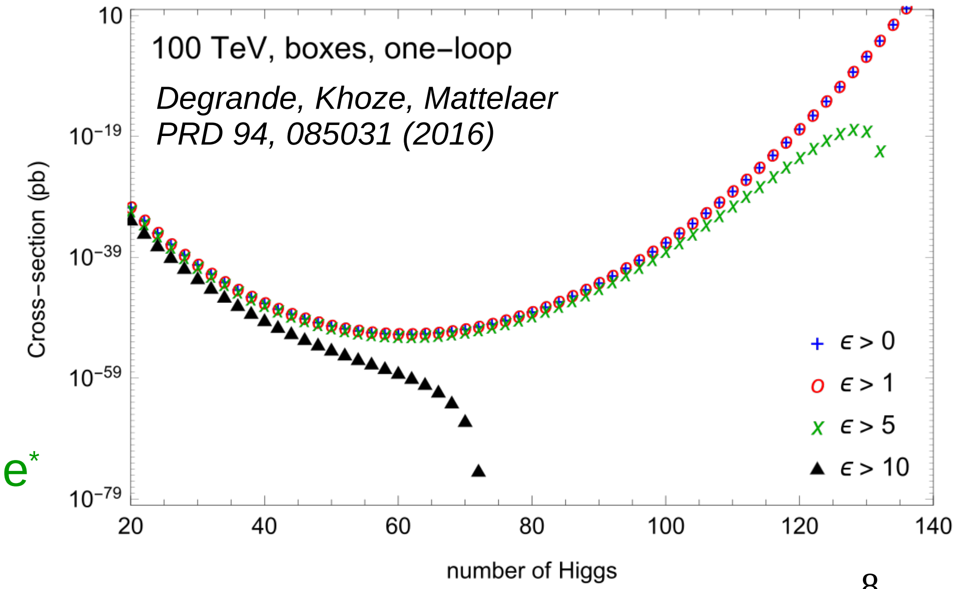
remaining energy for
underlying event




↱ e.m. cascade*

π K τ μ (+ν) e γ

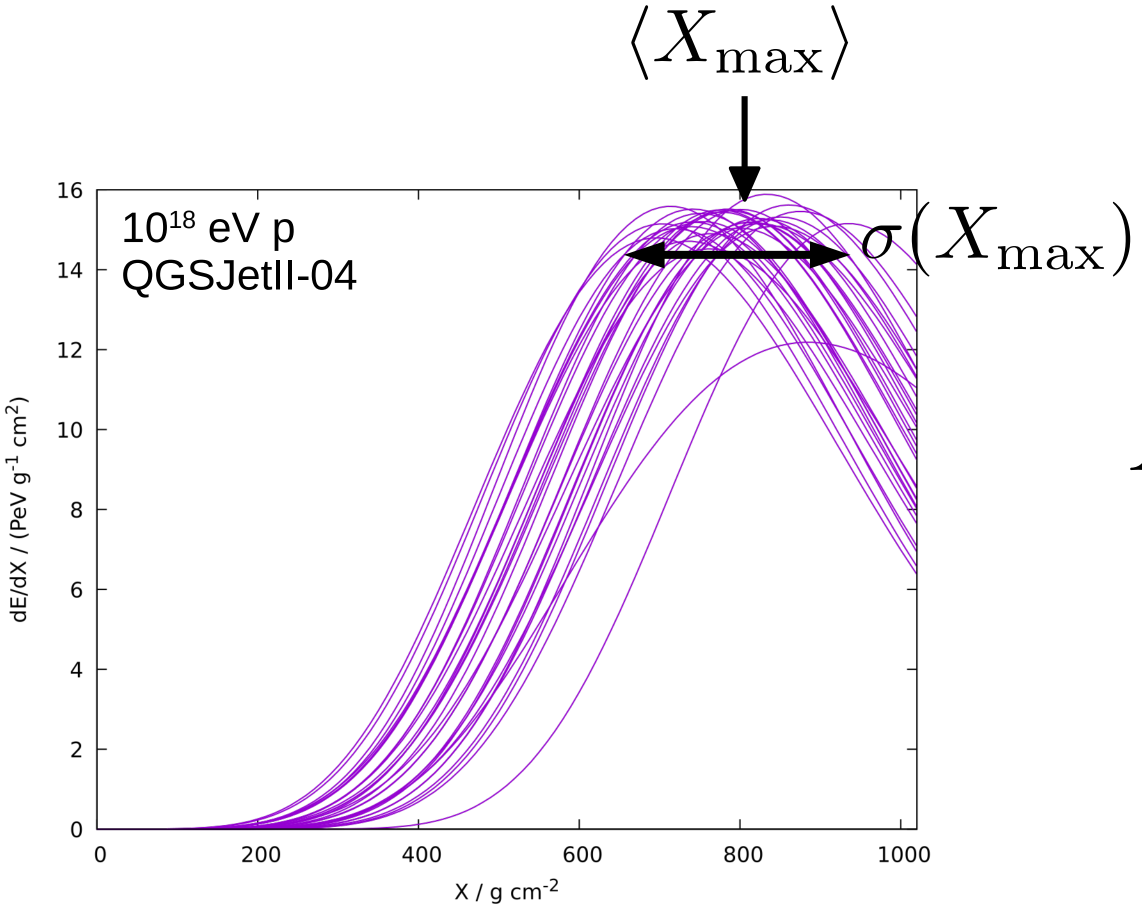
↳ had. cascade






* simulated with CONEX

# Shower maximum: $X_{max}$



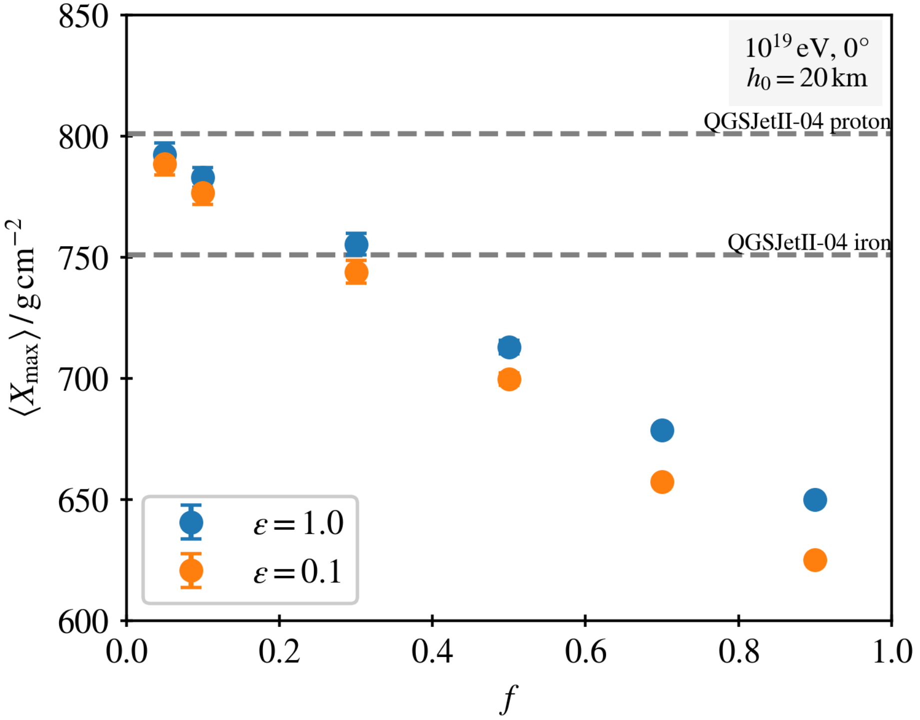

$$X_{\rm max} = X_0 + \tilde{X}_{\rm max}$$

point of first interaction

shower development

$$\langle X_0 \rangle = \lambda_{\rm int} = \frac{m_{\rm air}}{\sigma_{\rm inel.}}$$

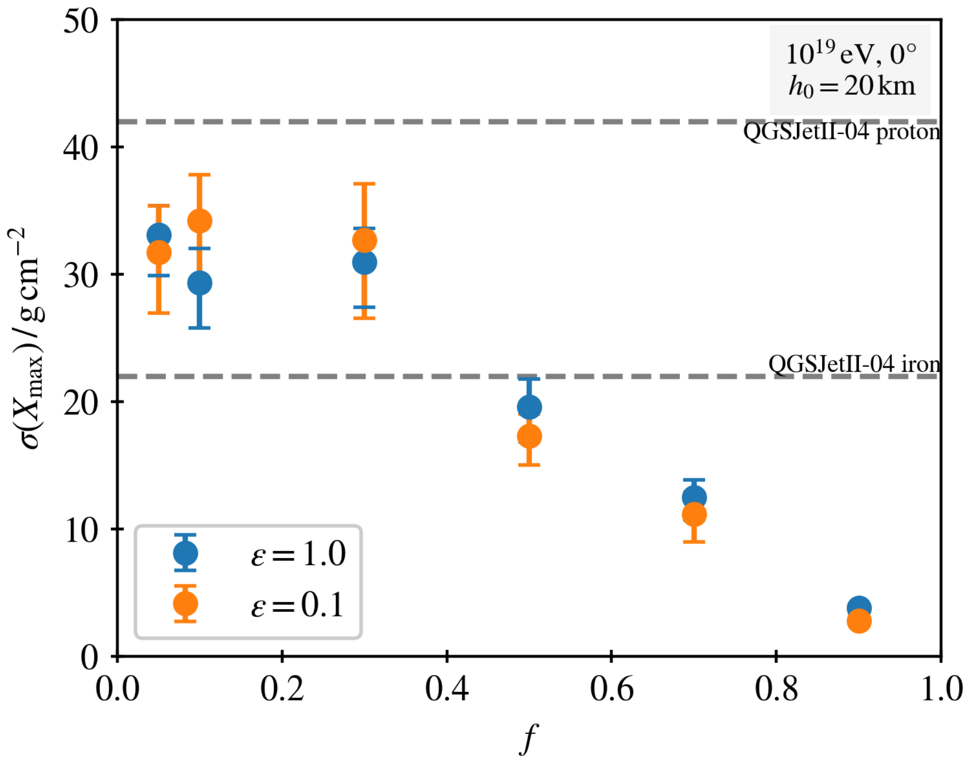
# Shower maximum: $X_{max}$




- cross-section not known
- study shower development with **fixed point of first interaction**

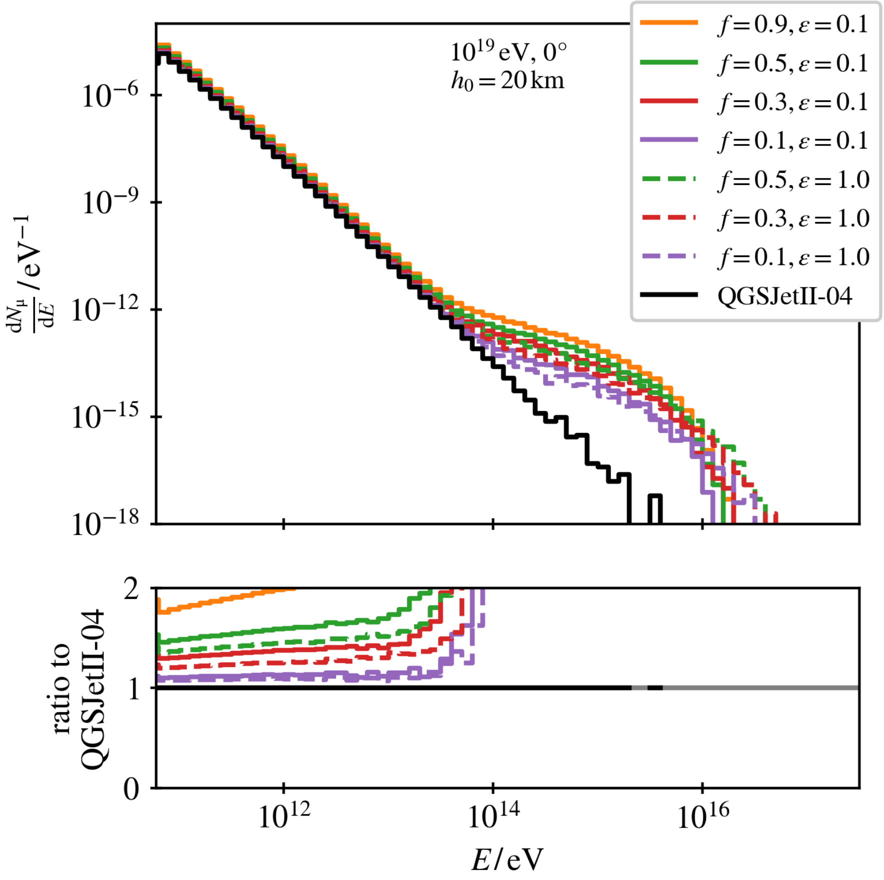
- strong dependence on f
- weak dependence on ε

# $X_{max}$ fluctuations




- fluctuations caused mainly by standard hadronic interactions
- possibly artifact of oversimplified model implementation
- N = 50 events probably insufficient statistics

# Muon energy spectrum



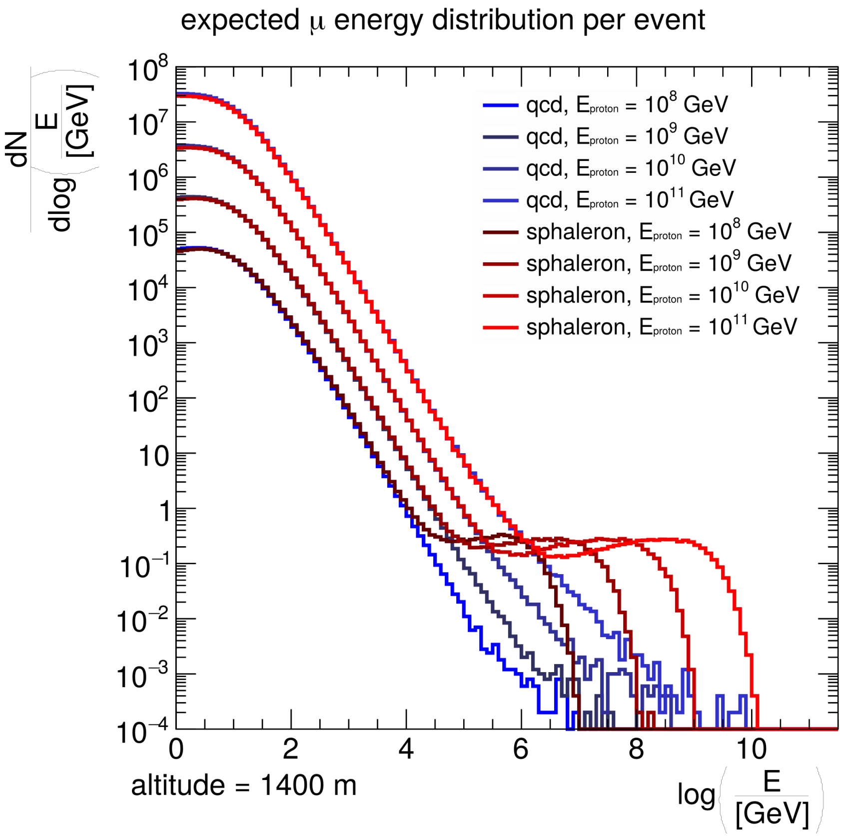

- bump of ~PeV prompt muons from Higgs decay
- overall increase of muon number

- muon production increasing with f
- decreasing with ε

| f | ratio $N_\mu$ | |
|---|---|---|
| | ε = 0.1 | ε = 1.0 |
| 0.1 | 1.11 | 1.08 |
| 0.3 | 1.31 | 1.21 |
| 0.5 | 1.49 | 1.38 |
| 0.9 | 1.82 | 1.82 |

$$\frac{N_\mu^{(\mathrm{Fe})}}{N_\mu^{(\mathrm{p})}} = A^{0.1} = 1.50$$

# Sphalerons in EAS




BLNV process generated with HERBVI

$$qq \to 7\bar{q} + 3\bar{l} + 24W/Z$$

similar signature!

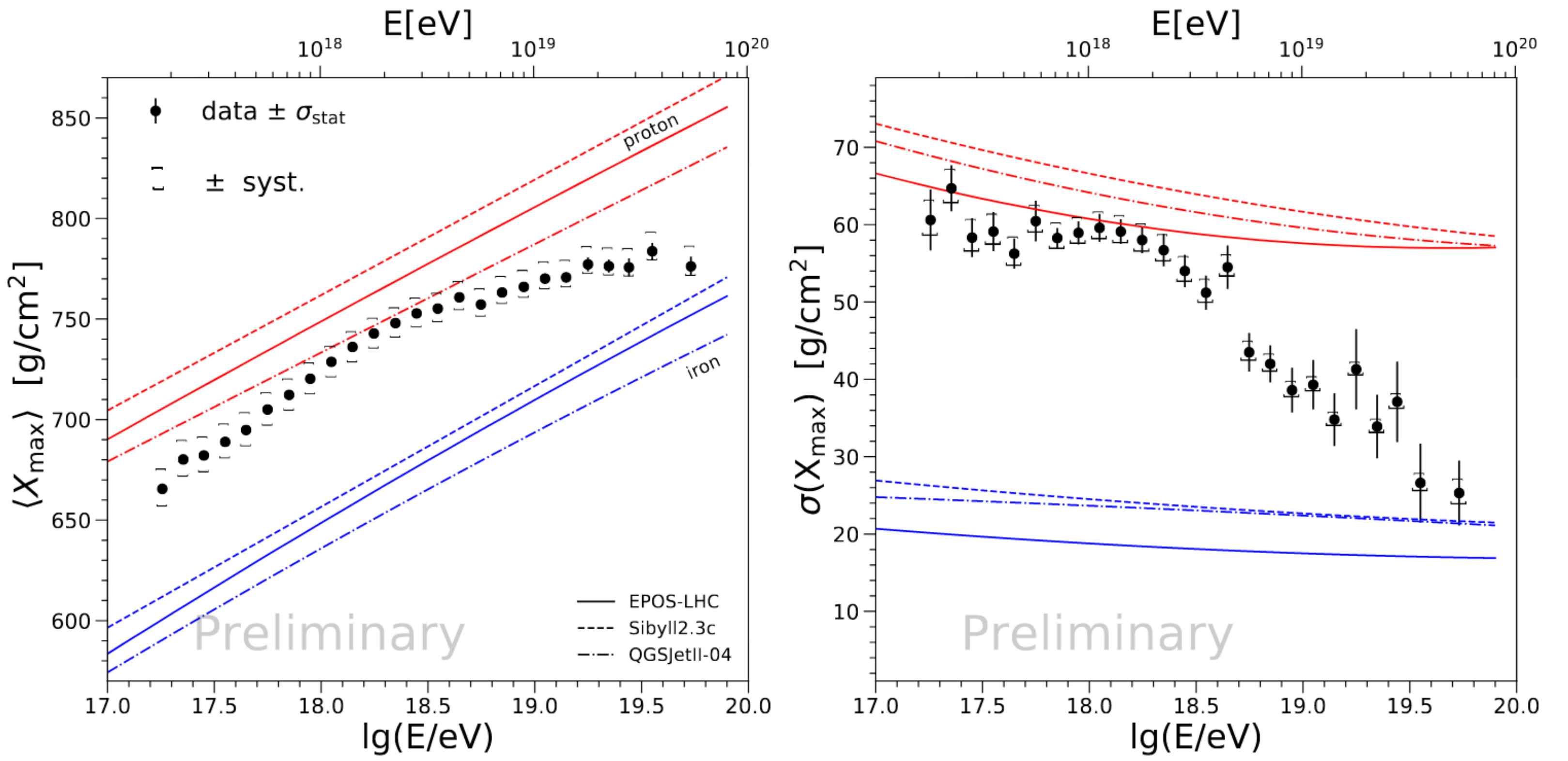
*Brooijmans, Schichtel, Spannowsky, PLB 761 (2016) 213*

# Conclusions

- CR provide O(10...100) TeV c.m. interactions
- with tiny luminosity
- large multiplicty Higgs production can have sizeable effect on EAS observables
  - decrease of $X_{max}$ and $\sigma(X_{max})$
  - increase of muon number O(10...50 %)
  - huge increase of high energy muons
- to do: comparisons with data, implications for composition, ν

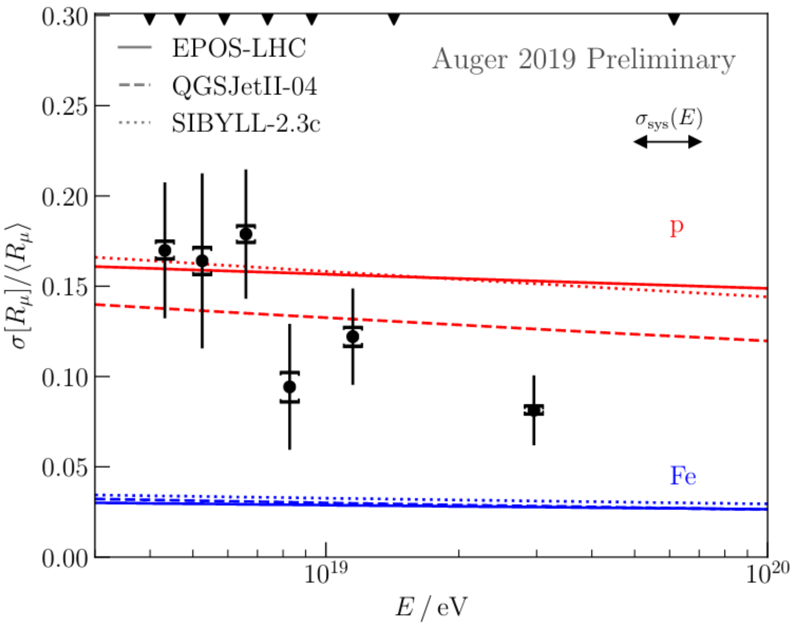
# Backup

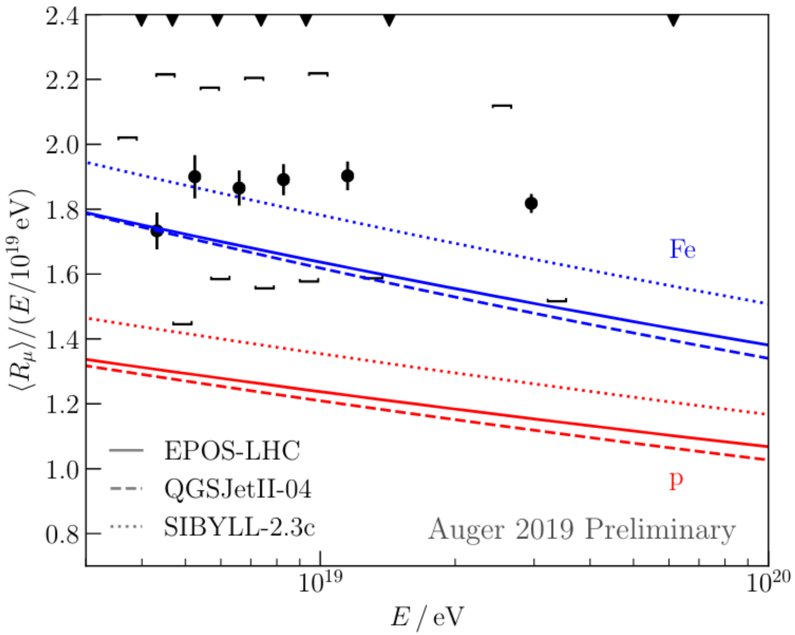
# Auger $X_{max}$




*Yushkov (Pierre Auger Collaboration), ICRC 2019*

# Auger muons

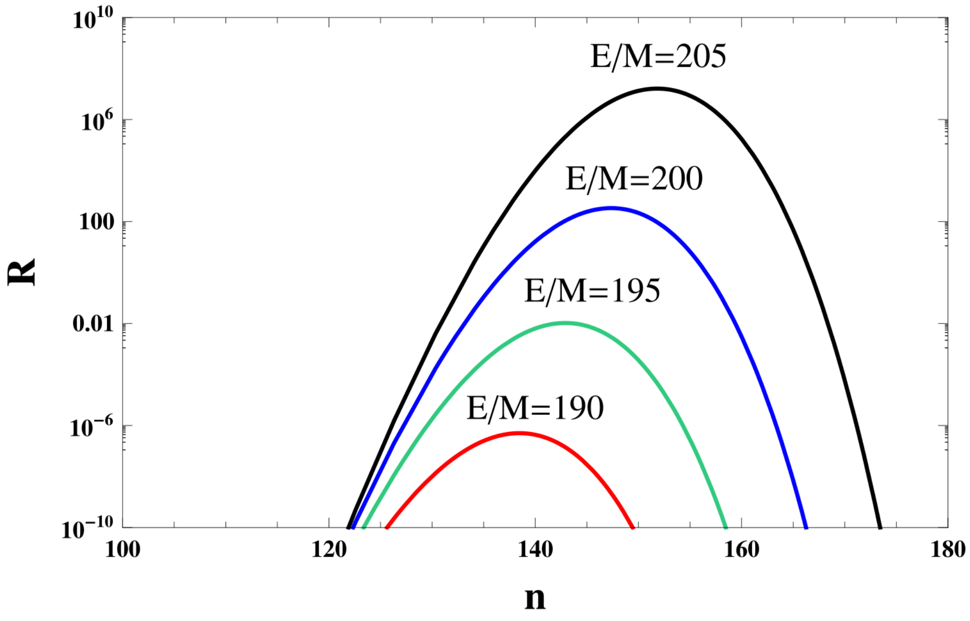





*Riehn (Pierre Auger Collaboration), ICRC 2019*

# Higgsplosion






*Khoze, Spannowsky, 1704.03447*

# Higgsplosion

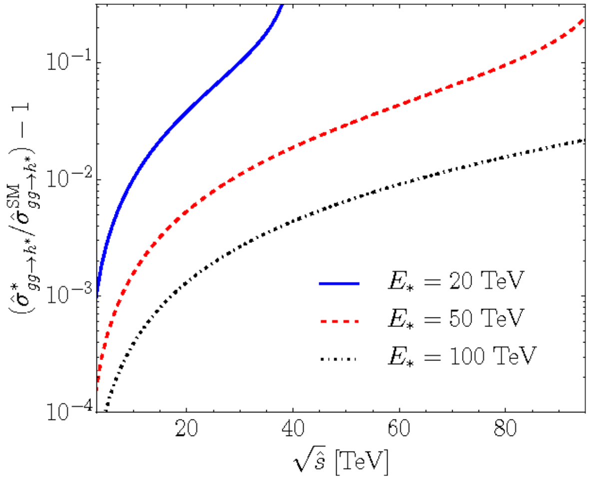
$h^*(p^2 \gg m_{\rm h}^2) \to n \times h$ transition rate growing with ***n!***

$$\mathcal{R} = \exp\left[\frac{\lambda n}{\lambda}\left(\log\frac{\lambda n}{4} + 3.02\sqrt{\frac{\lambda n}{4\pi}} - 1 + \frac{3}{2}\left(\log\frac{\epsilon}{3\pi}+1\right) - \frac{25}{12}\epsilon\right)\right]$$

in the limit of

$$\lambda \to 0$$
$$n \to \infty$$
$$\lambda n = \text{const.} \gg 1$$

$\mathcal{R} \sim 1$ defines Higgsplosion scale $\boldsymbol{E_*}$




*Khoze, Spannowsky, 1707.01531*
*Khoze et al., 1709.08655*

# Interaction lengths