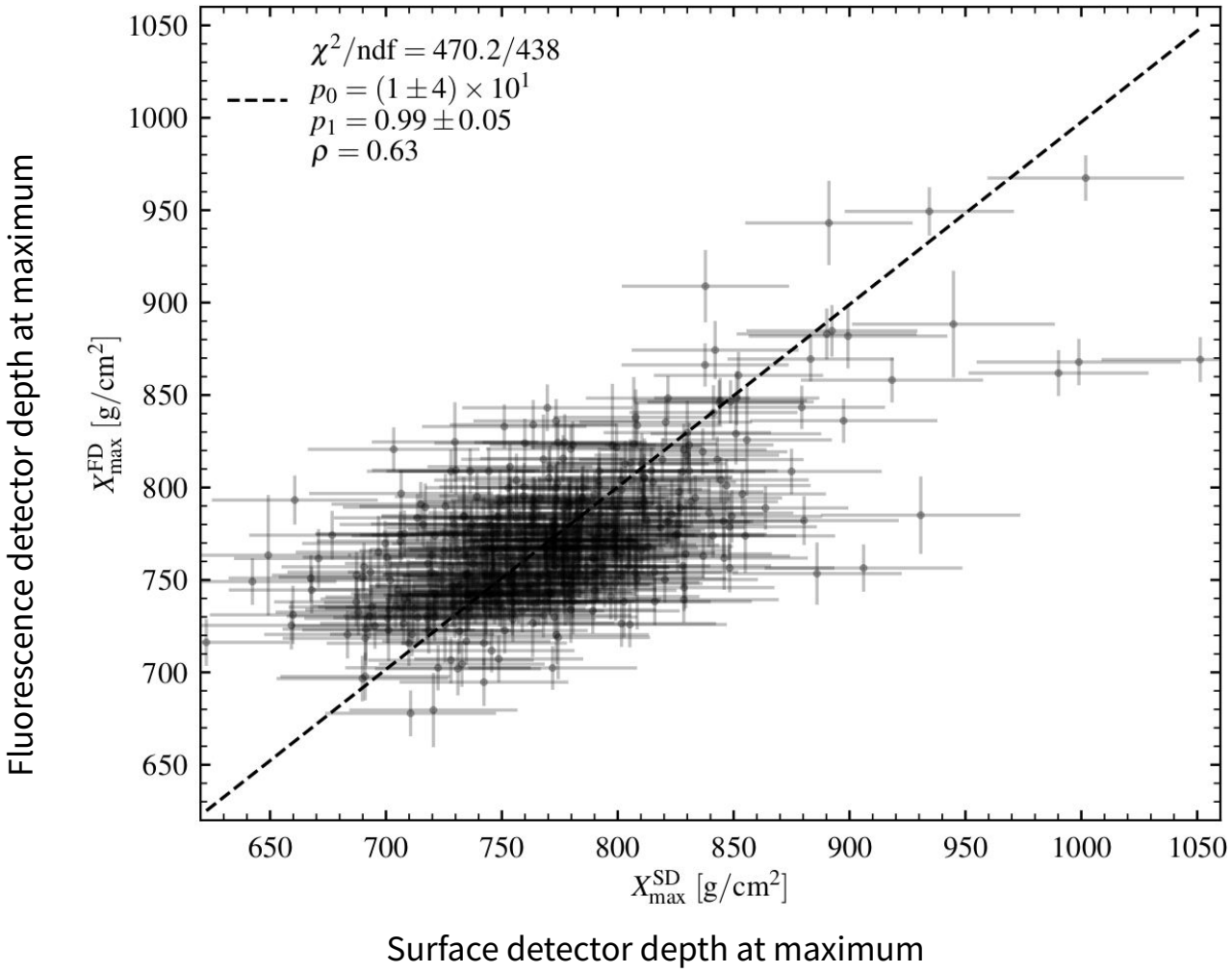
Thank you, any questions?

Take home message:

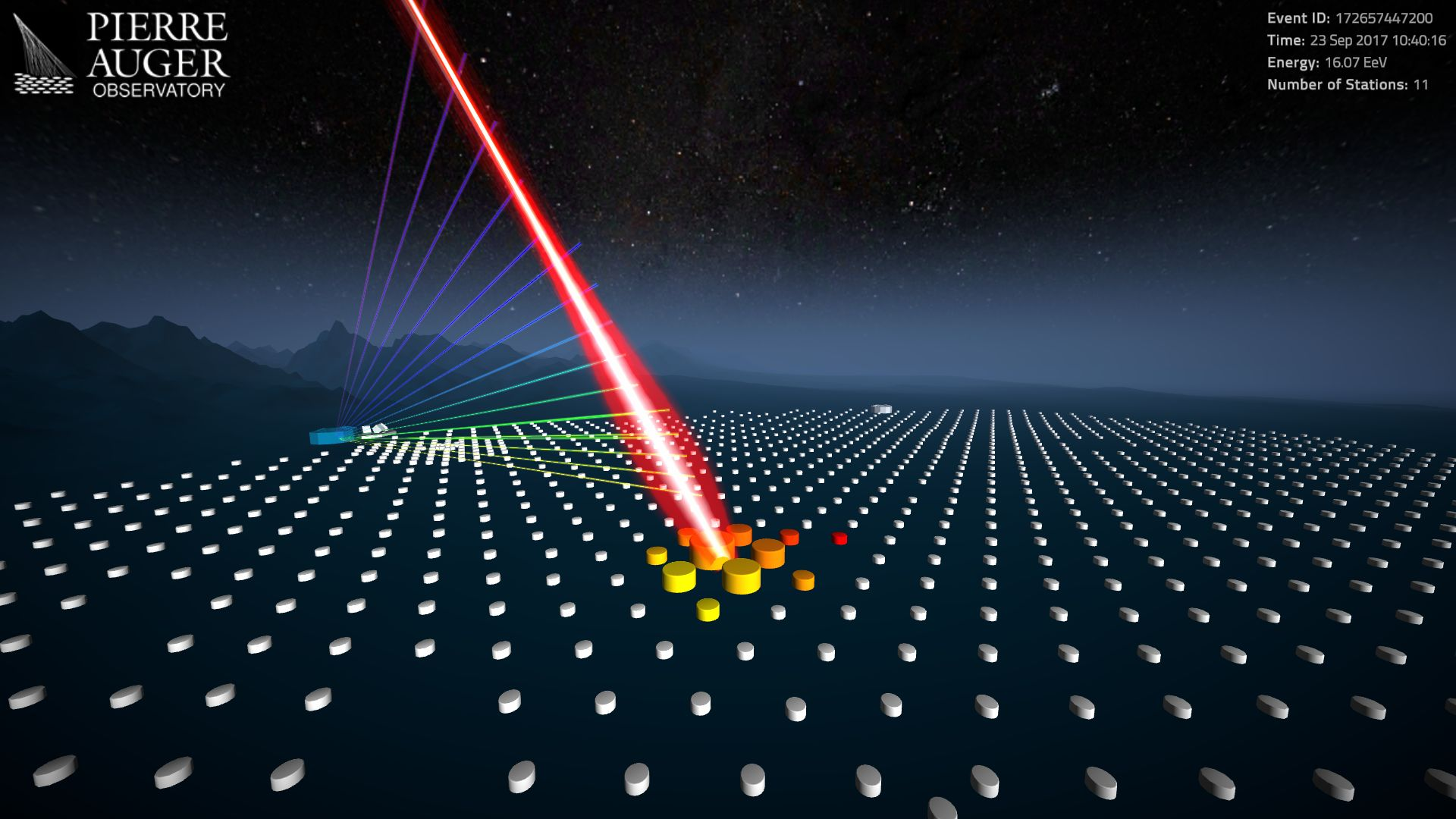
We are on our way to measure what are the highest energy cosmic rays using the full (timing) information from our surface particle detectors

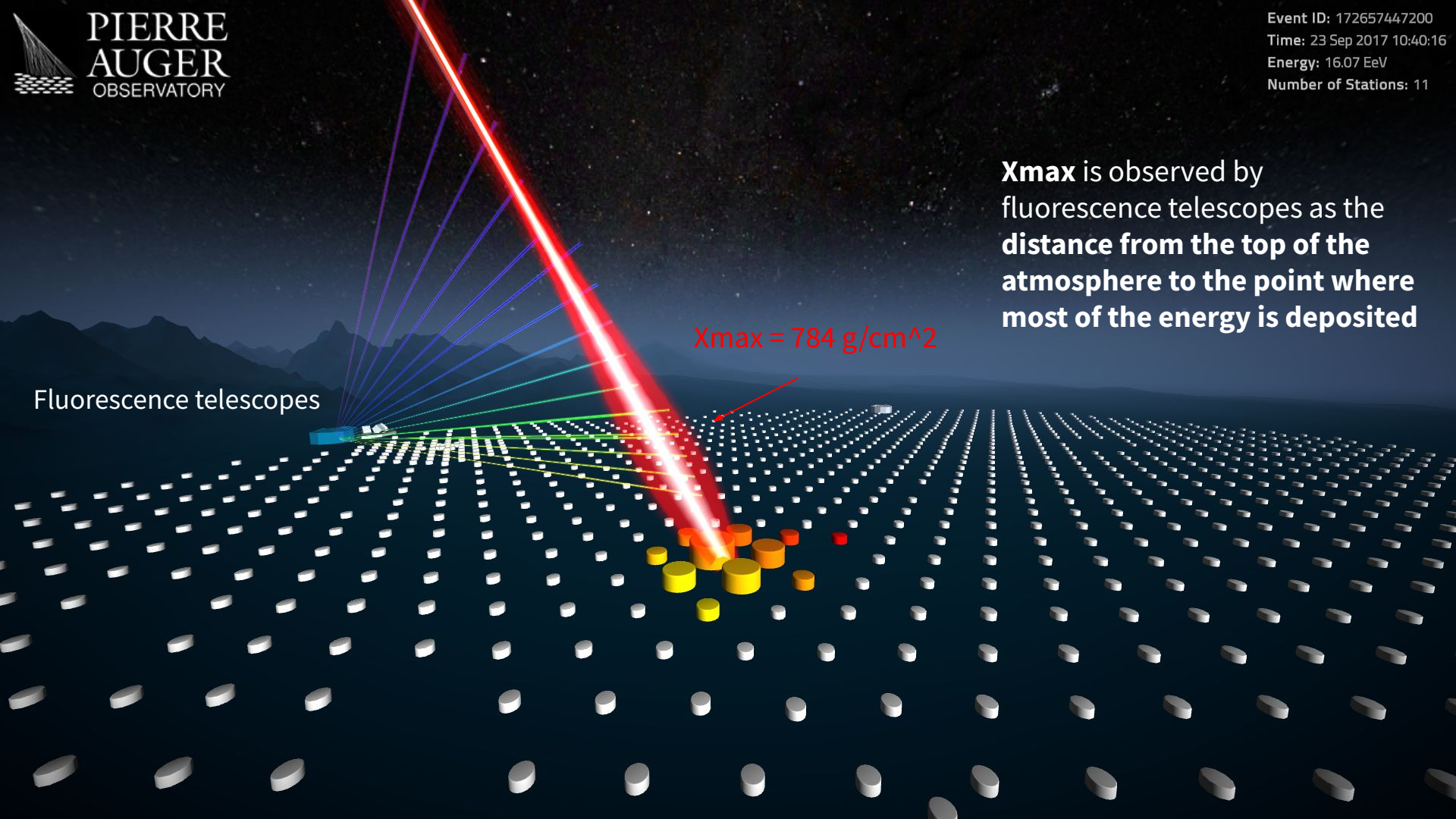
keywords: mass composition, Xmax, time trace templates



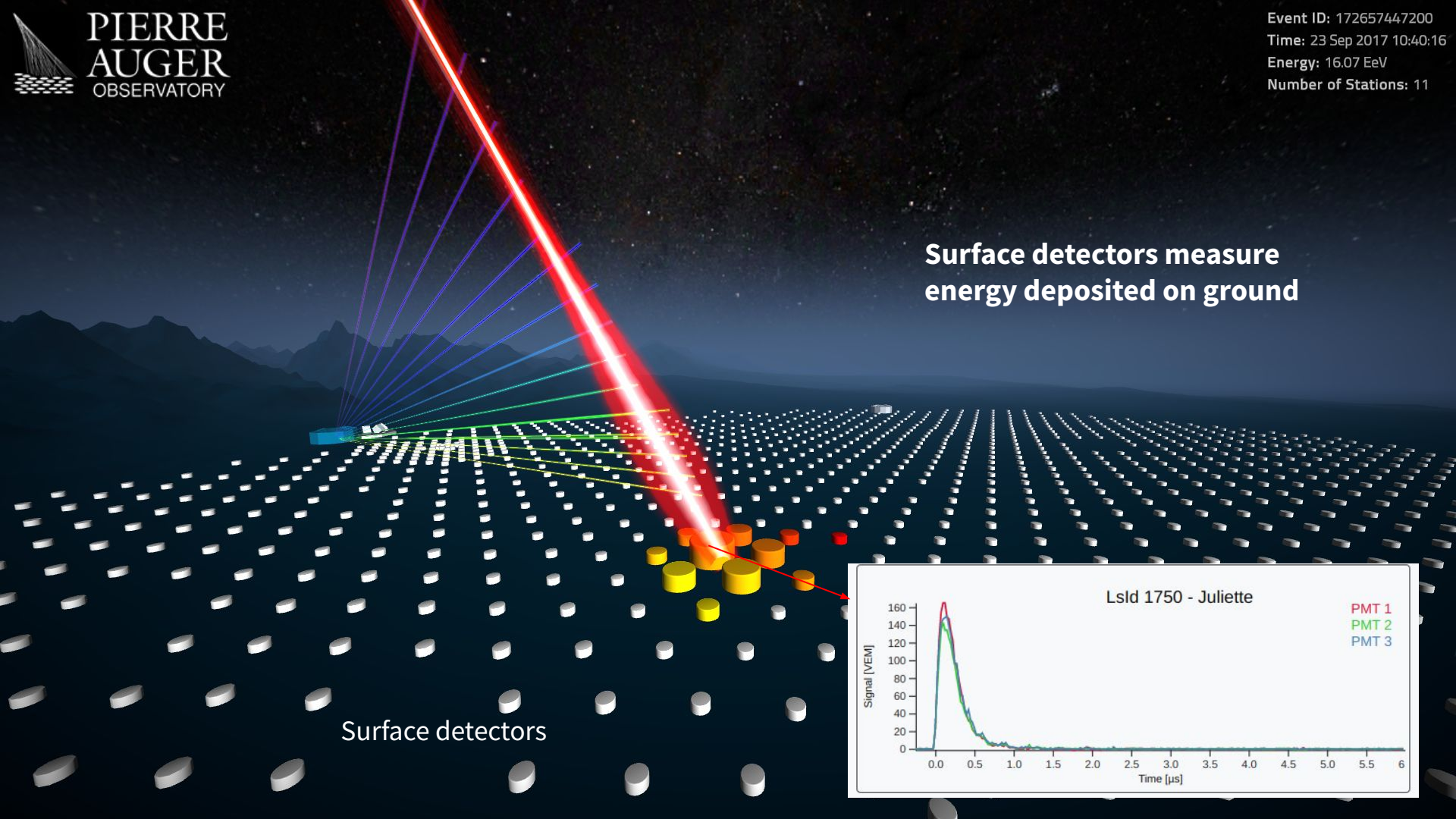
E > 10^19 eV

Resolution ~40 g/cm2
Proton-iron difference 100 g/cm2

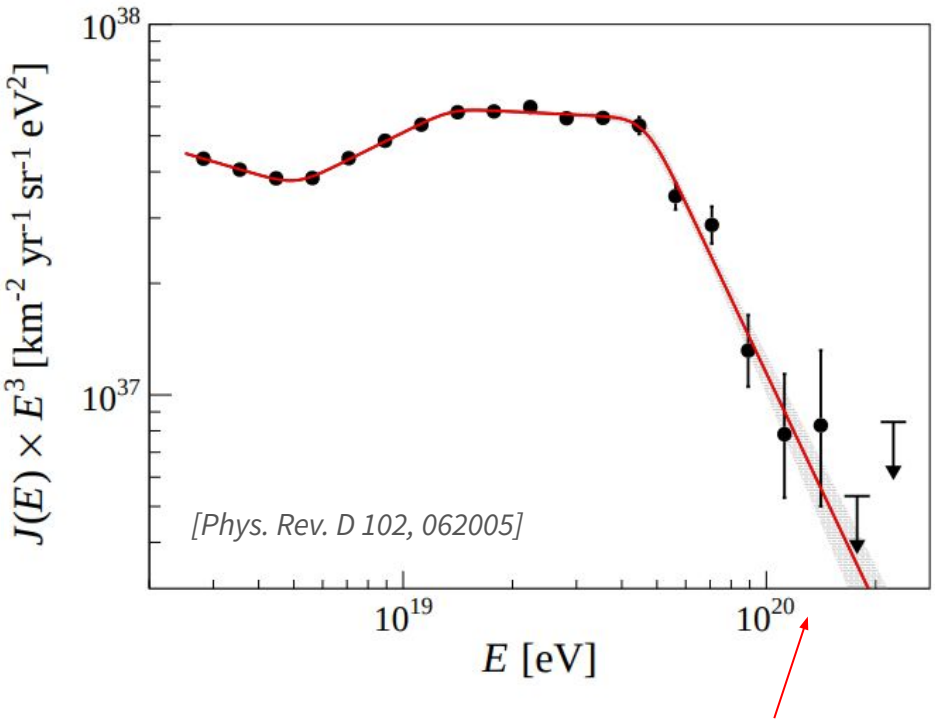

PIERRE
AUGER
OBSERVATORY
Event ID: 172657447200
Time: 23 Sep 2017 10:40:16
Energy: 16.07 EeV
Number of Stations: 11



Xmax is observed by fluorescence telescopes as the **distance from the top of the atmosphere to the point where most of the energy is deposited**


PIERRE AUGER OBSERVATORY
Event ID: 172657447200
Time: 23 Sep 2017 10:40:16
Energy: 16.07 EeV
Number of Stations: 11
Surface detectors measure energy deposited on ground
Surface detectors
LsId 1750 - Juliette
PMT 1
PMT 2
PMT 3
Signal [VEM]
Time [μs]

But we do not have enough events at the highest energy



1 event/km^2/1000 years

The number of events at ultra-high energies is super low
Virtually **no Xmax measurements around 10^20 eV**
Fluorescence method only works on dark clear nights (10% of the time)

Need to use surface detector data

- 10 m^2 water-Cherenkov detectors (and in the near future also scintillators)
- 100% uptime
- Adequate energy measurement calibrated to fluorescence data
- Already few tens of events above 10^20 eV

But…

- Not made for mass composition (Xmax) analyses
- Number of muons in air showers is not well understood *[see Harm's talk, Phys. Rev. D 91, 032003]*

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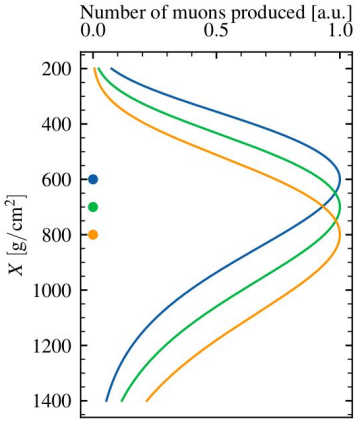
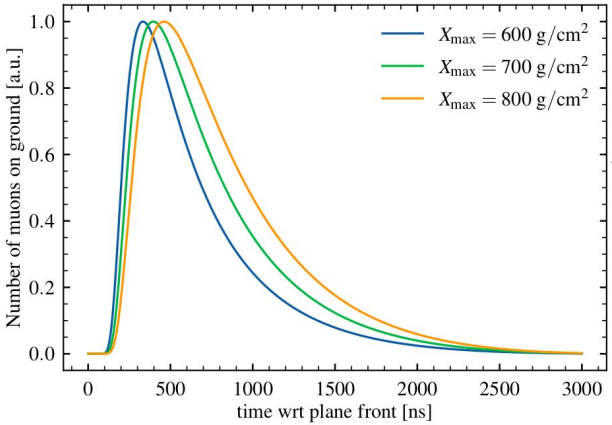
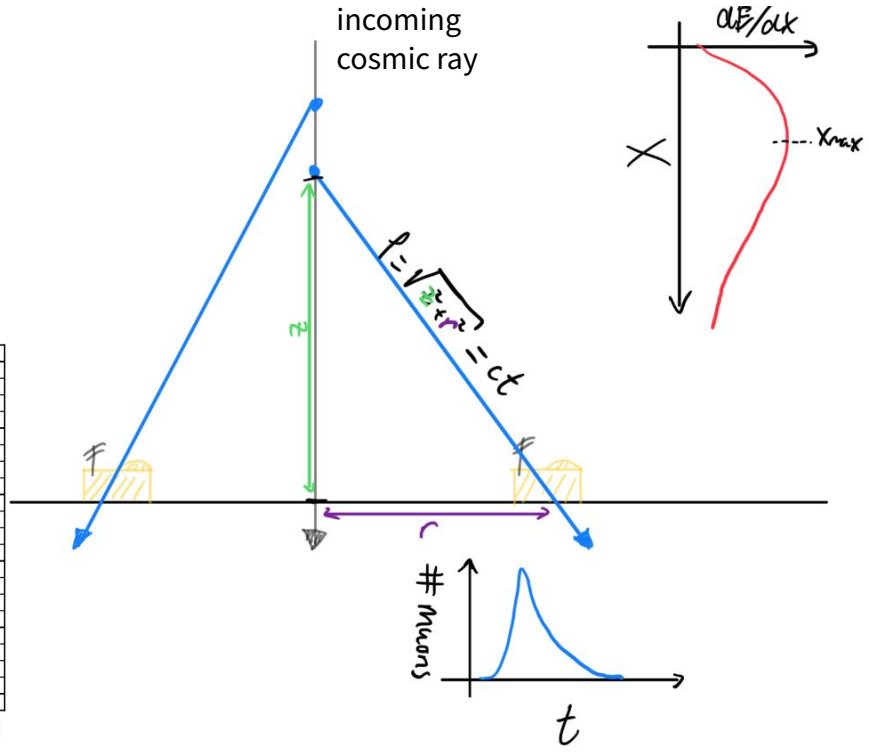
Can get more information from signal as a function of time

Timing connects to production depth (Xmax)

Assuming muons travel in straight lines with speed of light, it is straightforward to convert the arrival time to an atmospheric depth*





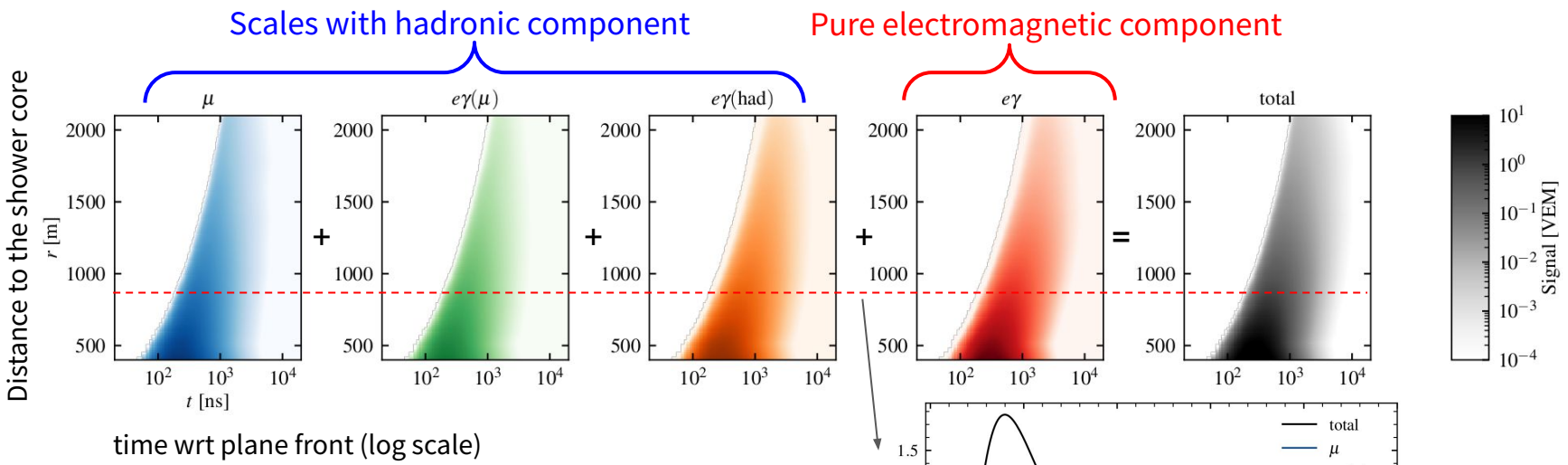


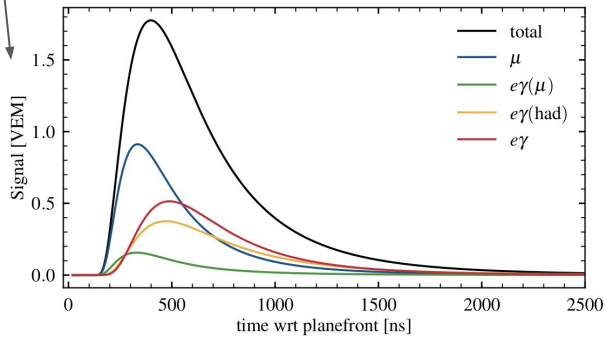
*This is complicated by energy and pT distribution, but can still do it semi-analytically *[Astropart.Phys. 21 (2004) 71-86, Astropart.Phys. 23 (2005) 393-409]*

Time Trace Templates

Signal at ground level behaves universal wrt to the distance to Xmax for 4 components

[Astroparticle Physics 87 (2017) 23–39, Astroparticle Physics (2008) 355-365]





theta = 0 deg
lgE/eV = 19
Xmax = 800 g/cm^2
Rmu = 1
EPOS-LHC proton

Signal at point on the ground and time:

relative number of muons

Xmax dependence

time dependent part

$$\widehat{S}(\vec{r}_i, t_j) = \sum_k S_k^{\mathrm{ref}} (1 + \alpha_k R^\mu) \left(\frac{E}{10^{19}\mathrm{eV}} \right)^{\gamma_k} f_k^{\mathrm{GH}}(\Delta X) \rho_k(\vec{r}_i) g_k(t_j, \vec{r}_i, \Delta X)$$

Detector i
Time bin j

sum over k components

Total energy

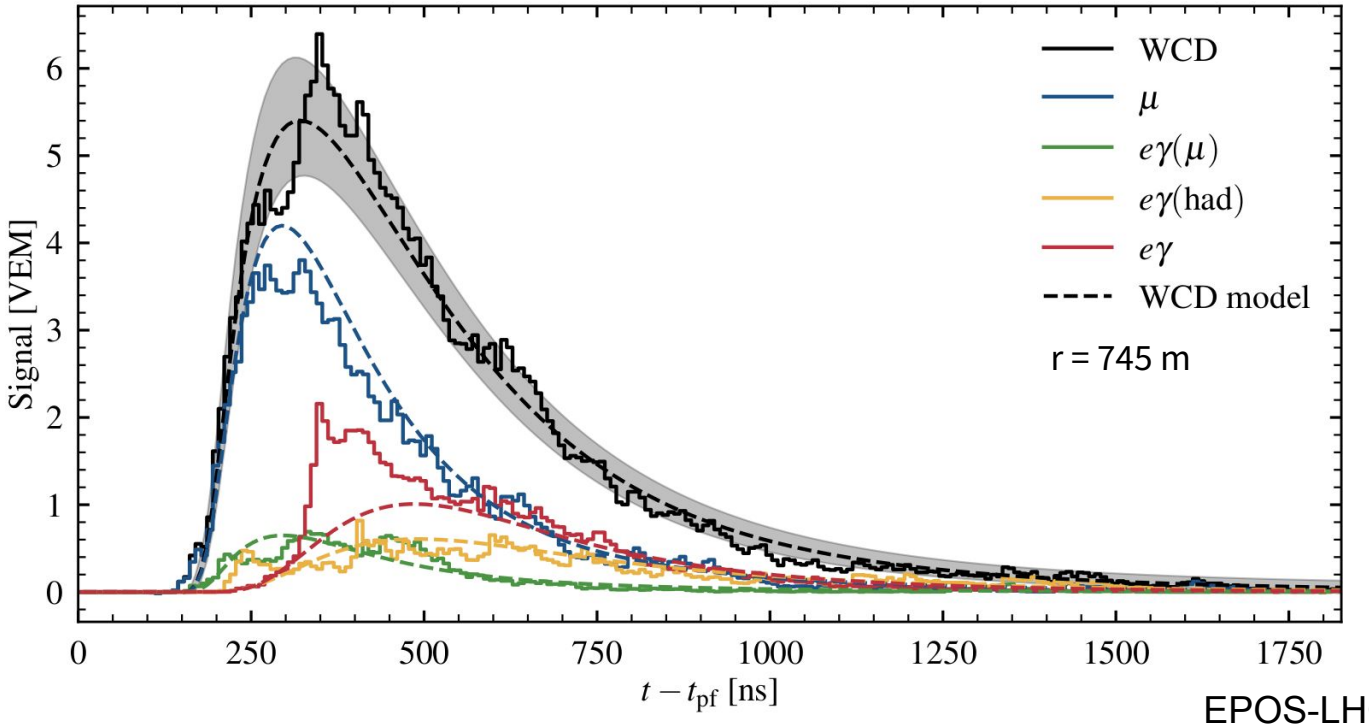
Density of particles as a function of distance to the core

Minimize negative log likelihood for Xmax:

$$\ln \mathcal{L} = \sum_i \sum_j \ln \mathcal{P} \left(S_{ij}, \widehat{S}(\vec{r}_i, t_j, X_{\max}) \right)$$

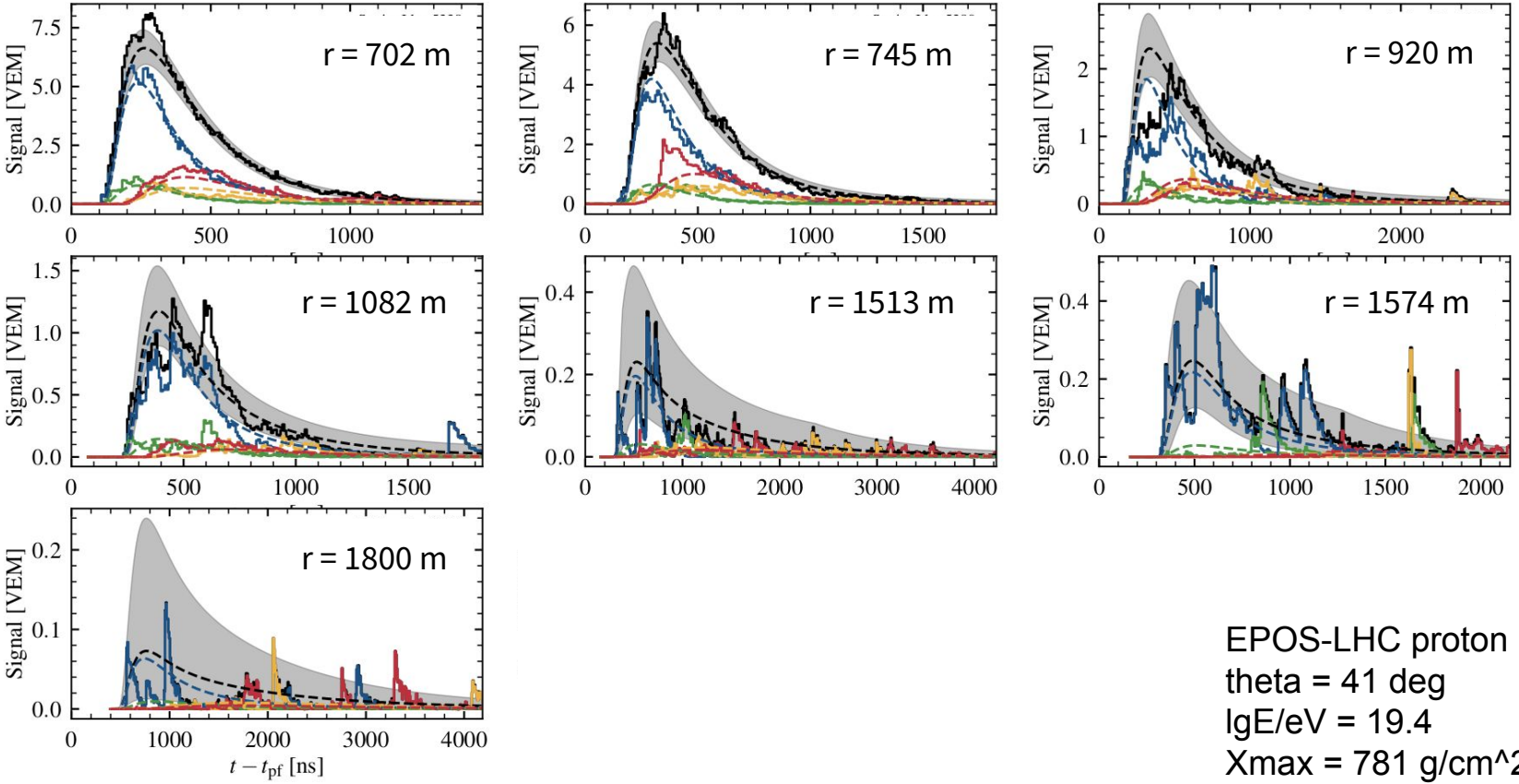
$$R^\mu = \frac{S_\mu}{\widehat{S}_\mu(E, \Delta X, \mathrm{p}, \text{EPOS-LHC})}$$

An example for 1 station



EPOS-LHC proton MC
theta = 41 deg
lgE/eV = 19.4
Xmax = 781 g/cm^2

An example event

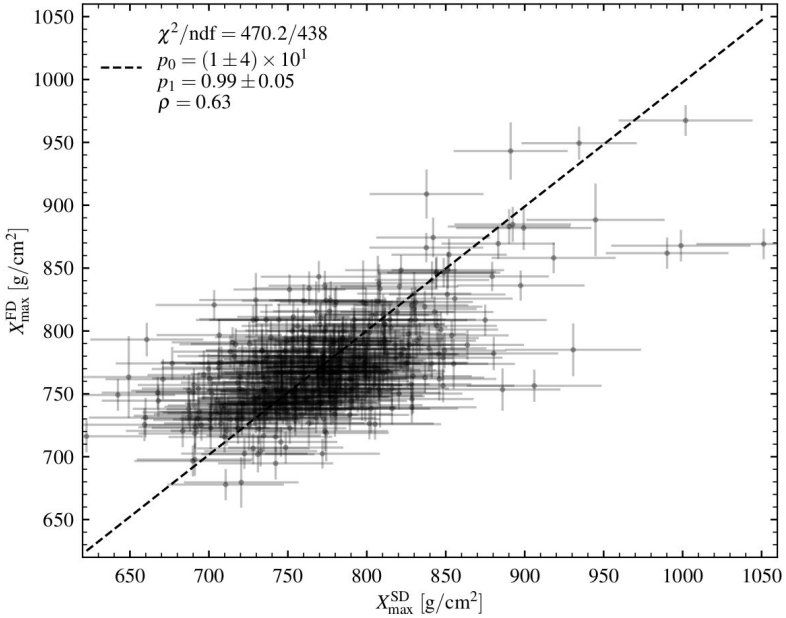


EPOS-LHC proton MC
theta = 41 deg
lgE/eV = 19.4
Xmax = 781 g/cm^2

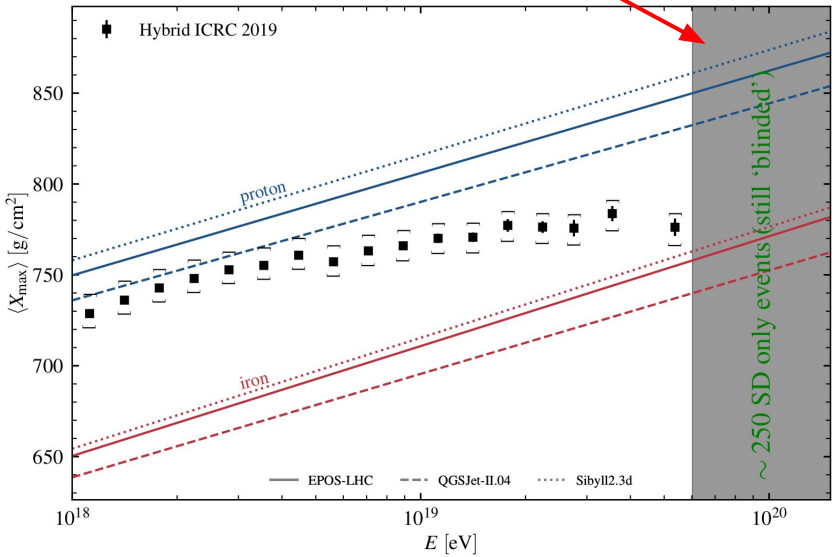
Content of this talk

1. Need to use surface detector data to determine mass composition at highest cosmic-ray energies
2. Interaction depth in the atmosphere is related to arrival time of particles on the ground
3. Signal as a function of time is well described by four component time trace template fit
4. Inferred Xmax from surface detector is calibrated with fluorescence data

Time Trace Templates: identifying the highest energy cosmic rays using particle detectors



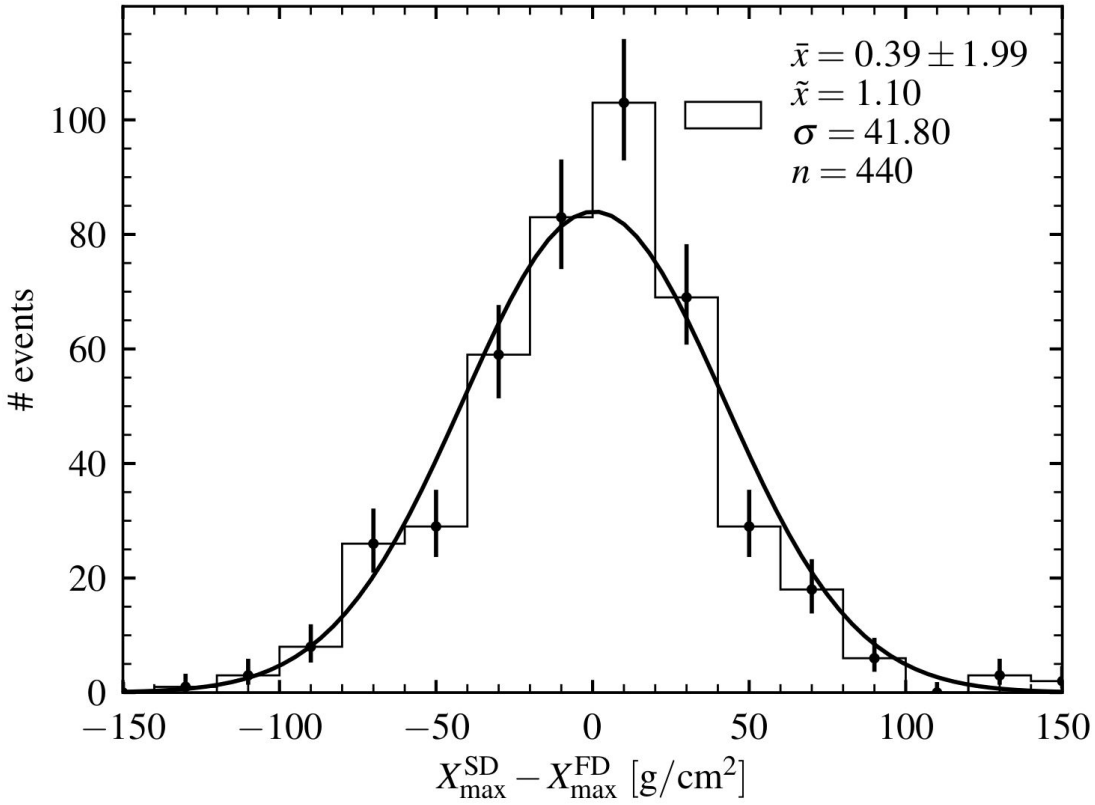
Soon: a measurement at the highest energies



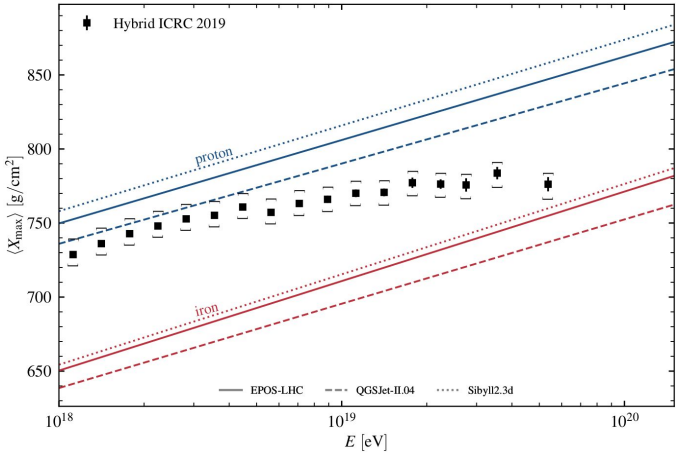
Mart Pothast, Nikhef Jamboree Maastricht 2022

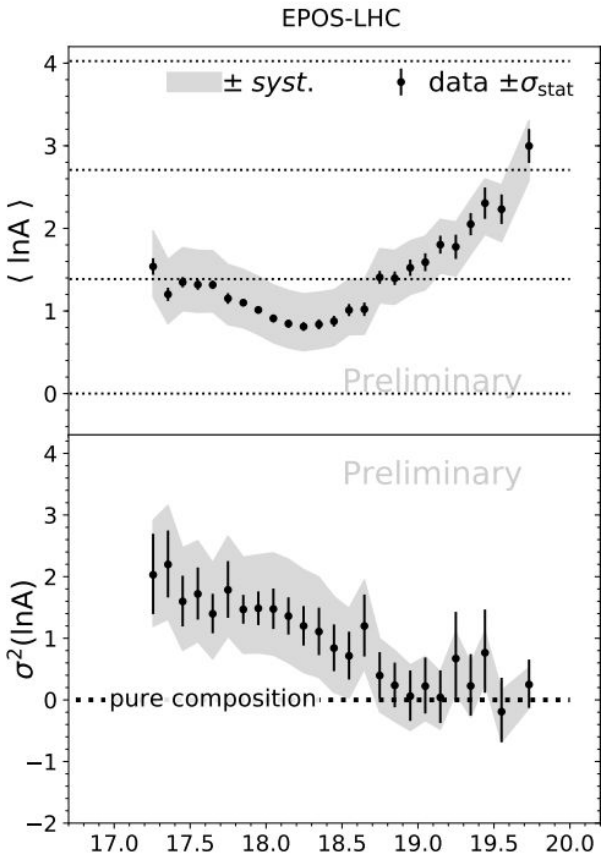
Backup

Resolution ~ 40 g/cm2



Xmax ~ ln(A)


Hybrid ICRC 2019
proton
iron
EPOS-LHC
QGSJet-II.04
Sibyll2.3d
⟨Xmax⟩ [g/cm²]
E [eV]


EPOS-LHC
± syst.
data ±σstat
⟨ lnA ⟩
Preliminary
Preliminary
σ²(lnA)
pure composition

MC tests

Good correlation

Hadronic interaction model/primary systematic bias ~10 g/cm2

Energy dependent bias probably due to the muons (but will be calibrated with FD data anyway)

Resolution 30-50 g/cm2