Cosmic-Ray Shower Longitudinal Profiles for Mass and Cross-Section Analyses

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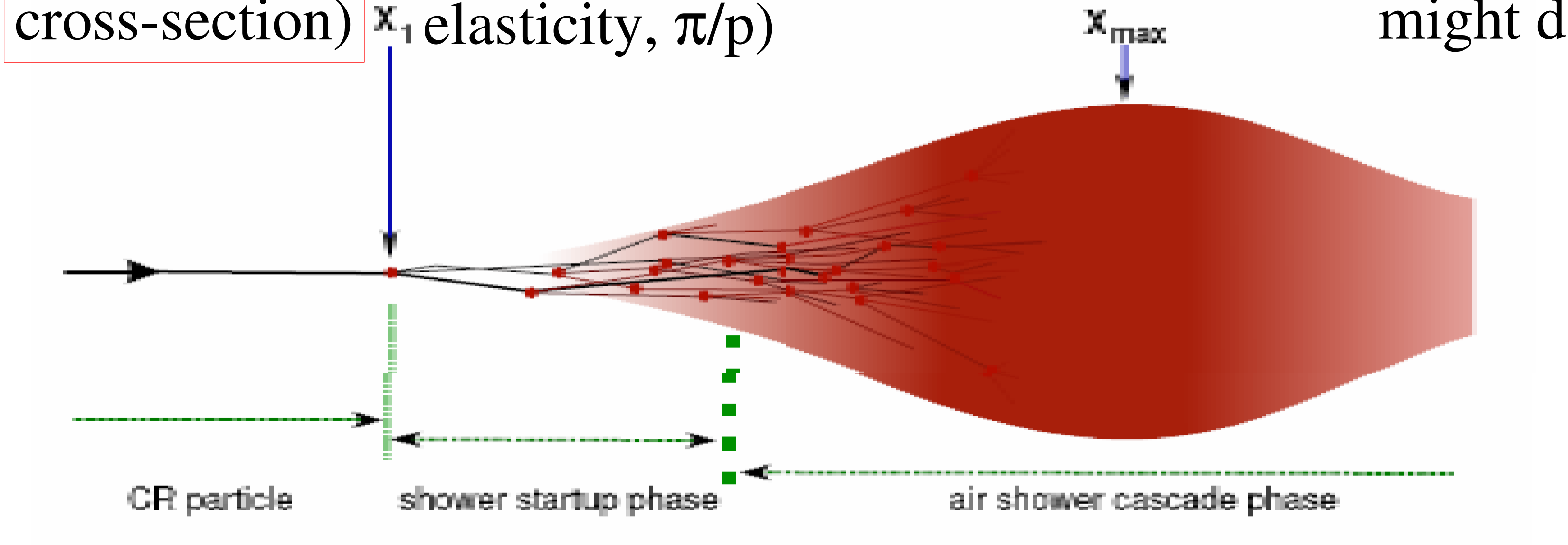
Extensive Air Showers



1st interaction (primary, cross-section)

hadronic part (multiplicity, elasticity, π/p)

electromagnetic cascade

eventually, hadronic component might dominate again?

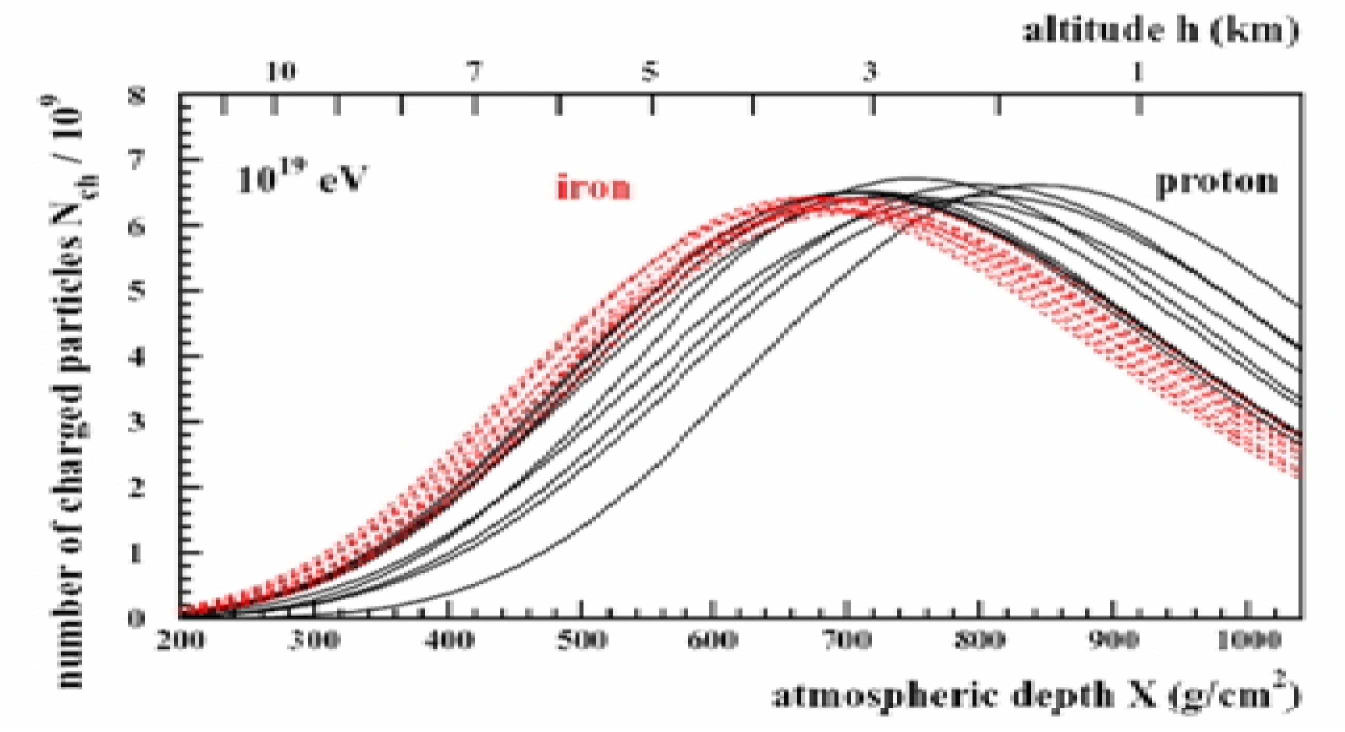
High numbers of low energy electrons excite N_2 producing fluorescence light (detected isotropically) and charged particles emit Cherenkov (directionally)

Muons (and electrons) will reach the ground and be detected in several km

Primary Composition and Cross-Section
“Classical” Analyses in EAS

Statistical analysis give average composition as a function of Energy from

* muon/electron densities (from Surface Array Detectors)
* position of shower maximum (from Fluorescence Detectors,
  analysis with Surface Array Detectors now being exploited
  and can allow combination of both variable types)



Historically we look at <Xmax> and its RMS, not yet the full distributions

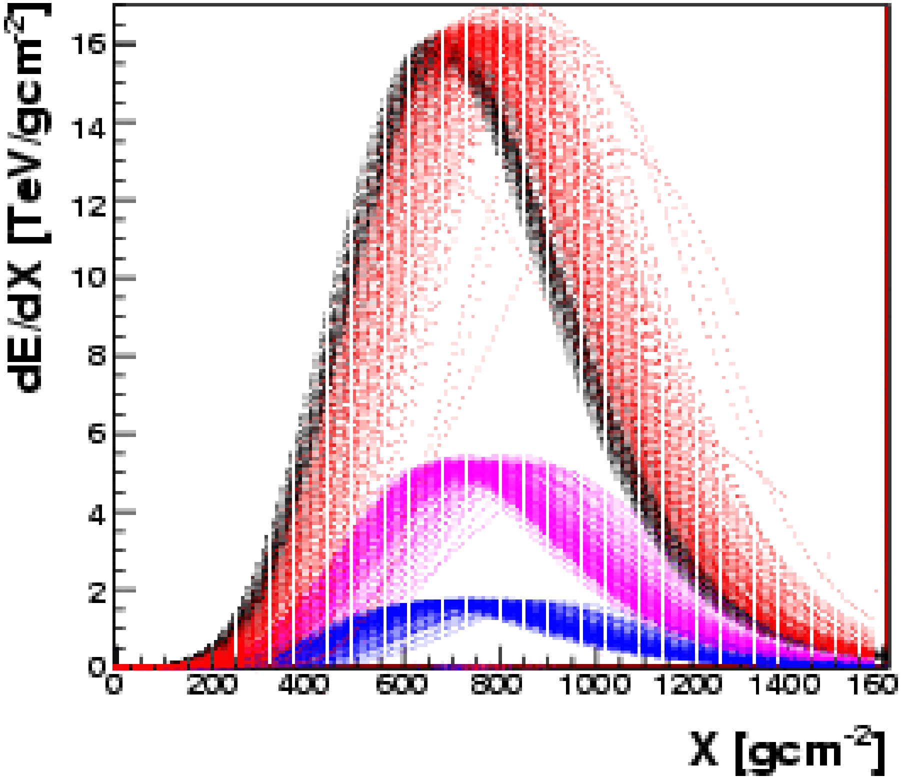
And not the shower shape!!!

Cross-section comes also from the Xmax distribution.

Parameterizing the Shower Profiles

Electromagnetic Showers
are parameterized from
cascade equations
(electron and gamma densities,
electron and gamma energies,
as a function of “shower-age”)

The hadronic component changes
the start-up and equilibrium
conditions:
empirical parameterization proposed
by Gaisser and Hillas (GH)



$$N = N_{max}\left(\frac{X-X_0}{X_{max}-X_0}\right)^{\frac{X_{max}-X_0}{\lambda}} \exp\left(\frac{X_{max}-X}{\lambda}\right)$$

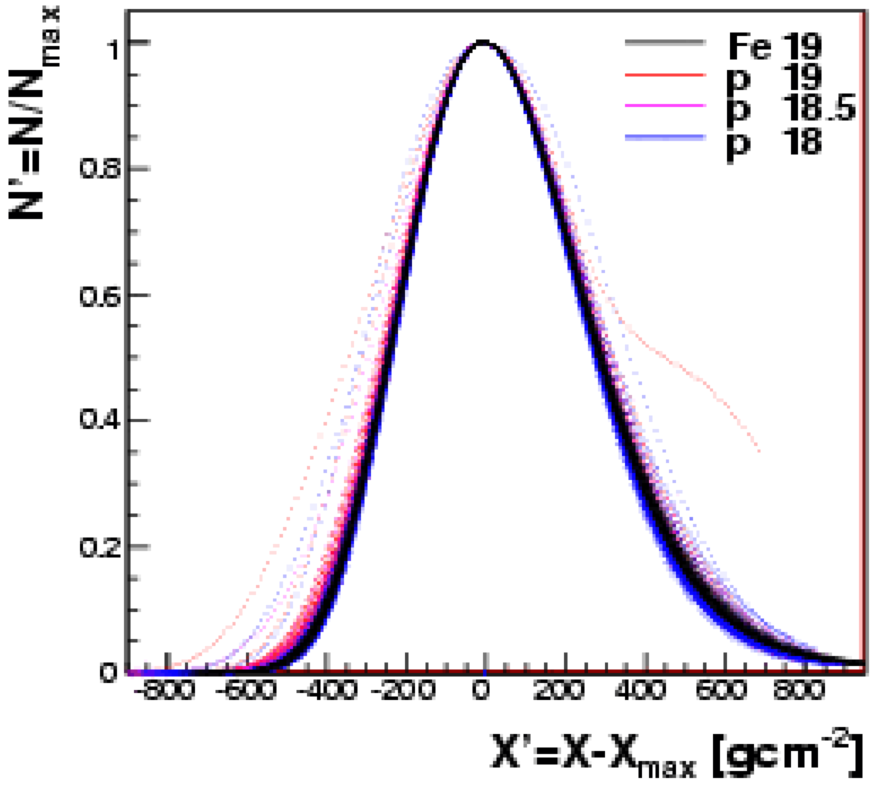
two variables describe the maximum;
two variables describe the shape:
Xo ~ shower start (~ -120 g/cm^2)?
λ ~ interaction length (~60 g/cm^2)?

Universal Shower Profile (USP)

Main shower characteristics are reflected in its maximum.

- Rescaling N/Nmax (=N')
- Shifting X-Xmax (=X')

gives an almost universal shape.
Which can be derived from data



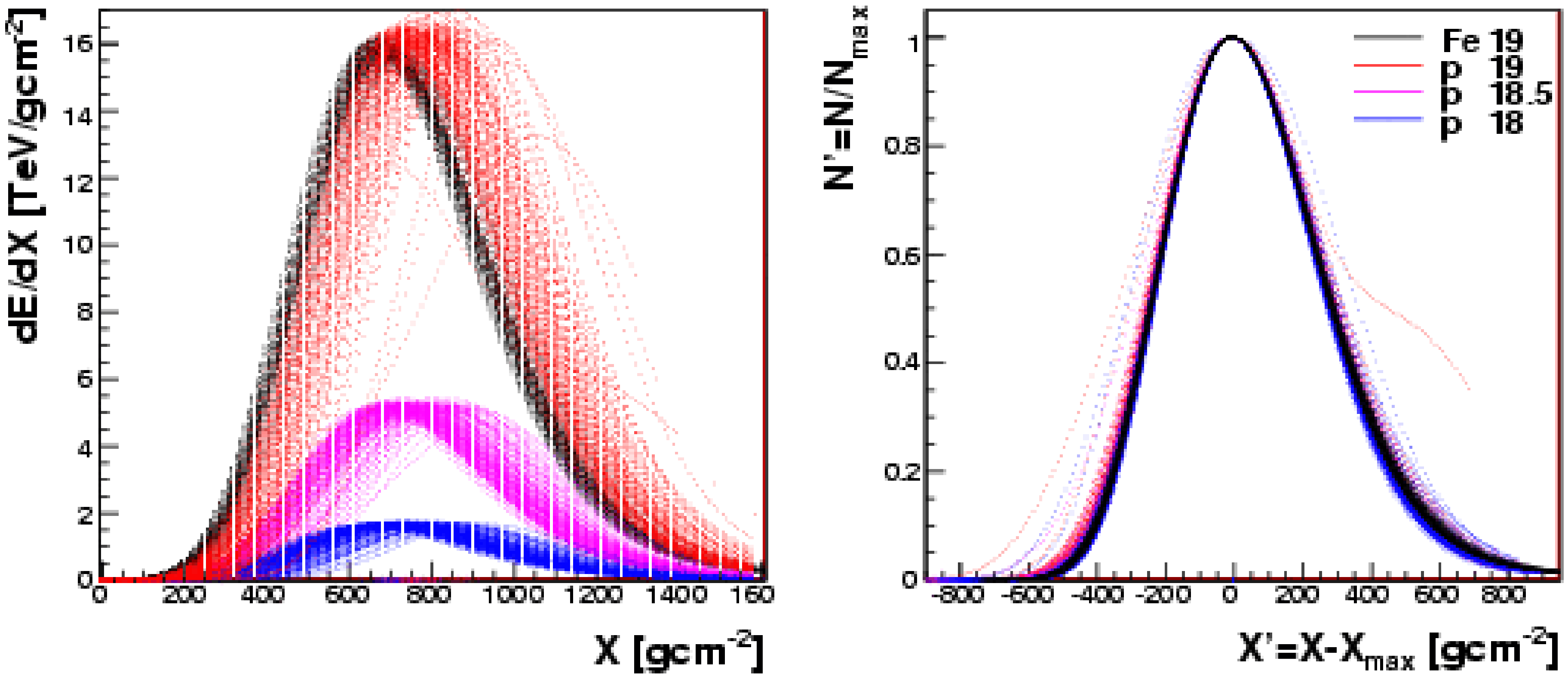
$$N' = (1. - \frac{X'}{X'_0})^{-\frac{X'_0}{\lambda}} \exp(-\frac{X'}{\lambda})$$

N' = N / Nmax
X' = X - Xmax
X'o = Xo – Xmax ~ shower length?
λ ~ interaction length?

The USP is a better way to extract the two extra parameters statistically, or find characteristic deviations!

[dE/dX α N;
dE/dXmax α Nmax]

Gaisser-Hillas -> Universal Shower Profile



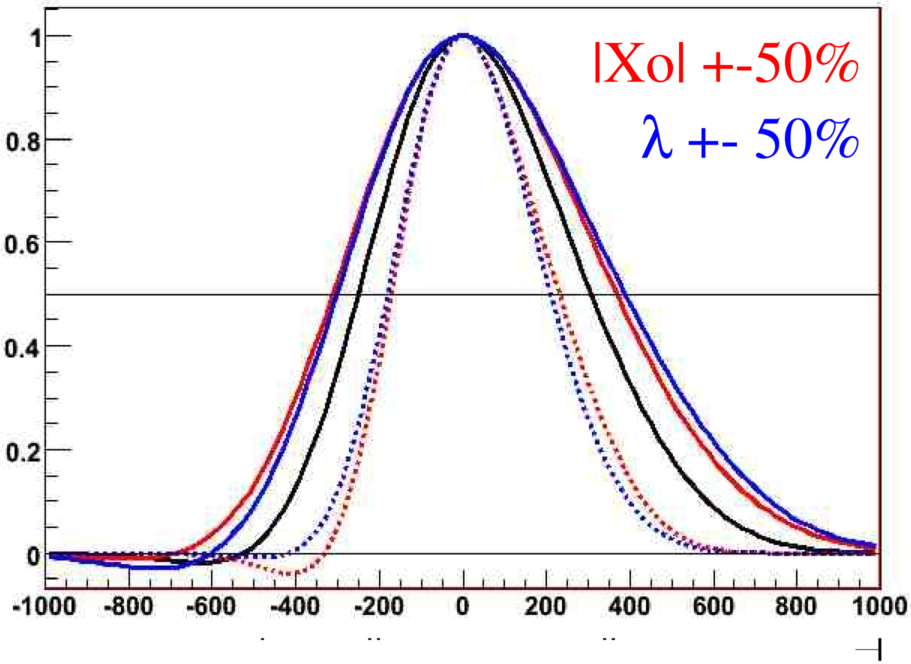
$$N = N_{\mathrm{max}}\left(\frac{X-X_0}{X_{\mathrm{max}}-X_0}\right)^{\frac{X_{\mathrm{max}}-X_0}{\lambda}} \exp\left(\frac{X_{\mathrm{max}}-X}{\lambda}\right)$$

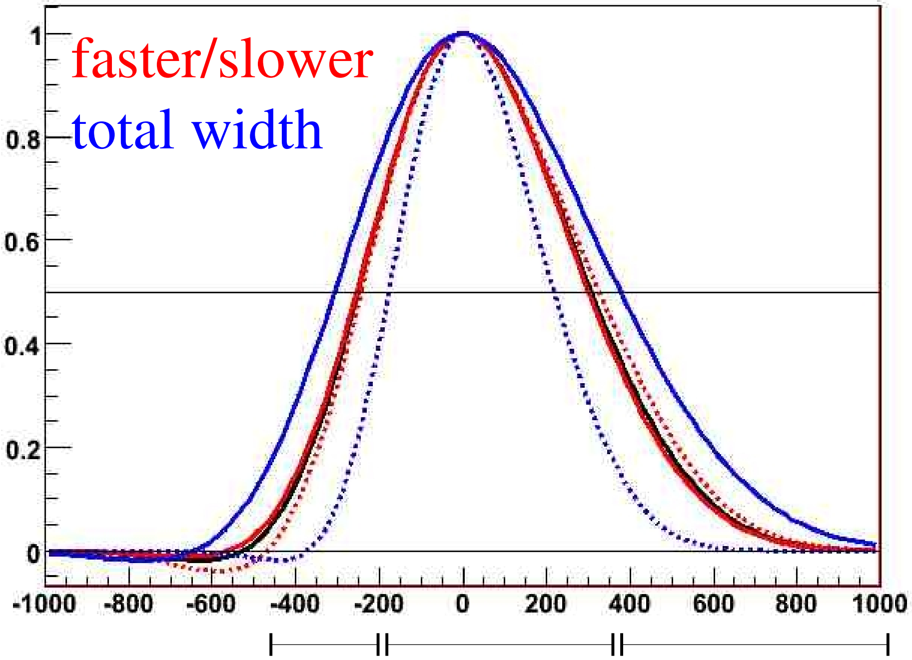
$$N' = \left(1. - \frac{X'}{X'_0}\right)^{-\frac{X'_0}{\lambda}} \exp\left(-\frac{X'}{\lambda}\right)$$

Xmax and dE/dXmax are good observables (easy to measure)

Xo and λ describe details of (almost universal) shower behaviour

Universal Shower Profile - Variables





$$\mathbf{N'} = (\mathbf{1}. - \frac{\mathbf{X'}}{\mathbf{X'_0}})^{-\frac{\mathbf{X'_0}}{\lambda}} \exp\left(-\frac{\mathbf{X'}}{\lambda}\right)$$

Xo and λ change distribution tails in similar ways (highly correlated)

typical values are -900. / 60. g/cm^2

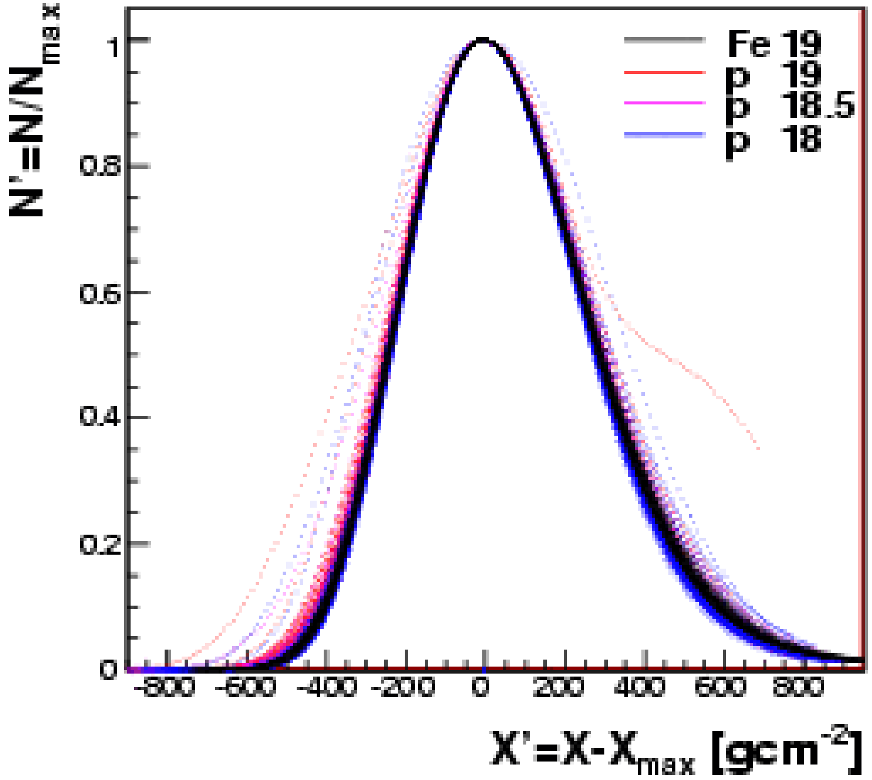
X'o λ – shower width

λ/X'o – shower asymmetry

easier to disentangle and measure;

easier to understand and constrain?

Universal Shower Profiles: L and R



$$N' = (1. - \frac{X'}{X'_0})^{-\frac{X'_0}{\lambda}} \exp\left(-\frac{X'}{\lambda}\right)$$

(expanding around X'=0): N' ~

$\exp(-1/2\,(X'/L)^2)$ $\exp(R/3\,(X'/L)^3)$

gaussian and "rotation"

λ and X'o=Xo-Xmax recombined:

$L = \sqrt{\lambda X'o}$

characteristic gaussian length

for electromagnetic cascades:

Evis ~ dE/dXmax $\sqrt{2\pi}$ L

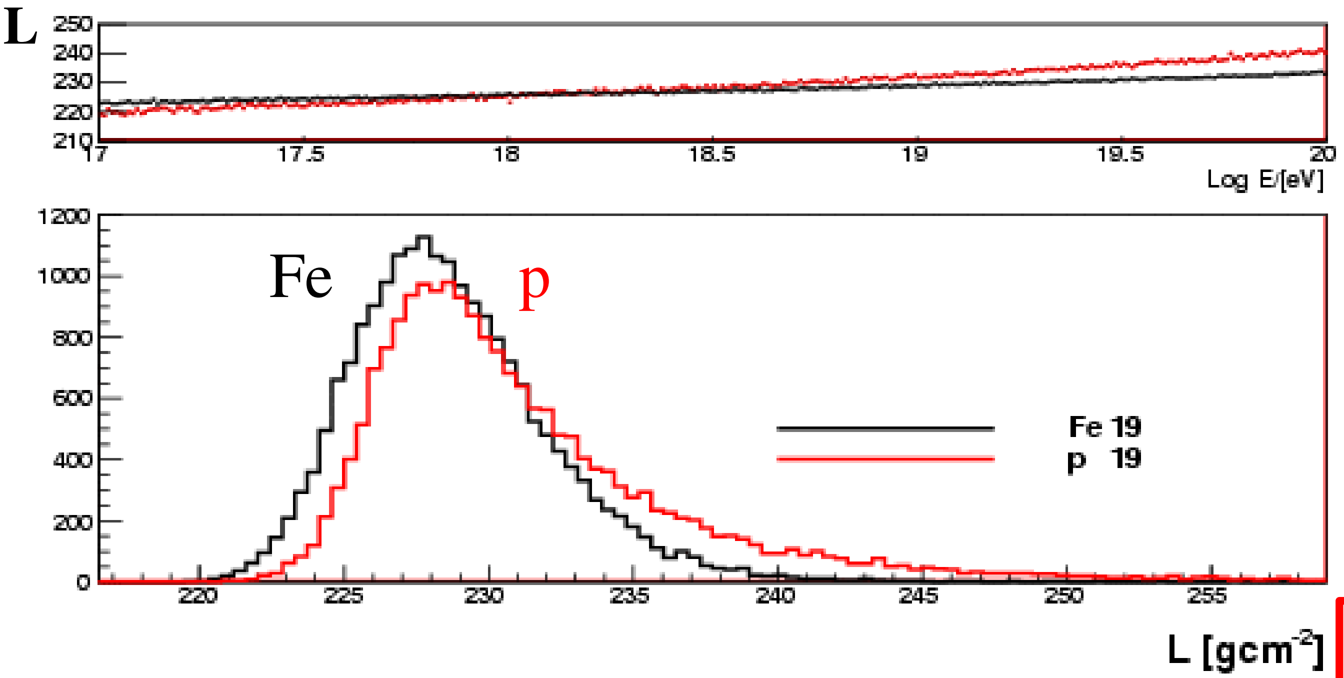
$R = \sqrt{\lambda / X'o}$

"rotation" parameter for energy transfer (hadronic -> electrom.)

Fe: "simultaneous" cascades

p: "consecutive" cascades

L for Energy Reconstruction



Fe/p reasonably similar
slow energy evolution
stable within models

$L = \sqrt{\lambda X'o}$

characteristic gaussian length
for electromagnetic cascades:

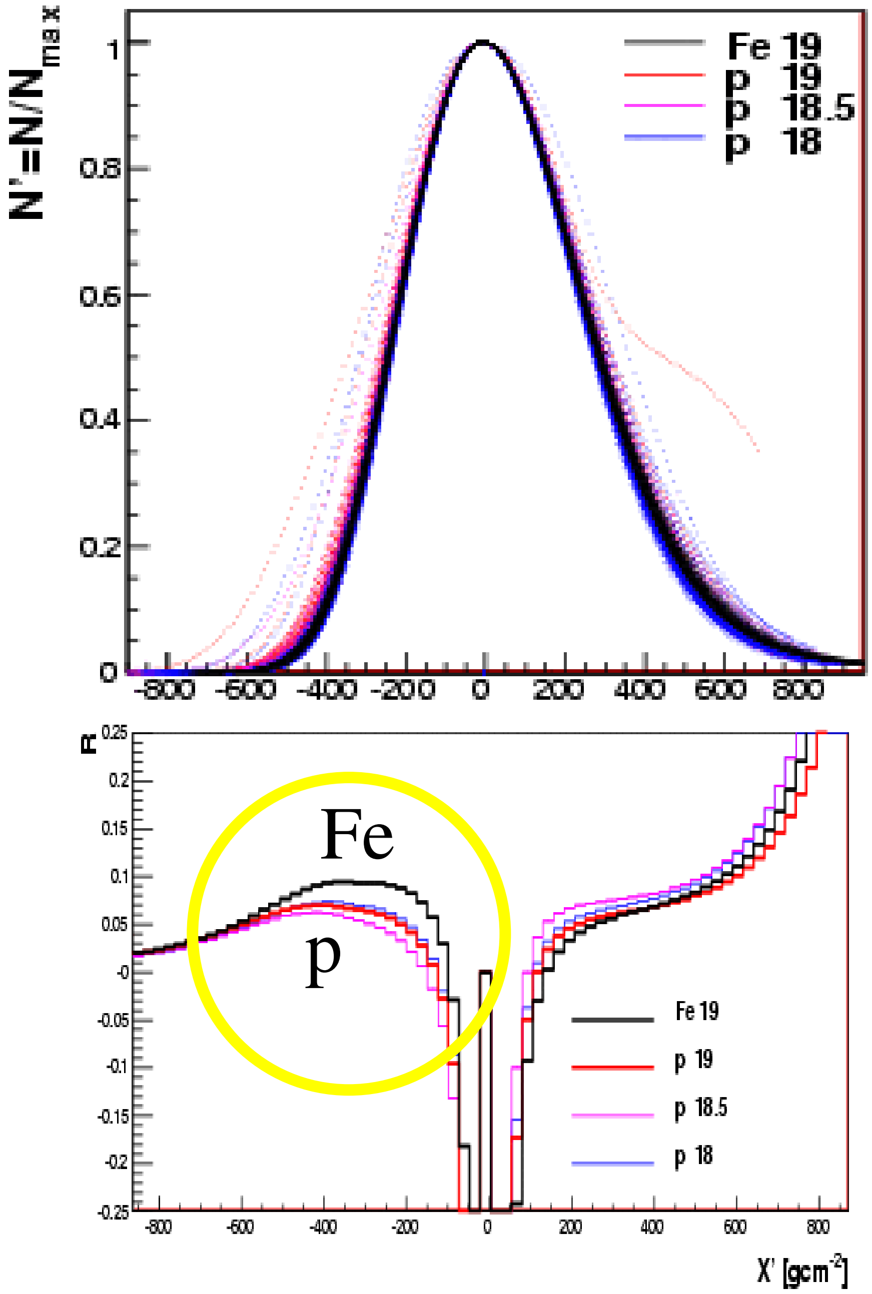
$Evis \sim dE/dXmax \sqrt{2\pi} L$

(5% correction for invisible E)

Energy α dE/dXmax
(L stable within 5%)

L can be constrained
instead of λ and Xo
in the GH profile fits

with constant L, R varies along X'



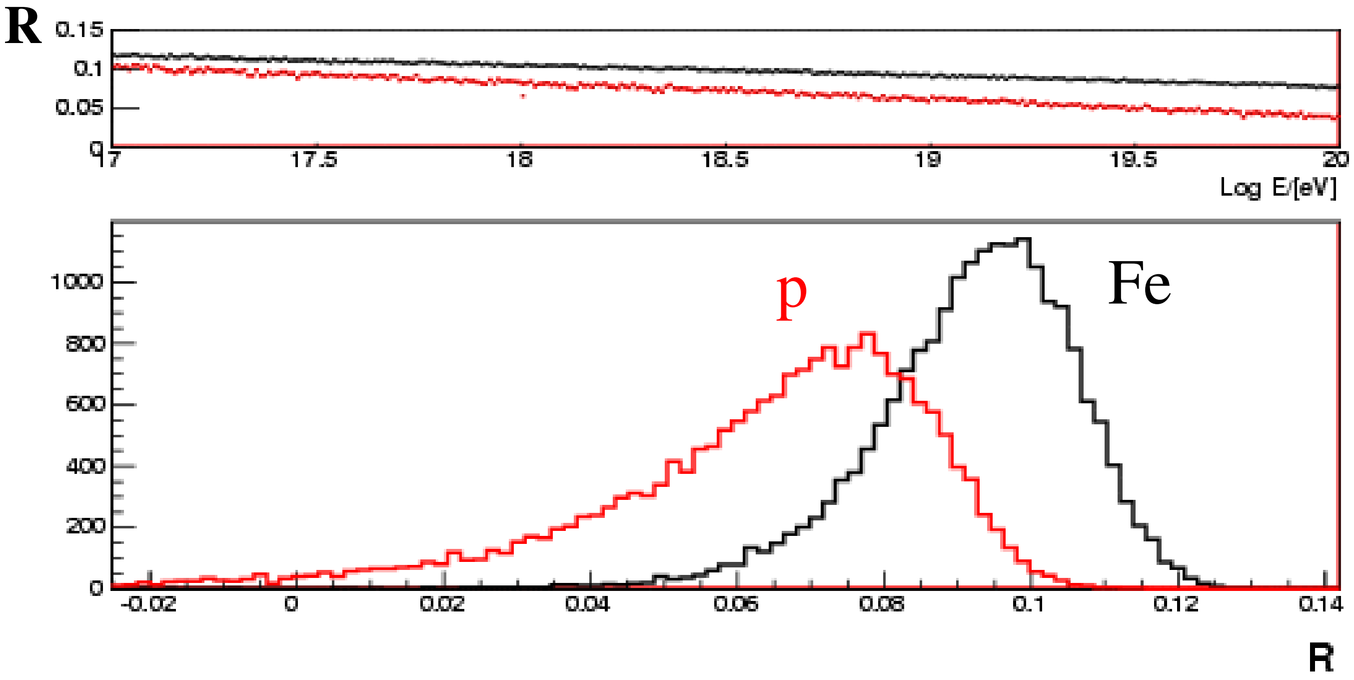
R(X') can be calculated from dE/dX(X') with fixed L

$[N' = \exp(-1/2\,(X'/L)^2)\ \exp(R/3\,(X'/L)^3)]$

R is not constant along all shower (can still be used in fits with full Gaisser-Hillas as $R=\sqrt{\lambda / X'o}$)

R ([-400,-200]g/cm^2) is stable and different for Iron and Proton: new composition variable!

R for mass composition



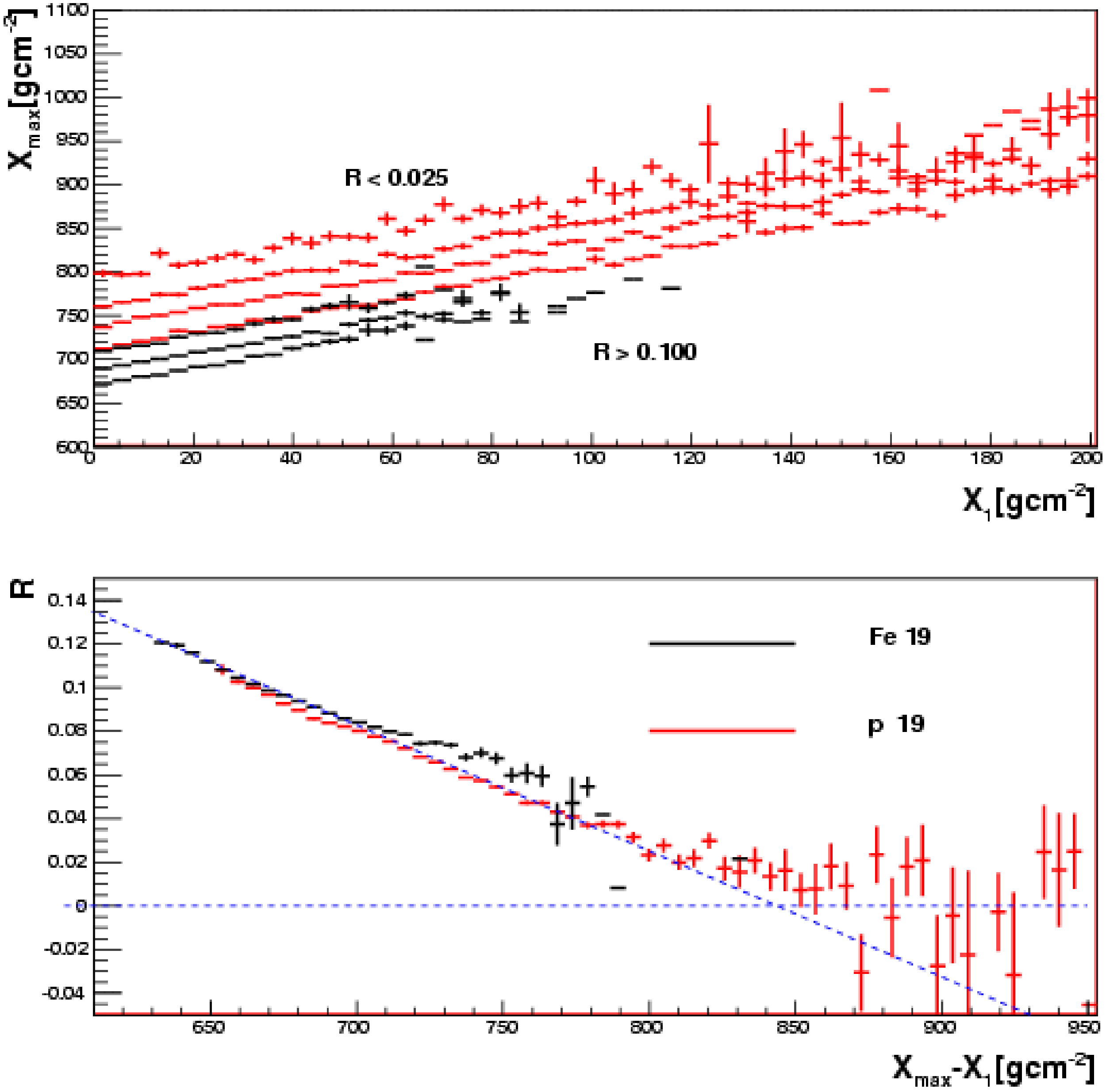
A new variable, R, can be measured in sub-set of showers with visible (Xmax– 300) g/cm^2

$$R = \sqrt{\lambda / X'o}$$

“rotation” parameter for energy transfer (hadronic -> electrom.)
Fe: “simultaneous” cascades
p: “consecutive” cascades

Composition parameter, from shower shape, independent of Xmax!

Shower Length from R



$$Xmax = X_1 + \Delta_o(R)$$

$\Delta_o = Xmax - X_1$

sensitive to mass

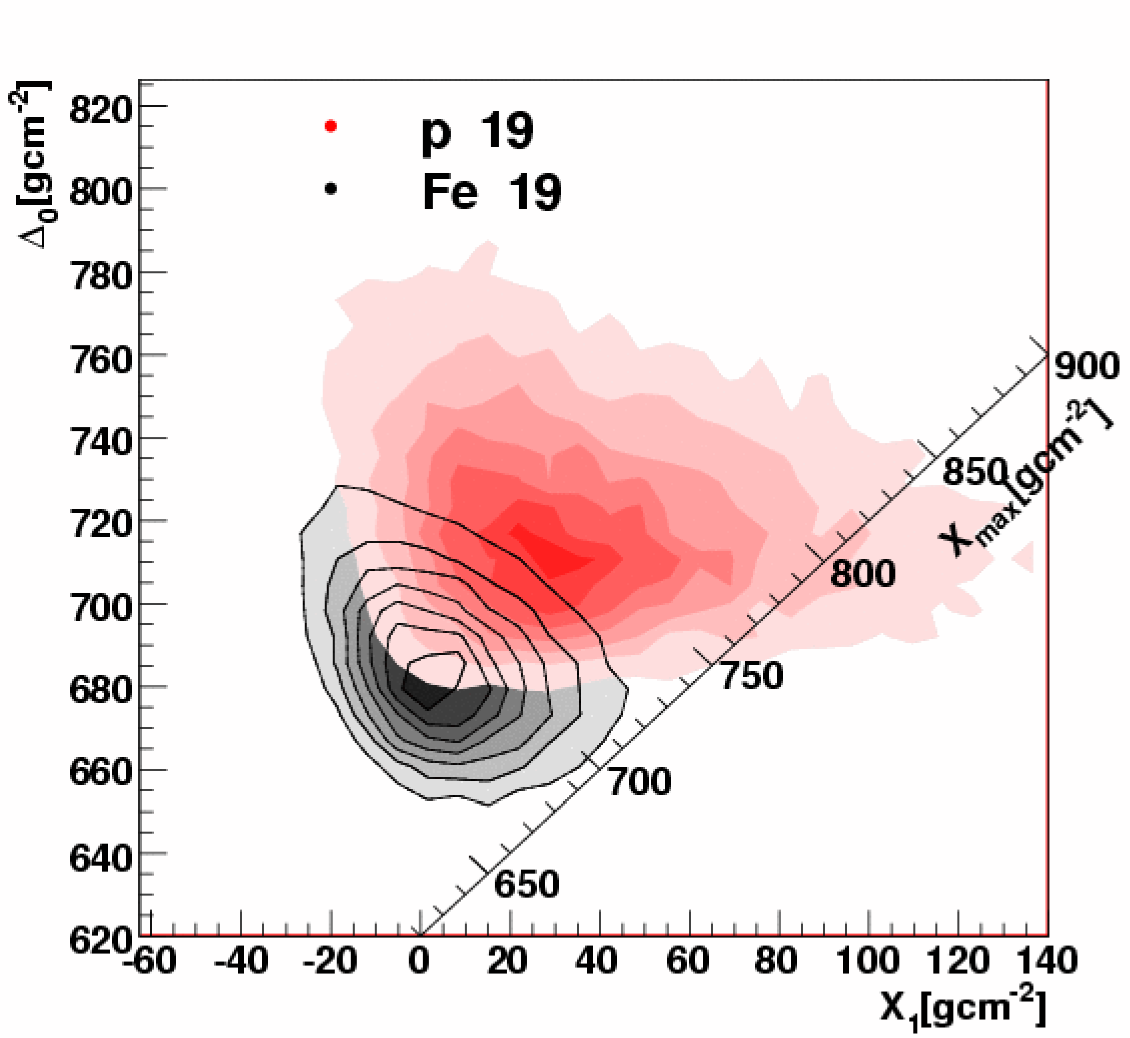
Can be reconstructed:

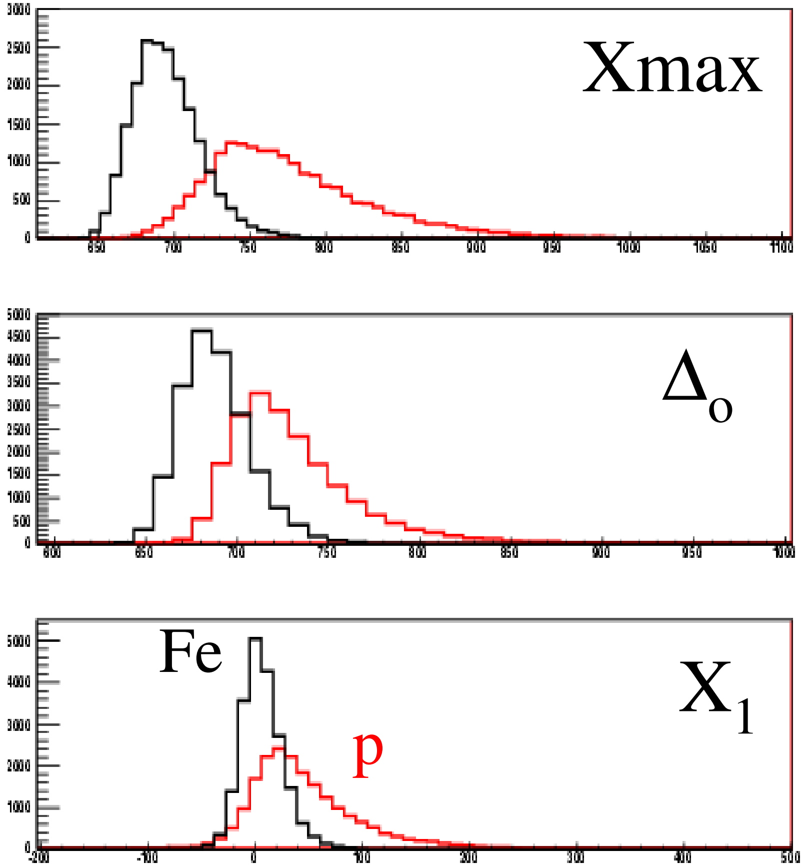
$\Delta_o(R) = a\,R + b$ (!?)

Cross-section isolated

as $X_1 = Xmax - \Delta_o\,(R)$

Mass composition and Cross-section



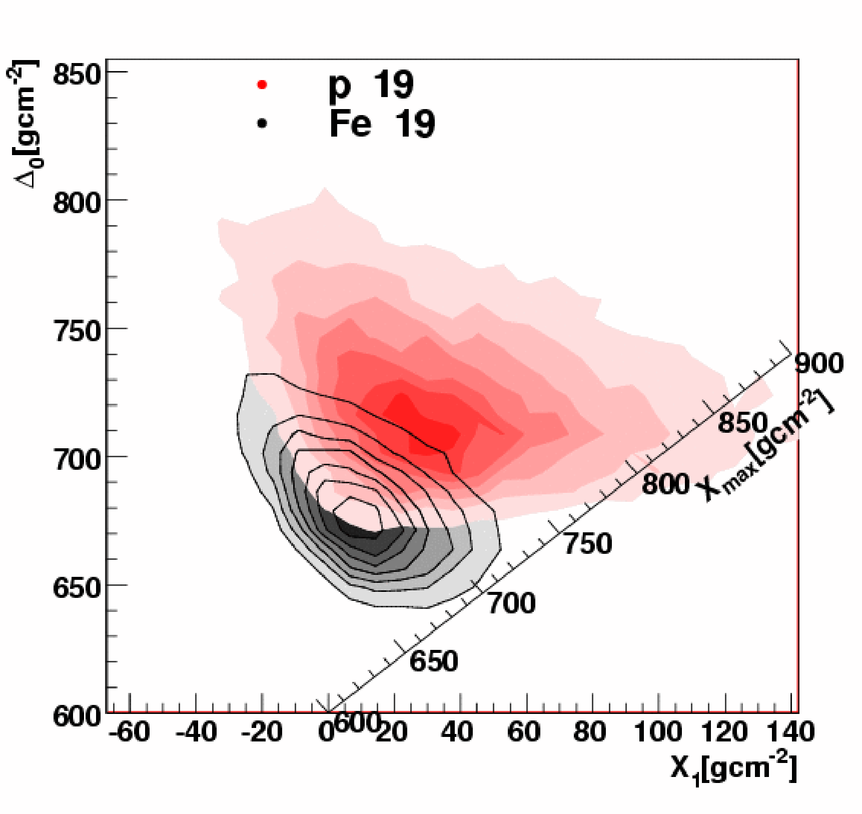


Δ_o, X_1 from R, Xmax
for each event

Xmax is best mass observable but
(Δ_o) = Mass / (X_1) = Cross-section

Sensitivity for different models

QGSJET - II



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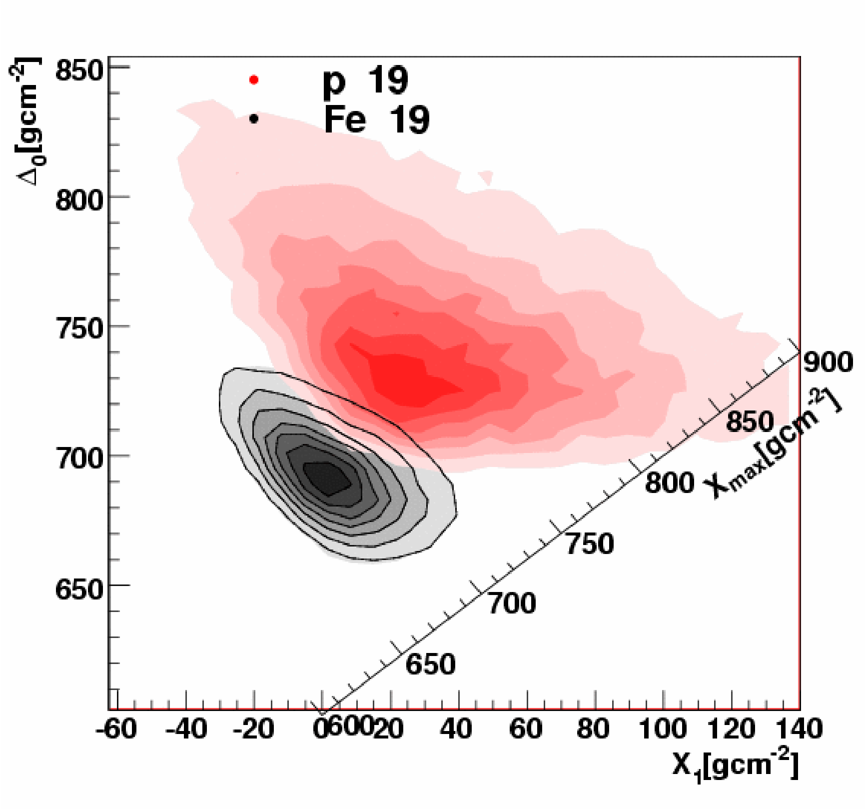


Δ_o, X_1 from R, Xmax for each event;

calibration Δ_o (R) and X_1(R, Xmax) is model independent

and should thus be derivable from data!

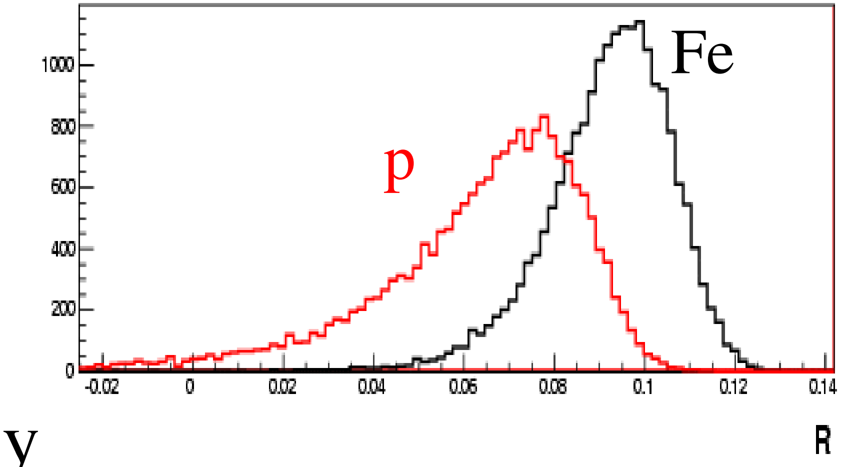
Mass Composition and Cross-section from Xmax distributions

Xmax distribution is
gaussian •exponential
for each energy bin

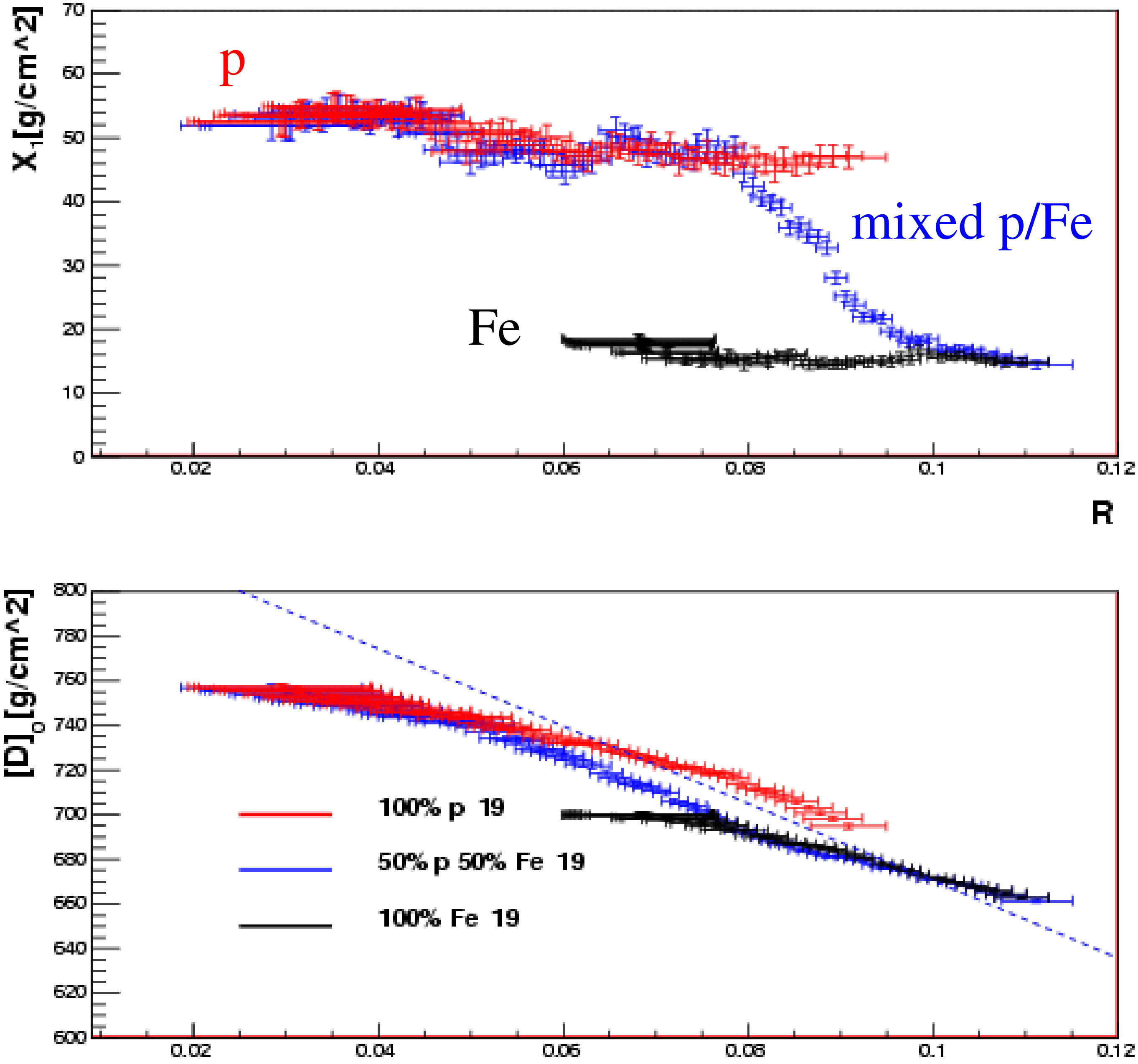
gaussian: with mean $<\Delta_o>$ and
event-by-event fluctuations
exponential with $<X_1>$
both have information on composition

Since $\Delta_o(R)$, R bins --> smaller width:
--> extra sensitivity in X_1

Different regions in R can isolate p/Fe
--> two cross-sections at same energy



Fits of Xmax distributions in R bins (fixed E)



Fit of Xmax dist. (R) give statistical means $\langle X_1 \rangle$ and $\langle \Delta_o \rangle$

$\langle X_1 \rangle$ recovered for Fe/p pure samples; or break for mixed p/Fe

$\langle \Delta_o \rangle$ changes with R; possibility to calibrate $\Delta_o(R)$ in data directly

Strategy for [future] data analysis

Reconstruction:

Shower profiles characterized by Xmax, dE/dXmax.

Confirm **L** in USP data is enough to reconstruct Energy (E).

R reconstruction from N'(X' ~ -300gcm2) and L (for long events).

Statistical Analysis:

Fit Xmax distributions in E, R bins.

Extract/confirm $\mathbf{\Delta_o}$(R) calibration and measure $\mathbf{X_1}$(R).

Possible evolution in $\mathbf{X_1}$(R) would indicate mixed composition.

Event-by-event Analysis:

Look for patterns in $\mathbf{\Delta_o}$ and $\mathbf{X_1}$: different species?

Analysis of $\mathbf{\Delta_o}$ vs. $\mathbf{X_1}$: different models?

Conclusions and Outlook

* Shower profiles characterized by Xmax, dE/dXmax, **L and R**
* Xmax and R separate $\mathbf{X_1}$ (cross-section) **and** $\mathbf{\Delta_o}$ (composition)
* Two independent event-by-event variables for both analysis

* **Resolution of L, R,** $\mathbf{X_1}$ **and** $\mathbf{\Delta_o}$ depend on detector performance
(and atmospheric conditions, possible only for long profile events)
* **Model independent**, data-driven analysis preferred

* **Statistical analysis** of cross-section and composition
* **Event-by-event separation** for cross-section/composition
* Extra information for analysis of **interaction model** parameters