Instituto de Tecnologías en Detección y Astropartículas

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Core-corona approach and the muon deficit

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Based on arXiv:1902.09265 from Baur, Dembinski, Perlin, Pierog, Ulrich, Werner

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Annual meeting of DDAp and HIRSAP 2020

Outline

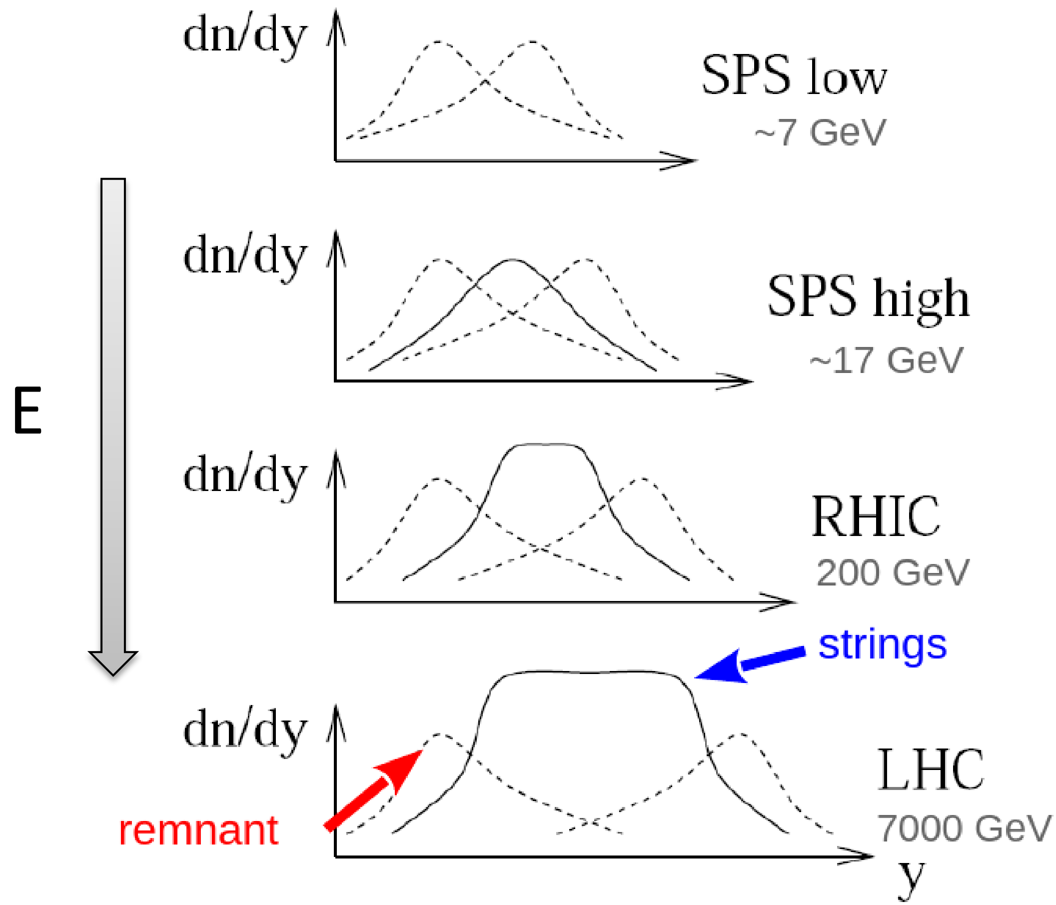
First part

- Particle production and collective flows
- *Core-Corona* approach
- Impact on the number of muons

Second part

- Muon Lateral Distribution analysis
- UMD data analysis

Particle Production



Only particles from remnants

Strong mixing

Mainly string contribution at mid rapidity with tail of remnants

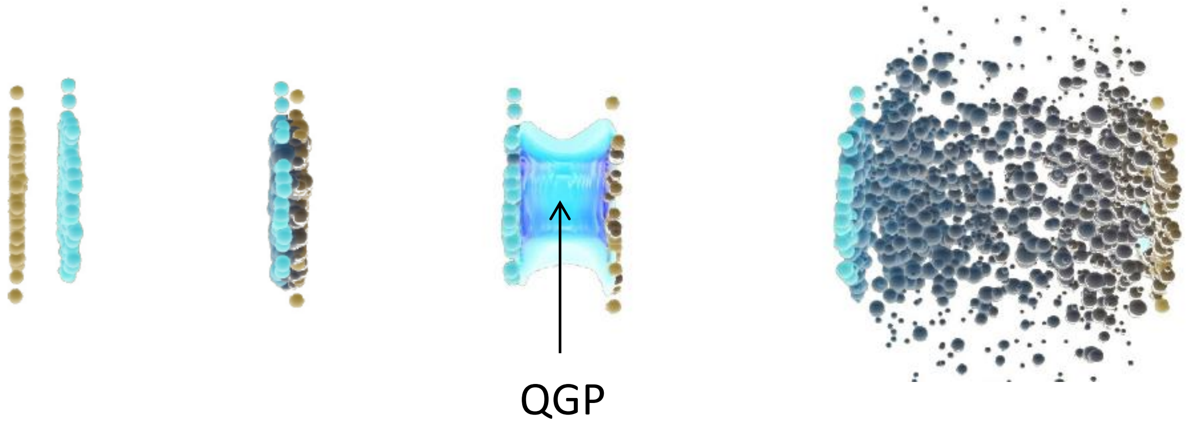
Only string contribution at mid rapidity

Forward particles are mainly from remnant

At higher energies it is necessary to modify the string fragmentation and/or to take a different approach

Collective flows

Evolution of high energy heavy-ion collision



Multiplicity of released partons is so large that
the existence of a quark-gluon-plasma (**QGP**) is commonly assumed

- Evolves according to the laws of hydrodynamics (**collective flow)**
- **Statistical Hadronization**
- It has already been observed at RHIC and LHC

Even **p-p interactions** at high enough energies can be viewed as collisions of light nuclei with collective flow in the highest multiplicity events.

The main goal is to show that collectivity in collisions of hadrons and nuclei can play a so far underestimated role in the understanding of muon production in air showers.

Core-Corona

The final state particles originate from three different production mechanisms

- **Core**: High density → **Statistical hadronization**
- **Corona**: Low density → **Standard string fragmentation (implemented in all HE models)**
- Decay of the beam remnants

Each one gives different particle ratios

We expect a larger muon production in the core. Why? → Heitler-Matthews Model

The number of muons depends strongly on the neutral pion and the total particle multiplicities of hadronic interactions.

$$N_\mu = \left(\frac{E_0}{E_{\mathrm{dec}}}\right)^\beta$$

These multiplicities depend on the hadronization model.

$$\beta = 1 + \frac{\ln(1-c)}{\ln N_{\mathrm{mult}}}$$

The core produces more baryons than the corona, hence *c* decreases and **the number of muon increases**.

$$c = N_{\pi^0} / N_{\mathrm{mult}}$$

We define a ratio sensitive to the hadronization and closely related to c.

$$R(\eta) = \frac{\langle \mathrm{d}E_{\mathrm{em}}/\mathrm{d}\eta \rangle}{\langle \mathrm{d}E_{\mathrm{had}}/\mathrm{d}\eta \rangle}$$

Core-Corona

At mid-rapidity the particles come from the core or the corona

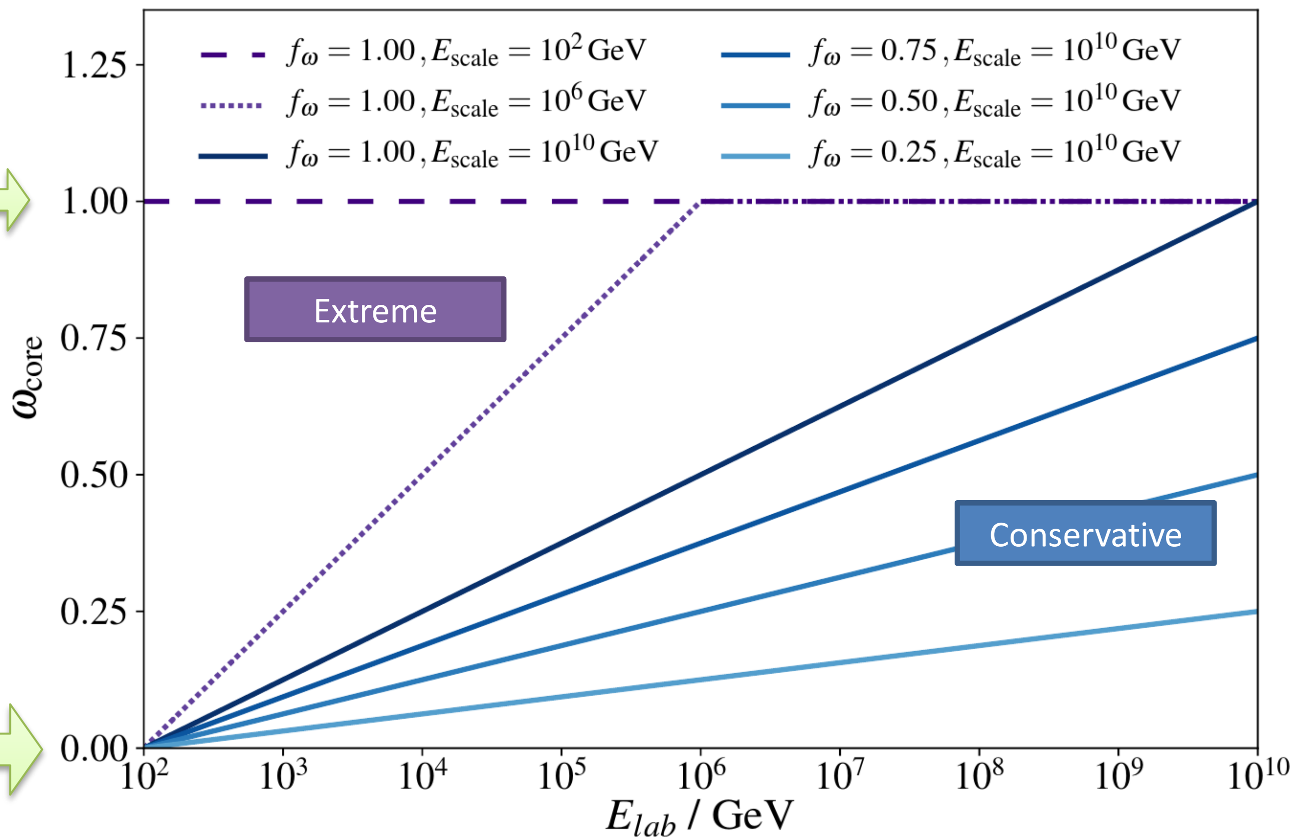
$$N_i = \omega_{\mathrm{core}}\, N_i^{\mathrm{core}} + (1 - \omega_{\mathrm{core}})\, N_i^{\mathrm{corona}}$$

$$\omega_{\mathrm{core}}(E_{\mathrm{lab}}) = f_\omega\, \underbrace{F(E_{\mathrm{lab}}; E_{\mathrm{th}}, E_{\mathrm{scale}})}_{\dfrac{\log_{10}(E_{\mathrm{lab}}/E_{\mathrm{th}})}{\log_{10}(E_{\mathrm{scale}}/E_{\mathrm{th}})} \text{ for } E_{\mathrm{lab}} > E_{\mathrm{th}}}$$

$$E_{\mathrm{th}} = 100\,\mathrm{GeV}$$

The particle ratios are modified from the corona to the core taking different values of f_ω and E_{scale}

Core hadronization



Corona hadronization (Unmodified Model)

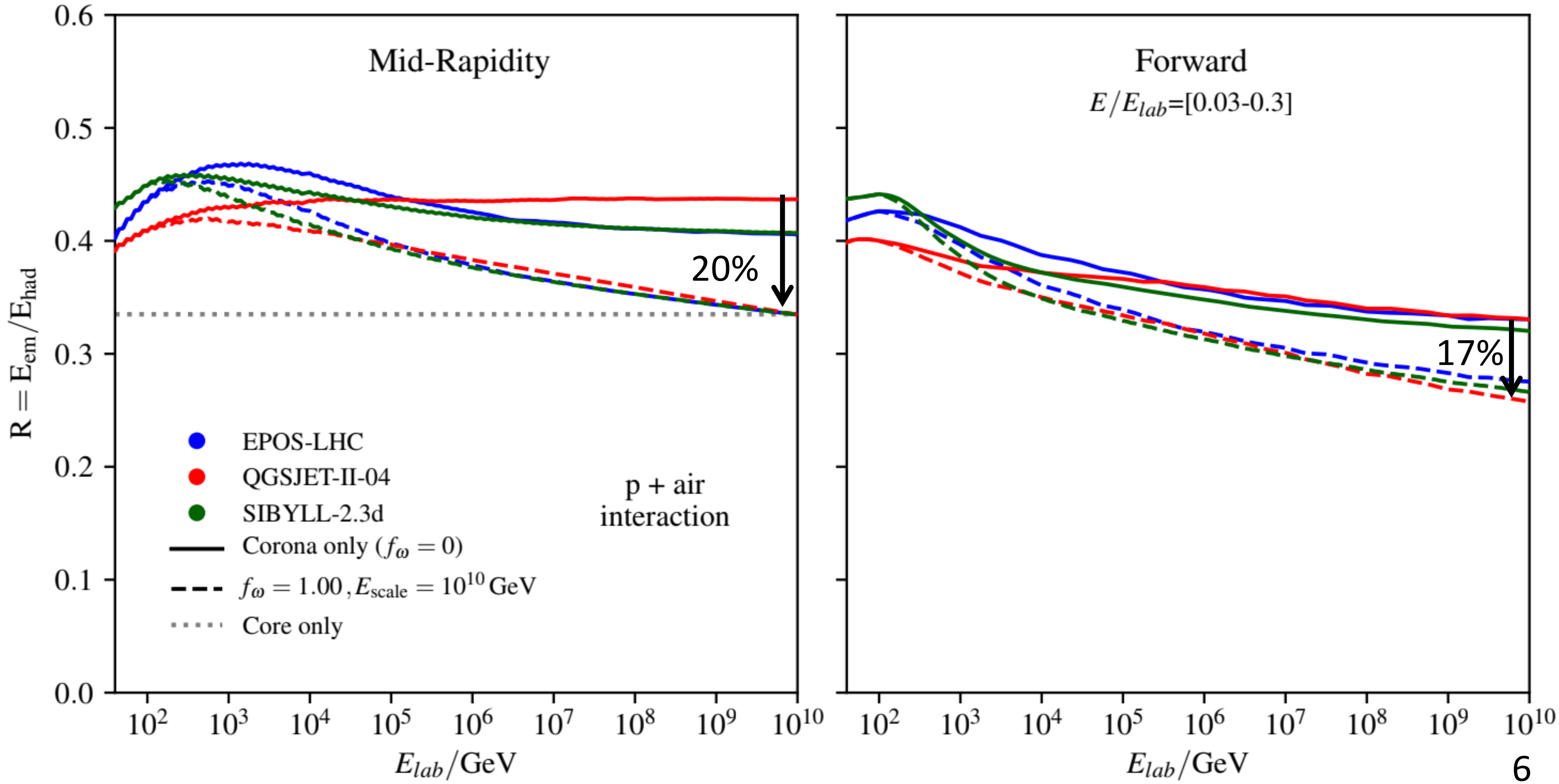
Core-Corona

The Core-Corona model is set by ω_{core} which gives different particle ratios.

$$N_i = \omega_{\rm core}\, N_i^{\rm core} + (1-\omega_{\rm core})\, N_i^{\rm corona}$$

See GAP 2020-041

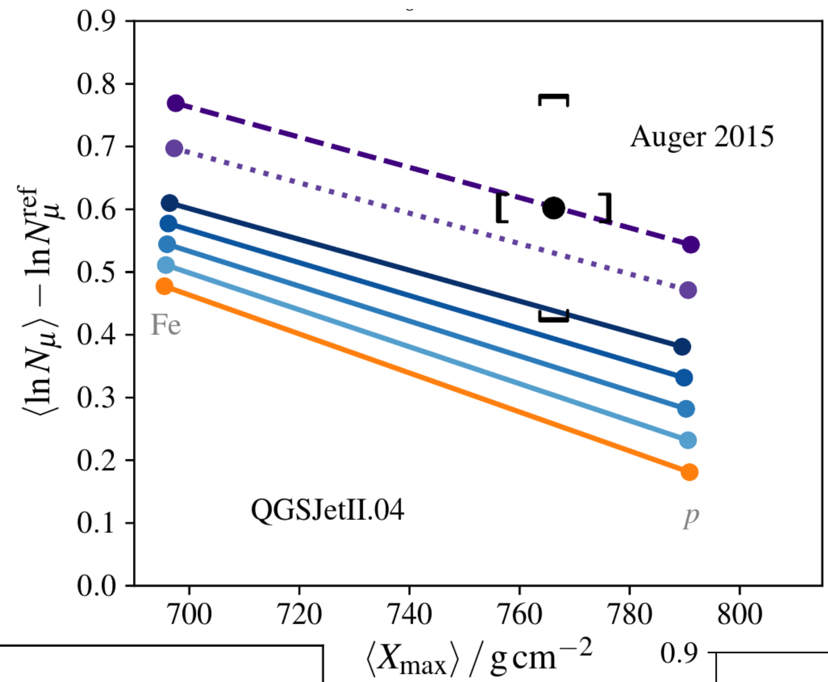
In order to get these ratios we modify the energy spectra used by CONEX in the cascade equation analysis (remnants are not modified)

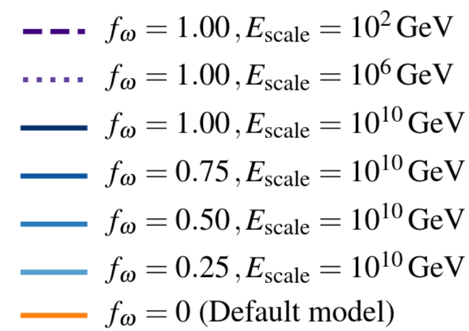


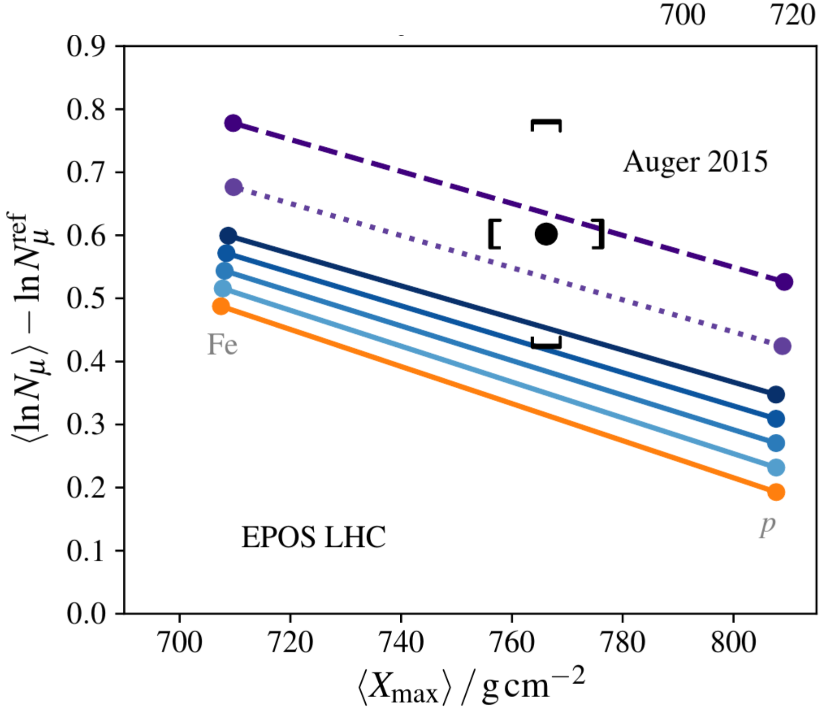
Number of muons vs X_{max}

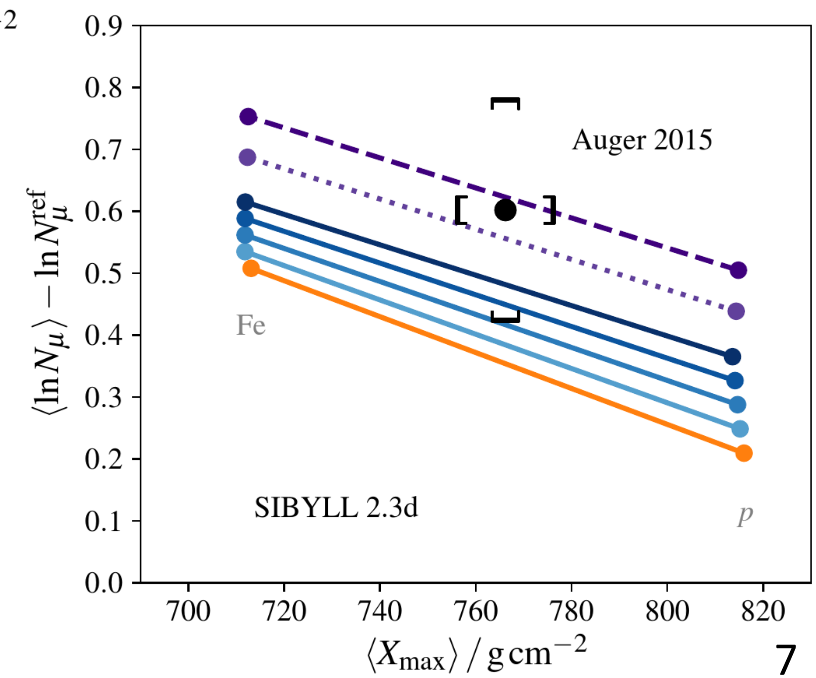
Full cascade equation showers

$E = 10^{19}$ eV





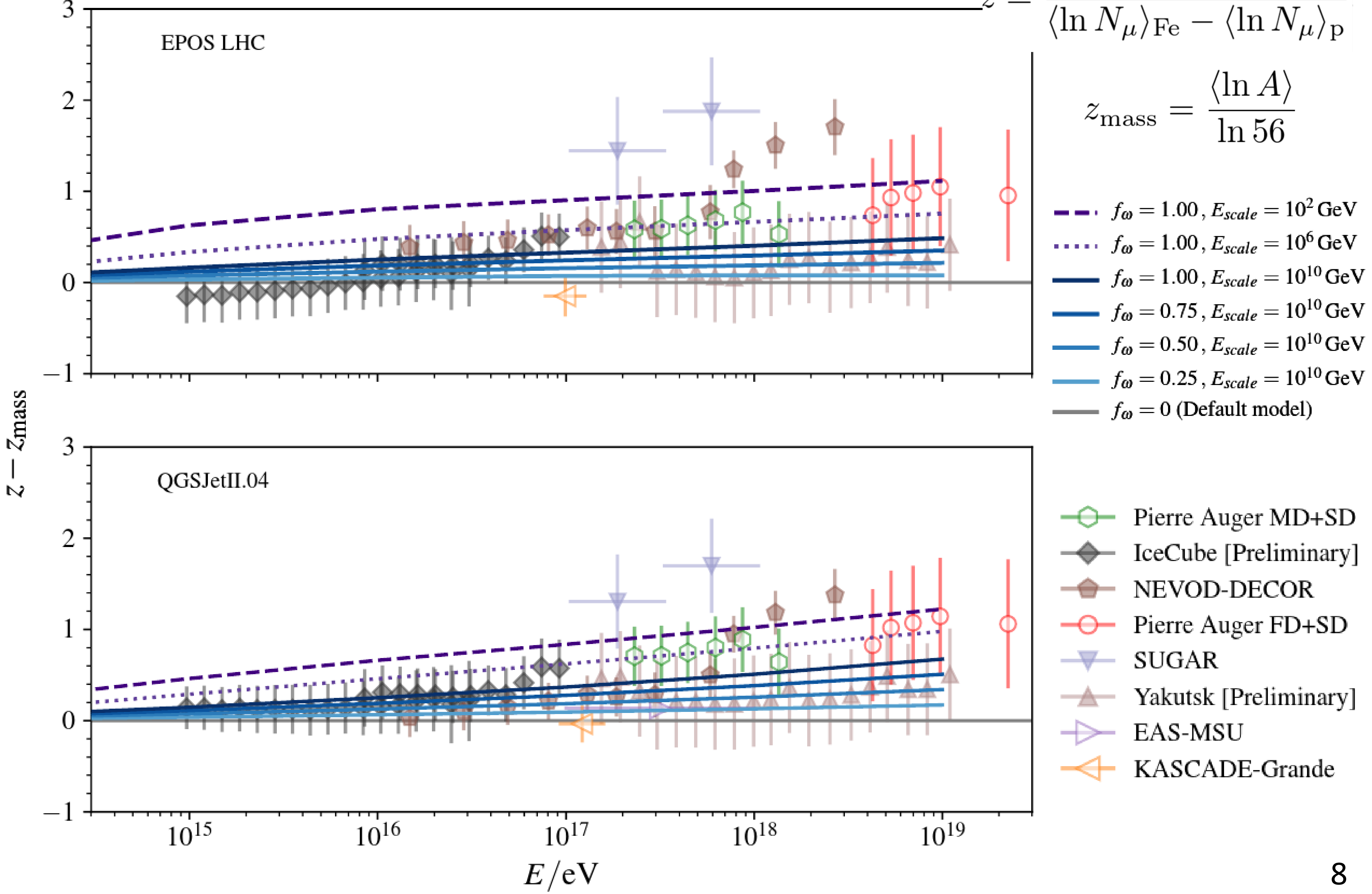




Z factor

$$z = \frac{\langle \ln N_\mu \rangle - \langle \ln N_\mu \rangle_\mathrm{p}}{\langle \ln N_\mu \rangle_\mathrm{Fe} - \langle \ln N_\mu \rangle_\mathrm{p}}$$

$$z_\mathrm{mass} = \frac{\langle \ln A \rangle}{\ln 56}$$



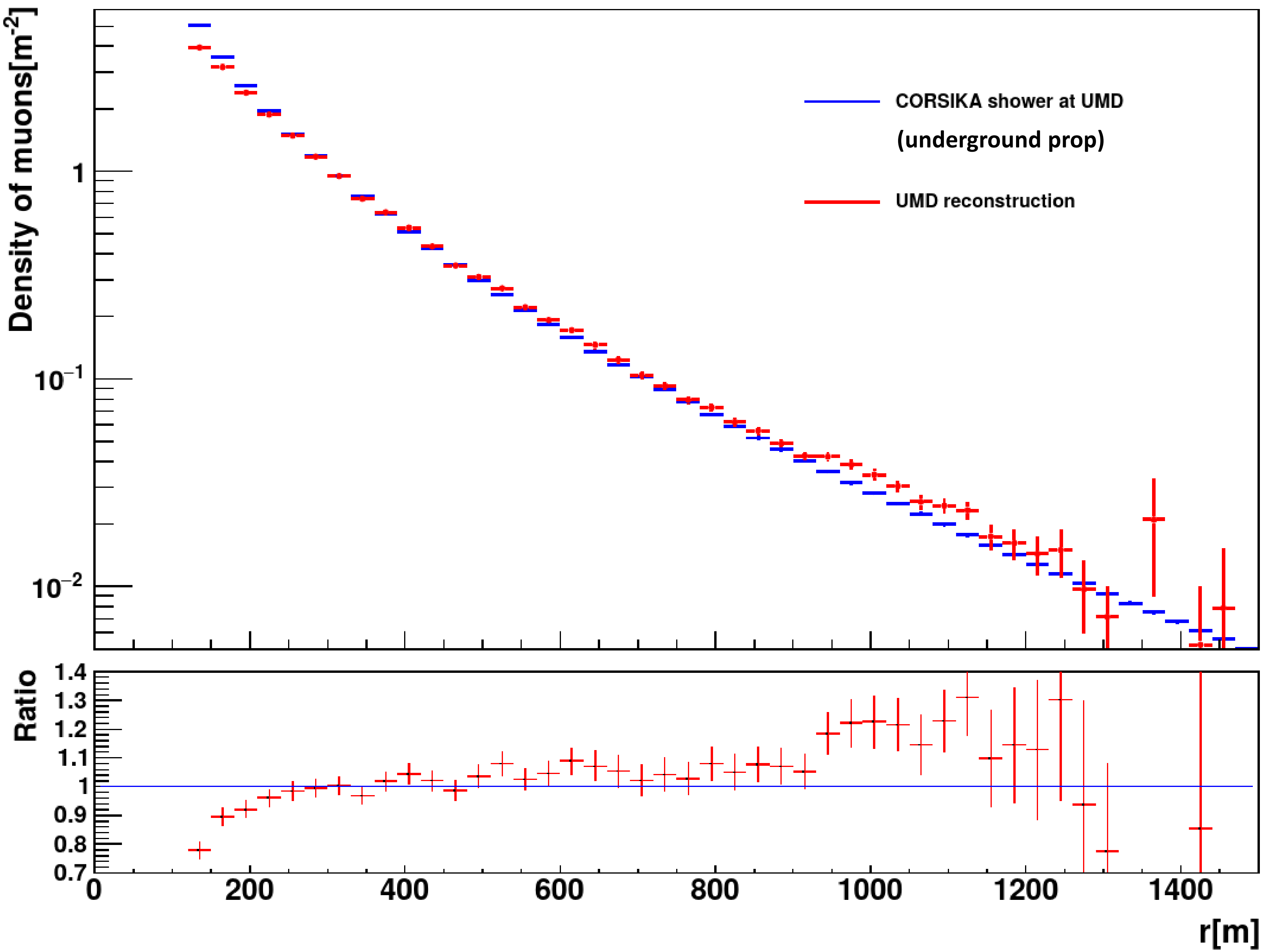
Muon Lateral Distribution Analysis

In the previous slides we have studied the muon production in 1D with showers from pure cascade equations (CONEX showers).

Now we focus on how the muon lateral distribution is affected by the Core-Corona model using 3D CONEX showers.

In particular we analyze the UMD data at $10^{17.5}$ eV.

CORSIKA showers vs UMD Reconstruction



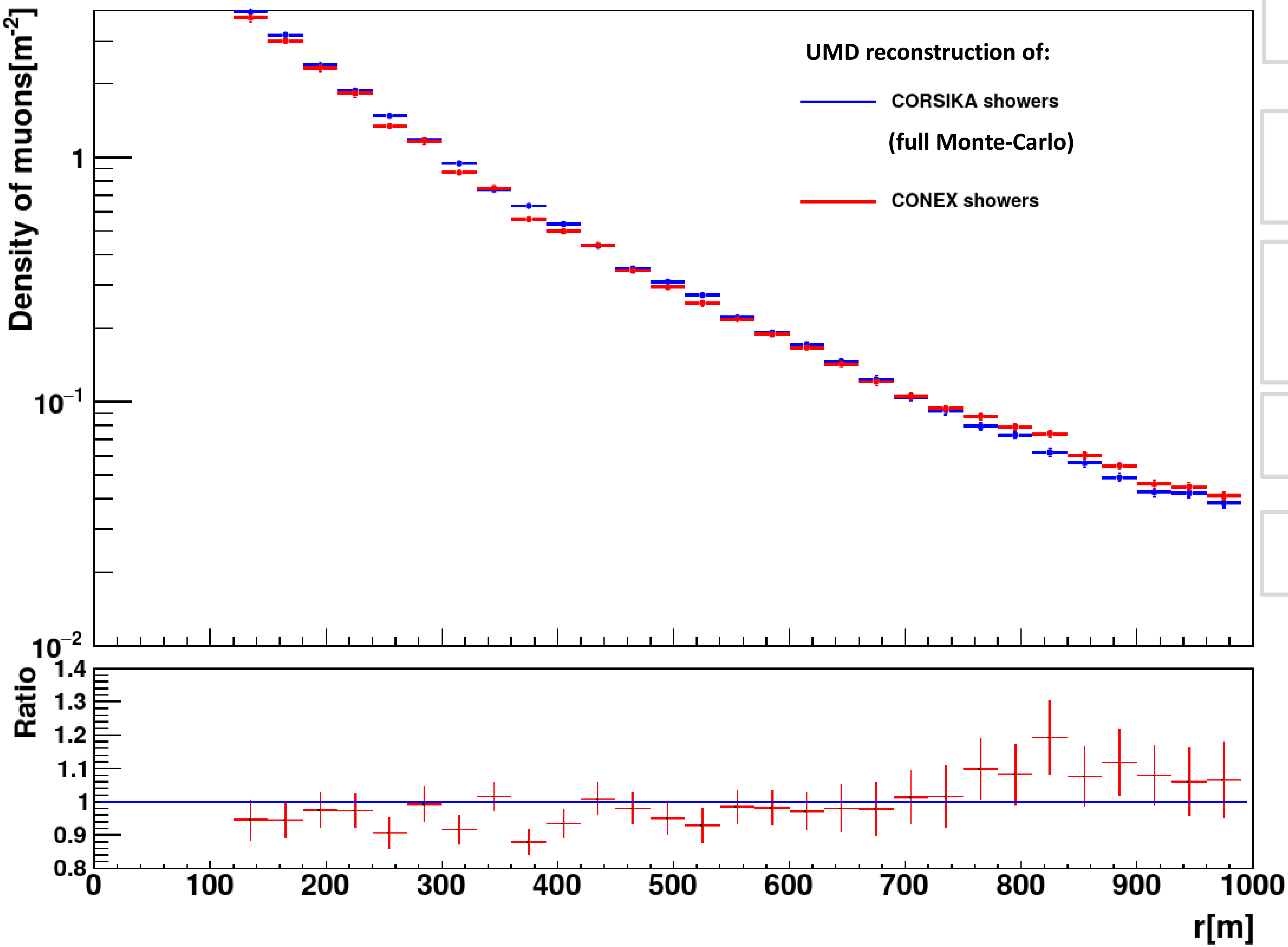
Proton Showers
Log(E/eV)=17.5
Theta=0

120 showers
Used 10 times

ToTd/MoPS
trigger

EPOS-LHC

UMD reconstruction: CORSIKA vs CONEX



Proton Showers
Log(E/eV)=17.5
Theta=0

120 showers
Used 10 times

240 CONEX
showers
Used 10 times

ToTd/MoPS
trigger

EPOS-LHC

UMD Data Analysis

Based on
GAP 2020-021
N. González et al.

- Period: January 2018 to August 2020
- Trigger at least T4
- Muon density was obtained from the binary traces
- Pattern "1111"
- Veto window of 56.25 ns (18 time bins)
- Reported bad periods were taken into account
- ToTd/MoPS were applied
- LDF is fit via least squares with a Modified NKG :

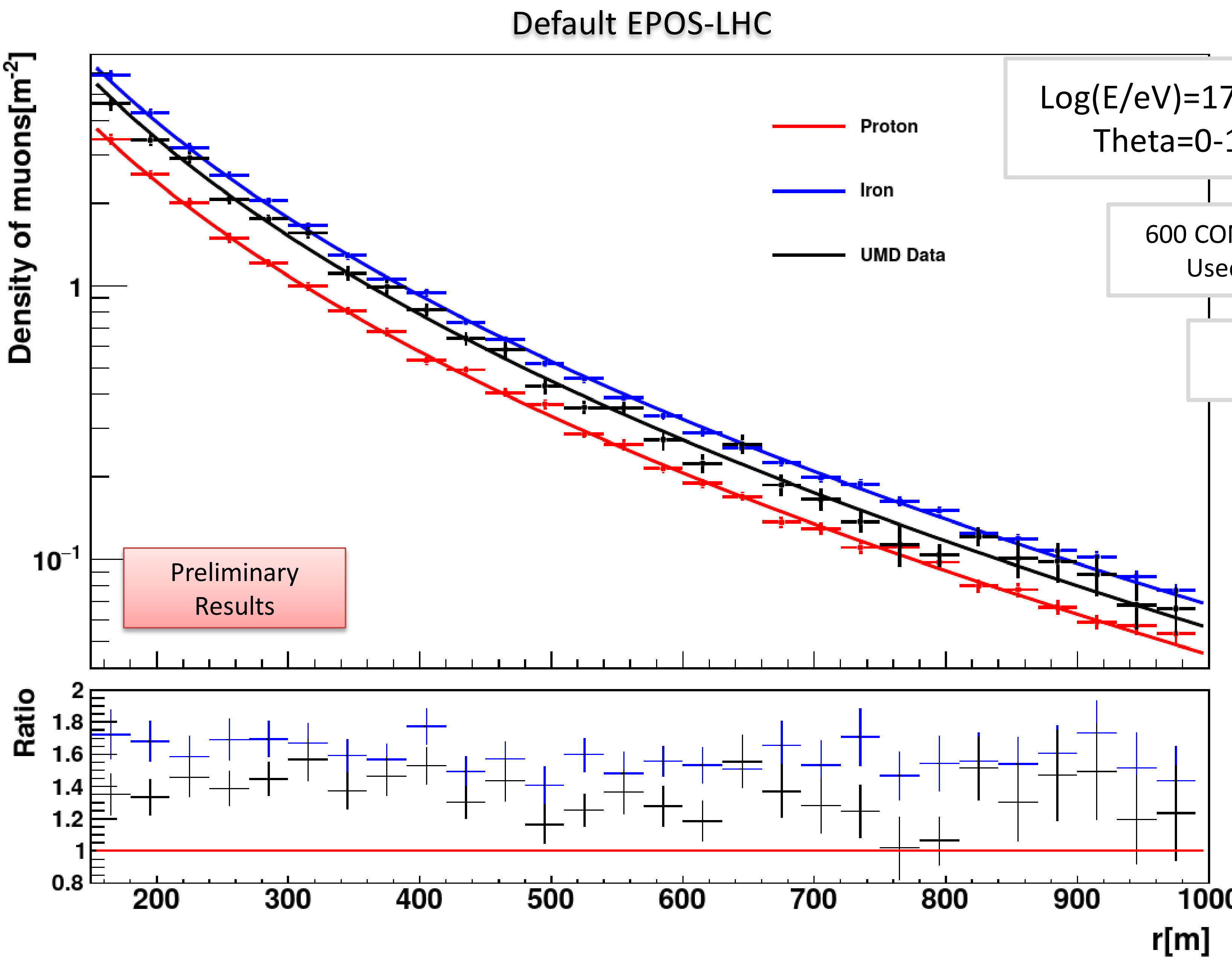
$$\rho_\mu^{\text{model}}(r \mid E, \theta) = \rho_0 \times \left(\frac{r}{r^*}\right)^{-\alpha} \times \left(1 + \frac{r}{r^*}\right)^{-\beta} \times \left(1 + \left(\frac{r}{10r^*}\right)^2\right)^{-}$$

$r^* = 32^{0}$ m
$\alpha = 0.75$
$\gamma = 3.0$

See F. Gesualdi’s talk

The measured muon density was averaged over each energy and theta bin

Data and Core-Corona

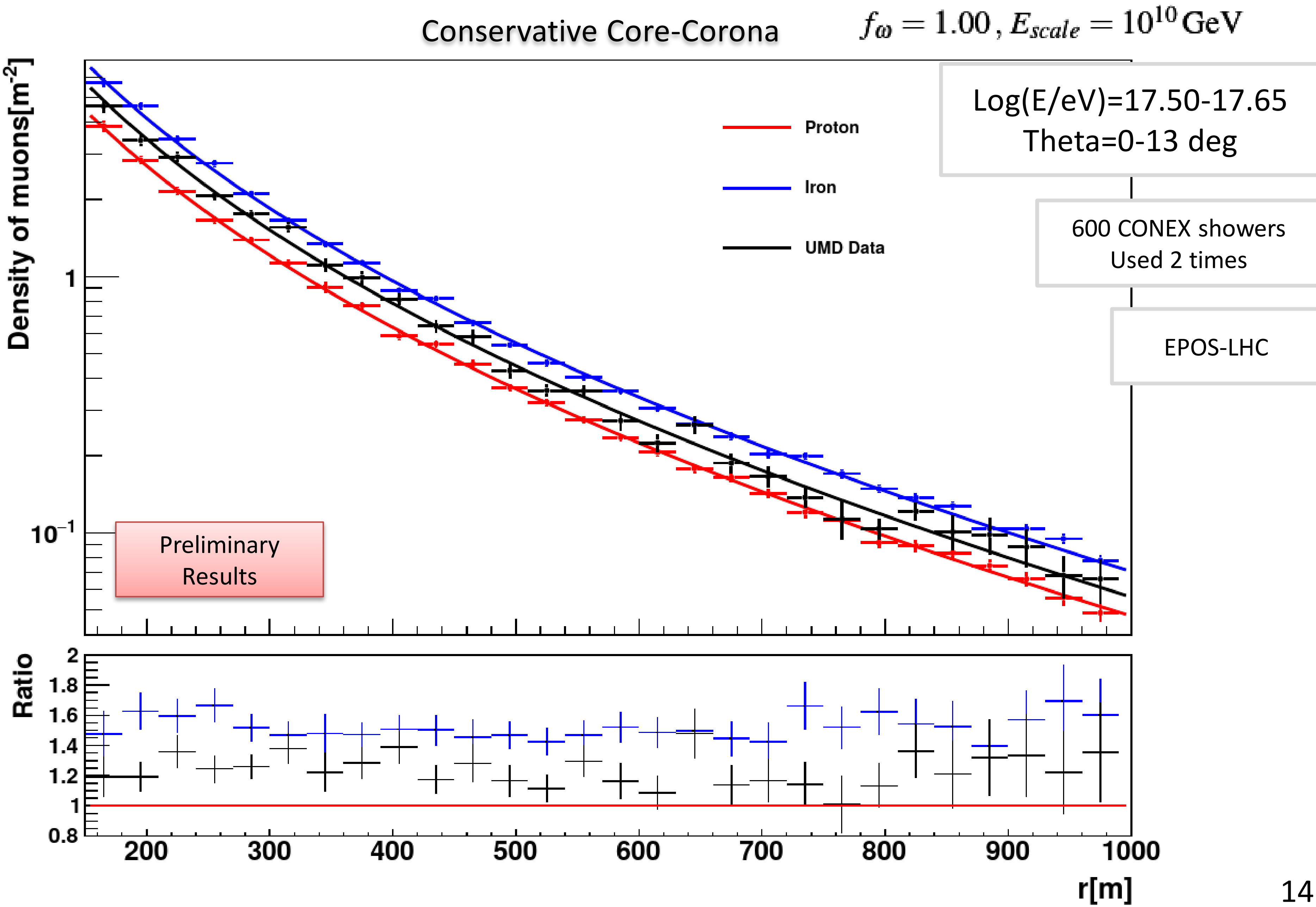


Log(E/eV)=17.50-17.65
Theta=0-13 deg

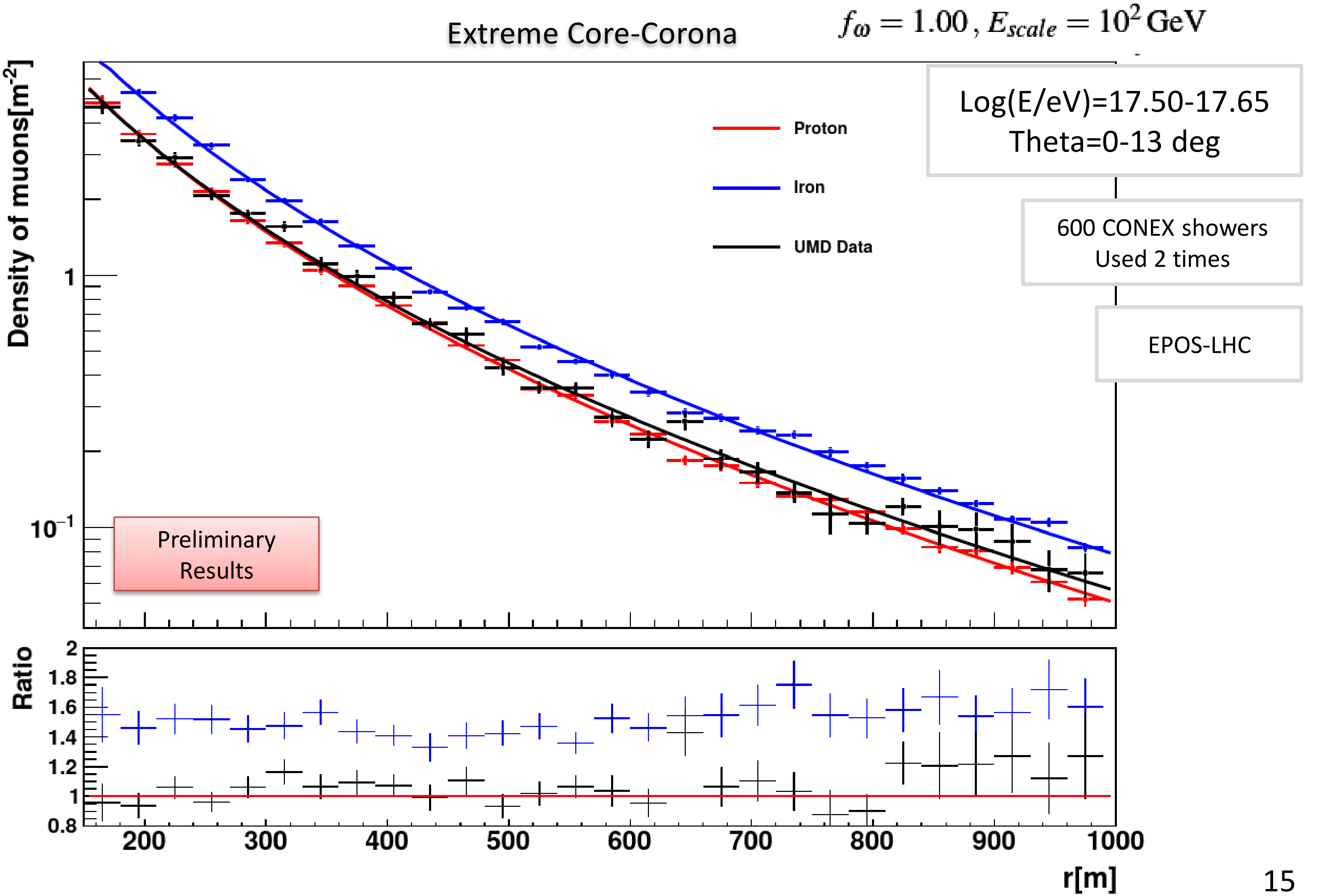
600 CONEX showers
Used 2 times

EPOS-LHC

Data and Core-Corona



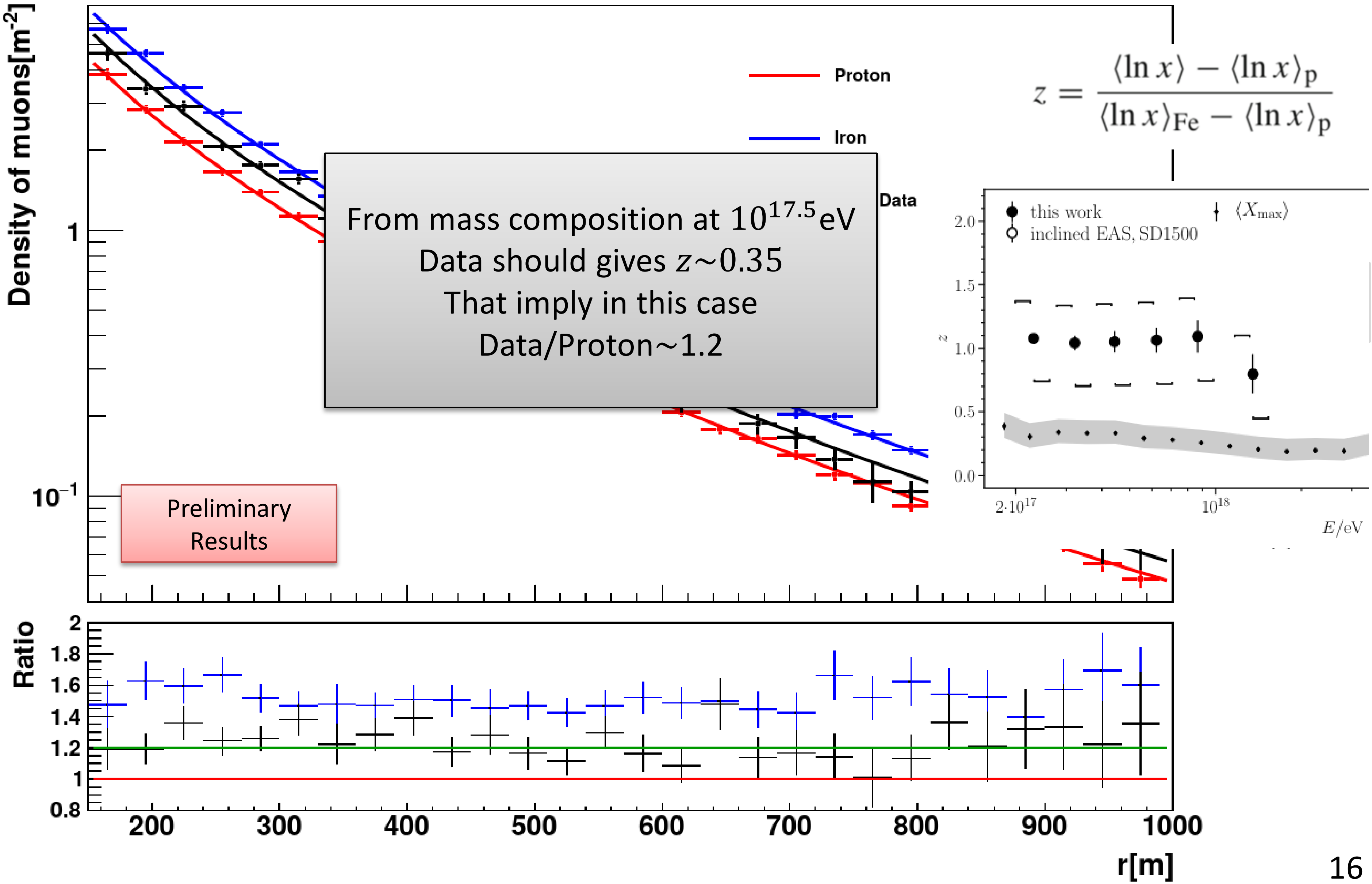
Data and Core-Corona



Data and Core-Corona

Conservative Core-Corona $f\omega = 1.00\,,\, E_{scale} = 10^{10}\,\mathrm{GeV}$

$$z = \frac{\langle \ln x \rangle - \langle \ln x \rangle_{\mathrm{p}}}{\langle \ln x \rangle_{\mathrm{Fe}} - \langle \ln x \rangle_{\mathrm{p}}}$$



From mass composition at $10^{17.5}$eV
Data should gives $z{\sim}0.35$
That imply in this case
Data/Proton~1.2

Preliminary Results

Summary

In the first part :

- We have shown that the muon production significantly depends on the ratio $R = E_{em} / E_{had}$, which depends on the hadronization mechanism.

- Conservative core-corona scenarios can reproduce the muon measurements for most experiments.

In the second part:

- UMD data was analyzed and compared successfully with the model.

- Conservative Core-Corona approach gives the expected lateral distribution by mass composition

Preliminary Results!!

Next step

- Extend the analysis to other energies and zenith angles and determine ω_{core} needed to reproduce data

Thanks for your attention

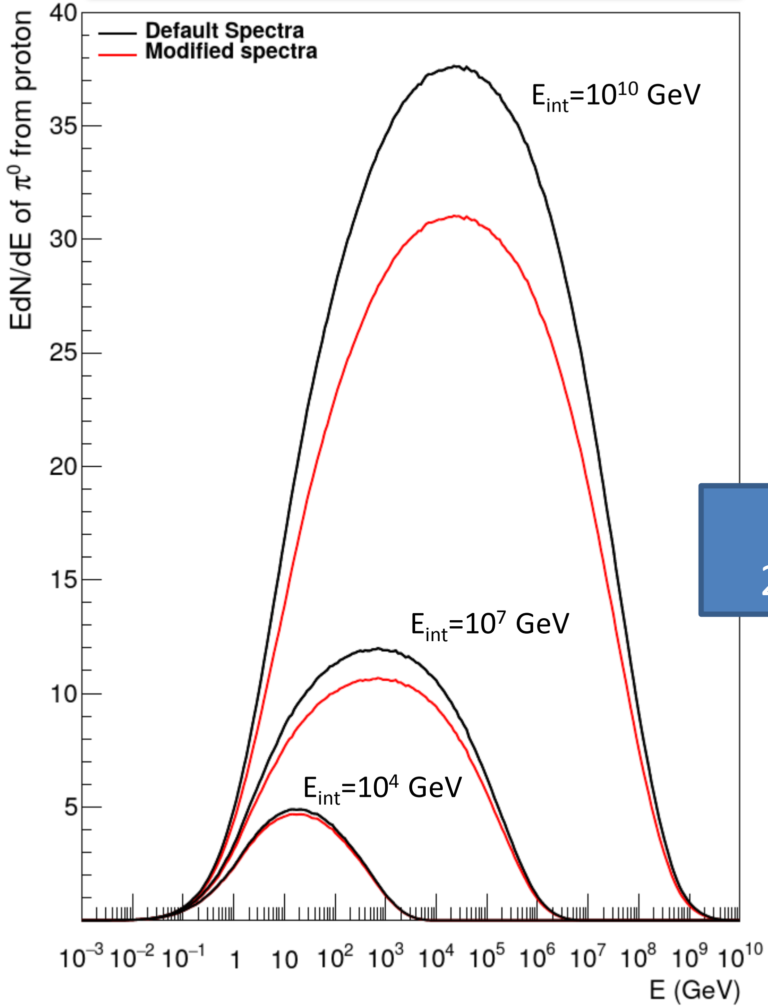
BACK-UP SLIDES

Energy spectra in CONEX

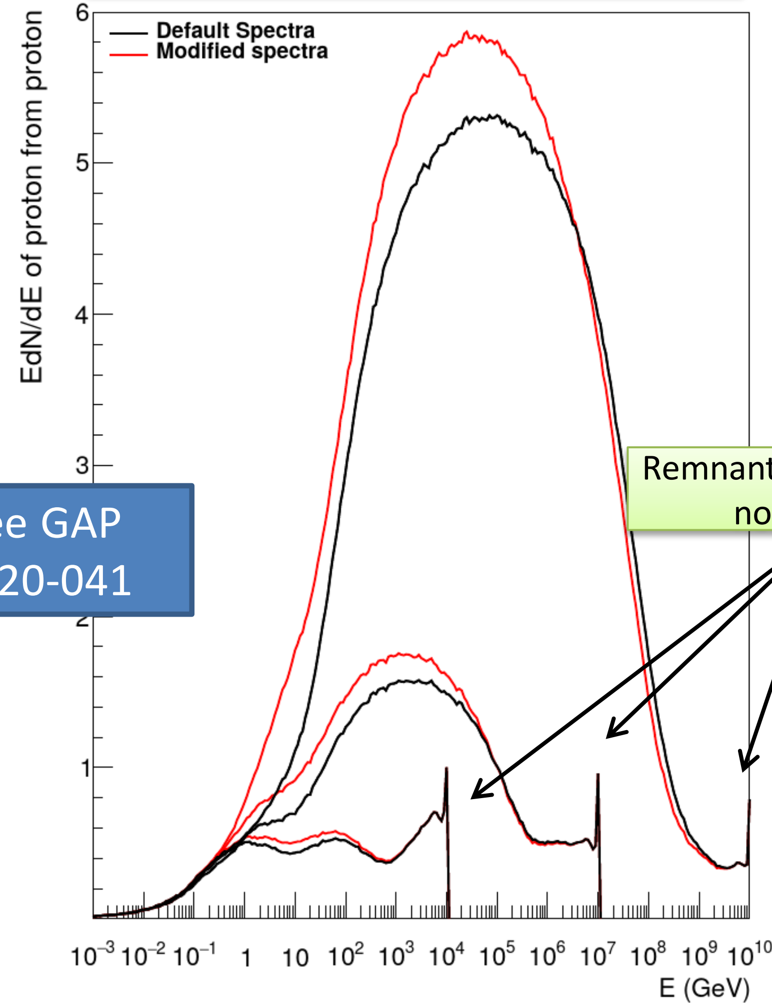
Let's see how the spectra change in proton-air interaction for the case

$$f_\omega = 1.00$$
$$E_{\rm scale} = 10^{10}\,\mathrm{GeV}$$

Spectra modified by a scale function



Spectra modified by E conservation



Remnant contribution is not affected

See GAP 2020-041

Spectra of neutral pions and protons in p + air interaction at three different proton energies

Core-Corona approach

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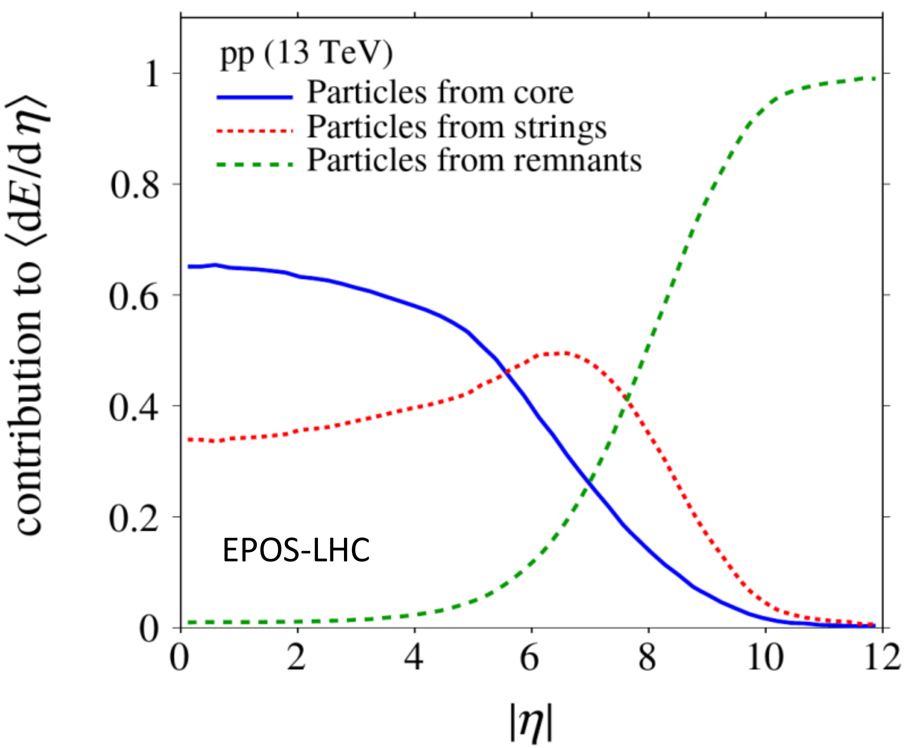
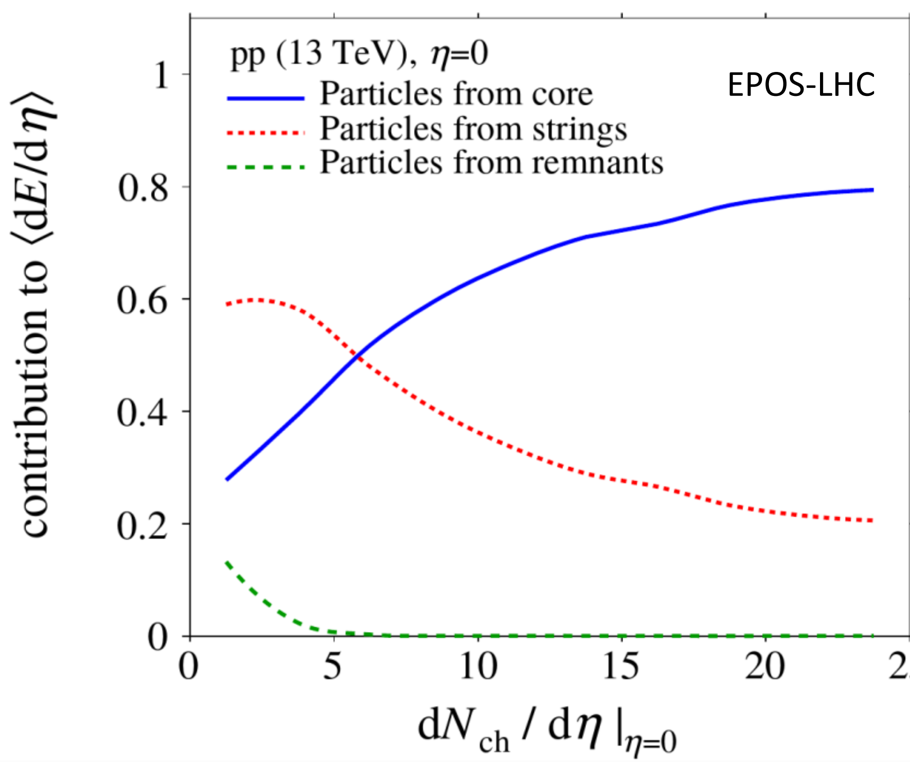


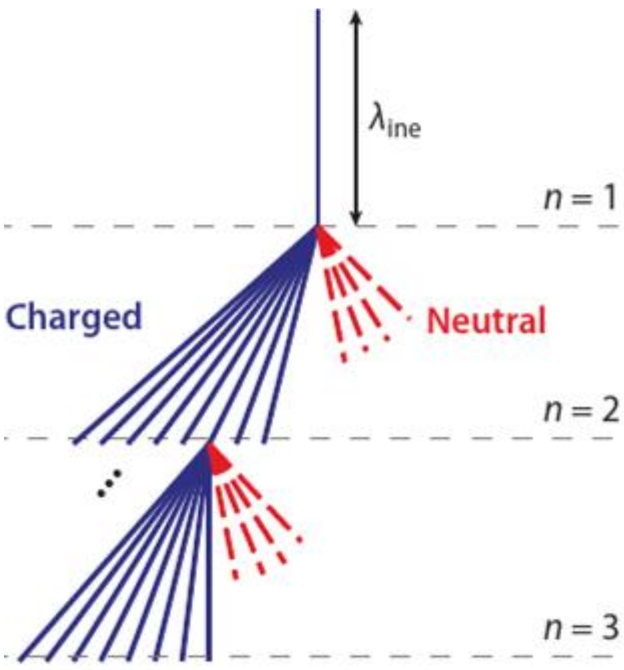


Heitler-Matthews Model

The number of muons depends strongly on the neutral pion and the total particle multiplicities of hadronic interactions.

$$N_\mu = \left(\frac{E_0}{E_{\rm dec}}\right)^\beta \qquad \beta = 1 + \frac{\ln(1-c)}{\ln N_{\rm mult}}$$

$$c = N_{\pi^0}/N_{\rm mult}$$



These multiplicities depend on the hadronization model.

The **core produces more baryons than the corona**, hence *c* decreases and the **number of muon increases**.

We define a ratio sensitive to the hadronization and closely related to c.

$$R(\eta) = \frac{\langle {\rm d}E_{\rm em}/{\rm d}\eta\rangle}{\langle {\rm d}E_{\rm had}/{\rm d}\eta\rangle}$$

Collective flows

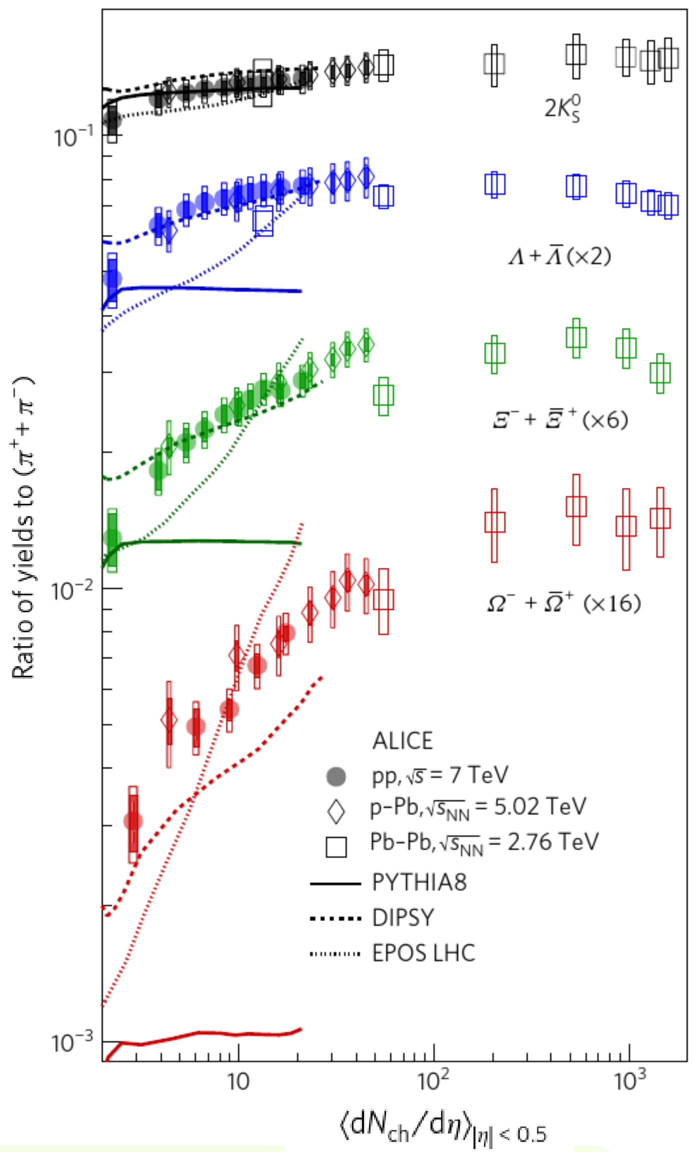
High-energy **A–A interactions**

Multiplicity of released partons is so large that they interact strongly among each other leading to "**collective flow**" behaviors, which has already been observed at RHIC and LHC.

The existence of a quark-gluon-plasma (**QGP**) is commonly assumed

- Evolves according to the laws of hydrodynamics
- **Statistical Hadronization**

Even **p-p interactions** at high enough energies can be viewed as collisions of light nuclei with collective flow in the highest multiplicity events.



The main goal is to show that collectivity in collisions of hadrons and nuclei can play a so far underestimated role in the understanding of muon production in air showers.

Statistical Hadronization Model (SHM)

It is mainly applied to heavy ion collision.
This model has given strikingly good results in elementary collisions as well.

The physical picture of a high energy collision is:
Underlying non-perturbative strong-interaction dynamics eventually giving rise to the formation of colourless extended massive objects

Clusters or fireballs

Clusters decay coherently into multihadronic states in a purely statistical fashion
Hadronization occurs at some critical energy density of a number of clusters.

The single cluster's decay rate into any channel would be determined only by its phase space with no special dynamical weight

Phase space dominance

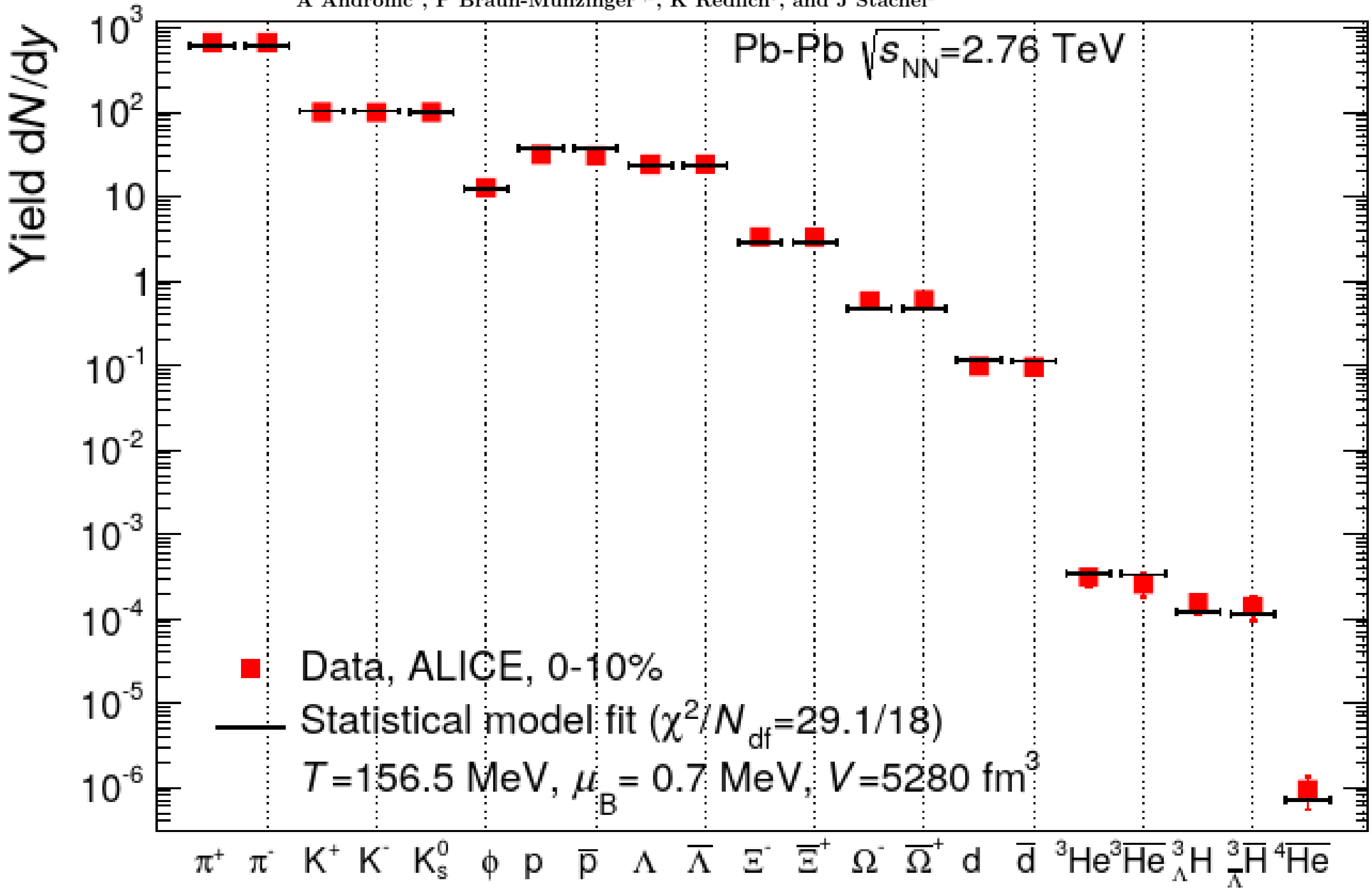
<u>SHM lies in two assumptions</u>

- In the late stage of a high energy collision, clusters are produced which decay into hadrons at a critical value of energy density or some other relevant parameter
- All multihadronic states within the cluster compatible with its quantum numbers are equally likely

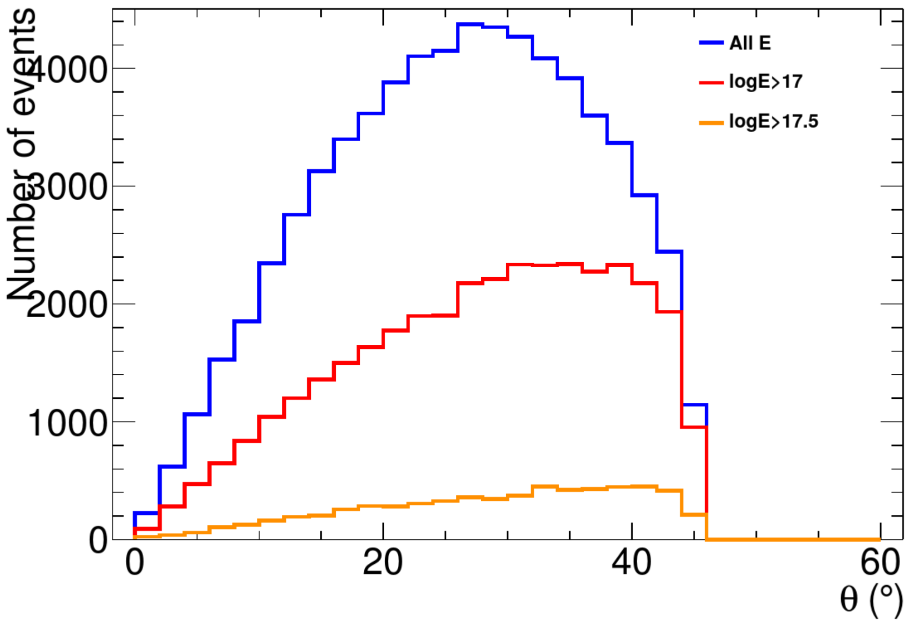
Statistical Hadronization Model (SHM)

Hadron yields, the chemical freeze-out and the QCD phase diagram

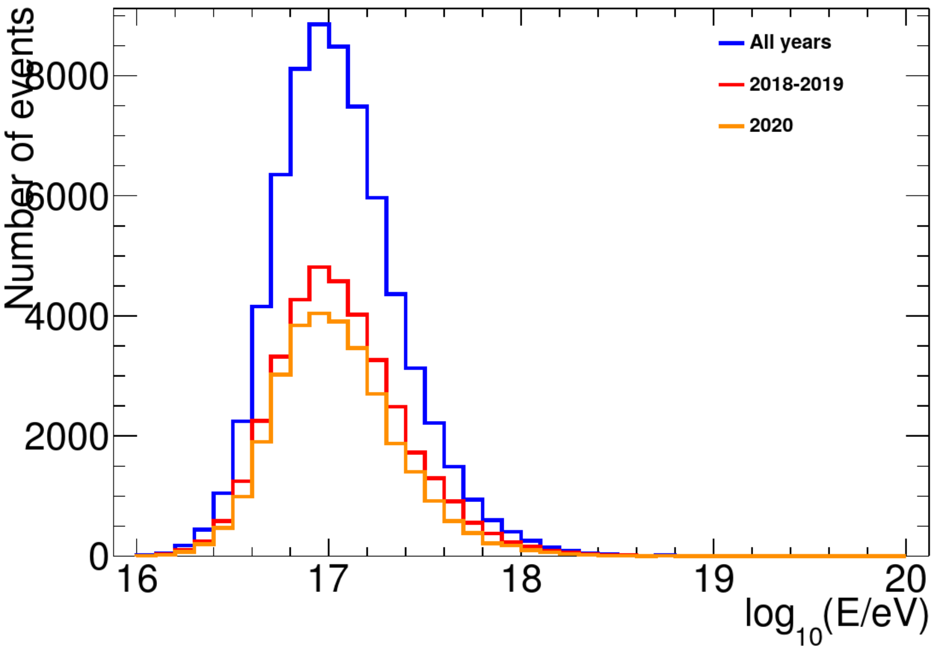
A Andronic[1], P Braun-Munzinger[1,2], K Redlich[3], and J Stachel[2]



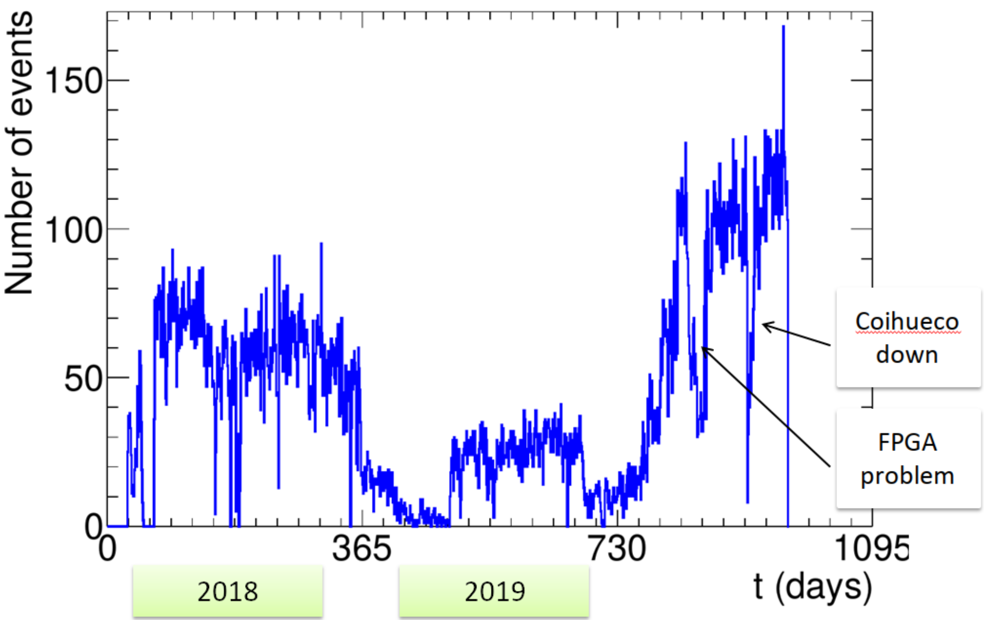
UMD Data



Number of events
All E
logE>17
logE>17.5
θ (°)

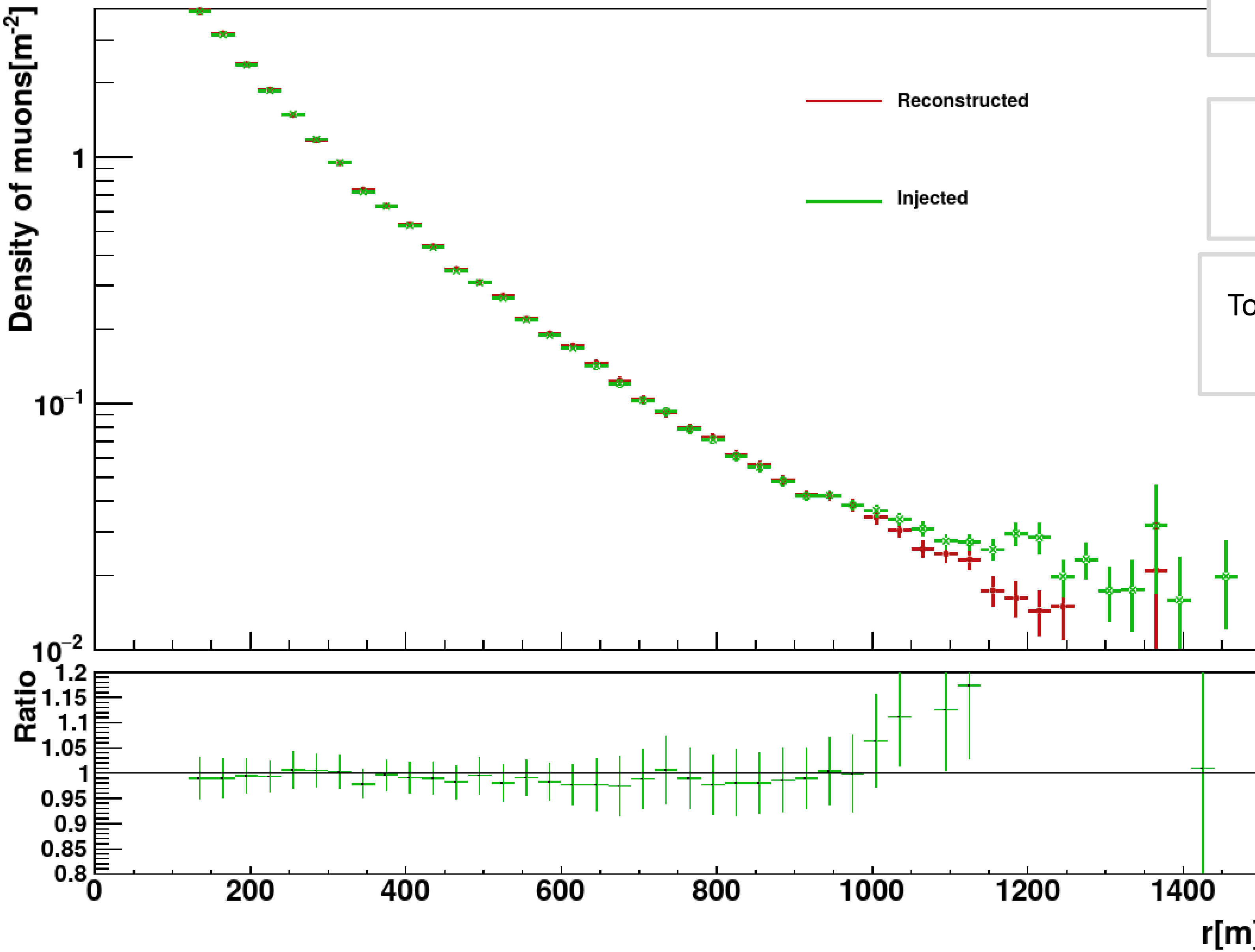


Number of events
All years
2018-2019
2020
$\log_{10}$(E/eV)



Number of events
Coihueco down
FPGA problem
t (days)
2018
2019

Reconstructed vs injected



Proton Showers
Log(E/eV)=17.5
Theta=0

Full MC
120 showers
Rec 10 times

ToTd and MOPS trigger