# Can We Observe the Quark Gluon Plasma in Cosmic Ray Showers ?

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## Outline.

- conditions for QGP creation in cosmic ray interactions
- QGP model & simulation
- detection
- observable effects
- conclusions

## Conditions for QGP Creation in CR

at the knee region $(5 \times 10^5 \div 10^8\ GeV)$

possible interactions $Fe^{56} - N^{14}$ and $Fe^{56} - O^{16}$

small baryon density - half of that in *Pb-Pb* interactions

however the energy density $\epsilon$ from Bjorken's expression

$$\epsilon = \frac{\Delta E/\Delta y}{\pi R^2 \tau},$$

$R$ … radius of $N^{14}$ or $O^{16}$ nucleus

$\tau$ … the formation time $(1 \div 2\ fm/c)$

$E$ … the c.m.s. energy of the final state particles

$y$ … the rapidity near $y_{cms} = 0$

two-flavour QGP … $150\ MeV < T_c < 200\ MeV$

$\sim$ critical energy density …

$$0.8\ GeV\, fm^{-3} < \epsilon_c < 2.5\ GeV\, fm^{-3}$$

VENUS simulations of $Fe^{56} - N^{14}$ give

$$\epsilon = 3.3\ GeV\, fm^{-3} \text{ at } E_{inc} = 10^{15}\ eV \text{ and } b < 2\ fm$$
$$\epsilon = 4.9\ GeV\, fm^{-3} \text{ at } E_{inc} = 10^{16}\ eV \text{ and } b < 2\ fm$$

## QGP Model

The key factor is …

number of interacting nucleons $N_{int}$

if sufficiently high … $N_{hot}$ of them melt down

the energy $E_{hot}$ is used to produce

$N_{hot}$ nucleons + $n(\pi^{\pm}$ and $\pi^{0})$

… all with Boltzmann distributed kinetic energy and isotropic momenta in c.m.s.

pions are generated until $E_{hot} < 2.5\ GeV$, all generated particles passed to CORSIKA for further processing

$56 + (14\ or\ 16) - N_{hot}$ nucleons processed by

VENUS & CORSIKA

used values:

$N_{hot} = 10$ %, 20 % or 40 % of $N_{int}$

with minimum values of $N_{int} = 15$, 13 and 19 nucleons

and

$< p^{\pi} > = 60\ MeV$, $120\ MeV$, $300\ MeV$ or $1\ GeV$

in the following we shall denote e.g.

$QGP(0.1, 0.3)$ … $\mathcal{R}_h \equiv N_{hot}/N_{int} = 0.1$ and

$< p^{\pi} > =\ 300\ MeV$

## QGP Model

if $N_{int} < limit$ then

use only VENUS

else if $N_{int} > limit$ then

generate QGP + use VENUS

end if

go to *next event*

2000 events generated for each combination of $\mathcal{R}_h$ and $< p^{\pi} >$

## QGP Model

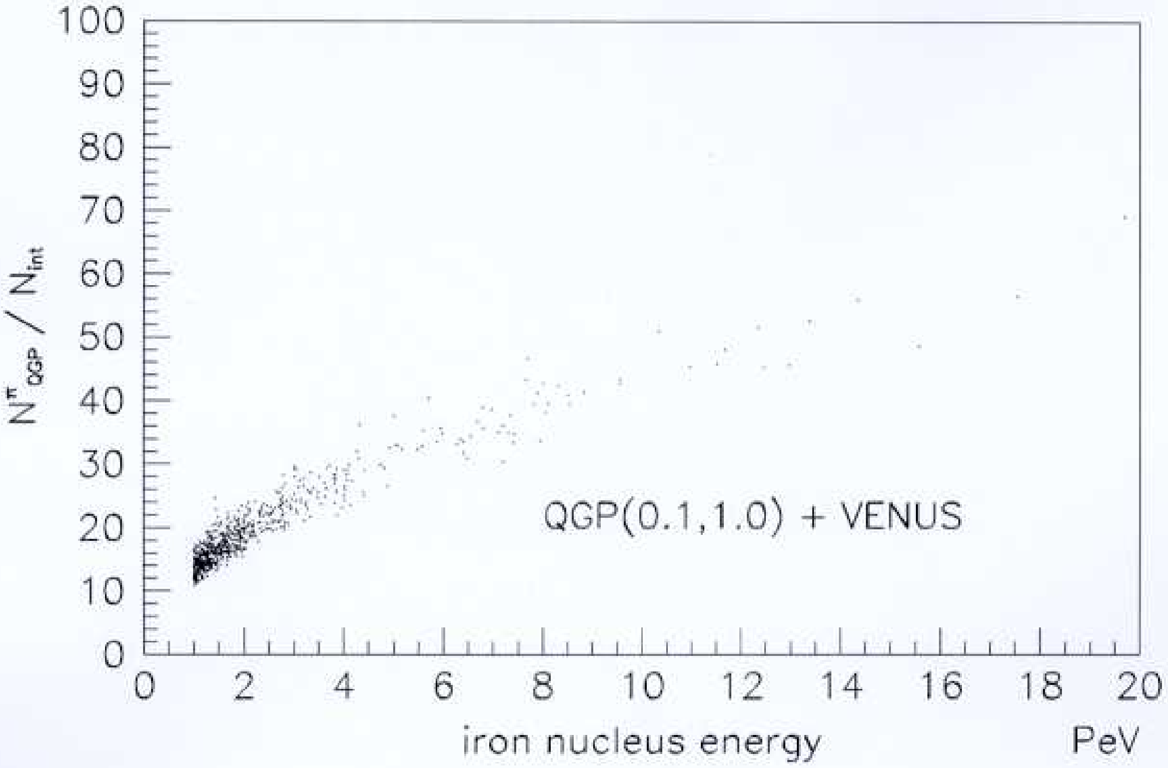
| $< p^{\pi} >$ MeV | $\mathcal{R}_h$ *ratio* 0.1 | 0.2 | 0.4 |
|---|---|---|---|
| 60 | 1492 (880) | 2743 (1717) | 6764 (3802) |
| 120 | 1389 (791) | 2610 (1634) | 6332 (3568) |
| 300 | 1074 (680) | 2165 (1398) | 4918 (2614) |
| 1000 | 674 (393) | 1260 (825) | 3093 (1808) |

The mean numbers of pions (both $\pi^{\pm}$ and $\pi^0$) produced in QGP. The figures given in the parentheses represent the R.M.S. values.

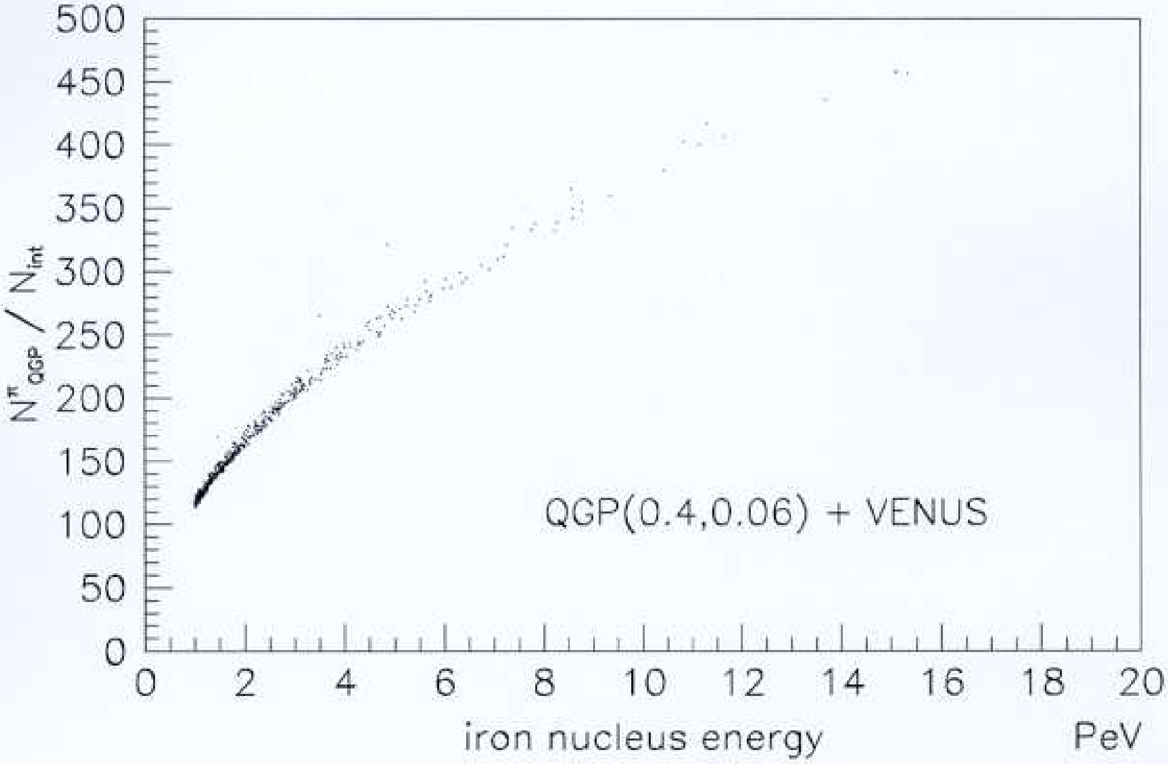
*Some models predict even decrease of multiplicity. This simple approach corresponds to statistical thermal models.*

at the knee energies we have in $Fe^{56} - N^{14}$ interactions $130 \div 600\ GeV$ per $NN$ collision in c.m.s.

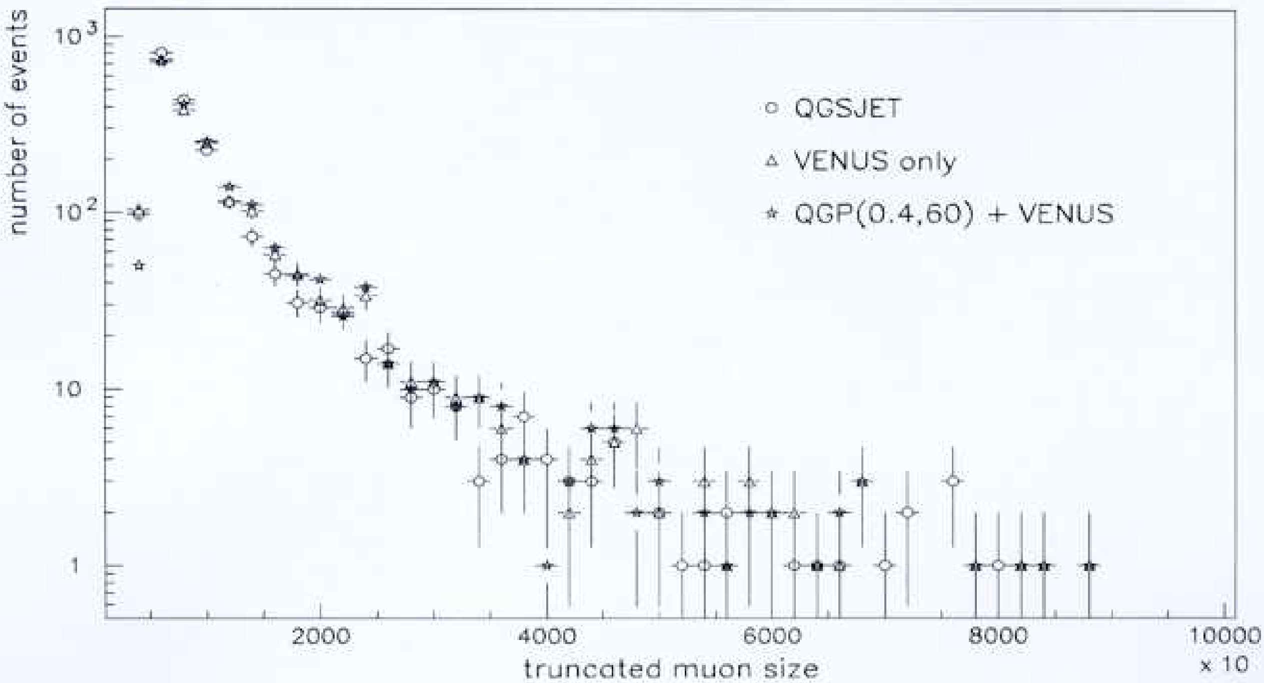
overlap with RHIC

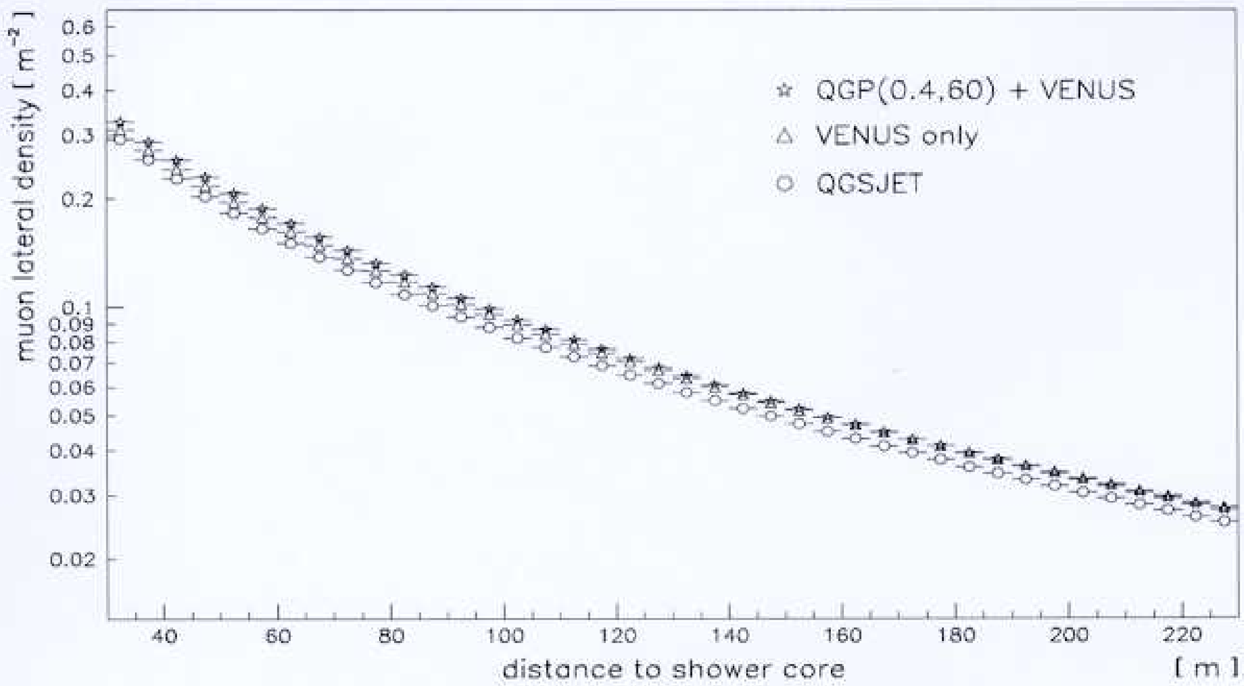


$N^{\pi}_{QGP} / N_{int}$
QGP(0.1,1.0) + VENUS
iron nucleus energy
PeV

$N^{\pi}_{QGP} / N_{int}$
QGP(0.4,0.06) + VENUS
iron nucleus energy
PeV


number of events
10³
10²
10
1
2000
4000
6000
8000
10000
x 10
truncated muon size
QGSJET
VENUS only
QGP(0.4,60) + VENUS


muon lateral density [ m⁻² ]
0.6
0.5
0.4
0.3
0.2
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
40
60
80
100
120
140
160
180
200
220
distance to shower core
[ m ]
QGP(0.4,60) + VENUS
VENUS only
QGSJET

# Detection

$\pi^0$ ..... electromagnetic cascades in the atmosphere

$\pi^\pm$ ..... significant part decays at high altitude $\pi \rightarrow \mu\nu$

...... decoupling from further cascade evolution, subjected to multiple scattering and ionization only

Due to Lorentz boost ... energetic muons

$\Longrightarrow$ ... detection underground

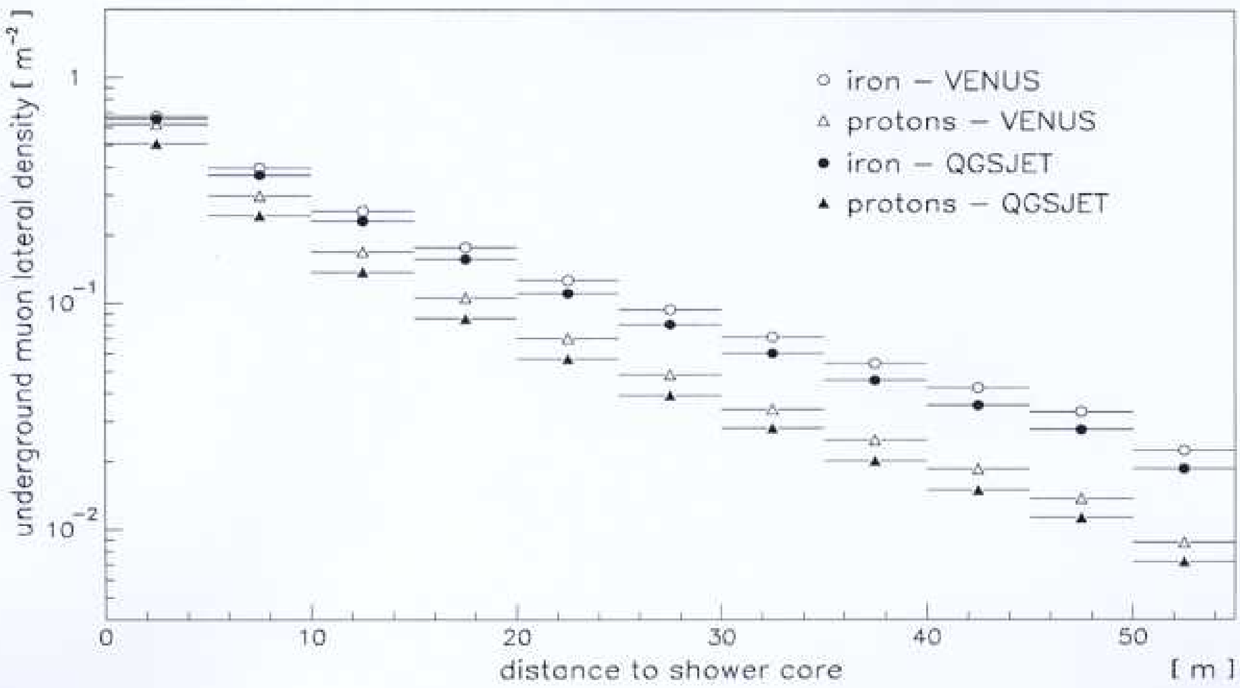
"virtual experiment" 110 meters underground - overburden 100 meters of standard rock, i.e.

$$A = 22, Z = 11, \rho = 2.65 g/cm^3.$$

$\Longrightarrow$ ... cutoff 53 $GeV$

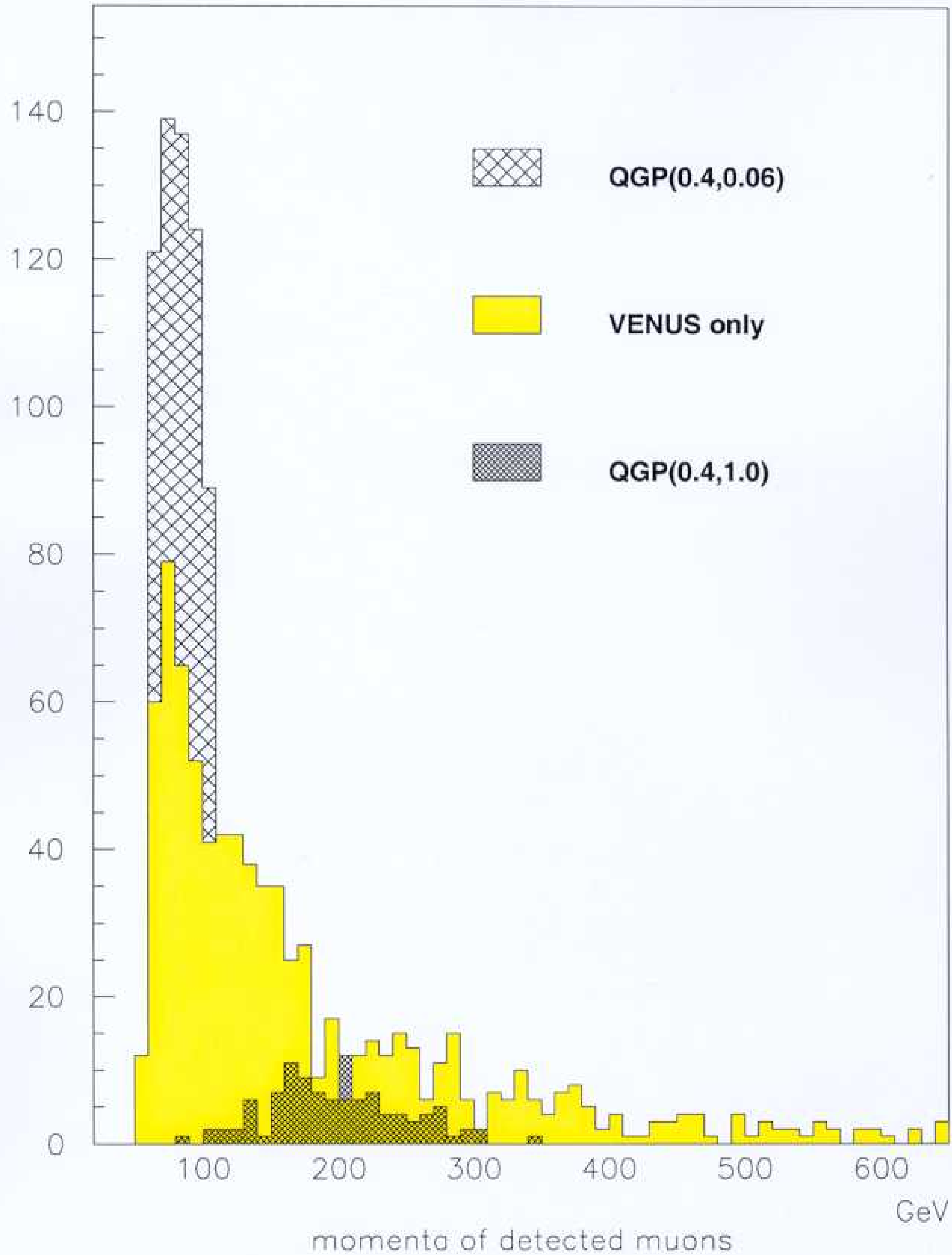
detection area $100 \times 100$ $m^2$ at 110 meters depth

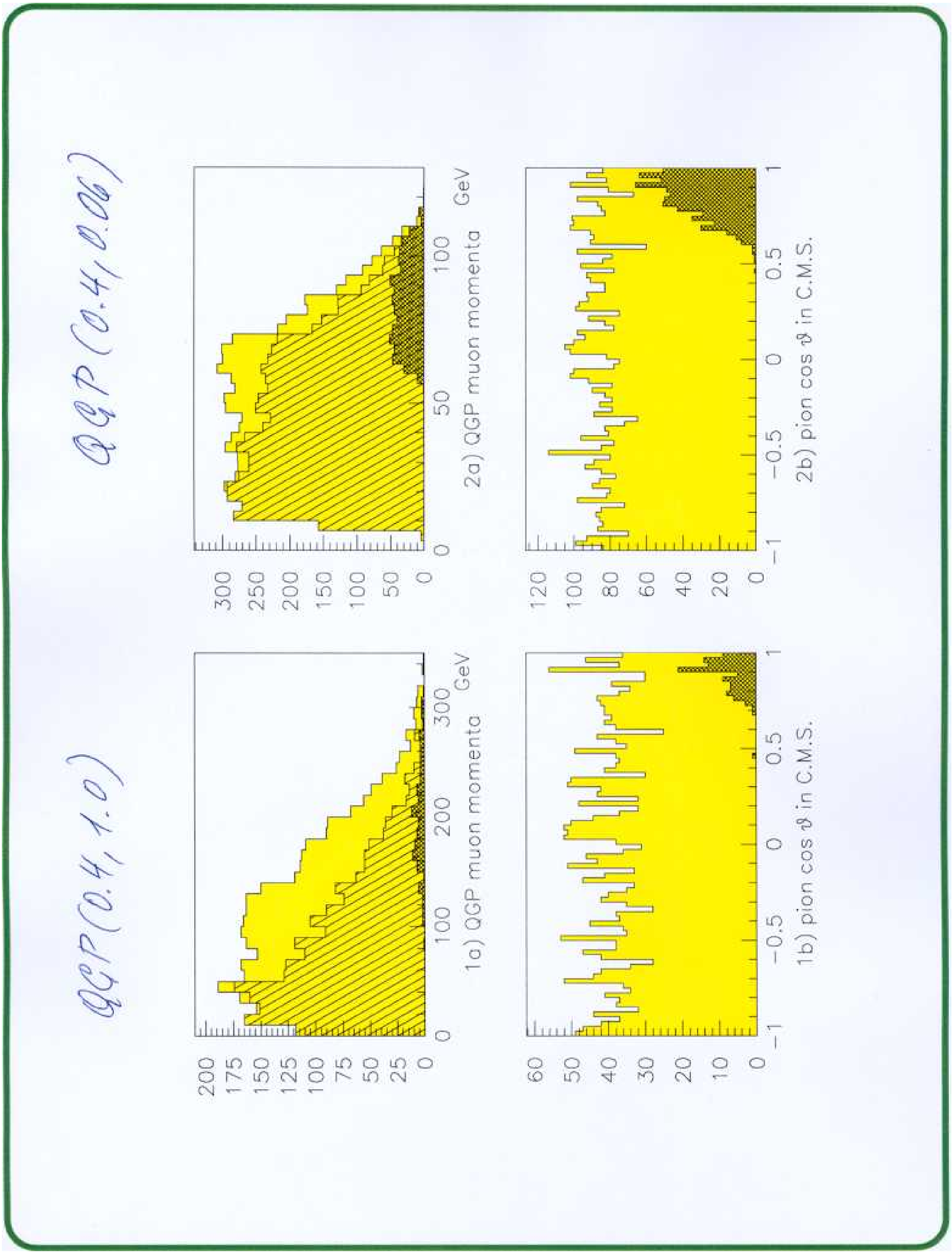
# Comparison of the Models Underground




| model | model only [GeV] | QGP + VENUS [GeV] |
|---|---|---|
| QGSJET | 287.5 (265.5) | - |
| VENUS | 287.2 (259.8) | - |
| QGP(0.4,0.06) | 99.9 (31.1) | 277.8 (225.8) |
| QGP(0.4,0.12) | 105.0 (33.6) | 277.9 (226.8) |
| QGP(0.4,0.3) | 130.3 (41.4) | 279.3 (232.6) |
| QGP(0.4,1.0) | 234.5 (73.7) | 282.2 (244.8) |

mean momenta of $\mu$ underground

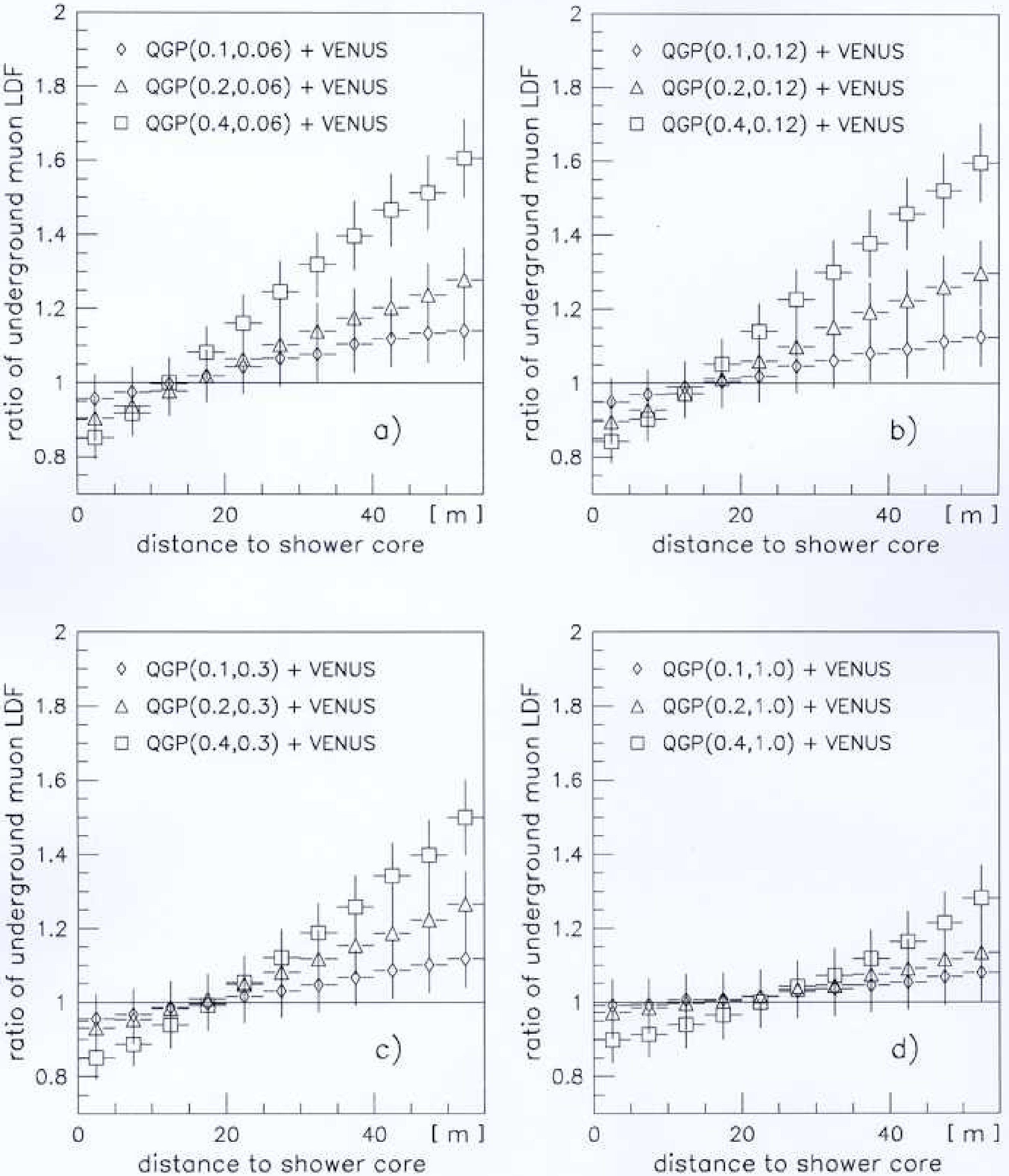

140
120
100
80
60
40
20
0
QGP(0.4,0.06)
VENUS only
QGP(0.4,1.0)
100
200
300
400
500
600
GeV
momenta of detected muons

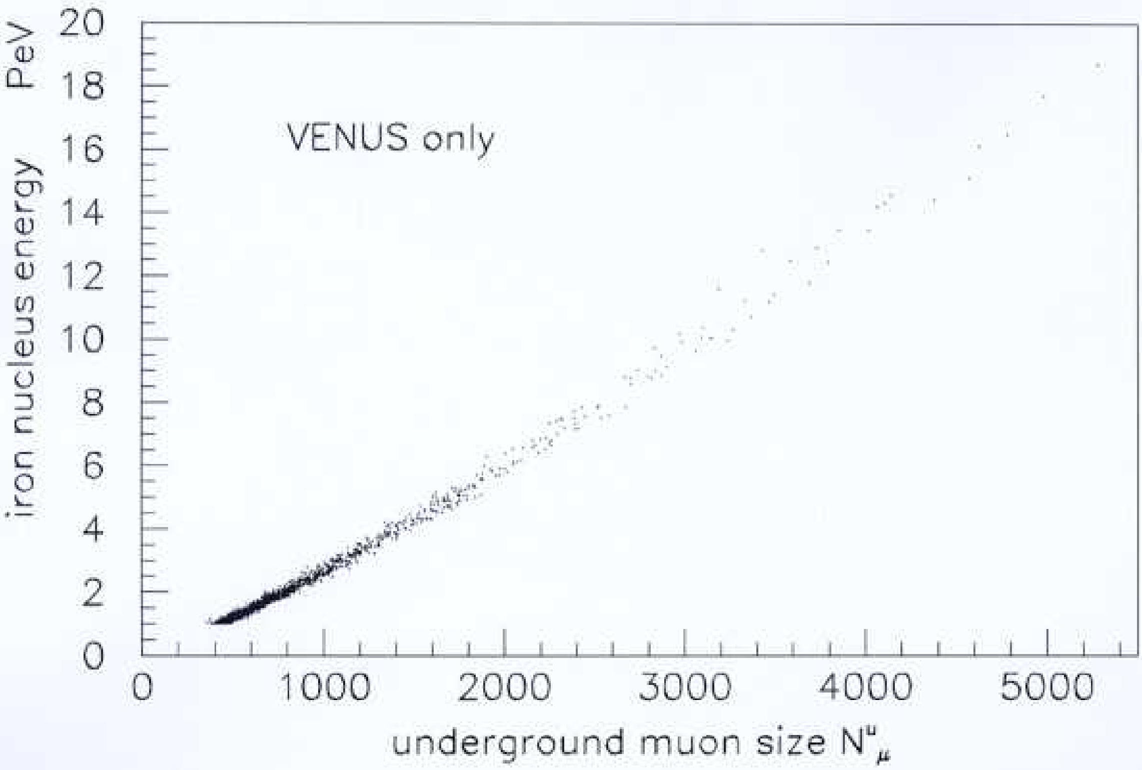

QGP(0.4,1.0)
QGP(0.4,0.06)
1a) QGP muon momenta
GeV
1b) pion cos ϑ in C.M.S.
2a) QGP muon momenta
GeV
2b) pion cos ϑ in C.M.S.

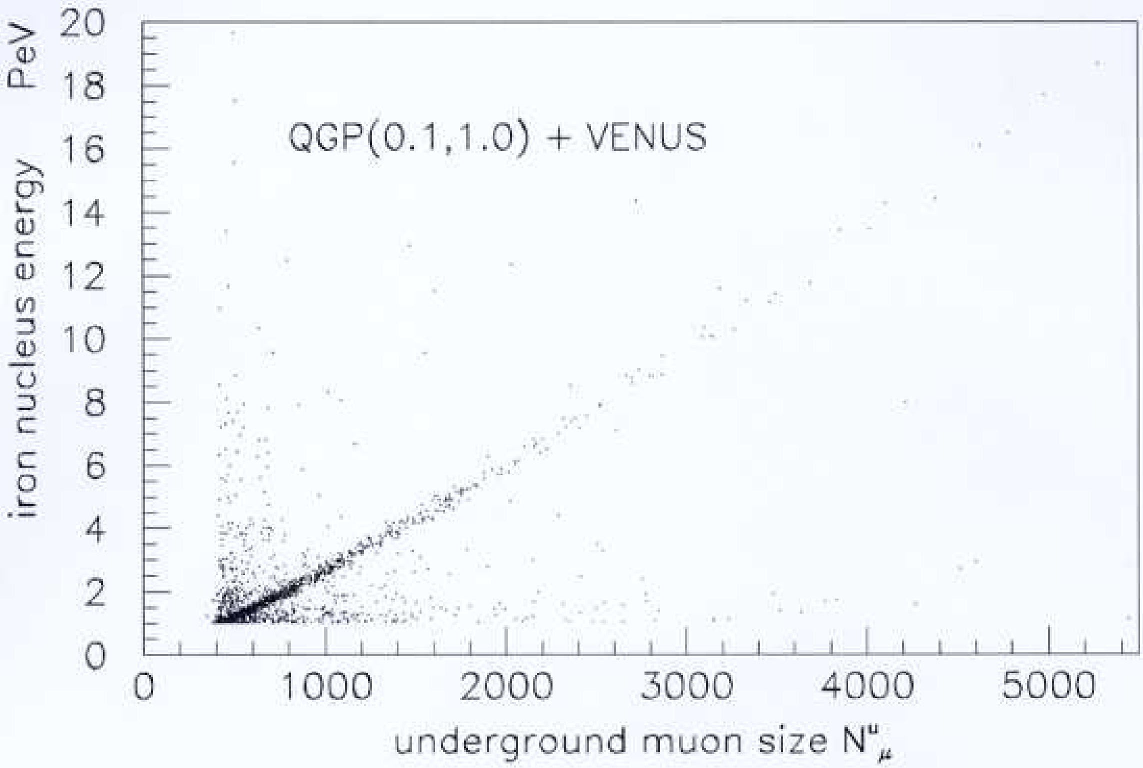
# Comparison of the Models Underground

| model | average $N_\mu^u$ | fraction of events with $N_\mu^u > 990$ (in %) |
|---|---|---|
| VENUS $p$ | 464 | $6.3 \pm 0.6$ |
| QGSJET $p$ | 378 | $3.7 \pm 0.4$ |
| VENUS $Fe$ | 807 | $20.1 \pm 1.1$ |
| QGSJET $Fe$ | 709 | $13.6 \pm 0.9$ |
| QGP(0.1,0.06) | 849 | $21.8 \pm 1.2$ |
| QGP(0.1,0.12) | 843 | $21.7 \pm 1.2$ |
| QGP(0.1,0.3) | 829 | $20.4 \pm 1.1$ |
| QGP(0.1,1.0) | 819 | $20.4 \pm 1.1$ |
| QGP(0.2,0.06) | 868 | $23.4 \pm 1.2$ |
| QGP(0.2,0.12) | 871 | $22.9 \pm 1.2$ |
| QGP(0.2,0.3) | 867 | $22.5 \pm 1.2$ |
| QGP(0.2,1.0) | 809 | $19.3 \pm 1.1$ |
| QGP(0.4,0.06) | 967 | $27.0 \pm 1.3$ |
| QGP(0.4,0.12) | 955 | $26.5 \pm 1.3$ |
| QGP(0.4,0.3) | 904 | $24.3 \pm 1.2$ |
| QGP(0.4,1.0) | 835 | $22.0 \pm 1.2$ |

The average underground muon size $N_\mu^u$ of events and the fraction of events with $N_\mu^u > 990$ . All QGP simulations were supplemented by VENUS.


ratio of underground muon LDF
distance to shower core
[ m ]
◊ QGP(0.1,0.06) + VENUS
△ QGP(0.2,0.06) + VENUS
□ QGP(0.4,0.06) + VENUS
a)
◊ QGP(0.1,0.12) + VENUS
△ QGP(0.2,0.12) + VENUS
□ QGP(0.4,0.12) + VENUS
b)
◊ QGP(0.1,0.3) + VENUS
△ QGP(0.2,0.3) + VENUS
□ QGP(0.4,0.3) + VENUS
c)
◊ QGP(0.1,1.0) + VENUS
△ QGP(0.2,1.0) + VENUS
□ QGP(0.4,1.0) + VENUS
d)


VENUS only
iron nucleus energy PeV
underground muon size $N^u_\mu$
0
2
4
6
8
10
12
14
16
18
20
0
1000
2000
3000
4000
5000


QGP(0.1,1.0) + VENUS
iron nucleus energy PeV
underground muon size $N^u_\mu$
0
2
4
6
8
10
12
14
16
18
20
0
1000
2000
3000
4000
5000

QGP distorts the *energy* $\sim$ *muon size* balance

$\rightarrow$ *comparison of the event muon size at the ground and underground can indicate deviation from the standard scenario*

several factors contribute to the muon deficit:

$N_{deff} = k_{std} \cdot E_{hot} - q_{std}$
$N_{QGP} = (k_{QGP} \cdot E_{hot} - q_{QGP}) \cdot f_{det}$

... & leading particle effect in standard interactions while $f_{det}$ is small
$\rightarrow (N_{QGP} - N_{deff})$ has positive intercept and negative slope

$N_{hot}$ nucleons exempted from the rest of interaction
$56 - N_{hot}$ nucleons with the energy $E_{inc} \cdot (56 - N_{hot})/56$

## Conclusions.

- QGP effects can be observed at medium depth underground at certain kinematical conditions
- QGP does not increase the muon density in the shower core
- well tuned high energy interaction models differ in description of hard muon component
- *simultaneous measurement on extended air showers both at surface and at medium depth underground is sensitive to the dynamics of the initial high energy interactions*

details: hep-ph/0012068