Probing Low-x QCD
With
High Energy Prompt Muons

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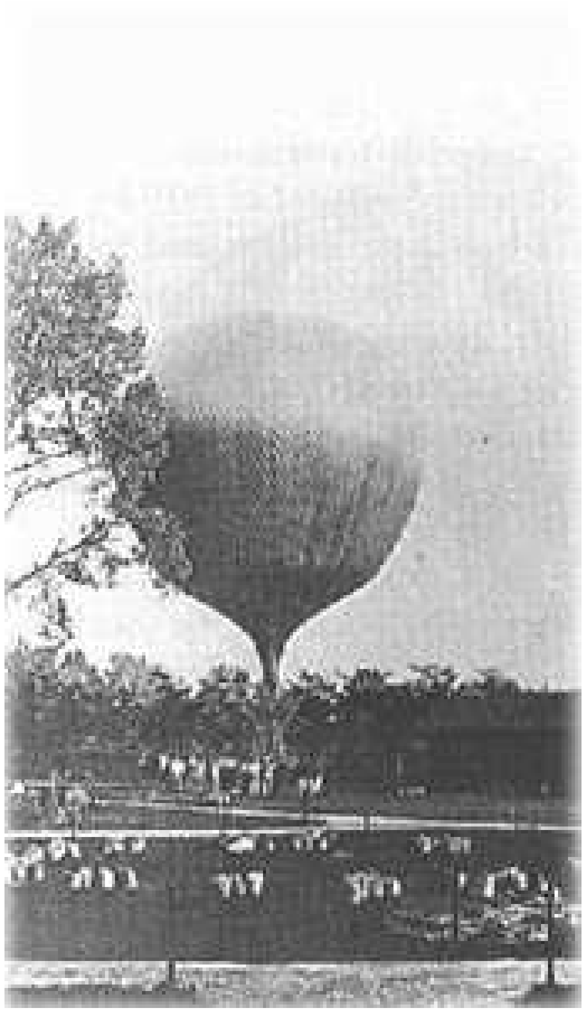
Outline

- Cosmic Rays - History, Relevance, Issues
- The QCD Connection
- Lepton Fluxes - Prompt Muons
- Muon energy spectrum measurement - Pair Meter Technique
- Results
- Related issues and future

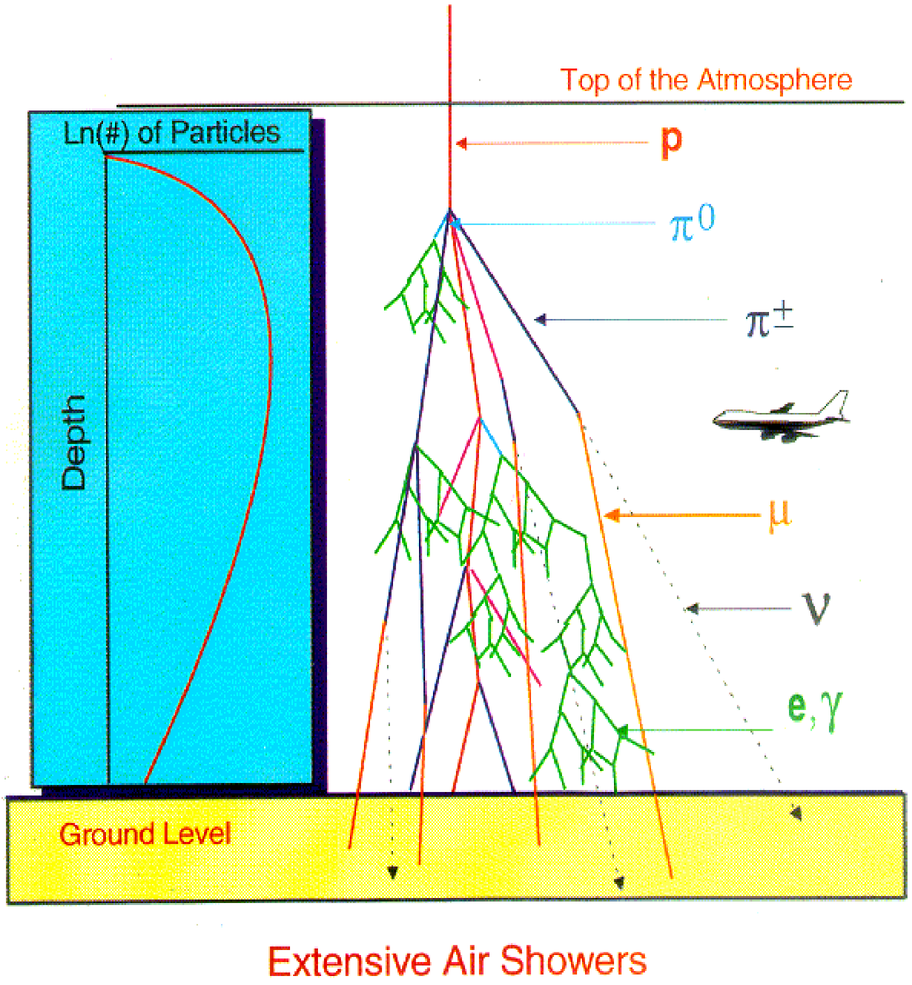


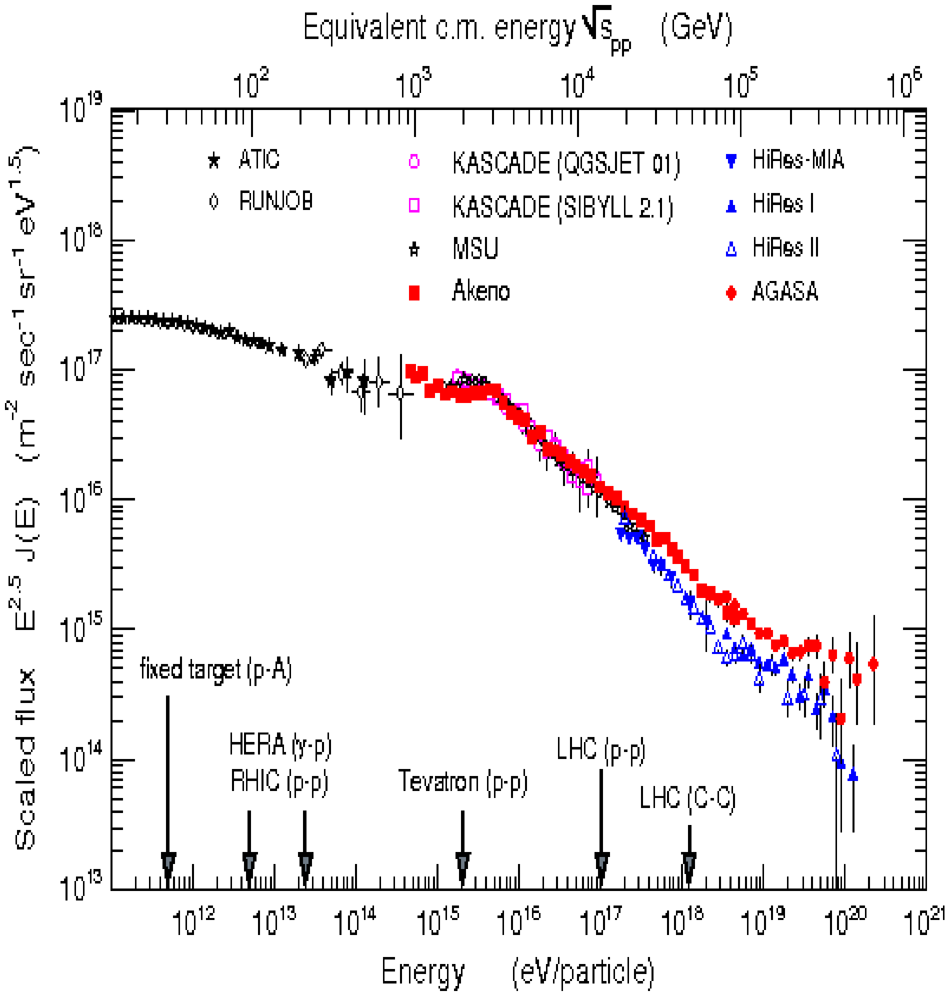
Victor Hess with his balloon

Pierre Auger

Cosmic Rays

- Penetrating particles coming from above the atmosphere
- It all really started in 1912 with Hess flying 17,500 feet without oxygen
- Found an unexpected sharp rise in levels of Cosmic Radiation - he was awarded Nobel Prize in 1936
- With this began the modern elementary particle physics as well
- Muons, Pions, positrons and strange particles were discovered in cosmic rays – a lot about neutrinos as well!!
- CR's are the strongest accelerators available to us - the highest energy particles observed have $E \sim 10^{21}$ eV
- Even with so much progress, CR's pose several interesting and totally mysterious issues
- Field is too vast and rich - experimentally and theoretically

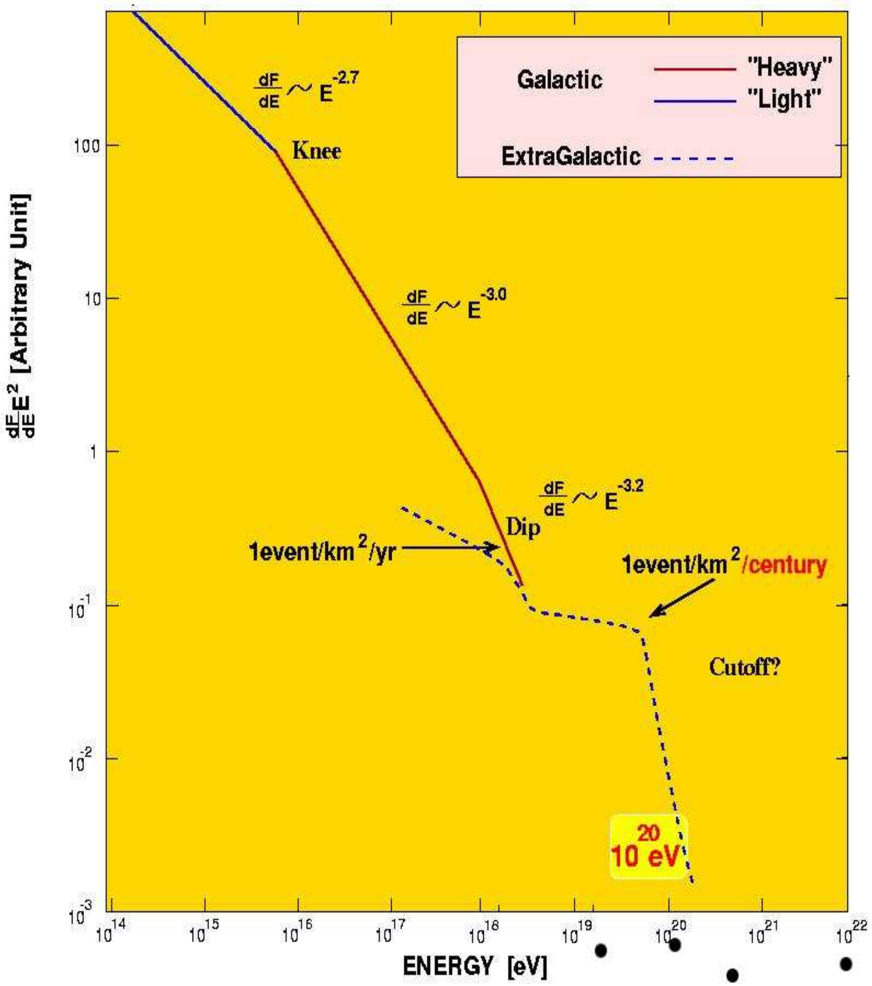


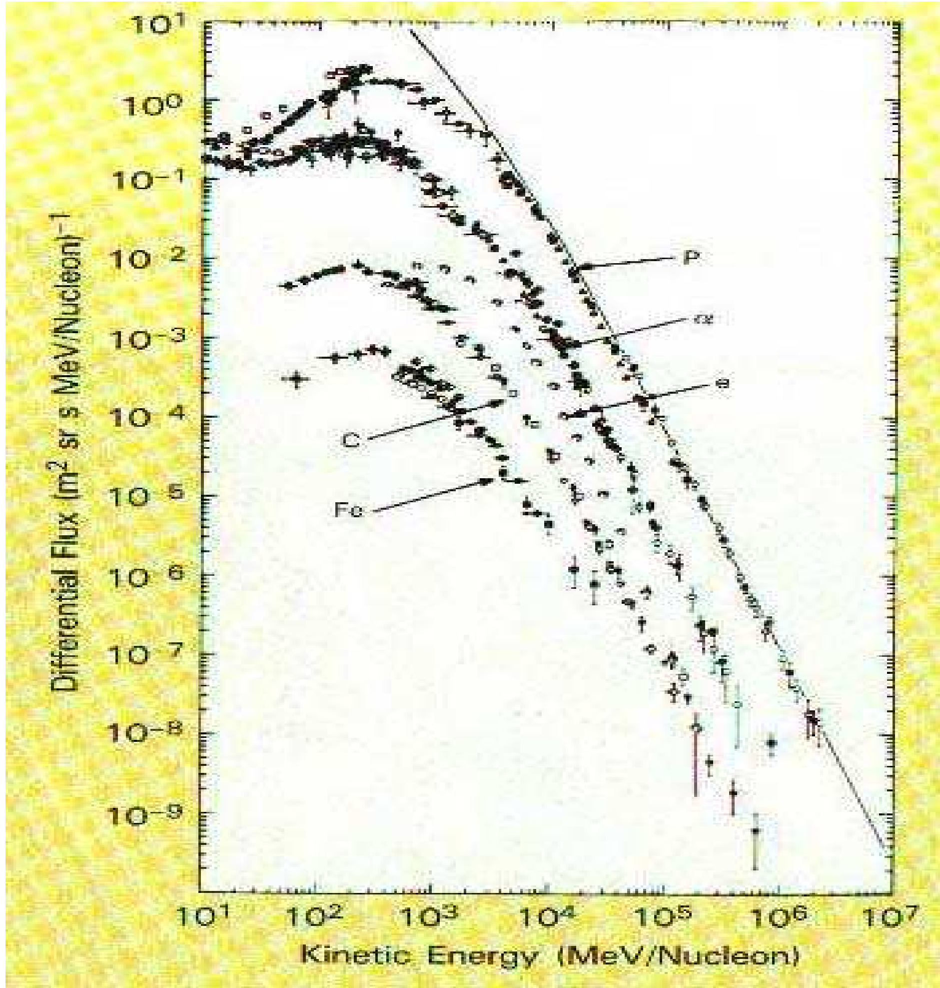


Typical CR event

Measured CR Flux

Almost 1000 CR particles hit earth's atmosphere per sec per sq. meter





CR Spectrum

CR Flux Composition

90% protons, 9% alpha, rest heavy nuclei

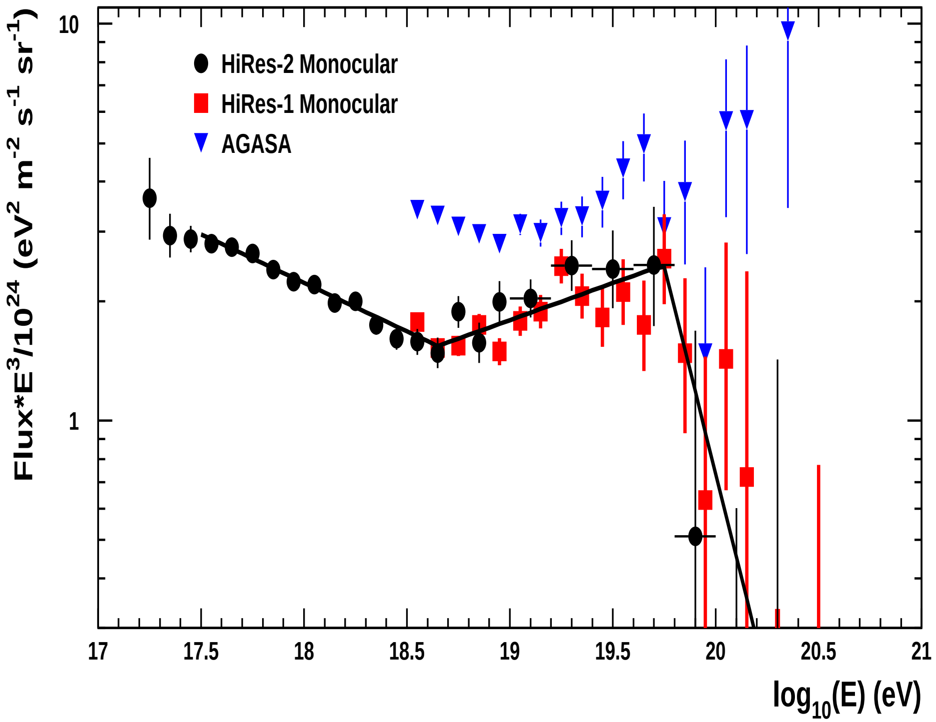
- Energy spectrum - sharply falling
- $\frac{dN}{dE} \sim E^{-(\gamma+1)}$ $\quad \gamma = 1.7 \;\; E \leq 10^{15}$ eV
- Around 10^{15} eV, $\gamma \rightarrow 2.1$ KNEE REGION
- Change in slope not understood though majority believe that its astrophysical in nature - change in composition speculated
- The slope changes again around 10^{18} eV with $\gamma \rightarrow 1.7$ - ANKLE
- $E > 10^{18}$ eV events have been observed - UHECRs - they pose a different puzzle regarding the nature and the acceleration mechanism
- This also defines the GZK cut-off $E_{GZK} \sim 4 \times 10^{19}$ eV - nucleons with that energy will photo-produce pions and thus lose energy while photons can't have so long path length
- Highest energy events are a mystery - can possibly be neutrinos

Have invited many speculations as well

GZK observed [HiRes]

Significance 6σ

(astro-ph/0703099)

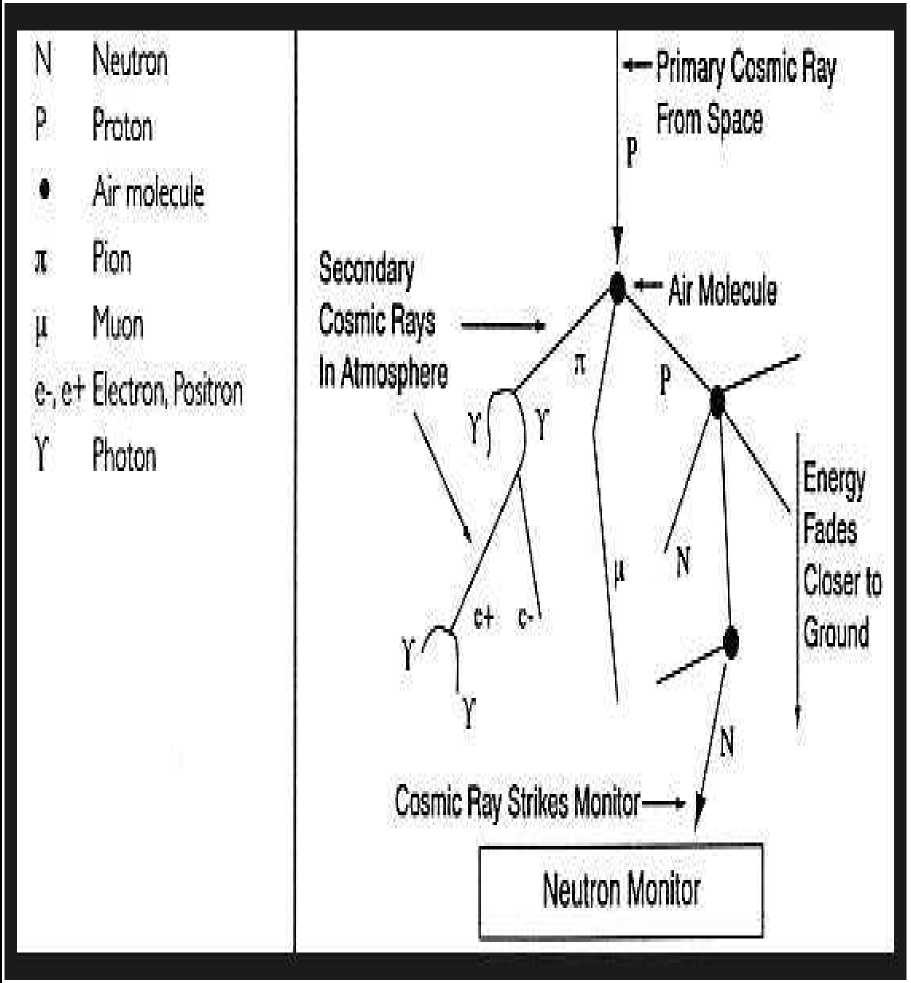


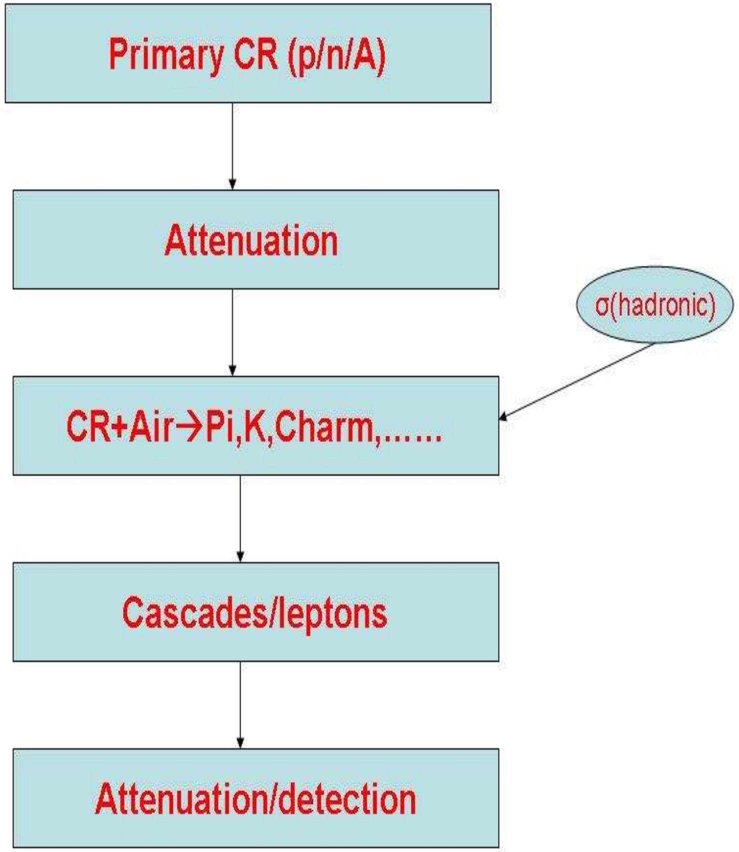
Events above $10^{19.8}$ GeV with (without) AGASA: 42 (28)

Expected without a GZK break point: 85 (67)

Expected with break point: 45.4 (30.1)

HiRes measures ratio of energies of GZK and Ankle $10^{19.75-18.65} = 12.6$





Schematic sketch of the process

Toy Model/Calculation

- A primary with energy E_0 splits into two segments (splitting into more than two possible and happens - this is an example)
- Branching occurs after every one interaction length λ
- After $n = X/\lambda$ branchings, # segments is $N(X) = 2^{X/\lambda}$
- Energy per particle $E(X) = E_0/N(X)$
- After reaching some critical energy E_c branching stops
- Number of particles at shower maximum $N(X_{max}) \propto E_0$ with $X_{max} \propto \lambda \ln(E_0/A)$ (A is the atomic number)
- Heavy primary showers develop more rapidly but effect is logarithmic - so hard to clearly distinguish

Muons are somewhat special

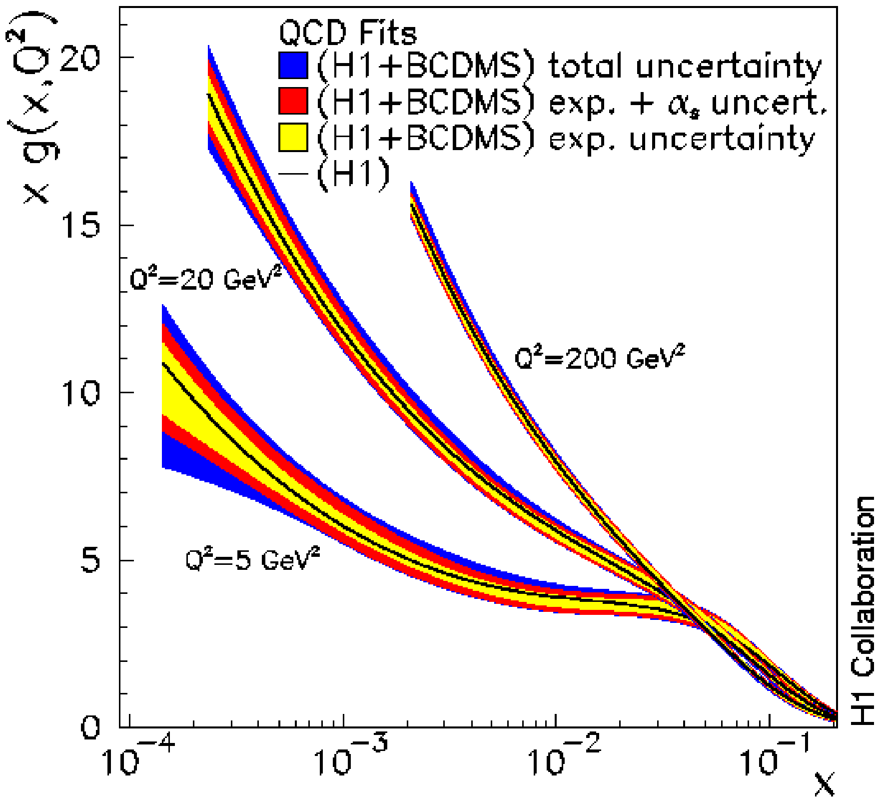
- Muons are expected to be rare in showers initiated by photons or electrons - its easier to produce more electrons-positrons
- Muons are produced by the decay of pions and kaons high in atmosphere - can give better measure of primary cosmic ray energy
- At ground level, thus, muon content for each shower of same primary energy and primary nucleus is same independent of cascade development details
- # of high energy muons increases less slowly as for higher energies, cascade penetrates deep before producing muons
- Muons don't multiply and attenuate slowly after the shower max. is built - more muons for heavy primary
- Electron component on the other hand degrades fast

Relevance/Importance for Particle Physics

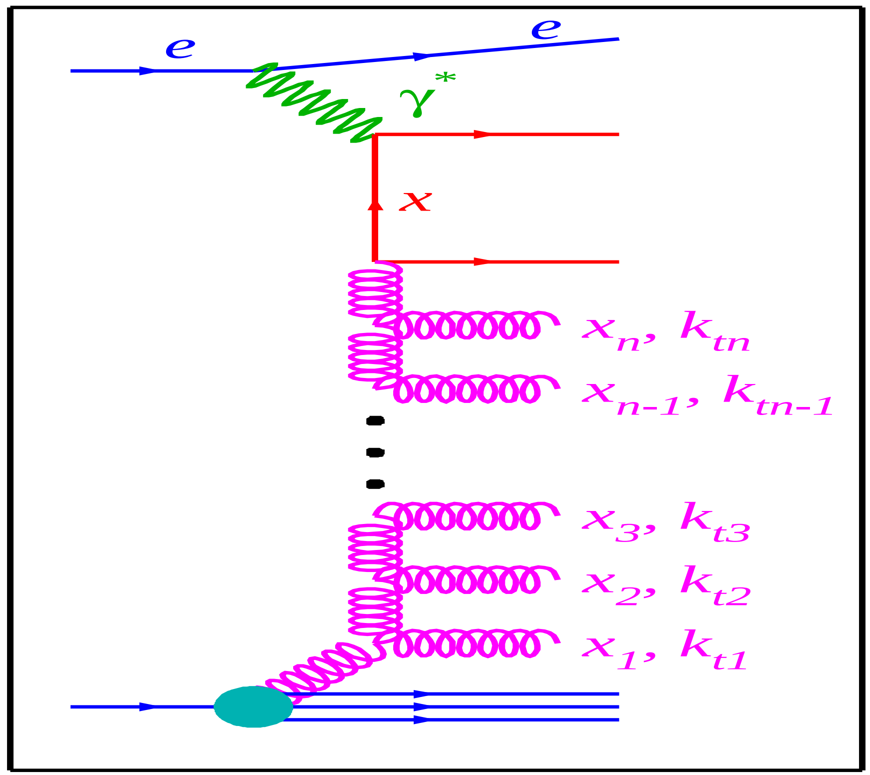
- Provide highest energy particles
- Background to neutrino and gamma-ray experiments
- Probe low-x behaviour via hadron production and subsequent decay - particularly for heavy hadrons like charmed ones
- Direct measurement of high energy lepton energy spectrum limited upto 50 TeV - can potentially provide the missing information
- Consider charm production - due to steeply falling spectrum, for the parent particle, $x_1 \sim 0.1$

$$\hat{s} = (2m_c)^2 = x_1 x_2 \otimes [s_{cm} \equiv 2m_N E_0]$$

- For E_0 in the range of hundreds/thousands of TeV, $x_2 < 10^{-6} - 10^{-5}$
- Probed (s_{cm}, x) is far from LHC reach - Info. on PDFs possible



Gluon PDF from data



Gluon cascade

At very small x values, expect a huge # of gluons $\Longrightarrow$ Cross-sections will rise steeply —— Violate unitarity eventually

- From data $xG(x, Q^2) \sim x^{-\lambda}, \quad \lambda = 0.1 - 0.5$
- The (Q^2, x) range probed in CRs is very different than in any accelerator based experiment
- Naive extrapolation of PDFs extracted from accelerator data will violate unitarity
- Physically, there should be some mechanism to tame this rising behaviour
- At very low-x, *gluon recombination* can become important and comparable to the splitting/cascade - Saturation scale
- Non-linear terms start playing a role
- HERA data and RHIC indicate some saturation behaviour
- Expect saturation behaviour in CRs as well - we employ one such model while comparing predictions

Lepton Fluxes from CRs

- Leptons can arise from the cascades or from the decay of hadrons produced in the collision of primary CR with air - We are interested in the latter
- Those produced from the decay of pions and kaons - Conventional while from heavy hadrons like charm or beauty hadrons - Prompt
- At very high energies, due to time dilation, pions and kaons travel a significant distance before decaying
- At such energies, the leptons are then originating from the decays of charm/beauty hadrons - chance to study heavy hadron production
- Conventional flux is rather well measured and the power law behaviour can be exploited to predict flux at high energies
- It is possible to measure or atleast constrain Prompt flux

Decay Length and Critical Energy

- Atm. vertical depth $X_v = \int_h^\infty dh' \rho(h')$, $X_v = X_0 e^{-h/(h_0=1030\ g/cm^2)}$
- At sea level, $h_0 \sim 8.4$ km - Average $h_0 = 6.4$ km as particle interactions take place within a few interaction lengths
- For zenith angle $< 60^\circ$, curvature effects of earth can be neglected

Decay length at depth X: $d_i = \rho(X)\gamma_{Lor} c\tau_i / X \sim c\tau_i E_i / m_i$

- When $d_i \sim h_0$, the particle travels before decaying. This happens for critical energy $\epsilon_i^{crit} = \frac{m_i h_0}{c\tau_i}$ $\gamma_{Lor} \sim E/m$

Particles	μ	$\pi^\pm$	π^0	$K^\pm$	$D^\pm$	D^0
$c\tau_0$(cm)	6.6×10^4	780	2.5×10^{-6}	371	0.028	0.013
ϵ_i(GeV)	1.0	115	3.5×10^{10}	850	4.3×10^7	9.2×10^7

Sample Flux Calculation

- Start with the initial CR flux which gets attenuated in the usual way
$\phi_N(E,X) = \phi_N(E,0)e^{-X/\Lambda_N}$ Λ_N - attenuation length of nucleon
- CRs collide with the air particles and produce secondaries - here charm hadrons, say - need two cross sections: charm production and nucleon-air total cross section (σ_{NA}^{tot})
- As the particles travel, number of interactions is coded in - interaction length, λ_N
- Charm hadrons decay semi-leptonically and the leptons travel to us - differential decay rate
- In general, all this is a set of highly coupled non-linear differential equations
- Within some approx. can be written in a simple form

- Assume infinite isothermal atmospheric depth and zenith angle $< 60^\circ$
- $\phi_N(E, X=0) = \phi_{0N} E_N^{-(\gamma+1)}$ - power law initial spectrum
- $\Lambda_N(E) = \frac{\lambda_N(E)}{1-Z_{NN}(E)}$ and $\lambda_N(E) = \frac{\rho_{atm}(X=h)}{\sigma_{NA} n_A(X=h)}$
- $\sigma_{NA}^{tot}(E) = \left[280 - 8.7 \ln\left(\frac{E}{GeV}\right) + 1.14 \ln^2\left(\frac{E}{GeV}\right)\right] mb$
- For lepton energies $E_l < \epsilon_{charm}^{crit} \approx 10^7$ GeV

$$\phi_l(E_l) = \underbrace{Z_{Y_c l}(E)}_{Y_c \to l} \underbrace{Z_{NY_c}(E)}_{N+A \to Y_c} \underbrace{\frac{\Lambda_N(E)}{\lambda_N(E)}}_{depletion} \phi_N(E, 0) \qquad Y_c = D^{0(\pm)}, D_s, \Lambda_c$$

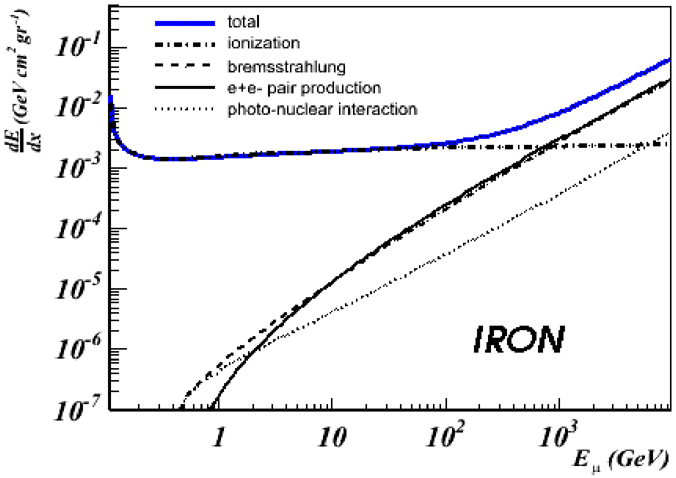
- Spectrum weighted moments for a power law initial flux

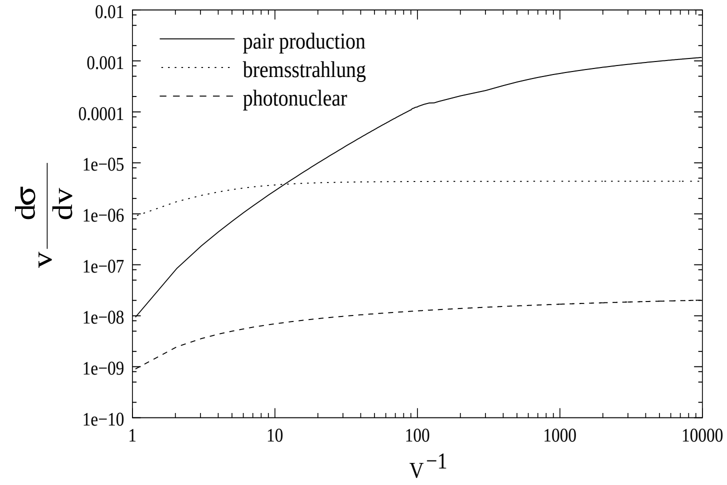
$$Z_{Nj}(E) = \int_0^1 dx x^{\gamma-1} \frac{1}{\sigma_{NA}^{tot}(E)} \frac{d\sigma_{NA\to j}(E,x)}{dx} \qquad x \approx \frac{E_j}{E}$$

- For lepton production Z moments - cross section $\longrightarrow$ decay rate

Observing Muons & Measuring Spectrum

- Muons are very penetrating particles
- Usual spectograph technique means unimaginable field strengths, size
- Known energy spectrum of muons quite limited - most obs. on high energy muons give (integrated) intensity vs depth or zenith angle
- Direct measurement of energy spectrum of high energy muons will be very useful
- Prompt muon flux can be used to probe the Knee region
- Prompt ν flux is almost same as muon flux - can act as normalization for ν flux
- Any method for direct measurement of energy spectrum will be more than welcome - Pair Meter Technique





- Proposed by Kokoulin and Petrokhin - let the muons pass through a dense material, say Iron

- At very high energies, the muon energy loss is almost linear in muon energy

- Energy loss is dominated by e^+e^- pair production - hence the name Pair Meter - count # pairs

$E_\mu \downarrow$ $E_0 \rightarrow$	5	10	20	50	100	500
1	3.08	2.56	3.78			
10	17.28	10.99	6.43	3.08	2.56	
50	38.58	28.26	19.67	10.99	6.43	2.56
100	50.63	38.58	28.26	17.28	10.99	3.08
200	64.43	50.63	38.58	25.30	17.28	5.34
500	85.33	69.24	54.89	38.58	28.26	10.99
1000	103.16	85.33	69.24	50.63	38.58	17.28
10000	174.84	151.24	129.38	103.16	85.33	50.63

Number of cascades per muon (E_μ in TeV) for different thresholds E_0 in GeV

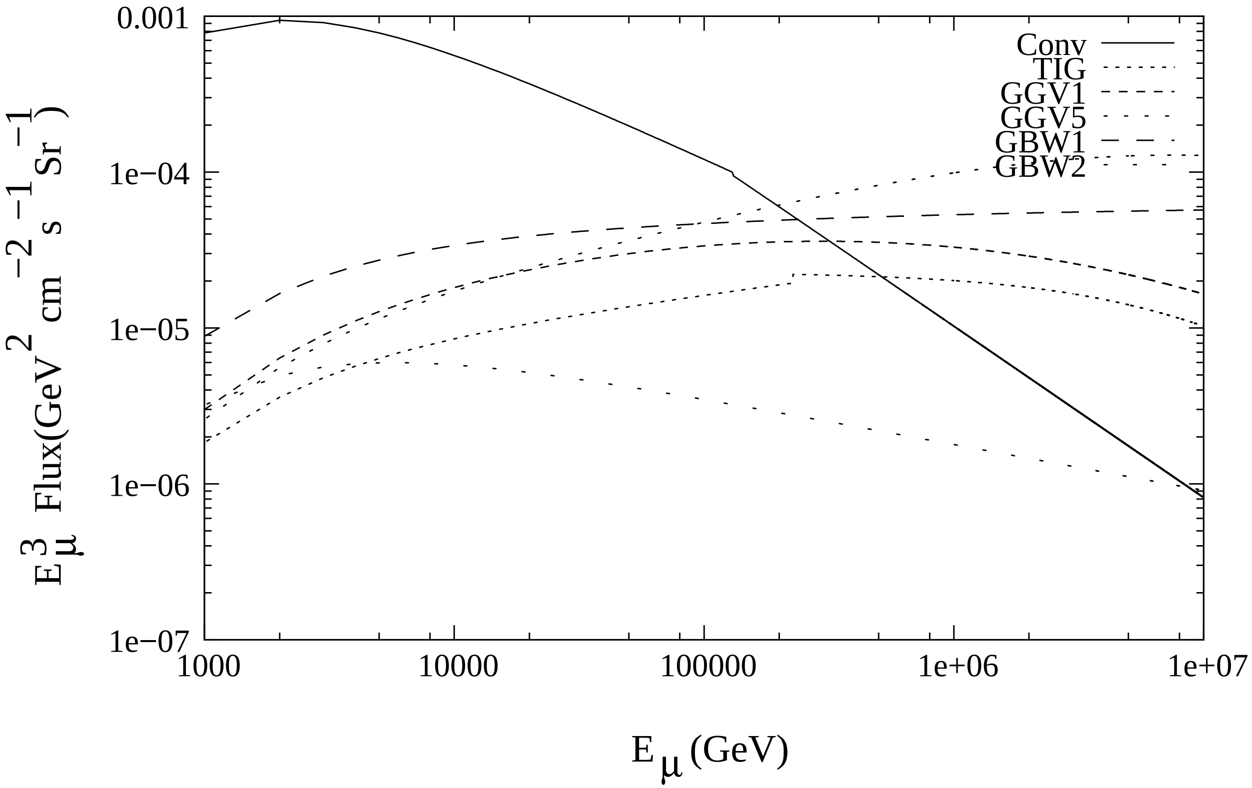
- We explore such a possibility with 50 kT iron calorimeter (16m x 48 m x 12m) with an exposure area $A = 3 \times 10^8\ cm^2$ in a time period of 5 years - planned at INO, India - but features apply to any other as well
- Potential of using Pair Meter technique for high energy muons already demonstrated by CCFR/NuTeV collab. in TeV range
- No upper limit to muon energy with this method
- Flux calculations depend sensitively on charm production model - predictions vary over two-three orders of magnitude
- Ambiguities/uncertainties due to choice of μ_R and μ_F in calculations
- Naive extrapolation of PDFs also gives uncertain estimates
- Measurement of prompt muon spectrum can be used to select or constrain charm production models - info. on PDFs - low-x behaviour

Survey of Charm Production Models

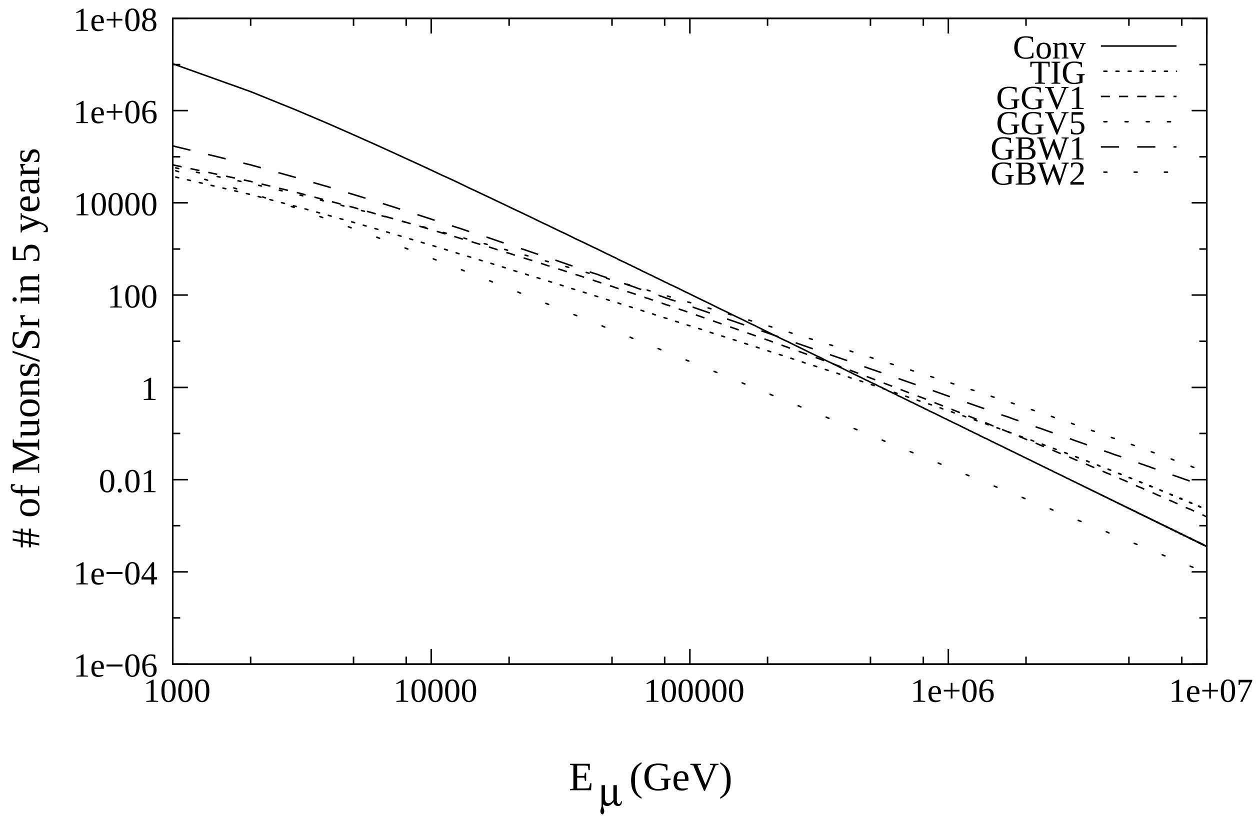
- Quark gluon string model - semi-empirical model based on non-pert. calculation normalised to accelerator data
- Recombination quark parton model - phenomenological non-perturbative approach with intrinsic charm of projectile
- PQCD based models - LO (TIG) and NLO (GGV) - with gluon distribution from accelerator data and fit to extract parameters
- Saturation based models - GBW model : we employ the simplest version here but the model has been improved to incorporate DGLAP and BFKL evolution information as well and recently heavy quark production also
- GBW1 model - for proton being the primary

  GBW2 model - including higher elements in the calculation

Results



Flux prediction for various models (underground detector after passing through the rock depth of $3.5 \times 10^5 gm/cm^2$.)



muons entering the detector in 5 years per solid angle

- $E_\mu^{sur} \sim 5E_\mu^{under}$, $E_{CR} \sim 20E_\mu^{prod} \Longrightarrow$ Muons can easily probe the knee and also possible composition change around it

E_μ (TeV)	Conv	TIG	GGV1	GGV5	GBW1	GBW2
1	10^7	37461	66927	58980	171625	51564
5	300322	3780	7920	7561	15160	2770
10	51282	1204	2618	2700	4452	638
50	696	74	154	214	219	18
100	106	21	42	69	58	4
200	16	6	11	22	15	1
300	5	3	5	11	7	0
400	2	2	3	7	4	0
500	1	1	2	4	3	0

Number of muons per solid angle entering the detector over 5 years

- Numbers quoted are for per solid angle
- To get total number of muons, perform angular integration - naively multiply by 2π
- Not completely wrong - for a detector placed under a triangular mountain at a depth of 1-1.5 km and base length 4-5 km, for zenith angle $< 60^\circ$, this is true
- To reduce energy loss while passing through rock, detector can be placed under water/ice
- This will increase the number of cascades into pairs - better accuracy can be achieved in measuring muon energy
- From Figures and Table, it is clear that various models can be distinguished and also change in composition can be probed

Conclusions

• Muon flux measurement is important in its own right - getting to know the CR spectrum better

• Can shed light on the charm production model at high energies and very low-x values - very important information about PDFs - compliment our knowledge

• Pair meter technique can be rather useful and is quite clean

• Direct link with astrophysics - testing the heavy composition proposal

• Use the muon flux calculations as normalization for neutrino fluxes

• Test for saturation picture as well

• Combination of direct measurement data with the data from under water/ice experiments will completely solve the puzzle about knee

Other Issues and Future Directions

- Most calculations employ Born level results - try to go beyond
- For the pair production, one group found that Coloumb corrections can be significant specially at low momentum transfer - for iron atmost few percent but for lead very large
- Energy loss in iron based on tree level cross section, neglects LPM effect - investigation necessary to estimate the cascade number
- Cross sections typically derived within QED however muons produced have a fixed chirality
- Contribution from b-hadrons to muon or ν_μ is few percent but for tau's it can be very large
- RHIC data shows enhancement in strangeness - expect more contribution from kaons