A new interpretation of the high energy atmospheric muon charge ratio

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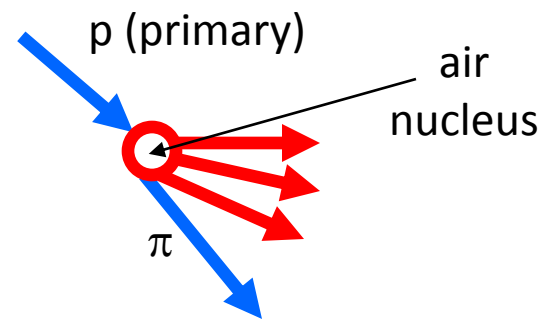
Atmospheric muon charge ratio

- The atmospheric muon charge ratio $R_\mu \equiv N_{\mu+}/N_{\mu-}$ is being studied and measured since many decades
  - Depends on the chemical composition and energy spectrum of the primary cosmic rays
  - Depends on the hadronic interaction feautures
  - At high energy, depends on the prompt component
- It provides the possibility to check HE hadronic interaction models (E>1TeV) in the fragmentation region, where no data exists
- Since atmospheric muons are kinematically related to atmospheric neutrinos (same sources), R_μ provides a benchmark for atmospheric ν flux computations (e.g. background for neutrino telescopes)

Analytic predictions

- Naive prediction:
  - Since charged multiplicity grows with the energy, the extra-charge of the primary proton is diluted and $R_\mu \to 1$ in the HE limit (WRONG!)
- A more elaborate model:
  - Suppose only primary protons with a spectrum $dN/dE = N_0 E^{-(1+\gamma)}$
  - Suppose only pions and neglect muon decays (HE limit)
  - Consider the inclusive cross-section for pions

$$f^{\pm}_{p\pi}(E_\pi, E_p) \equiv \frac{E_\pi}{\sigma^{inel}_{pp}} \frac{d\sigma^{\pm}_{p\to\pi}}{dE_\pi}$$



  - The pion spectrum is then

$$\pi(E_\pi) = \frac{(const)}{E_\pi} \int_{E_\pi}^{\infty} dE E^{-(1+\gamma)} f^{\pm}_{p\pi}(E_\pi, E_p)$$

Analytic predictions (cont'd)

– This expression can be simplified under the assumption

$$f^{\pm}_{p\pi}(E_\pi, E_p) \equiv \frac{E_\pi}{\sigma^{inel}_{pp}} \frac{d\sigma^{\pm}_{p\to\pi}}{dE_\pi} \xrightarrow[E\to\infty]{} \tilde{f}^{\pm}_{p\pi}(x)$$

Feynman scaling

and becomes

$$\pi^{\pm}(E_\pi) = (const) E_\pi^{-(1+\gamma)} Z_{p\pi^{\pm}}$$

$$\boxed{Z_{p\pi^{\pm}} \equiv \int_0^1 \tilde{f}^{\pm}_{p\pi}(x) x^{\gamma-1} dx}$$

Spectrum Weighted Moments

– Finally we have

$$R_\mu = \frac{\mu^+(E_\mu)}{\mu^-(E_\mu)} = \frac{\pi^+(E_\pi)}{\pi^-(E_\pi)} = \frac{Z_{p\pi^+}}{Z_{p\pi^-}}$$

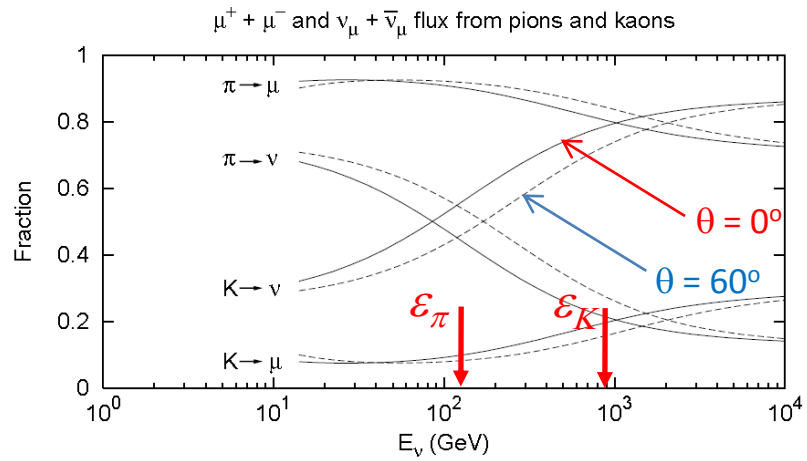
Kaon contribution

- At higher energy (>100 GeV) the contribution of K becomes important
- In general, the contribution of each component to the muon flux N_{par} = (π, K, charmed, etc.) depends on the relative contribution of decays and interaction probabilities:

$$\boxed{\Phi_\mu = \frac{\Phi_N(\mathcal{E}_\mu)}{1-Z_{NN}} \sum_{i=1}^{N_{par}} \frac{a_i Z_{Ni}}{1+b_i \mathcal{E}_\mu / \varepsilon_i(\theta)}}$$

where

$$\begin{cases} a_i = a_i(\gamma) = \dfrac{(1-r_i^{\gamma+1}) Br(i \to \mu)}{(1-r_i)(\gamma+1)} \\ b_i = b_i(\gamma) = \dfrac{(\gamma+2)(1-r_i^{\gamma+1})(\lambda_i - \lambda_N)}{(\gamma+1)(1-r_i^{\gamma+2})(\lambda_i \log \lambda_i / \lambda_N)} \\ r_i = (m_\mu / m_i)^2 \end{cases}$$



$\varepsilon_i = \varepsilon_i(\theta)$ is the "critical energy", i.e. the energy above which interactions dominate over decays. Along the vertical ($\theta = 0^o$)

$\varepsilon_i(0) = m_i c h / \tau_i$ (h = 6.5 km)

$\varepsilon_\pi = 115$ GeV

$\varepsilon_K = 850$ GeV

$\varepsilon_X > 10^7$ GeV

General form for R_μ

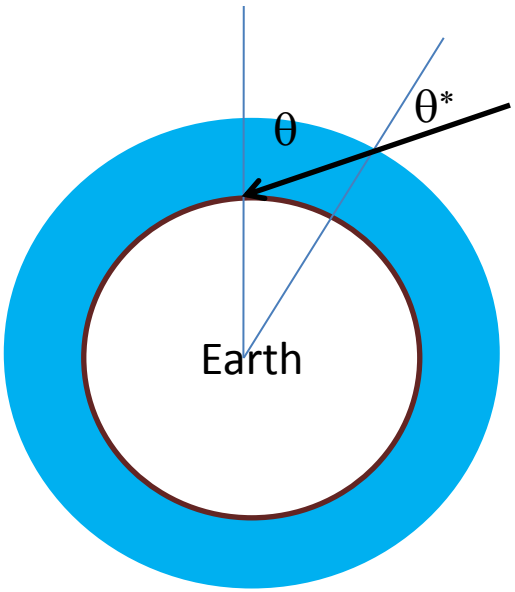
- Let us consider again the general form for the muon flux

$$\Phi_{\mu^\pm} = \frac{\Phi_N(\mathcal{E}_\mu)}{1-Z_{NN}} \sum_{i=1}^{N_{par}} \frac{a_i Z^\pm_{Ni}}{1+b_i \mathcal{E}_\mu \cos\theta^* / \varepsilon_i(0)}$$

where we have explicited the $\varepsilon_i(\theta)$ dependence on θ

$$\varepsilon_i(\theta) = \varepsilon_i(0) / \cos\theta^*$$

where θ^* is the zenith angle at the production point



- The correct variable to describe the evolution of R_μ is therefore $\mathcal{E}_\mu \cos\theta^*$
- The R_μ evolution as a function of $\mathcal{E}_\mu \cos\theta^*$ spans over the different sources

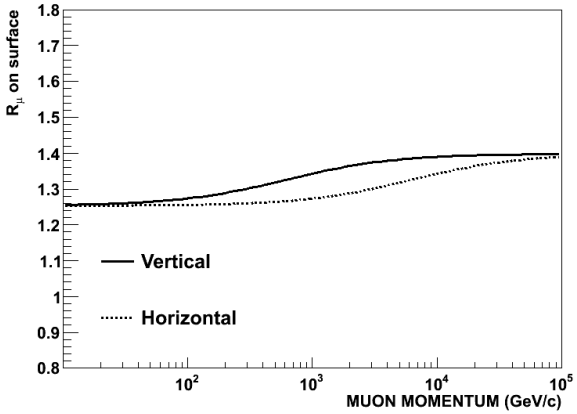
$$R_\mu = w_\pi R_\mu^\pi + w_K R_\mu^K + w_{charm} R_\mu^{charm} + \ldots$$

→ POWERFUL HANDLE TO DISCRIMINATE MODELS

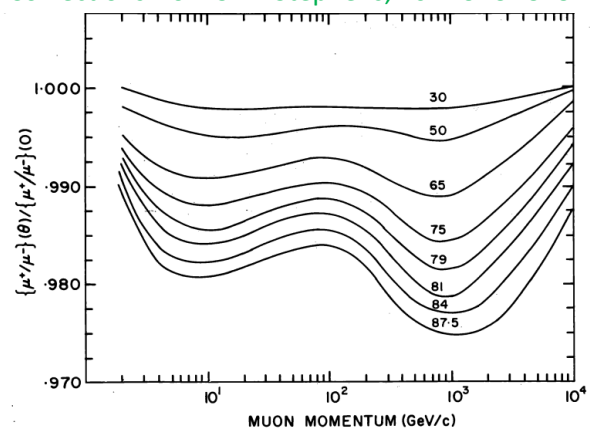
OPERA: $\langle \mathcal{E}_\mu \cos\theta^* \rangle \approx 2000$ GeV → **The (magnetized) experiment with the largest $\mathcal{E}_\mu \cos\theta$**

On the zenith dependence of R_μ

- R_μ exhibits a zenith dependence if:
  a) Muon contributions from different sources with different R_μ
  b) At least one source has a zenith dependence (e.g. π and K due their relatively long lifetimes)
- In the past several authors applied corrections to convert inclined to vertical R_μ measurements
- This procedure has a limit: it assumes no other sources apart from π and K and it assumes $Z_{p\pi}$ and Z_{pK} are known
- The projection on the vertical via $E_\mu \cos\theta$ is safer → capability to explore new (isotropic) components and to derive $Z_{p\pi}$ and Z_{pK} from data



Corrections from S. A. Stephens, 16th ICRC 1979 - Kyoto



R_μ measurements with $E_\mu \cos\theta^* > 1$ TeV

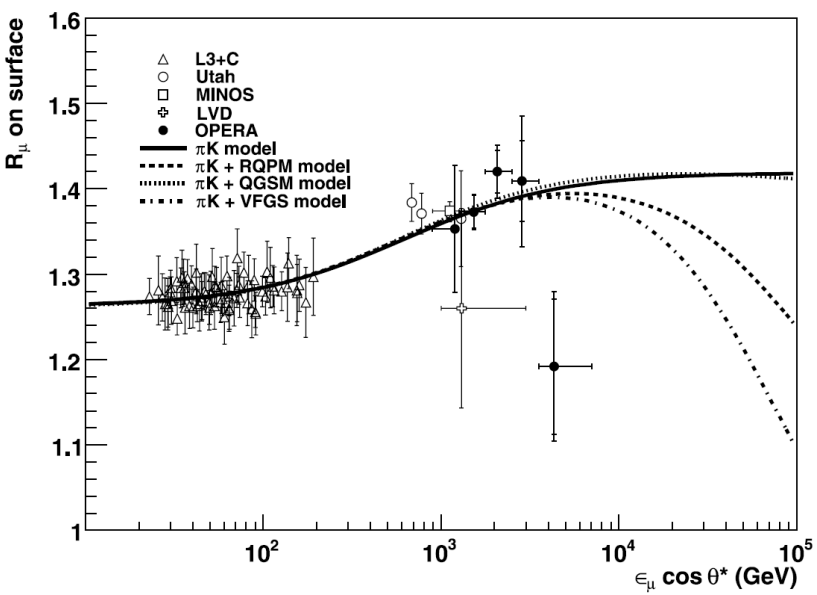
- Utah:
  G. K. Ashley et al., Phys. Rev. D12 (1975) 20
  - Underground at Utah University, flat surface above ~1400 m.w.e., magnetic spectrometer (1.63 T) + spark chambers, six bins with $46° < \theta < 78°$
- Kamiokande-II
  M. Yamada et al., Phys. Rev. D44 (1991) 617
  - Underground Cherenkov detector at Kamioka ~2700 m.w.e., delayed events on stopping muons, one bin with $0° < \theta < 90°$
- MINOS:
  P. Adamson et al., Phys. Rev. D76 (2007) 052003 + arXiv:0906.3726
  - Underground at Soudan, magnetized steel, flat surface above ~2000 m.w.e., $0° < \theta < 90°$
- LVD:
  N. Agafonova et al., Proc. 31th ICRC, ŁÓDZ 2009
  - Underground at LNGS, average overburden ~3800 m.w.e., scintillators, delayed events on stopping muons, one bin with $\theta < 15°$
- OPERA:
  N. Agafonova et al., Eur. Phys. J. C67 (2010) 25
  - Underground magnetic spectrometer (1.53 T) at LNGS, average overburden ~3800 m.w.e., drift tubes + RPC + scintillators, $0° < \theta < 90°$

New OPERA data

(on behalf of the OPERA Collaboration)

First results published in Eur. Phys. J. C 67 (2010) 25:

- 403069 μ collected during 2008 CNGS run corresponding to 113.4 days of livetime
- Underground R_μ = 1.377 ± 0.014 (stat) + 0.017 – 0.015 (syst)
- Separation of R_μ for single and multiple muons, different at 2.4 σ level
- Rise up to $E_\mu \cos\theta \approx 3$ TeV then indication of a decrease in R_μ



[from 2010 paper]

It is however intriguing to observe that our measurement lies in the region where the charmed particle production may start to give an observable contribution to the muon charge ratio. A larger statistical sample or an experimental measurement with a new detector at very large depths could shed light on the region $\mathcal{E}_\mu \cos\theta^* \gtrsim 10$ TeV. The data collected by OPERA at the end of its scientific program will allow to improve the measurement in this energy region.

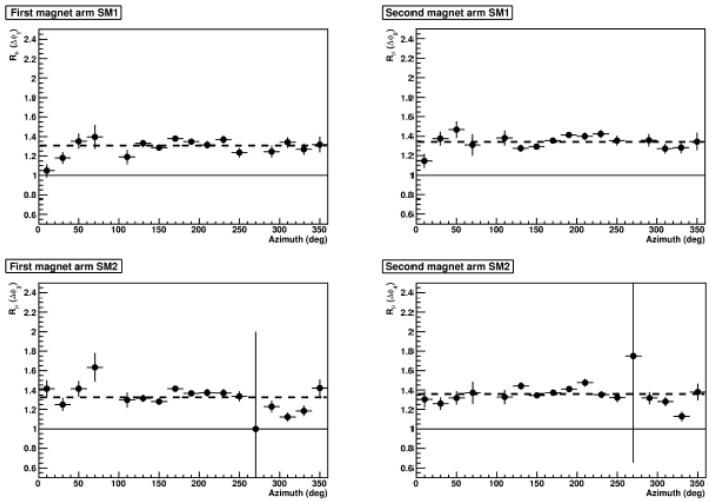
New OPERA data

Major improvements w.r.t. 2010 published analysis:

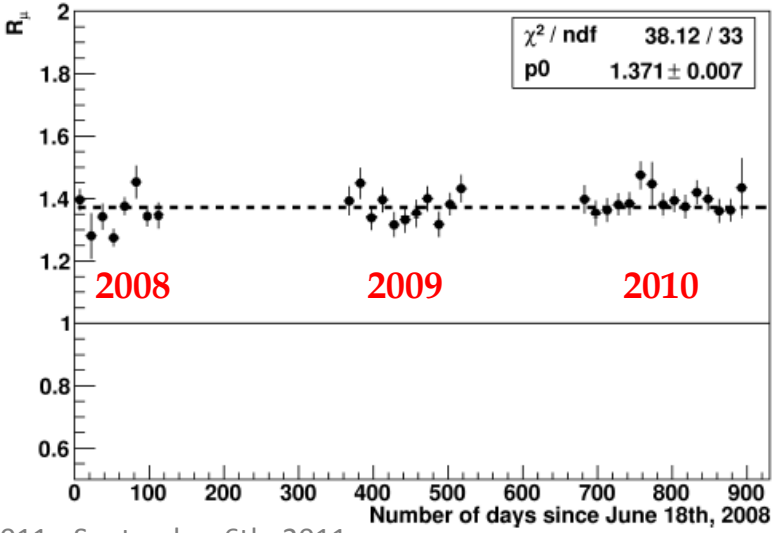
- **Statistics × 3:**
  1454057 μ collected during
  2008-2009-2010 CNGS runs corresponding to 407.1 days of livetime
- Underground R_μ = 1.403 ± 0.008 (stat) + 0.017 – 0.015 (syst)
- Separation of R_μ for single
  and multiple muons, different
  at 7.2 σ level
  - Convolution of two effects:
    larger n/p ratio in the all-nucleon spectrum $\otimes$ different X_F region
- Cosmic events selected outside the CNGS spill window
- Atmospheric neutrino events rejected on the basis of ToF
- Analysis cuts and details in:
  http://www.bo.infn.it/opera/docs/phd_thesis-BO-2011_05_20-mauri.pdf
- Drop in R_μ for $E_\mu \cos\theta$ > 3 TeV still persists with stronger significance

Consistency checks

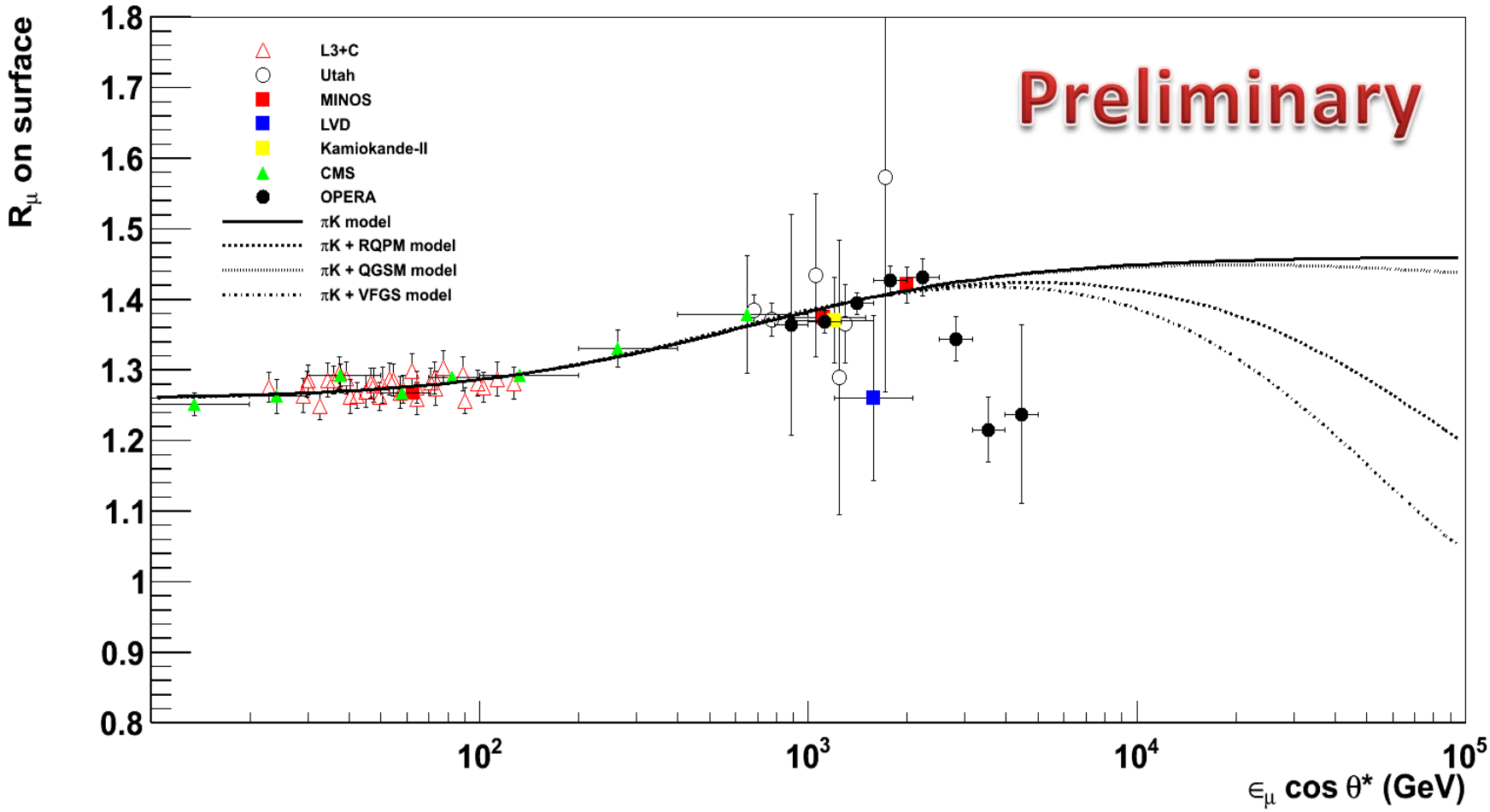
- R_μ as a function of the azimuth angle φ (mis-alignment check)



- The 4 R_μ values, computed separately for each magnet arm, fluctuate around the average of 0.016, which is within their statistical accuracy (0.018)
- Run with inverted polarity (9+7 days): $R_\mu^{inverted} = 1.39 \pm 0.04$
- Run with magnet off (13 days): $R_\mu^{off} = 1.02 \pm 0.04$
- Measurement stability as a function of the data taking: R_μ remains constant



R_μ measurements with $E_\mu \cos\theta^* > 1$ TeV



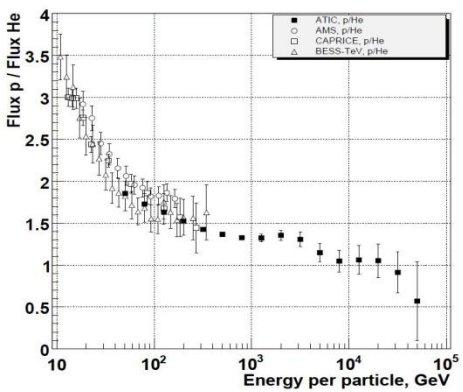
Interpretation of the results

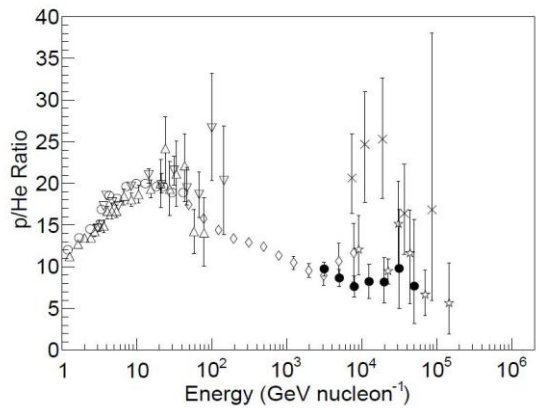
- There is a clear indication of a smooth transition between the low and high energy regimes as predicted by the π-K model

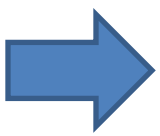
  $R_\mu \approx 1.25$ around 100 GeV →
  smooth transition to $R_\mu \approx 1.4$ in TeV region
- Sharp drop for $E_\mu \cos\theta^* > 2\text{-}3$ TeV in the OPERA data
- Since at present this drop is not explained by any systematic effect we can speculate on its possible physical nature
  - Sudden change in the n/p ratio in the all-nucleon spectrum?
  - Strong scaling violation in the forward fragmentation region for π/K mesons?
  - Upraise of a new muon component?

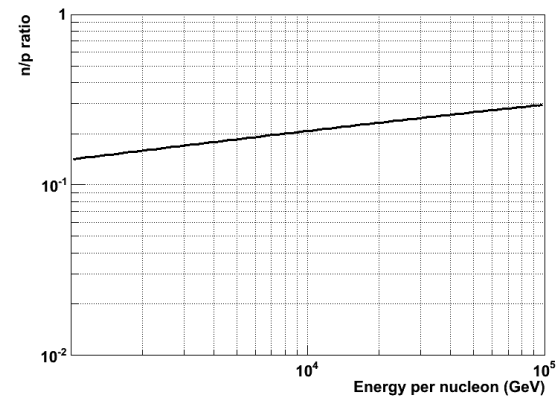
n/p ratio in the primary radiation?

- New precise measurements (CREAM, ATIC) of spectral indexes and abundance ratios in the primary region of interest (10 – 100 TeV/n)
- Smooth transition of n/p ratio as a function of E/A from 15% → 30%



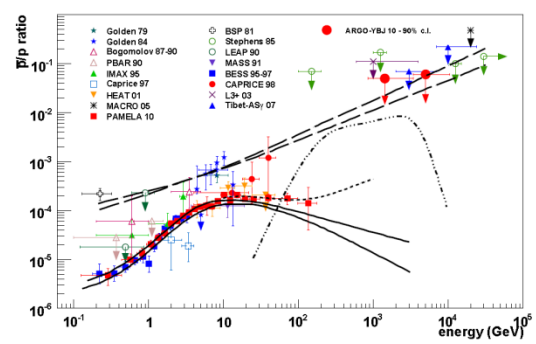






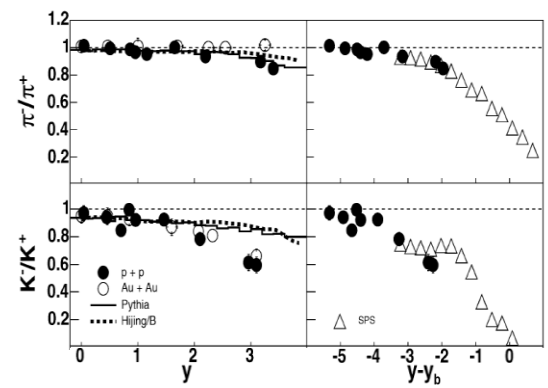
- Also anti-protons ruled out:
  $\bar{p}$/p ratio constrained around 10 TeV/n by ARGO-YBJ below 5%

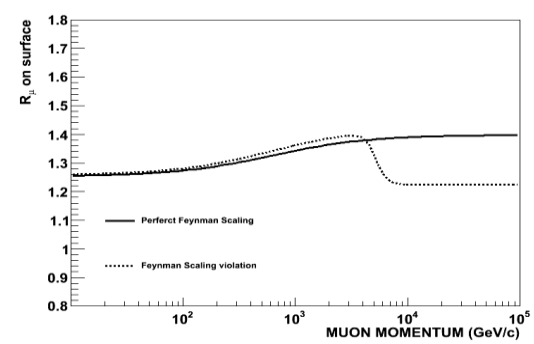
  see e.g. Astron. Astrophys. 149 (1985) 1



Feynman Scaling Violation?

- In the past FSV was often invoked to explain experimental results of R_μ [see e.g. PRD 41 (1990) 863]
- Recently new pp experimental data from BRAHMS @ RHIC in a phase space partially overlapping with the region of interest were released: pp at $\sqrt{s}$ = 200 GeV and $0 < y < 3$ [PLB 607 (2005) 42]
- Pion and kaon charge ratios exhibit good scaling when properly matched with low energy data at SPS (NA27)
- Positive excess starts at mid-rapidity towards the fragmentation region and is very similar to Au-Au interactions
- PHYTIA badly describes the kaon charge ratio but it's well predicted by CR codes (e.g. DPMJET)
- The anomaly is reproduced only with a sharp artificial transition of Z_{NK+}/Z_{NK-} from 2.2 → 1.25 at ~3 TeV





Upraise of a new muon component?

- The search for an extra muon component in the muon spectrum has a long history
- Heavy flavors are dynamically suppressed w.r.t. light mesons
- However their lifetimes are much shorter and decay instantaneously so they inherit the spectral index γ of the primary radiation. They are isotropic (conversely π and K have γ+1 and exhibit a secθ angular dependence)
- At a certain point the flavored component should dominate over the conventional component (cross-over in the energy spectrum is largely uncertain)
- Models with "intrinsic" charm component – which takes into account a $|uudc\bar{c}>$ state within the proton - predict a larger amount of charmed hadrons w.r.t. model without IC [see e.g. PRD58 (1998) 05401 and PRD78 (2008) 043005].
- Searched for as an enhancement of the verticalized depth-intensity-relation at large depth or – alternatively – as an enhancement of the surface muon spectrum
  - All these method are largely indirect and rely on the perfect knowledge of the detector acceptance
- Other methods include the search for enhancement of muon flux around the vertical at large depths (depth-angular-relation, see e.g. hep-ex/9906021)

Upraise of a new muon component?

- We use the approximate model to describe R_μ data

$$\Phi_\mu = \frac{\Phi_N(\mathcal{E}_\mu)}{1-Z_{NN}} \sum_{i=1}^{N_{par}} \frac{a_i Z_{Ni}}{1+b_i \mathcal{E}_\mu / \varepsilon_i(\theta)} = \frac{\Phi_N(\mathcal{E}_\mu)}{1-Z_{NN}} \left[\frac{a_\pi Z_{N\pi}}{1+b\pi \mathcal{E}_\mu / \varepsilon_\pi(\theta)} + \frac{a_K Z_{NK}}{1+b_K \mathcal{E}_\mu / \varepsilon_K(\theta)} + a_{charm} Z_{N-charm} \right]$$

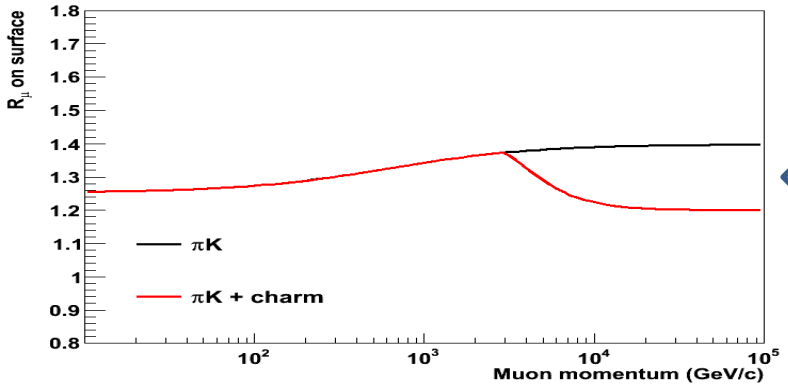
- Parameters for pions and kaons have been taken from Eur. Phys. J. C 67 (2010) 25
- Parameters for charm have been taken from PRL 105 (2010) 121102 admitting a scaling violation of the form

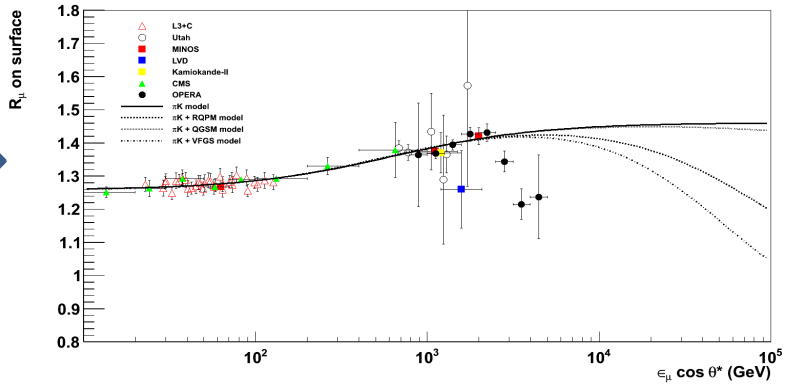
$$Z_{N\text{-}charm} = \begin{cases} Z^0_{N\text{-}charm} & \text{for } E < E^0_\mu \\ Z^0_{N\text{-}charm}\,[1+A(E_\mu - E^0_\mu)^{\Delta\gamma}] & \text{for } E > E^0_\mu \end{cases}$$

- We took $Z^0_{Ncharm} = 5\times10^{-4}$, $E^0_\mu = 3$ TeV, $A=1$, $\Delta\gamma = 0.5$

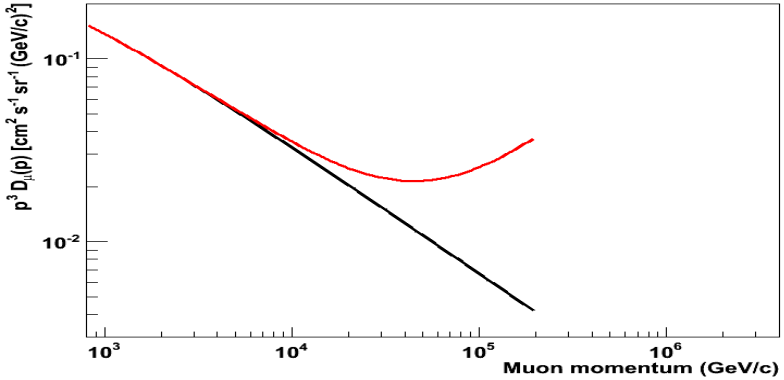
Upraise of a new muon component?

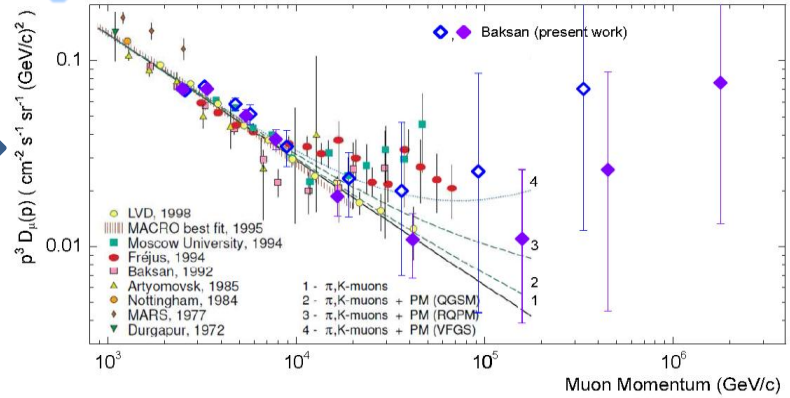
Muon charge ratio





Muon energy spectrum

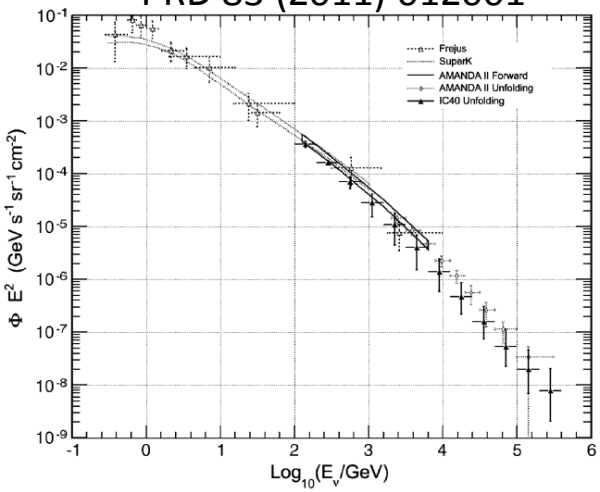




Conclusions

- We reviewed the present knowledge of the atmospheric muon charge ratio for $E_\mu \cos\theta > 1$ TeV
- The new OPERA data with a largely increased statistics were presented
- The transition between the pion and kaon region is still evident, with R_μ ranging from ~1.25 at low energies up to ~1.4 up at ~3 TeV
- Above 3 TeV a sharp drop in the R_μ is still present with a larger statistical significance
- Difficult to accommodate the effect within the present knowledge of the primary radiation and of the hadronic interaction features for light mesons in the kinematical region of interest
- A mild scaling-violating energy dependent Z factors for charm seems to accommodate both charge-ratio and high energy spectrum excesses
- What about neutrinos? Neutrinos are produced in the same decay chains as muons and share with them the same cascade equations
- Why no signature in the high-energy neutrino spectrum? Whatever, we should take into account that – according to the new muon charge ratio data - most of the neutrinos in "excess" should be anti-neutrinos and have therefore a smaller DIS cross-section
- New R_μ experimental measurements with $E_\mu \cos\theta > 1$ TeV would be highly desirable. The best would be an upward-facing spectrometer at very large depths.

PRD 83 (2011) 012001



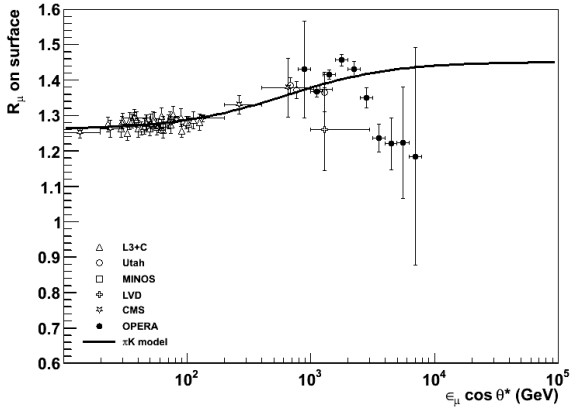
Spares

New OPERA data

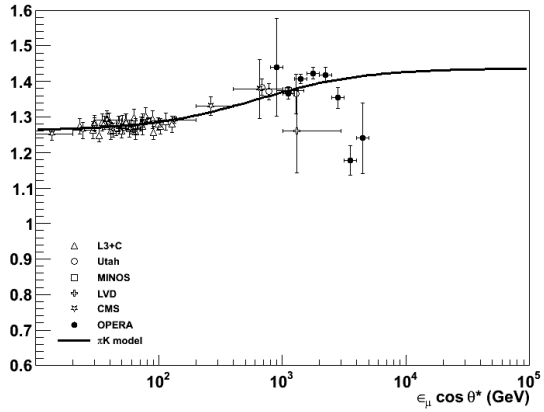
The cut on MDM is naturally embedded into the requirement:

$$\Delta\phi/\sigma_{\Delta\phi} > n$$

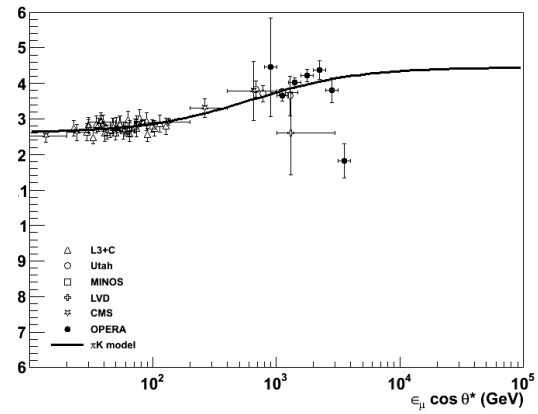
Note that $\sigma_{\Delta\phi} = \sigma_{\Delta\phi}(\phi)$ i.e. the angular resolution (hence the MDM) depends on the direction.



$\Delta\phi/\sigma_{\Delta\phi} > 1$

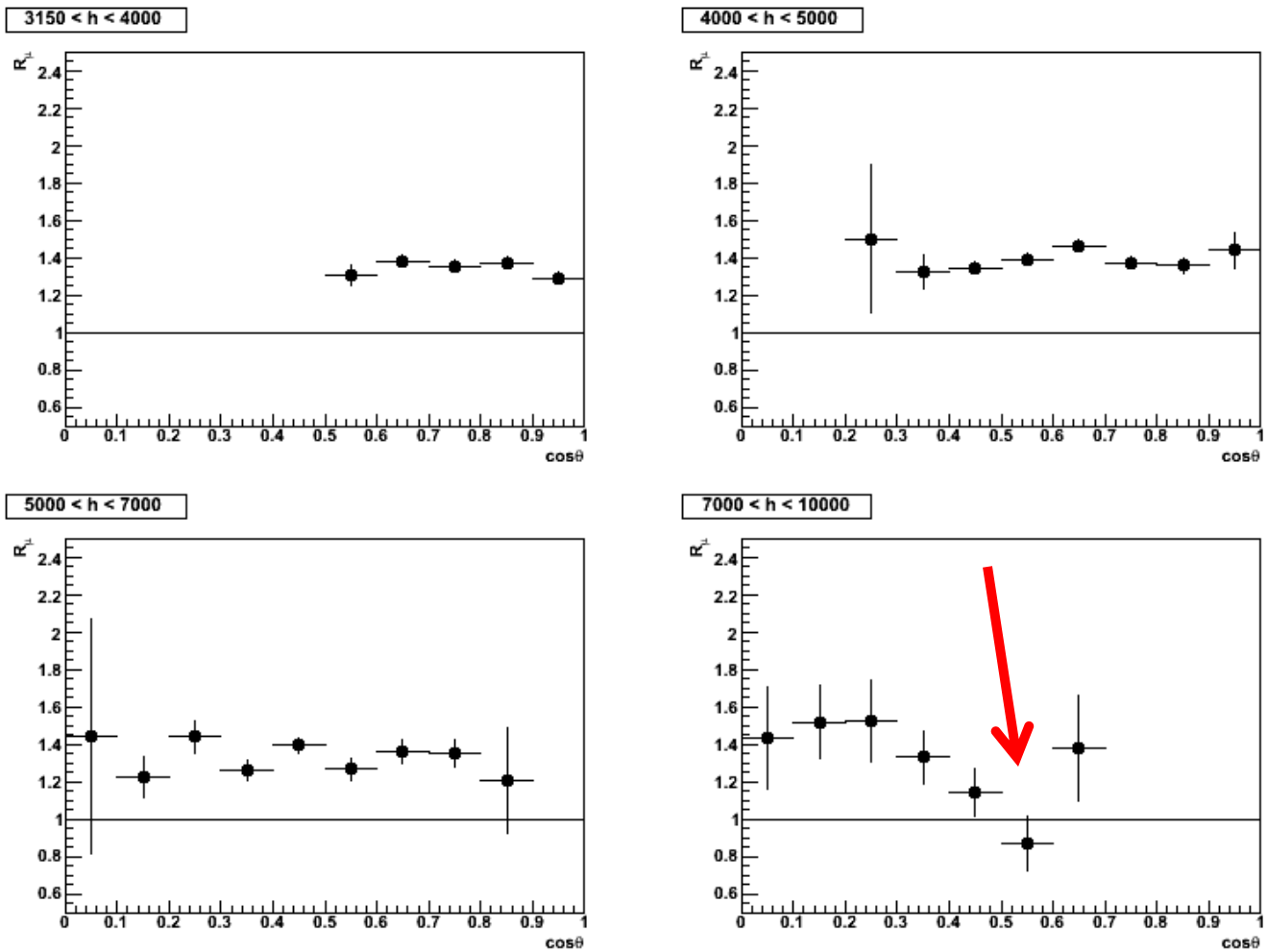


$\Delta\phi/\sigma_{\Delta\phi} > 3$



$\Delta\phi/\sigma_{\Delta\phi} > 5$

Depth-angular-R_μ (OPERA)



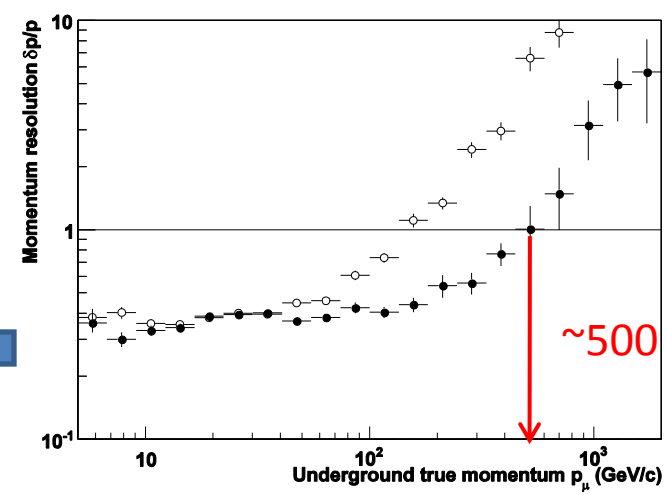
Maximum Detectable Momentum

- Consider the magnetic field bending and the total deflection spoiling (detector + MCS)

$$\Delta\phi_B = \frac{0.3Bd}{p} \qquad \sigma_{\Delta\phi} = \sqrt{\sigma_{\phi_1}^2 + \sigma_{\phi_2}^2 + \left(\frac{0.0136}{p}\right)^2 \frac{d}{X_0}}$$

- Requiring $\Delta\phi_B/\sigma_{\Delta\phi} > 1$ we obtain (for ϕ=0):
  - p_{max}(doublets) = 1.25 TeV
  - p_{max}(singlets) = 190 TeV
  - p_{max}(mixed) = 260 TeV

Exact computation at all angles (MC)



~500 GeV/c

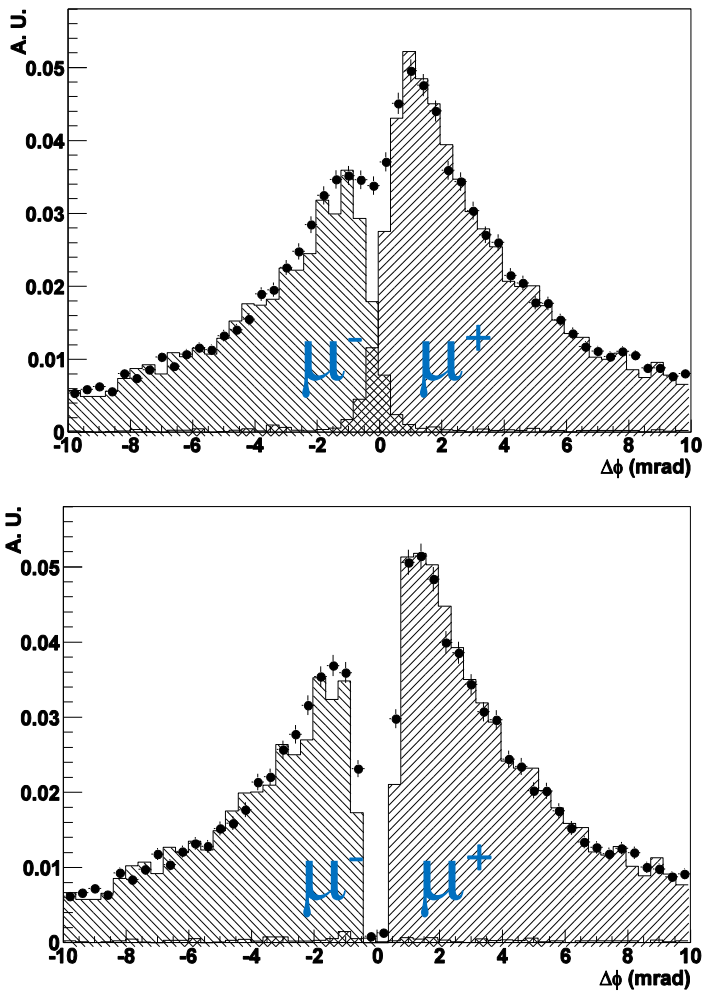
Charge mis-identification

- $\eta \equiv$ fraction of tracks reconstructed with wrong charge sign
- Used to correct data (unfold)

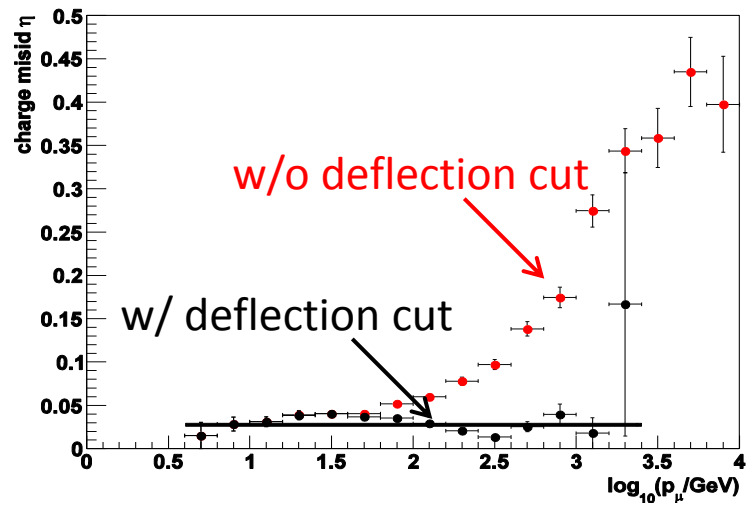
$$R_\mu^{unf} = \frac{(1-\eta)R_\mu^{meas} - \eta}{-\eta R_\mu^{meas} + (1-\eta)} \qquad \delta R_\mu^{unf} = \frac{\sqrt{(1-2\eta)^2(\delta R_\mu^{meas})^2 + (R_\mu^{meas}-1)^2(\delta\eta)^2}}{[\eta R_\mu^{meas} - (1-\eta)]^2}$$

- In the LE limit (only MCS) the estimate is ~10^{-3}
- Real η is larger due to spurious effects:
  - Secondary particles
  - Timing errors

Deflection cut: effects on $\Delta\phi$ and η



The charge mis-identification η is strongly reduced.
Possible differences between MC and real η is a source of systematic uncertainty on R_μ → considered in the analysis



$\eta \sim 3\%$