High p_T muons from cosmic ray air showers in IceCube

...going a bit more into detail

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Astroteilchenphysik
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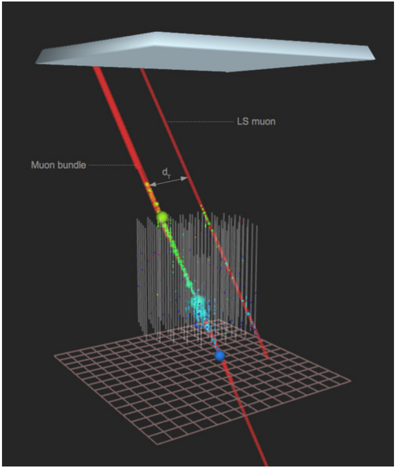
2. Simulation
   - Concept
   - p_{T} and energy spectra
   - Propagation/Decay
   - In-ice distributions
3. Open issues



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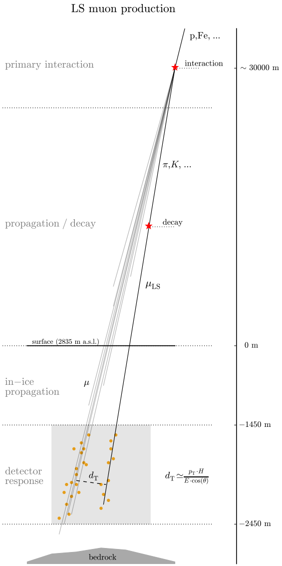
Signal signature

- High energy cosmic ray interactions can produce secondaries with large transverse momentum p_{T}
- Mesons that decay into muons:
  conventional: π^+, K^+, K^0
  prompt: $D^+, D^0, D_s^+, \Lambda_c, \Omega_c^0, B^+, B^0, B_c^+, \lambda_b^0$
  unflavored: $\eta, \eta', \omega, \rho^0, \phi$
  and anti-particles.
- Isolated muons (LS muons) separate from the shower core while travelling to the detector $\rightarrow$ **double track signature** in IceCube
- **Lateral separation**:

$$d_{\mathrm{T}} = \frac{p_{\mathrm{T}} \cdot H}{E_\mu \cdot \cos(\theta)}$$



Signal signature

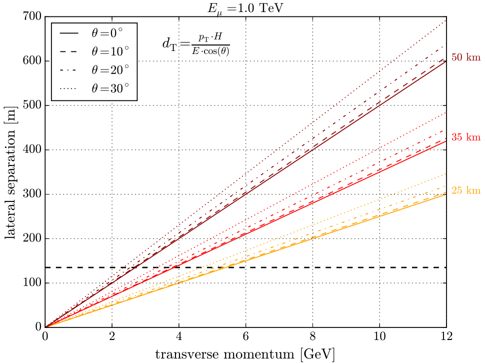
$$d_\mathrm{T} = \frac{p_\mathrm{T} \cdot H}{E_\mu \cdot \cos(\theta)}$$

- Minimal resolvable track separation: ~ 135 m

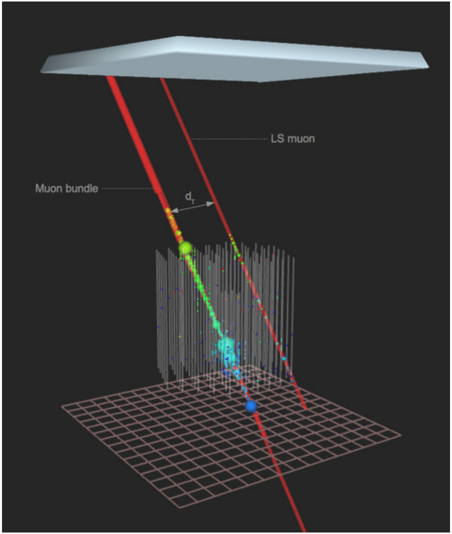
[R. Abbasi *et al.*, Phys. Rev. D **87**, 012005 (2013)]

- Typical muon energy: ~ 1 TeV

$\rightarrow$ Minimal p_T: ~ 2 GeV
$\rightarrow$ pQCD regime!



$\rightarrow$ 'High p_T' refers to $p_\mathrm{T} > 2$ GeV and $E > 500$ GeV



Simulation?

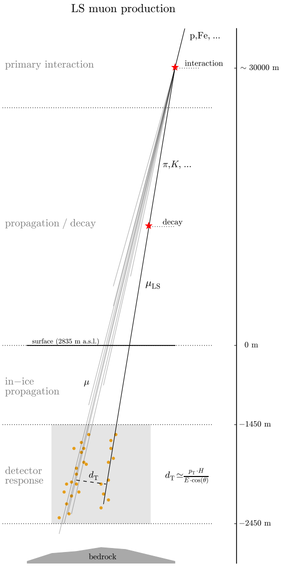
Concept

Simulate muon bundle and LS muon separately:

- Muon bundle obtained from pre-simulated CORSIKA dataset (11499, 11637)

LS muon:

- Primary energy, interaction height, direction from CORSIKA dataset
- p_T, energy distributions and production probability of high p_T mesons from any HE interaction model using CRMC*
- Propagation and decay into muons
- LS muon in-ice propagation (PPC)
- Detector response and Level2 filtering

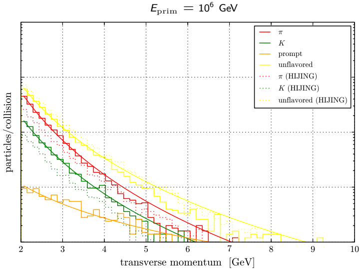


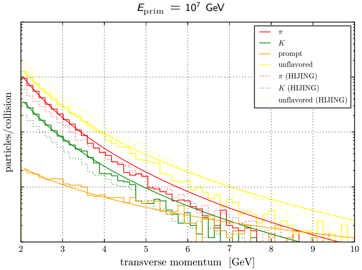
* [C. Baus *et al.*, http://web.ikp.kit.edu/rulrich/crmc.html (2013)]

Meson transverse momentum

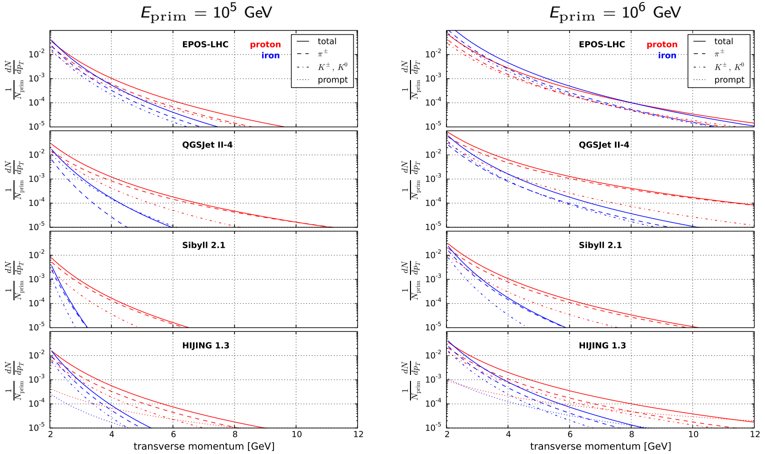
- **Assumption:** High p_T particle production only in primary interaction
- Simulate 100000 collisions using CRMC for initial energies $\log_{10}(E_{\text{prim}}) = 3.0, 3.1, \ldots, 9.0$
- EPOS-LHC and HIJING 1.3
- Initial particles: **proton**/**iron**
- Target particle: **nitrogen**
- **Power law fits** applied to final state meson p_T distributions:

$$N(p_T) = a \cdot p_T^b$$





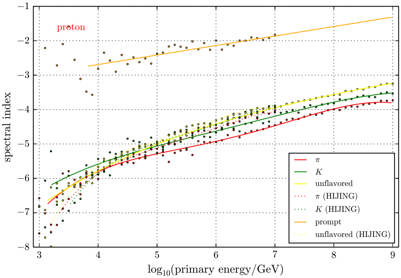
Composition

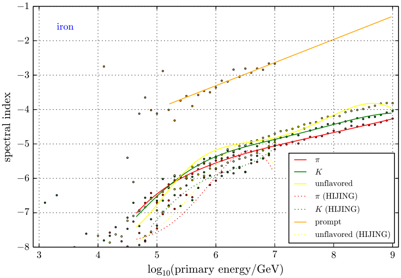


$p_{\rm T}$ spectra sensitive to mass composition!

Meson transversal momentum

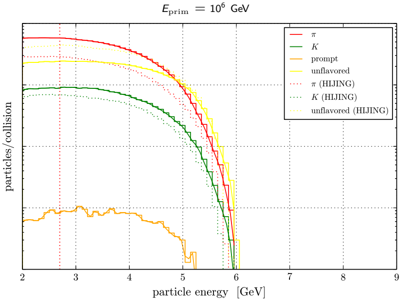
- **Spectral indices** *b* as a function of primary energy (spline interpolation)
- Secondary meson's p_{T} is generated from power law distribution with *b* according to the primary energy obtained from CORSIKA

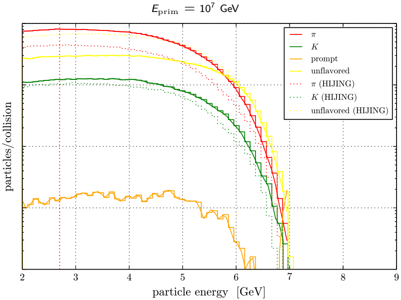




Meson energy

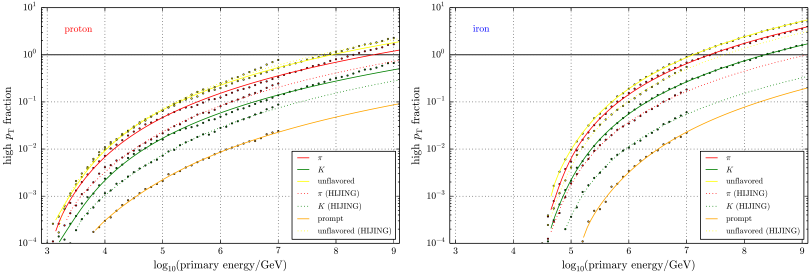
- Meson **energy distributions** obtained from EPOS and HIJING simulations (spline interpolation)
- Secondary meson's energy is generated from spline of the distribution closest to the primary energy



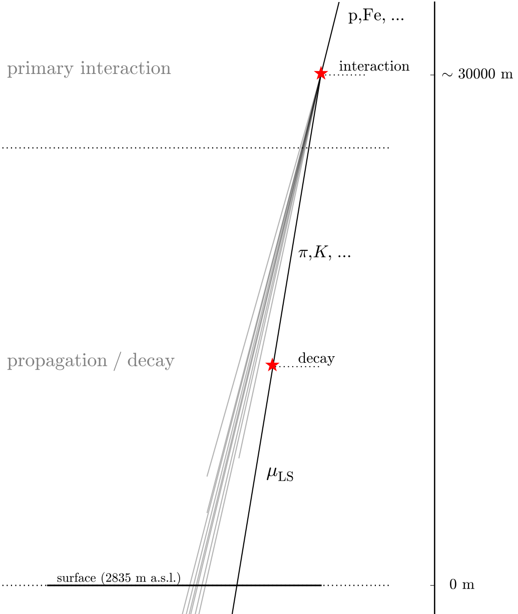


Production probability

- Probability to produce a high p_{T} meson as a function of primary energy obtained from EPOS and HIJING simulations (spline interpolation)
- Production probability according to the initial primary energy incorporated via **event weighting**



LS muon production



Decay

[M. Thunman *et al.*, Astropart. Phys. **5** (1996) 309]:

Compare **distance to point of decay**

$$L_{\rm dec}(E) = -c\beta\gamma\tau_M \ln(R_1)$$

and **distance to point of re-interaction**

$$L_{\rm int}(E) = H + h_0 \cdot \ln\left(e^{-H/h_0} - \frac{\lambda_M \cdot \ln(R_2)}{X_0}\right),$$

of secondary mesons M until $L_{\rm dec} < L_{\rm int}$ where

$$\lambda_M = \frac{\rho(H)}{\sum_A \sigma_M(E) \cdot n_A(H)} \simeq \frac{\langle A \rangle}{\sigma_M(E) \cdot N_0}$$

Decay probability: $P_{\rm dec} = n_{\rm try}^{-1}$

($\gamma = E/m_M$; lifetime τ_M; speed β; density ρ; $h_0 = 6.4$ km; $X_0 = 1300$ g/cm^2; R_1, R_2 random numbers $\in [0, 1]$)

Decay channels

Decay	BR	M abundance
pion $\rightarrow \mu$		
$\pi^{\pm} \rightarrow \mu^{\pm}\nu_{\mu}$	0.9998	0.2084
kaon $\rightarrow \mu$		
$K^{\pm} \rightarrow \mu^{\pm}\nu_{\mu}$	0.6355	0.0776
$K^0_L \rightarrow \mu^{\pm}\pi^{\mp}\nu_{\mu}$	0.2704	$0.5 \cdot 0.0762$
prompt $\rightarrow \mu$		
$D^{\pm} \rightarrow \mu^{\pm} + X$	0.1760	0.0042
$D^0 \rightarrow \mu^{\pm} + X$	0.0670	0.0042
unfl $\rightarrow \mu$		
$\eta \rightarrow \mu^+\mu^-\gamma$	$3.1 \cdot 10^{-4}$	0.0765
$\eta' \rightarrow \mu^+\mu^-\gamma$	$1.1 \cdot 10^{-4}$	0.0197
$\omega \rightarrow \mu^+\mu^-\pi^0$	$1.3 \cdot 10^{-4}$	0.0380

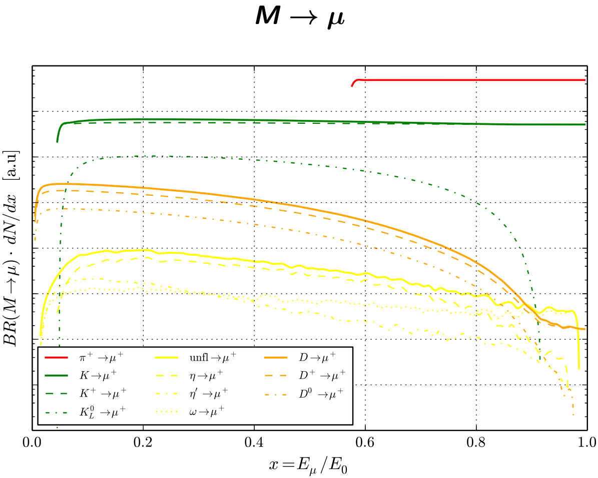
Decay	BR	M abundance
kaon $\rightarrow \pi$		
$K^0_L \rightarrow \pi^{\pm}e^{\mp}\nu_e$	0.4055	$0.5 \cdot 0.0762$
$K^0_L \rightarrow \pi^{\pm}\mu^{\mp}\nu_{\mu}$	0.2704	$0.5 \cdot 0.0762$
$K^0_S \rightarrow \pi^+\pi^-$	0.6920	$0.5 \cdot 0.0762$
unfl $\rightarrow \pi$		
$\eta \rightarrow \pi^+\pi^-\pi^0$	0.2810	0.0765
$\eta \rightarrow \pi^+\pi^-\gamma$	0.2292	0.0765
$\eta' \rightarrow \mu^{\pm}$	0.4290	0.0197
$\phi \rightarrow \pi^+\pi^-\pi^0 + \rho\pi$	0.1532	0.0246
$\rho^{\pm} \rightarrow \pi^{\pm}\pi^0$	~ 1	0.1836
$\rho^0 \rightarrow \pi^+\pi^-$	~ 1	0.1457
$\omega \rightarrow \pi^+\pi^-\pi^0$	0.8920	0.0380
unfl $\rightarrow K$		
$\phi \rightarrow K^+K^-$	0.4890	0.0246
$\phi \rightarrow K^0_L K^0_S$	0.3420	0.0246

$$\langle BR \rangle = \frac{\sum_M a_M \cdot BR_M}{\sum_M a_M}$$

a_M: abundance of meson M

Decay

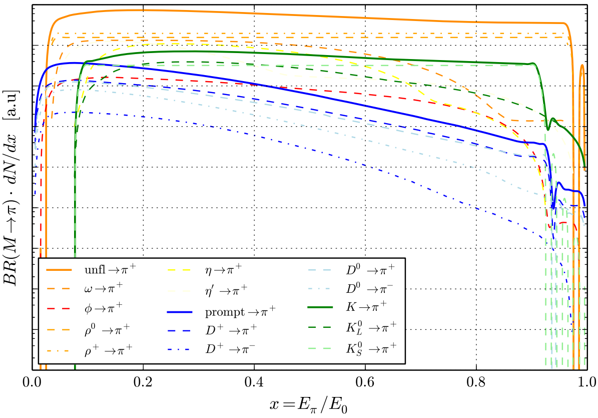
- Energy distributions after decay from PYTHIA 8



Decay

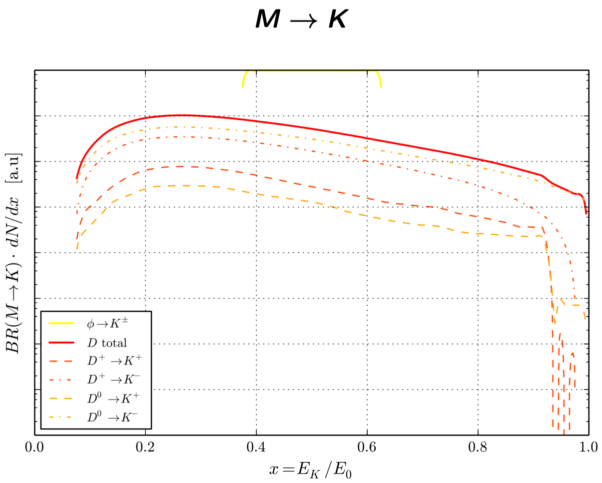
- Energy distributions after decay from PYTHIA 8

$M \to \pi$



Decay

- Energy distributions after decay from PYTHIA 8



Primary spectrum

- **Re-weighting** to any model of interest
- This work: **TIG parametrization**

$$\frac{dN}{dE}\left[\frac{\mathrm{nucleons}}{\mathrm{cm^2 s\,sr\,GeV/A}}\right] = \begin{cases} 1.7 \cdot E^{-2.7} & \text{for } E \leq 5 \cdot 10^6 \text{ GeV} \\ 174 \cdot E^{-3} & \text{for } E > 5 \cdot 10^6 \text{ GeV} \end{cases}$$

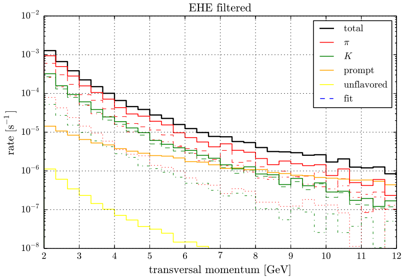
[M. Thunman *et al.*, Astropart. Phys. **5** (1996) 309]

- Pure-proton & pure-iron

In-ice distributions (proton, EHE filter)

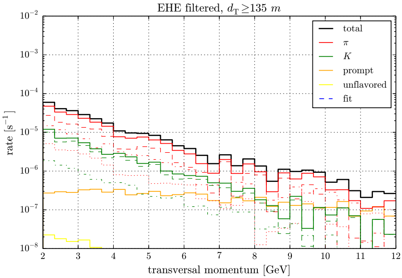
p_{T} distributions in IceCube

No d_{T} cut



Spectral index: -4.41 ± 0.025

$d_{\mathrm{T}} > 135\,\mathrm{m}$

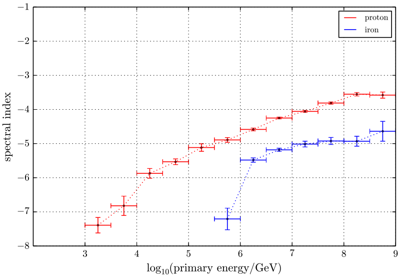


Spectral index: -2.86 ± 0.091

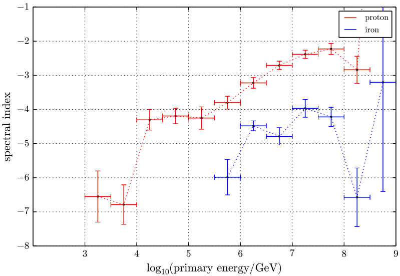
In-ice distributions (proton, EHE filter)

Composition studies in bins of primary energy or related observable

No d_{T} cut



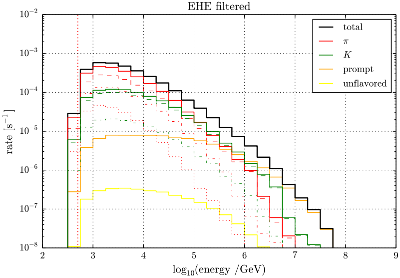
$d_{\mathrm{T}} > 135\,\mathrm{m}$



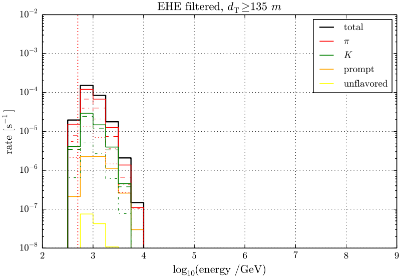
In-ice distributions (proton, EHE filter)

Energy spectrum in IceCube

No d_{T} cut



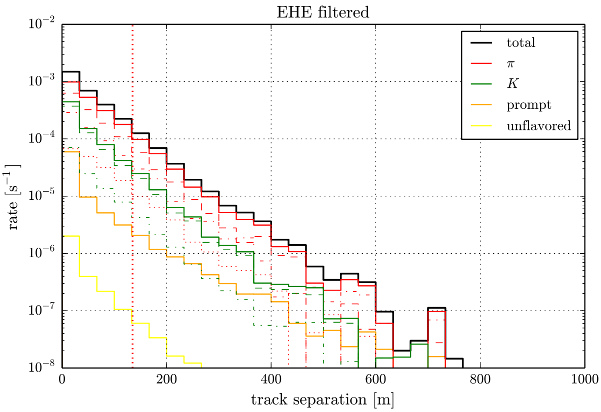
$d_{\mathrm{T}} > 135\,\mathrm{m}$



$$d_{\mathrm{T}} = \frac{p_{\mathrm{T}} \cdot H}{E_{\mu} \cdot \cos(\theta)}$$

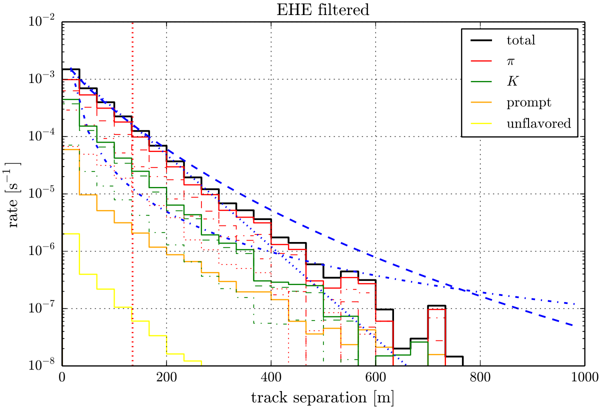
In-ice distributions (proton, EHE filter)

Lateral separation distribution in IceCube



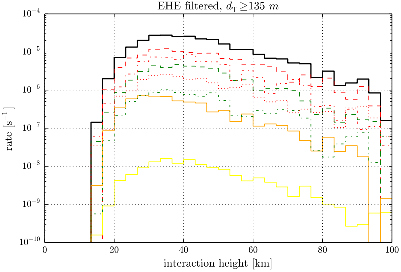
In-ice distributions (proton, EHE filter)

Lateral separation distribution in IceCube

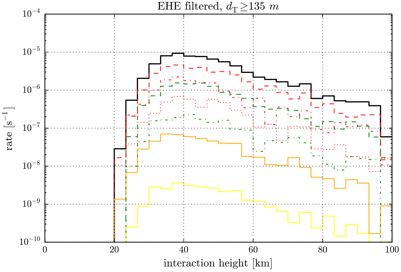


Interaction height

proton

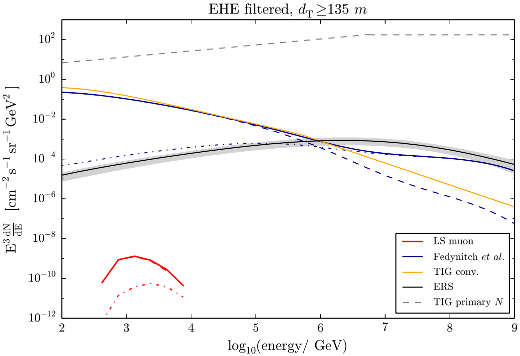


iron



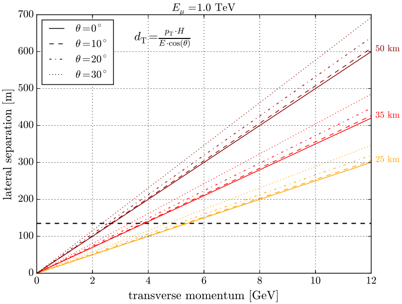
In-ice distributions (proton, EHE filter)

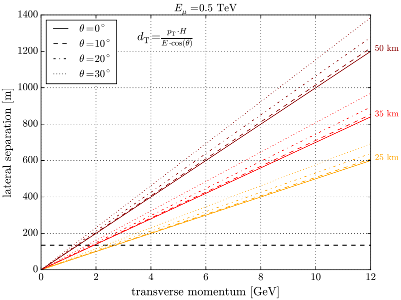
LS muon flux in IceCube (PRELIMINARY!)



- Event rate in IC86: ~ 0.3 mHz, IC59: ~ 1.1 mHz
- Why?

Track separations vs. transversal momentum





- Significant flux from lower p_T at low muon energies!
- Go to lower p_T ($\sim$ 1.5 GeV)
- Also lower E_μ?

CORSIKA simulation

- *'Interaction height fix'*

  → Write 'CorsikaInteractionHeight' to frame

- **LE dataset**: 11499
  - $E^{-2.6}$
  - 600 GeV - 10^5 GeV
  - **SpiceLea**

- **HE dataset**: 11637
  - E^{-2}
  - 10^5 GeV - 10^{11} GeV
  - **SpiceMie**

Thank you!

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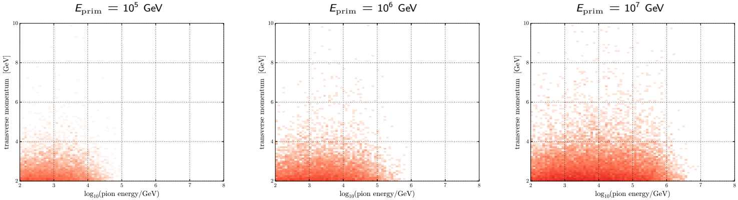
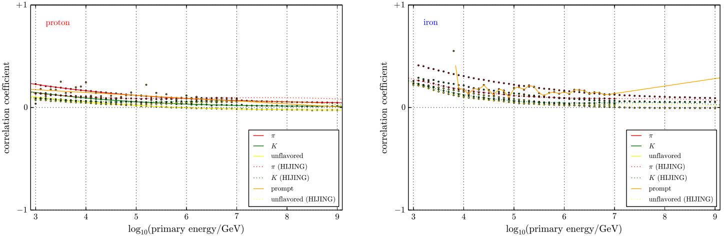
Backup

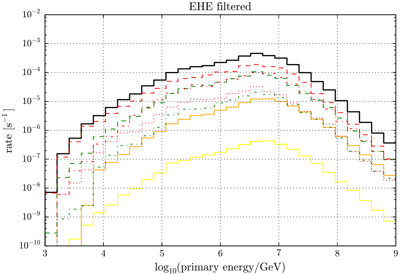
$p_\mathrm{T} \leftrightarrow$ energy correlation

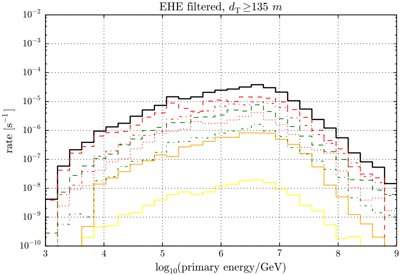


Pearson coefficients:

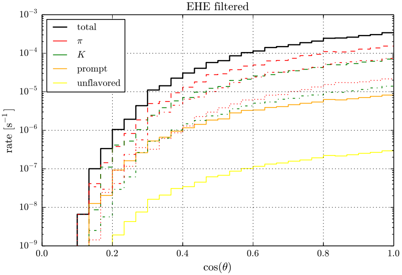


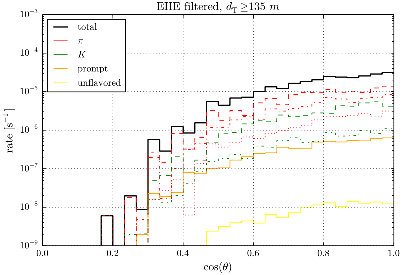
Primary energy (proton)



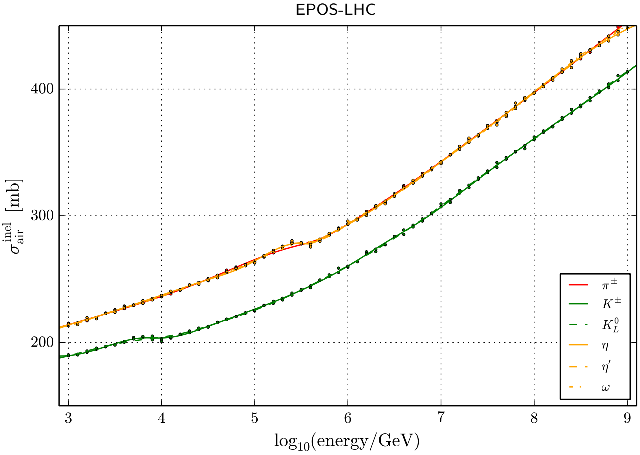


Zenith angle distribution (proton)

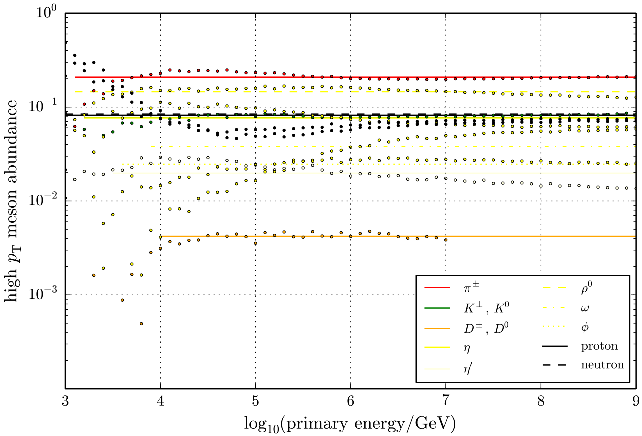




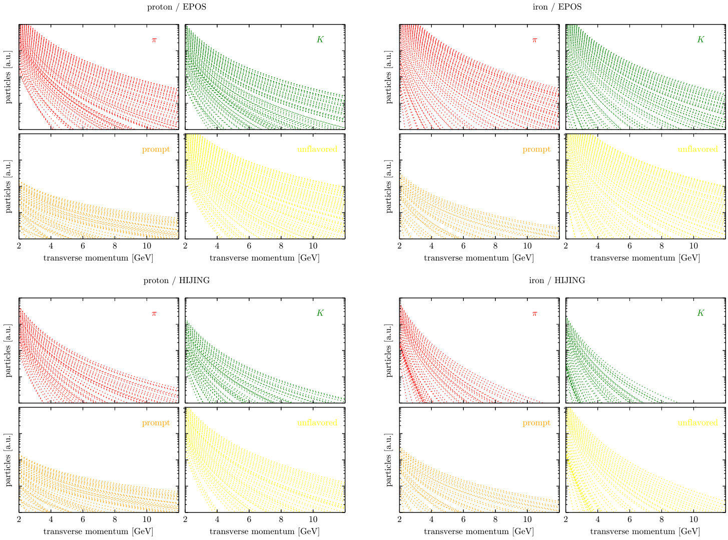
Meson-air cross sections



High p_{T} meson abundance (EPOS)



p_{T} power law fits



Energy splines