WISCONSIN ICECUBE PARTICLE ASTROPHYSICS CENTER

ILLINOIS INSTITUTE OF TECHNOLOGY

Cosmic Ray Atmospheric Showers and High Energy Hadronic Interaction Models

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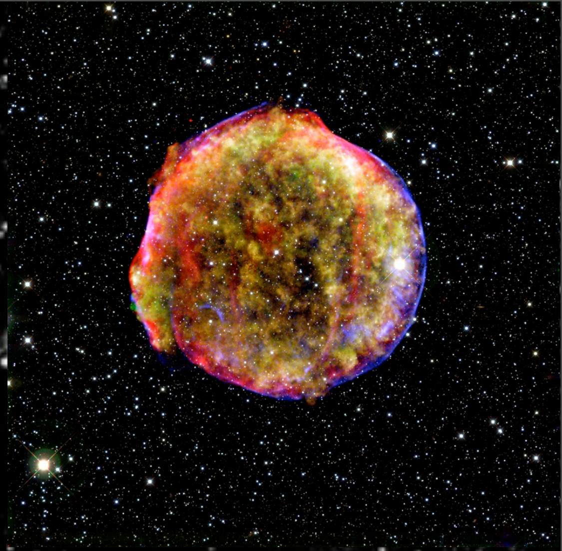
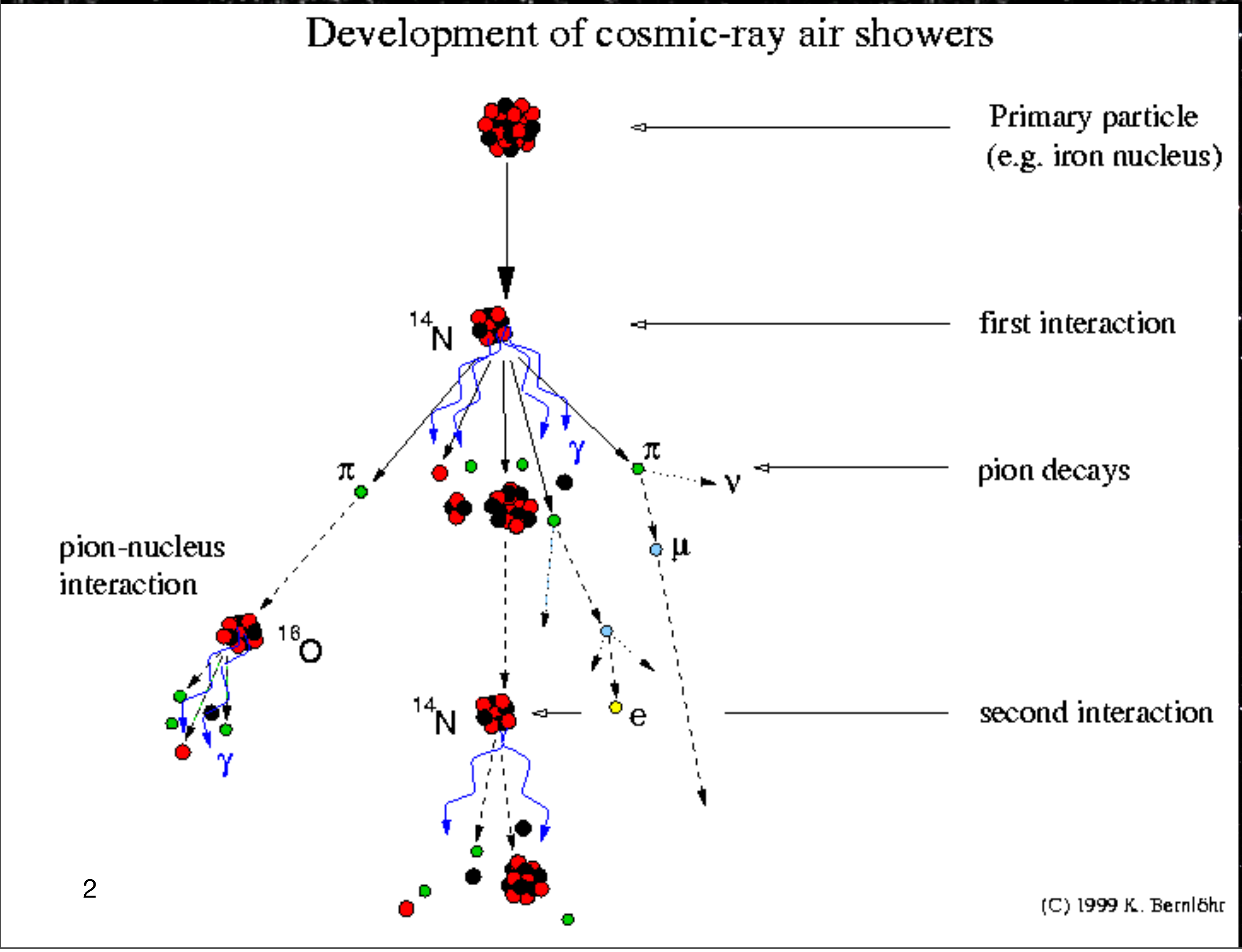
cosmic rays
bombarding Earth from space



astrophysical object as accelerator
Earth's atmosphere as particle detector



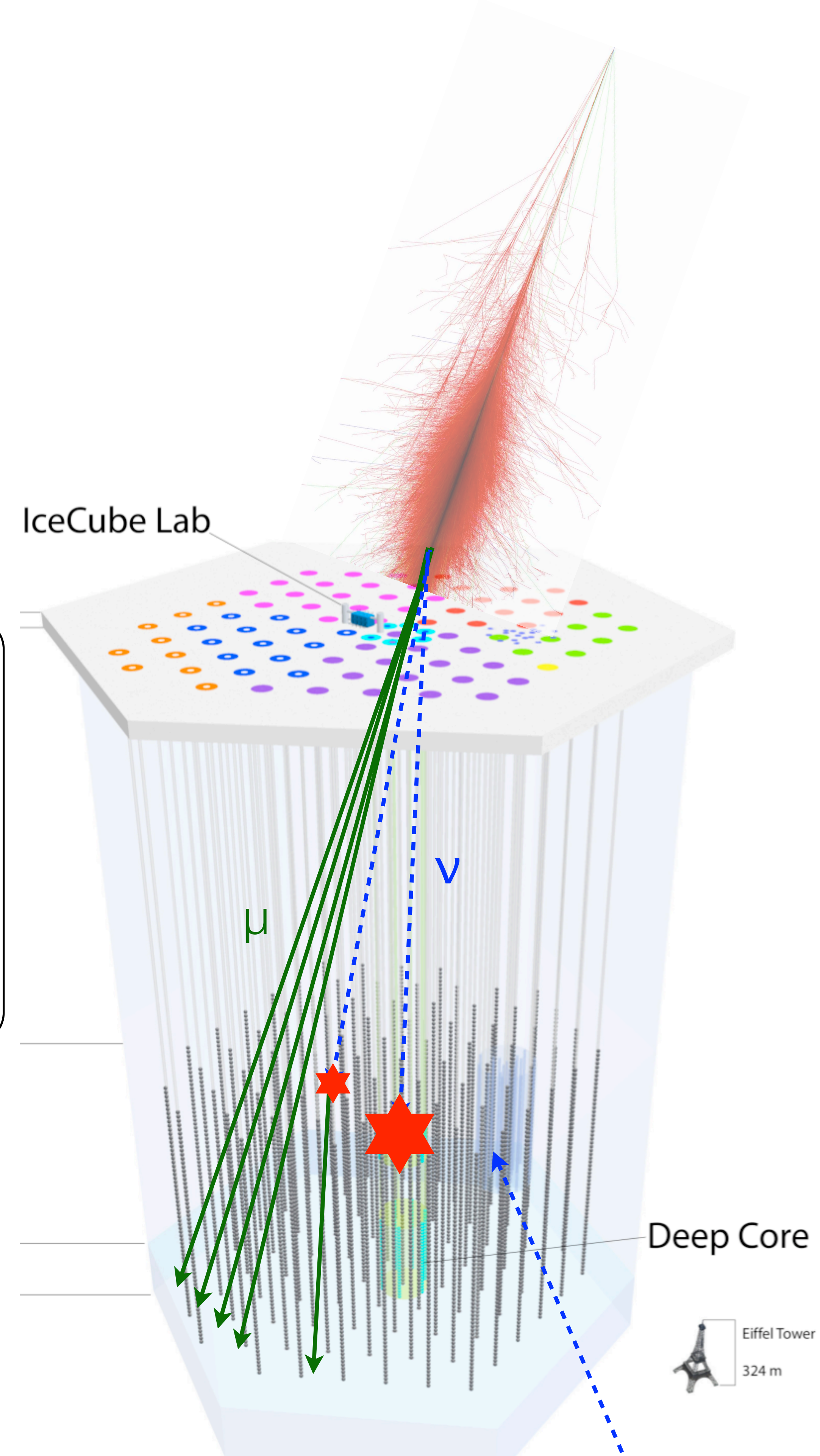
cosmic rays
decoding their properties

primary cosmic rays
- spectrum
- mass composition

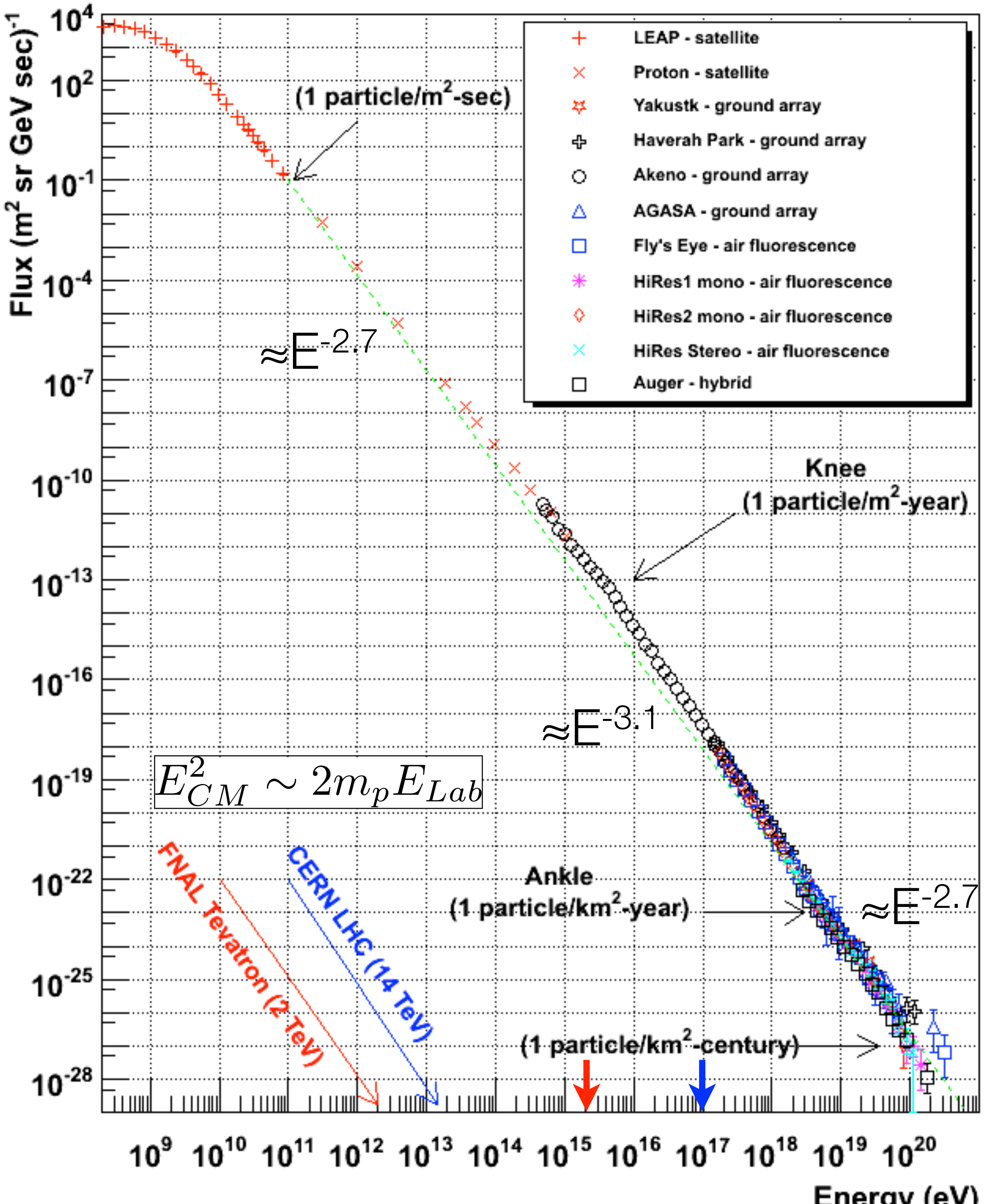
atmospheric target
- density & temperature profile

hadronic interaction models
- primary interaction
- secondary interactions
- interaction cross sections
- fragmentation & hadronization
- heavy quarks
- (non) perturbative processes

propagation
- electromagnetic component
- penetrating component

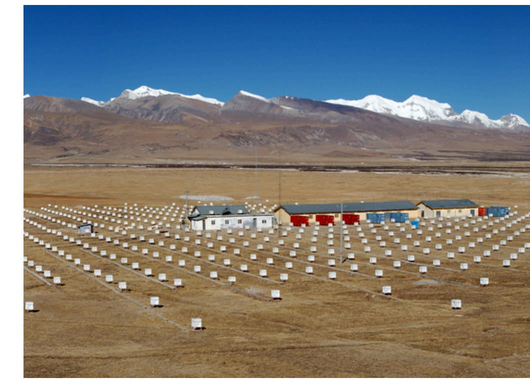


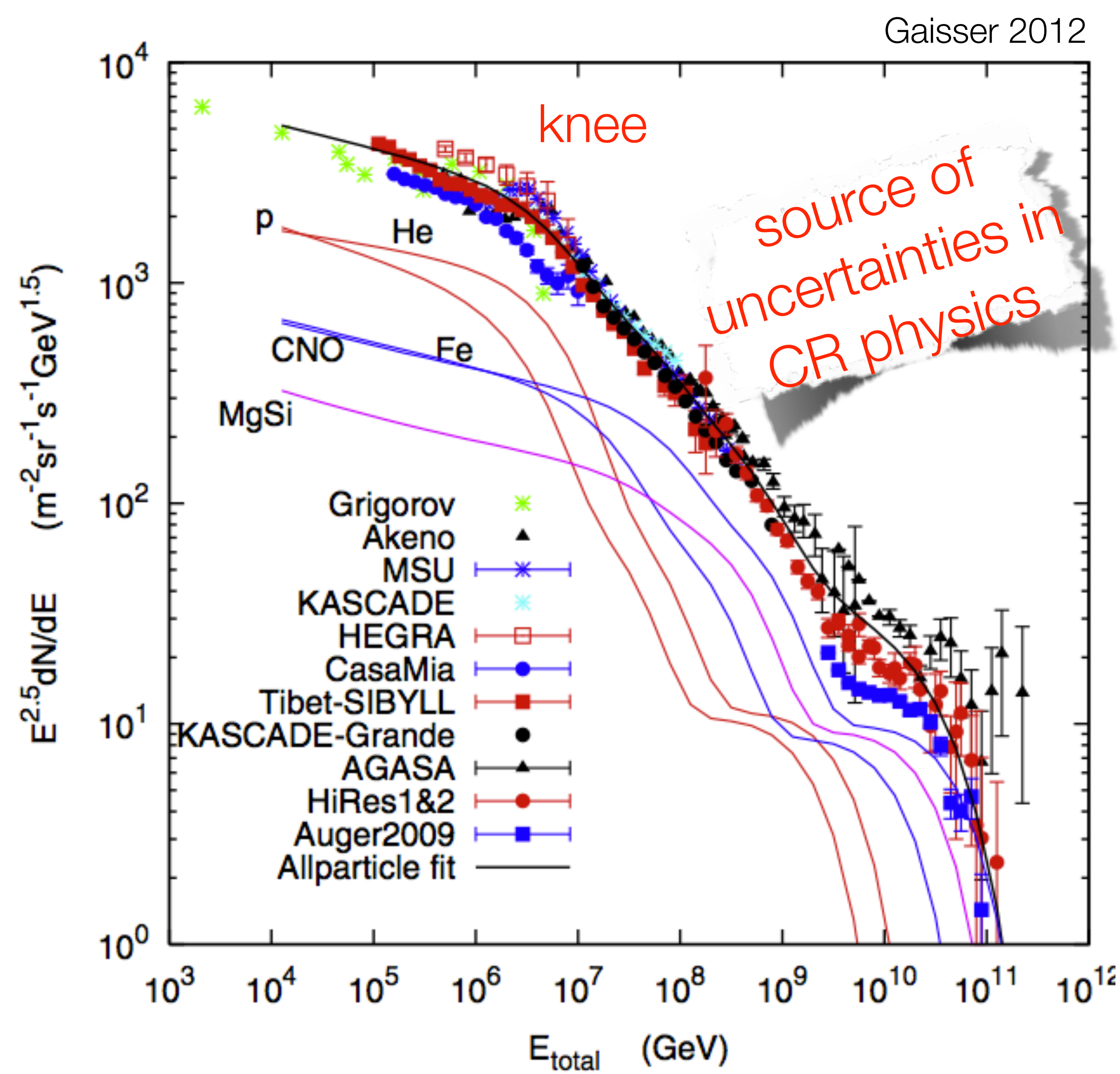
primary cosmic rays
spectrum & composition



direct measurements

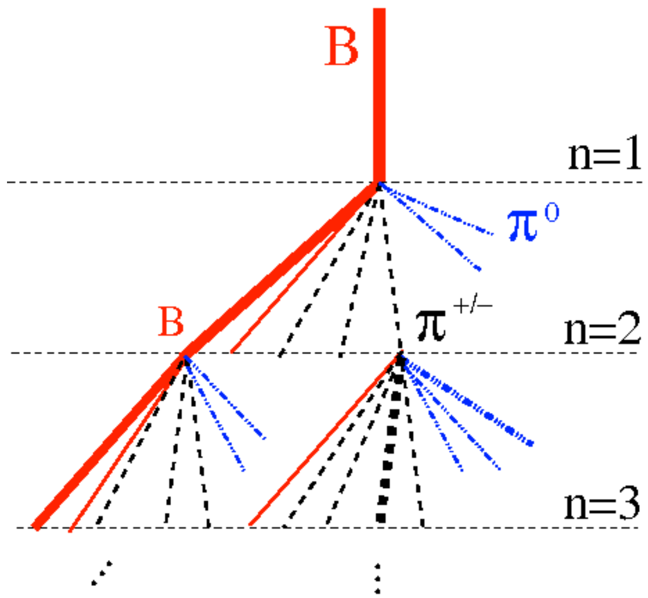
indirect measurements

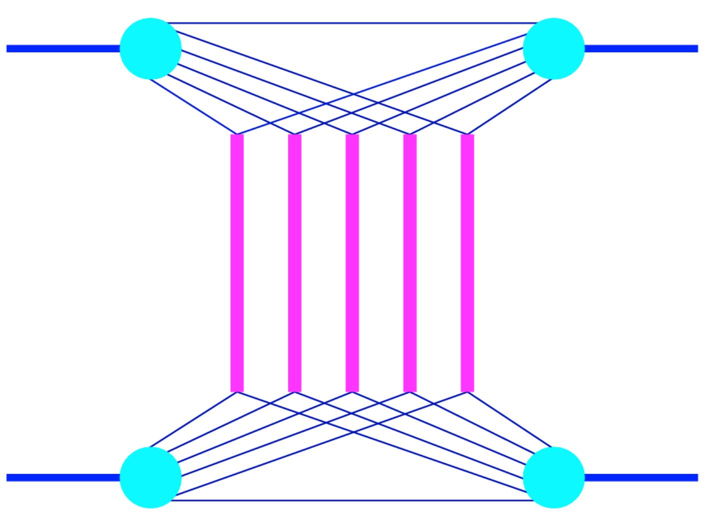




hadronic interactions

source of uncertainties in CR physics



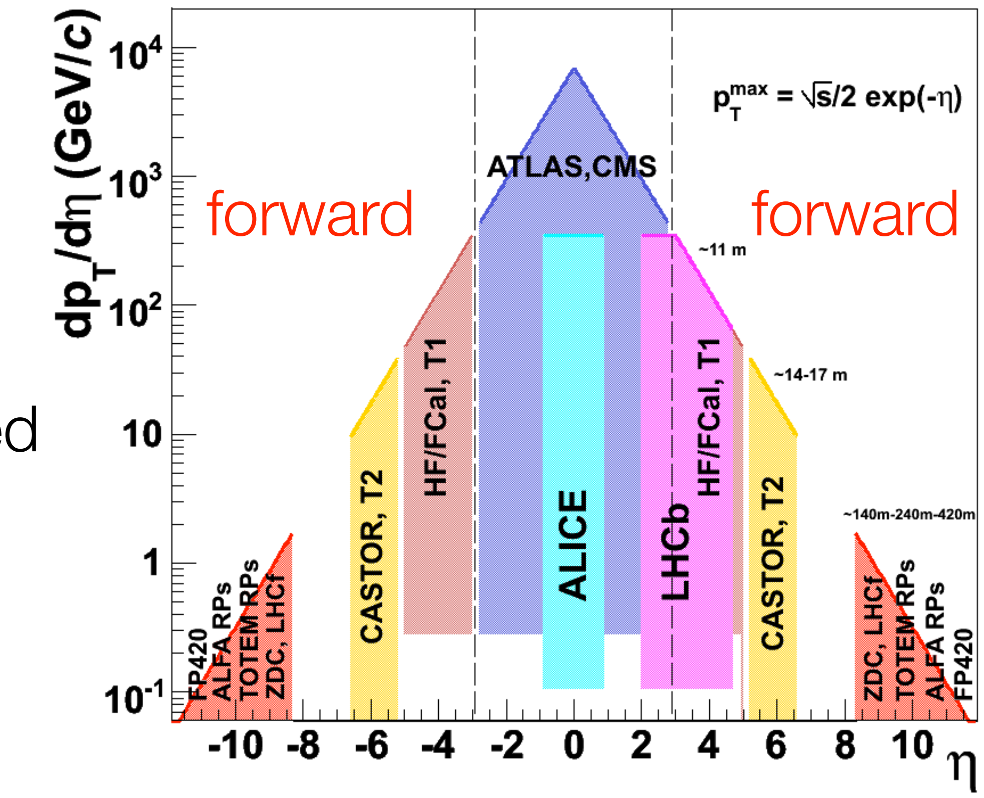


- CR showers dominated by **soft component with small p_T** (*non-perturbative QCD*)
- **hard component with high p_T** with heavy quarks (pQCD)
- **phenomenological** descriptions of hadronic interactions with minijet production for hard component
- **models** to describe soft/hard **interactions** in **forward region** & **extrapolated to high energy**

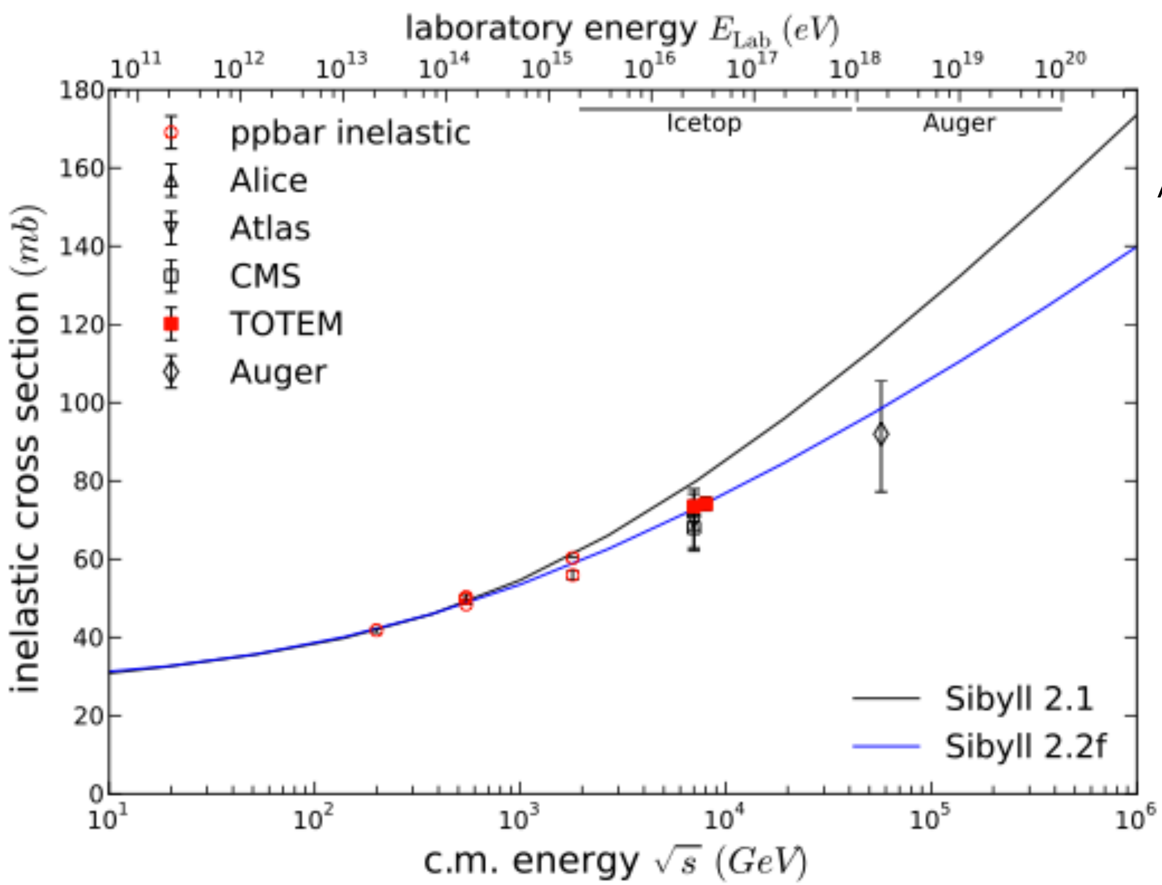
- **interaction models** from accelerators, **extrapolated** to forward region at high energy

hadronic interactions

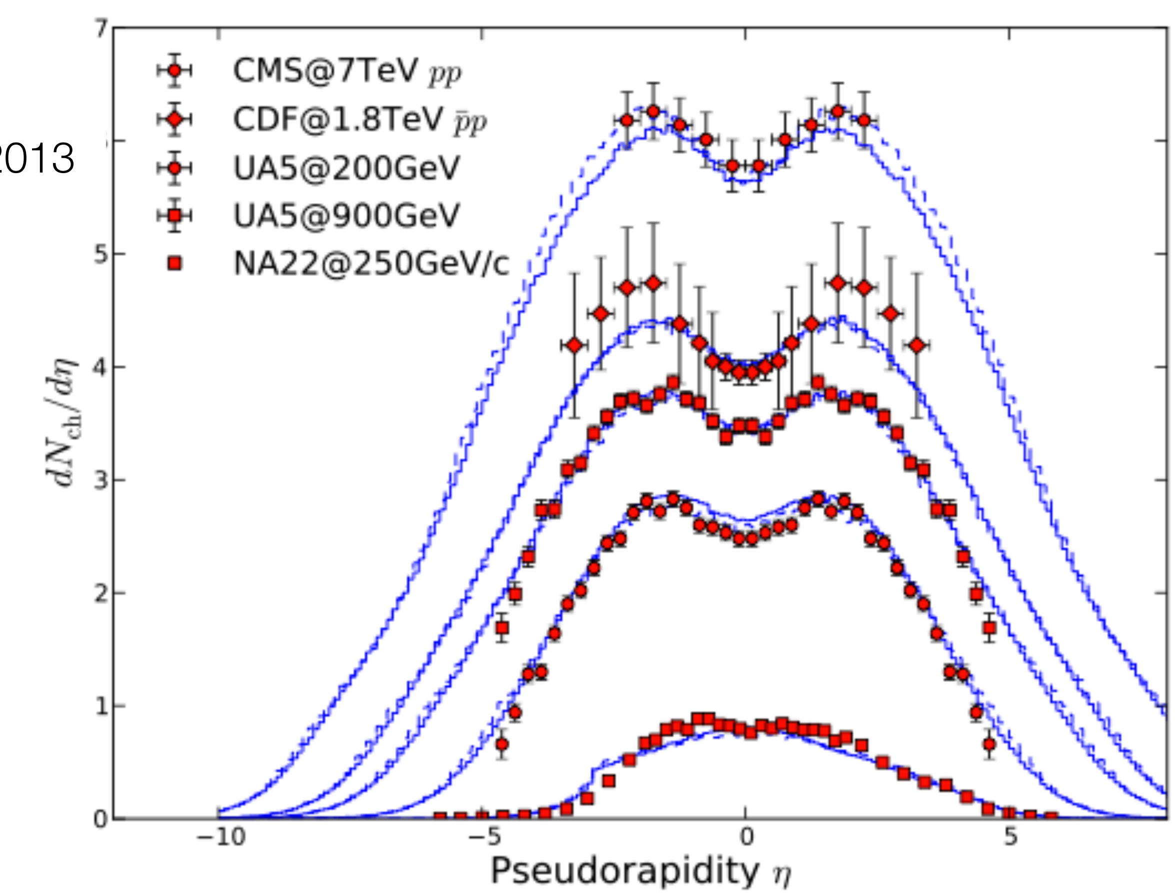
transverse momentum pT vs pseudo-rapidity



- **forward region** the most relevant in cosmic rays
- models **tuned** to accelerator measurements and extrapolated



Ahn et al., ICRC 2013



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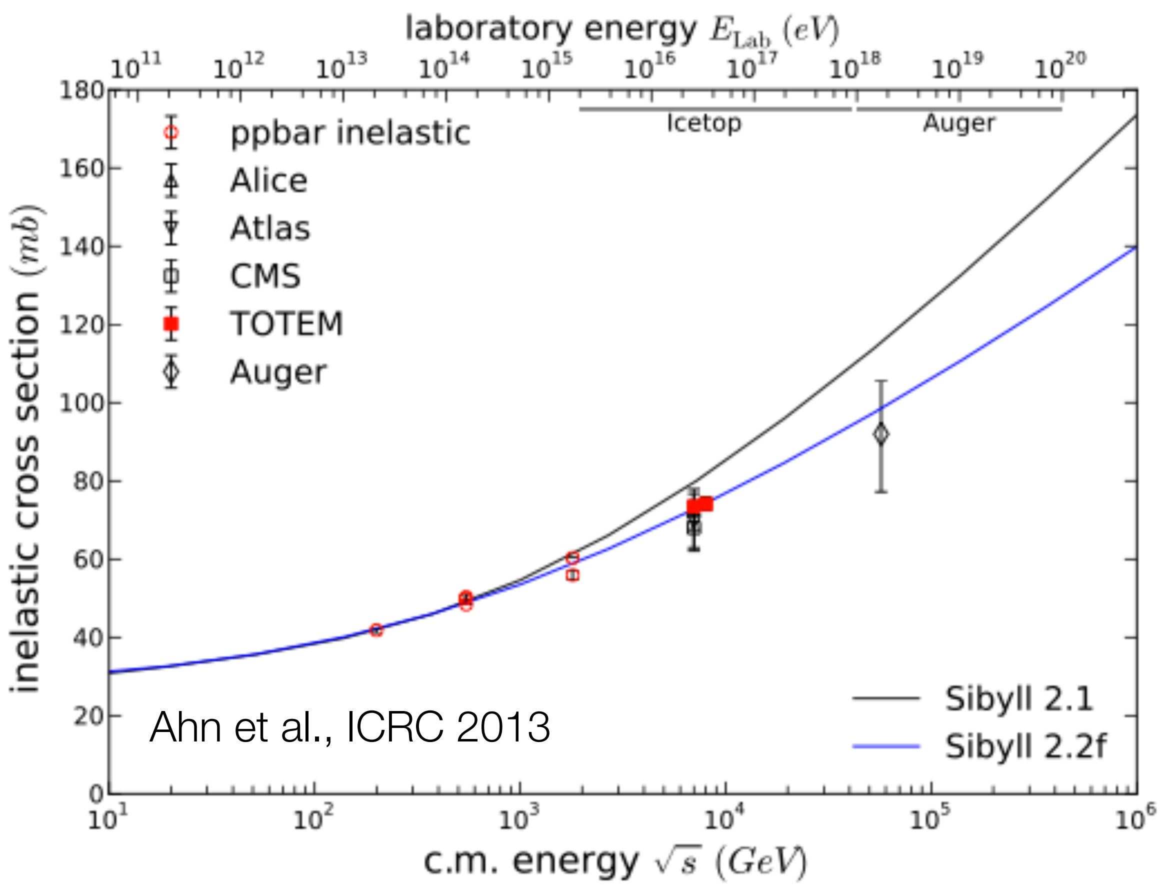
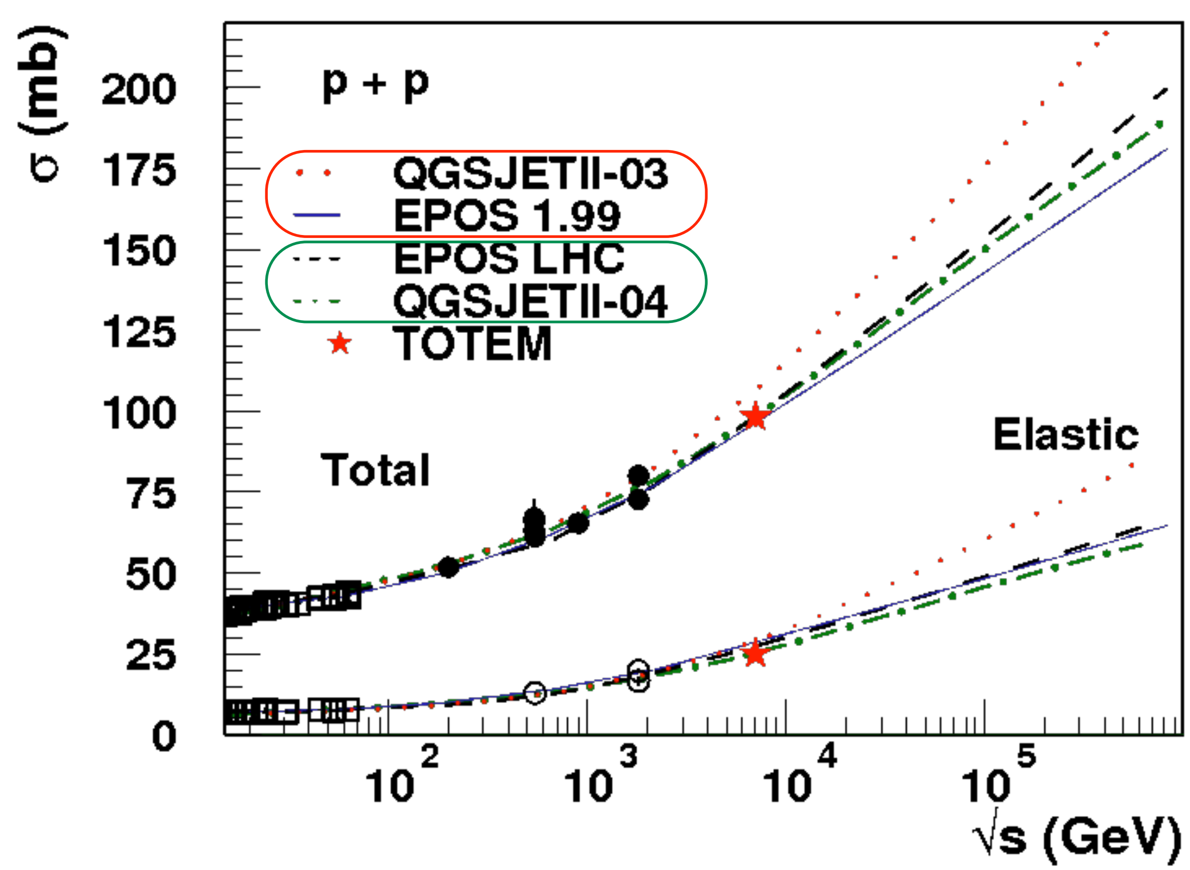
hadronic interactions

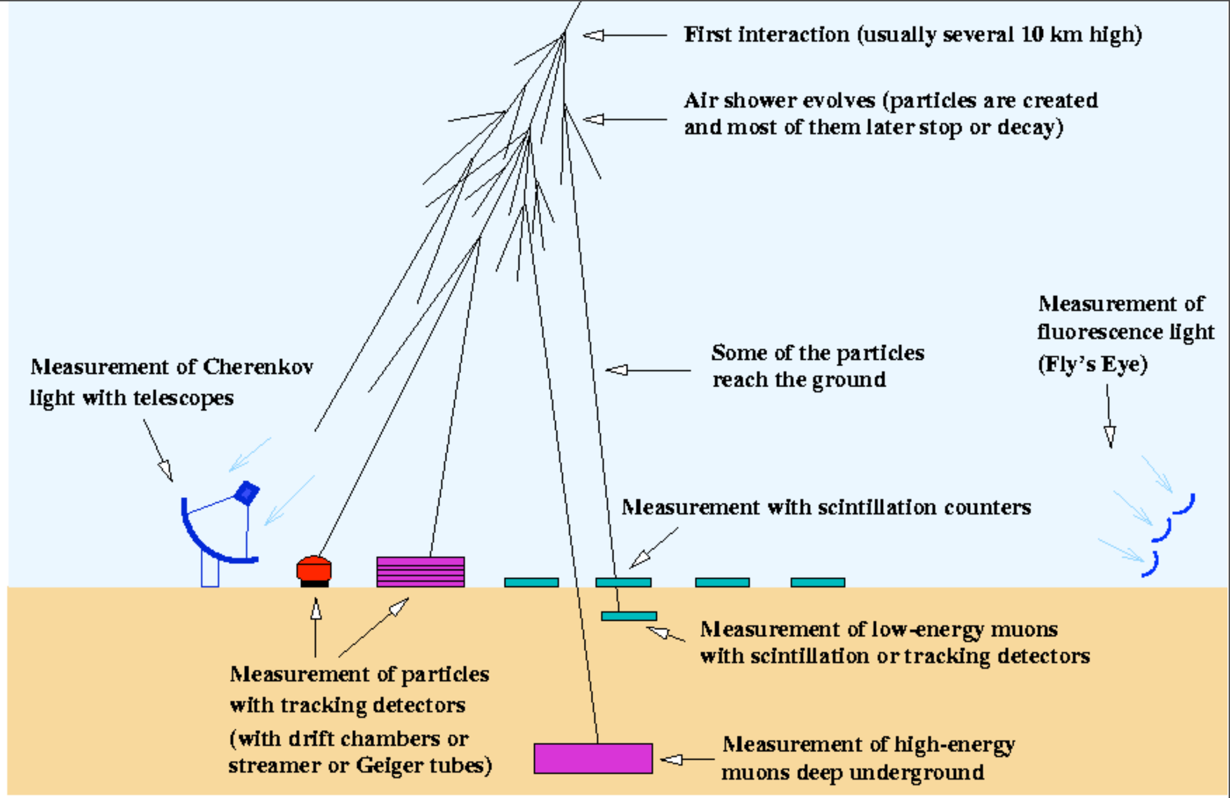
- **forward region** the most relevant in cosmic rays
- models **tuned** to accelerator measurements and extrapolated
- LHC experiments (e.g. TOTEM, LHCf) starting to fill the relevant parameter space





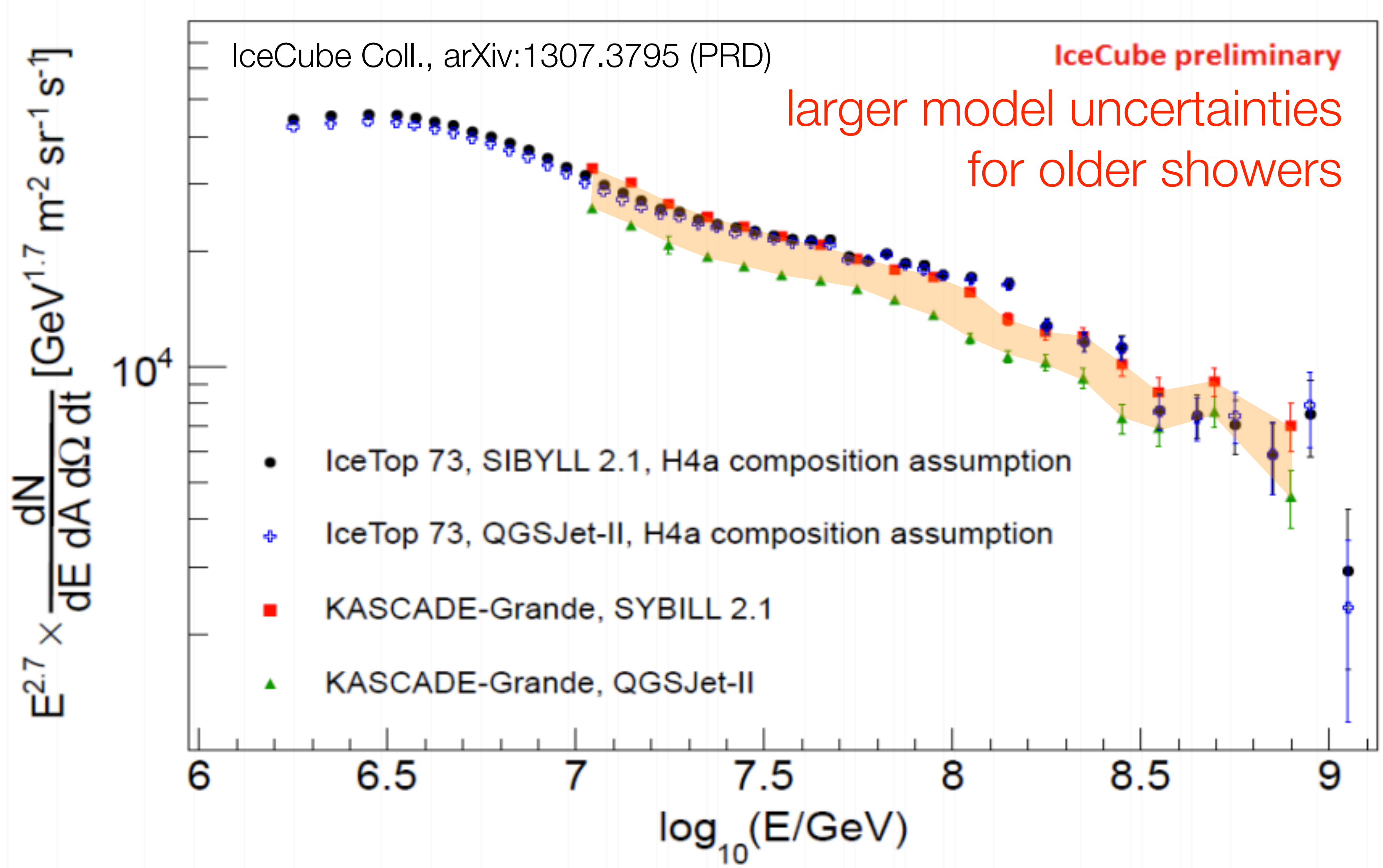
> 100s TeV cosmic rays

indirect observations



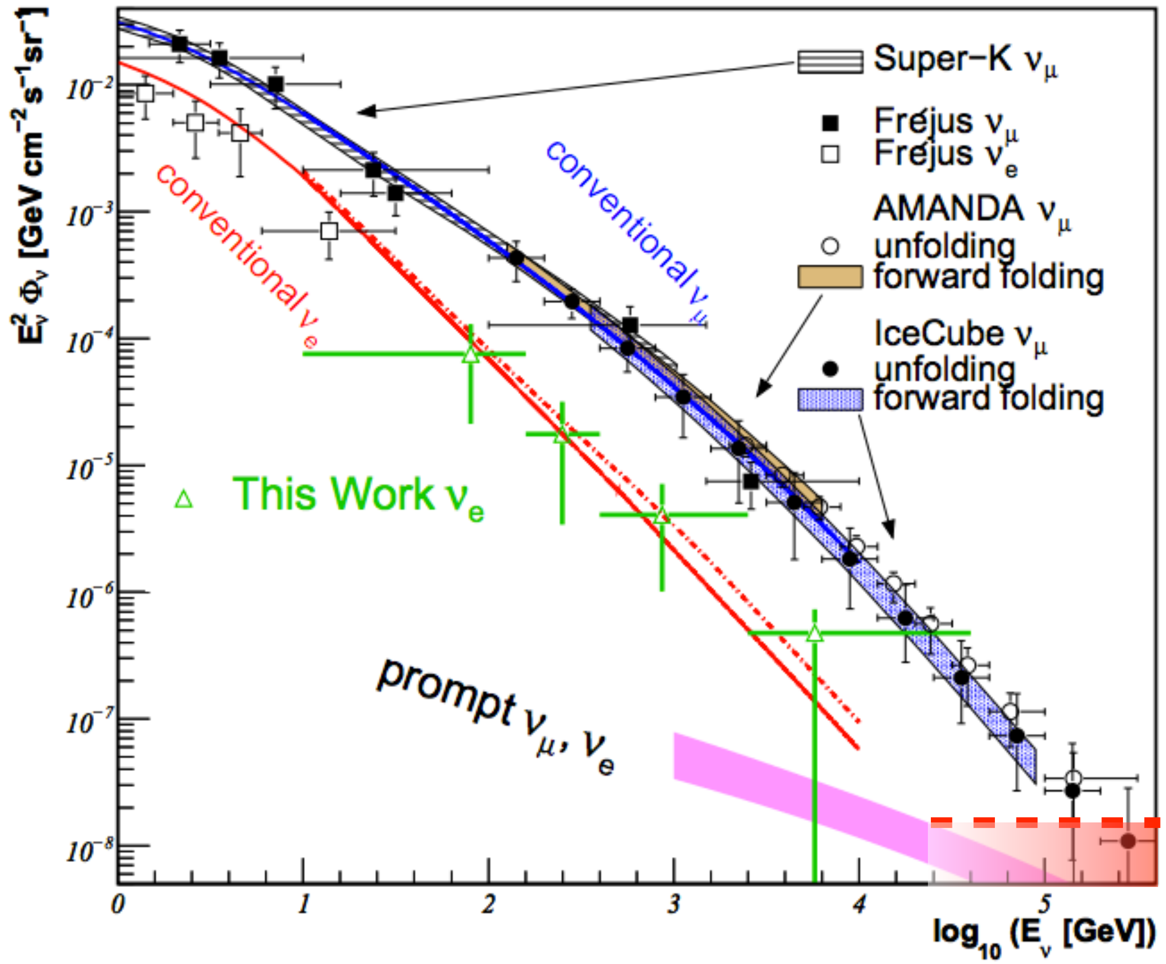
- e.m. & hadronic shower components observed at the Earth's surface
- measure energy deposited, temporal, longitudinal & lateral distributions, and unfold the primary energy & mass

- *KASCADE @ sea level*
- *IceTop @ 2800 m asl*



IceCube Coll., PRL 110, 151105 (2013)

atmospheric neutrinos
high energy and heavy quarks



- **neutrino telescopes** searching for high energy astrophysical neutrinos (*point to origin of CR*)
- **atmospheric neutrinos** a significant **irreducible background** at high energy where **heavy quark processes** are involved
- production of **hyperons** and particles with **charm** affected by increasing uncertainties

$$A_{i\nu} = \frac{Z_{Ni} \times BR_{i\nu} \times Z_{i\nu}}{1 - Z_{NN}}$$

$$Z_{N\pi^\pm}(E) = \int_E^\infty \mathrm{d}E' \frac{\phi_N(E')}{\phi_N(E)} \frac{\lambda_N(E)}{\lambda_N(E')} \frac{\mathrm{d}n_{\pi^\pm}(E',E)}{\mathrm{d}E}$$

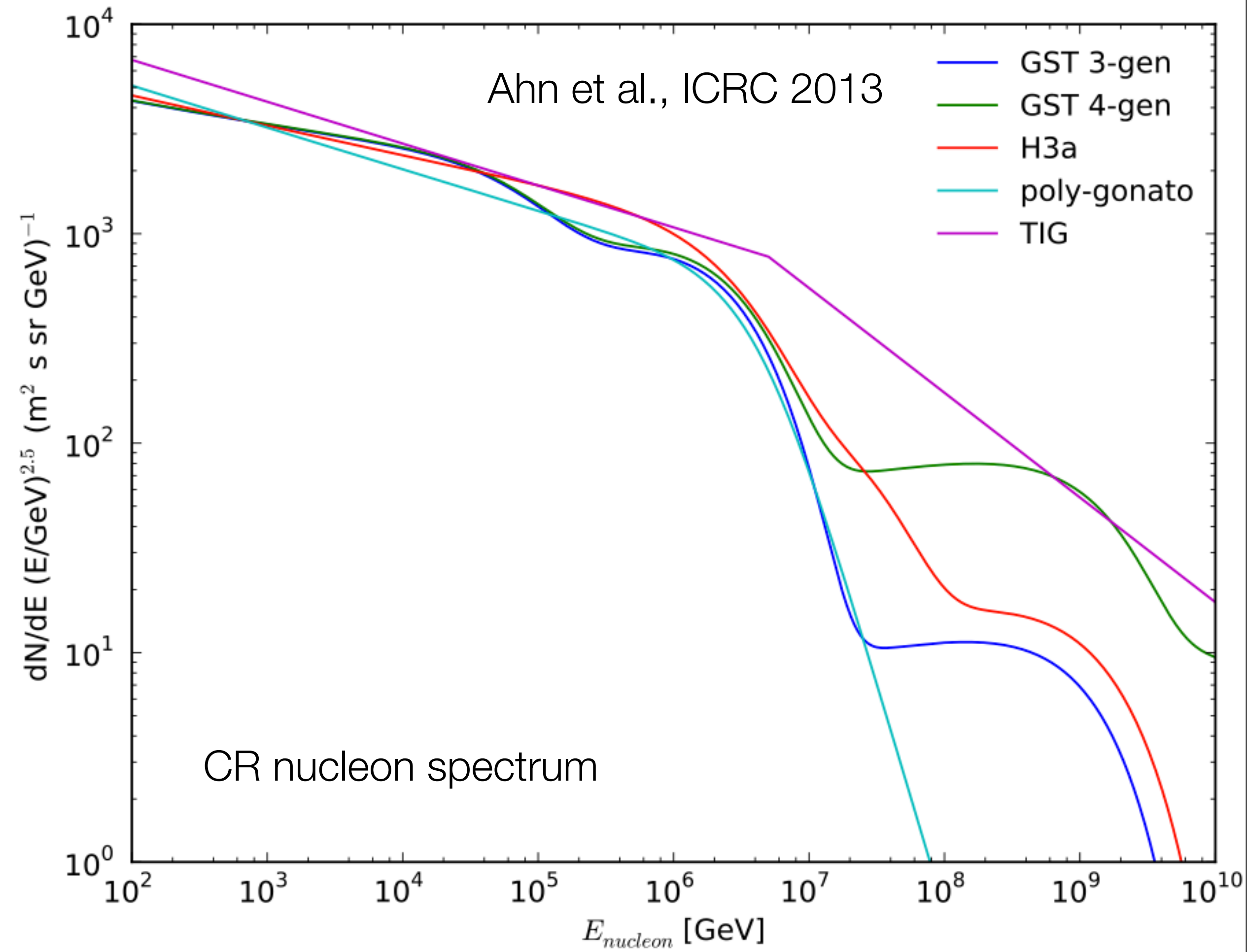
$$\phi_\nu(E_\nu) = \phi_N(E_\nu) \times \left\{ \frac{A_{\pi\nu}}{1 + B_{\pi\nu} \cos\theta\, E_\nu/\epsilon_\pi} + \frac{A_{K\nu}}{1 + B_{K\nu} \cos\theta\, E_\nu/\epsilon_K} + \frac{A_{\mathrm{charm}\,\nu}}{1 + B_{\mathrm{charm}\,\nu} \cos\theta\, E_\nu/\epsilon_{\mathrm{charm}}} \right\}$$

meson's characteristic energy

Particle (α):	$\pi^\pm$	$K^\pm$	K_L^0	Charm
ϵ_α (GeV):	115	850	205	$\sim 3 \times 10^7$

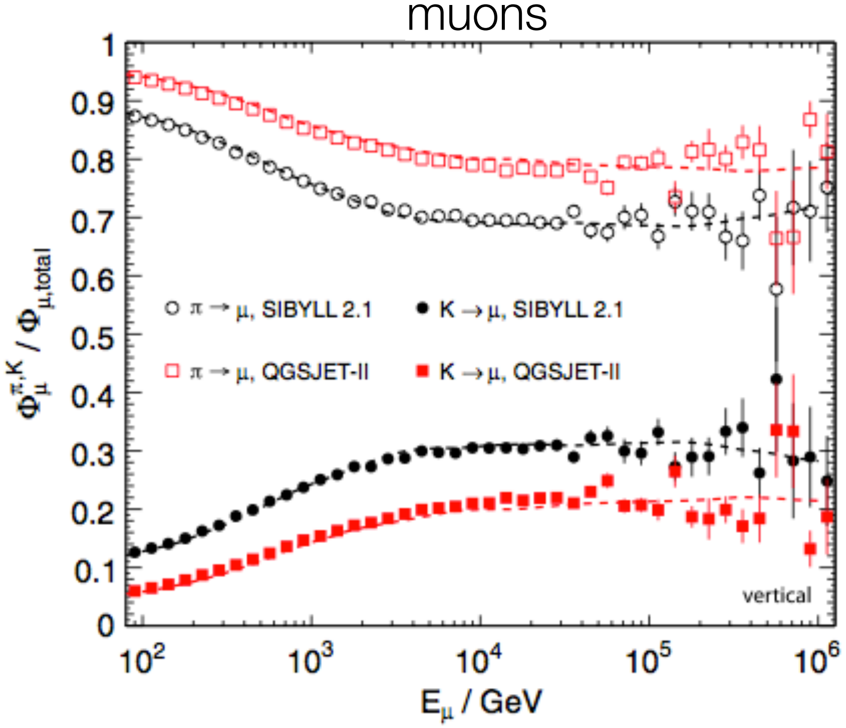
atmospheric neutrinos

high energy and heavy quarks

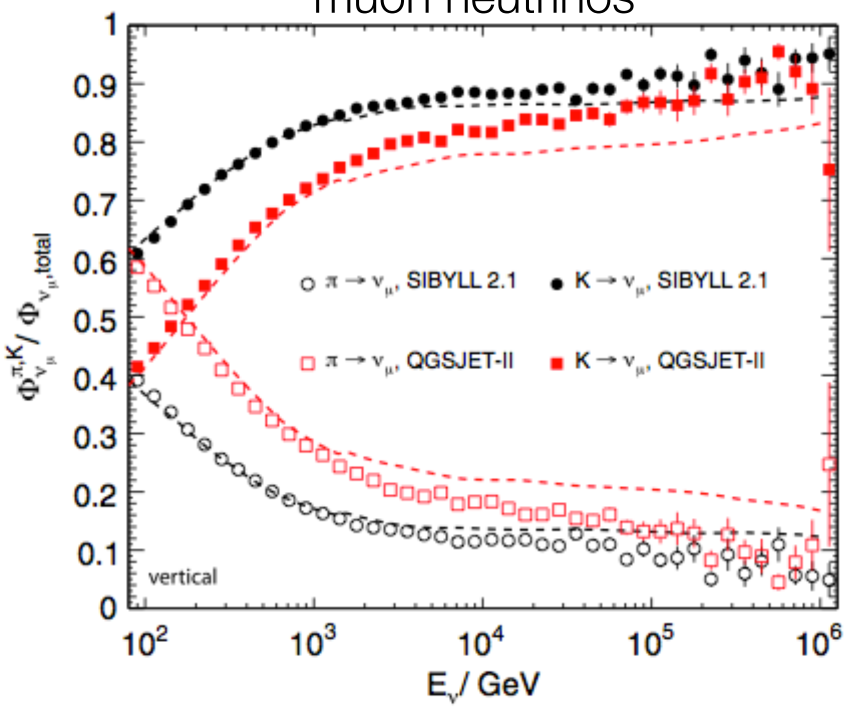


- large uncertainties in **cosmic ray composition** (nucleon spectrum) at high energy
- $K^{\pm}$ not same isospin group & K evolution equations coupled
- associated production   p + Air → Λ + K^+

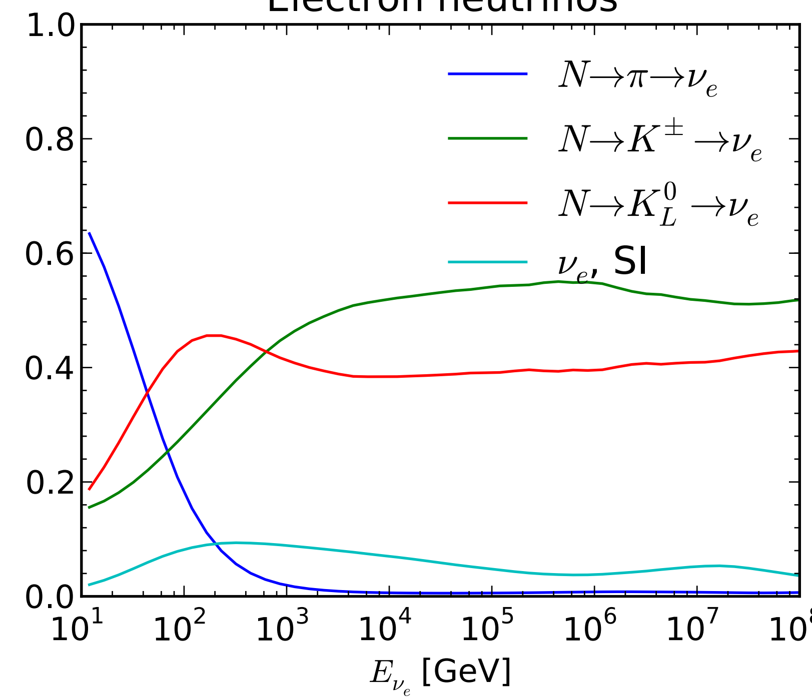
muons



muon neutrinos



Electron neutrinos



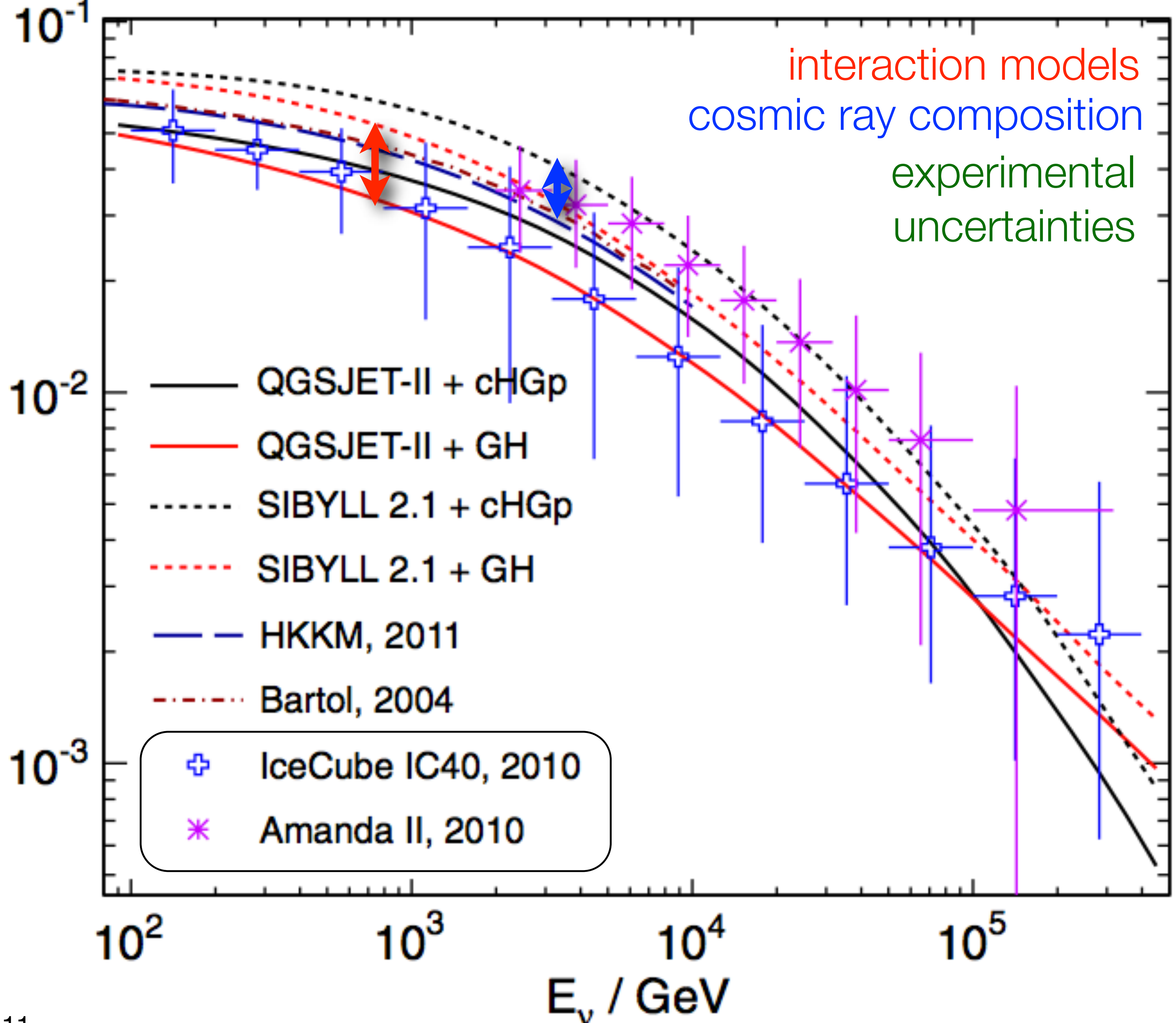
Fedynitch, Becker Tjus, PD 2012

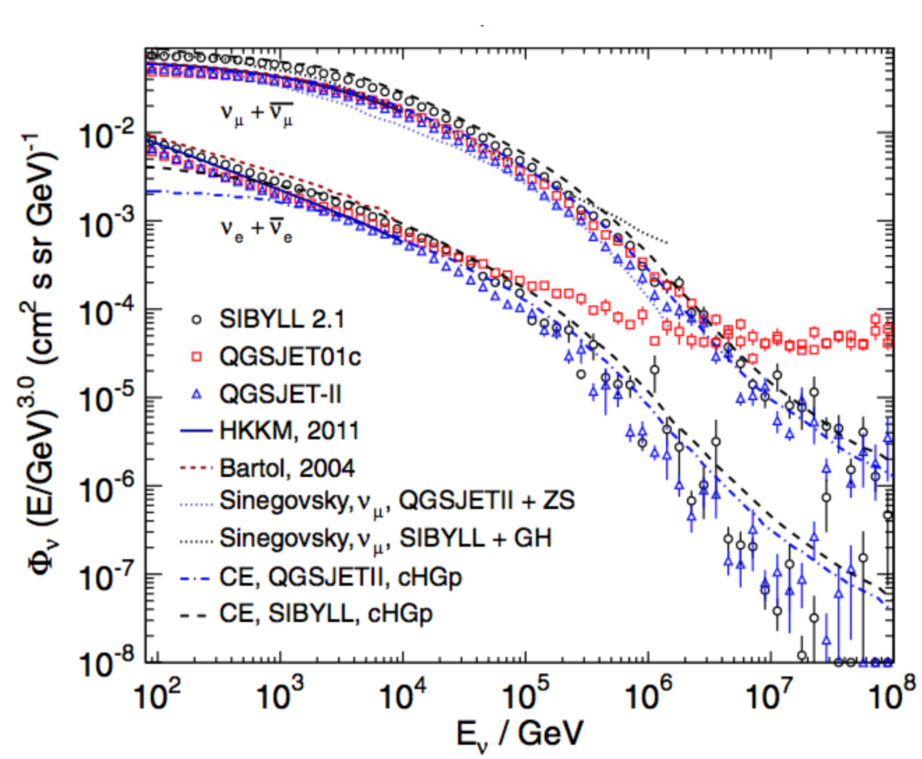
Sibyll 2.1 - Fedynitch

atmospheric neutrinos
experimental observations

observed through-going $\nu_\mu + \bar{\nu}_\mu$

Fedynitch, Becker Tjus, PD 2012





atmospheric neutrinos
charm production

- due to large quark mass, **perturbative QCD** can be used (hard component). However
  - significant charm production observed at $\sqrt{s}$ = 20 GeV
  - asymmetry in charm / anti-charm baryons (Selex Coll. 2002) → **intrinsic production**
- $|p\rangle = \alpha|uud\rangle + \beta|uudc\bar{c}\rangle + ...$: the **c-pair** produced in projective fragmentation can recombine with valence quarks and with sea-quarks to **produce charmed hadrons**.

$p \rightarrow \Lambda_c^+ + \bar{D}^0$ ~ order $(m_s/m_c)^2$ (~1%) compared to $p \rightarrow \Lambda K^+$

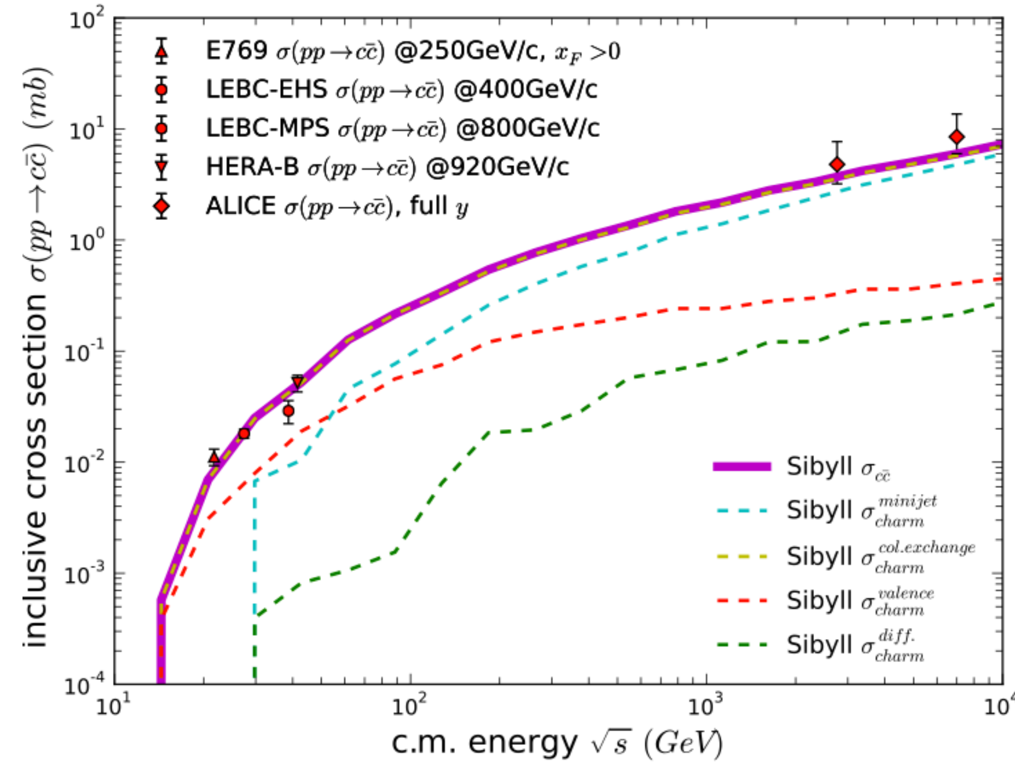
- inclusive D-meson spectrum dominated by intrinsic charm at high pseudo-rapidity & p_T

Lykasov+ 2012

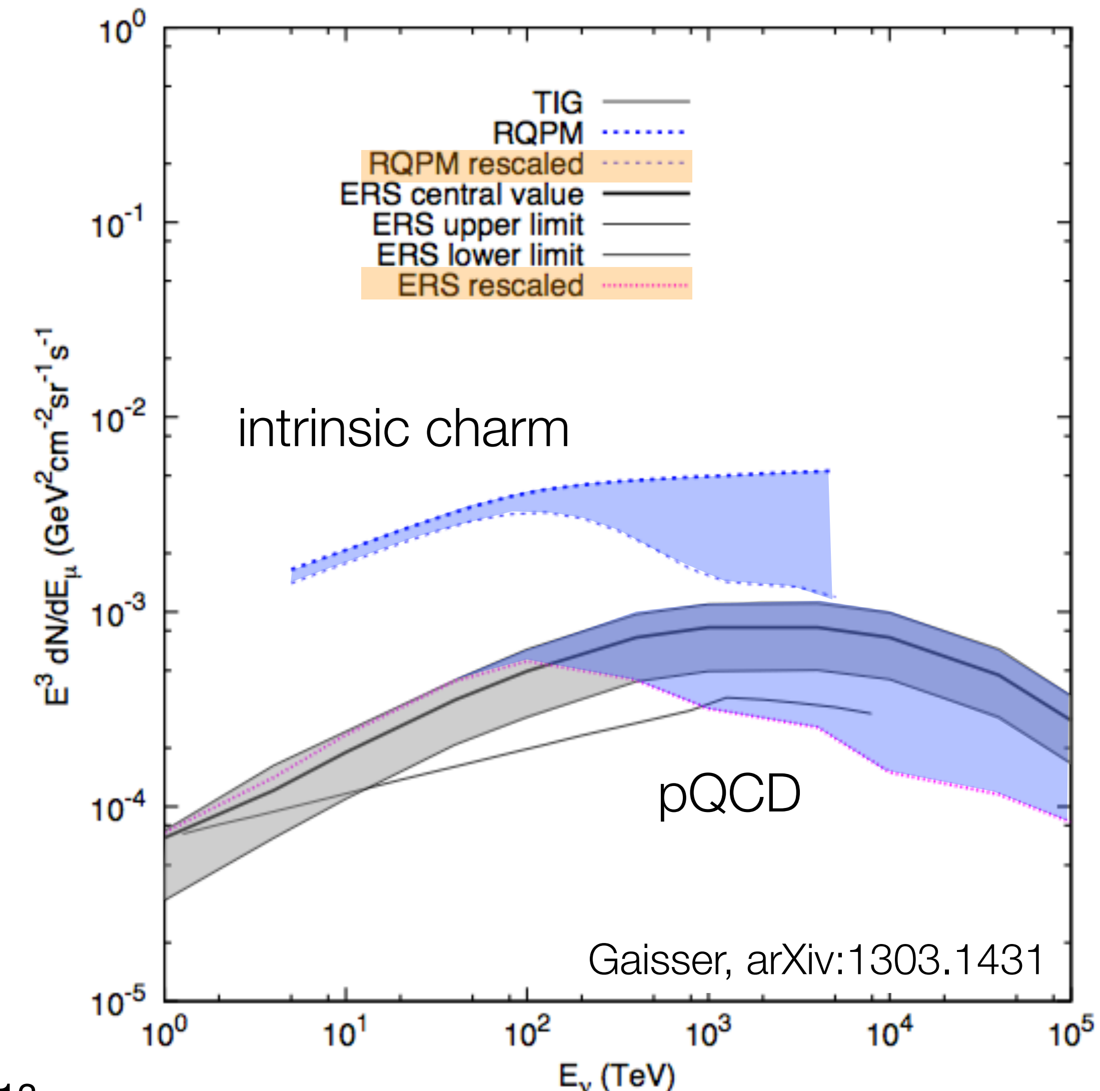
- steep cosmic ray spectrum might **enhance the effect of intrinsic production** of charm

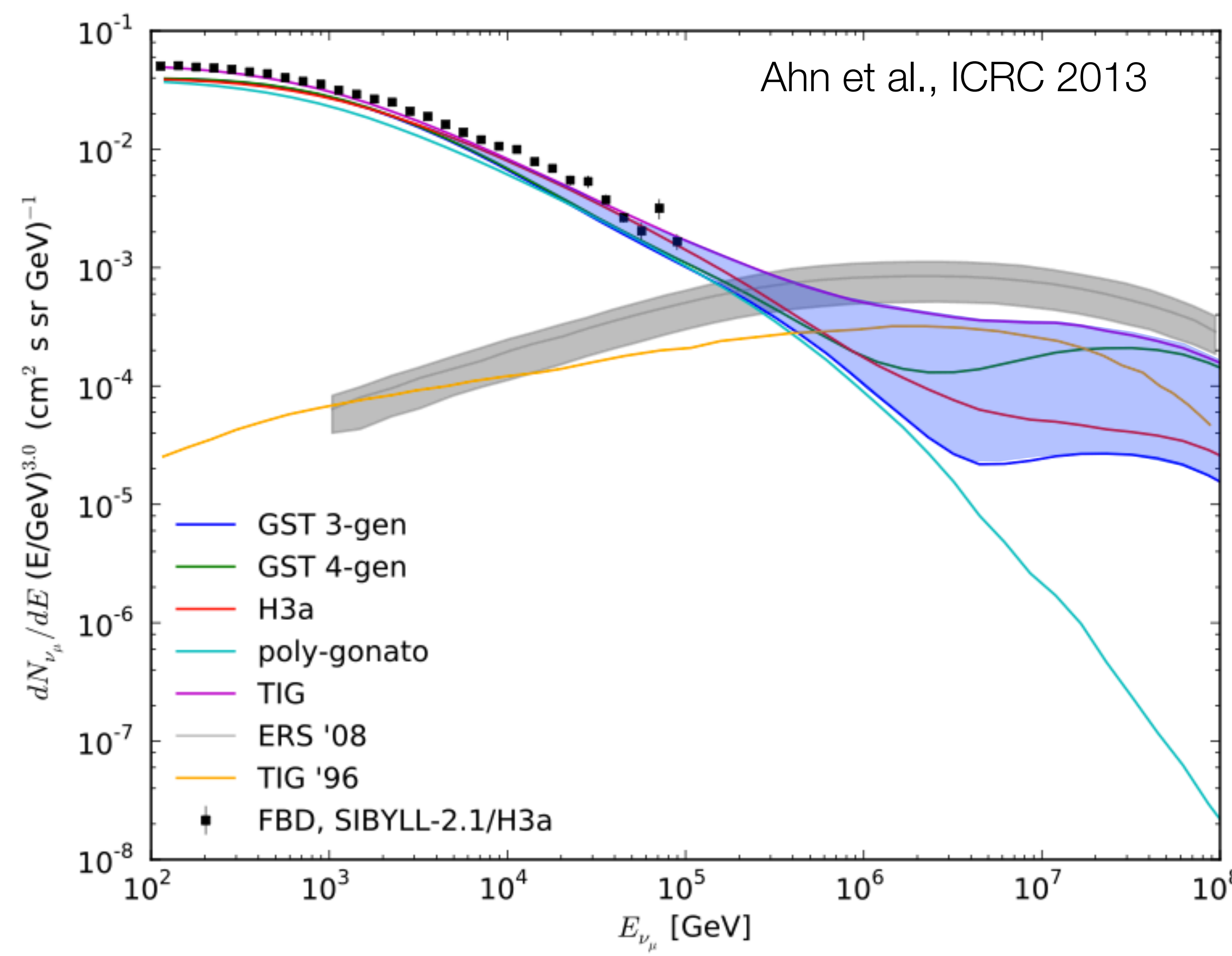
atmospheric neutrinos
charm production

- differences in production models
- effect of primary cosmic ray spectrum



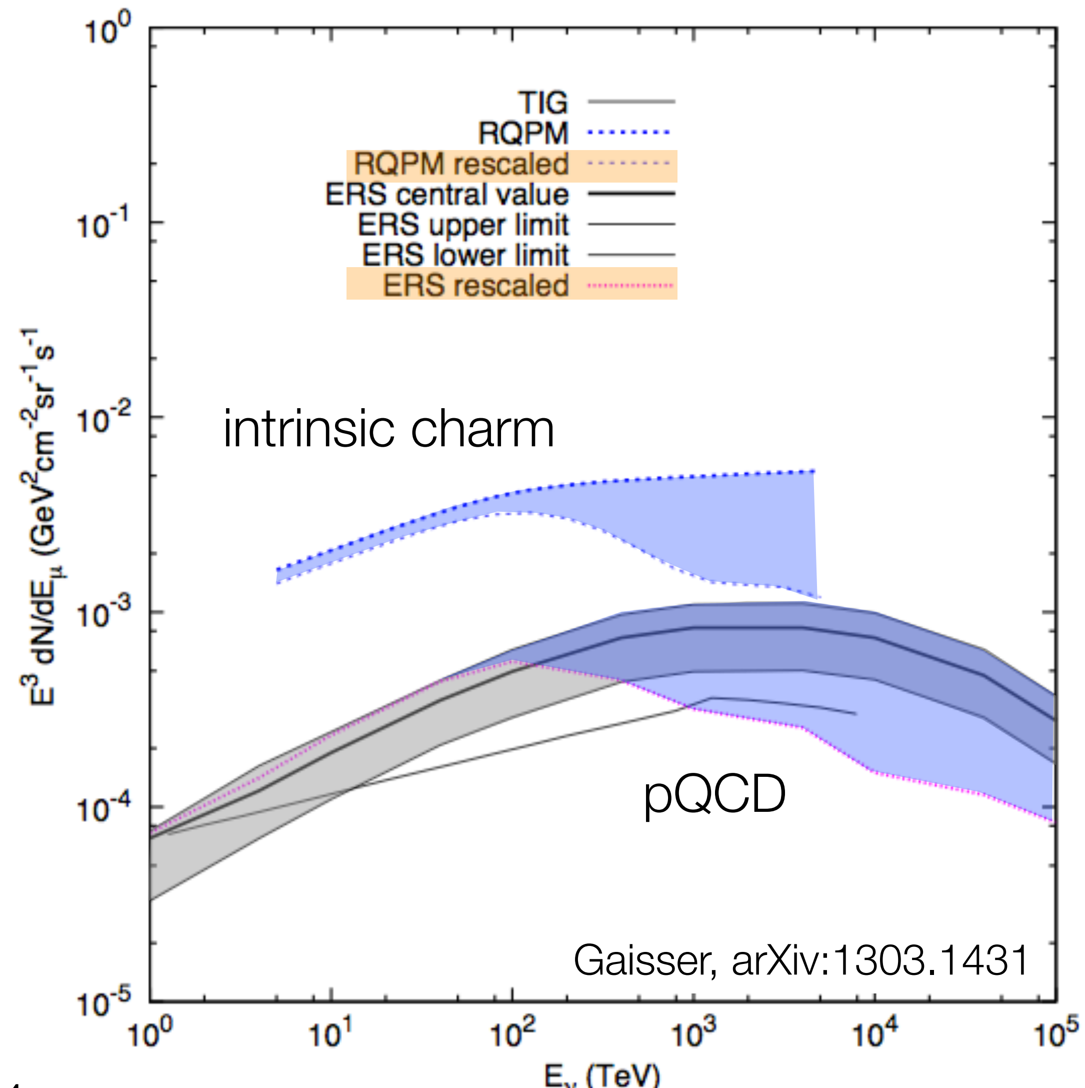
Sibyll 2.2f

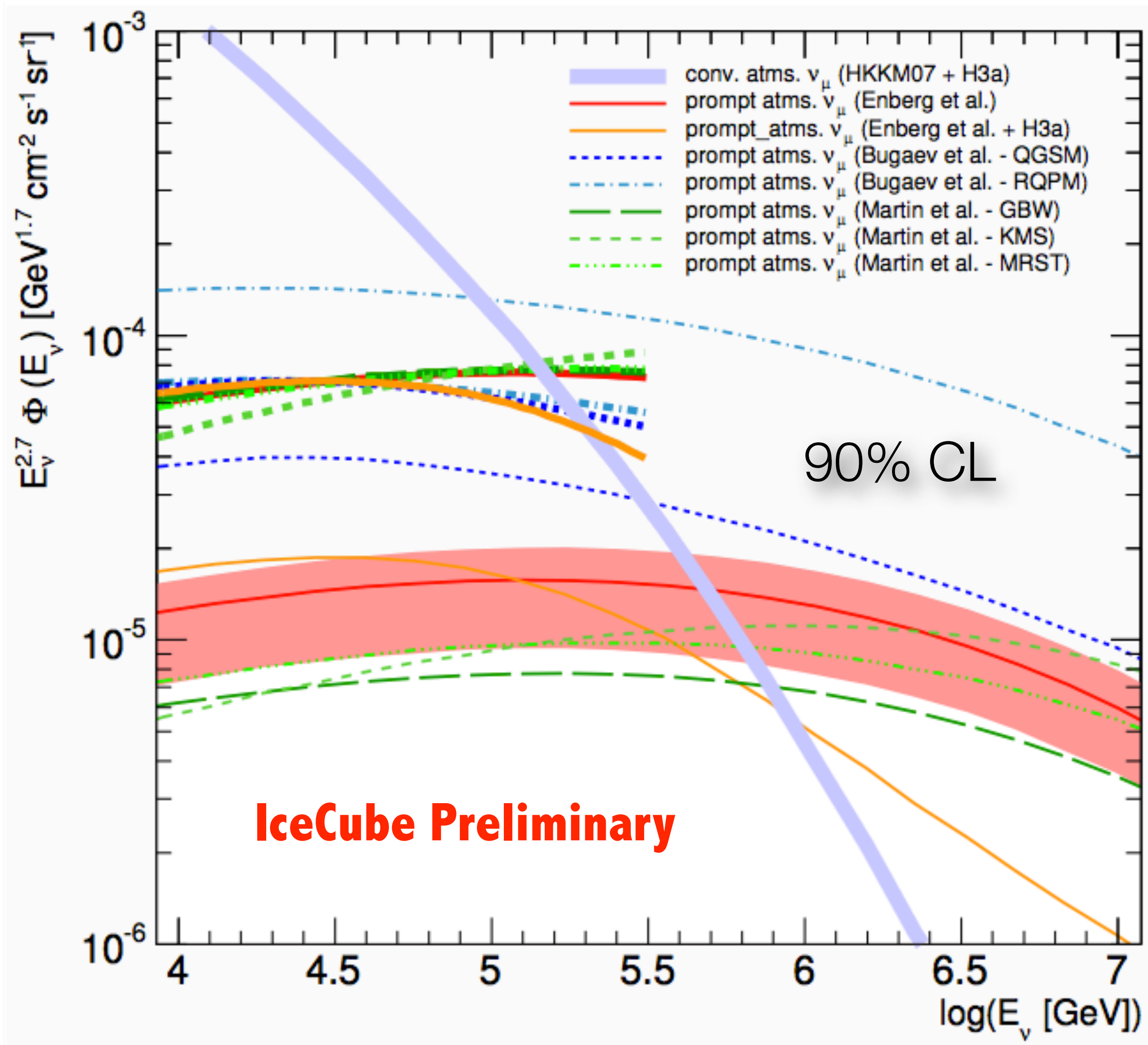




atmospheric neutrinos
charm production

- differences in production models
- effect of primary cosmic ray spectrum





good news for neutrino astrophysics ?

→ can neutrino telescope measure neutrinos from charm ?

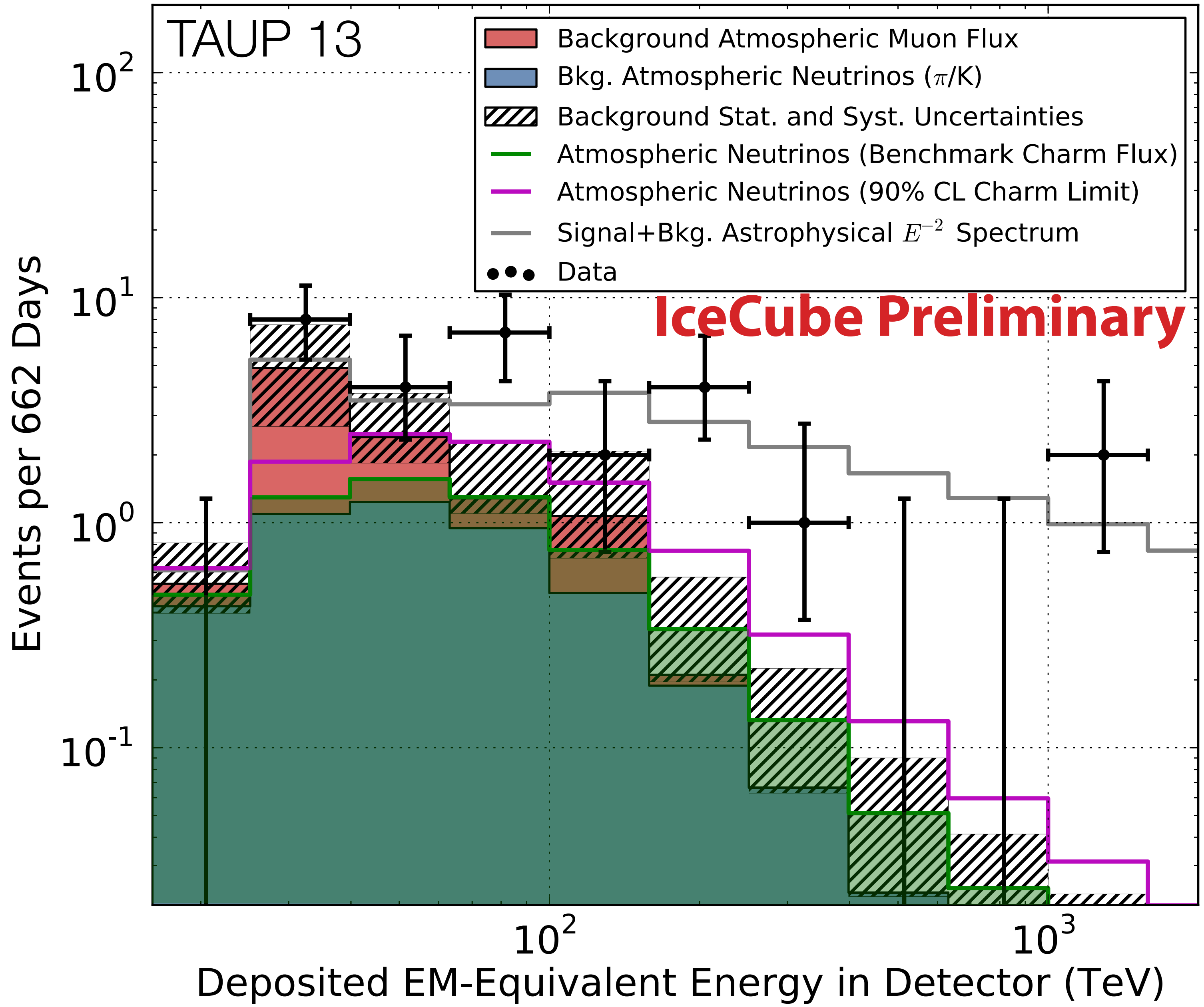
atmospheric neutrinos

charm and astrophysical neutrinos

- search for **high-energy all-flavor** neutrinos interacting inside (**contained**) from **all directions** the IceCube km3 instrumented volume

- new population of HE neutrinos ?

- where is the transition energy from charm to new population ?



atmospheric neutrinos
charm and astrophysical neutrinos

- search for **high-energy all-flavor** neutrinos interacting inside (**contained**) from **all directions** the IceCube km3 instrumented volume
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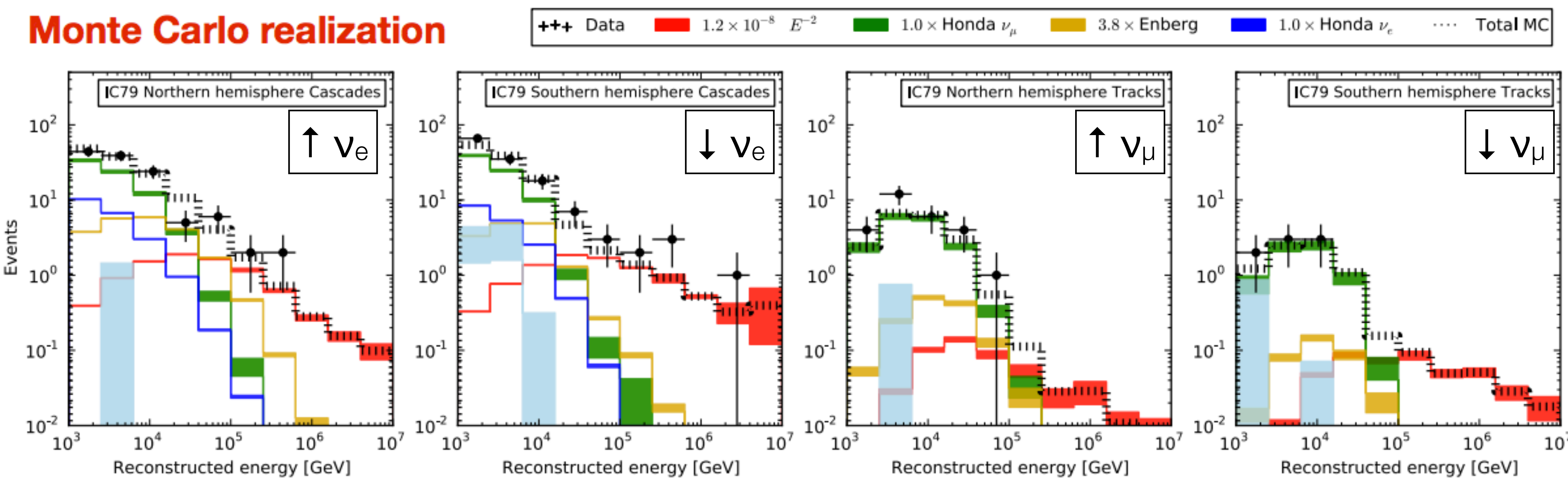
- where is the transition energy from charm to new population ?

TAUP 13

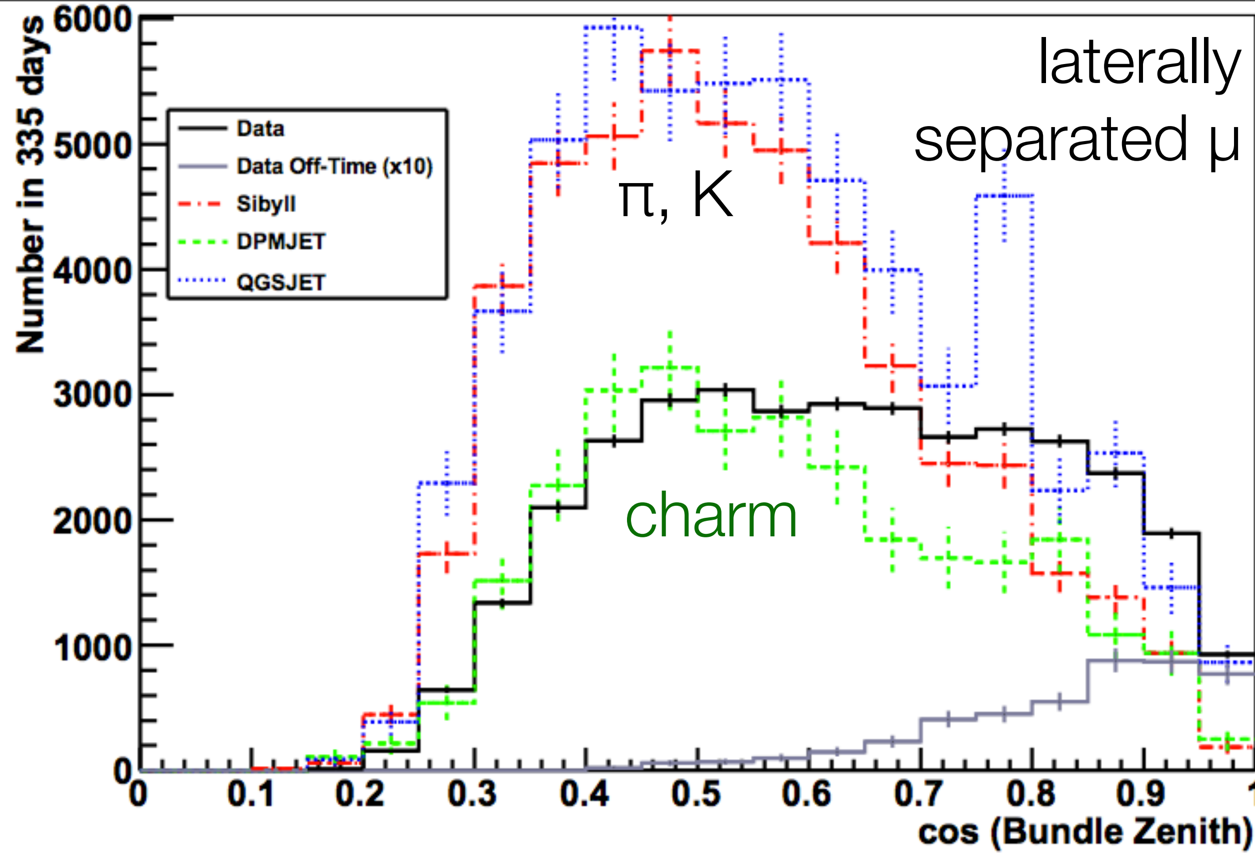
Monte Carlo realization



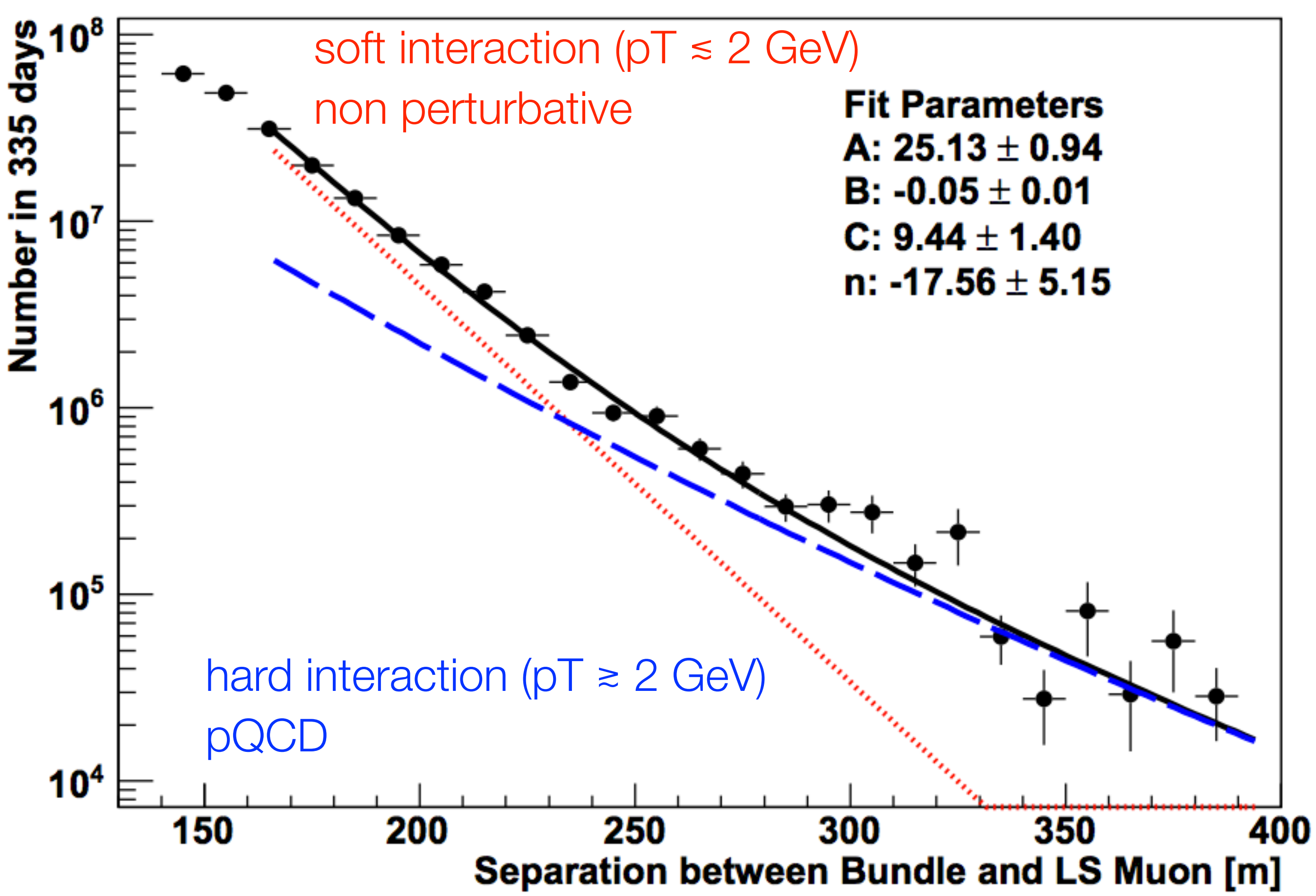
atmospheric neutrinos

charm and high p_T muons

- search for μ + μ bundle
- measure separation $$d_T \approx \frac{p_T H c}{E_\mu cos(\theta)}$$
- CR composition & interaction models



IceCube Coll., PRD 87, 012005, 2013
arXiv:1208.2979

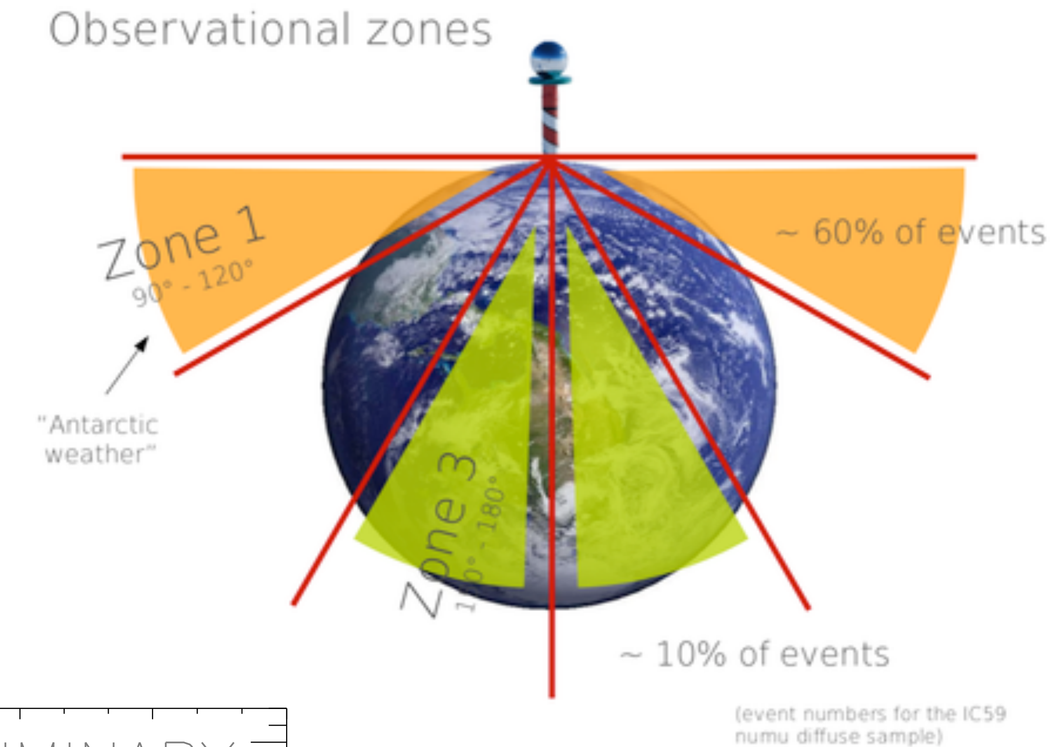


- increased K and charm contribution
  - improve forward region
- lighter cosmic ray composition

siati

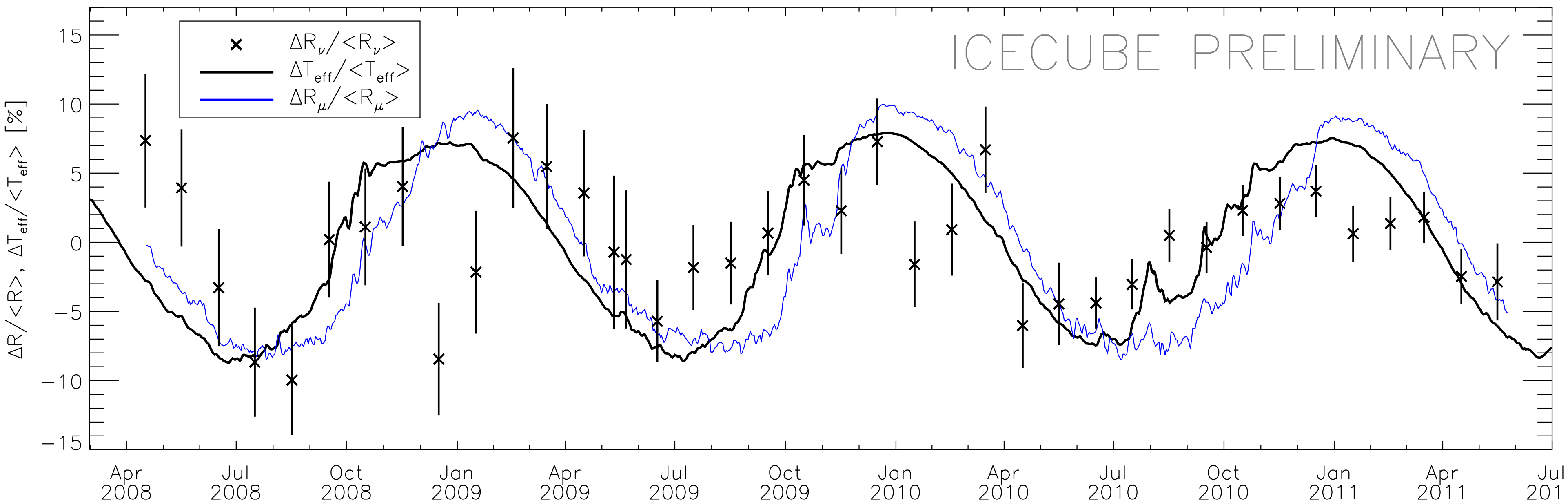
atmospheric neutrinos

charm & **ν** seasonal variations



effective temperature

$$T_{eff}(\theta) = \frac{\int dE_\nu \int dX \;\, A_{eff}(E_\nu,\theta)P(E_\nu,\theta,X)T(\theta,X)}{\int dE_\nu \int dX \;\, A_{eff}(E_\nu,\theta)P(E_\nu,\theta,X)}$$



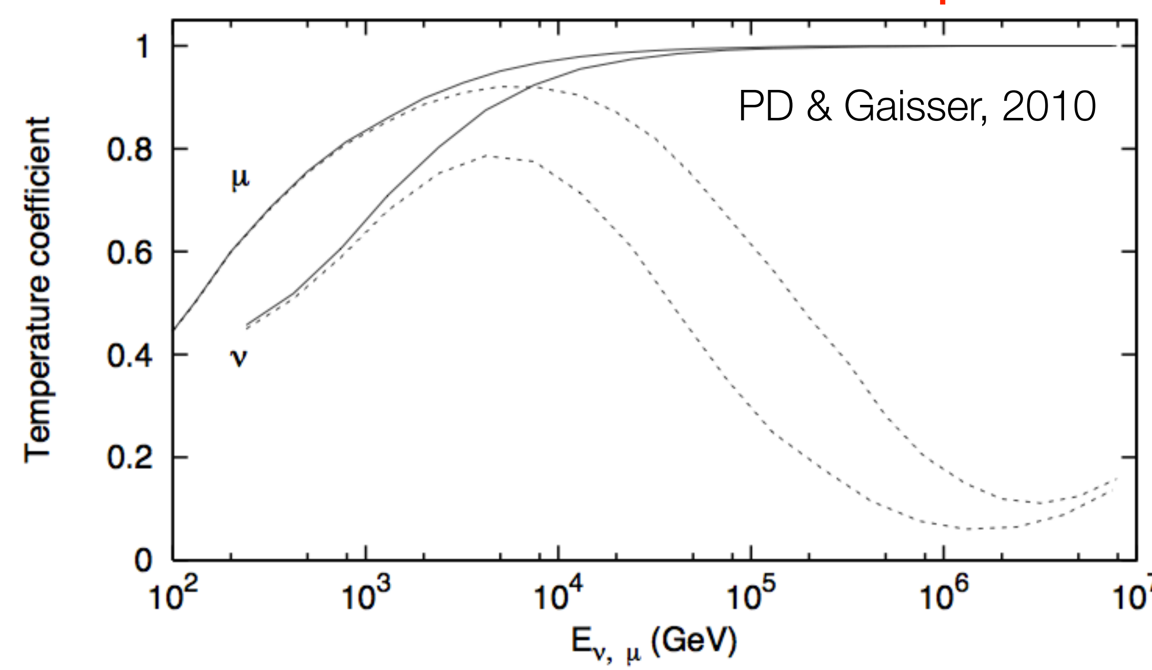
Tilav et al., ICRC 2009
PD et al., ICRC 2011
PD et al., ICRC 2013

seasonal variations decrease with prompt component

temperature coefficient

$$\alpha_T^{th}(\theta) = \frac{T \cdot \frac{\partial}{\partial T}\int dE_\nu\, \phi_\nu(E_\nu,\theta)A_{\rm eff}(E_\nu,\theta)}{\int dE_\nu\, \phi_\nu(E_\nu,\theta)A_{\rm eff}(E_\nu,\theta)}$$

$$\frac{\Delta R_\nu}{\langle R_\nu \rangle} = \alpha_T^{exp}\frac{\Delta T_{\rm eff}}{\langle T_{\rm eff}\rangle}$$



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Friday, September 20, 2013

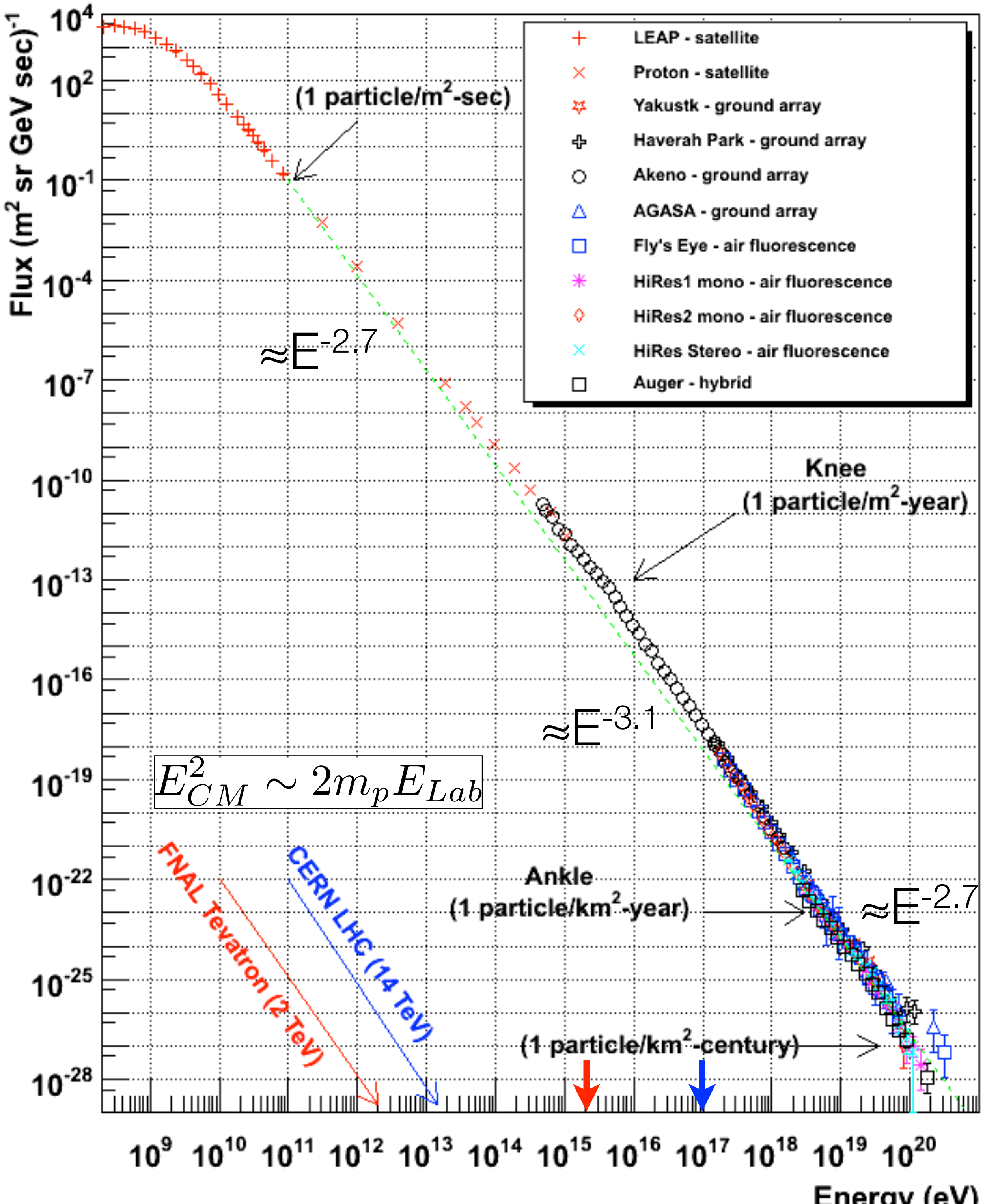
summary

- accelerator data used to interpret cosmic ray interaction processes in the atmosphere
- interaction models to cope with non pQCD of soft processes (phenomenological) in forward region and with extrapolation to high energy
- heavy quark production uncertain (both pQCD and intrinsic charm)
- important in cosmic ray and neutrino astrophysics
- large volume neutrino telescope to measure muons @ high energy and multi-flavor neutrinos to constrain heavy quark production in the atmosphere

backup slides

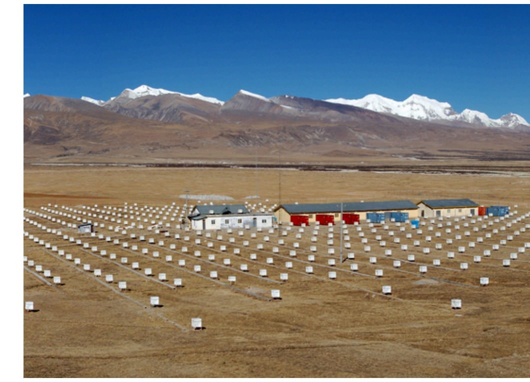
primary cosmic rays

spectrum & composition

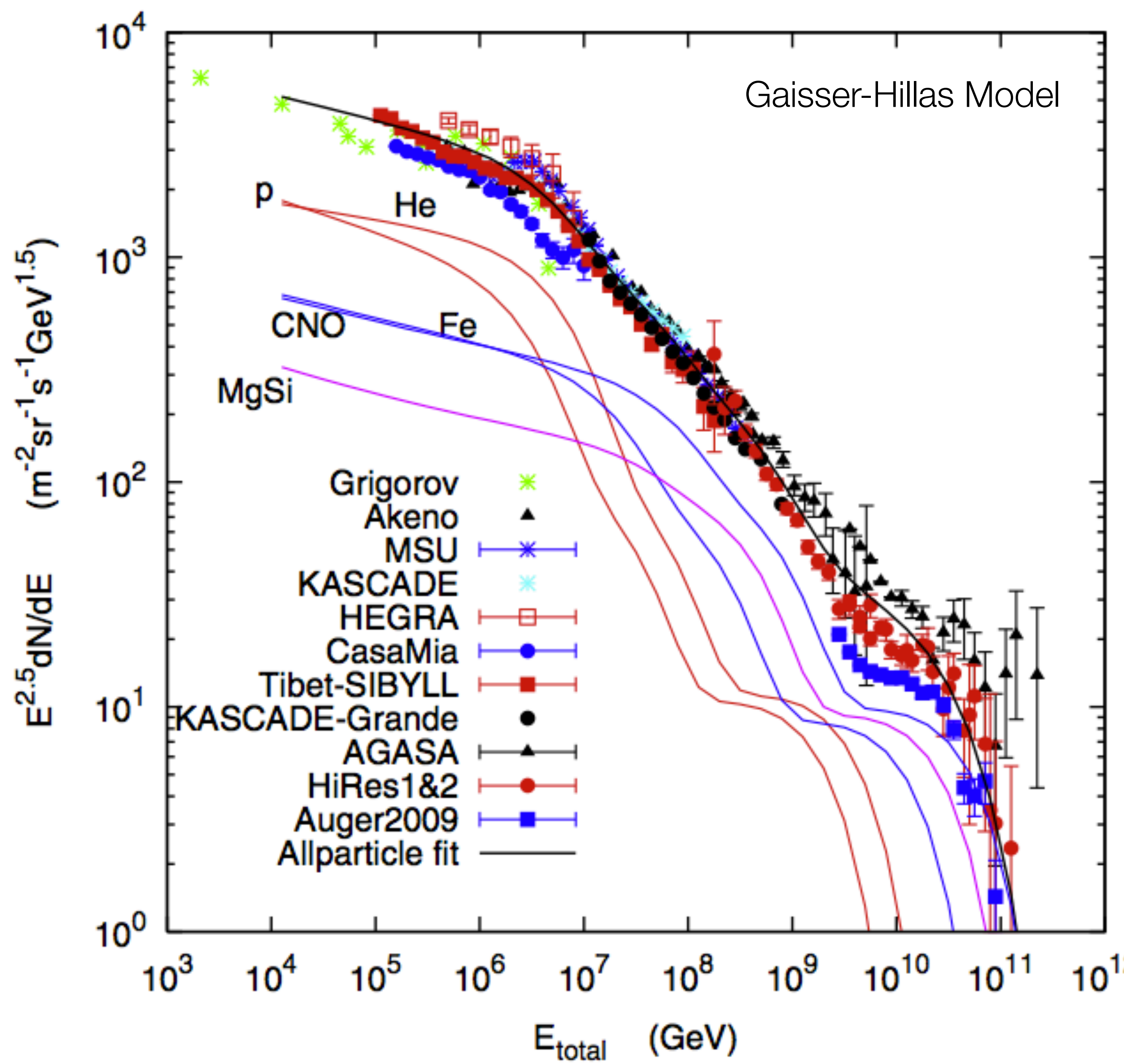


direct measurements

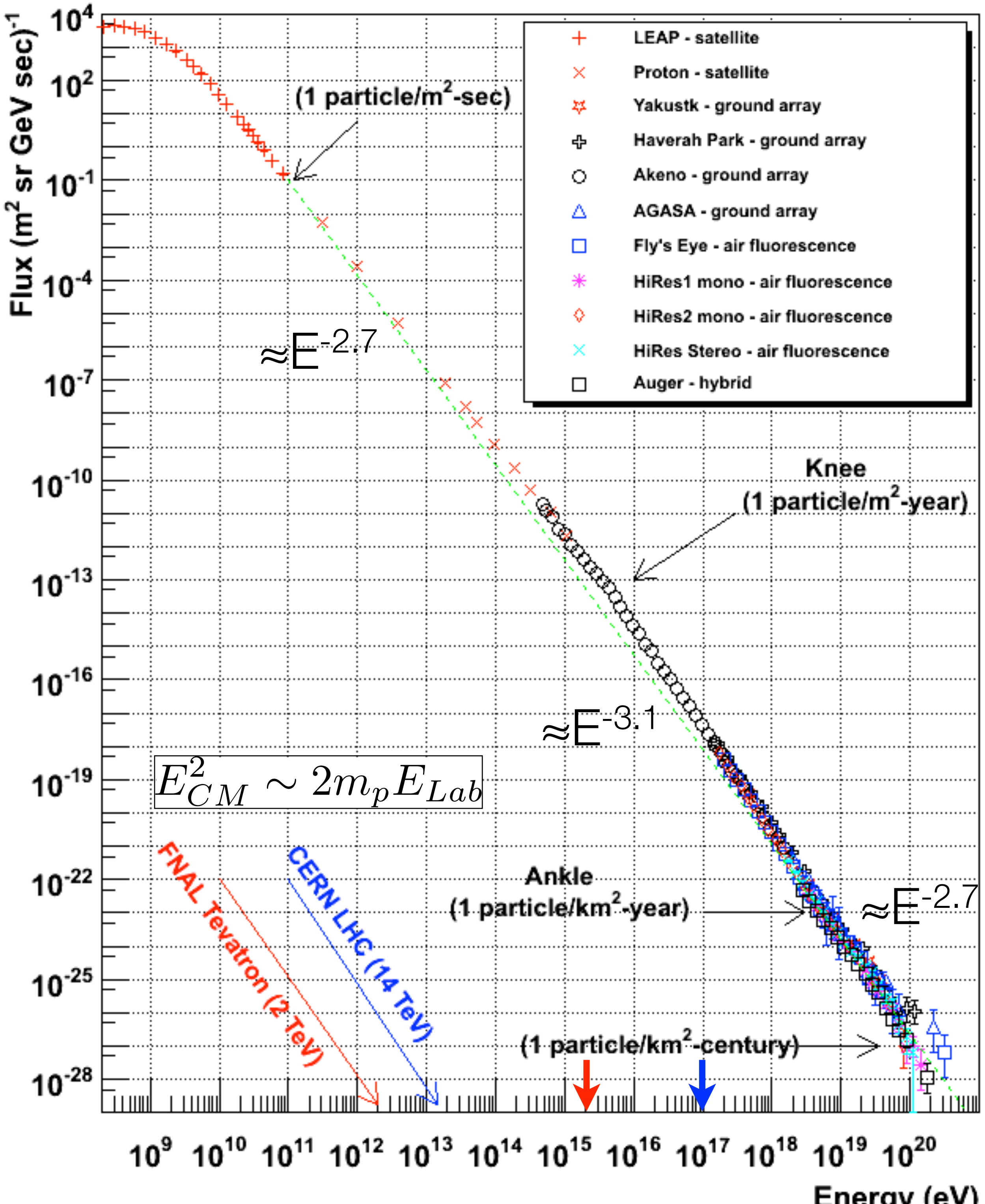
indirect measurements



Gaisser, Astropart. Phys. 35 (2012) 801

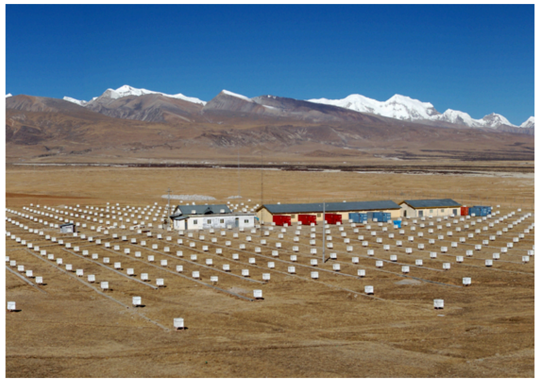


primary cosmic rays
spectrum & composition

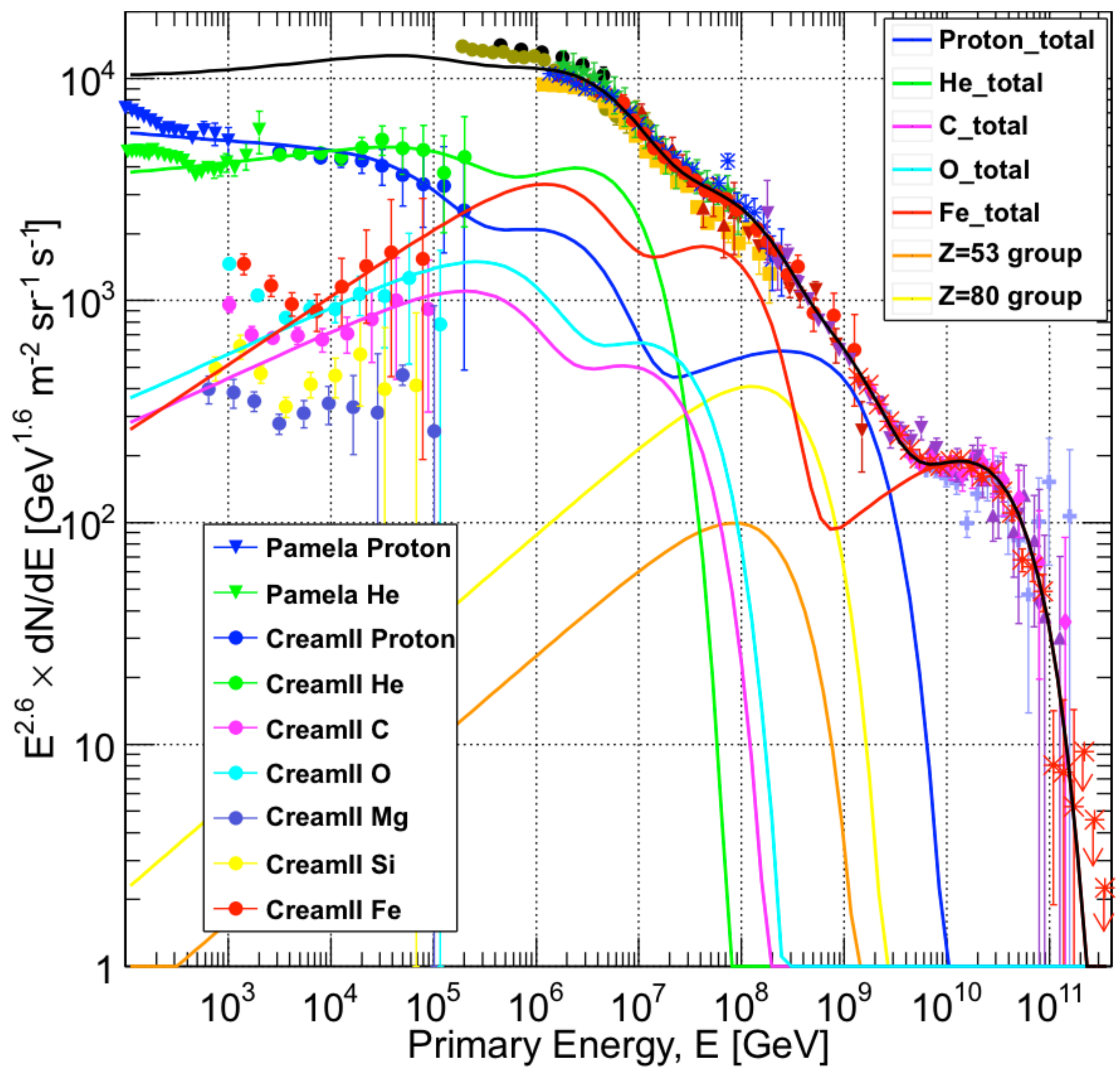


direct measurements

indirect measurements

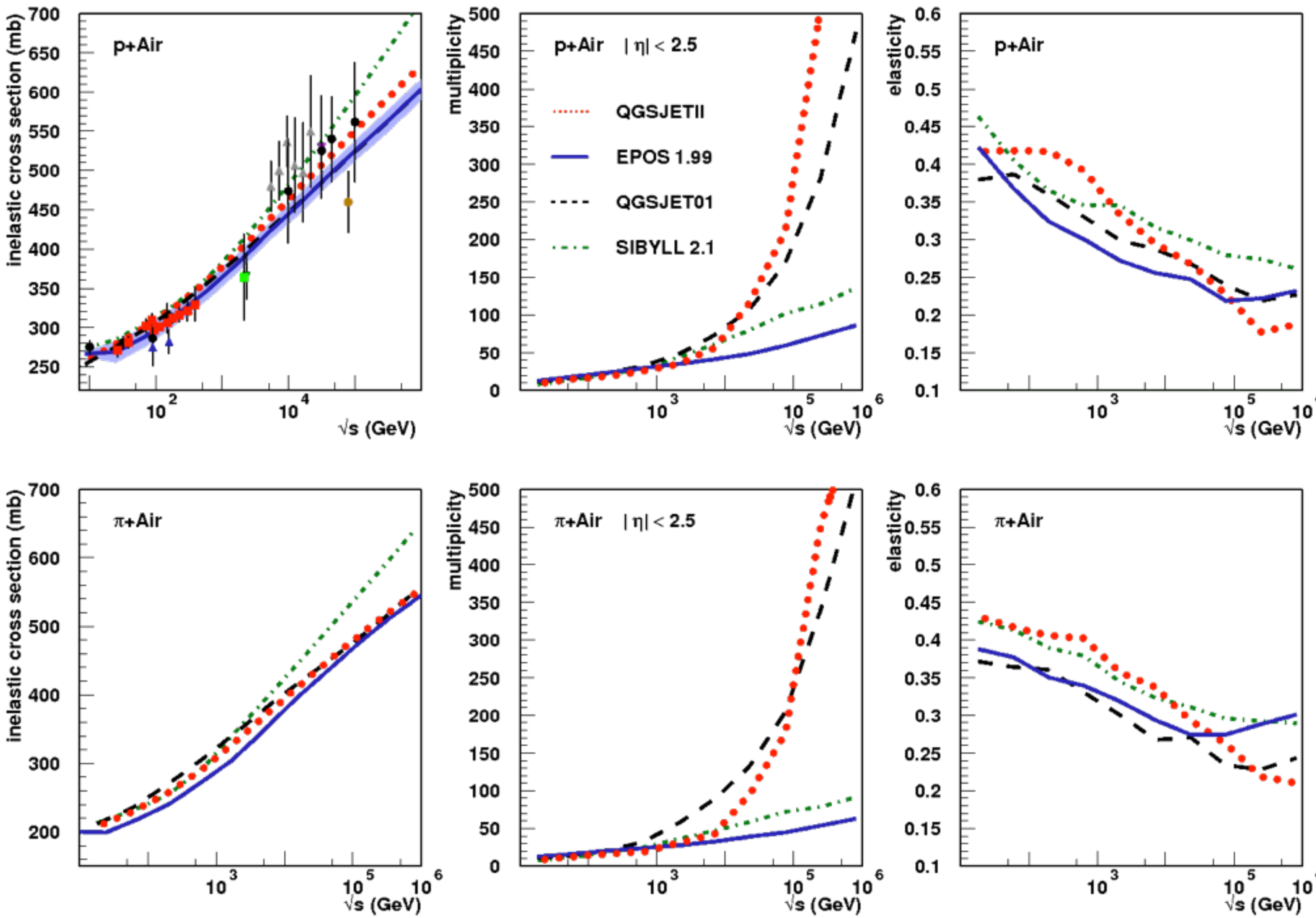


Gaisser, Stanev & Tilav, 2013 - arXiv:1303.3565

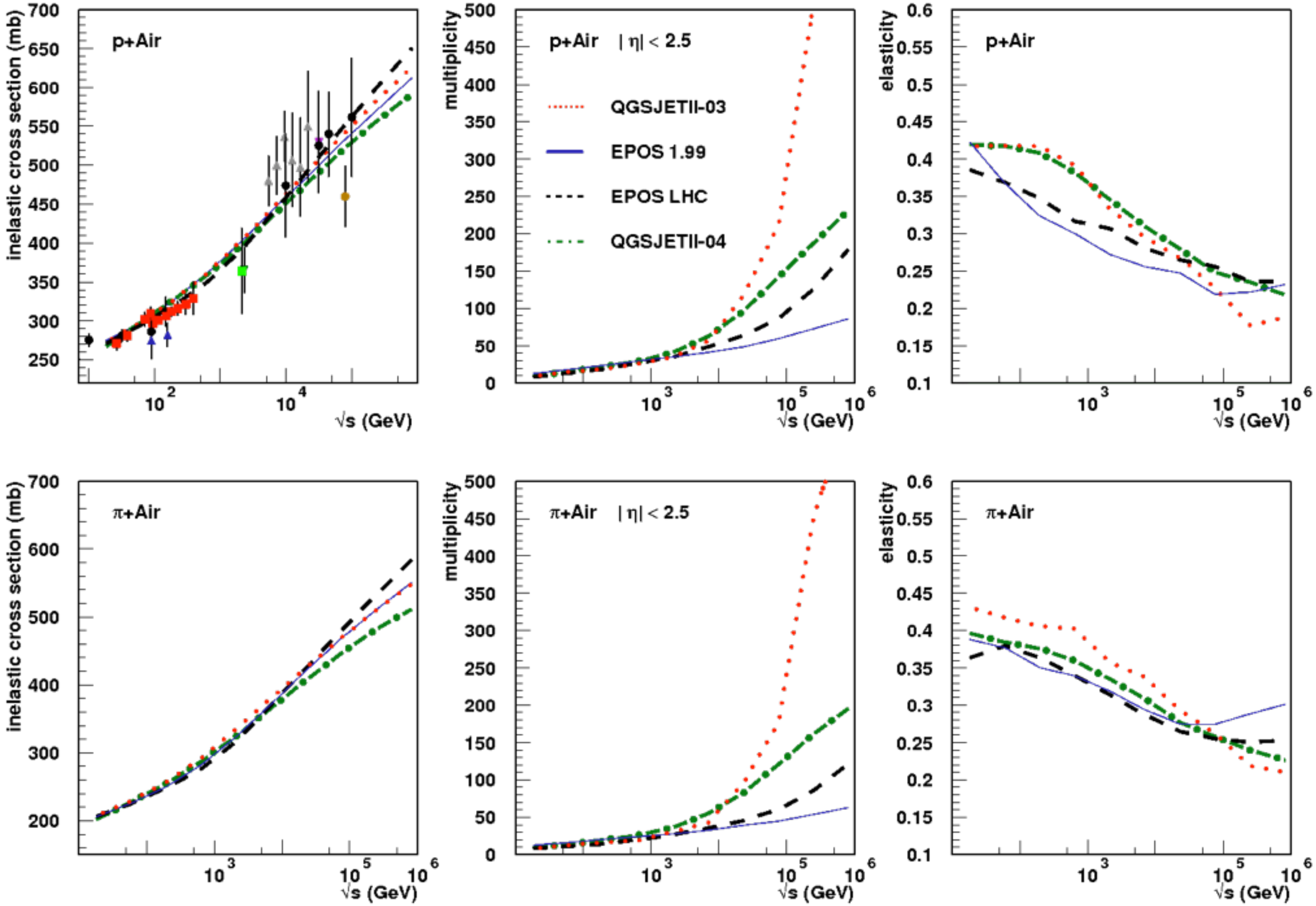


hadronic interactions

reduction of systematic uncertainties

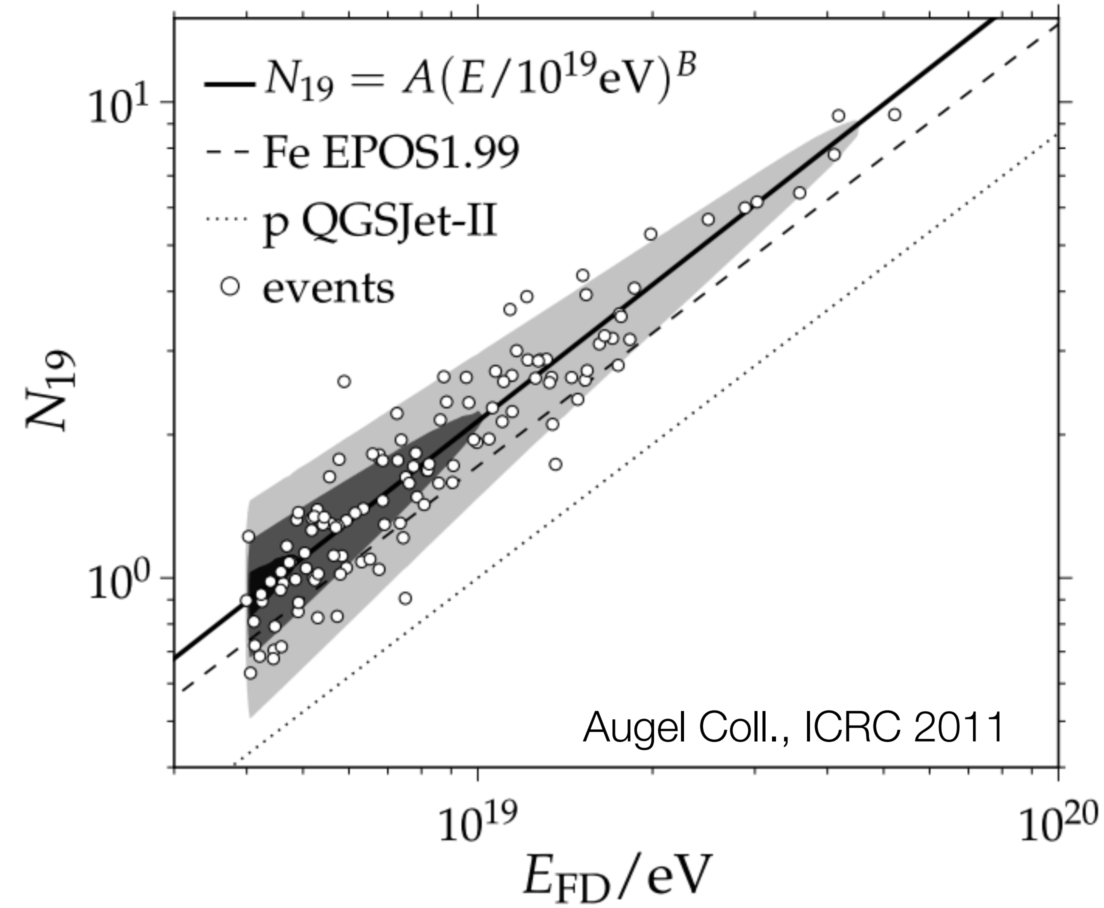


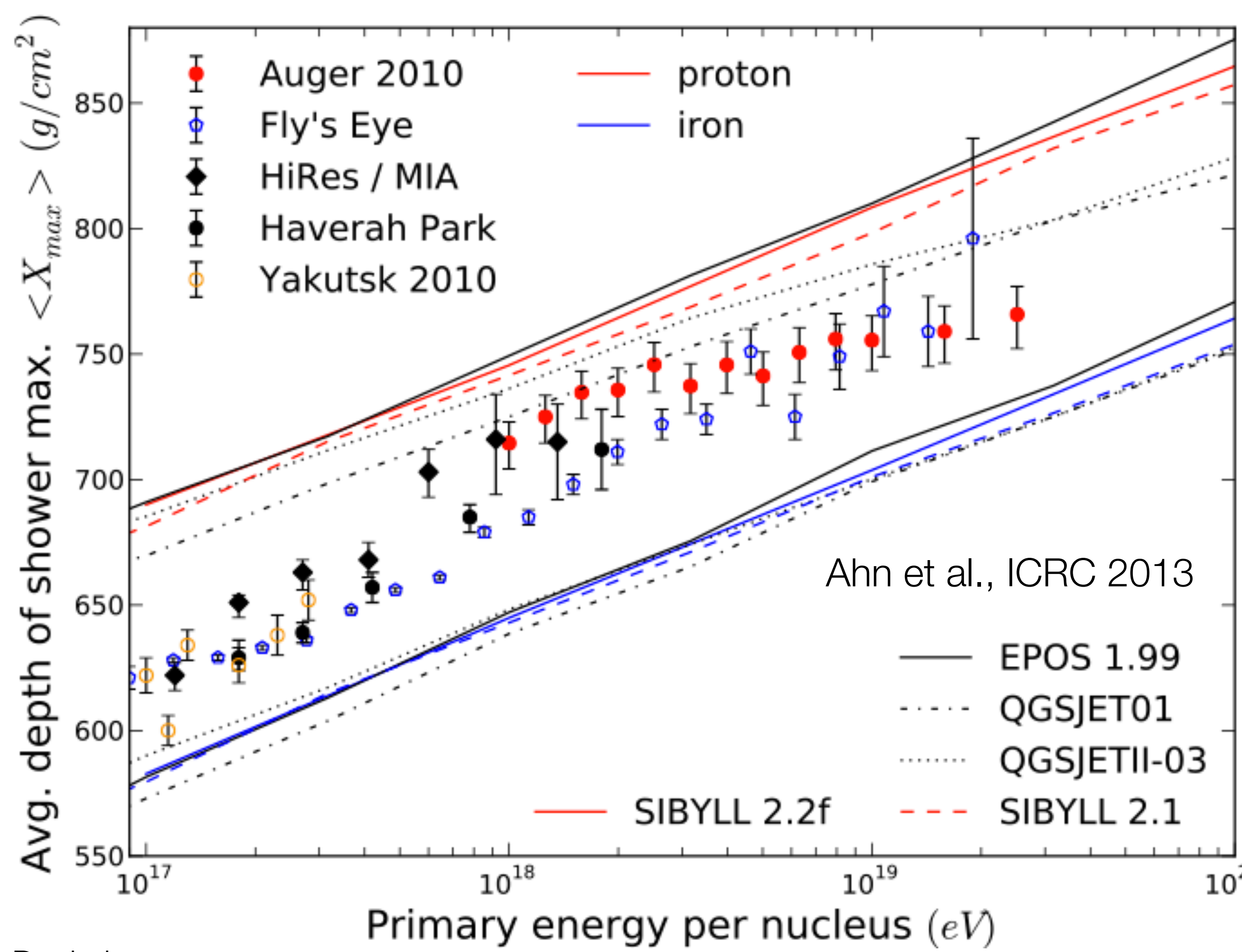
hadronic interactions
reduction of systematic uncertainties



> 100 PeV cosmic rays

- inclined showers develop earlier and exhaust higher in the atmosphere
- only penetrating muons reach the ground
- **higher μ flux** observed above 10^{18} eV
  - N_{19}/QGSJet-II(10^{19} eV) = **2.13**±0.04±0.11 (sys.)
- **mass composition** affected by the large systematic uncertainties of interaction models (+ experimental techniques)

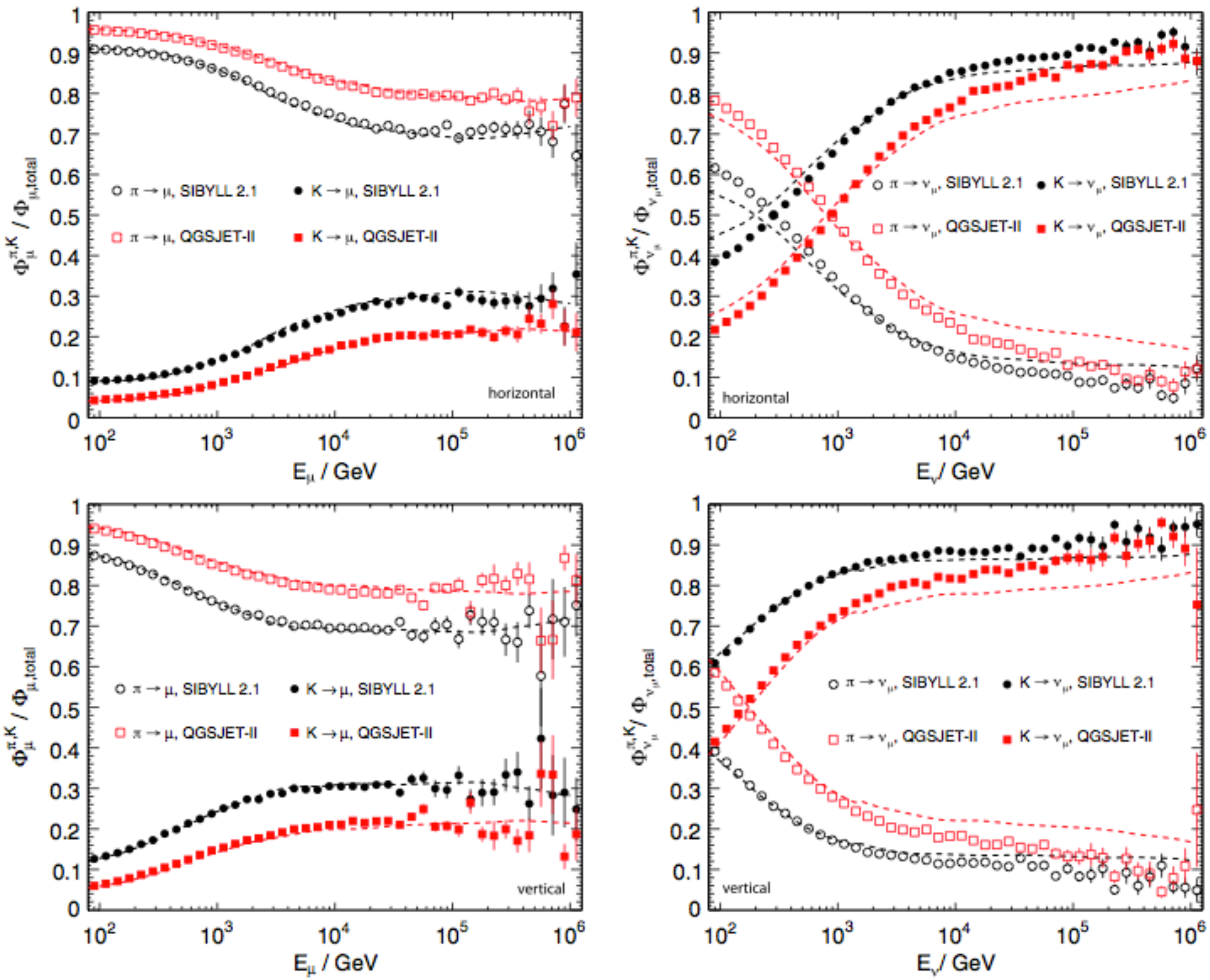




Fedynitch, Becker Tjus, PD 2012

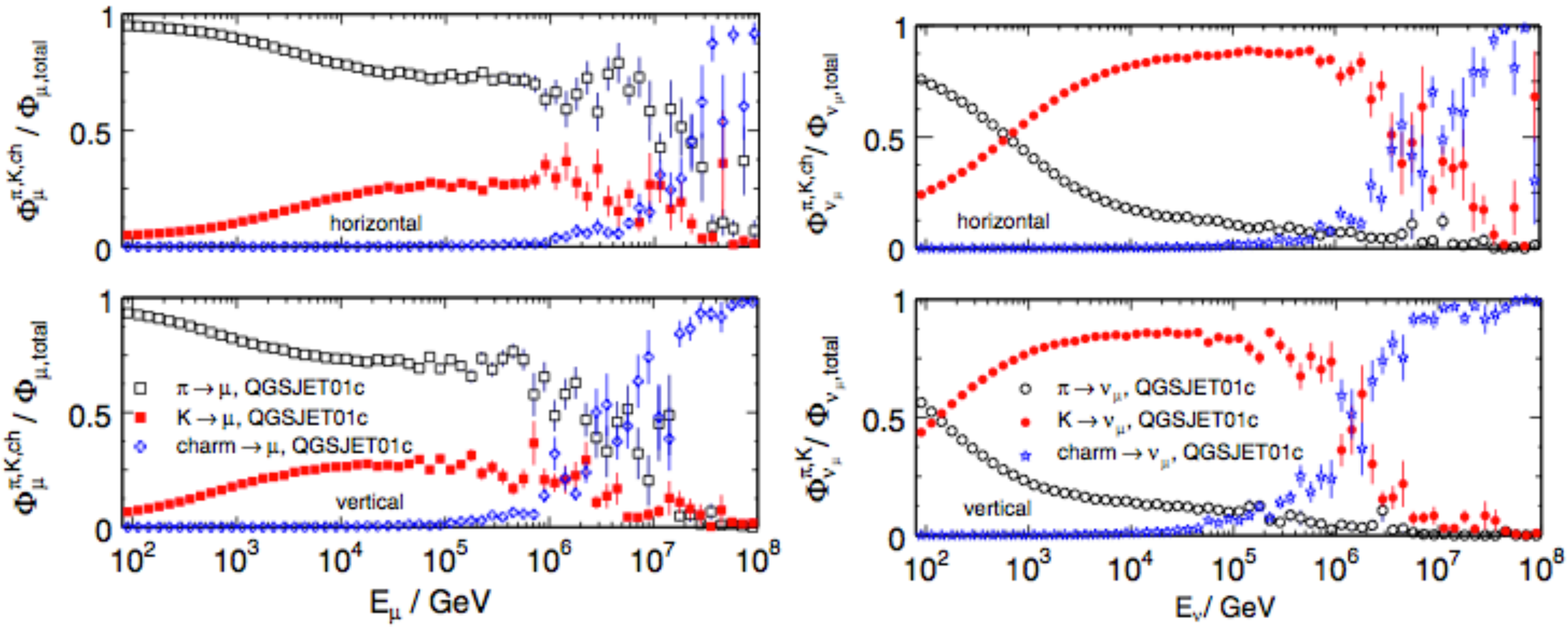
atmospheric neutrinos

high energy and heavy quarks



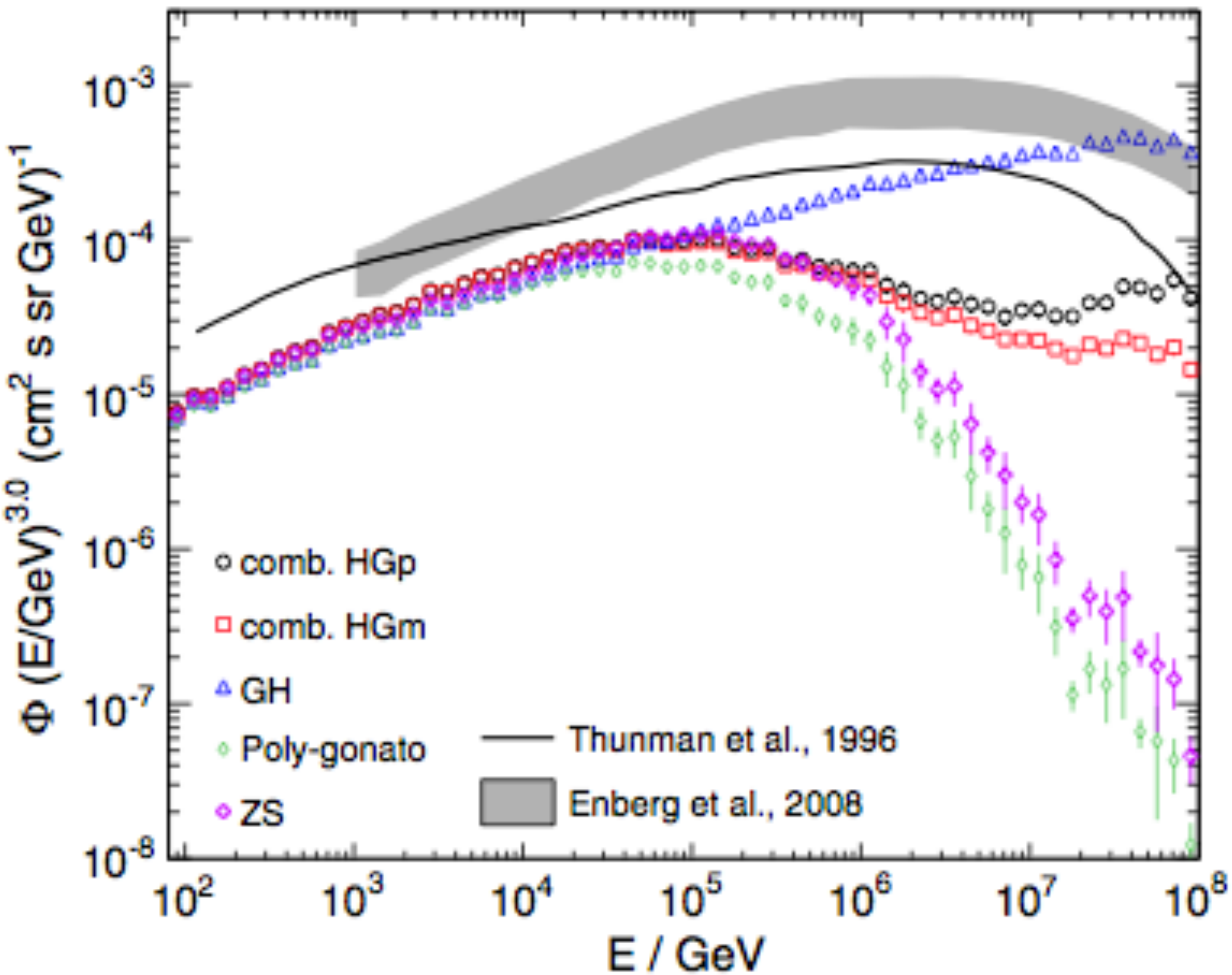
atmospheric neutrinos
high energy and heavy quarks

QGSJET01-c



Fedynitch, Becker Tjus, PD 2012

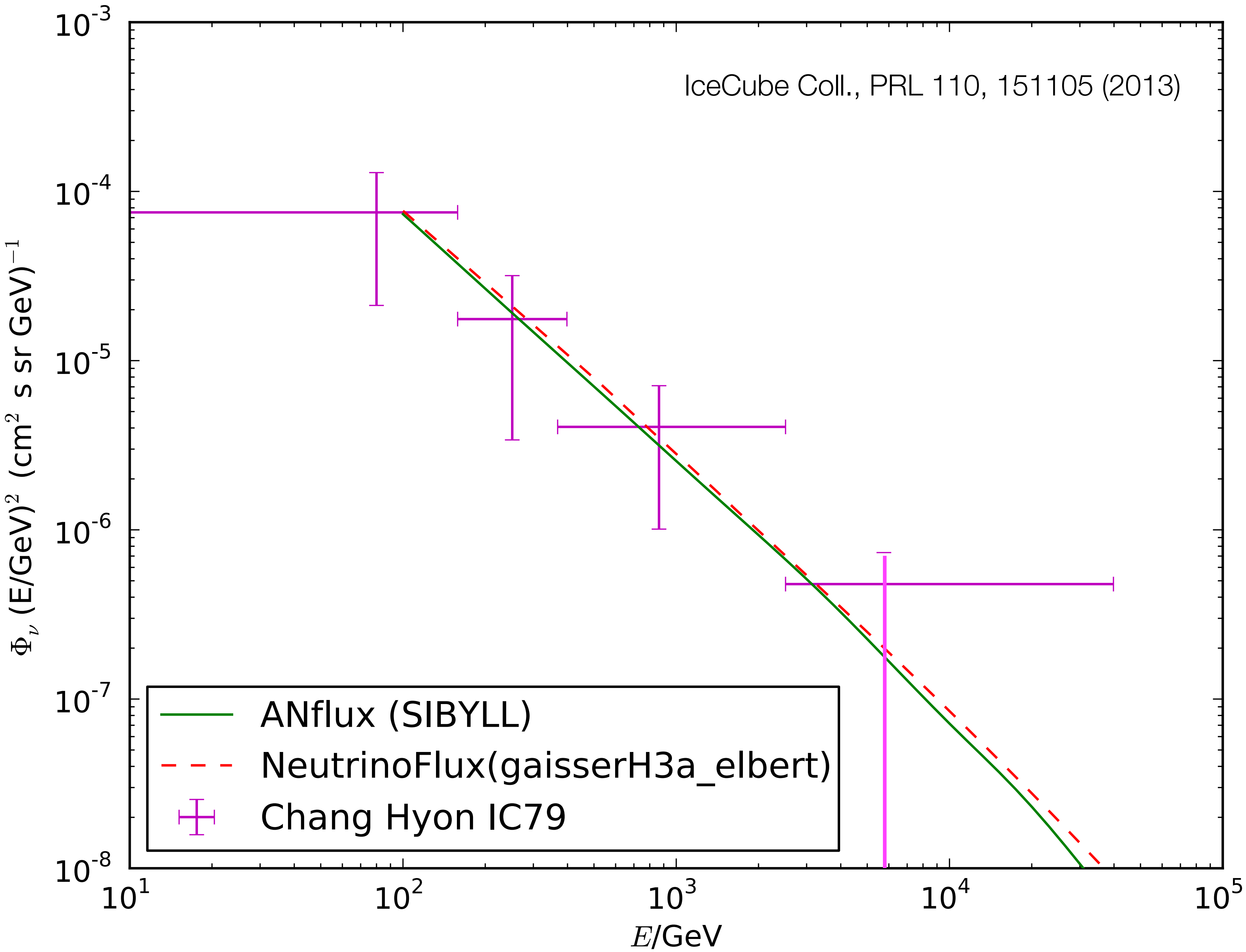
atmospheric neutrinos
high energy and heavy quarks



QGSJET01-c

atmospheric neutrinos
current status

observed cascading $\nu_e + \bar{\nu}_e$



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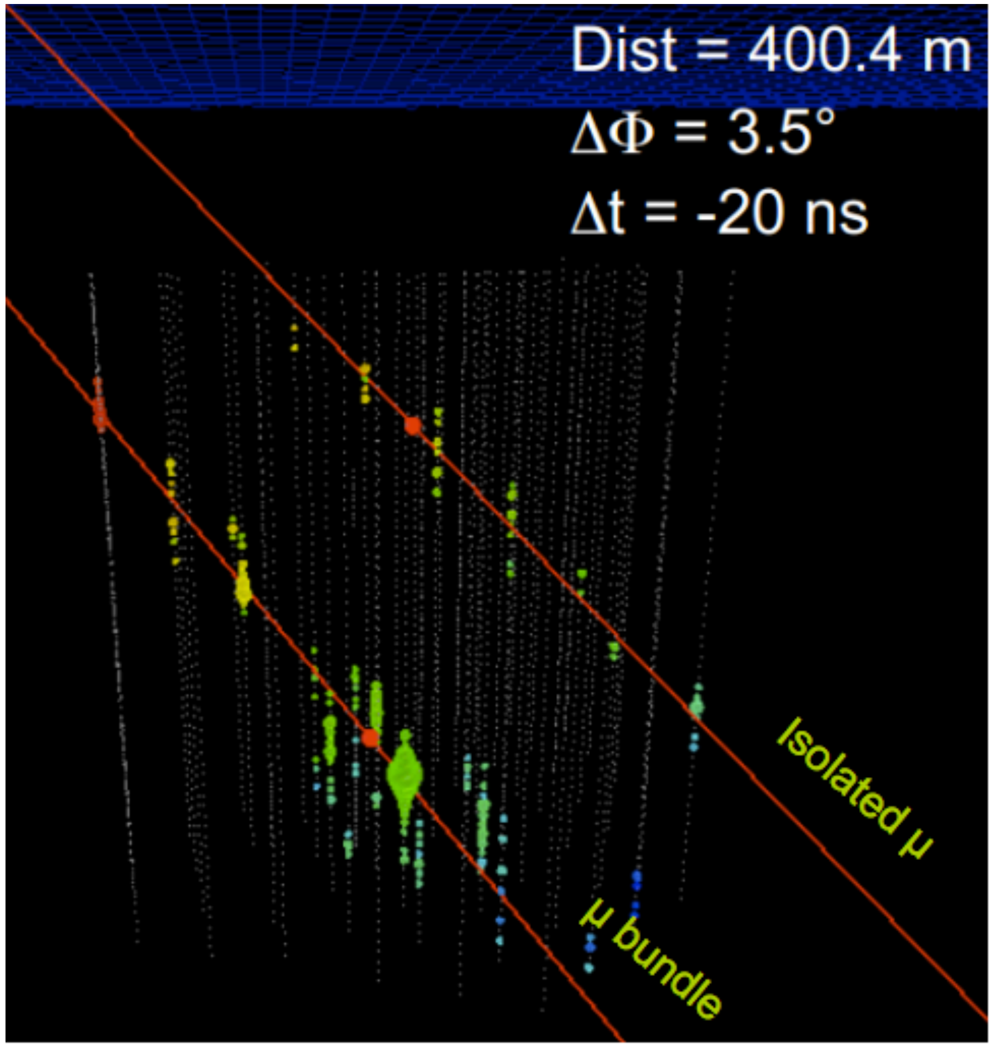
atmospheric neutrinos

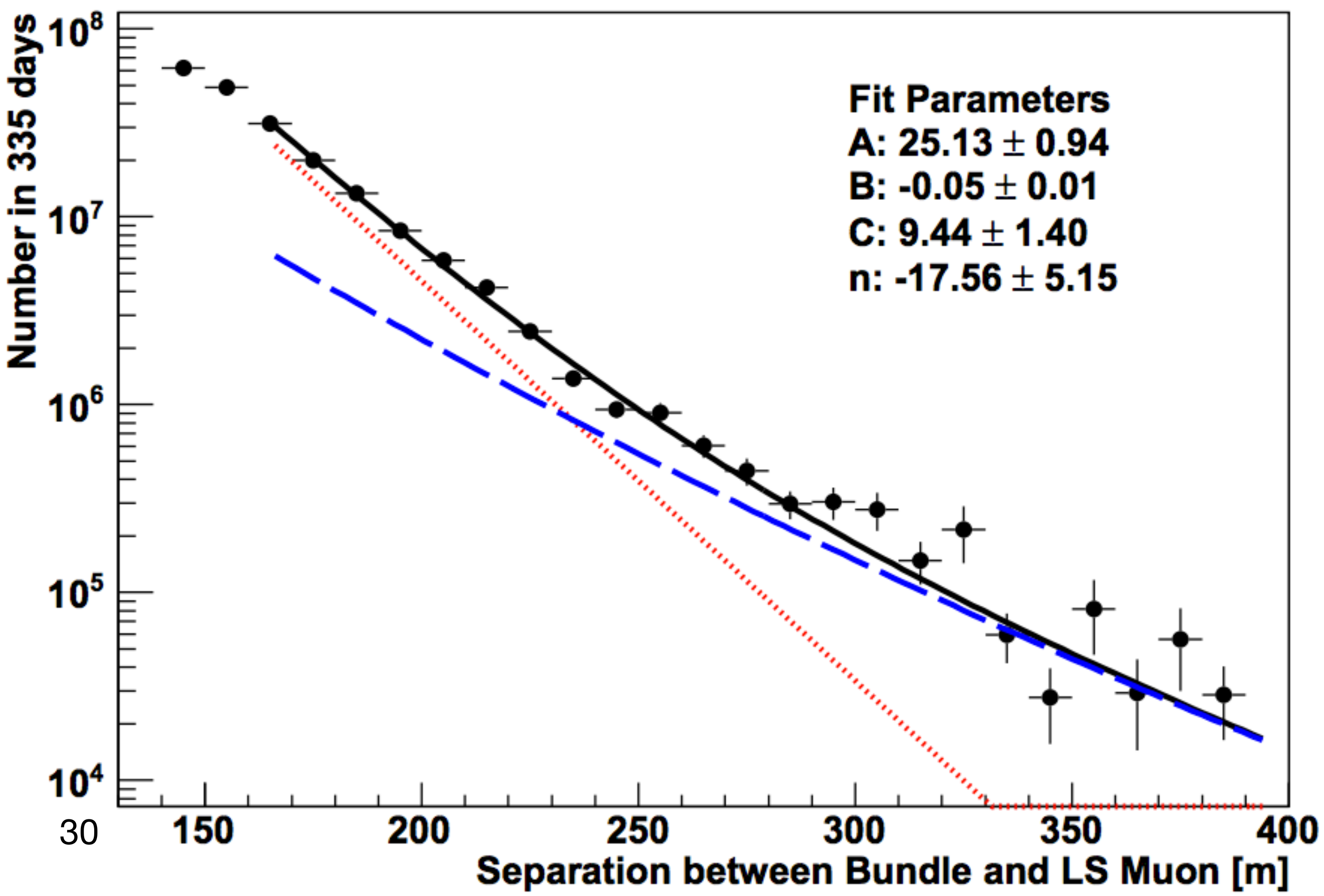
charm and high p_T muons

- search for μ + μ bundle
- measure separation

$$d_T \approx \frac{p_T H c}{E_\mu cos(\theta)}$$

- CR composition & interaction models





soft interaction (pT ≲ 2 GeV)
non perturbative

hard interaction (pT ≳ 2 GeV)
pQCD

IceCube Coll., PRD 87, 012005, 2013
arXiv:1208.2979

atmospheric neutrinos

charm and high p_T muons

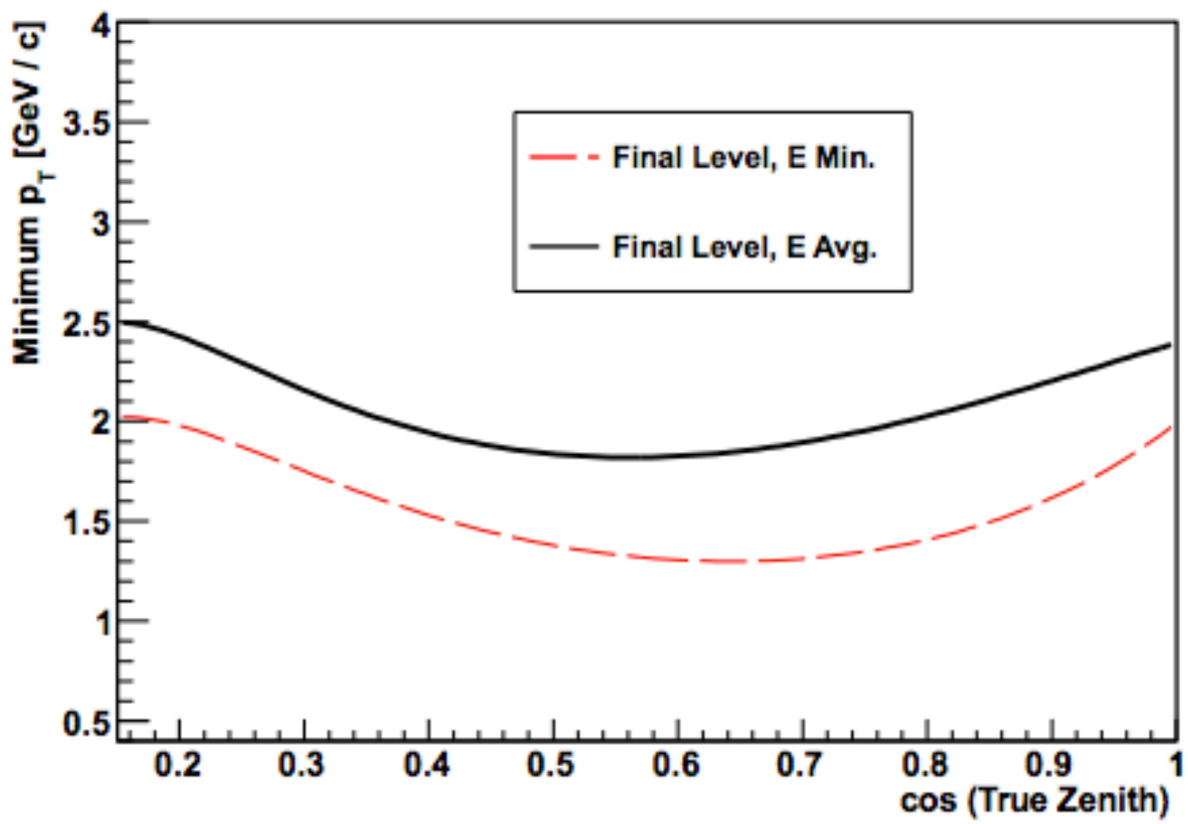
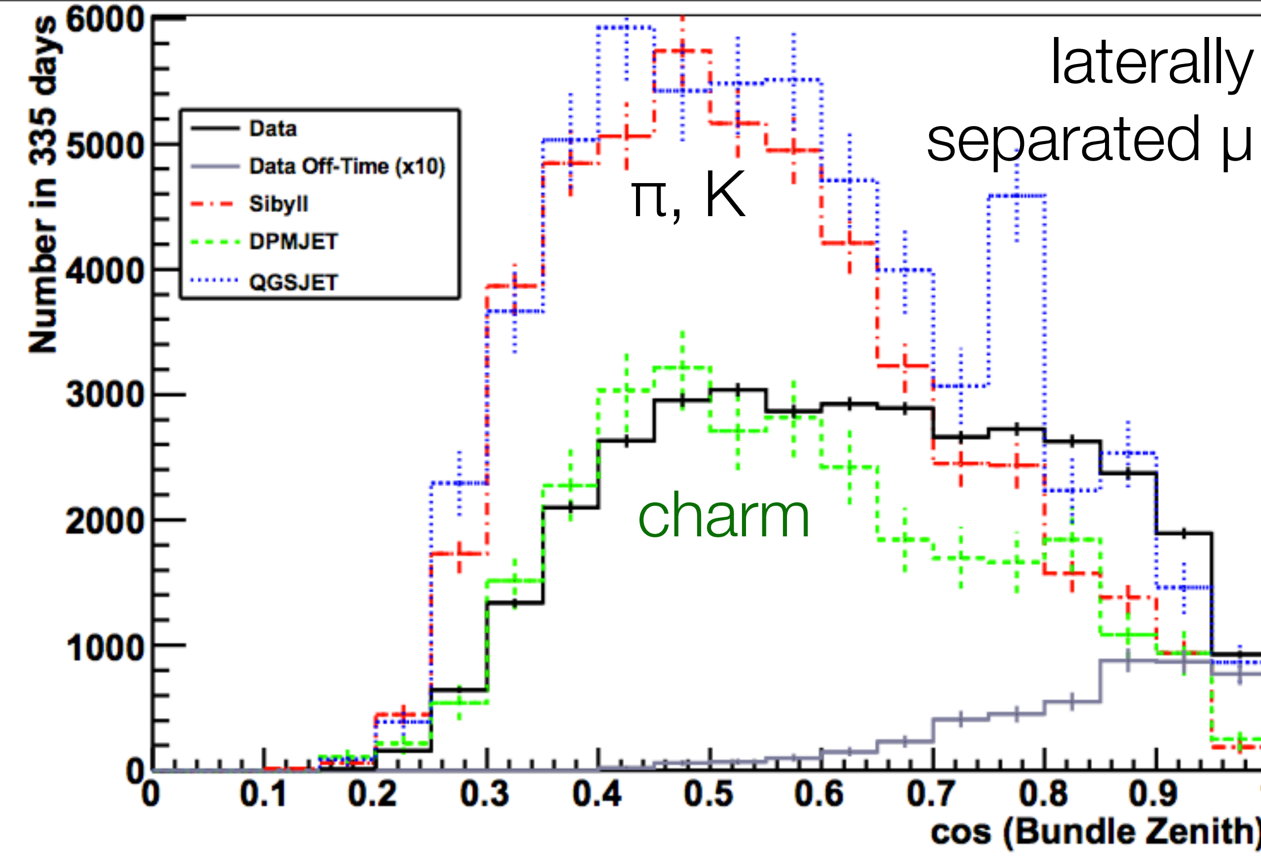


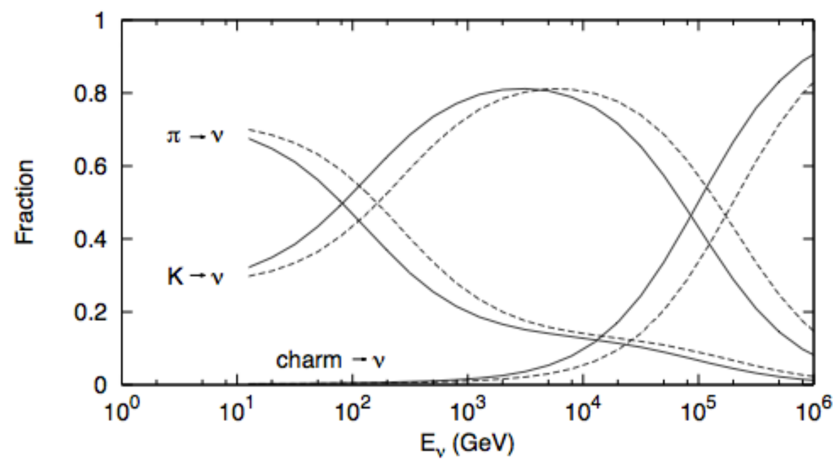
FIG. 14. (Color online). The minimum muon transverse momentum of DPMJET simulated shower events that pass all selection criteria for different energy parameterizations as a function of zenith angle. The interaction height comes from Fig. 1.

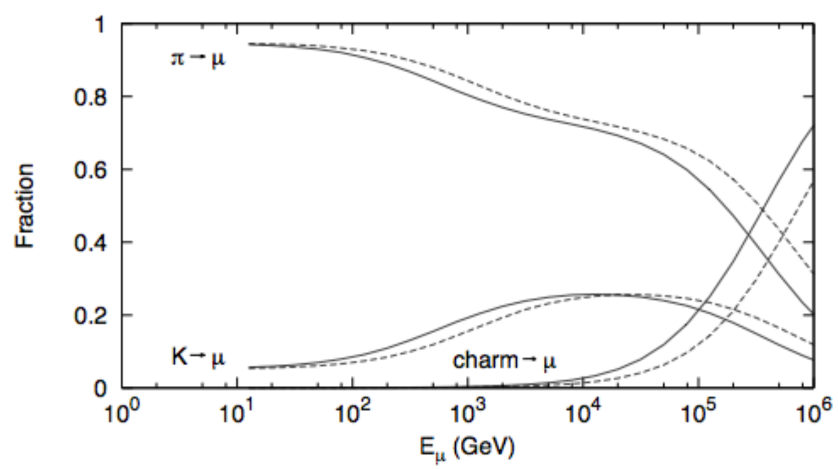


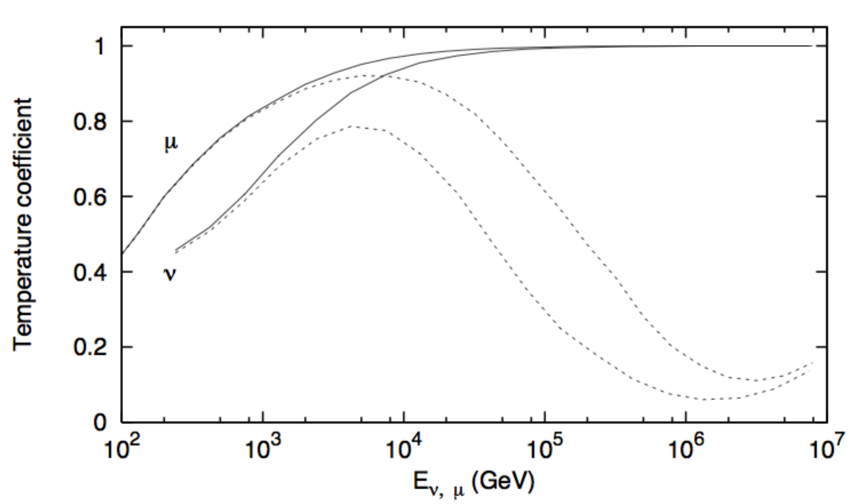
IceCube Coll., PRD 87, 012005, 2013
arXiv:1208.2979

atmospheric neutrinos

π/K & **ν** seasonal variations







PD & Gaisser, 2010

$E_{\mu,\min}$	no charm		RQPM charm		ERS charm		int. charm	
	α	Rate	α	Rate	α	Rate	α	Rate
0.5	0.83	2050	0.82	2070	0.82	2050	0.82	2060
10	0.98	1.26	0.89	1.40	0.97	1.26	0.94	1.34
100	1.0	0.0025	0.53	0.0049	0.91	0.0028	0.71	0.0036

TABLE I: Correlation coefficients for muons with ($\theta \leq 30°$) for three levels of charm (energy in TeV; rate in Hz/km^2).

$E_{\nu,\min}$(TeV)	no charm		RQPM charm	
Zone 1	α	Events/yr	α	Events/yr
all	0.54	16000	0.52	17000
3	0.70	5900	0.62	6300
30	0.94	350	0.72	450

$E_{\nu,\min}$(TeV)	no charm		RQPM charm	
Zone 2	α	Events/yr	α	Events/yr
all	0.66	6000	0.62	6400
3	0.88	1230	0.75	1450
30	0.98	37	0.46	80

$E_{\nu,\min}$(TeV)	no charm		RQPM charm	
Zone 3	α	Events/yr	α	Events/yr
all	0.68	1650	0.64	1750
3	0.91	260	0.75	320
30	0.99	5.2	0.41	13

TABLE II: Correlation coefficients with and without charm for neutrinos in three zones of the atmosphere (see text).

PD et al., ICRC 2013

configuration	α_T^{exp}	χ^2/ndf	α_T^{th}
IC40	0.27±0.21	22.85/12	$0.557^{+0.008}_{-0.007}$
IC59	0.50±0.15	12.30/11	$0.518^{+0.008}_{-0.007}$
IC79	0.45±0.11	4.48/10	$0.489^{+0.007}_{-0.005}$

atmospheric neutrinos

π/K & μ seasonal variations

PD et al., ICRC 2011