workshop in particle physics

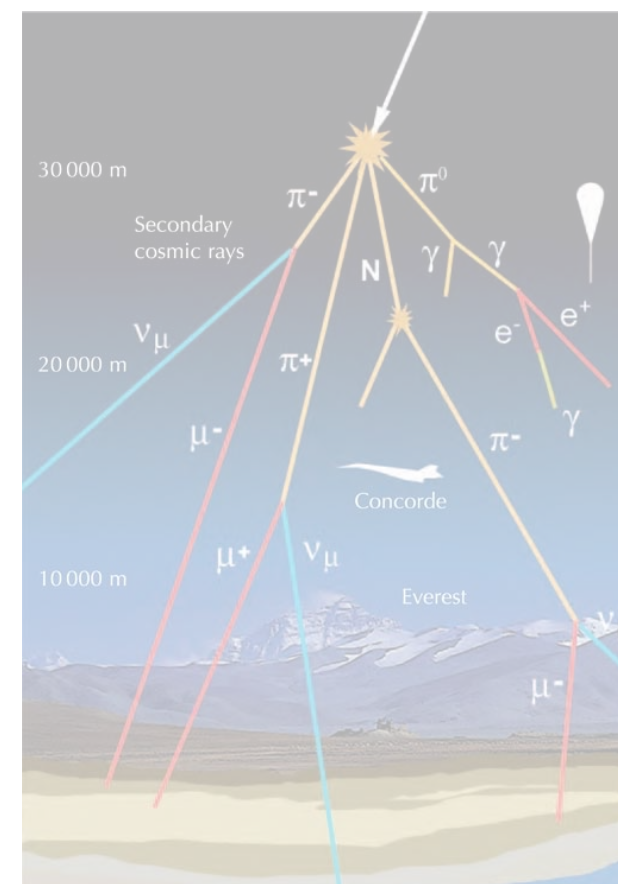
3

hadronic showers

Paolo Desiati
desiati@wipac.wisc.edu

Wisconsin IceCube Particle Astrophysics Center (WIPAC)
& Department of Astronomy

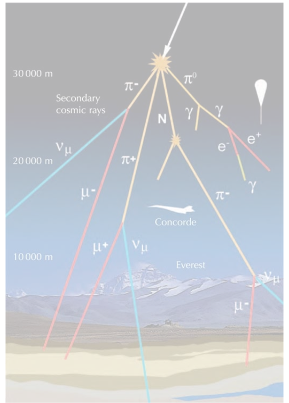
University of Wisconsin - Madison



RUB

lectures outline

workshop in particle physics



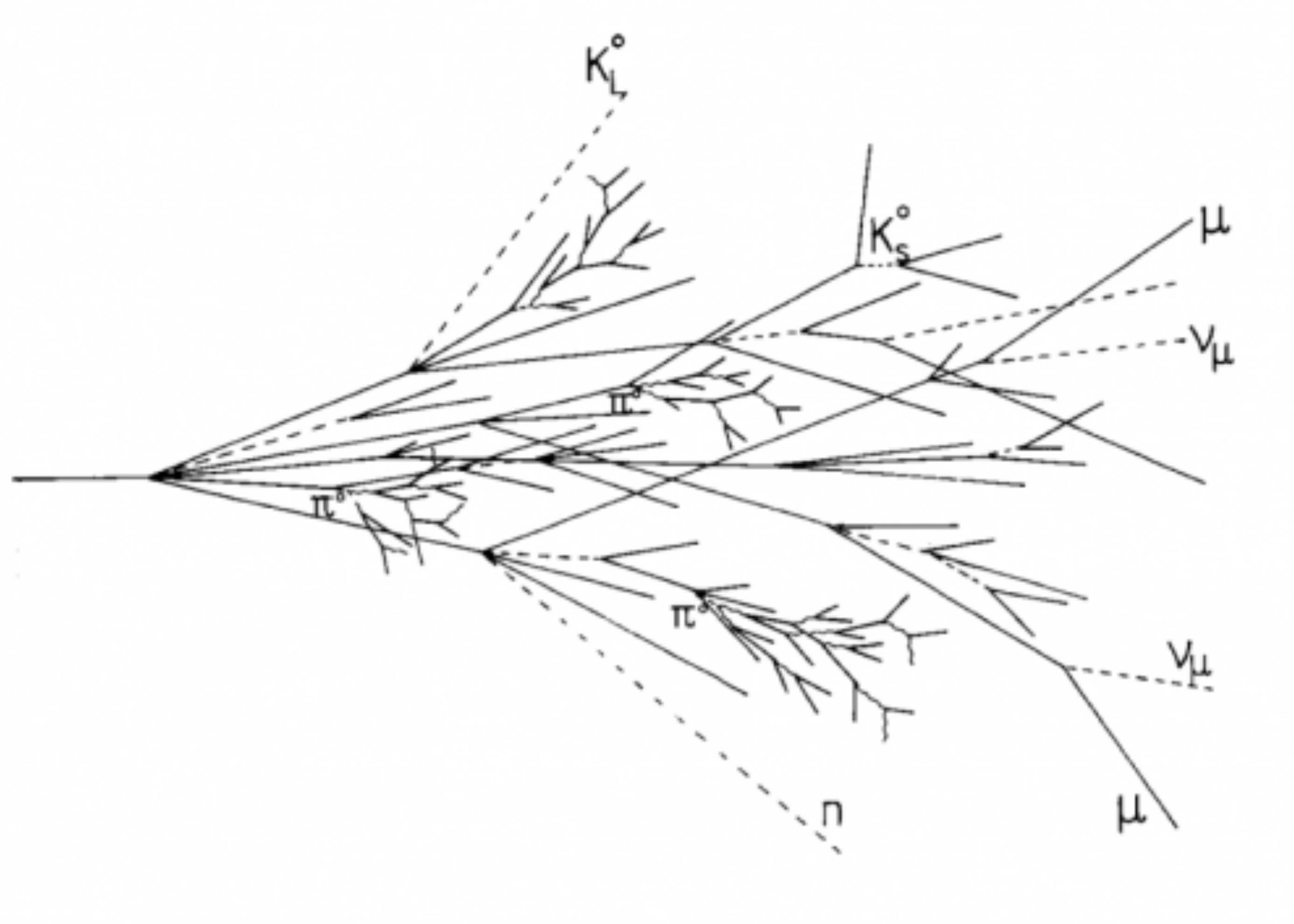
1. fundamental interactions & EM showers

2. development of electromagnetic showers

3. hadronic showers

outline
workshop in particle physics

- quantum electrodynamics
- color confinement: from parton to particles
- hadronization
- collider experiments feeding cosmic ray physics
- inclusive particle flux in the atmosphere

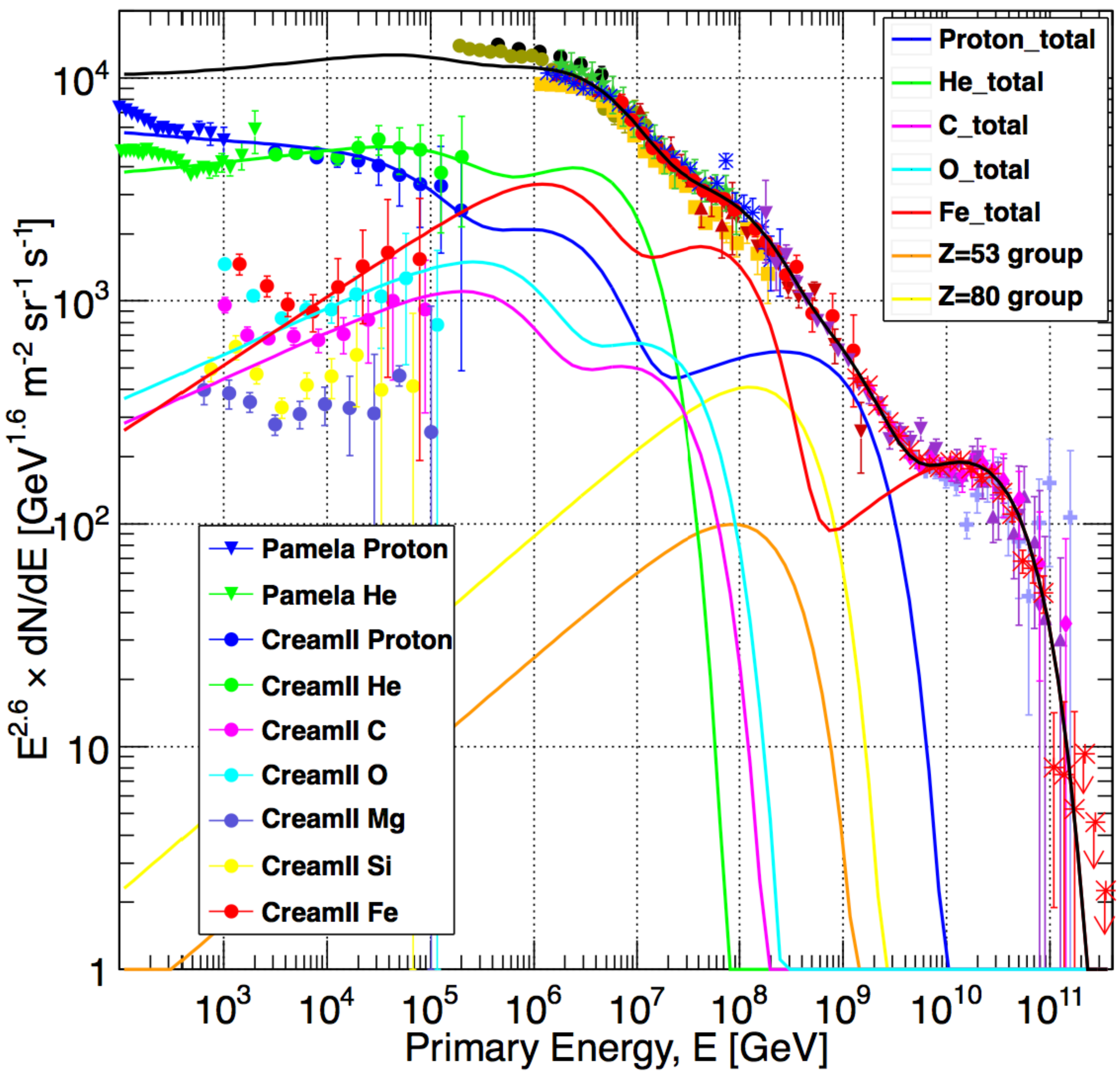


HADRONIC SHOWERS

primary cosmic rays

spectrum and composition

shape from astrophysics
(source & propagation)
and particle physics
(indirect detection)



Gaisser, Stanev, Tilav
arXiv:1303.3565

primary cosmic rays

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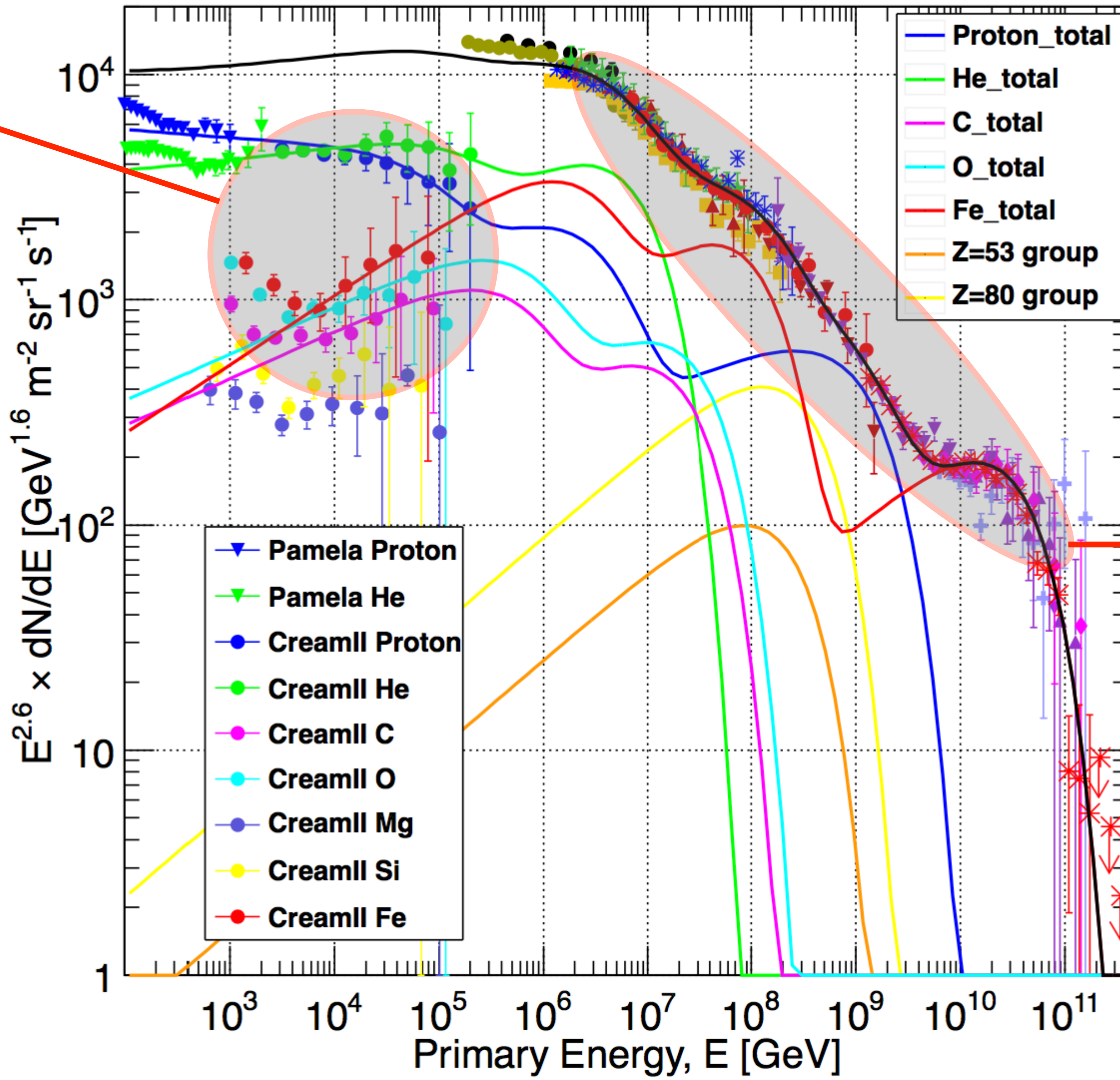
direct measurements



indirect measurements

Gaisser, Stanev, Tilav
arXiv:1303.3565

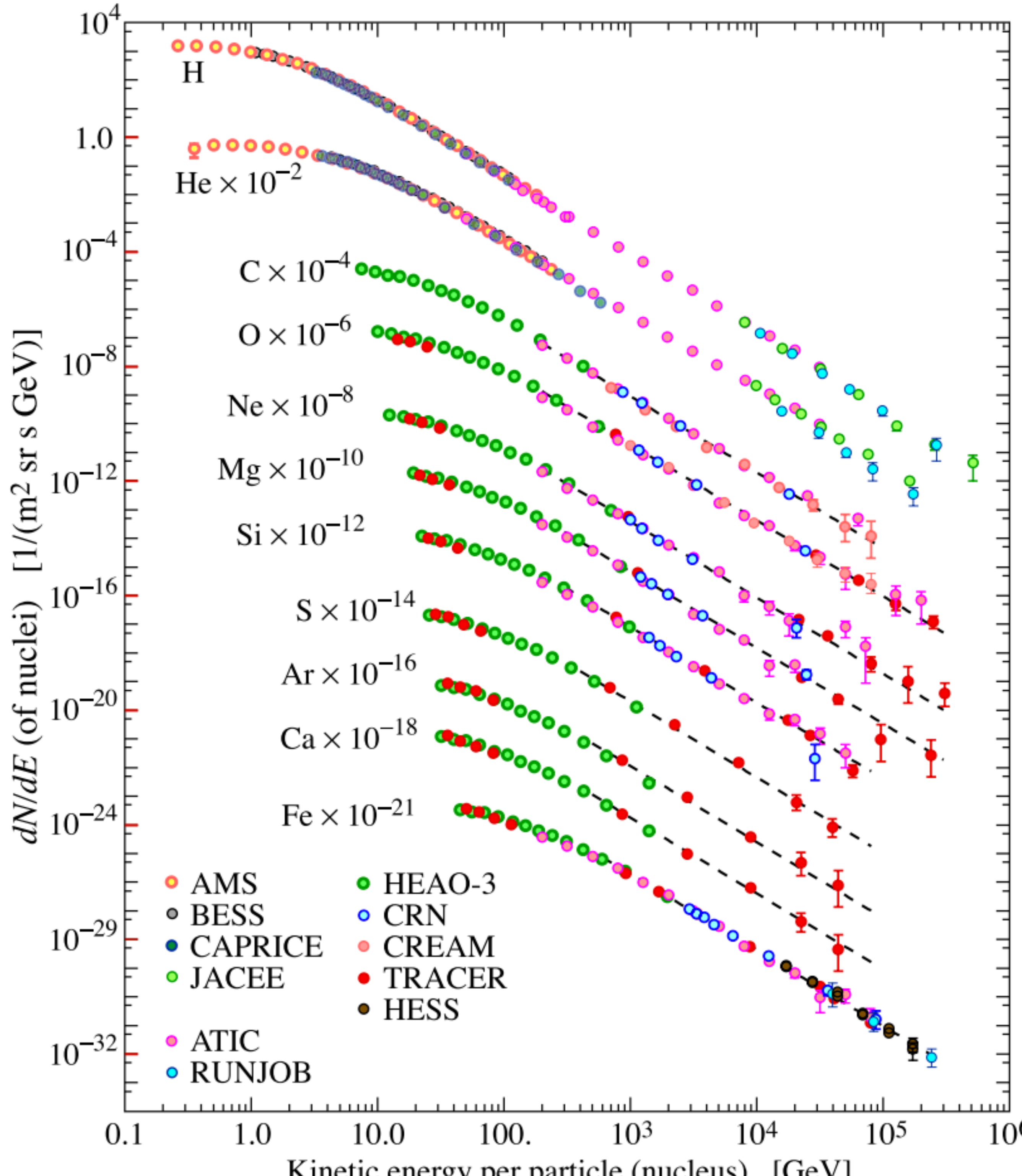
cosmic rays spectrum
direct observations

CREAM, ATIC, Bess-Polar
TRACER, TIGER

PAMELA, Fermi,
Gamma-400,...

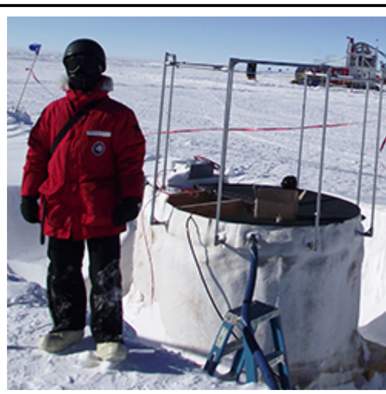
AMS2, Calet,
ISS-CREAM, ...

(from PDG)



cosmic rays spectrum
indirect observations

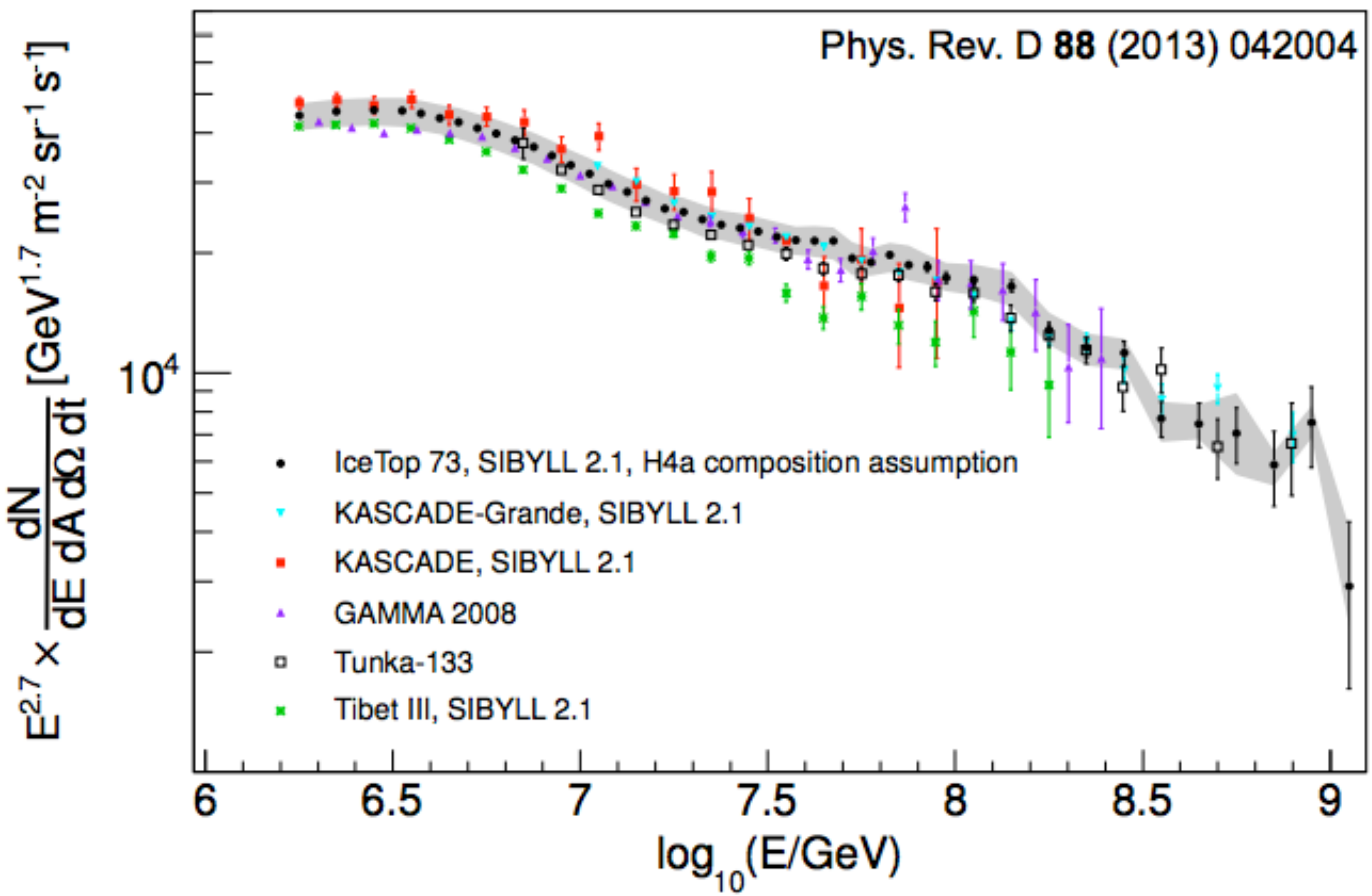
Tibet Array, ARGO-YBJ



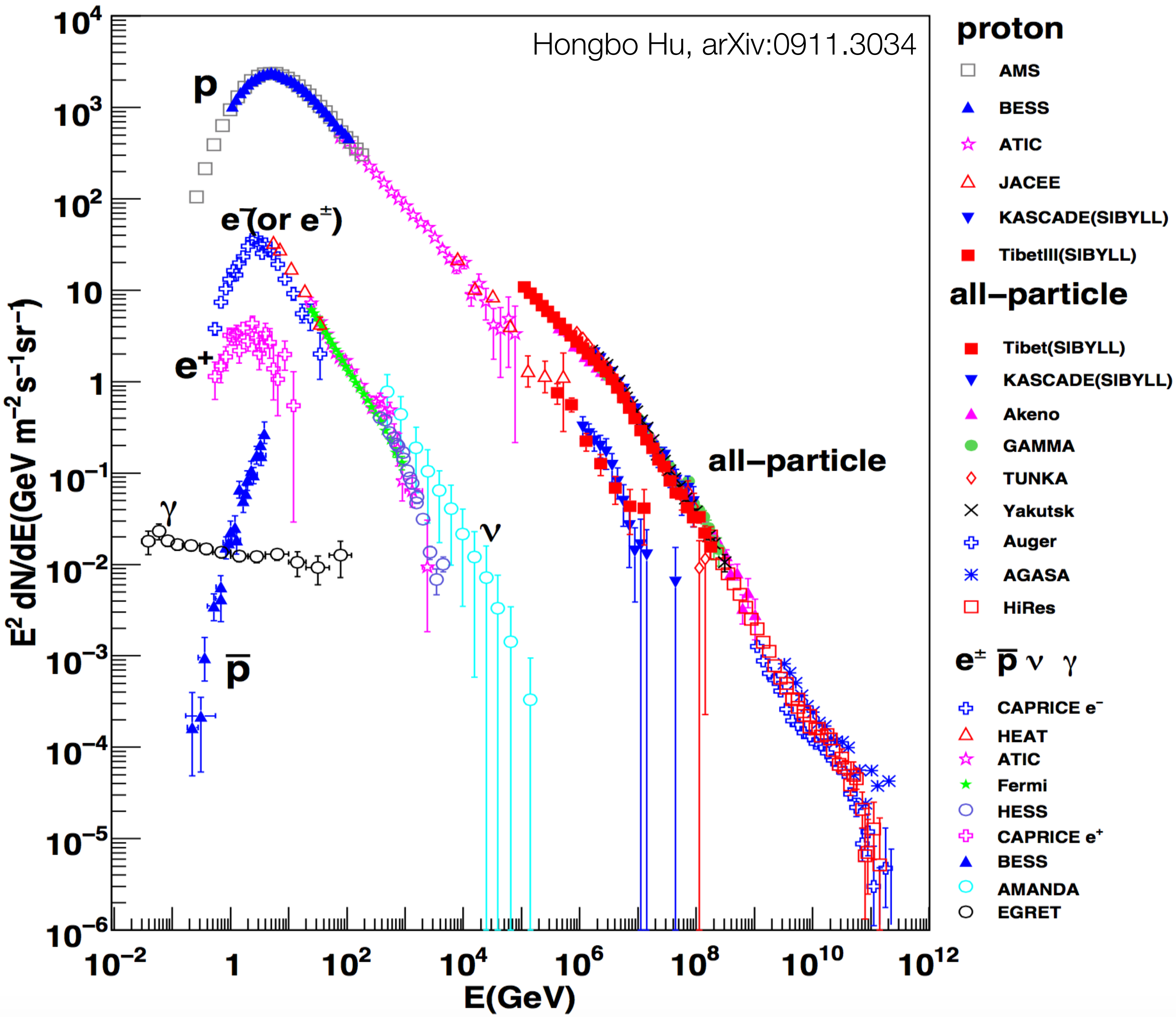
IceTop

KASKADE-Grande

…



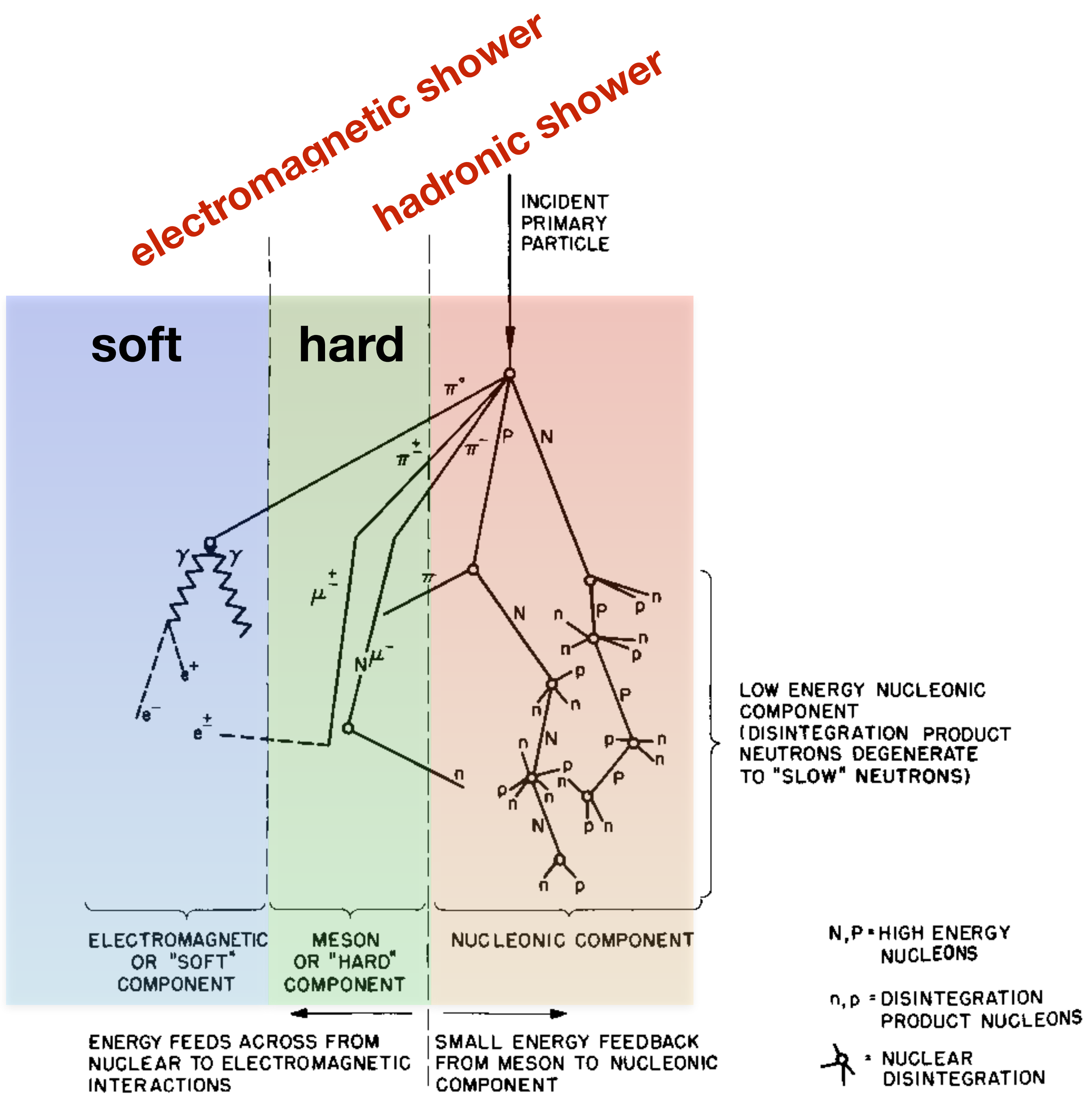
cosmic rays
bombarding Earth from space



extensive air showers

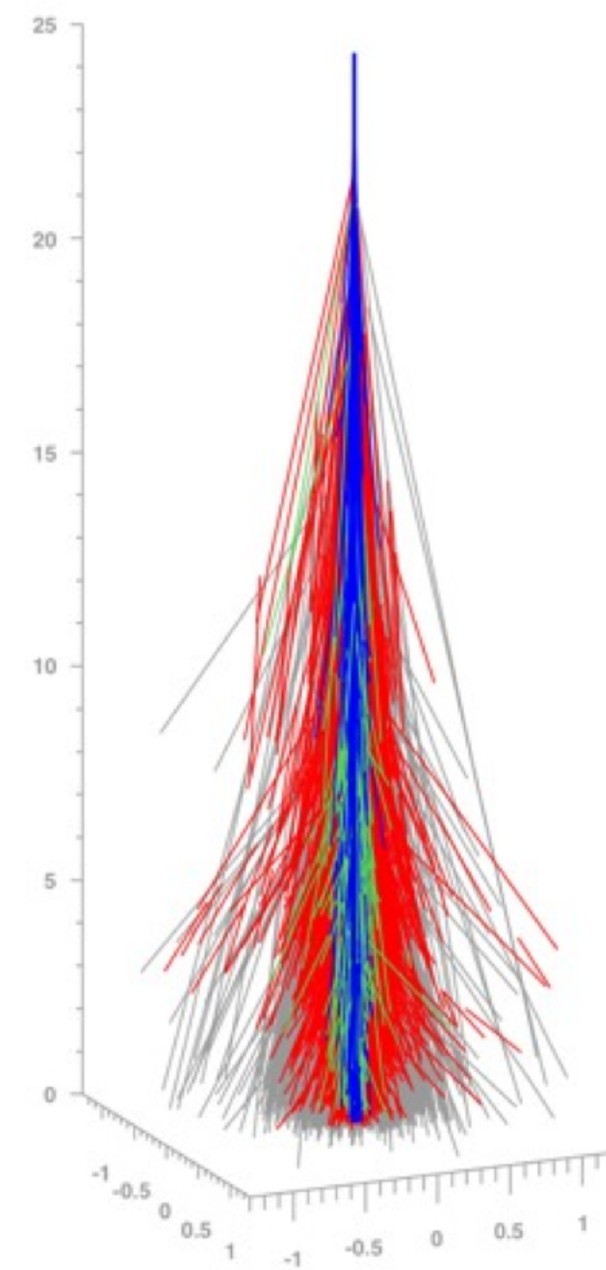
penetrating cosmic radiation

- **atmospheric air showers** of particles are **extended**



Schematic Diagram of Cosmic Ray Shower

proton-induced shower of 10^{19} eV



extensive air showers
EM and hadronic showers

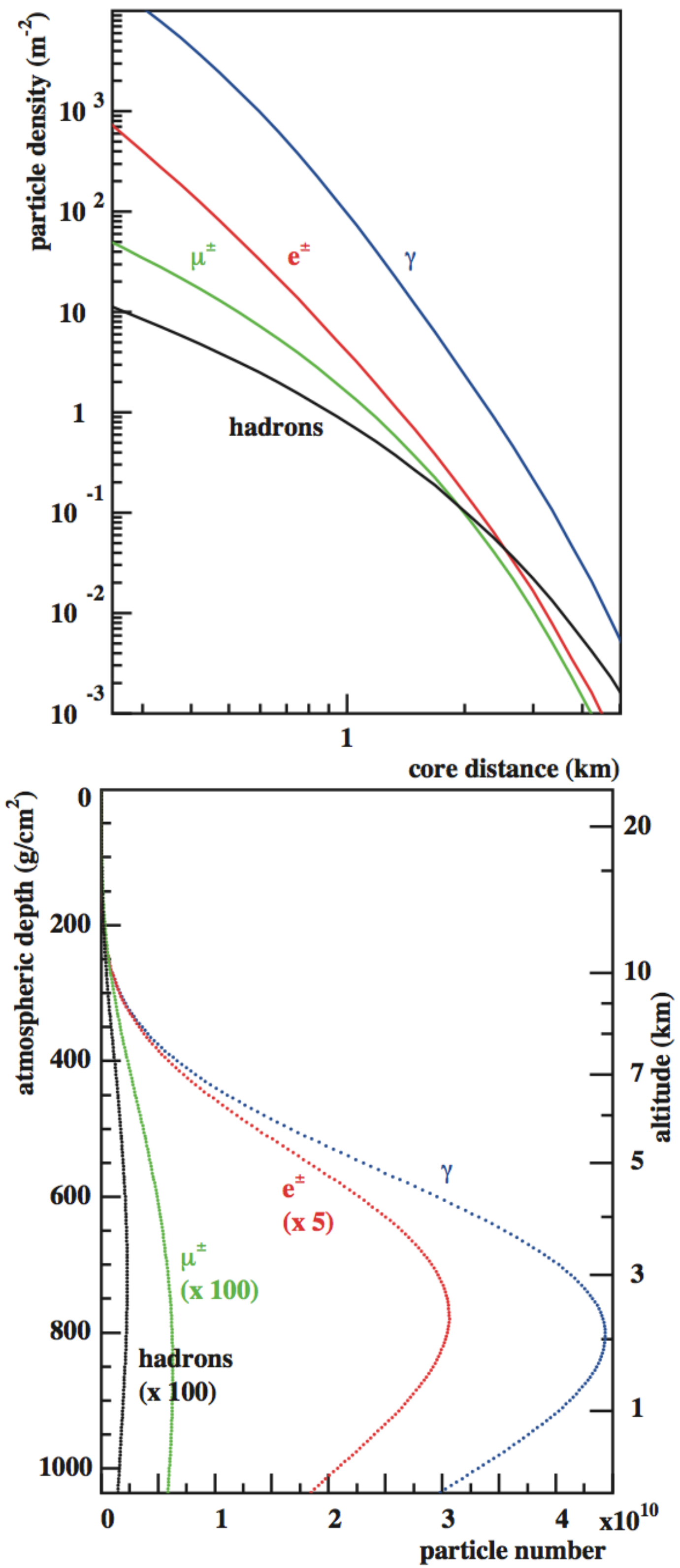
topologically complicated

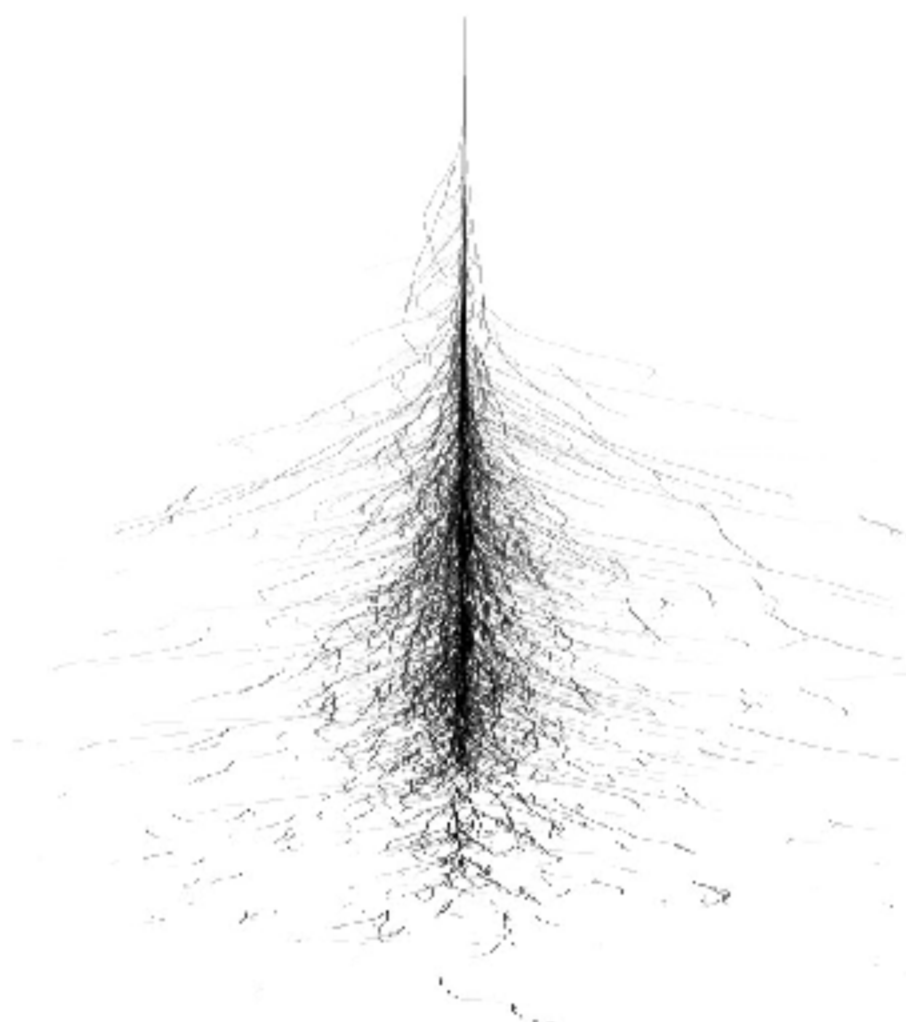
cannot be described from first principles

large uncertainties on interaction cross sections

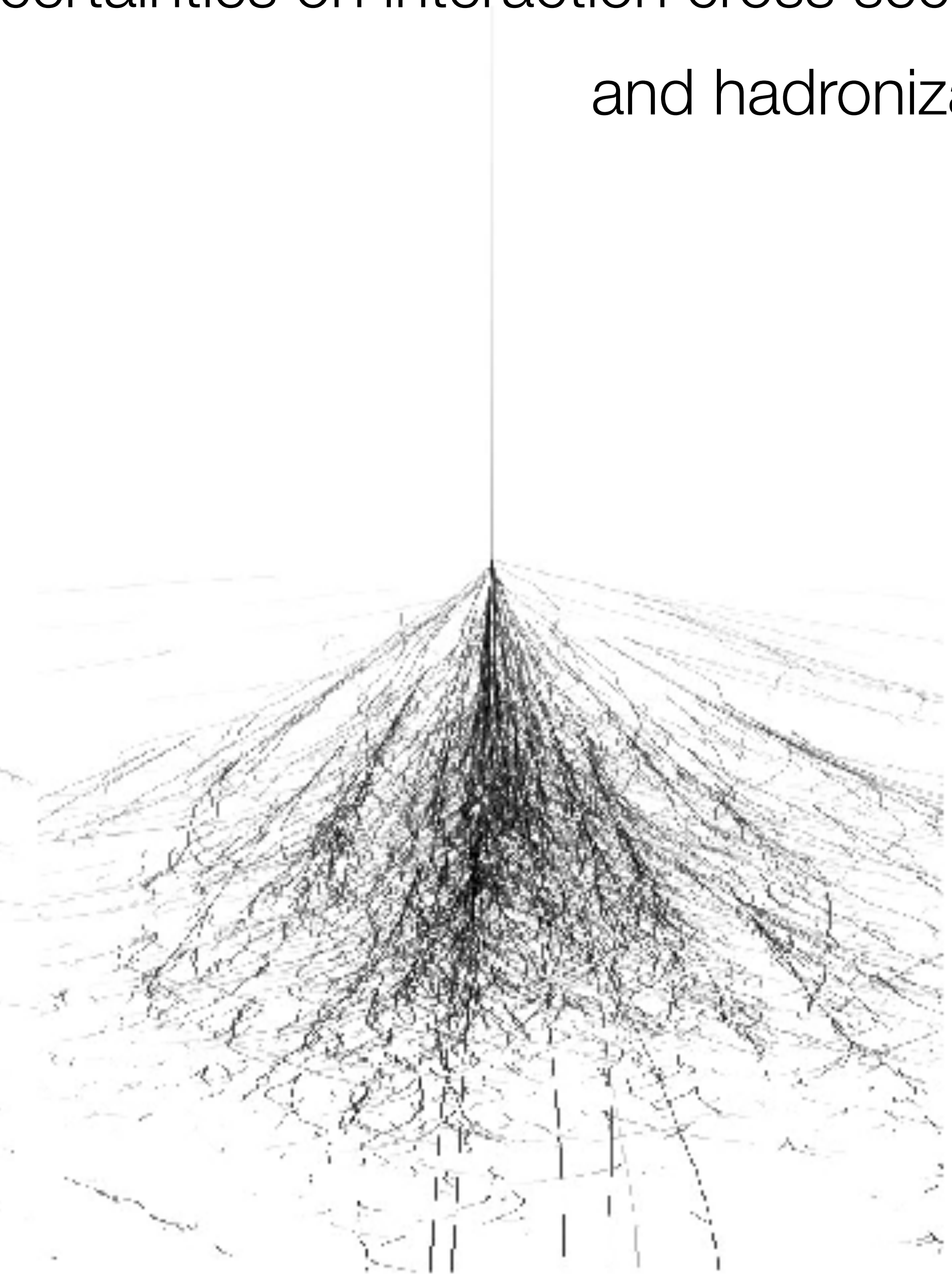
and hadronization

(RE, Pierog, Heck, ARNPS 2011)





Gamma shower



Hadronic shower

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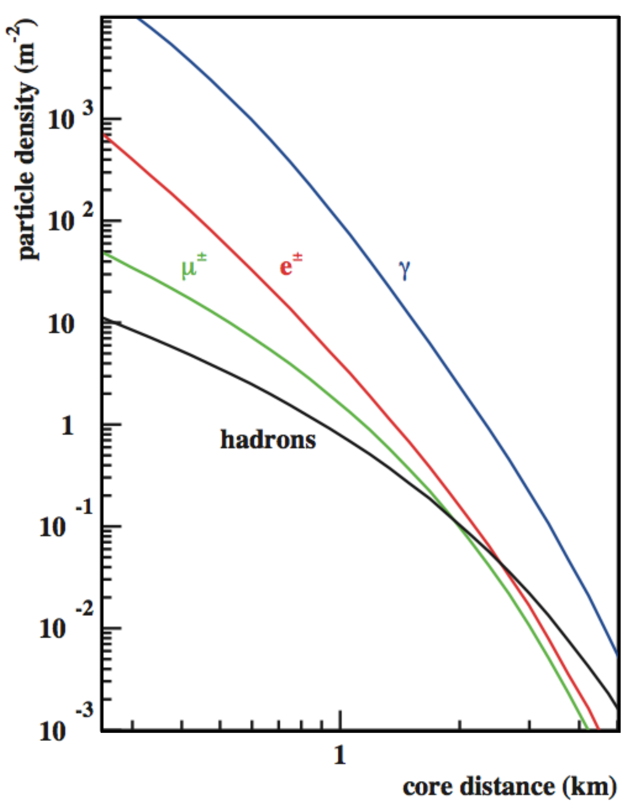
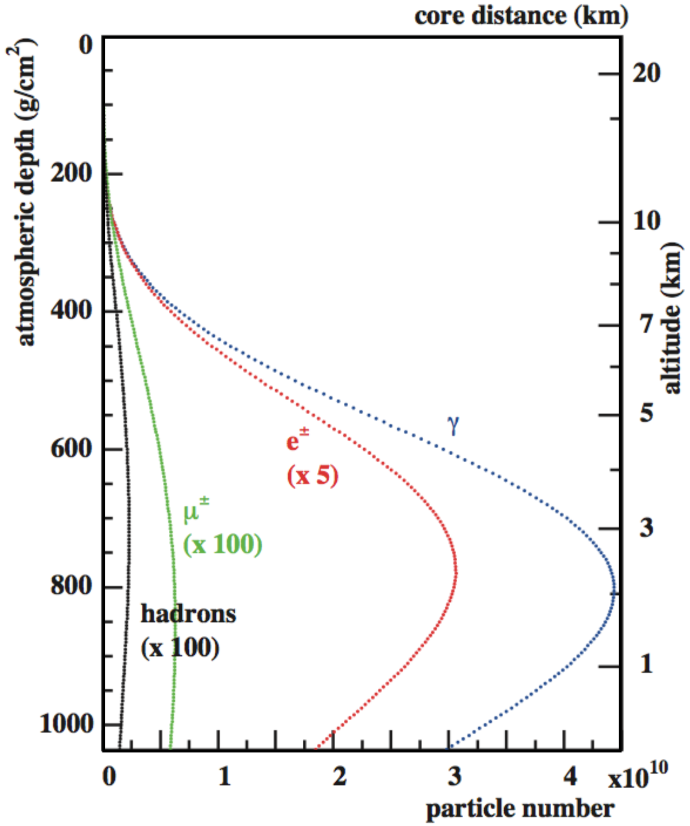
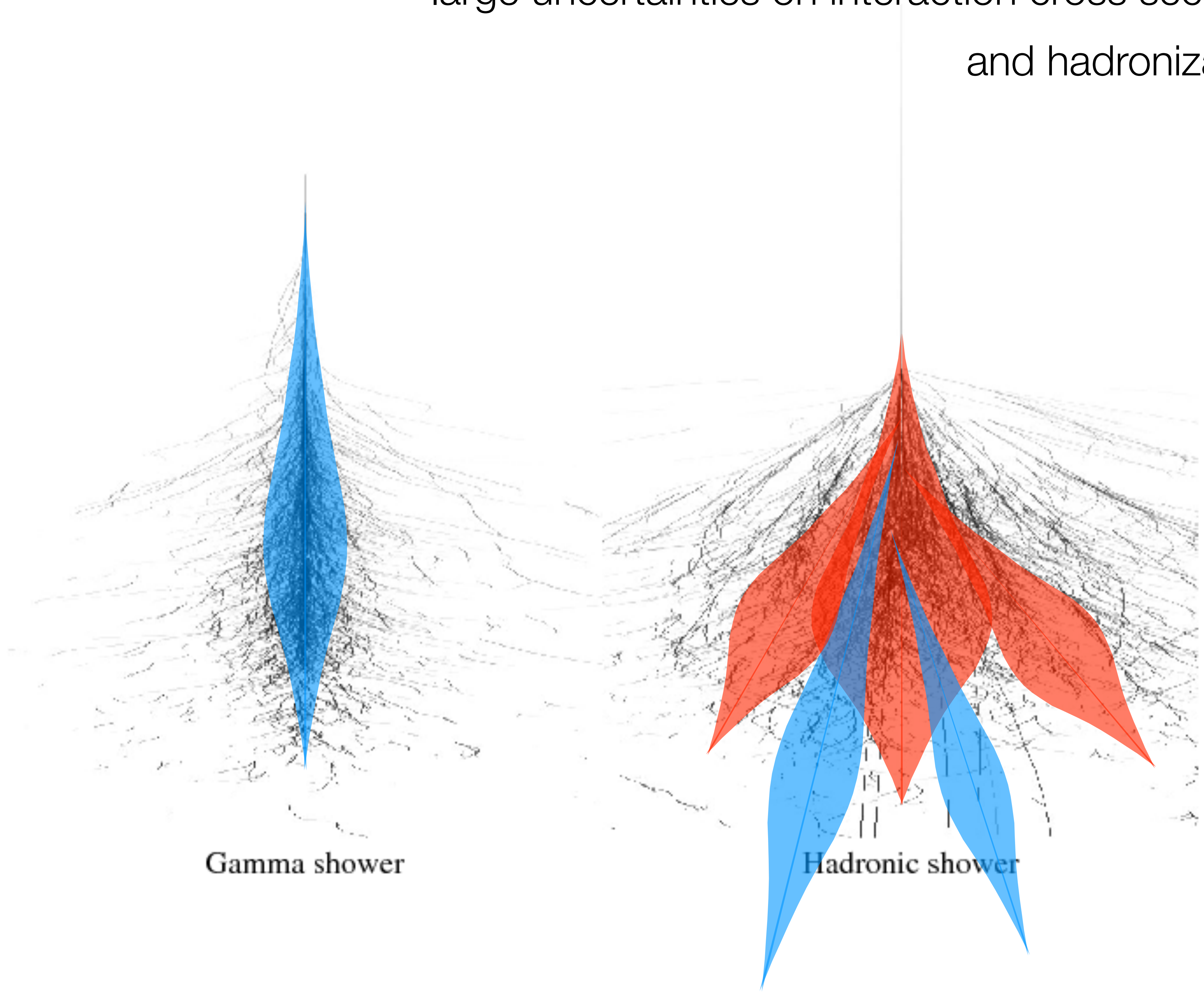
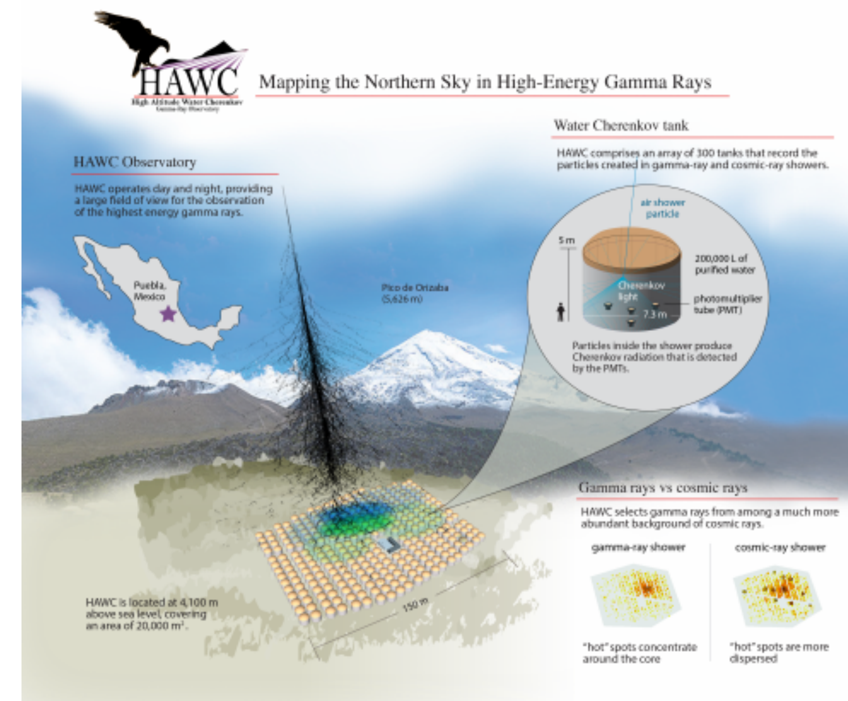






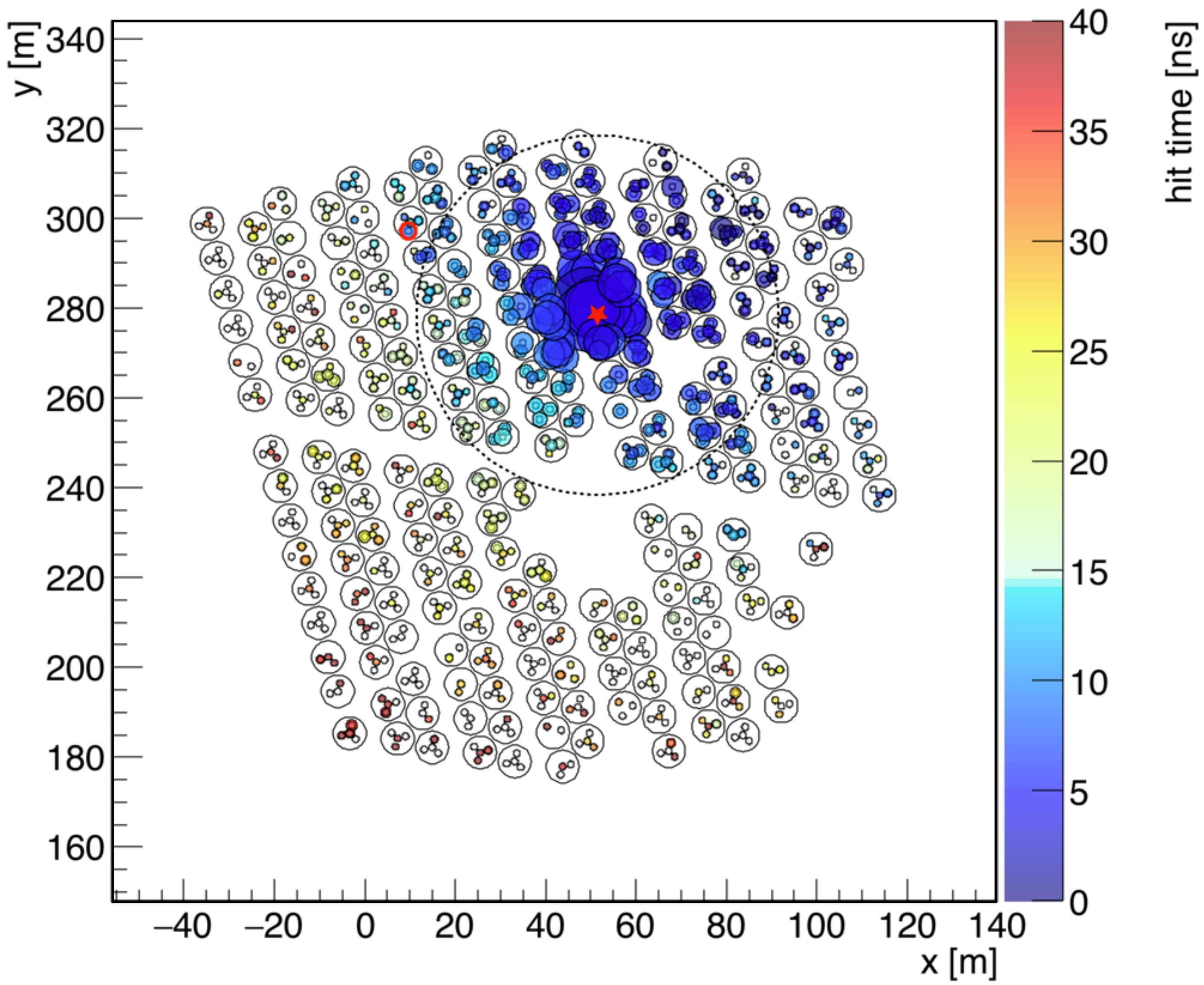
extensive air showers

experimental example: HAWC

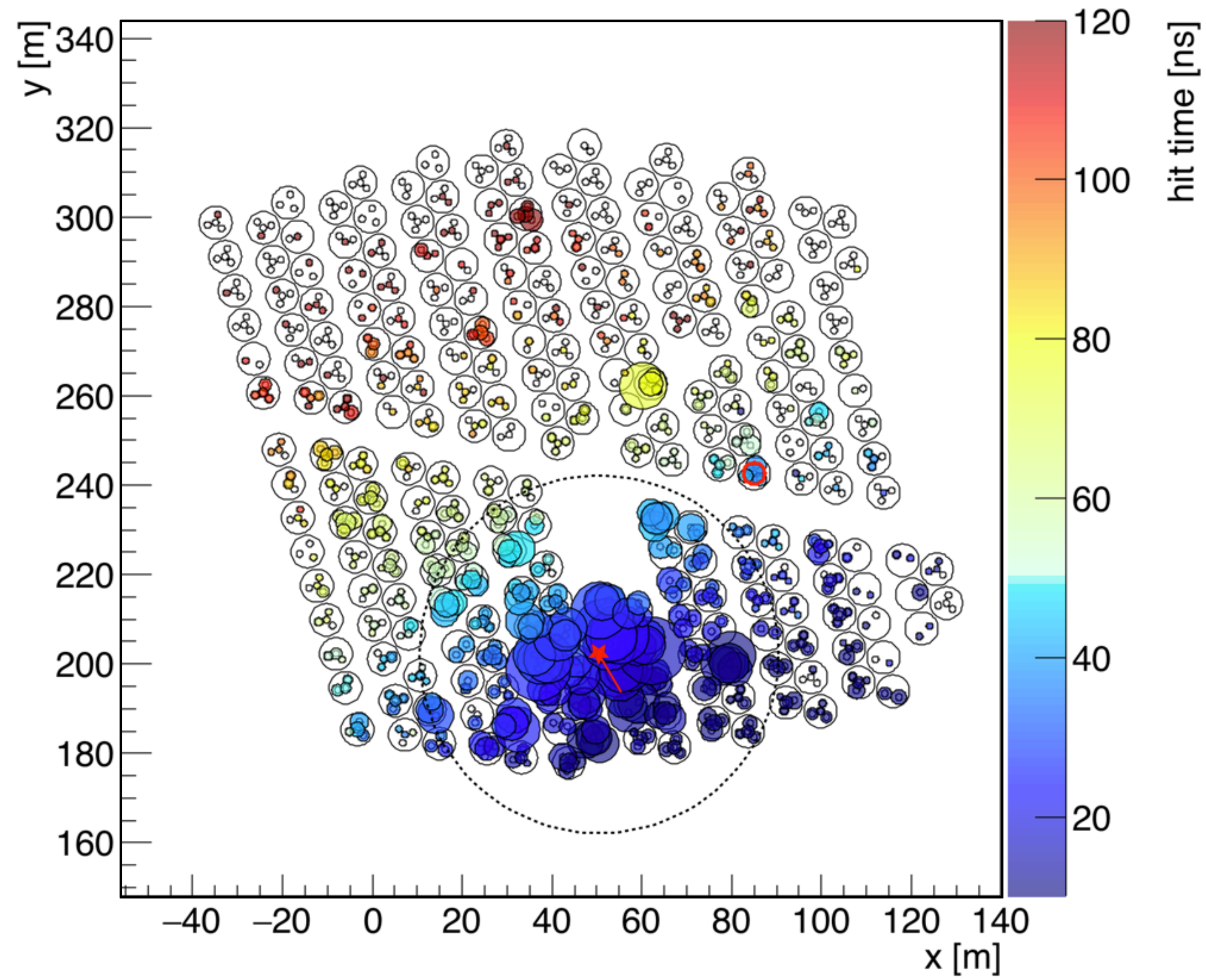


which event is induced by
a cosmic ray **particle** and which by
a **photon** ?

Run 2054, TS 584212, Ev# 226, CXPE40= 21.2, Cmptness= 28.3



Run 2118, TS 45004, Ev# 41, CXPE40= 55.7, Cmptness= 10.7



extensive air showers

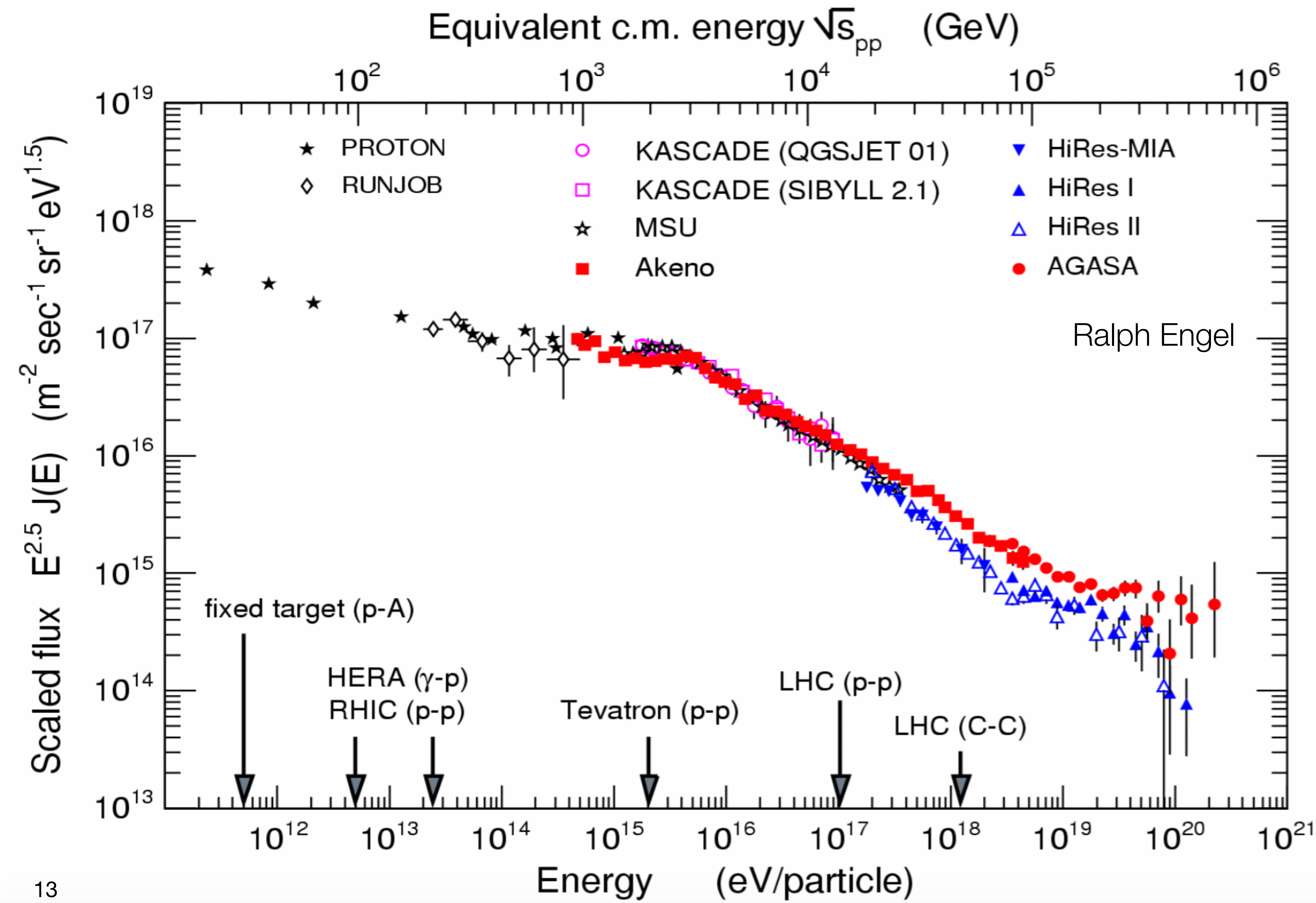
naturally and artificially generated energy

incident particles come

in different masses

with complicated spectra

largely uncertain at high energy



extensive air showers

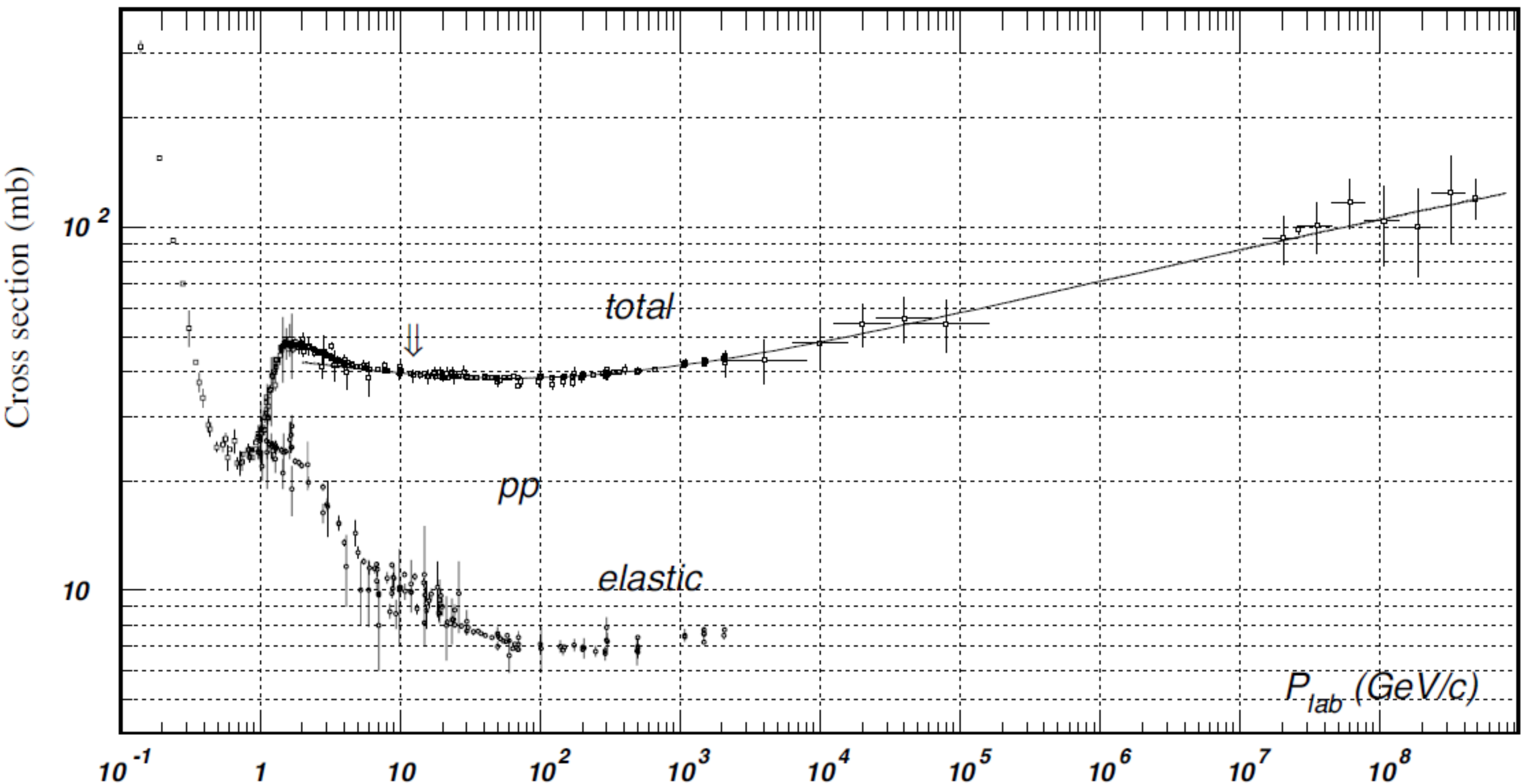
pp cross section

incident particles come

in different masses

with complicated spectra

largely uncertain at high energy



extensive air showers

EM and hadronic showers

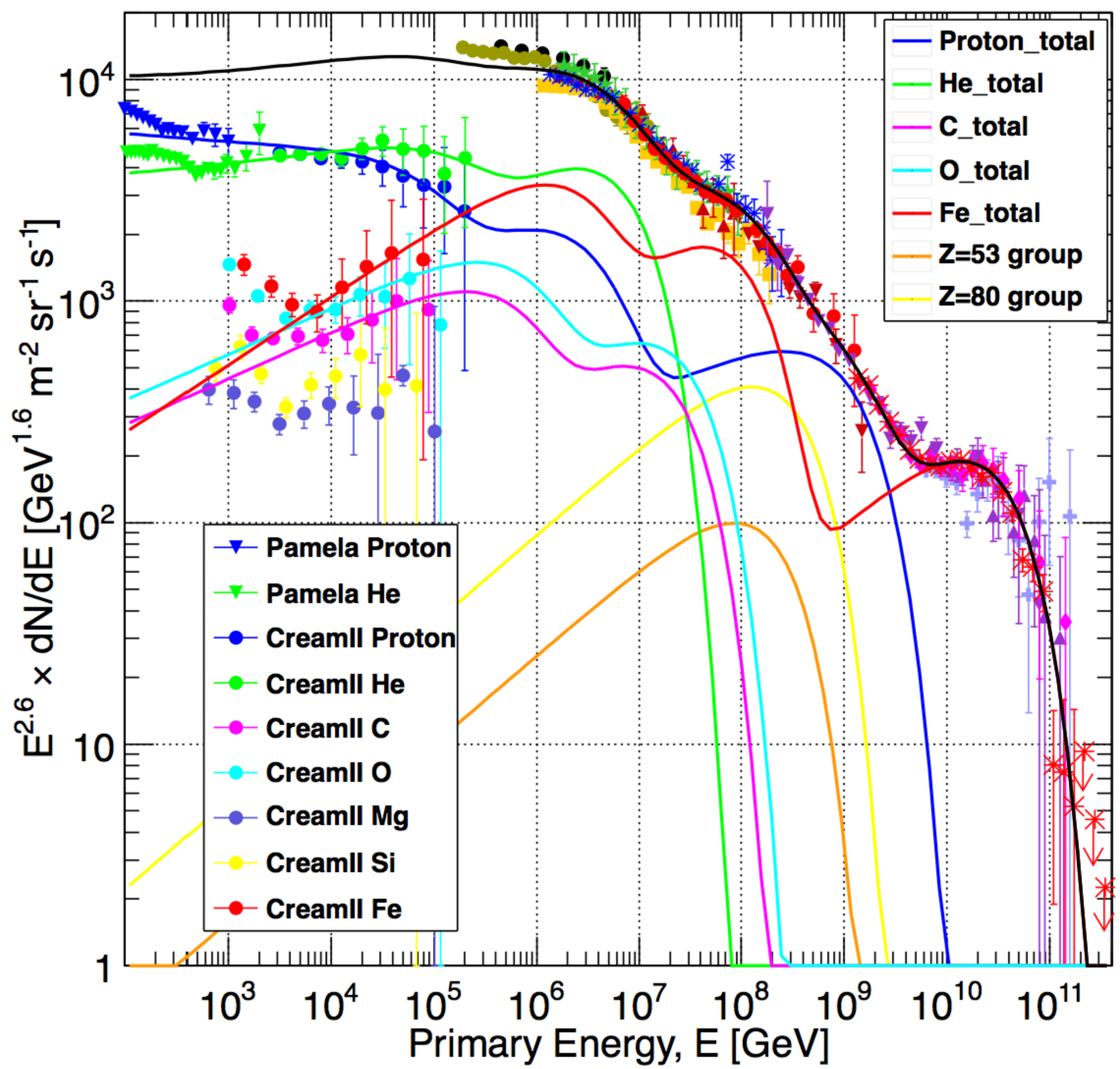
incident particles come

in different masses

with complicated spectra

largely uncertain at high energy

$$
\begin{aligned}
p + p \rightarrow \quad & p(n) + p(n) \\
& + \pi^+ + \pi^- + \pi^0 \\
& + K^+ + K^- + K^0 + \bar{K}^0 + \ldots \\
& + p(n) + \bar{p}(\bar{n}) \\
& + \text{charm} + \text{heavy quarks} + \ldots \\
& + e^\pm + \mu^\pm + \nu + \ldots \\
& + \ldots
\end{aligned}
$$



extensive air showers

EM and hadronic showers

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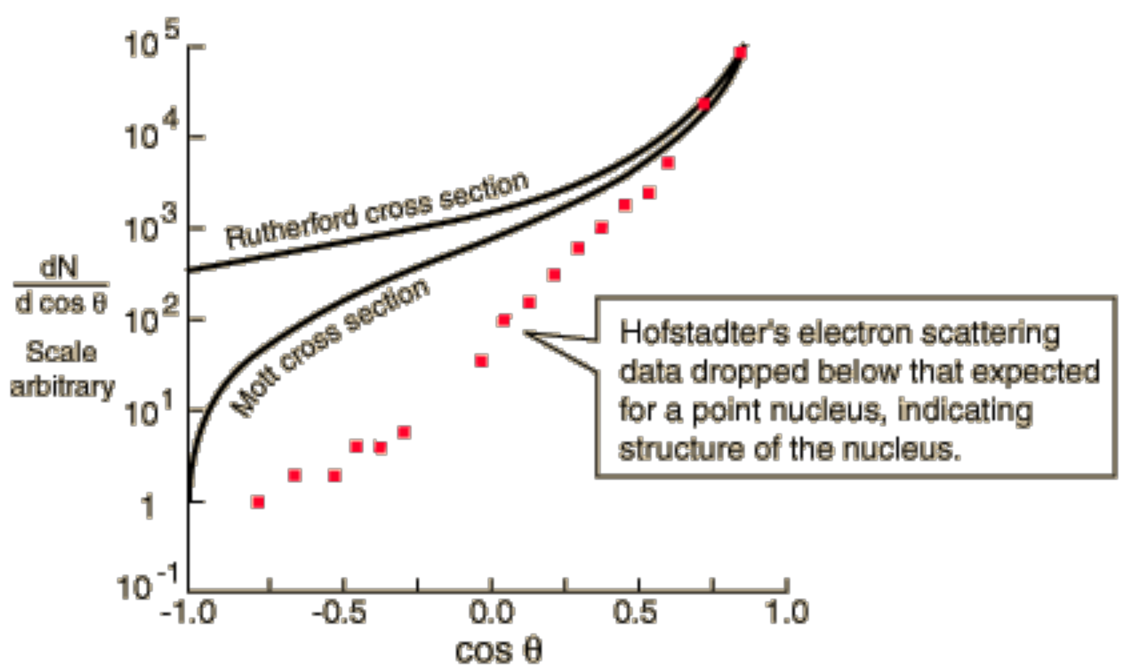
& +\text{charm} + \text{heavy quarks} + \ldots \\
& +e^\pm + \mu^\pm + \nu + \ldots \\
& +\ldots
\end{aligned}
$$

leading baryons: 40-50% of energy
pions: the most abundant particles
kaons: *strange* particles
baryon/anti-baryon pairs
heavy guard production
leptons
other mesons and baryons

Quantum Chromo-Dynamics

very quick overview … via 4 Nobel Prizes

- “for his *pioneering studies of electron scattering in atomic nuclei and for his consequent discoveries concerning the structure of nucleons*”



- atomic nuclei have a finite size

Robert Hofstadter

The Nobel Prize in Physics 1961
Robert Hofstadter, Rudolf Mössbauer

Robert Hofstadter - Biographical

Robert Hofstadter, Professor of Physics at Stanford University, was born in New York, N.Y., of parents Louis Hofstadter and Henrietta Koenigsberg, on February 5, 1915.

Hofstadter attended elementary and high schools in New York City, and was graduated in 1935 from the College of the City of New York with the B.S. degree, *magna cum laude*.

On graduation from college Hofstadter received the Kenyon Prize in Mathematics and Physics, and a little later the Coffin Fellowship, awarded by the General Electric Company. He went to graduate school at Princeton University where he studied physics from 1935 - 1938, and received both the M.A. and Ph.D. degrees in 1938 from that institution. His Ph.D. work was concerned with

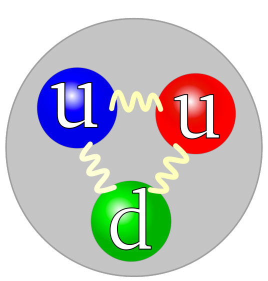
Quantum Chromo-Dynamics

very quick overview … via 4 Nobel Prizes

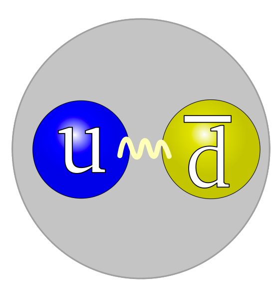
MURRAY GELL-MAN

- *“for his contributions and discoveries concerning the classification of elementary particles and their interactions”*

- introduced the **quark** - constituent of hadrons - independently from George Zweig



baryons



mesons

The Nobel Prize in Physics 1969
Murray Gell-Mann

The Nobel Prize in Physics 1969

Murray Gell-Mann
Prize share: 1/1

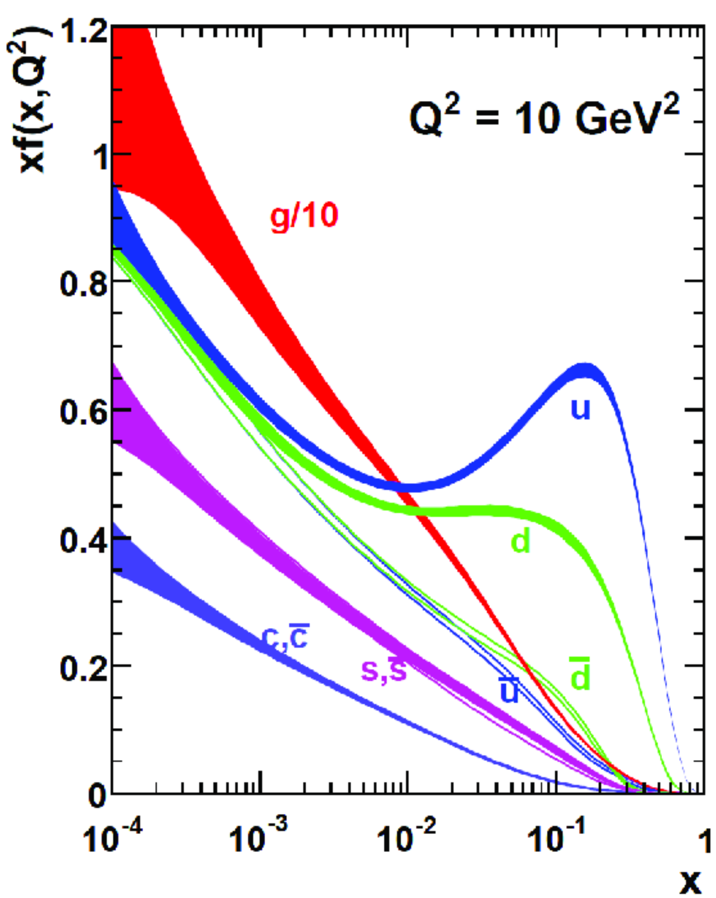
The Nobel Prize in Physics 1969 was awarded to Murray Gell-Mann *"for his contributions and discoveries concerning the classification of elementary particles and their interactions".*

Quantum Chromo-Dynamics

very quick overview … via 4 Nobel Prizes

Friedman, Kendall & Taylor

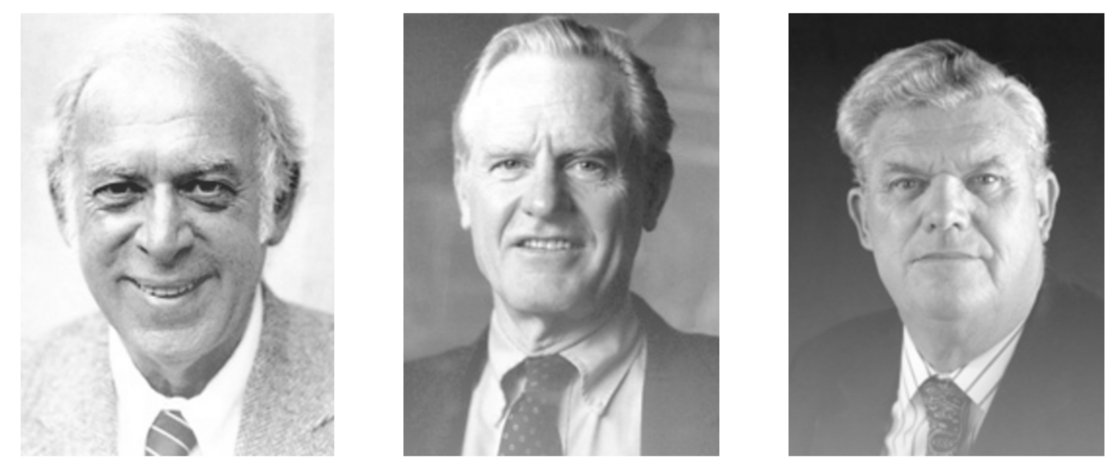
- *“for their pioneering investigations concerning deep inelastic scattering of electrons on protons and bound neutrons, which have been of essential importance for the development of the quark model in particle physics”*



parton distribution functions

The Nobel Prize in Physics 1990
Jerome I. Friedman, Henry W. Kendall, Richard E. Taylor

The Nobel Prize in Physics 1990



Jerome I. Friedman	Henry W. Kendall	Photo: T. Nakashima Richard E. Taylor
Prize share: 1/3	Prize share: 1/3	Prize share: 1/3

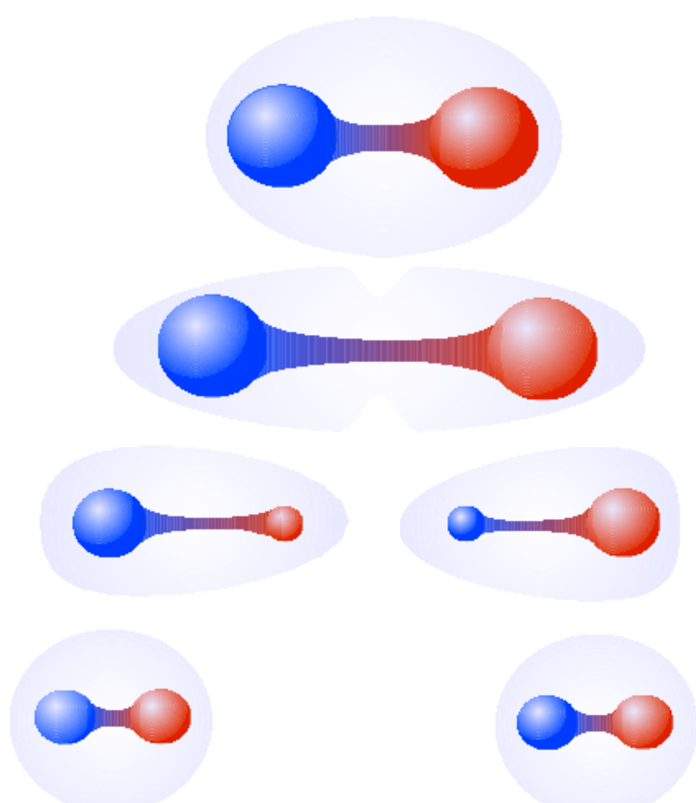
The Nobel Prize in Physics 1990 was awarded jointly to Jerome I. Friedman, Henry W. Kendall and Richard E. Taylor *"for their pioneering investigations concerning deep inelastic scattering of electrons on protons and bound neutrons, which have been of*

Quantum Chromo-Dynamics
very quick overview … via 4 Nobel Prizes

Gross, Politzer & Wilczek

- “*for the discovery of asymptotic freedom in the theory of the strong interaction*”

- color *charge* of quarks & confinement



The Nobel Prize in Physics 2004
David J. Gross, H. David Politzer, Frank Wilczek

The Nobel Prize in Physics 2004

David J. Gross
Prize share: 1/3

H. David Politzer
Prize share: 1/3

Frank Wilczek
Prize share: 1/3

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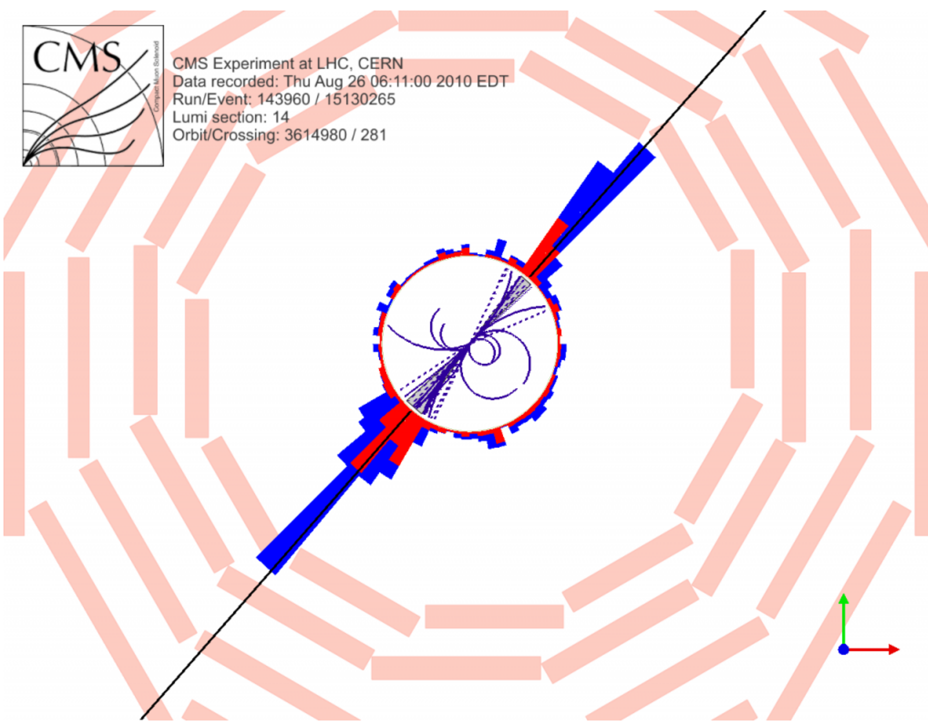
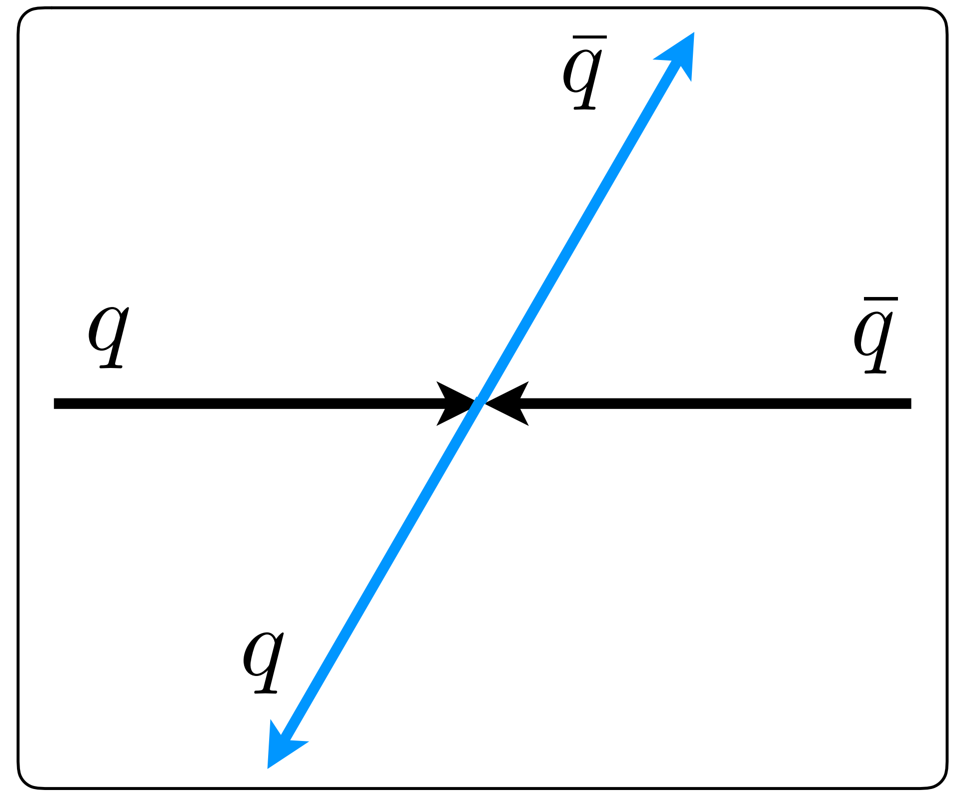
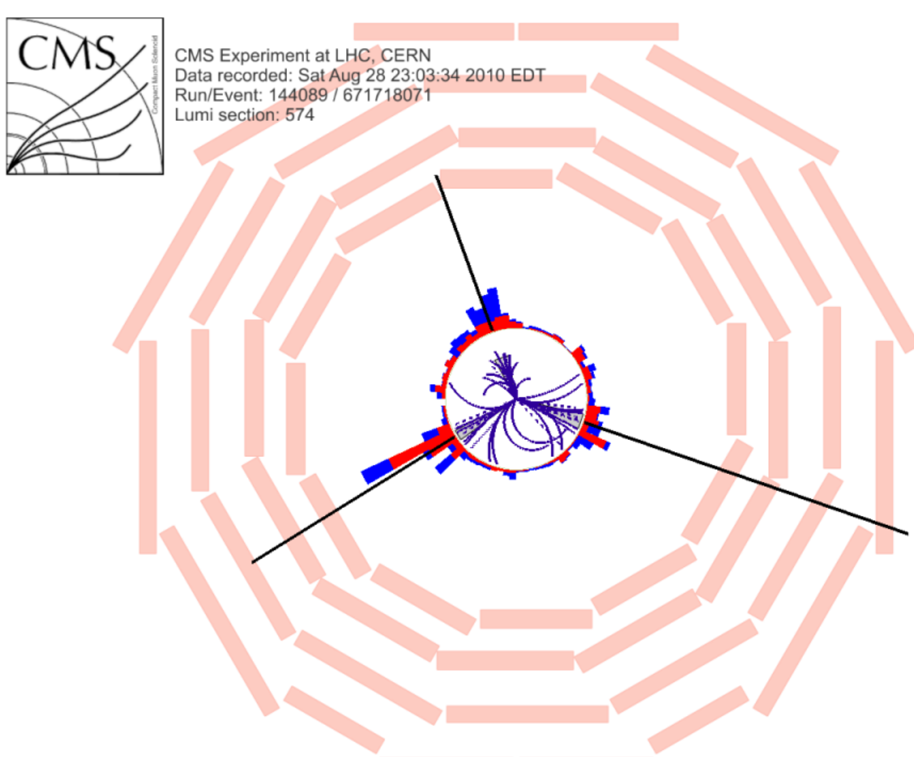
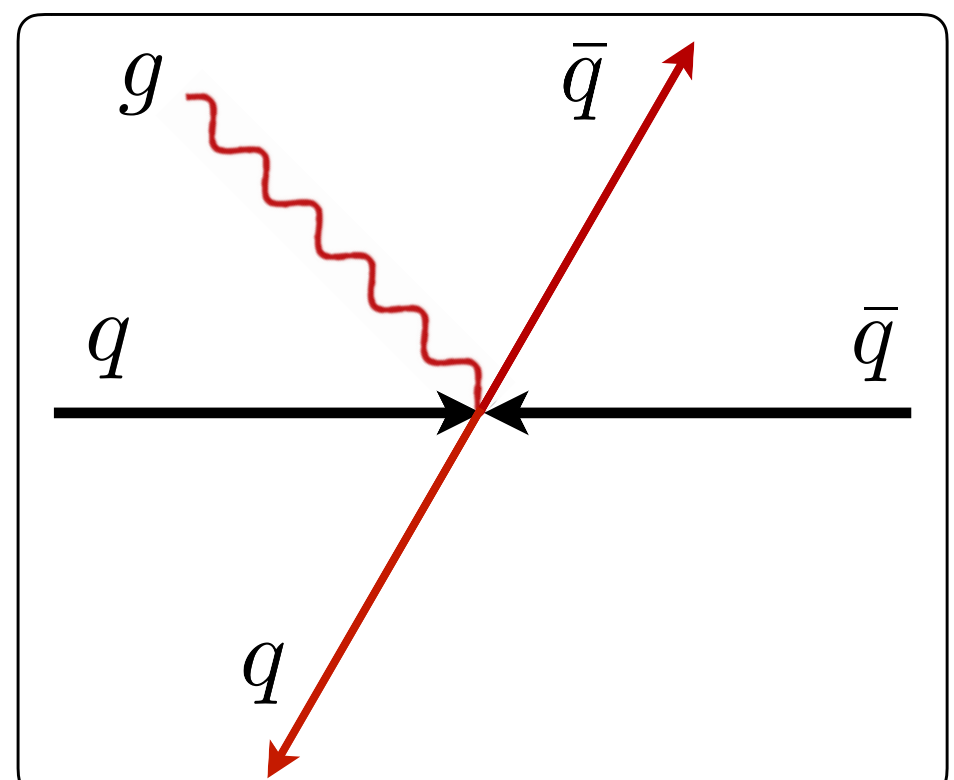
hadronization

from partons to particles



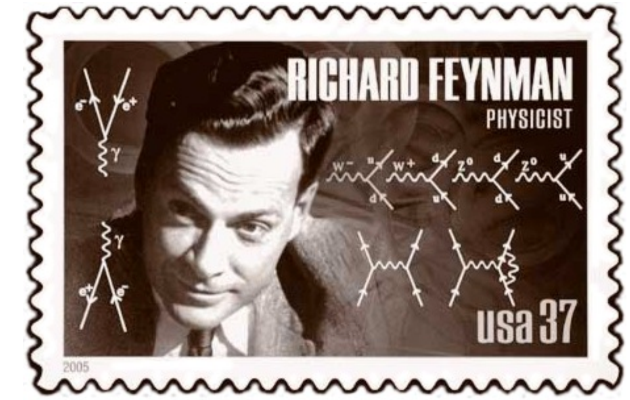


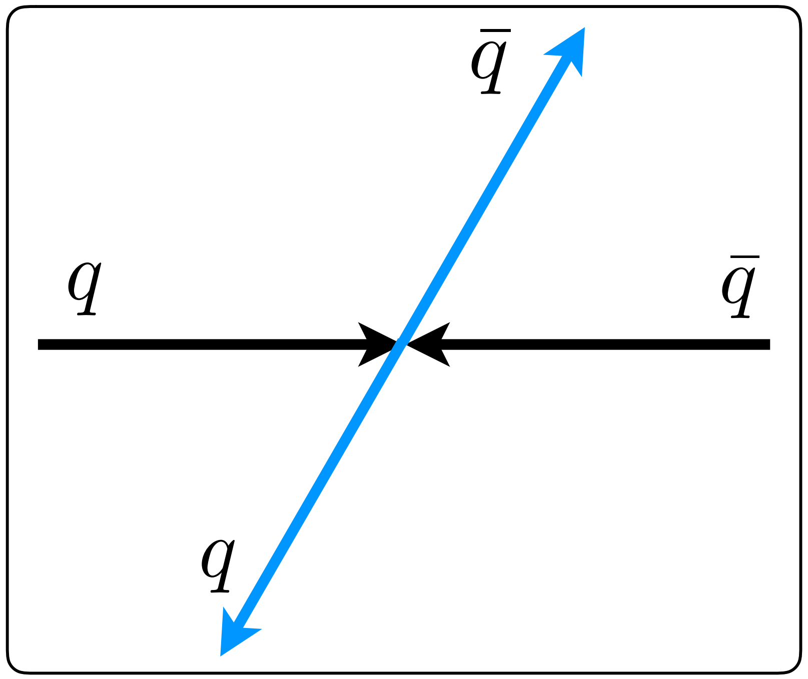


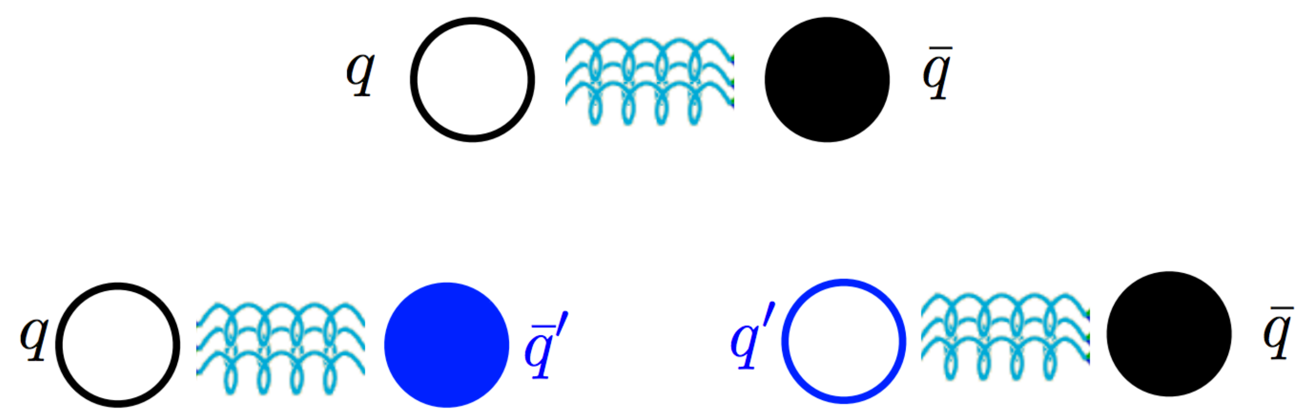


hadronization

from partons to particles



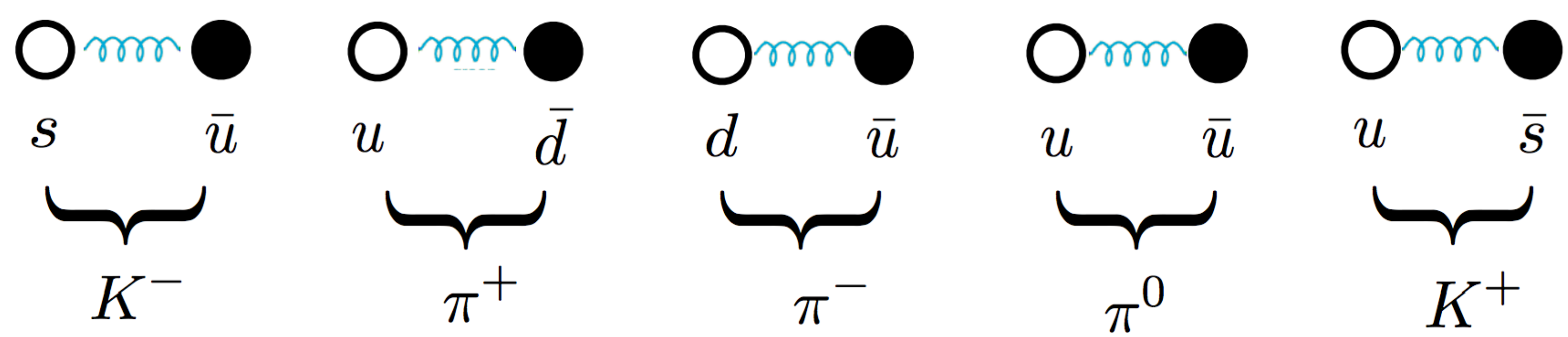




effects of

confinement and

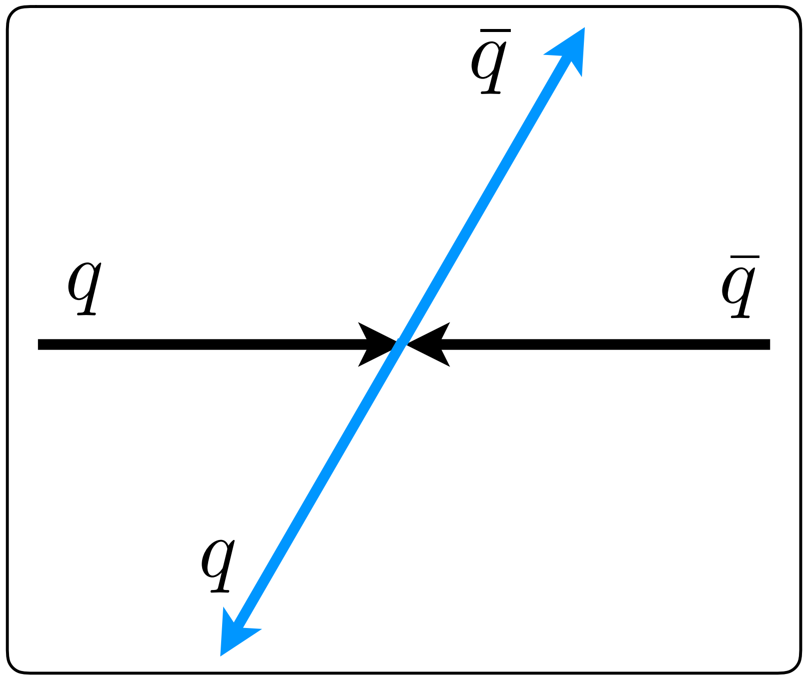
asymptotic freedom



mesons

hadronization

from partons to particles



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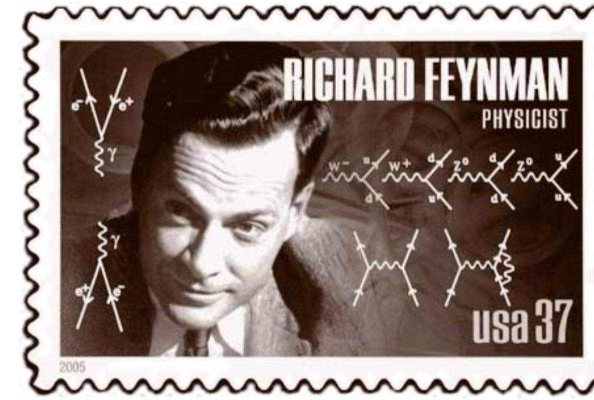
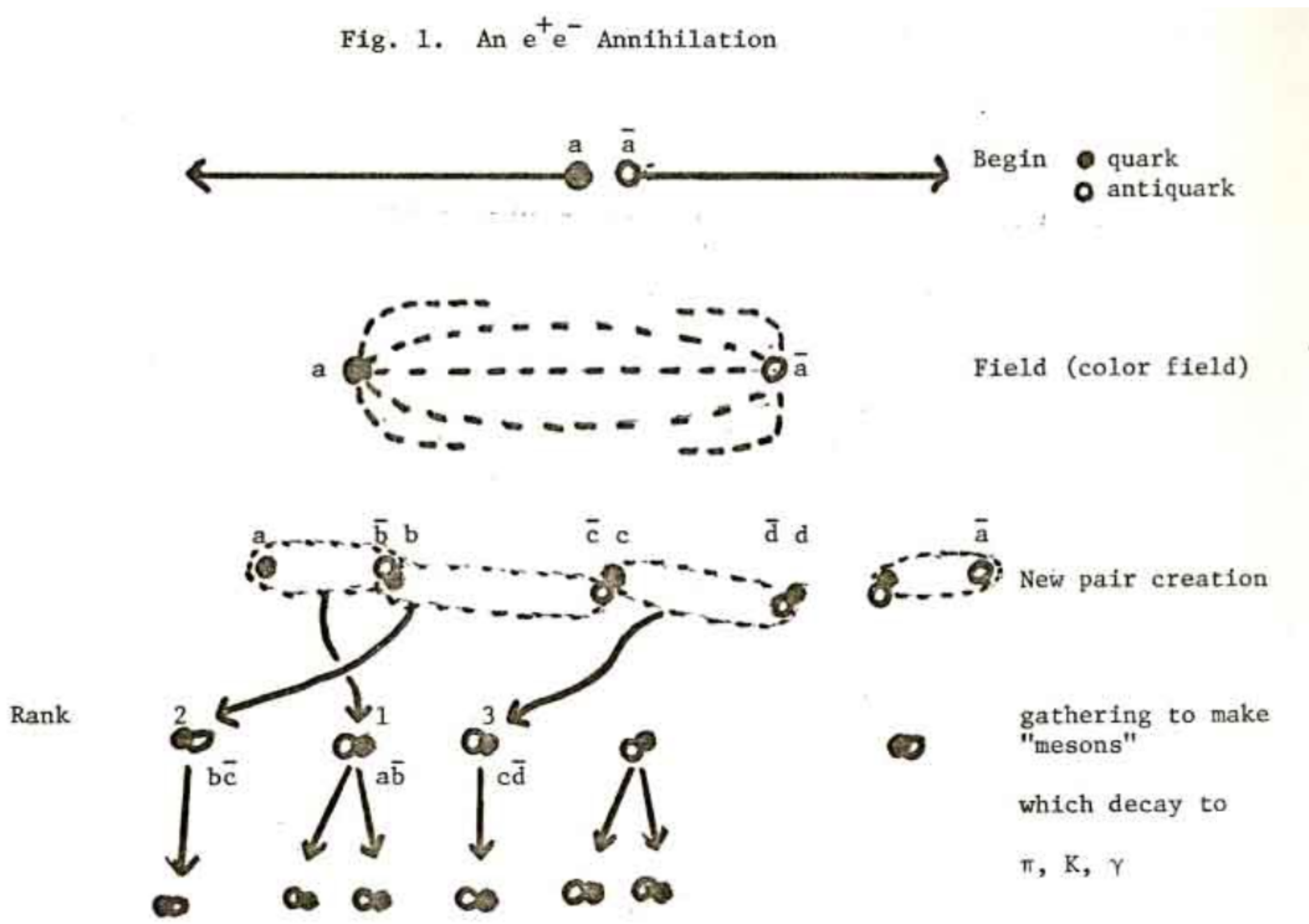


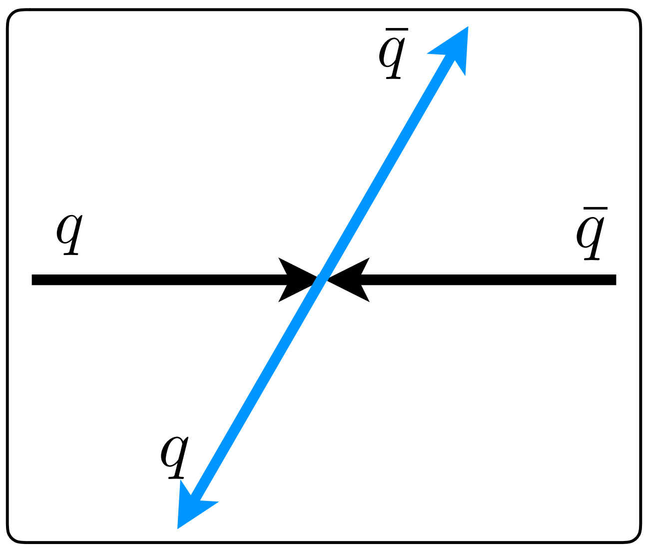


mesons

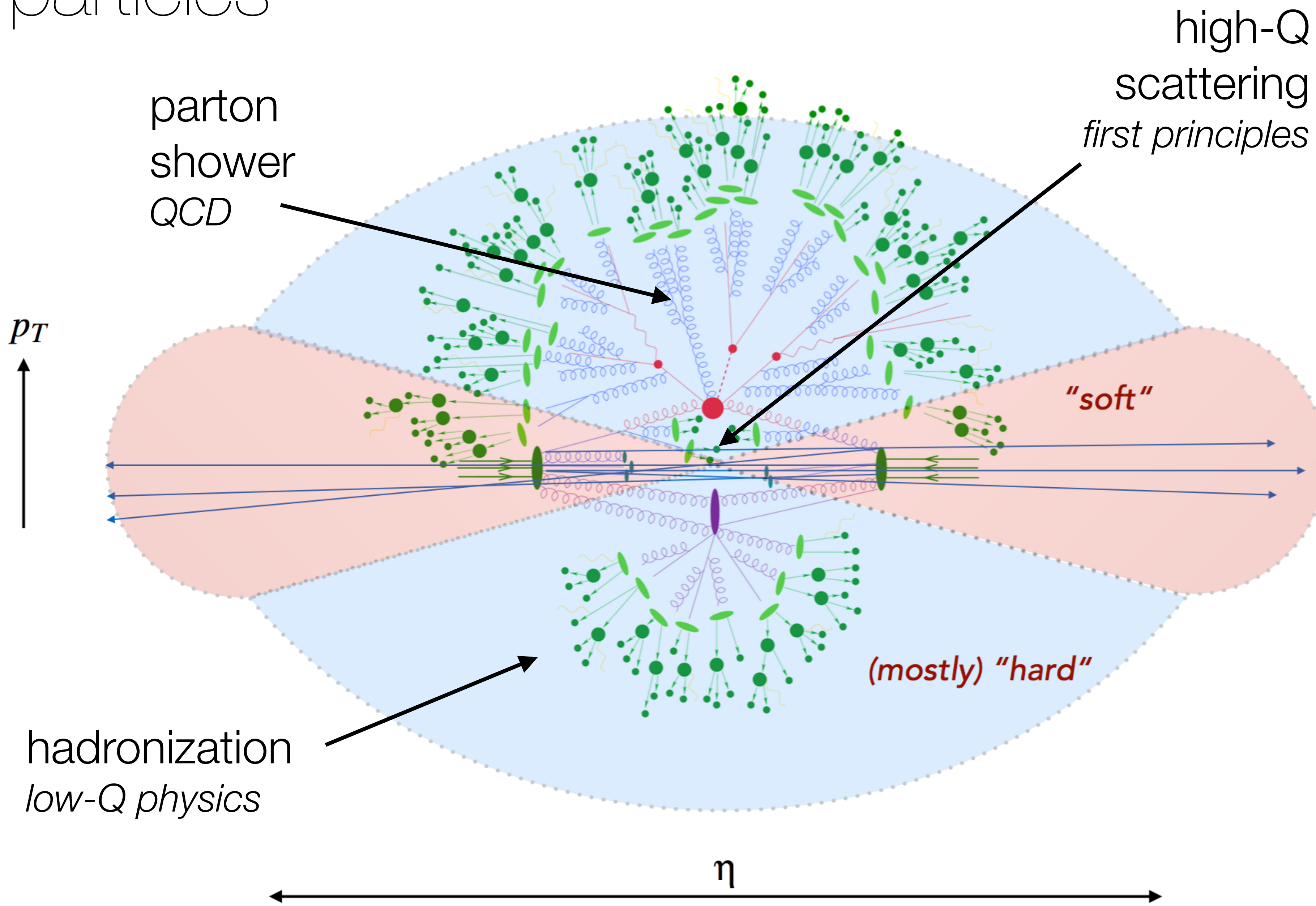
Richard Feynman

hadronization

from partons to particles



high-Q
scattering



hadronic interaction cross section
multiplicity of secondary particles
must be obtained from collider experiments

Lorentz covariance
rapidity & pseudo-rapidity

- Lorentz transformations are a hyperbolic rotation of space-time

rapidity $$\phi = \tanh^{-1}\left(\frac{|\vec{p}|}{E}\right)$$ $$\phi = \frac{1}{2}\ln\left(\frac{E+|\vec{p}|}{E-|\vec{p}|}\right)$$

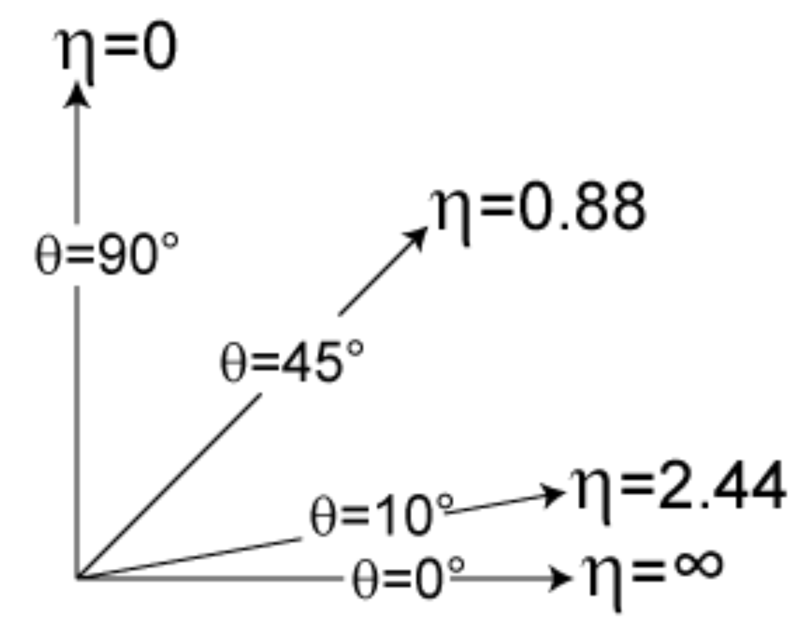
- in accelerator physics

$$y = \frac{1}{2}\ln\left(\frac{E+p_{||}}{E-p_{||}}\right)$$

- at ultra-relativistic limit (m ~ 0)

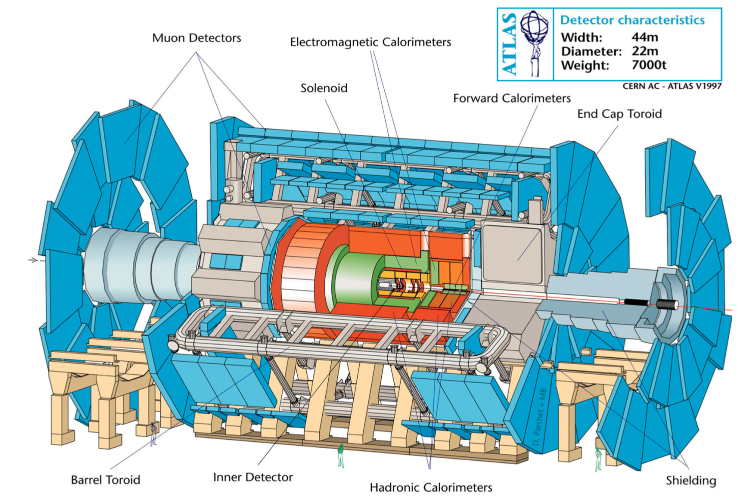
pseudo-rapidity $$\eta = \frac{1}{2}\ln\left(\frac{|\vec{p}|+p_{||}}{|\vec{p}|-p_{||}}\right)$$

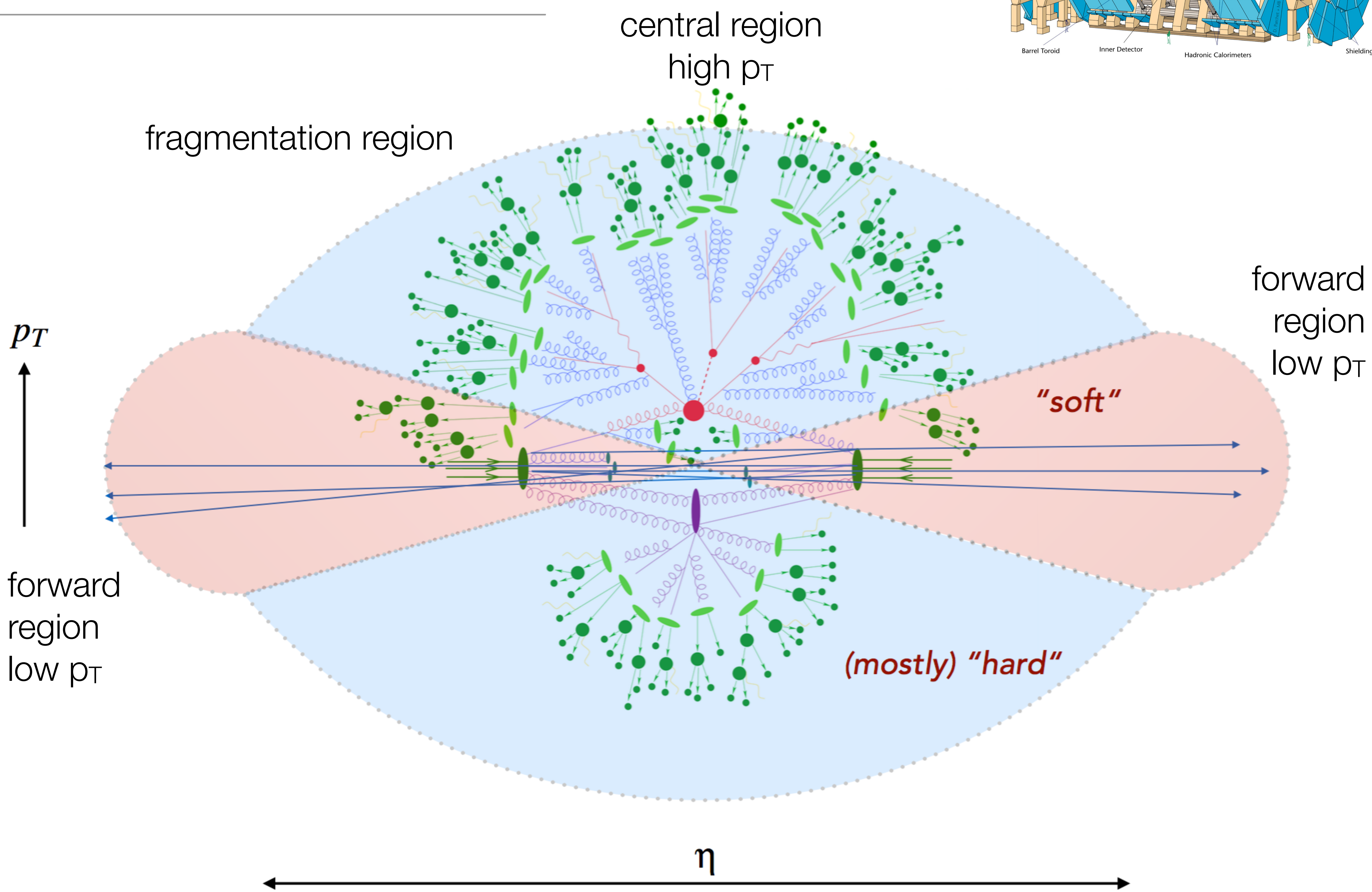
$$\eta = -\ln\left(\tan\frac{\theta}{2}\right)$$



hadronization

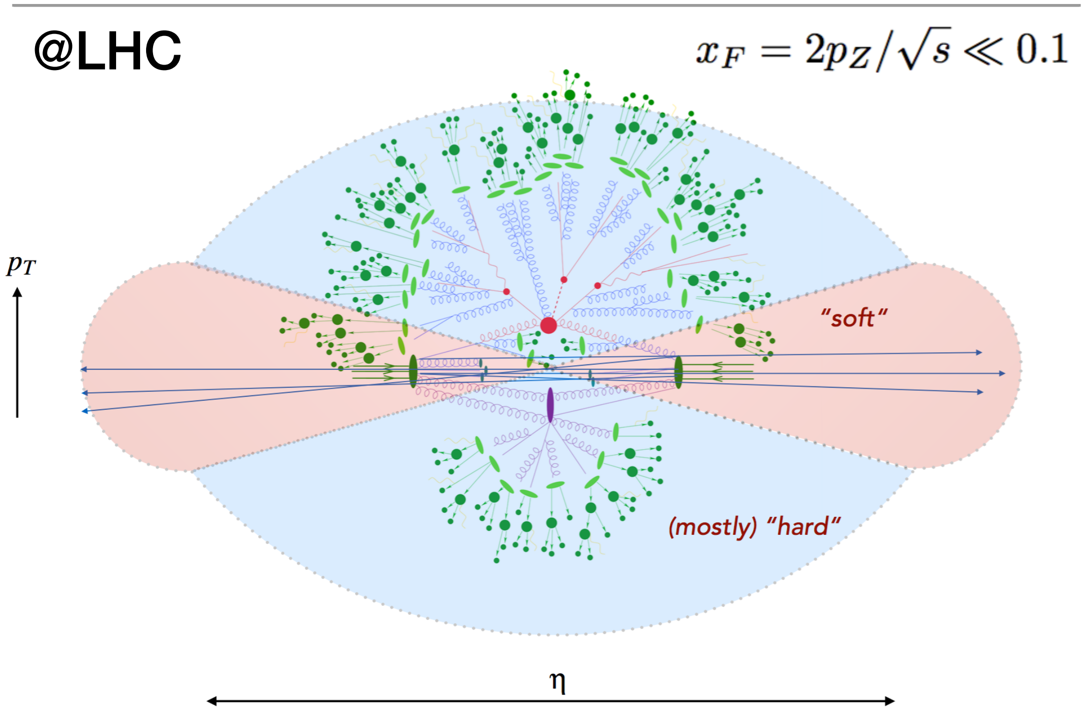
high energy particle interactions

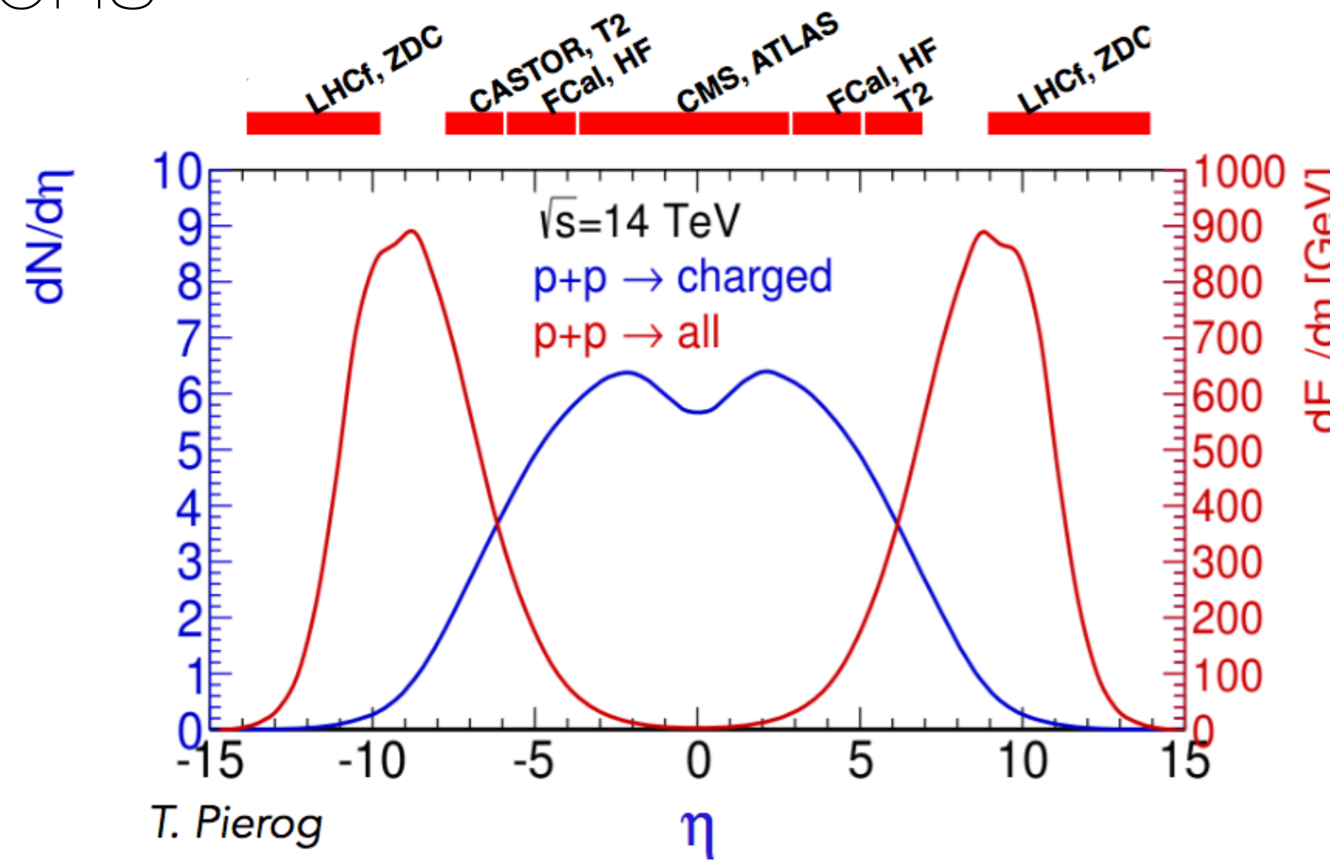




hadronization

high energy particle interactions





hard (central region)

- high particle number density
- low energy density
- heavy particles decay in this region
- observed by **collider experiments**

soft (forward region)

- low particle number density
- high energy density
- product of valence quark interactions
- crucial in **cosmic ray physics**

hadronization

high energy particle interactions

hard (central region)

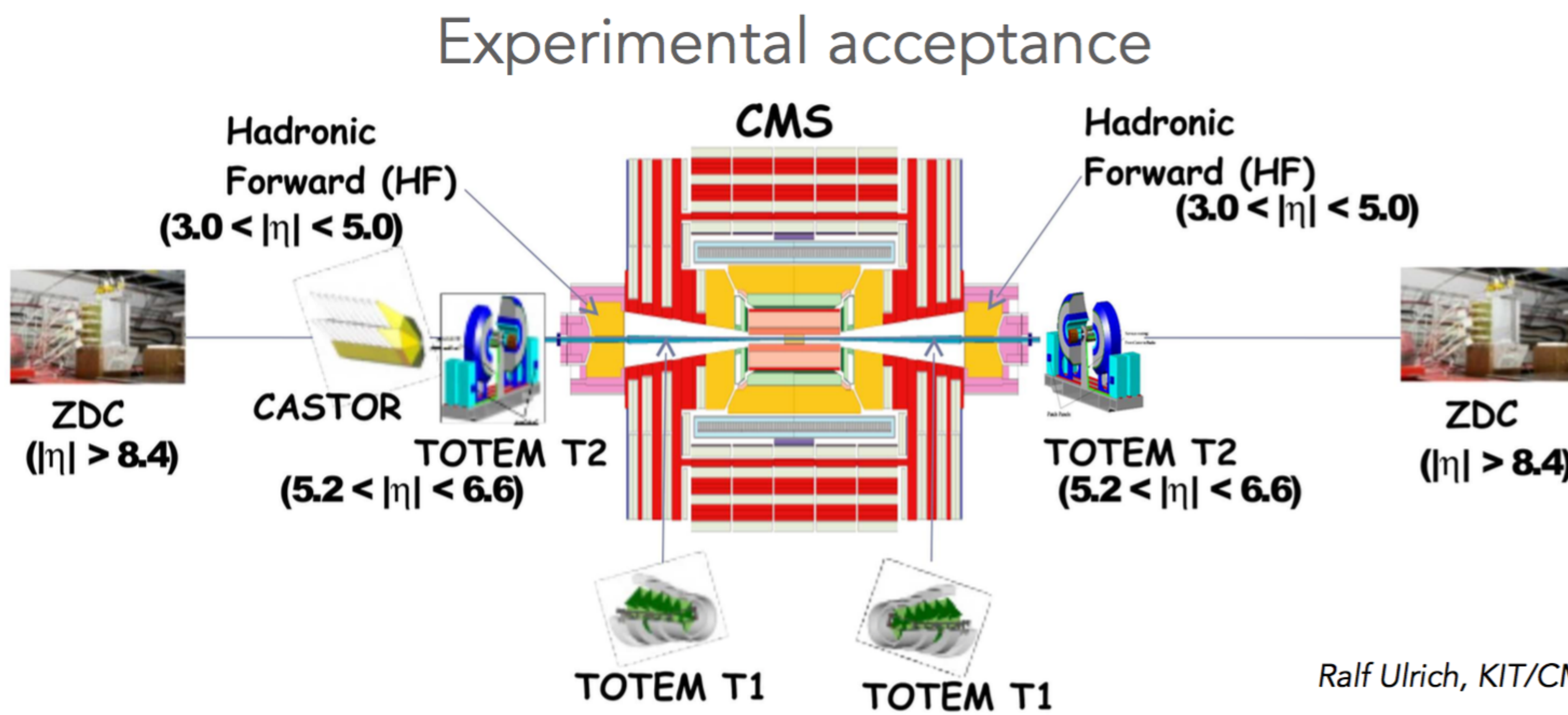
- high particle number density
- low energy density
- heavy particles decay in this region
- observed by **collider experiments**

soft (forward region)

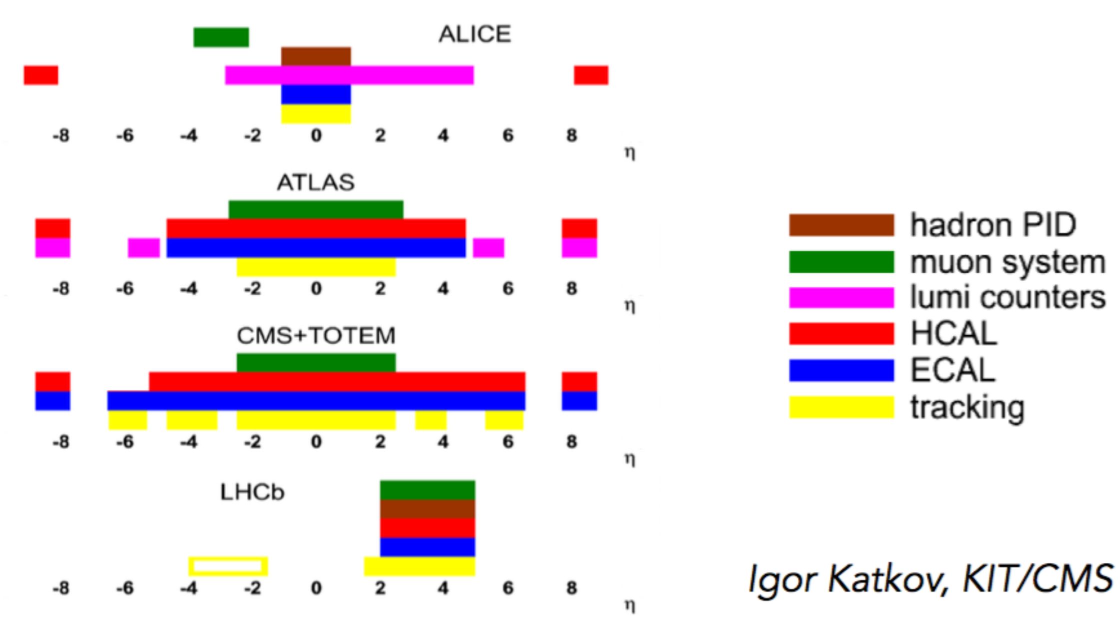
- low particle number density
- high energy density
- product of valence quark interactions
- crucial in **cosmic ray physics**

- QCD can be calculated only in **perturbative** limit (pQCD or hard QCD) when strong coupling constant is **small** (at high p_T)
- no calculable theory in diffractive **non-perturbative** (soft QCD) limit (at low p_T)
- Gribov-**Regge** theory (pomeron *color-singlet* exchange) successfully applied

particle detection
in colliders



Ralf Ulrich, KIT/CMS



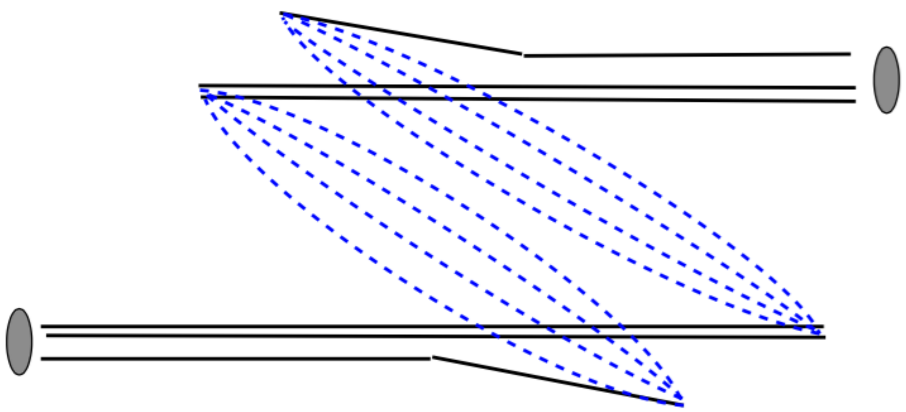
Igor Katkov, KIT/CMS

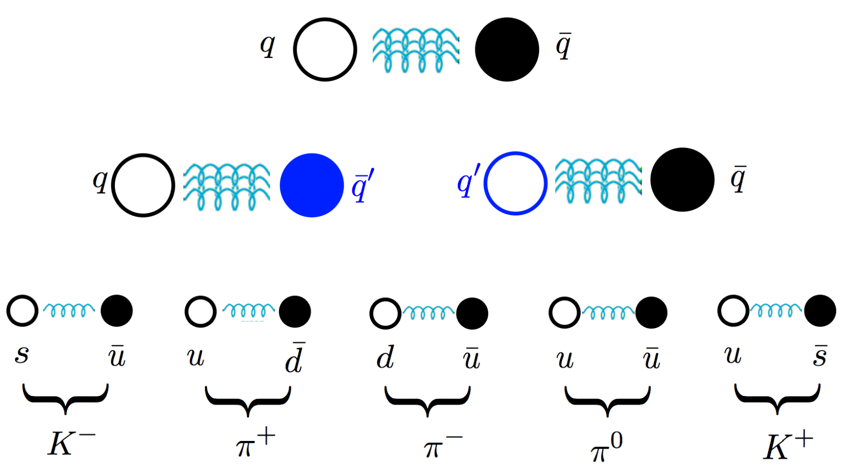
Pseudorapidity

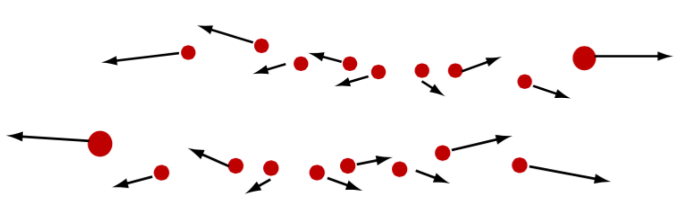
$$\eta = -\ln\left(\tan\frac{\theta}{2}\right)$$

hadronization

two string model





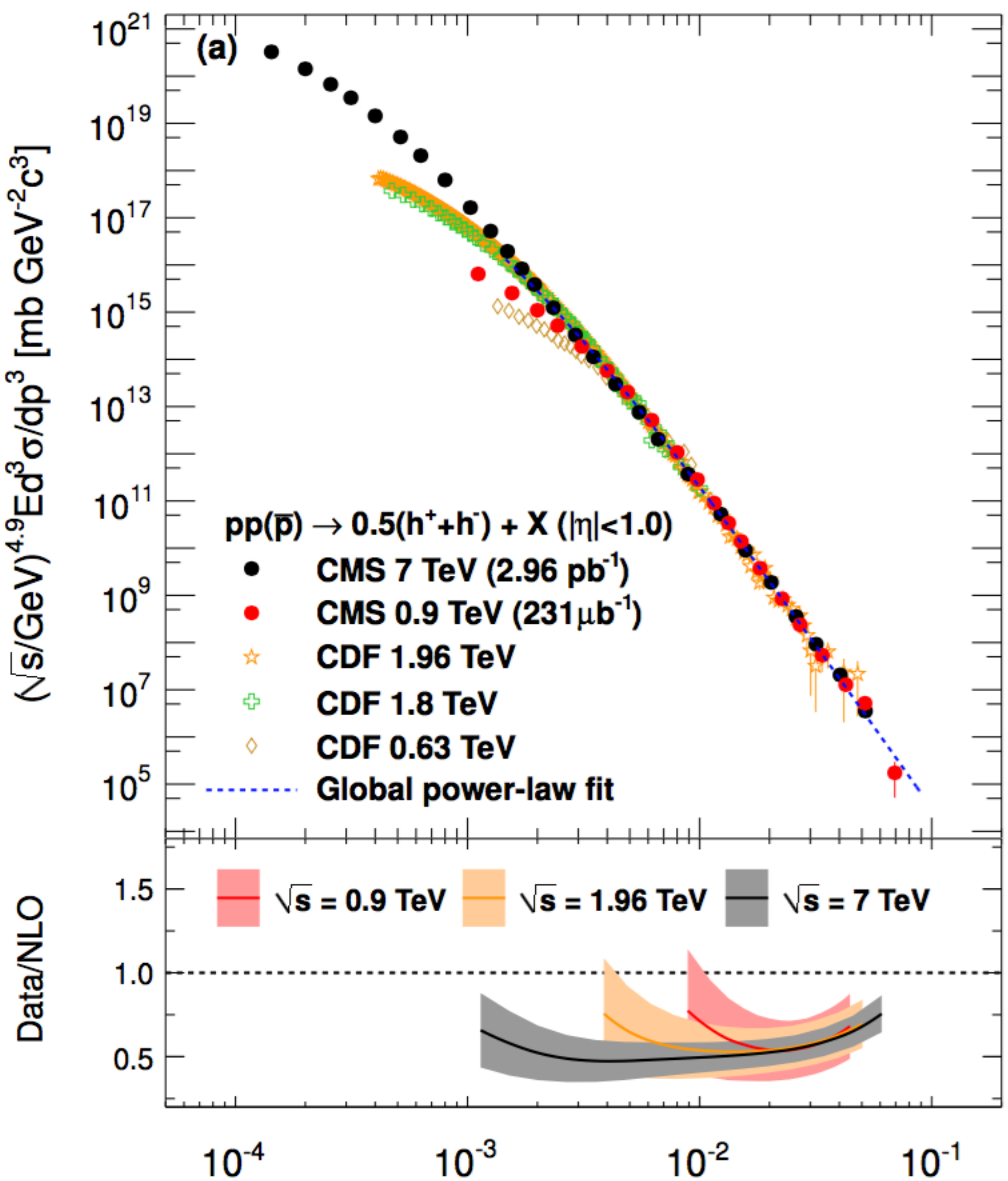


- the basic structure of a non diffractive pp interaction is made of **two strings** (colored partons). Flat rapidity dn/dy distributions.
- leading particle effects
- Feynman **scaling**: dn/dy independent of energy. (approximately valid in forward fragmentation region)
- distributions independent of energy

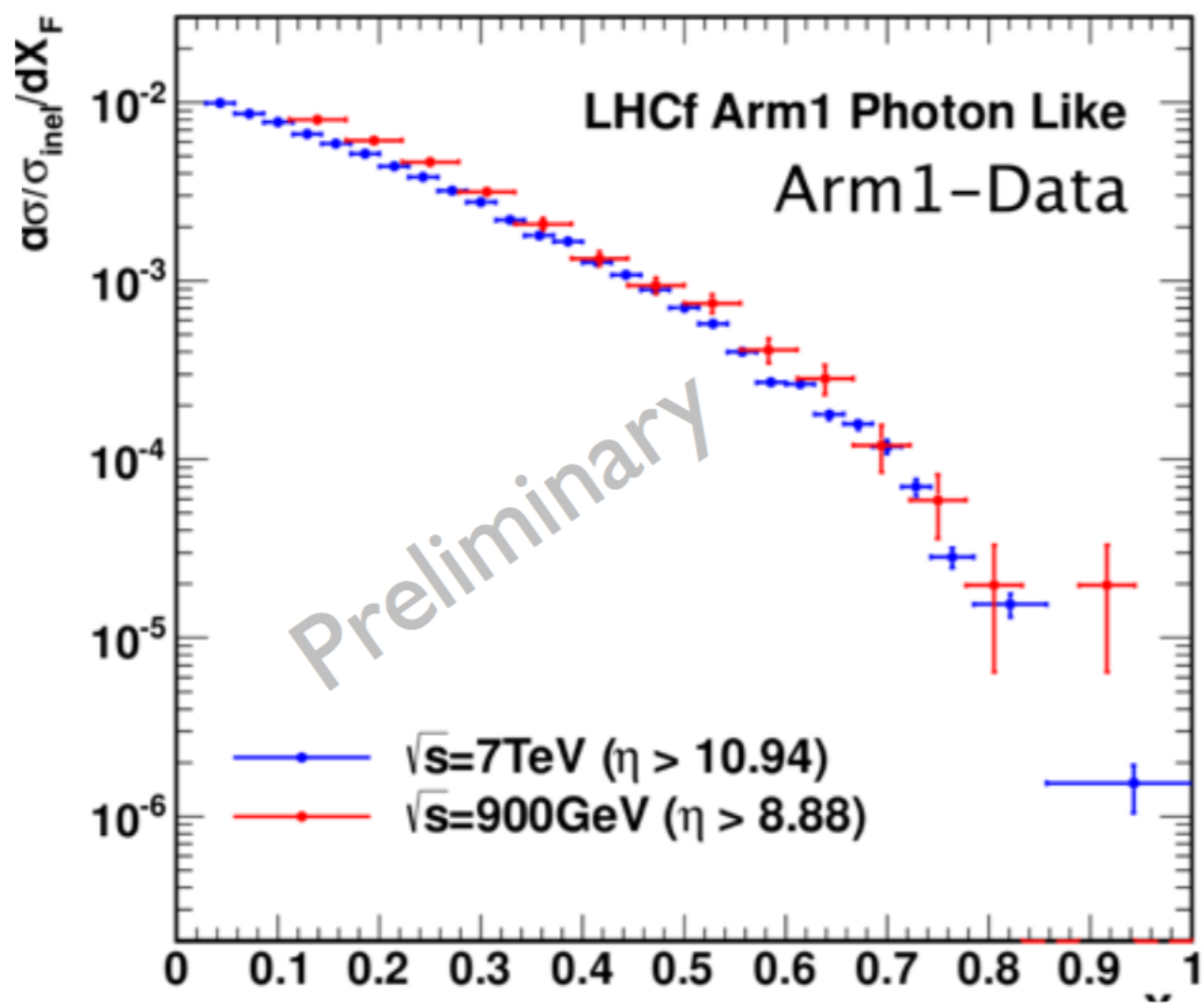
$$\frac{dN}{dx} \approx f(x) \qquad x = E/E_{\text{prim}}$$

hadronization

experimental evidence of scaling



$$x_T = 2\frac{p_T}{\sqrt{s}}$$

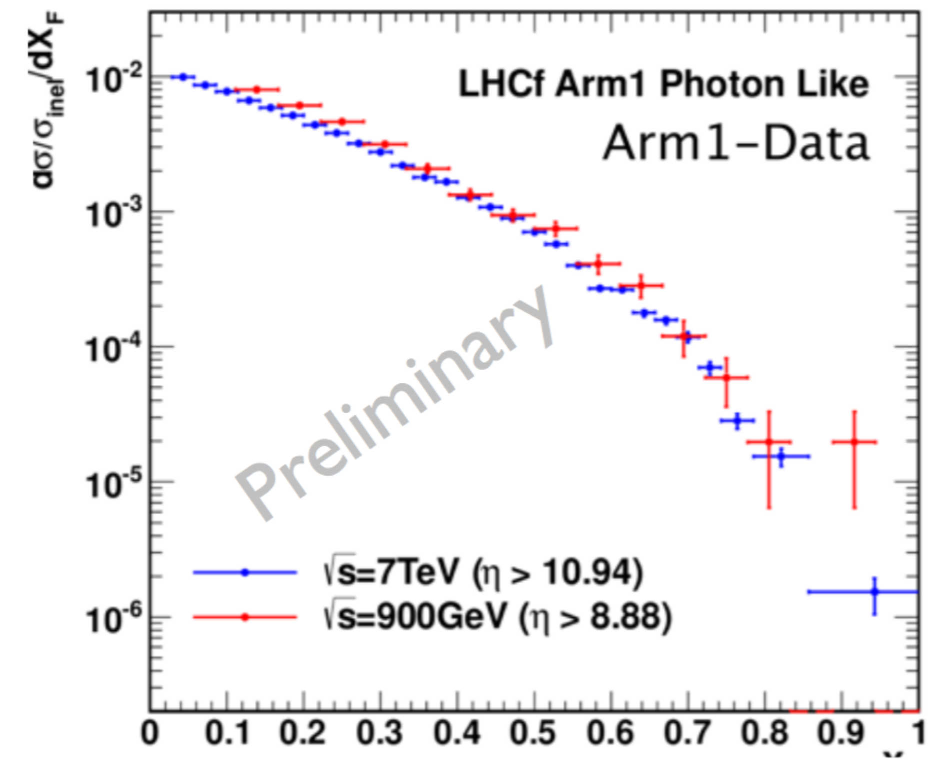


$$x_F = 2\frac{p_L}{\sqrt{s}}$$

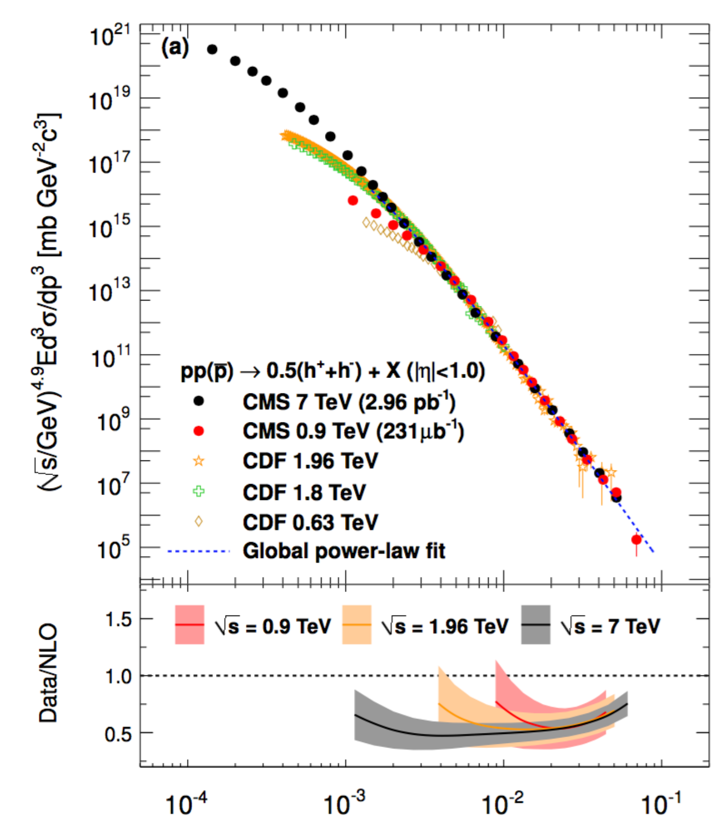
hadronization

experimental evidence of scaling

- **cosmic rays indicate approximate scaling**
- if scaling is perfect measurements at low energy would be sufficient for predictions at high energy
- in deep inelastic scattering at high momentum partons are *free* and collision with one parton is not affected by others: **scaling!**
- scaling in fractional momentum x is violated for low values of x. Patrons are not free: **scaling violation!**
- p = (uud) + (gqq sea)



$$x_F = 2\frac{p_L}{\sqrt{s}}$$



$$x_T = 2\frac{p_T}{\sqrt{s}}$$

hadronic interaction models

bridging particle physics to cosmic ray interactions

High energy models:

DPMJET II.5 and III (Ranft / Roesler, RE & Ranft)

neXus 2.0 and 3.0 (Drescher, Hladik, Ostapchenko, Pierog & Werner)

QGSJET 98 and 01 (Kalmykov & Ostapchenko)

SIBYLL 1.7 and 2.1 (Engel / RE, Fletcher, Gaisser, Lipari & Stanev)

- Gribov-Regge type models, minijets
- Parametrizations of data

Low/intermediate energy models:

GHEISHA (Fesefeldt)

Hillas' splitting algorithm (Hillas)

FLUKA (Fasso, Ferrari, Ranft & Sala)

UrQMD (Bass, Bleicher et al.)

TARGET (RE, Gaisser, Protheroe & Stanev)

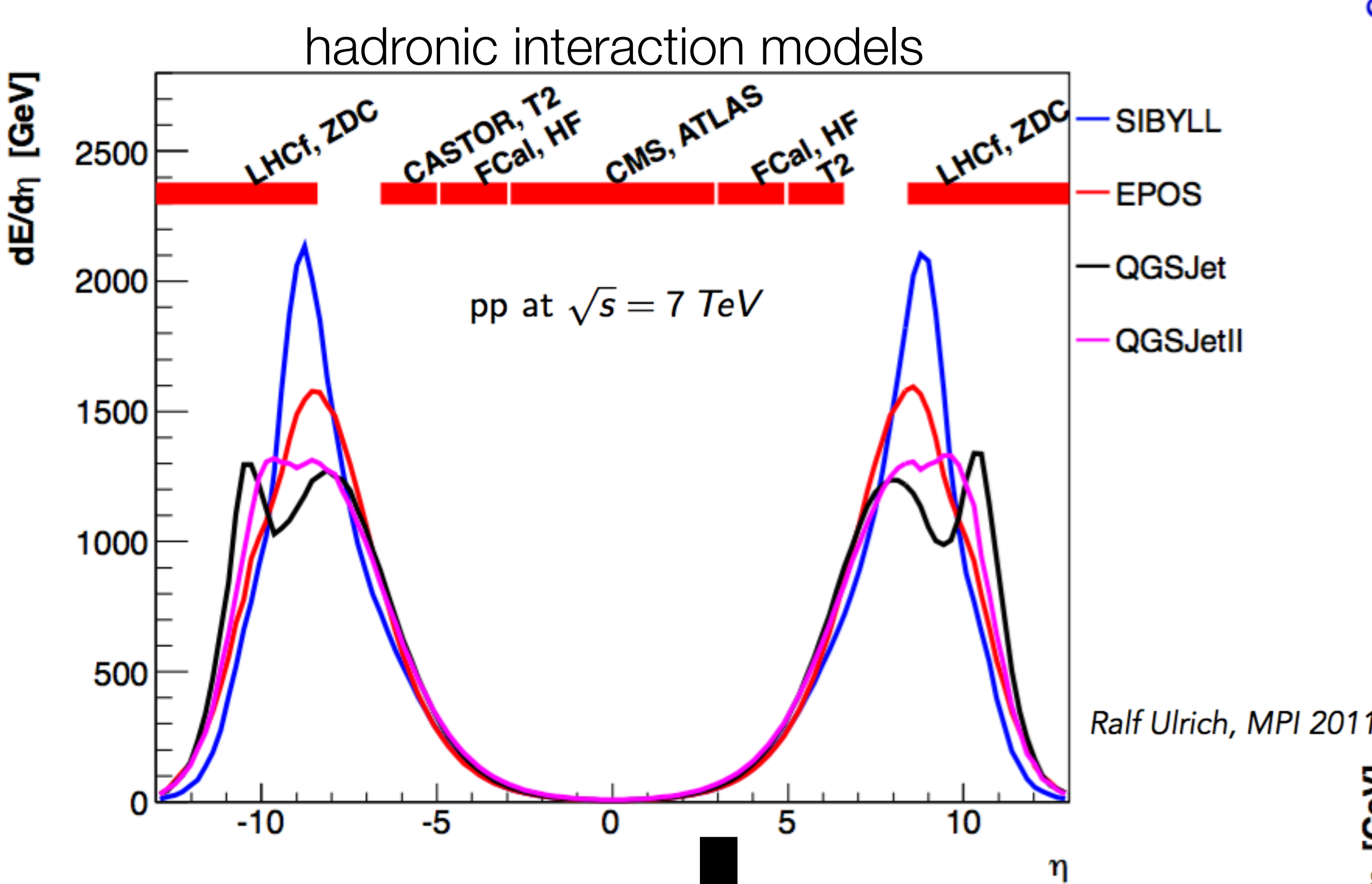
HADRIN/NUCRIN (Hänßgen & Ranft)

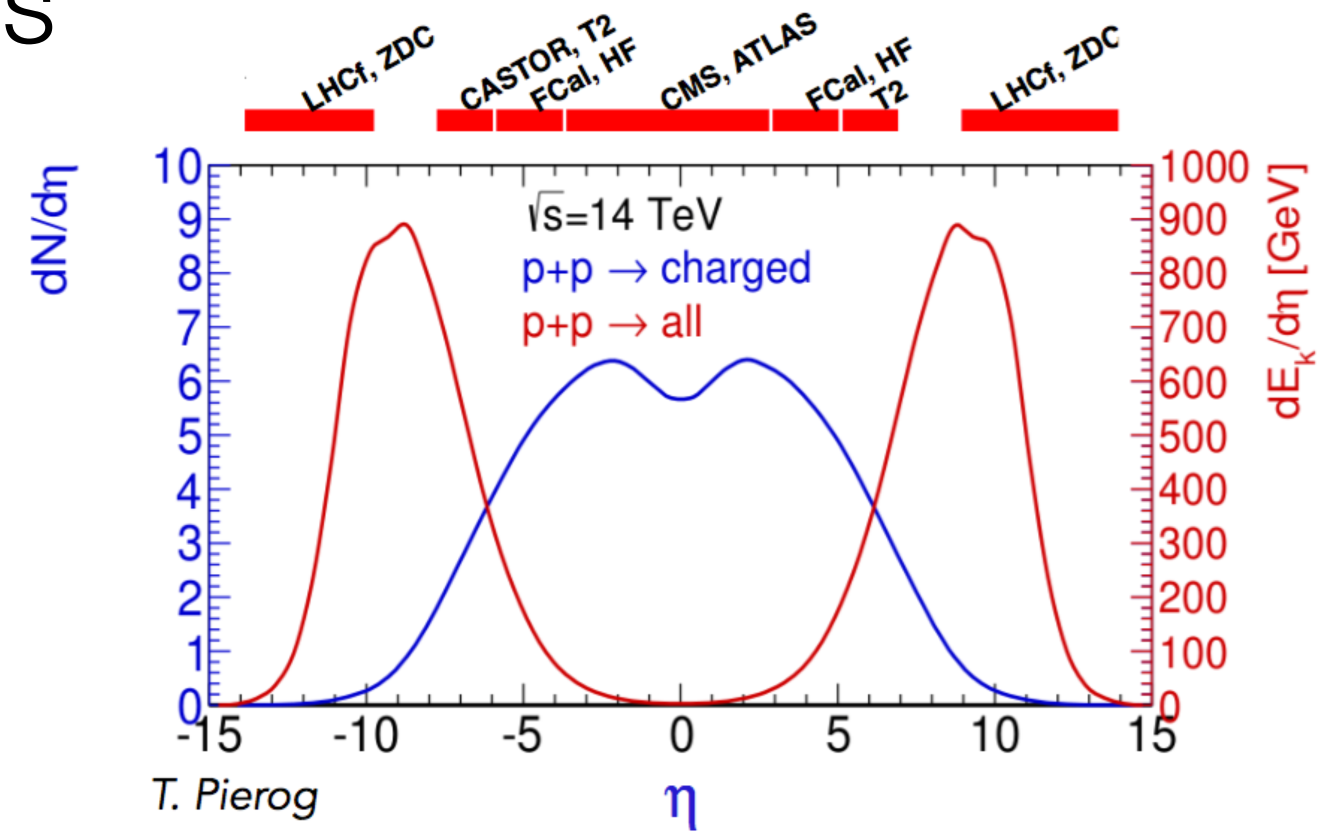
SOPHIA (Mücke, RE, Rachen, Protheroe, Stanev)

Ralph Engel

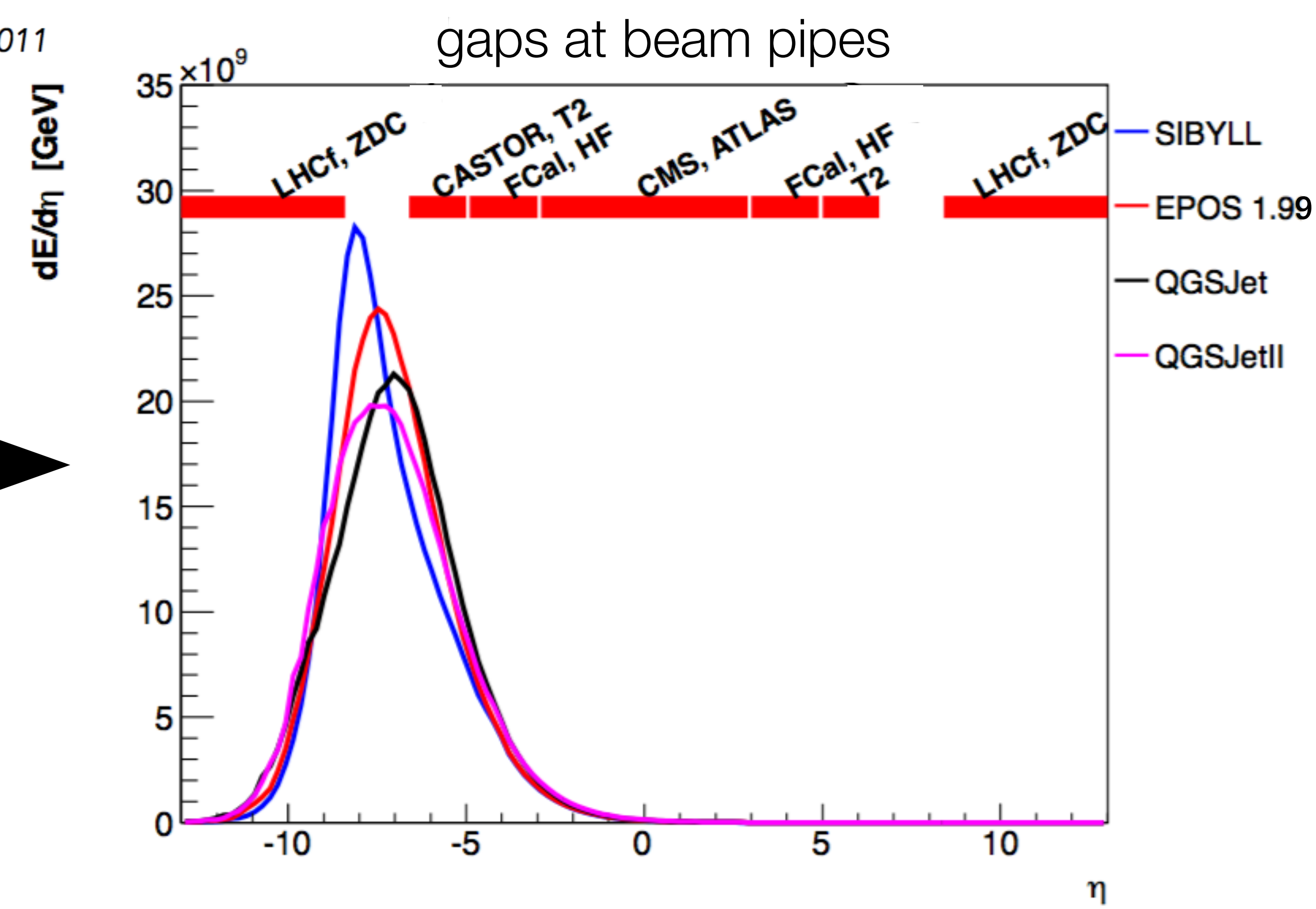
hadronic interaction models

treating the forward region





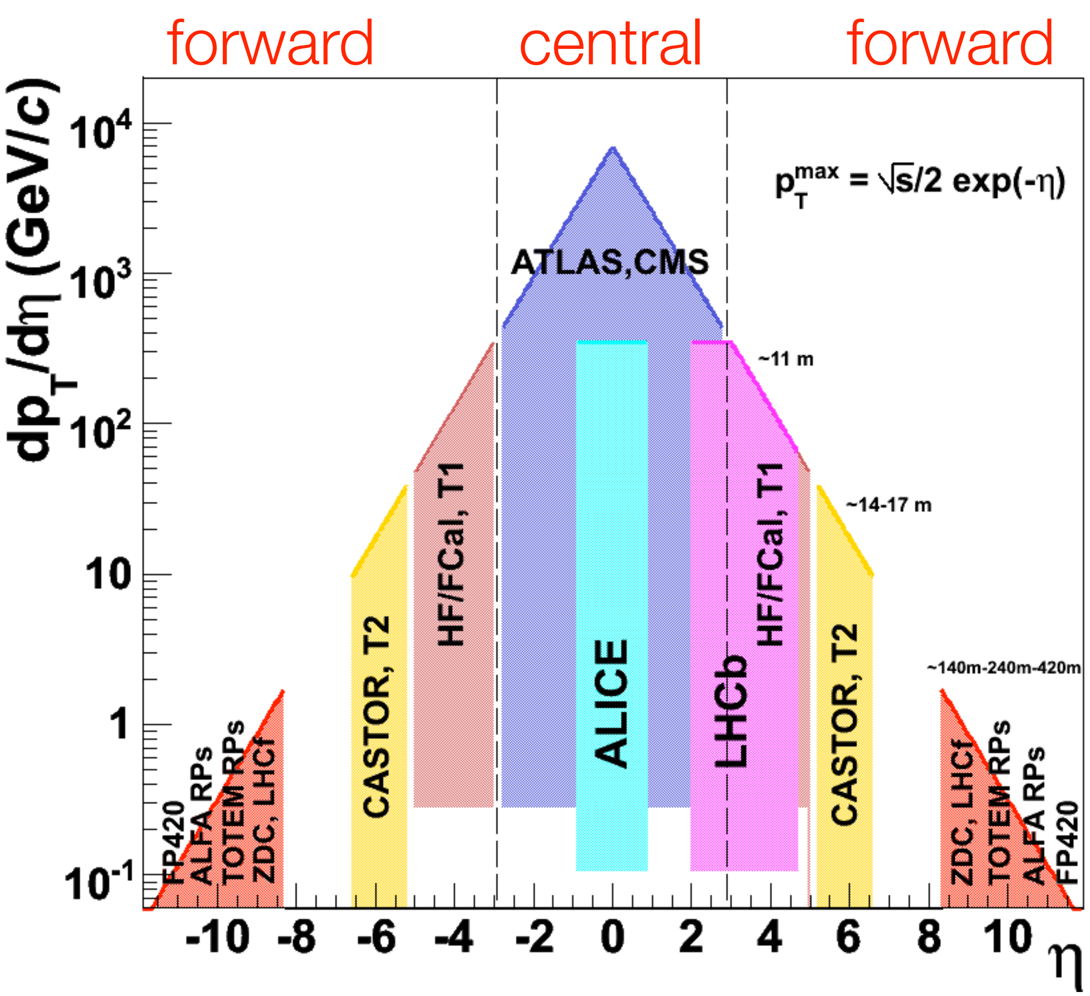
boosted from CM to air shower reference frame

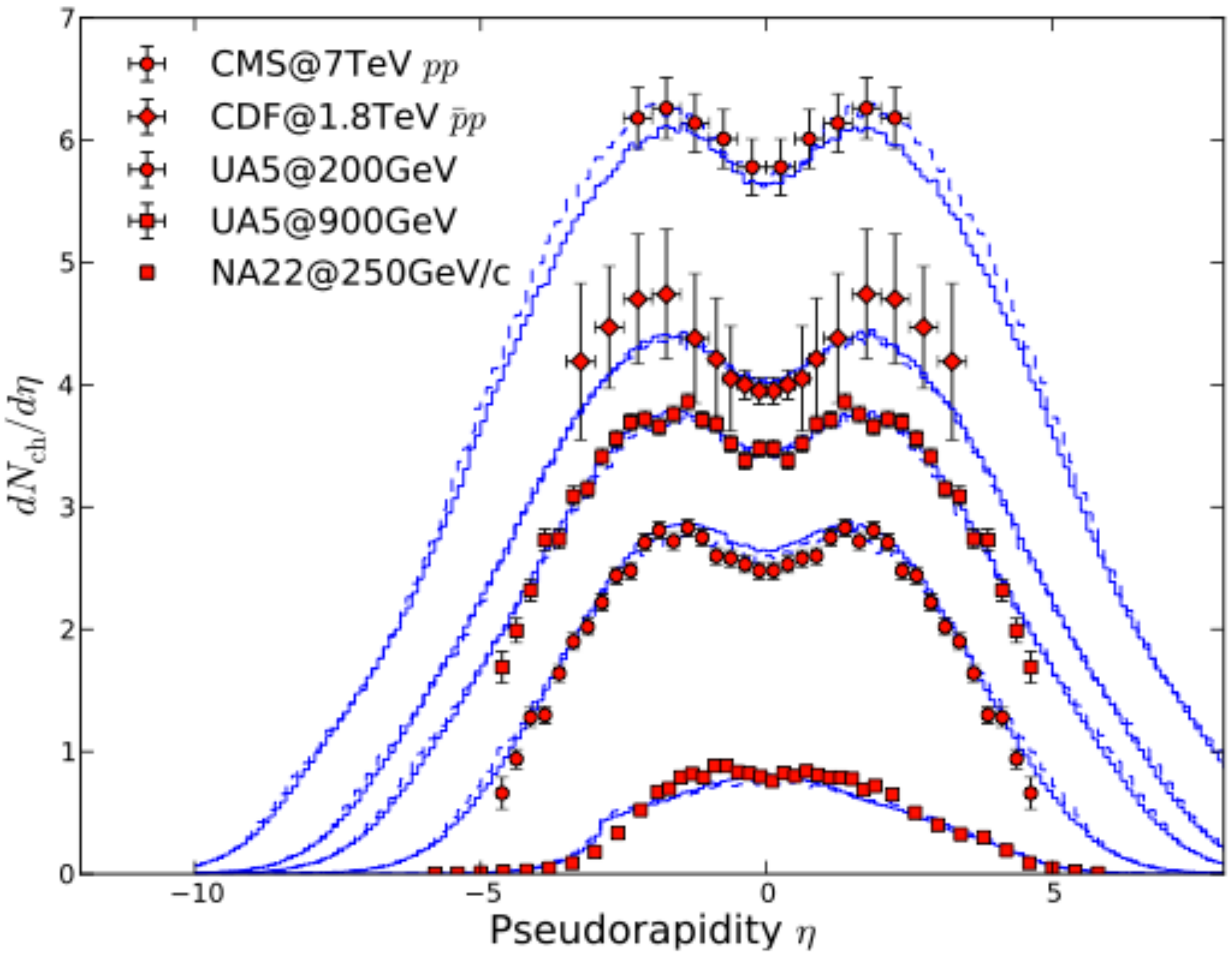


hadronic interaction models

treating the forward region

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



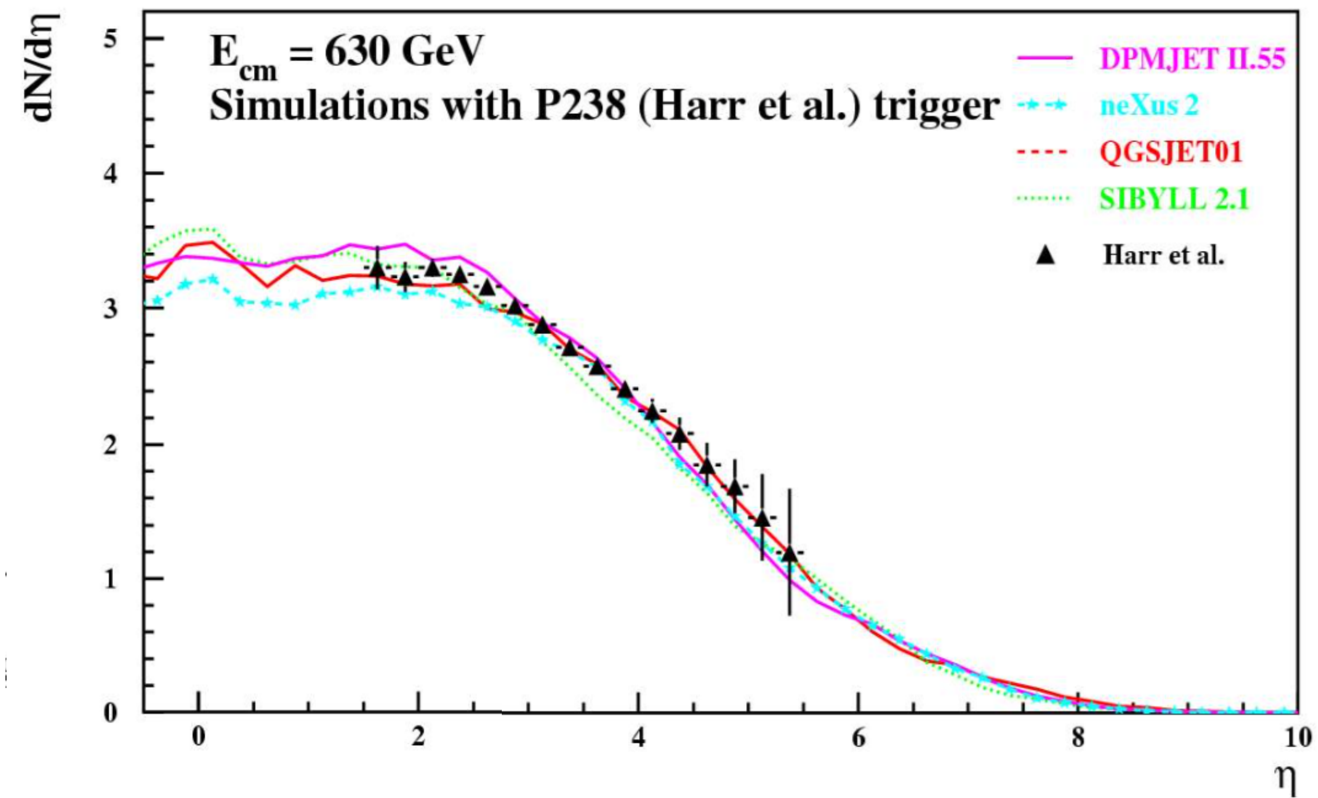


hadronic interaction models

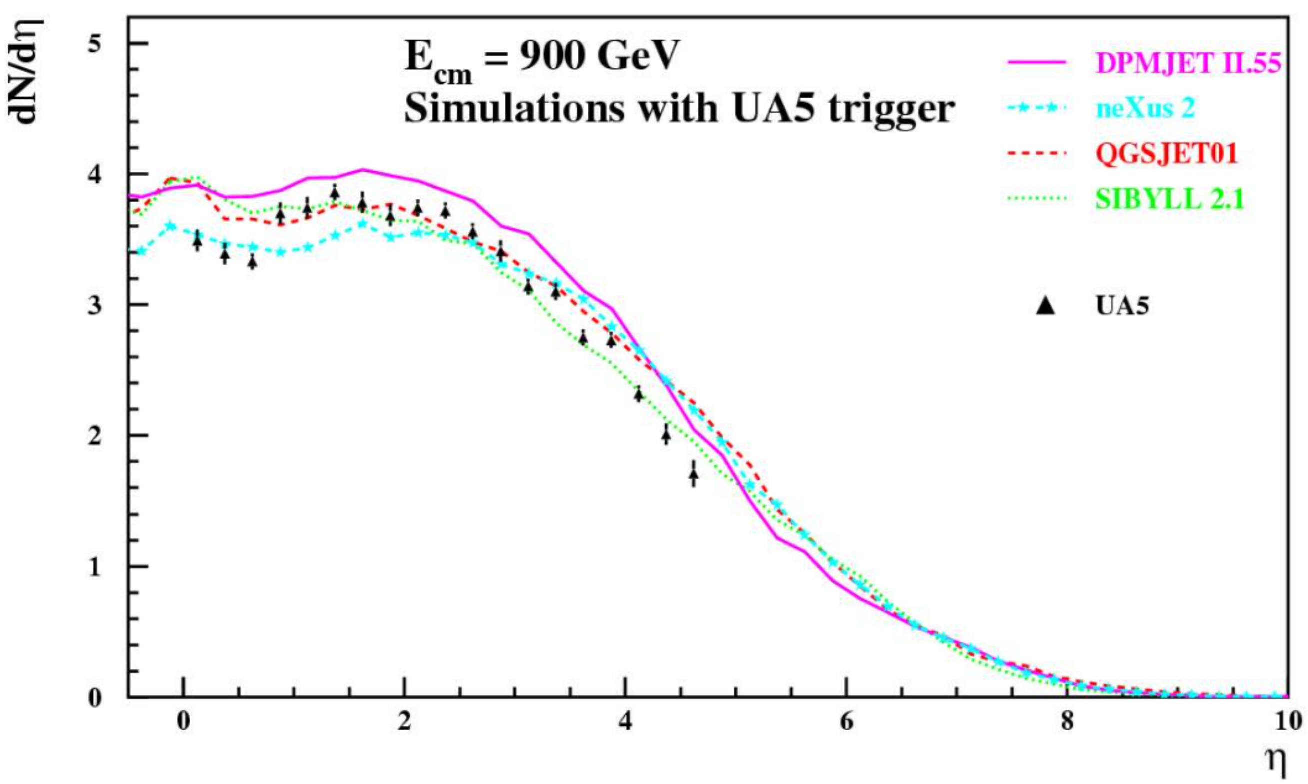
tuning to accelerator data

proton-antiproton @CERN-SPS

central forward



central forward

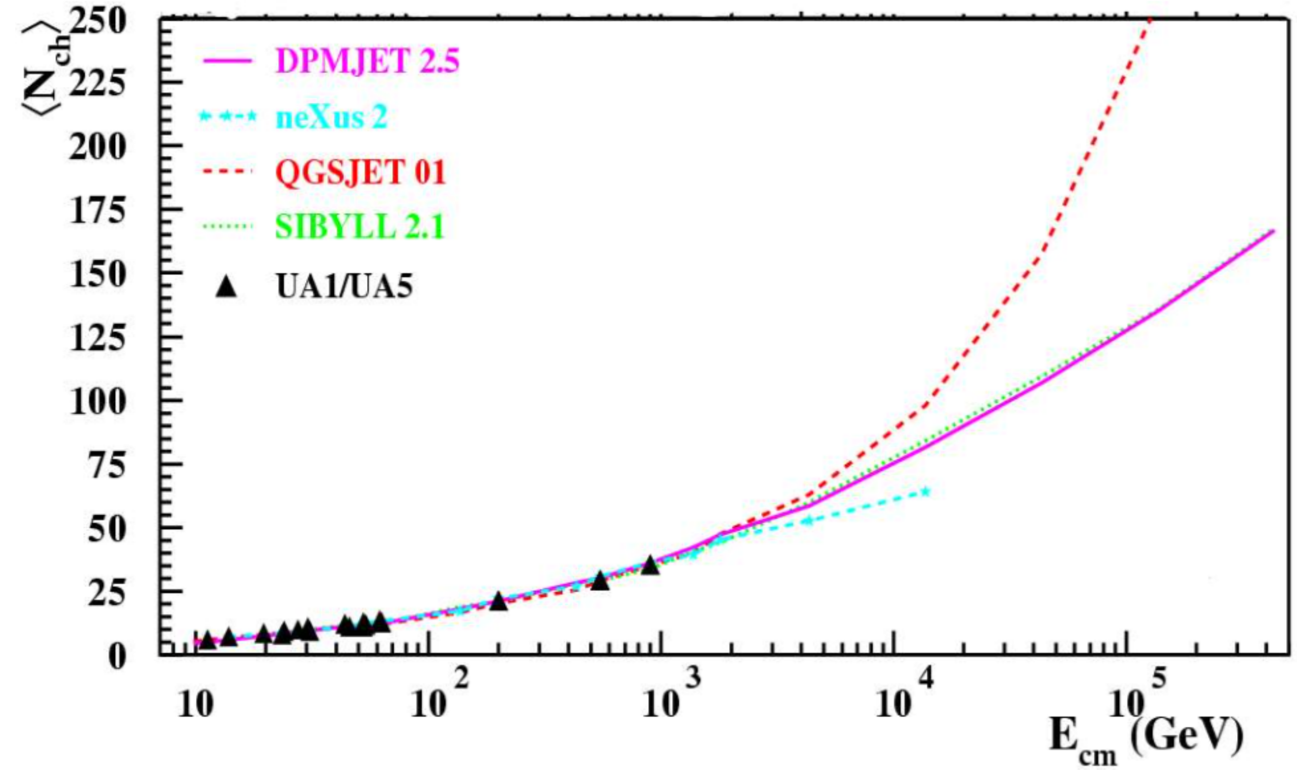


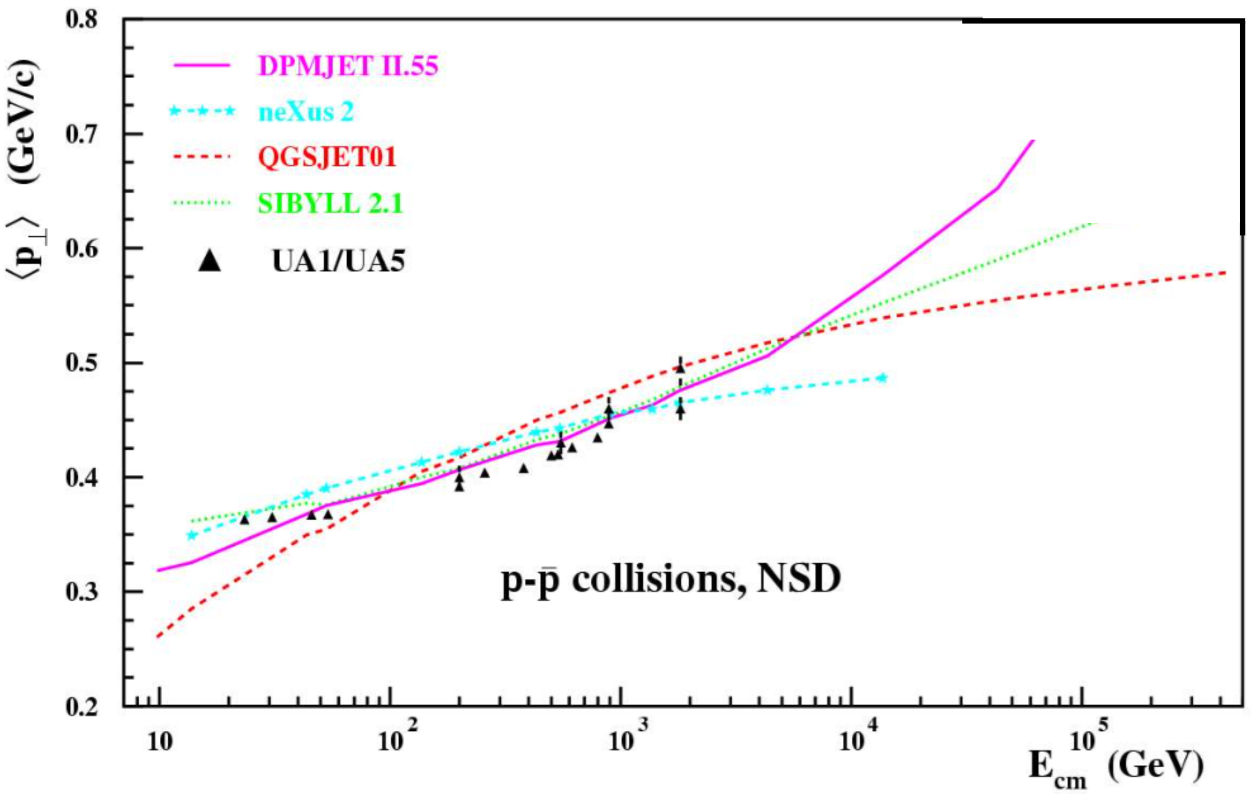
pseudo-rapidity distribution of charged particles

hadronic interaction models
tuning to accelerator data

proton-antiproton @CERN-SPS & Tevatron

mean charged particle multiplicity

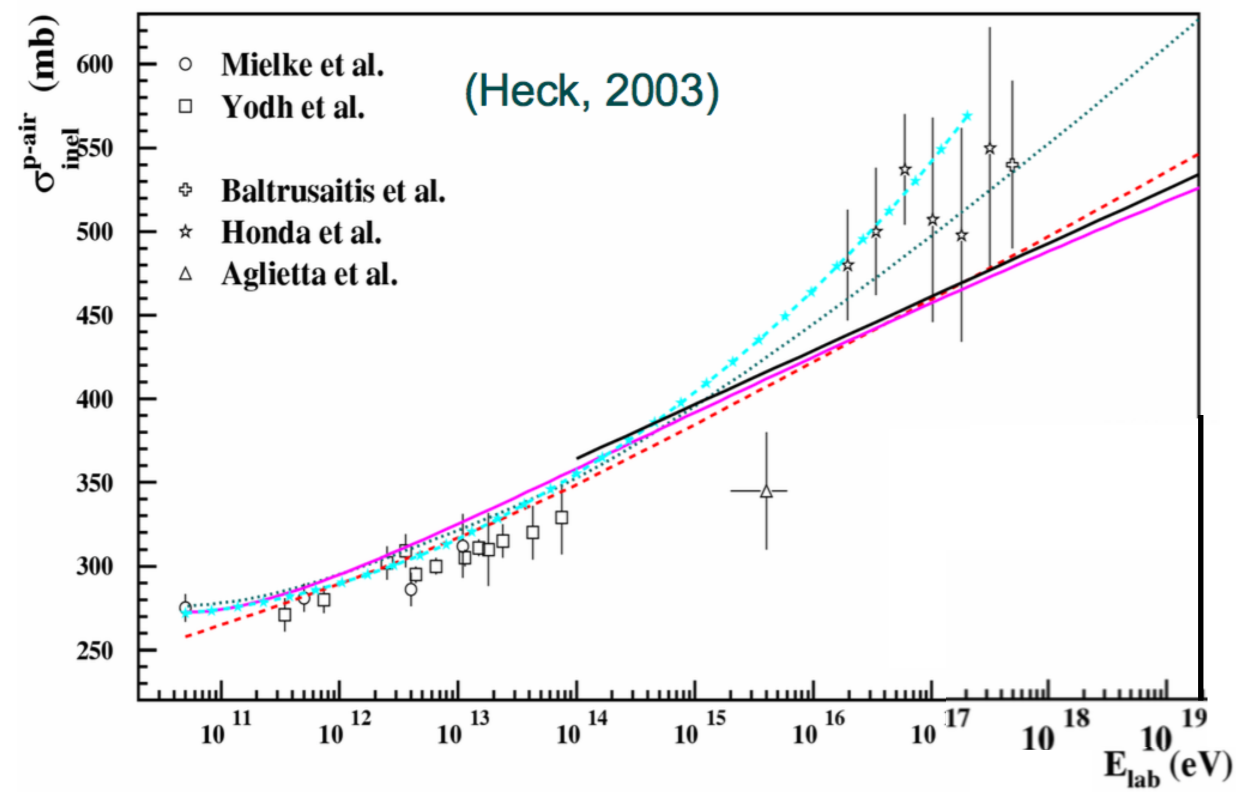




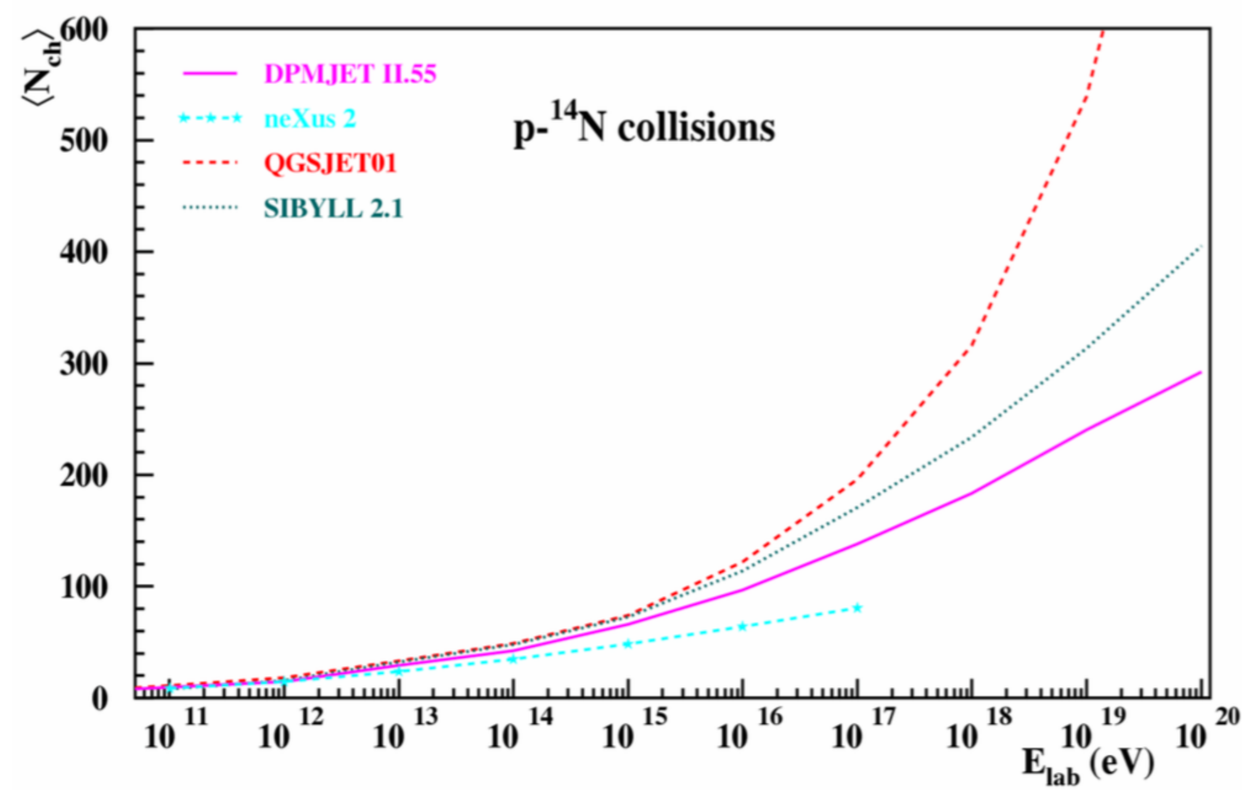
mean transverse momentum

hadronic interaction models
tuning to accelerator data

p-air production cross section
& model predictions



secondary charged particle
multiplicity predictions



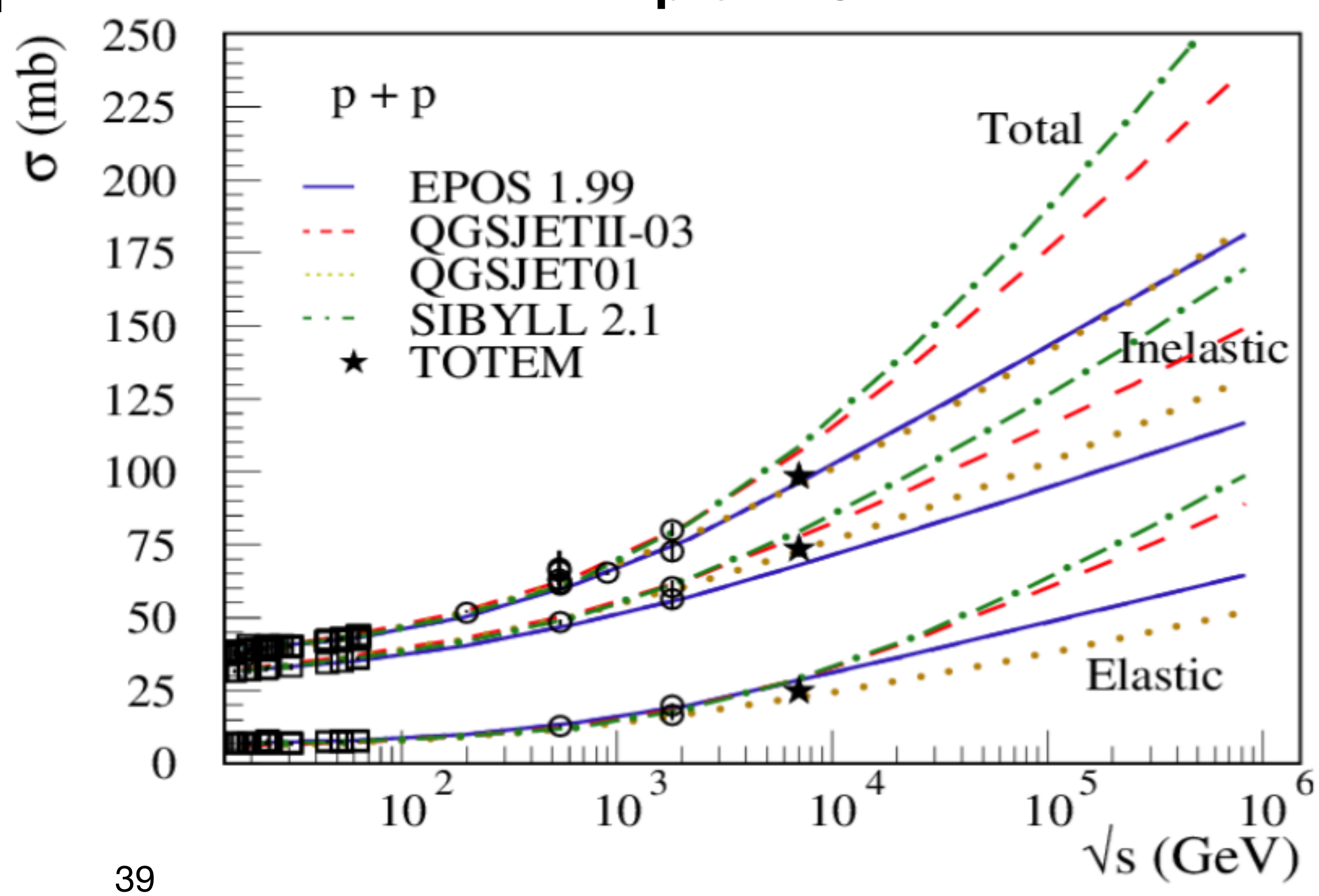
hadronic interaction models

treating the forward region

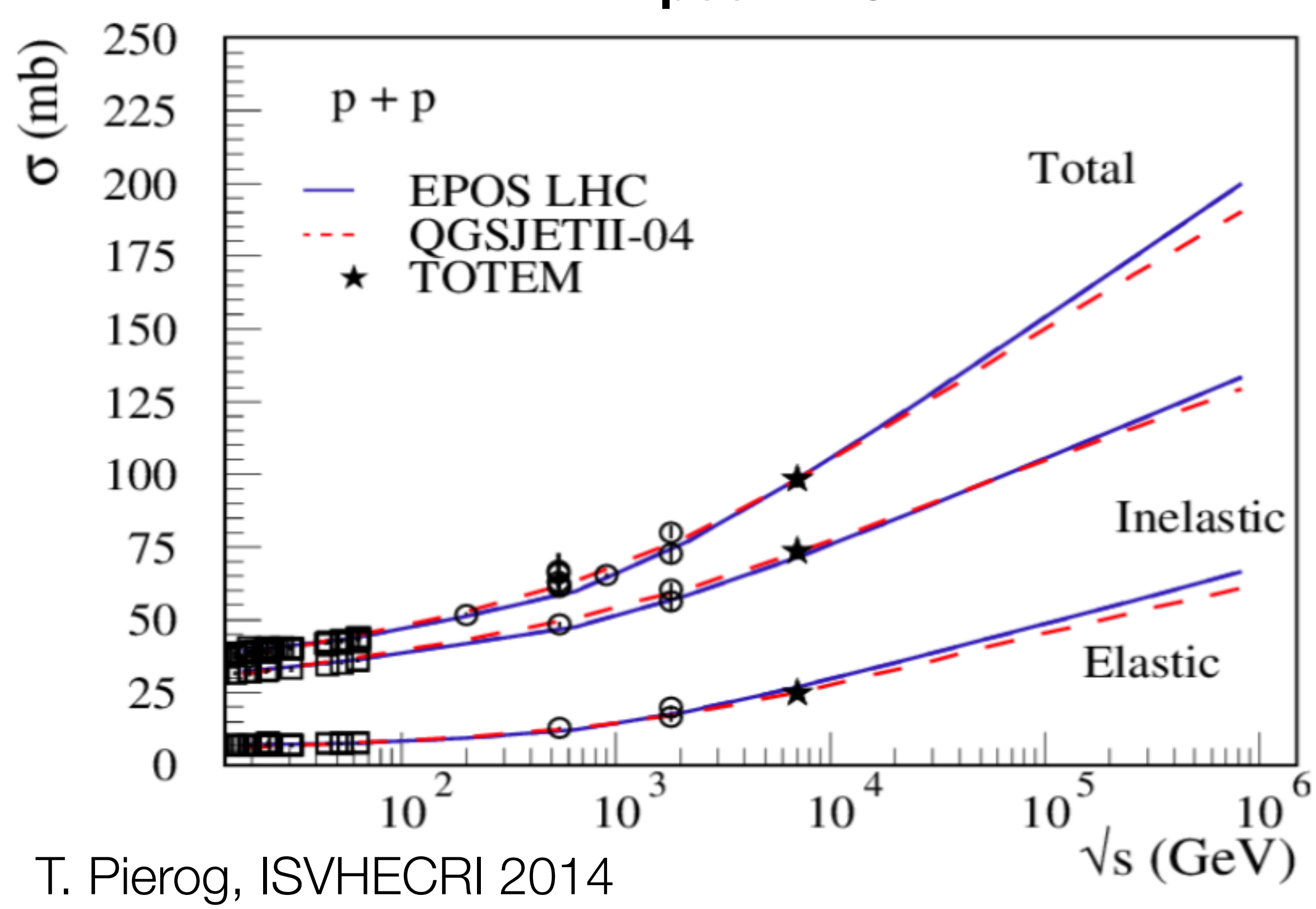
- **LHC** is providing good high energy data in wide range of pseudo-rapidity

- … although with important gaps … still

pre LHC



post LHC

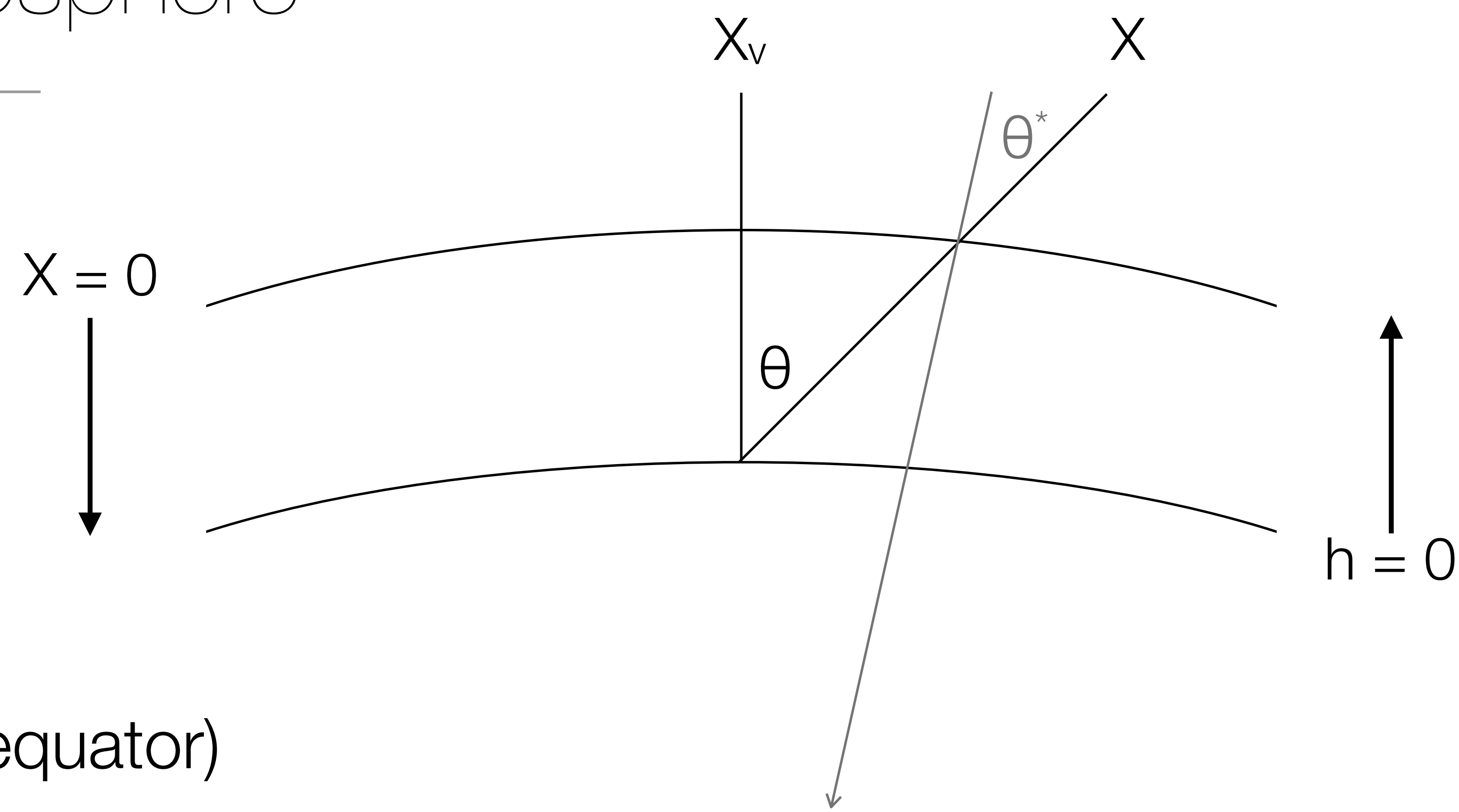


T. Pierog, ISVHECRI 2014

primary cosmic rays
interactions in the atmosphere

$$X_v = \int_h^\infty \rho_{air}(h')dh'$$

$$X \approx X_v \, \cos\theta^\star$$



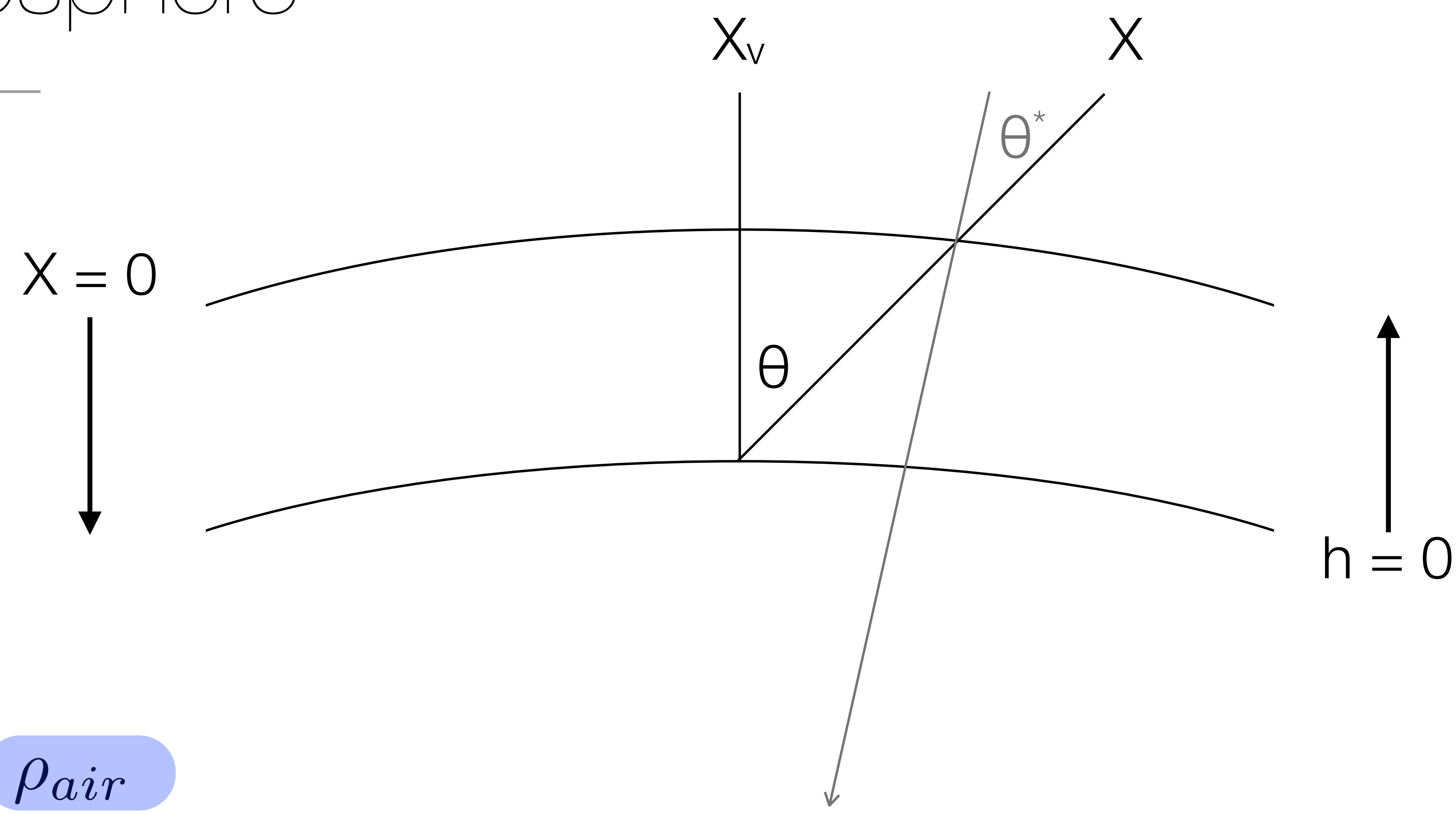
- isothermal atmosphere (7-50 km @poles - 17-50 km @equator)

$$\rho(h) \simeq \rho_0 \, e^{-h/h_0} \qquad \rho_0 \simeq 2.03 \times 10^{-3} \, \mathrm{g \ cm^{-3}} \qquad h_0 \simeq 6.4 \, \mathrm{km}$$

$$X(h) \simeq \rho_0 h_0 \, e^{-h/h_0} \simeq h_0 \rho(h)$$

primary cosmic rays

interactions in the atmosphere



$$X(h) \simeq \rho_0 h_0\, e^{-h/h_0} \simeq h_0 \rho(h)$$

- hadronic interactions $\lambda_N = \dfrac{\rho_{air}}{n_N \sigma_N^{air}}$

$$\pi^\pm \rightarrow \mu^\pm + \nu_\mu(\bar{\nu}_\mu)$$

$$\mu^\pm \rightarrow e^\pm + \nu_e(\bar{\nu}_e) + (\bar{\nu}_\mu)\nu_\mu$$

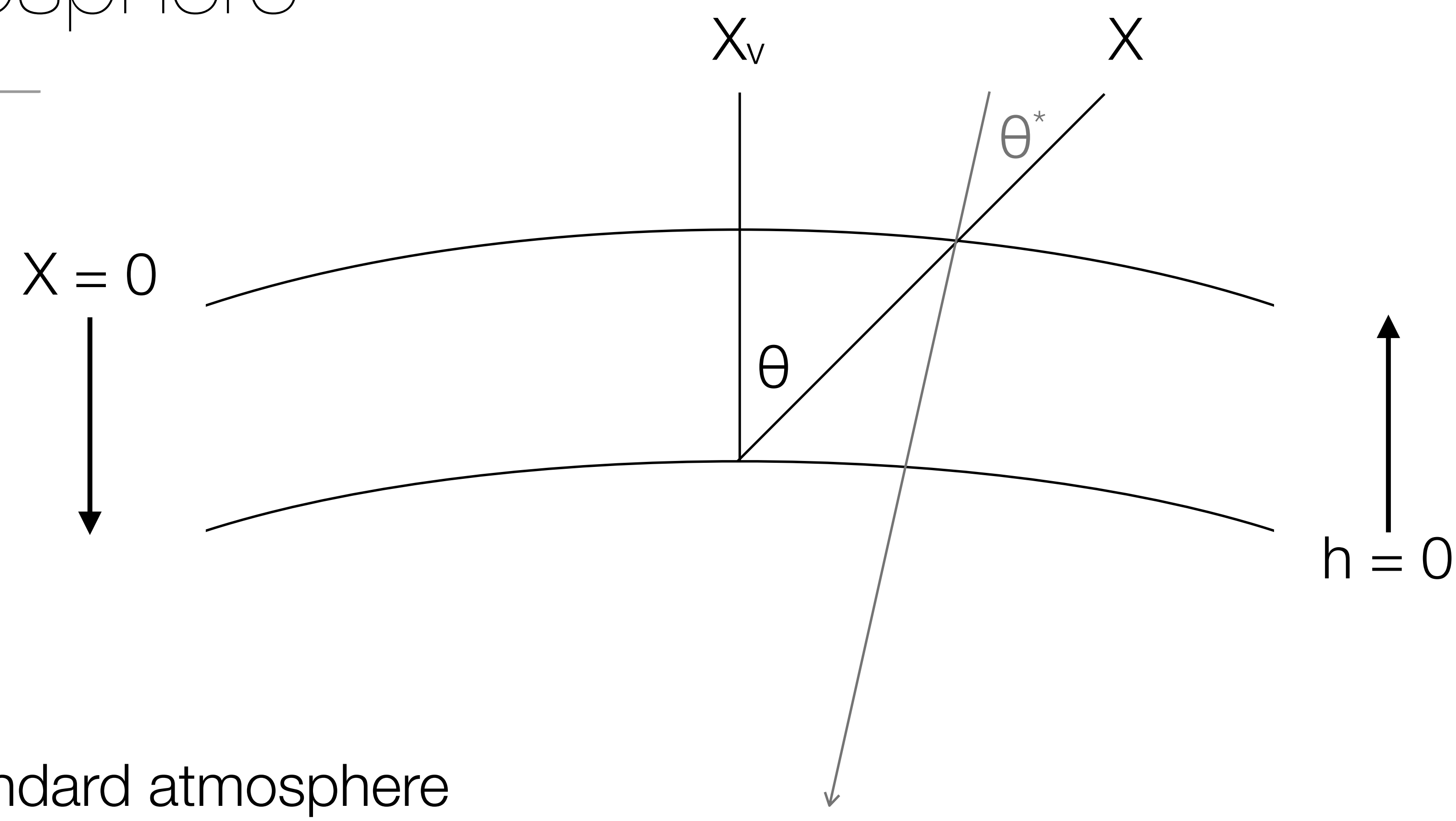
$$K^\pm \rightarrow \mu^\pm + \nu_\mu(\bar{\nu}_\mu)$$ (64 %)

$$K^\pm \rightarrow \pi^\pm + \pi^0$$ (21 %)

primary cosmic rays
interactions in the atmosphere

$$\lambda_N = \frac{\rho_{air}}{n_N \sigma_N^{air}}$$

$$\lambda_{int,p} \approx 90\,\mathrm{g\,cm^{-2}}$$
$$\lambda_{int,Fe} \approx 5\,\mathrm{g\,cm^{-2}}$$
$$\lambda_{int,\pi} \approx 120\,\mathrm{g\,cm^{-2}}$$
$$\lambda_{int,K} \approx 12\,\mathrm{g\,cm^{-2}}$$



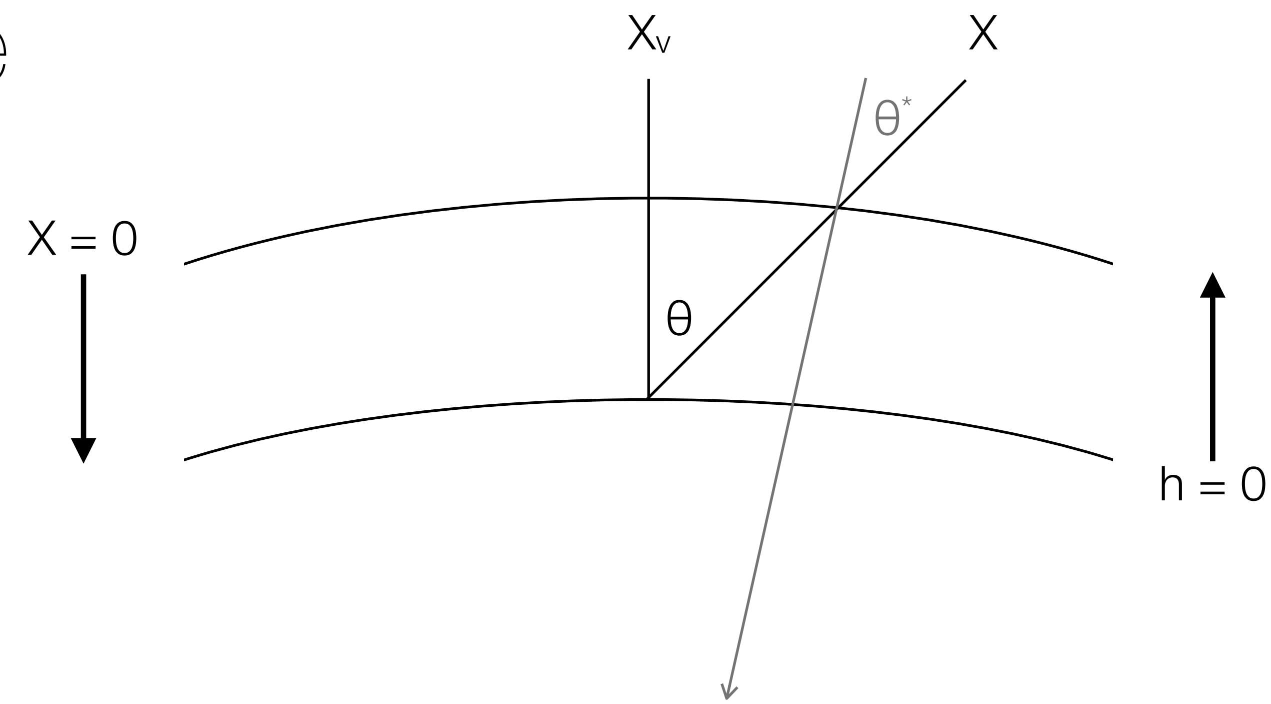
$$X_v = \int_h^\infty \rho_{air}(h')dh'$$

US standard atmosphere

Altitude (km)	Vertical depth (g/cm²)	Local density (10^{-3} g/cm³)	Molière unit (m)	Electron Cherenkov threshold (MeV)	Cherenkov angle (°)
40	3	3.8×10^{-3}	2.4×10^4	386	0.076
30	11.8	1.8×10^{-2}	5.1×10^3	176	0.17
20	55.8	8.8×10^{-2}	1.0×10^3	80	0.36
15	123	0.19	478	54	0.54
10	269	0.42	223	37	0.79
5	550	0.74	126	28	1.05
3	715	0.91	102	25	1.17
1.5	862	1.06	88	23	1.26
0.5	974	1.17	79	22	1.33
0	1,032	1.23	76	21	1.36

primary cosmic rays

interactions in the atmosphere



- hadronic interactions $\lambda_i = \dfrac{\rho_{air}}{\rho_i \sigma_i^{air}}$

- meson decay $\dfrac{1}{d_i} = \dfrac{\epsilon_i}{E_i X \cos\theta^\star}$ $\epsilon_i = \dfrac{m_i c^2}{c\tau_i} h_0(T)$

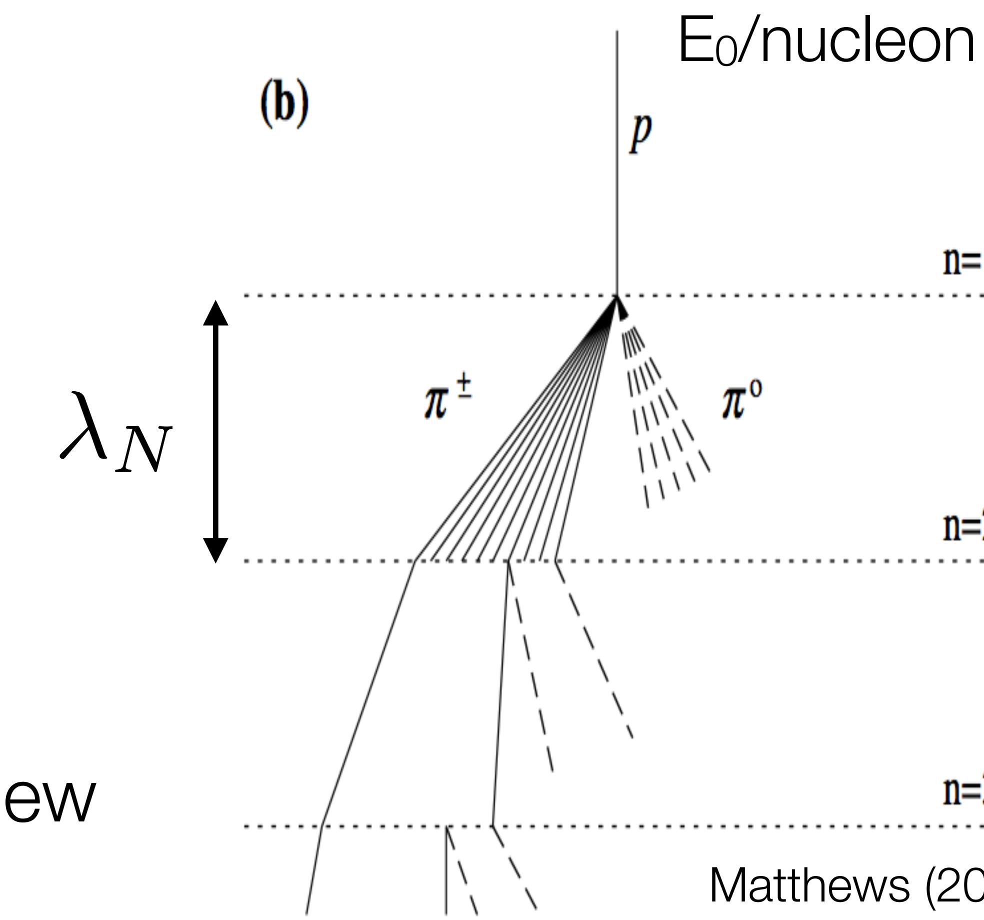
- **competition between interaction & decay** $\dfrac{1}{d_i} \approx \dfrac{1}{\lambda_i}$ which depends on $\dfrac{\epsilon_i}{E_i}$

$\epsilon_{\pi^0} = 3.5 \times 10^{10} GeV$	$\epsilon_{K_L^0} = 210 GeV$	$\epsilon_{D^0} = 9.2 \times 10^7 GeV$
$\epsilon_{\pi^\pm} = 115 GeV$	$\epsilon_{K^\pm} = 850 GeV$	$\epsilon_{D^\pm} = 4.3 \times 10^7 GeV$
	strange	charm

hadronic showers

Heitler model

- nucleons (E_0) ignites showers producing π's
  - $\pi^0 \rightarrow \gamma\gamma$ (fast electromagnetic process)
  - $\pi^\pm \rightarrow \mu^\pm + \nu_\mu$ (slow weak process) OR initiate new cascades until E_c



Matthews (2005)

$$\lambda_N = \frac{\rho_{air}}{n_N \sigma_N^{air}}$$

- assume one muon produced for each hadron

$$N_\mu = \left(\frac{E_0}{E_c^\pi}\right)^\alpha \approx 10^4 \left(\frac{E_0}{1\,PeV}\right)^\alpha$$

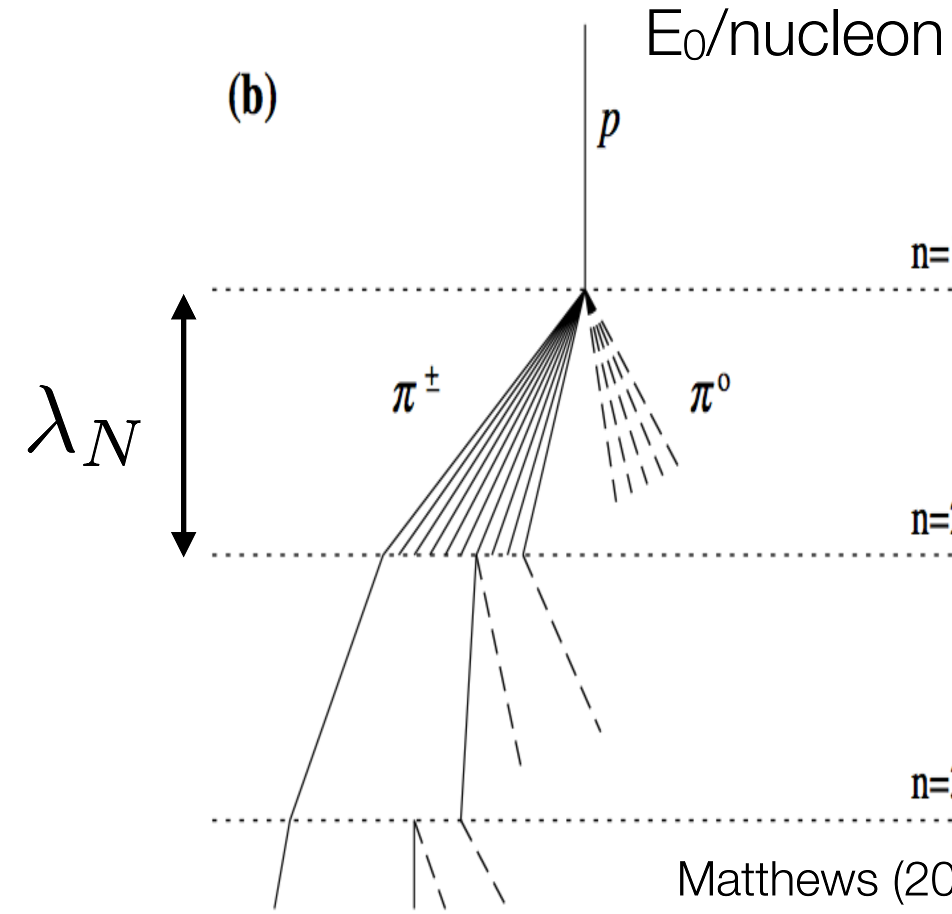
$$\alpha = \frac{\ln(n_{ch})}{\ln(n_{tot})} \approx 0.85 - 0.92$$

hadronic showers
superposition model

- atomic nucleus of mass A and energy $E_0 \approx$ A nucleons of energy E_0/A

$$N_\mu^A = A\left(\frac{E_0}{AE_c^\pi}\right)^\alpha = A^{1-\alpha} N_\mu$$

$$N_\mu(>E_\mu) \approx A \times \frac{14.5\,GeV}{E_\mu \cos\theta}\left(\frac{E_0}{AE_\mu}\right)^{0.757}\left(1-\frac{AE_\mu}{E_0}\right)^{5.25}$$ Elbert Formula



Matthews (2005)

$$\lambda_N = \frac{\rho_{air}}{n_N \sigma_N^{air}}$$

- mass-dependent quantities

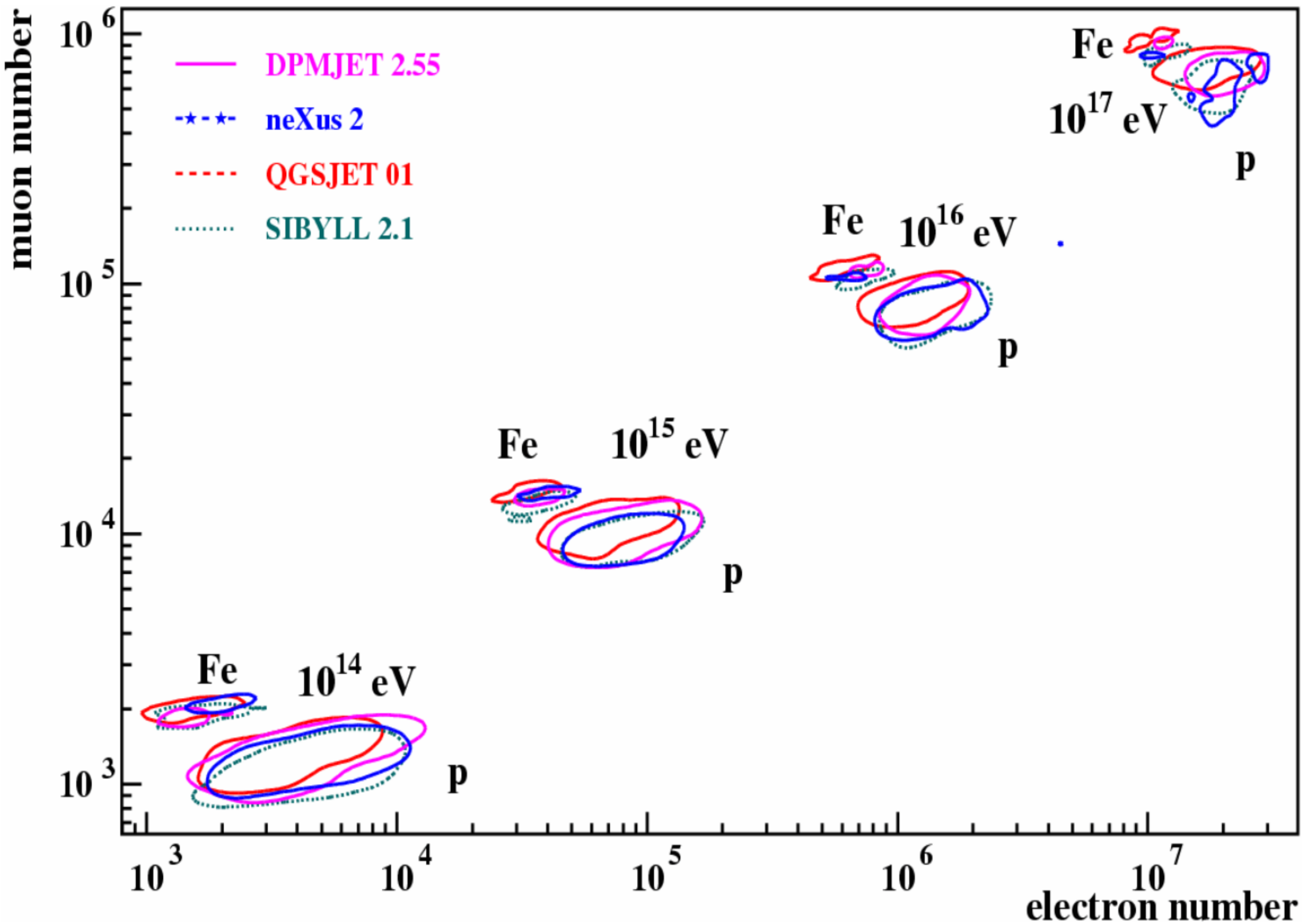
$$X_{max}^A \approx \lambda_{eff} \ln(E_0/A)$$

λ_{eff} the effective interaction length for pions

$$E_0 \approx 0.85(N_e + 25N_\mu)$$

hadronic showers
energy & mass composition

Ralf Engel

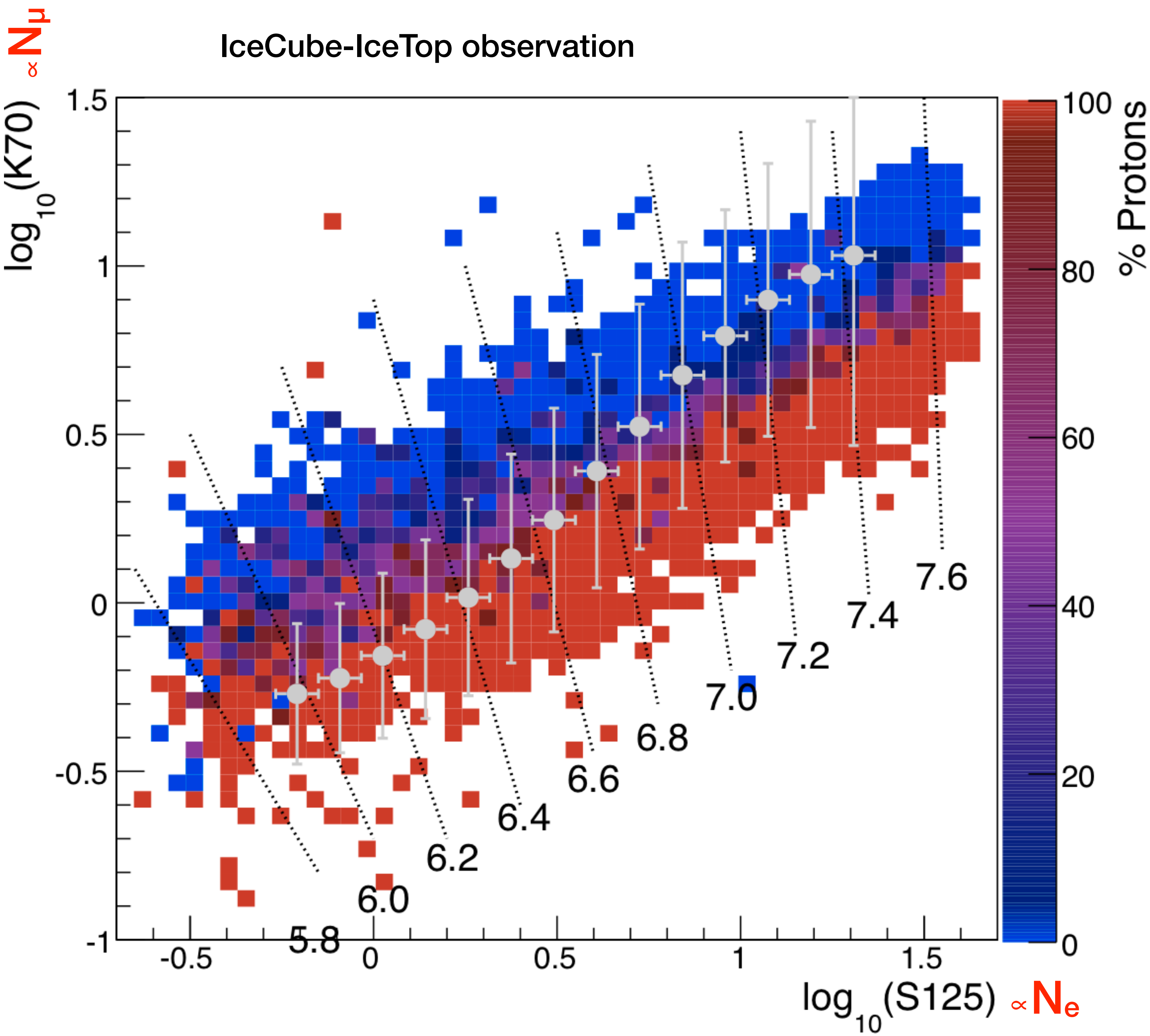


$$N_\mu^A = A^{1-\alpha}\left(\frac{E_0}{E_c^\pi}\right)^\alpha$$

$$N_e^\gamma \propto \frac{0.31}{\sqrt{\ln(E_0/\epsilon_c)}}\, e^{-X/\lambda_{rad}}$$

hadronic showers

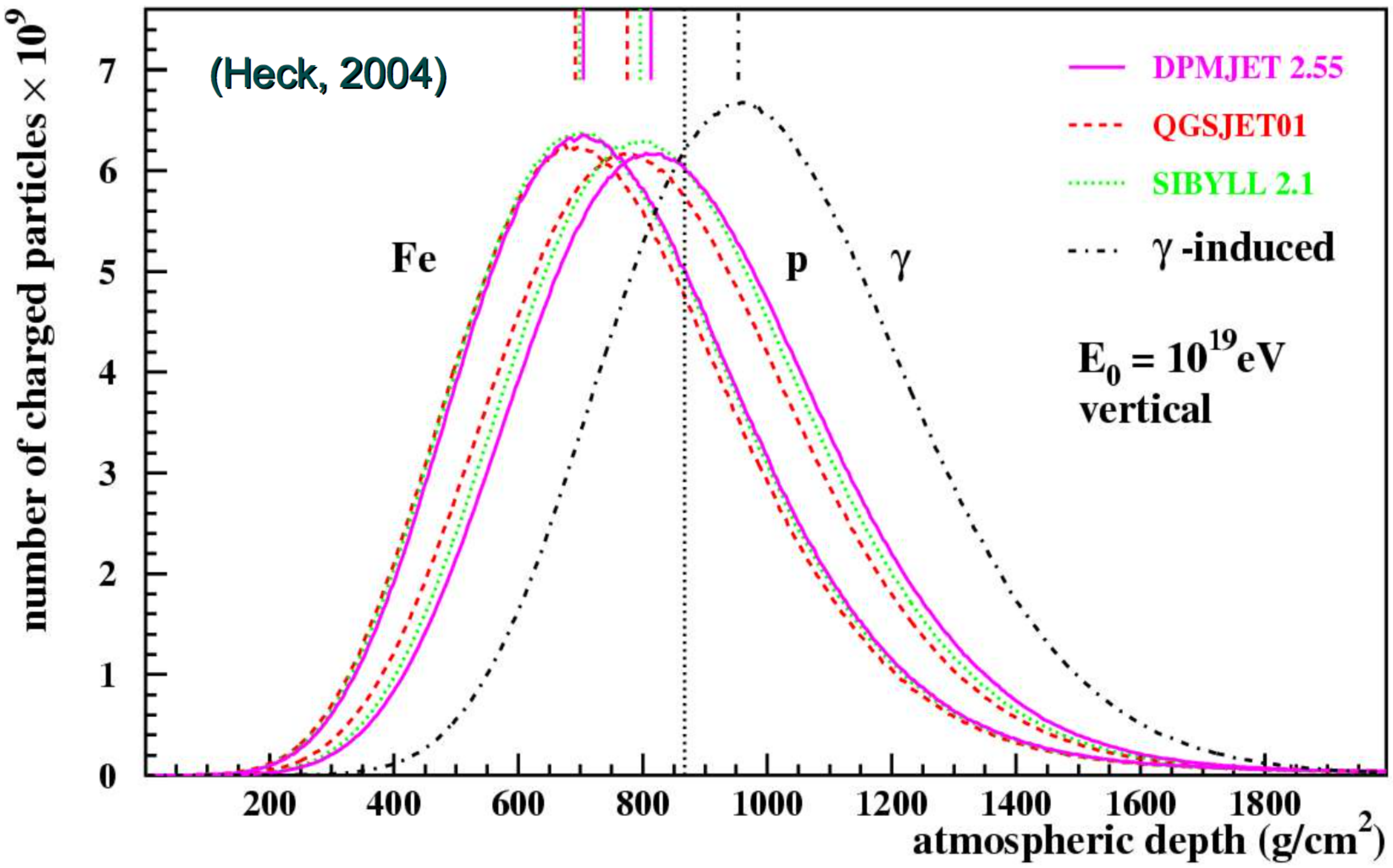
energy & mass composition



$$N_\mu^A = A^{1-\alpha}\left(\frac{E_0}{E_c^\pi}\right)^\alpha$$

$$N_e^\gamma \propto \frac{0.31}{\sqrt{\ln(E_0/\epsilon_c)}}\, e^{-X/\lambda_{rad}}$$

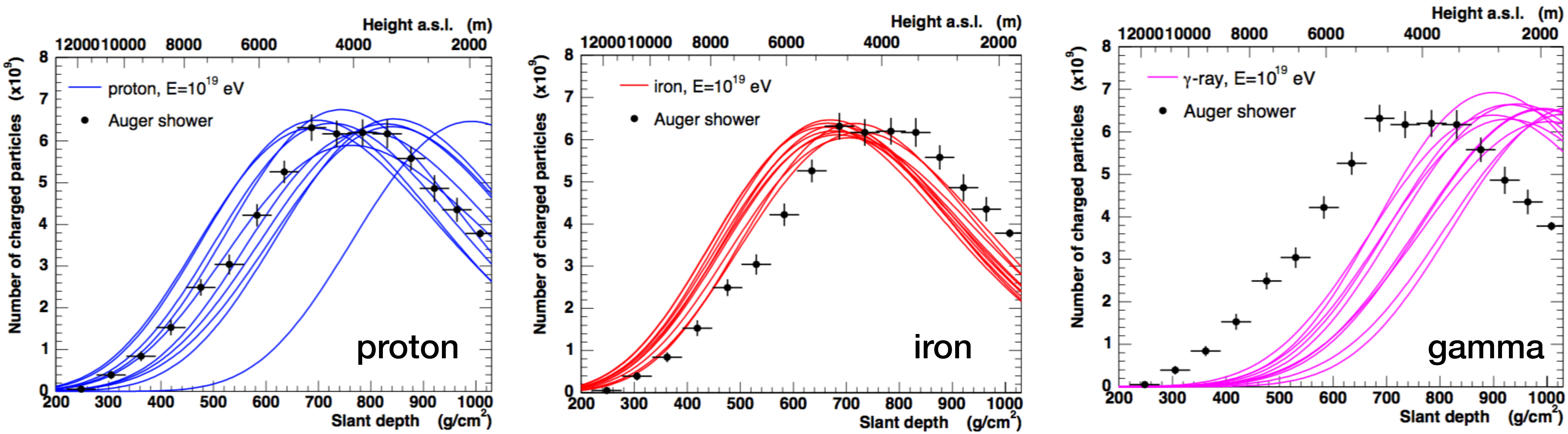
hadronic vs. electromagnetic showers



$$X_{max}^{EM} \approx \lambda_{int} \ln\left(E_0/\epsilon_c\right)$$

$$X_{max}^{A} \approx \lambda_{eff} \ln(E_0/A)$$

hadronic vs. electromagnetic showers



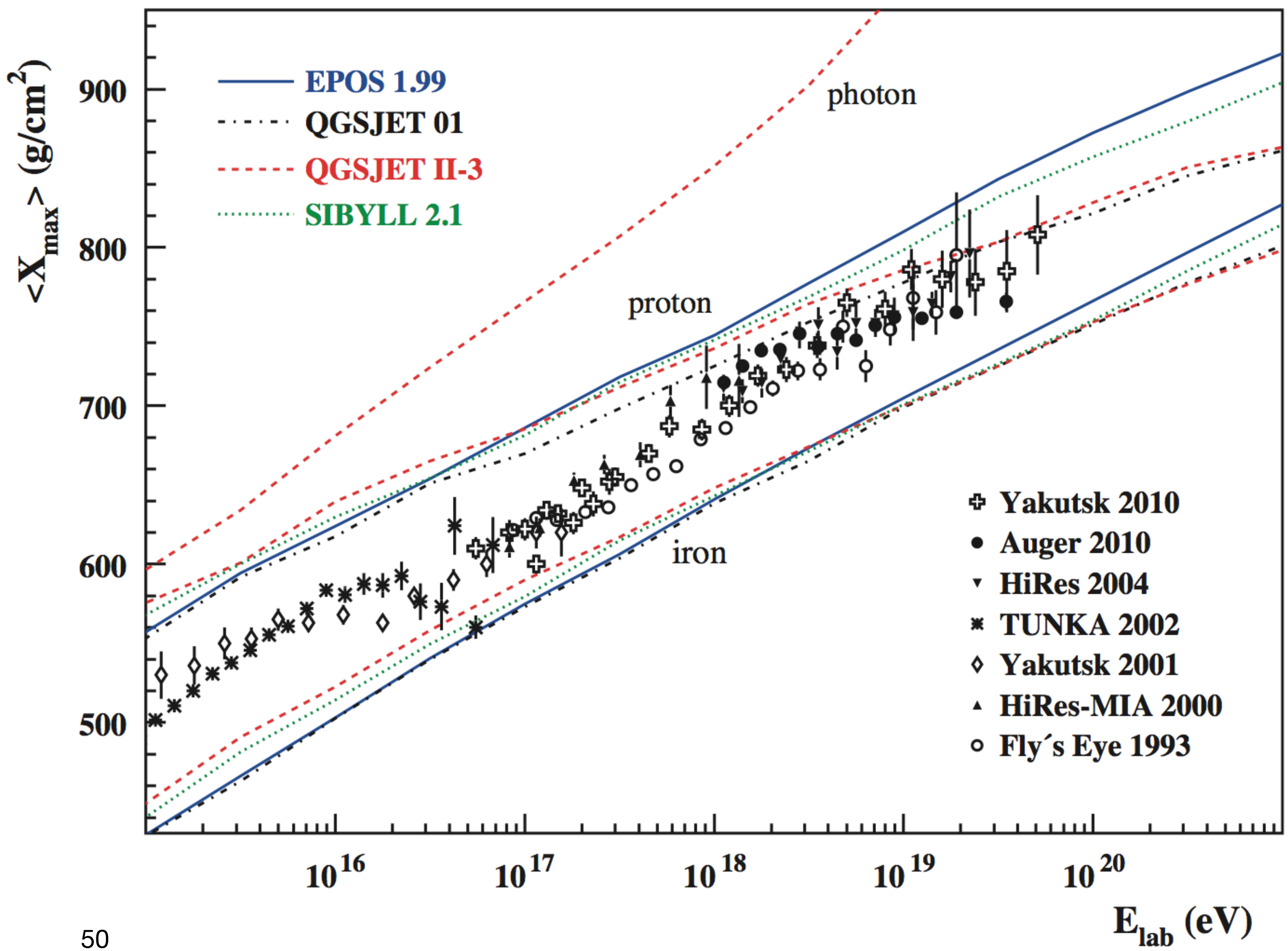
$$X_{max}^{EM} \approx \lambda_{int} \, \ln\left(E_0/\epsilon_c\right)$$

$$X_{max}^{A} \approx \lambda_{eff} \ln(E_0/A)$$

hadronic showers

energy & mass composition

Engel, Pierog & Heck, ARNPS 2011



$$X_{max}^{EM} \approx \lambda_{int} \ln \left(E_0 / \epsilon_c \right)$$

$$X_{max}^{A} \approx \lambda_{eff} \ln(E_0/A)$$

elongation rate theorem

constraint on elongation rate of hadron-induced showers

- elongation rate (change of X_{max} vs. energy)

$$D_e = \frac{\langle dX_{max} \rangle}{d\ \ln E}$$

$$D_{10} = \frac{\langle dX_{max} \rangle}{d\ \log E} = \ln(10)\, D_e$$

- photon-induced shower

$$\langle X^{\gamma}_{max} \rangle \approx \lambda_{int} \ln(E_0/\epsilon_c)$$

$$D^{\gamma}_{10} = \ln(10)\, \lambda_{int} \approx 84\, \mathrm{g/cm^2}$$

- hadron-induced shower (**elongation theorem**)

$$D^{had}_{10} = D^{\gamma}_{10}\, (1 - B_n - B_\lambda)$$

$$B_n = \frac{d \ln \langle n(E) \rangle}{d \ln E}$$

$$B_\lambda = -\frac{\lambda_{int}}{\lambda_{rad}} \frac{d \ln \lambda_{int}}{d \ln E}$$

Lindsey & Watson PRL 46, 459, 1981

hadronic showers
cascade equations

- particle flux $\Phi(E,X) = \frac{dN}{dt\,dA\,dE}$

- evolution with column depth (for protons)

$$\frac{\partial \Phi_p(E,X)}{\partial X} = -\frac{\Phi_p(E,X)}{\lambda_{int,p}(E)} \qquad \text{loss}$$

$$+ \int_E^\infty \frac{1}{\lambda_{int,p}(E)}\,\Phi_p\left(\tilde{E},X\right)\,\frac{dn_{p\to p}}{dE}(\tilde{E},E)\,d\tilde{E} \qquad \text{production}$$

- **reminds you anything familiar ?**

$$\frac{\partial n_\gamma(E,t)}{\partial t} = -\sigma_0\, n_\gamma(E,t) + \int_0^1 \frac{dv}{v}\,\varphi(v)\,n_e\left(\frac{E}{v},t\right)$$

$t = \frac{X}{\lambda_{rad}}$ $\qquad v = \frac{E_e}{E_\gamma}$

$n_\gamma(E,t) = K\, r_\gamma^{(1)}(s)\, E^{-(s+1)}\, e^{\lambda_1(s)\,t}$ ansatz

hadronic showers
cascade equations

- evolution with column depth (for protons)

$$\frac{\partial \Phi_p(E,X)}{\partial X} = -\frac{\Phi_p(E,X)}{\lambda_{int,p}(E)} \qquad \text{loss}$$

$$+\int_E^\infty \frac{1}{\lambda_{int,p}(E)}\,\Phi_p\left(\tilde{E},X\right)\,\frac{dn_{p\to p}}{dE}(\tilde{E},E)\,d\tilde{E} \qquad \text{production}$$

- ansatz $\Phi(E,X) = A(X)\,E^{-(\gamma+1)}$

- factorized equation

$$E^{-(\gamma+1)}\,\frac{\partial A_p(X)}{\partial X} = -E^{-(\gamma+1)}\,\frac{A_p(X)}{\lambda_{int,p}}\left[1-\int_E^\infty\left(\frac{\tilde{E}}{E}\right)^{-(\gamma+1)}\frac{dn_{p\to p}}{dE}\,d\tilde{E}\right]$$

hadronic showers
cascade equations

- factorized equation

$$E^{-(\gamma+1)} \frac{\partial A_p(X)}{\partial X} = -E^{-(\gamma+1)} \frac{A_p(X)}{\lambda_{int,p}} \left[1 - \int_E^\infty \left(\frac{\tilde{E}}{E}\right)^{-(\gamma+1)} \frac{dn_{p\to p}}{dE} \, d\tilde{E}\right]$$

- assume scaling $\frac{dn_{p\to p}}{dE}(E,\tilde{E}) = \frac{1}{\tilde{E}} \frac{dn_{p\to p}}{dx_{\mathrm{LAB}}}$ $\quad dx_{\mathrm{LAB}} = \frac{E}{\tilde{E}}$

$$\frac{\partial A_p(X)}{\partial X} = -\frac{A_p(X)}{\lambda_{int,p}} \left[1 - \int_0^1 x_{\mathrm{LAB}}^{\gamma} \frac{dn_{p\to p}}{dx_{\mathrm{LAB}}} \, dx_{\mathrm{LAB}}\right]$$

$$\frac{\partial A_p(X)}{\partial X} = -\frac{A_p(X)}{\lambda_{int,p}} \left[1 - Z_{pp}\right]$$

Z_{pp} - spectrum-weighted moment

hadronic showers
cascade equations

- equation

$$\frac{\partial A_p(X)}{\partial X} = -\frac{A_p(X)}{\lambda_{int,p}} \left[1 - Z_{pp}\right]$$

- solution (inclusive flux can be numerically calculated)

$$\Phi_p(E, X) = A_0 \, e^{-X/\Lambda_{pp}} \, E^{-(\gamma+1)} \qquad \Lambda_{pp} = \frac{\lambda_{int,p}}{1 - Z_{pp}}$$

attenuation length

- in reality the hadronic cascade equations contains **many loss and coupled production channels** and the Z-factors need to be determined using **collider data** or **calculated multiplicity spectra**

hadronic showers
cascade equations

Anatoli Fedynitch, ISVHECRI 2014
MCEq cascade equations integrator
https://github.com/afedynitch/MCEq

- in reality the hadronic cascade equations contains **many loss and coupled production channels** and the Z-factors need to be determined using **collider data** or **calculated multiplicity spectra**

$$\frac{\mathrm{d}\Phi_h(E,X)}{\mathrm{d}X} =$$

LOSSES

$$-\frac{\Phi_h(E,X)}{\lambda^h_{int,h}(E)}$$ loss due to interaction

$$-\frac{\Phi_h(E,X)}{\lambda_{dec,h}(E,X)}$$ loss due to decays

$$+\frac{\partial}{\partial E}(b(E)\Phi_h(E,X))$$ continuous energy loss

GAINS

$$+\sum_l S(l \rightarrow h, E)$$ production due to interactions of other particles

$$+\sum_l S^D(h \rightarrow h, E)$$ production due to decays of other particles

hadronic showers
couplings in cascade equations

- assuming p, n and pion system only

- pion inclusive flux

$$\frac{d\Phi_\pi}{dX} = \underbrace{-\frac{\Phi_\pi}{\lambda_{int,p}} - \frac{\Phi_\pi}{\lambda_{dec,\pi}}}_{\text{loss}} + \underbrace{Z_{\pi\pi}\frac{\Phi_\pi}{\lambda_{int,\pi}} + \underbrace{Z_{p\pi}\frac{\Phi_p}{\lambda_{int,p}} + Z_{n\pi}\frac{\Phi_n}{\lambda_{int,n}}}_{\text{nucleon-pion coupling}}}_{\text{production}}$$

loss: feeds cascade; μ,ν

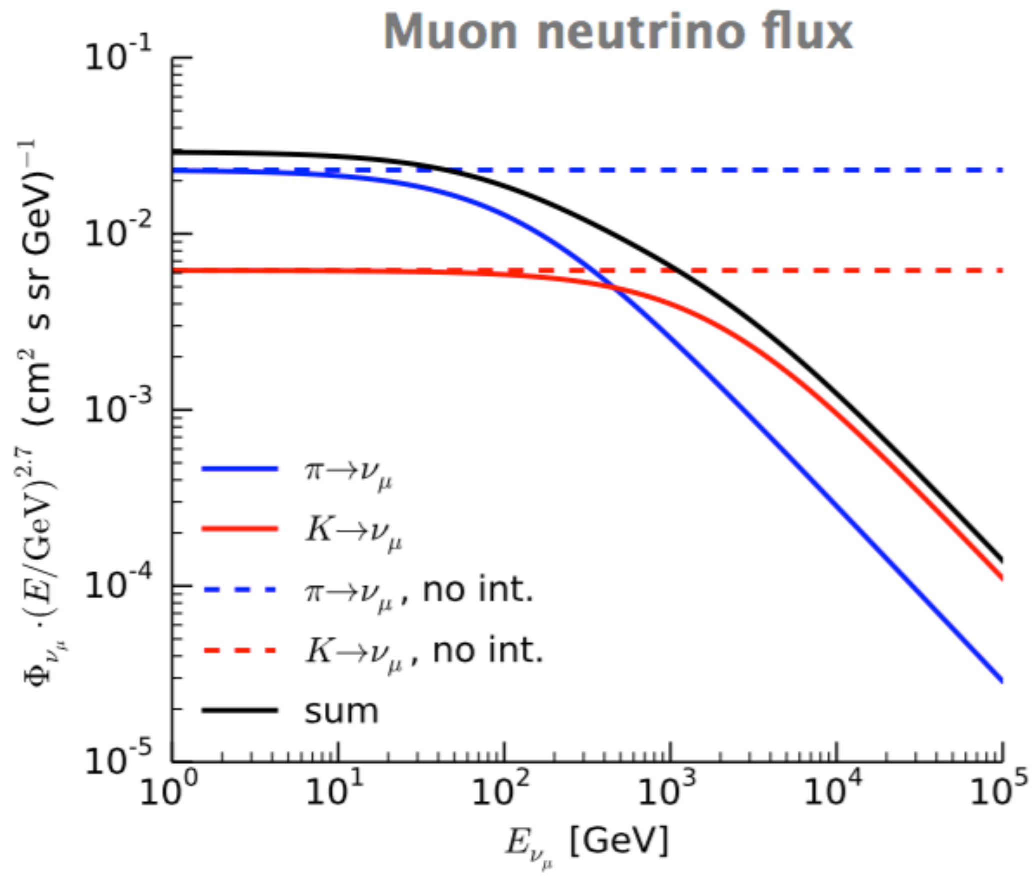
- muon inclusive flux $$\frac{d\Phi_\mu}{dX} = -\frac{\Phi_\mu}{\lambda_{dec,\mu}} + Z^{\text{decay}}_{\pi\to\mu}\frac{\Phi_\pi}{\lambda_{dec,\pi}}$$

- neutrino inclusive flux $$\frac{d\Phi_\nu}{dX} = Z^{\text{decay}}_{\pi\to\nu}\frac{\Phi_\pi}{\lambda_{dec,\pi}}$$

- competition between decay and interaction

hadronic showers
inclusive neutrino flux

Anatoli Fedynitch



- low energy (no pion interaction term)

$$\Phi_\nu(E) \propto \Phi_\pi \propto E^{-\gamma_{CR}}$$

- high energy (no pion decay term)

$$\Phi_\nu(E) \propto \Phi_\pi \propto E^{-(\gamma_{CR}+1)}$$

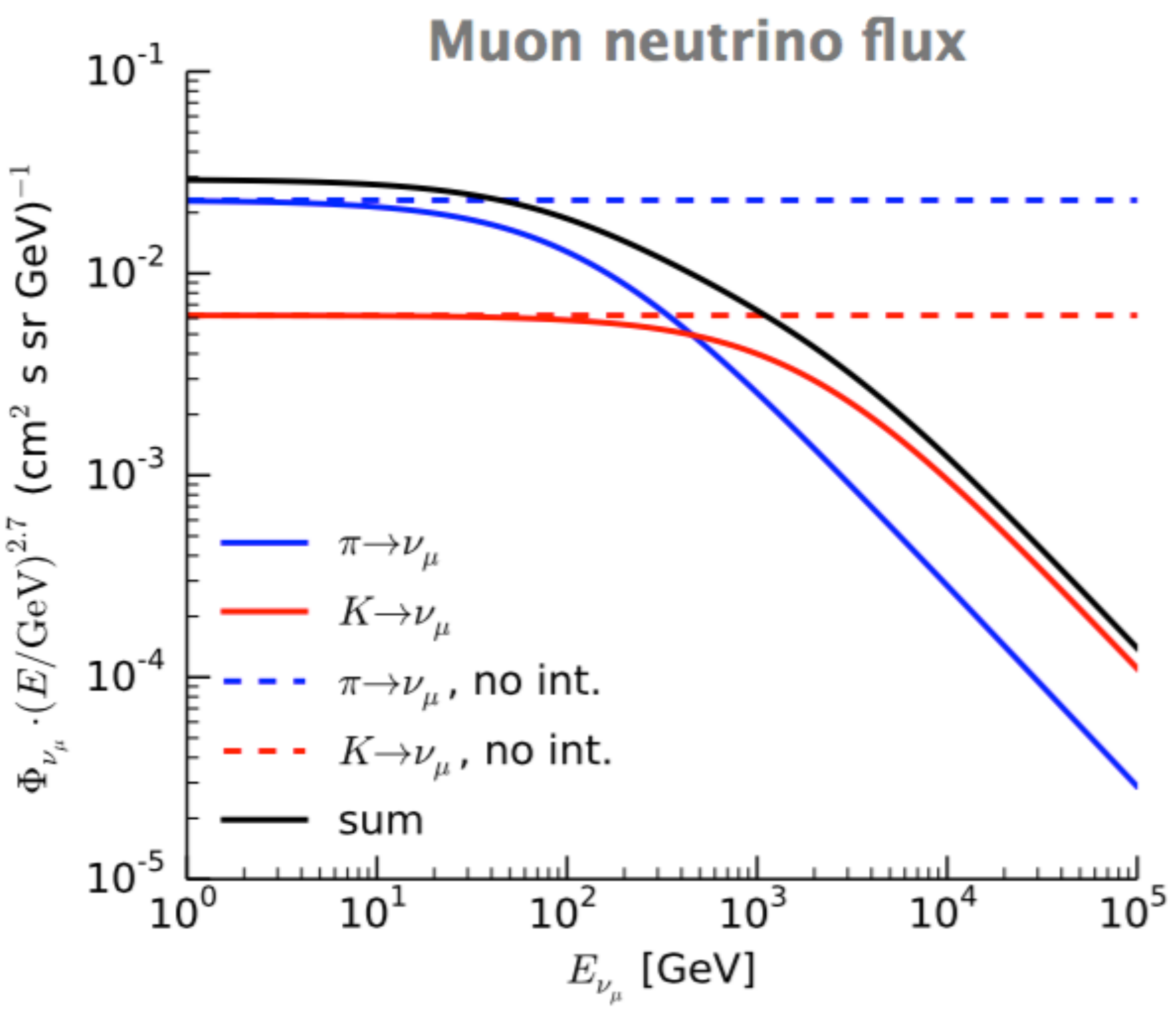
- interpolation

$$\frac{\Phi_{LE}\,\Phi_{HE}}{\Phi_{LE} + \Phi_{HE}}$$

hadronic showers
inclusive neutrino flux

- neutrino flux

$$\Phi_\nu(E) = \frac{\Phi_N(E)}{1 - Z_{NN}} \left(\frac{A_{\pi\nu}}{1 + B_{\pi\nu}\, E\, cos\theta^\star / \epsilon_\pi} + \frac{A_{K\nu}}{1 + B_{K\nu}\, E\, cos\theta^\star / \epsilon_K} \right)$$



Anatoli Fedynitch

inclusive spectrum
convolution with primary cosmic ray spectrum

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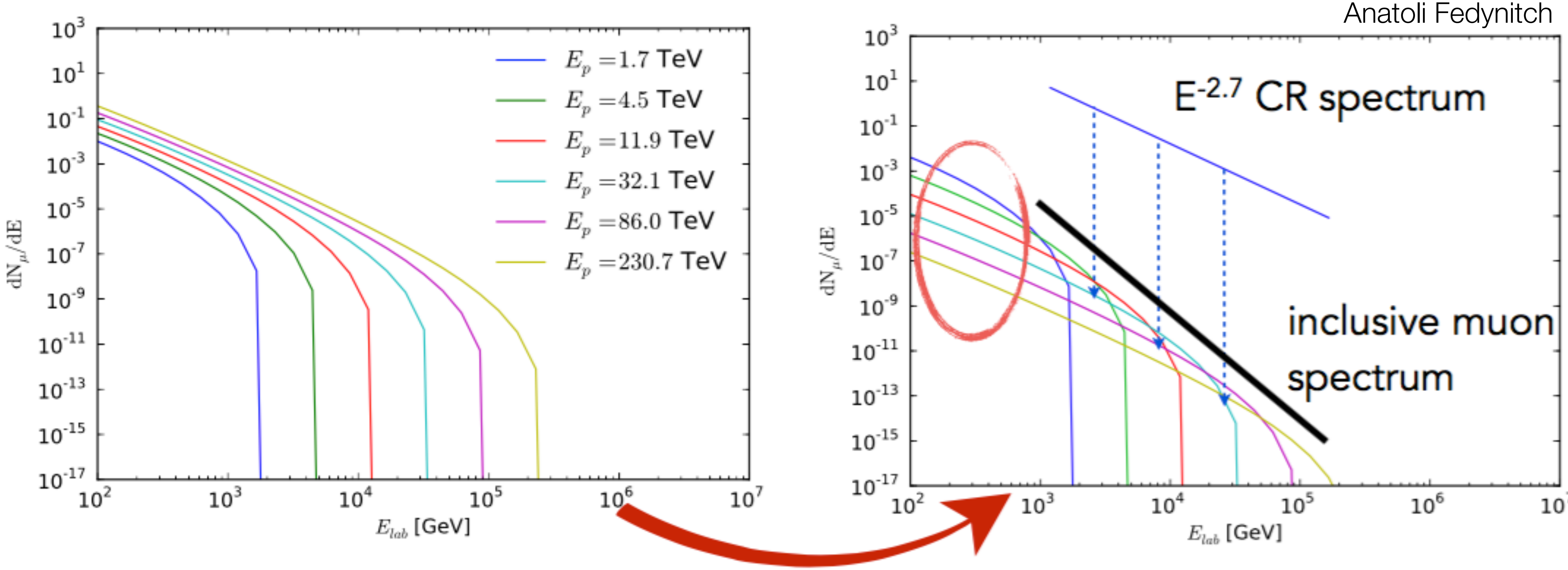


$$\Phi_\mu(E_\mu) = \sum_p \sum_{E_i} w_p(E_i) \times Y_{p\rightarrow\mu}(E_\mu, E_i)$$

nuclei composition

primary spectrum

μ production yield
e.g. from MC calculations

inclusive lepton spectra
interactions in the atmosphere

- inclusive lepton spectrum in the atmosphere

$$\phi_l(E_l) = \phi_N(E_l) \times \left\{ \frac{A_{\pi l}}{1 + B_{\pi l} \cos\theta \, E_l/\epsilon_\pi} + \frac{A_{Kl}}{1 + B_{Kl} \cos\theta \, E_l/\epsilon_K} + \ \ldots \right\}$$

$\phi_N(E) \approx E^{-(\gamma+1)}$

hadronization & cascading

- spectrum-weighted Z-moments

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

$i = \pi, K$

- for inclusive π^+ production

$$Z_{N\pi^+} = \frac{1}{\sigma_N^{air}} \int_0^1 x^\gamma \frac{d\sigma_{N\pi^+}(x)}{dx} \, dx$$

$\gamma \approx 1.7$

(Feynman scaling)

$$x \equiv \frac{p_\parallel}{p_{\parallel,max}} \sim \frac{2p_\parallel}{\sqrt{s}}$$

spectrum-weighted moments

- energy-independent form

$$Z_{kh} = \int_0^1 x_{\mathrm{LAB}}^{\gamma} \frac{dn_{k\to h}}{dx_{\mathrm{LAB}}} \, dx_{\mathrm{LAB}}$$

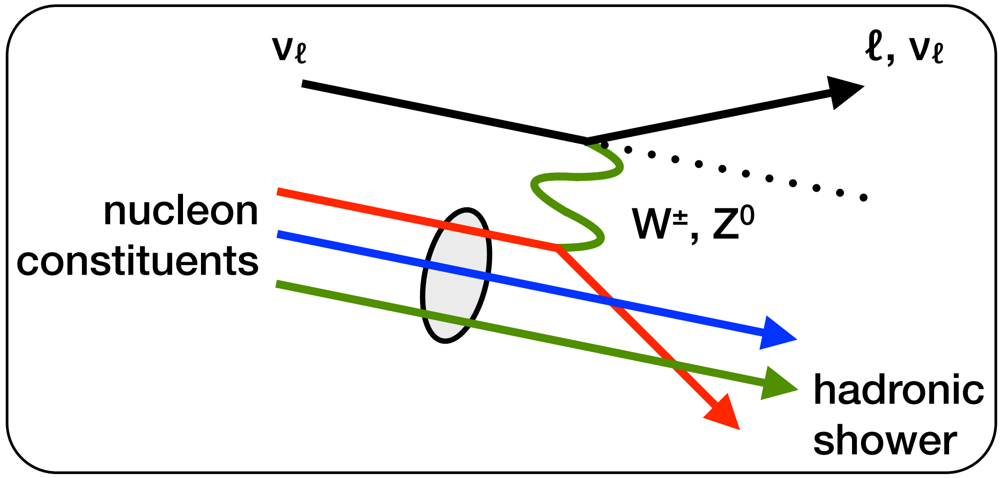
- energy-dependent with generic cosmic ray primary spectrum

$$Z_{kh}(E) = \int_E^{\infty} dE' \, \frac{d\Phi_N(E',\theta)}{d\Phi_N(E,\theta)} \, \frac{\sigma_{kA}(E')}{\sigma_{kA}(E)} \, \frac{dn_{k\to h}(E',E)}{dE}$$

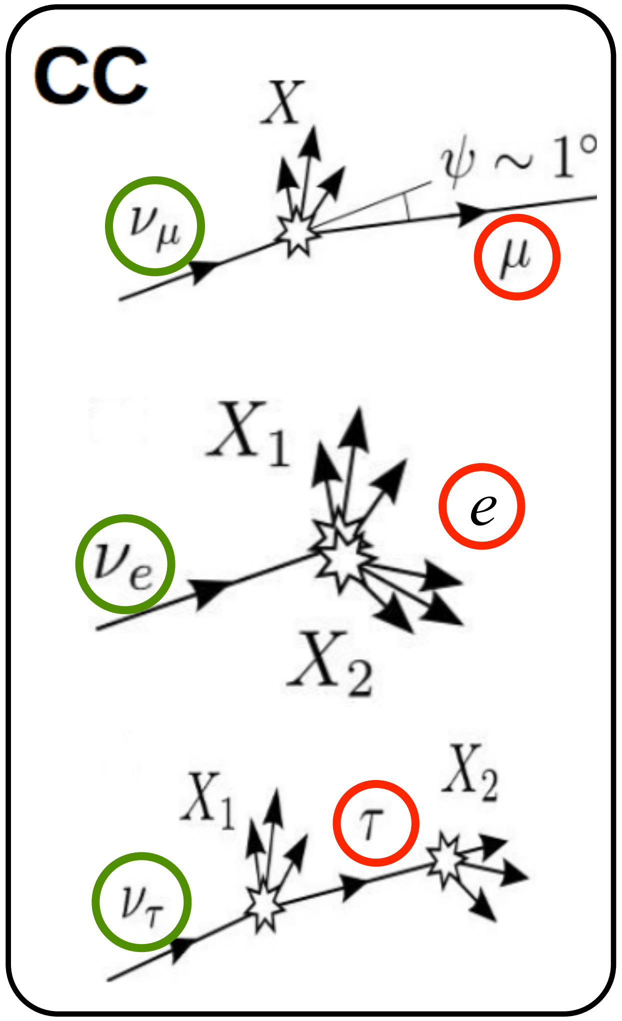
M. Thunman et al., Astropart. Phys. 5, 309 (1996)

detecting neutrinos

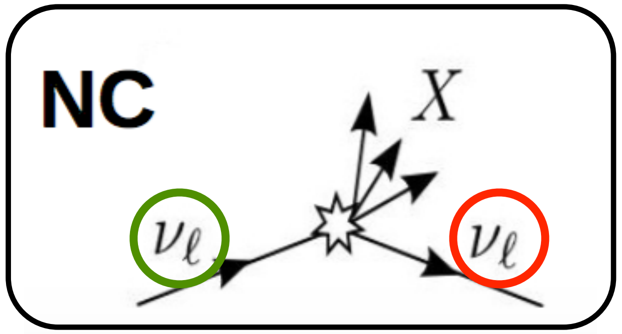
neutrino interactions with matter



- neutrino interacts with quark constituents of nucleons
- they exchange Z^0 (**neutral**) or $W^\pm$ (**charged**) bosons
  - **charged current** interaction
  - **neutral current** interaction



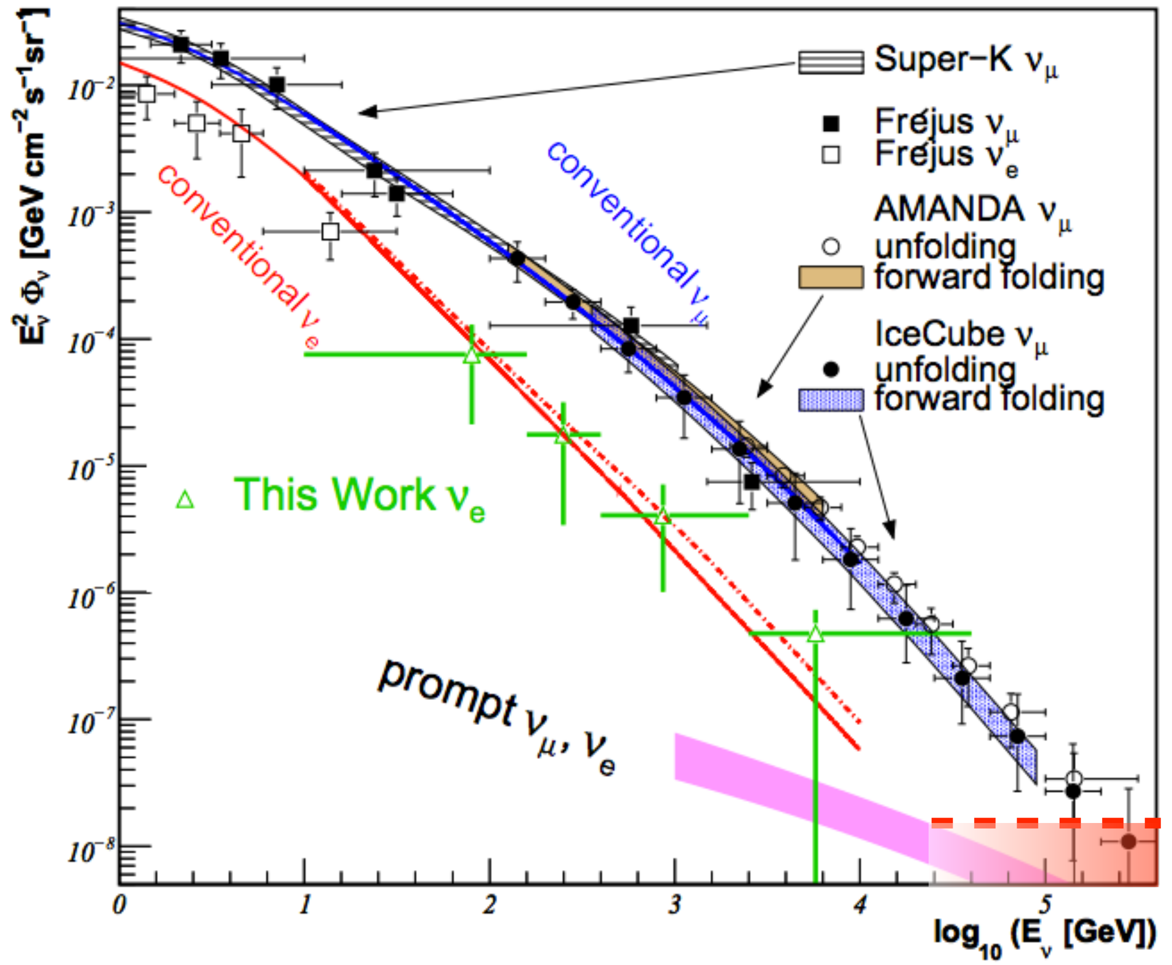
- **indirect detection of neutrinos**



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

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

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

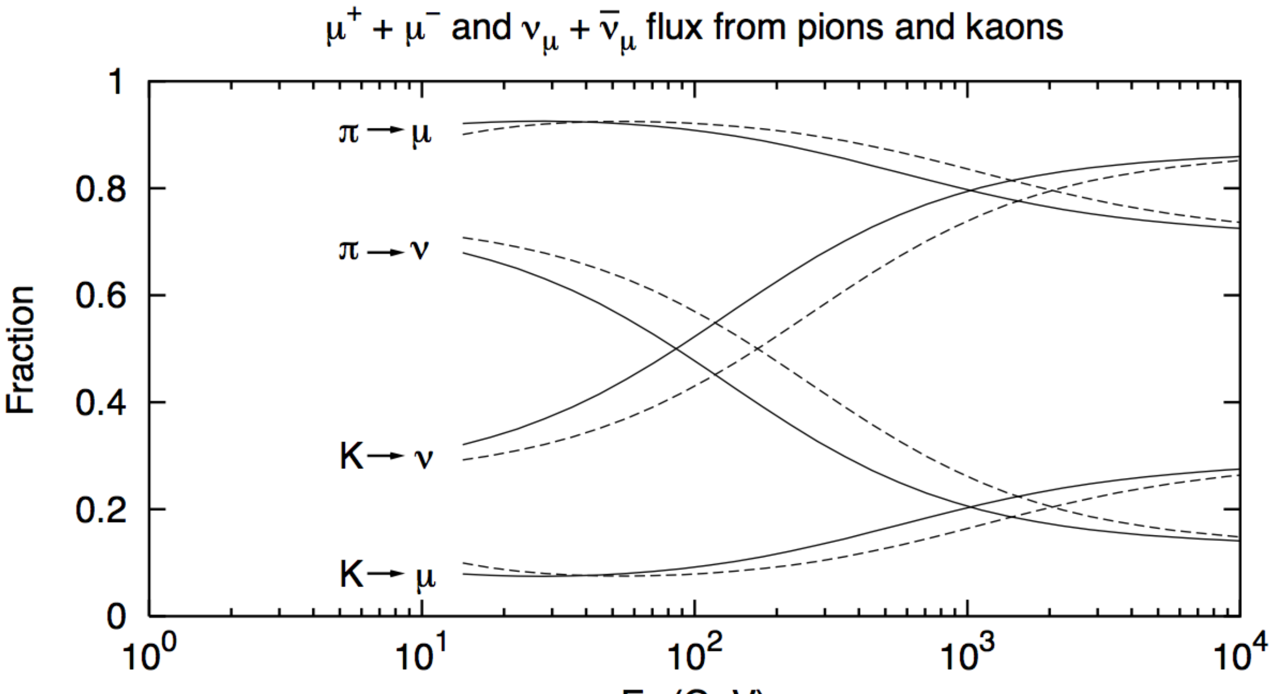
meson's characteristic energy

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

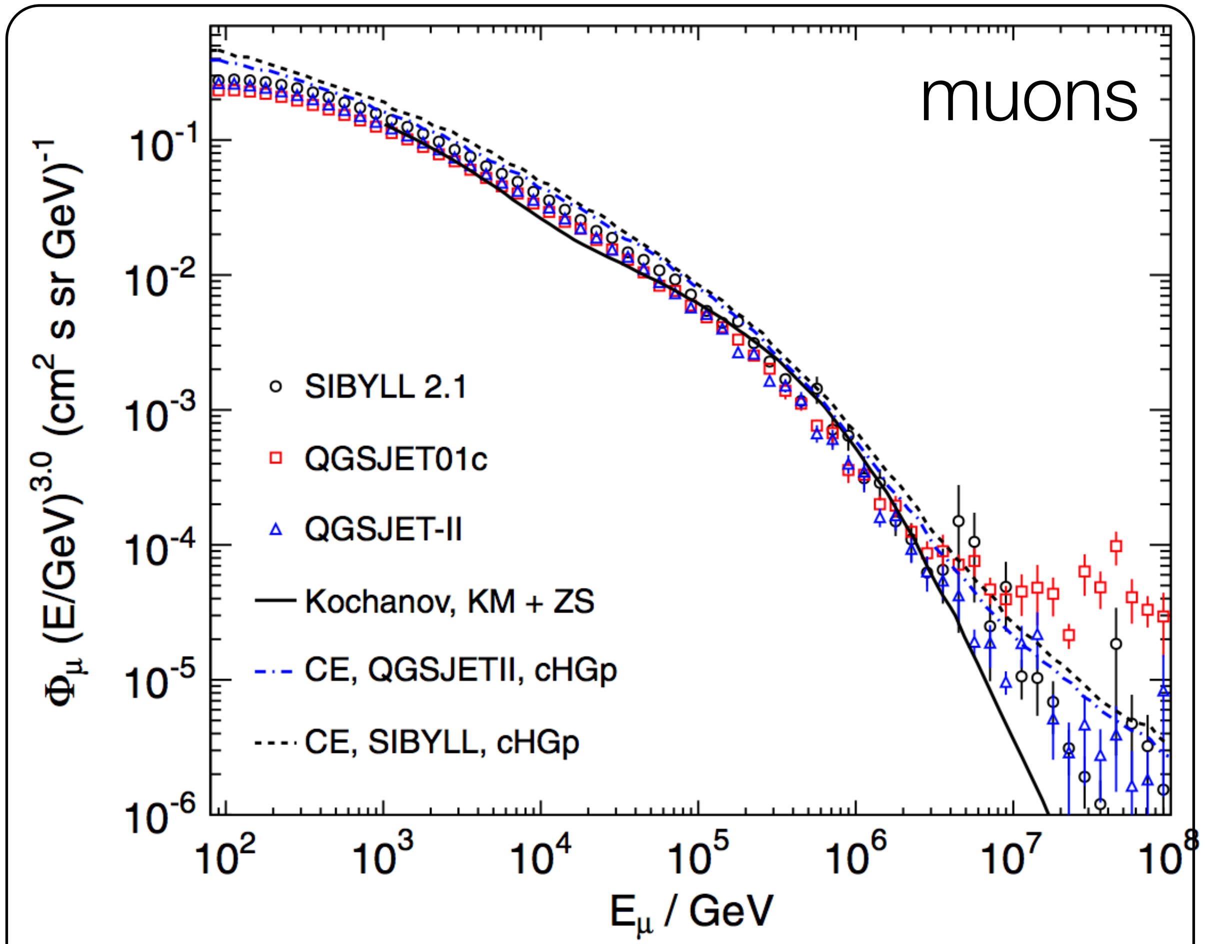
$$\phi_\nu(E_\nu) = \phi_N(E_\nu) \times \left\{ \frac{A_{\pi\nu}}{1 + B_{\pi\nu}\cos\theta\, E_\nu/\epsilon_\pi} + \frac{A_{K\nu}}{1 + B_{K\nu}\cos\theta\, E_\nu/\epsilon_K} + \frac{A_{\mathrm{charm}\,\nu}}{1 + B_{\mathrm{charm}\,\nu}\cos\theta\, E_\nu/\epsilon_{\mathrm{charm}}} \right\}$$

cosmic ray induced leptons

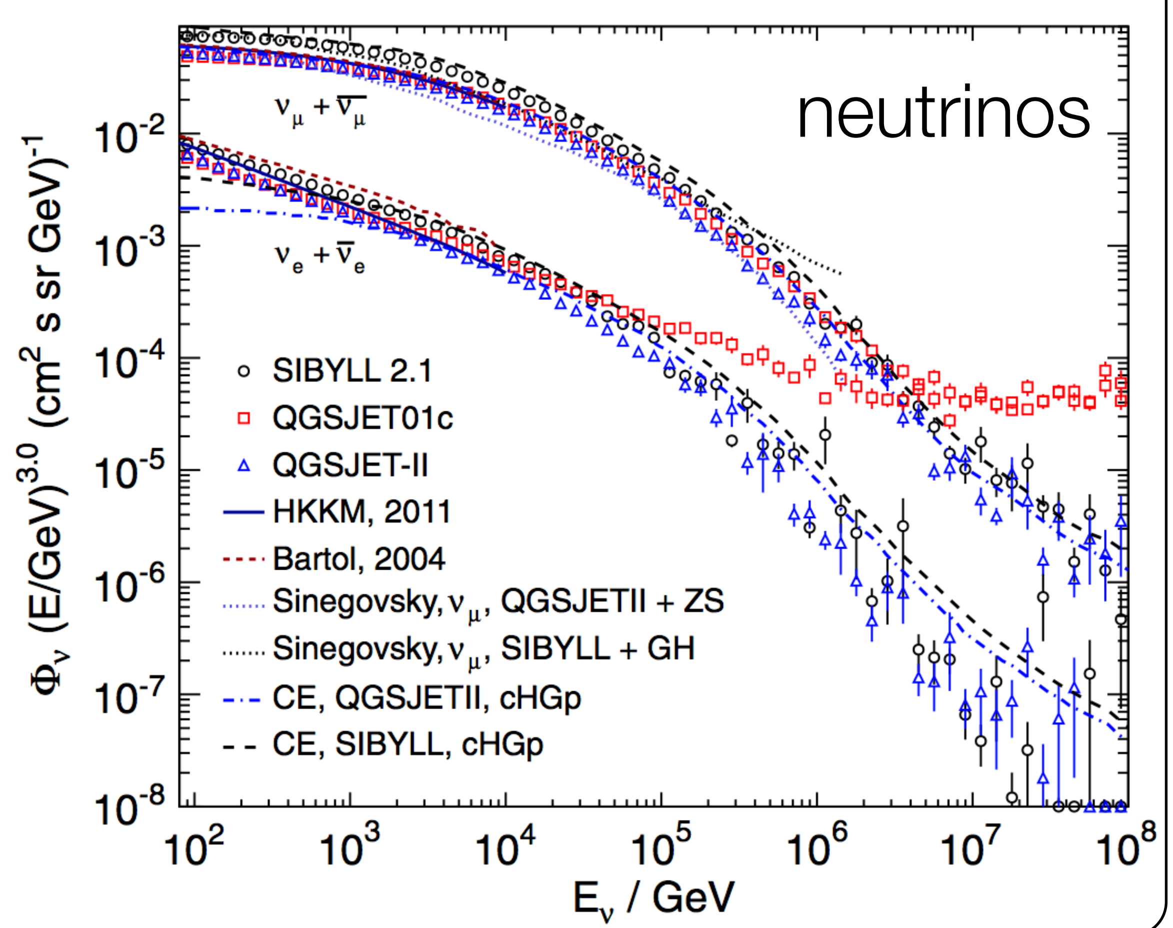
interactions in the atmosphere



Gaisser & Honda 2002



Fedynitch, Becker & PD 2013

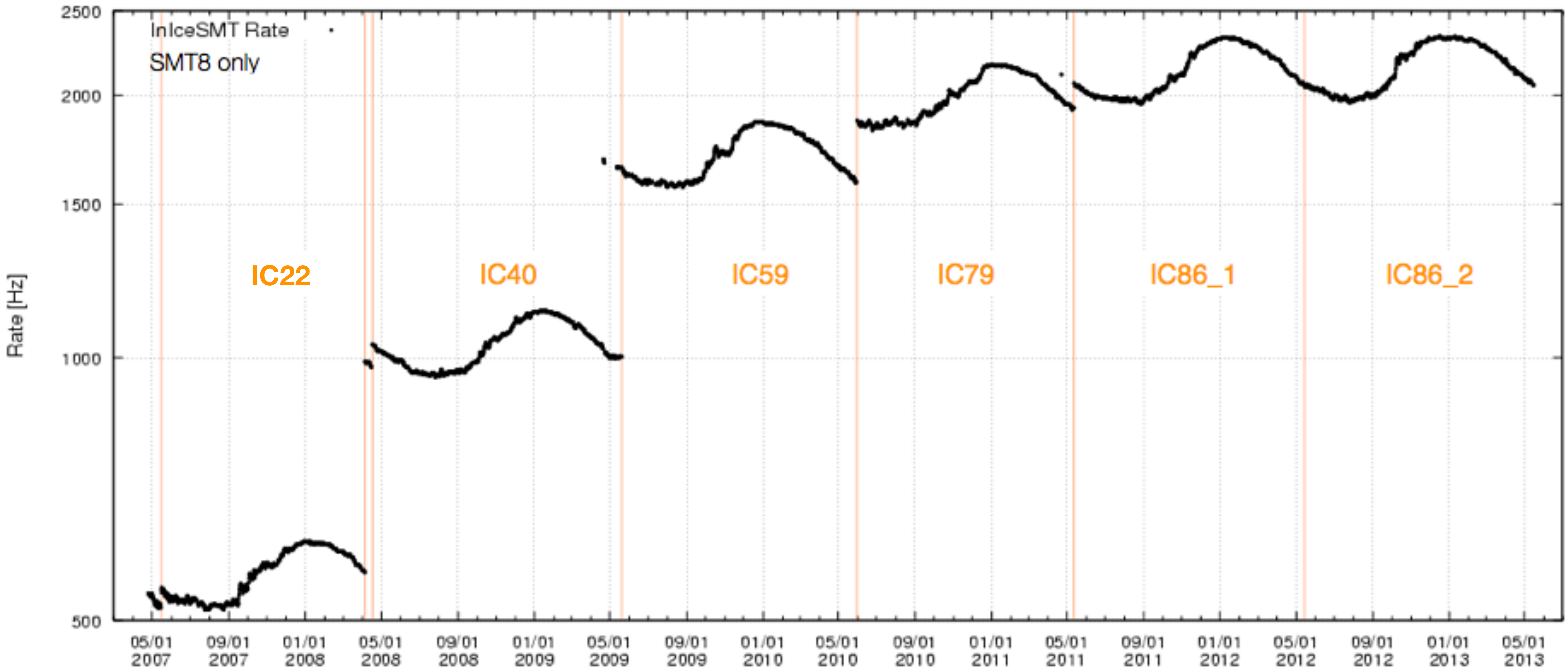


- kinematics: differences between π & K
- e neutrinos from (5%) $K^{\pm} \rightarrow \pi^0 e^{\pm} \nu_e(\bar{\nu}_e)$

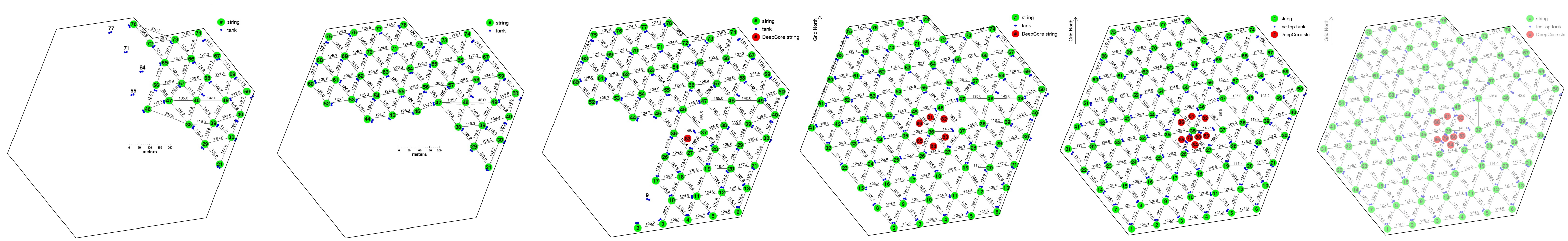
  and (41%) $K_L^0 \rightarrow \pi + e + \nu_e$

event rate in IceCube

growing experiment

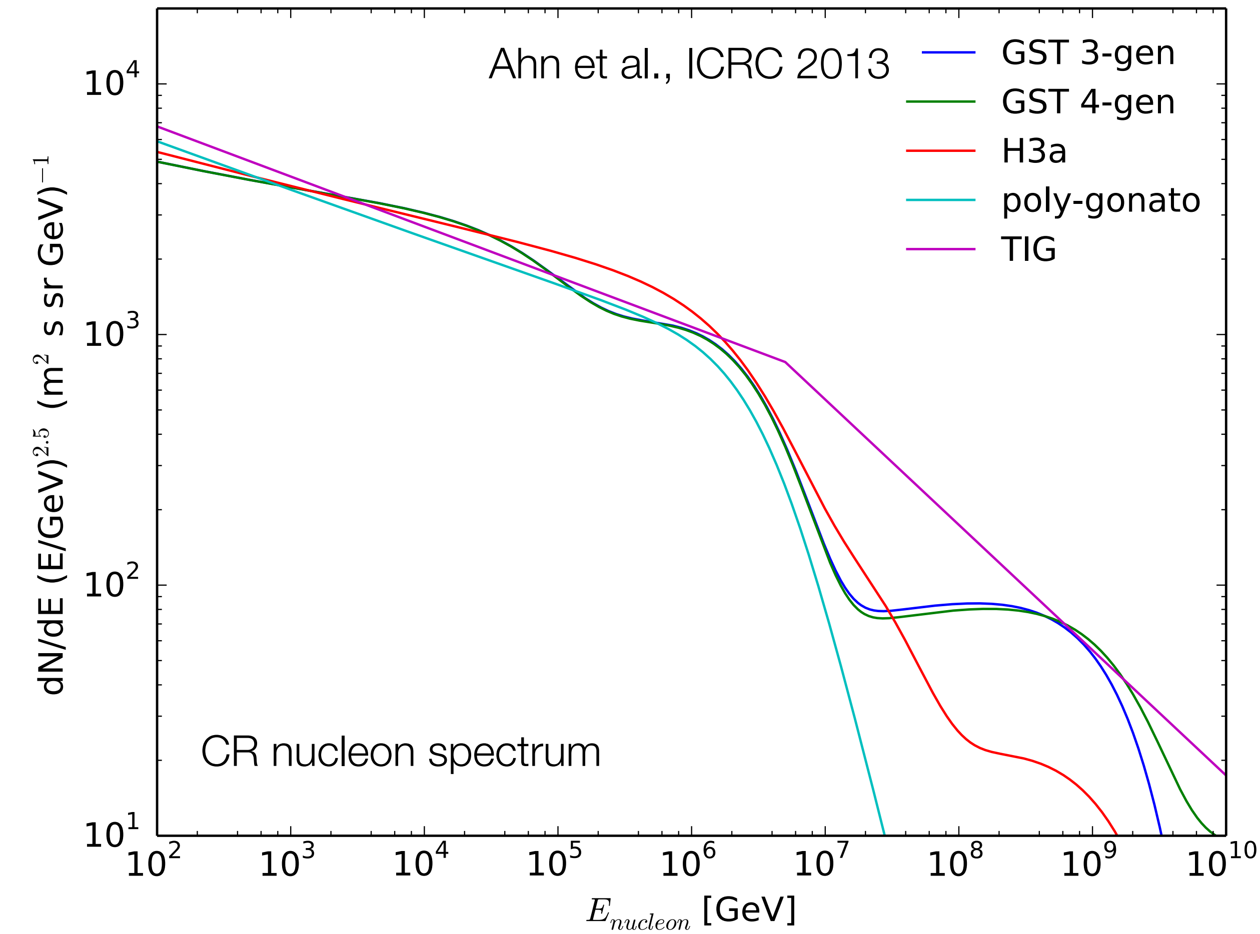


2007-08 2008-09 2009-10 2010-11 2011-12 2012-13 >>

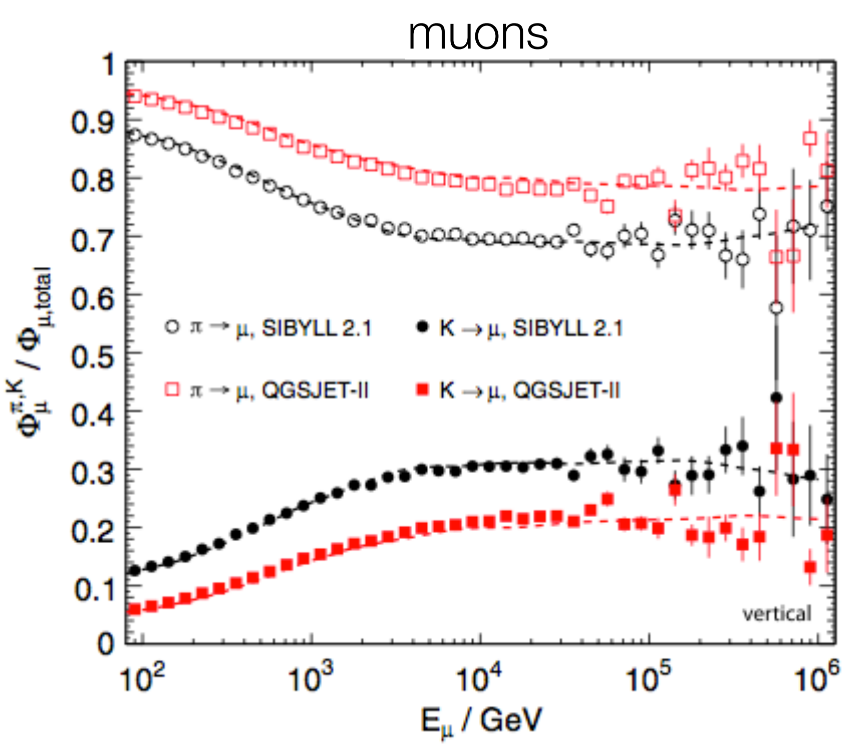


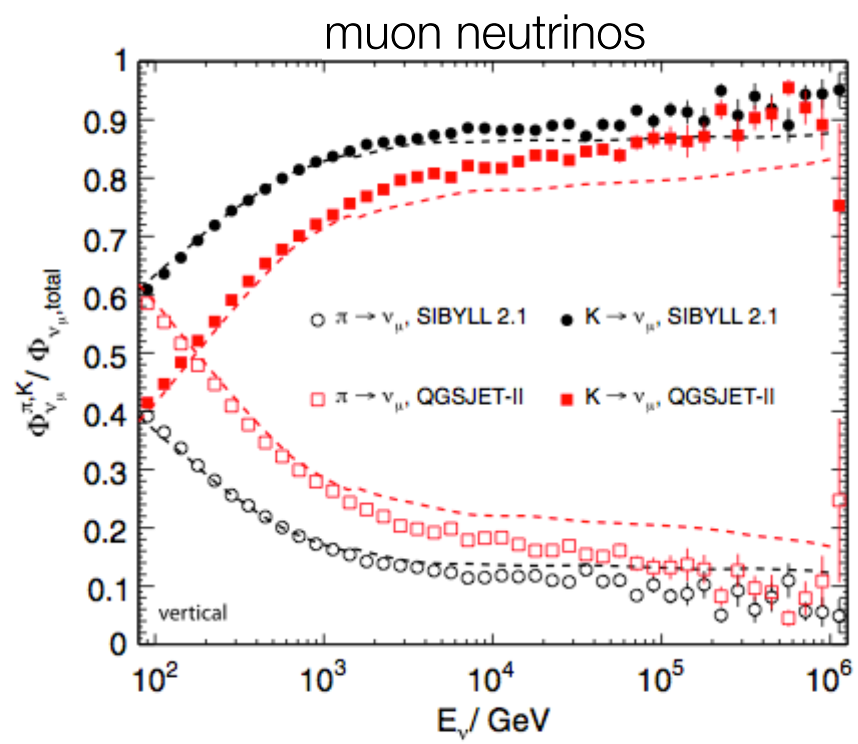
atmospheric neutrinos

high energy and heavy quarks

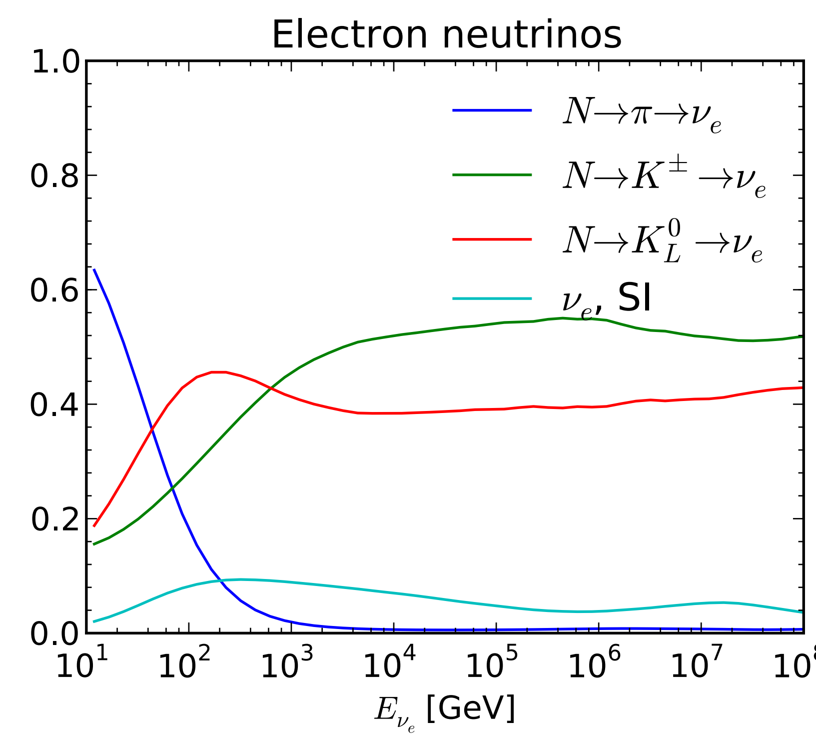


- large uncertainties in **cosmic ray composition** (nucleon spectrum) at high energy
- $K^{\pm}$ not same isospin group & K evolution equations coupled
- **associated production** p + Air → Λ + K^+





Fedynitch, Becker Tjus, PD 2012



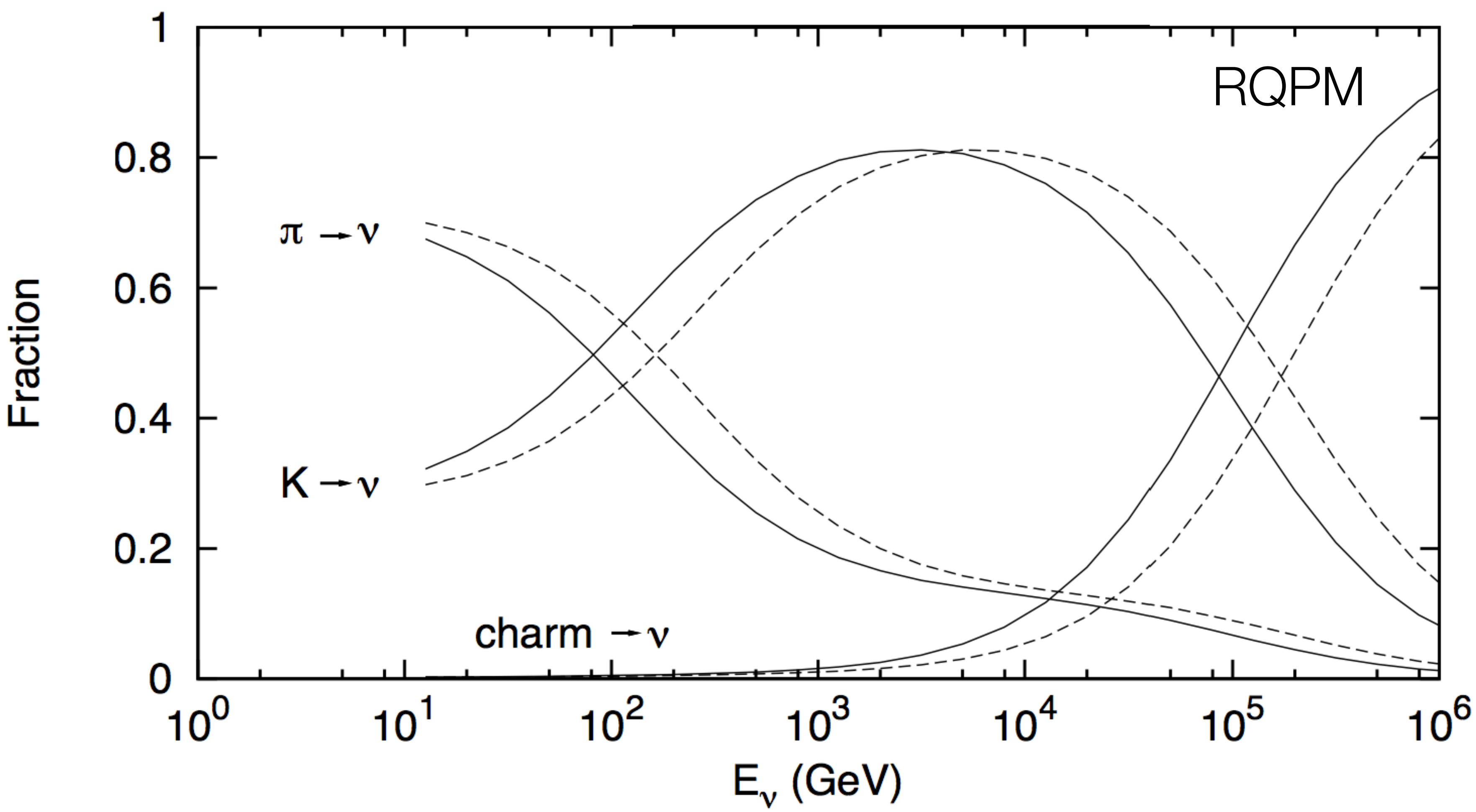
Sibyll 2.1 - Fedynitch

heavy quark production in the atmosphere

charm and prompt component

- **D** mesons and $\mathbf{\Lambda^+_c}$ baryons (with charm quark) decay "**promptly**"

$$\phi_l(E_l) = \phi_N(E_l) \times \left\{ \frac{A_{\pi l}}{1 + B_{\pi l} \cos\theta \, E_l/\epsilon_\pi} + \frac{A_{Kl}}{1 + B_{Kl} \cos\theta \, E_l/\epsilon_K} + \frac{A_{charm\, l}}{1 + B_{charm\, l} \cos\theta \, E_l/\epsilon_{charm}} \right\}$$



$$\tau_D \approx 10^{-12} sec$$

$$\tau_{\Lambda_c^+} \approx 10^{-13} sec$$

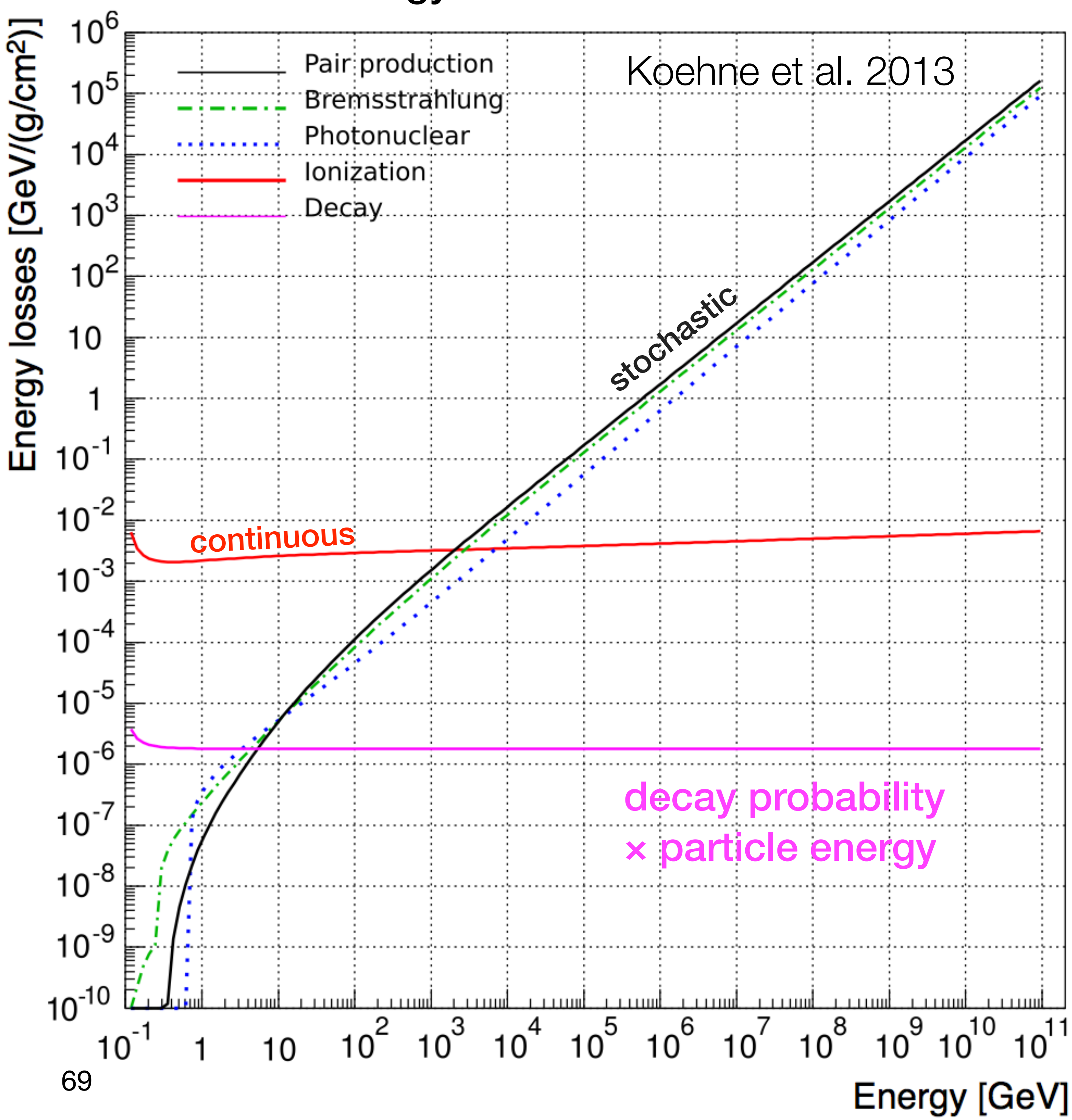
$$\epsilon_{D^0} = 9.2 \times 10^7 GeV$$

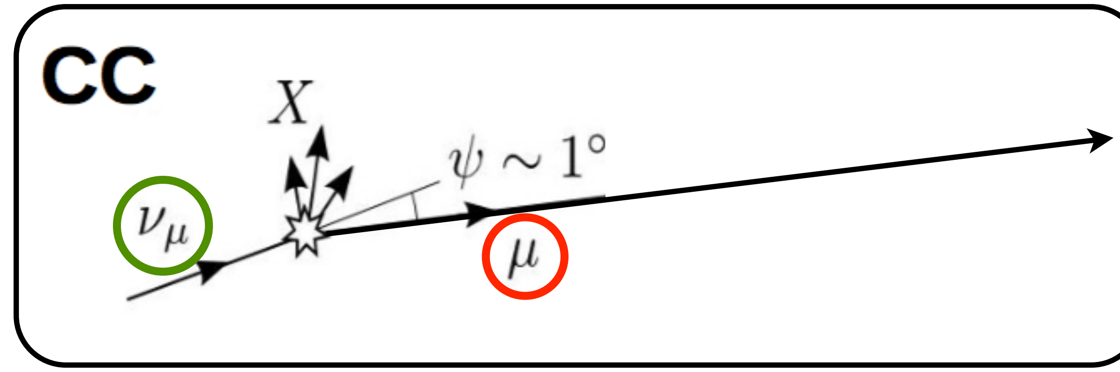
$$\epsilon_{D^\pm} = 4.3 \times 10^7 GeV$$

detecting neutrinos

detection of charged leptons

energy losses of muons in ice





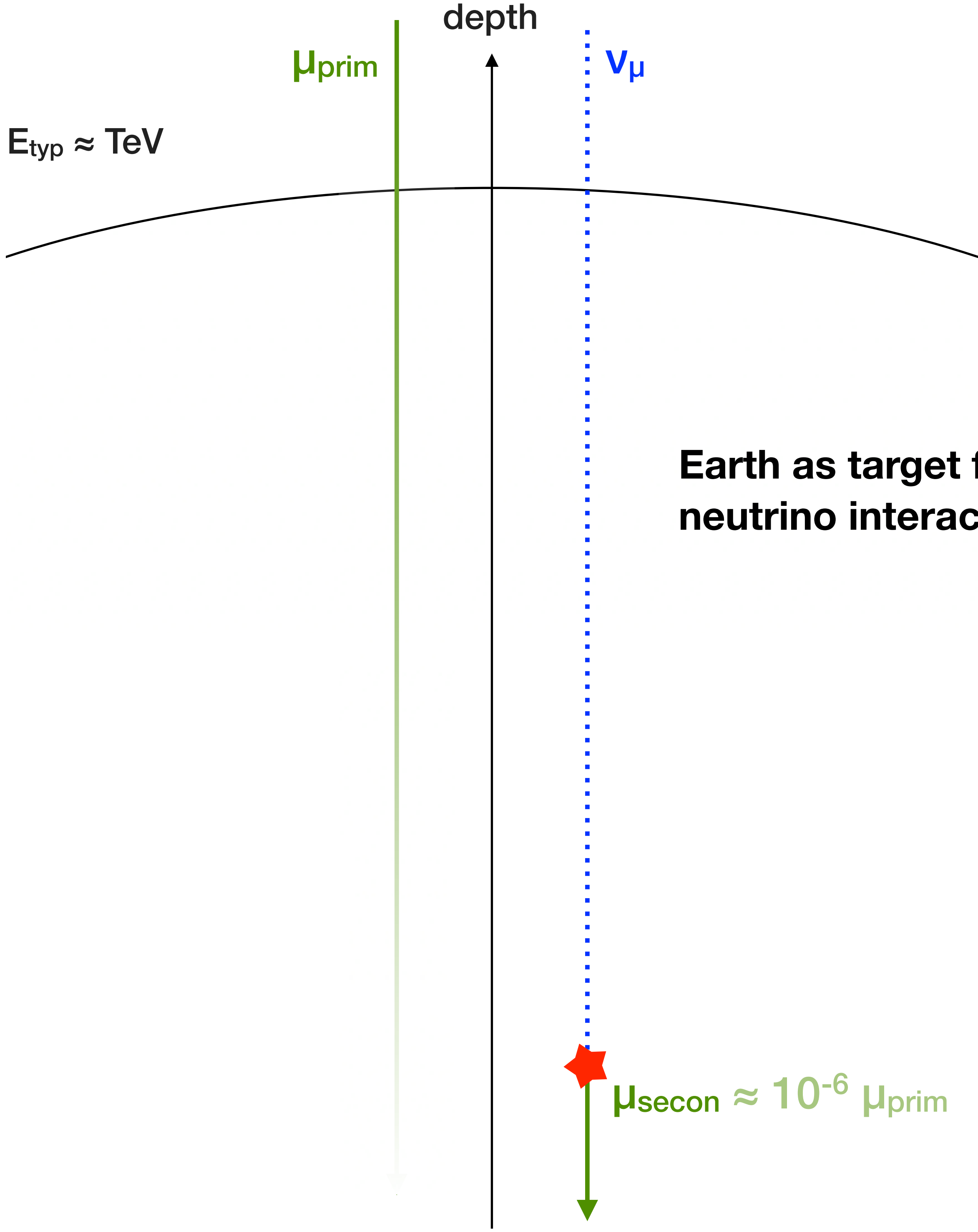
- **indirect detection of ν_μ neutrinos**

$$-\frac{dE_\mu}{dX} = a(E_\mu) + b(E_\mu)\,E_\mu$$

$$a = a_{ionization}$$

$$b = b_{brems} + b_{pair} + b_{nucl}$$

detecting neutrinos
detection of charged leptons



Earth as target for neutrino interactions

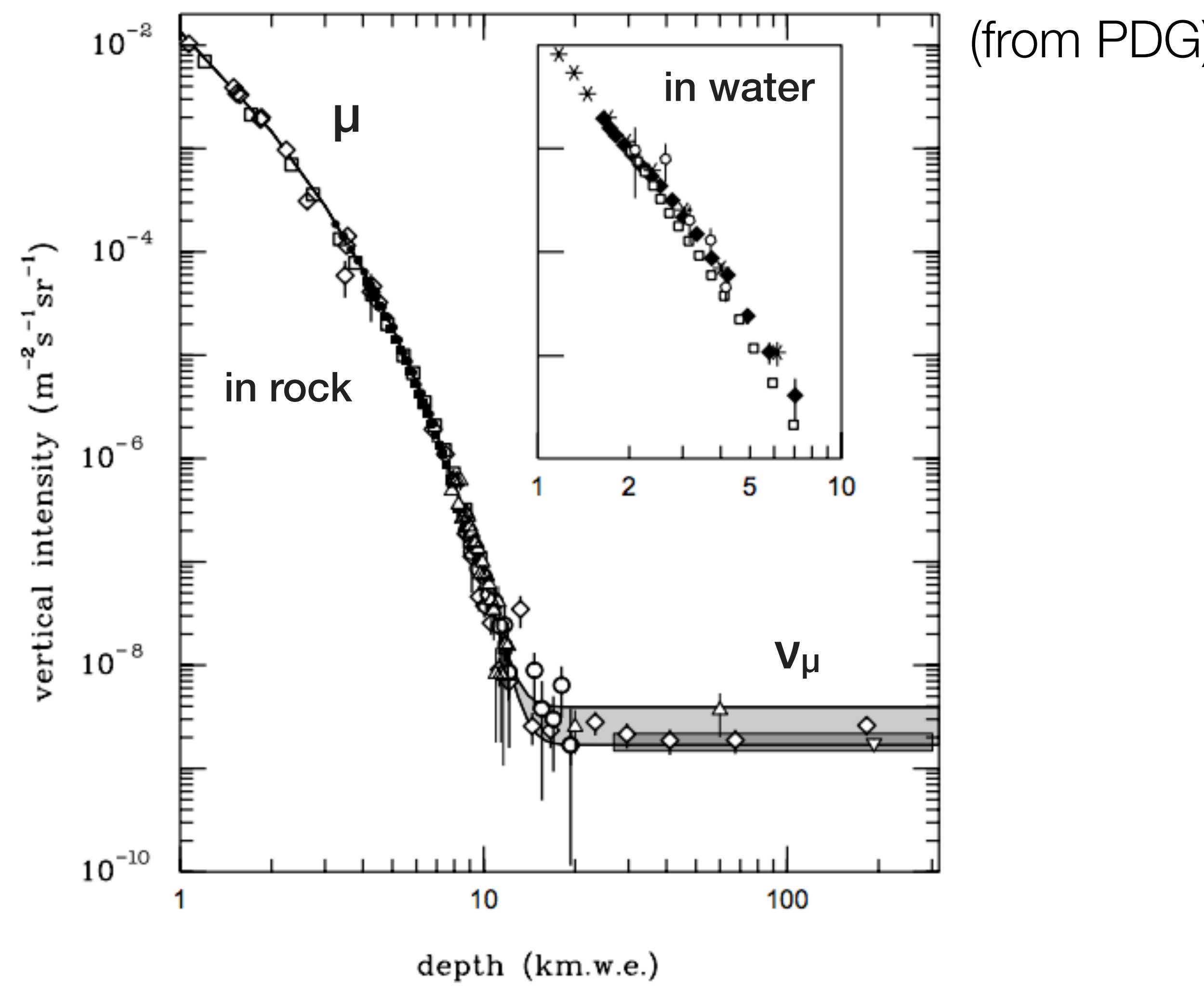
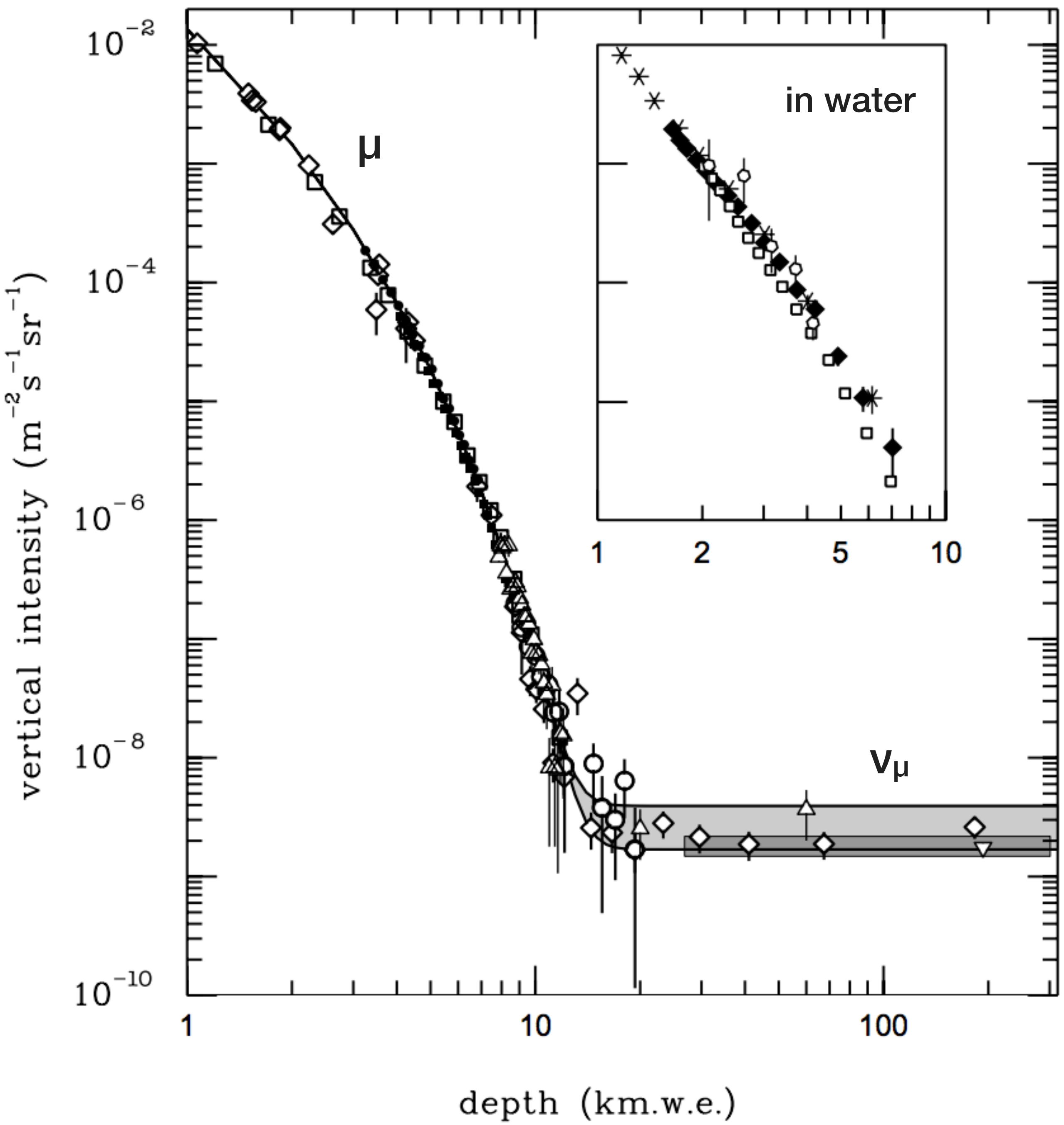


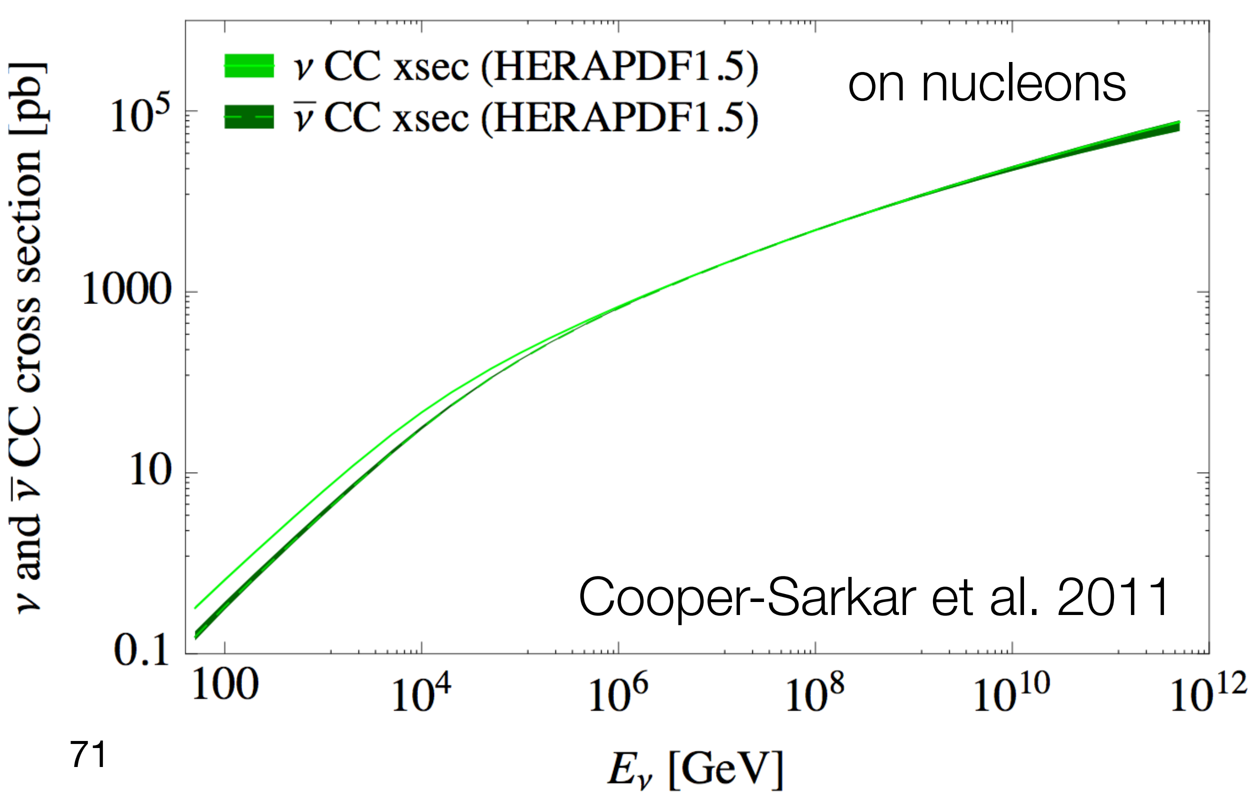
Figure 27.7: Vertical muon intensity vs depth (1 km.w.e. = 10^5 g $cm^{-2}$of standard rock). The experimental data are from: ◊: the compilations of Crouch [67], □: Baksan [72], ∘: LVD [73], •: MACRO [74], ■: Frejus [75], and △: SNO [76]. The shaded area at large depths represents neutrino-induced muons of energy above 2 GeV. The upper line is for horizontal neutrino-induced muons, the lower one for vertically upward muons. Darker shading shows the muon flux measured by the SuperKamiokande experiment. The inset shows the vertical intensity curve for water and ice published in Refs. [68–71].

primary cosmic rays
underground detection

- muons are penetrating but they lose energy within 10-20 km
- at greater depths experiments observe neutrino-induced muons
- $\nu_\mu(\bar{\nu}_\mu) + N \to \mu^\pm + X$ (CC interaction)

(from PDG)



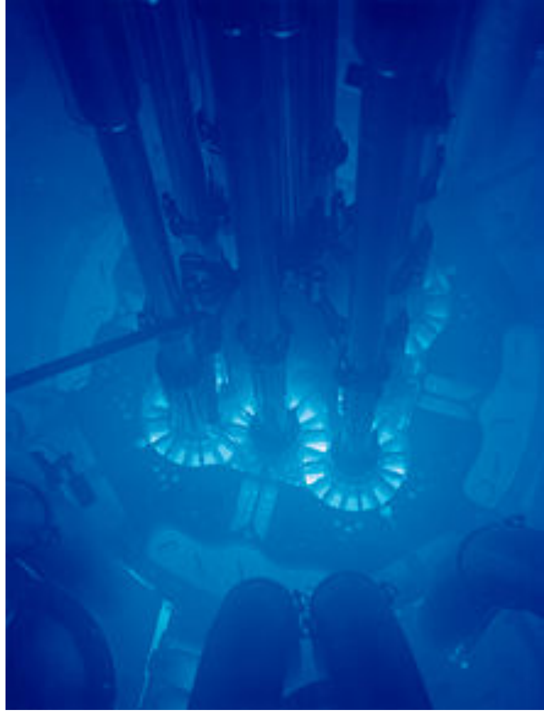


$$\Phi_\mu(E_\mu) \approx \Phi_\nu(E_\nu) \times P_{\nu\mu}(E_\nu, E_\mu)$$

$$P_{\nu\mu}(E_\nu, E_\mu) \approx \frac{N_A}{A_{ice}} \times \sigma^{CC}_{\nu\mu}(E_\nu) \times R_\mu(E_\mu)$$

detecting neutrinos in transparent media

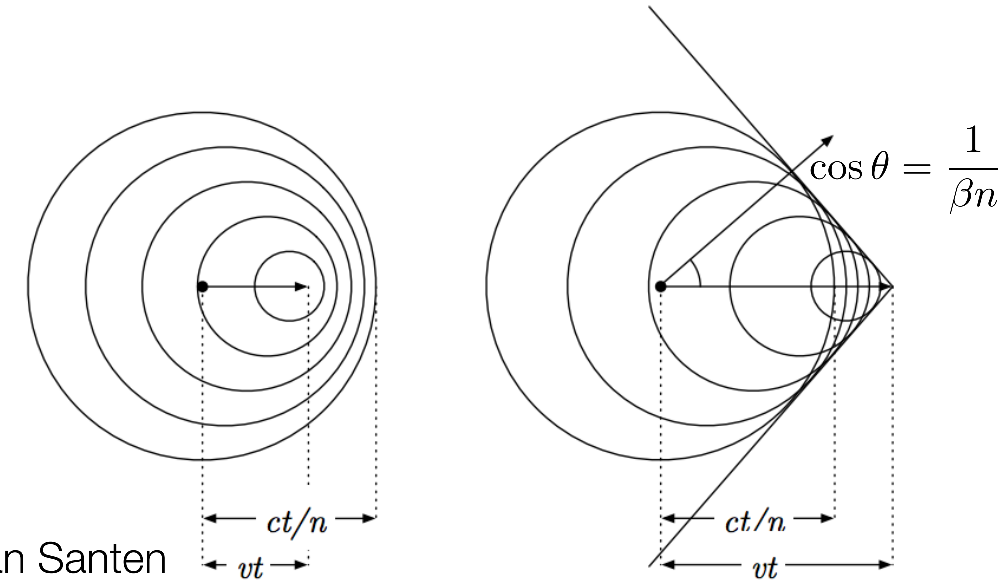
Cherenkov Effect



- electromagnetic radiation emitted when a charged particle passes through a **dielectric** medium at a speed greater than the phase velocity of light in that medium ($v > c/n_{medium}$)

- atoms near the particle become polarized and emit coherent radiation when returning to equilibrium

$$\frac{dN^2}{dx\,d\lambda} = \frac{2\pi\alpha}{\lambda^2}\left(1 - \frac{1}{\beta^2 n^2}\right)$$



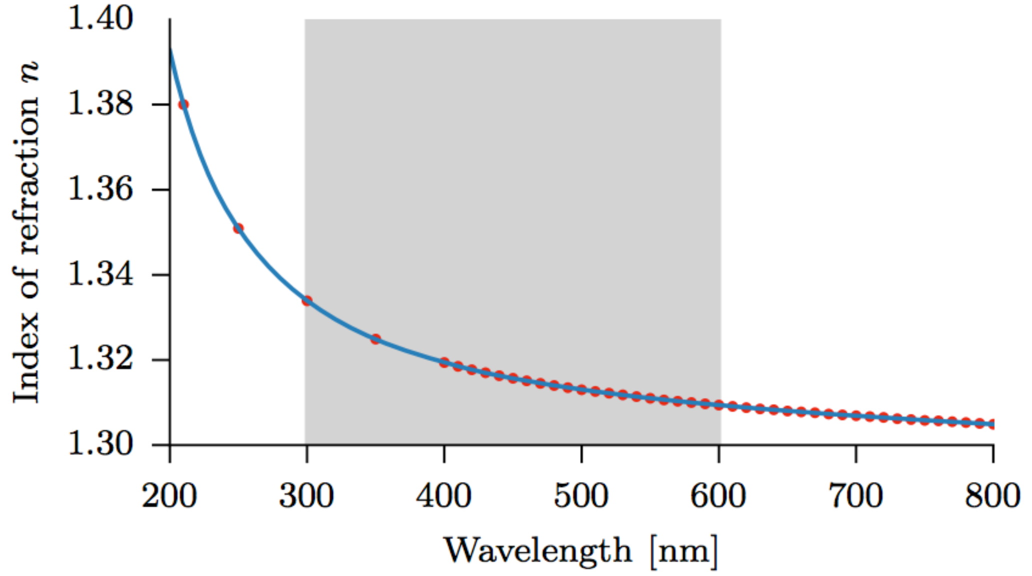
credit: J. van Santen

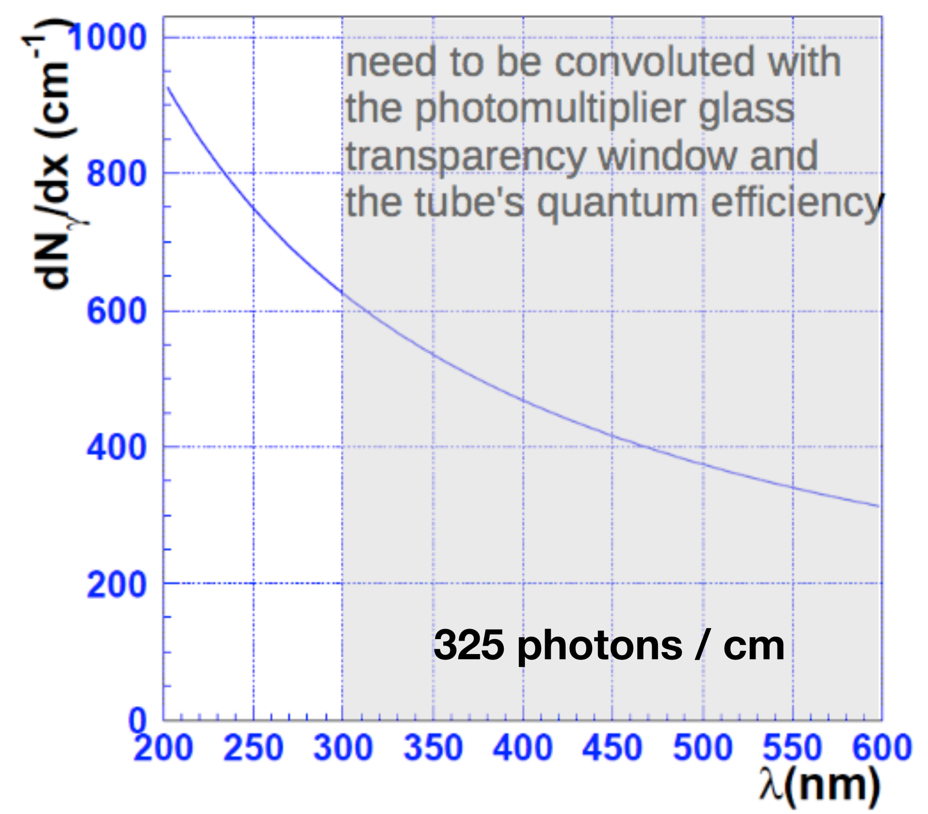
detecting neutrinos in transparent media
Cherenkov Effect

$$\frac{dN^2}{dx\,d\lambda} = \frac{2\pi\alpha}{\lambda^2}\left(1 - \frac{1}{\beta^2 n^2}\right)$$

$$\frac{dN}{dx} = 2\pi\alpha\sin^2\theta\left(\frac{1}{\lambda_1} - \frac{1}{\lambda_2}\right)$$

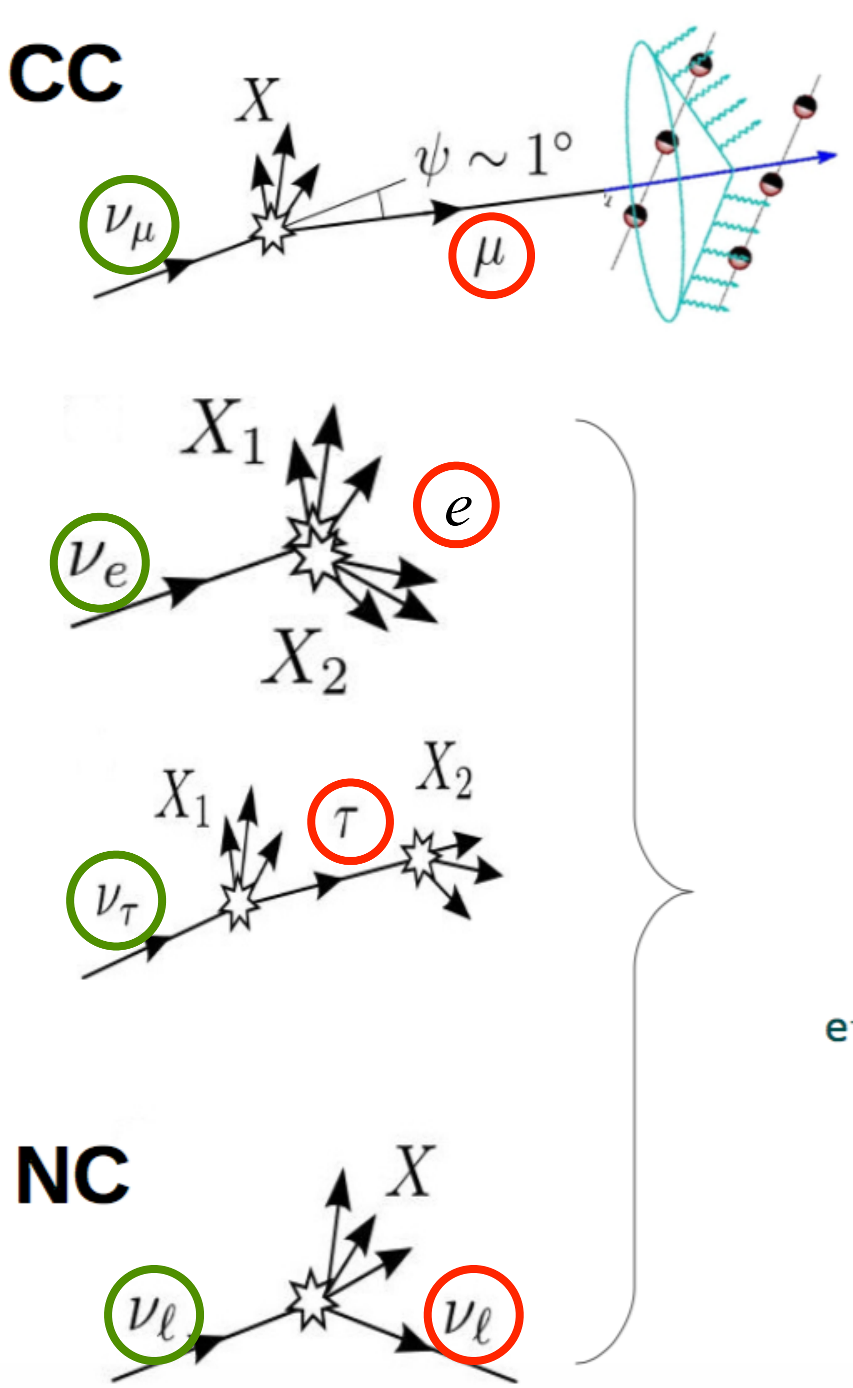
credit: J. van Santen



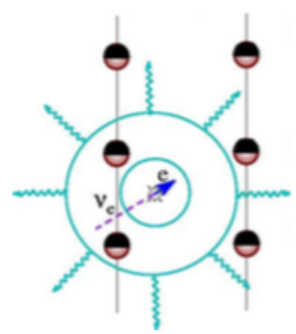


detection technique
Cherenkov radiation

photon scattering in the transparent medium

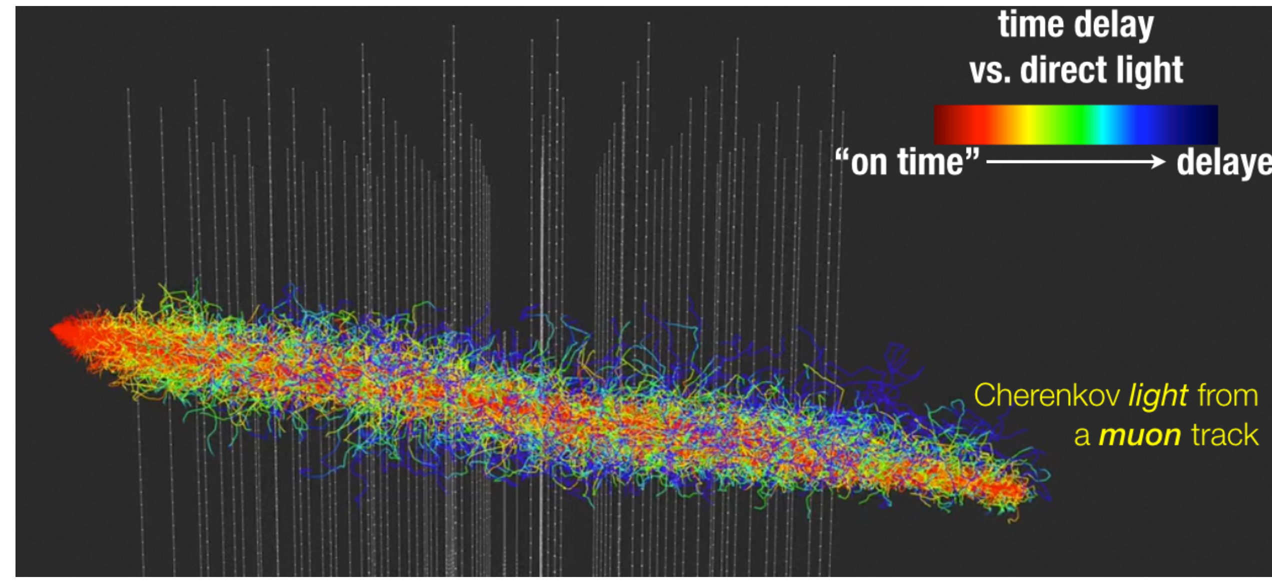


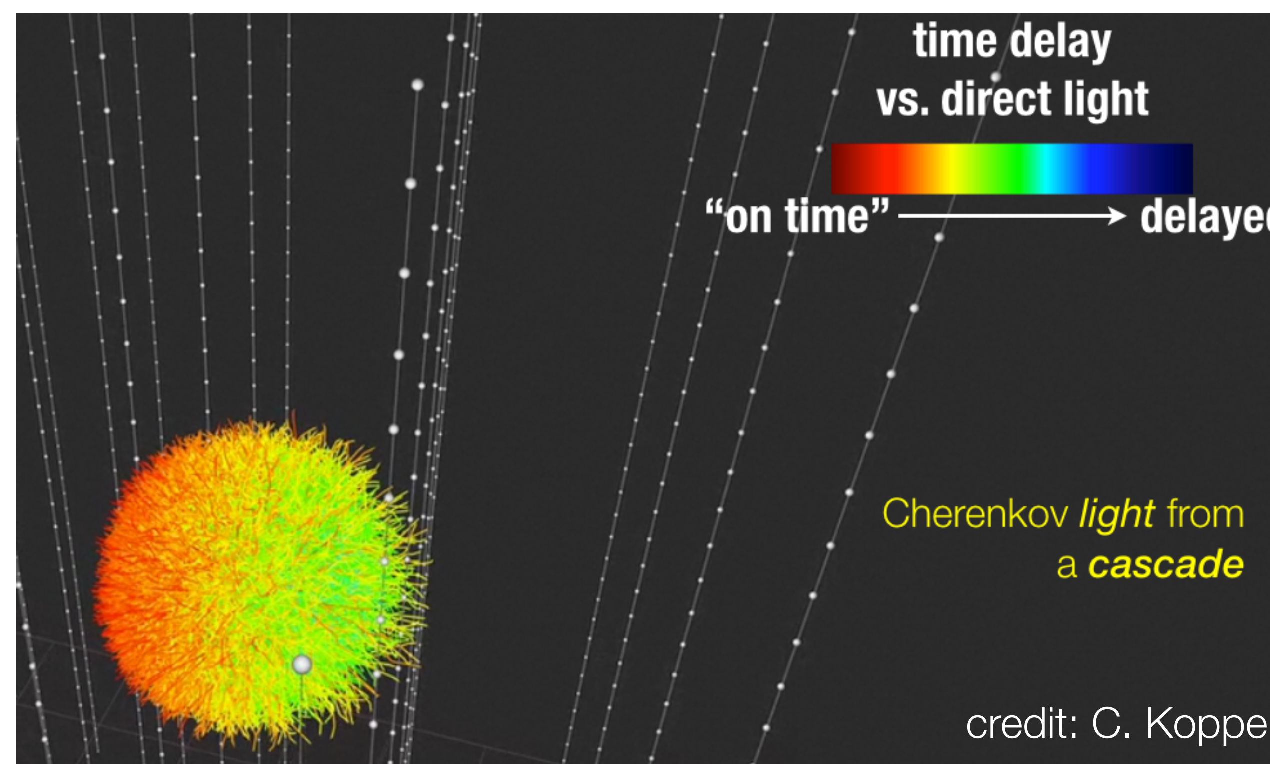
μ tracks >100m @ E>100 GeV



e+- :electromagnetic shower

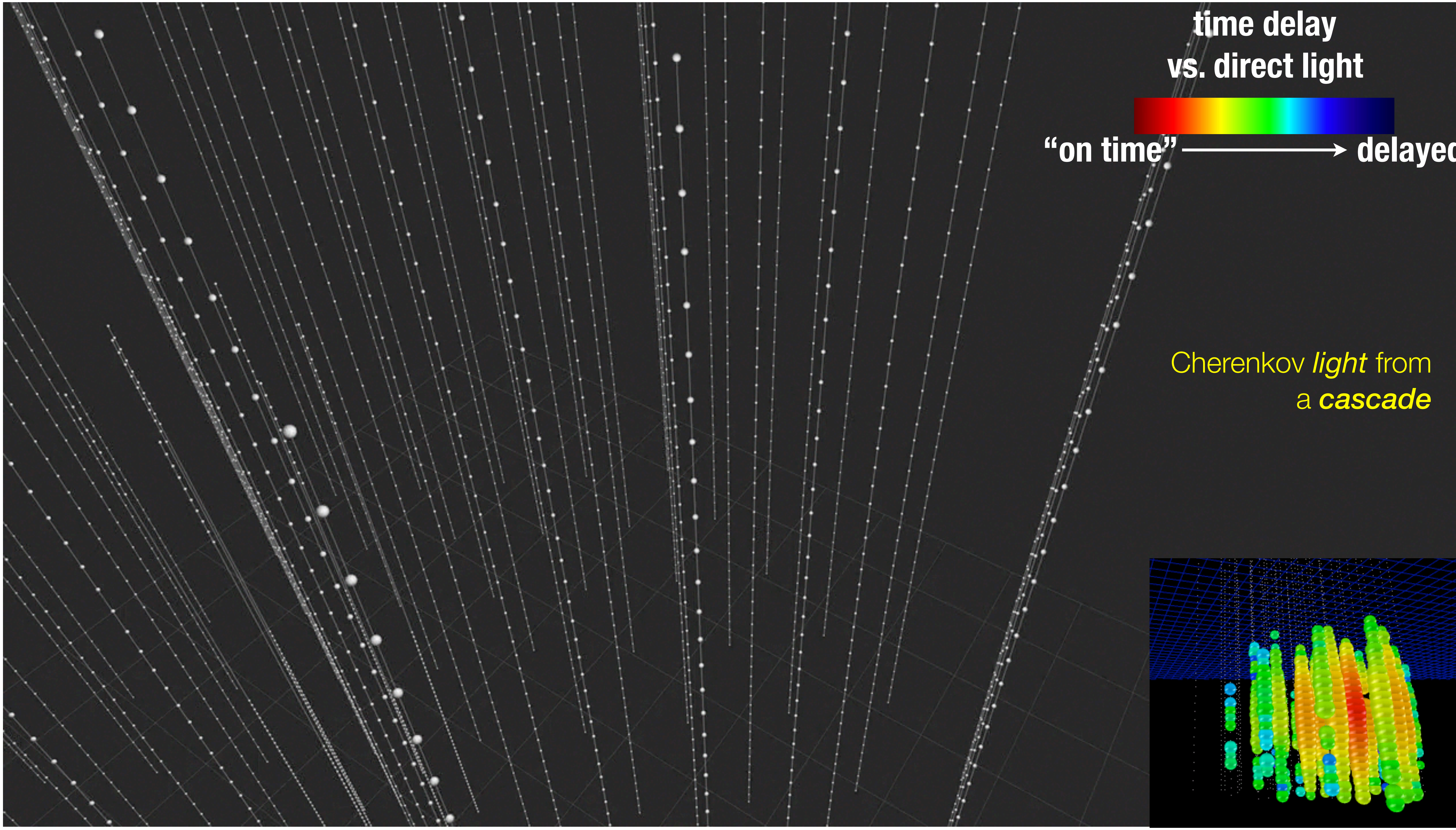
τ+- : hadronic shower





detection principle - *cascade*

ν_e ν_τ CC-int & ν_i NC-int

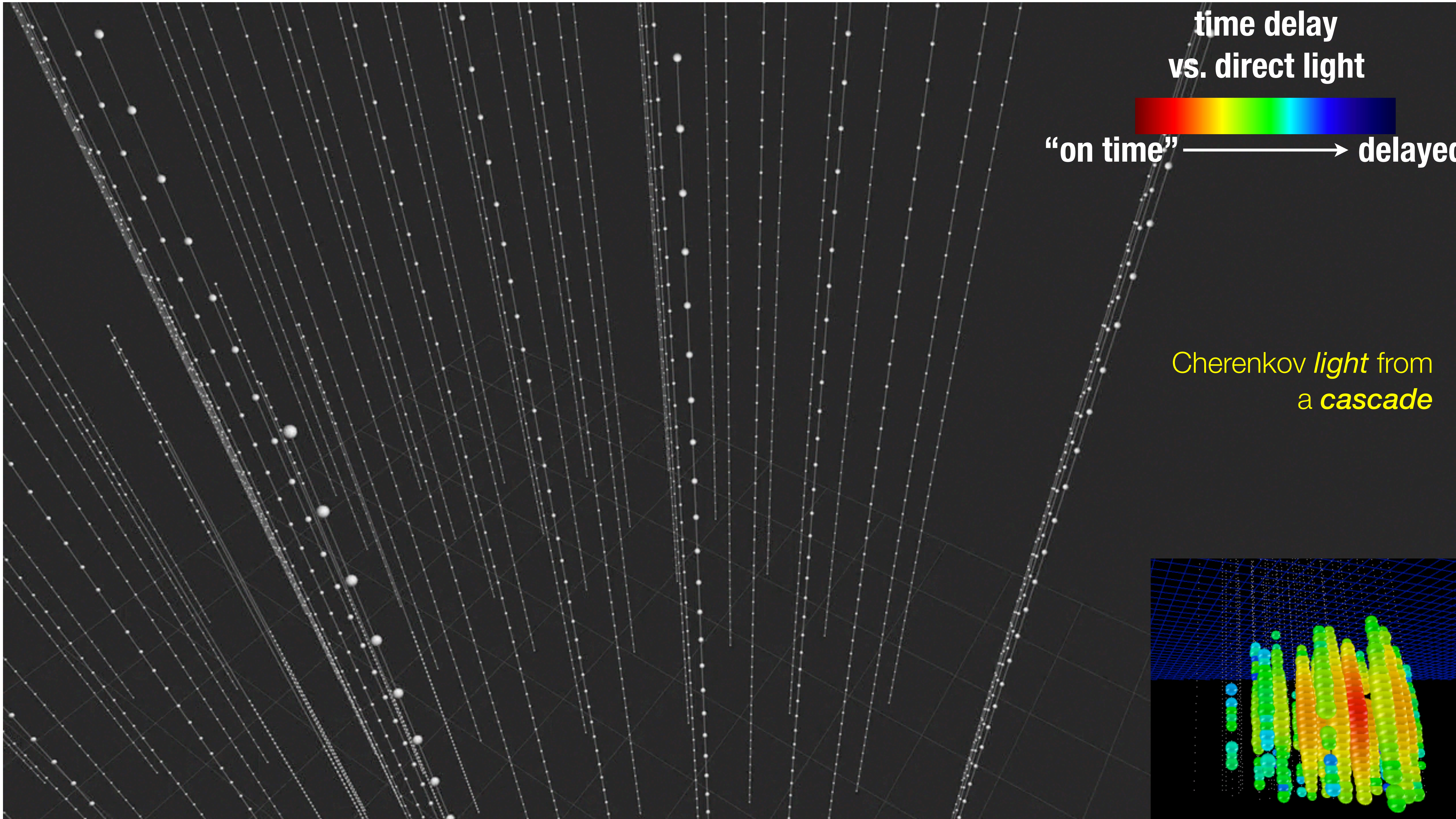


Claudio Kopper - WIPAC

≈ ±15% deposited energy resolution
≈ 10° angular resolution
(at energies ≳ 100TeV)

detection principle - *cascade*

ν_e ν_τ CC-int & ν_i NC-int

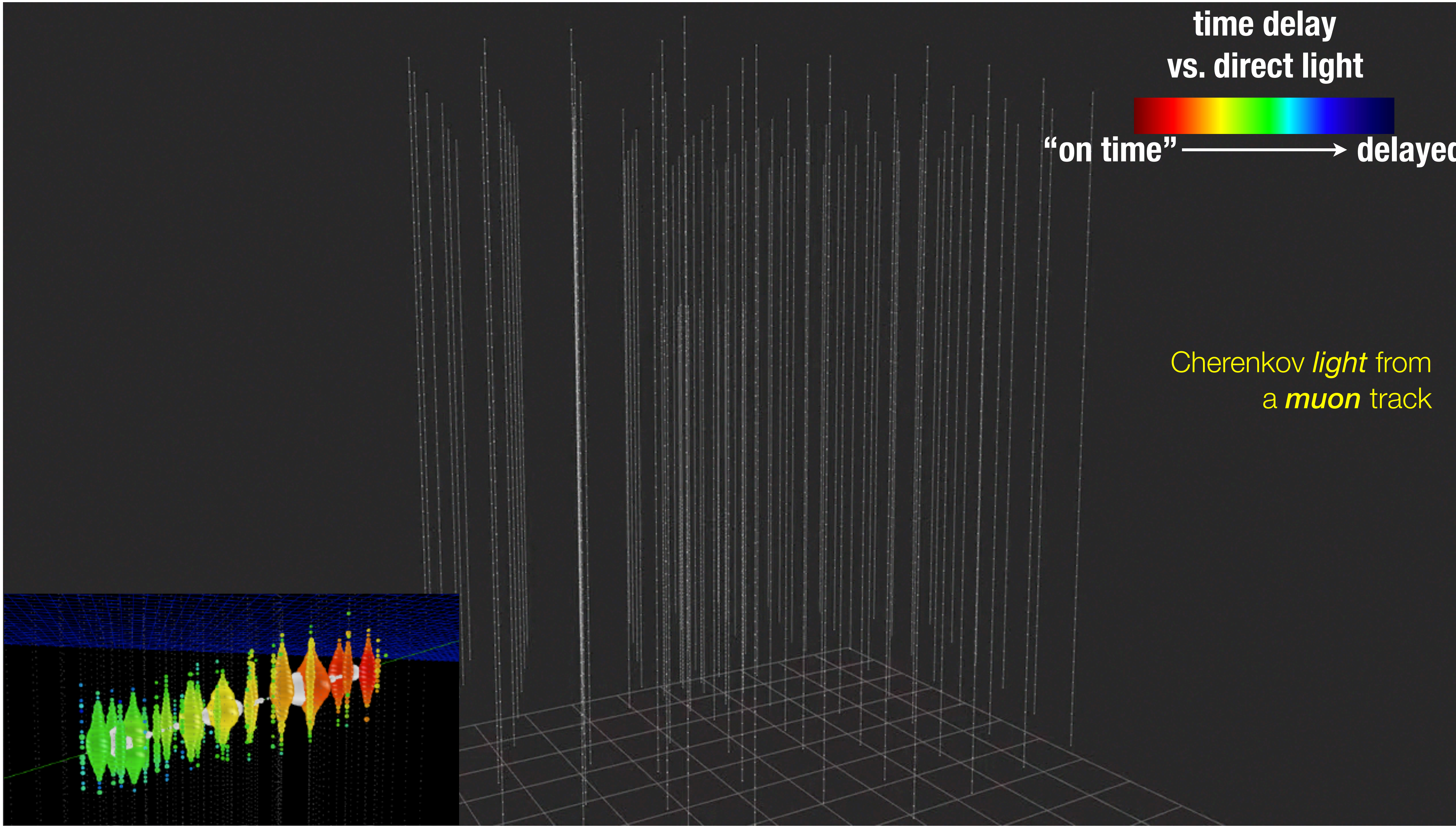


Claudio Kopper - WIPAC

≈ ±15% deposited energy resolution
≈ 10° angular resolution
(at energies ≳ 100TeV)

detection principle - *track*

ν_μ CC-int

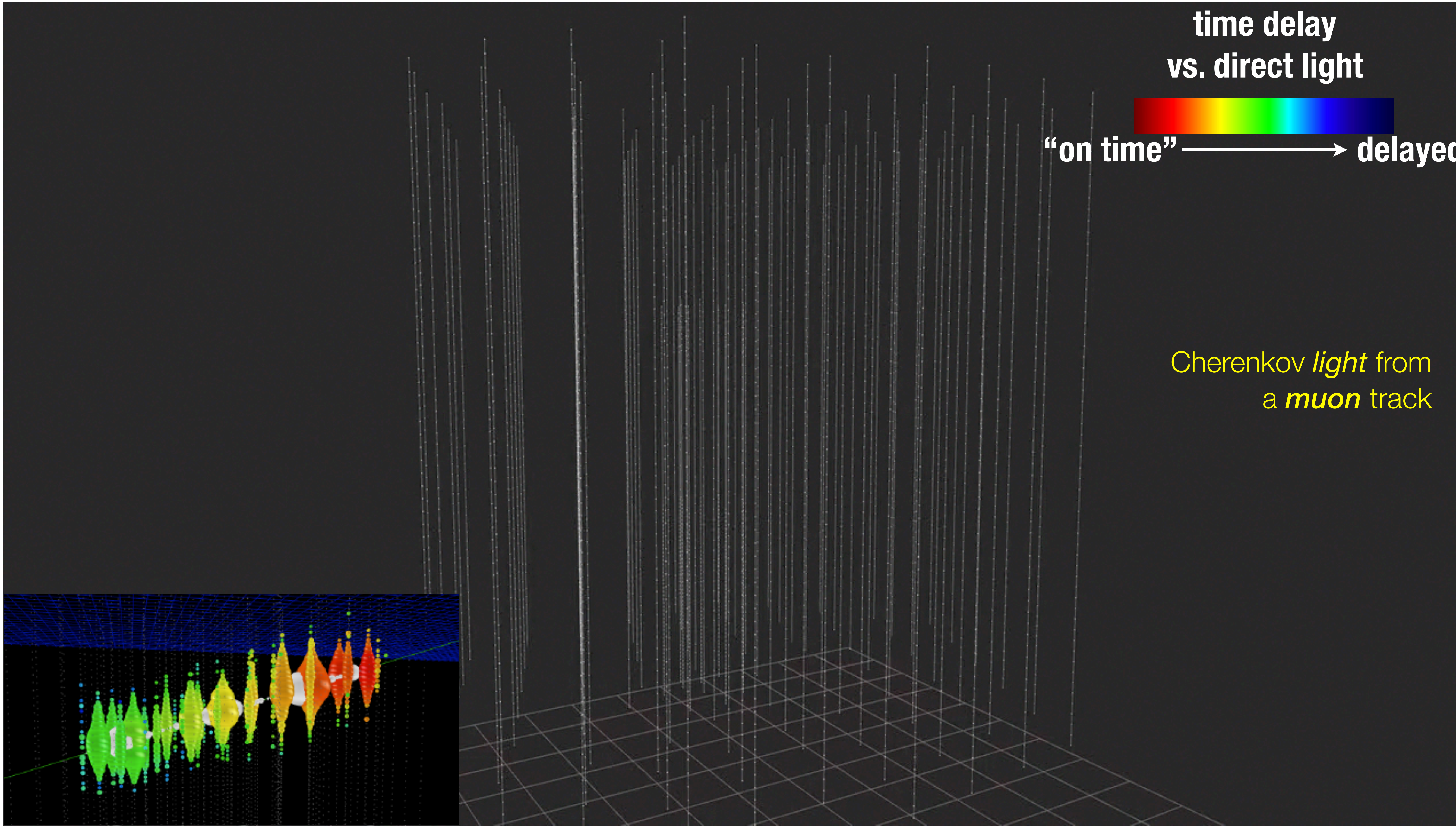


Claudio Kopper - WIPAC

factor of ≈ 2 energy resolution
< 1° angular resolution

detection principle - *track*

ν_μ CC-int



Claudio Kopper - WIPAC

factor of ≈ 2 energy resolution
< 1° angular resolution

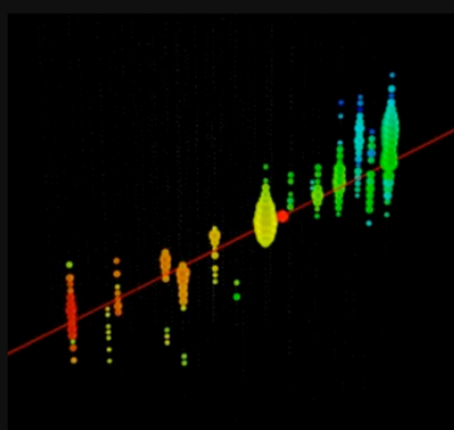
neutrino detection

event topologies

time

track

CC Muon Neutrino



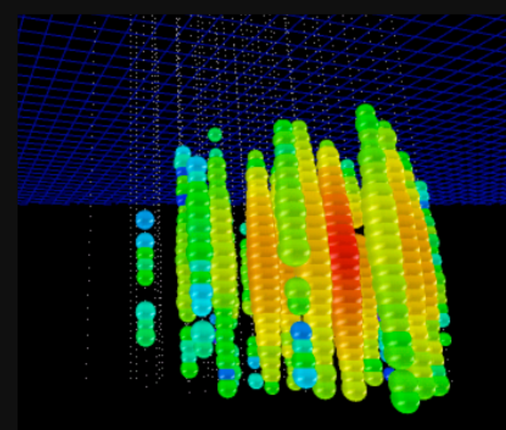
$$\nu_\mu + N \rightarrow \mu + X$$

track (data)

factor of ≈ 2 energy resolution
< 1° angular resolution

cascade

Neutral Current /Electron Neutrino



$$\nu_e + N \rightarrow e + X$$

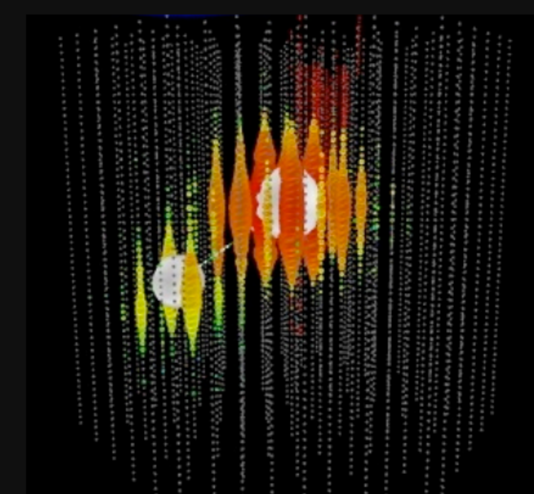
$$\nu_x + N \rightarrow \nu_x + X$$

cascade (data)

≈ ±15% deposited energy resolution
≈ 10° angular resolution
(at energies ≳ 100 TeV)

hybrid

CC Tau Neutrino



$$\nu_\tau + N \rightarrow \tau + X$$

“double-bang” and other signatures (simulation)

(not observed yet)

C. Kopper

Thank You

for any question do not hesitate to contact me
desiati@wipac.wisc.edu

Lectures & Exercises will be uploaded to the School portal (under Workshops)

3

references

- **printed material**

    - *A Heitler model of extensive air showers* - J. Matthews, Astrop. Whys. 22, 287, 2005
    - *Cosmic Rays and Particle Physics* - Thomas K. Gaisser