# What can we learn about New Physics with Ultra-High-Energy Cosmic Rays?

**Yongsoo Jho (曺容秀) (Yonsei University)**

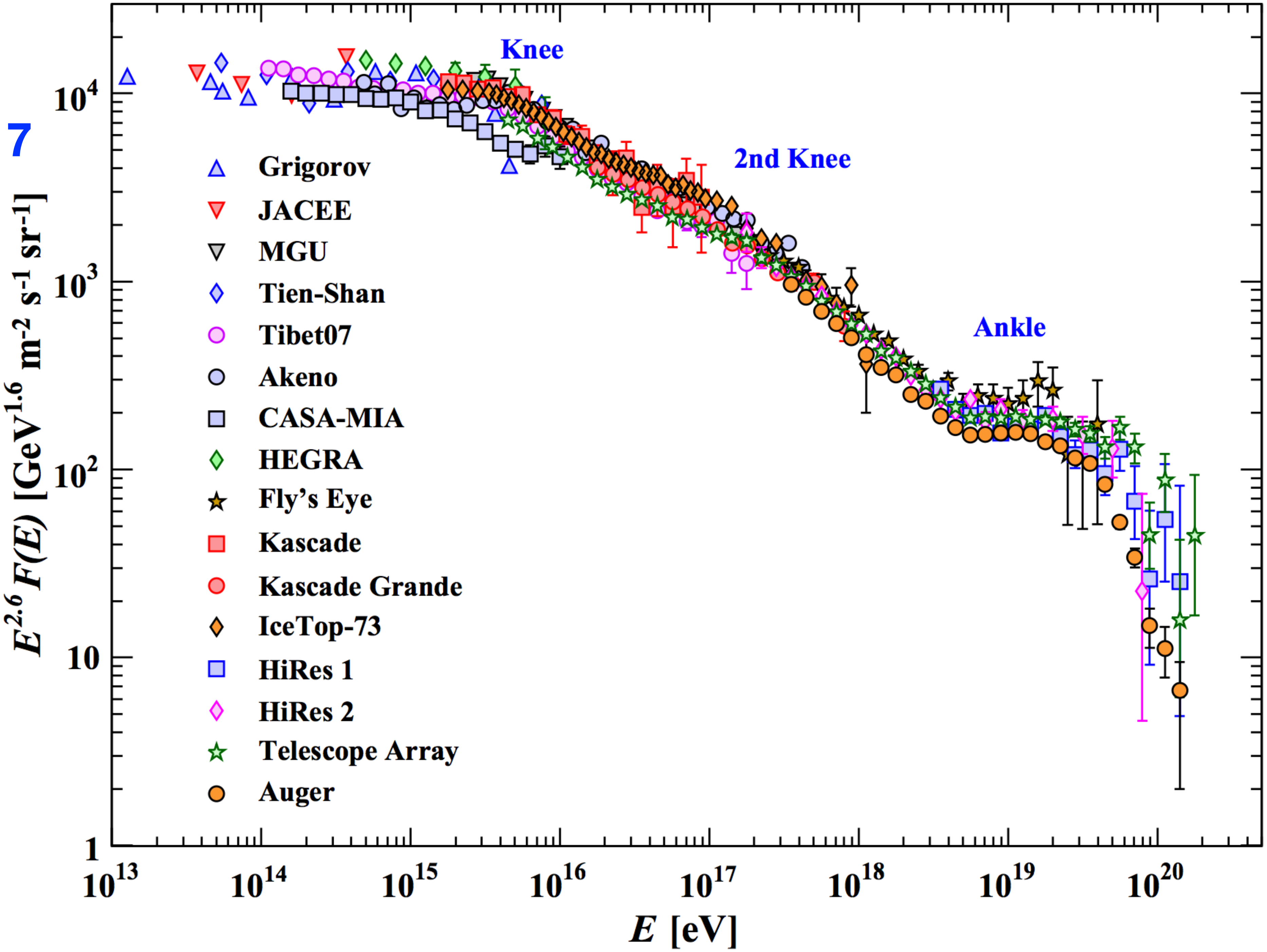
**Based on arXiv:1806.03063 [hep-ph]**
**with Seong Chan Park (Yonsei University)**

**Summer Institute 2018**
**(Tianjin, 2018 Aug 13)**

# UHE cosmic rays

- Ultra-High Energy cosmic ray (UHECRs) spectrum

PDG 2017




**Maximum E up to**

$\sim 10^{20}$ eV

# UHE cosmic rays

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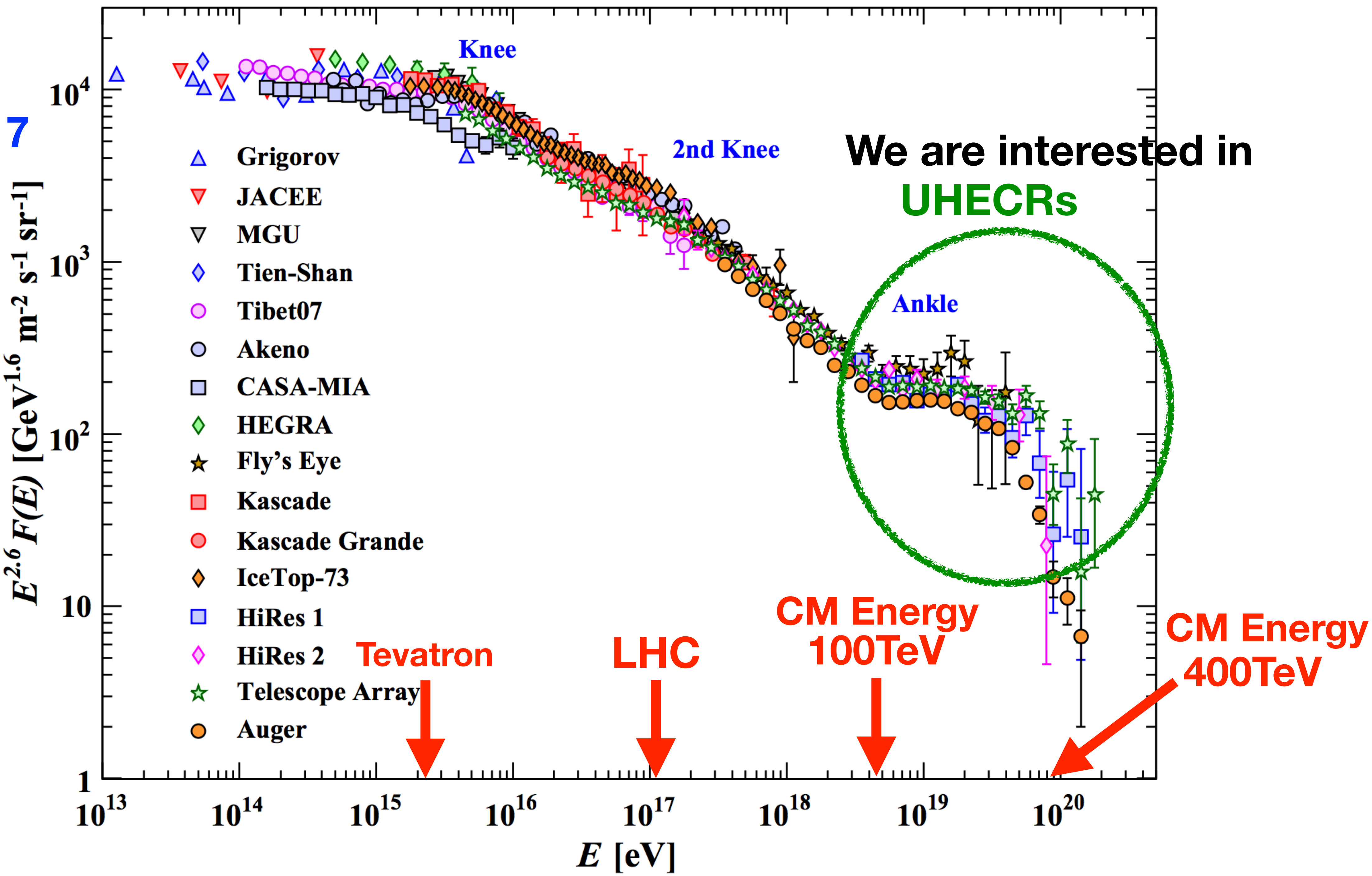
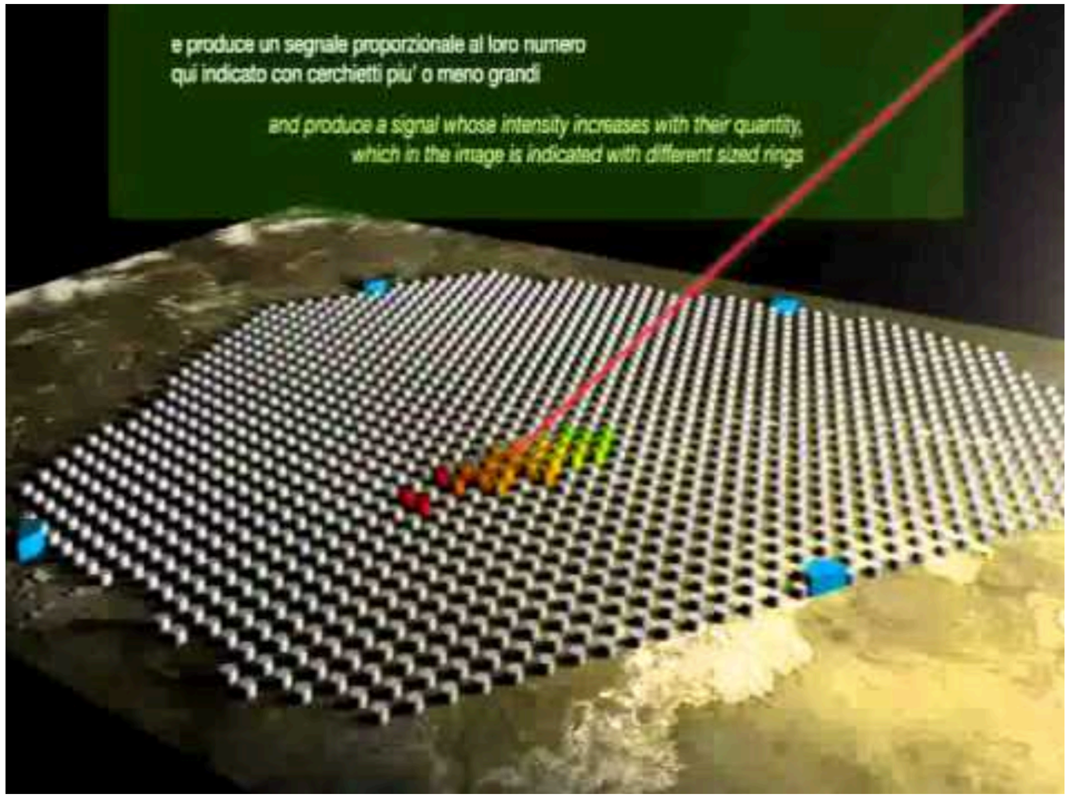
PDG 2017

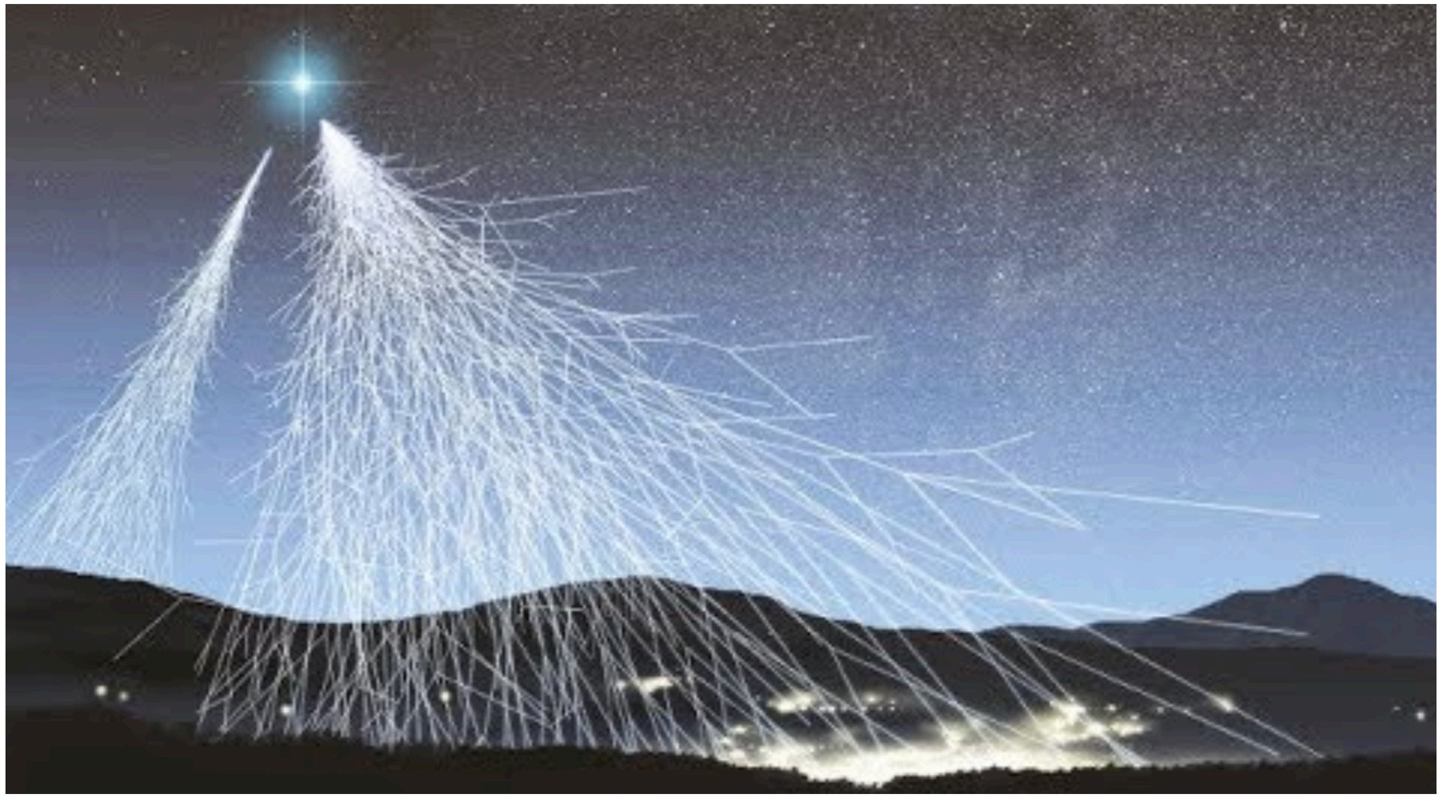


# New Physics from UHE cosmic ray event

- Ultra-High Energy cosmic ray events
  : up to ~ **400 TeV** in the center-of-mass frame
  (It is the only way to reach above 10 TeV scale now.)

- Studying high E new physics event at ground air-shower detector arrays can be very important.



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**New Physics Search using UHE cosmic rays!**

**Pros) Can be much more Energetic. (up to CME 400 TeV)**

**Cons) The flux of UHE cosmic rays cannot be controlled.**

**Q) What kinds of New Physics Search are expected in UHECR observations?**

# New Physics from UHE cosmic ray event

- New Physics candidates above 10 TeV
  - **Most of new physics expected in TeV-scale**
  - **Electroweak (B+L)-violating process** $E_{\mathrm{Sph}} \sim \mathcal{O}\left(\frac{m_W}{\alpha_W}\right)$
  - **and so on…**

# New Physics from UHE cosmic ray event

- New Physics candidates above 10 TeV (with **High multiplicity**)
  - **Microscopic BH production in O(1-10) TeV-scale gravity**
  - **Electroweak (B+L)-violating process** $E_{\rm Sph} \sim \mathcal{O}\left(\frac{m_W}{\alpha_W}\right)$
  - **Enhanced Multi-Higgs production, …**

**Q) What kinds of New Physics Search are expected in UHECR observations on air-shower arrays?**

**A) Process with high multiplicity of particles in the final state.**

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  - **Enhanced Multi-Higgs production, …**

**we will focus on them.**

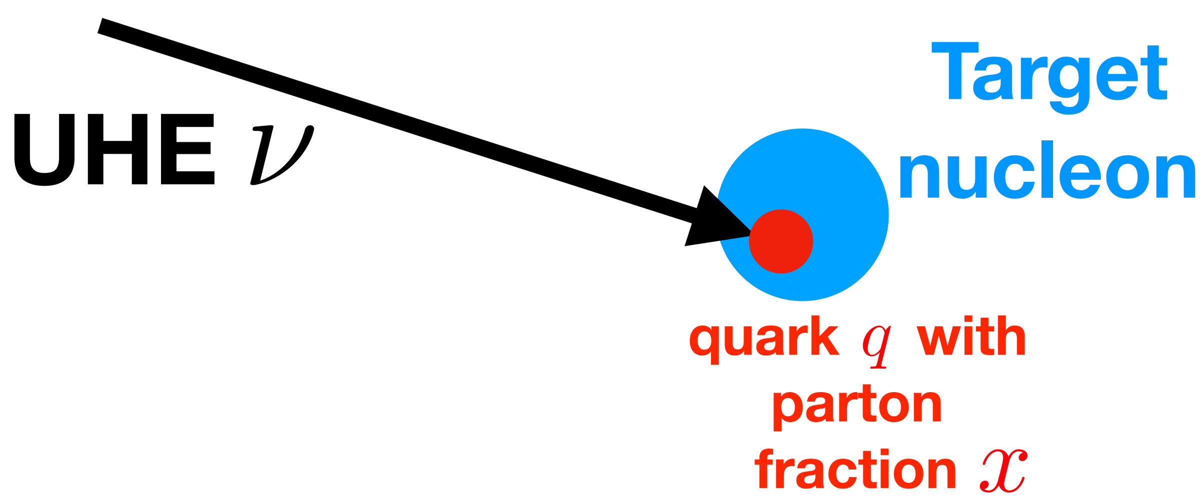
**Q) What kinds of New Physics Search are expected in UHECR observations on air-shower arrays?**

**A) Process with high multiplicity of particles in the final state.**

# High multiplicity new physics cross section

- Ultra-High E neutrino-nucleon collision cross section

$$E_\nu \sim \mathcal{O}(10^{17} - 10^{21})\ \mathrm{eV}$$




$$\nu + q \to X$$

$$\sigma(E_\nu) = \sum_a \int dx\ f_a(\underline{x}, q^2)\ \hat{\sigma}(\hat{s} = 2\underline{x} m_N E_\nu)$$

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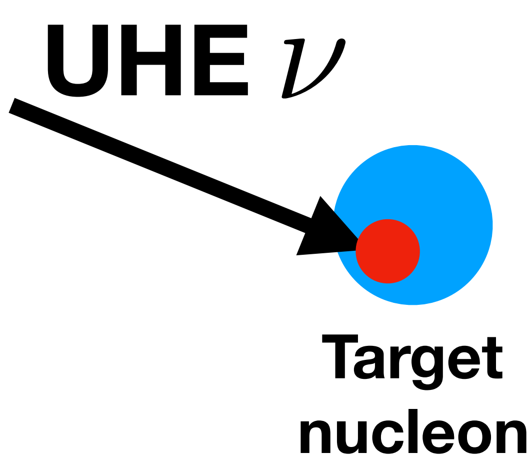
**Depend on New physics origin**

$E_\nu \sim \mathcal{O}(10^{17} - 10^{21})$ eV




**Parton distribution uncertainties at small** $x \leq 10^{-5}$ **high** $\sqrt{\hat{s}} \geq \mathcal{O}(10)$ TeV

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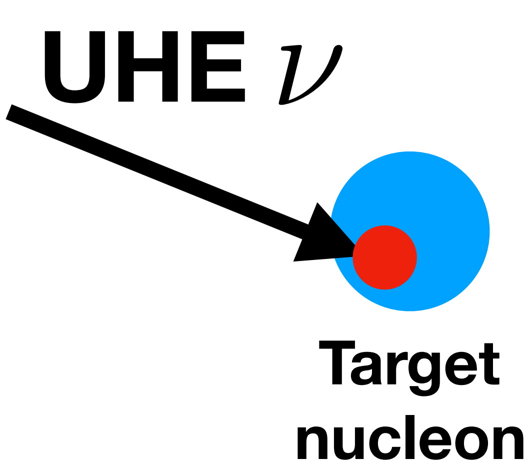



**Parton distribution uncertainties at small $x \leq 10^{-5}$ high $\sqrt{\hat{s}} \geq \mathcal{O}(10)$ TeV**

**Depend on New physics origin**
**i) EW Sphaleron**
**ii) Microscopic BH**
**iii) Multi-Higgs prod**
**...**

# Sphaleron cross section

$$\sigma(E_\nu) = \sum_a \int dx \; f_a(x, q^2) \; \hat{\sigma}(\hat{s} = 2xm_N E_\nu)$$

- New Physics case: Electroweak sphaleron

$$\partial_\mu j_B^\mu = \partial_\mu j_L^\mu = N_f \left( \frac{g^2}{32\pi^2} W^a_{\mu\nu} \tilde{W}^{a\mu\nu} - \frac{g'^2}{32\pi^2} B_{\mu\nu} B^{\mu\nu} \right)$$

$$N(u) + \nu_e \to L + Q + (W, Z, \text{ Higgs bosons})$$

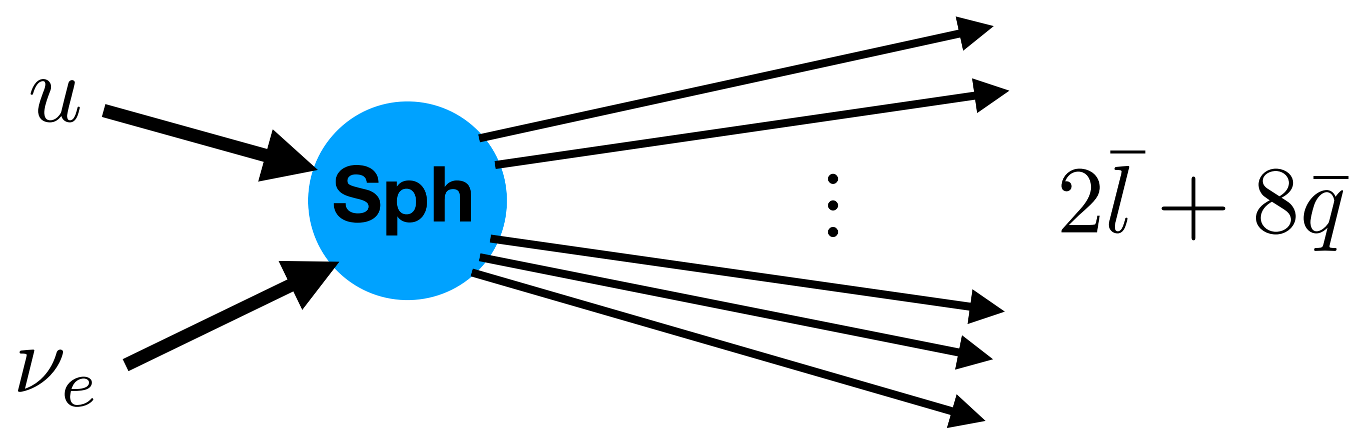
$$L = \mu^+ + \bar{\nu}_\tau$$

$$Q = \bar{t} + 2\bar{b} + 2\bar{c} + \bar{s} + \bar{u} + \bar{d}$$

**EW Sphaleron-induced**

$B - L$ **Conserving,**

$B + L$ **Violating process**



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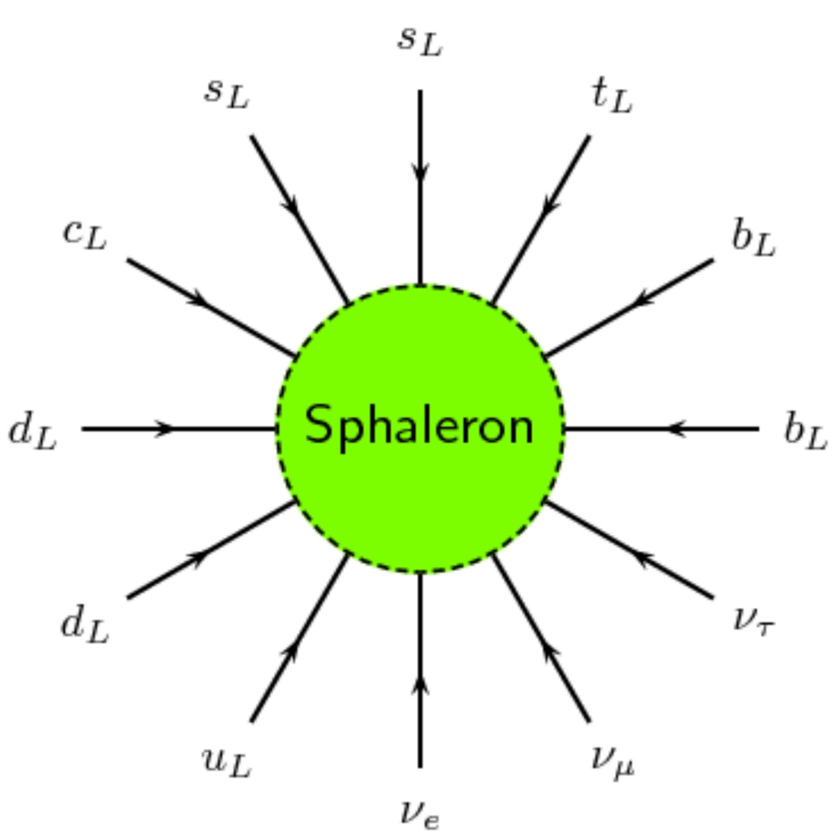
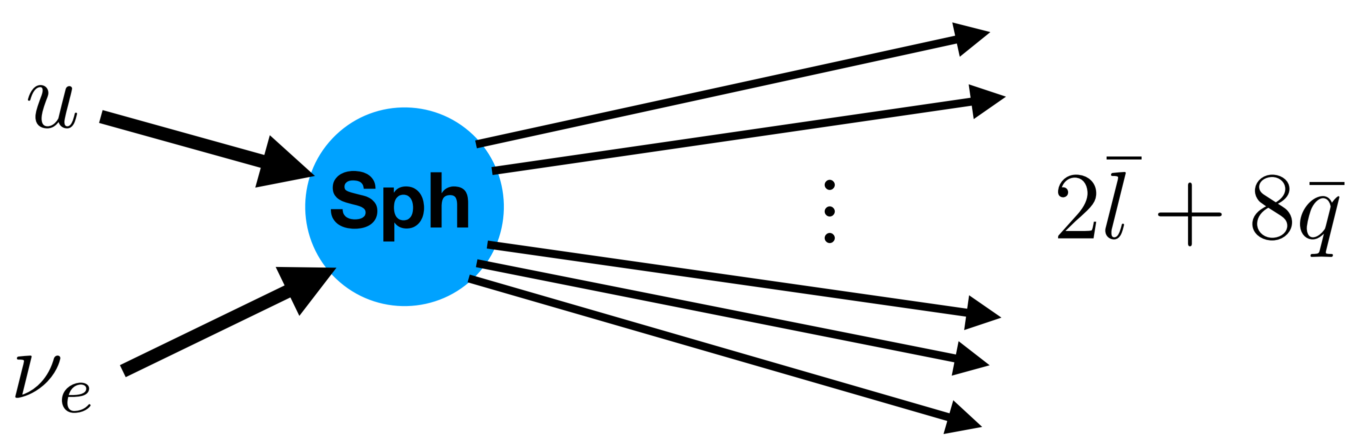



Actually, it is already predicted in the Electroweak theory. (not experimentally observed yet.)

$$N(u) + \nu_e \to L + Q + (W, Z,\ \text{Higgs bosons})$$

$$L = \mu^+ + \bar{\nu}_\tau$$

$$Q = \bar{t} + 2\bar{b} + 2\bar{c} + \bar{s} + \bar{u} + \bar{d}$$



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- New Physics case: Electroweak sphaleron

[ Klinkhamer and Manton, 1984 ]
[ Rubakov and Shaposhnikov, 1987, 1996 ]
[ Ringwald et al., 1990 ]
[ Tye and Wong, 2015, 2017 ]

unknown parameter
typically, $p \sim \mathcal{O}(10^{-1} - 10^{-2})$
is expected

$$\hat{\sigma}_{\rm Sph}(\hat{s}) = \frac{p}{m_W^2} \underline{\mathcal{S}(\sqrt{\hat{s}})}$$

Exponentially suppressed
At low energies, but
can be unsuppressed
at $\sqrt{\hat{s}} > E_{\rm Sph} \simeq 10 \text{ TeV}$

# Microscopic BH cross section

$$\sigma(E_\nu) = \sum_a \int dx \; f_a(x, q^2) \; \underline{\hat{\sigma}(\hat{s} = 2x m_N E_\nu)}$$

- New Physics case: Microscopic BH in TeV-scale gravity

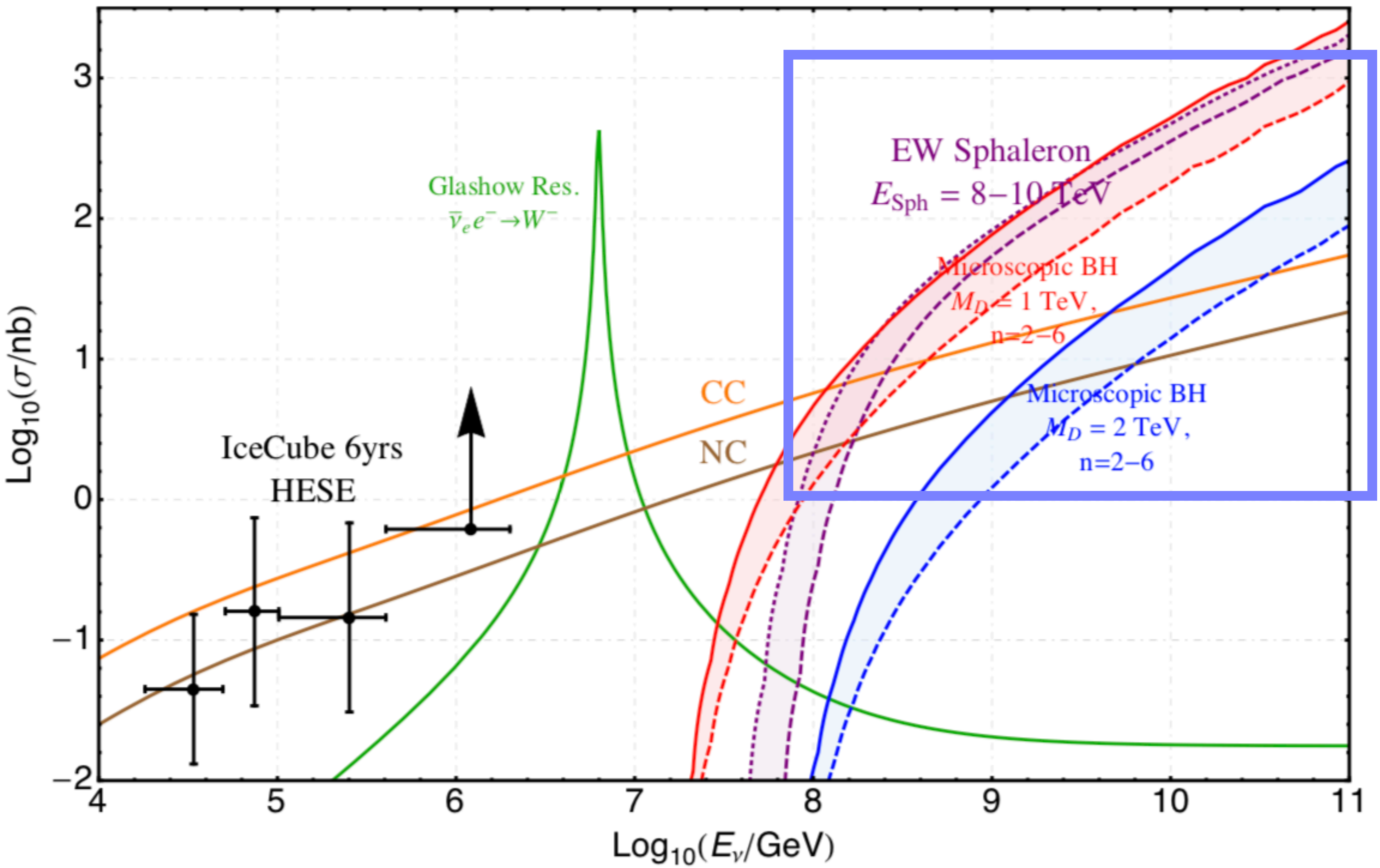
[ Arkani-Hamed, Dimopoulos, and Dvali 1998 ]
[ Randall and Sundrum, 1999 ]

$$\hat{\sigma}_{\mathrm{BH}}(\hat{s}) \approx \pi b_{\mathrm{BH}}^2 = \pi \left( G_D \sqrt{\hat{s}} \right)^{\frac{2}{D-3}}$$

- Higher-dimensional gravity scale can be low as ~ O(1) TeV

- Current p-p collider bounds are $M_{\min} \approx 8 - 10 \ \mathrm{TeV}$ (from lepton+jet and multi-jet searches)

# UHE neutrino cross section



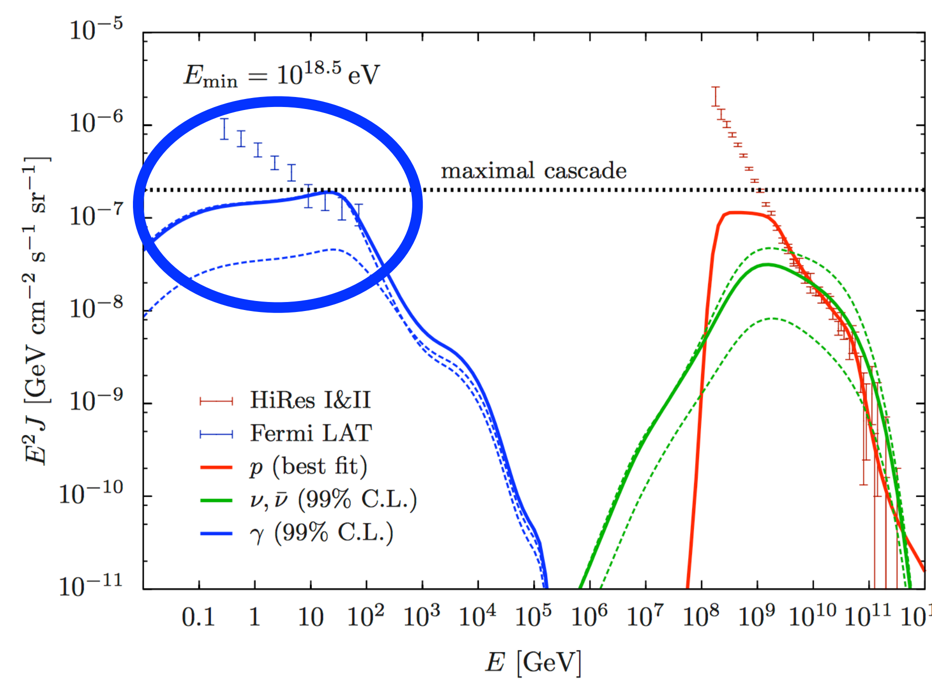
# Event rate at ground arrays

$$\frac{dN}{dt} \propto \int_{E_{\rm th}}^{E_{\rm max}} dE_{\rm sh} \int_0^1 dy \frac{d\phi_\nu(E_\nu)}{dE_\nu} \frac{d\sigma_{\nu N \to X}(E_\nu, y)}{dy} \mathcal{A}(E_{\rm sh})$$

SM or NP

One guaranteed source
: GZK neutrinos

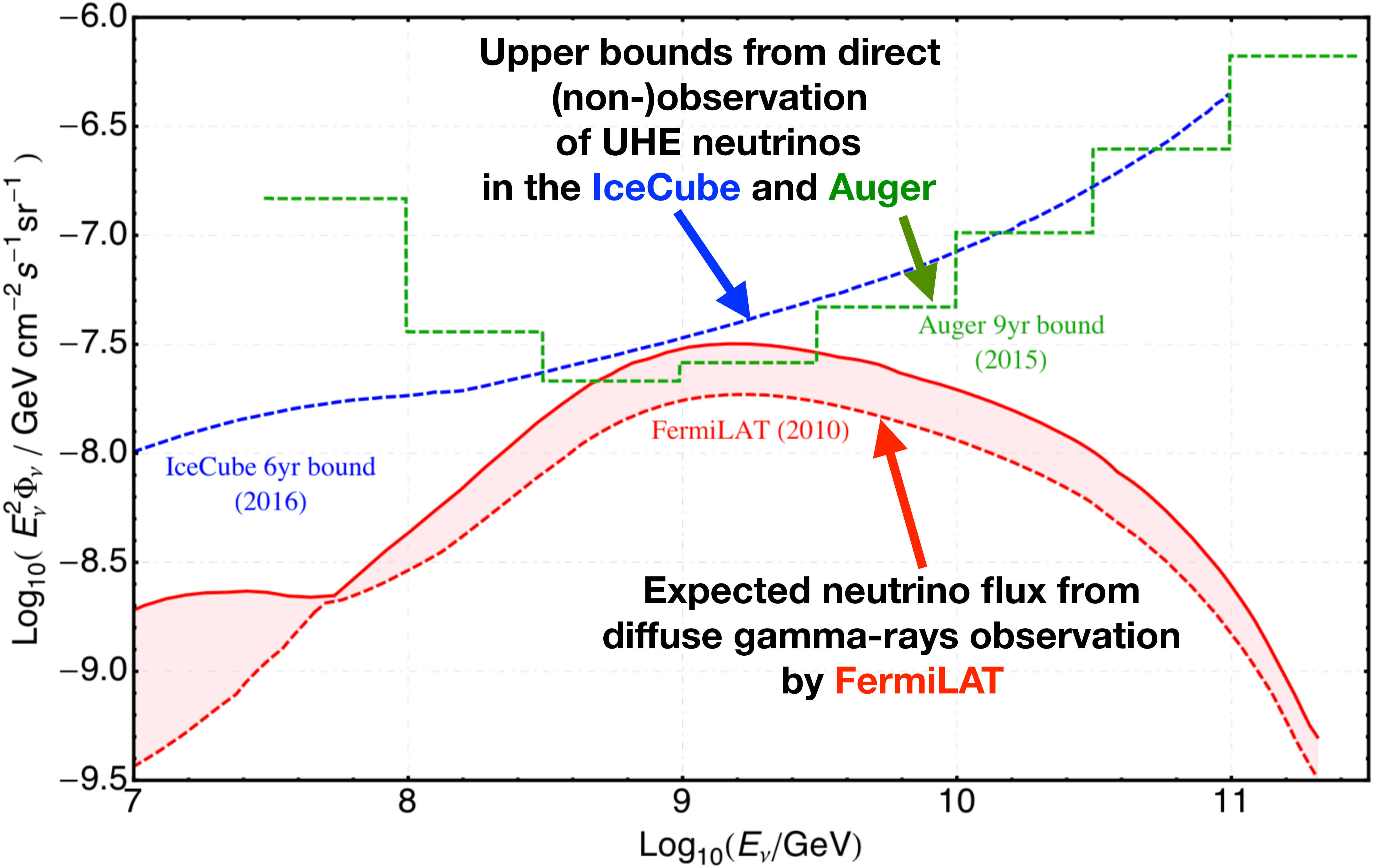
$$p + \gamma_{\rm CMB} \to \pi^+ + n$$
$$\pi^+ \to \mu^+ + \nu_\mu$$
$$\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu,$$
$$p + \gamma_{\rm CMB} \to \pi^0 + p$$
$$\pi^0 \to \gamma + \gamma$$



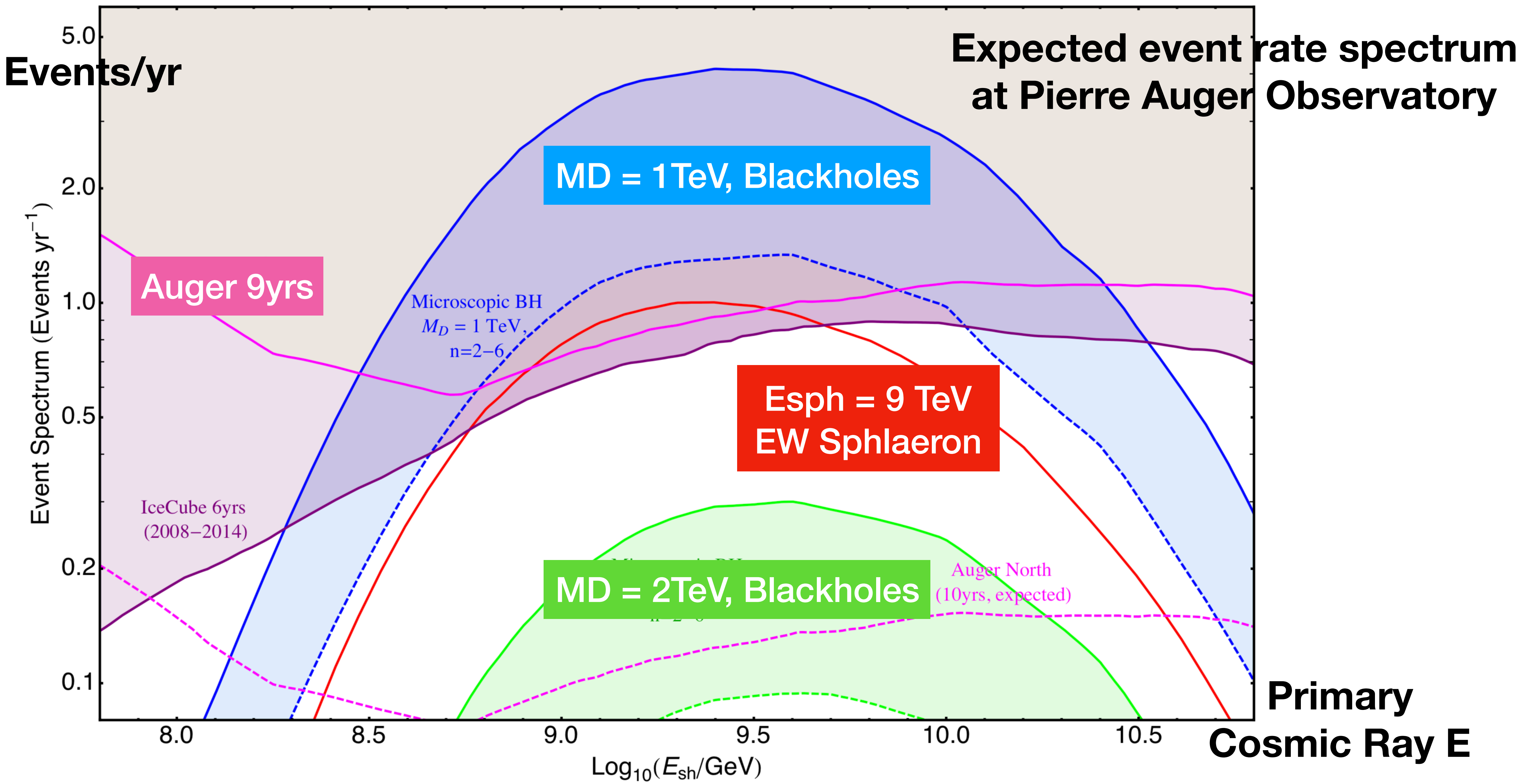

**Fermi-LAT observed diffuse gamma-rays**

$$\gamma + \gamma_{\rm bkg.} \to e^+ + e^-$$
$$e^\pm + \gamma_{\rm bkg.} \to e^\pm + \gamma$$

# GZK neutrino flux from various experiments



# Expected NP event rates on air-shower detector arrays



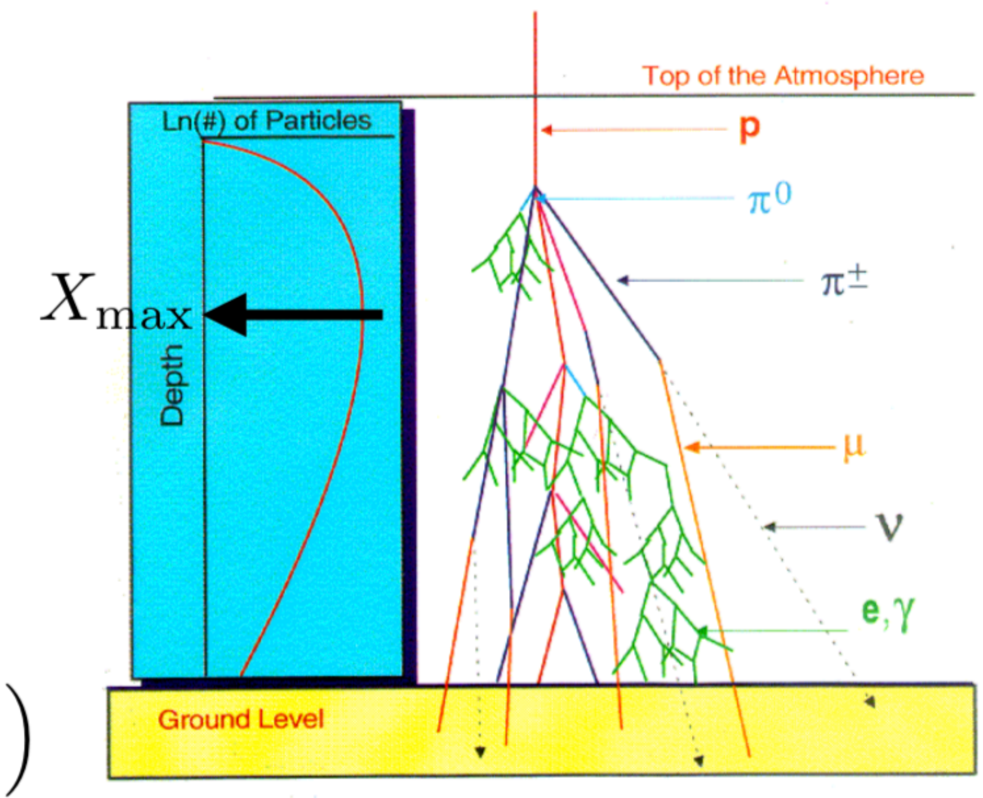

Sphaleron bounds : Auger 9yrs search $p \leq 2.5 \times 10^{-1}$

Auger North 10yrs (expected) $p \leq 3.4 \times 10^{-2}$

# Extensive air shower in the atmosphere

- Air shower cascades in the atmosphere are described in terms of

Atmospheric Interaction Depth $$X = \int_{x_0}^{x_f} \rho(x)\ dx$$



Extensive Air Showers

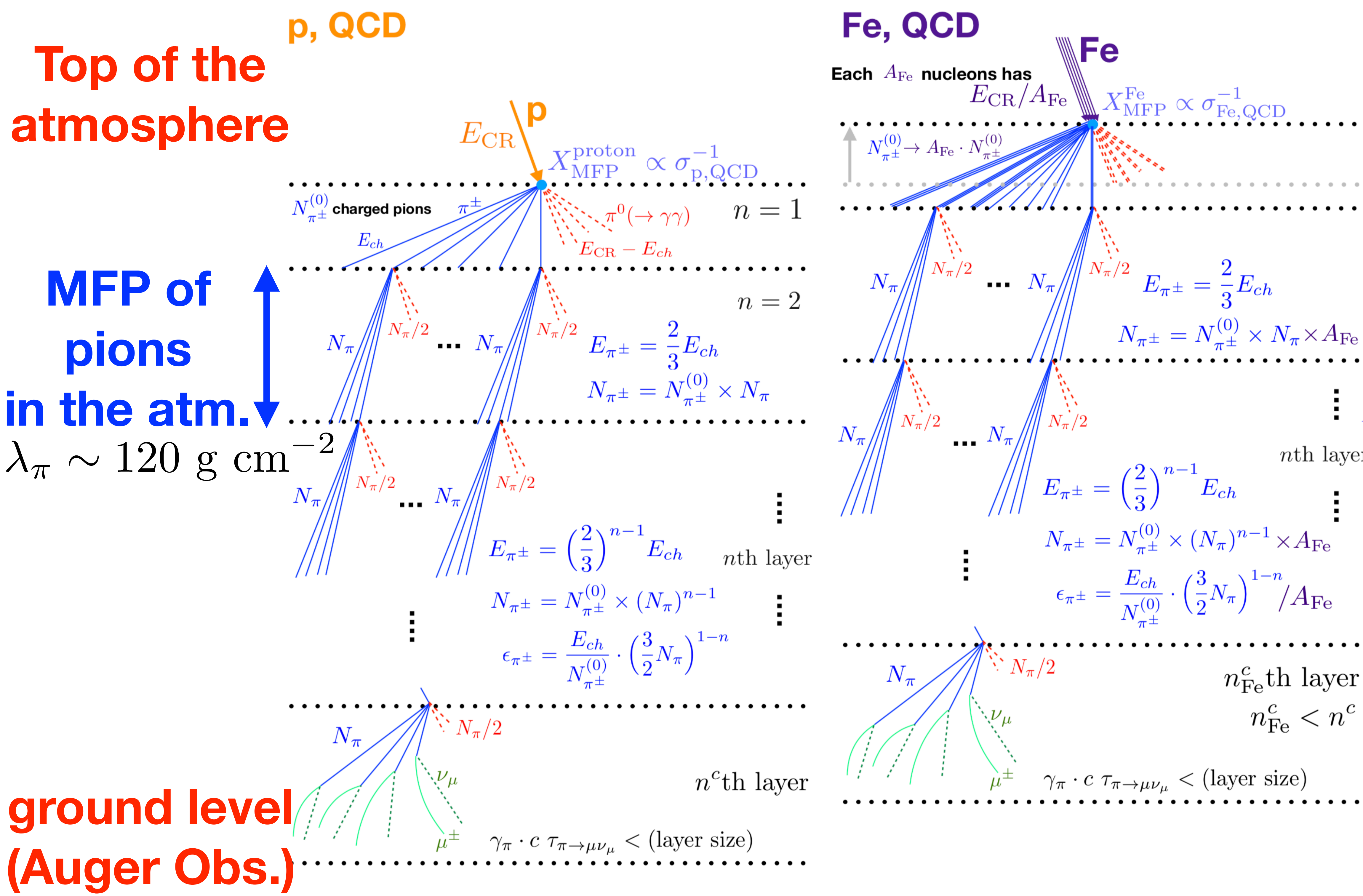
- The Gaisser-Hillas function for the fitting

$$N(X) = N_{\rm max}\left(\frac{X - X_0}{X_{\rm max} - X_0}\right)^{\frac{X_{\rm max} - X_0}{\lambda}} \exp\left(\frac{X_{\rm max} - X}{\lambda}\right)$$

- In the longitudinal distribution, Sphaleron and BH air-showers are very similar to heavy-nuclei showers (smaller $X_{\rm max}$ than proton QCD case)

[ L. Anchordoqui et al, 2004]
[ E. J. Ahn et al., 2005]
[ M.Spannowsky et al., 2016]

# Extensive air shower: p vs. Fe primary CR

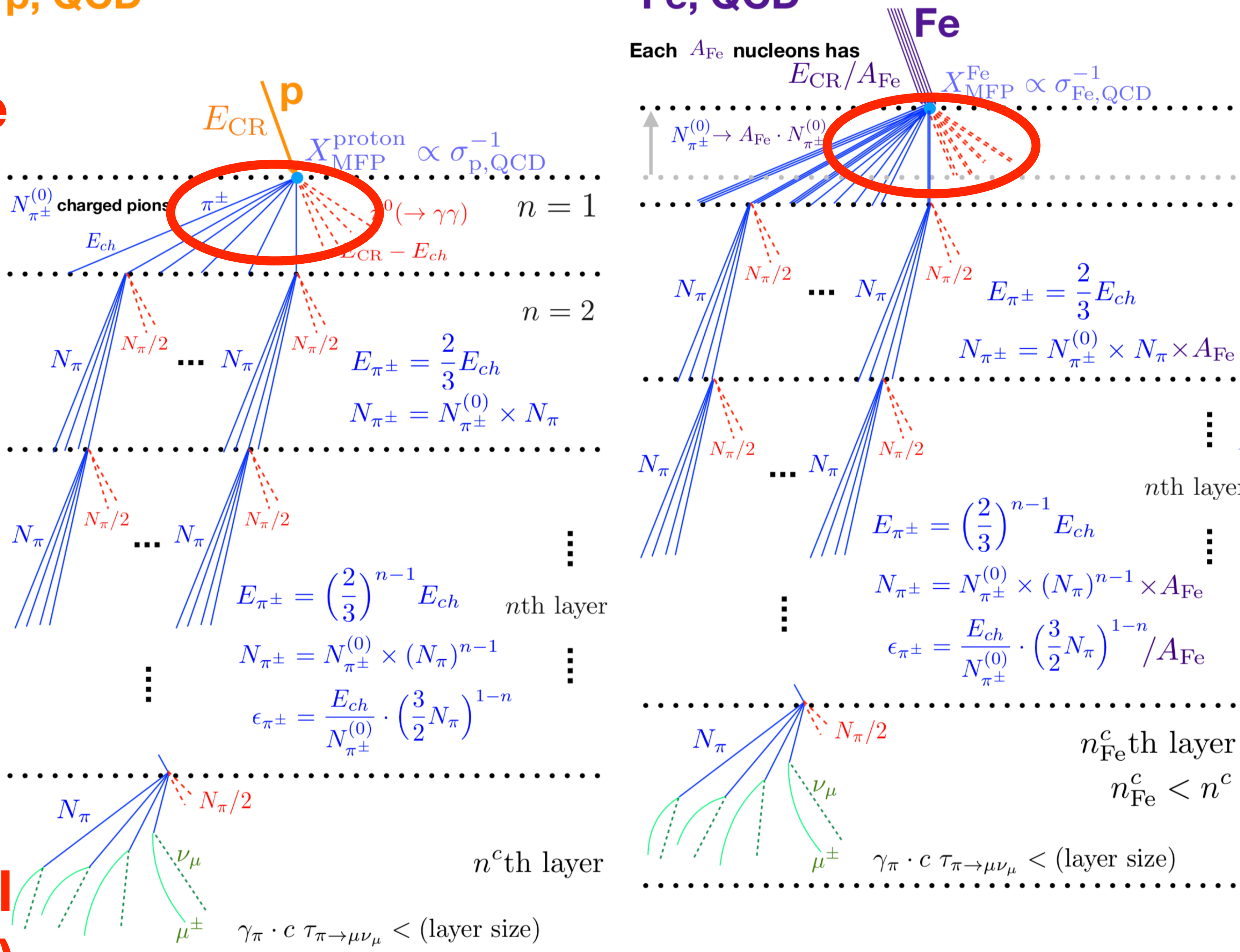


# Extensive air shower: p vs. Fe primary CR

Top of the atmosphere

p, QCD

Fe, QCD




ground level (Auger Obs.)

# Extensive air shower:
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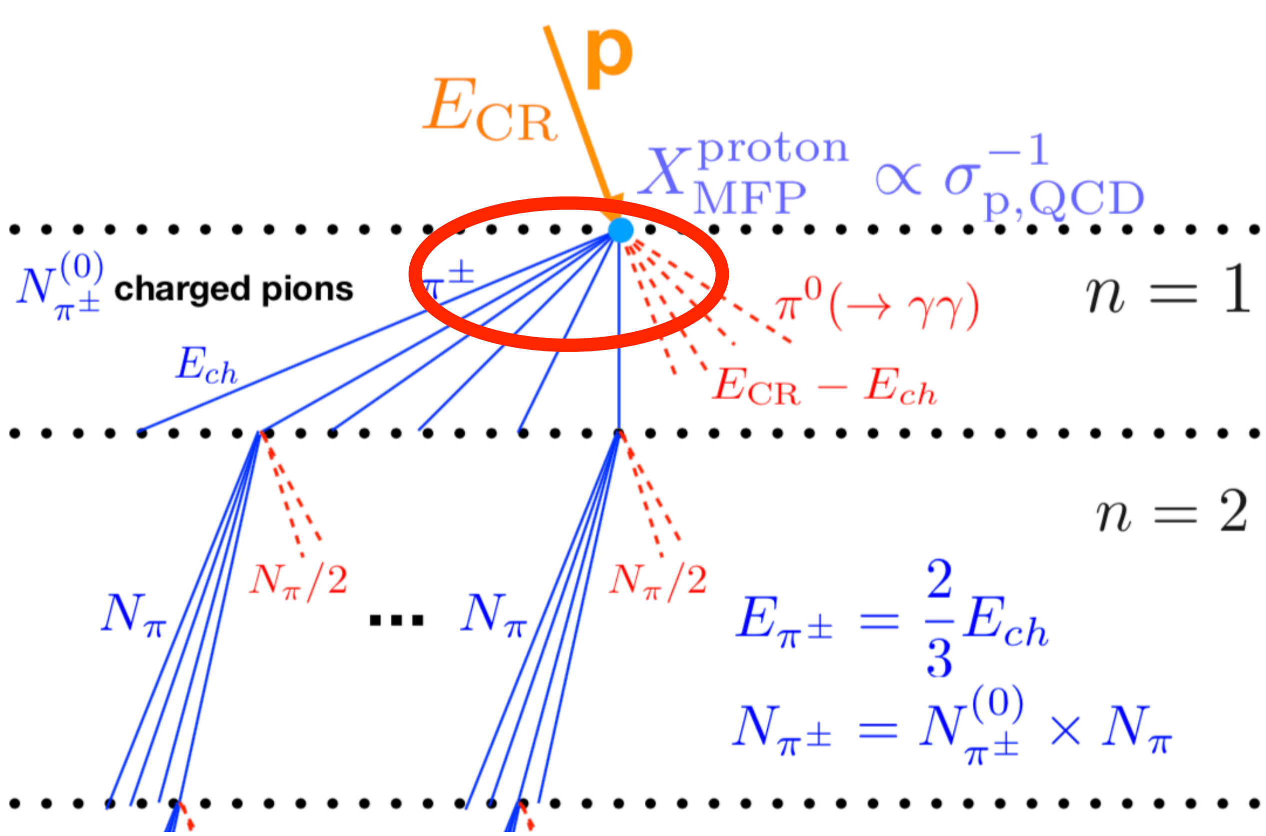
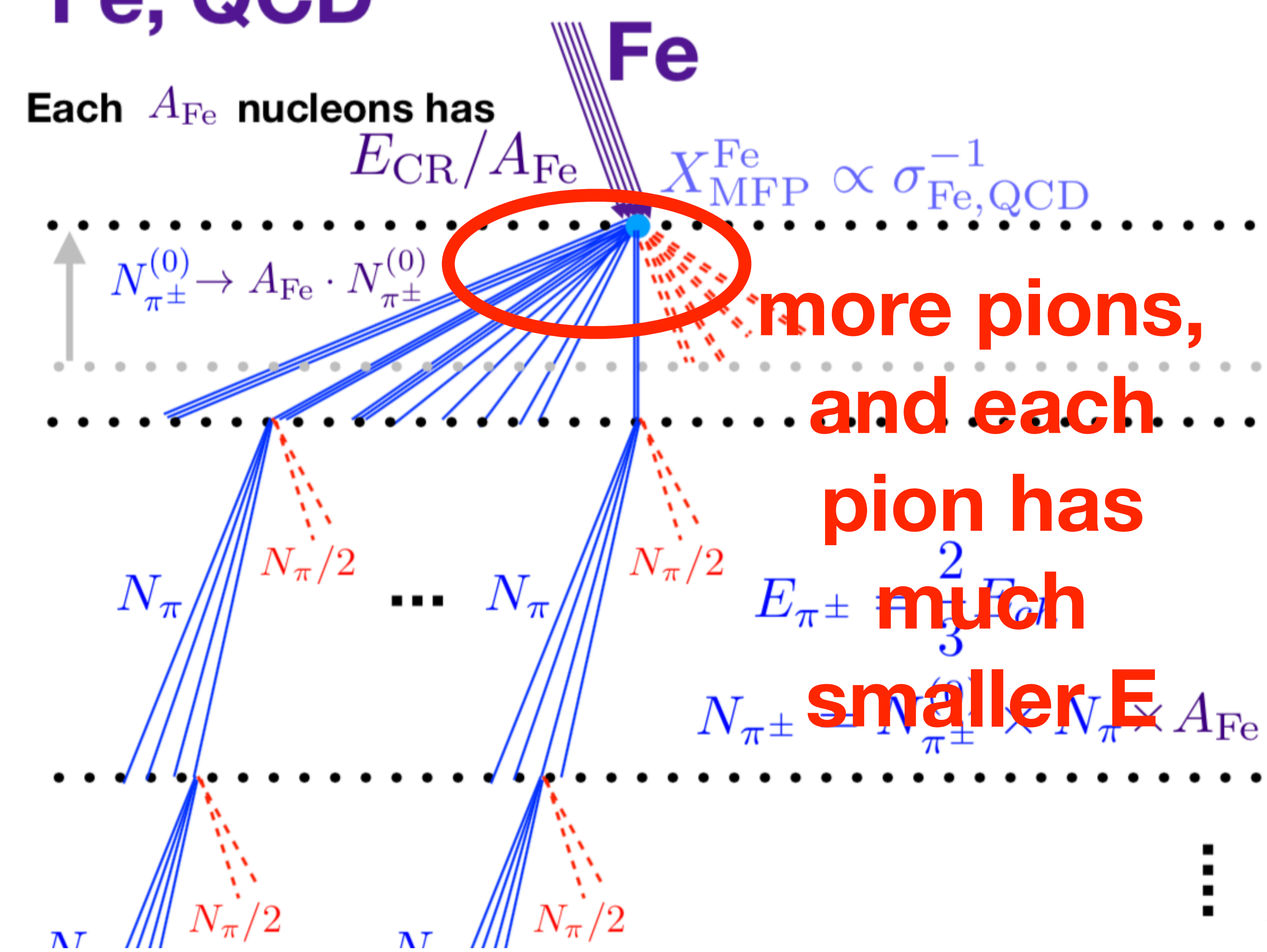
**p, QCD**




**Fe, QCD**



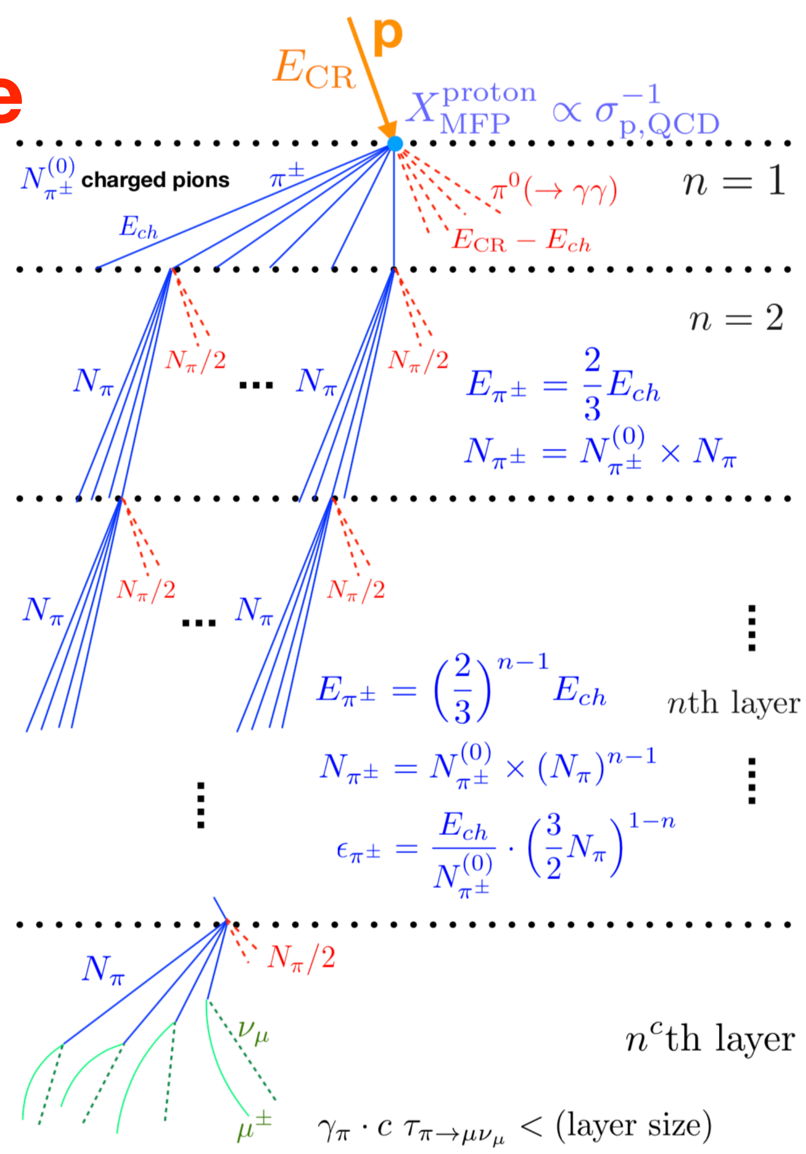

**more pions, and each pion has much smaller E**

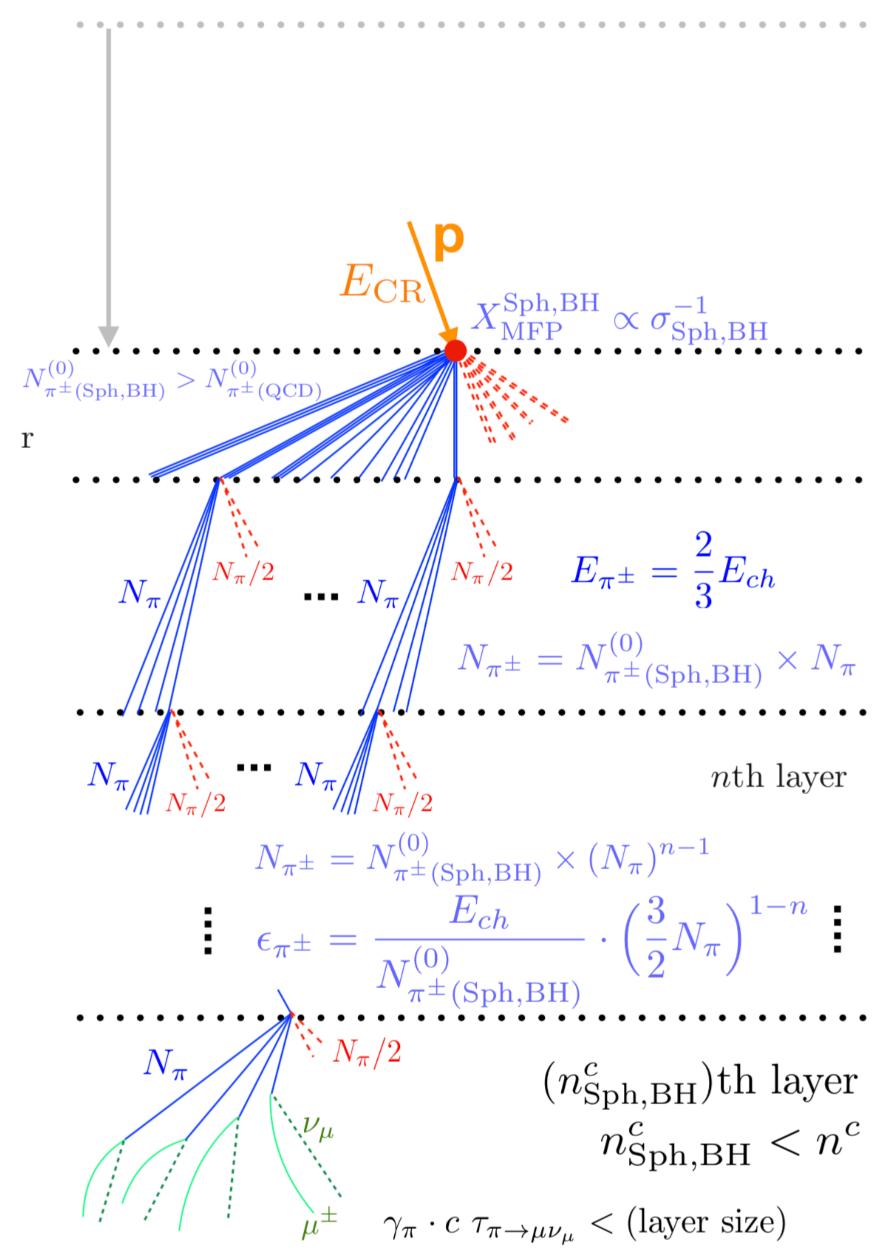
# Extensive air shower: QCD vs. NP (Sph, BH)

p, QCD

p, Sph or BH

Top of the atmosphere

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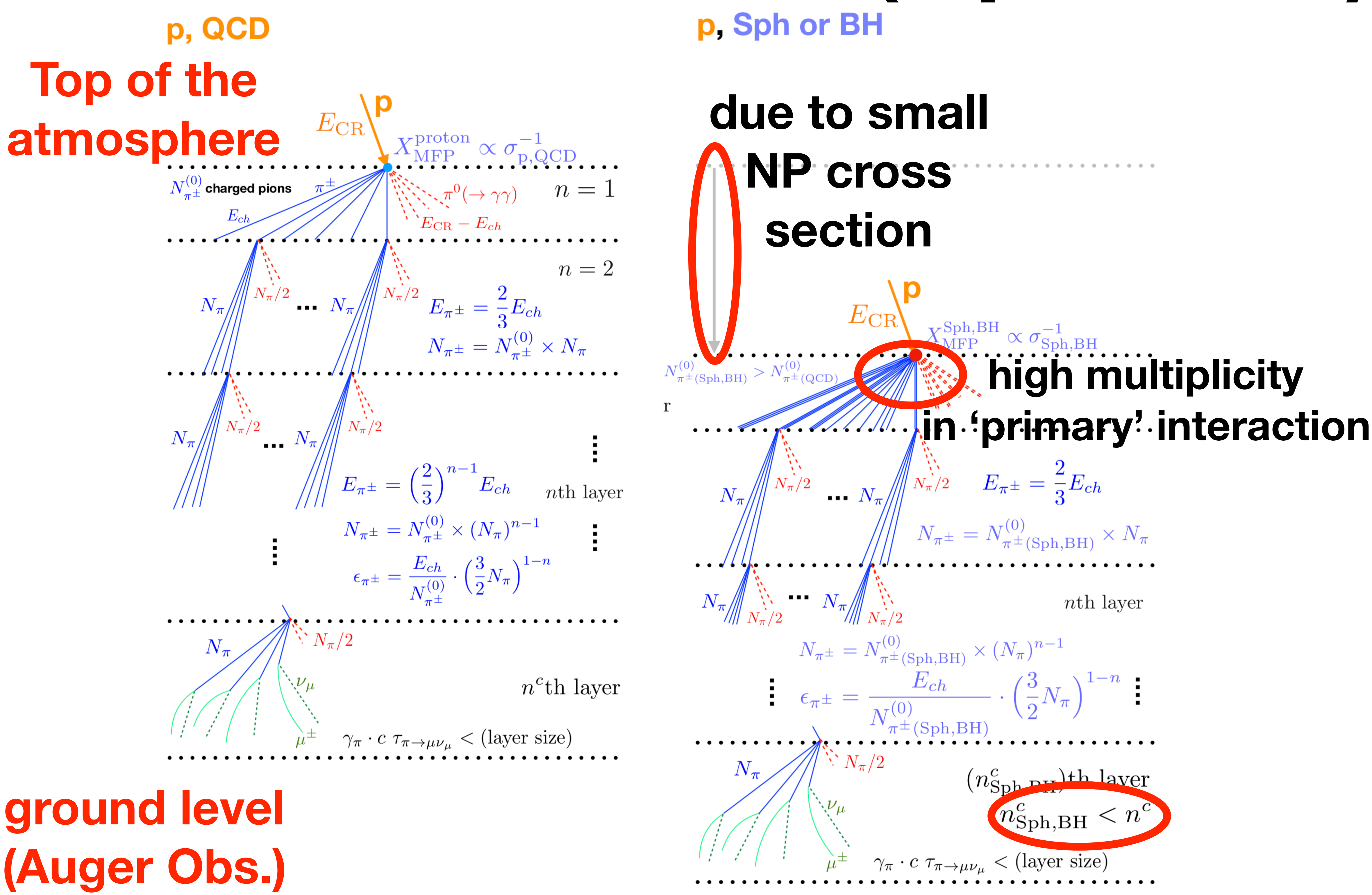

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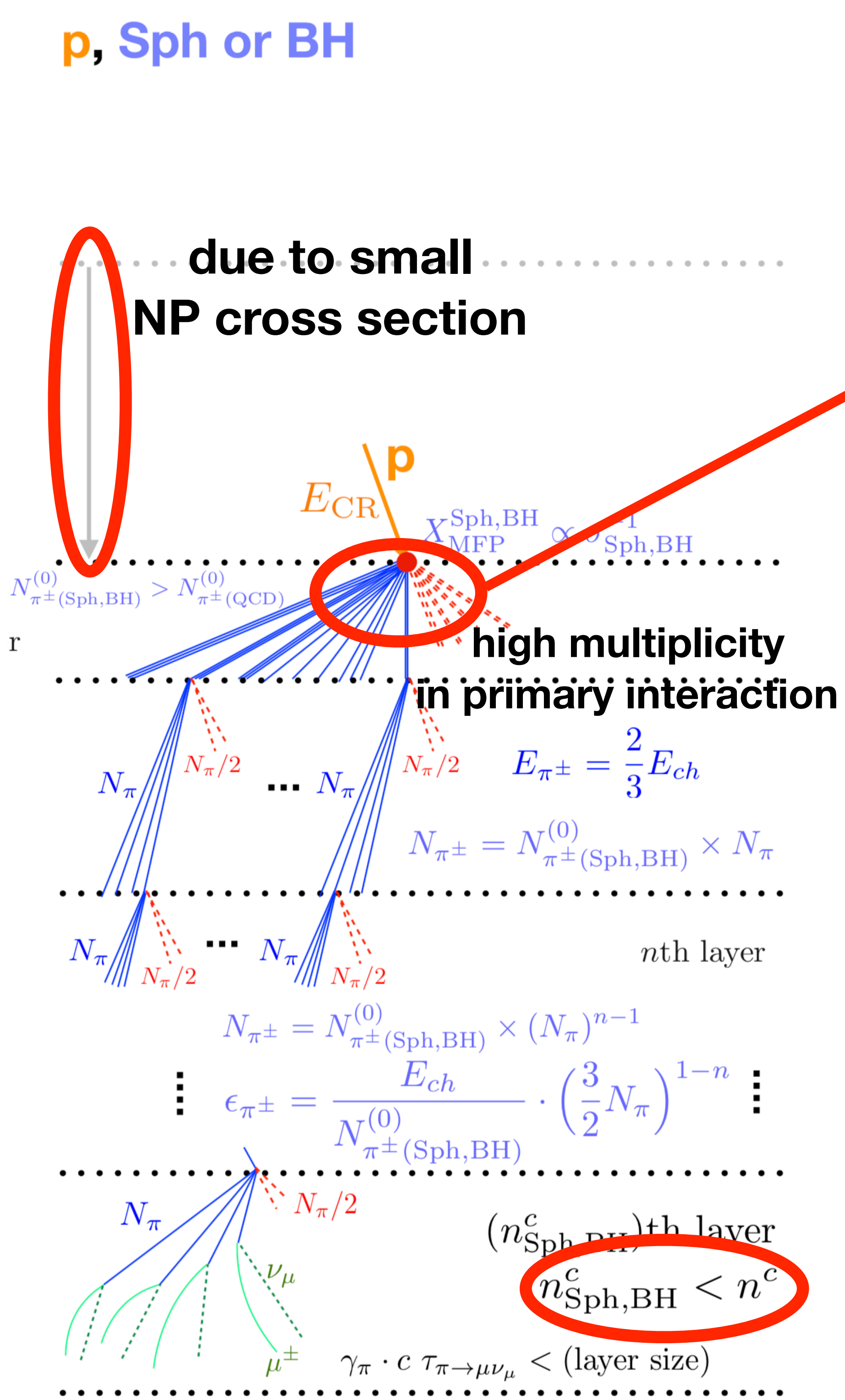
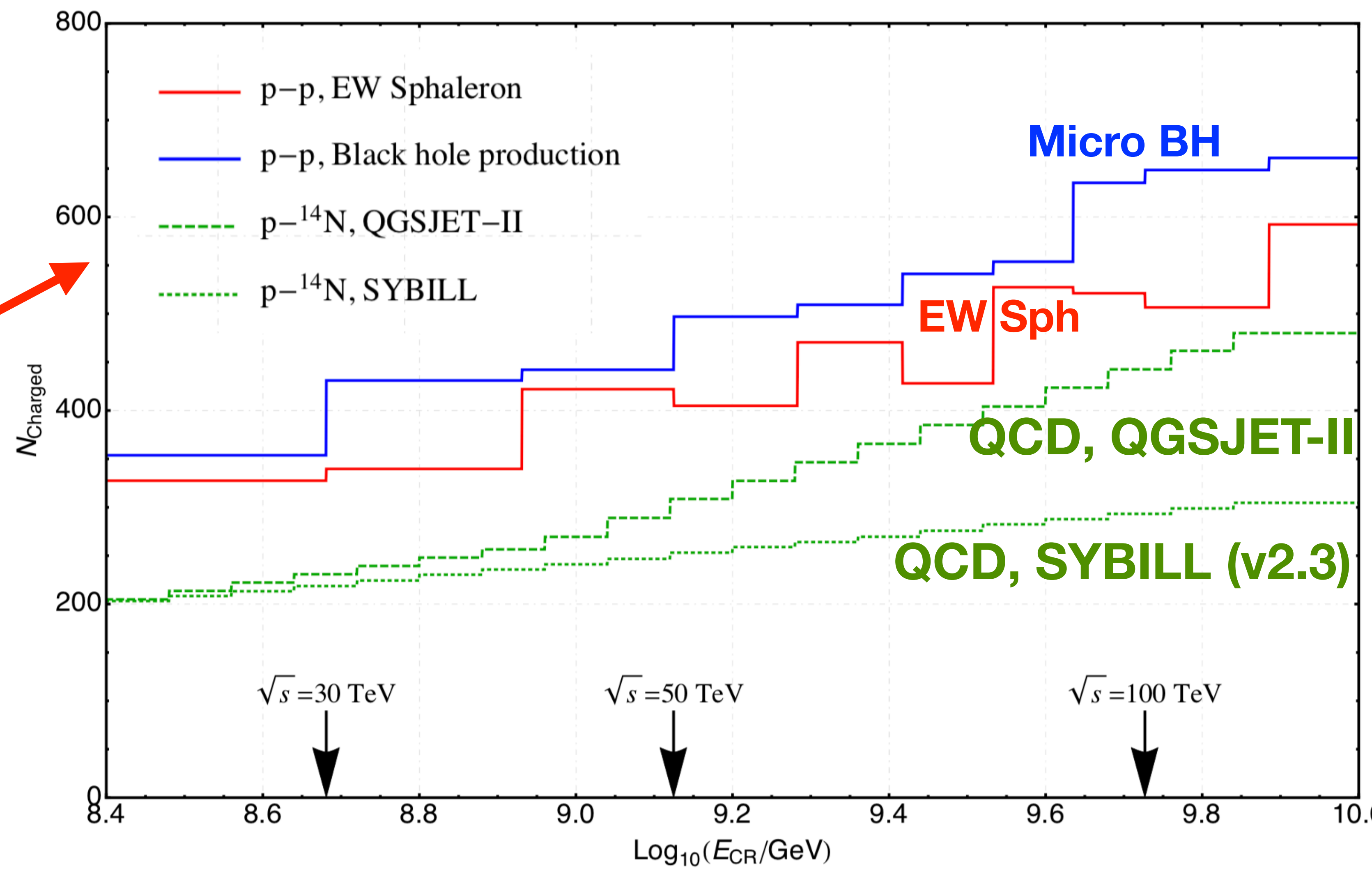
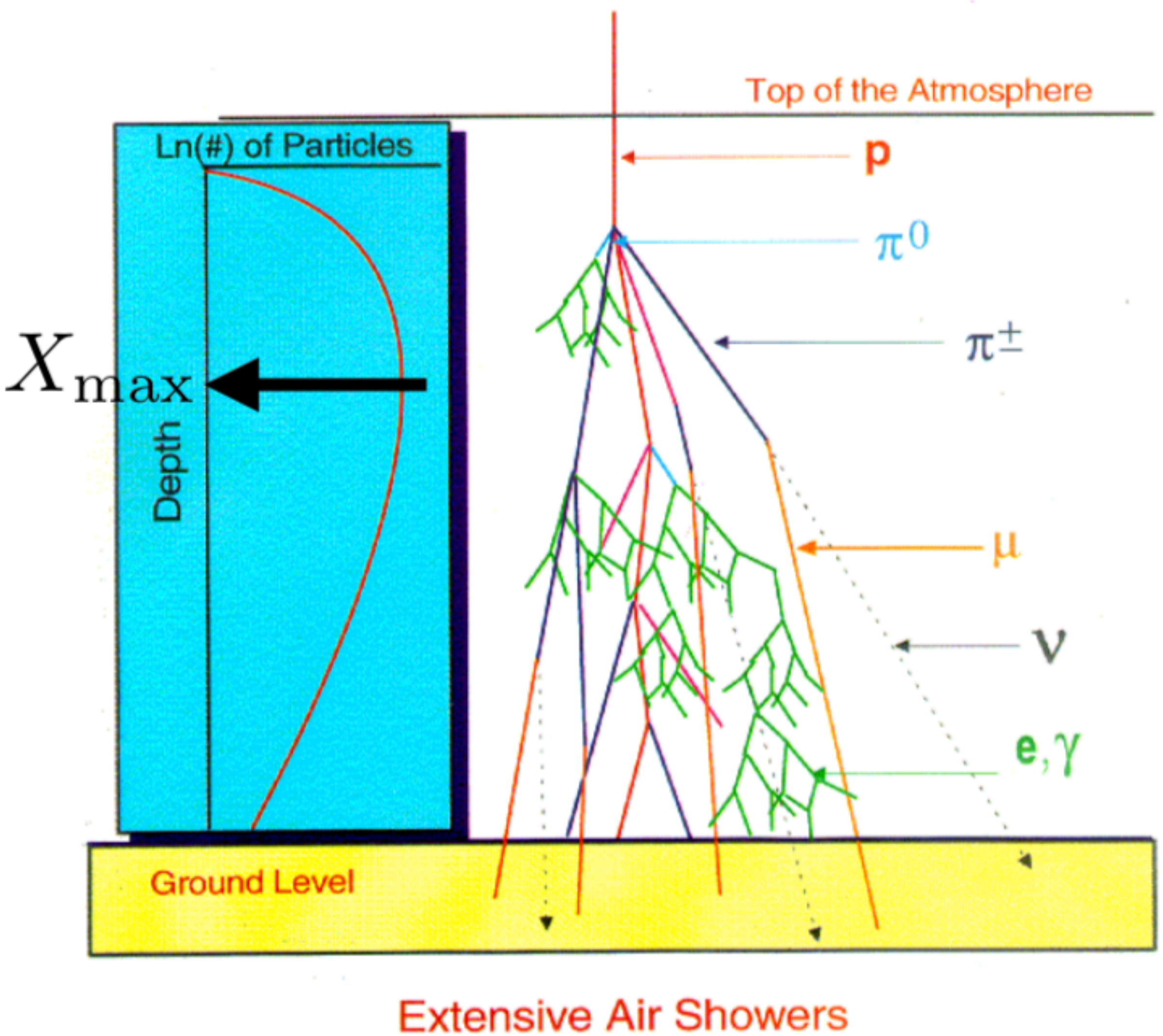


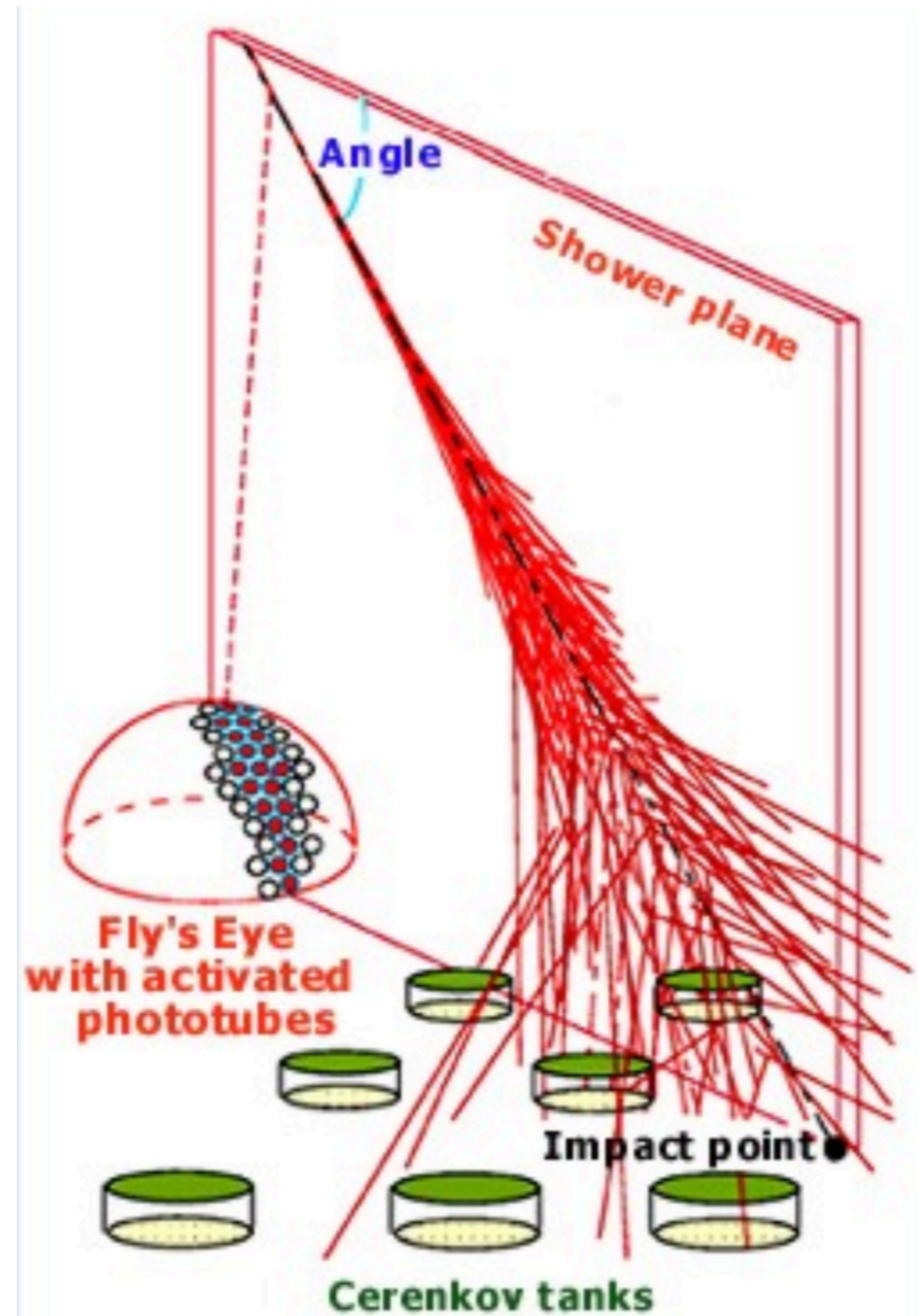




**High multiplicity NP makes highly inclined & deep air showers!**

**(and NP air showers more quickly develop.)**

# Longitudinal development: Observation of Longitudinal profiles




**Longitudinal development of air-shower can be observed by the fluorescence light detector (FD) (in the range of 300-430 nm)**

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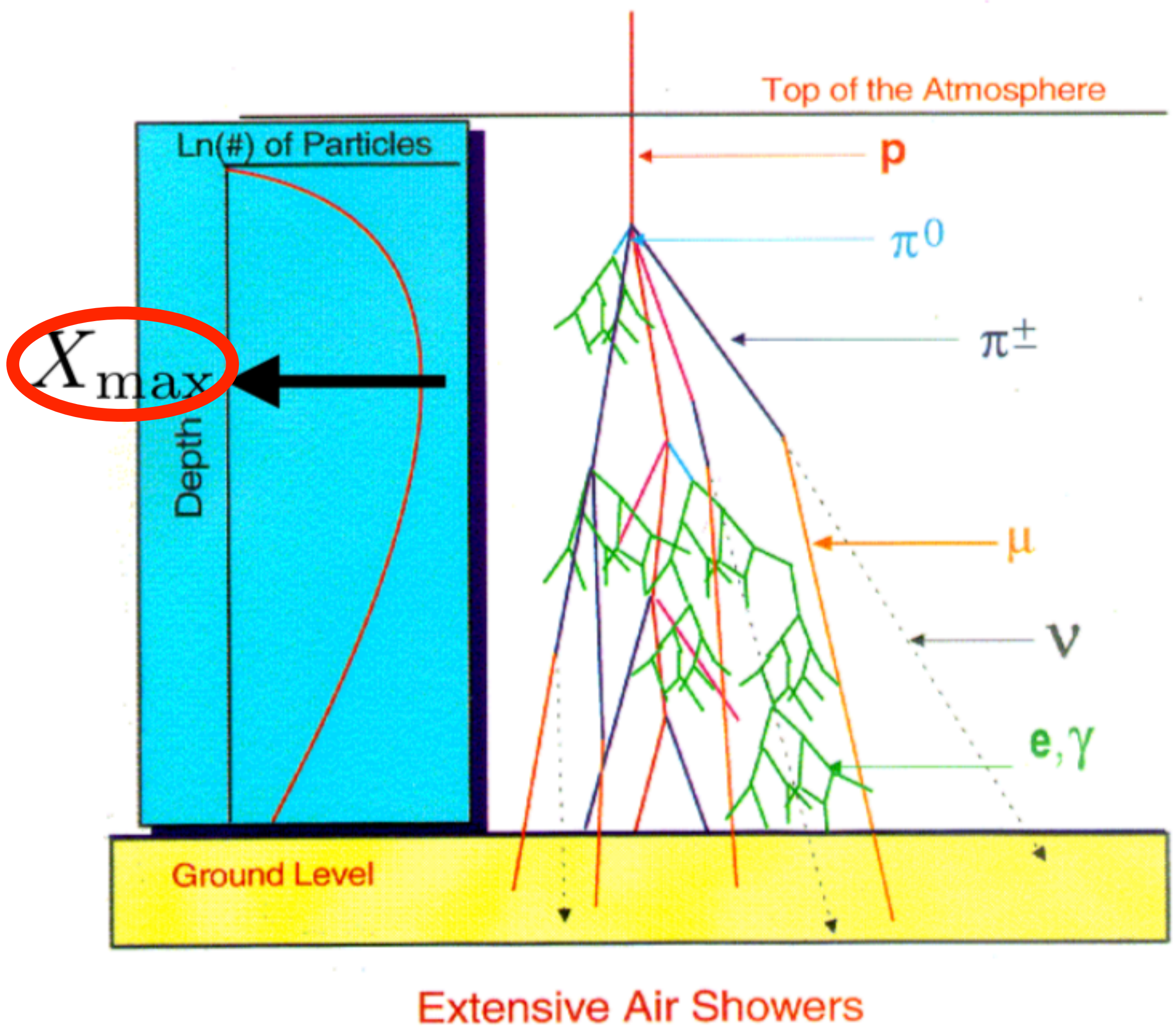
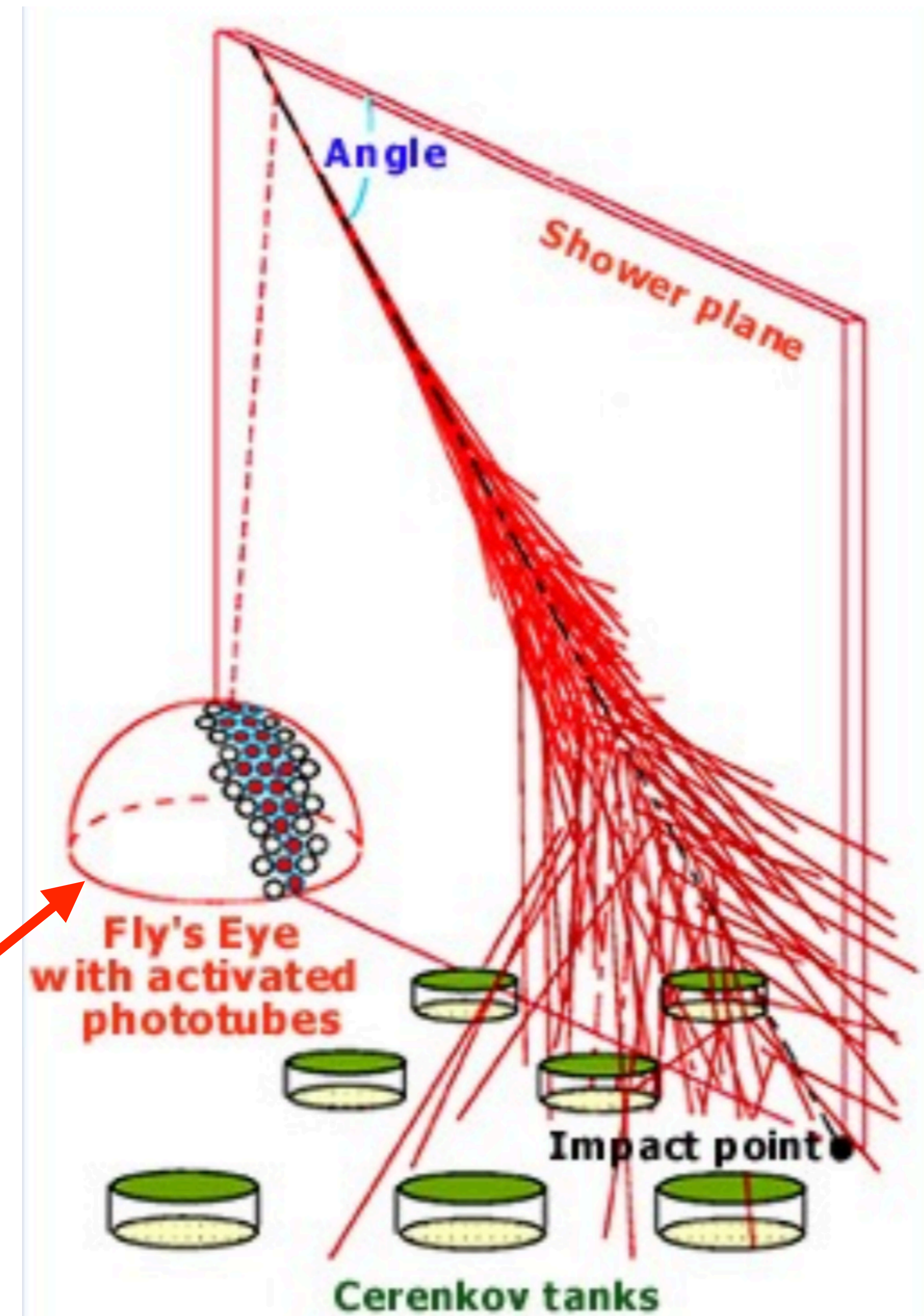
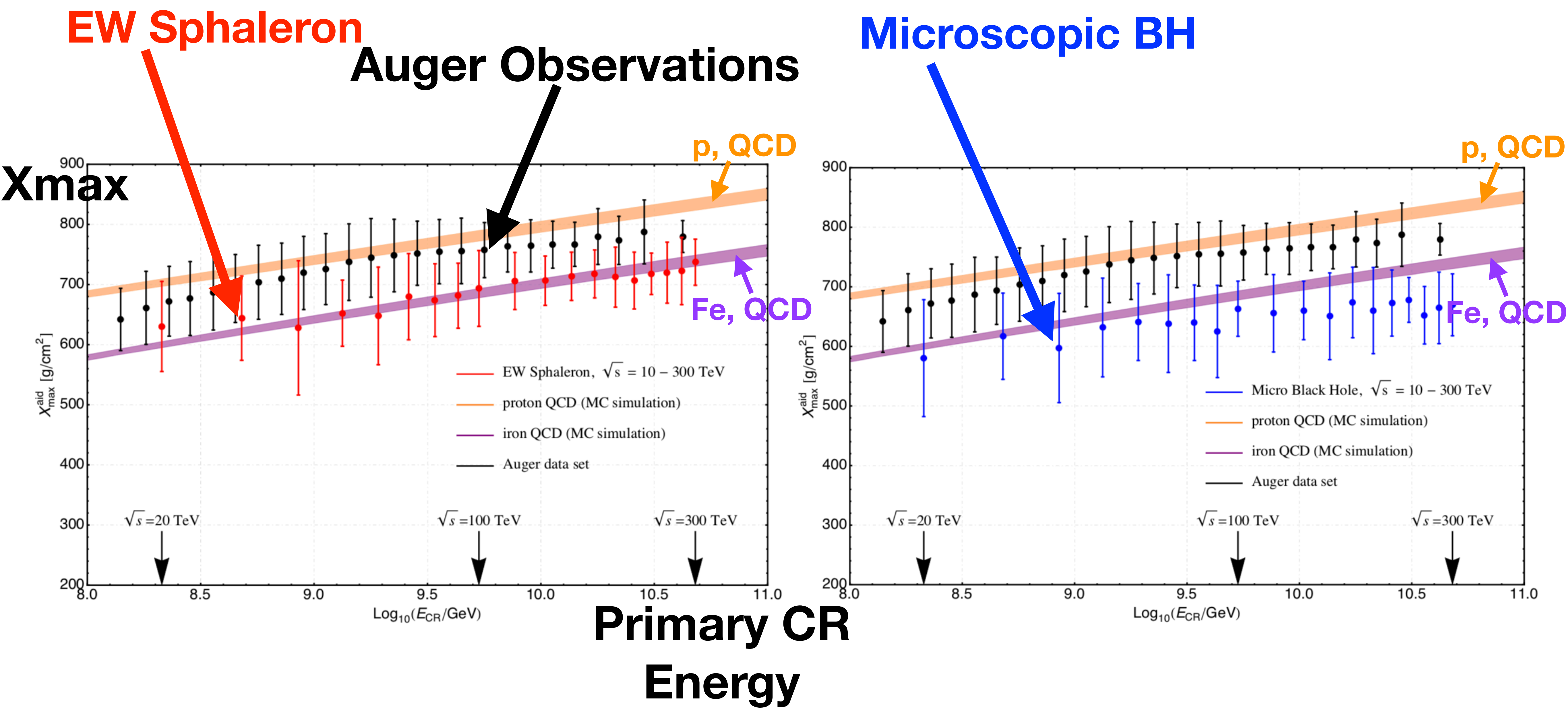



**Longitudinal development of air-shower can be observed by the fluorescence light detector (FD) (in the range of 300-430 nm)**

# Longitudinal development: QCD vs. NP (Sph, BH)

**primary parton shower : PYTHIA8**
**cascade in the atmosphere : CORSIKA**

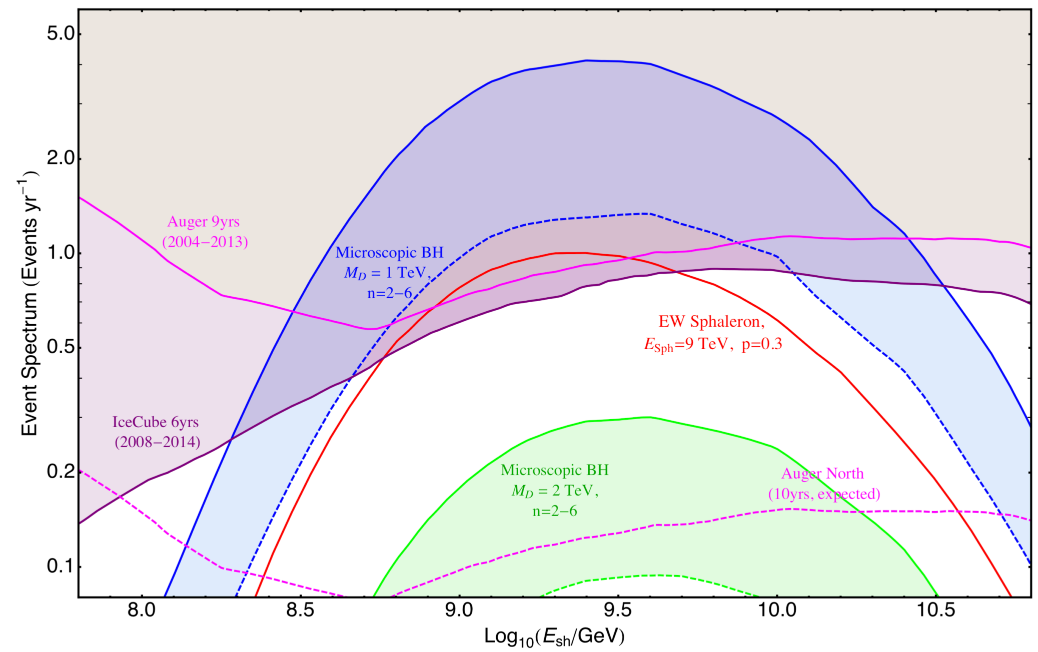


# Conclusion

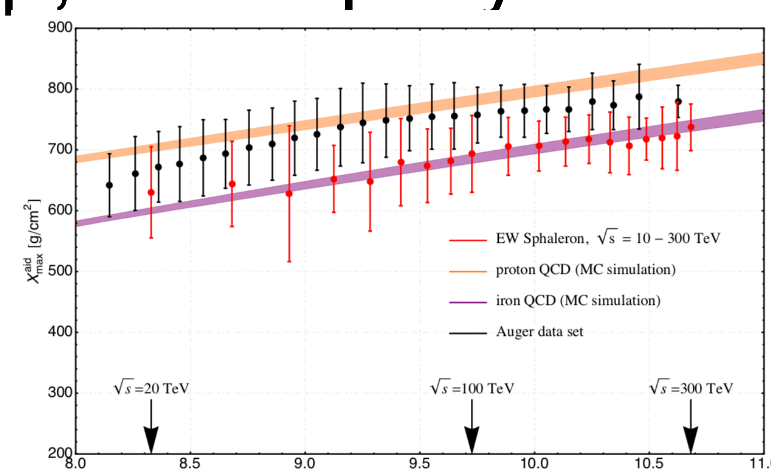
- High Multiplicity New Physics can be above TeV-scale, which can be probed by Ultra-High-Energy Cosmic Rays, up to ~400 TeV in the center-of-mass frame energies.
- Electroweak sphaleron process can be tested as

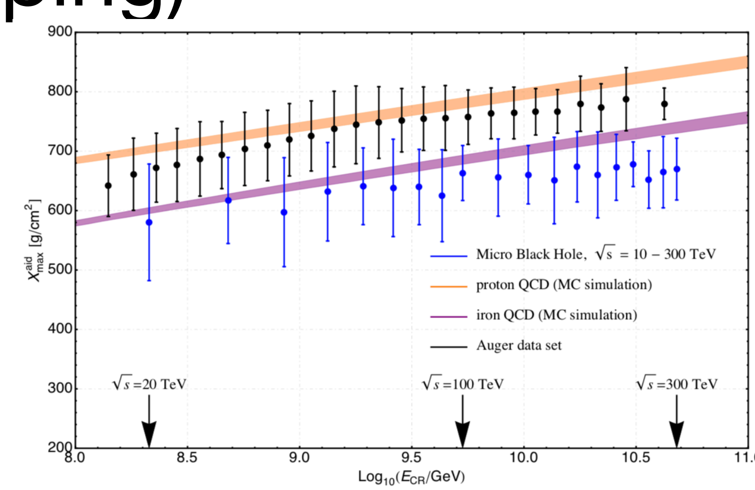
$p \leq \mathcal{O}(10^{-1})$ Auger 9yrs

$p \leq \mathcal{O}(10^{-2})$ Auger North 10yrs (expected)



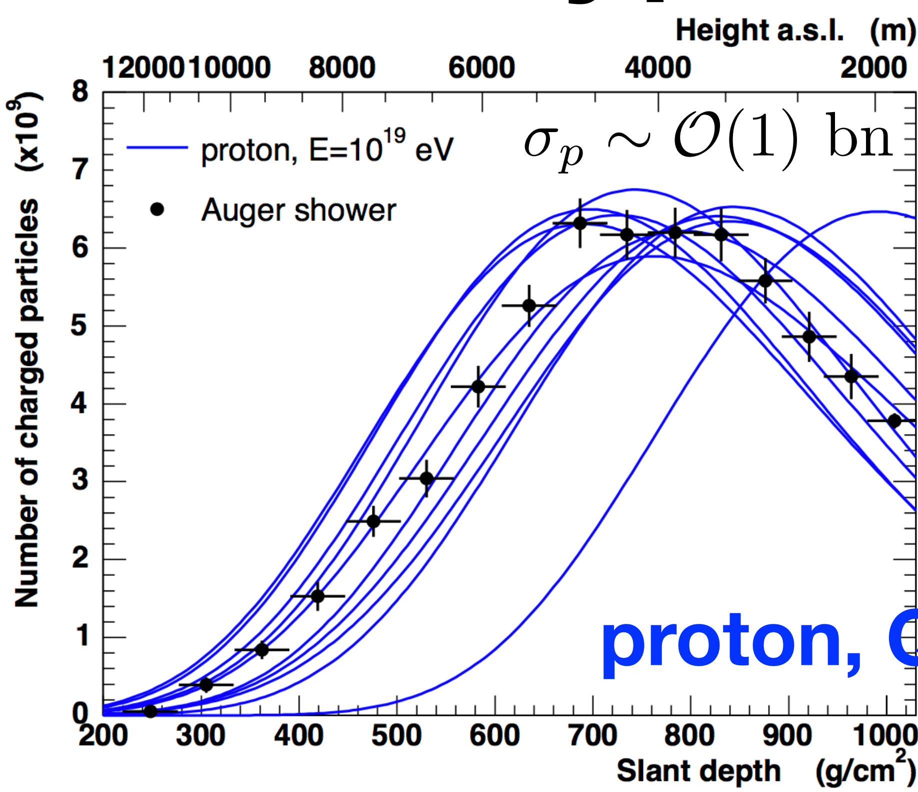

- Even though the NP event rates are expected to be small, their features in extensive air shower (highly inclined, deep, and rapidly developing) can be helpful to distinguish signal events from QCD showers



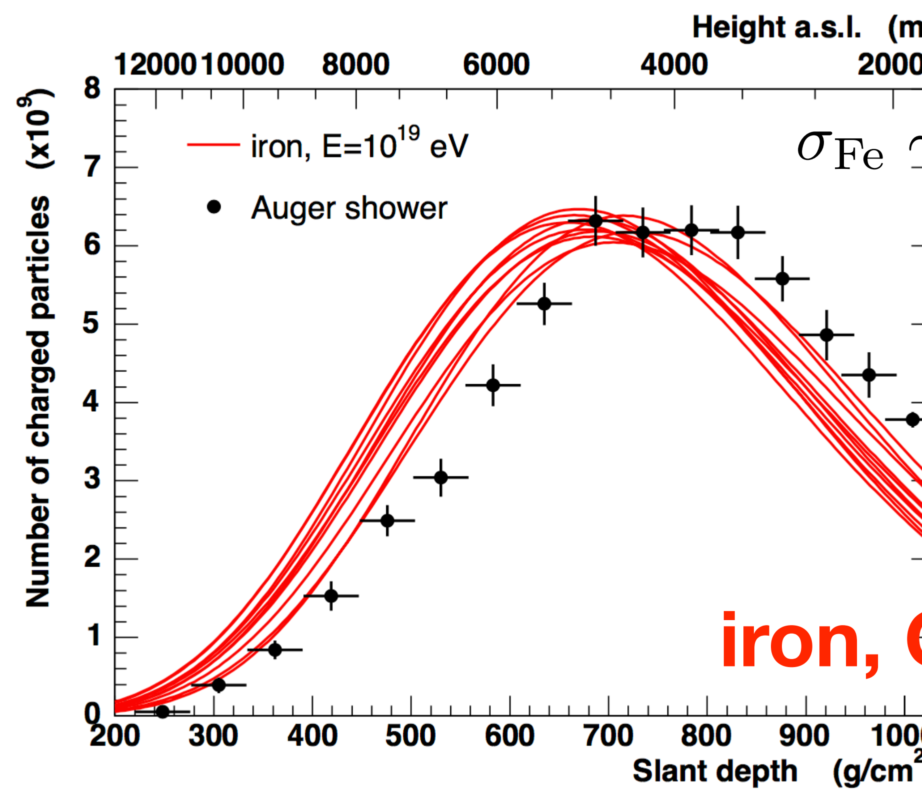
# backup slides

# Longitudinal development: Typical QCD showers




$\sigma_p \sim \mathcal{O}(1)$ bn

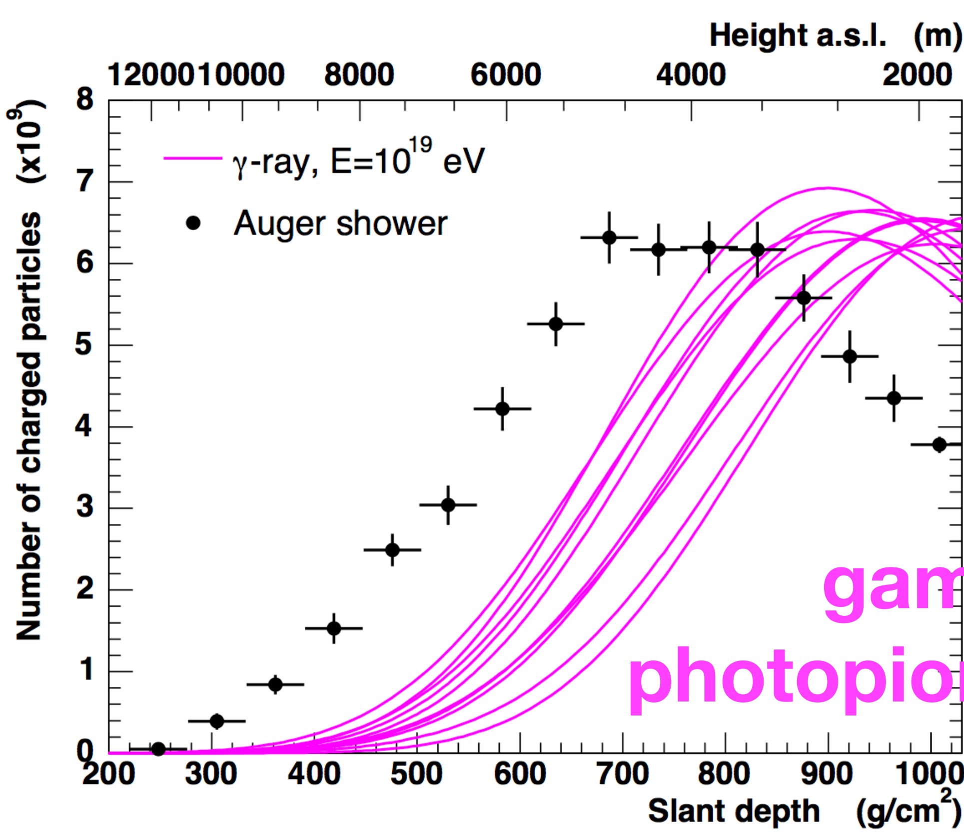
**proton, QCD**




$\sigma_{\rm Fe} \sim \mathcal{O}(10)$ bn

**iron, QCD**

**Large Cross section & High multiplicity**




**much smaller Cross sections**

$\sigma_{p\gamma \to n\pi} \sim \mathcal{O}(100)\ \mu b$

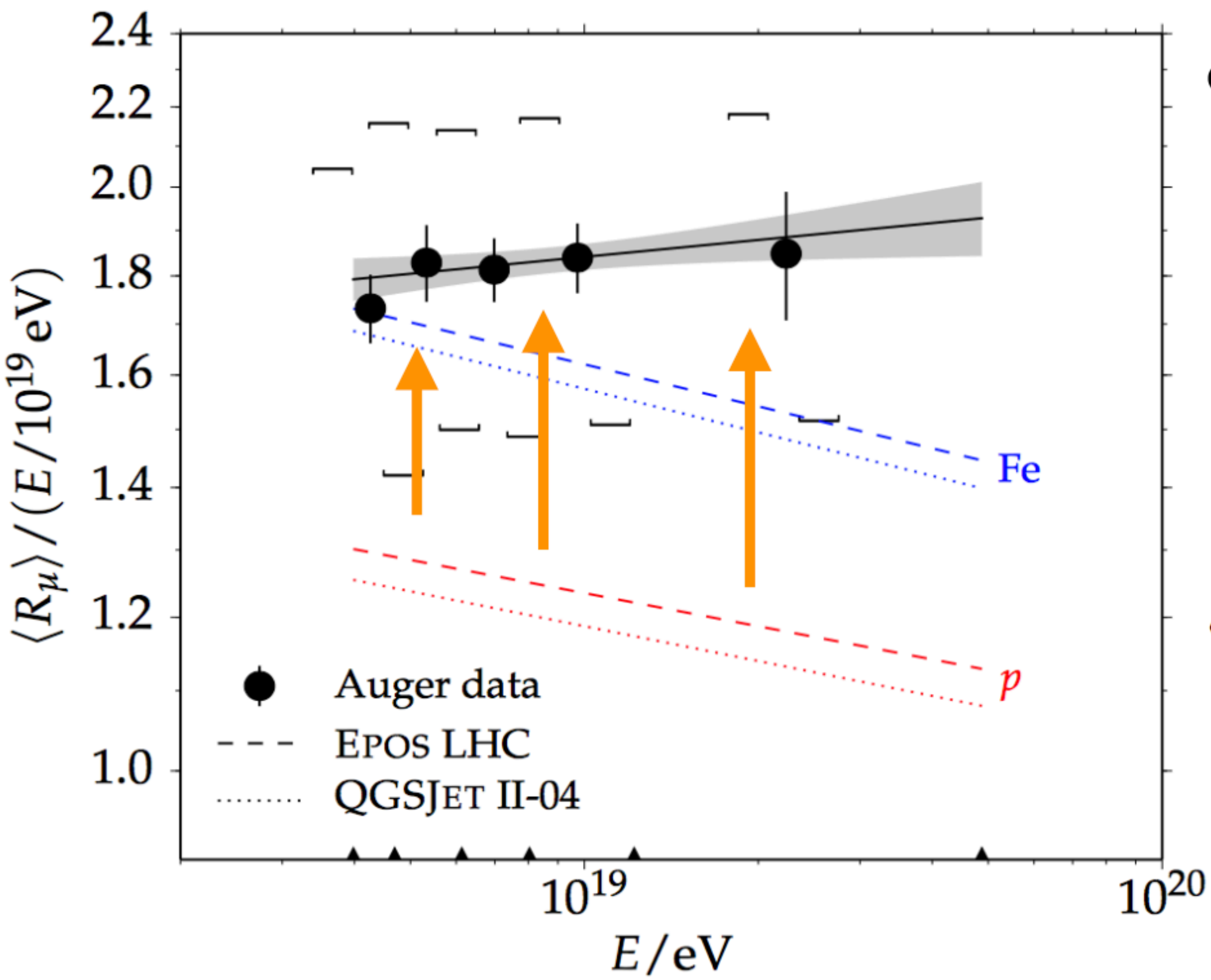
**gamma, photopion process**

**Q) How about NP with High multiplicity?**

$\sigma_{\rm Sph,BH} \ll \sigma_{\rm QCD}$

# Auger $\mu$-excess in UHECRs

- 174 selected events in 9-yrs data set with
- $E_{\mu^\pm} > 0.3\ \mathrm{GeV}$ for each muons and $E_{\rm CR} \geq 10^9\ \mathrm{GeV}$
- $62^\circ < \theta_{\rm zenith} < 80^\circ$ and $\theta^{\rm avg.}_{\rm zenith} = 67^\circ$ (highly inclined)




- Normalized muon number

$$R_\mu = \frac{N_{\mu^\pm}}{N_{\rm ref}} = \frac{N_{\mu^\pm}}{1.2 \times 10^7}$$

$$\langle R_\mu \rangle = \int_0^{X_{\rm max}} P(X, \sigma_{\rm NP})\ R_\mu(X)\ dX$$

PRD 91 (2015) no.3, 032003
[arXiv:1408.1421]

# $\mu$-excess in other CR obs.

Astropart. Phys. 92 (2017) 1-6
[arXiv:1609.05764]

No muon excess for

$$E_{\rm CR} \lesssim 5 \times 10^8 \ {\rm GeV}$$

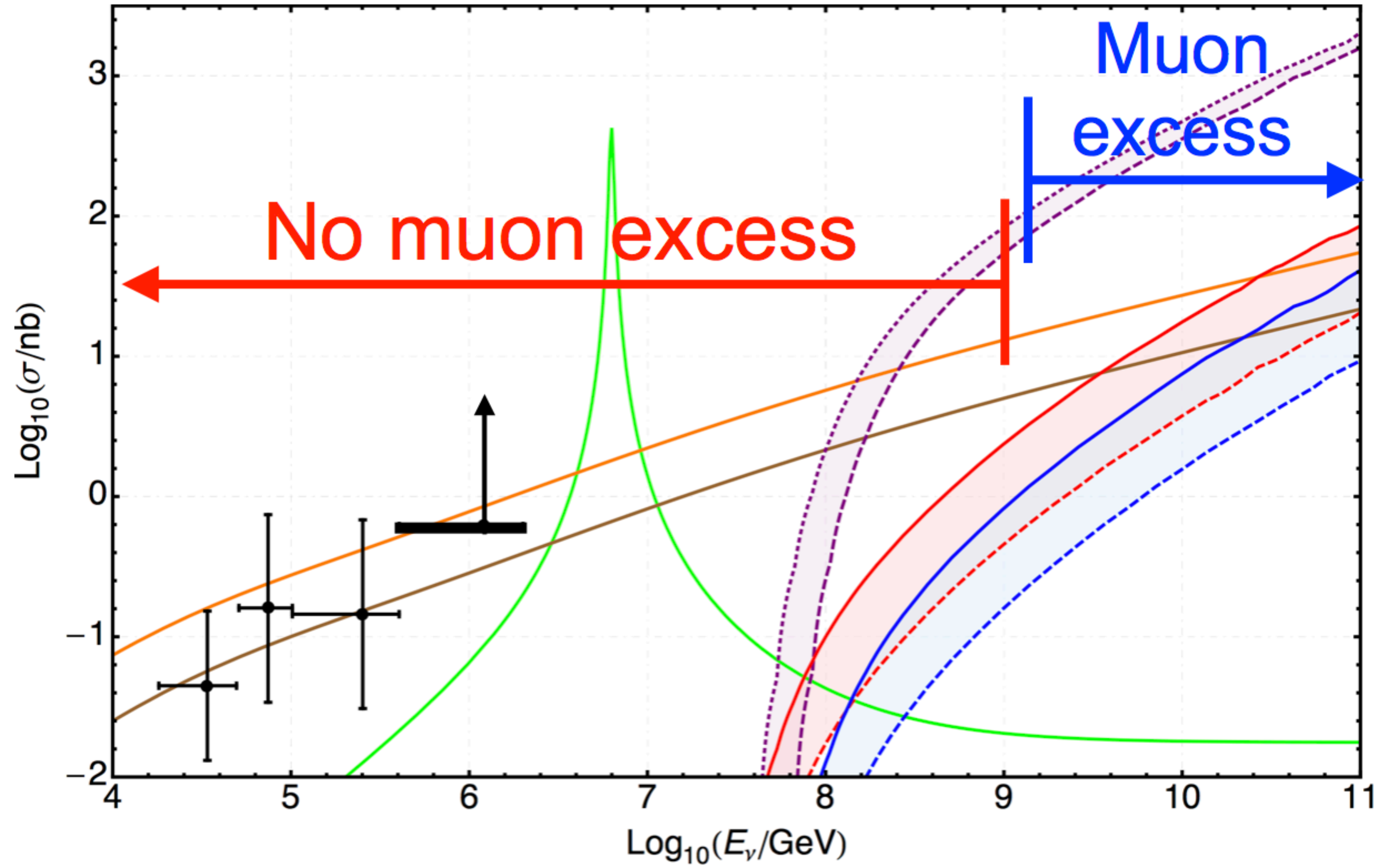
Low E CR

$$E_{\mu^\pm} > 10.0 \ {\rm GeV}$$

Energetic $\mu$

$$\theta_{\rm zenith} < 30^\circ$$

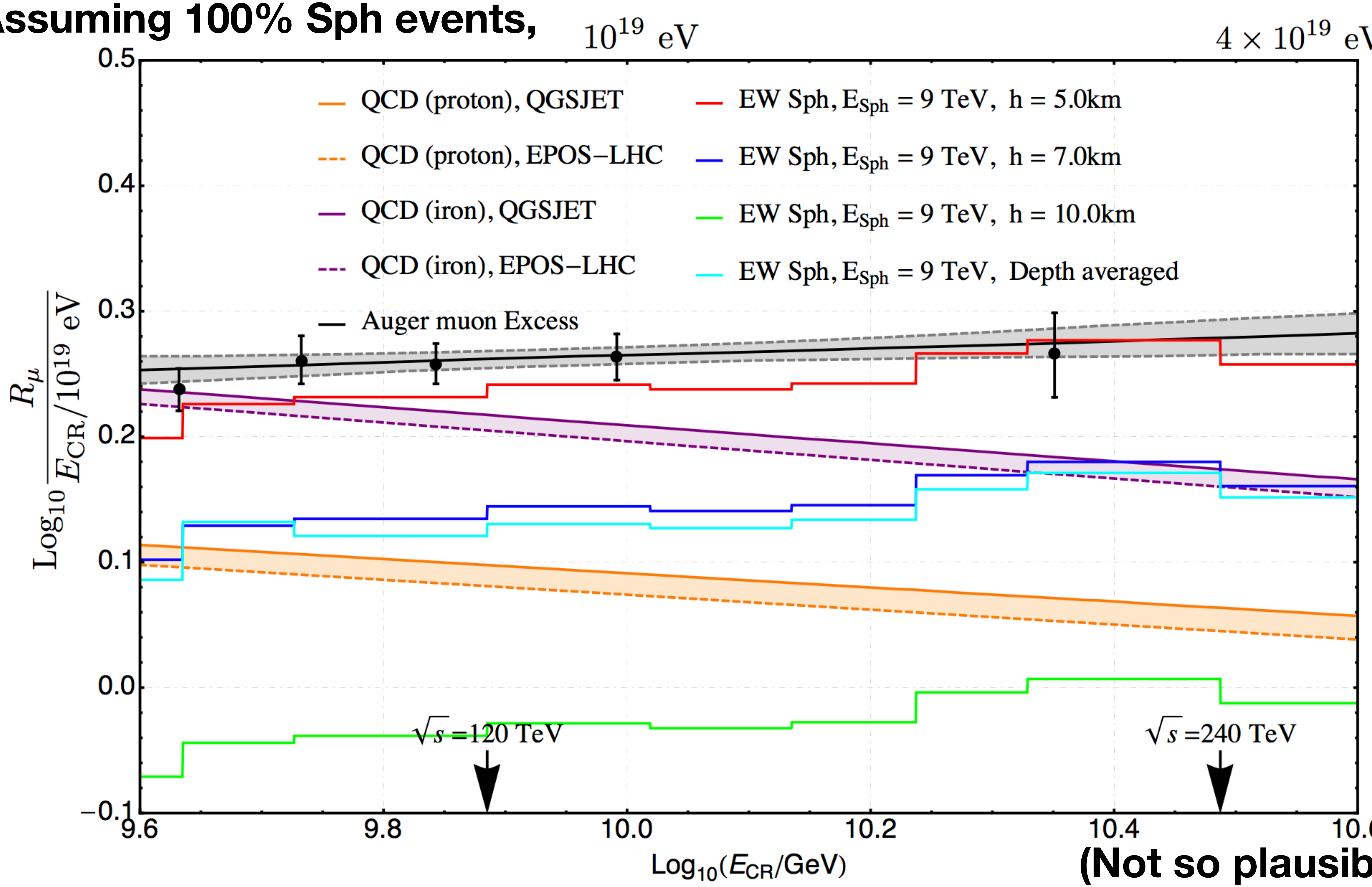
Vertical air-showers




| Experiment | altitude, m a.s.l. | $X$, g/cm$^2$ | $E$, eV | $E_\mu$, GeV | $r/R_0$ | $\theta$ | muon excess (data over MC) |
|---|---|---|---|---|---|---|---|
| HiRes-MIA [6] | 1500 | 860 | $10^{17} - 10^{18}$ | $\gtrsim 0.85$ | $\gtrsim 10$ | N/A | yes |
| PAO [2, 4] | 1450 | 880 | $\gtrsim 10^{19}$ | $\gtrsim 1$ | $\gtrsim 10$ | 70° | yes |
| Yakutsk [5] | 100 | 1020 | $\gtrsim 10^{19}$ | $\gtrsim 1$ | $\gtrsim 10$ | 45° | yes |
| IceTop [26] | 2835 | 680 | $10^{15} - 10^{17}$ | $\gtrsim 0.2$ | $\gtrsim 3$ | 13° mean | no |
| EAS-MSU (this work) | 190 | 990 | $10^{17} - 10^{18}$ | $\gtrsim 10$ | $\lesssim 3$ | 30° | no |

# NP interpretation of $\mu$-excess

**Assuming 100% Sph events,**




**(Not so plausible)**

**Only highly deep air-showers can contribute to the muon excess.**