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Search for new physics from ultra high energy cosmic rays and neutrinos

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Work in progress, collaborated with
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KEK-PH2018
KEK@Japan, Feb 13, 2018

New Physics from UHE cosmic ray event

- Ultra-high E cosmic rays events : up to 400 TeV in CME. (It is the only way to reach above 10 TeV now.)
- Studying high E new physics event at ground detector arrays is important.

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- Above 10 TeV, there are some High multiplicity process possibilities:
  - (B+L)-violating electroweak sphaleron process
  - BH production in TeV (or higher)-scale gravity models

High multiplicity NP cross section

- UHE neutrino-nucleon collision cross section

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

depend on new physics example.

PDF uncertainties at small $x \leq 10^{-5}$ high $\sqrt{q^2} \geq O(10)$ TeV

Sphaleron cross section

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

- NP case : Electroweak sphaleron

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

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

can be unsuppressed
at $\sqrt{\hat{s}} > E_{\mathrm{Sph}}$

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

Microscopic BH cross section

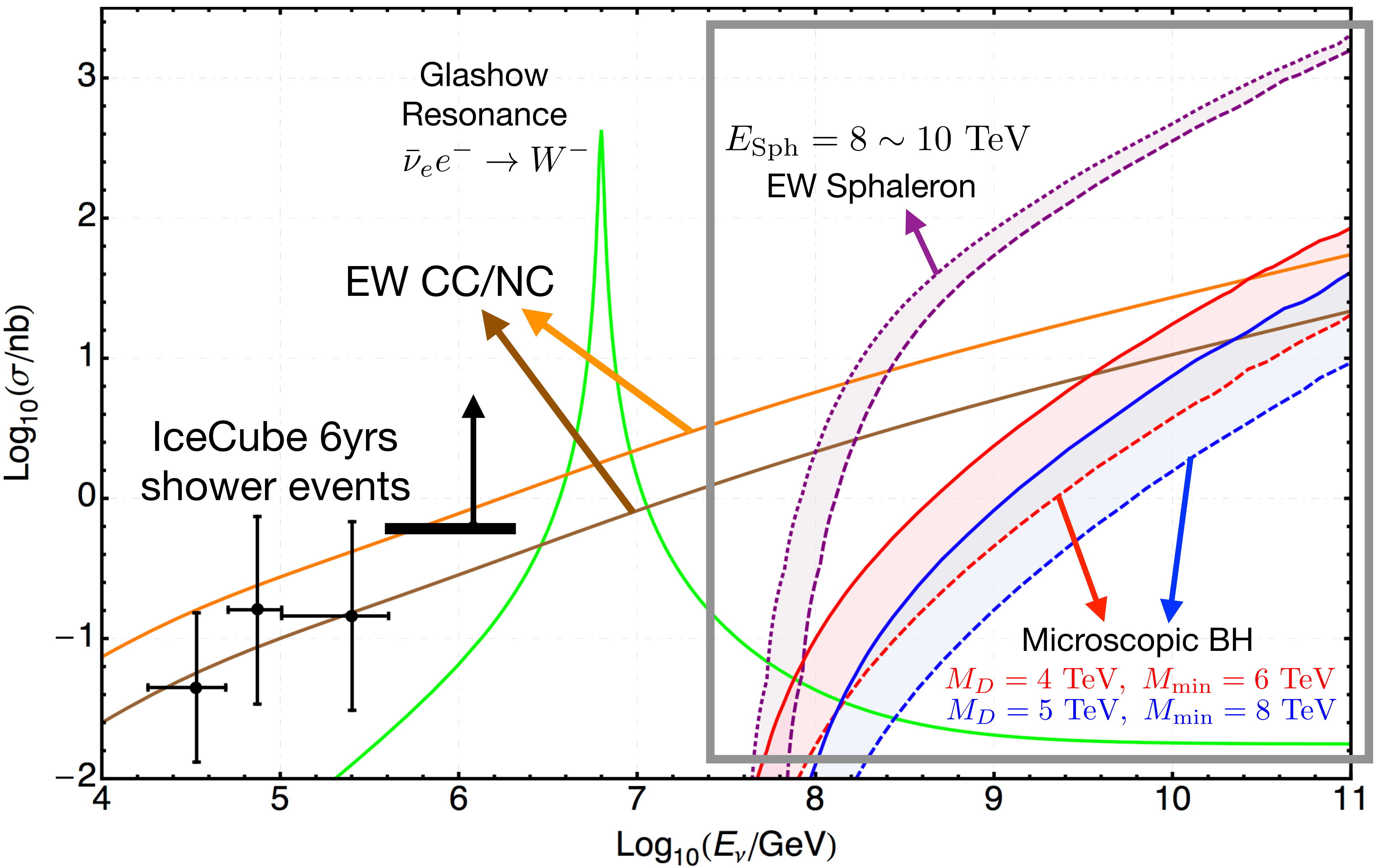
$$\sigma(E_\nu) = \sum_a \int dx \;\; f_a(x, q^2) \;\; \underline{\hat{\sigma}(\hat{s} = 2x m_N E_\nu)}$$

- NP case : Microscopic BH in TeV-scale gravity

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

Current pp Collider bounds are $M_{\rm D} \sim 5 - 6 \ {\rm TeV}$

UHE neutrino cross section



Event rate at ground arrays

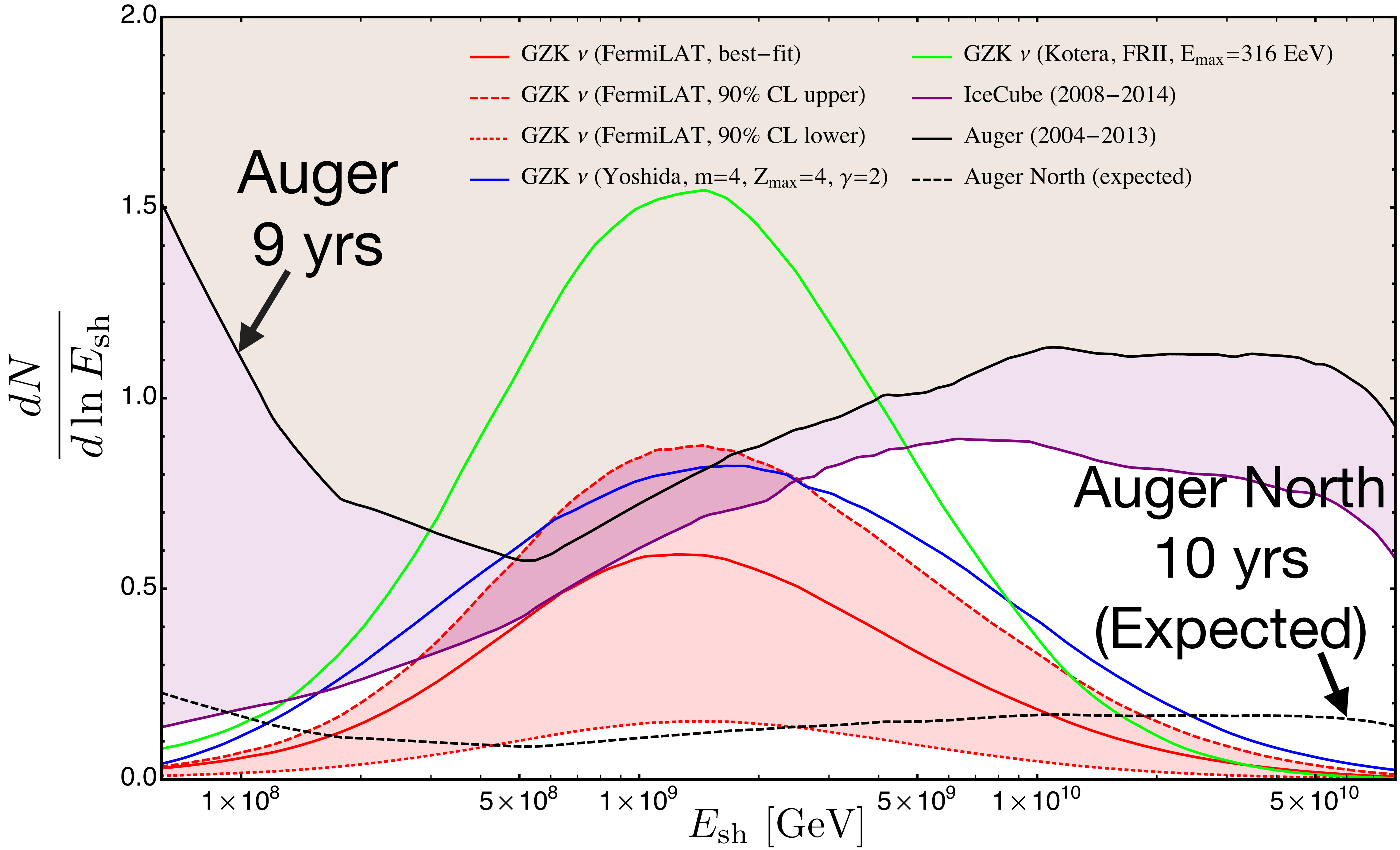
$$\frac{dN}{dt} \propto \int_{E_{\rm th}}^{E_{\rm max}} dE_{\rm sh} \int_0^1 dy \frac{d\phi_\nu(E_\nu)}{dE_\nu} \frac{d\sigma_{\nu N\to X}(E_\nu, y)}{dy} \mathcal{A}(E_{\rm sh})$$

SM or NP

One guaranteed source
: GZK neutrinos

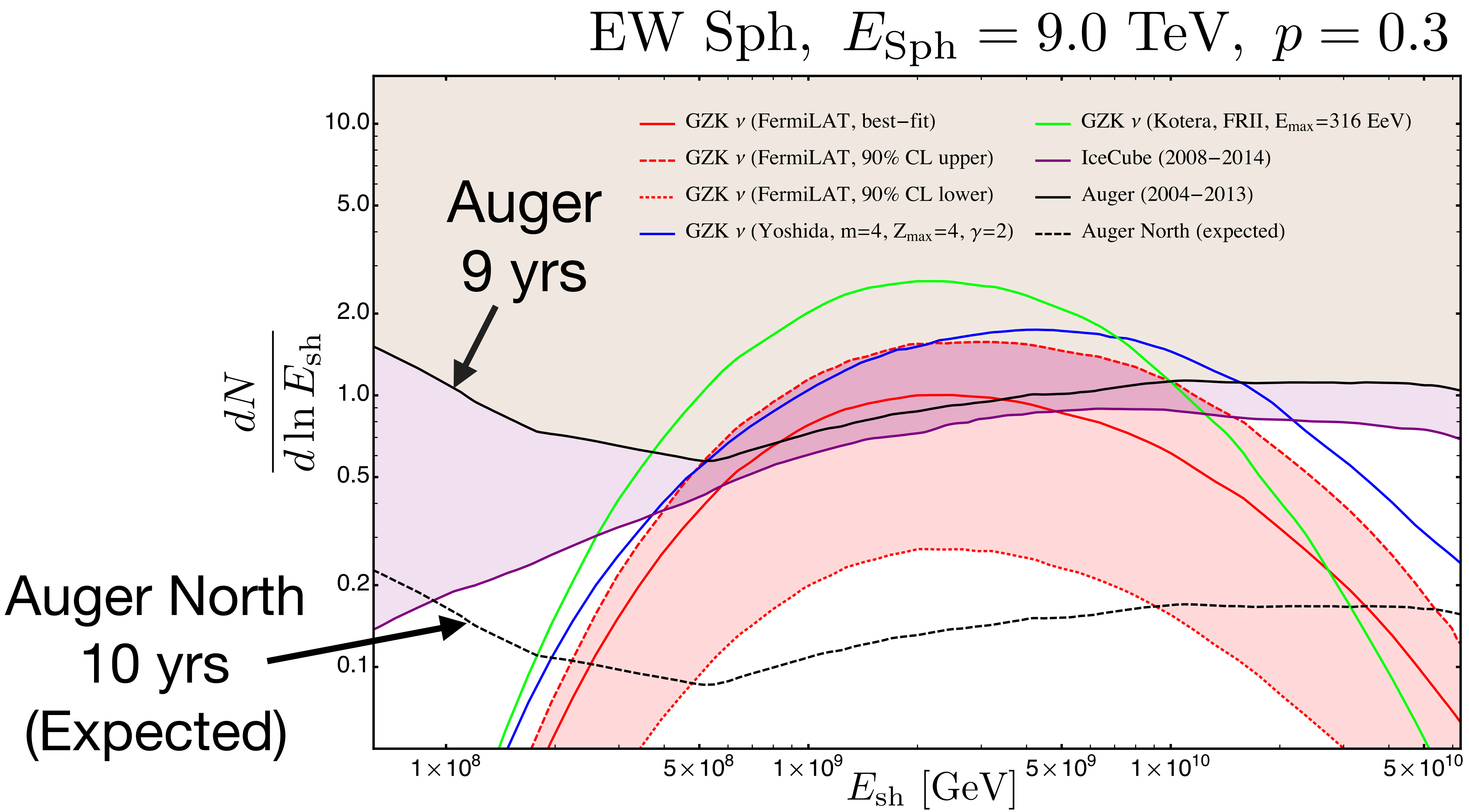
$$\begin{aligned} p + \gamma_{\rm CMB} &\to \pi^+ + n \\ \pi^+ &\to \mu^+ + \nu_\mu \\ \mu^+ &\to e^+ + \nu_e + \bar{\nu}_\mu, \\ p + \gamma_{\rm CMB} &\to \pi^0 + p \\ \pi^0 &\to \gamma + \gamma \end{aligned}$$

SM CC/NC air-shower at Auger observatory



No direct detection of UHE ν-induced, highly inclined air-shower yet.

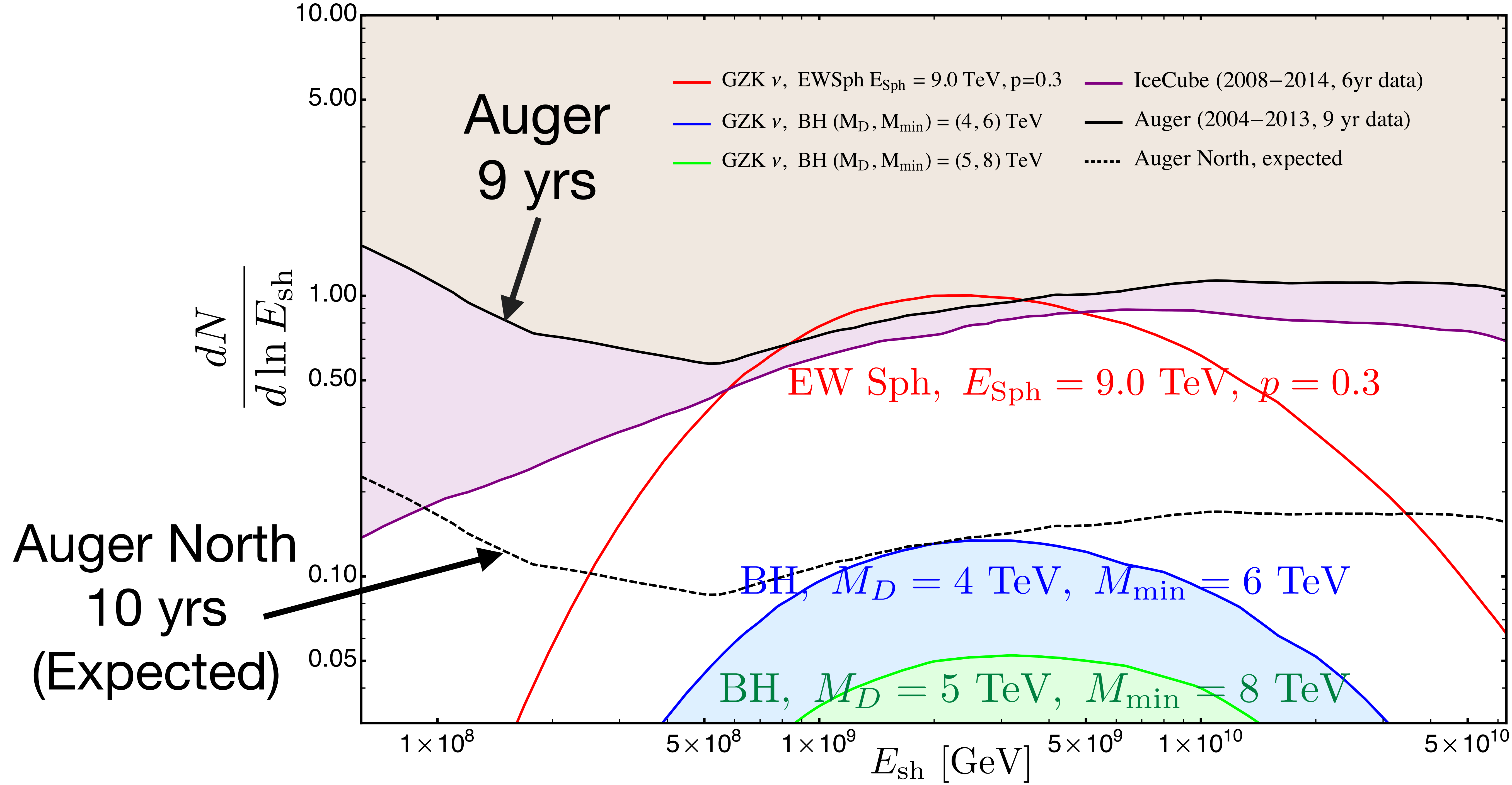
New Physics air-shower with various GZK ν flux assumptions



NP event rate bounds : Auger 9yrs search $p \leq 10^{-1}$

Auger North 10yrs

BH vs. Sphaleron on air-shower detector array

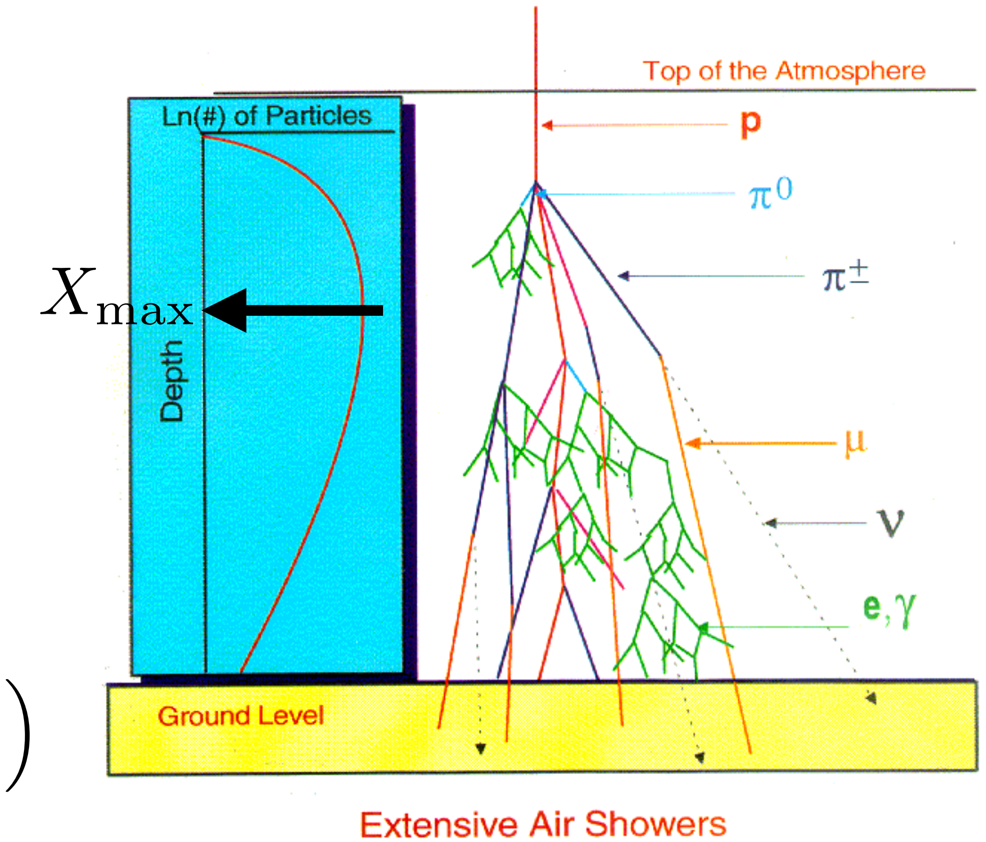


No expectation to observe blackhole air-shower with $(M_{\rm D}, M_{\rm min}) \geq (4, 6)$ TeV in near future.

Extensive air shower in the atmosphere

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

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



- The Gaisser-Hillas function for the fitting

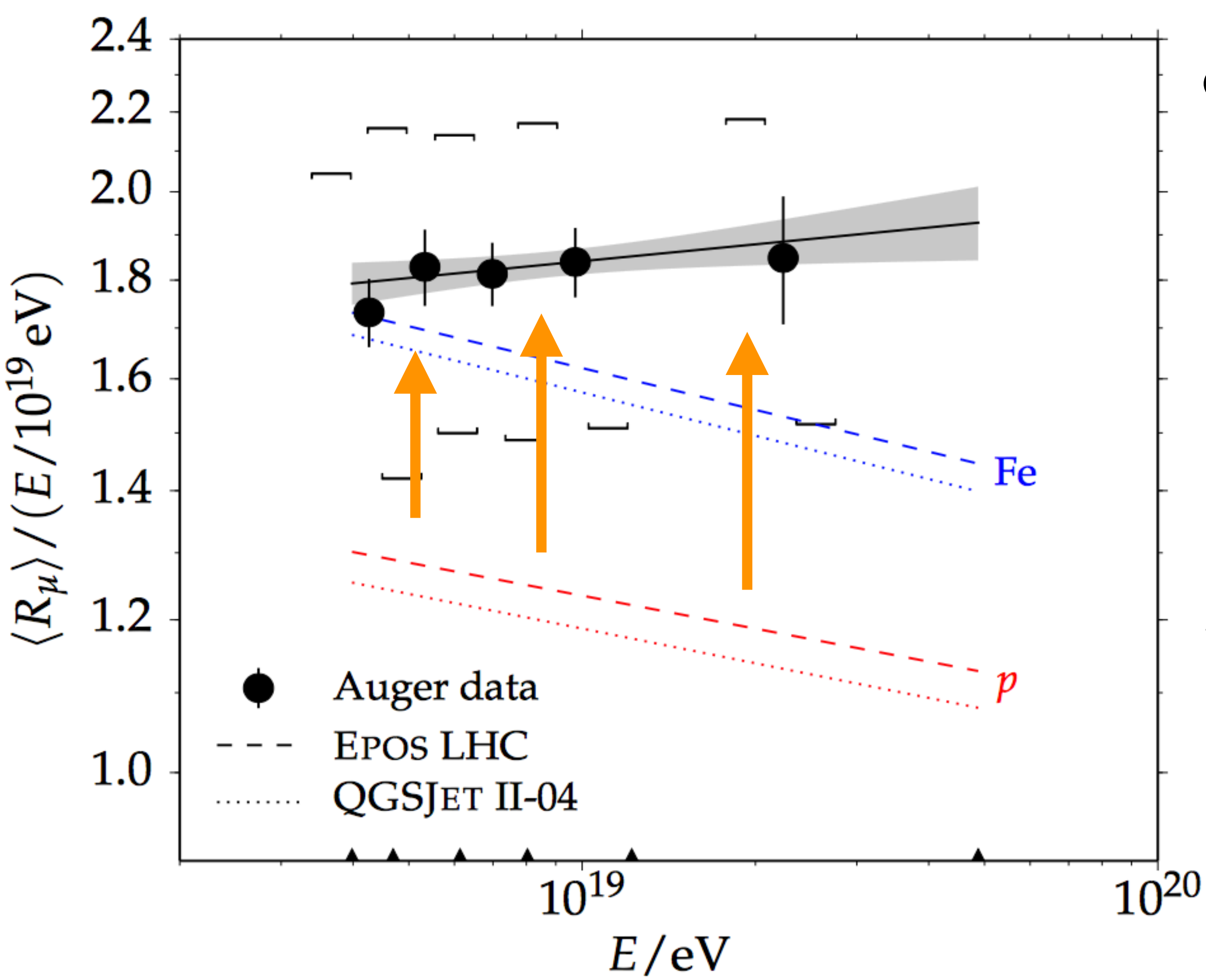
$$N(X) = N_{\rm max}\left(\frac{X - X_0}{X_{\rm max} - X_0}\right)^{\frac{X_{\rm max} - X_0}{\lambda}} \exp\left(\frac{X_{\rm max} - X}{\lambda}\right)$$

- 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]

Auger μ-excess in UHECRs

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



- Normalized muon number

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

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

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

μ-excess in other CR obs.

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

No muon excess for

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

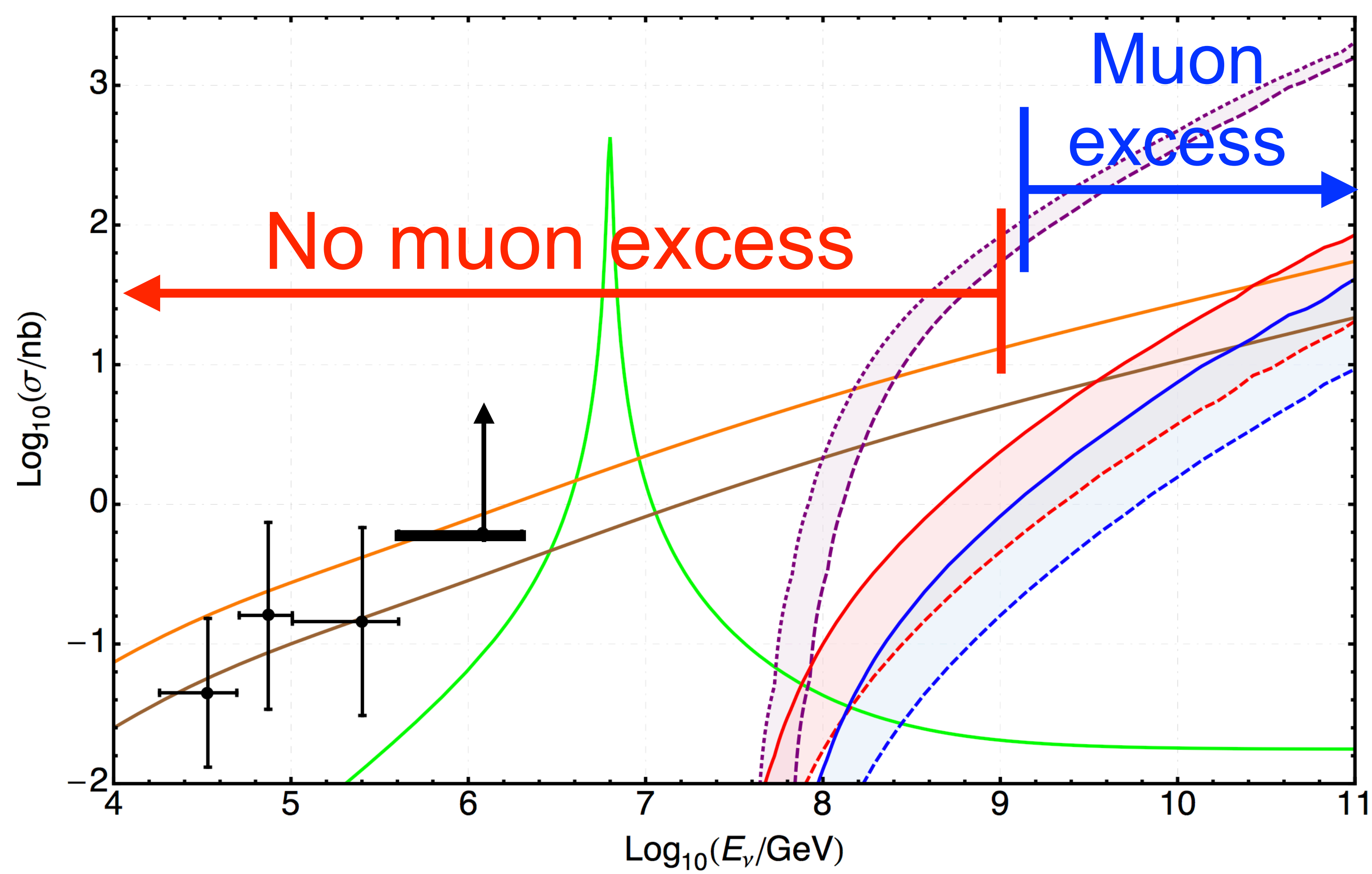
Low E CR

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

Energetic μ

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

Vertical air-showers

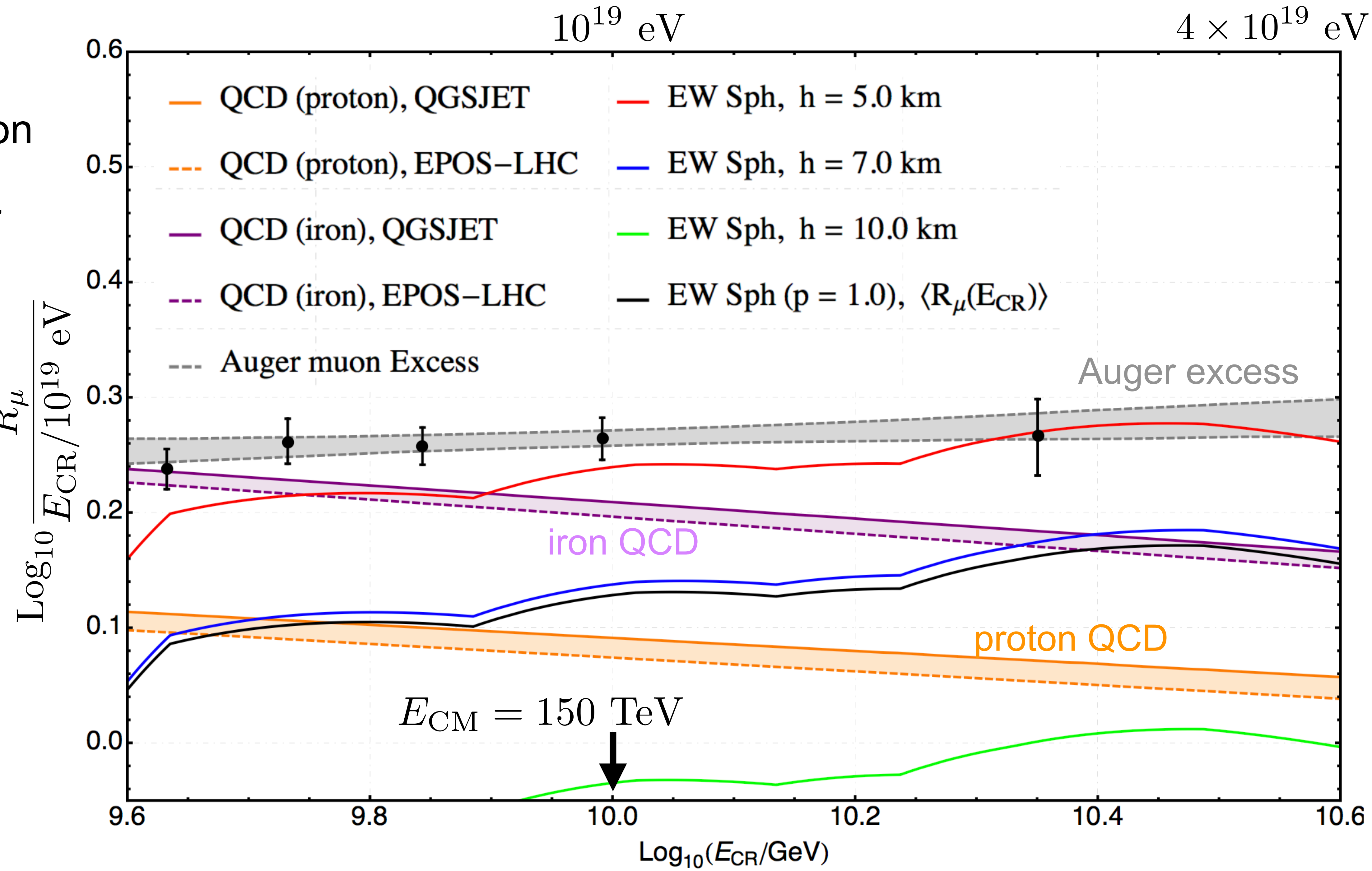


Experiment	altitude, m a.s.l.	X, g/cm^2	E, eV	E_μ, GeV	r/R_0	θ	muon excess (data over MC)
HiRes-MIA [6]	1500	860	$10^{17} - 10^{18}$	$\gtrsim 0.85$	$\gtrsim 10$	N/A	yes
PAO [2, 4]	1450	880	$\gtrsim 10^{19}$	$\gtrsim 1$	$\gtrsim 10$	70°	yes
Yakutsk [5]	100	1020	$\gtrsim 10^{19}$	$\gtrsim 1$	$\gtrsim 10$	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 μ-excess

For EW Sph with $p \sim \mathcal{O}(1-10^{-1})$, assuming 100% Sph events

- PYTHIA8 for hadronization
- CORSIKA 7.57 for cascade



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

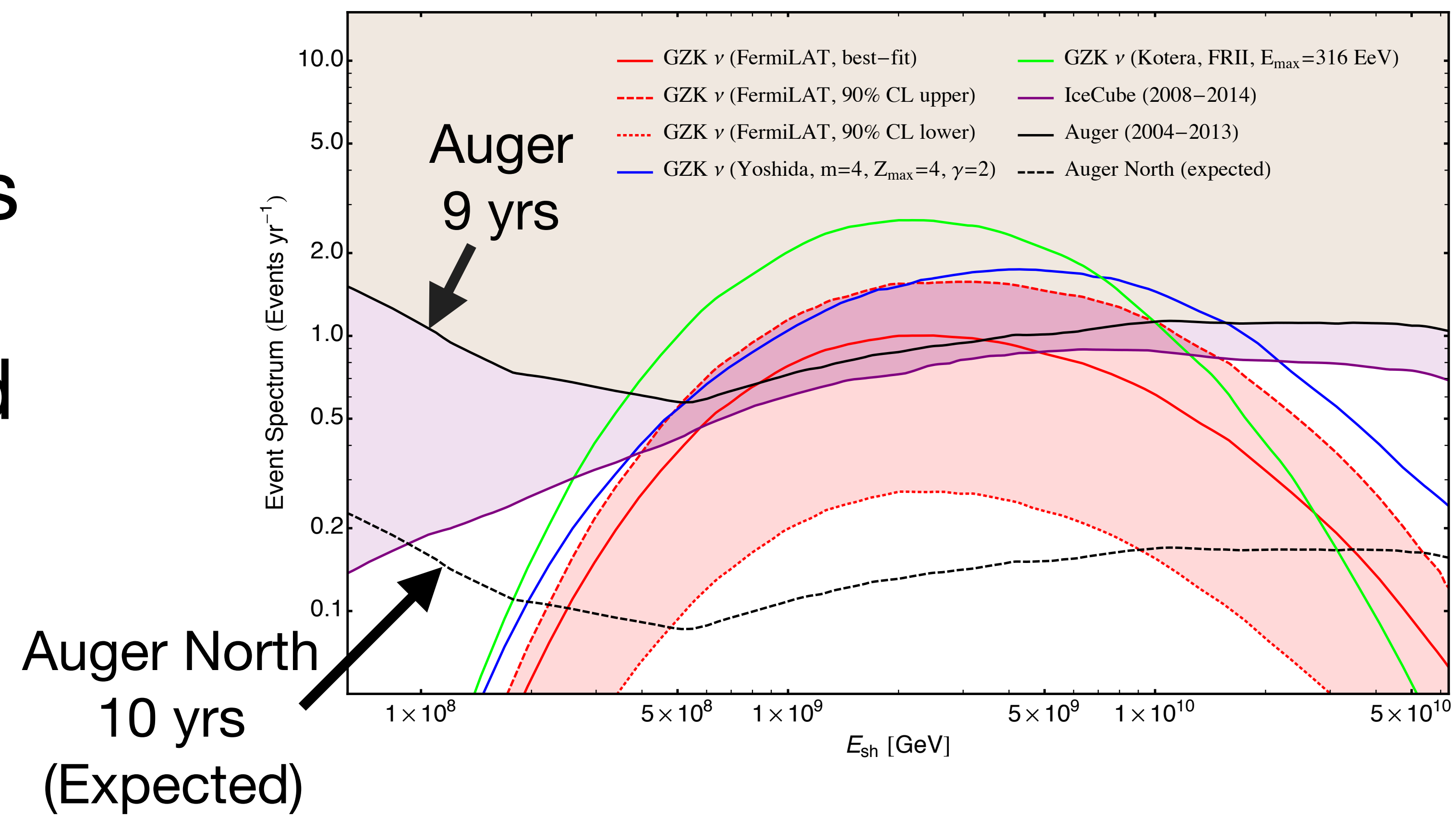
Conclusion

- **Sphaleron** air-shower event rate can be tested as

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

  $p \leq \mathcal{O}(10^{-1} - 10^{-2})$ (Auger North 10yrs, expected)

- With the stringent bounds from pp collider search, **Microscopic BH** induced UHE air-showers are not expected in near future.



- High multiplicity NP (Sphaleron and BH) does not provide a good fit to the recent Auger **muon excess**, except highly deep air-shower cases.