

Final state radiation (FSR) impacts high and ultrahigh energy neutrino observations

Bei Zhou

**Research Associate, Theoretical Physics Department, Fermi National Accelerator Laboratory
Associate Fellow, Kavli Institute for Cosmological Physics, University of Chicago**

Based on arXiv: 2403.07984 Ryan Plestid (Caltech), Bei Zhou (Fermilab & KICP)

More than half a century after the establishment of the quantum electrodynamics, it still has a radiative correction of as large as 25% to be studied.

And it has also been overlooked by current experiments on HE and UHE neutrinos.

Why do we study HE&UHE neutrinos

- Astrophysics (highlighted by astro2020): Origin of HE/UHE astrophysical neutrinos
 - Sources of HE/UHE cosmic rays (> 60-year problem)
 - Cosmic particle acceleration, propagation
 - Cosmic gamma ray sources, hadronic vs leptonic mechanism
 - Dense astrophysical environments
 - Essential for multi-messenger astrophysics
- Particle physics (highlighted by P5 report):
 - **Neutrino interactions in the SM** (Deep-inelastic scattering, W-boson production, Glashow resonance, **final state radiation**, etc.)
 - Measure neutrino mixing parameters
 - Test BSM (ν portal to DM, new ν interactions, sterile ν , magnetic moment, etc.)



Lots of HE/UHE nu telescopes running or to build

HE neutrino telescopes (~100 GeV--100 PeV)

Detector	Size	Status
IceCube	1 km ³	Running for ~14 yrs
KM3NET	1 km ³	Running, constructing
Baikal-GVD	1 km ³	Running, constructing
P-ONE	multi-km ³	Proposed
IceCube-Gen2	7.9 km ³	Proposed
TRIDENT	7.5 km ³	Prototype
Etc....		

Laboratory HE nu experiments (~10 GeV--5 TeV)

Detector	Size	Status
FASERv	Neutrino beam	Running
SND@LHC	Neutrino beam	Running
FASERv2	Neutrino beam	Proposed
AdvSND@LHC	Neutrino beam	Proposed
FLArE	Neutrino beam	Proposed

UHE neutrino telescopes (>~100 PeV)

Detector	Size	Status
ANITA		Finished
ARA		Running
ARIANNA		Running
RNO-G		Constructing
PUEO		Constructing
POEMMA		Prototype
GRAND		Prototype
IceCube-Gen2 radio		Proposed
BEACON		Prototype
Etc....		

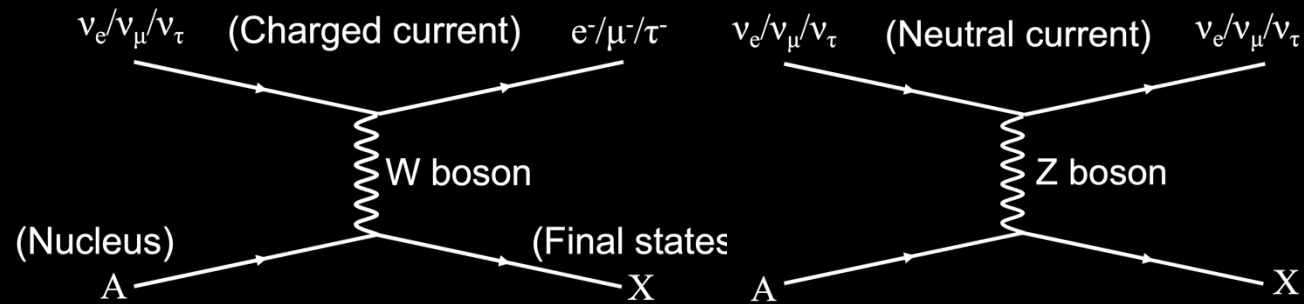
2203.08096, Ackermann, ..., BZ (Snowmass) for a complete list

Increasing statistics requires studies of HE/UHE ν interactions

- **Neutrino interactions are the cornerstone of all kinds of neutrino-related measurements**
 - Astrophysics: energy spectrum, flavor composition, arrival direction, etc.
 - Particle physics: mixing parameters; all BSM studies contingent on well-understood SM interactions
- **Help us to find new event classes: useful for both astrophysics and particle physics studies**
 - E.g., dimuons for high-energy neutrino detection (2110.02974 [BZ](#), *Beacom*).
- **Neutrino(-nucleus) interaction theory is interesting (and sometimes difficult):**
 - Neutrino only has weak interactions, but neutrino interaction studies involves much more
 - Weak, electroweak
 - QED (e.g., final state radiation, W-boson and trident production)
 - Strong interactions: QCD (parton distribution functions), nuclear model, resonance prod., etc.
 - (Also detection physics because you need to detect them.)

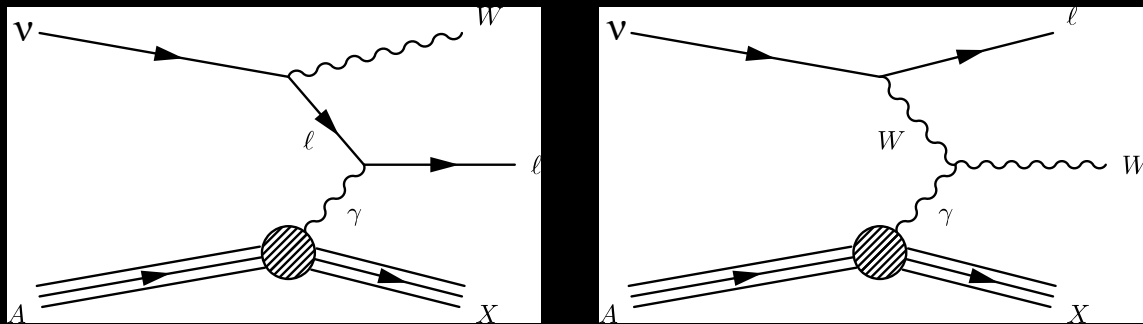
Overview of HE&UHE neutrino interactions

Deep inelastic scattering (DIS) dominates
(as good as ~1% precision)



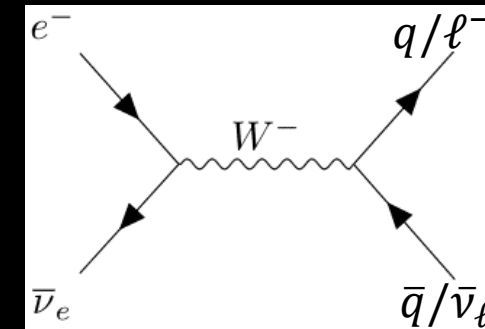
Gandhi+ 96&97, Connolly+ 11, Cooper-Sarkar+ 11, Bertone+ 16, etc.
Most recent: Xie, et al. 2303.13607

W-boson production (WBP) is subdominant



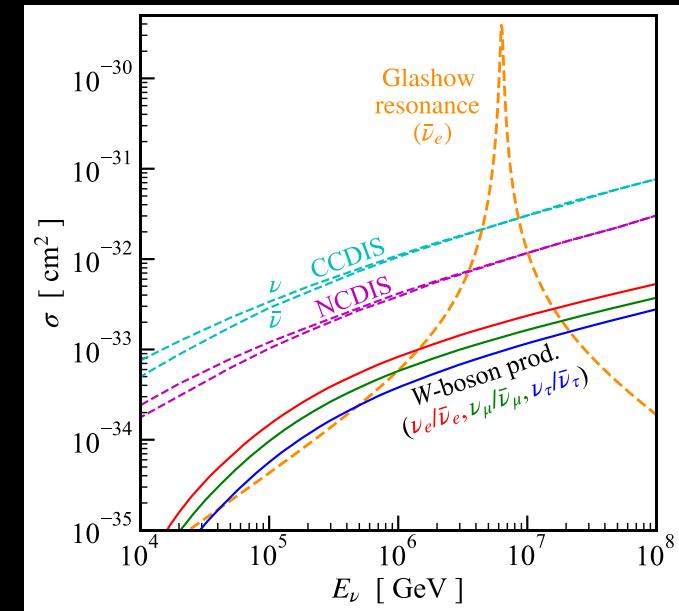
(Seckel 1997, Alikhanov 2015, BZ, Beacom, 1910.08090)

Glashow resonance for $\bar{\nu}_e$



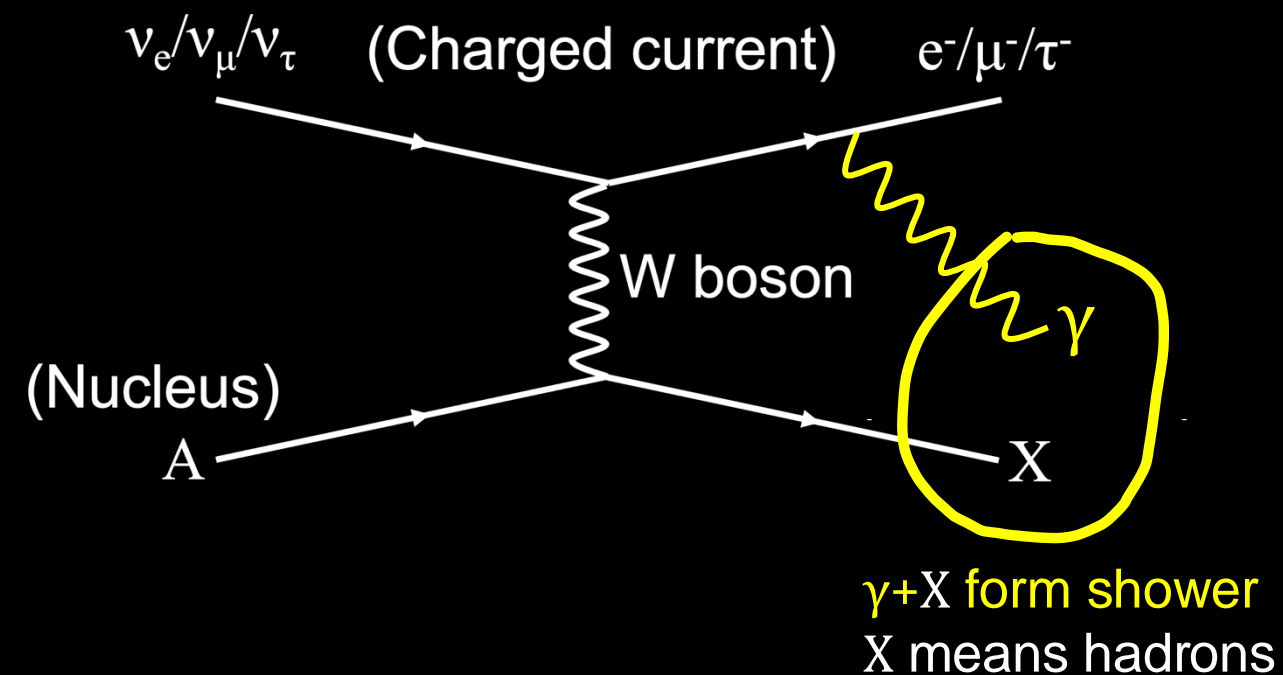
Glashow 1960
IceCube 2021

Cross sections



(BZ, Beacom, 1910.10720)

Our work: final state radiation (FSR) on top of neutrino CC DIS

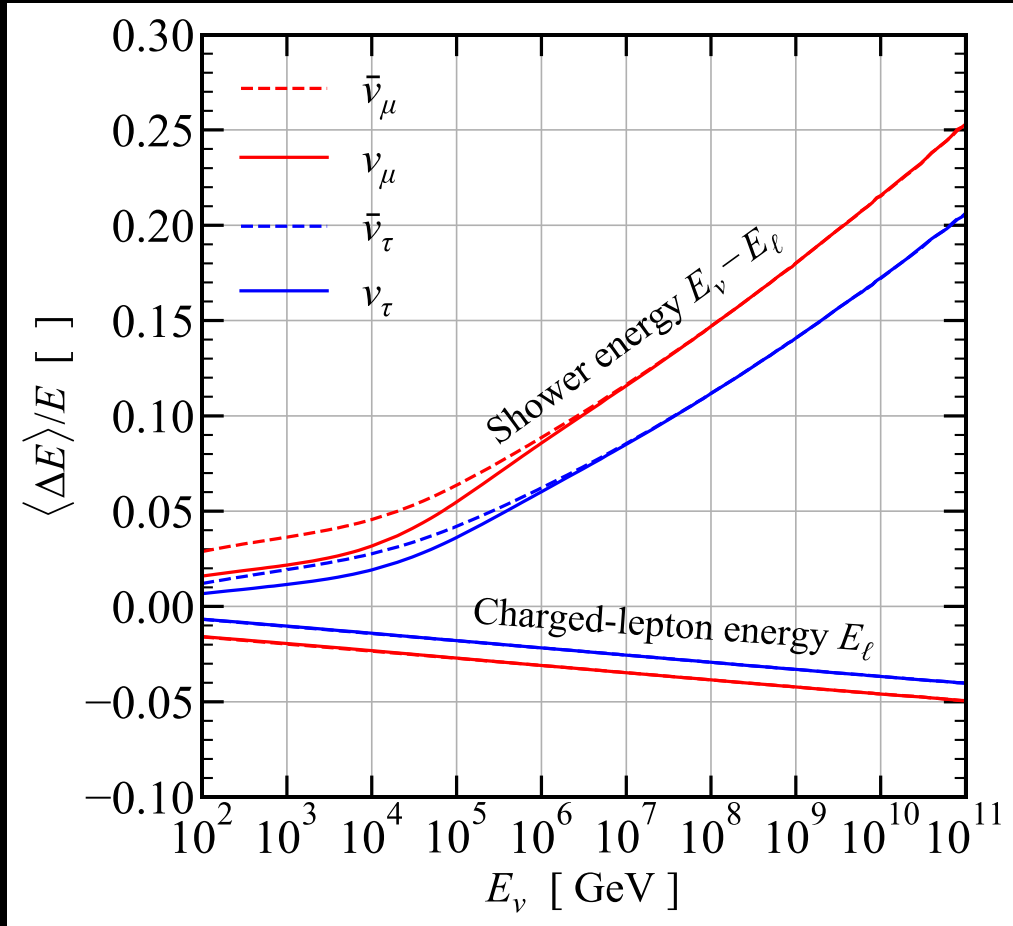


Effect on total xsec: small ($\sim 1\%$, c.f.).

Effects on the differential xsec: big, due to the kinematic logs.

→ So, it affects observation if charged lepton and shower are separate.

FSR impacts the energies of the final states from HE/UHE interactions



Correction increases with energy, up to **25%(!)**

Correction on $\nu_\mu > \nu_\tau$, cuz $m_\mu < m_\tau$

Correction on shower $>$ charged lepton

Correction on shower **further enhanced by 10—20%** due to light yields from EM shower $>$ hadronic shower

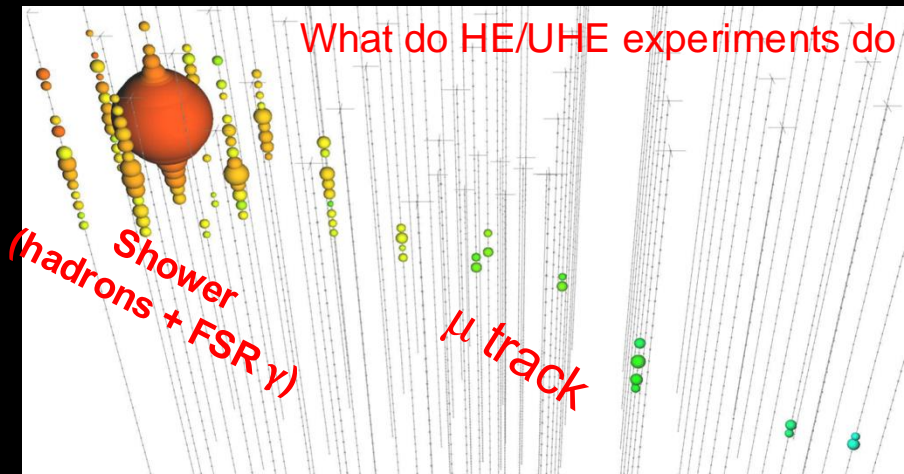
Difference between nu and nubar

Photon takes energy from the charged lepton to the shower

(Plestid, BZ, 2303.08984)

Final state radiation impacts the inelasticity (y) measurements

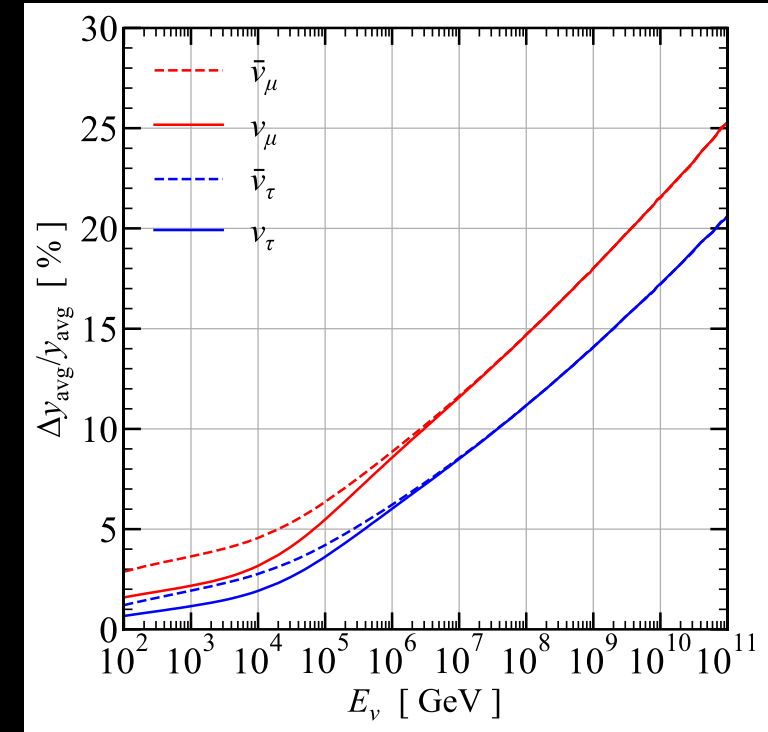
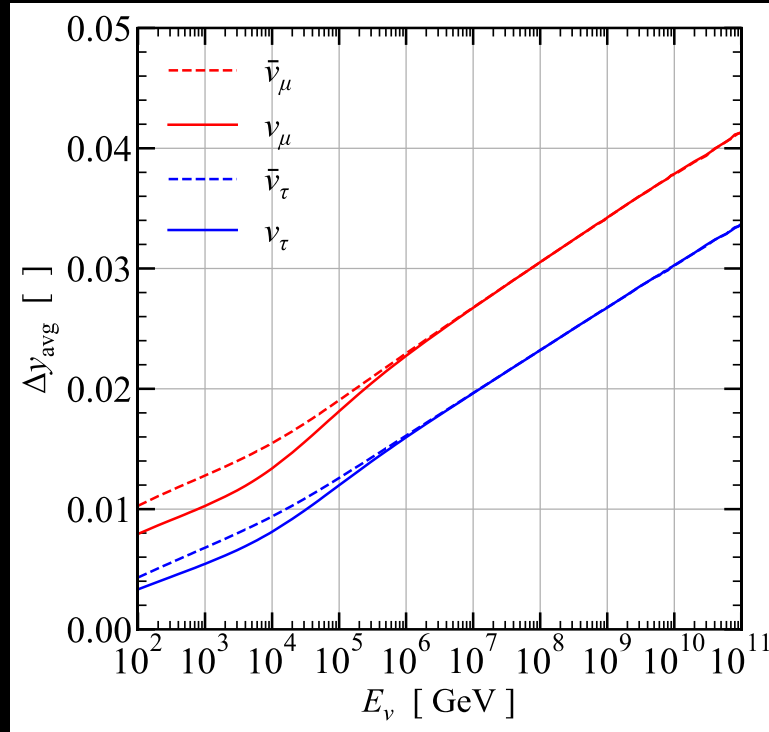
$$y_{\text{QCD}} \equiv \frac{E_X}{E_\nu} = \frac{E_\nu - E_\ell}{E_\nu}$$



$$y_{\text{exp}} \equiv \frac{E_{\text{shower}}}{E_{\text{track}} + E_{\text{shower}}} = y_{\text{QCD}} + \frac{E_\gamma}{E_\nu}$$

$$\Delta y_{\text{avg}} \equiv \langle y_{\text{exp}} \rangle - \langle y_{\text{QCD}} \rangle = \langle E_\gamma \rangle / E_\nu$$

So, photon takes energy from the charged lepton to the shower, increasing $\langle y \rangle$



(Plestid, BZ, 2303.08984)

Correction increases with energy, up to **25%(!)**

Final state radiation impacts high-energy (~ 100 GeV—100 PeV) neutrino observations

Measurements based on inelasticity measurement

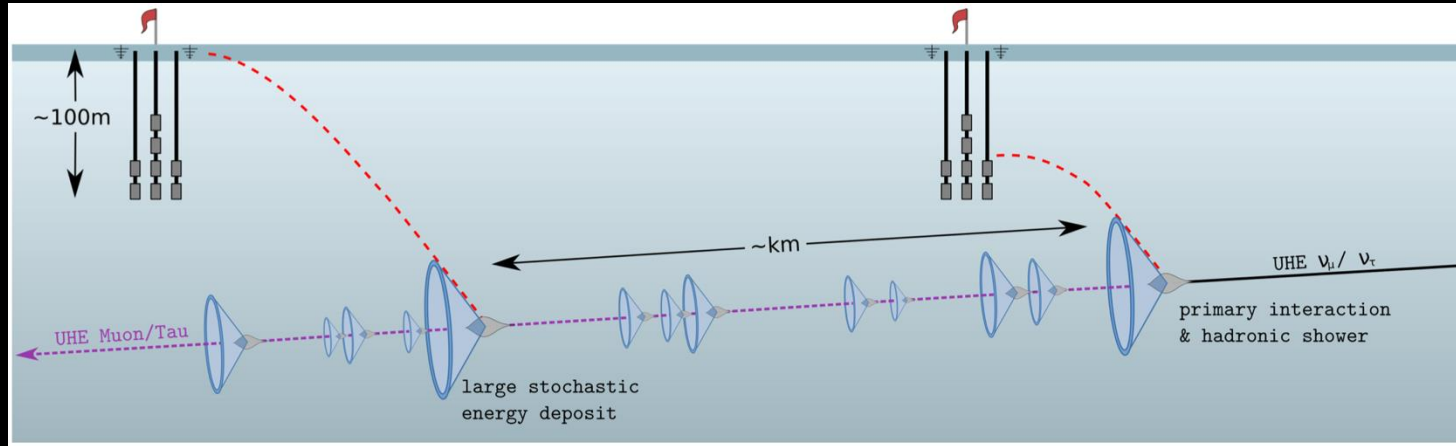
1. Neutrino-antineutrino flux ratio (5% shift)
2. Neutrino mixing parameters
 - Inel. dist. helps to separate $\nu/\bar{\nu}$
3. Charm production from ν interactions
 - CCDIS /w charm production has higher inelasticity

Other measurements

1. Throughgoing muons
 - Without FSR, underestimate parent E_ν ($\sim 5\%$)
2. Double bang signature from tau neutrinos
 - Inference of the parent neutrino energy
 - Reduce the detectability

FSR impacts UHE nu observations: in-ice radio detectors (e.g., ANITA, PUEO)

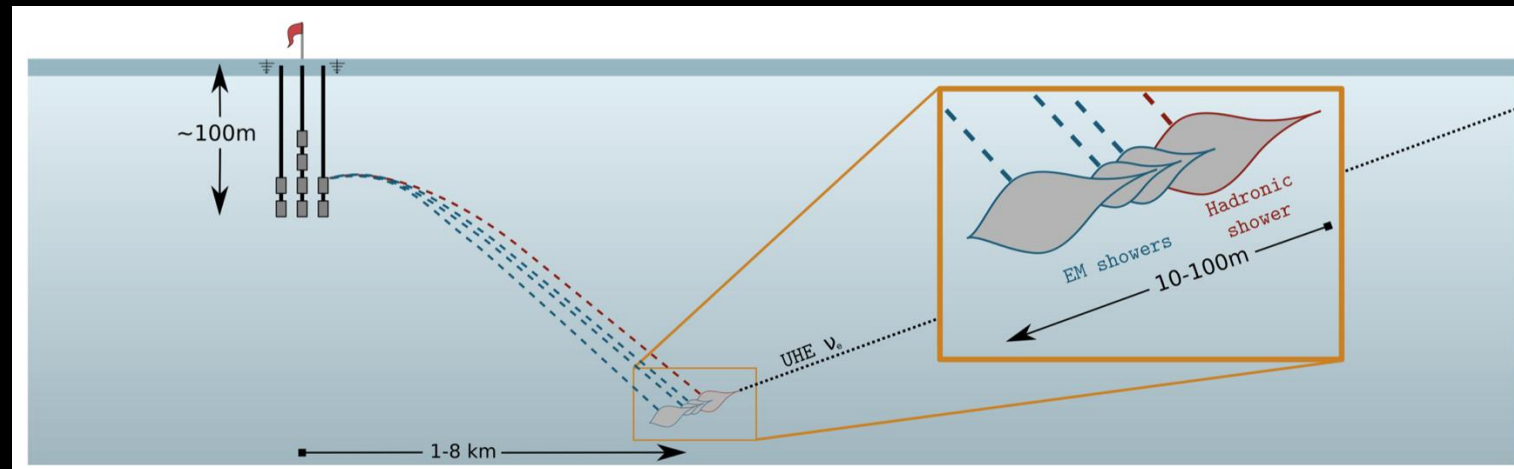
For CCDIS, FSR enhances the **overall detectable (shower) energy** by as much as $\approx 20\%$, which effectively lowers the energy thresholds.



ν_τ CC, big, up to $\approx 20\%$

ν_μ CC, mild

ν_e CC, negligible



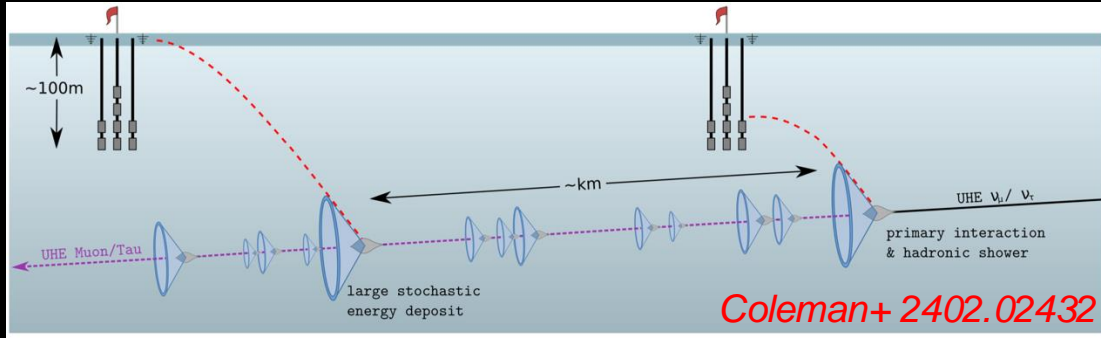
2402.02432
Coleman et al.

Final state radiation impacts ultrahigh-energy (>~100 PeV) neutrino observations

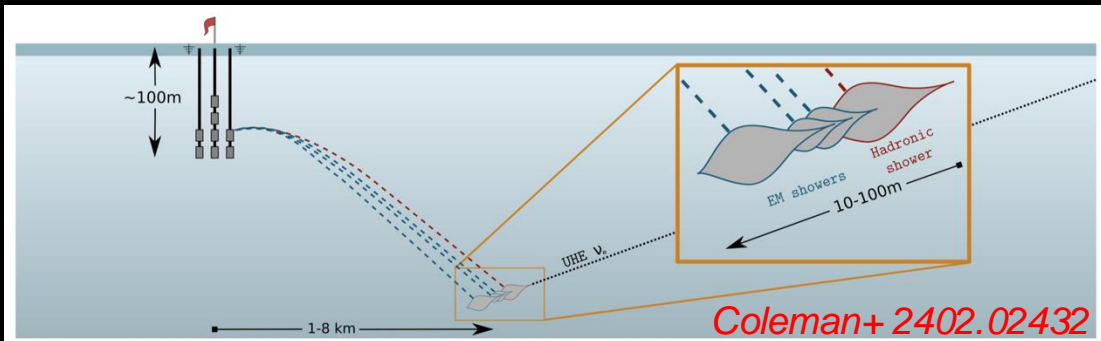
In-ice radio detectors (e.g., ANITA, PUEO)

1) If charged lepton barely detectable, FSR enhances detectable (shower) energy by ~20%.

2) A way to measure ν_μ/ν_τ , FSR reduces the detectability (~5%)



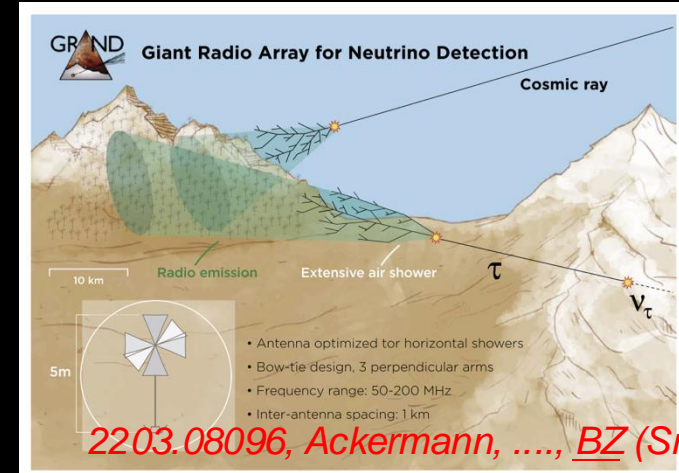
3) A way to measure ν_e (using LPM effect);



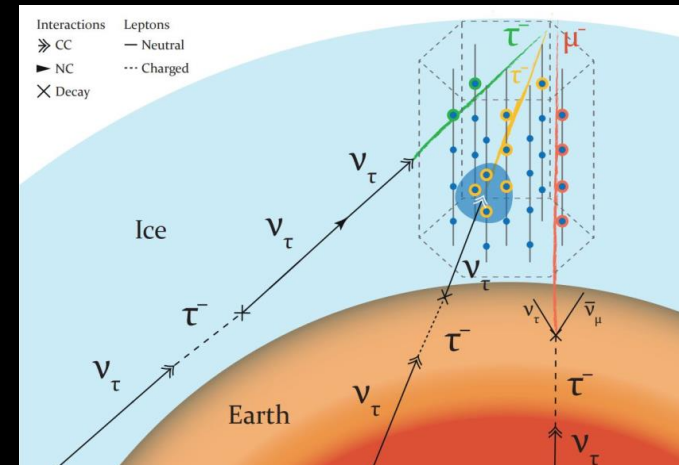
Bkgd rate: 0% (w/o FSR) VS ~30% (w/ FSR)

Air shower detectors (main for ν_τ , e.g., POEMMA)

1) Earth emergent τ ; w/o FSR underestimates parent E_ν by ~5%



2) nutau regeneration, 5%*N



FSR impacts on the neutrino flux and spectrum measurement

Flux normalization:

Any bias on the total detectable energy due to FSR in the previous slides will be amplified when measuring the neutrino flux normalization due to the steeply falling spectrum

$$(1 - \delta_E)^{-\Gamma} \simeq 1 + \Gamma \delta_E$$

For example,

$\Gamma=3, \delta_E=5\%$, the bias is 15%

$\Gamma=3, \delta_E=20\%$ (UHE $\nu\tau$ CCDIS), the bias is 60%

Spectral shape:

FSR's effect is energy dependent, so it affects the spectrum shape measurement.

Thanks for your attention!

Calculation

DIS cross section

$$\frac{d^2\sigma_{\nu,\bar{\nu}}^{(0)}}{dx dy} = \frac{G_F M E_\nu}{\pi(1 + Q^2/M_W^2)^2} \times \left[y^2 F_1 + (1 - y)F_2 \pm xy(1 - y/2)F_3 \right]$$

from Xie et al. 2303.13607, CTEQ collaboration

Collinear log

Splitting function

$$P_{\ell \rightarrow \ell \gamma}(z) = \frac{\alpha}{2\pi} \log \left(\frac{s}{m_\ell^2} \right) \left[\frac{(1 + z^2)}{[1 - z]_+} + \frac{3}{2} \delta(1 - z) \right], \quad (6)$$

$$\frac{d\sigma^{(1)}}{dE_\ell} = \frac{\alpha}{2\pi} \int dy \int dz \frac{d\sigma^{(0)}}{dy} \delta(E_\ell - (1 - y)zE_\nu) \times \log \left(\frac{s}{m_\ell^2} \right) \left[\frac{1 + z^2}{[1 - z]_+} + \frac{3}{2} \delta(1 - z) \right]. \quad (7)$$

(Pleštid, BZ, 2303.08984)

A rough estimate using Sudakov form factor

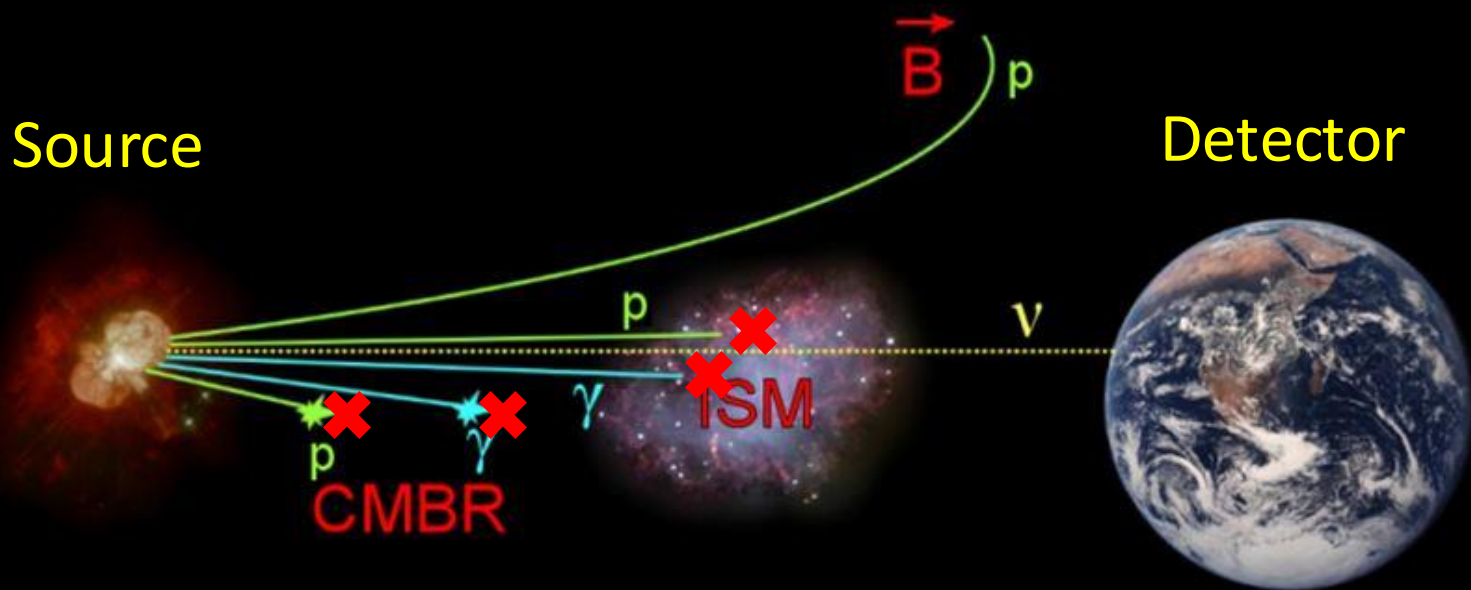
Collinear log Soft log

$$F_S(s, E_{\min}) \sim \exp \left[-\frac{\alpha}{2\pi} \log \left(\frac{s}{m_\ell^2} \right) \log \left(\frac{E_\ell^2}{E_{\min}^2} \right) \right]$$

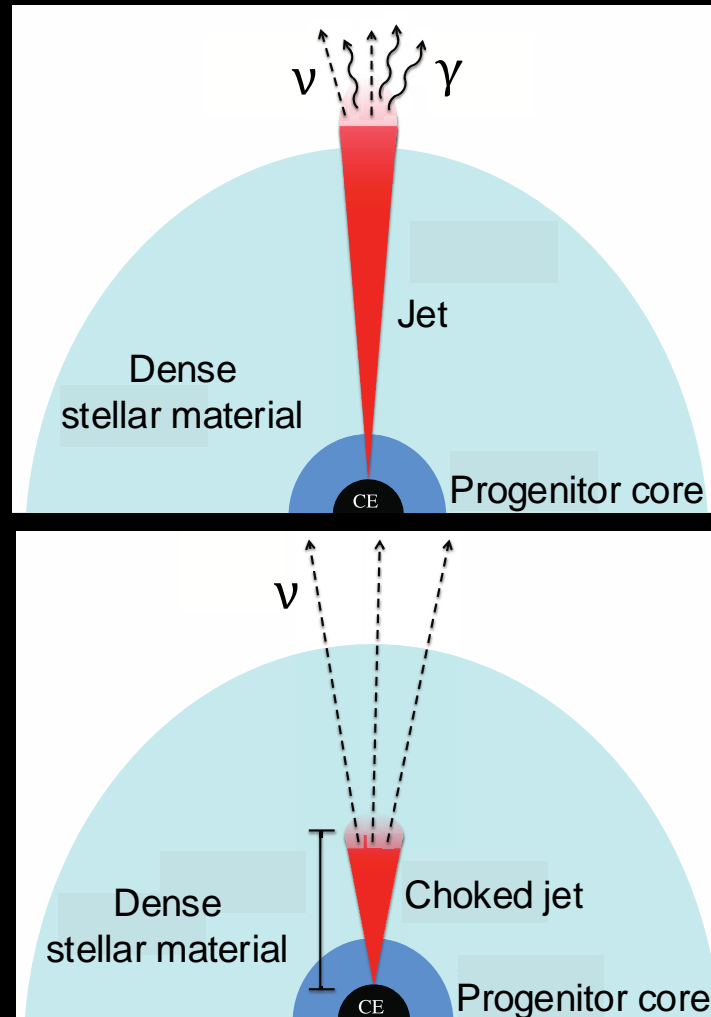
which gives the probability to *not* radiate any photons above E_{\min} in a collision with center-of-mass energy \sqrt{s} and final-state charged-lepton energy E_ℓ . Taking ℓ as the muon (μ), $E_{\min} \simeq \frac{1}{10} E_\mu$, and $s \simeq 2E_\nu m_N$ (m_N is the nucleon mass) with $E_\nu = 10$ TeV, we find $F_S \sim 0.9$. This implies that roughly 10% of all events will contain some prompt real and energetic photon radiation.

Why do we study high-energy neutrinos: astrophysics

Cosmic ray sources



Dense environment

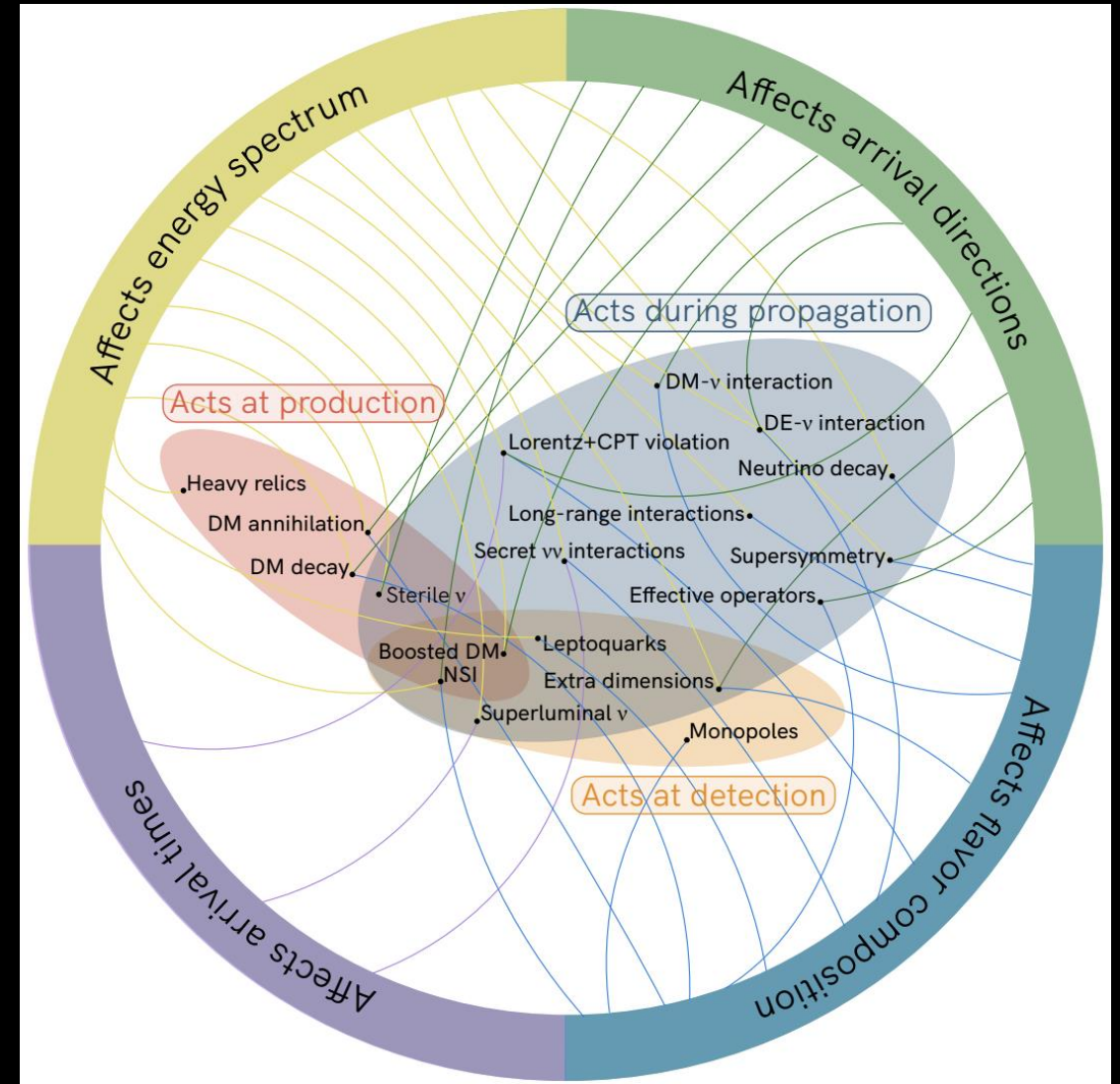


1512.08513 Senno, Murase, Mészáros
2210.03088 Chang, BZ, Murase, Kamionkowski

Why do we study high-energy neutrinos: BSM

Why HE neutrinos special for BSM:

- High energy, inaccessible by lab ν experiments
- Known direction
- Travel cosmic distance, small effects accumulates to big effects
- Extremely high column density (through Earth)



2203.08096, Ackermann, ..., BZ (Snowmass WP); 1907.08690 Argüelles et al.

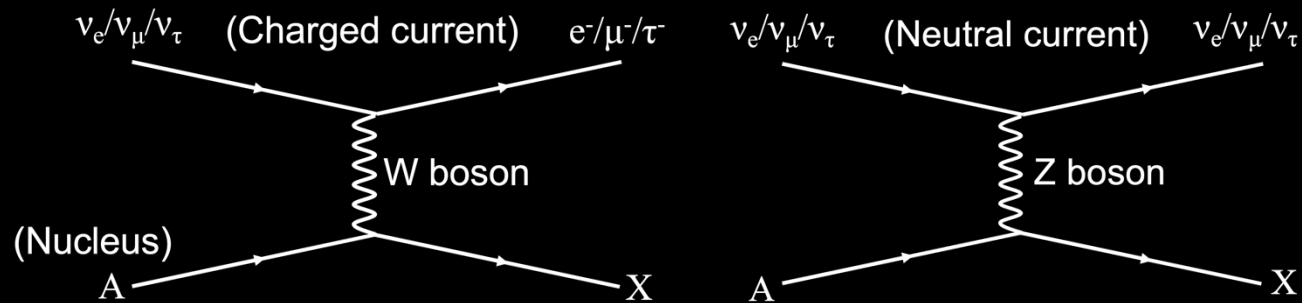
TeVPA 2024 (08/28/2024)

Bei Zhou (Fermilab & KICP)

17

HE/UHE neutrino interaction studies so far, not enough

Deep inelastic scattering (DIS) dominates
(~1% precision)



*Gandhi+ 96&97, Connolly+ 11, Cooper-Sarkar+ 11, Bertone+ 16, etc.
Most recent: Xie, et al. 2303.13607*

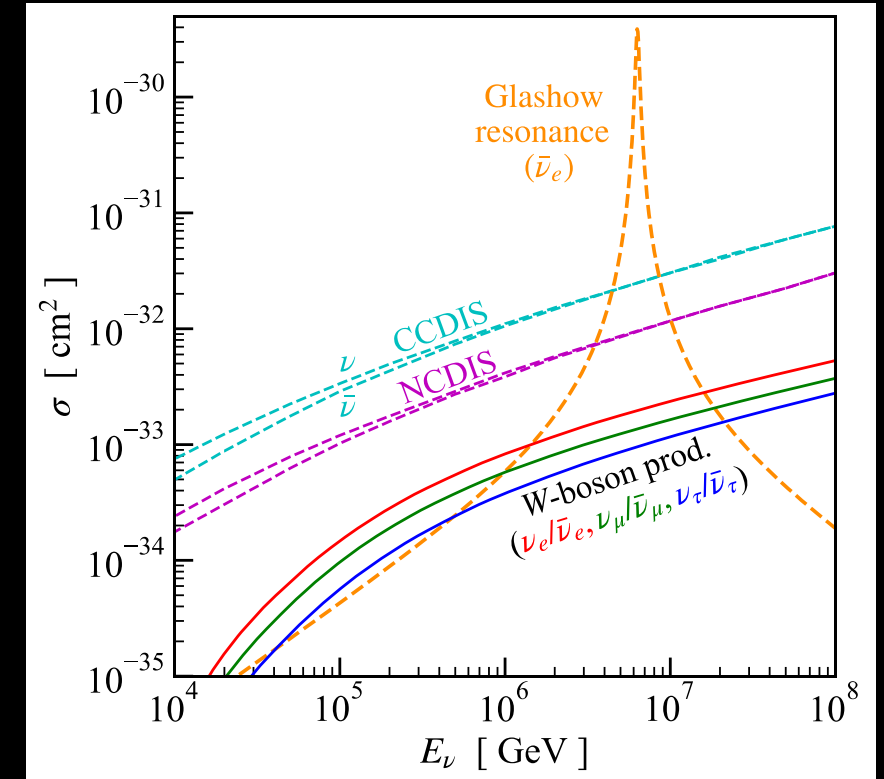
W-boson production is subdominant

Seckel 1997; Alikhanov 2015; BZ, Beacom 1910.08090, 1910.10720

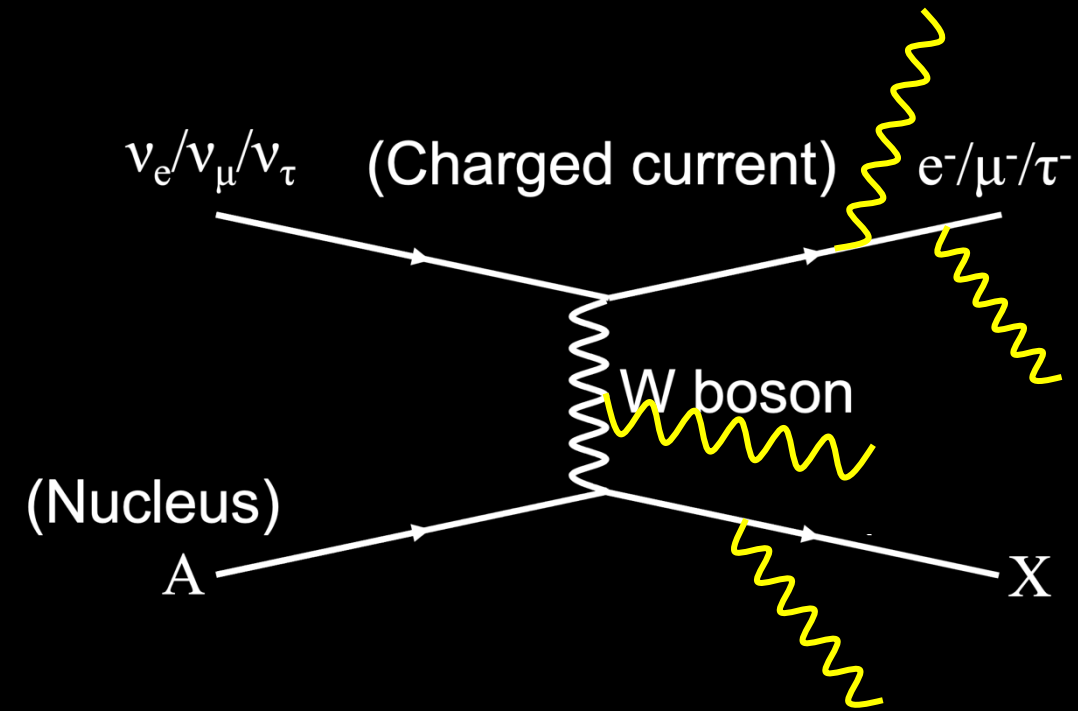
Glashow resonance important for $\bar{\nu}_e$

Glashow 1960, IceCube 2021

Cross sections



Photons from other parts of the diagram: not important



Photon from W boson: suppressed by W mass

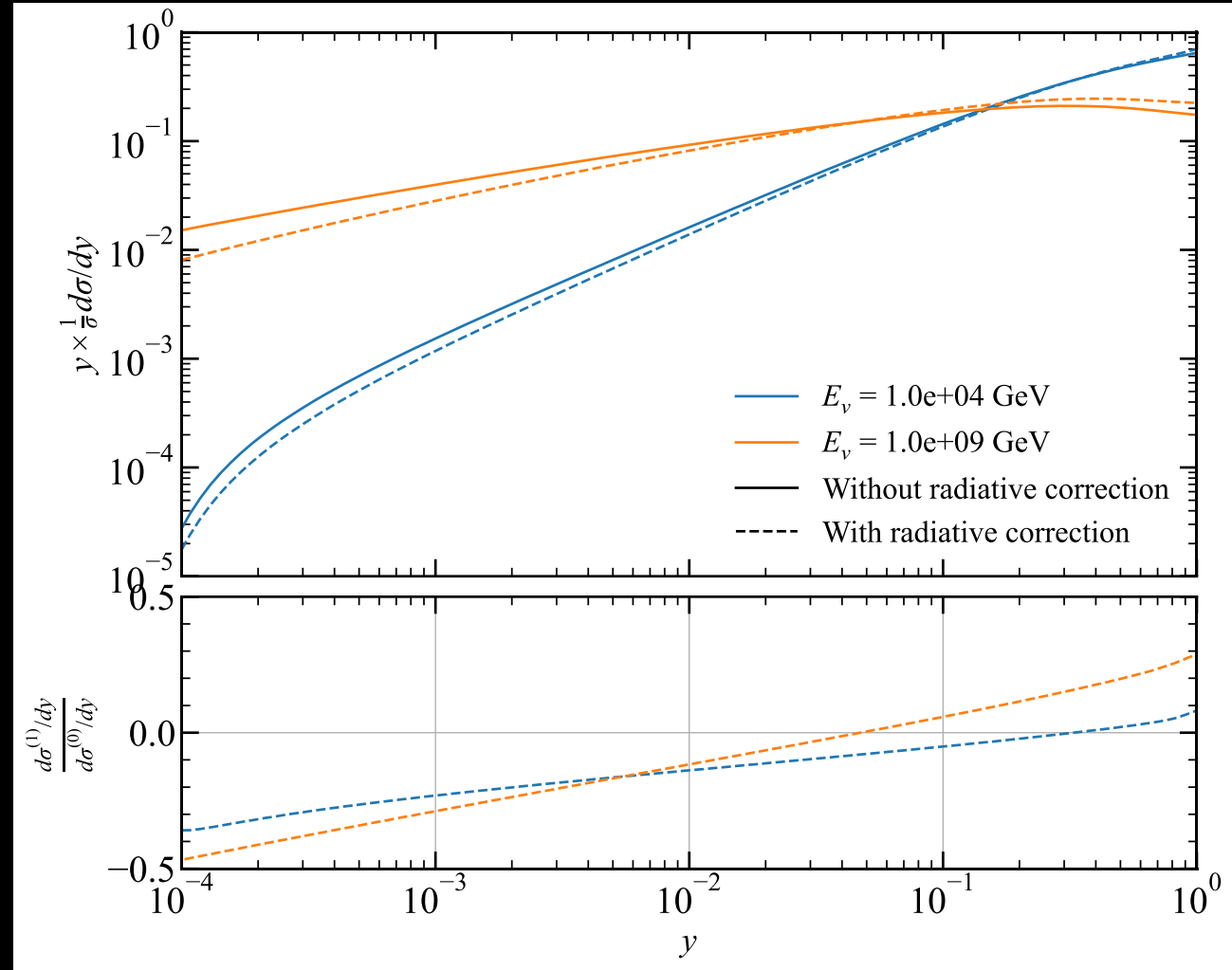
Photon from quarks:

- 1) hard to distinguish from the hadronic cascade
- 2) E_γ small as quark energy \ll lepton energy

Multi-photon emission: higher order, small

Illustration of FSR impacts on DIS differential xsec

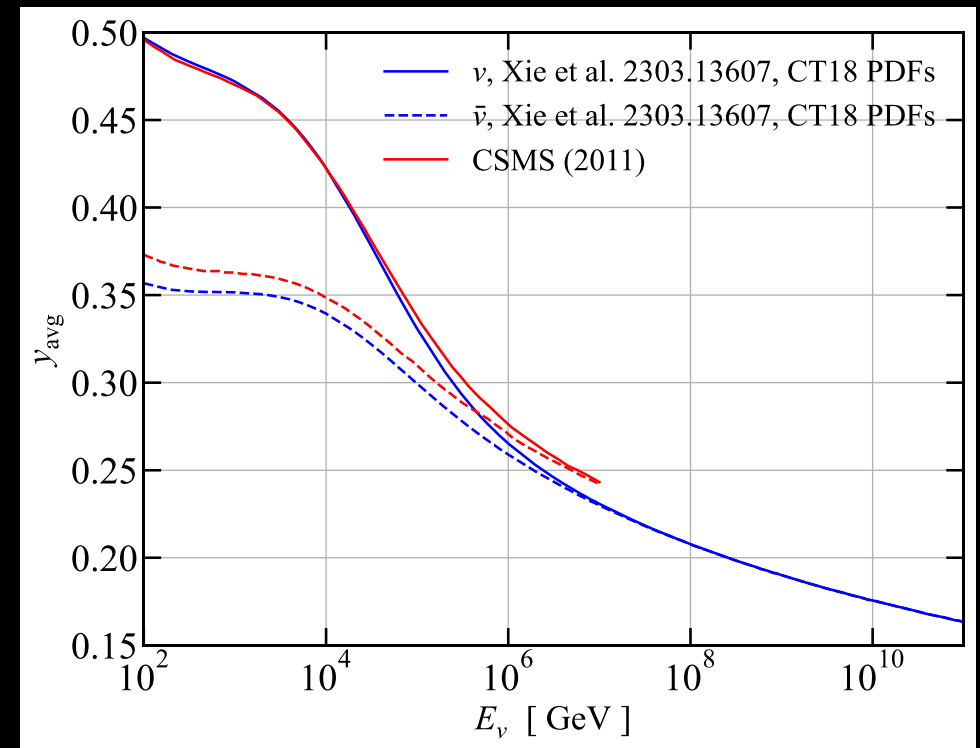
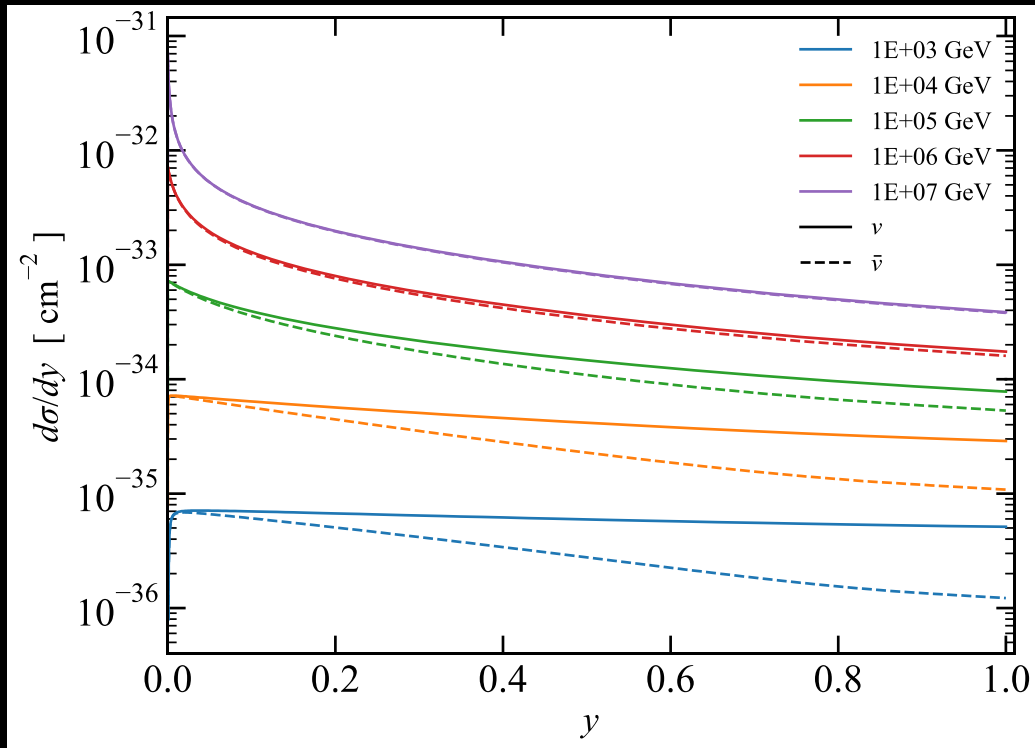
$$y_{\text{QCD}} \equiv \frac{E_X}{E_\nu} = \frac{E_\nu - E_\ell}{E_\nu}$$



FSR impacts on the inelasticity

Theoretical definition:

$$y_{\text{QCD}} \equiv \frac{E_X}{E_\nu} = \frac{E_\nu - E_\ell}{E_\nu}$$



FSR impacts HE nu observation: nu mixing parameters & charm production

Neutrino mixing

Inelasticity measurements help to separate ν and $\bar{\nu}$, which helps with measuring neutrino mass hierarchy and CP violation. The sensitivity can be increased by $\simeq 30\%$.
(1303.0758, 1312.0457, 2402.13308)

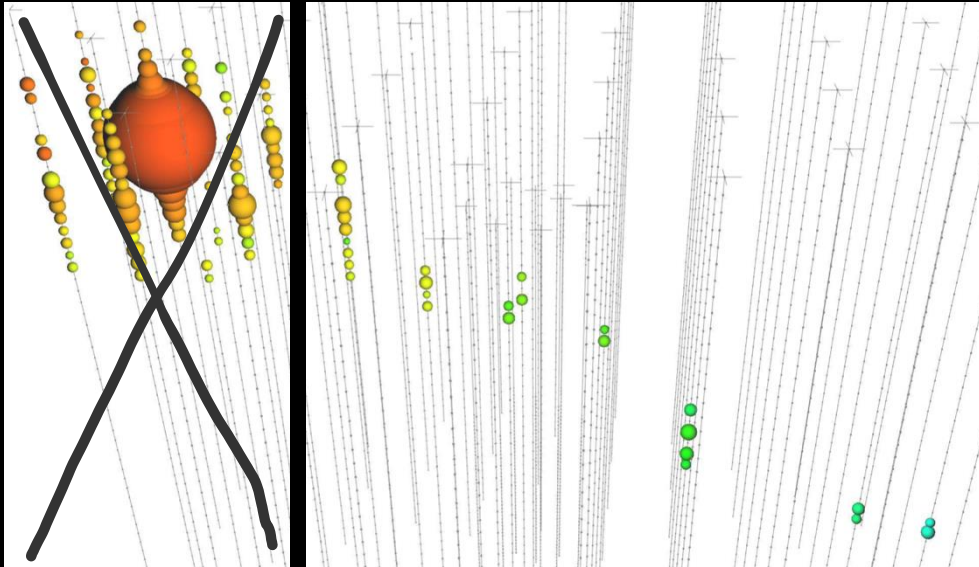
And FSR will affect the measurements

Charm production

Neutrino DIS with charm production has a larger inelasticity than those without...

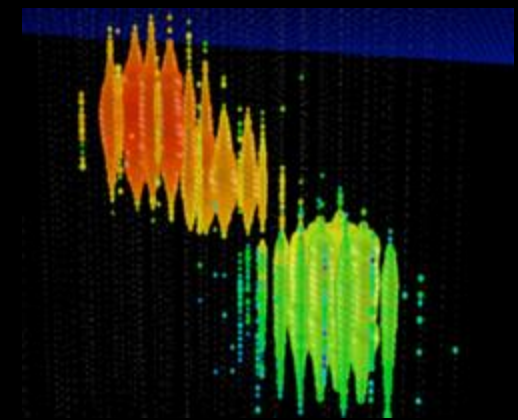
FSR impacts HE nu observation: throughgoing muons & ν_τ double bang

Throughgoing muon



Not including FSR underestimates the parent neutrino energy

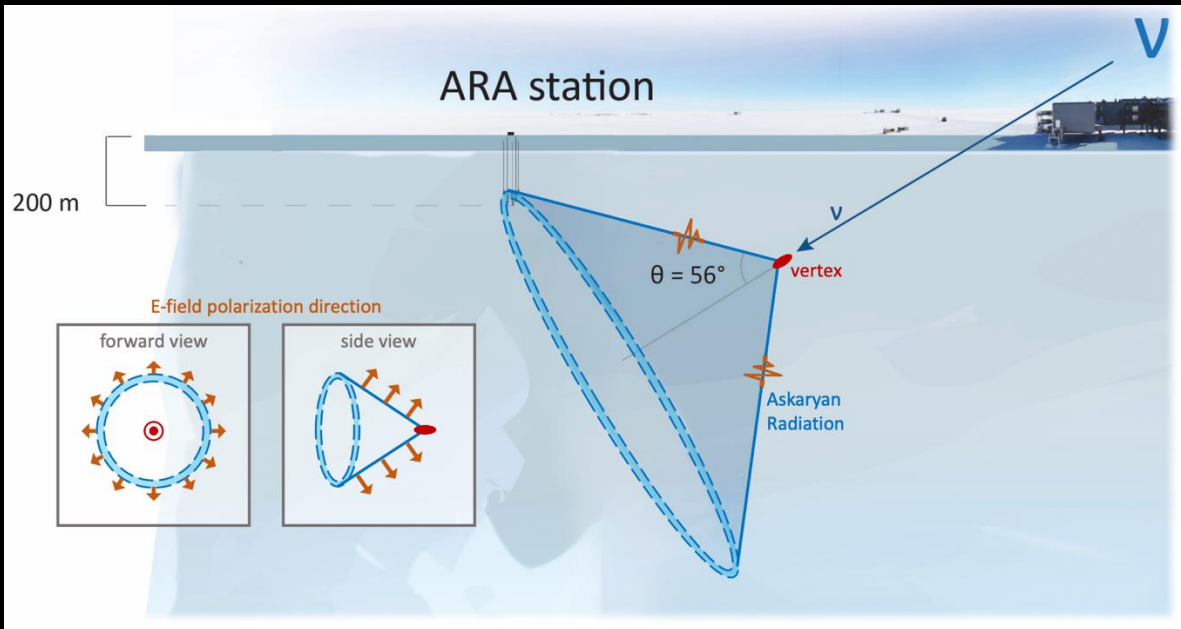
ν_τ induced double bang



FSR 1) distort the energy balance the two bangs 2) reduce the detectability of the double bang signature.

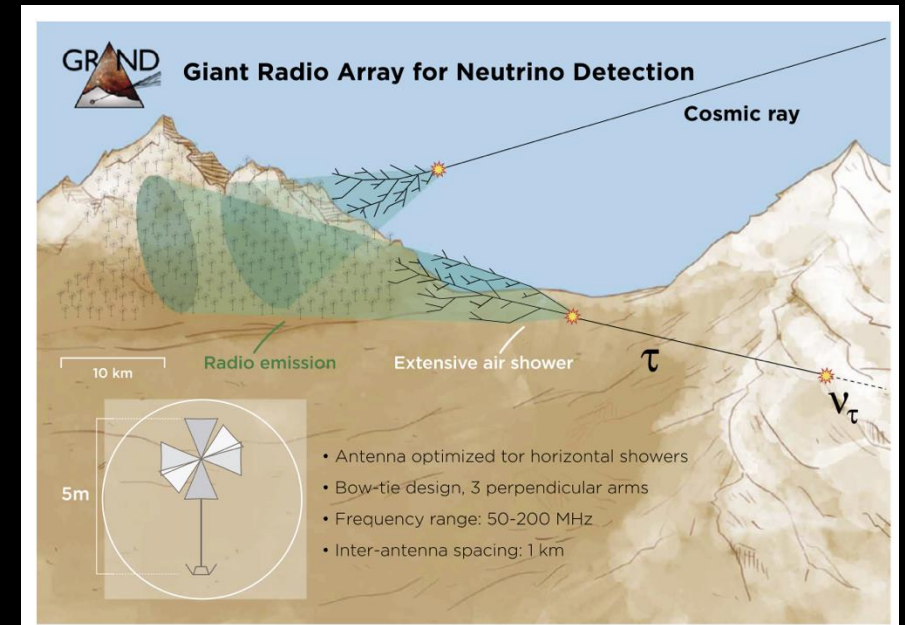
HE nu observation: two basic kinds of detectors

In-ice radio detectors
(all flavors; hard to distinguish flavors)



1912.00987 ARA collaboration

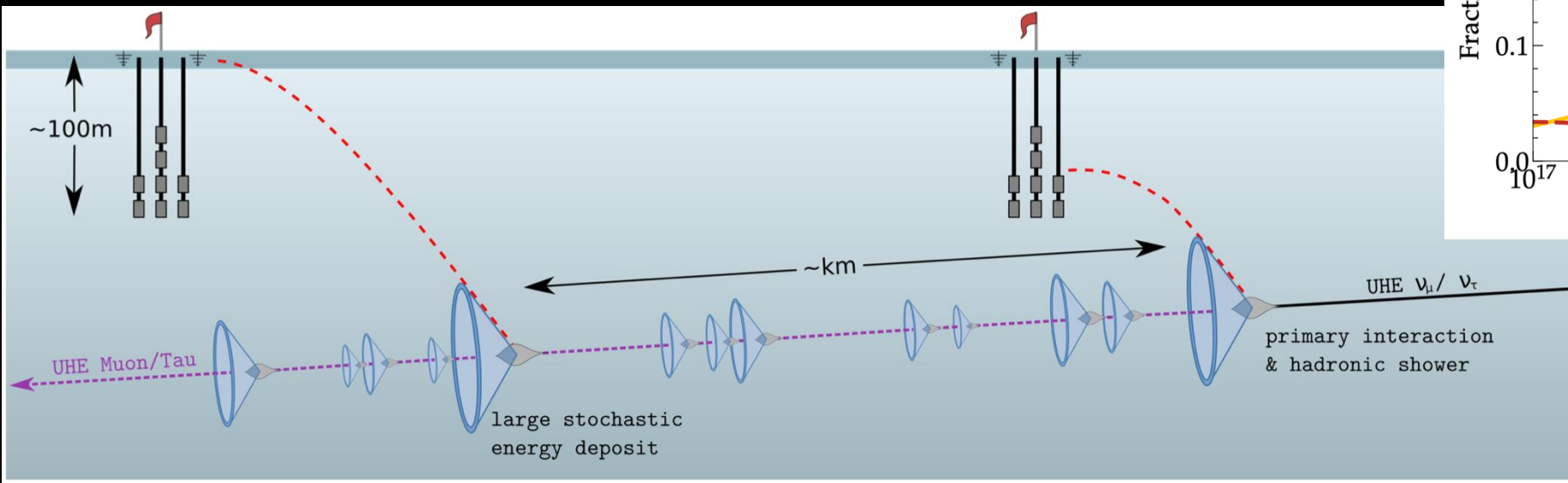
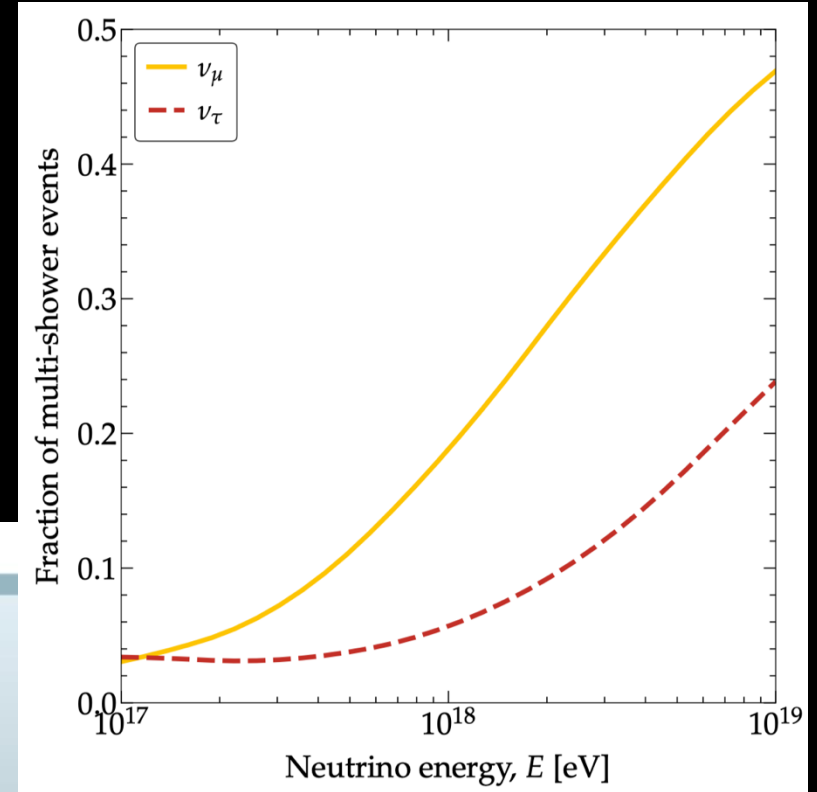
Air shower detectors
(main for ν_τ)



2203.08096, Ackermann, ..., BZ (Snowmass WP)

FSR impacts UHE nu observation: in-ice radio detectors

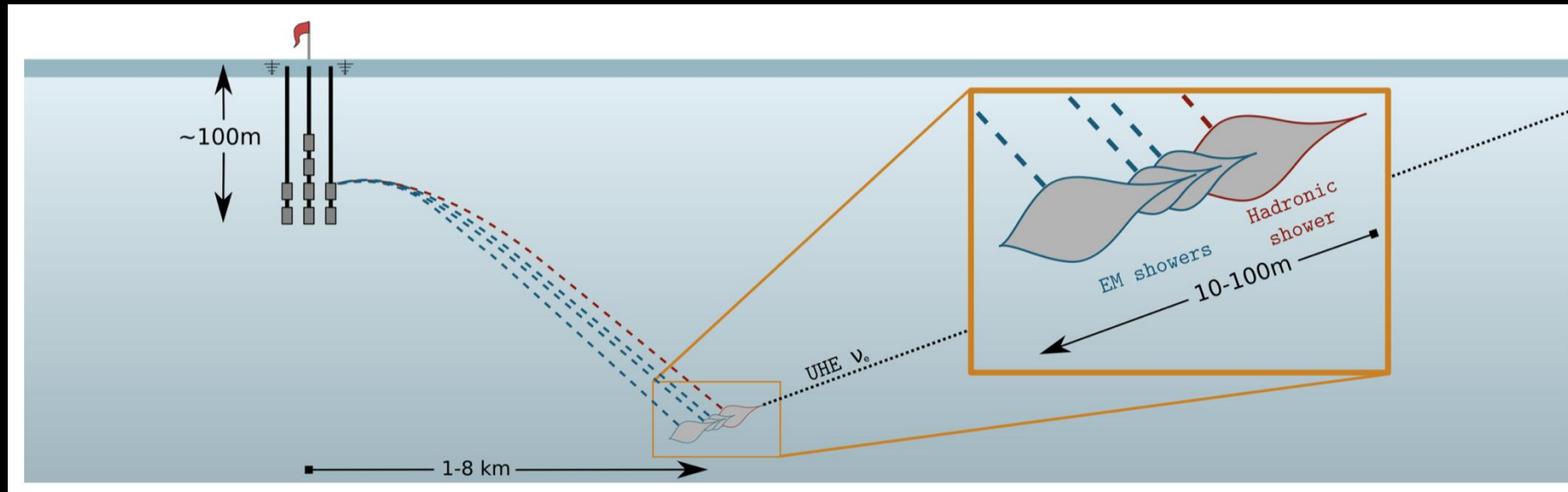
A way to measure muon and tau neutrinos



2402.02432
Coleman et al

FSR impacts UHE nu observation: in-ice radio detectors

A way to measure electron neutrinos (using LPM effect)

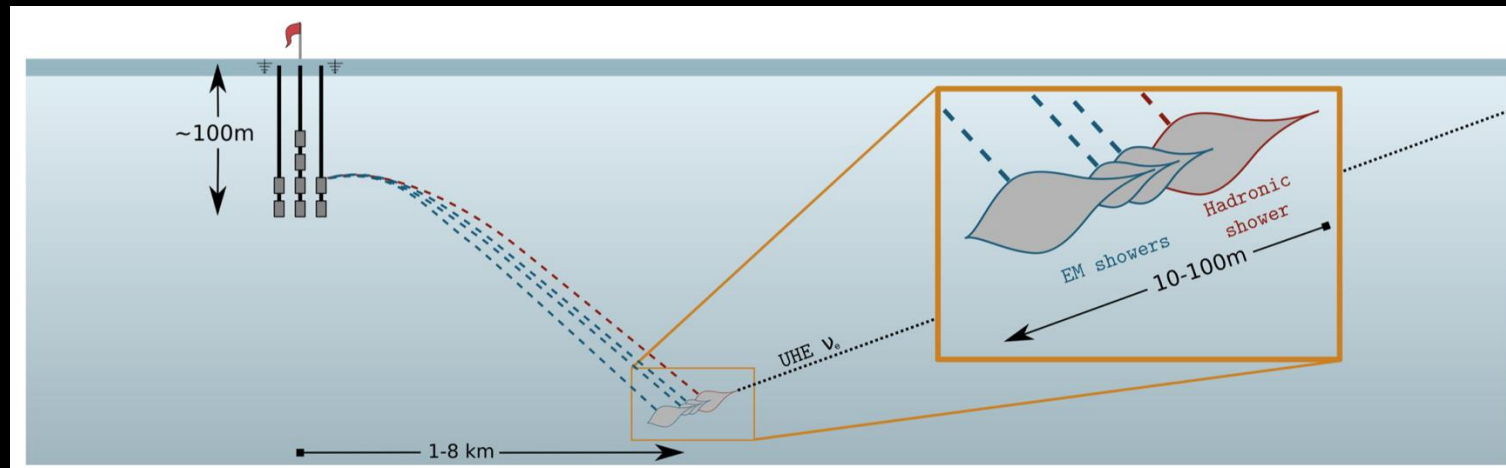
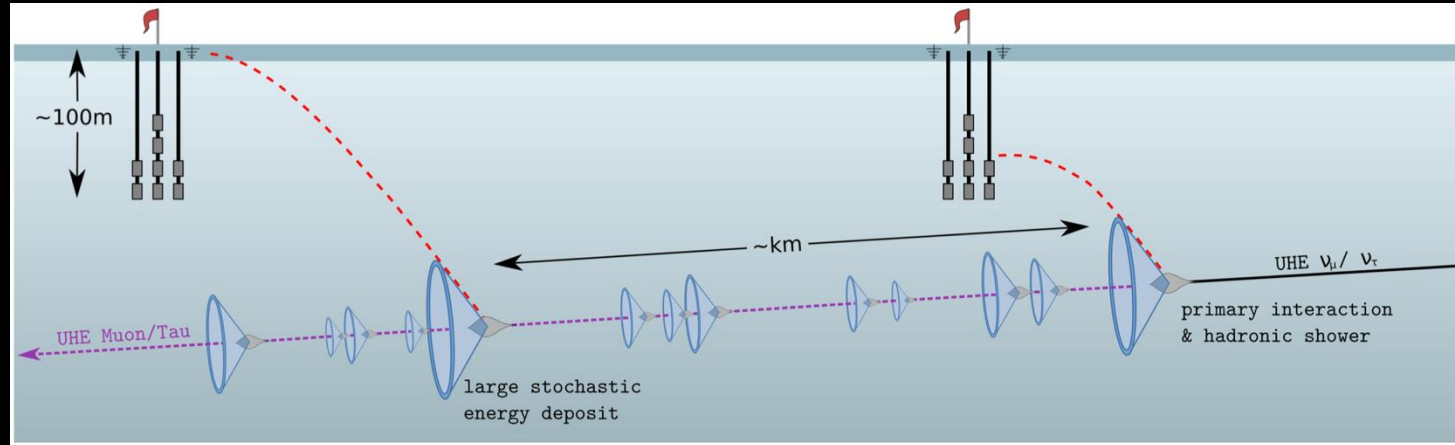


Background could be from muon/tau neutrino CC interactions.
Without FSR, the paper estimates that bkgd rate is negligible
With FSR, we estimate that bkgd rate is $\sim 30\%$ of signal rate

2402.02432
Coleman et al

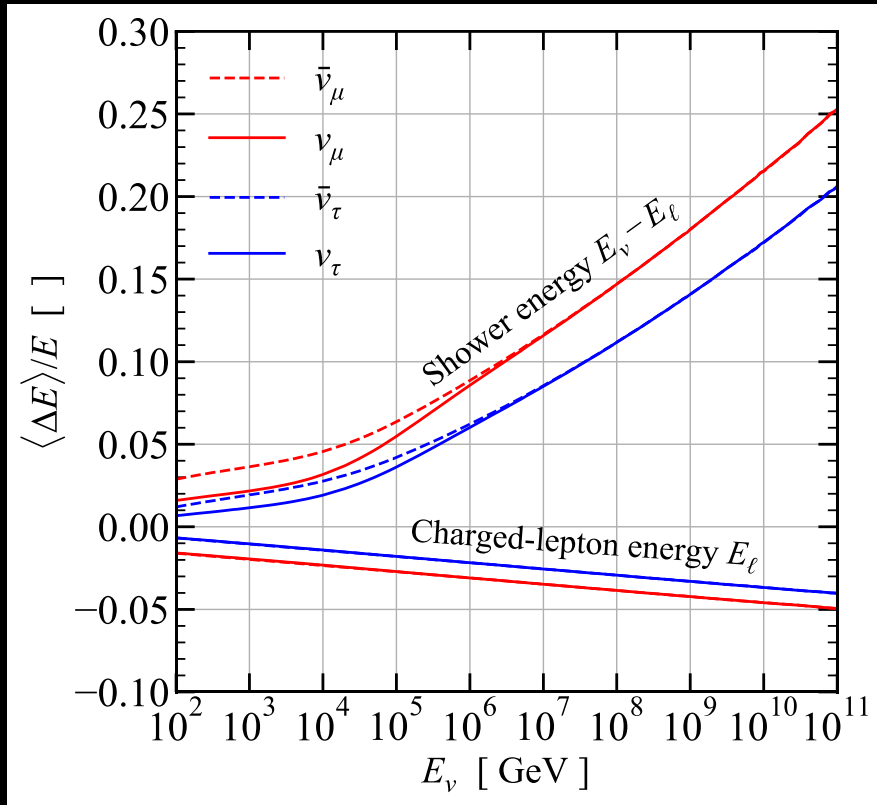
FSR impacts UHE nu observation: in-ice radio detectors

If the charged from CC interaction barely deposit energies to the antenna, then FSR enhances the detectable (shower) energy by as much as 25%!

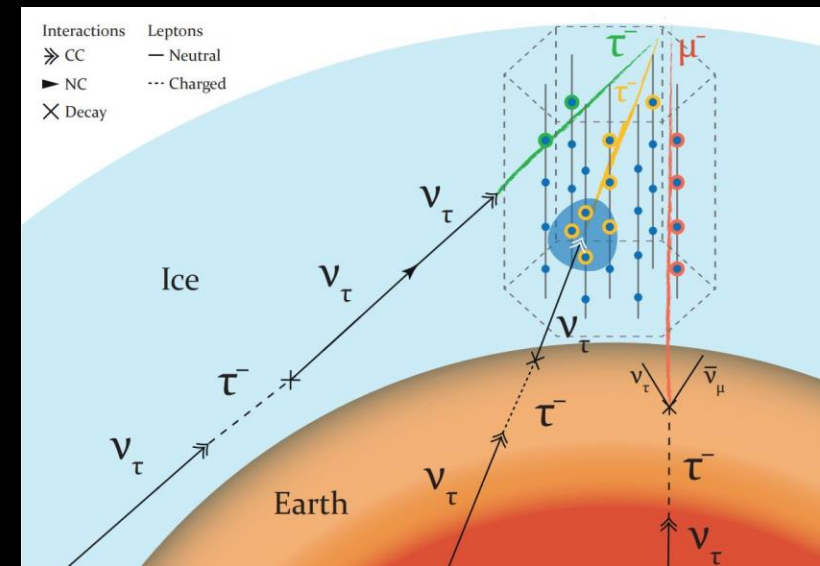
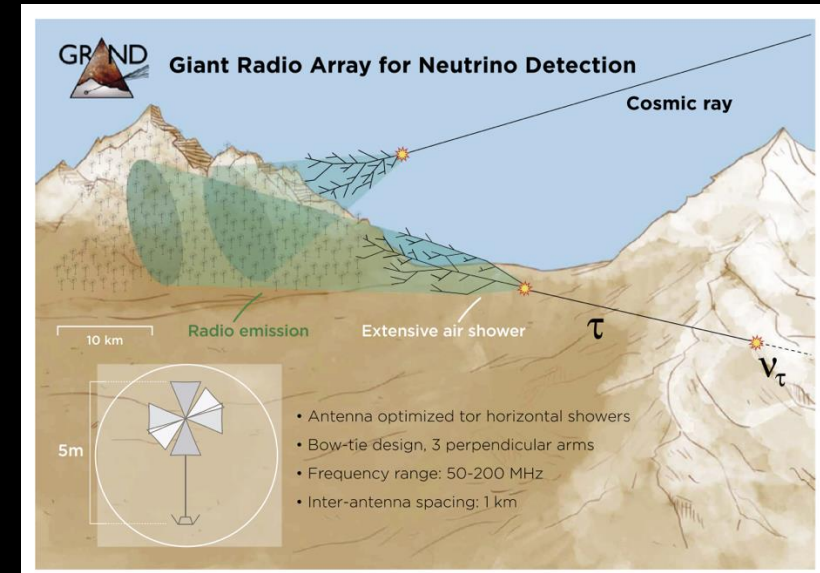


2402.02432
Coleman et al

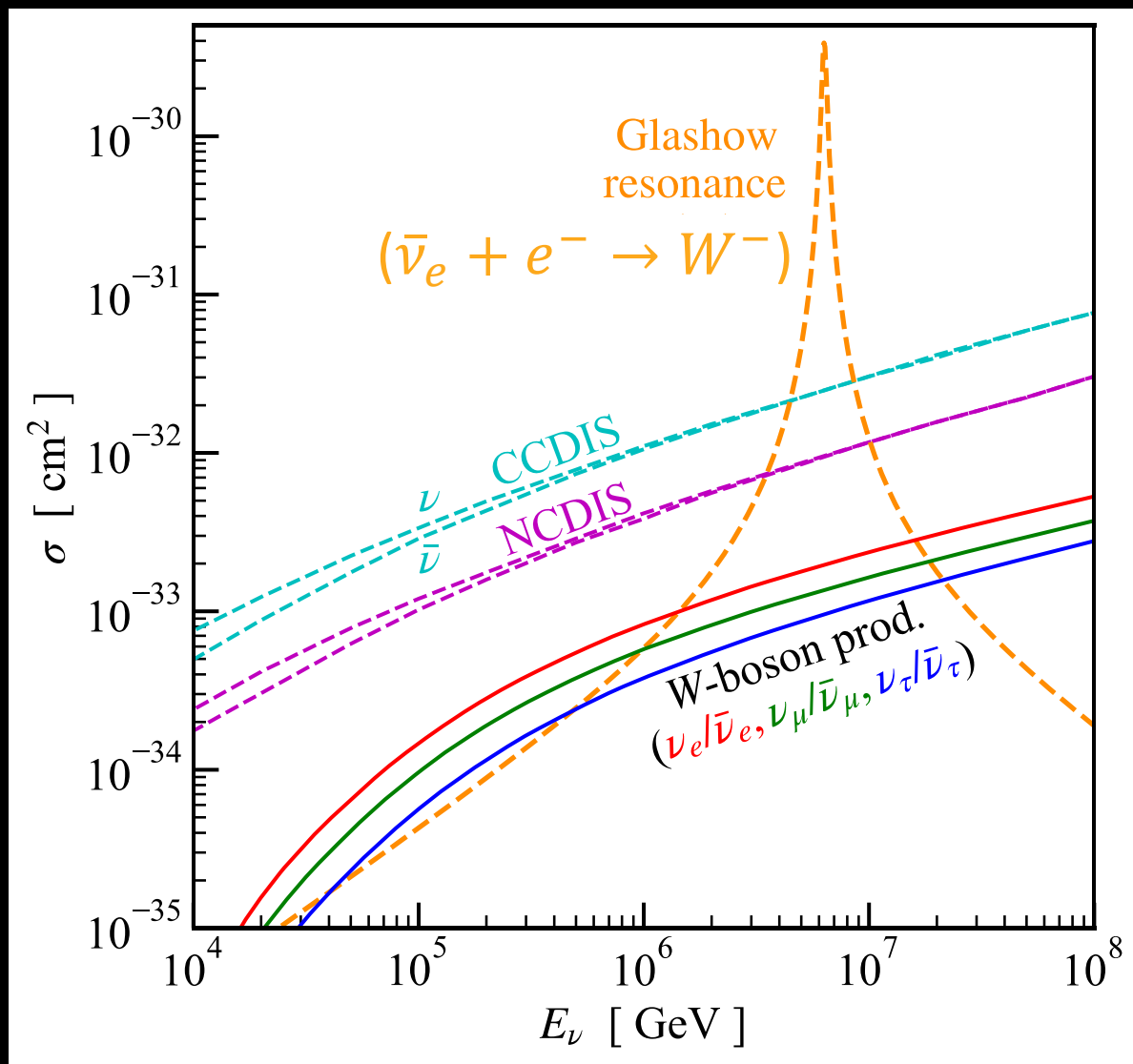
FSR impacts UHE nu observation: air shower detectors for ν_τ



(Plestid, BZ, 2303.08984)



2203.08096, Ackermann, ..., BZ (Snowmass WP)



FSR impacts HE nu detection in collider/accelerator neutrinos

Example: measuring parton distribution function (PDF) using data of FASERv (running) and future FASERv2

FASERv (running) will have $\sim 2 \times 10^4$ neutrino CCDIS events

FASERv2 (proposed) will have $\sim 10^6$.

Enough data to perform $\text{PDF}(x, Q^2)$ measurements

Without FSR:

$$x_{(0)} = \frac{Q_{(0)}^2}{2m_N E_X}; \quad Q_{(0)}^2 = 4E_\nu E_\ell \sin^2\left(\frac{\theta_\ell}{2}\right)$$

With FSR:

$$\frac{\Delta Q^2}{Q_{(0)}^2} \simeq -\frac{E_\gamma}{E_\ell} \quad \text{A few percent but large statistics}$$

$$\frac{\Delta x}{x_{(0)}} \simeq -\frac{E_\gamma}{E_X} - \frac{E_\gamma}{E_\ell} \quad \sim 10\%$$