Final state radiation from high and ultrahigh energy neutrino interactions

Bei Zhou

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

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

I cannot make it to the meeting due to other travels. I didn't register and sent an email a few weeks ago asking to withdraw my talk, but it's now still on the timetable and today I got an email asking for slides. Here are the relevant slides that you can enjoy. Thanks very much for keeping the time slot to advertise our work!

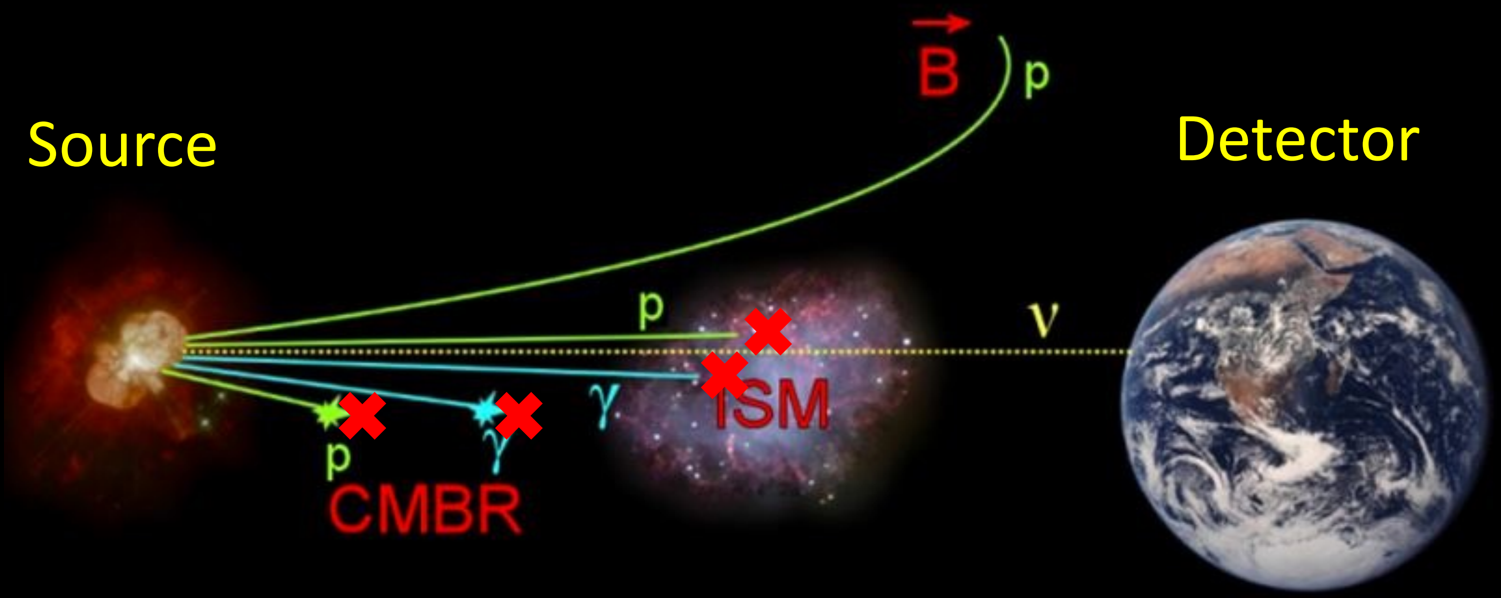
Why do we study HE&UHE neutrinos

- 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

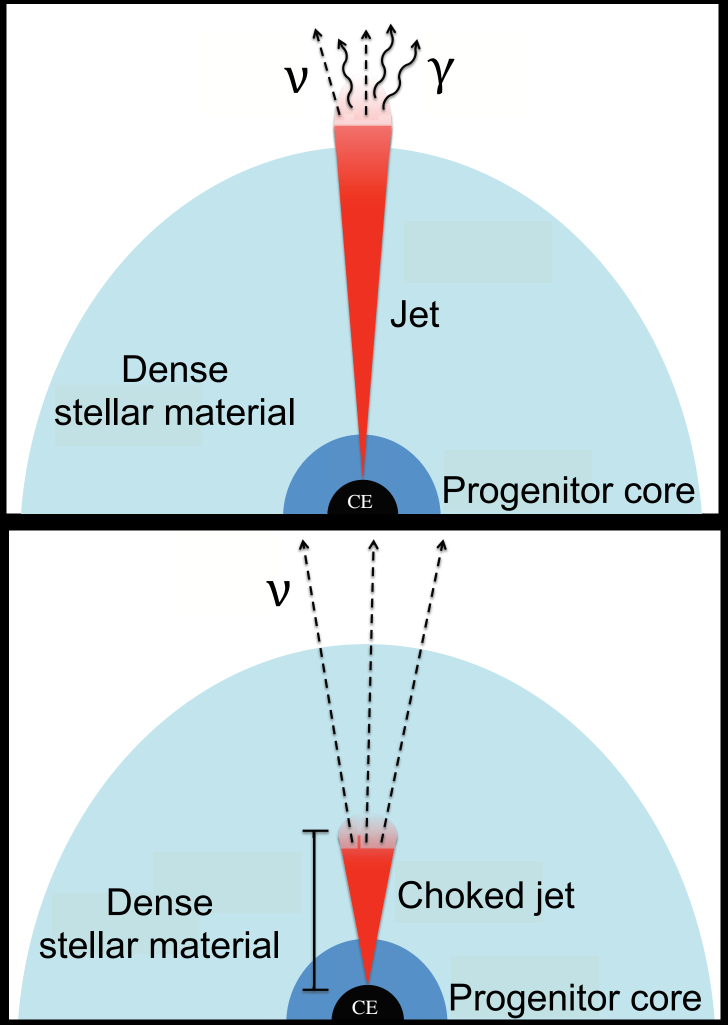
- Particle physics (highlighted by P5 report):
  - Neutrino interactions in the SM (Deep-inelastic scattering, W-boson production, Glashow resonance, final state radiation, etc.)
  - Measure neutrino mixing parameters
  - Test BSM (ν portal to DM, new ν interactions, sterile ν, magnetic moment, etc.)

Why do we study HE&UHE neutrinos: astrophysics

Cosmic ray sources



Dense environment



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

Why do we study HE&UHE neutrinos

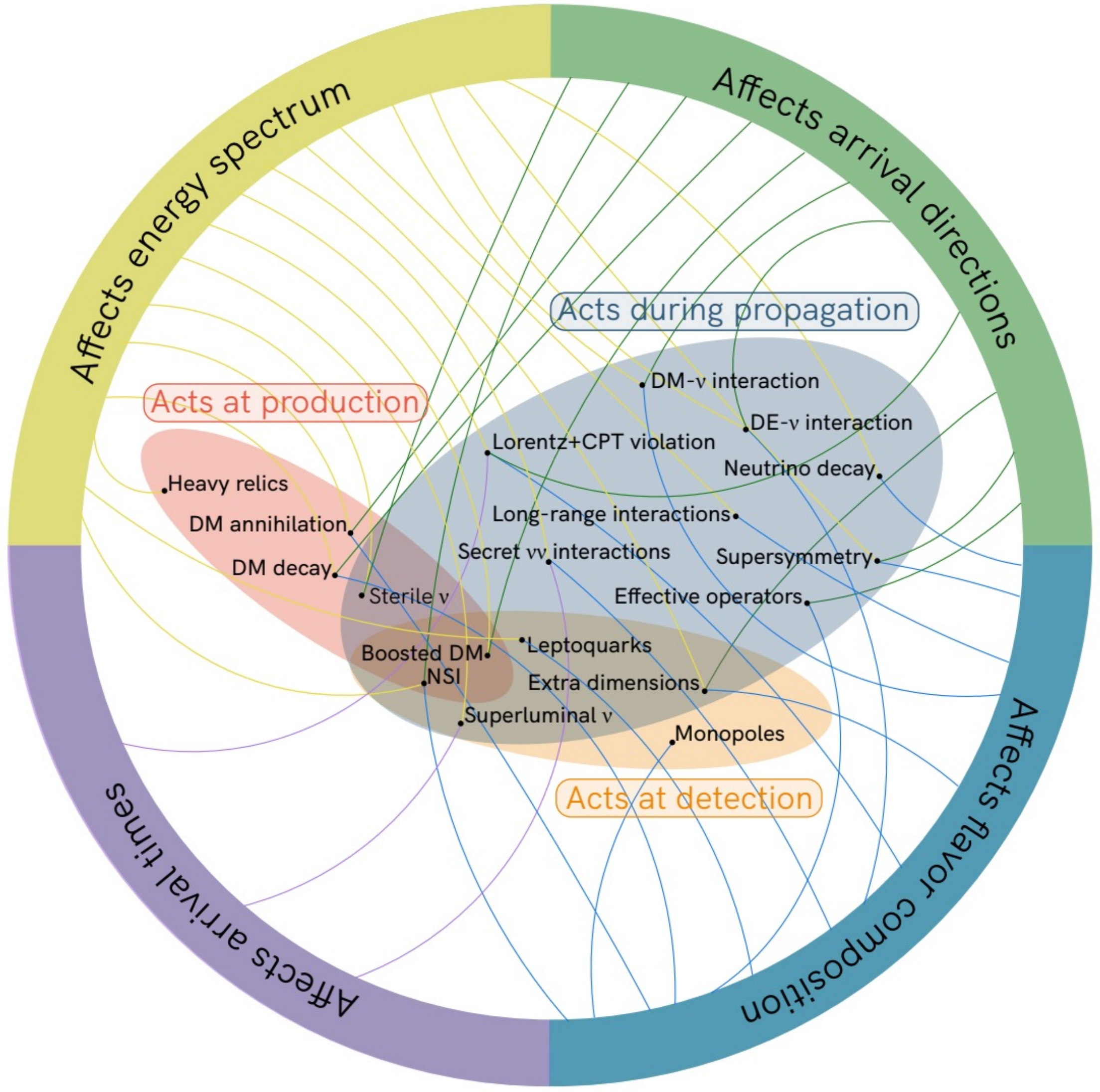
- Astrophysics (highlighted by astro2020): Origin of HE/UHE astrophysical neutrinos
  - Sources of HE/UHE cosmic rays (> 60-year problem)
  - Cosmic particle acceleration, propagation
  - Cosmic gamma ray sources, hadronic vs leptonic mechanism
  - Dense astrophysical environments
  - Essential for multi-messenger 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.)

Why do we study HE&UHE 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.

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 nu 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

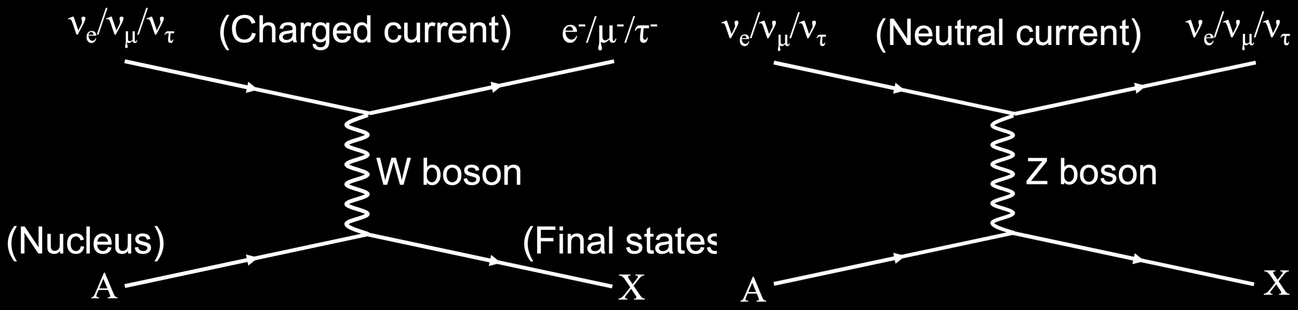
- Help us to find new event classes: useful for both astrophysics and particle physics studies
  - E.g., dimuons for high-energy neutrino detection (*2110.02974 BZ, Beacom*).

- 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 ration, 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

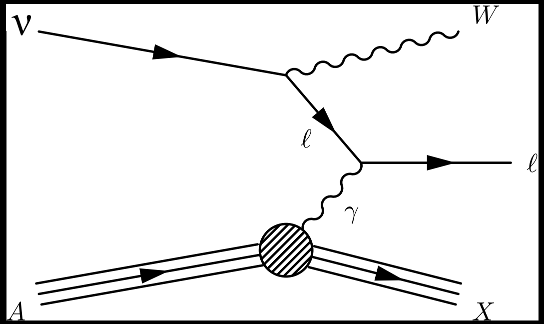
(as good as ~1% precision)

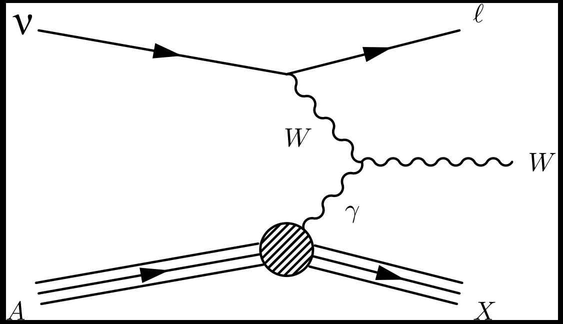


Gandhi+ 96&97, Connolly+ 11, Cooper-Sarkar+ 11, Bertone+ 16, etc.

Most recent: Xie, et al. 2303.13607

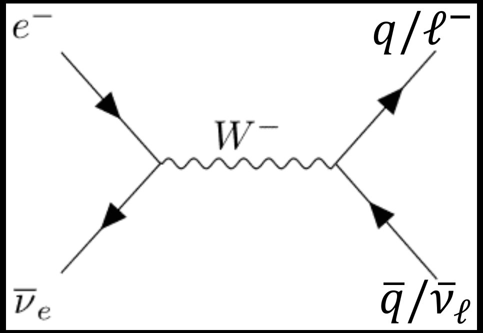
W-boson production (WBP) is subdominant





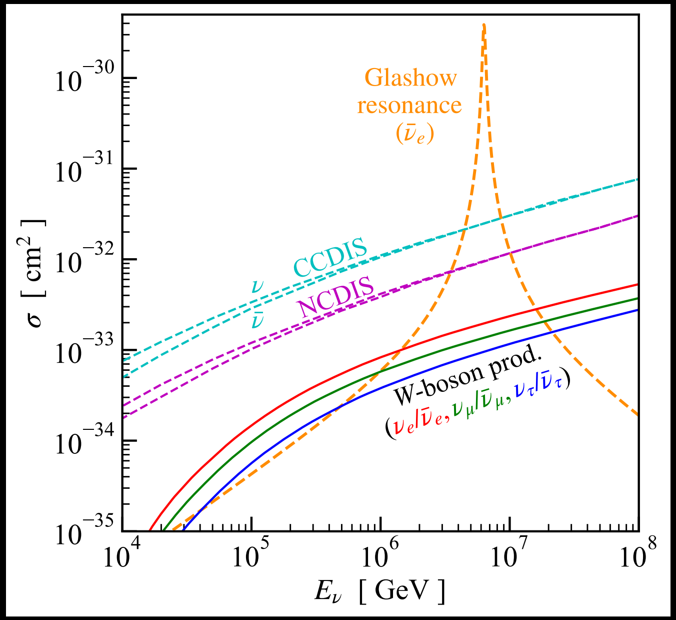
(Seckel 1997, Alikhanov 2015, BZ, Beacom, 1910.08090)

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



Glashow 1960
IceCube 2021

Cross sections



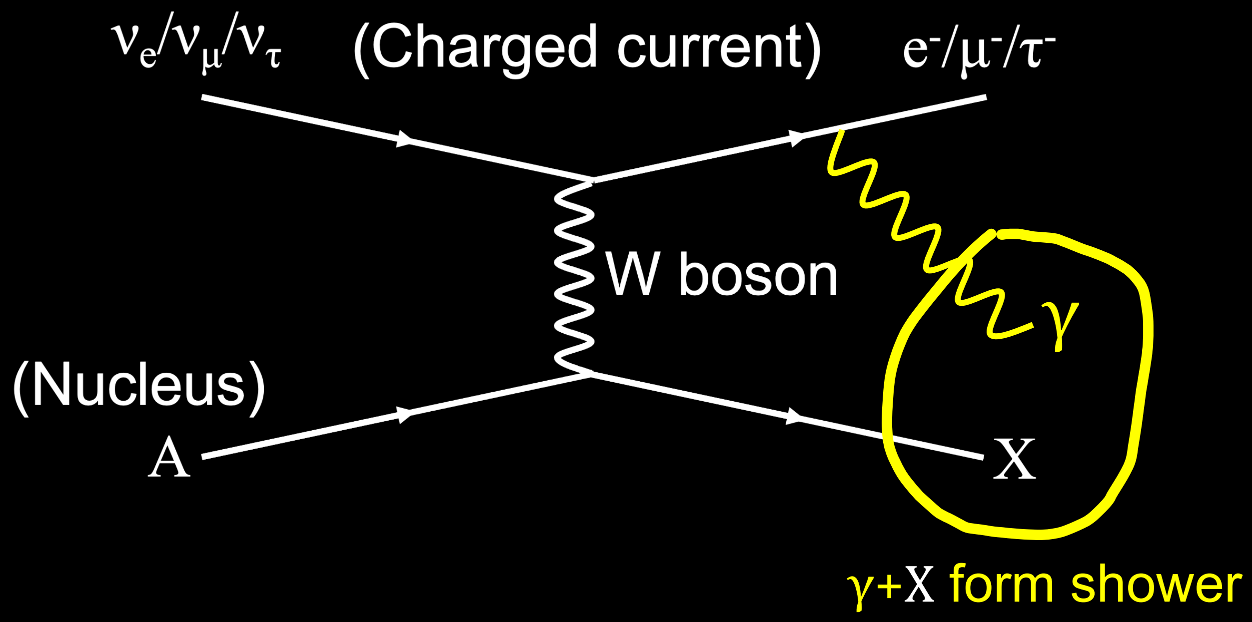
(BZ, Beacom, 1910.10720)

Final state radiation (FSR)

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.

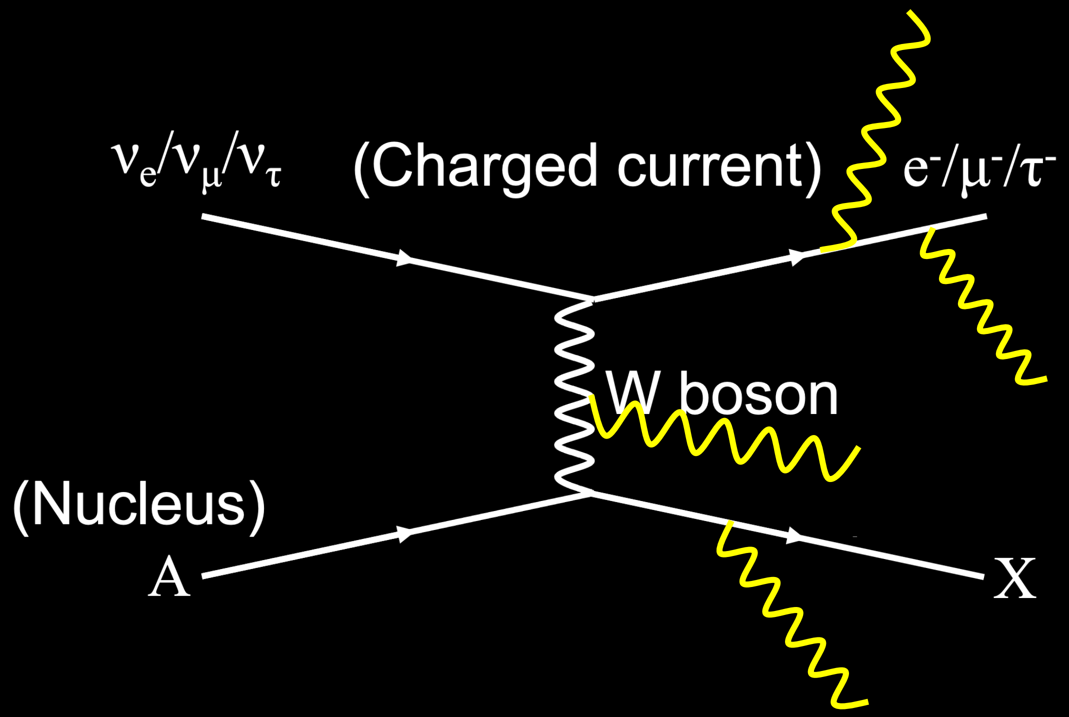
Final state radiation (FSR)



Effect on total xsec: small (~1%, c.f. KLN theorem).

Effects on the differential xsec: big, due to the kinematic logs.
→ So, it affects observation if charged lepton and shower are separate.

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) $E\gamma$ small as quark energy << lepton energy

Multi-photon emission: higher order, small

A rough estimate using Sudakov form factor

Collinear log Soft log

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

$1\text{-}F_S$ gives the probability of radiating any photons above threshold E_{min}

For ν_μ CCDIS (ℓ=μ), if we take E_ν = 10 TeV, and $E_{min} = 0.1E_\mu$,
we get $1\text{-}F_S$ = 10%.

→ So FSR is important.

Calculation, leading log approximation

DIS cross section

$$\frac{\mathrm{d}^2\sigma^{(0)}_{\nu,\overline{\nu}}}{\mathrm{d}x\mathrm{d}y} = \frac{G_F M E_\nu}{\pi(1+Q^2/M_W^2)^2} \times \left[y^2 F_1 + (1-y)F_2 \pm xy(1-y/2)F_3\right]$$

from Xie et al. 2303.13607, CTEQ collaboration

Collinear log

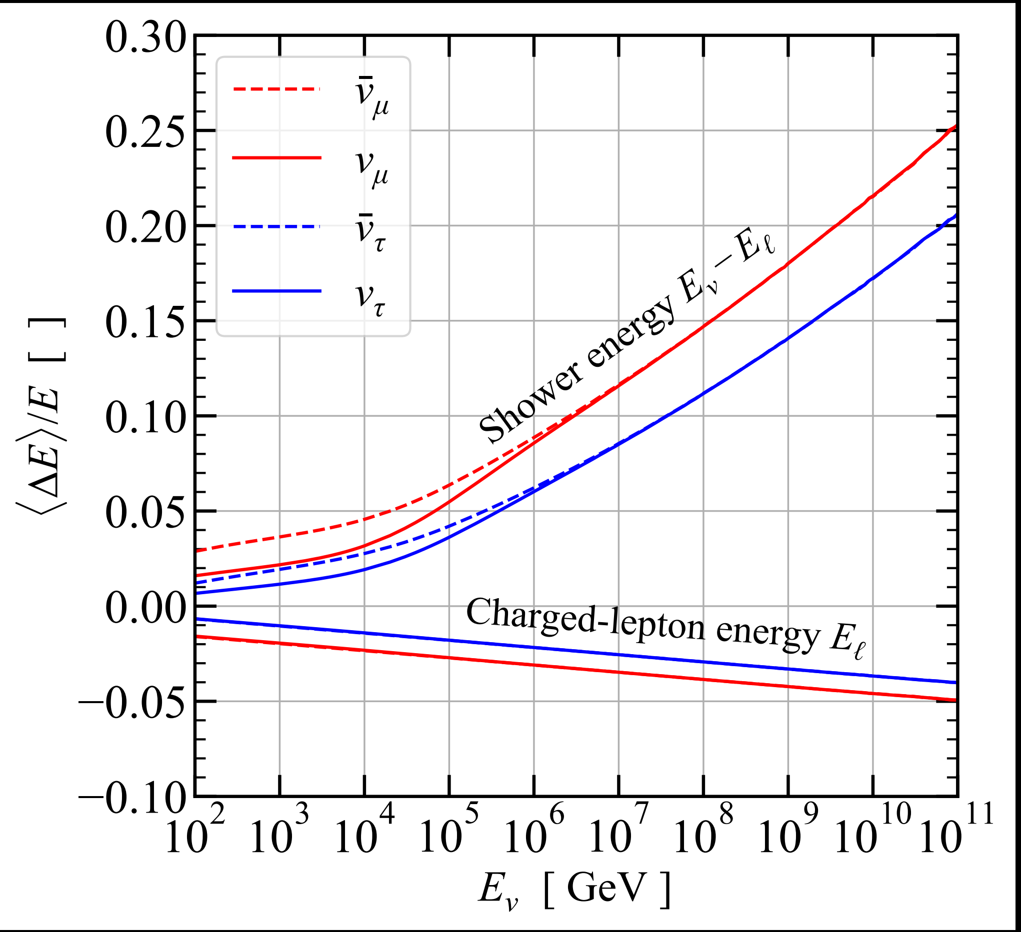
Splitting function

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

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

(Plestid, BZ, 2303.08984)

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



Photon takes energy from the charged lepton to the shower

(Plestid, BZ, 2303.08984)

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

Correction on νμ > ντ, cuz m_μ < m_τ

Correction on shower > charged lepton

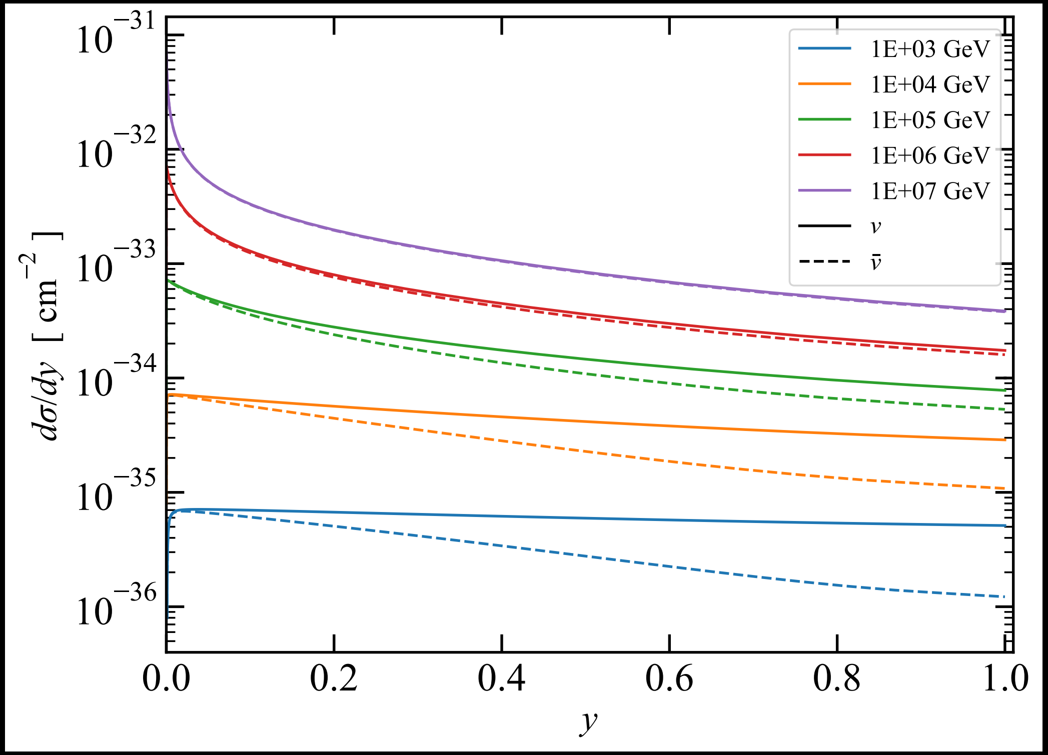
Correction on shower further enhanced by 10—20% due to light yields from EM shower > hadronic shower

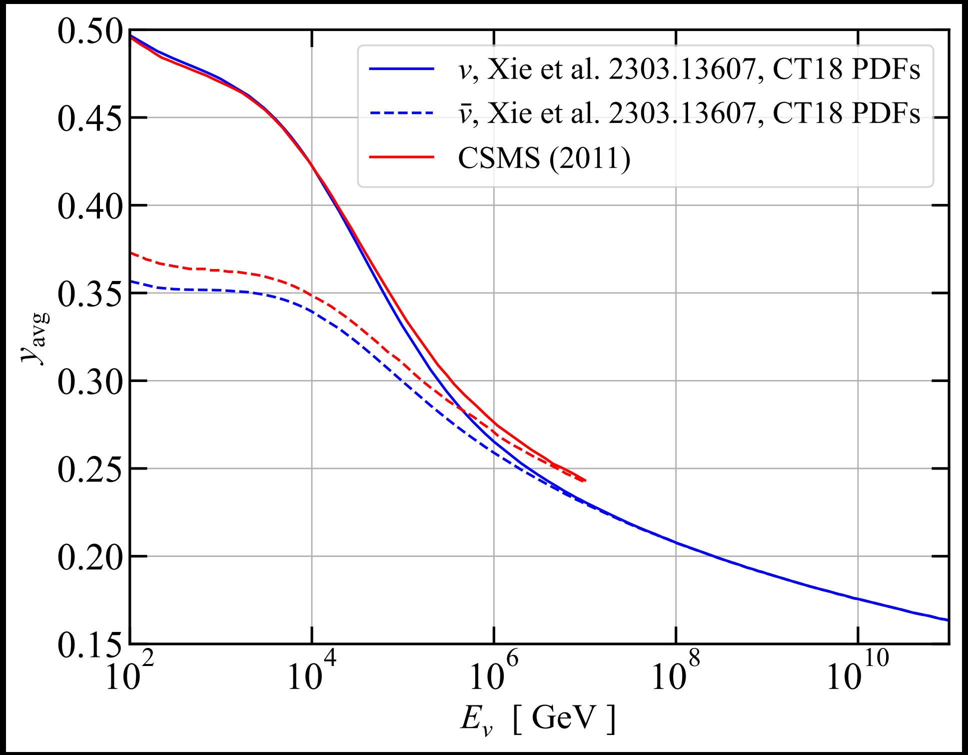
Difference between nu and nubar

FSR impacts on the inelasticity measurements

Theoretical definition:

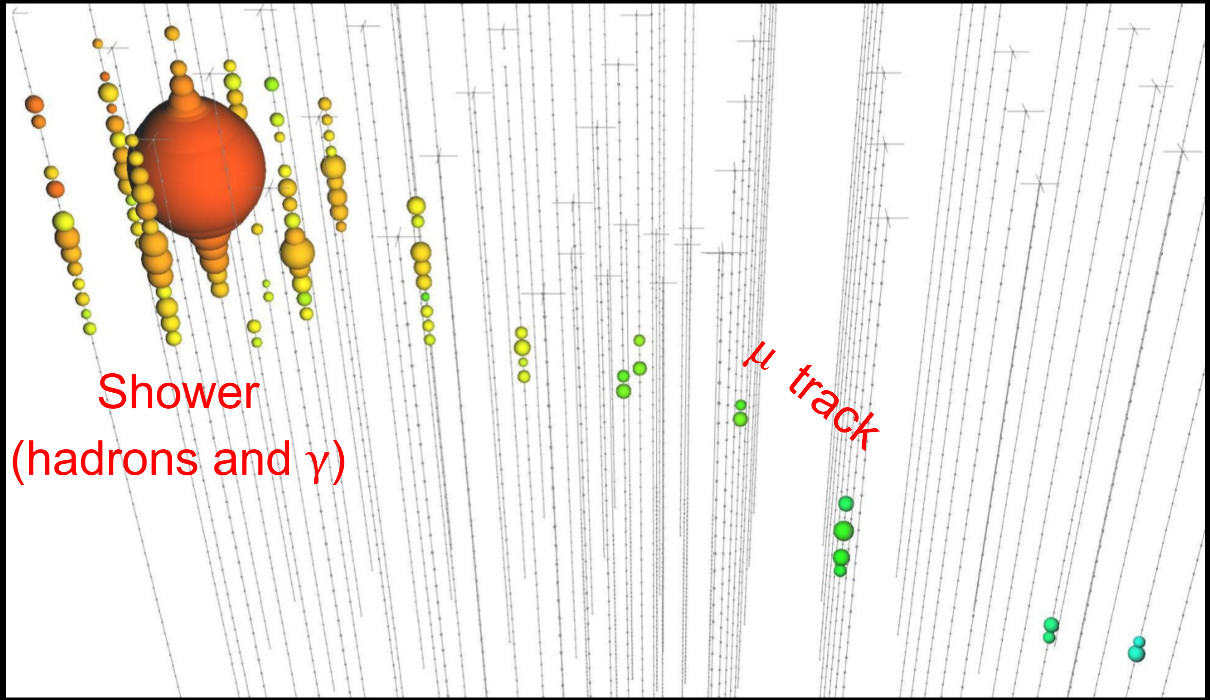
$$y_{\rm QCD} \equiv \frac{E_X}{E_\nu} = \frac{E_\nu - E_\ell}{E_\nu}$$



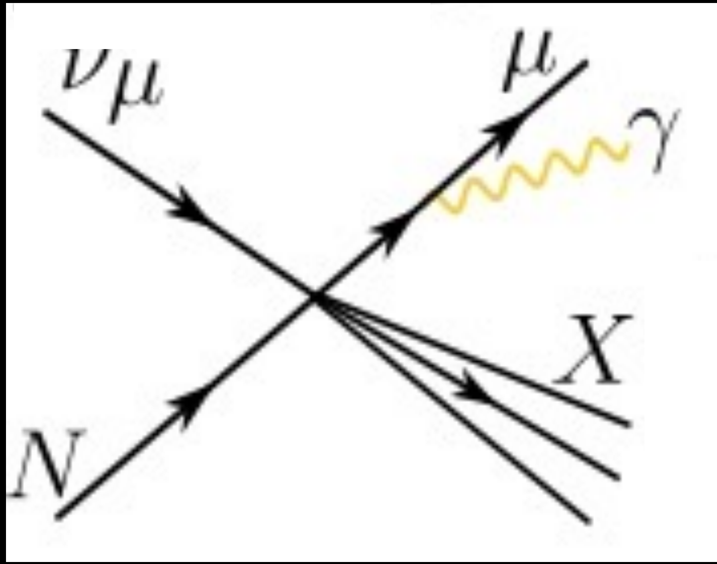


FSR impacts on the inelasticity measurements

Experimental definition:



1311.5238 IceCube coll. Science



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

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

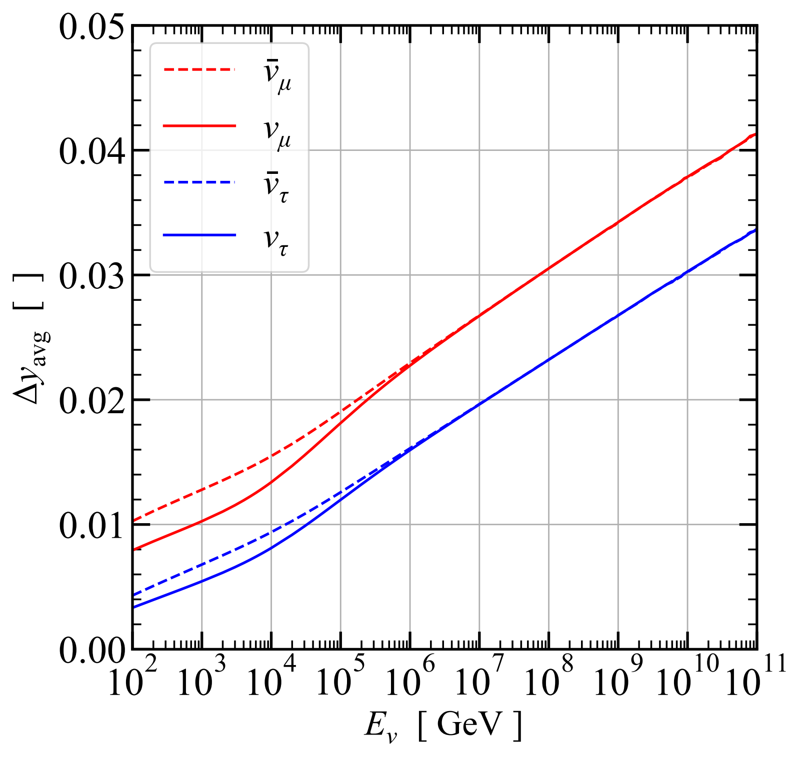
Photon takes energy from the charged lepton to the shower, increasing <y>

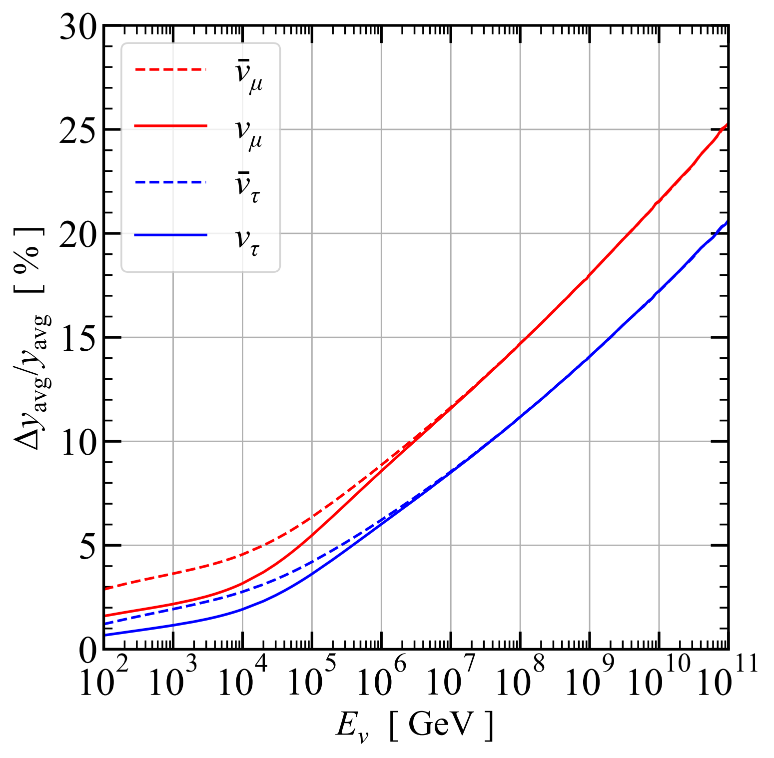
FSR impacts on the inelasticity measurements: average y

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

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

Photon takes energy from the charged lepton to the shower, increasing <y>

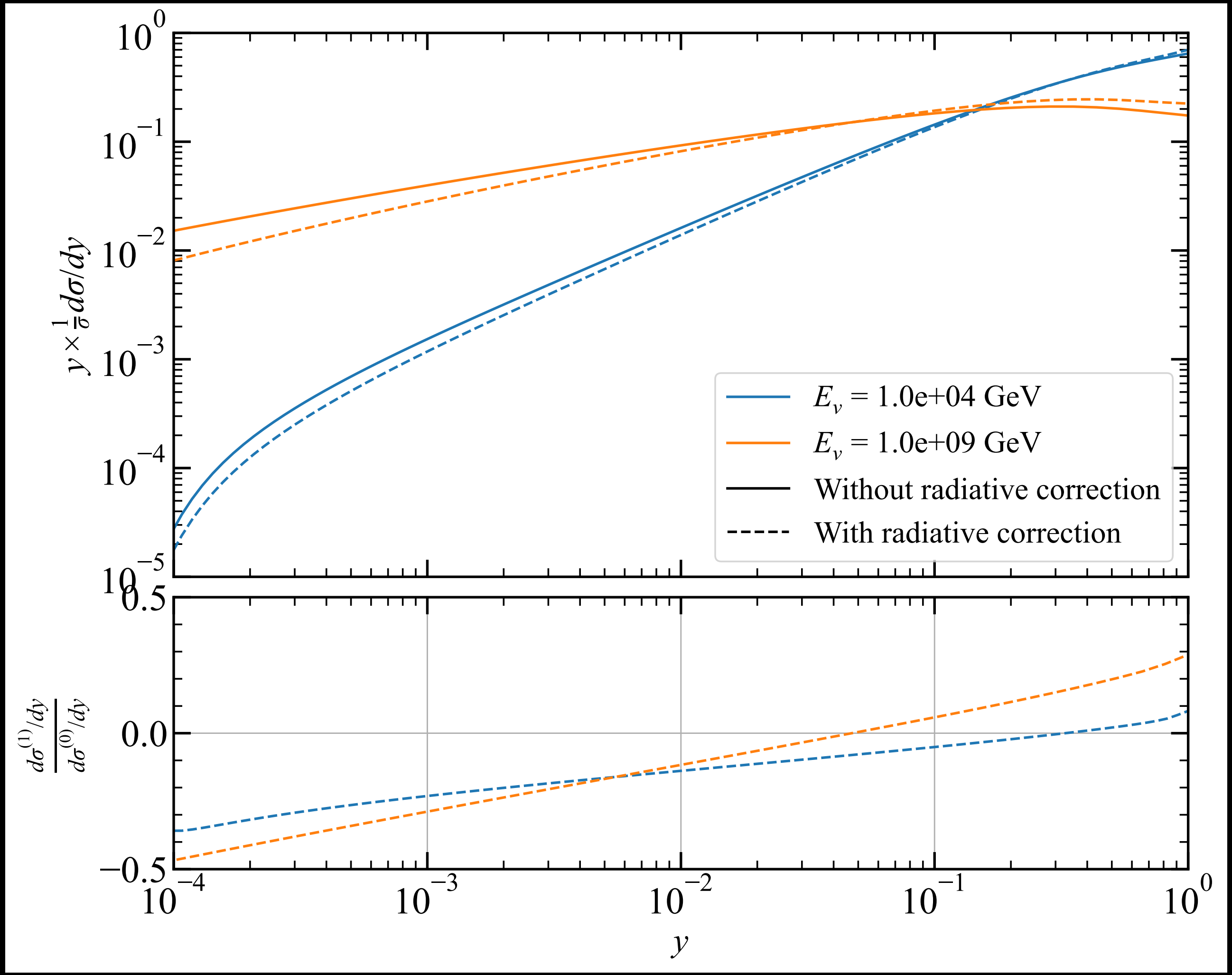




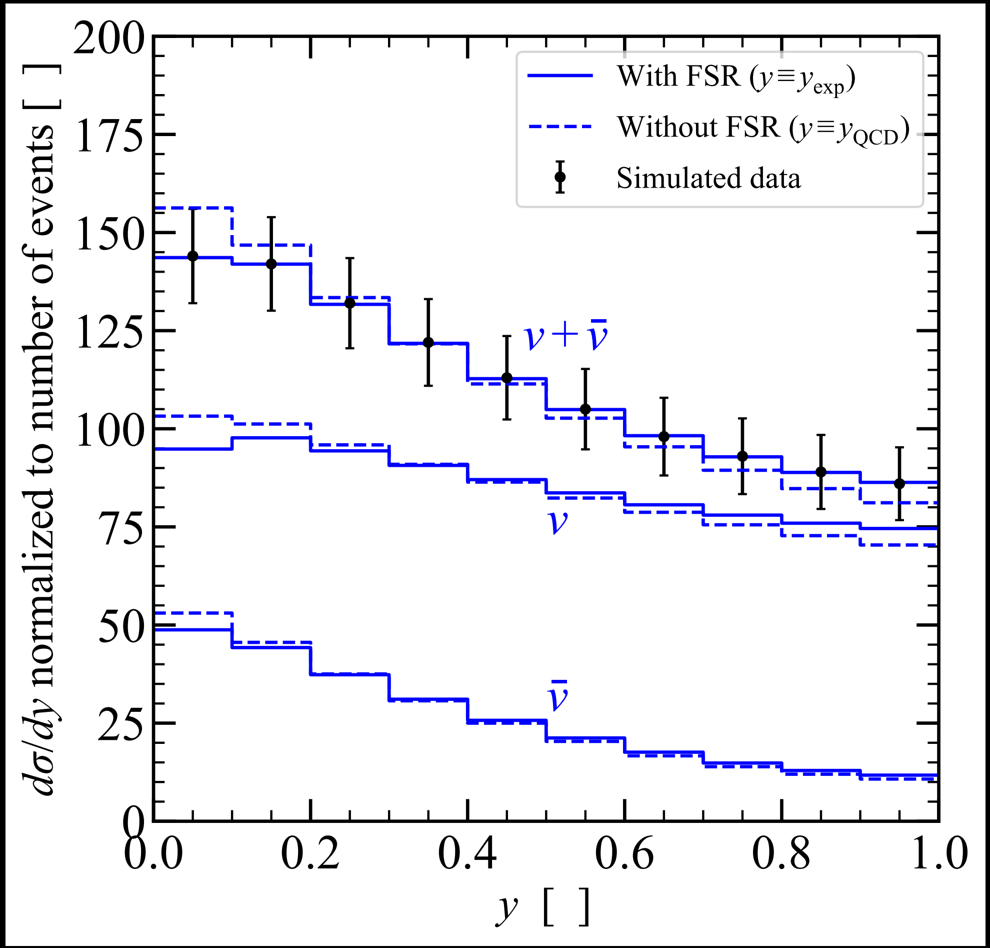
(Plestid, BZ, 2303.08984)

Correction increases with energy, up to 25%

FSR impacts on the inelasticity measurements: differential



FSR impacts HE nu observations: nu/nubar flux ratio



(Plestid, BZ, 2303.08984)

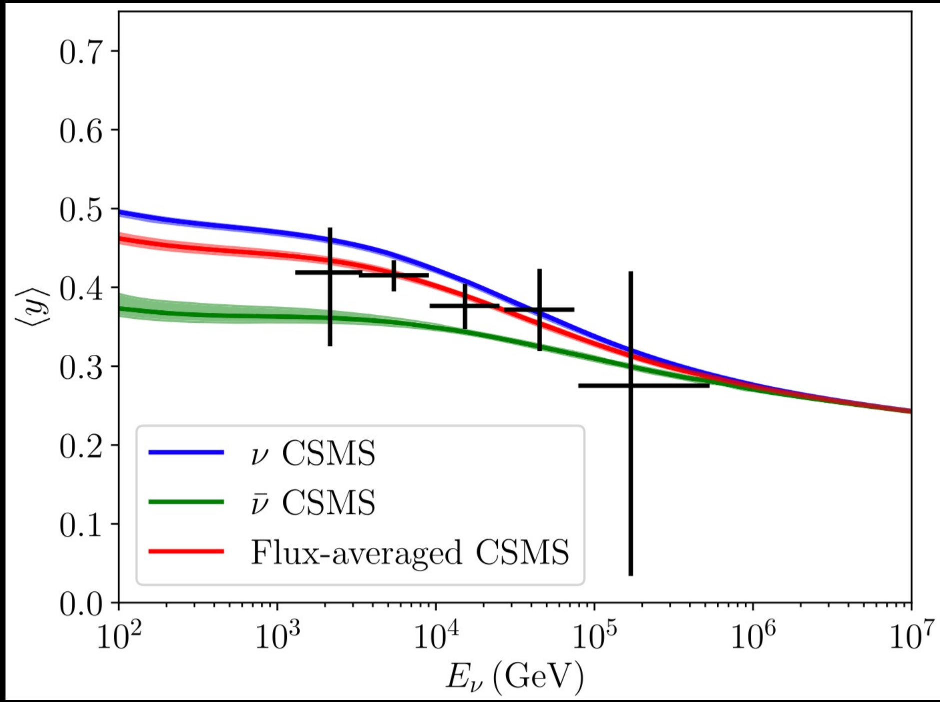


Fig 8 of 1808.07629 IceCube Coll.

FSR affects largest and smallest y bins the most, where experimental effects are also the largest

Our estimates give ~5% shift in the nu/nubar flux measurement due to FSR

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

Neutrino mixing

Inelasticity measurements help to separate nu and nubar, which helps with measuring neutrino mass hierarchy and CP violation. The sensitivity can be increased by ≃30%. (*1303.0758, 1312.0457, 2402.13308*)

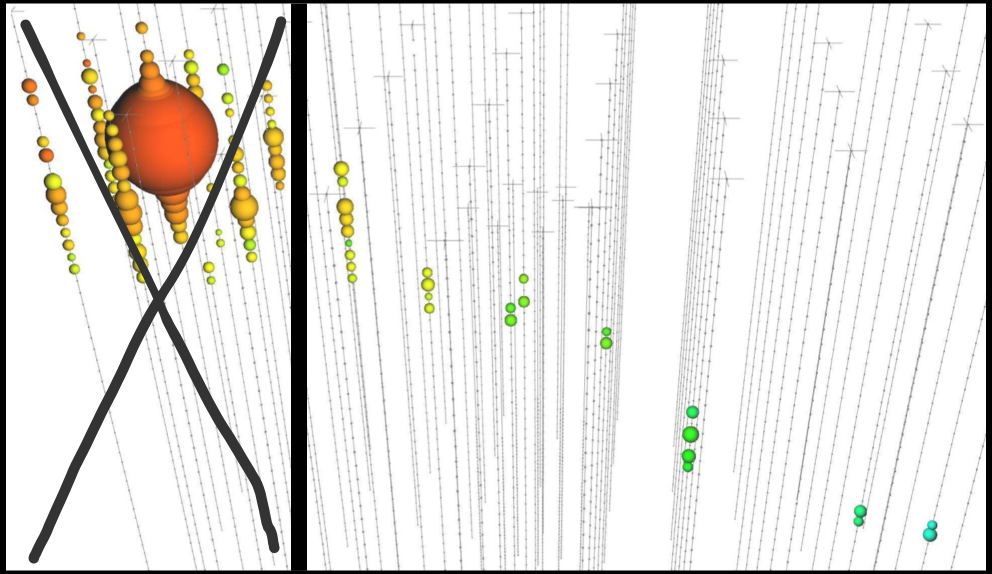
Charm production

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

And FSR will affect these measurements through its affect on the inelasticity

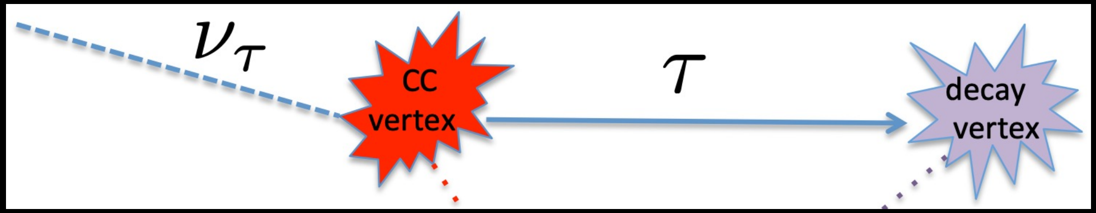
FSR impacts HE nu observations: throughgoing muons & ν_τ double bang

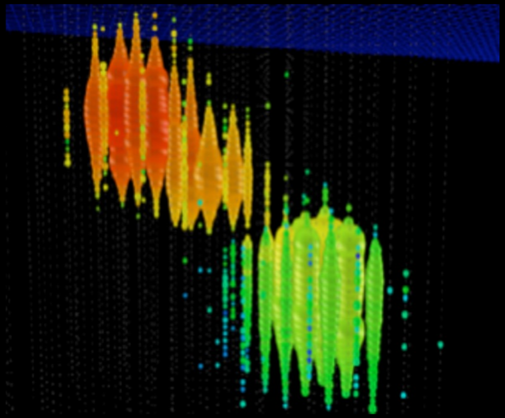
Throughgoing muons



Not including FSR underestimates the parent neutrino energy

ν_τ induced double bang

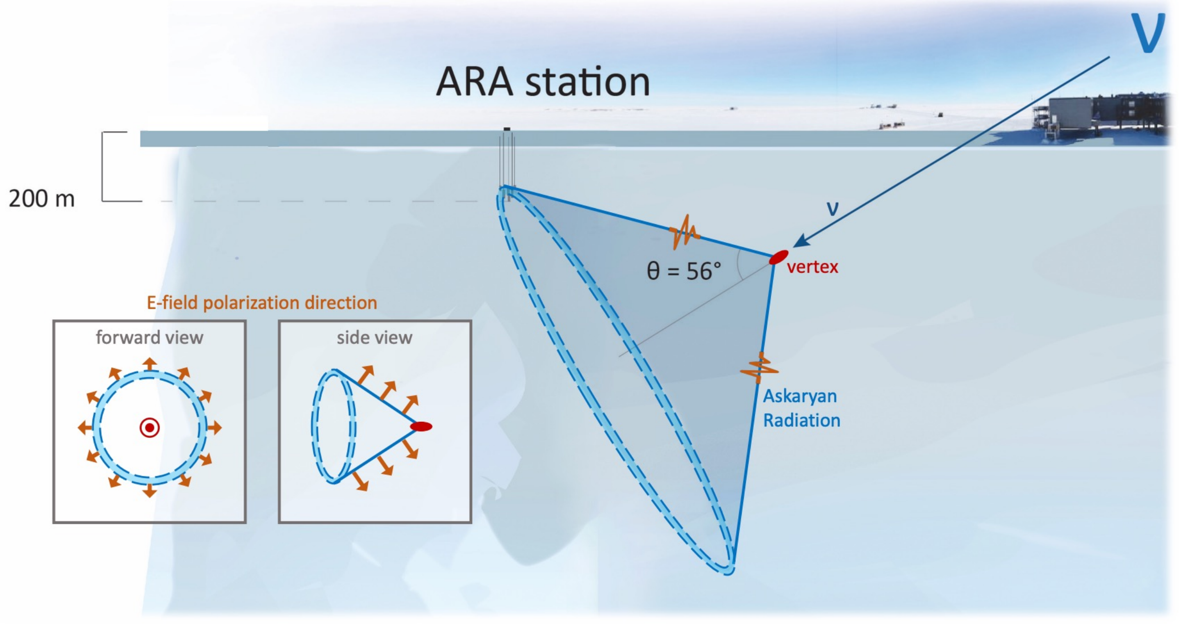




FSR 1) distort the energy balance the two bangs 2) reduce the detectability of the double bang signature.

UHE nu observations: two basic kinds of detectors

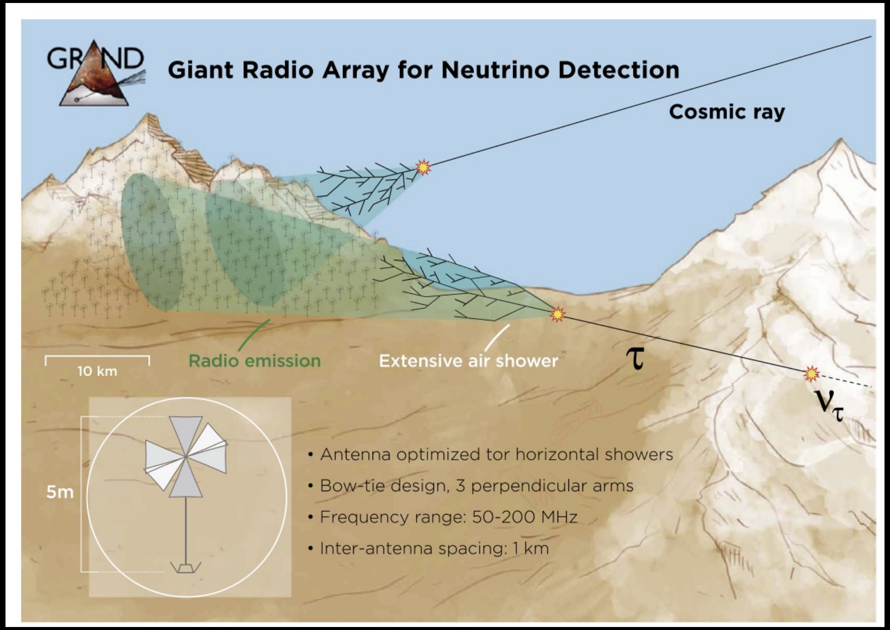
In-ice radio detectors (all flavors; could distinguish flavors)



1912.00987 ARA collaboration

E.g., ARA, IceCube-Gen2 radio, PUEO, etc.

Air shower detectors (main for $\nu\tau$)



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

E.g., GRAND, POEMMA, etc.

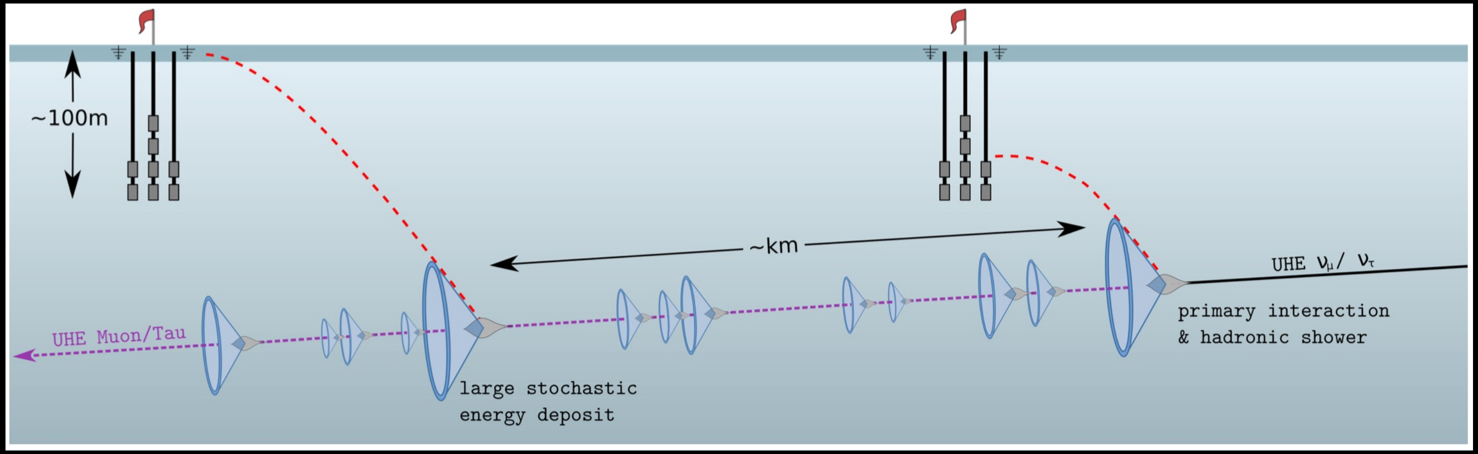
FSR impacts UHE nu observations: in-ice radio detectors

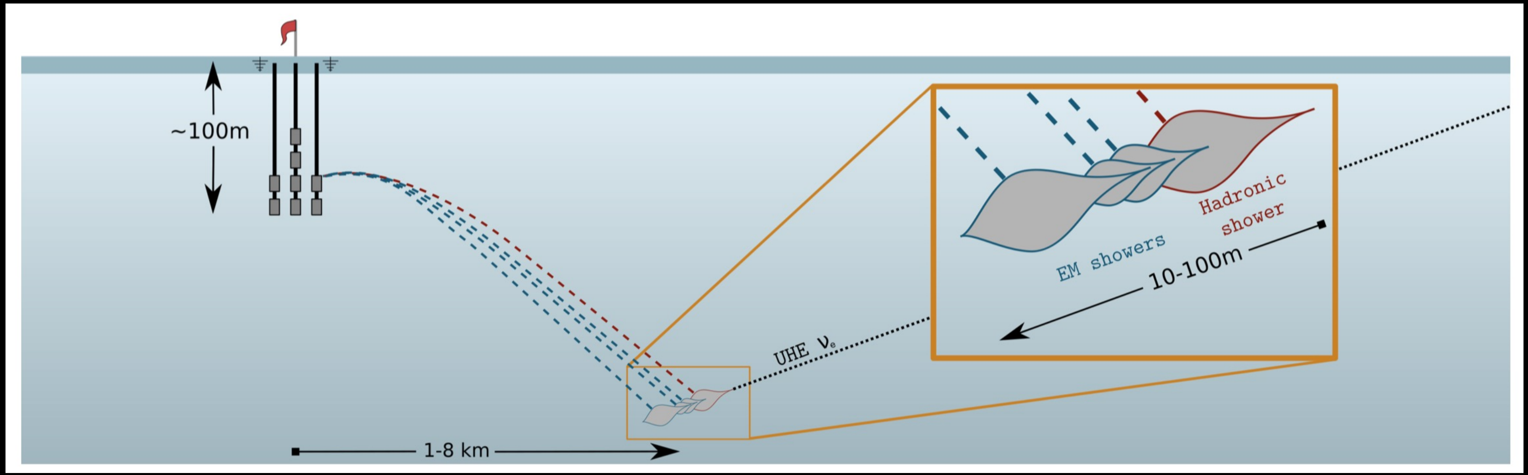
For CCDIS, FSR enhances the overall detectable (shower) energy by as much as ≃20% and lowers the energy thresholds.

ντ CC, big, up to ≃20%

νμ CC, mild

νe CC, negligible



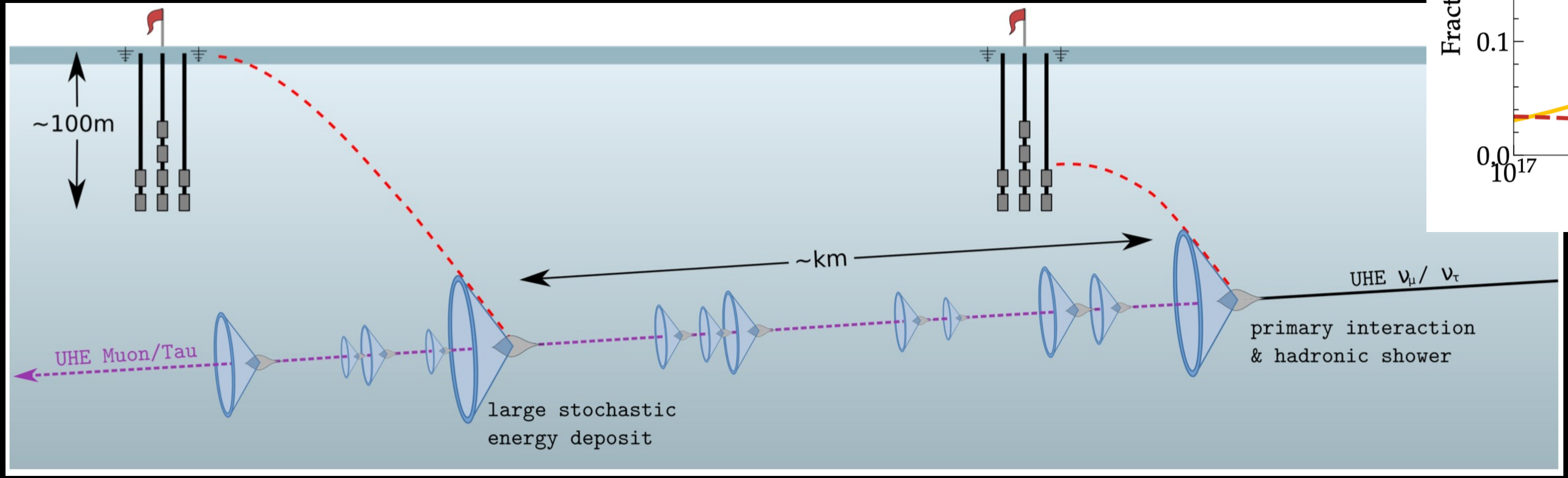


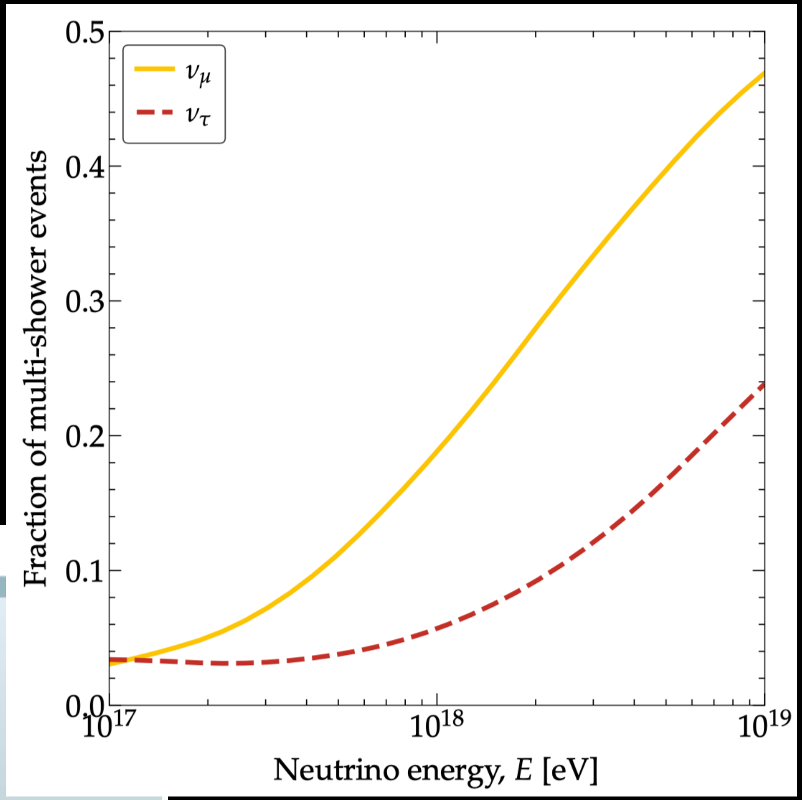
2402.02432 Coleman et al.

FSR impacts UHE nu observations: in-ice radio detectors

FSR reduces the flavor measurements

A way to measure νμ/ντ, FSR reduces the detectability (~5%)



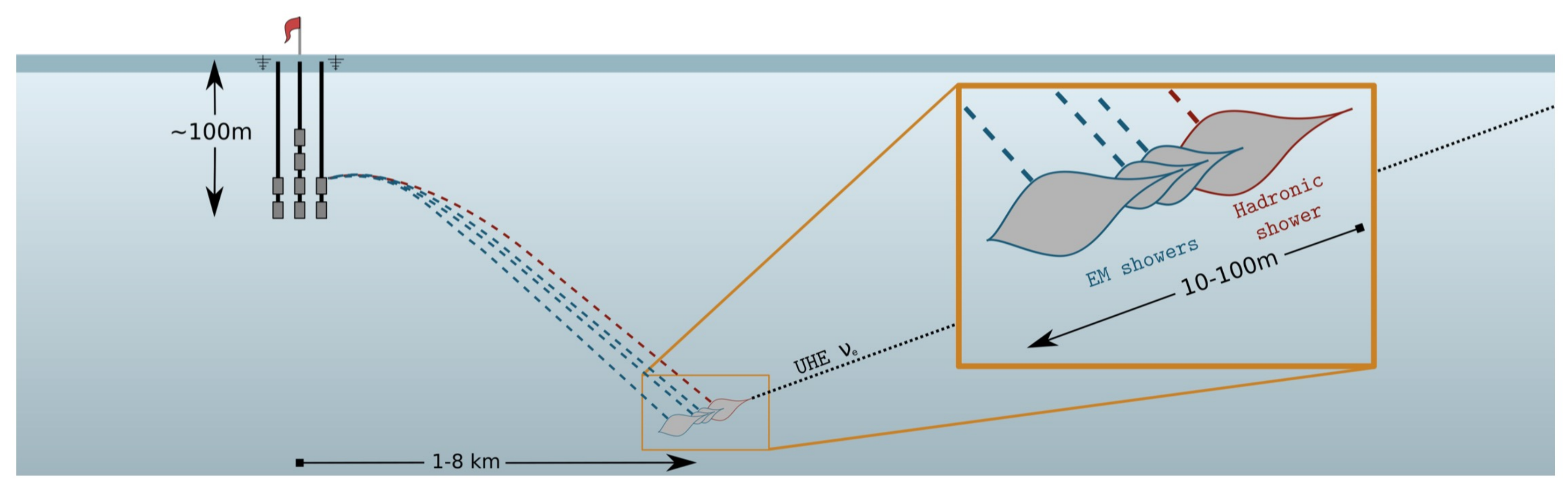


2402.02432
Coleman et al.

FSR impacts UHE nu observations: in-ice radio detectors

FSR reduces the flavor measurements

A way to measure electron neutrinos (using LPM effect)



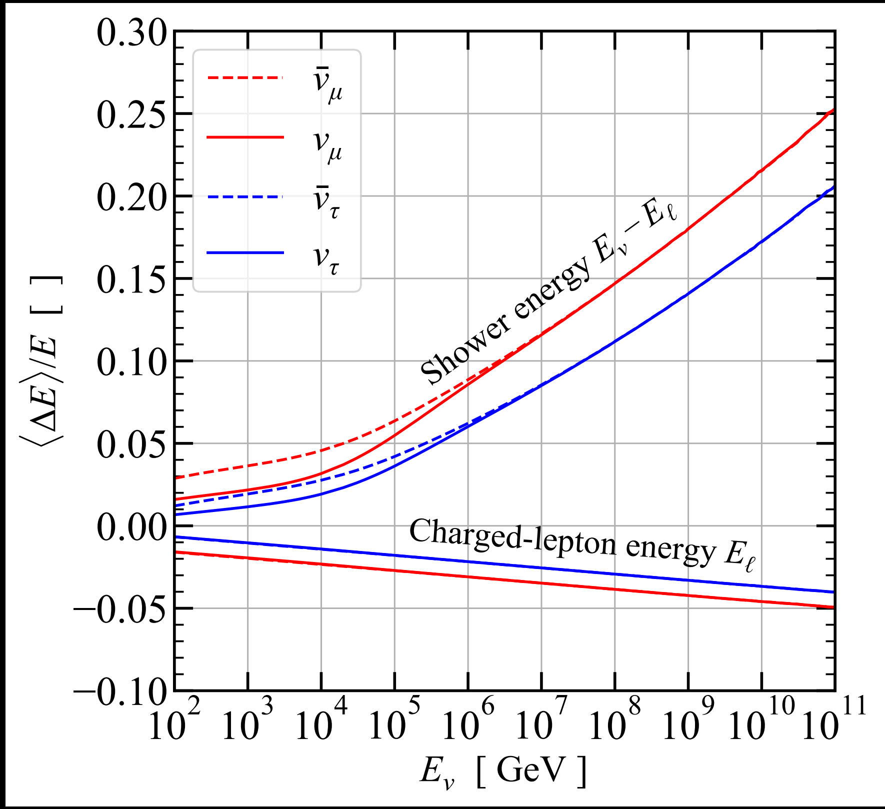
2402.02432
Coleman et al.

Background could be from muon/tau neutrino CC interactions.

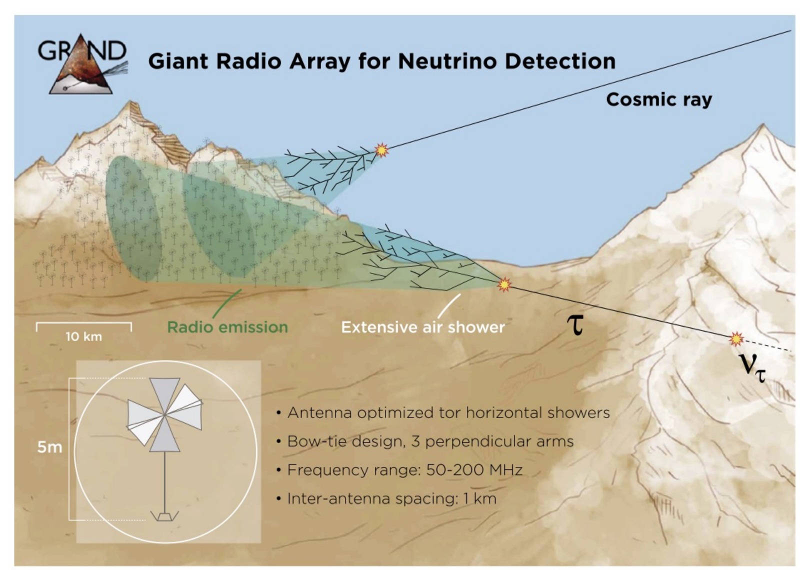
Without FSR, the paper estimates that bkgd rate is ~0%.

With FSR, we estimate that bkgd rate is ~30% of signal rate

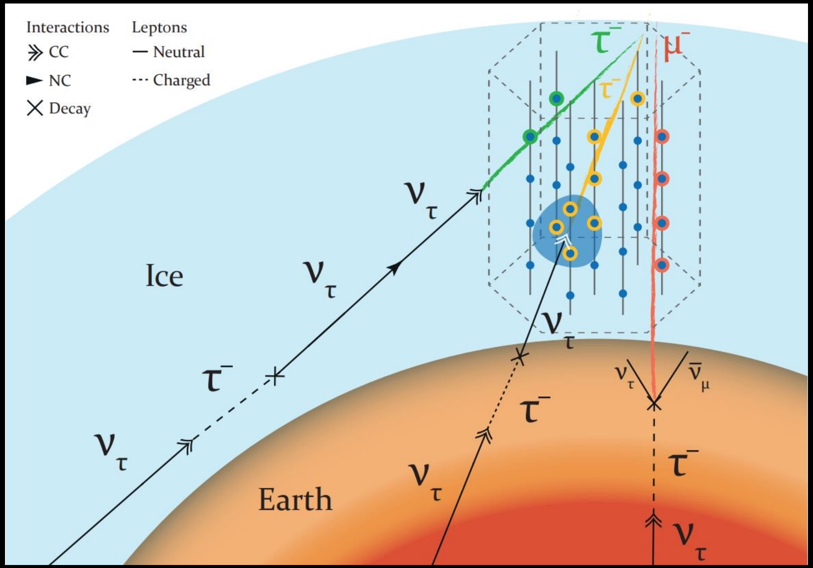
FSR impacts UHE nu observations: air shower detectors for ντ



(Plestid, BZ, 2303.08984)



Earth emergent tau
~5% effect



ντ regeneration

~N*5% effect

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

FSR impacts on the neutrino flux measurement

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,

Γ=3, δ_E=5%, the bias is 15%

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

FSR impacts HE nu detection in collider/accelerator neutrinos

Example: measuring parton distribution function (PDF) using data of FASERν (running) and future FASERν2

FASERν (running) will have ~2×10^4 neutrino CCDIS events
FASERν2 (proposed) will have ~10^6.
Enough data to perform PDF(x, Q^2) measurements

Without FSR:
$$x_{(0)} = \frac{Q^2_{(0)}}{2m_N E_X}; \qquad Q^2_{(0)} = 4E_\nu E_\ell \sin^2\left(\frac{\theta_\ell}{2}\right)$$

With FSR:
$$\frac{\Delta Q^2}{Q^2_{(0)}} \simeq -\frac{E_\gamma}{E_\ell}$$
A few percent but large statistics

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

Thanks for your attention!