Final state radiation (FSR) from high and ultrahigh energy neutrino interactions

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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.

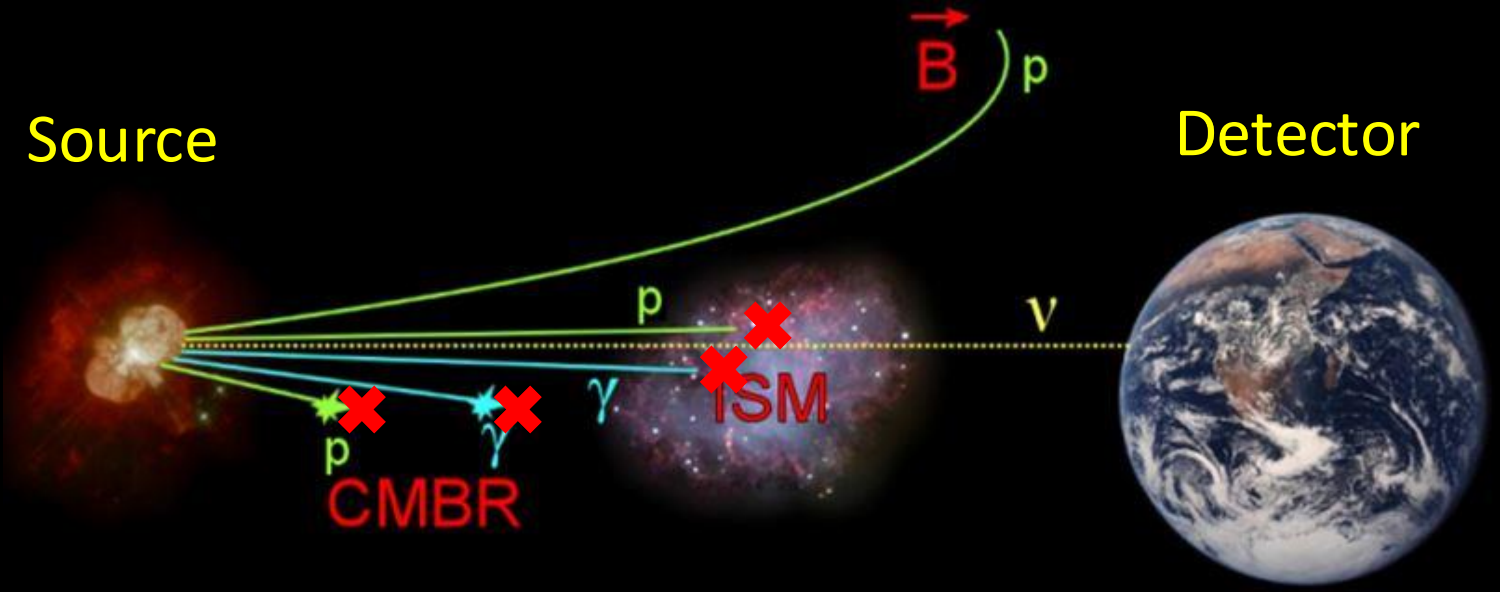
Why do we study HE&UHE neutrinos

- 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

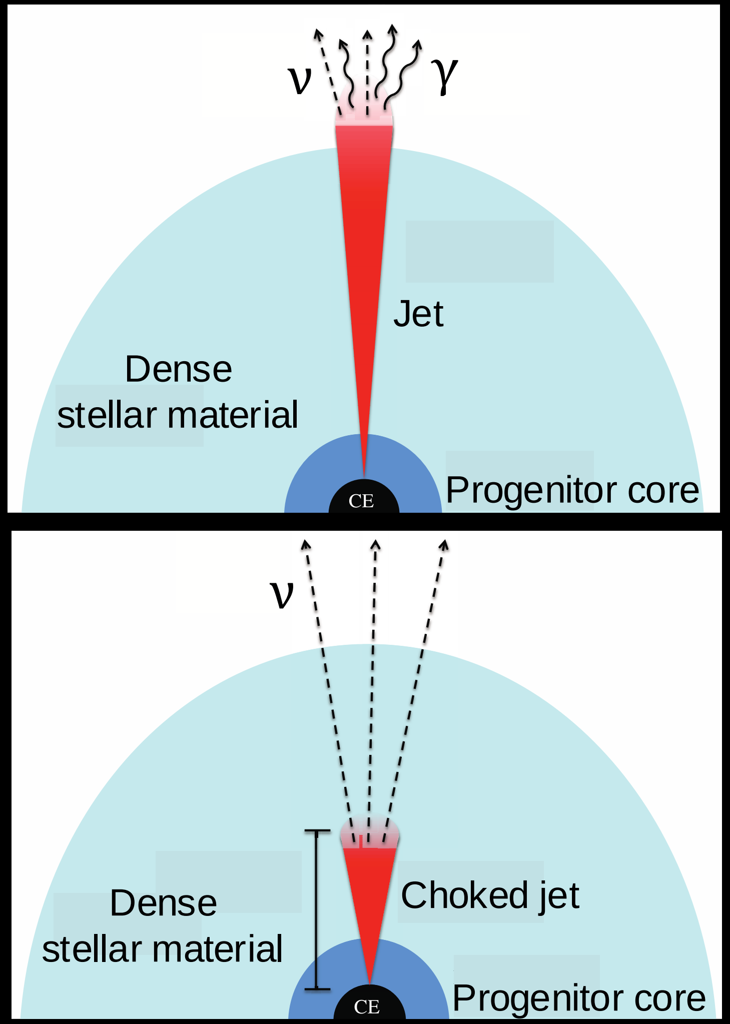
- Particle physics (highlighted by P5 report):
  - Neutrino interactions in the SM (Deep-inelastic scattering, W-boson production, Glashow resonance, final state radiation, etc.)
  - Measure neutrino mixing parameters
  - Test BSM (ν portal to DM, new ν interactions, sterile ν, magnetic moment, etc.)

Why do we study high-energy neutrinos: astrophysics

Cosmic ray sources



Dense environment



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

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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
TRINITY		Demonstrator
TAMBO		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

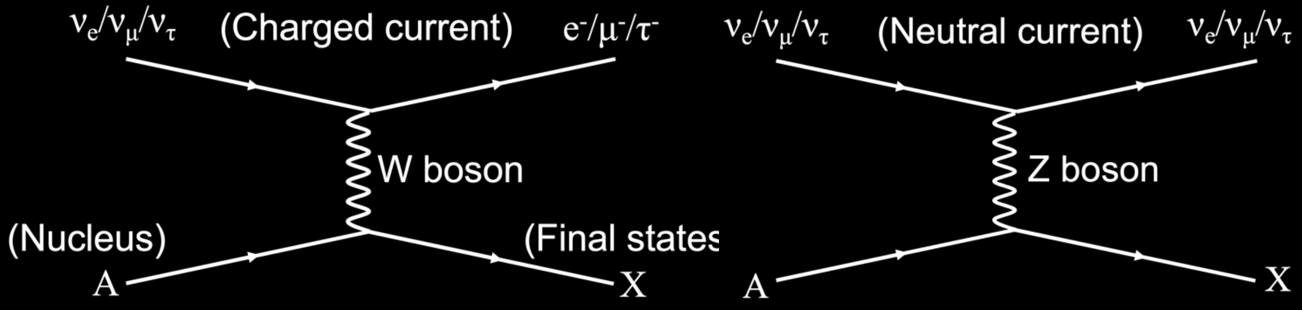
- Help us to find new event classes: useful for both astrophysics and particle physics studies
  - E.g., dimuons for high-energy neutrino detection (*2110.02974 BZ, Beacom*).

- 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

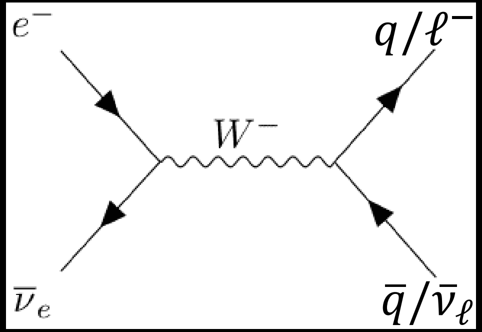
(as good as ~1% precision)



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

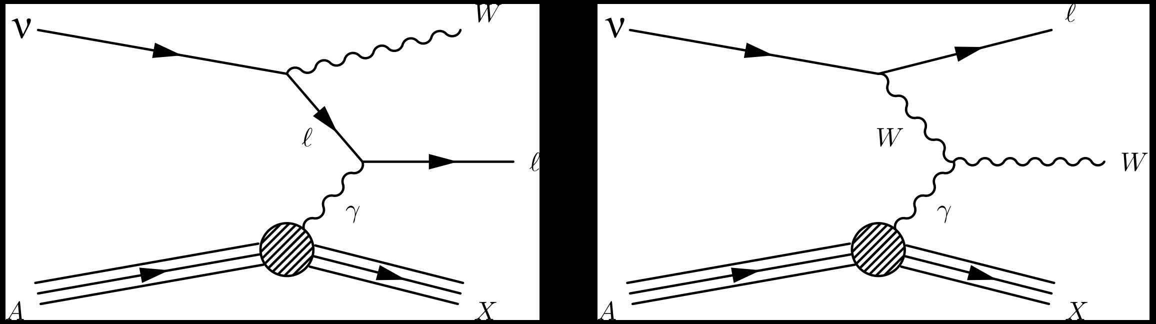
Most recent: Xie, et al. 2303.13607; Weigel, et al 2408.05866

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



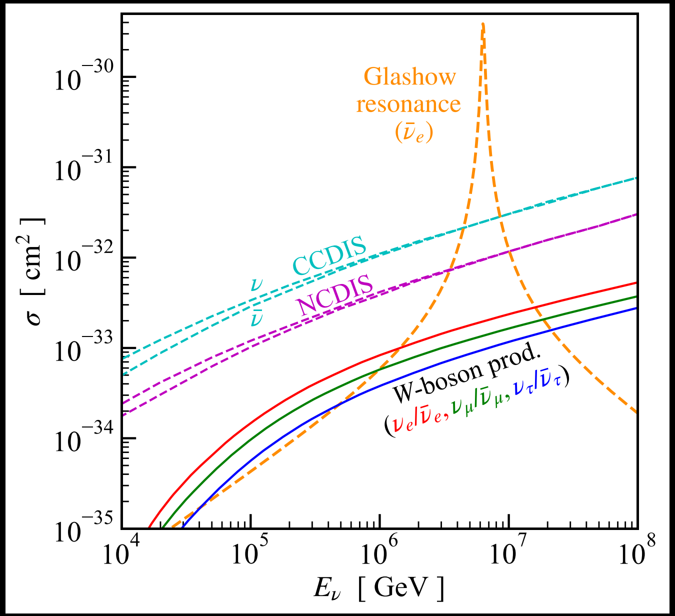
Glashow 1960
IceCube 2021

W-boson production (WBP) is subdominant



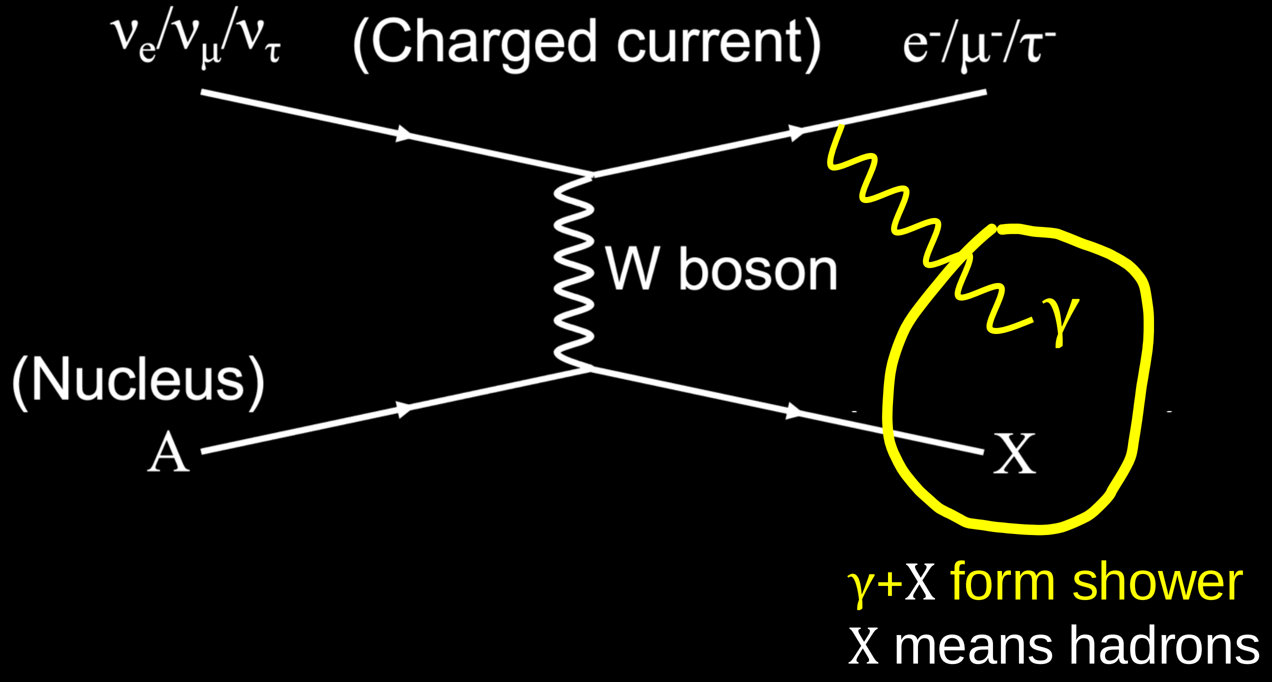
(Seckel 1997, Alikhanov 2015, BZ, Beacom, 1910.08090)

Cross sections



(BZ, Beacom, 1910.10720)

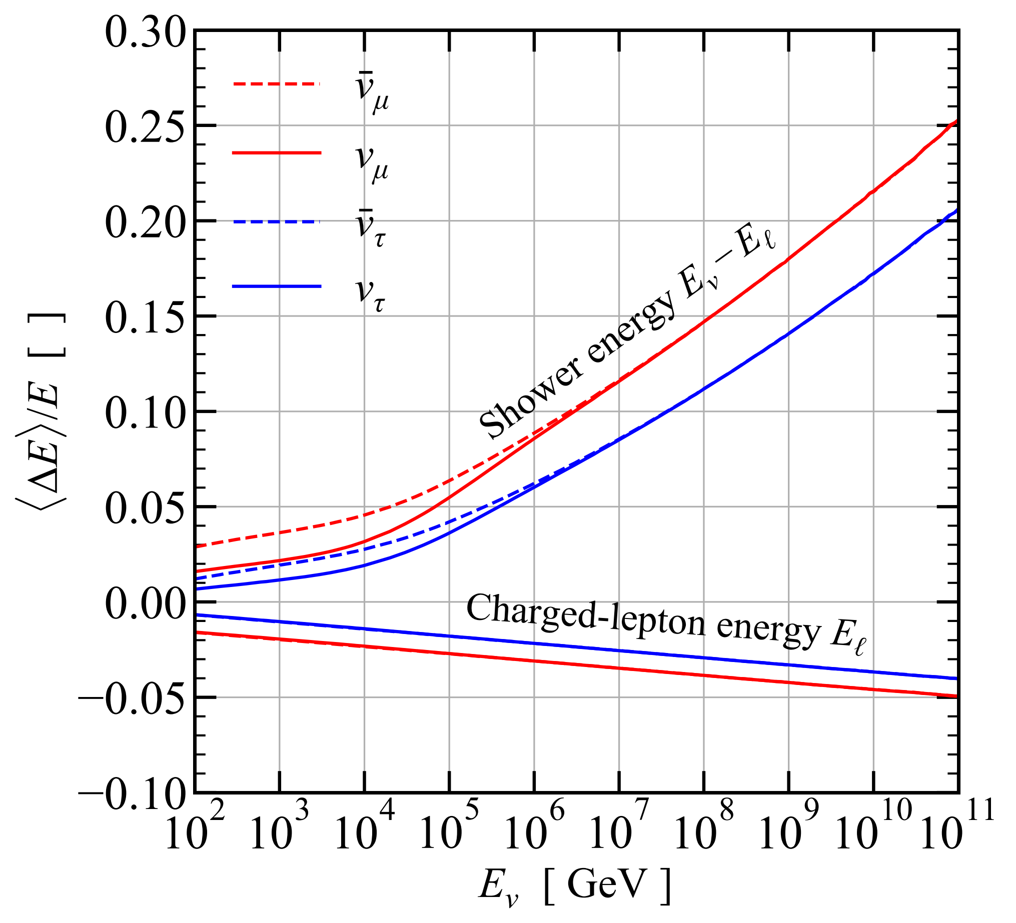
Our work: final state radiation (FSR) on top of neutrino CC DIS



Effect on total xsec: small (~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



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

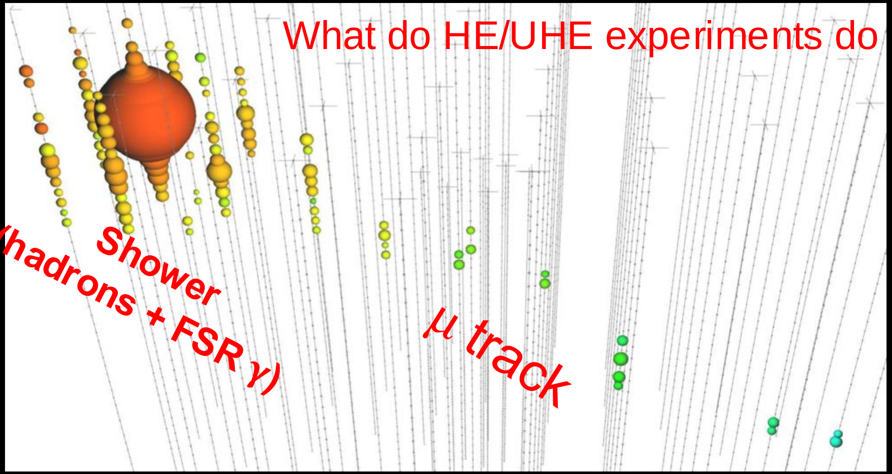
Correction on shower > charged lepton

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

Difference between nu and nubar

Final state radiation impacts the inelasticity (y) measurements

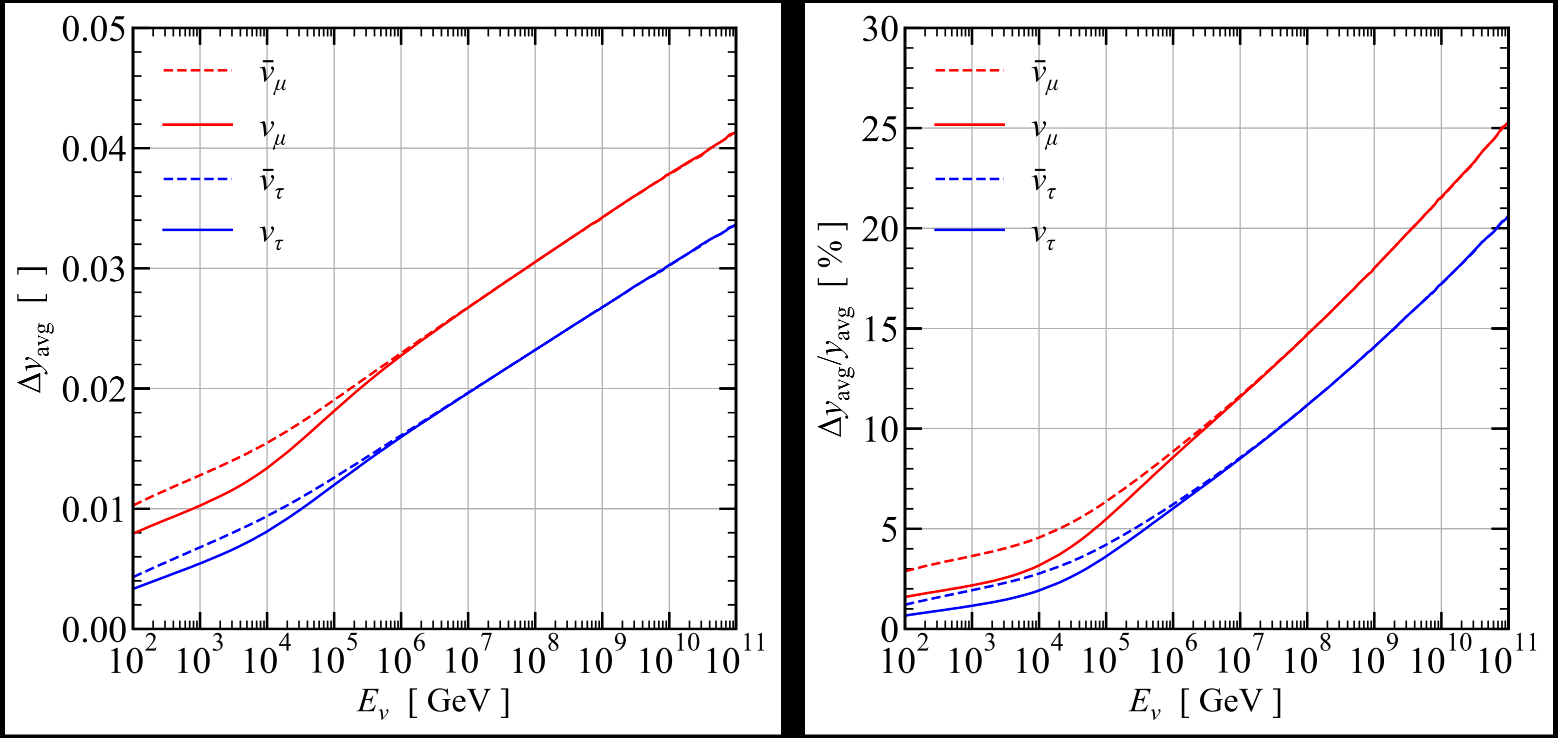
$$y_{\rm QCD} \equiv \frac{E_X}{E_\nu} = \frac{E_\nu - E_\ell}{E_\nu}$$



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

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

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



(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

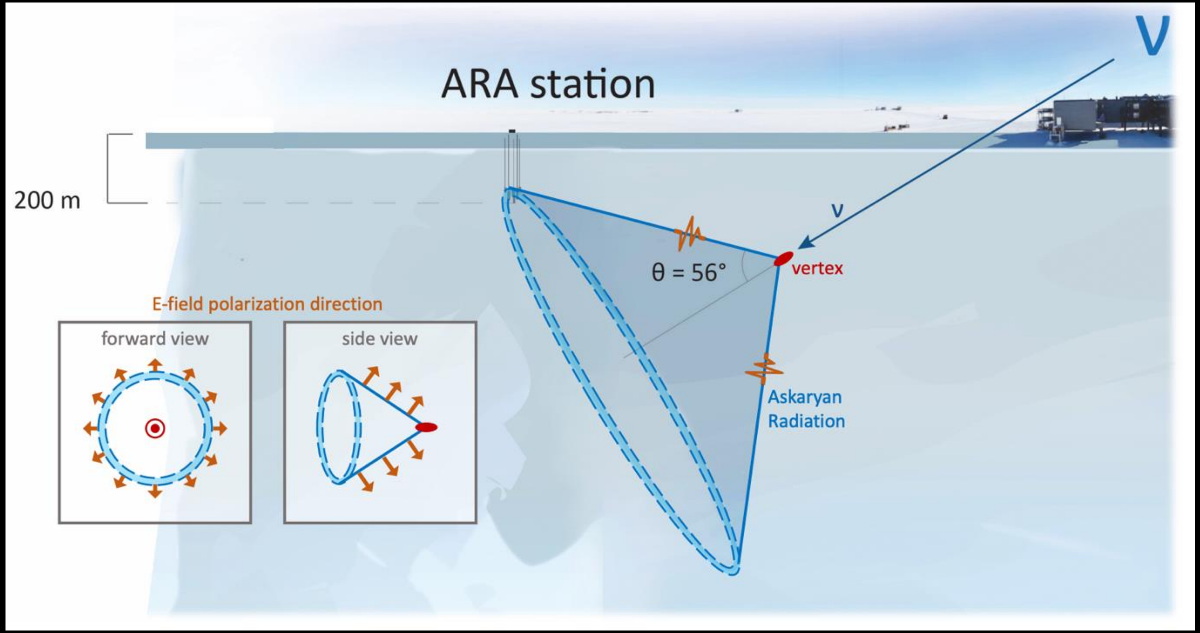
1. Neutrino-antineutrino flux ratio (5% shift)
2. Neutrino mixing parameters
   - Inel. dist. helps to separate nu/nubar
3. Charm production from nu interactions
   - CCDIS /w charm production has higher inelasticity

Other measurements

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

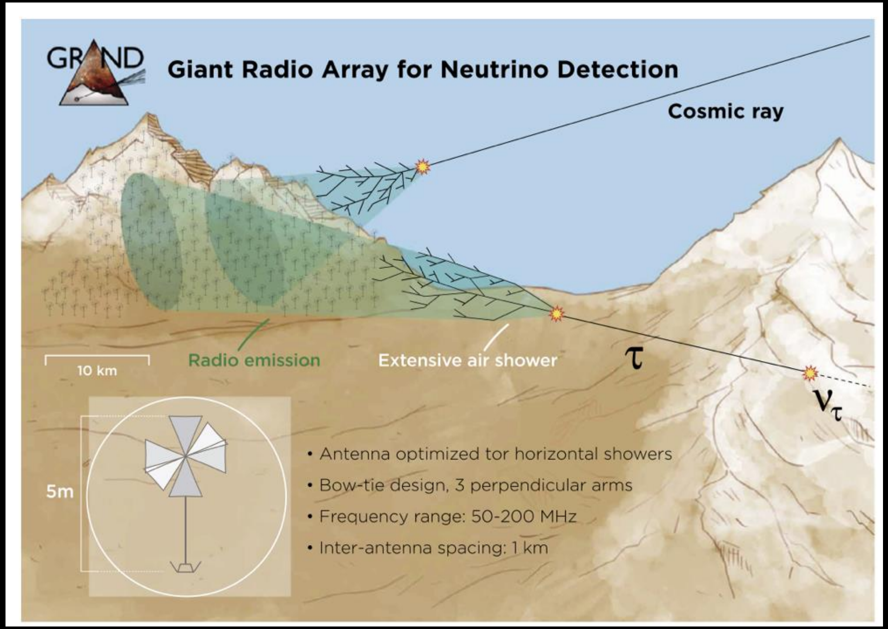
UHE nu observation: two basic kinds of detectors

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



1912.00987 ARA collaboration

Air shower detectors
(main for ντ)



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

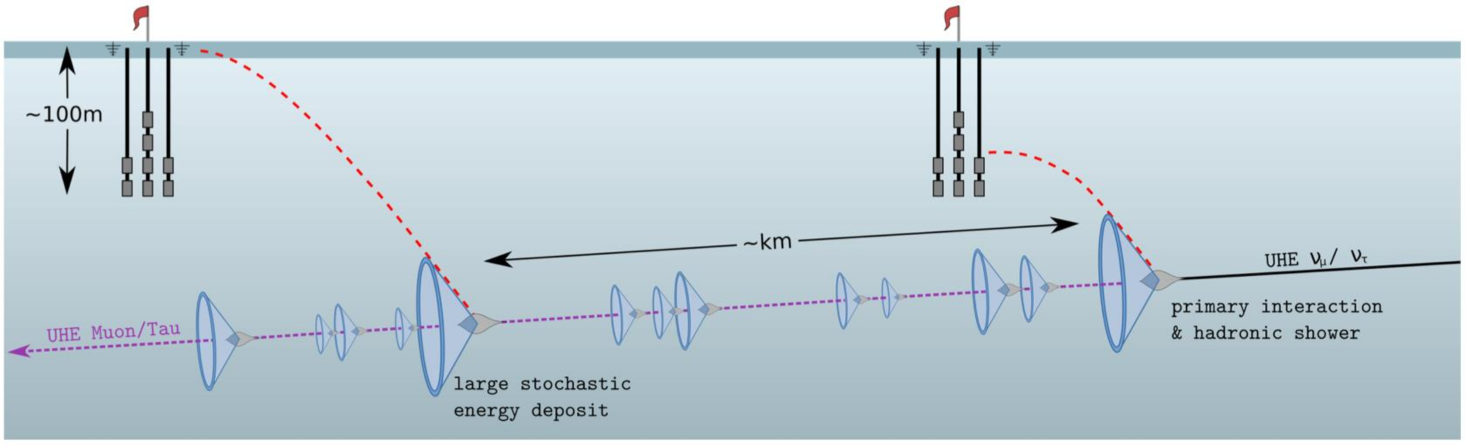
FSR impacts UHE nu observations: in-ice radio detectors (e.g., ANITA, PUEO)

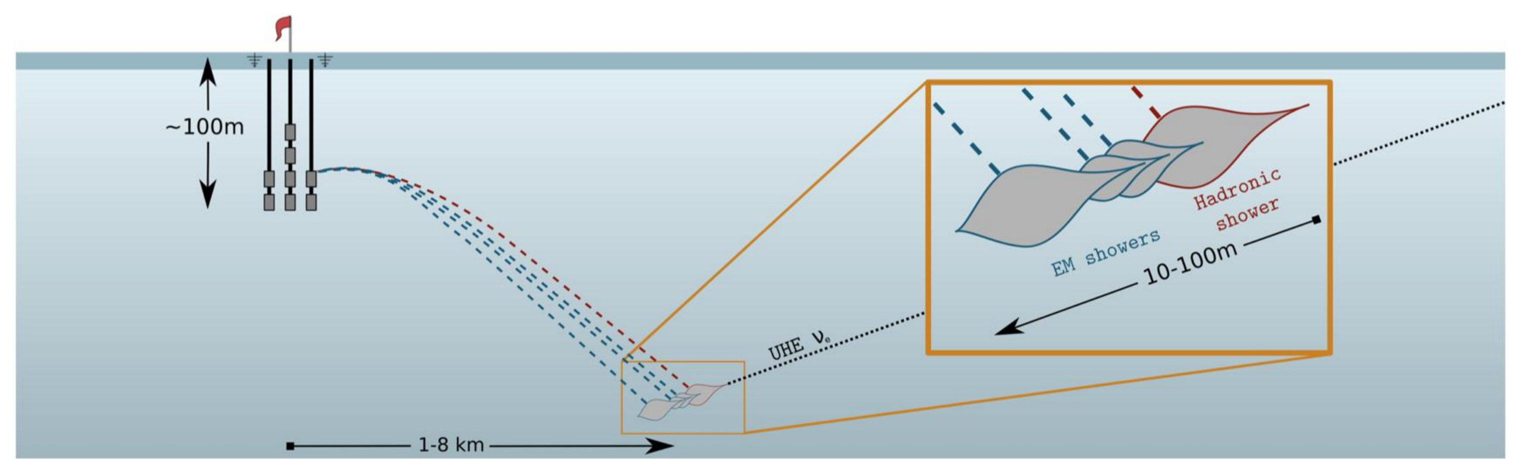
For CCDIS, FSR enhances the overall detectable (shower) energy by as much as ≃20% , which effectively lowers the energy thresholds.

ντ CC, big, up to ≃20%

νμ CC, mild

νe CC, negligible





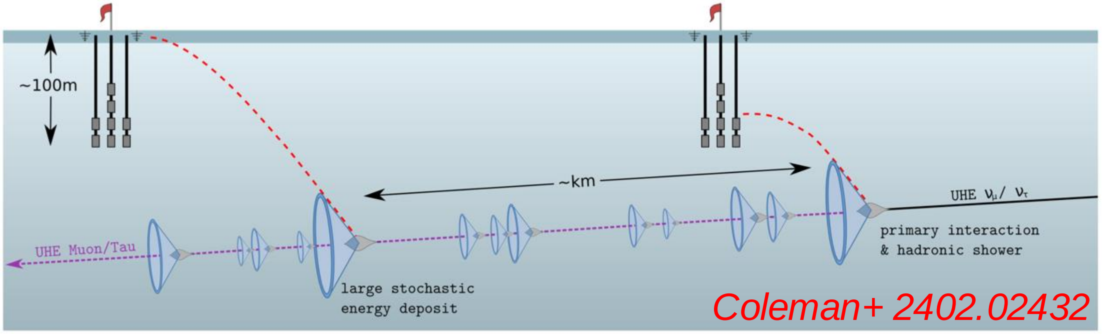
2402.02432
Coleman et al.

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

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

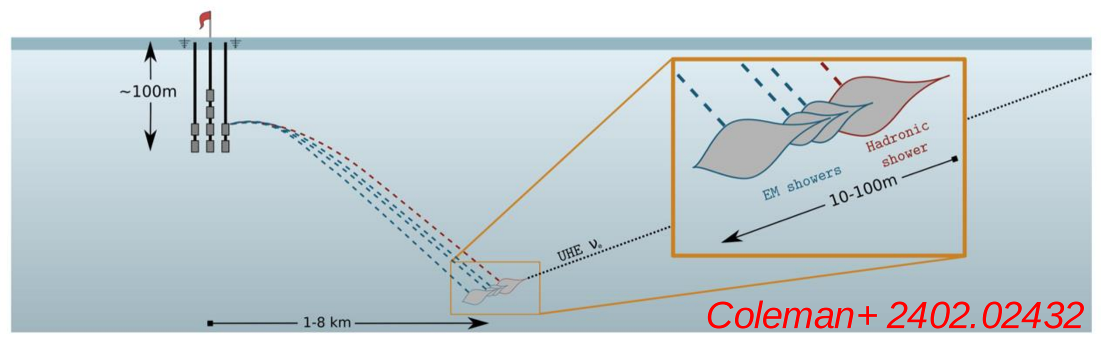
1) If charged lepton barely detectable, FSR enhances detectable (shower) energy by ~20%.

2) A way to measure $\nu\mu/\nu\tau$, FSR reduces the detectability (~5%)



Coleman+ 2402.02432

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

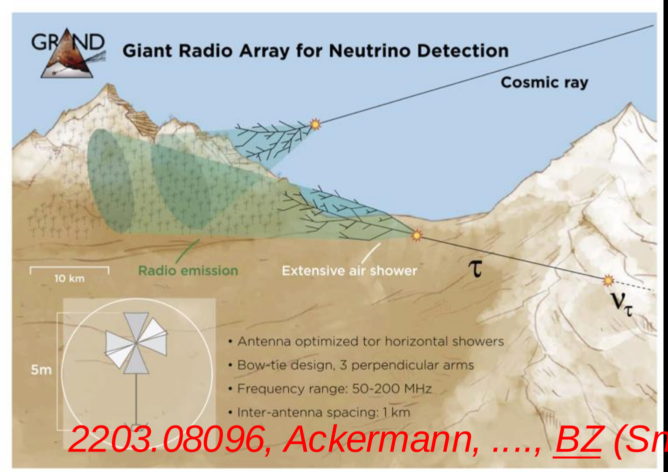


Coleman+ 2402.02432

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

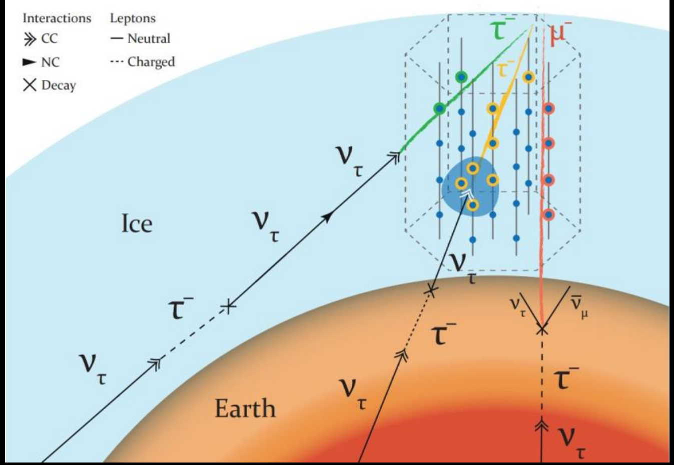
Air shower detectors (main for $\nu\tau$, e.g., POEMMA)

1) Earth emergent τ; w/o FSR underestimates parent $E\nu$ by ~5%



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

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.

Collider Neutrinos: FSR's impacts

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:

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

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%

Accelerator neutrinos?

Thanks for your attention!

Calculation

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

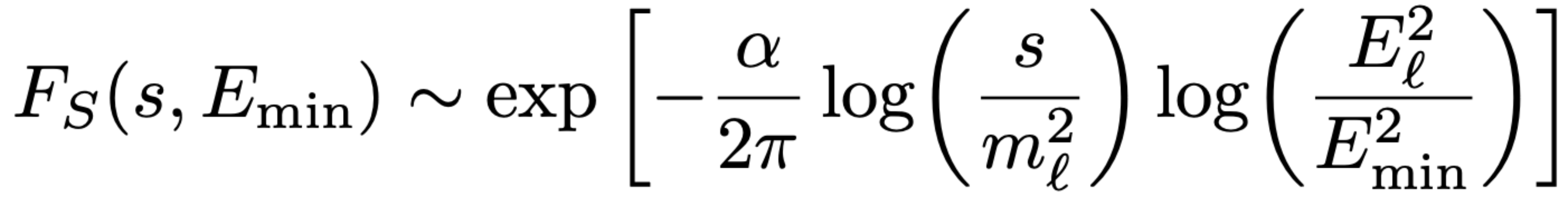
$$P_{\ell\to\ell\gamma}(z) = \frac{\alpha}{2\pi}\log\left(\frac{s}{m_\ell^2}\right)\left[\frac{(1+z^2)}{[1-z]_+} + \frac{3}{2}\delta(1-z)\right], \quad (6)$$

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

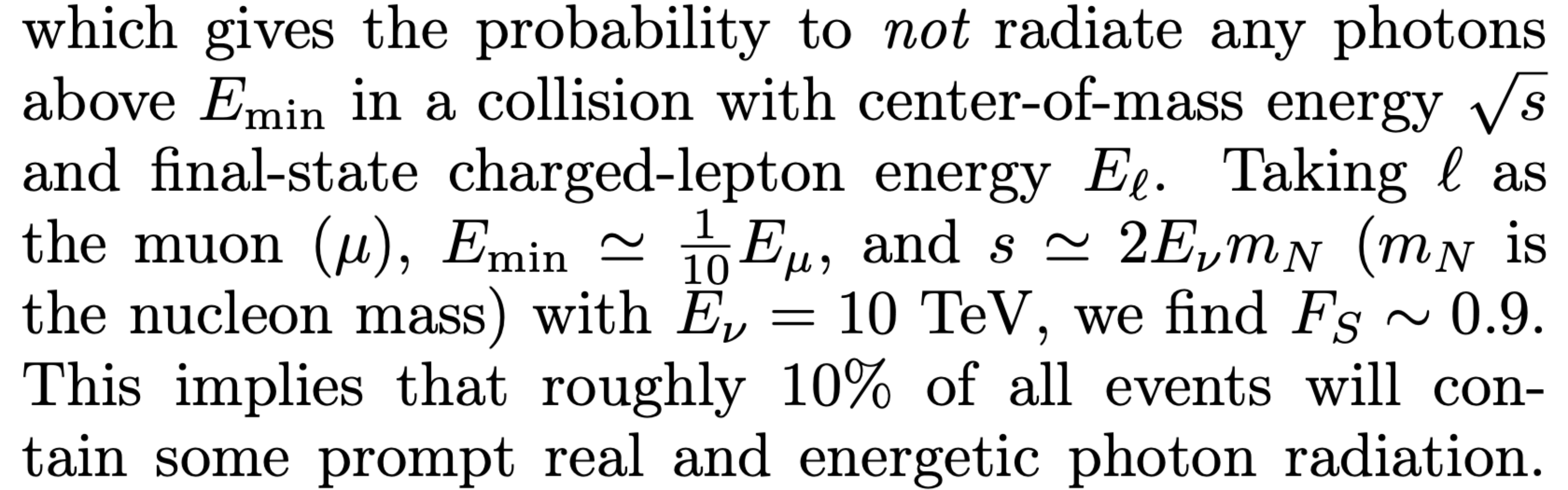
(Plestid, BZ, 2303.08984)

A rough estimate using Sudakov form factor

Collinear log Soft log



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

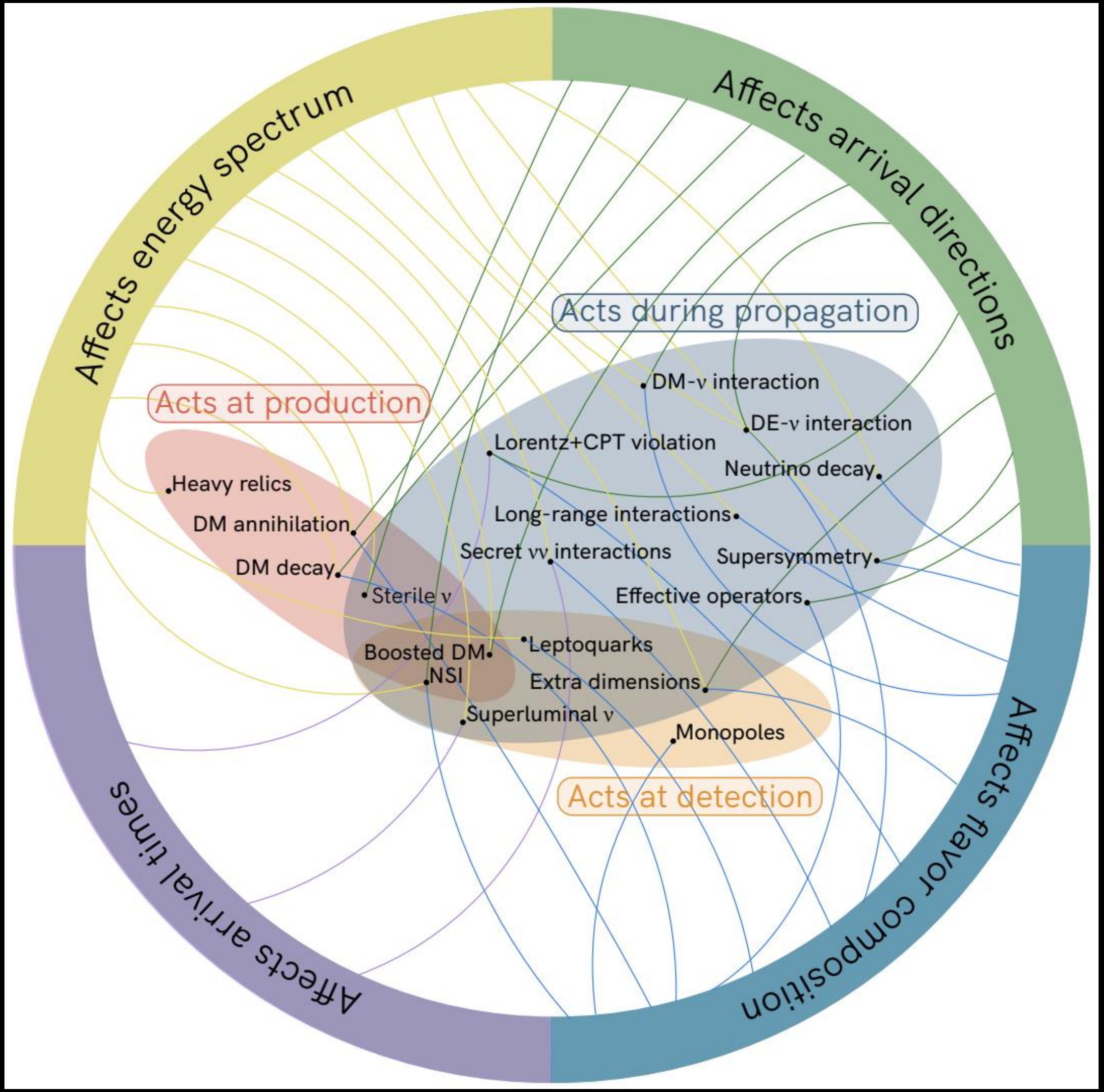


which gives the probability to *not* radiate any photons above $E_{\min}$ in a collision with center-of-mass energy $\sqrt{s}$ and final-state charged-lepton energy E_ℓ. Taking ℓ as the muon (μ), $E_{\min} \simeq \frac{1}{10}E_\mu$, and $s \simeq 2E_\nu m_N$ (m_N is the nucleon mass) with $E_\nu = 10$ 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: 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)

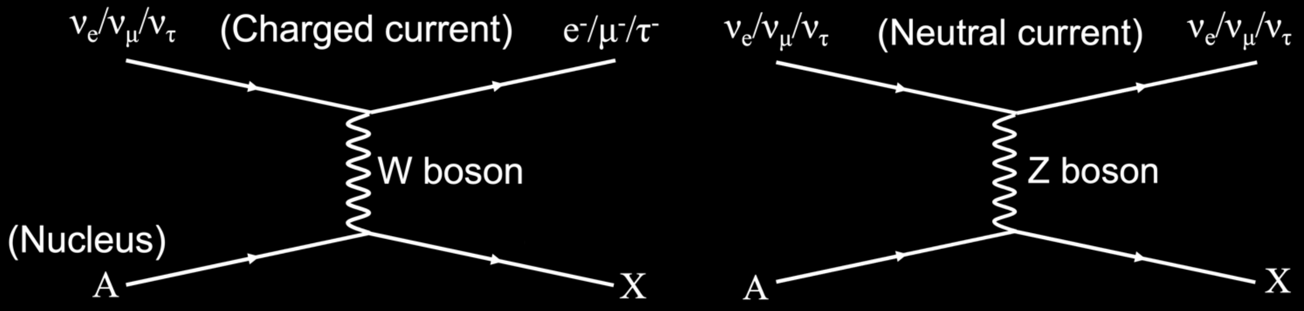


2203.08096, Ackermann, …., BZ (Snowmass WP); 1907.08690 Argüelles et al.

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

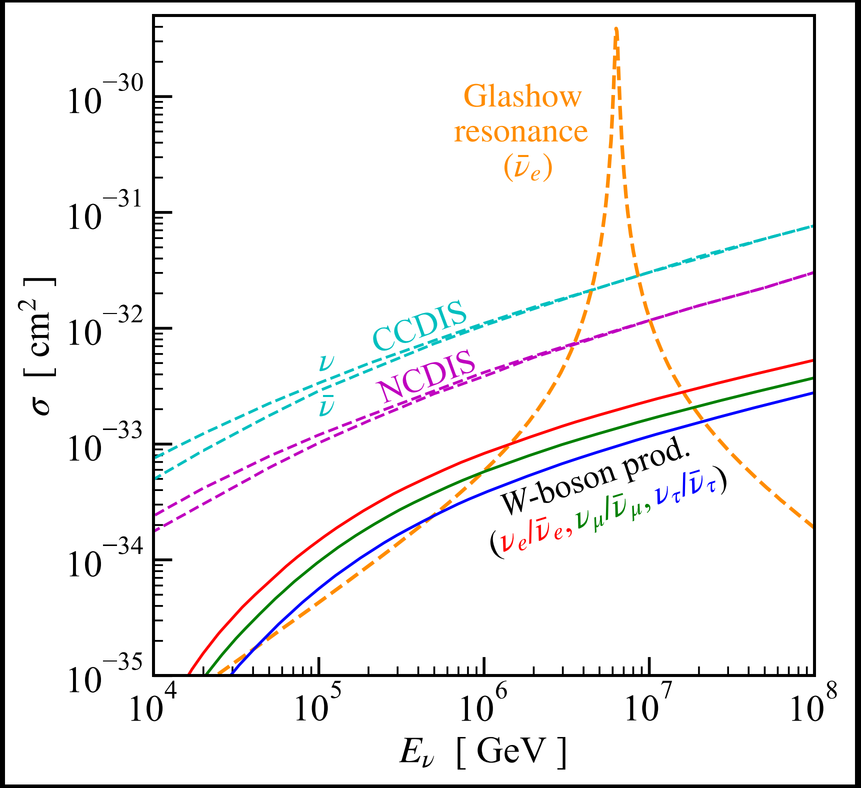
W-boson production is subdominant

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

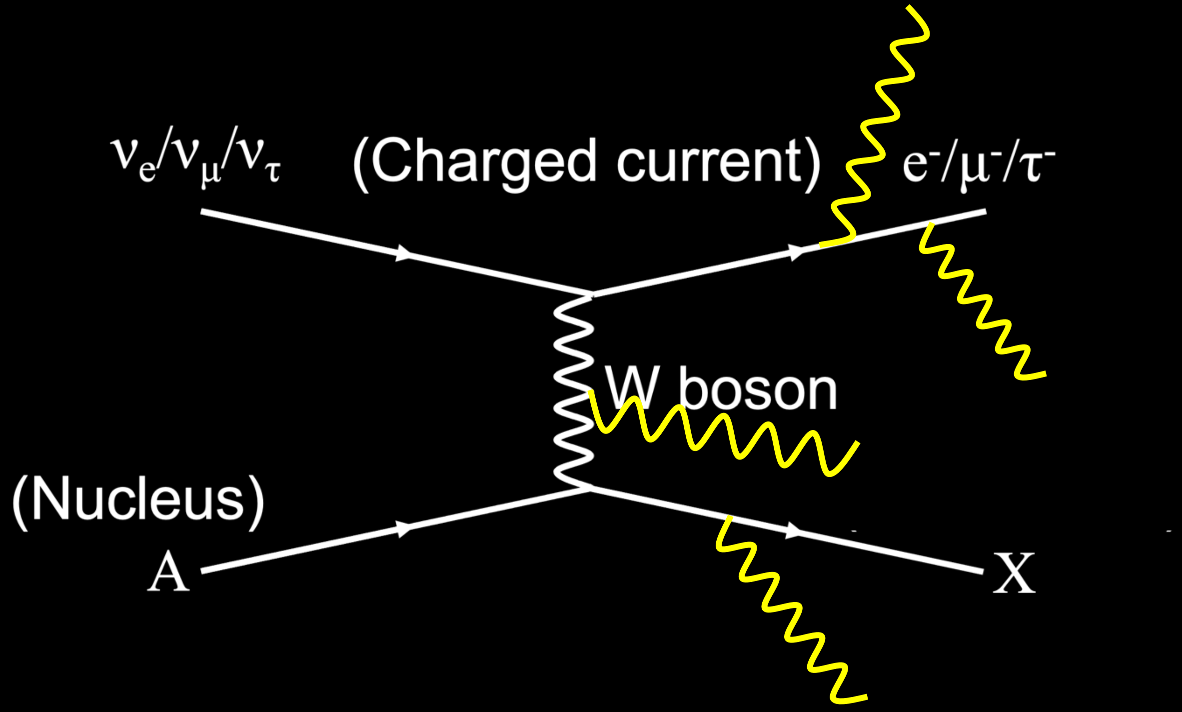
Glashow resonance important for $\bar{\nu}_e$

Glashow 1960, IceCube 2021

Cross sections



Photons from other parts of the diagram: not important



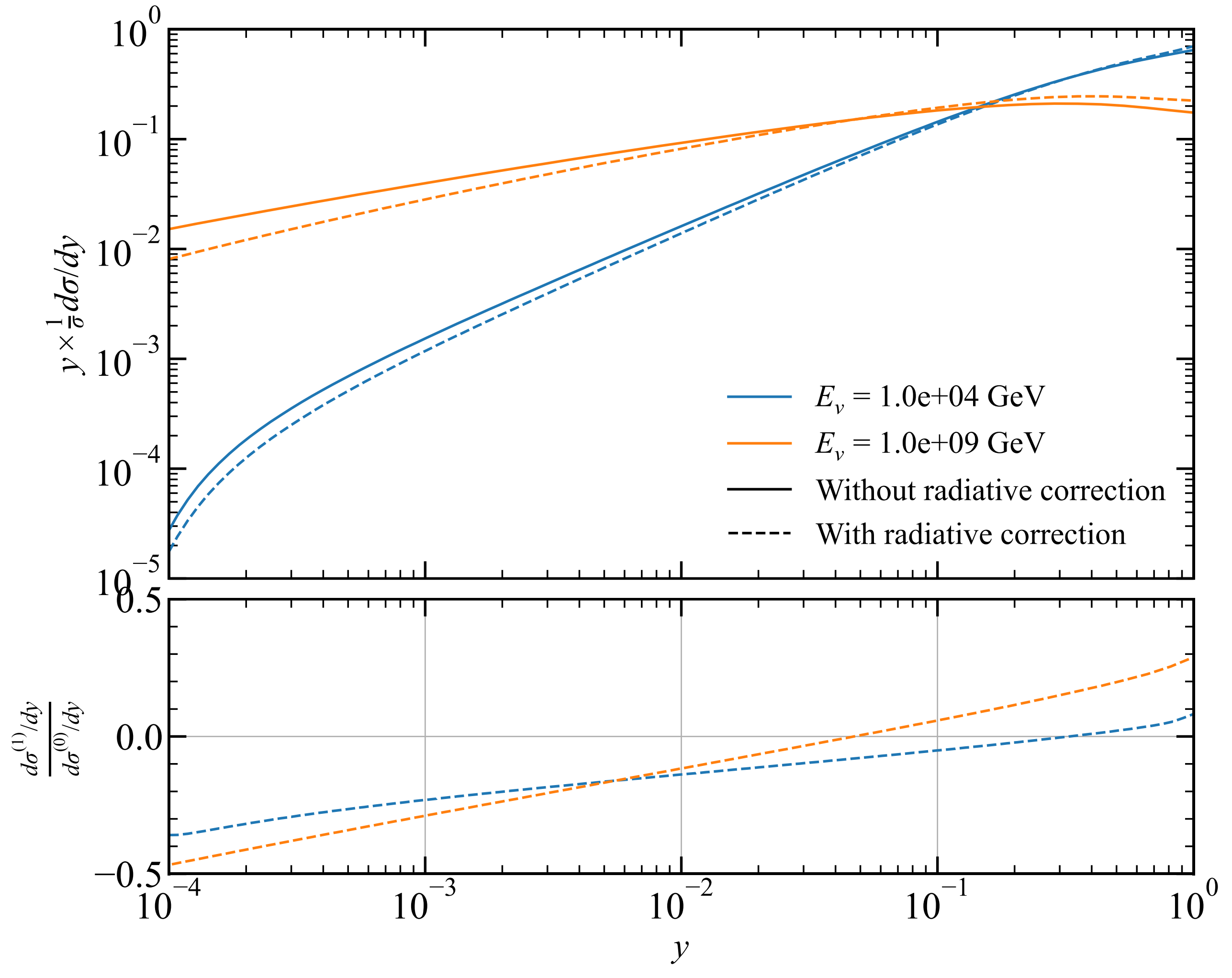
Photon from W boson: suppressed by W mass

Photon from quarks:
1) hard to distinguish from the hadronic cascade
2) $E\gamma$ small as quark energy << lepton energy

Multi-photon emission: higher order, small

Illustration of FSR impacts on DIS differential xsec

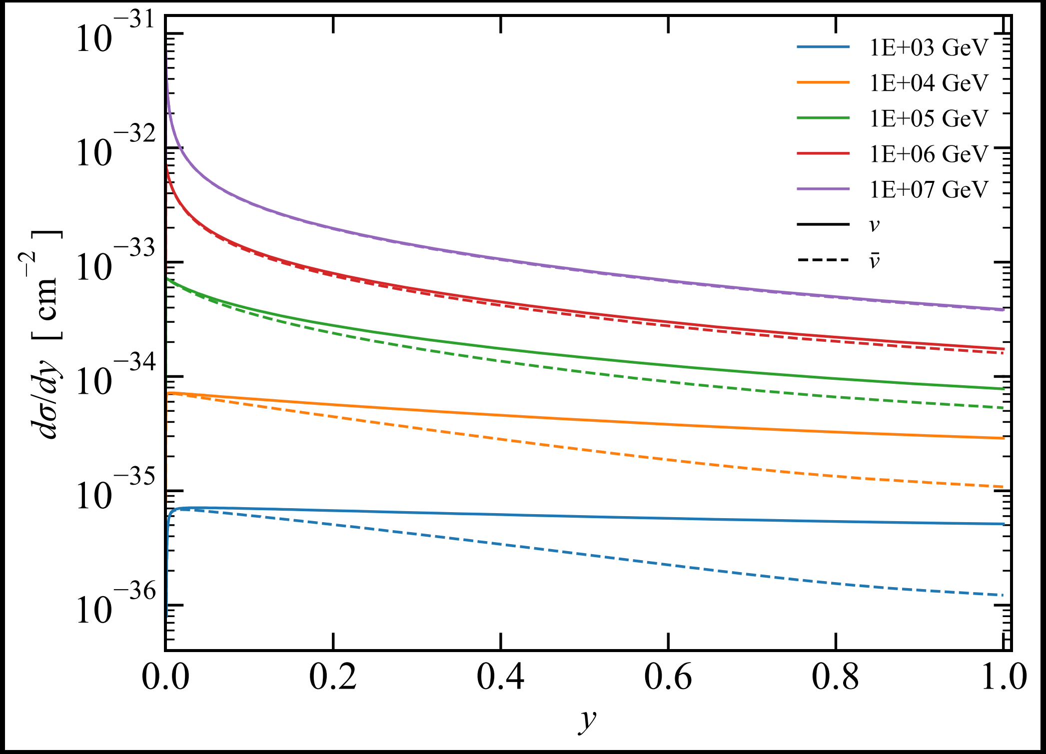
$$y_{\mathrm{QCD}} \equiv \frac{E_X}{E_\nu} = \frac{E_\nu - E_\ell}{E_\nu}$$

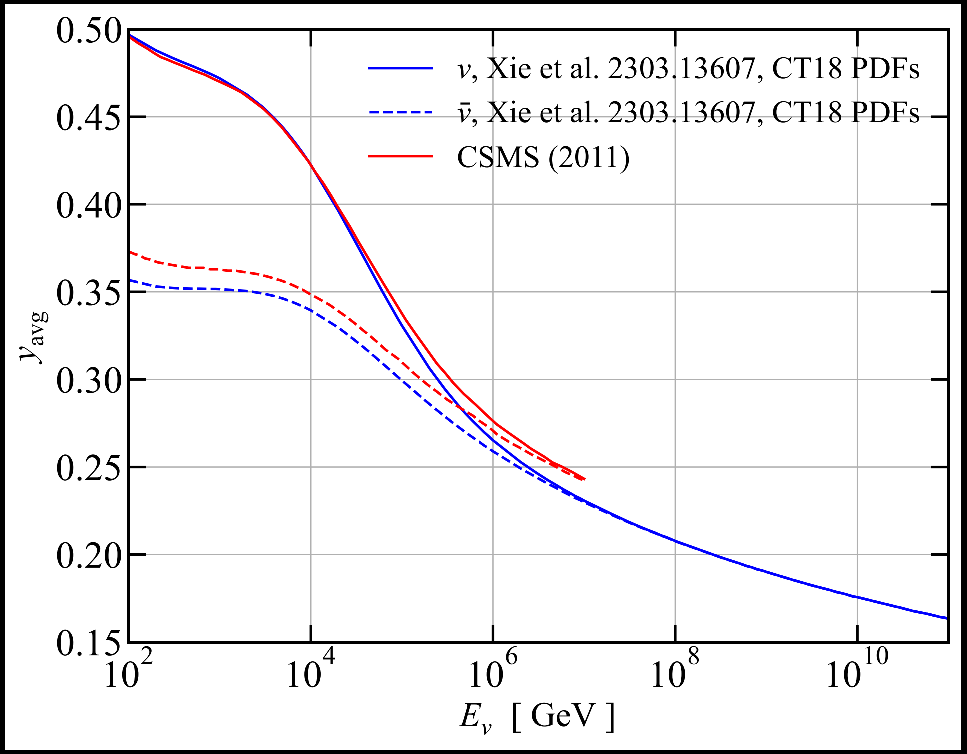


FSR impacts on the inelasticity

Theoretical definition:

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





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

Neutrino mixing

Inelasticity measurements help to separate 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*)

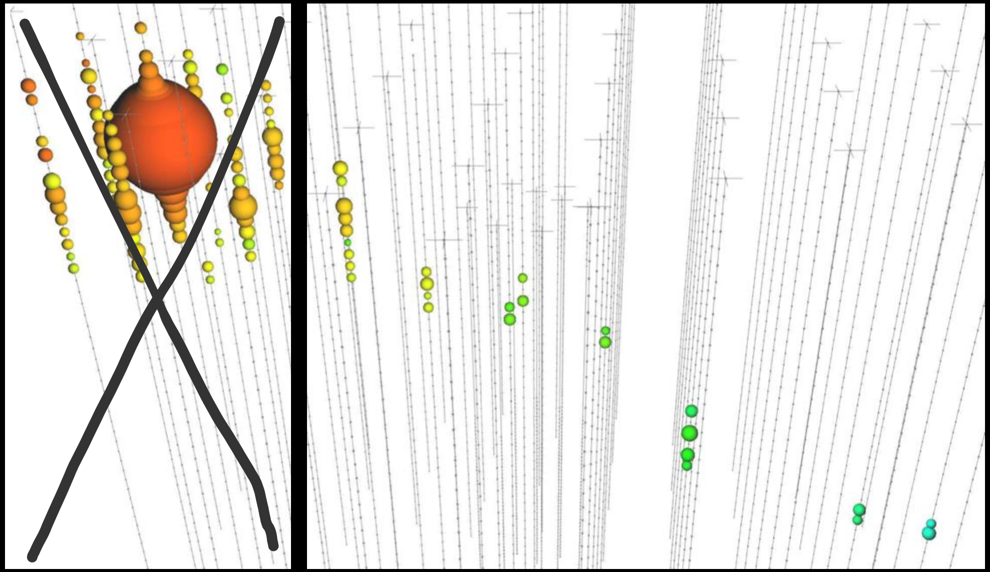
And FSR will affect the measurements

Charm production

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

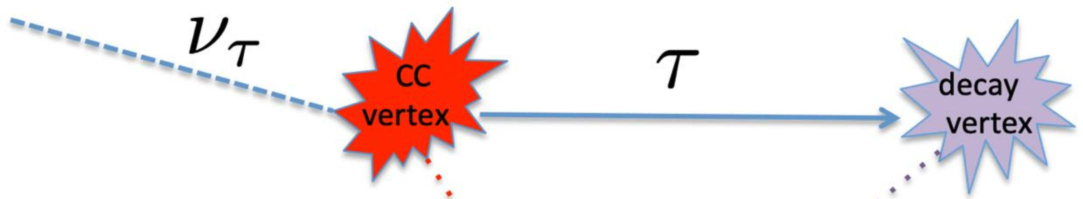
FSR impacts HE nu observation: throughgoing muons & ν_τ double bang

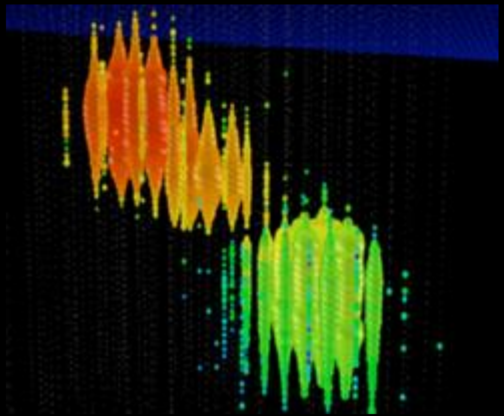
Throughgoing muon



Not including FSR underestimates the parent neutrino energy

ν_τ induced double bang

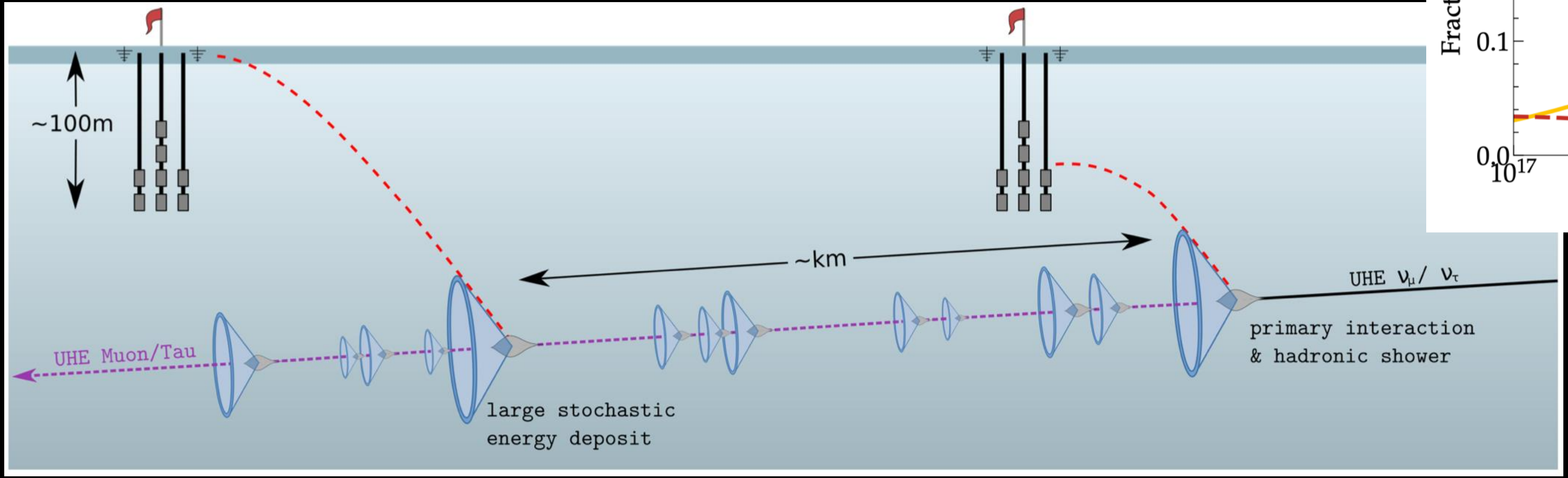


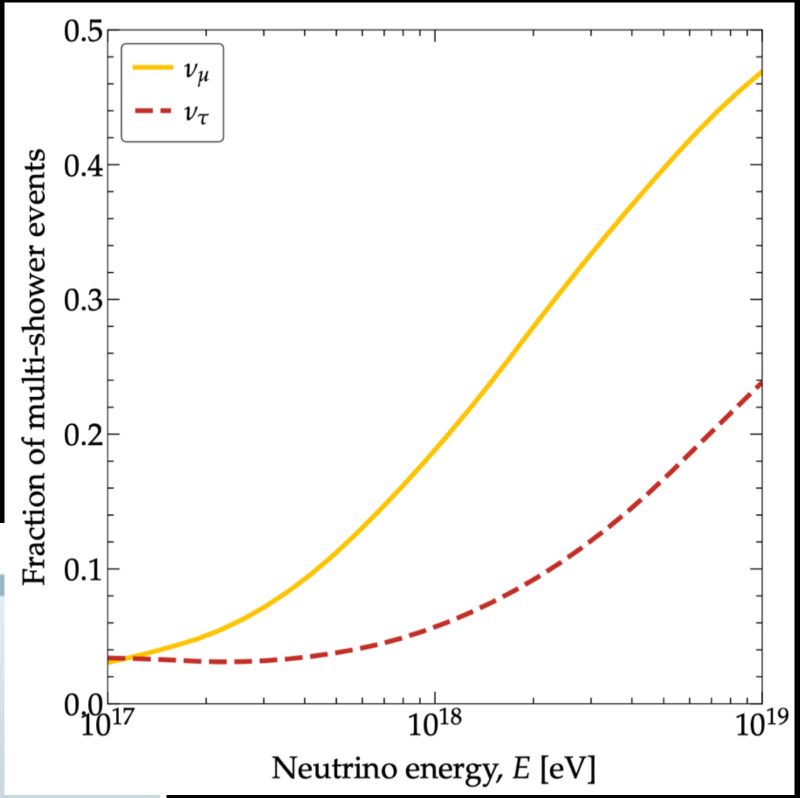


FSR 1) distort the energy balance the two bangs 2) reduce the detectability of the double bang signature.

FSR impacts UHE nu observation: in-ice radio detectors

A way to measure muon and tau neutrinos

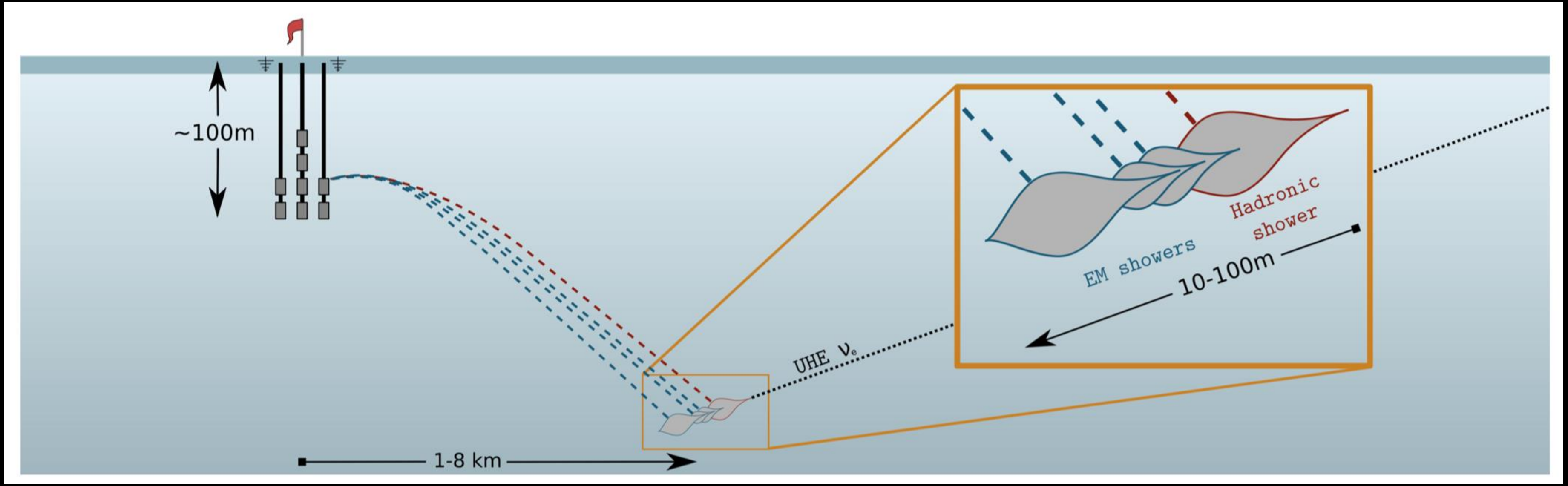




2402.02432
Coleman et al

FSR impacts UHE nu observation: in-ice radio detectors

A way to measure electron neutrinos (using LPM effect)

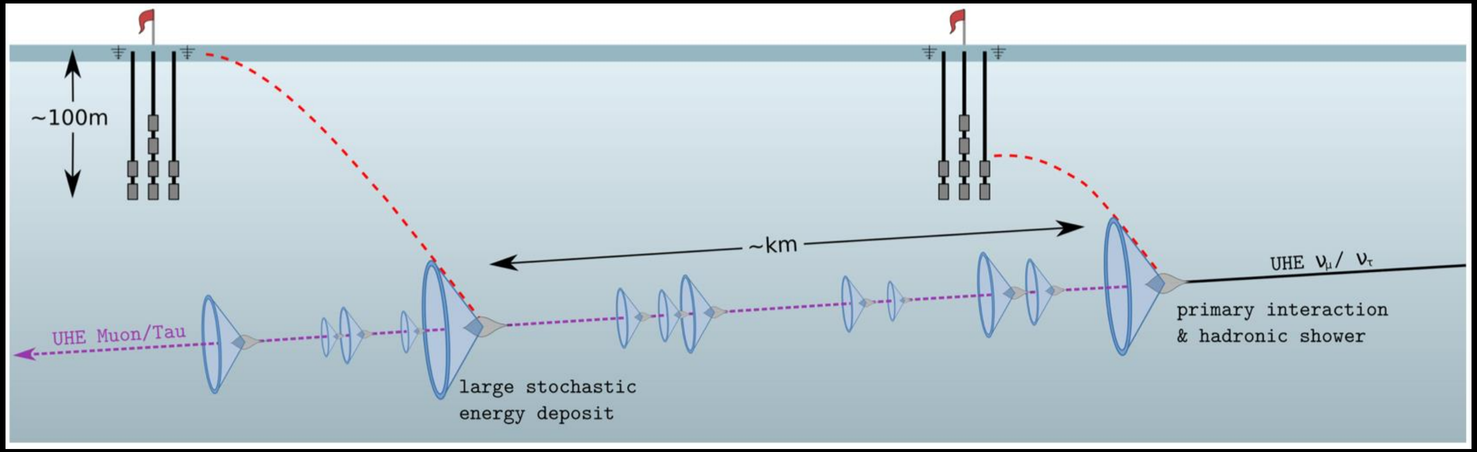


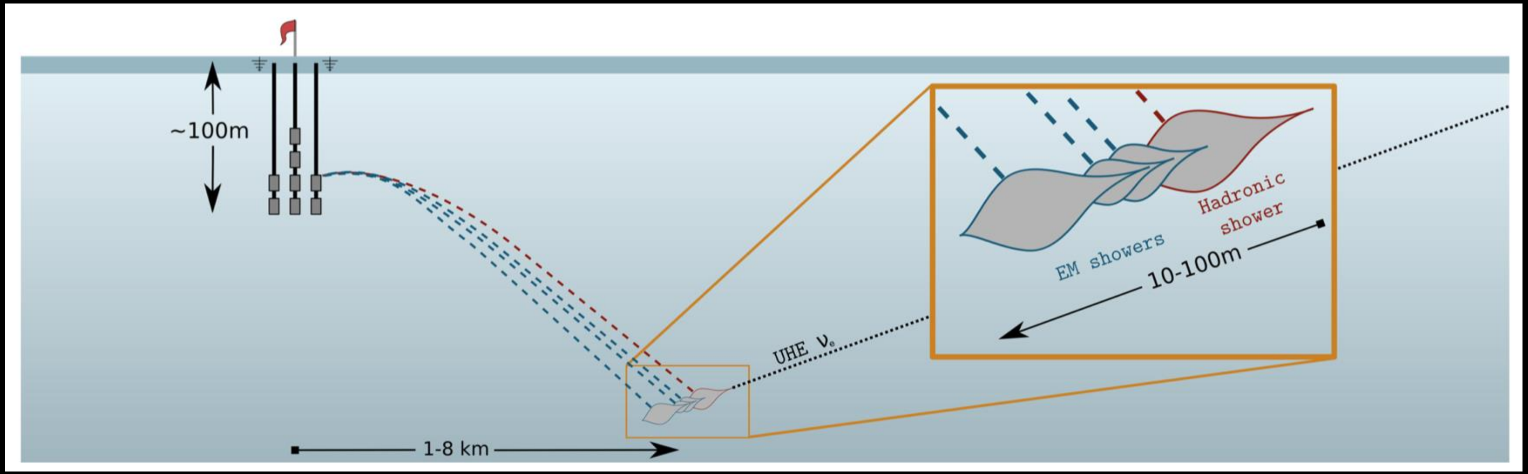
2402.02432
Coleman et al

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 ~30% of signal rate

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%!





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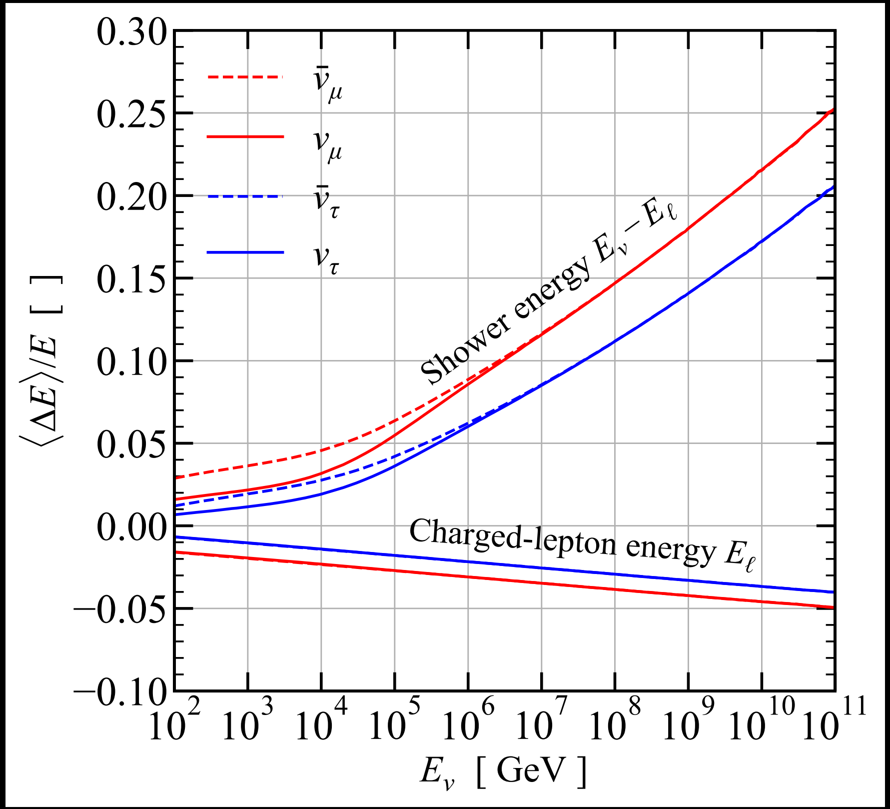
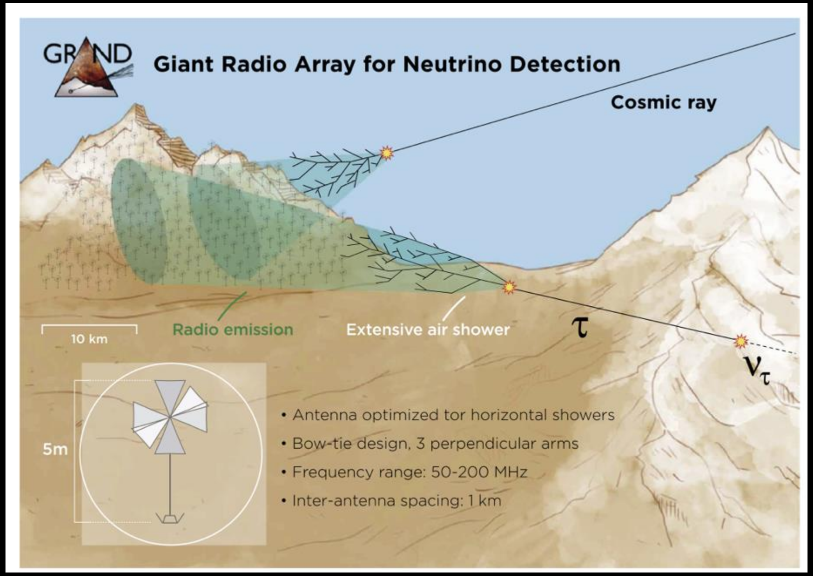
Coleman et al

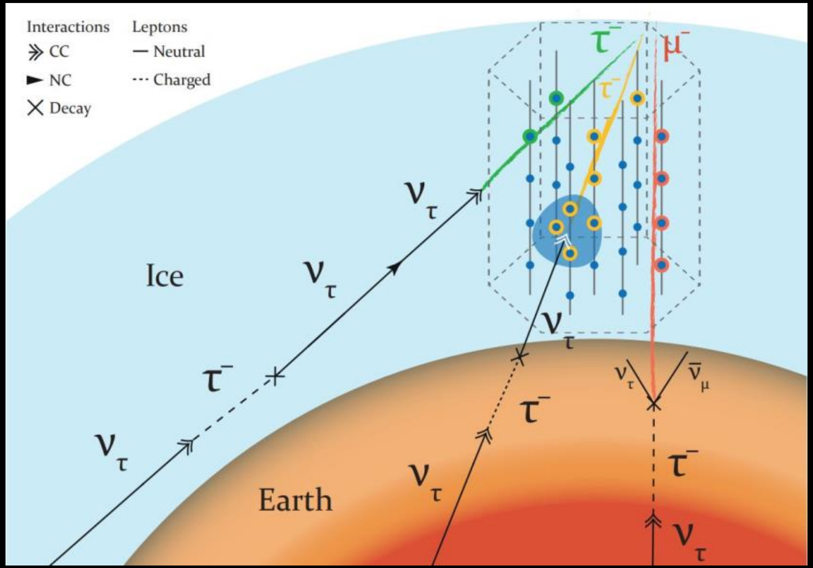
FSR impacts UHE nu observation: air shower detectors for ντ



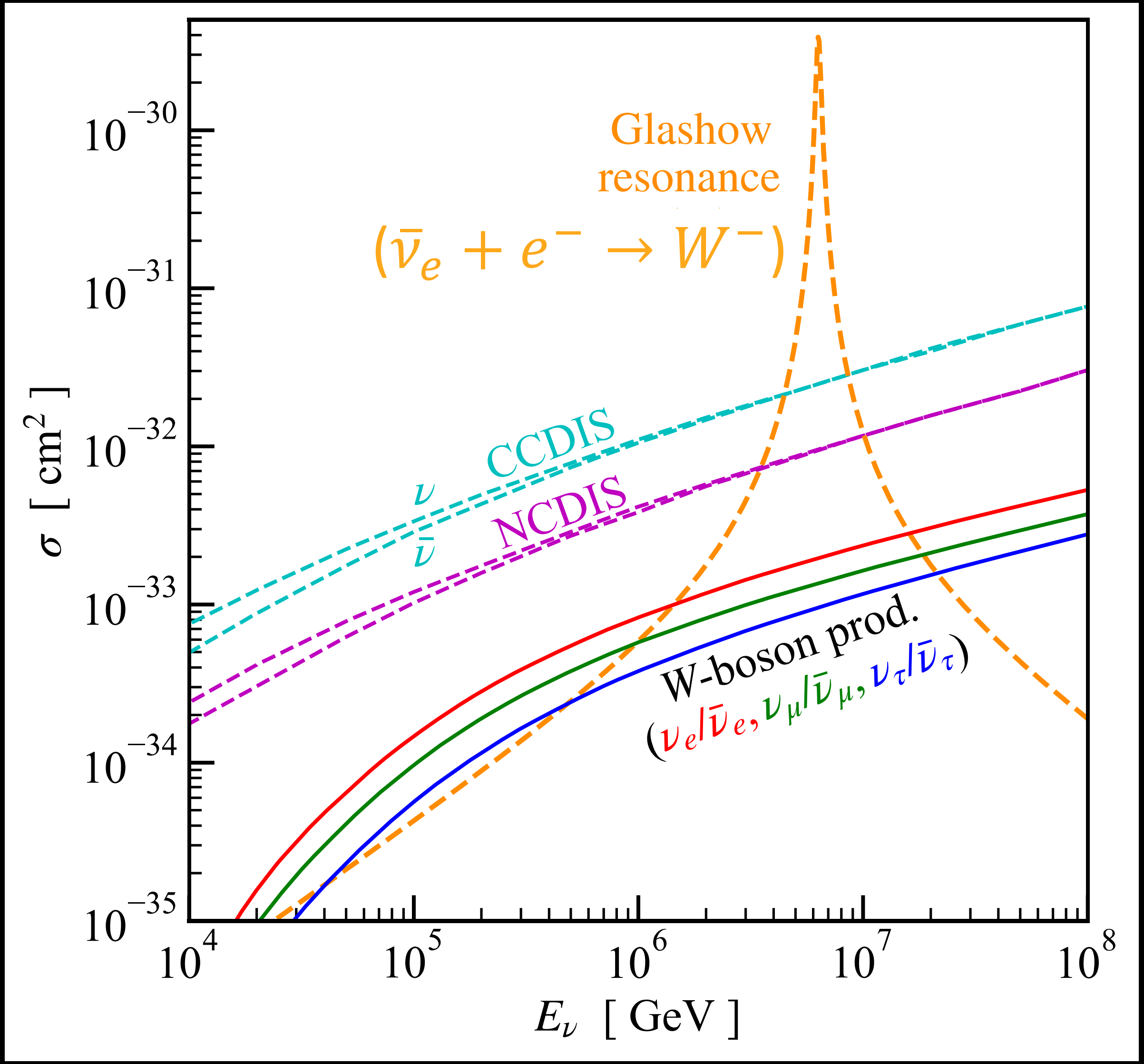
(Plestid, BZ, 2303.08984)



- Antenna optimized tor horizontal showers
- Bow-tie design, 3 perpendicular arms
- Frequency range: 50-200 MHz
- Inter-antenna spacing: 1 km



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


Glashow resonance
$(\bar{\nu}_e + e^- \rightarrow W^-)$
ν
$\bar{\nu}$
CCDIS
NCDIS
W-boson prod.
$(\nu_e/\bar{\nu}_e, \nu_\mu/\bar{\nu}_\mu, \nu_\tau/\bar{\nu}_\tau)$
σ [cm^2]
10^{-30}
10^{-31}
10^{-32}
10^{-33}
10^{-34}
10^{-35}
10^4
10^5
10^6
10^7
10^8
E_ν [GeV]