High-energy and ultrahigh-energy neutrinos: a new window for astrophysics and particle physics

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Outline

0. Introduction

1. Final state radiation from high and ultra high energy neutrino interactions

2. Search for high-energy neutrinos from choked-jet supernovae using IceCube public data

3. Improving WBP cross section precision using 2^{nd} generation photon PDF

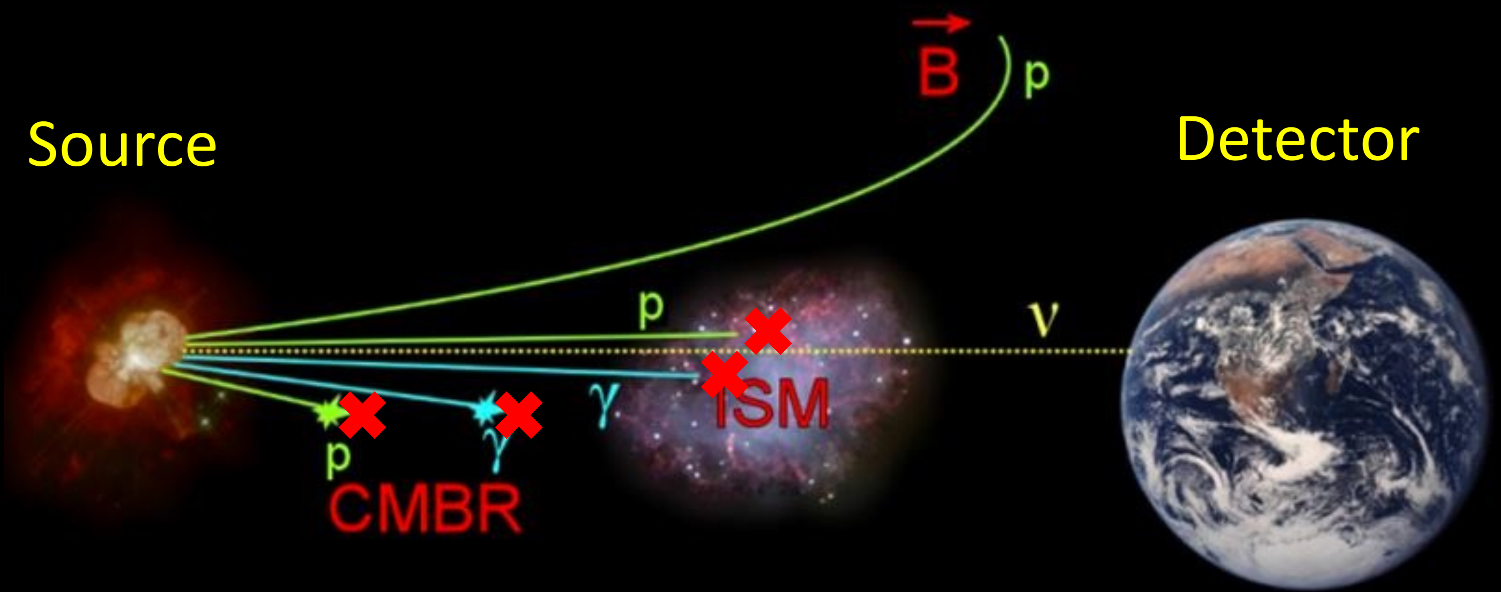
Why do we study HE&UHE neutrinos

- 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

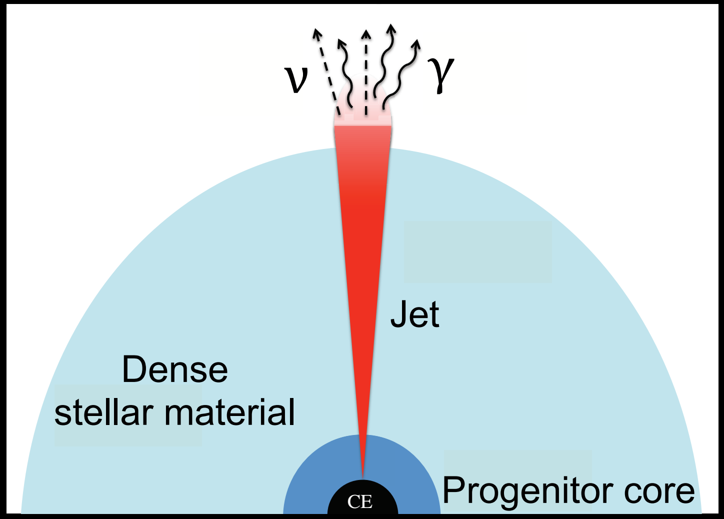
- Particle physics (highlighted by P5 report):
  - Neutrino interactions in the SM (Deep-inelastic scattering, W-boson production, Glashow resonance, final state radiation, etc.)
  - Measure neutrino mixing parameters
  - Test BSM (ν portal to DM, new ν interactions, sterile ν, magnetic moment, etc.)

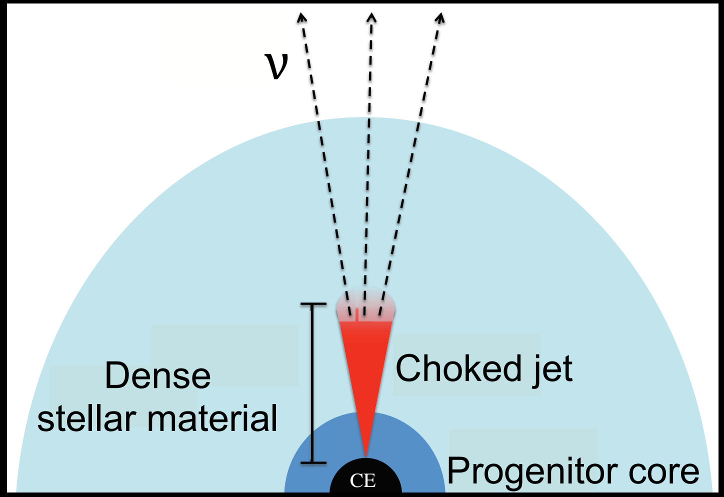
Why do we study HE&UHE neutrinos: astrophysics

Cosmic ray sources



Dense environment





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

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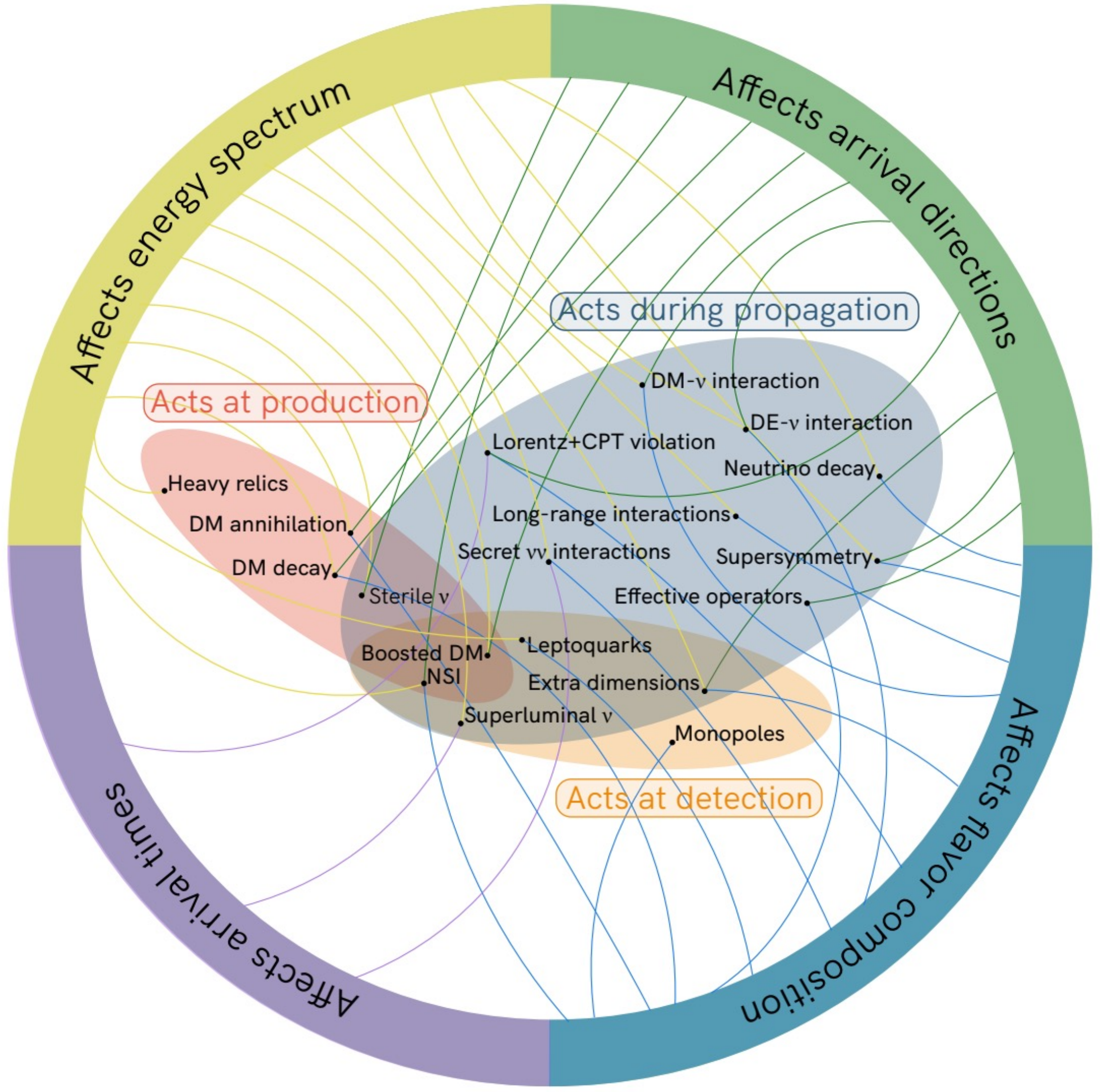
Why do we study HE&UHE neutrinos: BSM

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.

Final state radiation from high and ultrahigh energy neutrino interactions

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

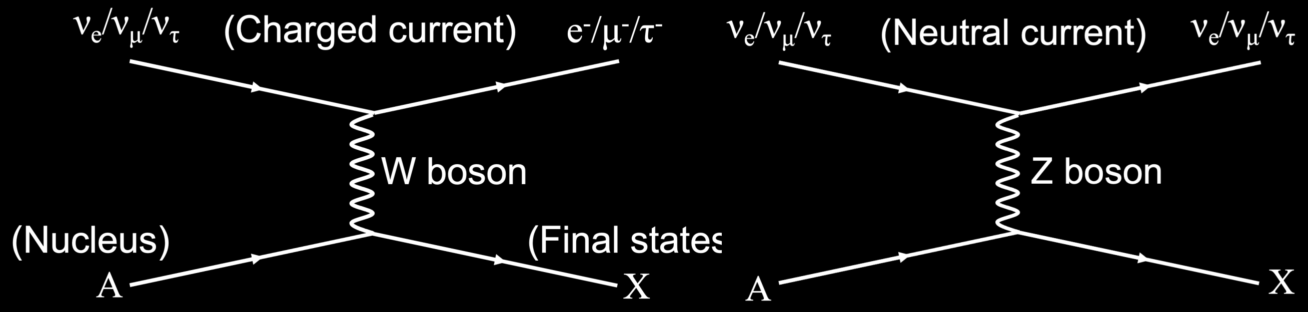
- Help us to find new event classes: useful for both astrophysics and particle physics studies
  - E.g., dimuons for high-energy neutrino detection (*2110.02974 BZ, Beacom*).

- 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

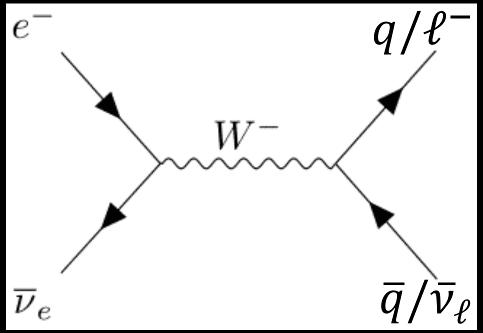
(as good as ~1% precision)



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

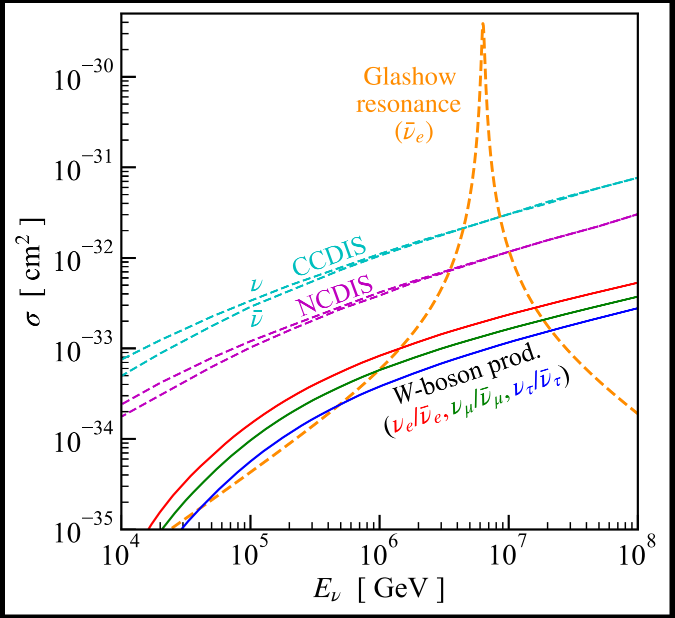
Most recent: Xie, et al. 2303.13607

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



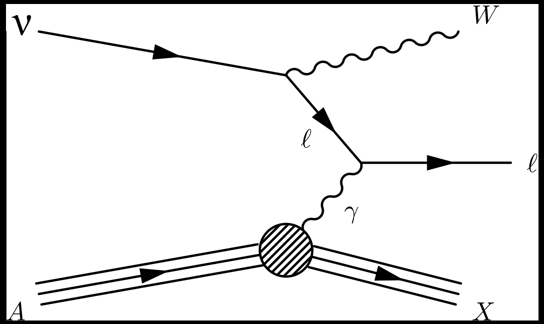
Glashow 1960
IceCube 2021

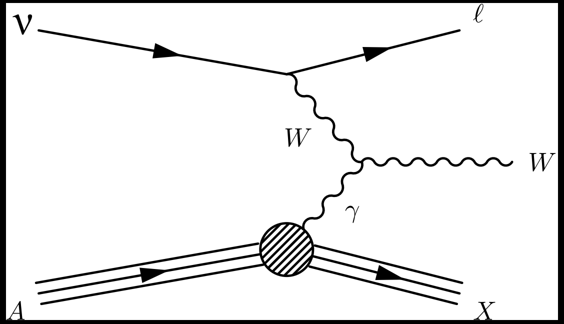
Cross sections



(BZ, Beacom, 1910.10720)

W-boson production (WBP) is subdominant





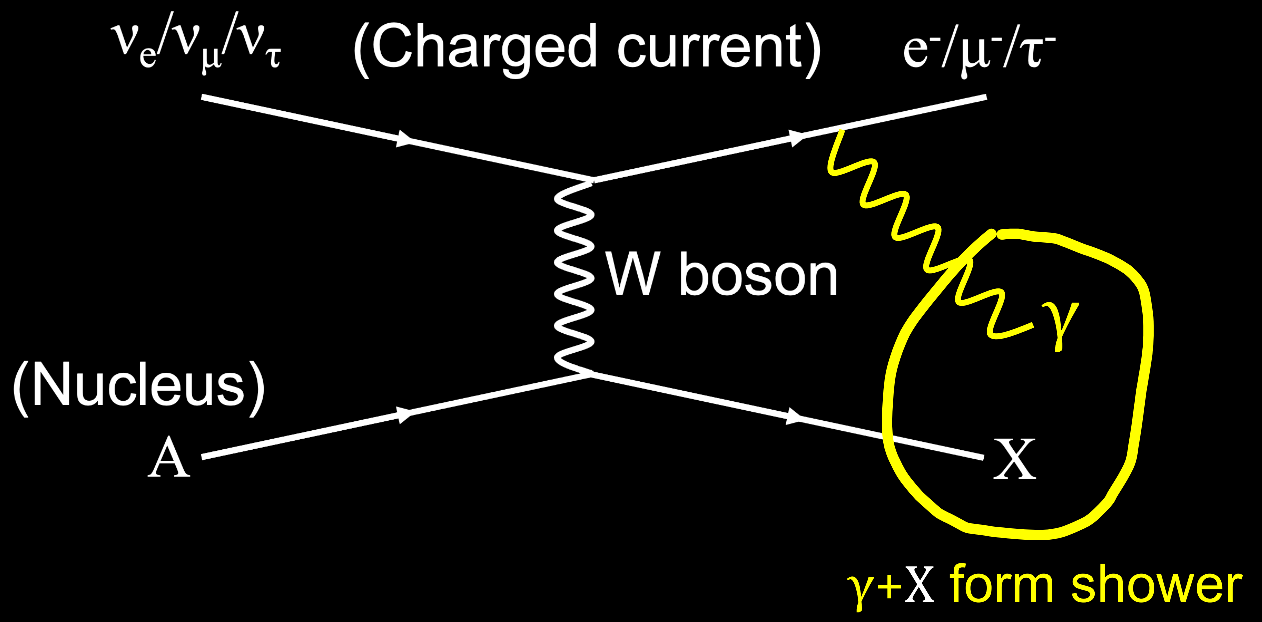
(Seckel 1997, Alikhanov 2015, BZ, Beacom, 1910.08090)

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 tens percent to be studied.

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

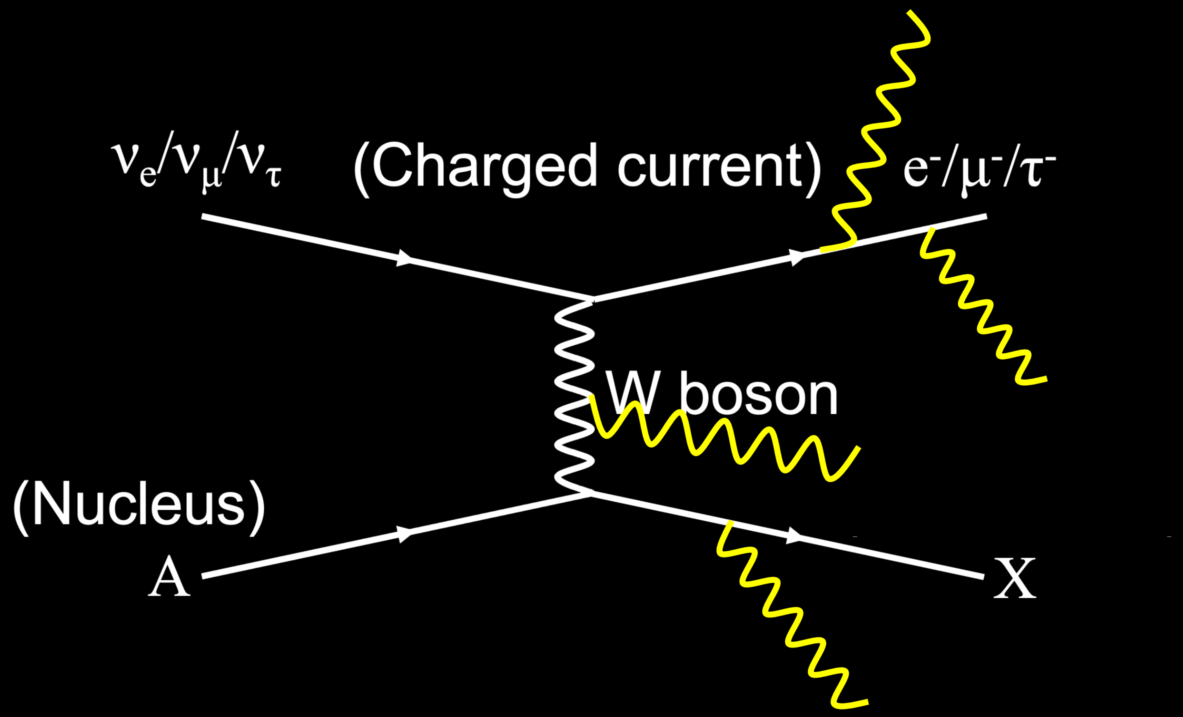
Final state radiation (FSR)



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

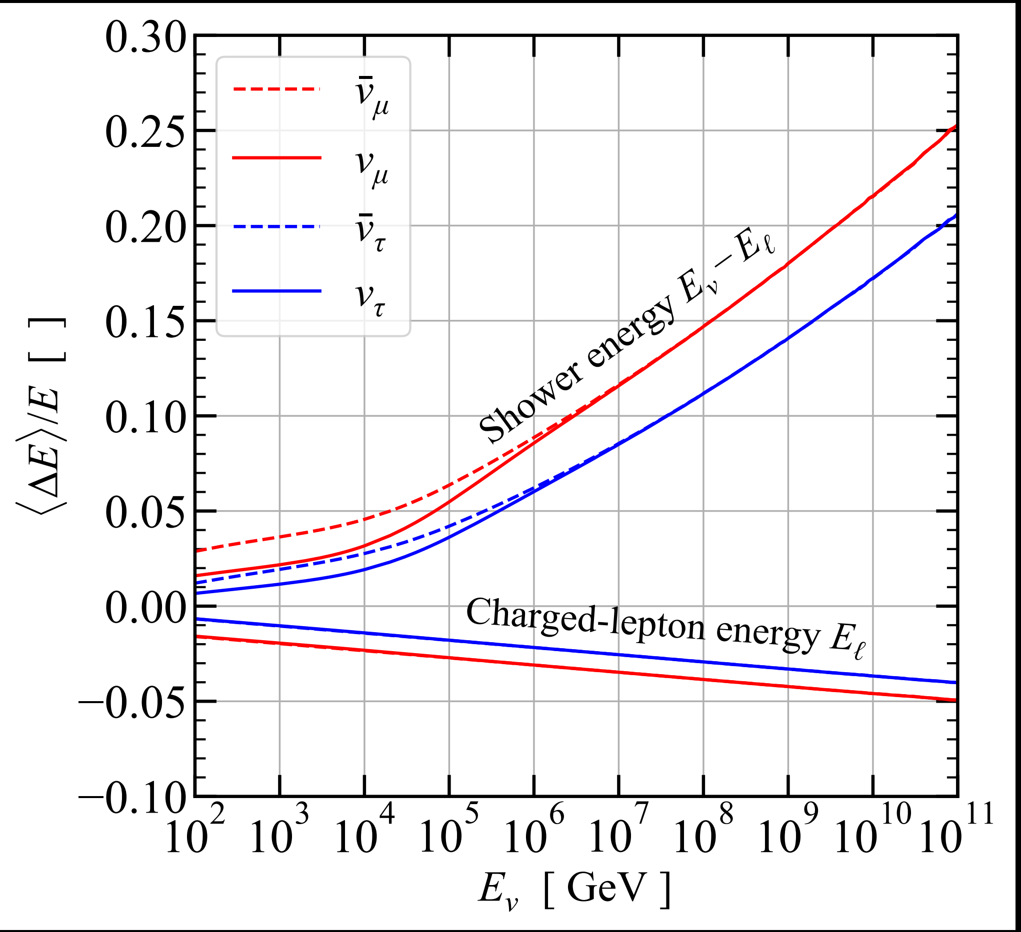
Splitting function

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

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

(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 vμ > vτ, cuz m_μ < m_τ

Correction on shower > charged lepton

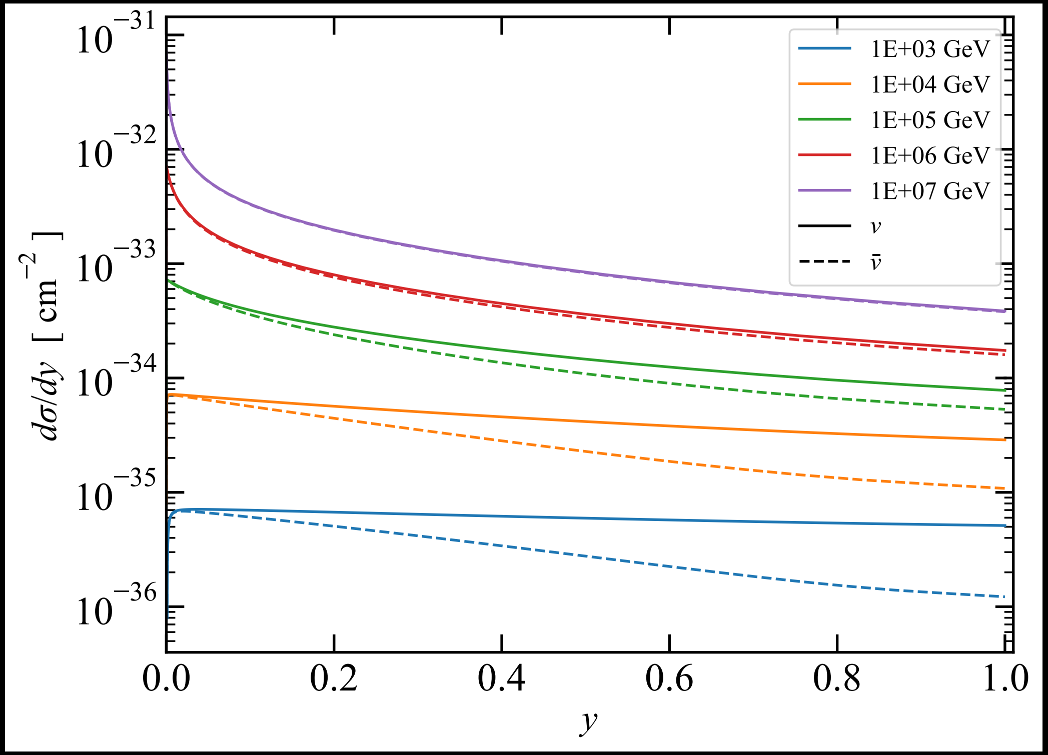
Correction on shower further enhanced by 10—20% due to light yields from EM shower > hadronic shower

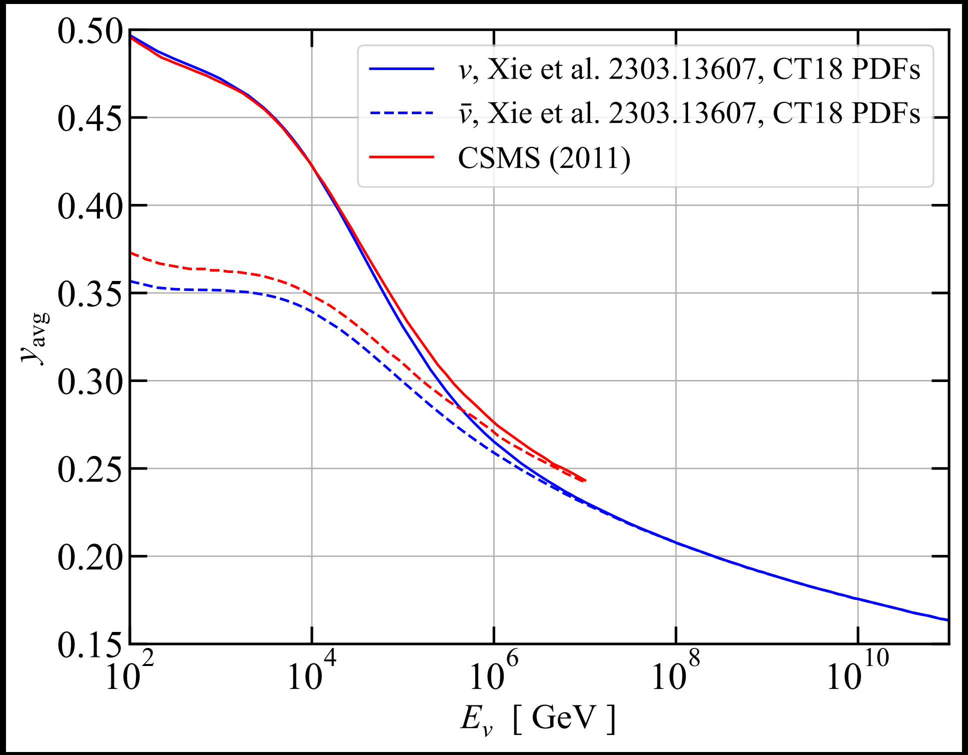
Difference between nu and nubar

FSR impacts on the inelasticity measurements

Theoretical definition:

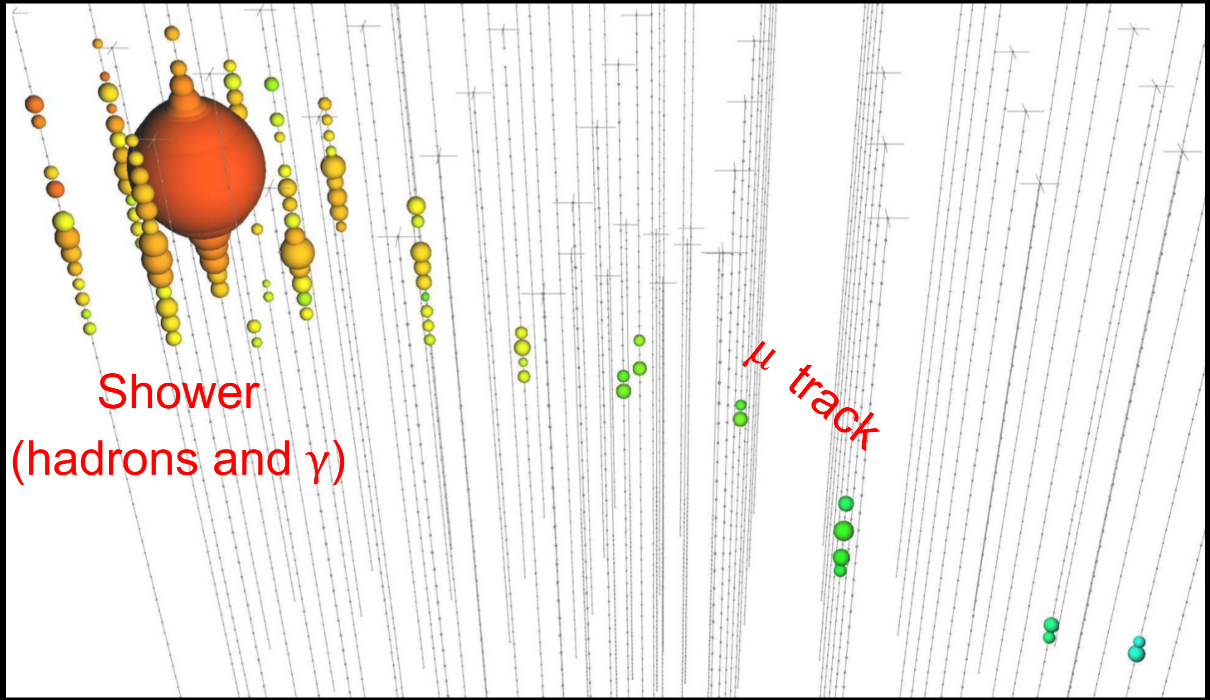
$$y_{\mathrm{QCD}} \equiv \frac{E_X}{E_\nu} = \frac{E_\nu - E_\ell}{E_\nu}$$



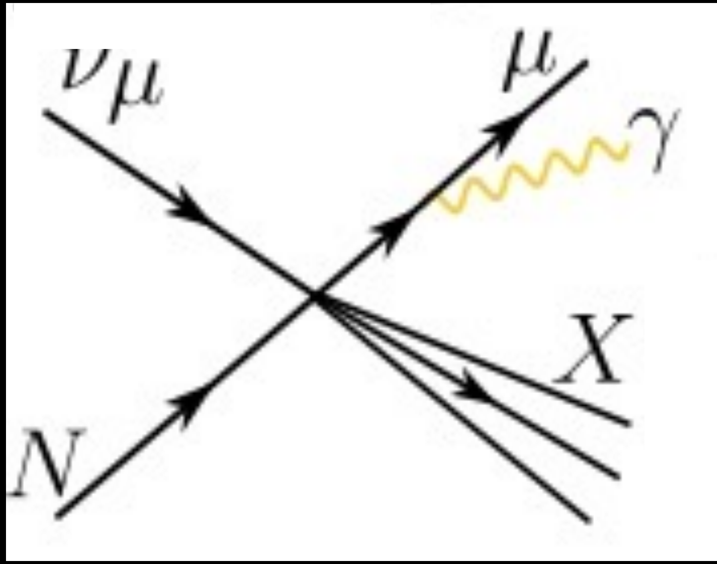


FSR impacts on the inelasticity measurements

Experimental definition:



1311.5238 IceCube coll. Science



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

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

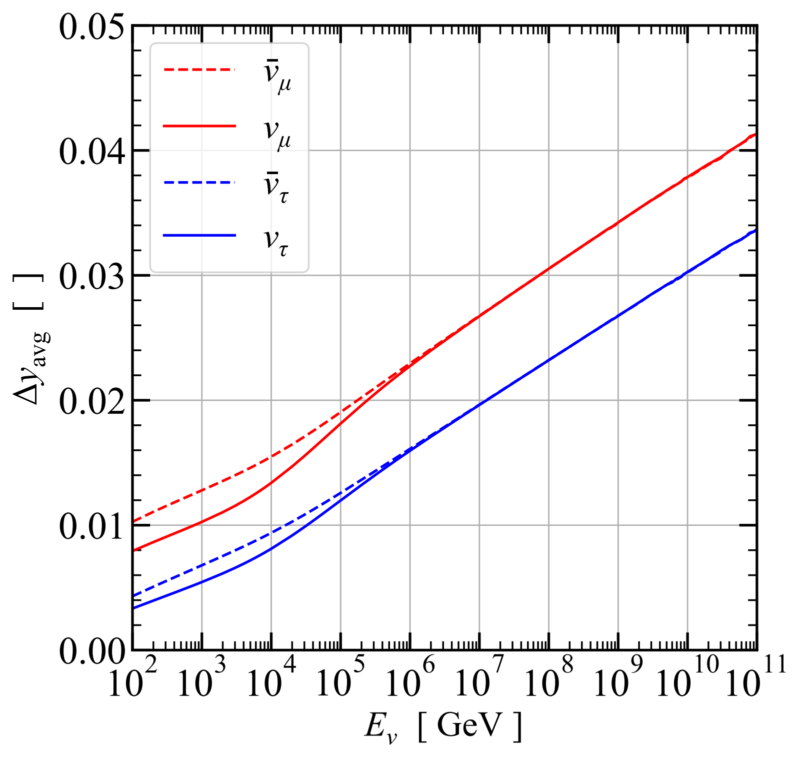
Photon takes energy from the charged lepton to the shower, increasing <y>

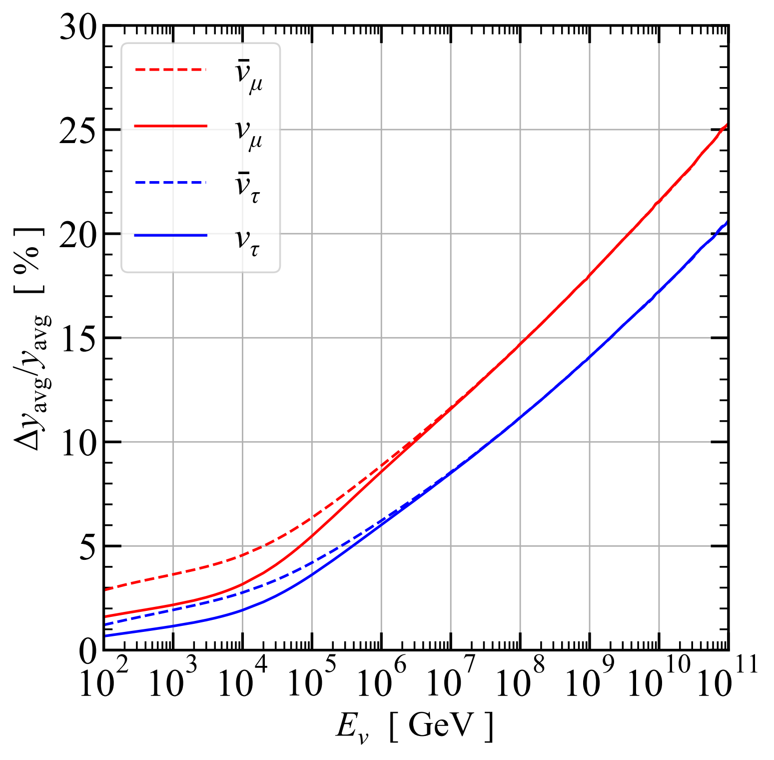
FSR impacts on the inelasticity measurements: average y

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

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

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

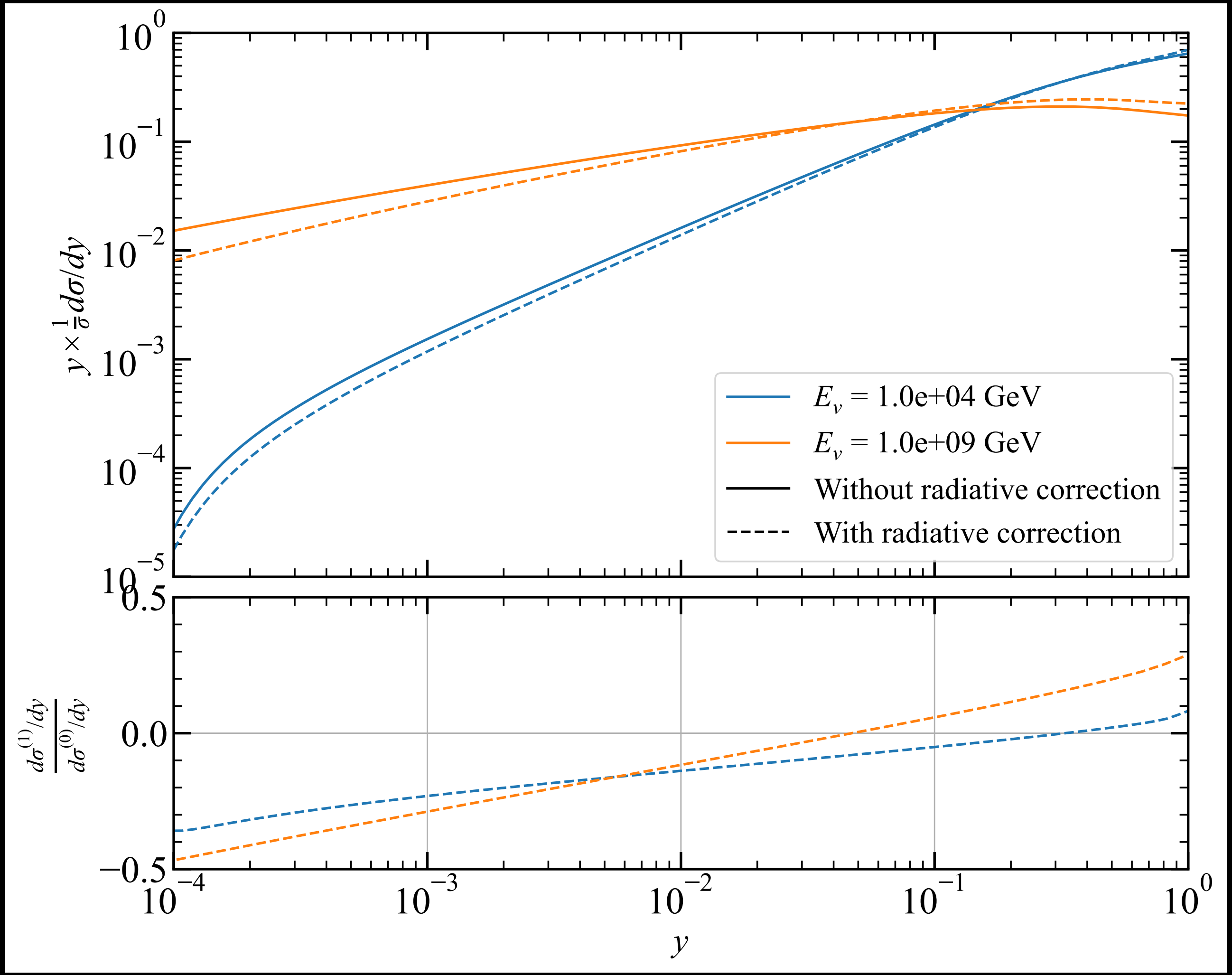




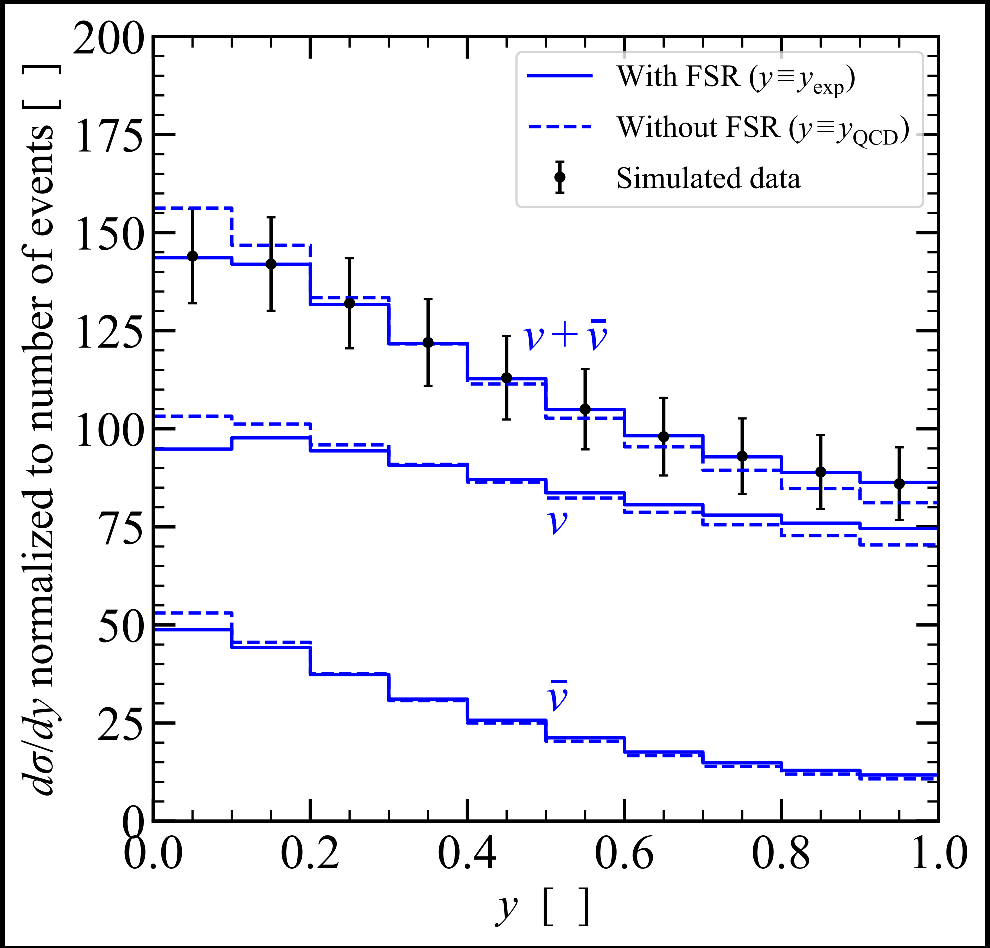
(Plestid, BZ, 2303.08984)

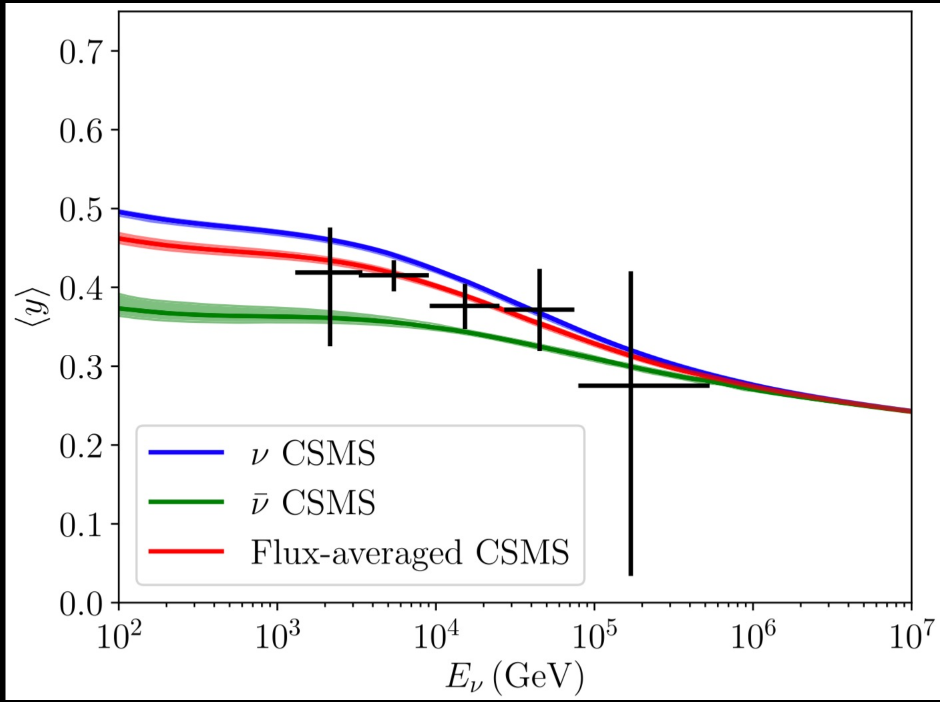
Correction increases with energy, up to 25%

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 $\simeq$30%. (*1303.0758, 1312.0457, 2402.13308*)

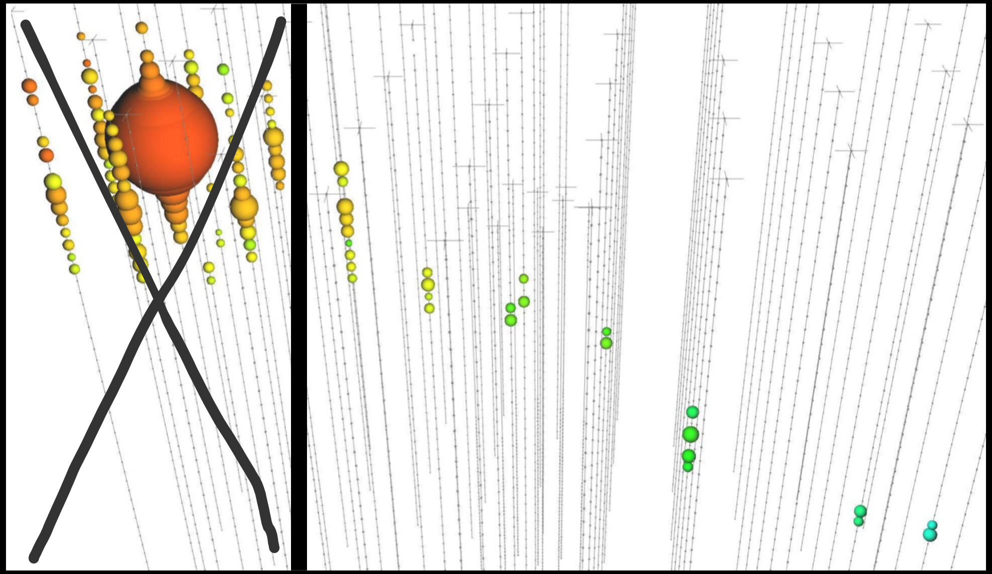
Charm production

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

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

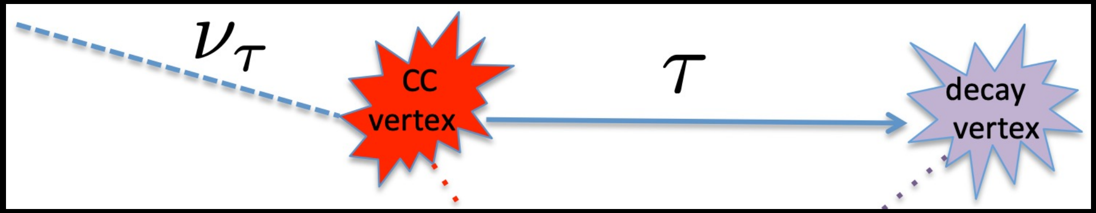
FSR impacts HE nu observations: throughgoing muons & ν_τ double bang

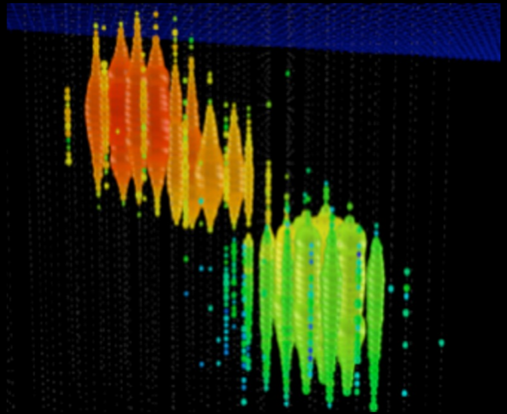
Throughgoing muons



Not including FSR underestimates the parent neutrino energy

ν_τ induced double bang

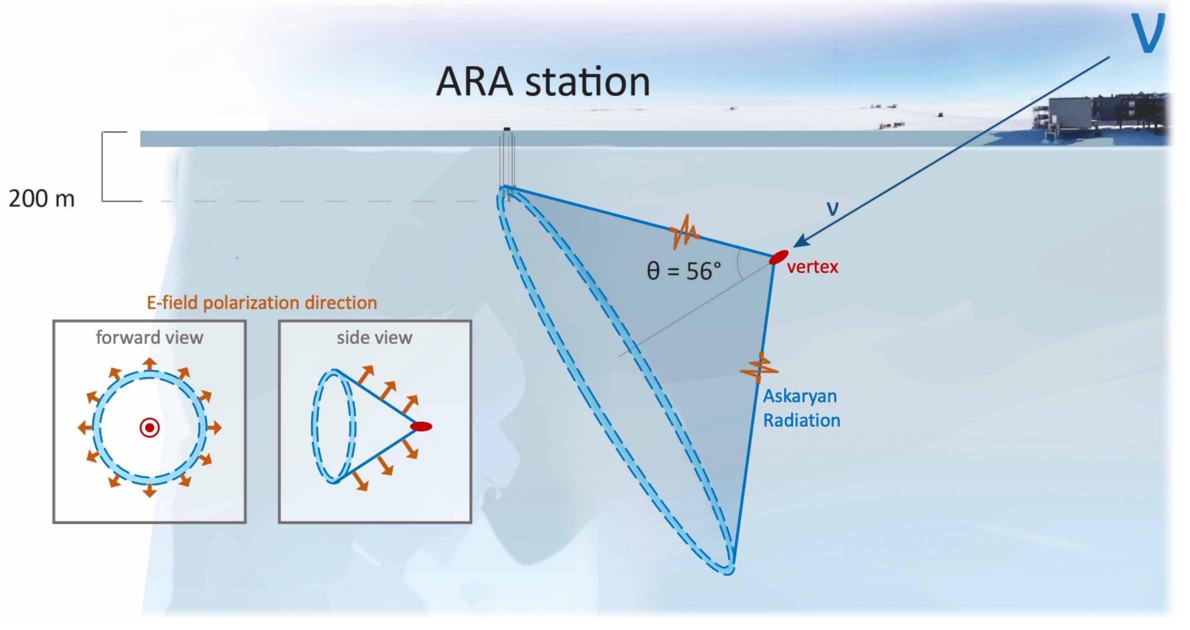




FSR 1) distort the energy balance the two bangs 2) reduce the detectability of the double bang signature.

UHE nu observations: two basic kinds of detectors

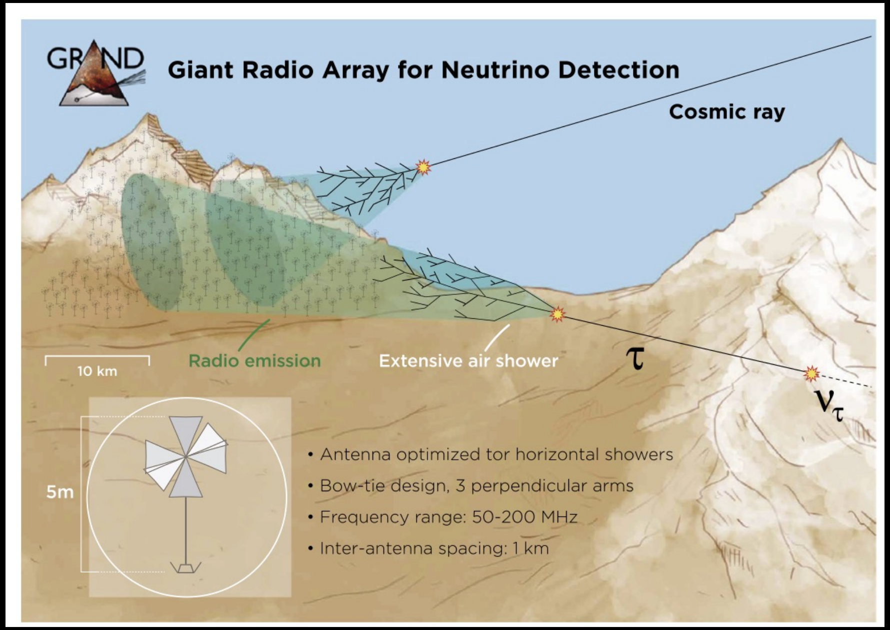
In-ice radio detectors (all flavors; could distinguish flavors)



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.

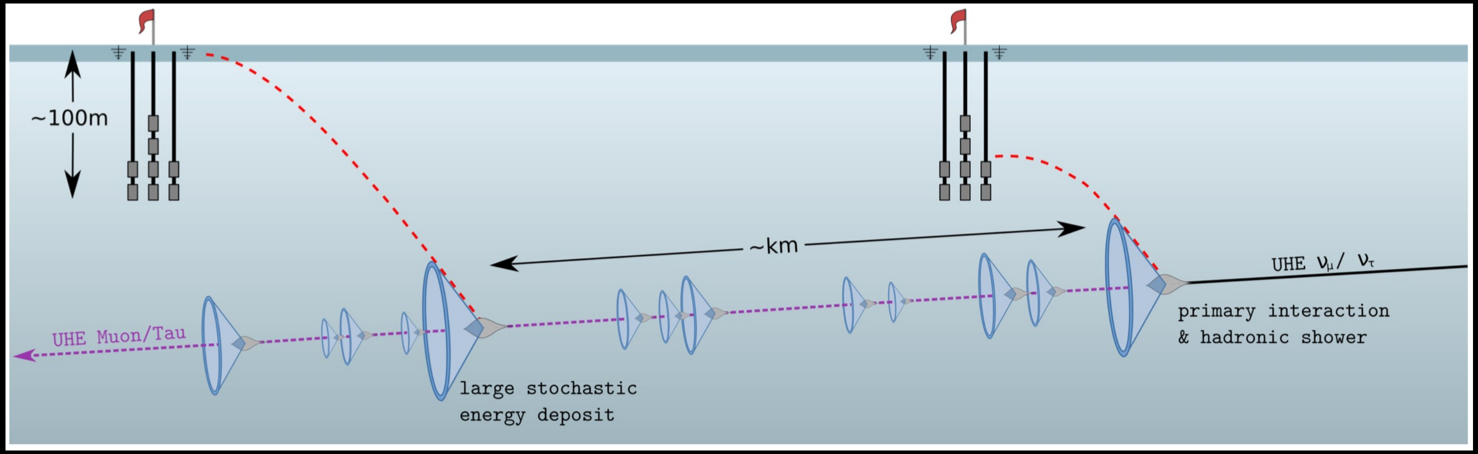
FSR impacts UHE nu observations: in-ice radio detectors

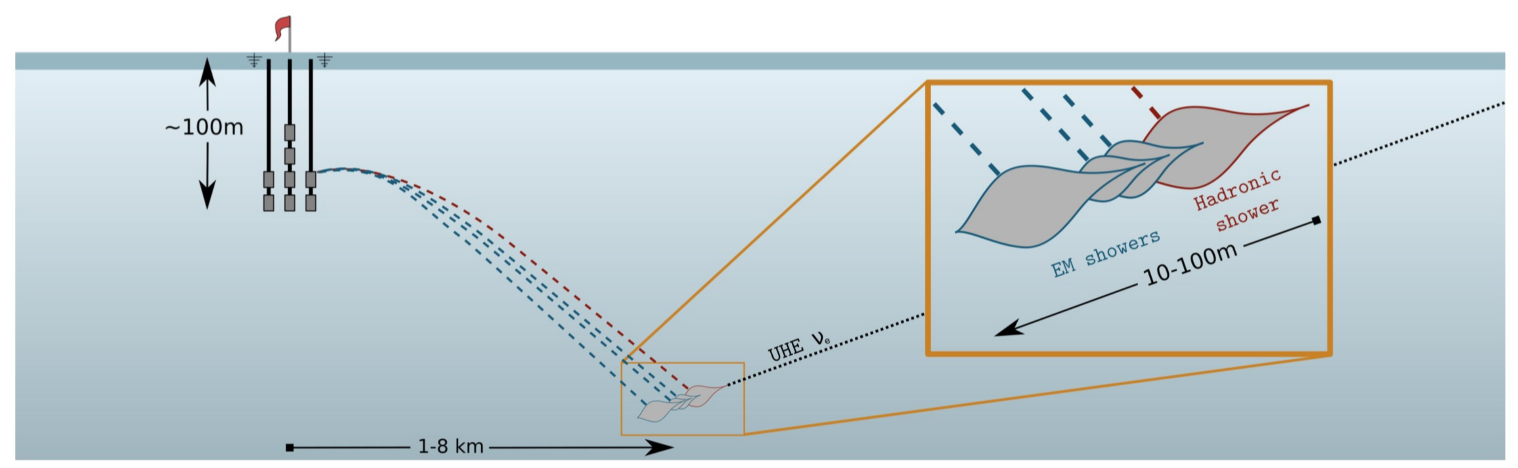
For CCDIS, FSR enhances the overall detectable (shower) energy by as much as ≃20% and lowers the energy thresholds.

$\nu\tau$ CC, big, up to ≃20%

$\nu\mu$ CC, mild

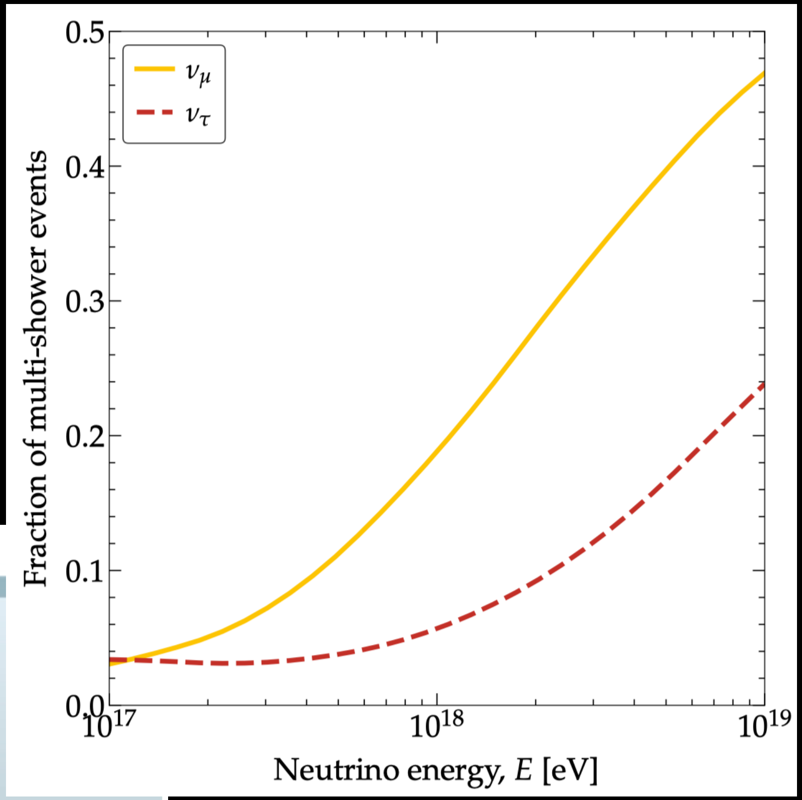
νe CC, negligible





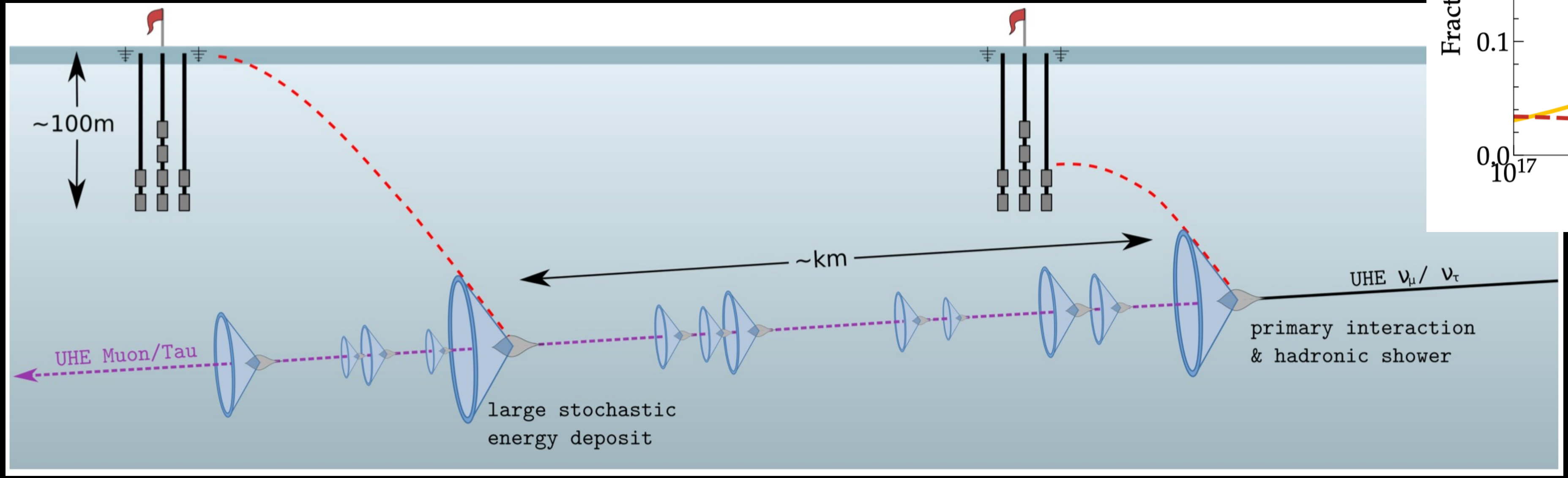
2402.02432
Coleman et al.

FSR impacts UHE nu observations: in-ice radio detectors



FSR reduces the flavor measurements

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

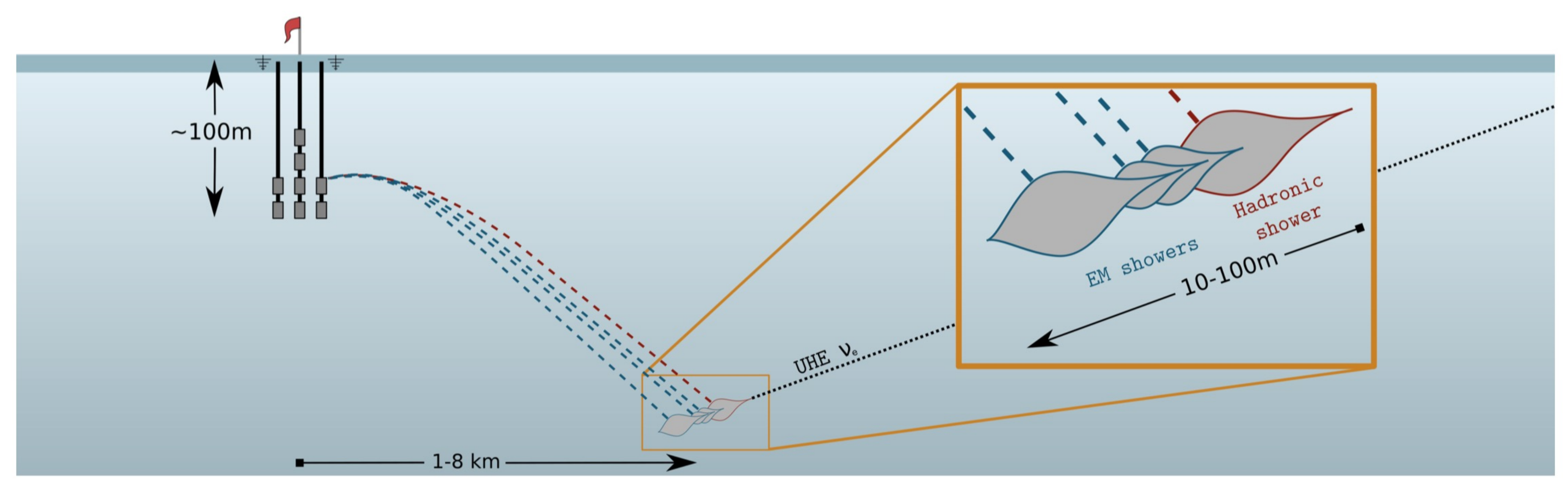


2402.02432
Coleman et al.

FSR impacts UHE nu observations: in-ice radio detectors

FSR reduces the flavor measurements

A way to measure electron neutrinos (using LPM effect)



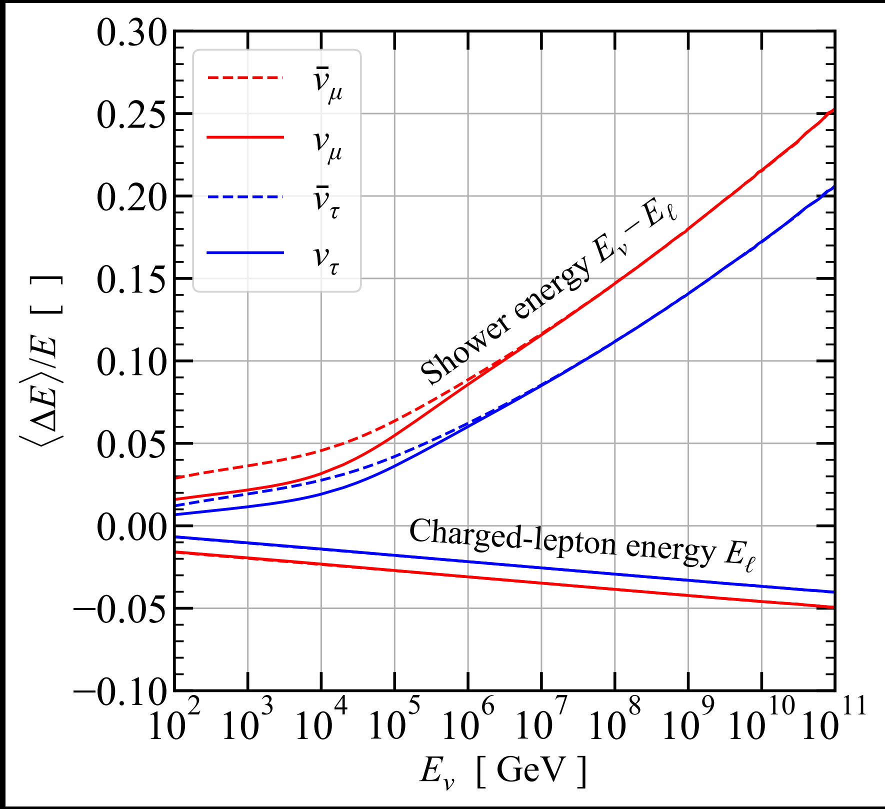
Background could be from muon/tau neutrino CC interactions.

2402.02432 Coleman et al.

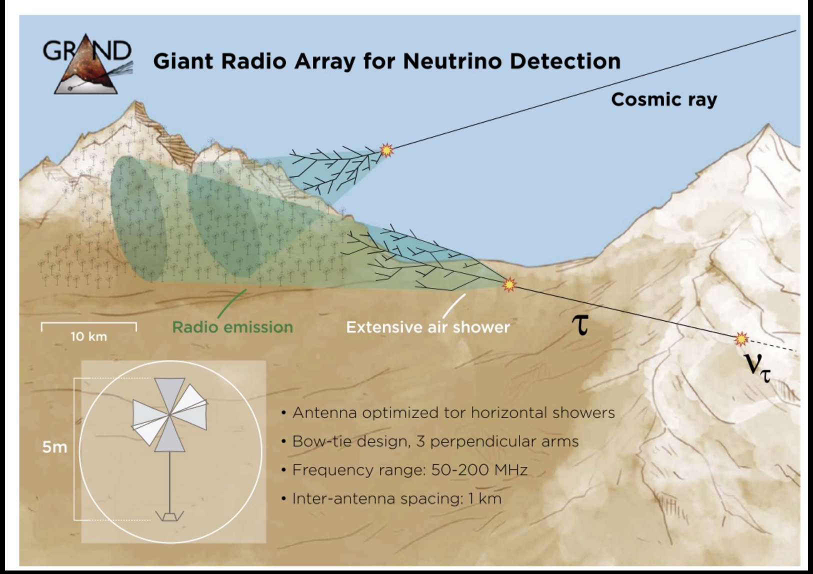
Without FSR, the paper estimates that bkgd rate is ~0%.

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

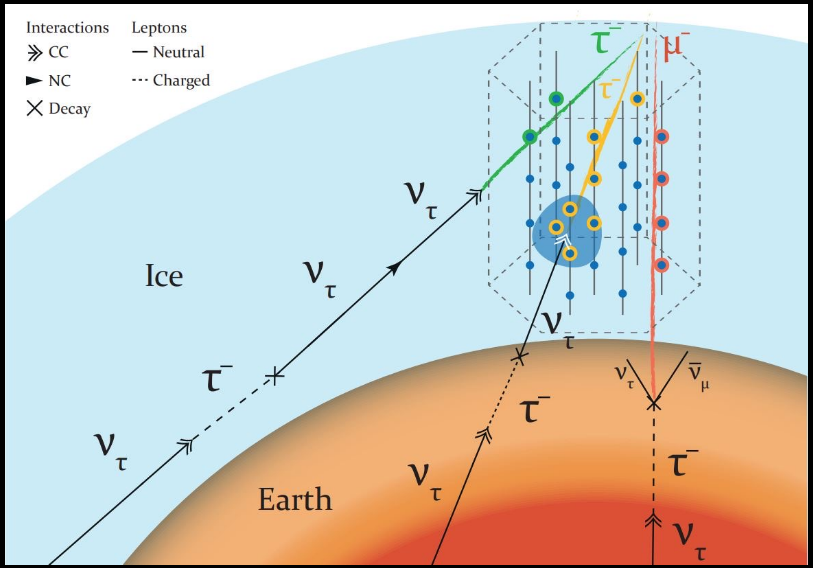
FSR impacts UHE nu observations: air shower detectors for ντ



(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 FASERv (running) and future FASERv2

FASERv (running) will have ~2×10^4 neutrino CCDIS events
FASERv2 (proposed) will have ~10^6.
Enough data to perform PDF(x, Q^2) measurements

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

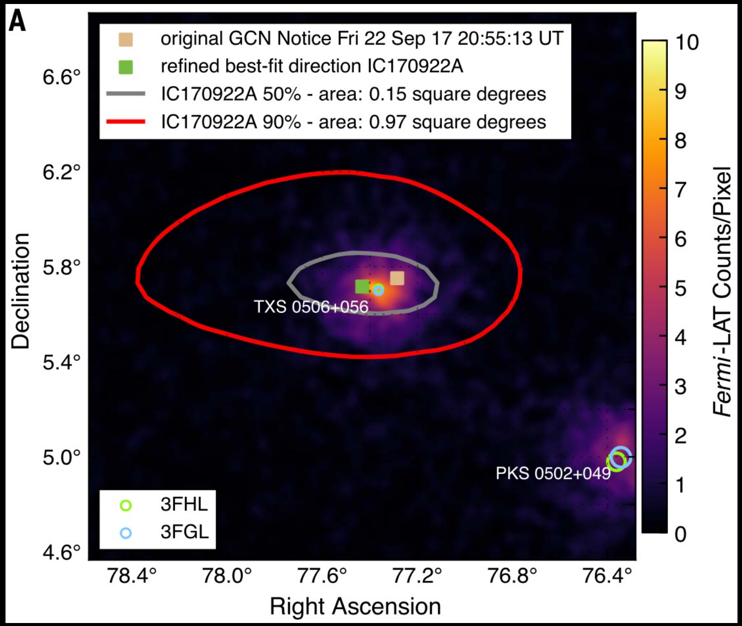
With FSR: $$\frac{\Delta Q^2}{Q^2_{(0)}} \simeq -\frac{E_\gamma}{E_\ell}$$ A few percent but large statistics

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

Search for HE neutrino emission from choked-jet supernova using IceCube 10 yrs of public data

Searches for the sources of high-energy neutrinos

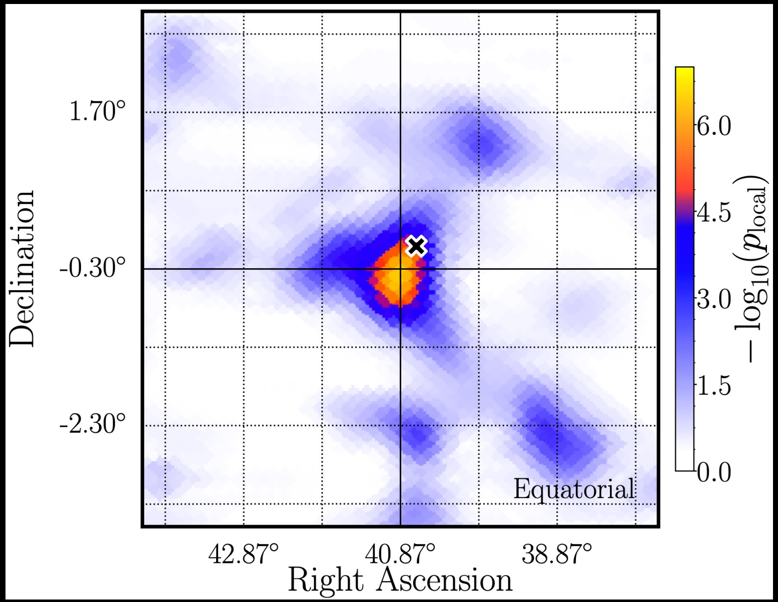
TXS 0506+056 (Blazar)



Association with ~300 TeV neutrino
3.0σ (global)
1807.08816 Science, IceCube

Neutrino flare ~2015
3.5σ (global);
1807.08794 Science, IceCube

NGC 1068 (Seyfert II galaxy)



2.9σ (global)
1910.08488 PRL, IceCube

4.2σ (global)
2211.09972 Science, IceCube

Tidal disrupt events

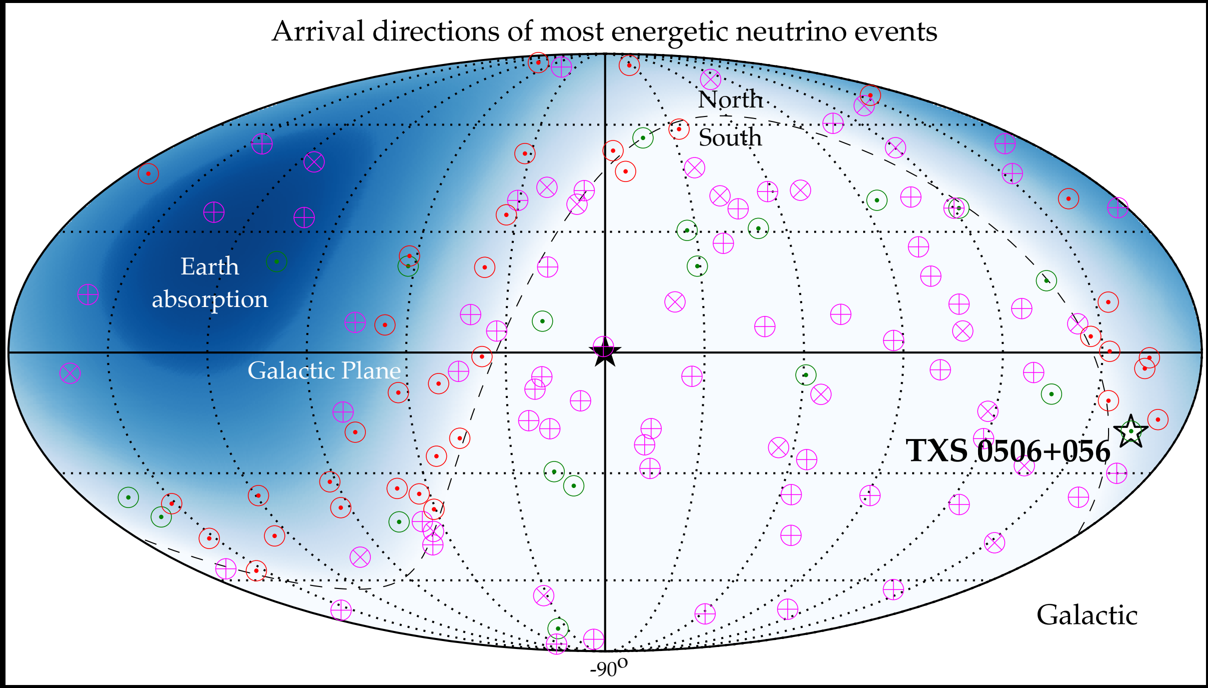
AT2019dsg (2005.05340),

AT2019fdr (2111.09390),

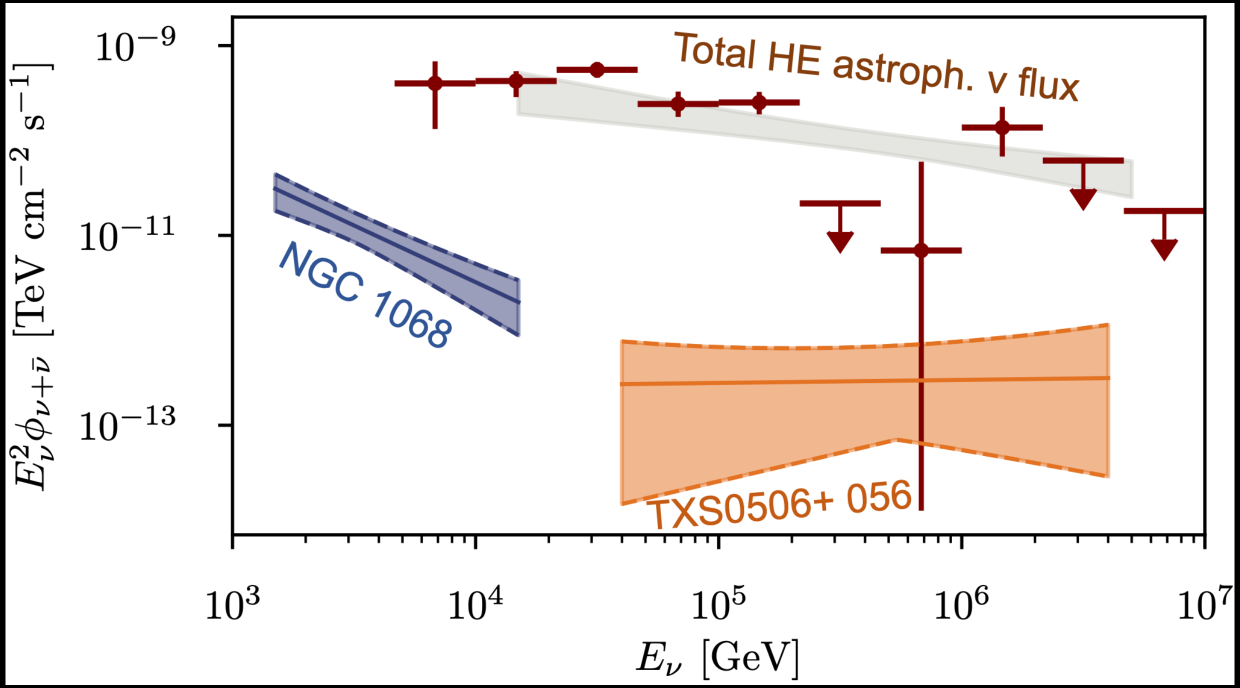
AT2019aalc (2111.09391)

possibly associated with HE neutrinos found in multi-messenger follow-ups

Vast majority of HE astrophysical neutrinos remain unexplained



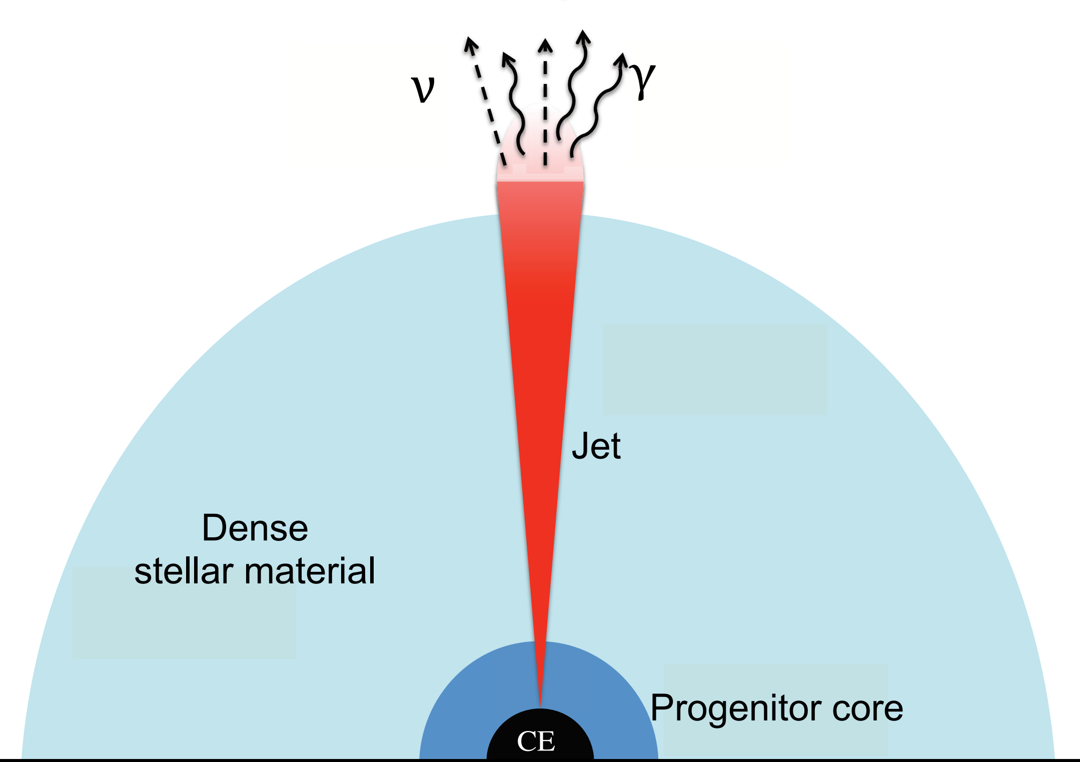
1903.04334 Ackermann et al



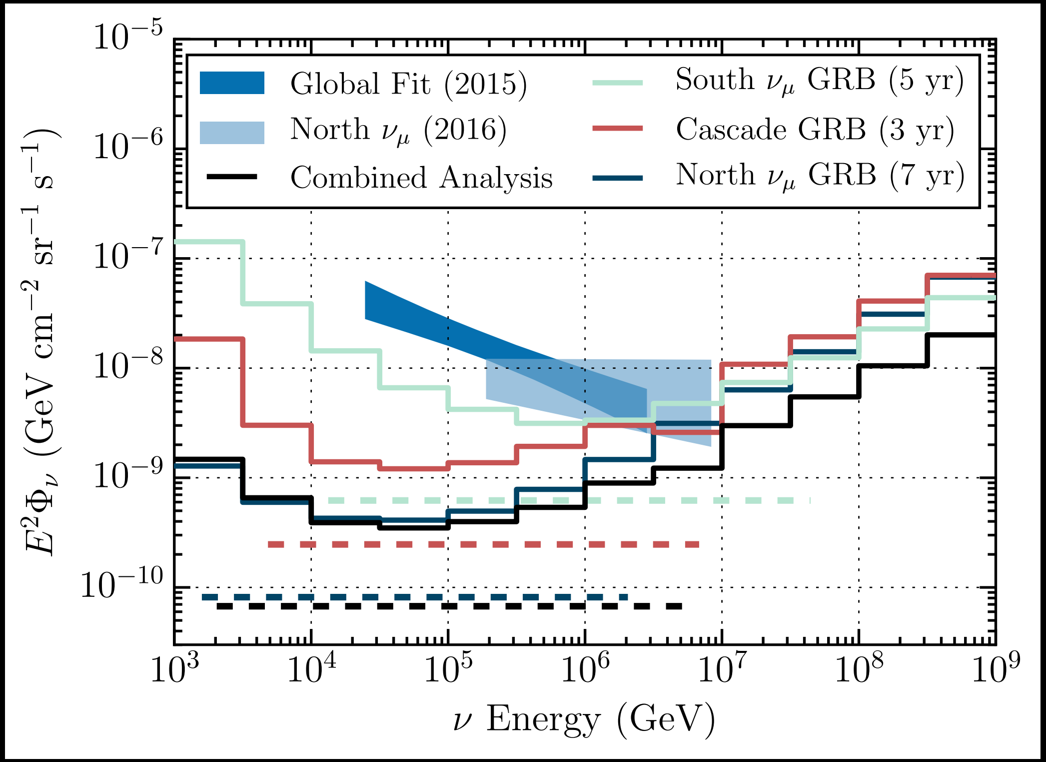
2211.09972 IceCube

We must find the dominant sources of the all-sky diffuse HE astrophysical neutrinos

Transients: gamma-ray bursts (GRBs) (<1%)



Long gamma-ray burst



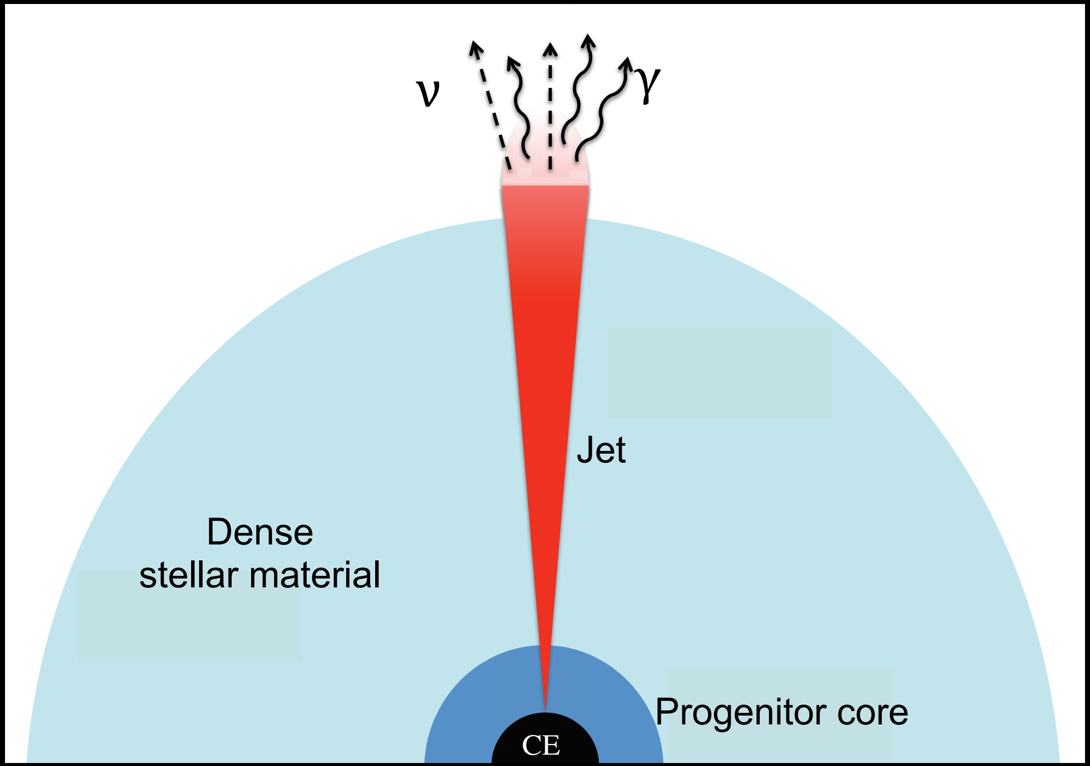
1702.06868 IceCube

5-year IceCube data and 1172 GRBs

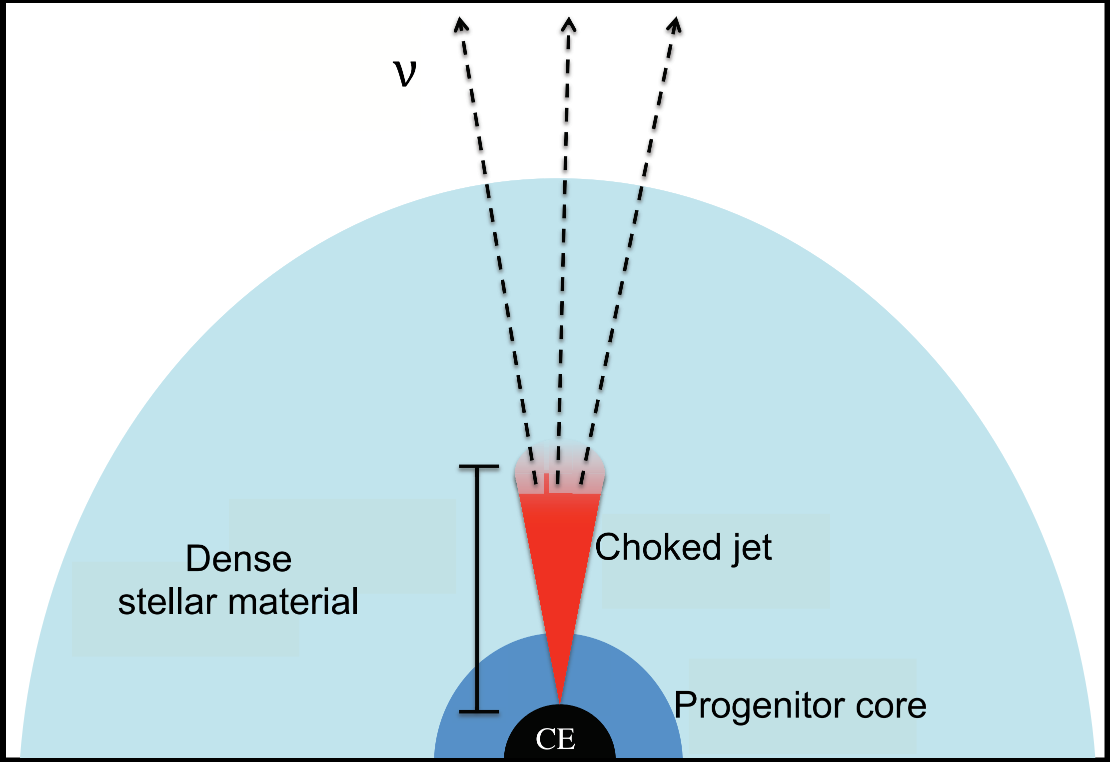
GRBs contribute < 1% of HE nu

Short GRBs could also produce HE neutrinos

Transients: choked-jet supernovae as source of HE neutrinos



Long gamma-ray burst



Choked-jet scenario

1512.08513 Senno, Murase, Meszaros

Choked-jet SN: new analysis considerations

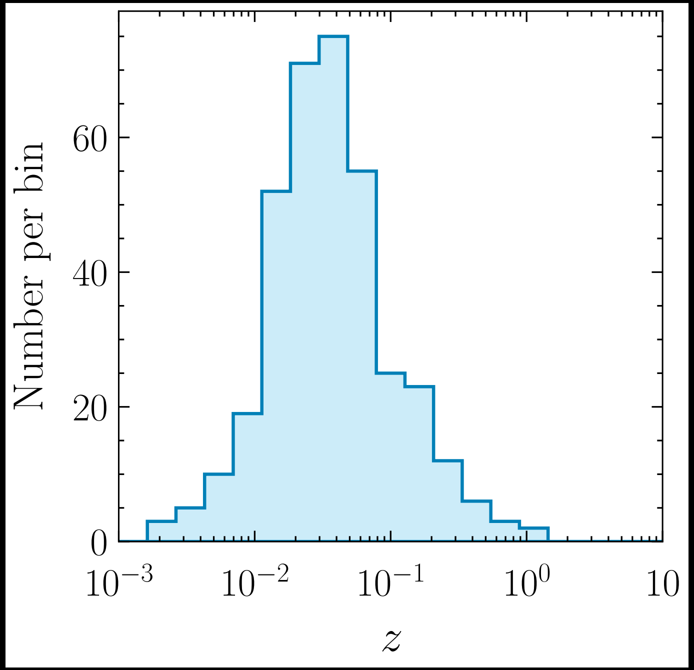
Data

Ten-years of IceCube public data

Remove the 19*2 double-counted events due to a misreconstruction error
(*found by 2110.02974 BZ, Beacom*).

SN sample

Collected 386 type Ib/c SN between 2008—2018, from several public SN catalogs



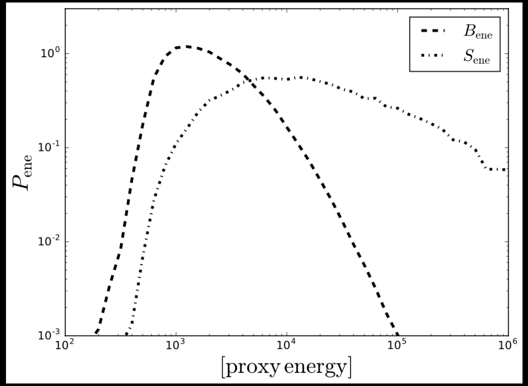
Likelihood method

Spatial PDF: 2D gaussian

Temporal PDF

1D gaussian of T
Center: 13 days before SN max
σ_T = 4 days

Energy pdf



Found 19 dimuon candidates in IceCube public data

- Ten years of public IceCube data (1,134,450 muon events; 2008--2018)
- Data obtained after multiple strong cuts optimized for point-source search, not dimuon search.
- We analyze the data by looking for muon pairs arriving close in time and direction

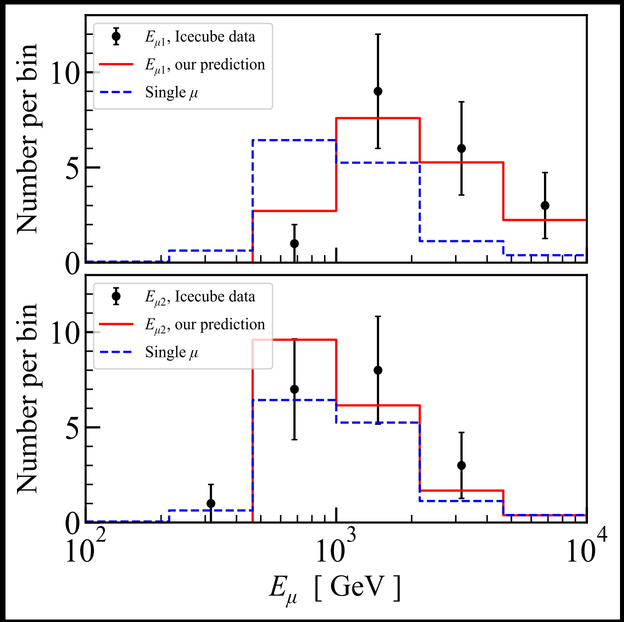
List of the 19 dimuon candidates we found

MJD1 [day]	MJD2 (= MJD1)	$E_{\mu 1}$ [TeV]	$E_{\mu 2}$	RA1 [deg]	RA2	Dec1	Dec2	AngErr1	AngErr2	AngDis	DisErr
56068.26557772	56068.26557772	1.23	1.05	25.065	25.860	18.168	18.466	0.38	1.85	0.81	1.89
56115.78056499	56115.78056499	2.29	0.65	296.835	296.891	41.777	46.922	3.10	0.41	5.15	3.13
56235.14756523	56235.14756523	2.19	2.19	179.781	185.182	20.271	28.274	2.50	1.57	9.39	2.95
56582.68675378	56582.68675378	2.29	1.35	120.687	121.892	26.630	24.994	1.47	0.78	1.96	1.66
56653.19502448	56653.19502448	3.31	1.48	48.106	47.781	30.840	30.100	0.75	1.19	0.79	1.41
56784.87114671	56784.87114671	1.35	0.35	126.690	126.357	69.524	70.871	1.97	2.83	1.35	3.45
56813.78701082	56813.78701082	0.91	0.83	184.136	181.708	31.627	31.957	3.01	0.83	2.09	3.12
56895.78341718	56895.78341718	1.91	0.79	295.288	303.817	14.387	16.670	1.94	1.61	8.53	2.52
56932.15214130	56932.15214130	1.70	0.98	175.546	173.549	36.710	35.972	1.17	0.86	1.77	1.45
56940.02405671	56940.02405671	5.13	3.72	1.404	0.541	11.716	9.353	3.13	2.38	2.51	3.93
57214.99298310	57214.99298310	1.51	0.83	13.089	14.760	39.101	39.034	3.50	0.85	1.30	3.60
57376.46221142	57376.46221142	1.66	1.55	326.795	328.022	17.543	15.199	2.11	1.15	2.62	2.40
57461.19606500	57461.19606500	1.35	1.10	308.771	307.274	31.268	30.077	1.08	1.37	1.75	1.74
57499.81363094	57499.81363094	5.89	1.70	199.430	201.527	16.454	15.029	2.55	1.30	2.47	2.86
57560.74070687	57560.74070687	1.74	0.79	219.566	219.023	12.582	13.008	1.62	0.74	0.68	1.78
57650.26270928	57650.26270928	6.17	2.40	256.189	255.088	19.588	20.293	2.03	0.77	1.25	2.17
57661.79317519	57661.79317519	1.45	0.91	24.276	21.095	23.145	24.317	1.72	2.22	3.14	2.81
58003.09416087	58003.09416087	2.29	1.23	349.095	345.586	21.328	19.554	2.17	1.30	3.74	2.53
58266.46093610	58266.46093610	2.63	1.48	296.881	294.994	19.596	20.896	1.57	1.45	2.20	2.14

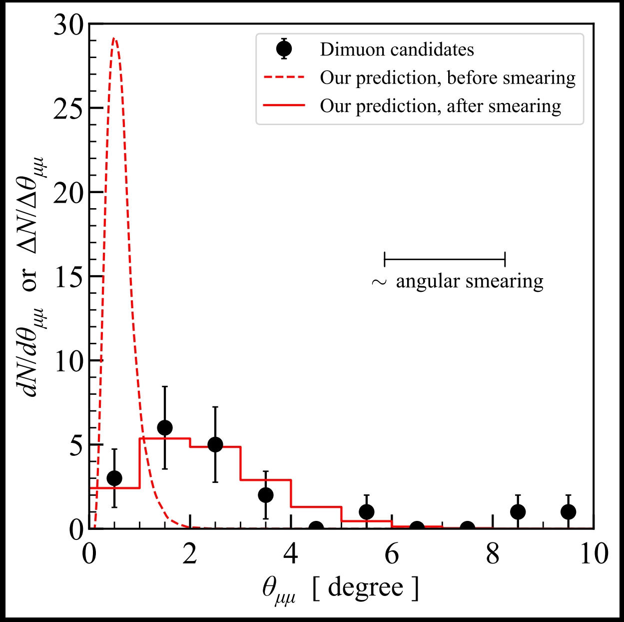
(BZ, Beacom, 2110.02974)

Agree with our prediction that matches the cuts of the dataset

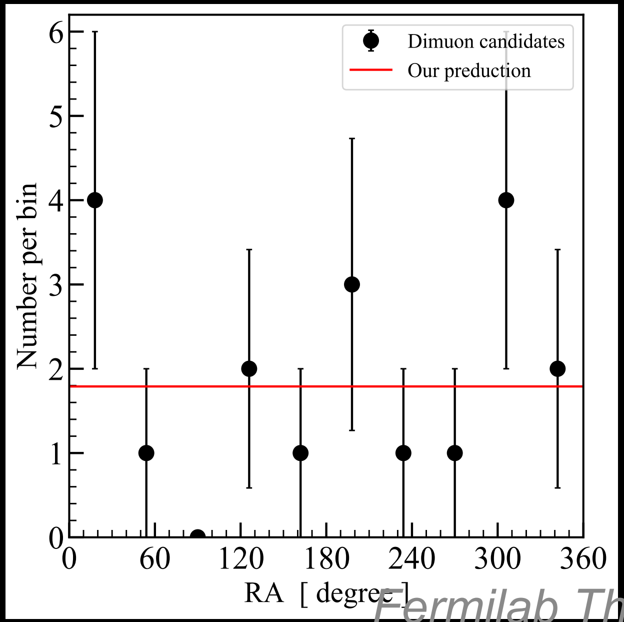
Energy distribution

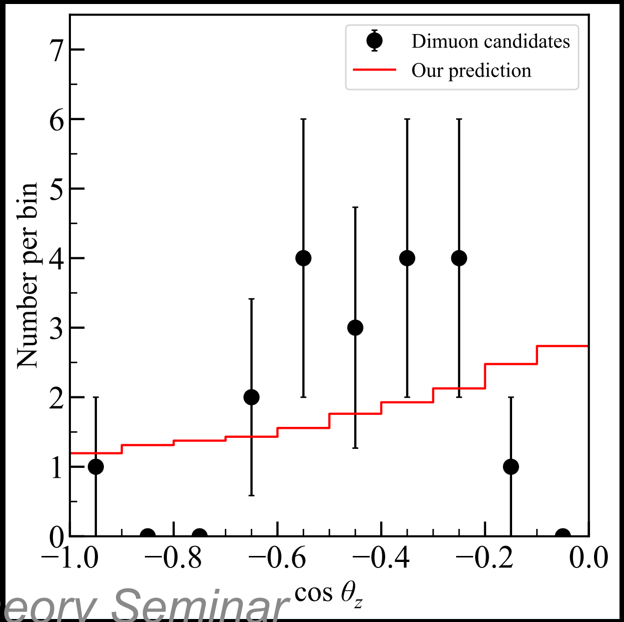


Angular distribution



RA distribution





Zenith distribution

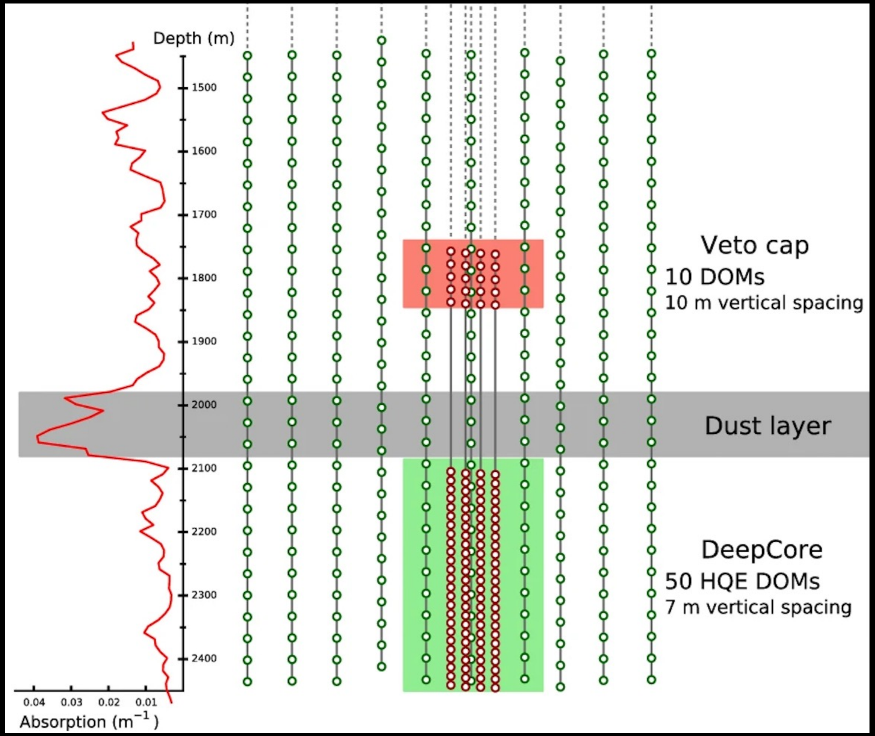
(BZ, Beacom, 2110.02974)

19 dimuon candidates turned out to be misreconstruction error

- After our paper out, IceCube collaboration did a visual inspection to these candidates, and found that they are not real dimuons.

- They are, instead, due to an internal reconstruction error that identifies some single muons crossing the dust layer as two separate muons.

Inside IceCube detector



Digression: A bit more about dimuons…

Our predicted number of dimuons, in an ideal situation

	Starting		Throughgoing	
	DIS	WBP	DIS	WBP
IceCube, 10 yrs	37	0.3	85	6.0
IceCube-Gen2, 10 yrs	370	5.8	231	22

(Note IceCube has run for > 10 years)

Dimuons have important physical uses. For example:

1) measure strange quark PDF at higher Q^2.
2) Make the first detection of W-boson production using showerless starting dimuons.

(BZ, Beacom, 2110.02974)

Remove the double counted events in the IceCube public data

MJD1 [day]	MJD2 (= MJD1)	$E_{\mu 1}$ [TeV]	$E_{\mu 2}$	RA1 [deg]	RA2	Dec1	Dec2	AngErr1	AngErr2	AngDis	DisErr
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56582.68675378	56582.68675378	2.29	1.35	120.687	121.892	26.630	24.994	1.47	0.78	1.96	1.66
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57661.79317519	57661.79317519	1.45	0.91	24.276	21.095	23.145	24.317	1.72	2.22	3.14	2.81
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58266.46093610	58266.46093610	2.63	1.48	296.881	294.994	19.596	20.896	1.57	1.45	2.20	2.14

We remove the double counted events by combining the 19*2=38 events into 19 events

(BZ, Beacom, 2110.02974)

Corrected data on GitHub:
https://github.com/beizhouphys/IceCube_data_2008--2018_double_counting_corrected
((Or just google "[my name] github")
and has been used by, e.g., 2401.06571, 2404.06539

Choked-jet SN: new analysis considerations

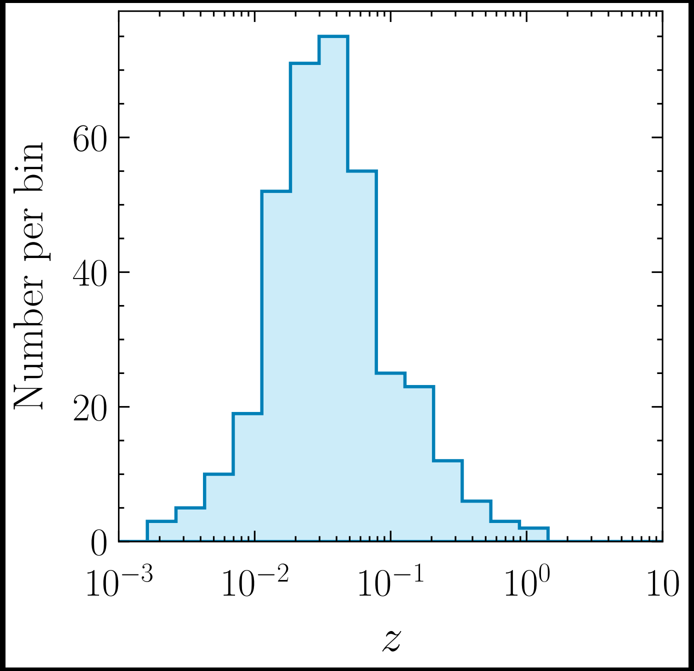
Data

Ten-years of IceCube public data

Remove the 19 double-counted events due to a misreconstruction error
(*found by 2110.02974 BZ, Beacom*).

SN sample

Collected 386 type Ib/c SN between 2008—2018, from several public SN catalogs

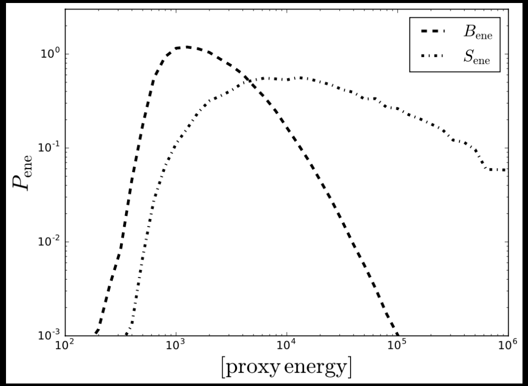


Likelihood analysis

Spatial PDF:
Kent distribution (a generalized 2D gaussian)

Temporal PDF
Gaussian time window
σ_T = 4 days
Center: 13 days before SN max

Energy pdf



Choked-jet SN models

Two classes of models

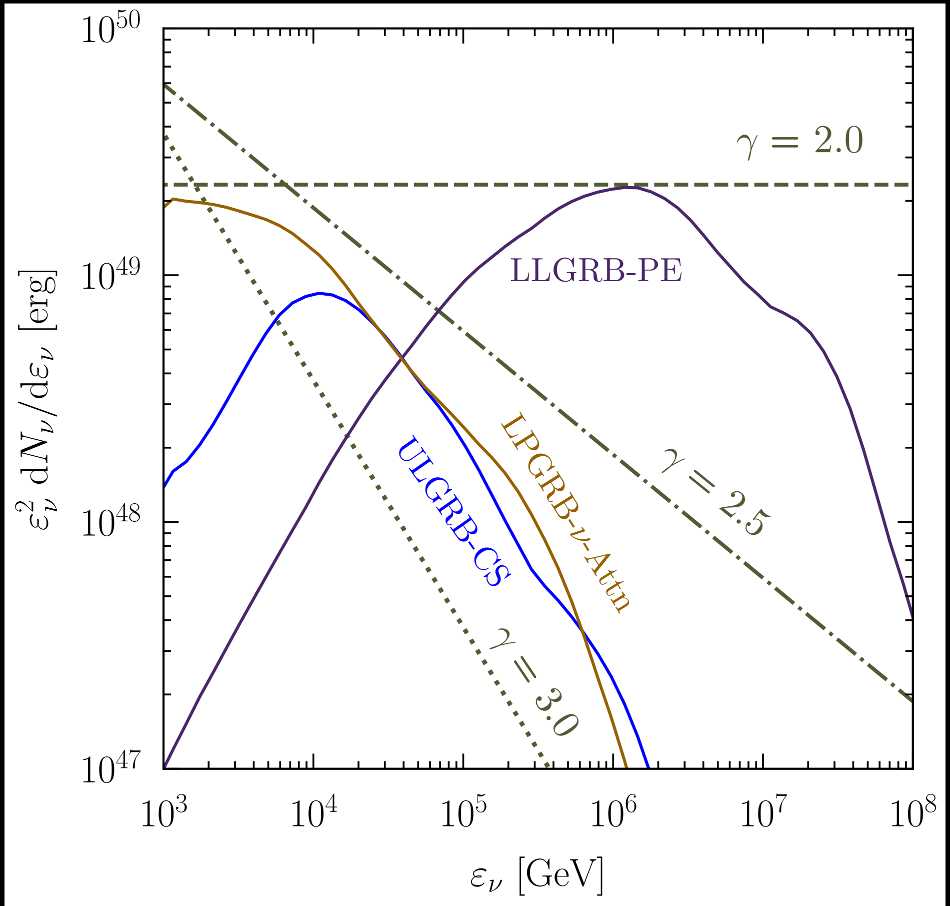
1. Power-law
   1706.02175 Senno, Murase, Mészáros

2. More realistic model (first time)
   astro-ph/0607104 Murase et al.
   1306.2274 Murase & Ioka

Universal parameters

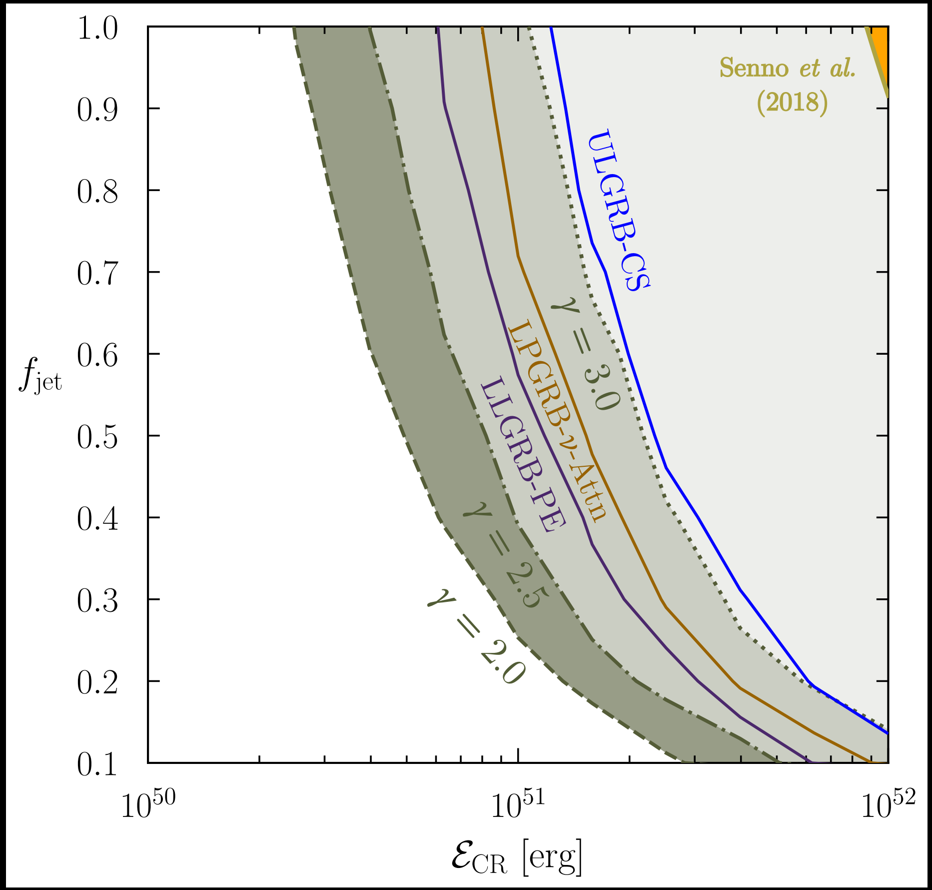
$\mathcal{E}_{CR}$: isotropic equivalent cosmic ray energy injection

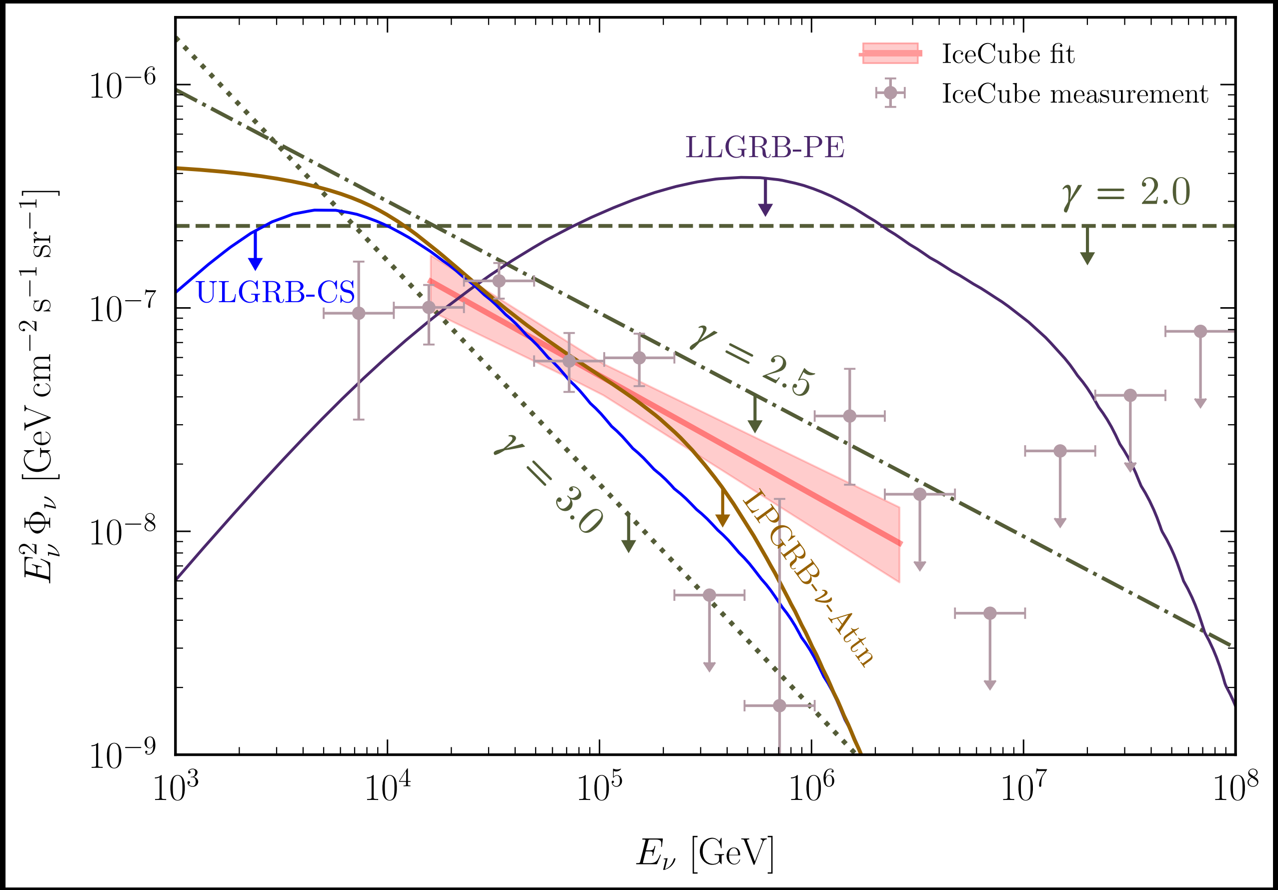
f_{jet}: fraction of type Ib/c SNe that have jet pointing towards us



2210.03088 Chang, BZ, Murase, Kamionkowski

Choked-jet SNe: could still explain most/all of IceCube observation



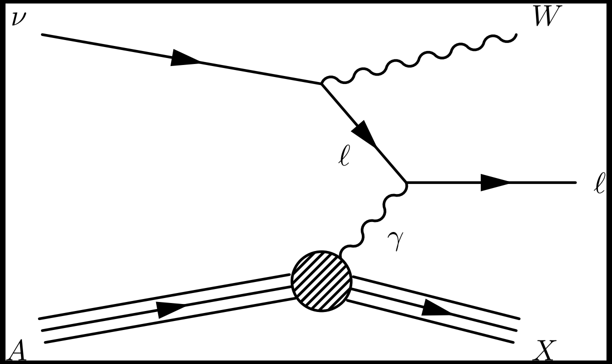


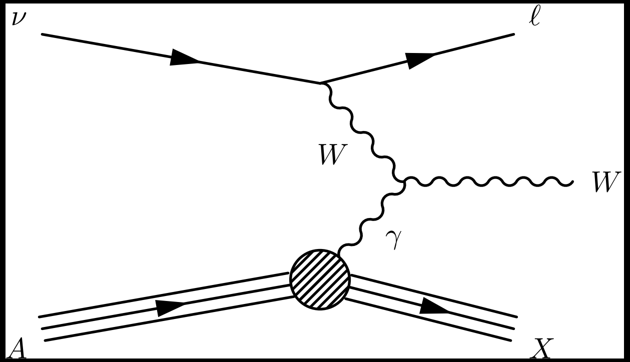
≃40 times stronger than previous work
1706.02175 Senno, Murase, Mészáros
1809.09610 Esmaili, Murase

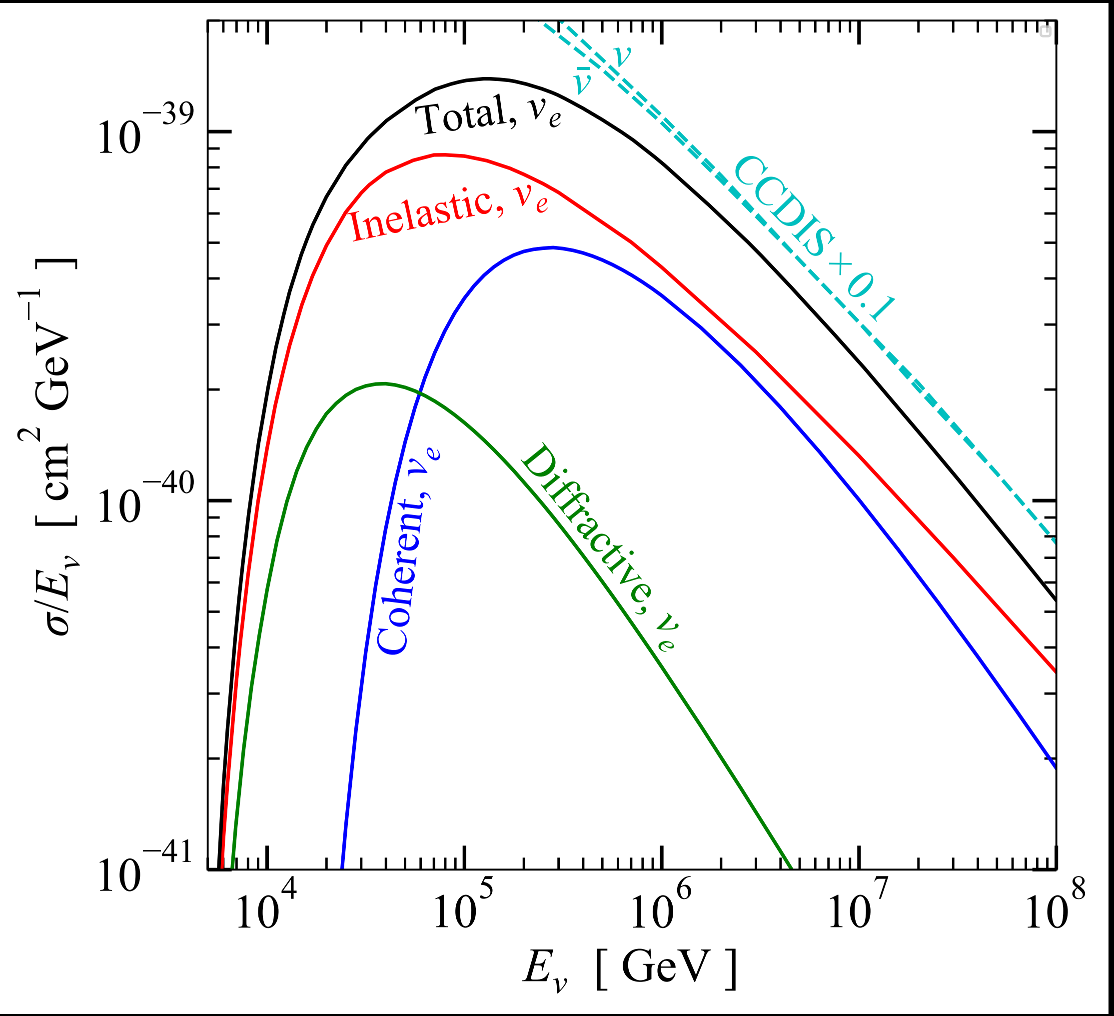
2210.03088 Chang, BZ, Murase, Kamionkowski
(See also 2303.03316 by IceCube collaboration for a different scenario, f_jet≃1)

Improving the precision of WBP calculation using 2nd generation photon PDF

W-boson production xsec (on oxygen): inelastic component dominates





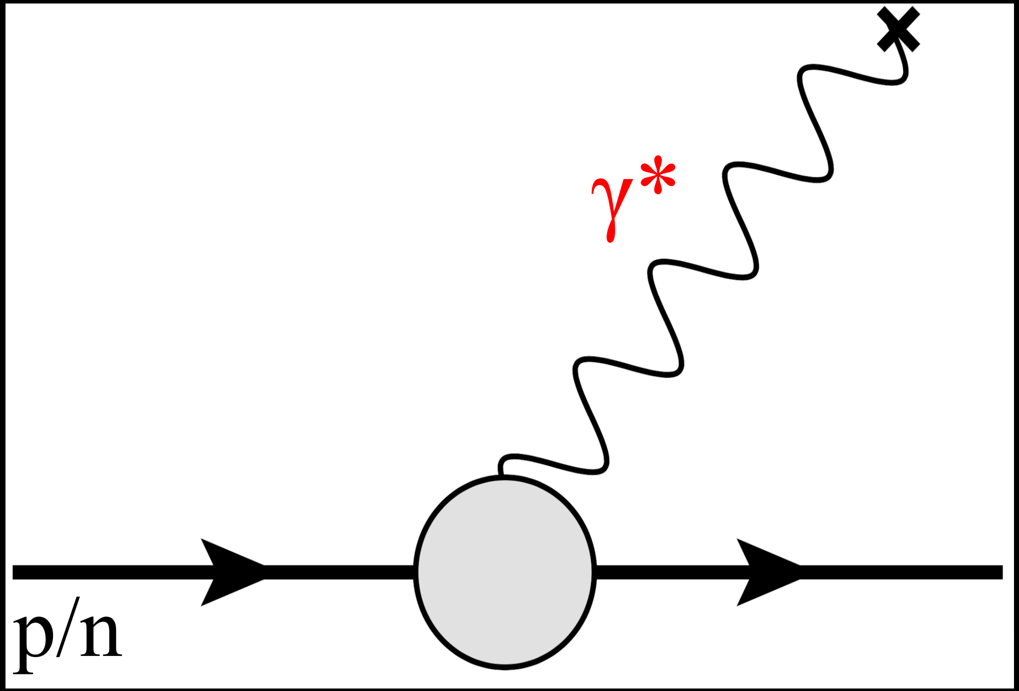


(BZ, Beacom, 1910.08090)

Inelastic component:

- Largest cross section
- Sets the threshold (FASERν, FASERν2)
- Largest uncertainty, especially near threshold

Inelastic component relies on the photon PDF



Increasing precision in collider physics and others requires:

- NNLO in QCD
- NLO in electroweak → photon PDF (and QED correction to the DGLAP equation)

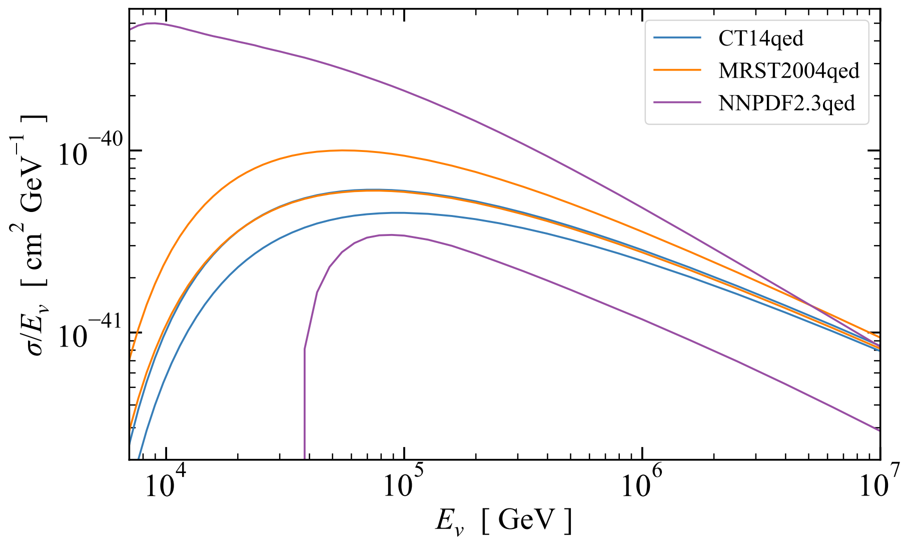
How different photon PDFs affects WBP precision

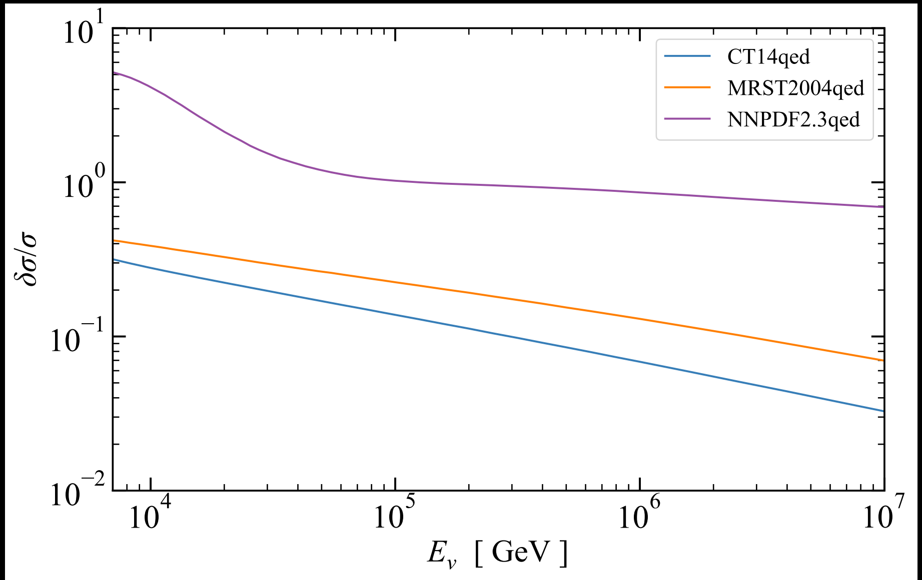
First generation photon PDFs

NNPDF2.3_qed:
Model-indep parameterization of photon pdf + LHC Drell-Yan data

MRST2004qed:
Collinear photon emission from valence quark at low scale + DGLAP evolution to high scale

CT14qed:
Similar to MRST, but further constrained by ZEUS ep → eγ + X, which is important





(Xie, BZ, Hobbs CTEQ-TEA Coll., 2305.10497)

How different photon PDFs affect WBP precision

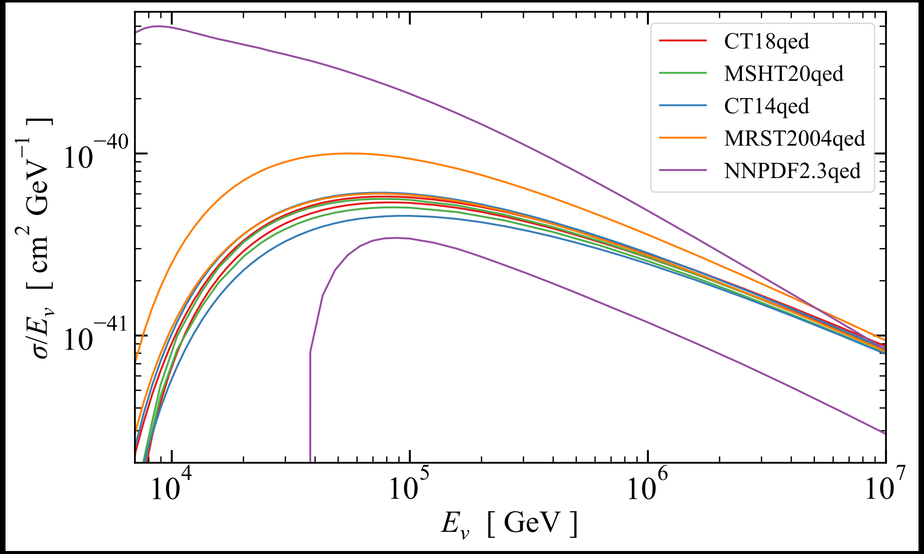
Second generation photon PDFs

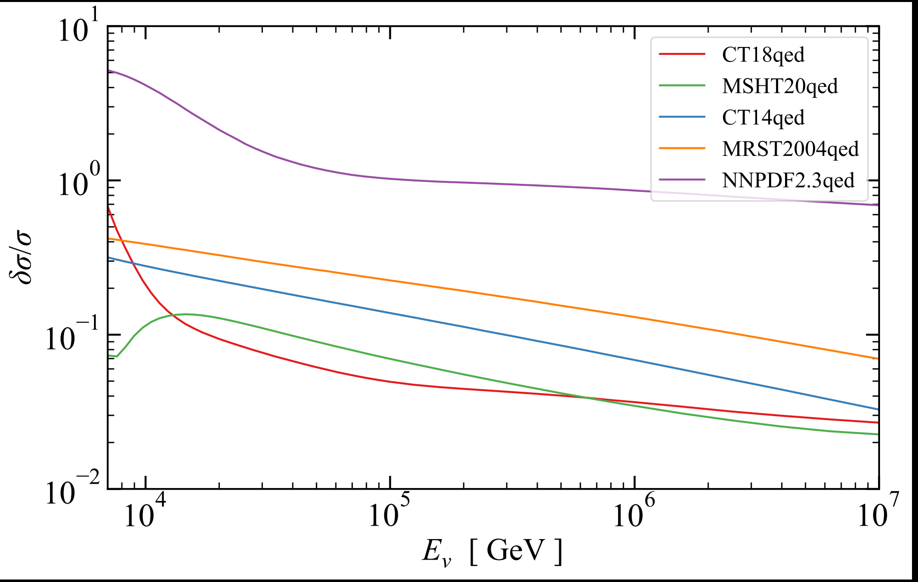
LUXqed formalism (game changer):
(1607.04266 Manohar et al. PRL)
Proton photon PDFs written into proton structure functions $\rightarrow$ percent level precision

MSHT20qed, first neutron photon PDF using the LUXqed formalism

CT18qed, better calculation, especially the error estimation at large x (smaller Eν).

The 2nd generation photon PDF increase WBP precision to percent level

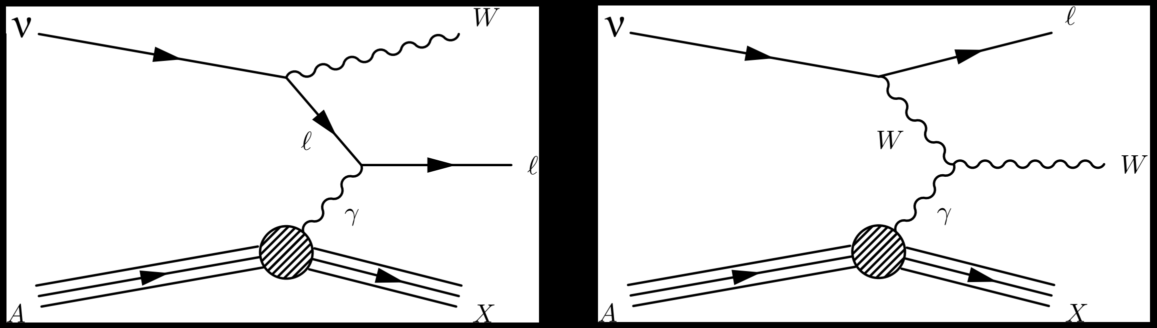




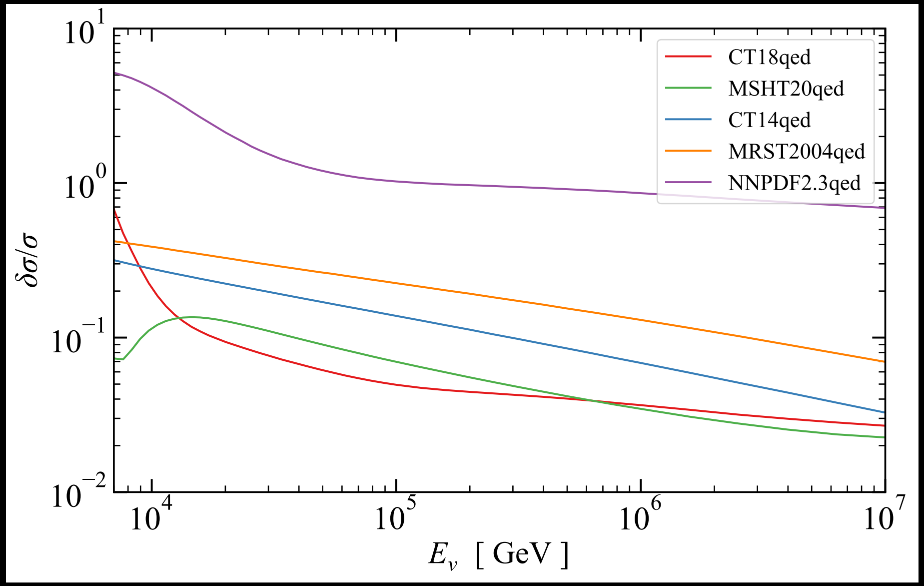
(Xie, BZ, Hobbs CTEQ-TEA Coll., 2305.10497)

WBP: most precise calculation so far, using 2nd generation photon PDF

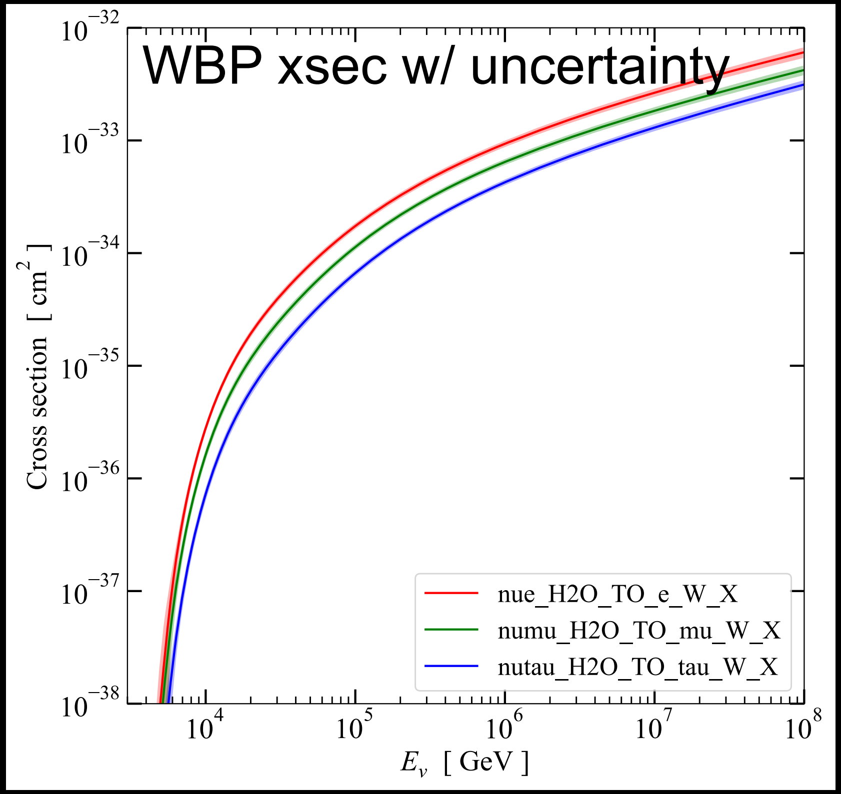
WBP diagrams



WBP xsec uncertainty



(Xie, BZ, Hobbs CTEQ-TEA Collaboration, 2305.10497)



The cross section data with uncertainties can be found on the GitHub webpage

https://github.com/beizhouphys/neutrino-W-boson-and-trident-production
(Or just google "bei zhou github")

W-boson production vs. Glashow resonance

	Glashow resonance	W-boson production
Process	$\bar{\nu}_e + e^- \to W^-$	$\nu_l + A \to l^- + W^+ + A'$ $\bar{\nu}_l + A \to l^+ + W^- + A'$
Neutrino energy	$E_\nu \simeq$ 6.3 PeV	E_ν > ~10 TeV
First predicted by	Sheldon L. Glashow	T. D. Lee & C. N. Yang
First predicted in	1960 (Phys. Rev.)	1960 (PRL)
First "Detected" in	March 2021, IceCube (2.3σ; *Nature*)	

WBP could produce ~10 times more W bosons than Glashow resonance in IceCube

(BZ, Beacom, 1910.10720)

Summary

HE/UHE neutrino interactions

- Cornerstone for all physics measurements
- FSR (affects final state energy by up to 25%):
  - HE nu: inelasticity, nu/nubar flux ratio, neutrino mixing, charm prod., throughgoing muons, double bang
  - UHE nu: overall detectable energy, energy threshold, flavor measurements, earth emergent tau, nutau regeneration
- WBP: most precise calc using 2nd generation photon PDF

Choked jet SNe searches

- A very natural scenario to be studied
- Using IceCube 10 yr data but removing the double counting found in our dimuon work
- First time using realistic spectrum
- cjSN will soon be verified or excluded as the dominant HE nu source

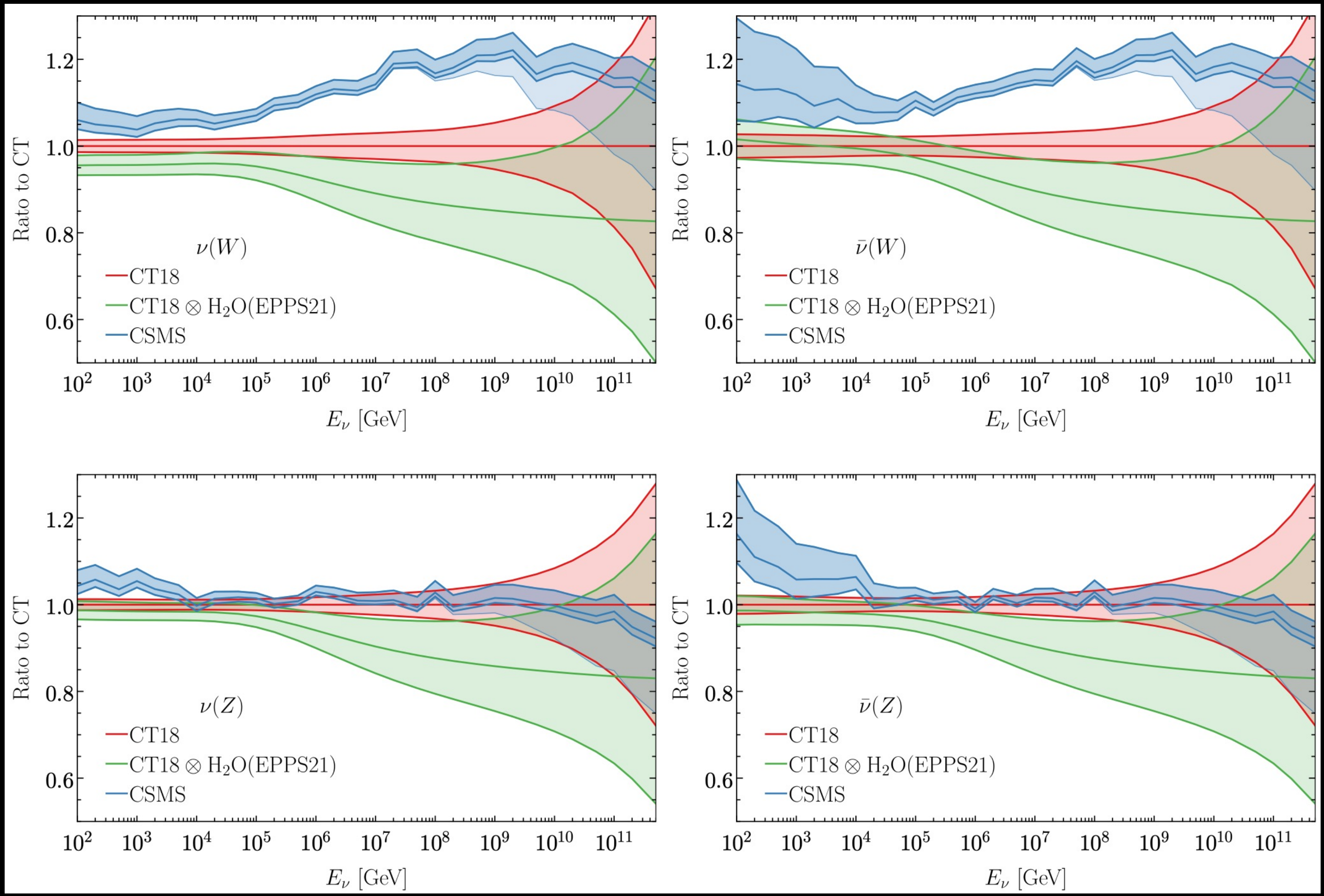
Thanks for your attention!

Deep inelastic scattering: CSMS2011(HERAPDF1.5@NLO) vs CT18NNLO

Neutrino | Antineutrino

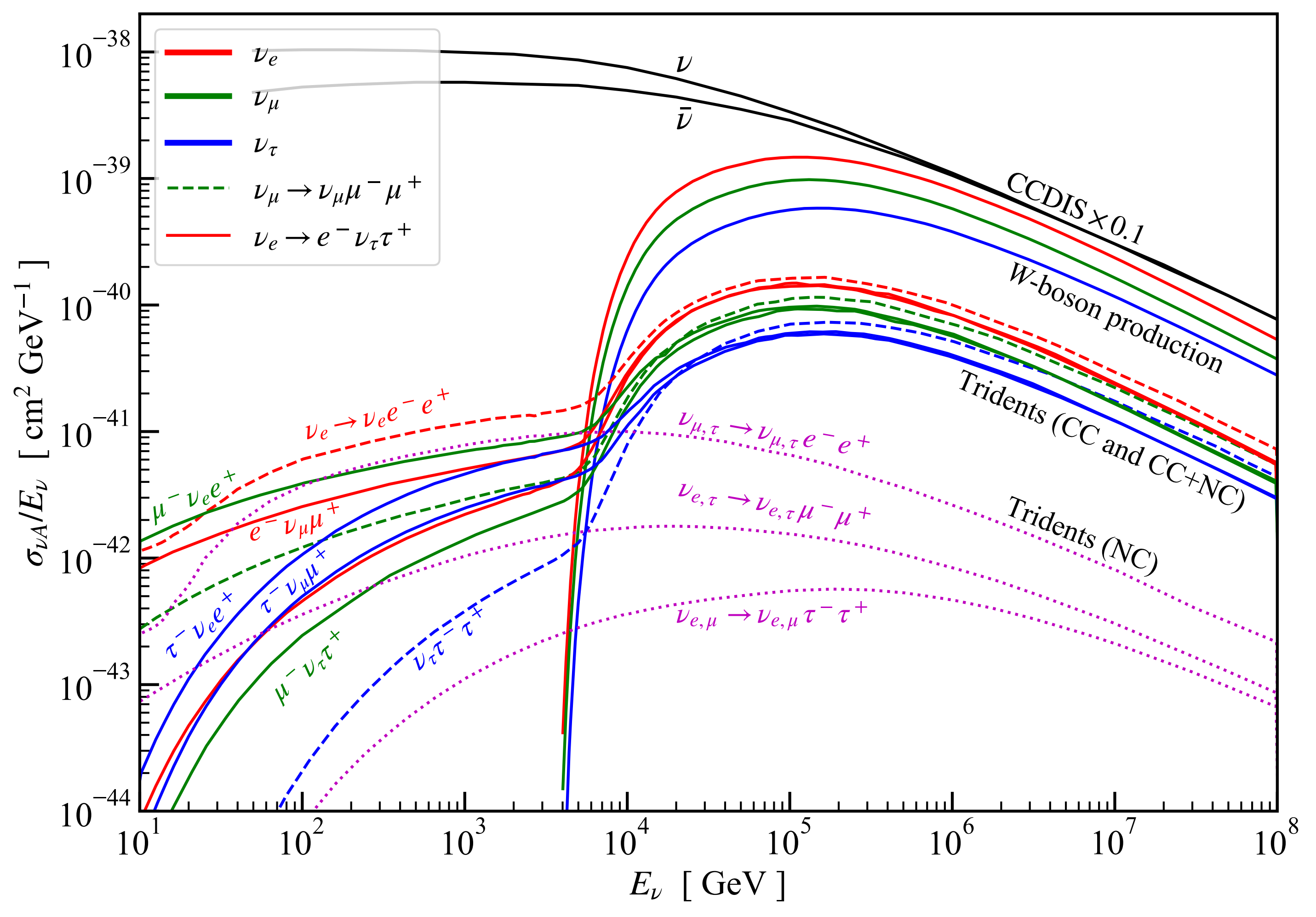
Charged current

Neutral current



Xie et al. (CTEQ collaboration) 2303.13607

Total neutrino-nucleus (Oxygen) cross section

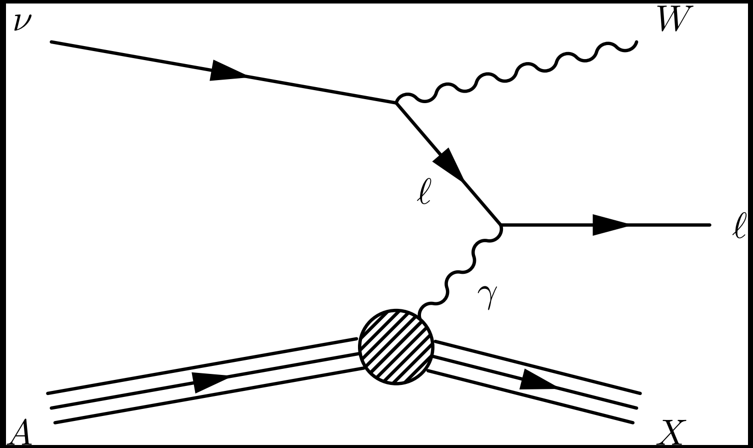


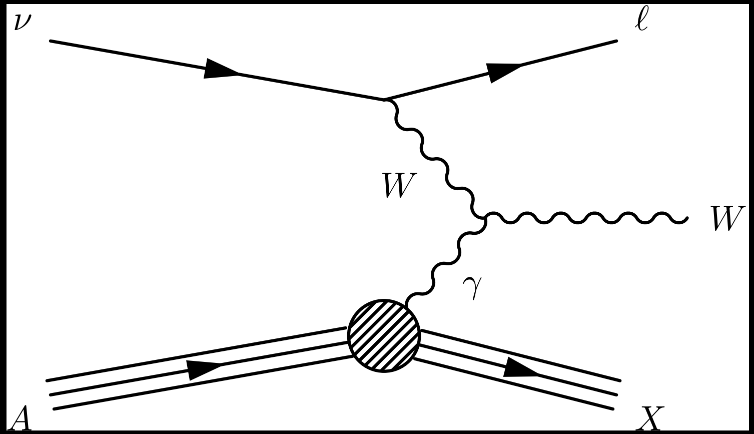
(BZ, Beacom, 1910.08090)

W-boson production:
First comprehensive calculation

Tridents:
First calculation at TeV—PeV

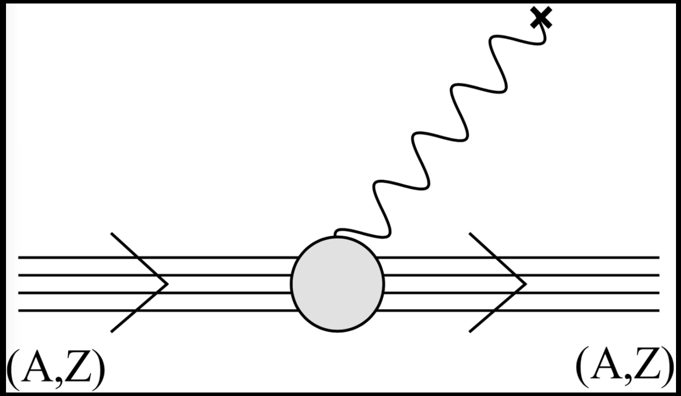
Subdominant interactions: W-boson production



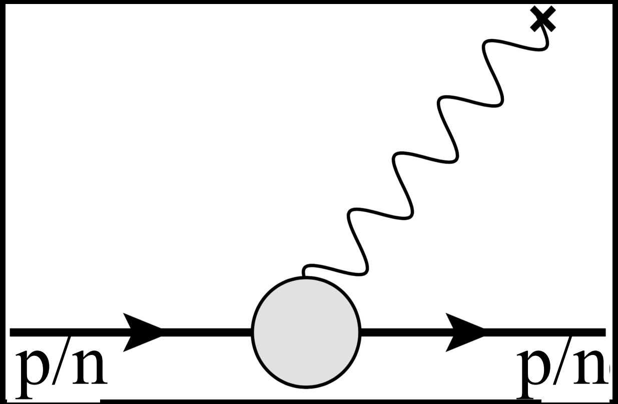


Three kinematic regimes

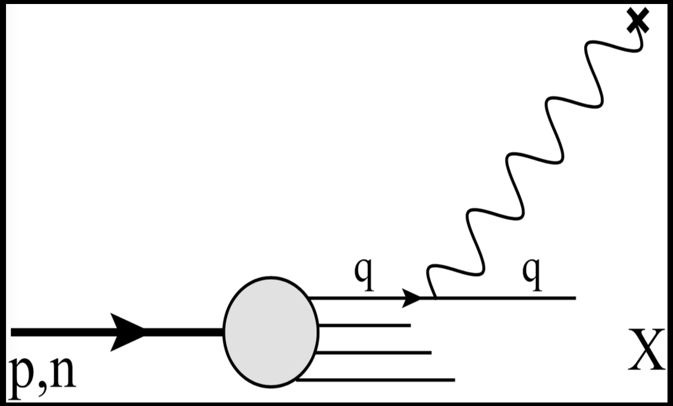
Coherent (elastic)



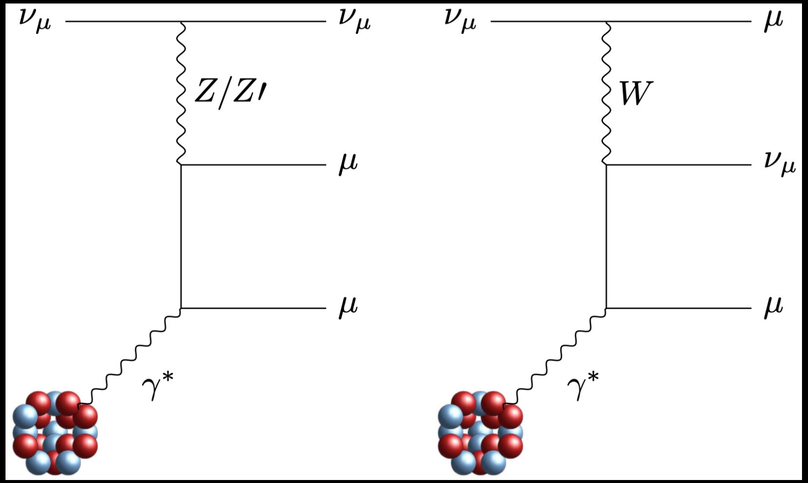
Diffractive (elastic)

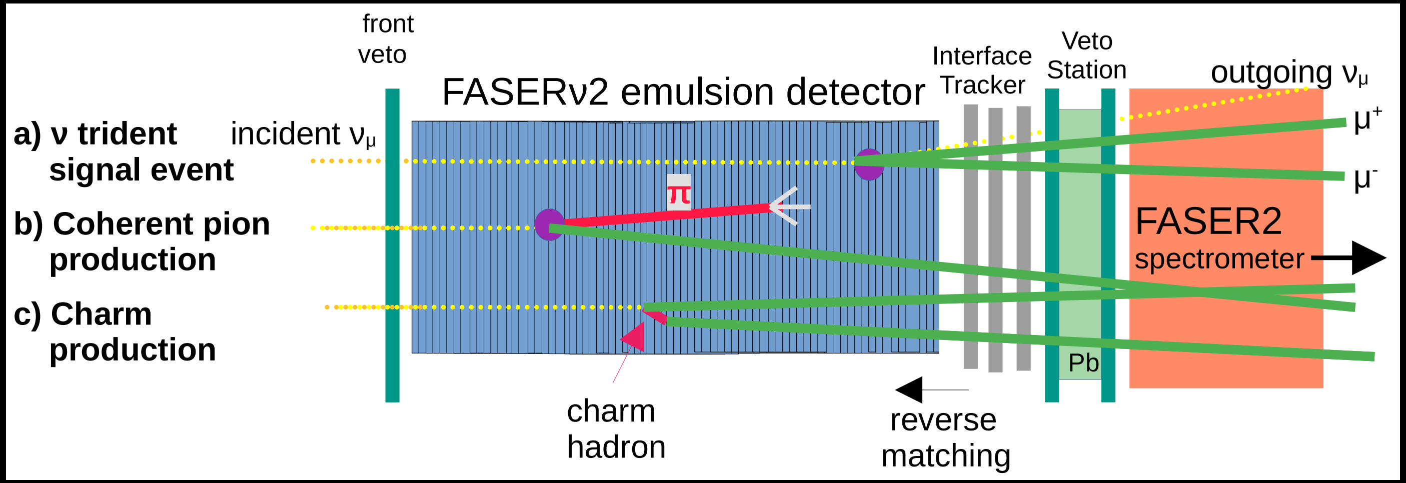


Inelastic



A bit more about FASERnu, tridents discovery (not about FSR)





Previous experiments:
CHARM-II and CCFR (1990s)
only had significance of ~3σ.

FASERnu2, proposed, High-Luminosity LHC era.
Preliminary results:
Tridents signal (μ μ): ≃40
Background: ≃4(+3-1)
Significance: ≃10(+2.5-3)σ

(Altmannshofer, Makela, Sarkar, Trojanowski, Xie, BZ, in prep)
Stay tuned!