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Final State Radiation And (Ultra)High Energy Neutrinos

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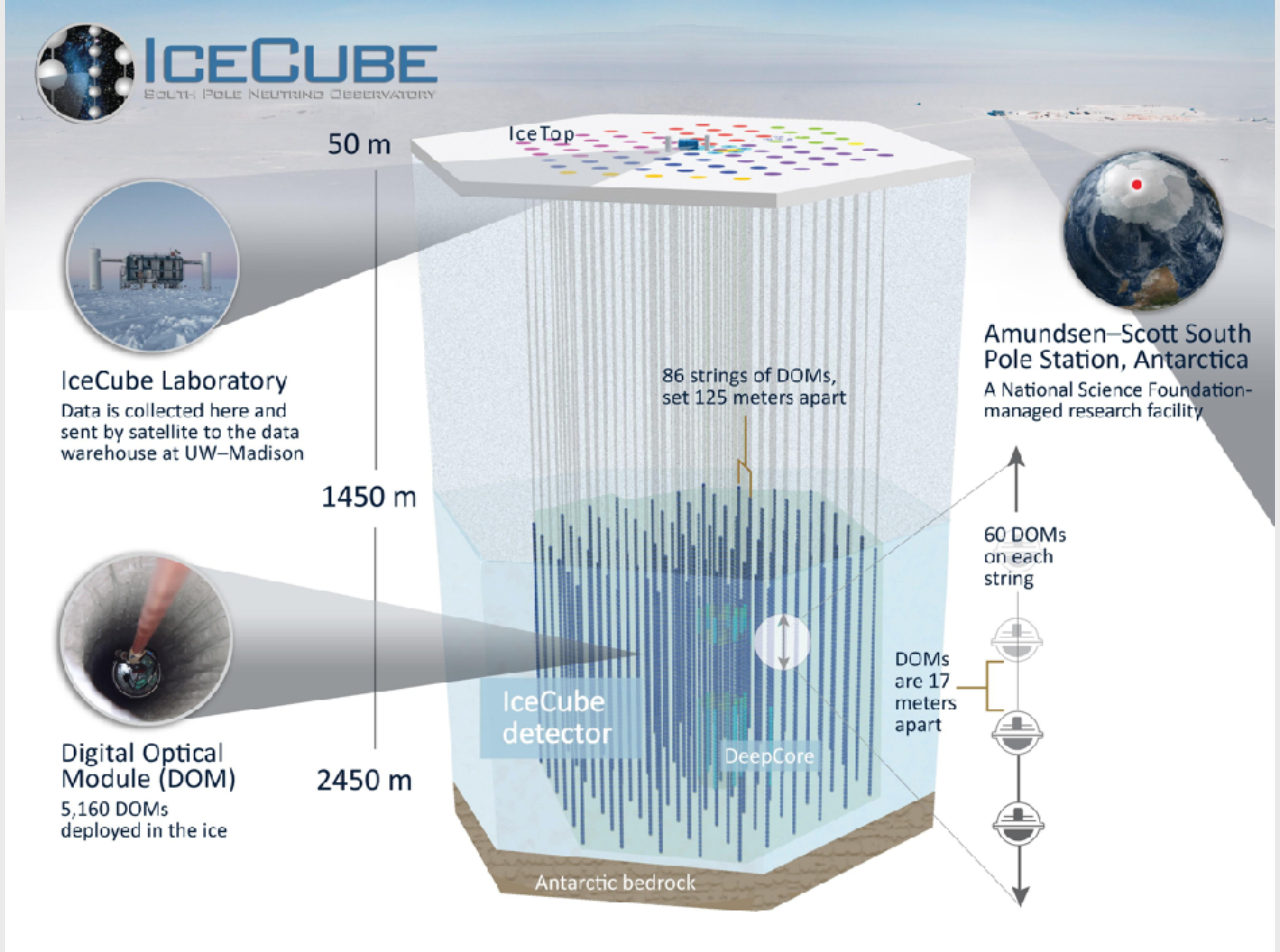
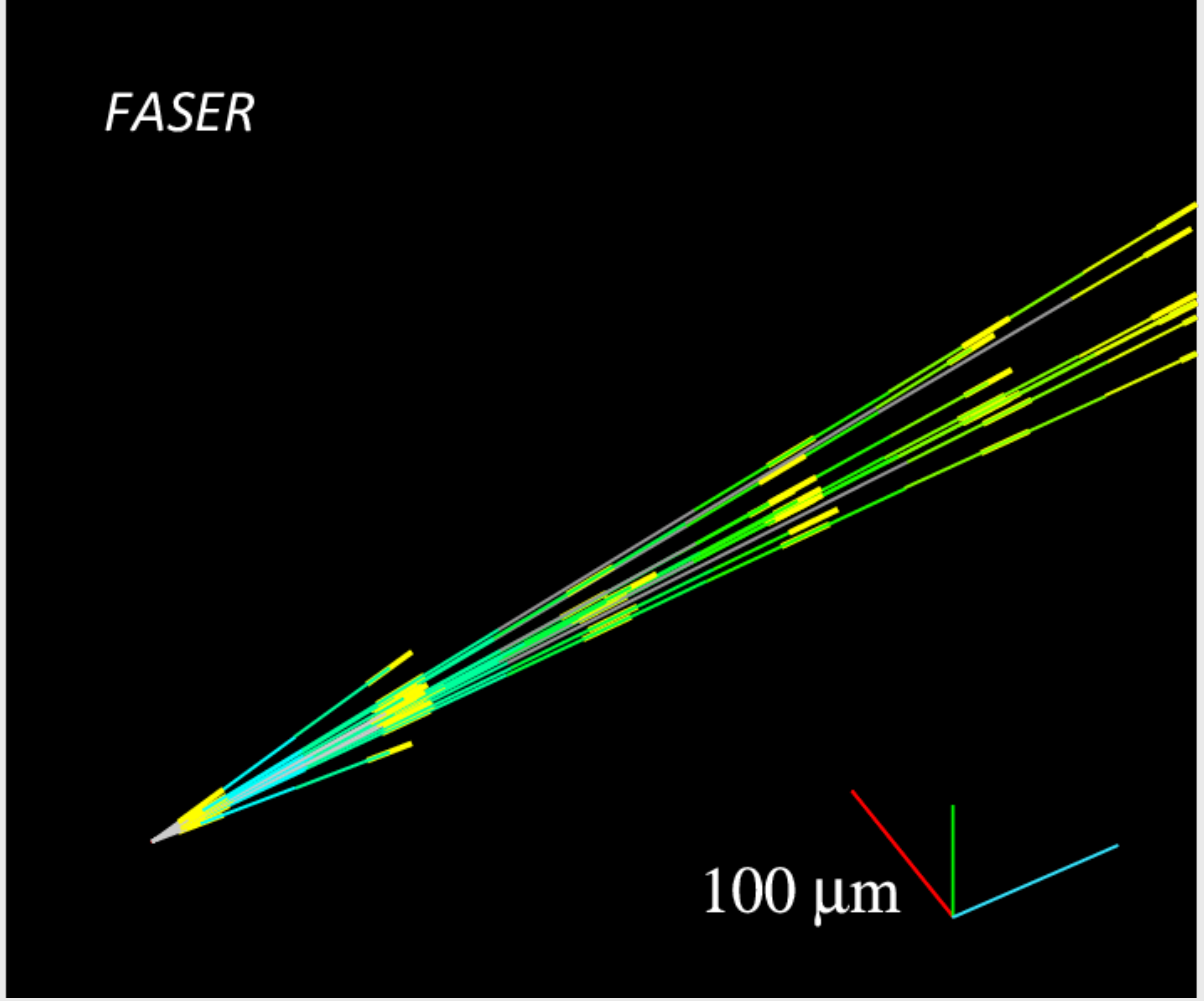
Caltech

Neutrino Theory Network





Motivation & Context

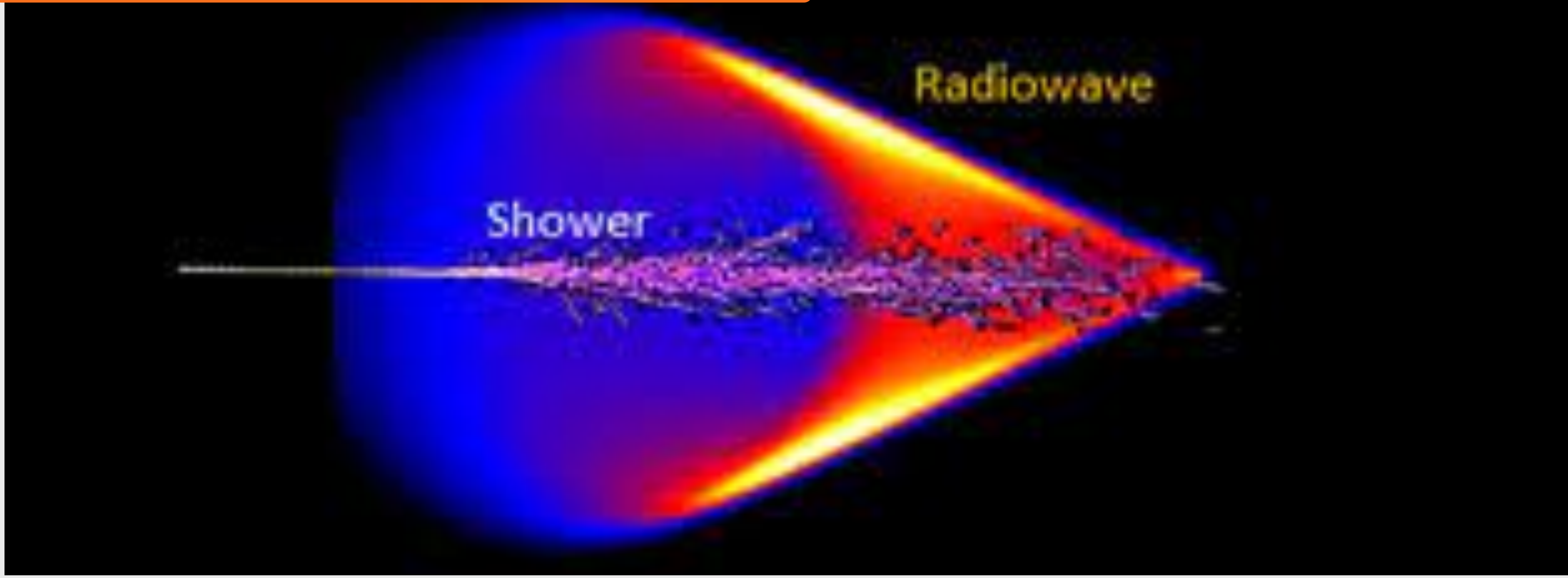
MULTI-MESSENGER ASTRONOMY

- Neutrinos are an increasingly important for astrophysics.
- Neutrino interactions are crucial to interpret data.

HIGH ENERGY NEUTRINO TELESCOPES

- Neutrinos offer a "sterile" messenger of astrophysical phenomena.
- IceCube Gen-2 will instrument a very large area,
- Few singlet operators available.
  Focus on "portals".

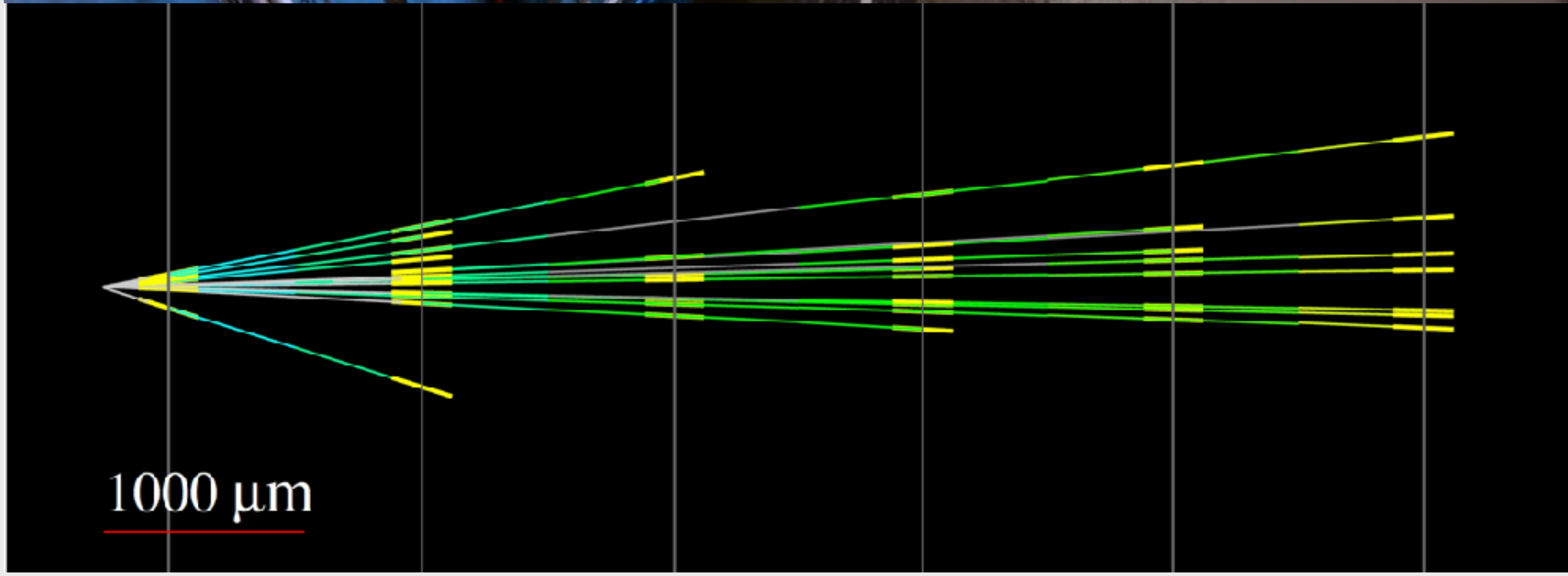
ULTRAHIGH ENERGY NEUTRINO DETECTION



- Ultra high energy neutrinos (above 100 PeV) are difficult to study due to their much smaller flux.
- Near-term telescopes/facilities planned.
- Use very different detection strategies.

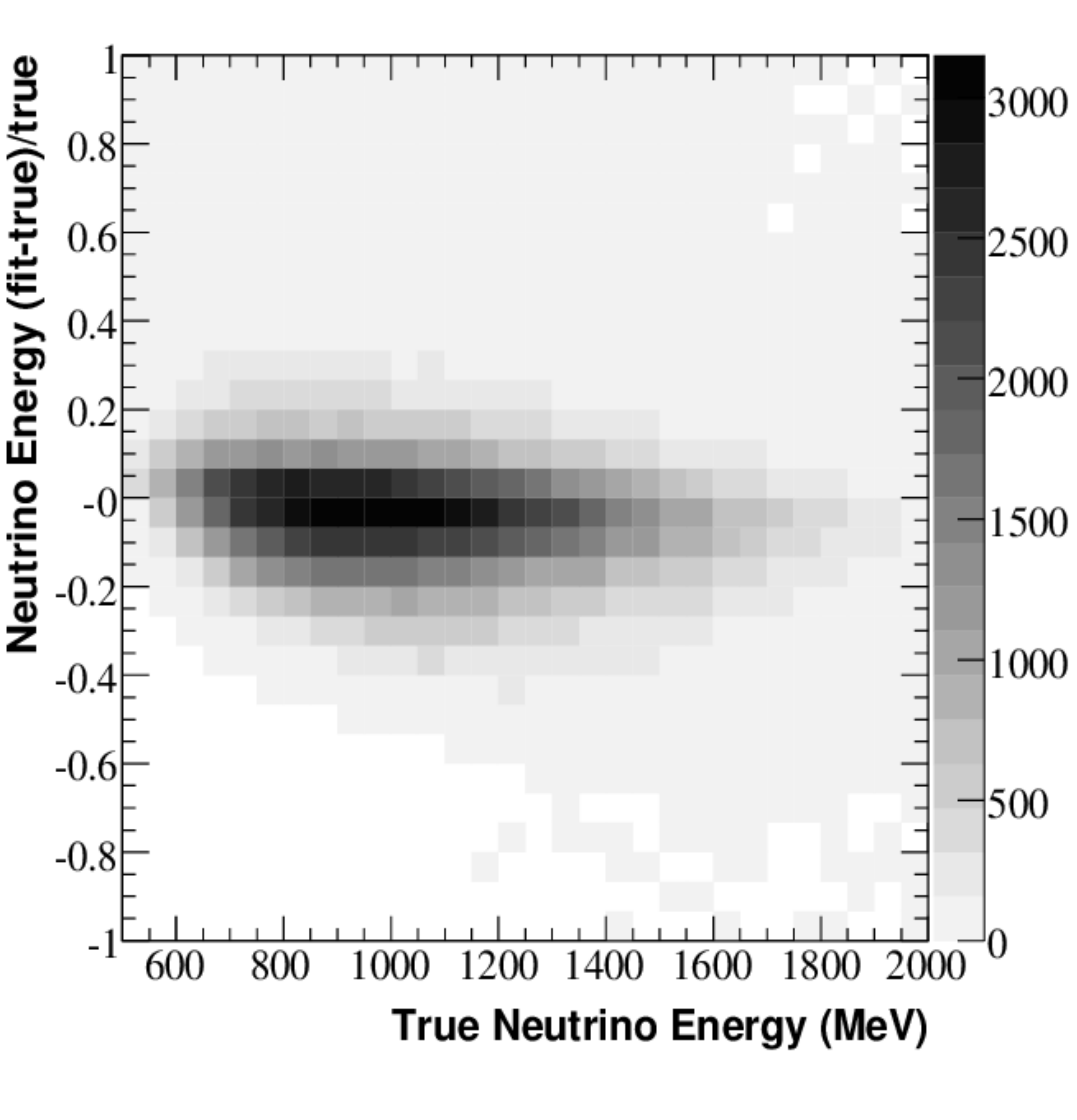
COLLIDER NEUTRINOS

- New collider based experiments at the LHC.
- Lab-measurements of ~TeV neutrino energies.
- Granular detectors with high vertex resolution.



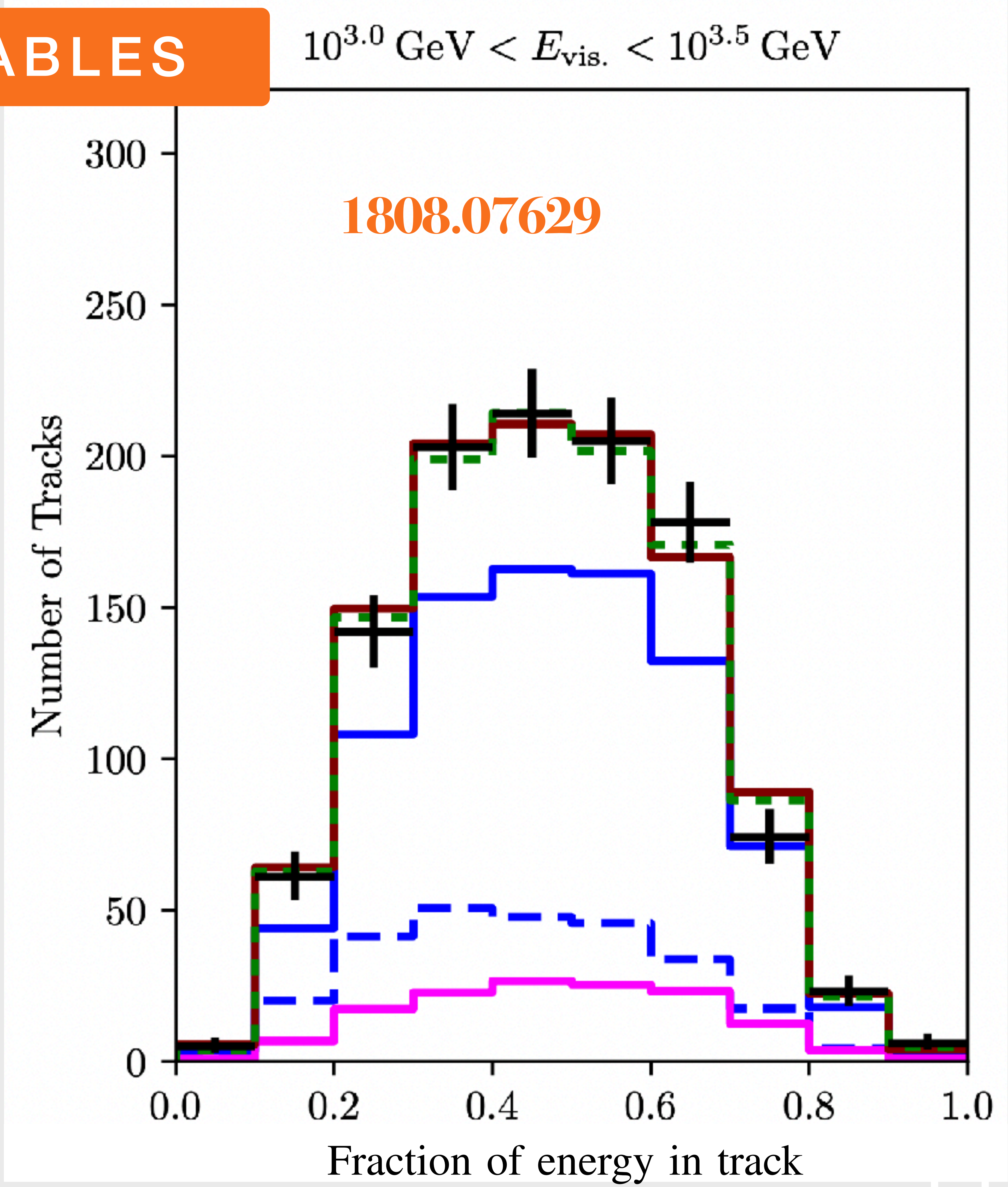
ENERGY ESTIMATORS

- Estimating the parent neutrino energy is important for all experiments.
- Any effect which causes a systematic bias in energy reconstruction is important.
- Photons and muons "look" very different in a detector.



INCLUSIVE VS EXCLUSIVE OBSERVABLES

- Data sets are growing and can bin events.
- Differential distributions with respect to e.g. lepton energy.
- Goal of ~10% accuracy as a heuristic benchmark.



Radiative Corrections : The Basics

OLD IDEA

USE SPLITTING FUNCTION

NEW APPLICATIONS

Nuclear Physics B154 (1979) 394–426

RADIATIVE CORRECTIONS TO HIGH-ENERGY NEUTRINO SCATTERING

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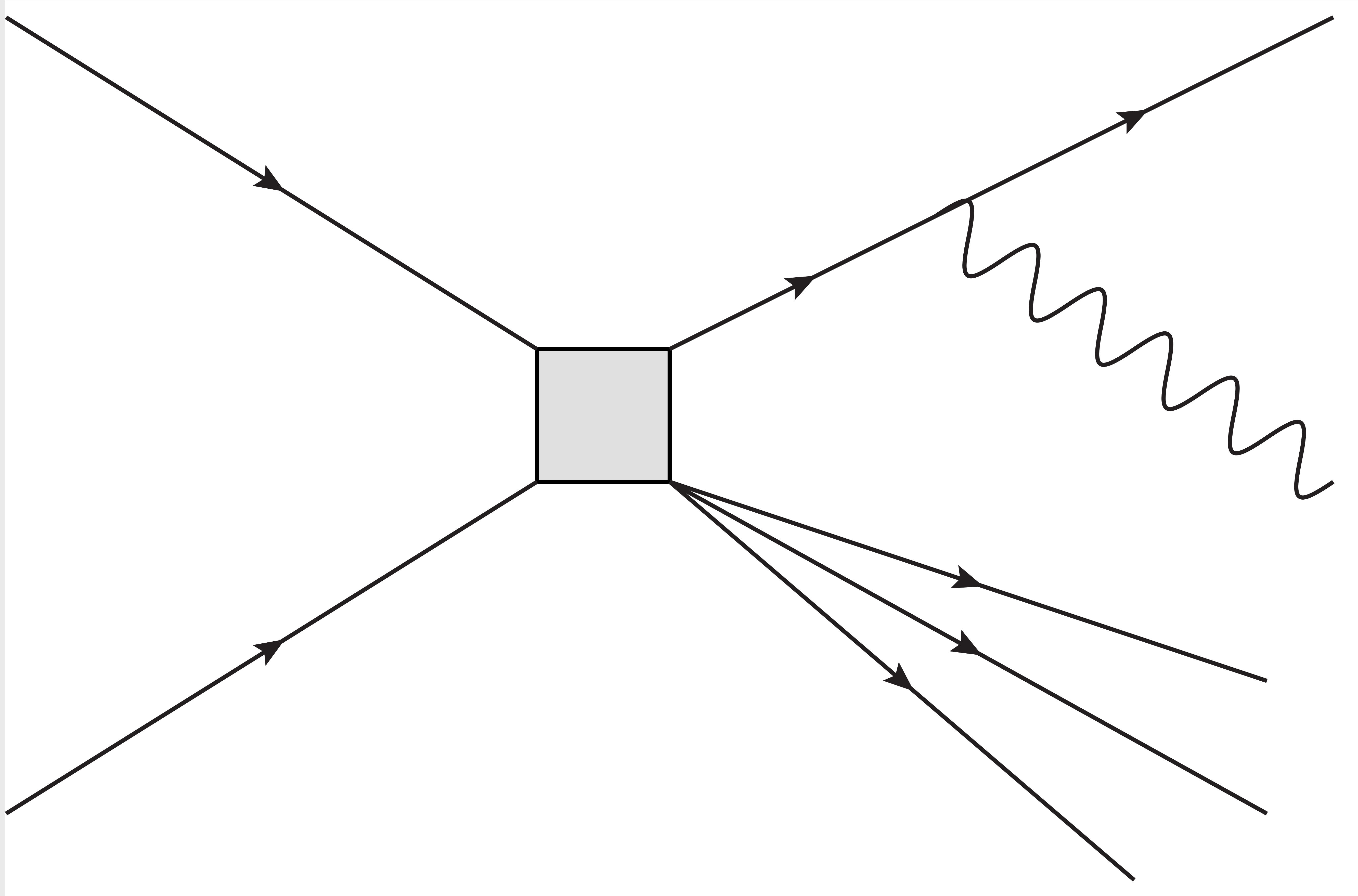
Received 19 January 1979

REAL PHOTON EMISSION

- Lepton radiates a photon.

$$\frac{1}{2p\cdot q+q^2}\to\frac{1}{2p\cdot q}$$

$$\int\frac{d^3q}{2E_q}|\mathscr{M}|^2\sim\int\frac{d\omega}{\omega}$$



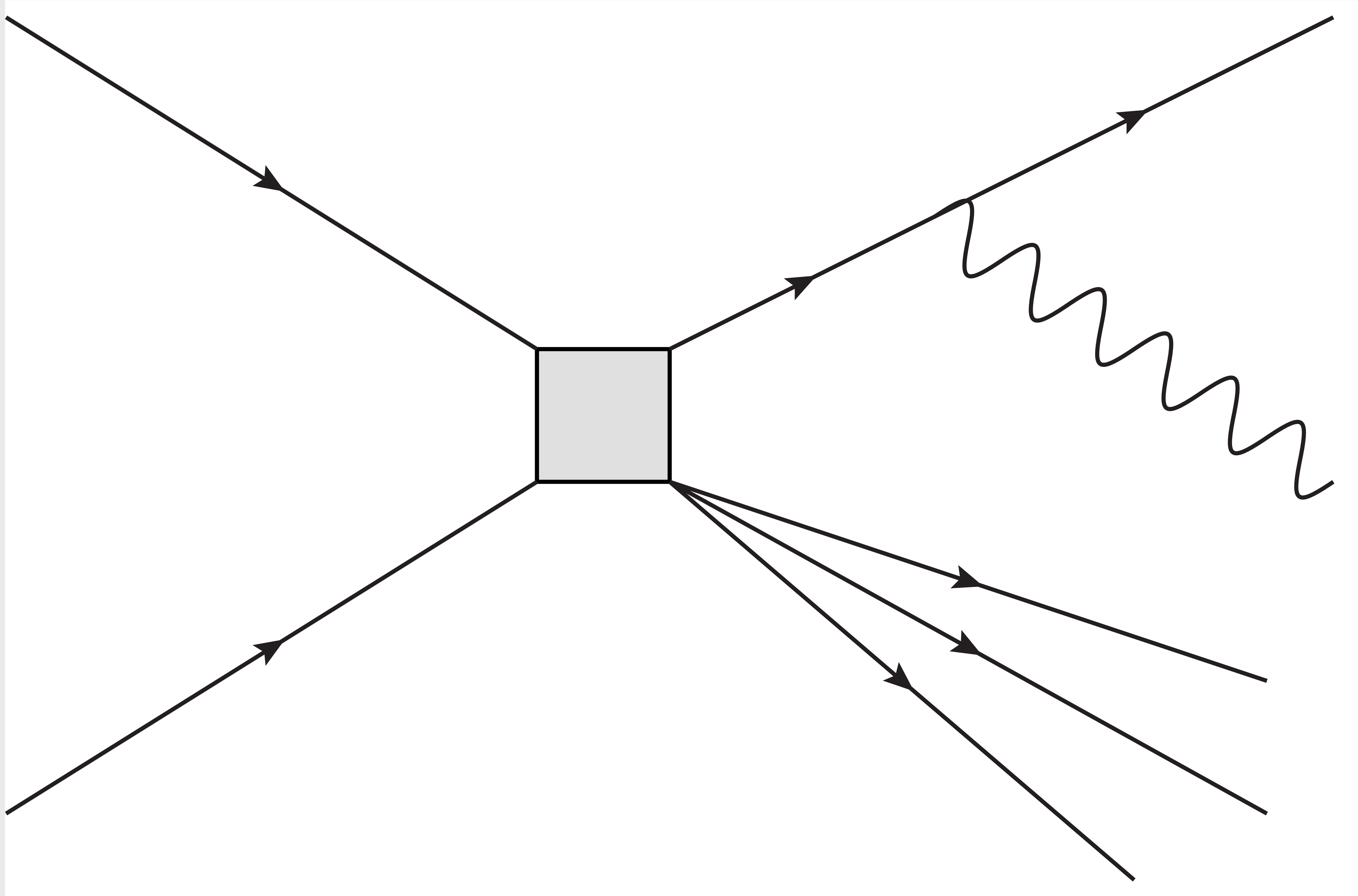
- Infrared divergence

REAL PHOTON EMISSION

- Lepton radiates a photon.

$$\frac{1}{2p \cdot q + q^2} \to \frac{1}{2p \cdot q}$$

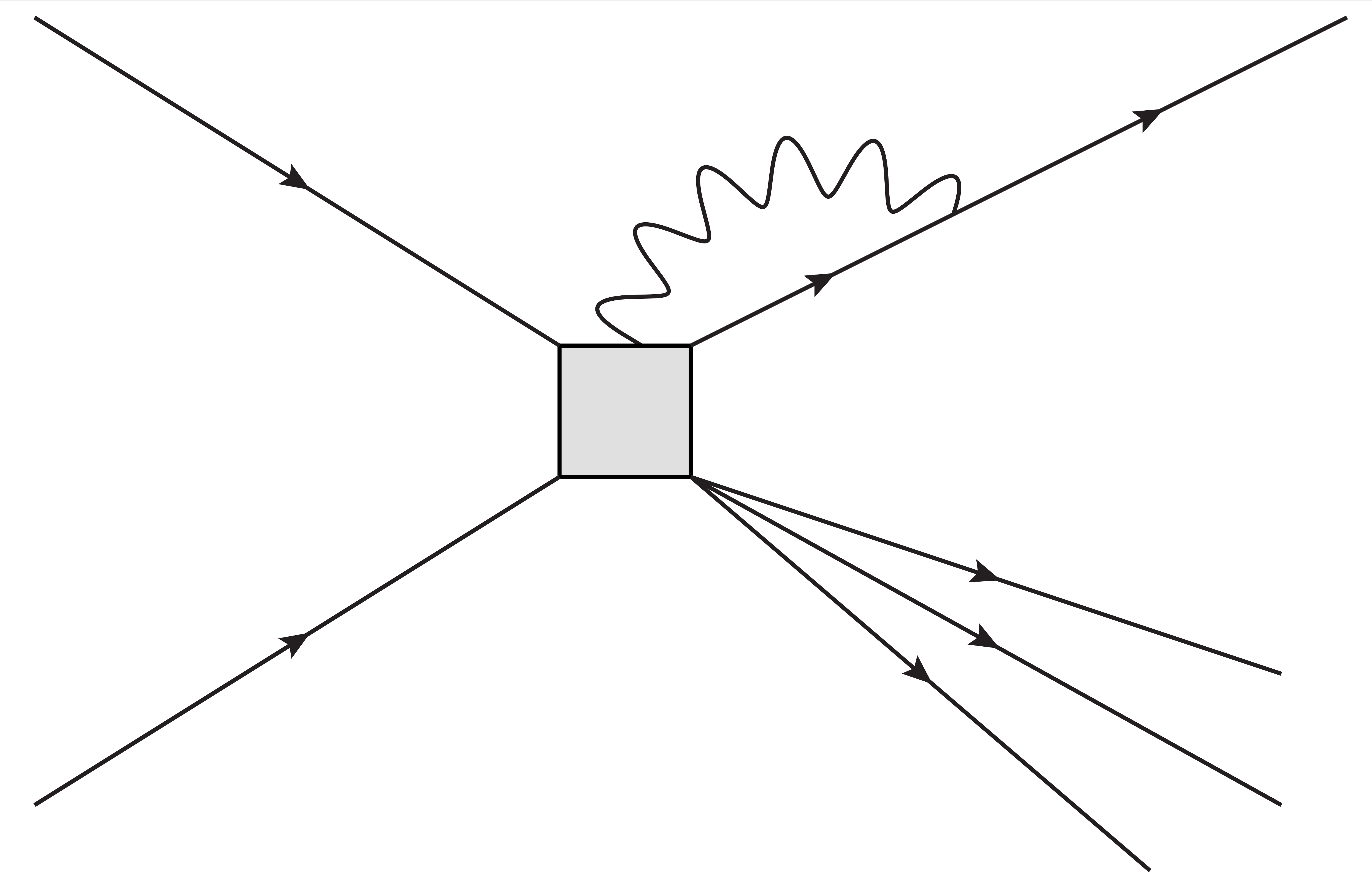
$$\int \frac{\mathrm{d}^3 q}{2E_q} |\mathscr{M}|^2 \sim \int \frac{\mathrm{d}\theta^2}{\theta^2 + m_\ell^2}$$



- Collinear divergence

VIRTUAL CORRECTIONS

- In addition to diagrams where a photon is explicitly radiated, we have to include corrections to the process where no photon is radiated.
  - These diagrams ***decrease*** the cross section.



CANCELS AGAINST REAL RADIATION CONTRIBUTION

REAL + VIRTUAL CORRECTIONS

- KLN Theorem implies that IR divergences must cancel between real and virtual corrections.
- Implies the same for collinear divergences.

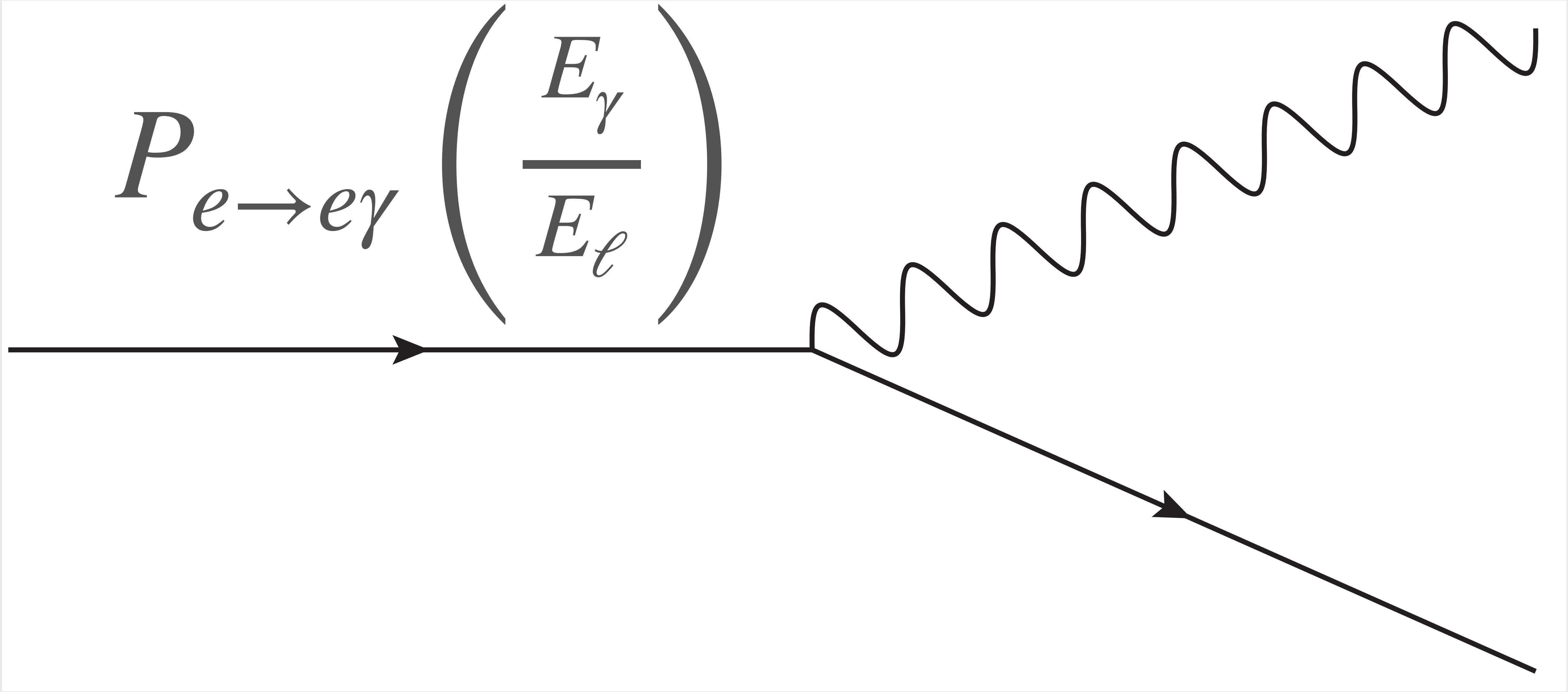
$$\mathrm{d}\sigma = \mathrm{d}\sigma^{(0)} + \left(\mathrm{d}\sigma_R^{(1)} + \mathrm{d}\sigma_V^{(1)}\right) + \ldots$$

$$\int \mathrm{d}\Pi \ \mathrm{d}\sigma_R^{(1)} + \mathrm{d}\sigma_V^{(1)} = O\left(\frac{\alpha}{4\pi}\right)$$

IR AND COLLINEAR DIVERGENCES ARE RELATED

SPLITTING FUNCTIONS

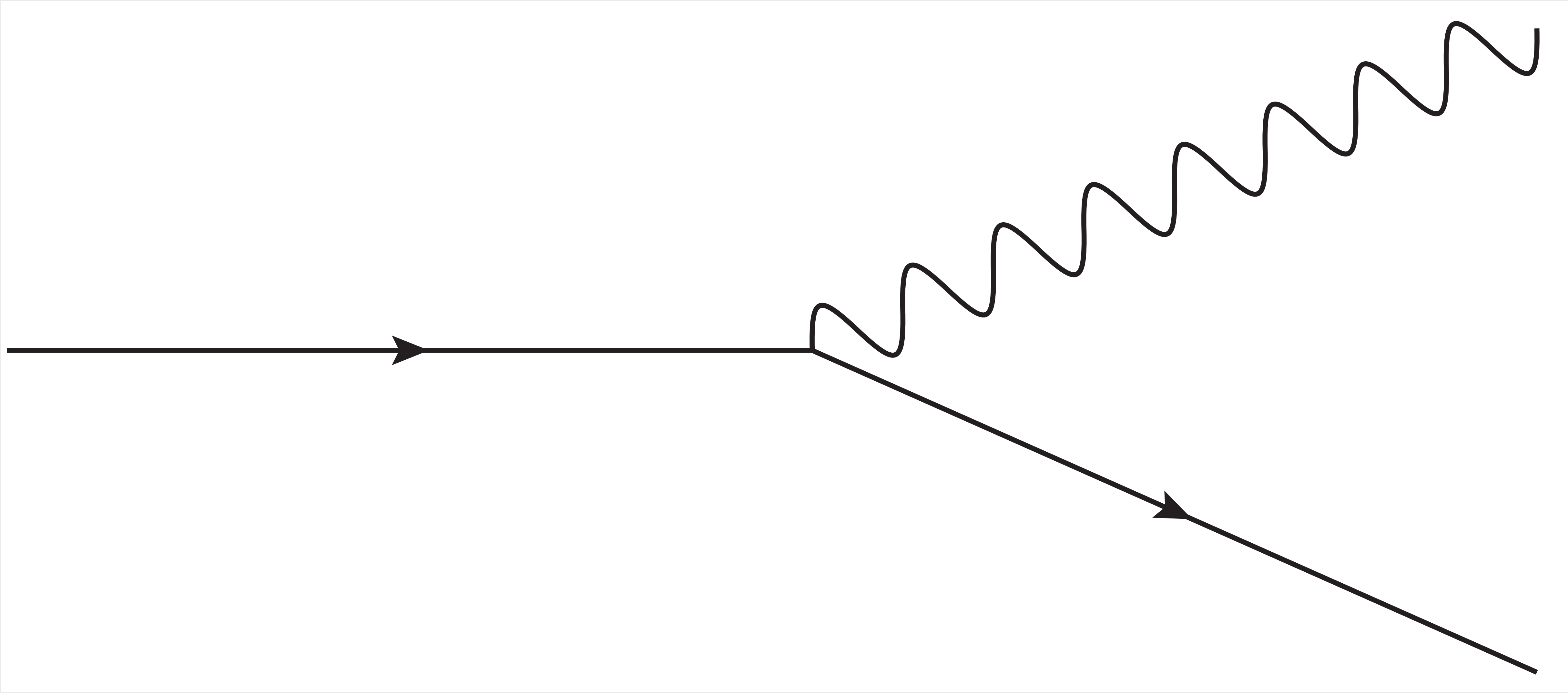
- We can use a calculation of real radiation to predict logarithmically enhanced parts of virtual correction.
- Result is effectively classical.
- Think of electron as having a distribution of QED-partons.



SPLITTING FUNCTIONS

- We can use a calculation of real radiation to predict logarithmically enhanced parts of virtual correction.

$$\mathrm{d}\sigma_V^{(1)} \simeq -\int \mathrm{d}\Pi_\gamma \, \mathrm{d}\sigma_R^{(1)}$$



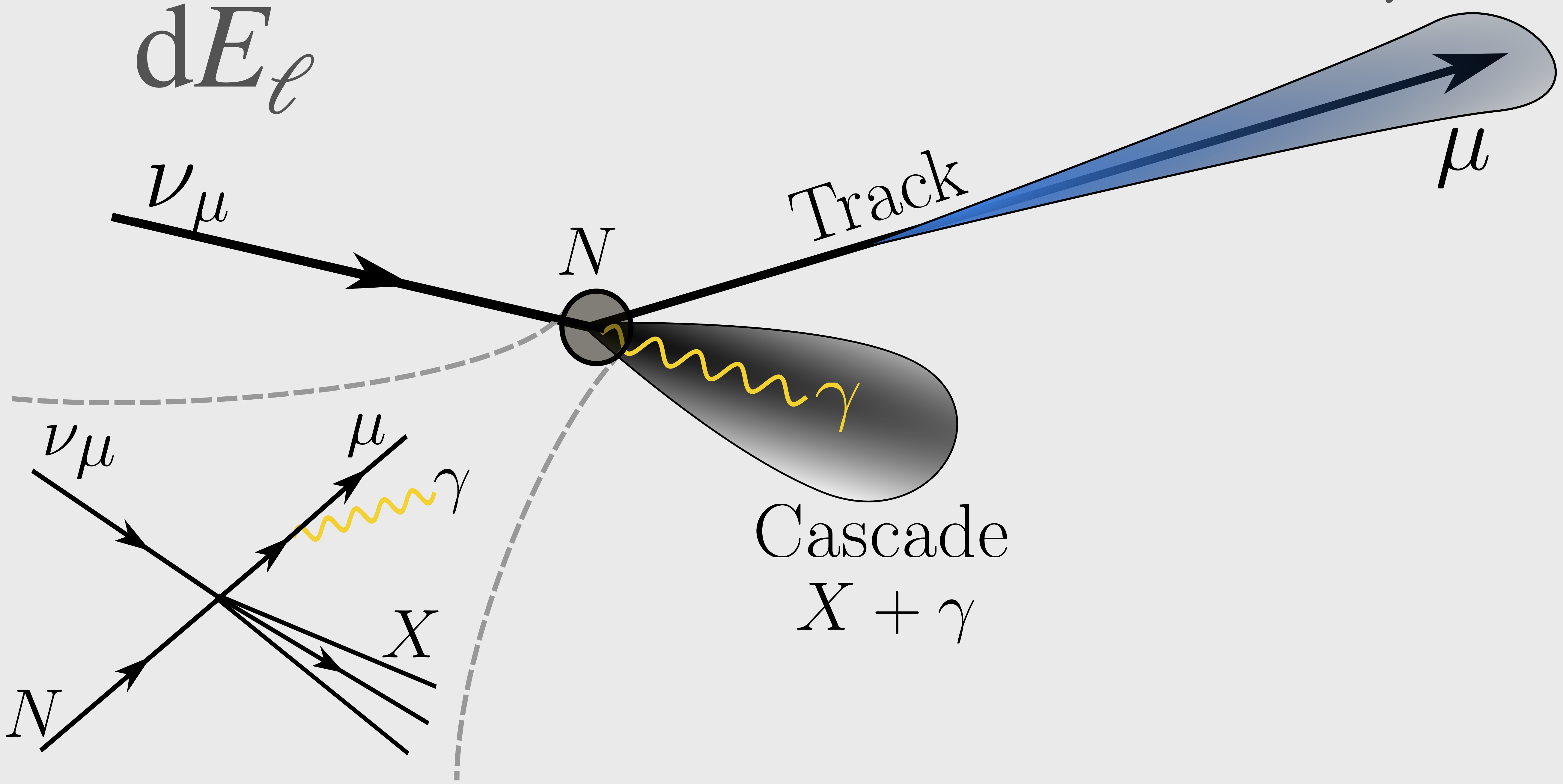
- This works for the largest parts of the corrections (double logs)

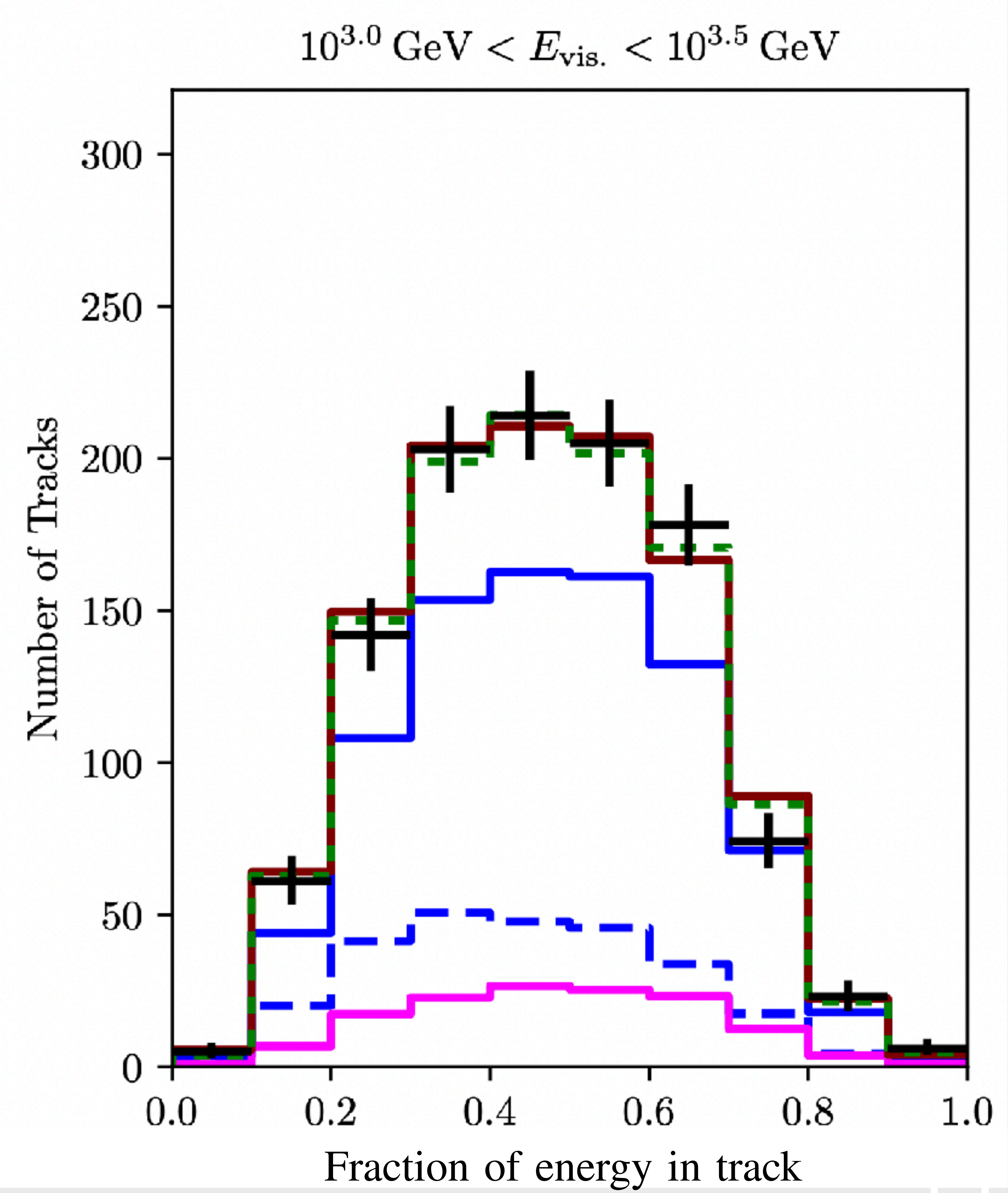
"TRUE" INELASTICITY: INCLUSIVE

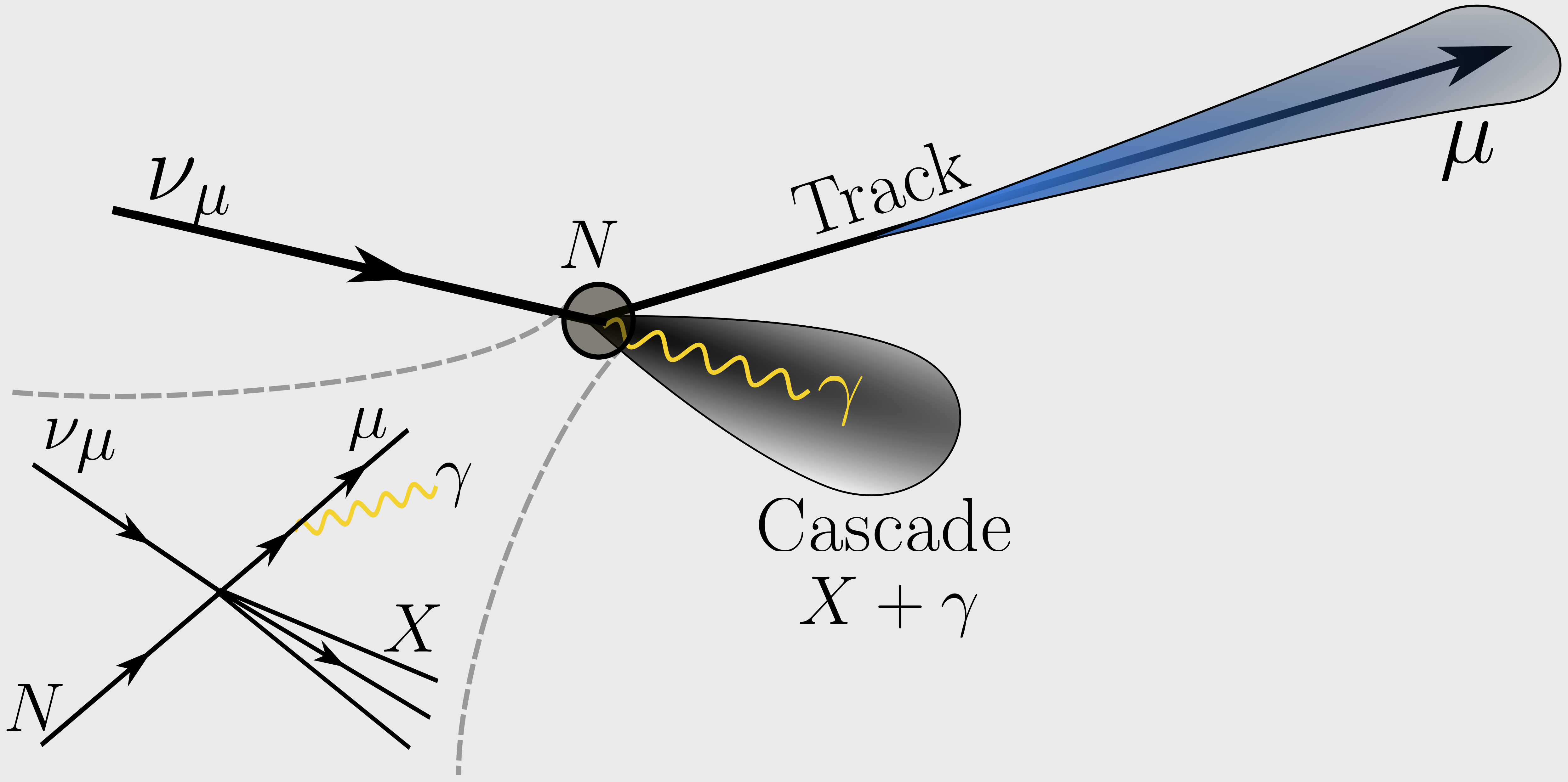
$$\frac{d\sigma}{dy} \qquad y = E_{had}/E_{\nu}$$

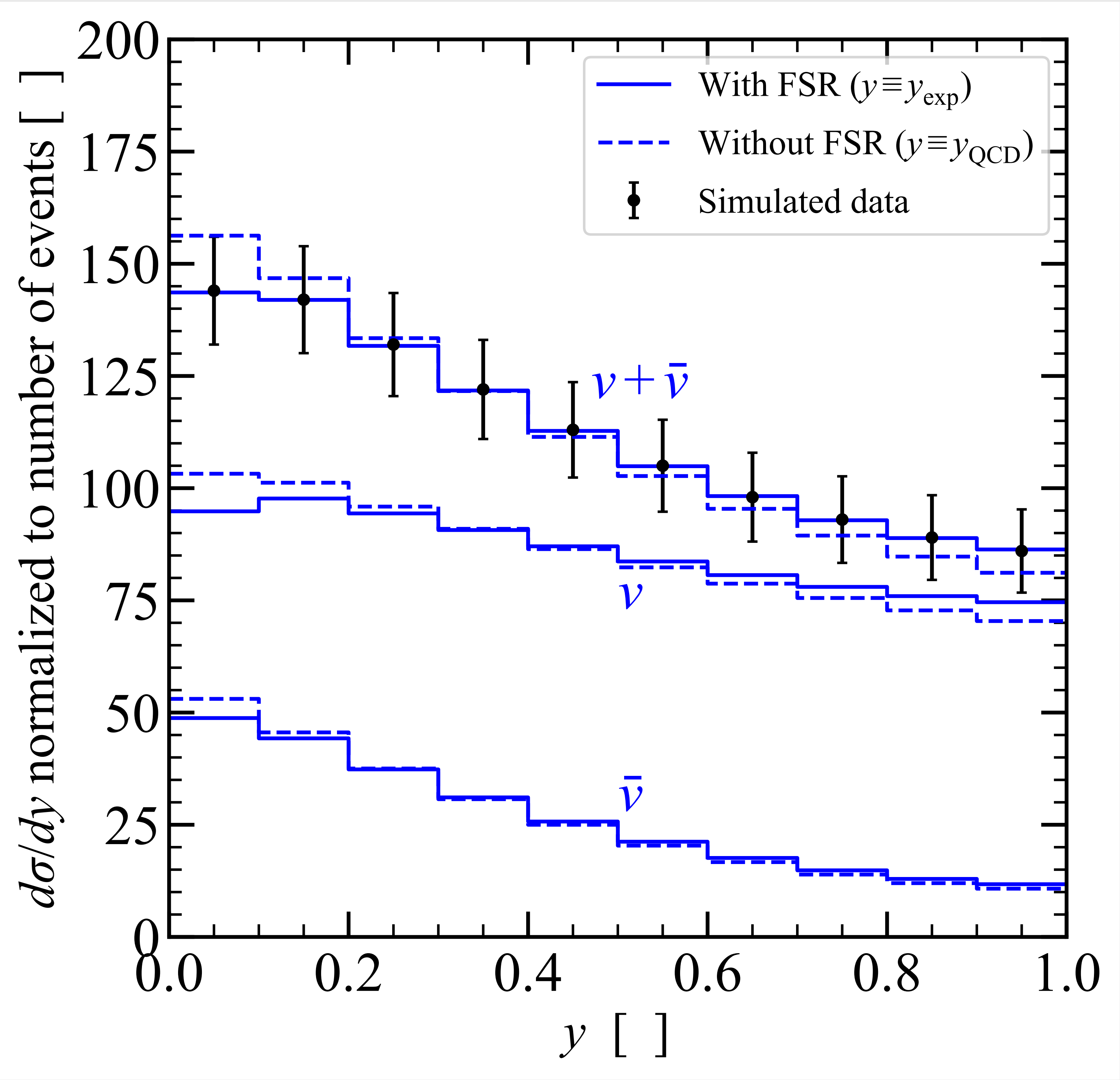
LEPTON ENERGY: EXCLUSIVE

$$\frac{d\sigma}{dE_{\ell}} \qquad E_{\nu} = E_{had} + E_{\ell} + E_{\gamma}$$









Neutrino Applications

TOTAL CROSS SECTIONS

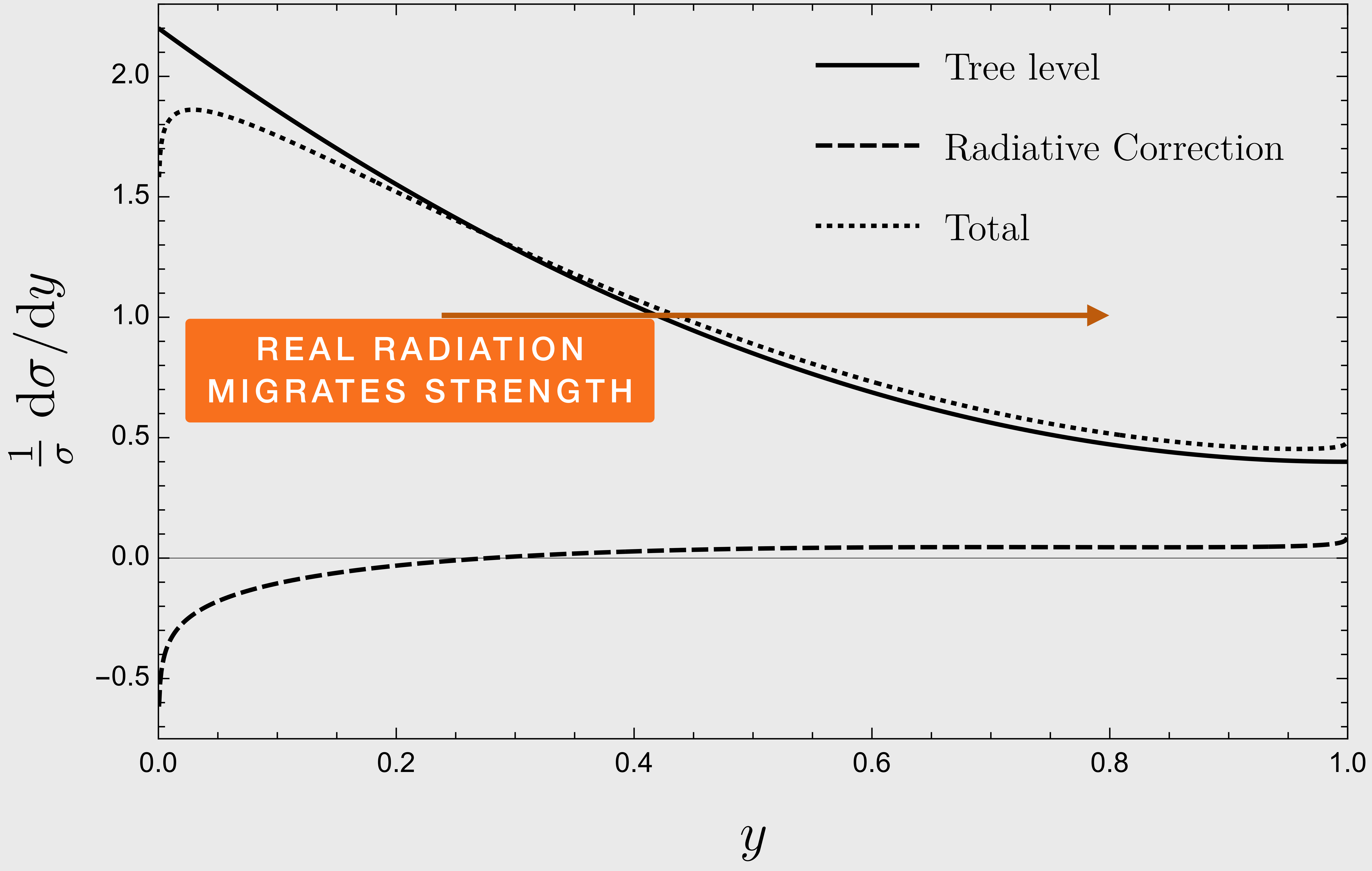
- The total cross section is by definition inclusive, up to very small bits of phase space that fall below detector threshold.
- KLN theorem guarantees that there are no kinematic logs.

RADIATION OFF NUCLEONS

- If radiaton comes from hadrons, then the "cascade" or "shower" topology is completely inclusive.
- We can therefore neglect QED radiative corrections of the nucleon lines.

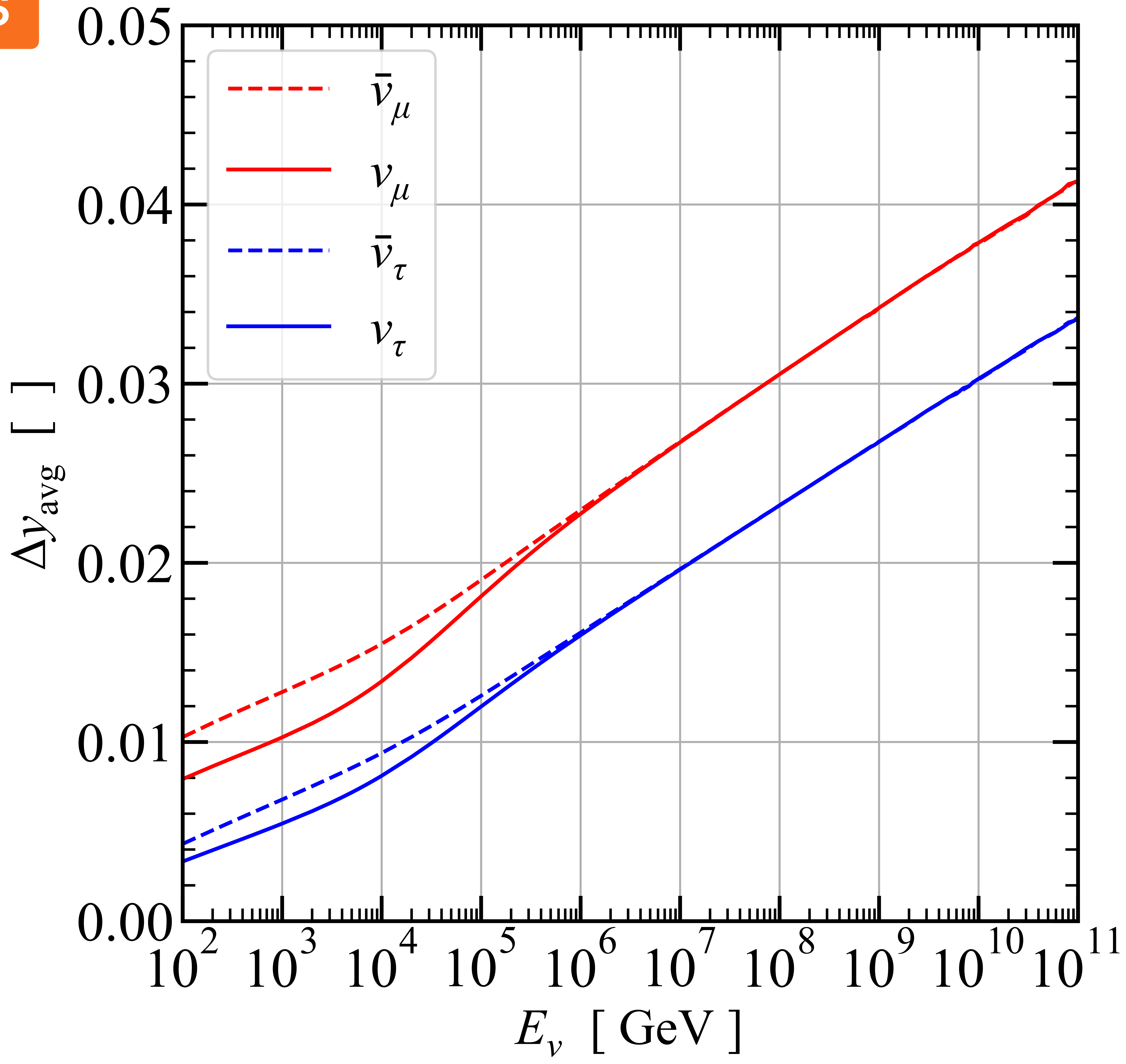
LEPTON ENERGY DISTRIBUTIONS: TOY DISTRIBUTION

- Emitting a photon shifts inelasticity strength.
- Systematically shifts $\langle y \rangle$ to larger values.



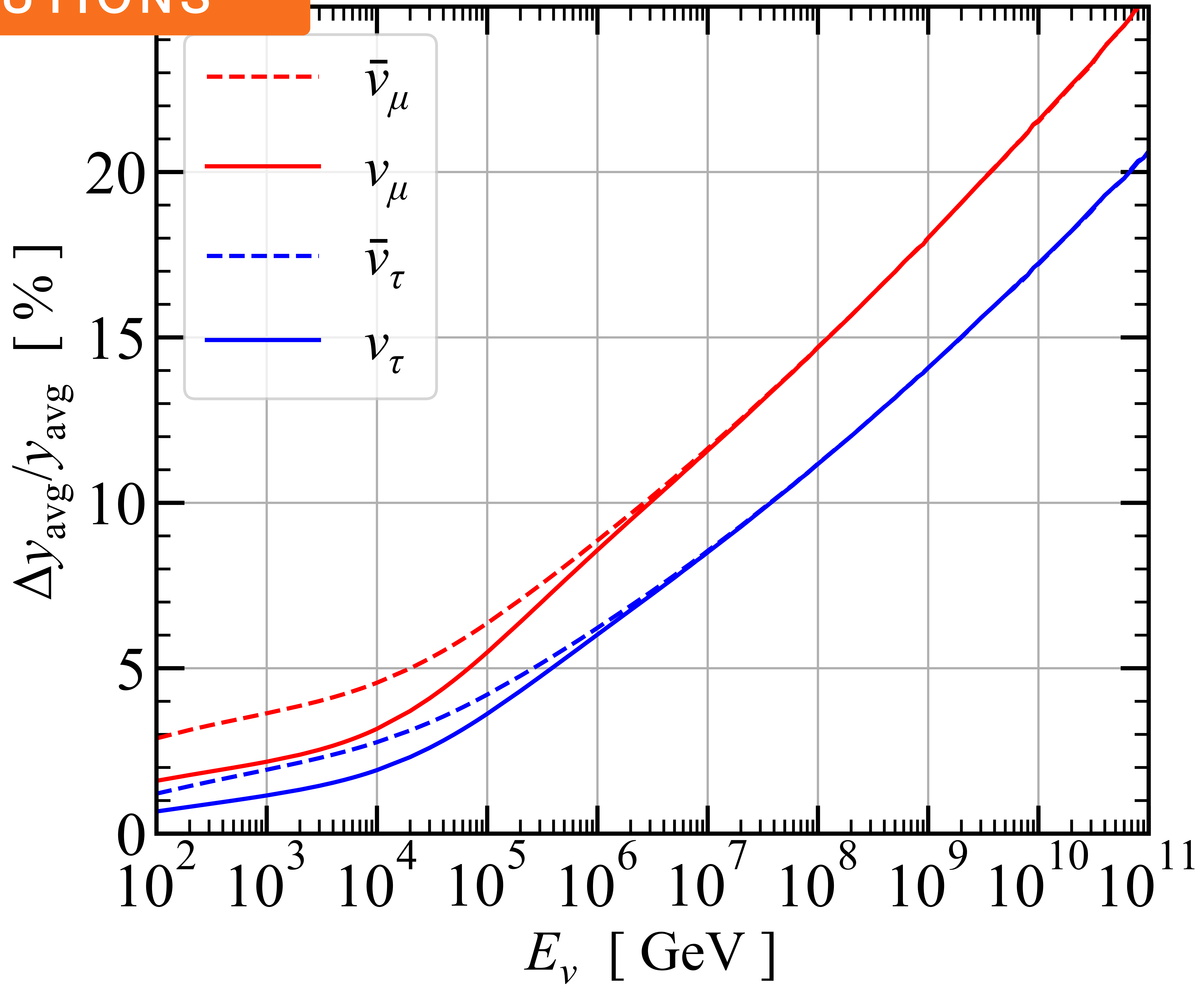
INELASTICITY DISTRIBUTIONS

- Shifts in inelasticity are modest $\delta\langle y \rangle \sim 0.03$
- Approximate size agrees with counting logarithms.



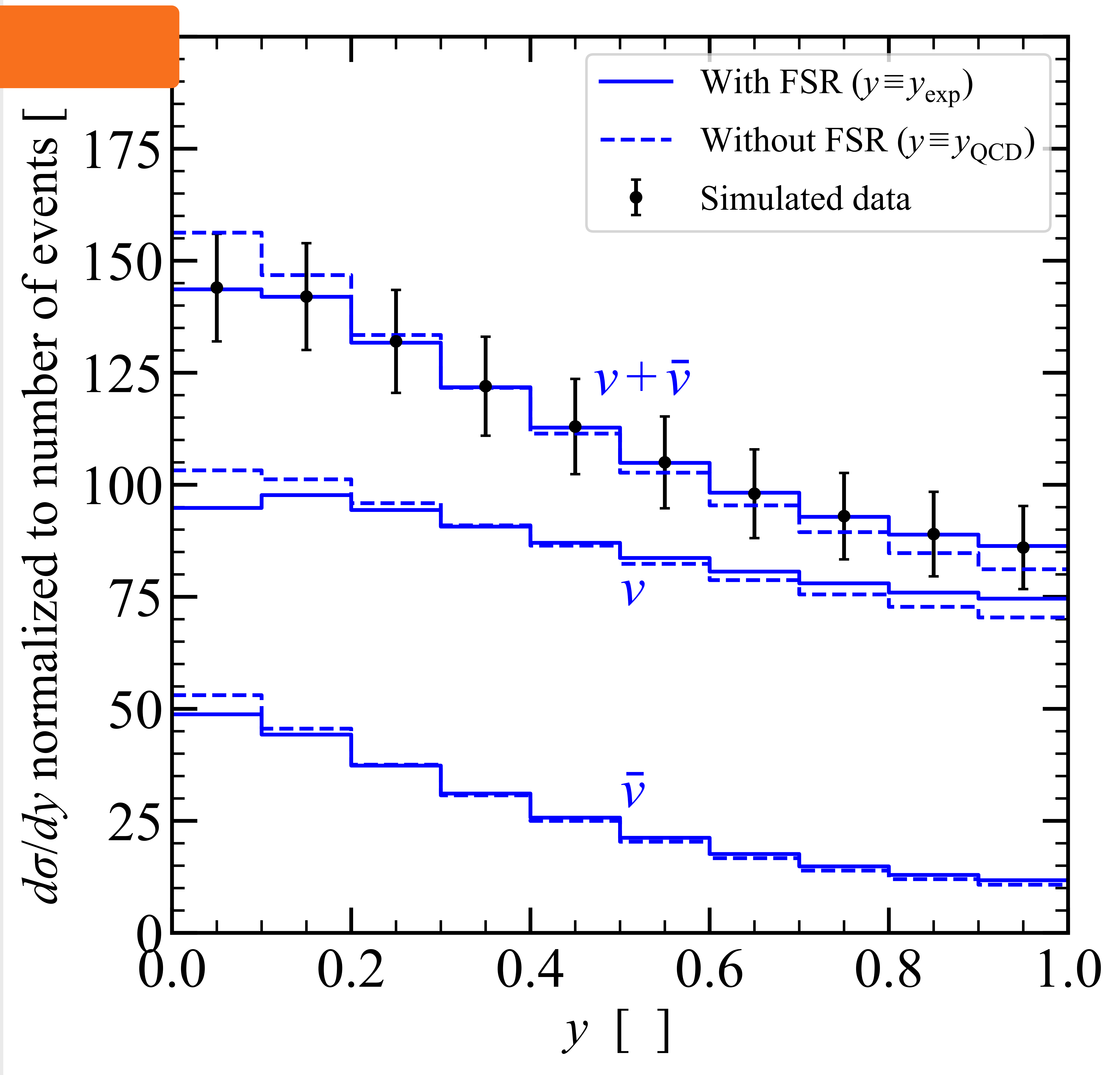
INELASTICITY DISTRIBUTIONS

- In relative terms the shift can be very large.
- This is because $E_\ell \sim 4 \times E_{\rm had}$



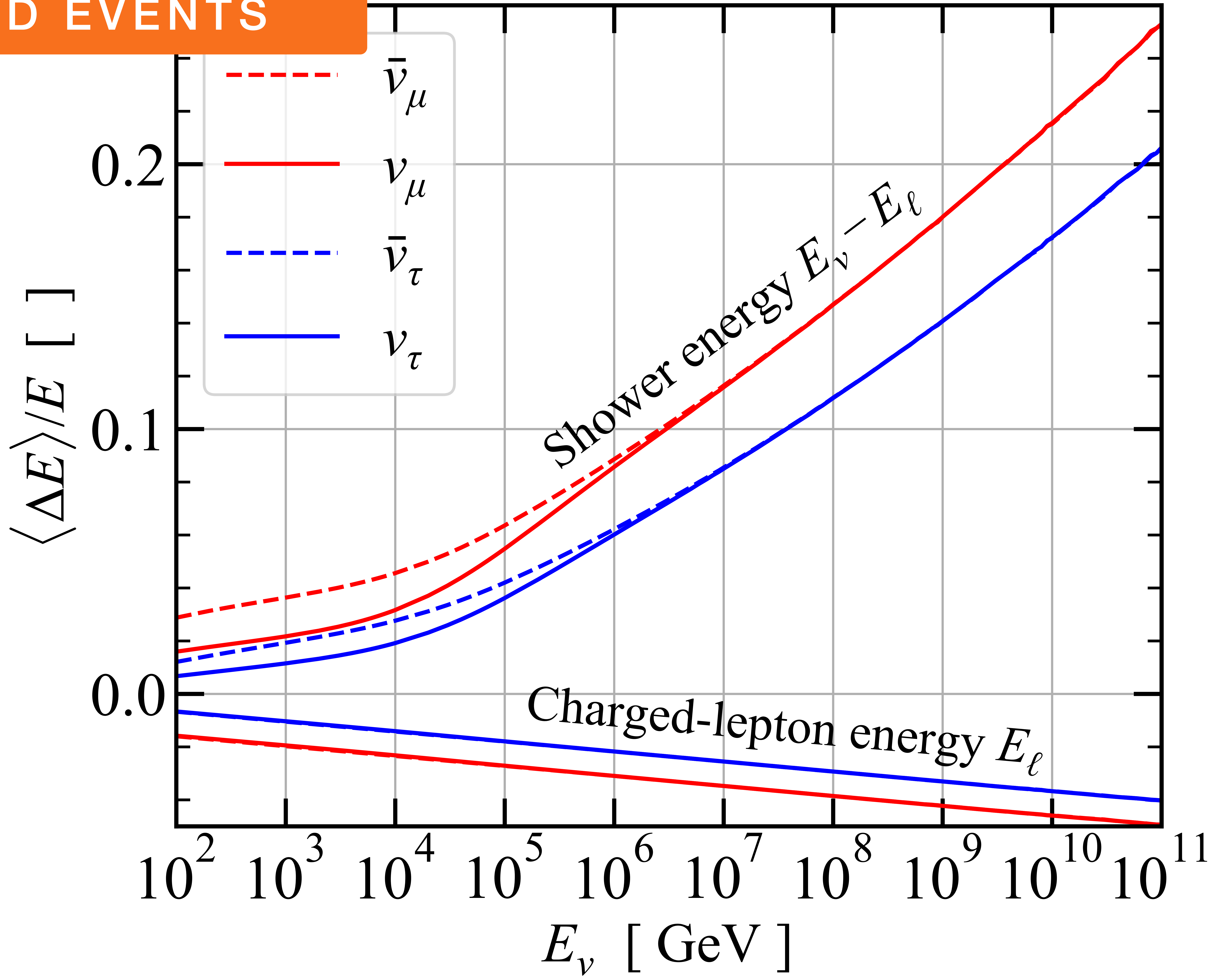
APPLICATION: $\nu/\bar{\nu}$ RATIO

- FSR distorts shape of $\mathrm{d}\sigma/\mathrm{d}y$
- Significant impact for some observables.
- E.g. $\nu/\bar{\nu}$ ratio.
- Sensitive to systematics in y.

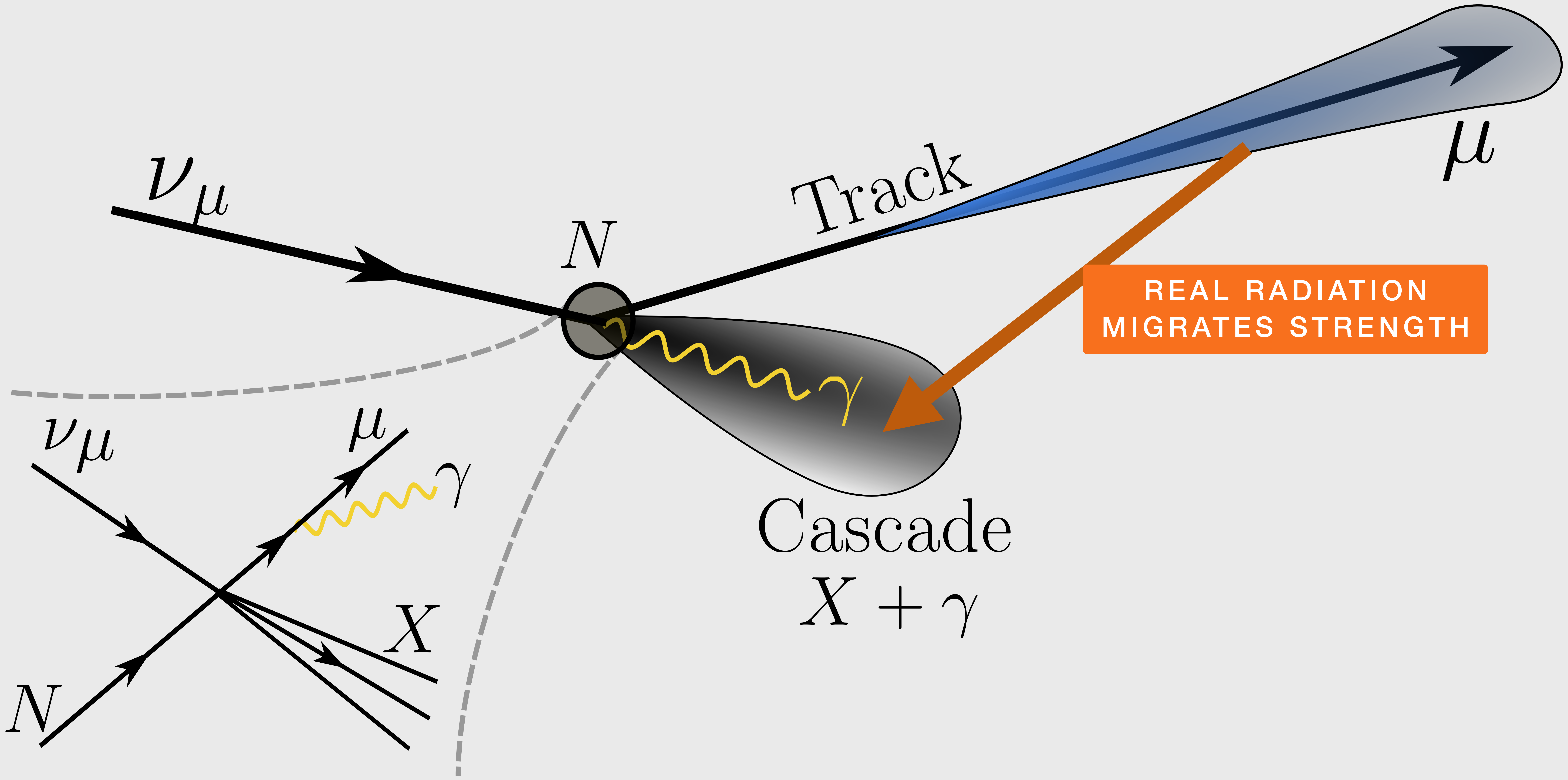


STARTING/CONTAINED EVENTS

- Re-balancing of shower vs track energy.
- Can effect energy estimators.

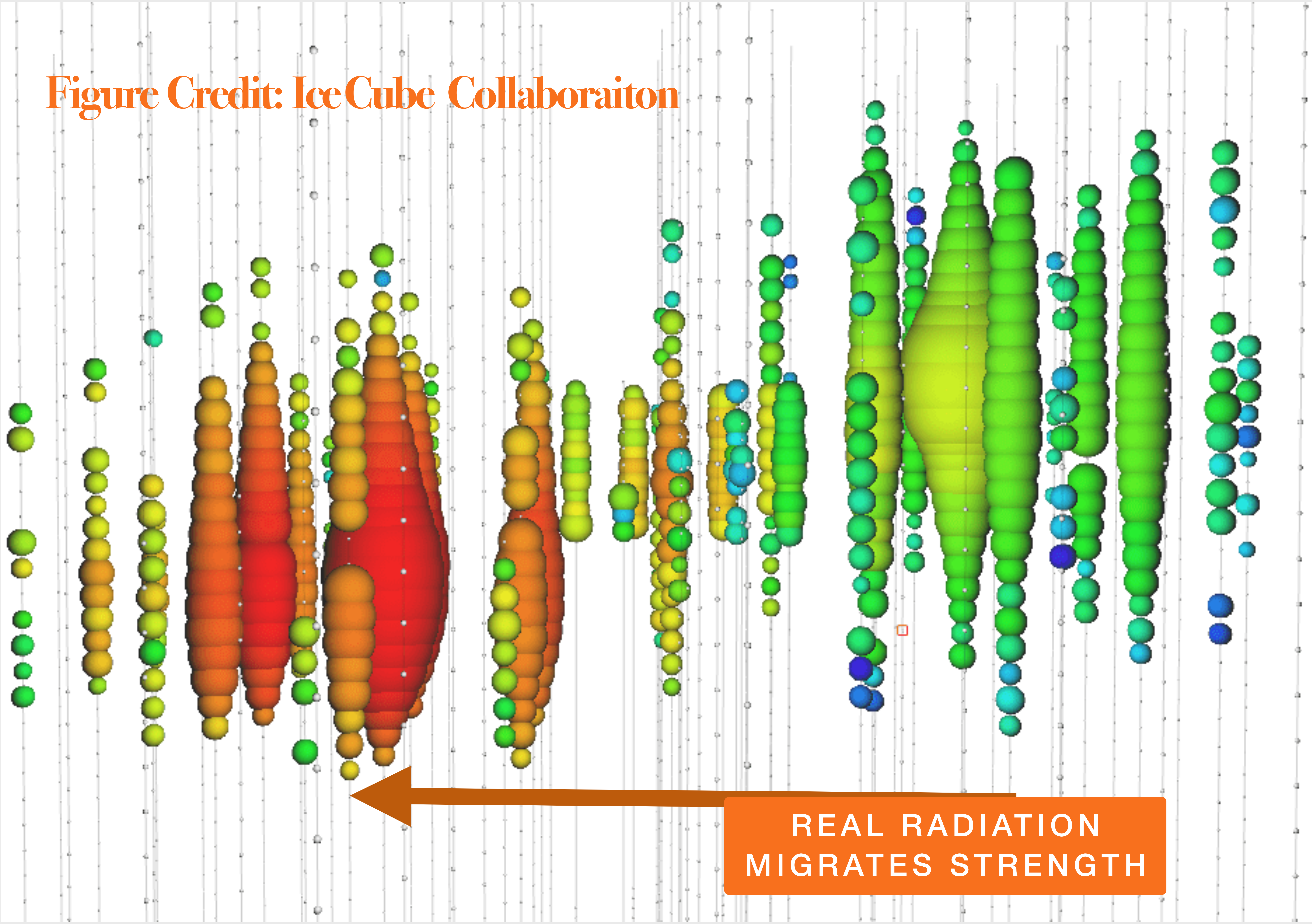


MUON TRACKS


ν_μ
N
Track
μ
γ
Cascade
$X + \gamma$
REAL RADIATION
MIGRATES STRENGTH
ν_μ
μ
γ
X
N

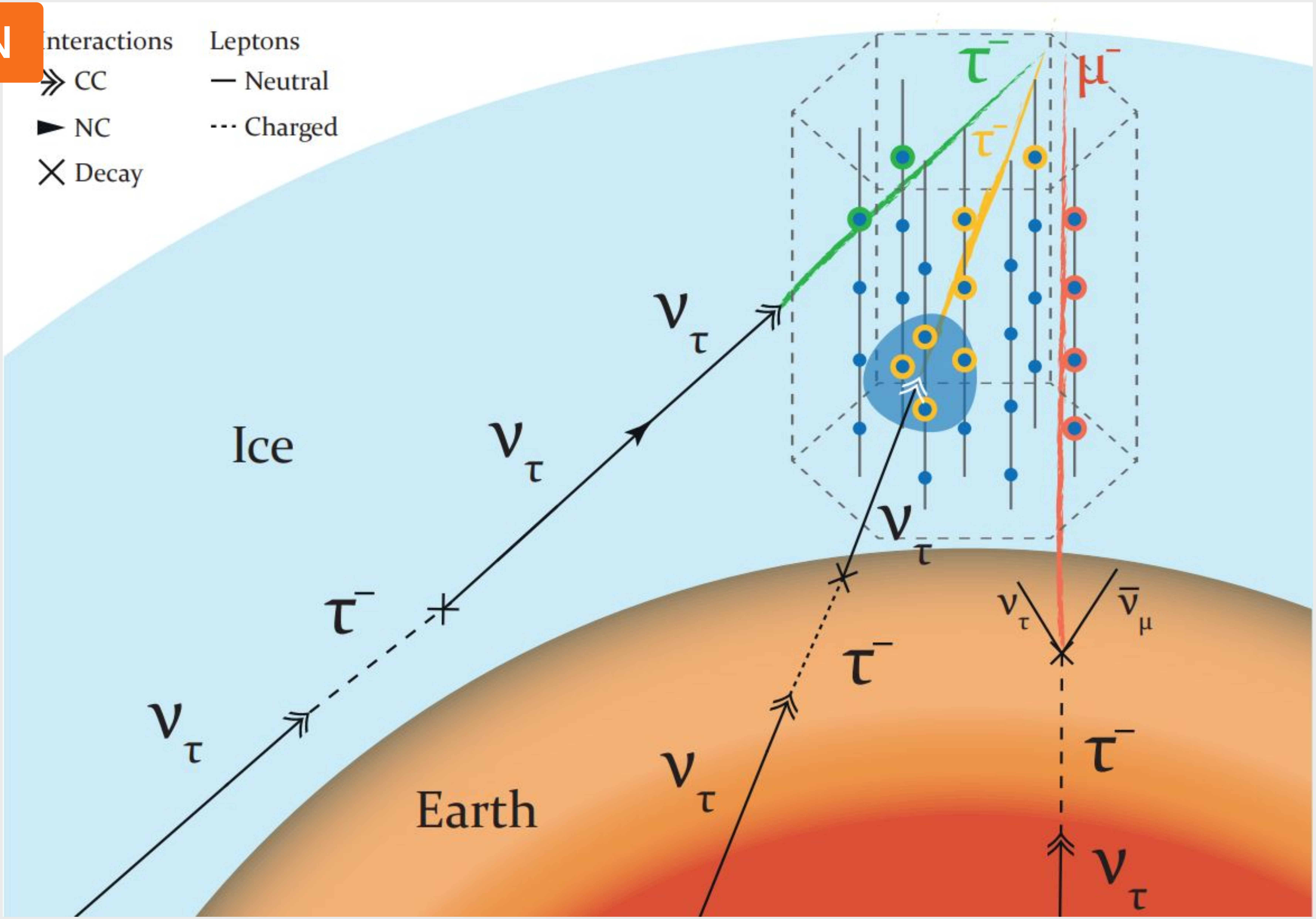
DOUBLE BANG SIGNATURE

- Reshuffles energy between bangs.
- First bang will have more energy.



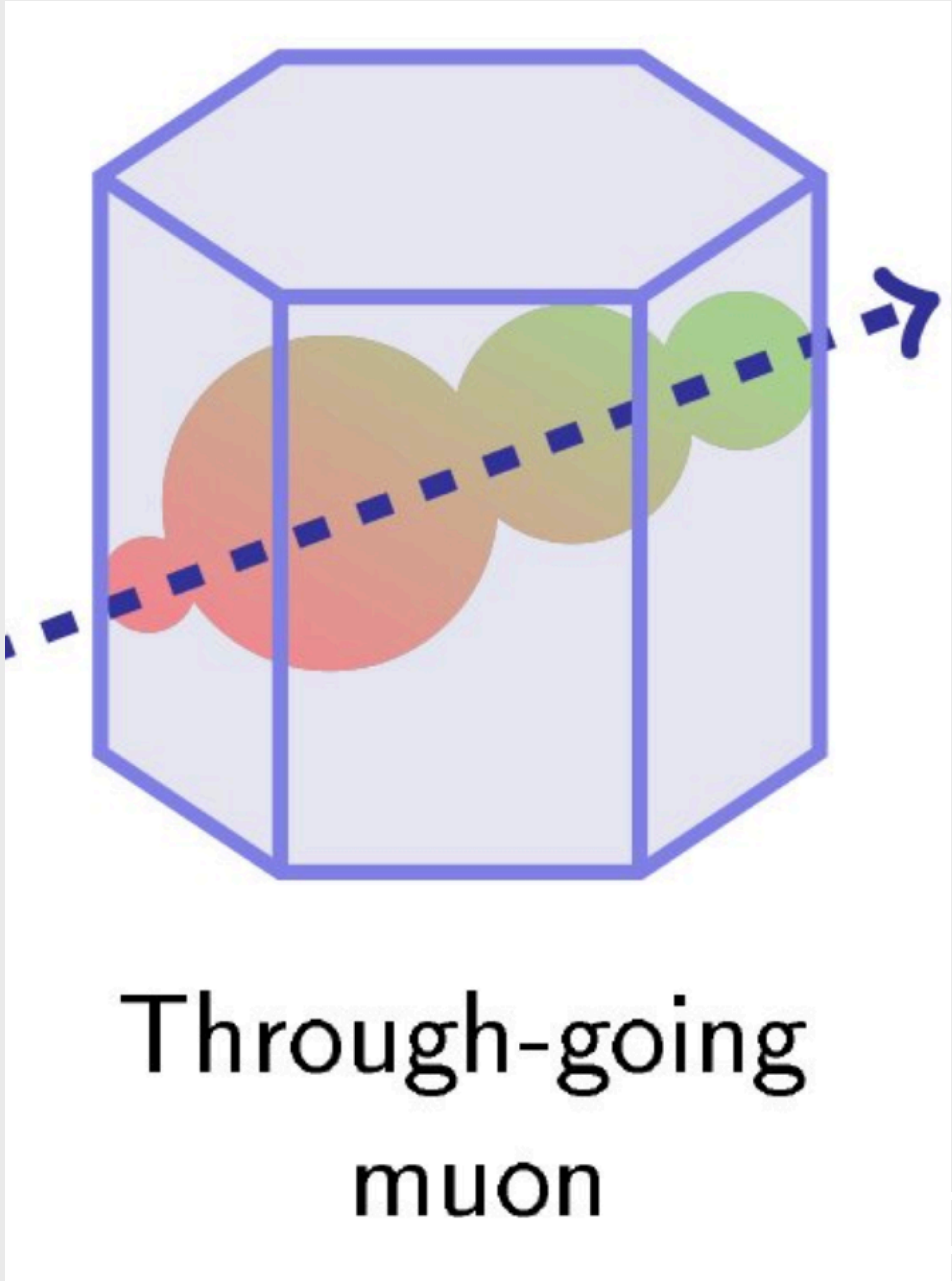
TAU REGENERATION

- For regenerated neutrinos FSR can "build up".
- Many interactions means more chances for FSR.

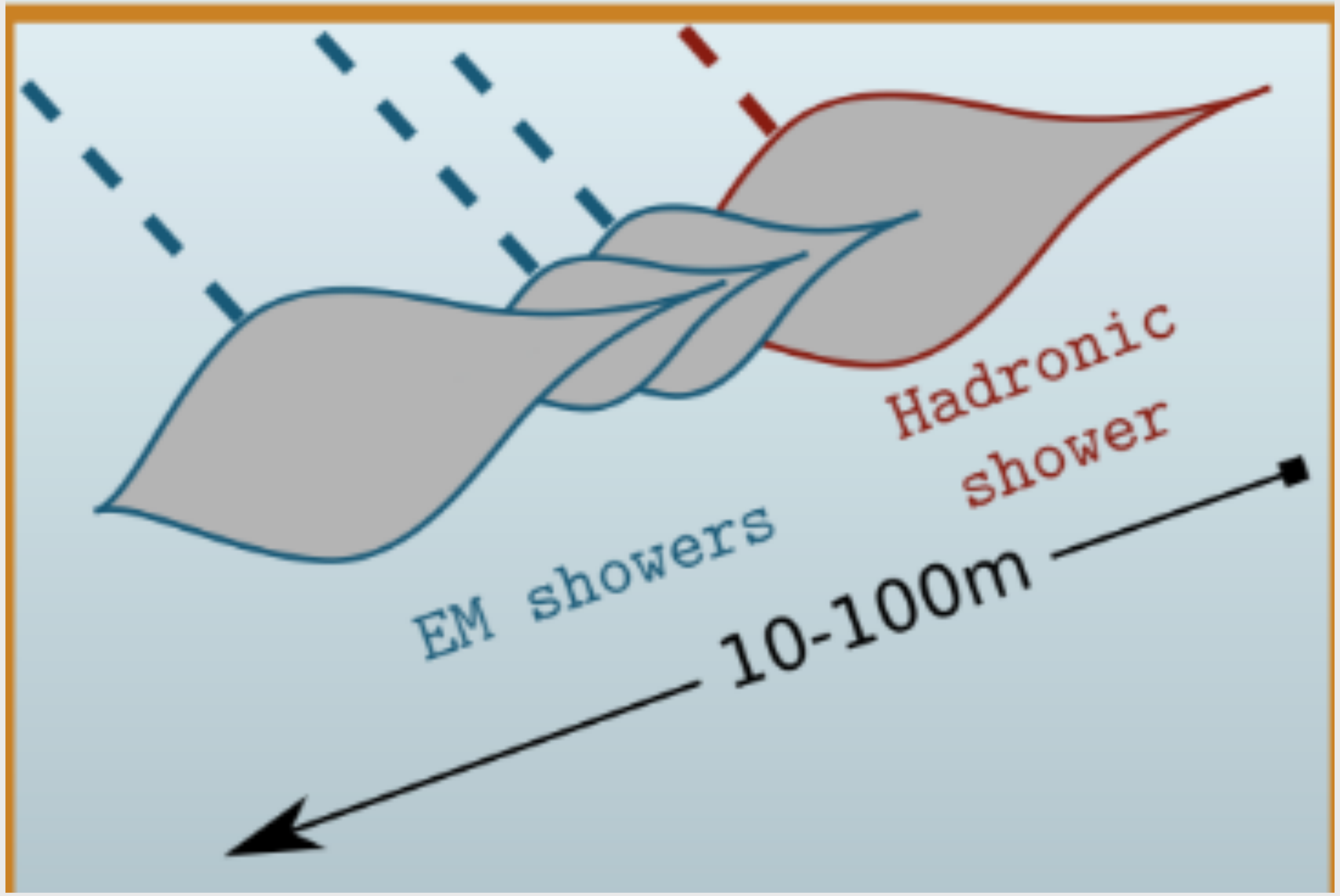


UHE NEUTRINOS

- External leptons can be necessary to increase effective area.
- FSR will be lost outside detector.
- Introduces ~5% bias in neutrino energy estimator.



- Recent proposal to use LPM elongated showers to distinguish flavour.
- Relies on "subtle waveforms".
- FSR will distort these and should be included in templates.



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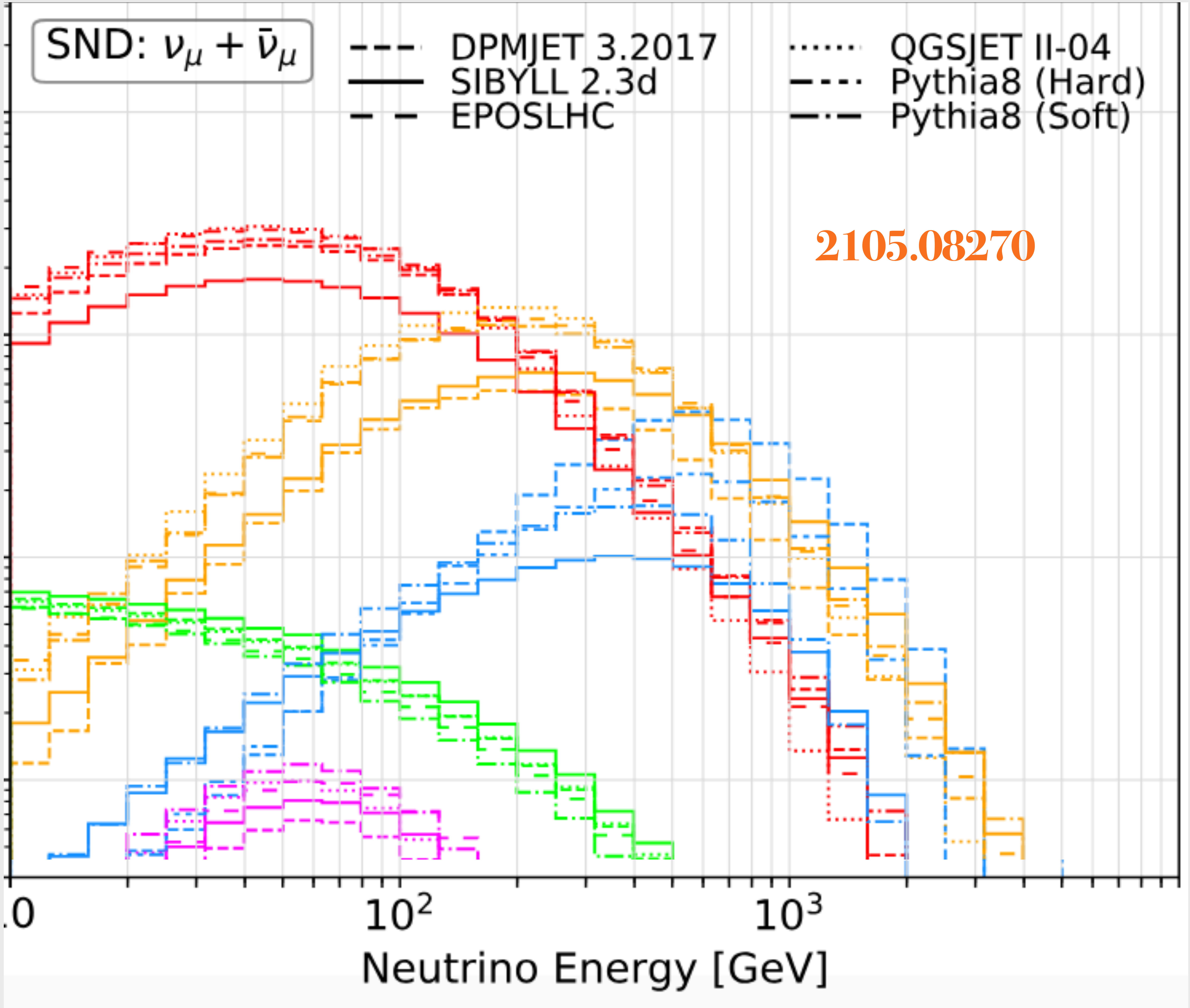
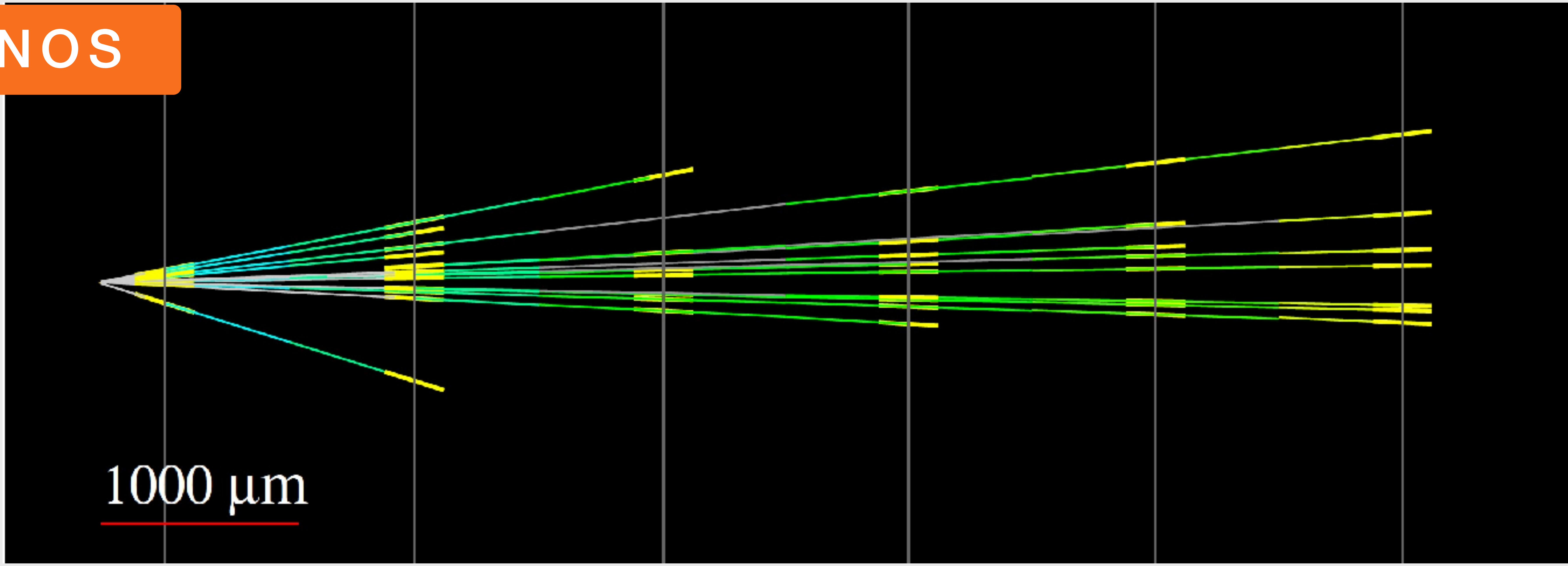
COLLIDER NEUTRINOS

- Event rate peaks near TeV energies.
- Detectors are very different than neutrino telescopes.
- Warrants separate discussion.





- Photon still gets absorbed into shower energy (hard to distinguish from $\pi^0 \rightarrow \gamma\gamma$.
- Electrons may be identifiable with primary vertex ID.

KINEMATICS

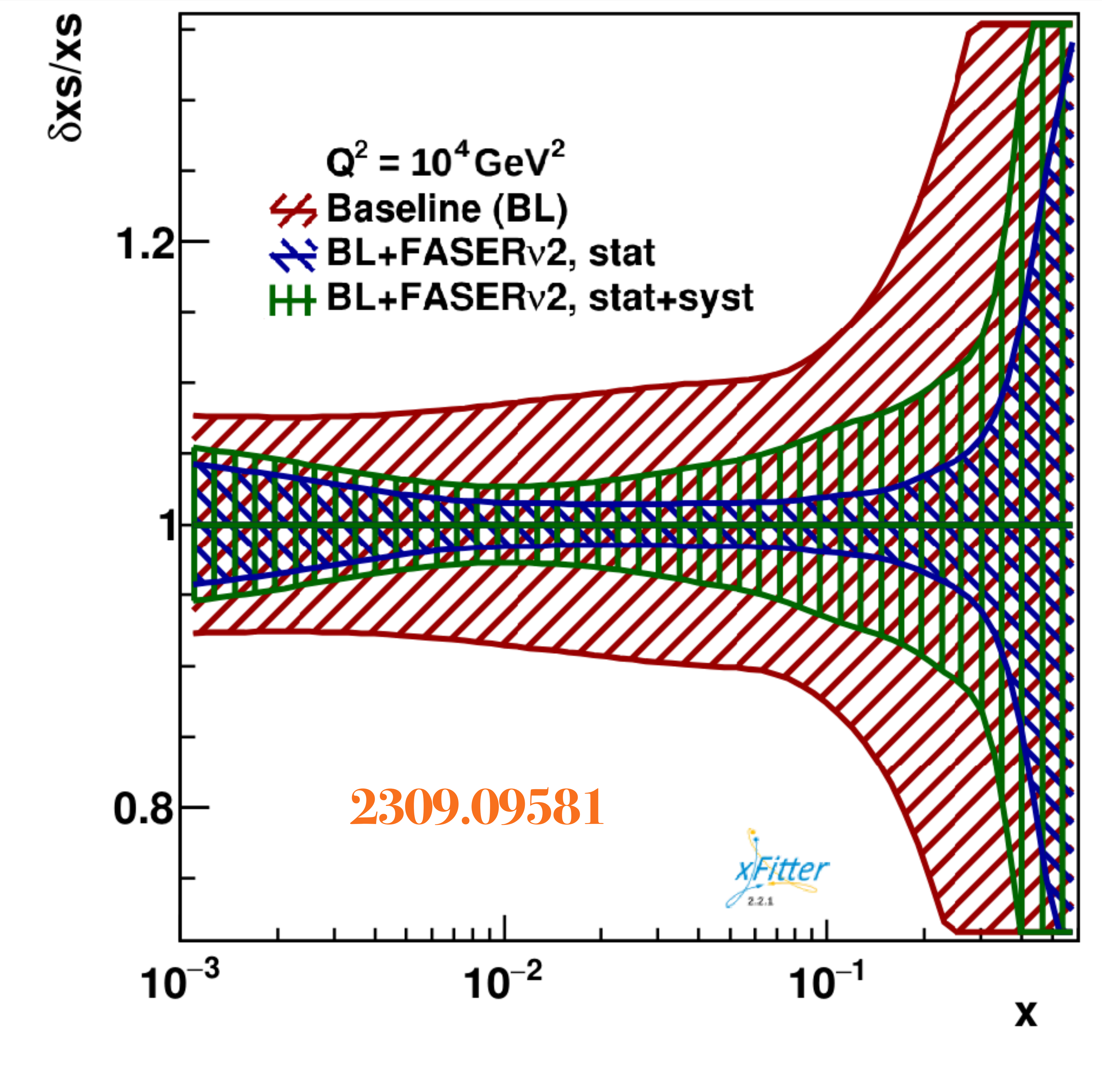
- Reconstructed DIS variables get distorted.

$$[\Delta Q^2]_{\rm FSR} \simeq -\,4E_\nu E_\gamma \sin^2(\theta_\ell/2)$$

$$[\Delta x]_{\rm FSR} \simeq \frac{[\Delta Q^2]_{\rm FSR}}{2m_N E_X} - \frac{E_\gamma}{E_X}x^{(0)}$$

IMPACT ON PDF EXTRACTIONS

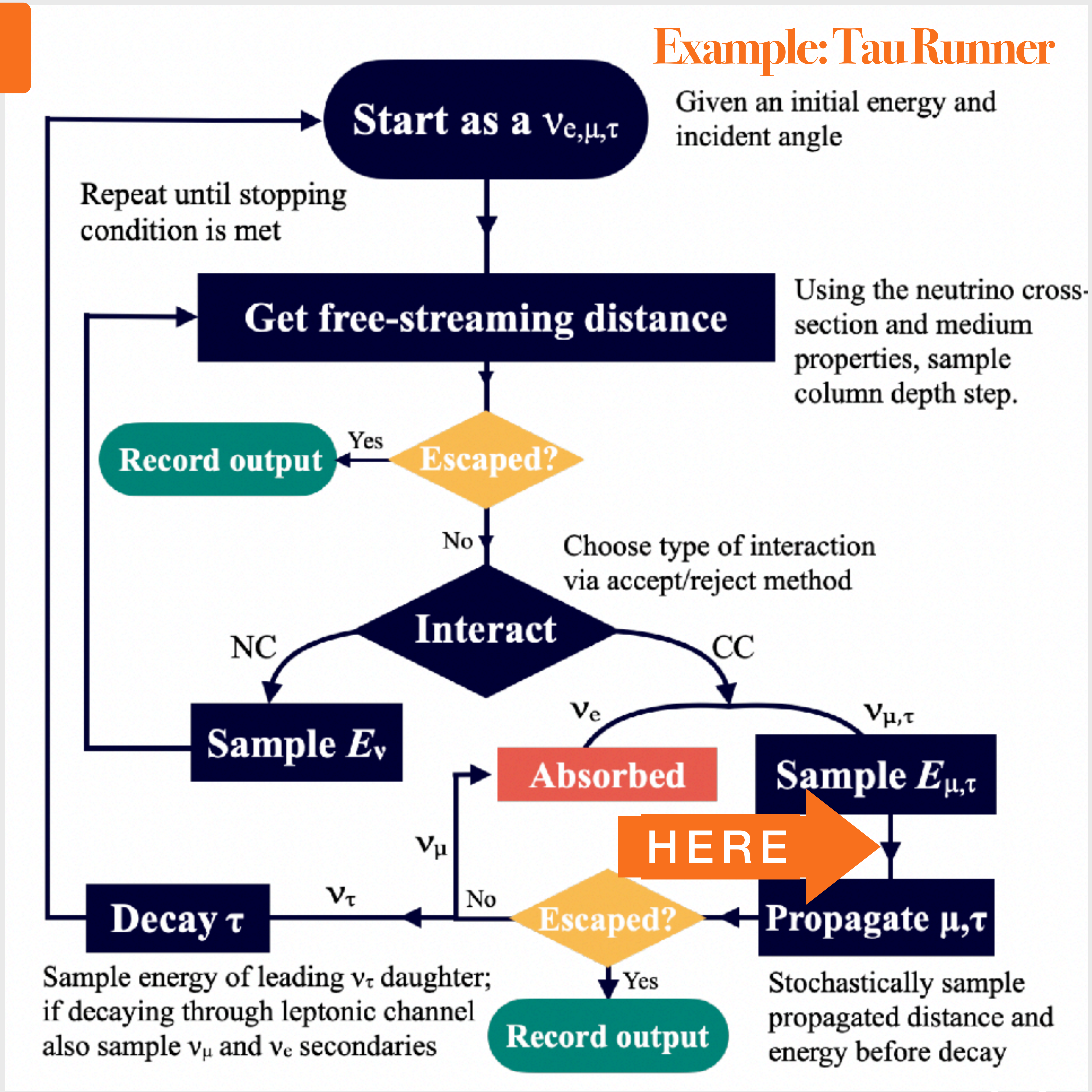
- LHC neutrinos can supply best constraints on certain PDFs.
- Specifically strange and quark singlet PDFs.
- Will be important to include radiative corrections for these.



Monte Carlo Implementation

HOW TO IMPLEMENT FSR

- At leading-log accuracy process is essentially classical.
- Can generate lepton "as is".
- Perform a final step where energy fraction to photon is sampled.



Conclusions & Outlook

Conclusions

- Final state radiation can be enhanced by large kinematic logarithms.
- Effects are ~10% in size when lepton energy is measured.
- Influences reconstruction of kinematic variables and estimates of neutrino energy