Leptonic sources of (ultra)high-energy neutrinos: Key physics and a new public code

Based on

A. Esmaeili, A. Capanema, A. Esmaili and P. D. S.,

"*Ultrahigh energy neutrinos from high-redshift electromagnetic cascades*," Phys. Rev. D 106 (2022) 123016

&

A. Esmaeili, A. Esmaili and P. D. S.,

"*Neutrinos from muon-rich ultra high energy electromagnetic cascades: The* MUNHECA *code*," [2310.01510]

Pasquale Dario Serpico (Annecy, France)

Re[incontri] di Fisica Partenopea 21/12/2023

Leptonic sources of (ultra)high-energy neutrinos: Key physics and a new public code

Based on

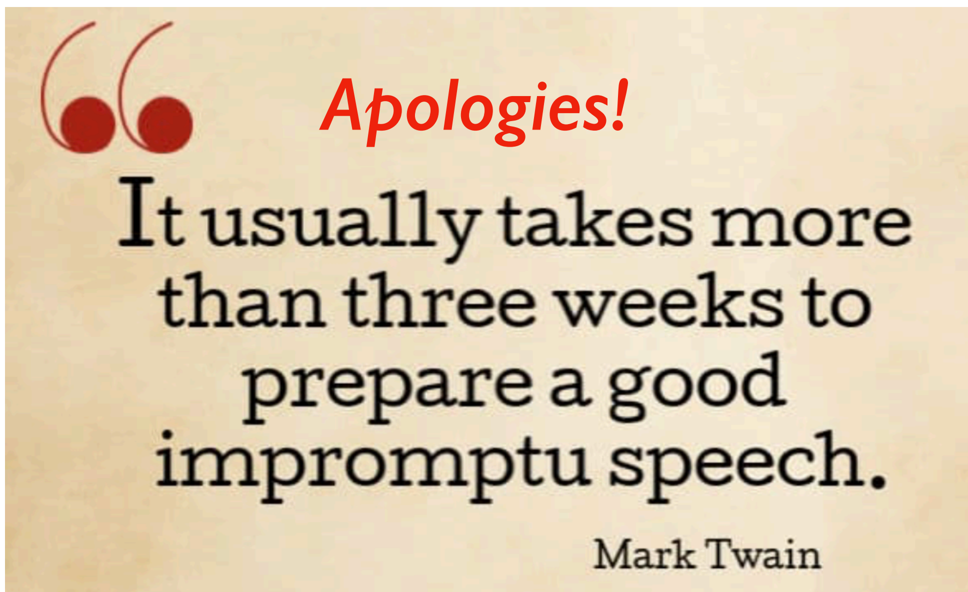
A. Esmaeili, A. Capanema, A. Esmaili and P. D. S.,

"*Ultrahigh energy neutrinos from high-redshift electromagnetic cascades*," Phys. Rev. D 106 (2022) 123016

&

A. Esmaeili, A. Esmaili and P. D. S.,

"*Neutrinos from muon-rich ultra high energy electromagnetic cascades: The* MUNHECA *code*," [2310.01510]

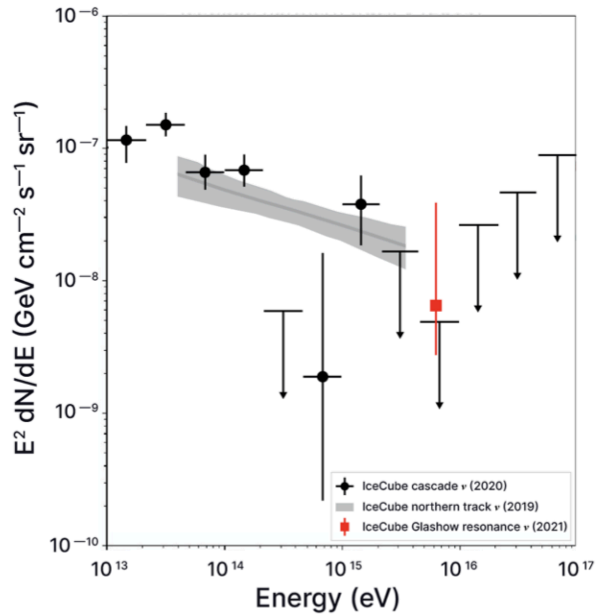


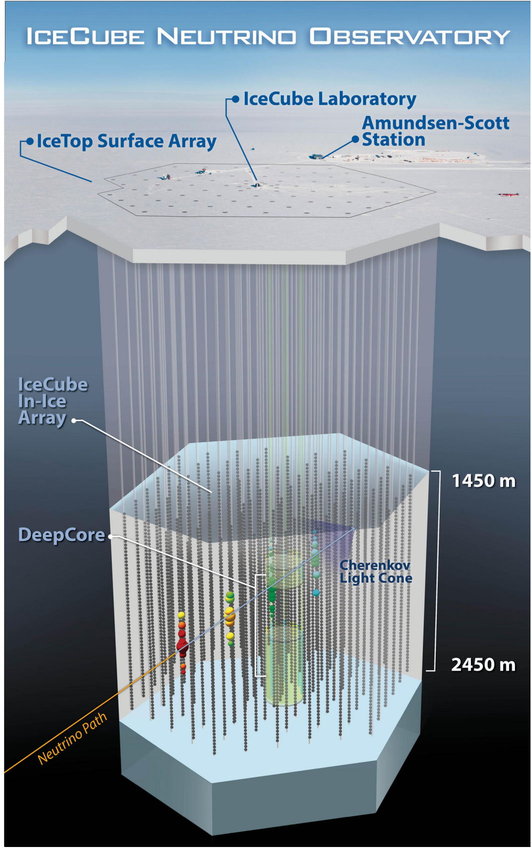
Pasquale Dario Serpico (Annecy, France)

Re[incontri] di Fisica Partenopea 21/12/2023

Recently opened HE window: Neutrinos

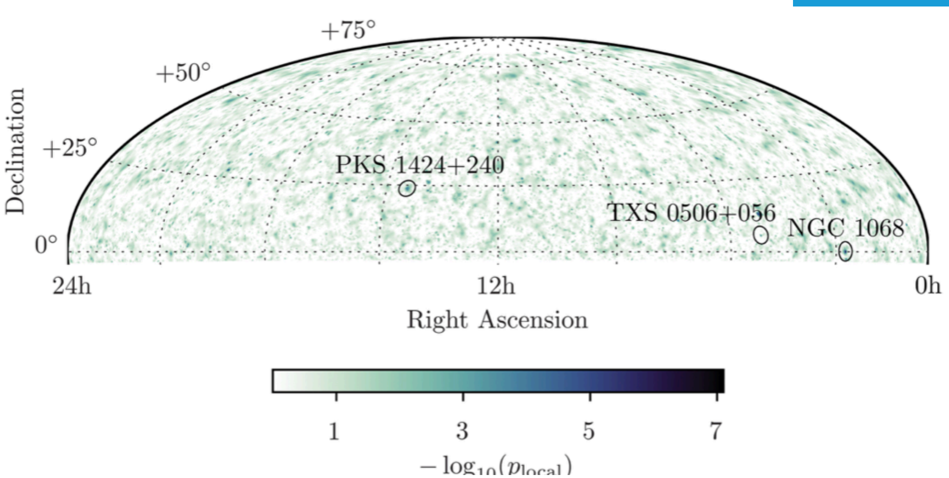
- Decade-old observations of diffuse (extragalactic) flux
- 2018-2022: first evidences for a few point-sources
- 2023: first evidences for diffuse Gal. Component

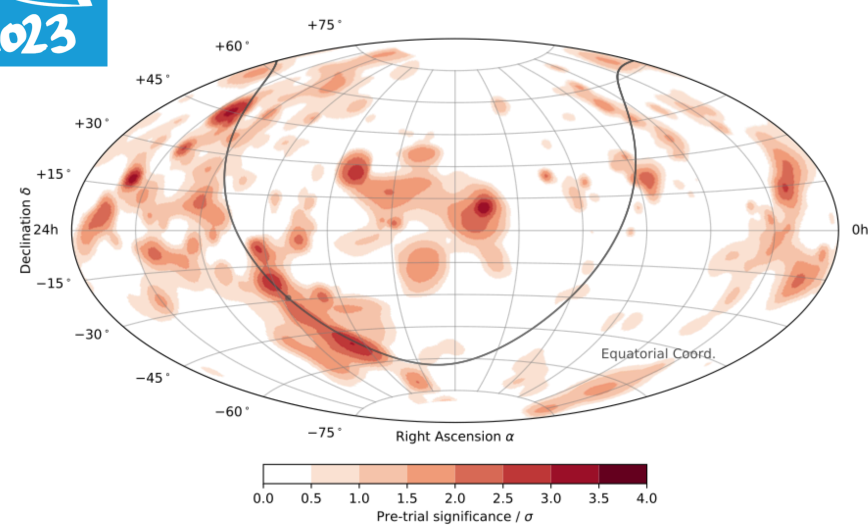




Recent review, e.g. Halzen 2305.07086

ICRC 2023 proceeding in 2307.14842, also discussed at TeVPA 2023

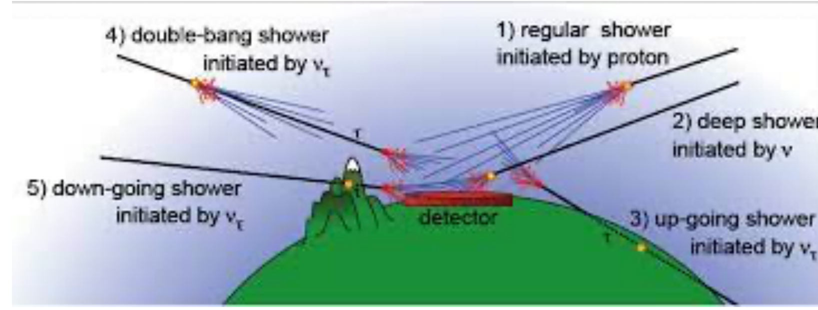


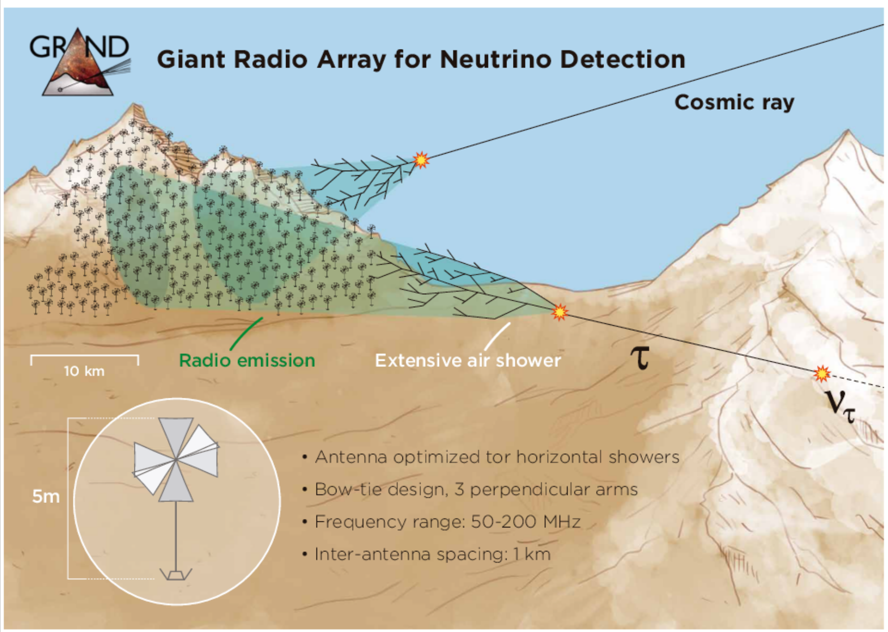


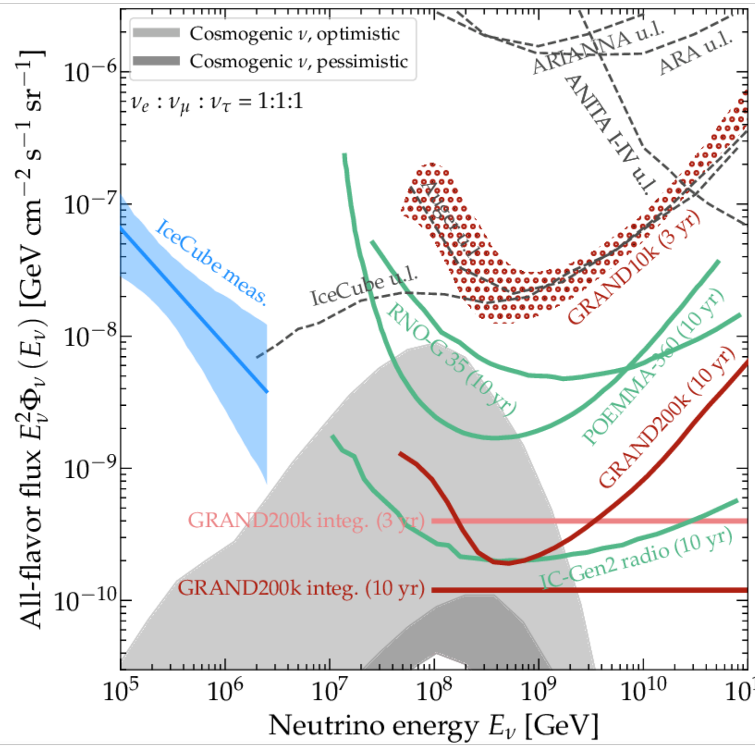
Other searches at high energy: current and future

Nature accelerates at least up to 3x10[20] eV (UHECRs)

- Searches in shower experiments like Pierre Auger,
- Radio detection projects: IceCube-gen2, GRAND…



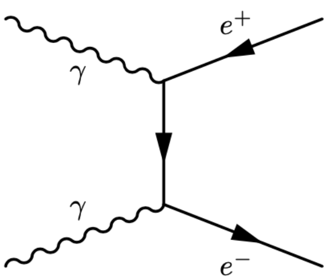


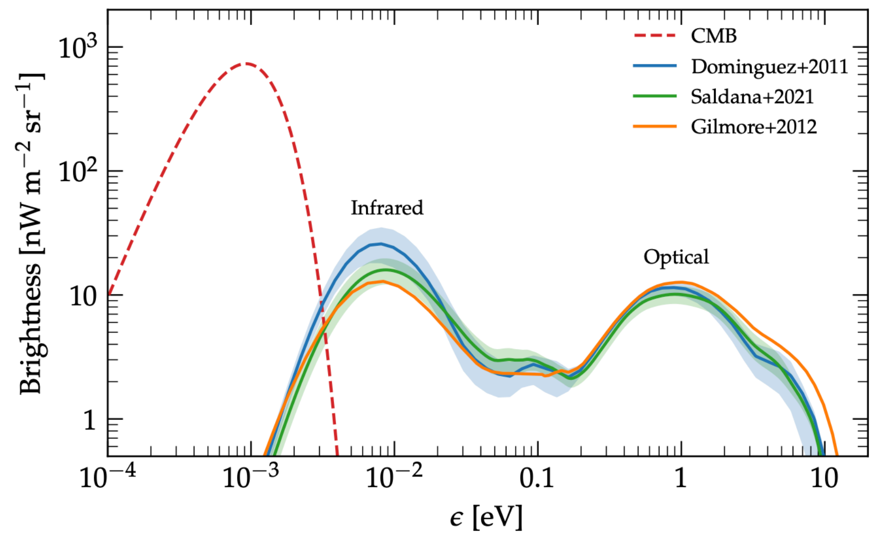


- We do not know where the bulk of detected IceCube ν's come from (not only type of object, also redshift!)
- UHEν window (≳10[17] eV) yet to be opened, but technology exists and fluxes should be there

High-energy sky at high-z is precluded to photons!

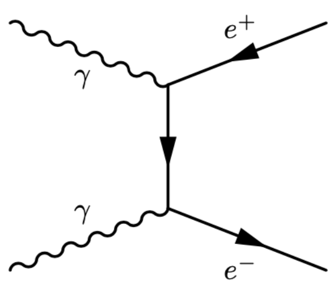
Gamma-rays (produced either leptonically or hadronically) are further subject to absorption via pair-production onto CMB (and other backgrounds)!

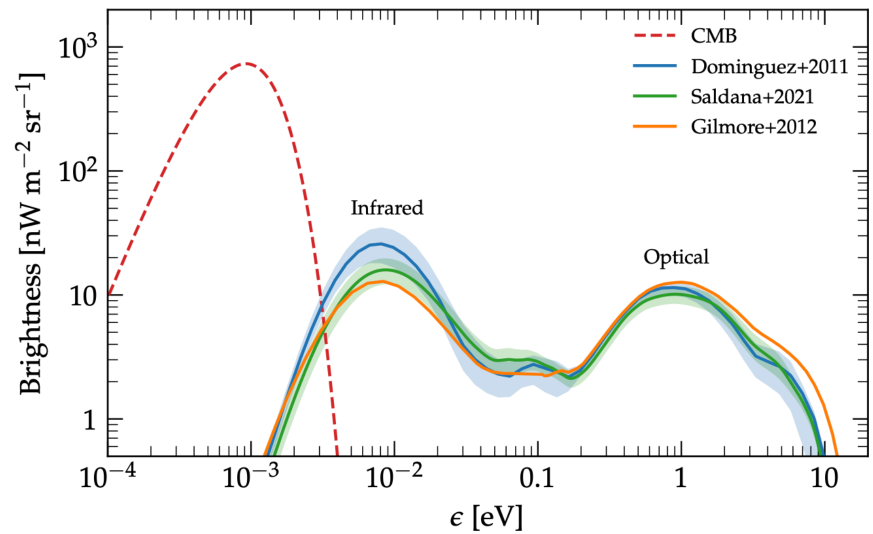




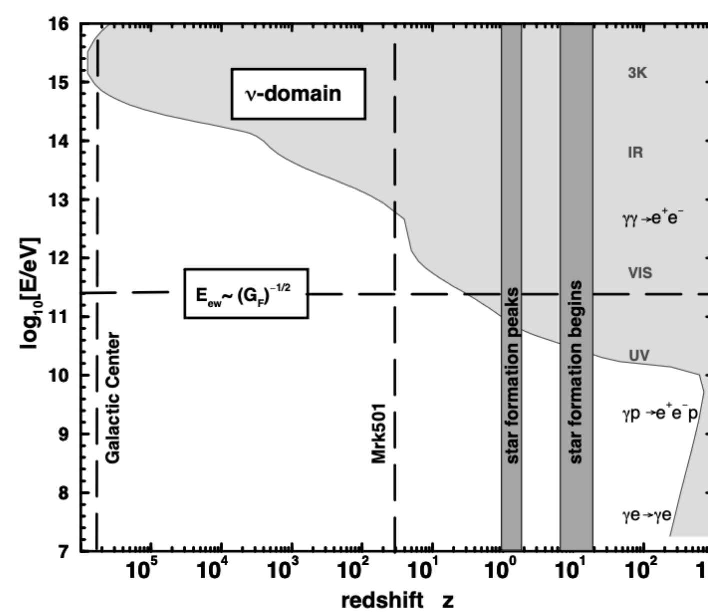
High-energy sky at high-z is precluded to photons!

Gamma-rays (produced either leptonically or hadronically) are further subject to absorption via pair-production onto CMB (and other backgrounds)!





Essential limitation to Extragalactic astronomy already at ~TeV, even to Galactic astronomy at PeV!



J. G. Learned and K. Mannheim, "High-energy neutrino astrophysics," Ann. Rev. Nucl. Part. Sci. 50 (2000), 679-749

…and to charged UHECRs, too! Photomeson production

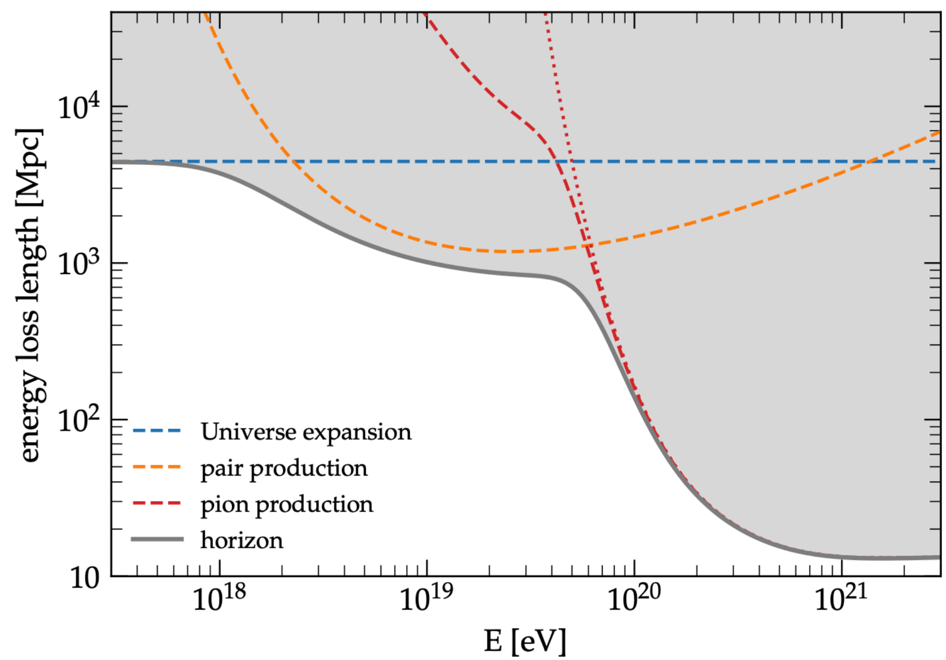
$$p + \gamma_{\text{CMB}} \rightarrow n(p) + \pi^+(\pi^0)$$ (Also for nuclei)

- Threshold $m_p^2 + 4\epsilon_\gamma E_p > (m_p + m_\pi)^2 \Longrightarrow E_p > \frac{2m_p m_\pi + m_\pi^2}{\epsilon_\gamma} \simeq 4 \times 10^{19}\,\text{eV}$

- Inelasticity of order $m_\pi/m_p \sim 0.15$

- Most important process limiting the propagation of extragalactic protons, so dramatic to be known as Greisen-Zatsepin-Kuzmin limit or cutoff (predicted soon after CMB discovery)

- Associated to a "guaranteed" UHE neutrino production (*cosmogenic*), via charged pion decays



V. Berezinsky and G. Zatsepin, Cosmic rays at ultrahigh-energies (neutrino?), Phys.Lett. B28 (1969) 423–424.

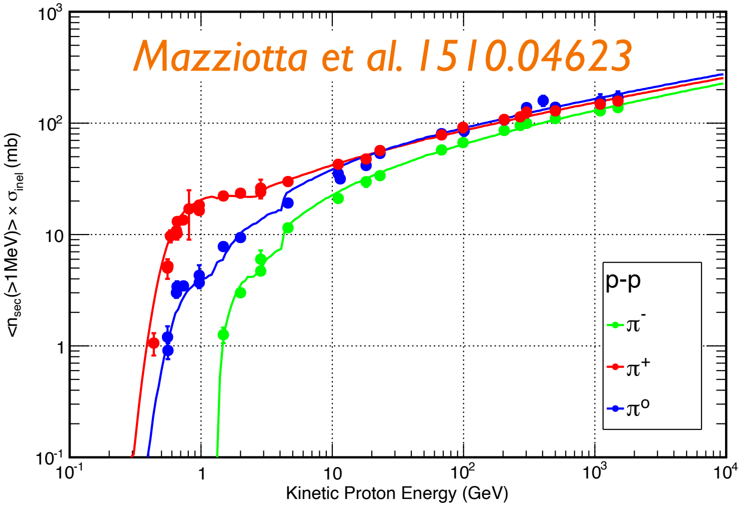
V. Berezinsky and A.Y. Smirnov, Cosmic neutrinos of ultra-high energies and detection possibility, Astrophys.Space Sci. 32 (1975) 461–482

The standard lore

Assumed ν from hadronic production of pions, either via $p\gamma$ (at source or in propagation) or pp (at source) which creates tight ν-γ flux link

E.g. for pp, well above threshold, almost 1:1:1 ratio of pions of different charges

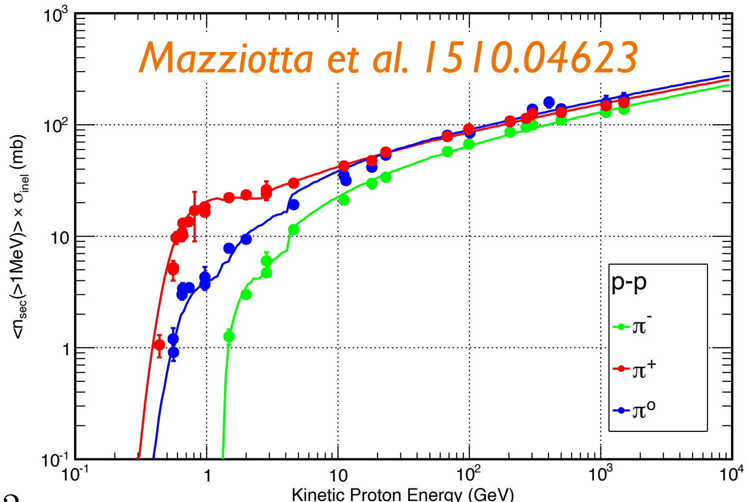
(manifestation of isospin symmetry)



The standard lore

Assumed ν from hadronic production of pions, either via $p\gamma$ (at source or in propagation) or pp (at source) which creates tight ν-γ flux link

E.g. for pp, well above threshold, almost 1:1:1 ratio of pions of different charges
(manifestation of isospin symmetry)



There are 2x3 neutrinos $\pi \to \nu + \mu \to \nu + \nu + \nu + e$

each 1x2 photons $\pi \to \gamma\gamma$

Relation among (average) energies $E_\gamma = E_\pi/2$; $E_\nu \simeq E_\pi/4 \simeq E_\gamma/2$

Hence between spectra

$$\frac{1}{2}\frac{\mathrm{d}N_\gamma}{\mathrm{d}E_\gamma} \simeq \frac{1}{6}\left[\frac{\mathrm{d}N_\nu}{\mathrm{d}E_\nu}\right]_{E_\nu=E_\gamma/2}$$

The standard lore

Assumed ν from hadronic production of pions, either via $p\gamma$ (at source or in propagation) or pp (at source) which creates tight ν-γ flux link

E.g. for pp, well above threshold, almost 1:1:1 ratio of pions of different charges

(manifestation of isospin symmetry)

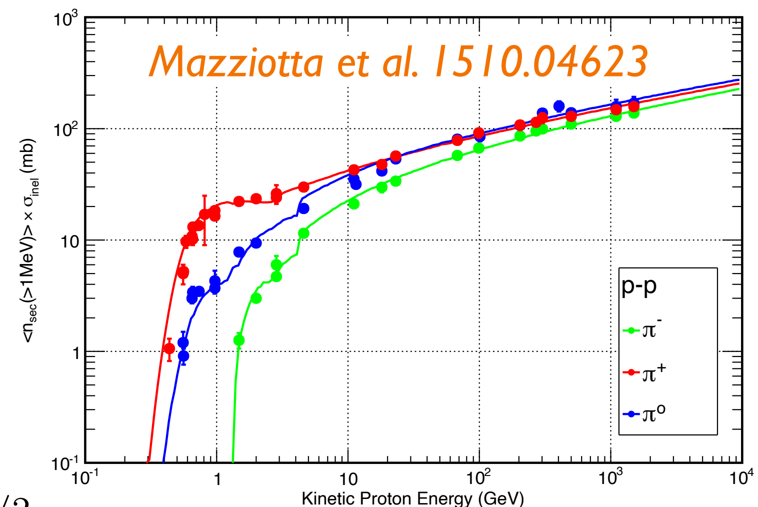
There are 2x3 neutrinos $\pi \to \nu + \mu \to \nu + \nu + \nu + e$

each 1x2 photons $\pi \to \gamma\gamma$

Relation among (average) energies $E_\gamma = E_\pi/2 \,;\, E_\nu \simeq E_\pi/4 \simeq E_\gamma/2$

Hence between spectra

$$\frac{1}{2}\frac{\mathrm{d}N_\gamma}{\mathrm{d}E_\gamma} \simeq \frac{1}{6}\left[\frac{\mathrm{d}N_\nu}{\mathrm{d}E_\nu}\right]_{E_\nu = E_\gamma/2}$$



This link is 'as it is' if the sky is transparent to gammas, otherwise…

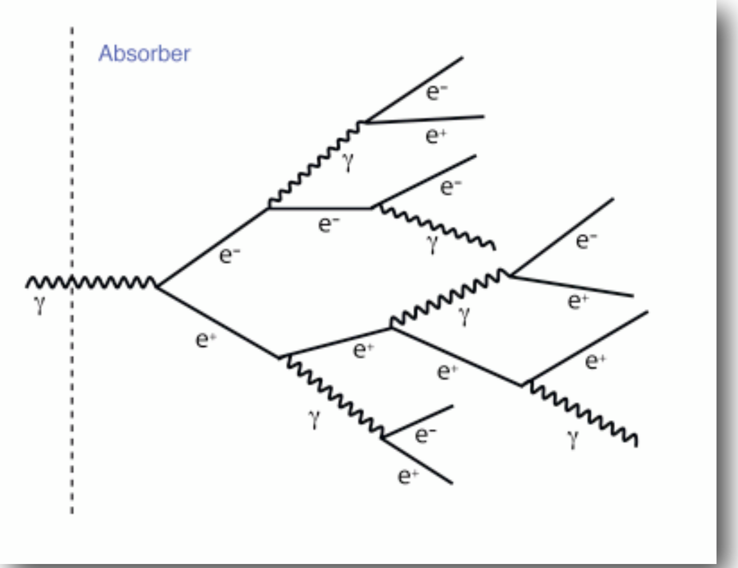
"Bolometric" link between 'degraded' photon (diffuse) spectra and neutrino ones

Electromagnetic cascades

Basic processes are

$$\gamma\,\gamma_{\text{bck}} \rightarrow e^{+}e^{-}$$

$$e\,\gamma_{\text{bck}} \rightarrow e\,\gamma$$



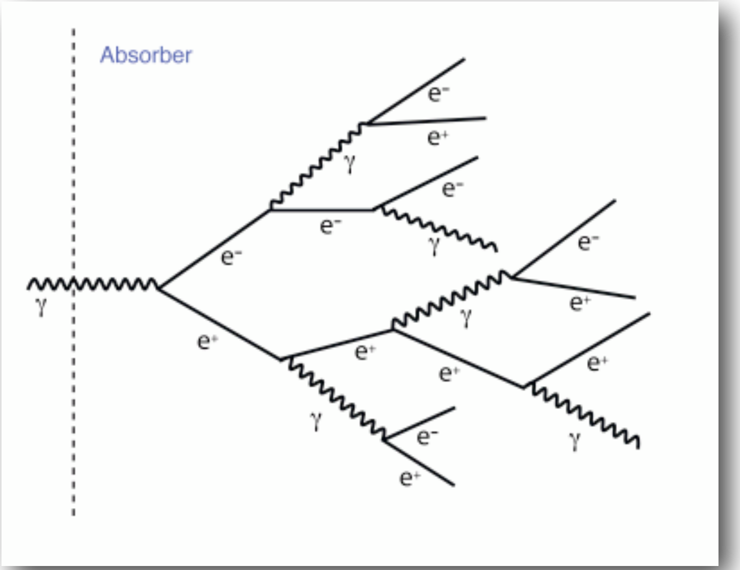
Electromagnetic cascades

Basic processes are

$$\gamma\,\gamma_{\text{bck}} \rightarrow e^+ e^-$$

Particle multiplication and energy redistribution

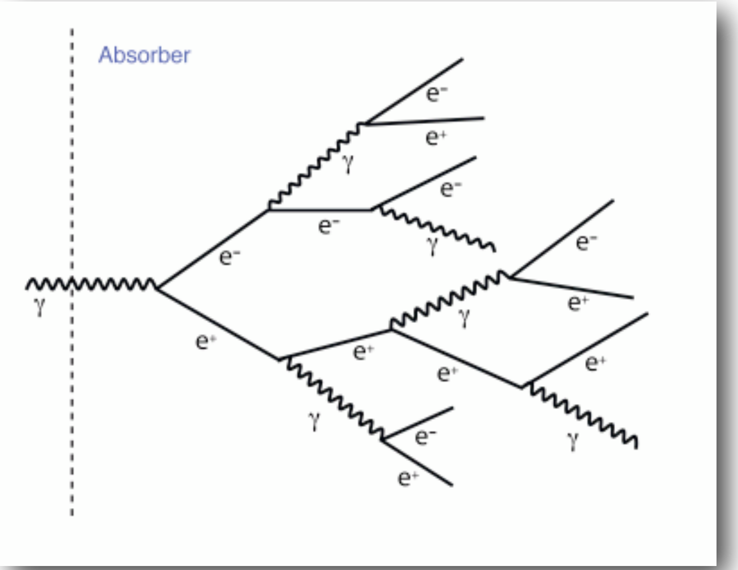
$$e\,\gamma_{\text{bck}} \rightarrow e\,\gamma$$



Electromagnetic cascades

Basic processes are $\gamma\,\gamma_{\rm bck} \rightarrow e^+ e^-$

Particle multiplication and energy redistribution $e\,\gamma_{\rm bck} \rightarrow e\,\gamma$



At threshold for P.P., $E_e \sim E_{thresh}/2$ and the corresponding maximal IC photon energy $E_X \sim E_{thresh}/3$

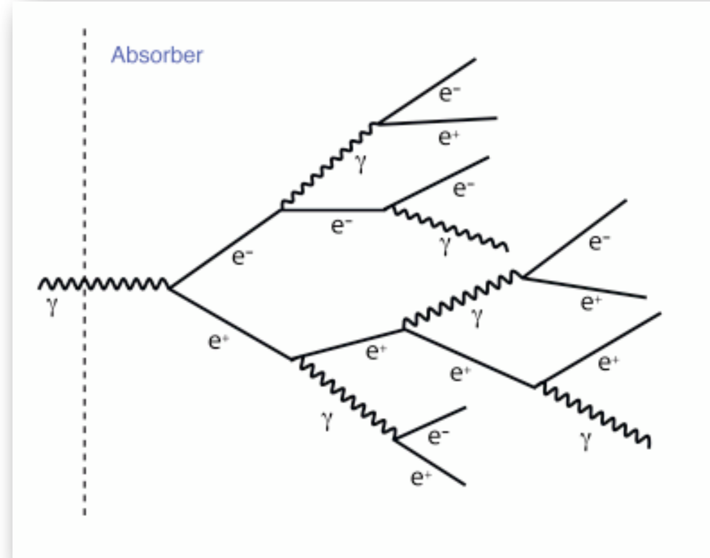
Below this energy, the number of particles is fixed by the number of e "available" (no more multiplication possible), the resulting scale-invariant spectrum goes as $\mathbf{E^{-3/2}}$

Above E_X and below the effective cutoff imposed by P.P., the **energy** of particles in the cascade is **conserved** ($E^2 dN/dE \sim$ const), hence spectrum $\mathbf{E^{-2}}$

Electromagnetic cascades

Basic processes are $\gamma\,\gamma_{\rm bck} \rightarrow e^+ e^-$

Particle multiplication and energy redistribution $e\,\gamma_{\rm bck} \rightarrow e\,\gamma$



At threshold for P.P., $E_e \sim E_{thresh}/2$ and the corresponding maximal IC photon energy $E_X \sim E_{thresh}/3$

Below this energy, the number of particles is fixed by the number of e "available" (no more multiplication possible), the resulting scale-invariant spectrum goes as $\mathbf{E^{-3/2}}$

Above E_X and below the effective cutoff imposed by P.P., the **energy** of particles in the cascade is **conserved** ($E^2 dN/dE \sim$ const), hence spectrum $\mathbf{E^{-2}}$

Some 'leakage' at low energy via synchrotron radiation if ***B***-fields present

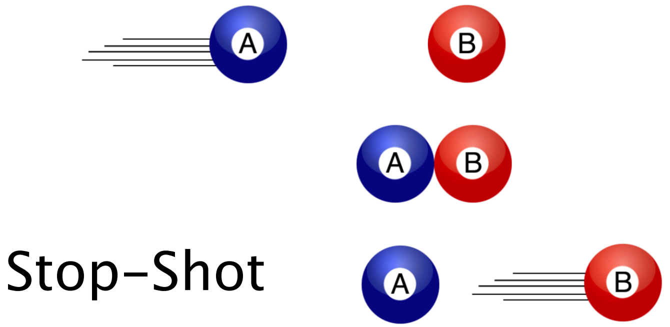
A different environment at high-z (≳5-10): 2208.06440

- Photon backgrounds (radio, UV…) other than CMB go to zero.
- The medium, at least the extragalactic one, should be unmagnetised

What's the fate of an UHE electron or photon in this environment?
Quite different if muon production threshold is open!

Notably

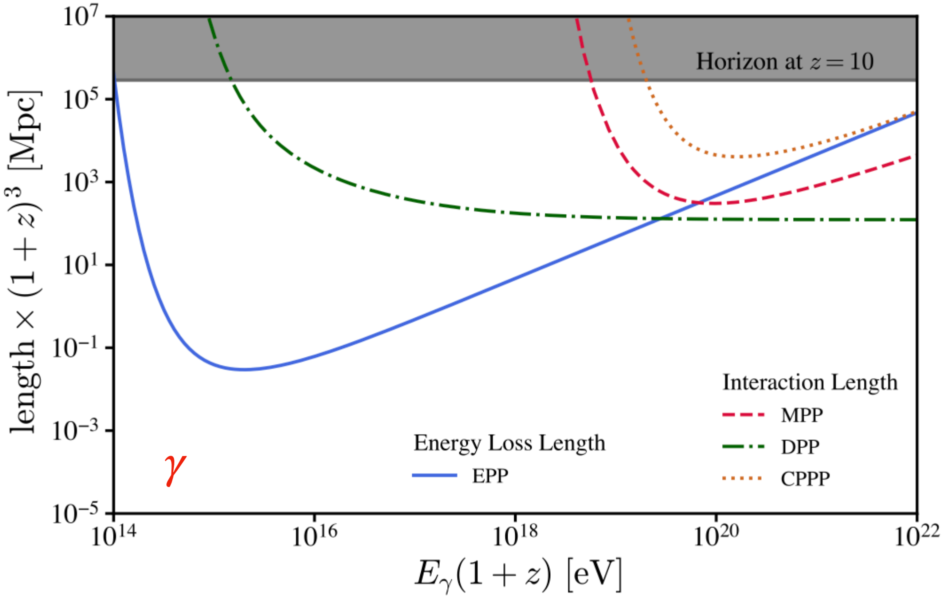
- IC in the deep Klein-Nishina regime, so even 'frequent' e-γ interactions not associated to significant *E*-loss

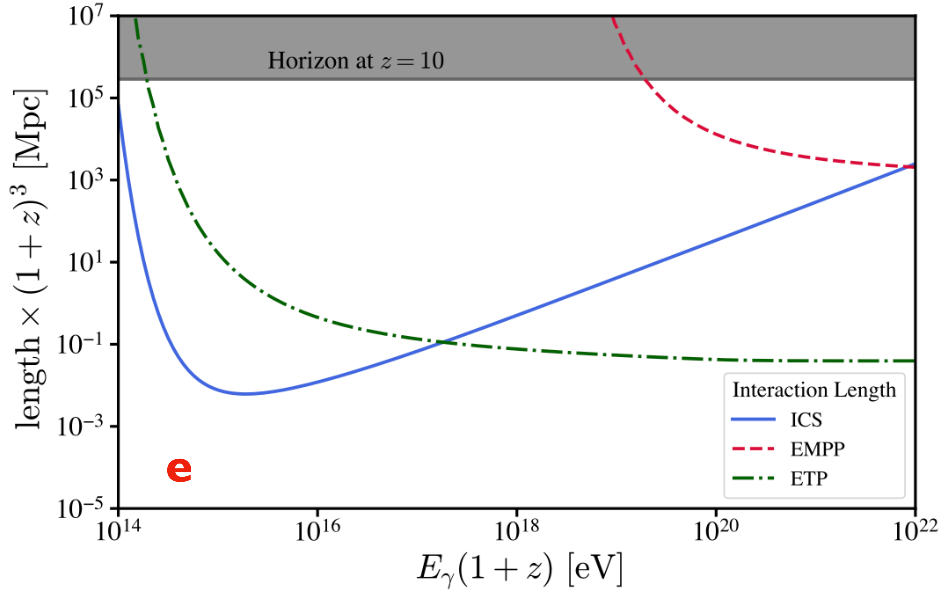


- Need to compare the rare (but highly inelastic) μ production processes **mean free path** with the 'traditionally considered' **E-loss** range (as well as some usually neglected QED processes…)

A different environment at high-z (≳5-10): 2208.06440

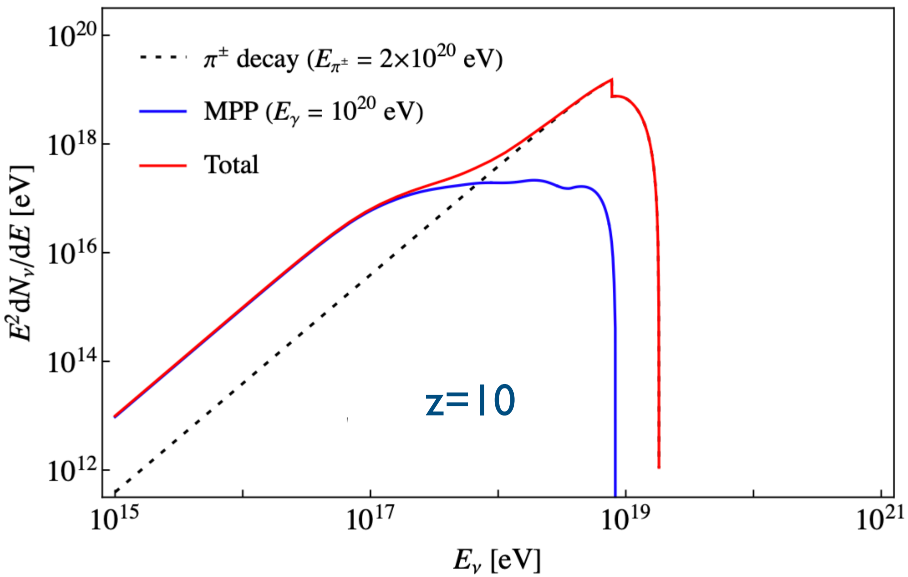
Process	Name	Acronym
$\gamma\gamma \to e^+e^-$	Electron Pair Production	EPP
$\gamma\gamma \to \mu^+\mu^-$	Muon Pair Production	MPP
$\gamma\gamma \to e^+e^-e^+e^-$	Double Pair Production	DPP
$\gamma\gamma \to \pi^+\pi^-$	Charged Pion Pair Production	CPPP
$e\gamma \to e\gamma$	Inverse Compton Scattering	ICS
$e\gamma \to e\mu^+\mu^-$	Electron Muon-Pair Production	EMPP
$e\gamma \to ee^+e^-$	Electron Triplet Production	ETP

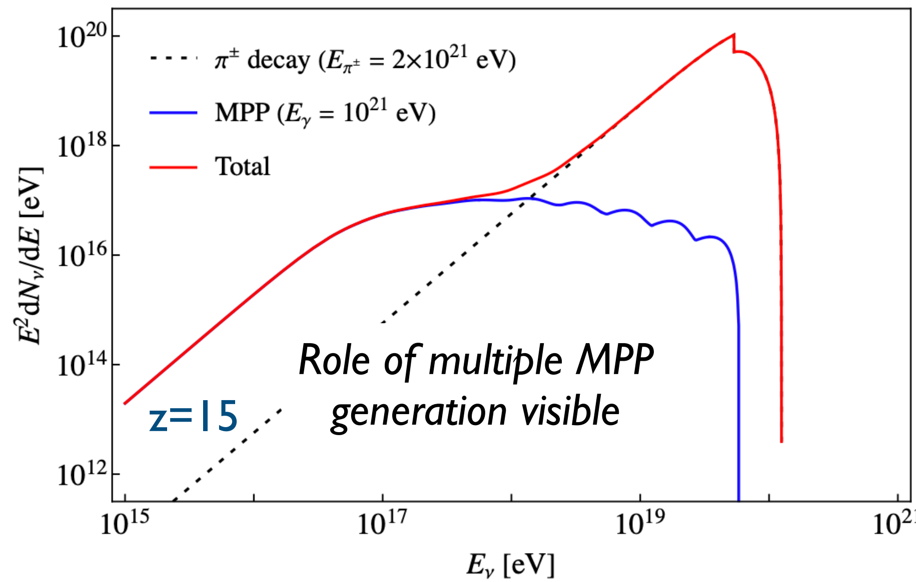




Impact

Assuming 'conventional' hadronic production:
Monochromatic π^+ π^- π^0 at $2\times10^{20\text{-}21}$ eV, hence photons from π^0 @ $10^{20\text{-}21}$ eV



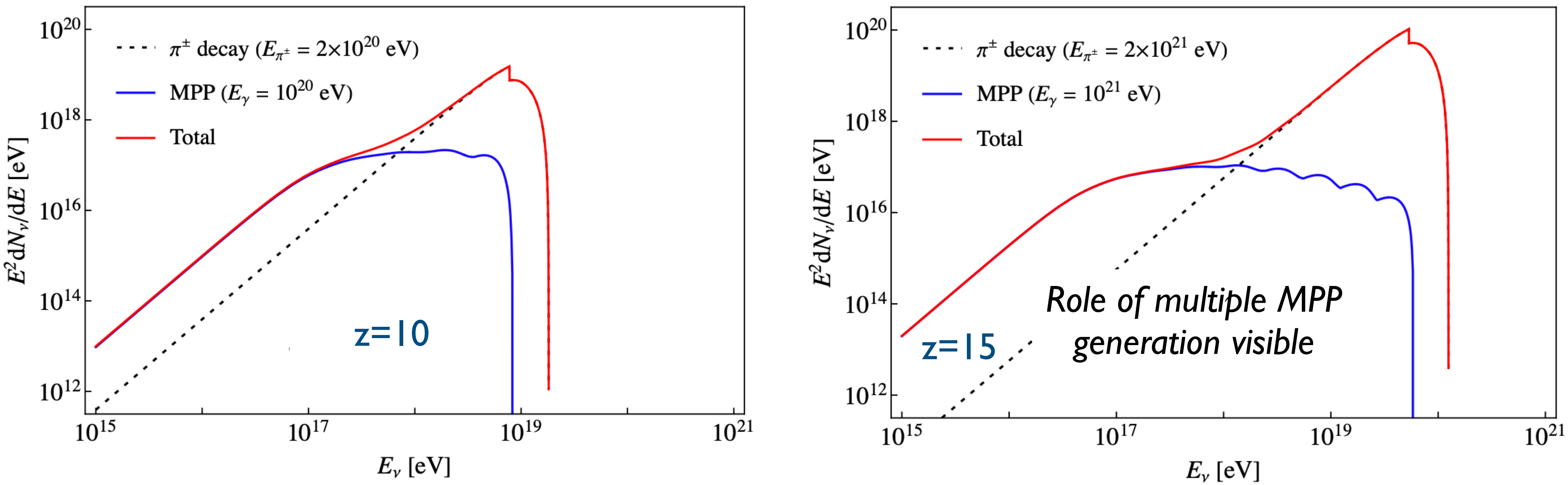


- 1-2 orders of magnitude enhancement of flux at peak sensitivity e.g. of GRAND,
- 'Shoulder' could be a signature of prominent emission from high-z

Impact

Assuming 'conventional' hadronic production:

Monochromatic π^+ π^- π^0 at $2\times10^{20\text{-}21}$ eV, hence photons from π^0 @ $10^{20\text{-}21}$ eV



- 1-2 orders of magnitude enhancement of flux at peak sensitivity e.g. of GRAND,
- 'Shoulder' could be a signature of prominent emission from high-z

Remember the "tight ν-γ (calorimetric) flux link" ?

Can be altered by a factor ~2!

$$\mathcal{E}_\gamma \simeq 2/3(4/3)\,\mathcal{E}_\nu$$

pp $\quad$ $p\gamma$

$$\mathcal{E}'_\gamma \simeq 0.44(0.77)\,\mathcal{E}'_\nu$$

(New) features of the new public code, 2310.01510

MUons and Neutrinos in High-energy Electromagnetic CAscades

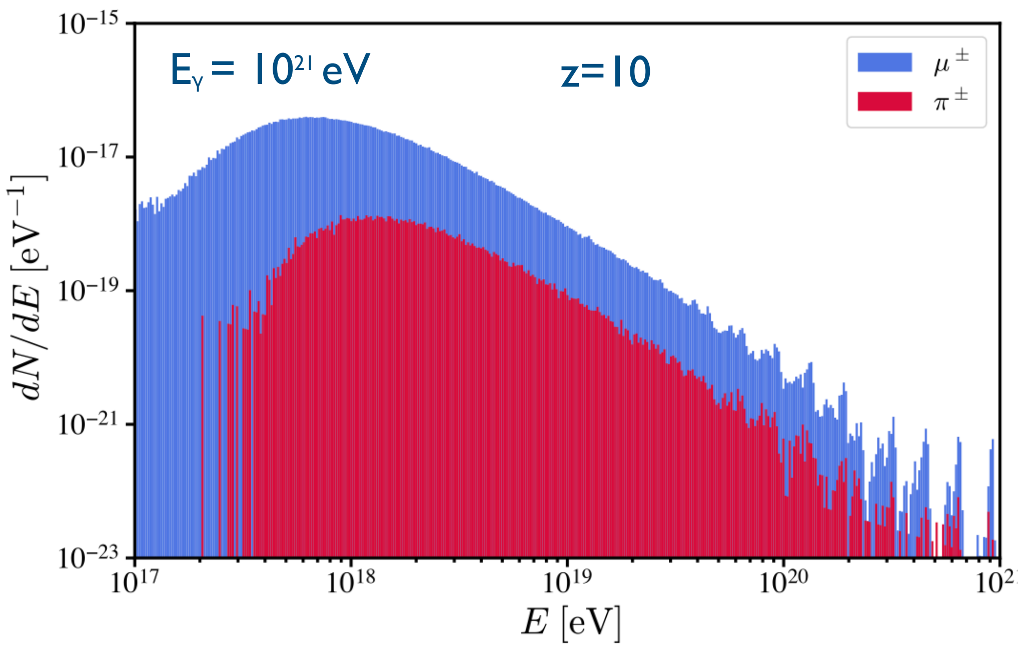
https://github. com/afesmaeili/MUNHECA.git

- Monte Carlo tracking of particles along the cascade evolution (recording all the μ, $\boldsymbol{\pi}$, $\boldsymbol{\nu}$, γ,e spectra), occurrences of $\boldsymbol{\nu}$-producing processes for each injected γ realisation.
- Secondary routine reads the μ, $\boldsymbol{\pi}$ outputs & yields the corresponding $\boldsymbol{\nu}$ spectra @ Earth

Input background:
- CMB
- other blackbody (T)
- power-Law (E_{min}, E_{max})

Input spectrum:
- Monochromatic
- Power-law (w or w/o exp cutoff)
- user-defined

Other:
- Free redshift z
- Free lowest E of followed particles
- More processes included (CPPP, EMPP)
- New evaluation of DPP



μ, $\boldsymbol{\pi}$ spectra generated in the evolution of a cascade

Spectral modeling of IceCube ν candidate NGC 1068

arXiv:2305.06375

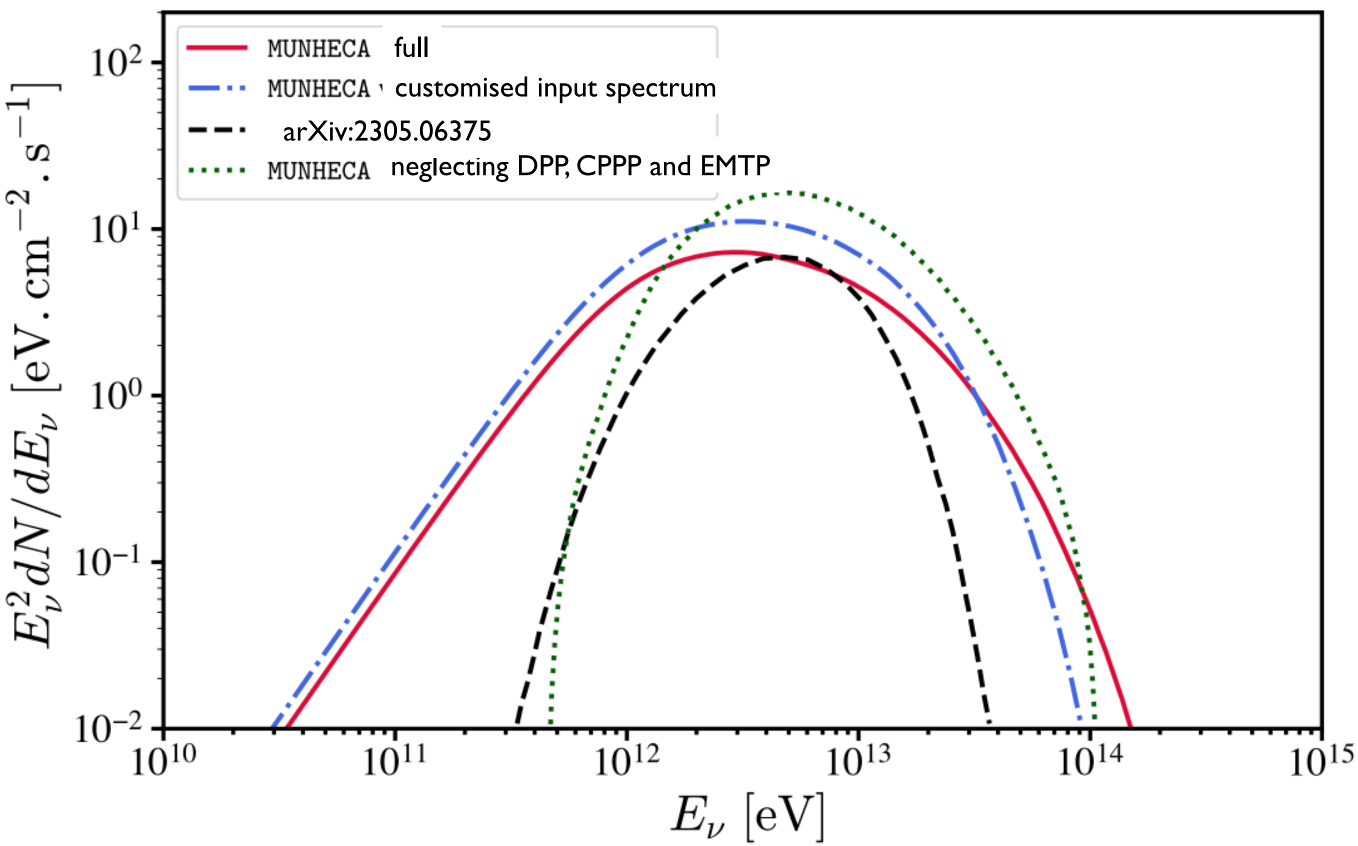
A Leptonic Model for Neutrino Emission From Active Galactic Nuclei

Dan Hooper[1,2,3]* and Kathryn Plant[4]†
[1] *Fermi National Accelerator Laboratory, Theoretical Astrophysics Department, Batavia, IL, USA*
[2] *University of Chicago, Department of Astronomy & Astrophysics, Chicago, USA*
[3] *University of Chicago, Kavli Institute for Cosmological Physics, Chicago, IL, USA and*
[4] *California Institute of Technology, Department of Astronomy, Pasadena, CA, USA*
(Dated: May 22, 2023)

cascade development
inside a source

target: X-rays in the SMBH corona, T_X = 1 keV
(Threshold ~10 TeV)

μ multiplicity matters
(green vs. black)
extra reactions matter
(red vs. green)



Extra slides

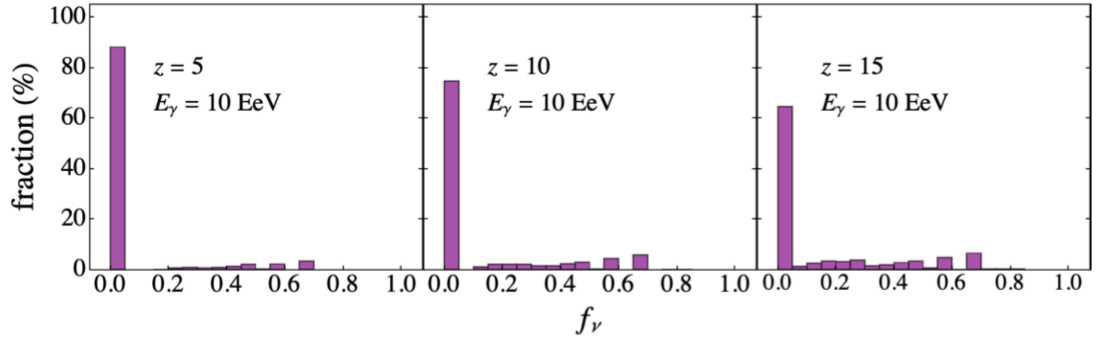
Result of earlier simulations - Q1

We follow the QED cascade with a dedicated Monte Carlo (Here 10^4 photon simulations)

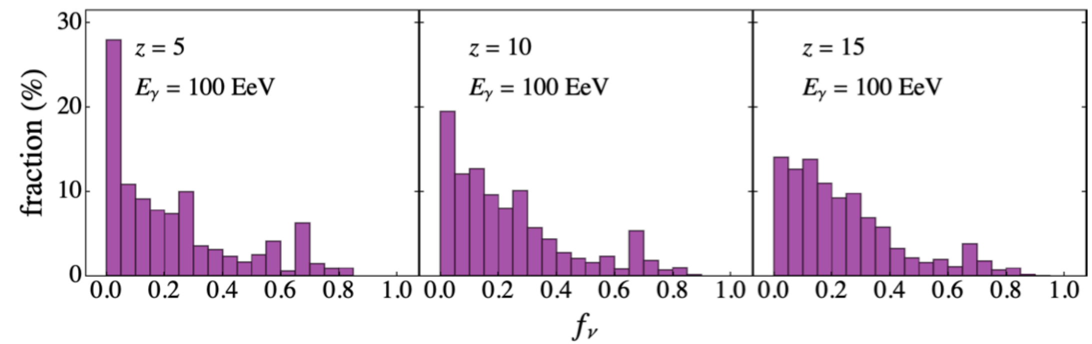
Question 1
How many γ's induce cascades experiencing MPP, hence producing ν's?

@E=10^{19} eV
z = 5 , ~12% of the photons experience MPP.
At z=10 grows to ~25% and at z=15 it grows to~ 35%

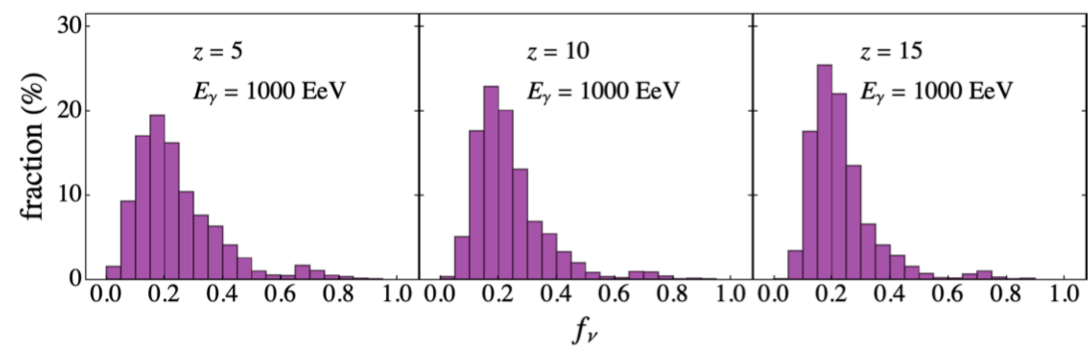
@E=10^{20} eV,
>70% of photons experience MPP at z ≥ 5,
with this fraction exceeding 94% at z = 15.



$E_\gamma = 10^{19}$ eV



$E_\gamma = 10^{20}$ eV



$E_\gamma = 10^{21}$ eV

QII: fraction of initial γ energy channelled into ν's

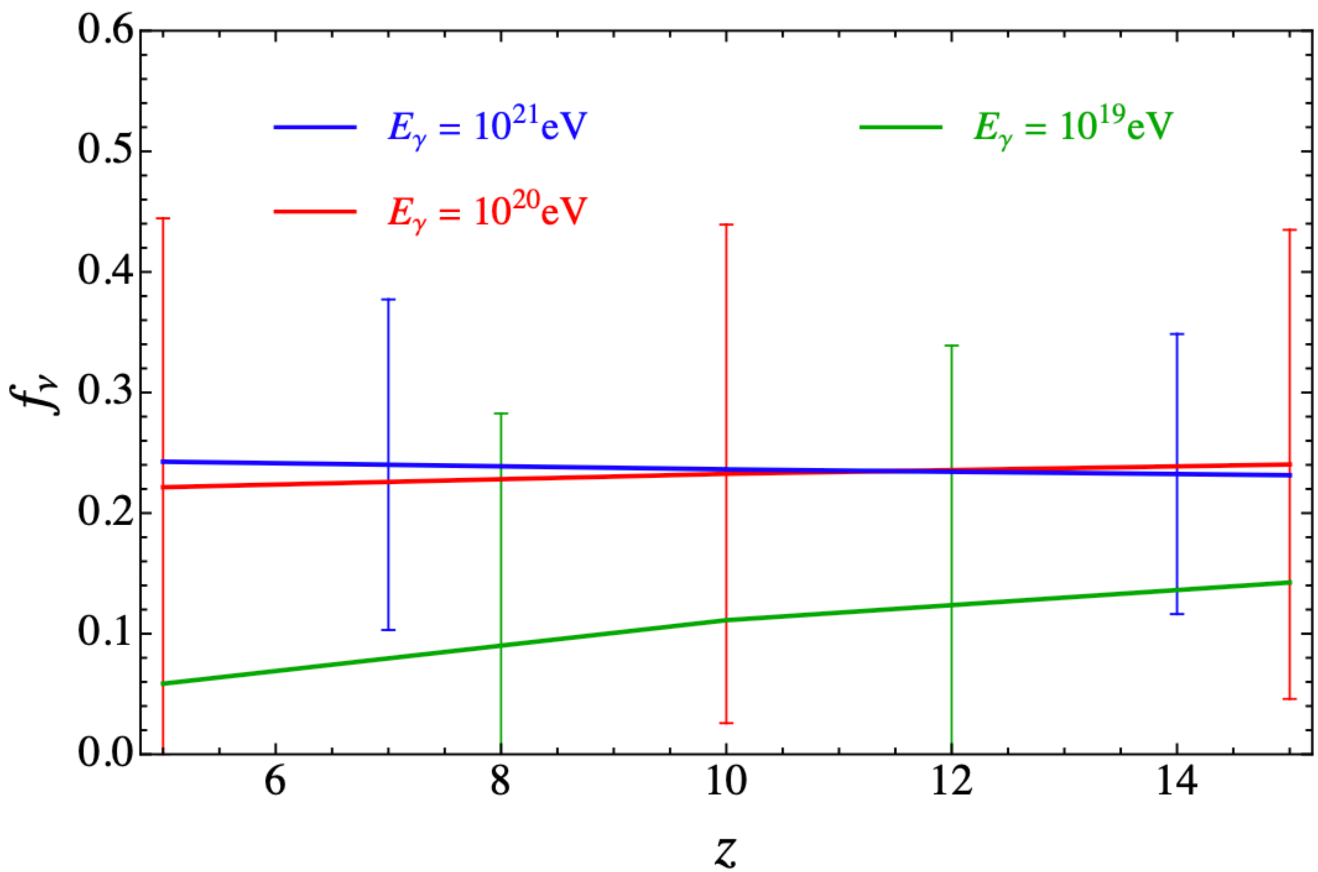
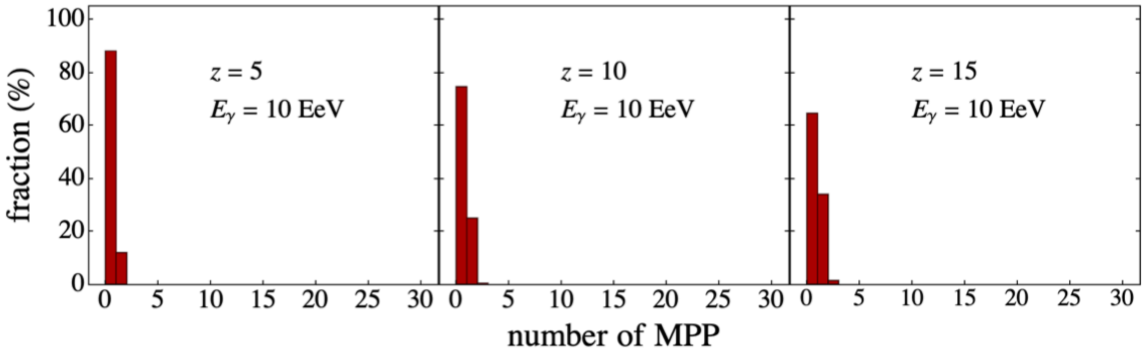


FIG. 3. The mean fraction of the initial photon's energy ending up in neutrinos, f_ν, for three different energies of the initial photon. The bars show the standard deviation around the mean value depicted by solid curves.

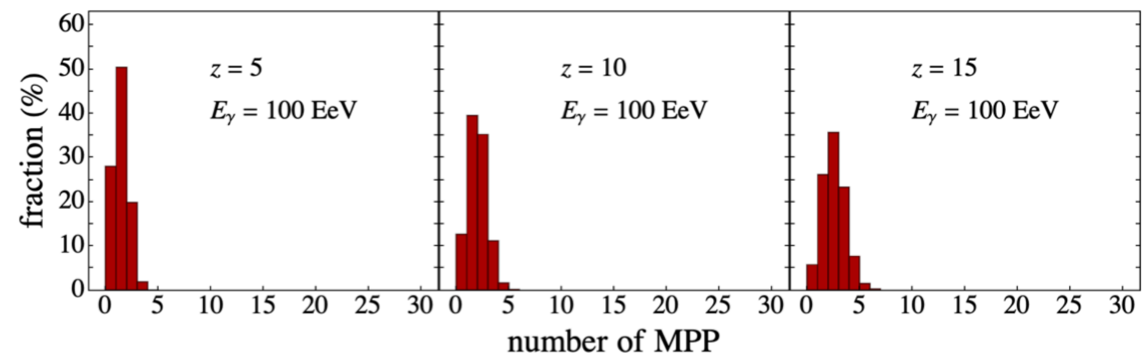
QIII: How many MPP events?

Multiple productions more and more relevant at high-E and/or high-z!

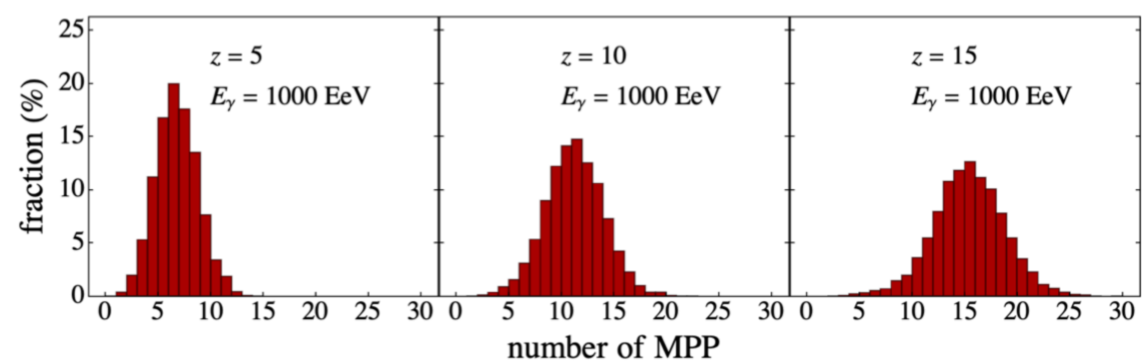
This effect is virtually impossible to quantify without MC simulations…



$E_\gamma = 10^{19}$ eV

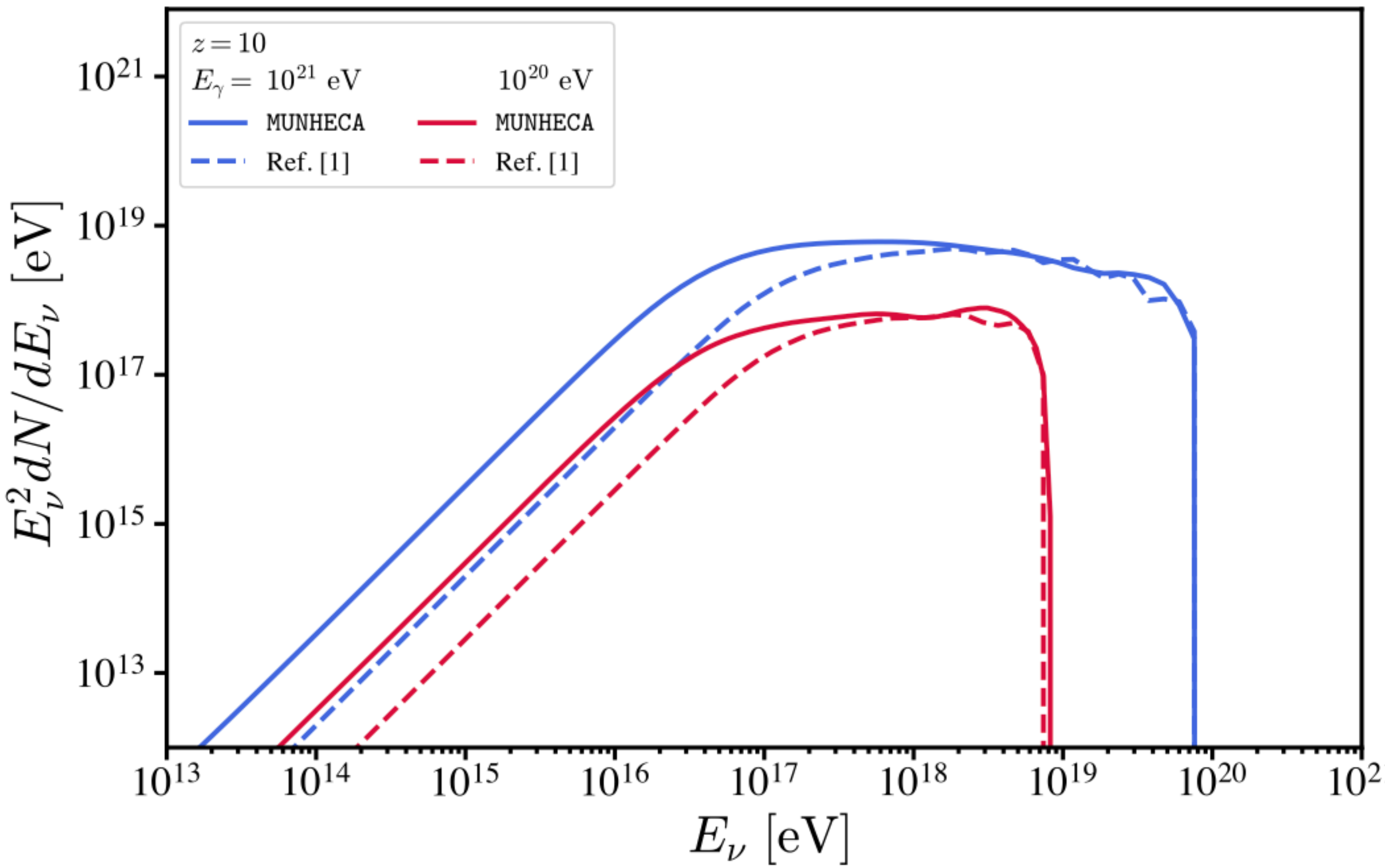


$E_\gamma = 10^{20}$ eV



$E_\gamma = 10^{21}$ eV

New vs. earlier simplified calculation of cosmo cascade



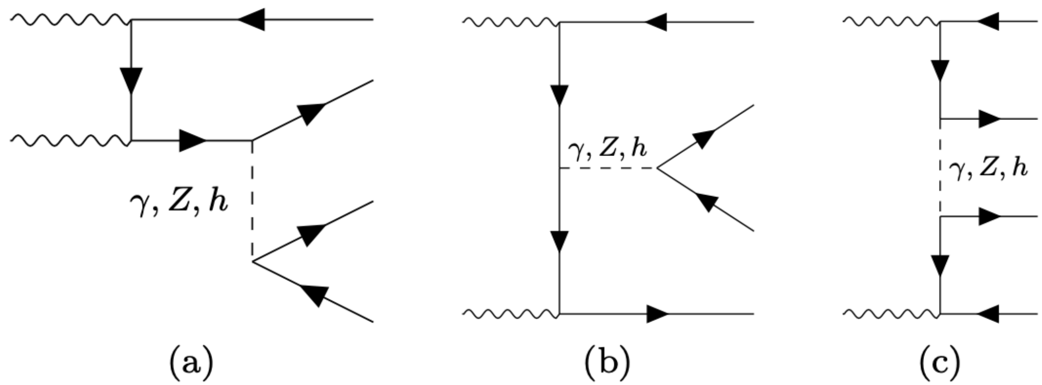
Slight (~10%) enhancement at high-*E* (***π***$^\pm$ production, here Born approx of spinless elementary particle…)

Enhanced tail (improved description of cascade, extra processes…)

Ancillary results: Double pair production

$$\gamma\gamma \to e^+e^-e^+e^-$$

calcHEP-based,
leading order calculation

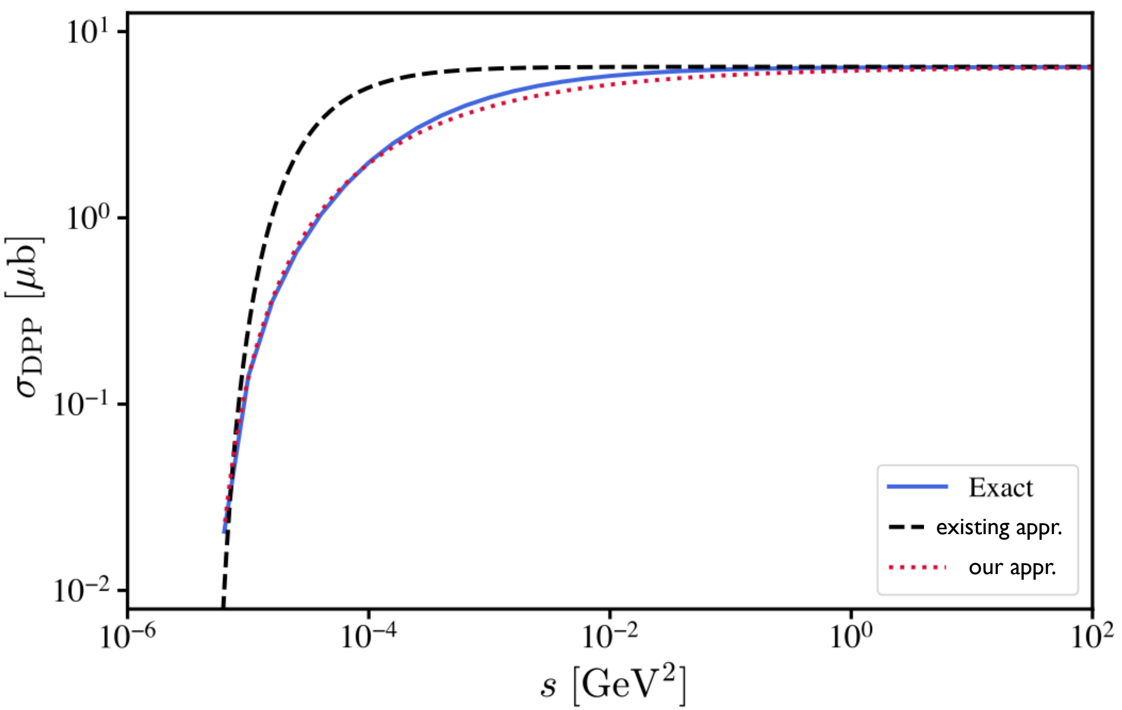


$$\sigma_{\rm DPP}(s) \simeq \frac{\alpha^4 \theta(s-s_{\rm th})}{\pi m_e^2}\left(\frac{175}{36}\zeta(3)-\frac{19}{18}\right)\left(1-\frac{s_{\rm th}}{s}\right)^6$$

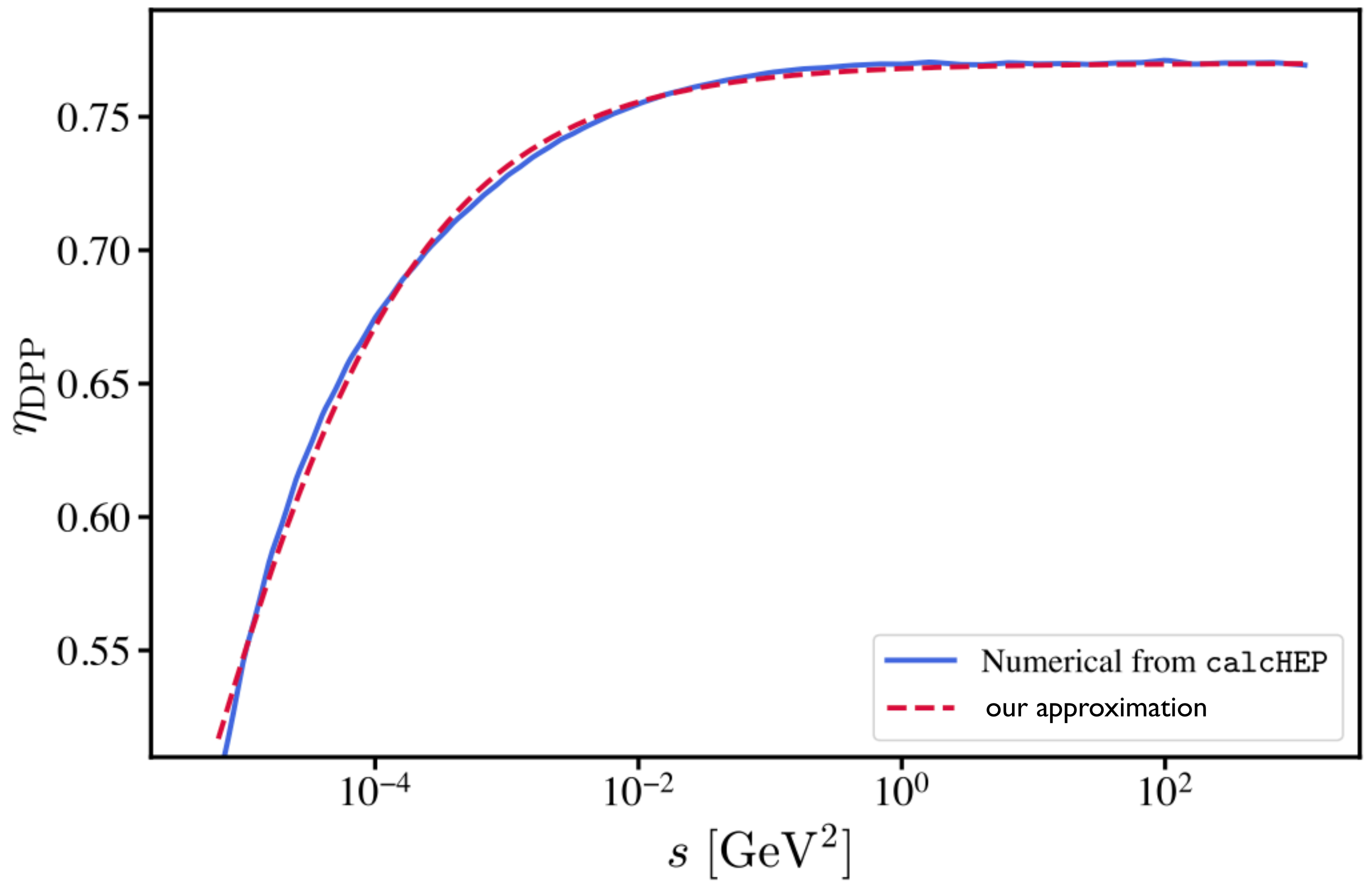
existing approximation

$$\sigma_{\rm DPP}(s) \simeq 6.45\,\mu{\rm b}\left[1-\left(\frac{s_{\rm th}}{s}\right)^{1/3}\right]^{14}$$

our approximation



Ancillary results: DPP inelasticity (leading particle)



$$\eta(s) \approx a + b\,\exp\left[-(s_{\rm th}/s)^c\right]$$

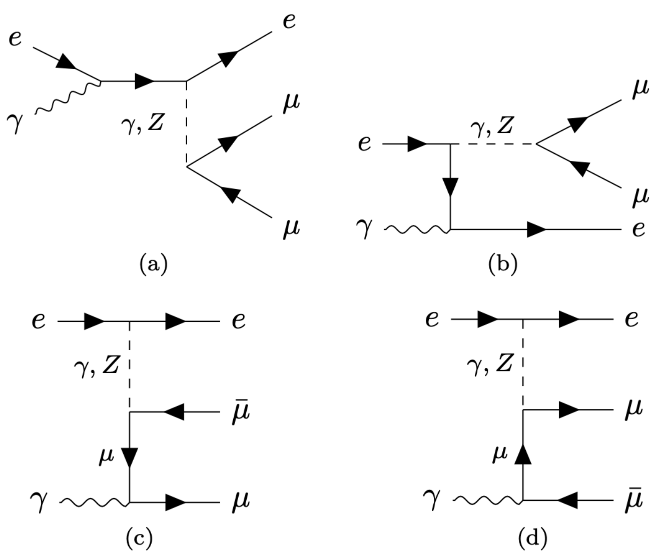
a = 0.32, b = 0.45, c = 0.44

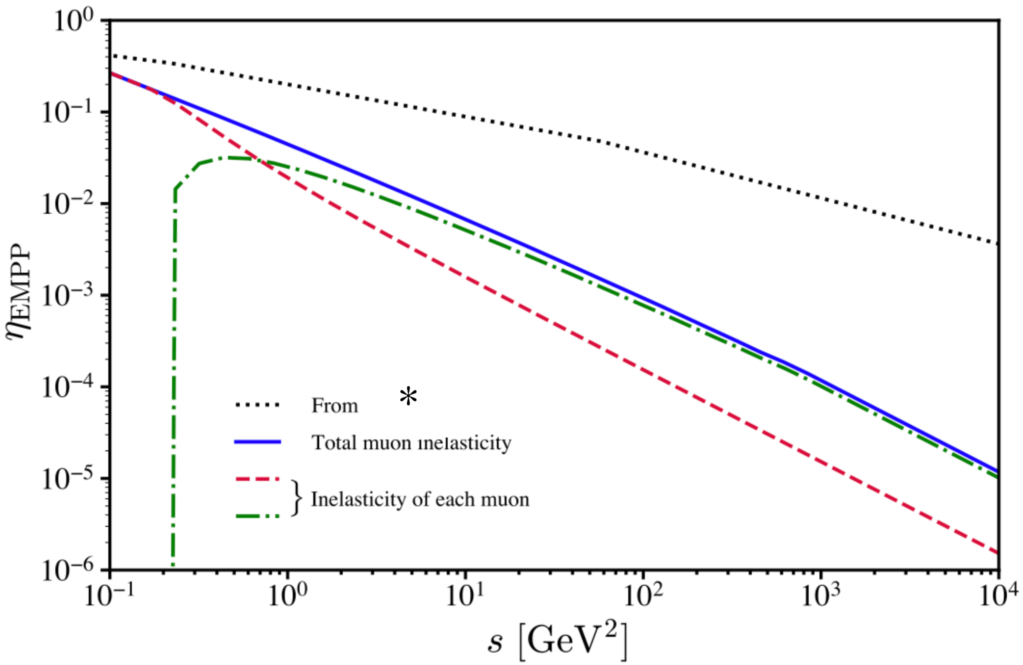
Approximations suggested in the only existing treatment* lead to~30% errors

*S. V. Demidov and O. E. Kalashev, J. Exp. Theor. Phys. 108, 764 (2009), arXiv:0812.0859

Ancillary results: EMPP

$$\gamma\gamma \to \mu^+\mu^-e^+e^-$$





calcHEP-based,
leading order calculation

Approximation in * acceptable (at the ~ 30% level) only at the lowest energies considered, near threshold

*H. Athar, G.-L. Lin, and J.-J. Tseng, Phys. Rev. D 64, 071302(R) (2001), arXiv:hep-ph/0104185.