The Hadronic Code Comparison Project: First Results

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Lepto-Hadronic modeling of Blazars

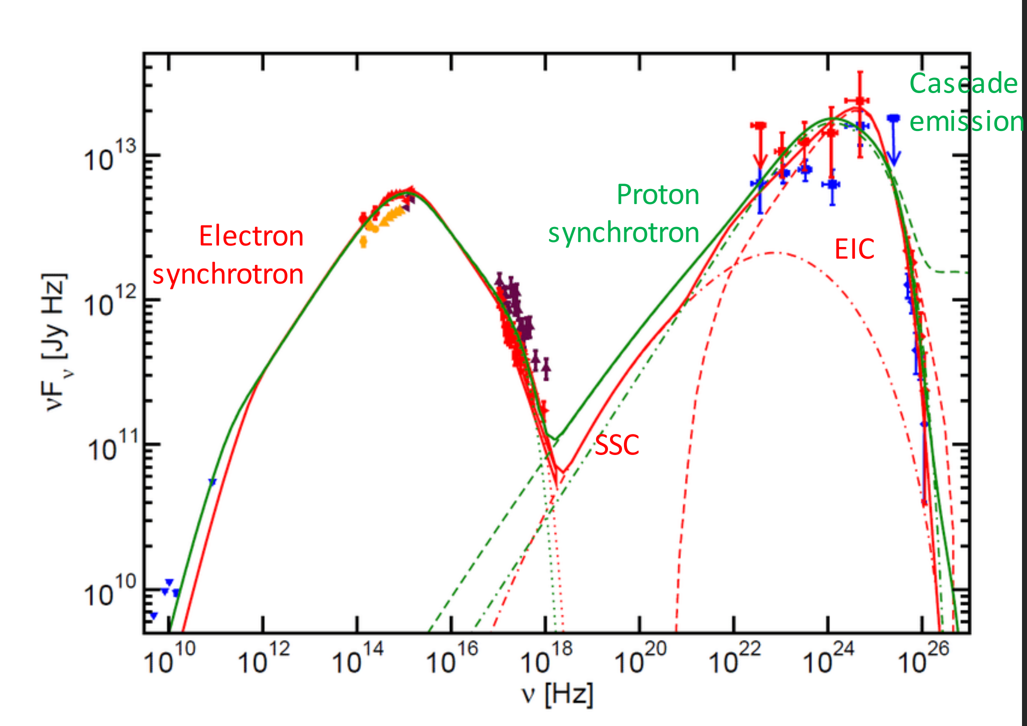
Blazar SED either:

(A) purely leptonic
electron synchrotron, self-compton, external inverse compton

(B) from both hadronic and leptonic processes
electron and proton synchrotron, cascade emission

Neutrino emission only in lepto-hadronic scenario possible!

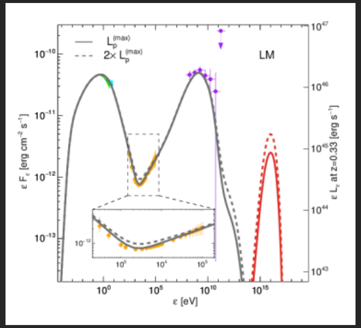
Modeling BL Lac object 3C66A



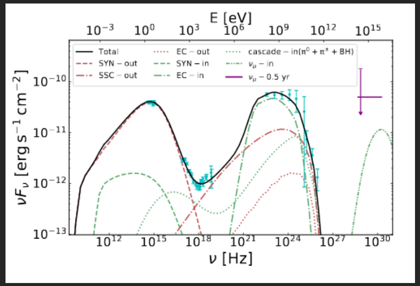
Romero et al 2016

Red: Leptonic scenario
Green: Lepto-hadronic scenario

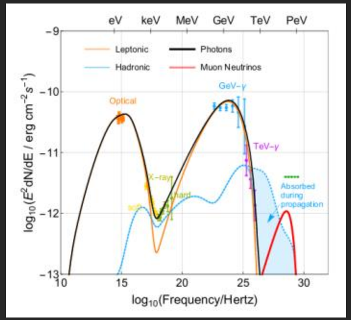
Hadronic models in the light of TXS



Keivani et al 2018

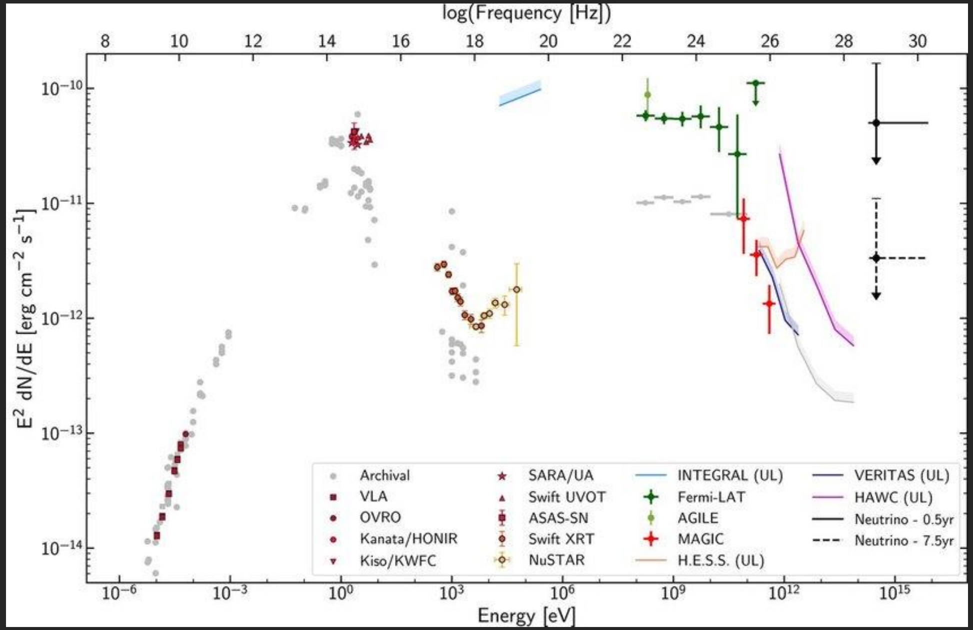


Xue et al 2019

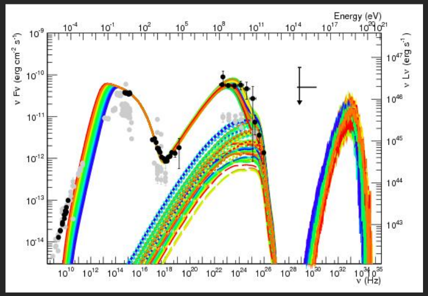


Gao et al 2018

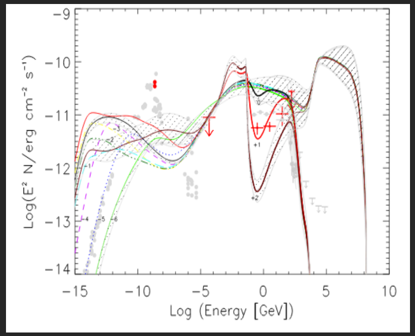
Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A



Aartsen et al 2018

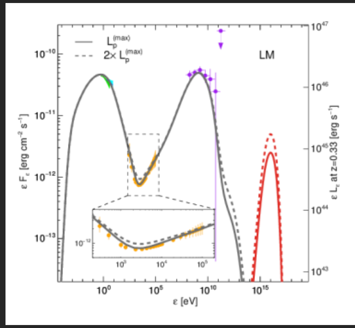


Cerutti et al 2019



Reimer et al 2019

Hadronic models in the light of TXS



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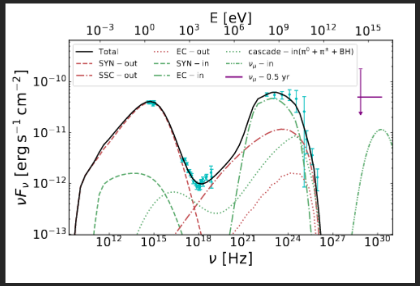

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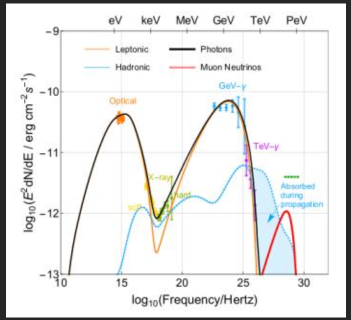

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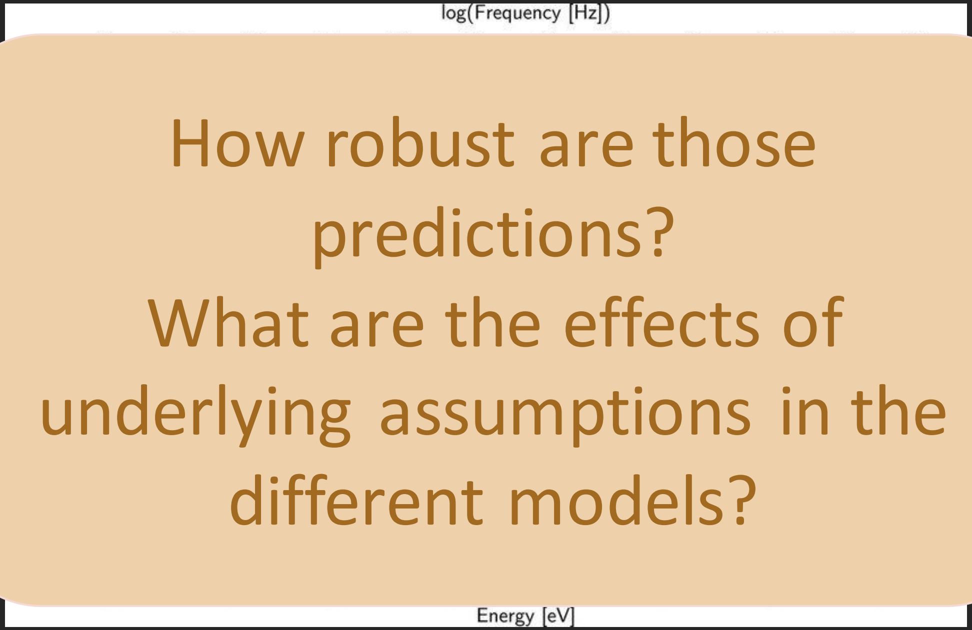
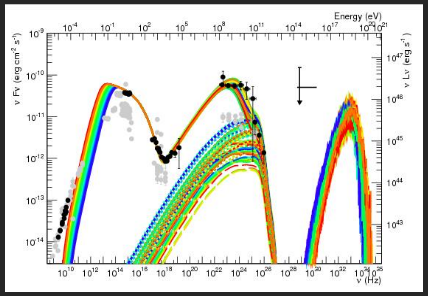
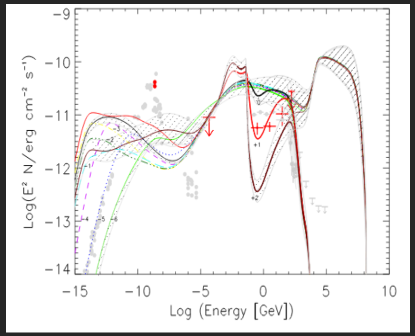


How robust are those predictions?
What are the effects of underlying assumptions in the different models?

Aartsen et al 2018



Cerutti et al 2019



Reimer et al 2019

What and how to compare?

Physical processes entering the models:

Leptonic: Synchrotron, synchrotron self-absorption, Inverse Compton, photo-pair production

Hadronic: Synchrotron, Inverse Compton, Bethe-Heitler pair production, photo-meson processes

Quantities used in the comparison:

- Observed spectra (photons and neutrinos)
- Injection rates in the source

(- source spectra of primaries like protons and electrons)

Cases that will be compared:

1. Leptonic: steady state and time-dependent
2. Hadronic: steady state and time-dependent, non-linear hadronic cascades

The Codes (I)

ATHEνA

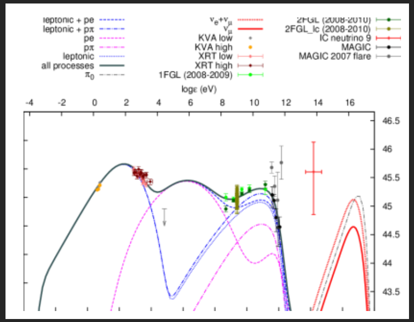
Mastichiadis & Kirk 1995, Mastichiadis et al 2005, Dimitrakoudis et al 2012

- Time-dependent code solving a series of coupled PDEs
- Photopion interactions from SOPHIA
  Photopair interactions Protheroe & Johnson
  Leptonic and hadronic feedback channels
- Applied eg. to GRBs and several AGNs (TXS)

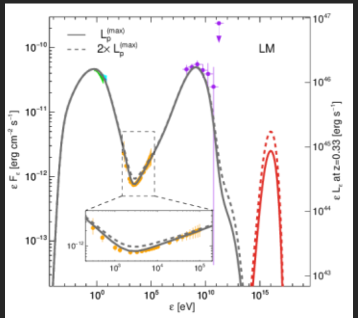
Paris

Cerruti et al 2015

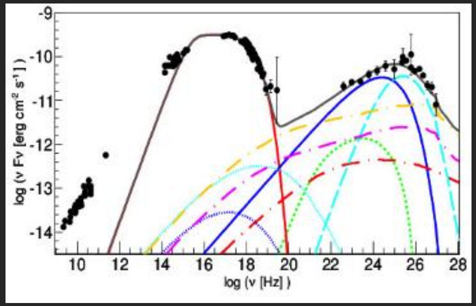
- Steady-state solver
- Photopion interactions from SOPHIA
  Bethe-Heitler from Kelner & Aharonian
  Iterative computation of pair cascades
- Applied eg. to EHBLs and TXS



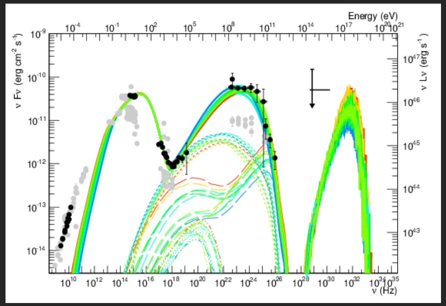
Petropoulou et al 2015



Keivani et al 2018



Cerutti et al 2015



Cerutti et al 2019

The Codes (II)

AM3

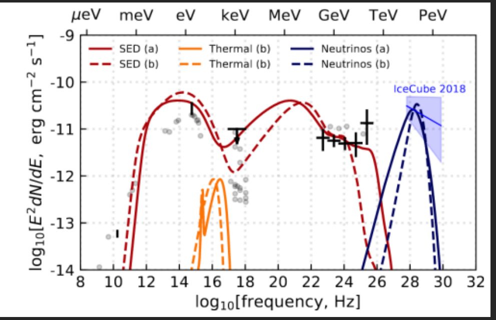
Gao et al 2016

- Time-dependent code solving a series of coupled PDEs
- Photohadronic following Hümmer et al
  Pair-annihilation Vurm & Poutanen
  Leptonic and hadronic feedback channels
- Applied eg. to PKS 1424-418 and TXS

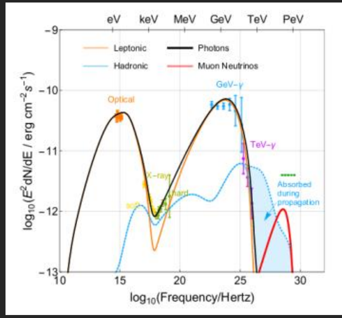
Boettcher

Boettcher et al 2013

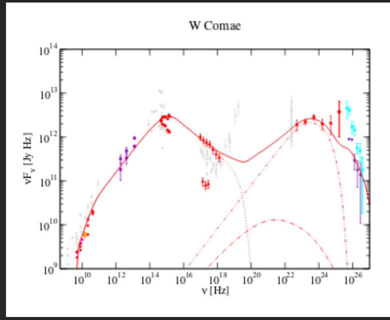
- Steady-state solver
- Photopion interactions and Bethe-Heitler from Kelner & Aharonian (2008, based on SOPHIA)
- Applied eg. Fermi Blazars

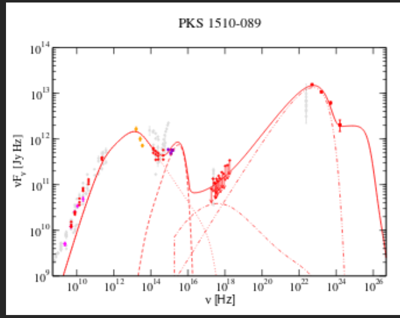


Rodrigues et al 2018



Gao et al 2018

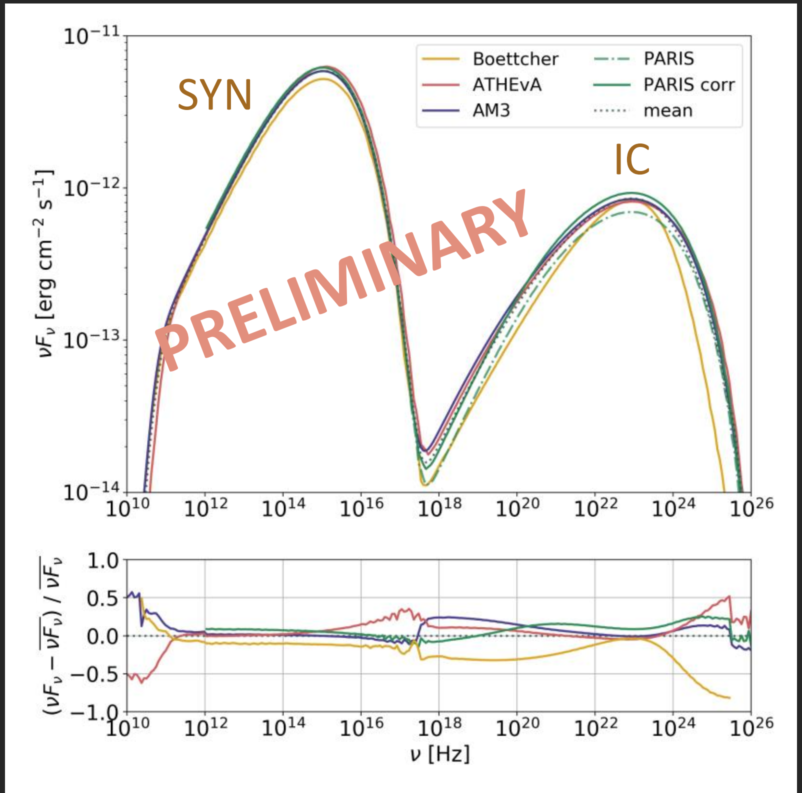




Boettcher et al 2013

Leptonic solutions: SSC cases

Observed spectrum



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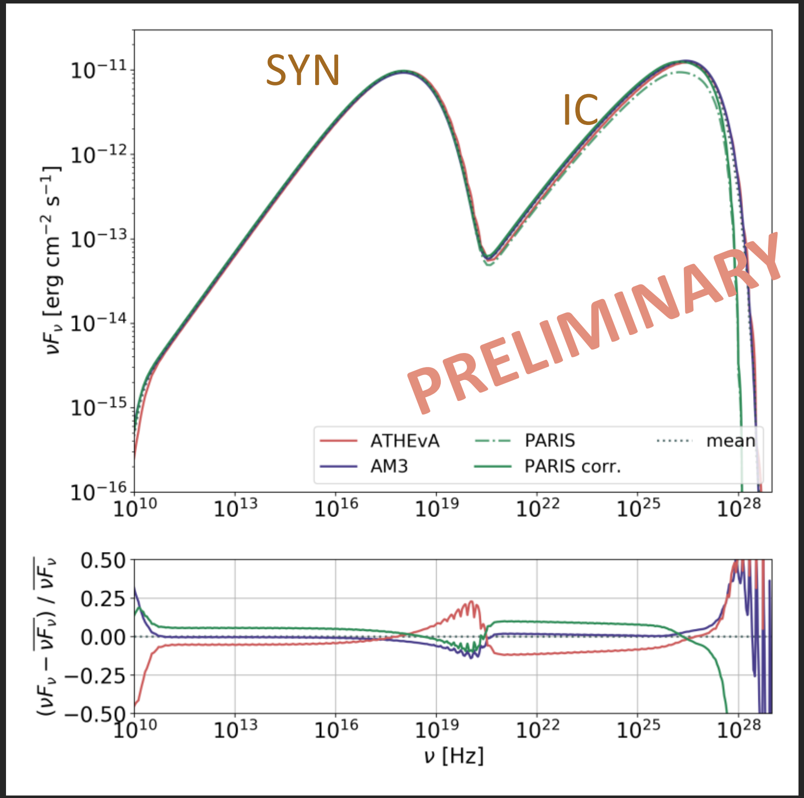


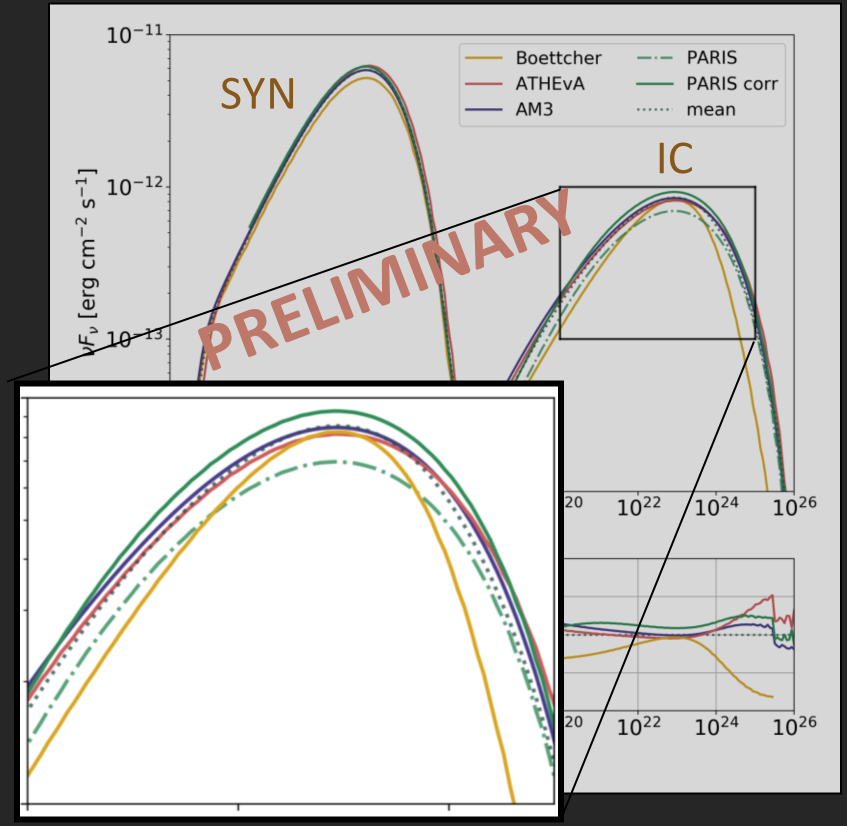
← Deviation with respect to mean →

A simple case: Low magnetic field (0.1 G) no pair-annihilation, simple electron power-law

Slightly more complicated: Higher Lorentz factor of electrons -> pair-annihilation effects

Leptonic solutions: SSC cases

Observed spectrum

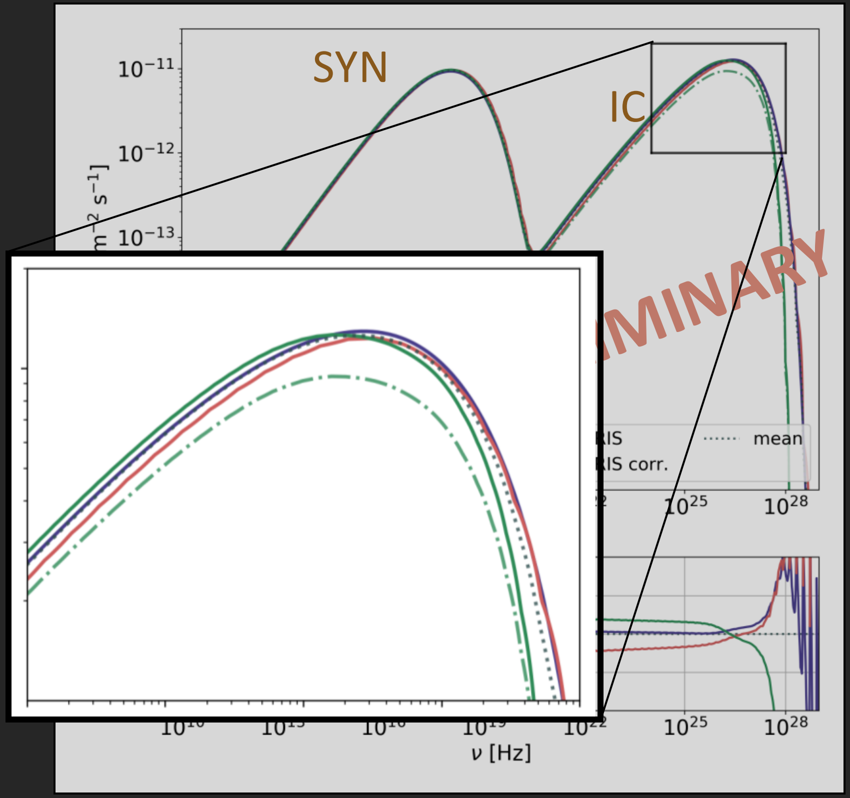


A simple case: Low magnetic field (0.1 G) no pair-annihilation, simple electron power-law

Paris Code: geometrical factor of ¾ in target photons for IC Component

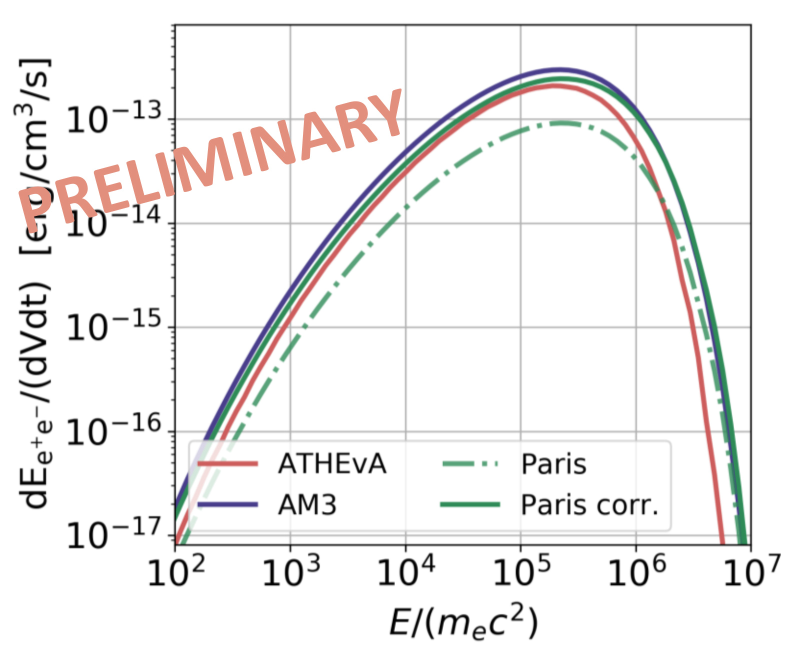
When corrected for this: good agreement!

Observed spectrum



Slightly more complicated: Higher Lorentz factor of electrons -> pair-annihilation effects

Pair production rates

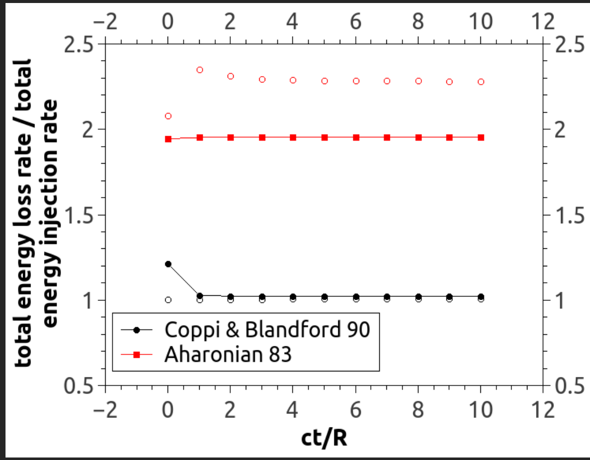


AM3: Higher IC Component -> Higher pair production rate

Paris: 1. ¾ factor from IC component

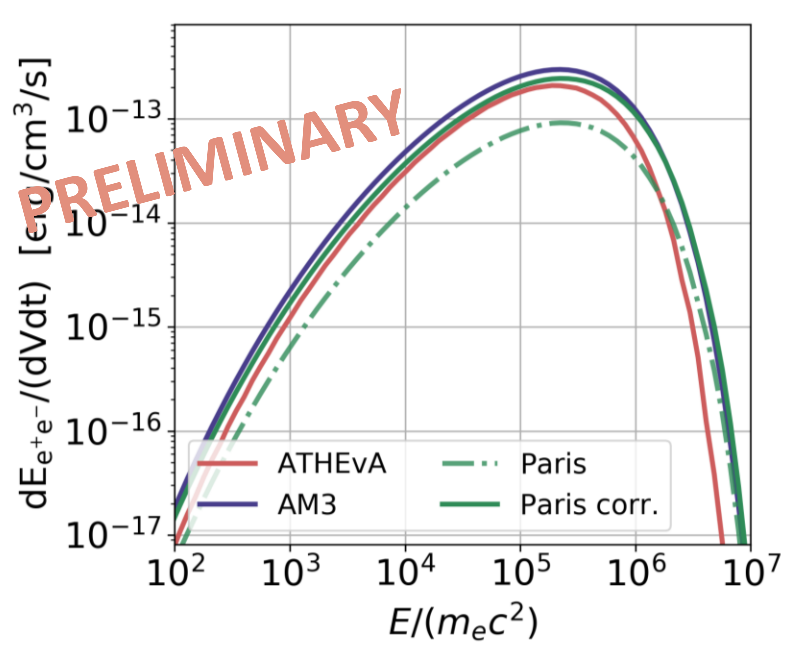
2. Aharonian (83) formula instead of Coppi & Blandford (90)
Resulting in factor ½

-> when correcting for both, good agreement!



Main conclusion: If one uses the γγ absorption rate from CB90 and the Aharonian+83 rate for pair production, one underestimates the production rate by a factor of **~2**

Pair production rates



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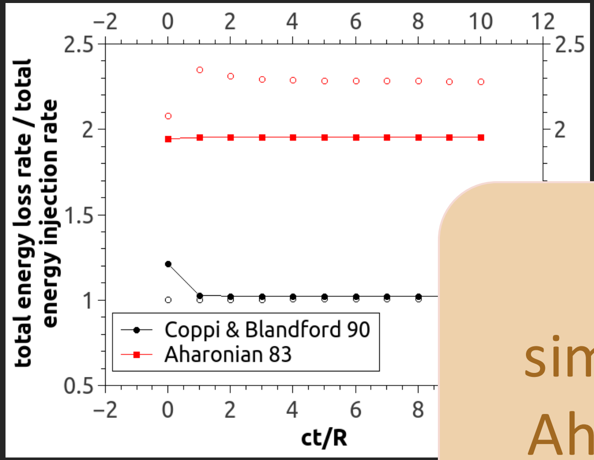
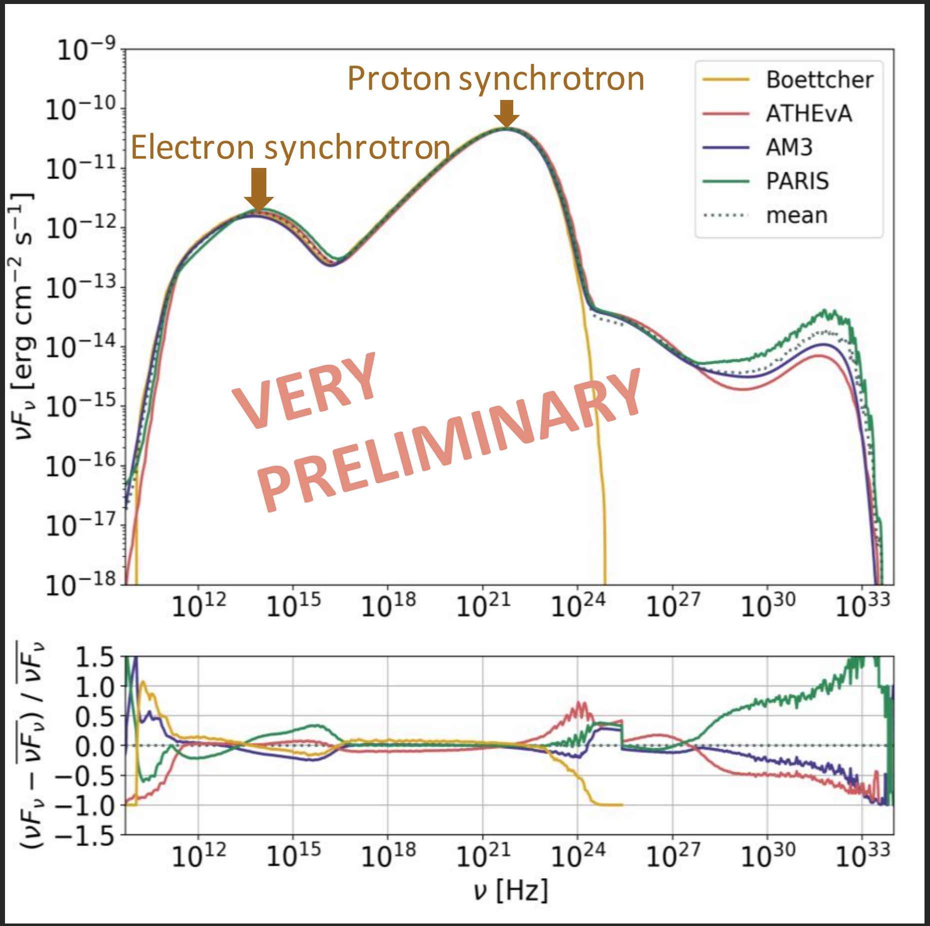


Main conclusion: If one uses the γγ absorption rate from ... +83 ... ne ... uction

Monte-Carlo simulations confirm Aharonian formula!

A first lepto-hadronic scenario

Observed SED



Proton Synchrotron Case

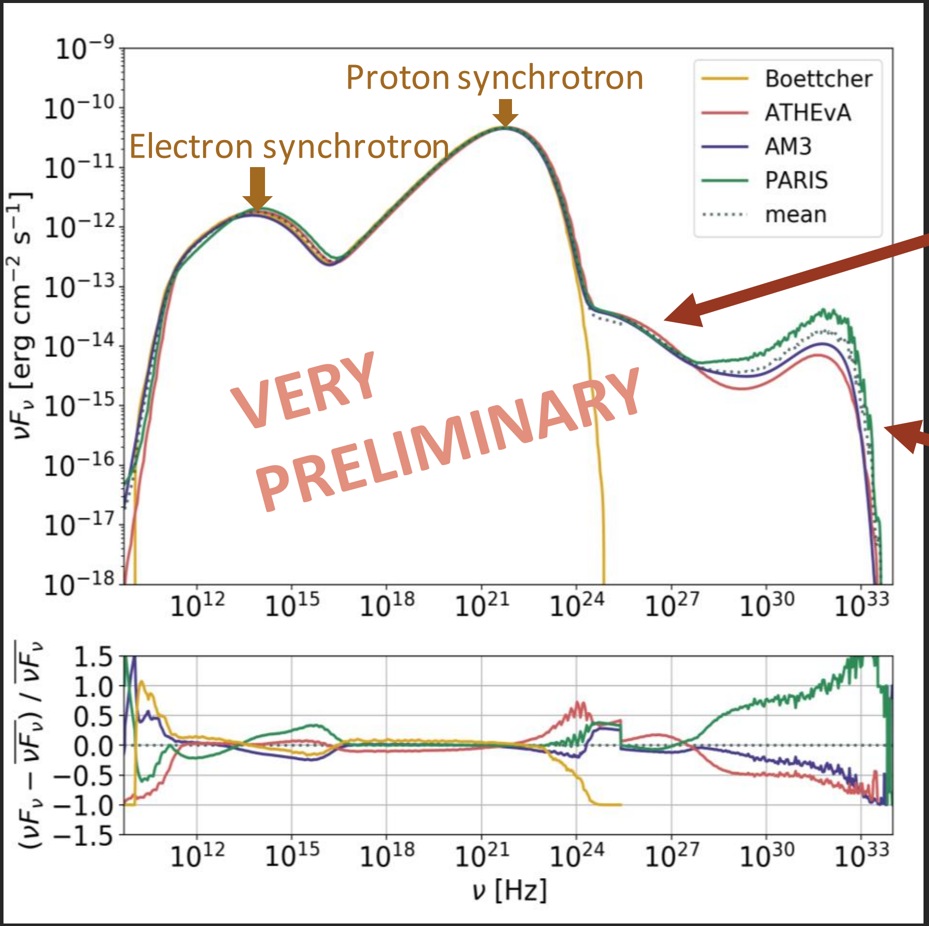
Parameters:

- Large magnetic field (10 G)
- Large baryonic loading
- Simple power-law for both electrons and protons (s = 2.9)
- no pair-annihilation -> study photo-hadronic processes in detail

Good agreement on leptonic and hadronic synchrotron peaks!

A first lepto-hadronic scenario

Observed SED



Bethe-Heitler pair injection

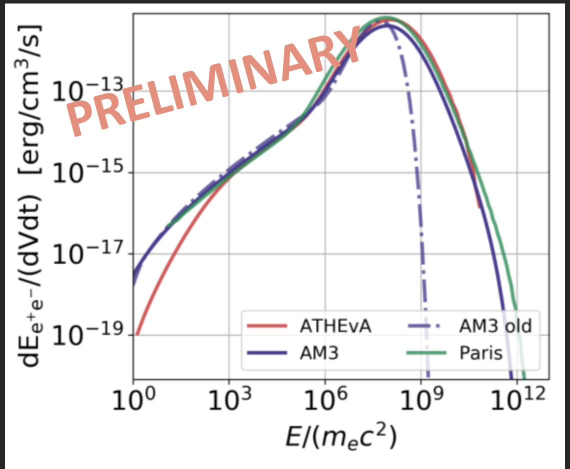
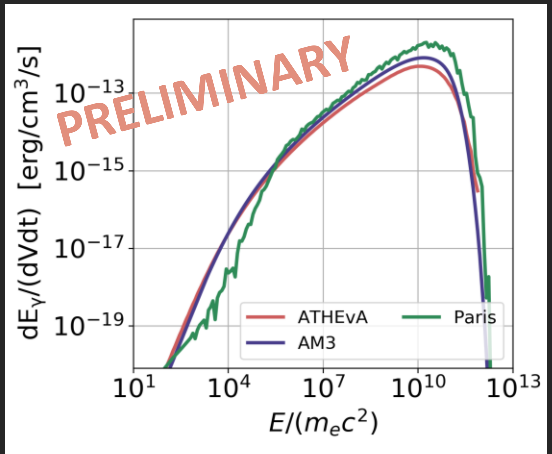


Photo-hadronic processes

Injection rates in the source

Pion-decay photon injection



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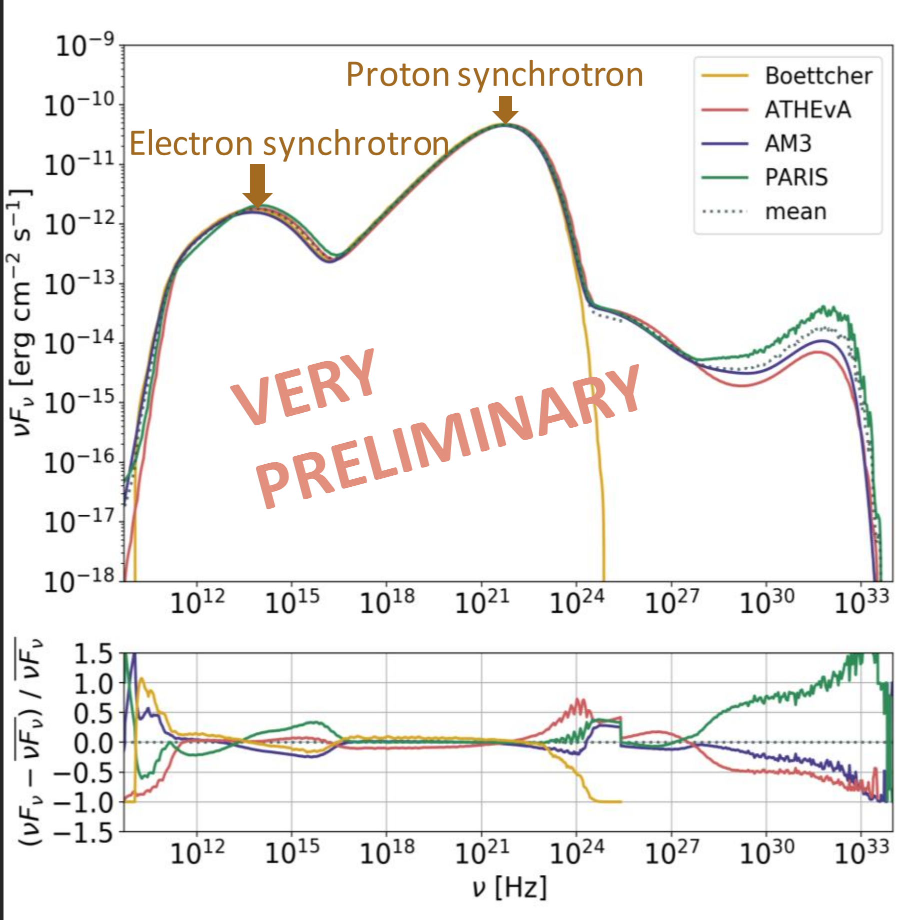
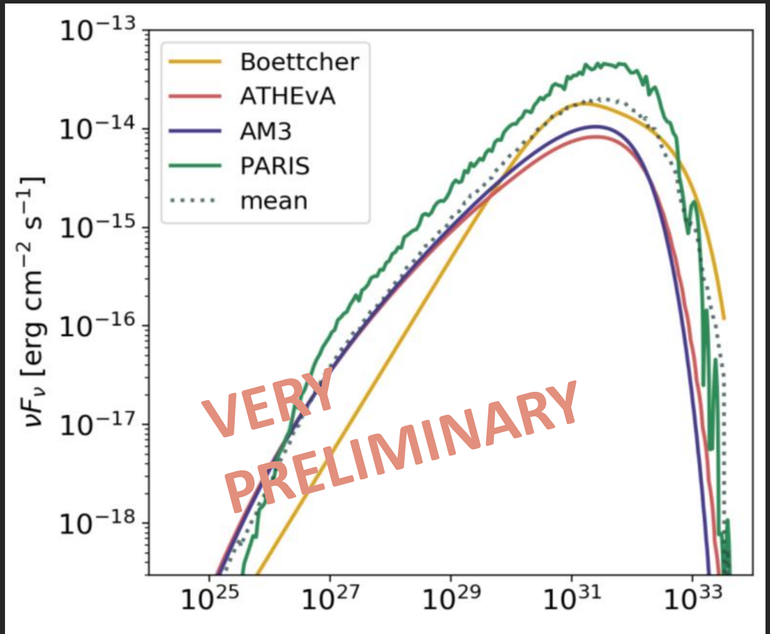


Predicted neutrino fluxes



Summary and future perspectives

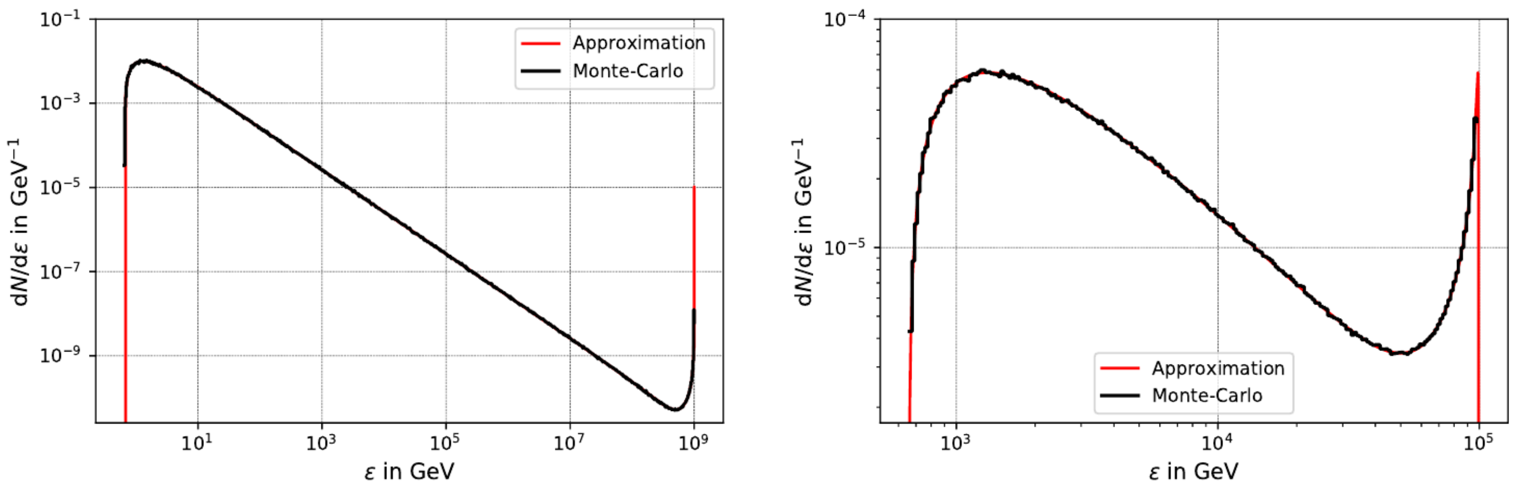
Done:

- Successful comparison of leptonic scenarios, differences in pair-production rates understood and resolved
- Started comparison on lepto-hadronic scenarios. Good agreement for proton synchrotron, solved issues on Bethe-Heitler production. Discrepancies in energy spectra/ rates of photo-meson secondaries. Why?

On the agenda:

- Compton catastrophe comparison
- Compare photo-meson module of codes using a black-body target photon field -> cleaner case
- Compare more realistic lepto-hadronic scenario

MC comparison for pair-annihilation



(e) $\omega_1 = 100\,\mathrm{eV}$ and $\omega_2 = 10^{18}\,\mathrm{eV}$
$\omega_1\omega_2 = 10^{20}\,\mathrm{eV}^2$

(f) $\omega_1 = 0.1\,\mathrm{eV}$ and $\omega_2 = 10^{14}\,\mathrm{eV}$
$\omega_1\omega_2 = 10^{13}\,\mathrm{eV}^2$

Gabriel Schmid

- ω_1: frequency of soft target photon
- ω_2: frequency of incident HE photon
- ε : energy of created electron/ positron

Comparison to Aharonian+ (83)

For ω_1 approx. 1, the Aharonian formula shows different behavior at low electron/positron energies, is ok at higher energies

Good agreement for cases with incident photons in VHE /UHE range which are relevant in relativistic jets