Astrophysical (PeV) neutrinos

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Neutrinos: the quest for a new physics scale
CERN

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Contents

> Introduction
> Particle astrophysics of neutrino sources
> On the signal interpretation
> Flavor composition for test of fundamental physics
> Glashow resonance for astrophysical source diagnostics?
> Summary
IceCube: Event topologies?

Muon track:
- From $\nu_\mu$ (mostly)

Cascade (shower):
- From $\nu_e$
- From $\nu_\tau$
- [From $\nu_e$, $\nu_\mu$, $\nu_\tau$ neutral current interactions]

Better directional info

Better energy info

The ratio between muon tracks and showers $\sim \nu_\mu / (\nu_e + \nu_\tau)$, roughly
54 high energy cosmic neutrinos

ICECUBE PRELIMINARY

No evidence for Galactic origin, no significant clustering: diffuse extragalactic flux?

The Earth is intransparent for $E >> 10$ TeV

+ Cascades
× Muon tracks

TS=2log(L/L0) 0 10.9

The universe in multiple messengers ... as theory challenge

**Physics of astrophysical neutrino sources = physics of cosmic ray sources**

**Multi-messenger interpretations must rely on theory** (acceleration, radiation processes, particle escape, geometry, ...)

**Large astrophysical uncertainties**

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**Theory** (signal shape)

**Theory** (radiation model)

**Theory** (source distribution)

**Theory** (magn. fields, ...)

**Astrophysical beam dump**

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Fundamental physics, new physics?
A simple toy model for the source

If neutrons can escape:
Source of cosmic rays

\[ n \rightarrow p + e^- + \bar{\nu}_e \]

Neutrinos produced in ratio \((\nu_e : \nu_\mu : \nu_\tau) = (1:2:0)\)

\[ \pi^+ \rightarrow \mu^+ + \nu_\mu, \]

\[ \mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu \]

Delta resonance approximation:

\[ p + \gamma \rightarrow \Delta^+ \rightarrow \left\{ \begin{array}{ll}
  n + \pi^+ & 1/3 \text{ of all cases} \\
  p + \pi^0 & 2/3 \text{ of all cases}
\end{array} \right. \]

Cosmic messengers

\[ \pi^0 \rightarrow \gamma + \gamma \]

High energetic gamma-rays; typically cascade down to lower E
Additional constraints!

(Same process during propagation of cosmic rays in CMB: “cosmogenic neutrinos”)
Particle astrophysics of neutrino sources
Cosmic vs. terrestrial particle accelerators

Lorentz force = centrifugal force $\Rightarrow E_{\text{max}} \sim q B R$

- $E_{\text{max}} \sim 300,000,000 \text{ TeV}$
- $B \sim 1 \text{ mT} - 1 \text{ T}$
- $R \sim 100,000 - 10,000,000,000 \text{ km}$

Which mechanisms can accelerate particles to such extreme energies?

- $E_{\text{max}} \sim 7 \text{ TeV}$
- $B \sim 8 \text{ T}$
- $R \sim 4.3 \text{ km}$

AGN, GRB

LHC
Acceleration of primaries (protons, nuclei)

Example: Fermi shock acceleration

> Fractional energy gain per cycle: $\eta$
> Escape probability per cycle: $P_{\text{esc}}$
> Yields a **power law** spectrum $\sim E \frac{\ln P_{\text{esc}}}{\ln \eta} - 1$
> $\ln P_{\text{esc}}/\ln \eta \sim -1$ (from compression ratio of a strong shock), and $E^{-2}$ is the typical “textbook” spectrum

> Although theory of acceleration at relativistic shocks challenging, we **do observe** power law spectra in Nature

> For neutrino production: adopt pragmatic point of view! *(we know that it works, somehow ...)*
Secondary production: Particle physics 101

> Beam dump picture (particle physics)

Beam of p, A, ...

Target (p, γ, A, ...)

> Interaction rate \( \Gamma \sim c N [\text{cm}^{-3}] \sigma [\text{cm}^2] \)

Target density (e.g. \( N_\gamma \)) critical for \( \nu \) production!

> Astrophysical challenges:

- Feedback between beam and target (e.g. photons from \( \pi^0 \) decays); need self-consistent description called radiation model
- What you see is, in general, not what you get in the source

(Mücke, Rachen, Engel, Protheroe, Stanev, 2008; SOPHIA)
Kinetic equations for self-consistent treatment (steady state)

- Treat energy losses/escape in continuous limit in radiation zone:
  
  \[ Q(E) = \frac{\partial}{\partial E} \left( b(E) N(E) \right) + \frac{N(E)}{t_{\text{esc}}} \]

- Injection
- Energy losses
- Escape

One equation for each particle species!

- \( b(E) = -E t^{-1}_{\text{loss}} \)
- \( Q(E,t) \) [GeV\(^{-1}\) cm\(^{-3}\) s\(^{-1}\)] injection per time frame (e.g. from acc. zone)
- \( N(E,t) \) [GeV\(^{-1}\) cm\(^{-3}\)] particle spectrum including spectral effects

Need \( N(E) \) to compute particle interactions

- Simple case: No energy losses \( b=0 \):
  \[ N(E) = Q(E) t_{\text{esc}} \]

- Special case \( t_{\text{esc}} \sim R/c \) (free-streaming, aka “leaky box“)
Neutrino production (example: $p\gamma$ interactions)

Dashed arrows: kinetic equations include cooling and escape

Input ⇒ Object-dependent ⇒ Astrophysics!

Q(E) [GeV$^{-1}$ cm$^{-3}$ s$^{-1}$] per time frame
N(E) [GeV$^{-1}$ cm$^{-3}$]
density in source

Optically thin to neutrons

Critical: Density $N/V \sim E/V$

Need production volume from
geometry estimators

Example: Causality argument:
time variability indicative for size
of region

Baerwald, Hümmer, Winter,
Astropart. Phys. 35 (2012) 508
In the presence of strong B: Secondary cooling

Secondary spectra ($\mu$, $\pi$, K) loss-steepend above critical energy

\[ E'_c = \sqrt{\frac{9\pi\epsilon_0 m^5 c^7}{\tau_0 e^4 B'^2}} \]

- $E'_c$ depends on particle physics only ($m$, $\tau_0$, and $B'$)
- Leads to characteristic flavor composition and shape

Example: GRB

Decay/cooling: charged $\mu$, $\pi$, K

Muon damped source: 0:1:0 ($\pi$ decays only)

also: Kashti, Waxman, 2005; Lipari et al, 2007; ...
Neutrino propagation: From source to detector

In environments with high densities (e.g. jets choked in envelope): neutrino oscillations in matter

If $E >> 10$ TeV and passage through Earth: Absorption/regeneration (typically included in $A_{\text{eff}}$)

The typical case: decoherent neutrino oscillations/flavor mixing

$$P_{\alpha\beta} = \sum_{i=1}^{3} |U_{\alpha i}|^2 |U_{\beta i}|^2$$

Source $\nu_e : \nu_\mu : \nu_\tau = 1:2:0 \quad \Rightarrow \quad$ Detector $1:1:1$

+ redshift of energy if cosmological distance

Fundamental physics, new physics?
On the signal interpretation
Can the signal come from cosmogenic neutrinos?
(or other contributions which we know that they are there?)

- PeV neutrinos from extragalactic (infrared) background interactions of UHECRs (here: protons)

- Even if protons, soft spectra etc, difficult to reach required flux

Figures: Bustamante. See also Roulet, Sigl, van Vliet, Mollerach, JCAP 1301 (2013) 028
Source candidates: Starburst galaxies?

The origin of IceCube's neutrinos: Cosmic ray accelerators embedded in star forming calorimeters

E. Waxman
(Submitted on 3 Nov 2015)

Evidence against star-forming galaxies as the dominant source of IceCube neutrinos

Keith Bechtol, Markus Ahlers, Mattia Di Mauro, Marco Ajello, Justin Vandenbroucke
(Submitted on 2 Nov 2015)

> For pp interactions: $\pi^+$, $\pi^-$, and $\pi^0$ same production spectrum

> Constraints from Fermi diffuse extragalactic background flux
Murase, Ahlers, Lacki, 2013

> Problem may be even more severe: A large fraction of that background can be attributed to blazars
Bechtol et al, 2015
Gamma-ray bursts (GRBs)

- Most energetic electromagnetic (gamma-ray) outburst class
- Several populations, such as
  - Long-duration bursts (~10 – 100s), from collapses of massive stars?
  - Short-duration bursts (~ 0.1 – 1 s), from neutron star mergers?
- Typical redshift ~ 1-3 (cosmological distances)
  Useful as “standard candles”?
- Observed light curves come in large variety
Neutrino constraints on GRBs (one zone model)

- Idea: Use timing and directional information to suppress atm. BGs

  (Source: NASA)

  GRB gamma-ray observations
  (e.g. Fermi, Swift, etc)

  Coincidence!

  Neutrino observations
  (e.g. IceCube, …)

- Best tested astrophysical object class from stacking
  *IceCube, Nature 484 (2012) 351; see arXiv:1702.06868 for latest update*

- Not the dominant source of observed diffuse $\nu$ flux!

- Nominal prediction (depends on GRB sample)

- Current limit constrains average parameters relevant for $\nu$ production
  (e.g. **baryonic loading** $f_e^{-1}$, $\Gamma$, $z$)

*GRB gamma-ray observations (e.g. Fermi, Swift, etc) *(Source: NASA)*

*Neutrino observations (e.g. IceCube, …)*(Source: IceCube)

But: are these models realistic? Multi-zone models

- Set our shells with $\Gamma$ distribution
- The light curves can be predicted as a function of the engine parameters
- Consequence: Collisions radii are widely distributed!
- Neutrino flux not linearly proportional to gamma-ray flux!

Bustamante, Baerwald, Murase, Winter, Nature Commun. 6, 6783 (2015)
The different messengers originate from different regimes of the GRB where the photon densities are very different.

Fundamental problem? Quantities inferred from $\gamma$-ray observations not representative for neutrinos and UHECRs?

Neutrino flux prediction from collisions beyond photosphere $E^2 \phi \sim 10^{-11}$ GeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$

Bustamante, Baerwald, Murase, Winter, Nature Commun. 6, 6783 (2015);
Bustamante, Heinze, Murase, Winter, Astrophys. J. 837 (2017) 33
So how about AGN blazars?

- AGN blazar search with 2nd Fermi-LAT catalogue (stacking analysis)
- No excess found, contribution to diffuse flux < 27%
- Not dominant contribution to neutrino flux
- Nevertheless few events from individual AGNs plausible

### PeV neutrino diffuse flux budget table (biased)

<table>
<thead>
<tr>
<th>Object class</th>
<th>Contr.</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Starburst galaxies + other “pp-calorimeters”</td>
<td>20%</td>
<td>From diffuse extragalactic gamma-ray background</td>
</tr>
<tr>
<td>AGN blazars</td>
<td>7-27%</td>
<td>From AGN stacking</td>
</tr>
<tr>
<td>Gamma-Ray Bursts</td>
<td>&lt;5%</td>
<td>From GRB stacking</td>
</tr>
<tr>
<td>Cosmogenic neutrinos</td>
<td>&lt;10%</td>
<td>Composition + model dependent</td>
</tr>
<tr>
<td>Galactic cosmic ray-hydrogen interactions</td>
<td>&lt;10%</td>
<td>Disputed (depends on Galactic cosmic ray distribution)</td>
</tr>
<tr>
<td>Other Galactic sources</td>
<td>1-16%</td>
<td>See e.g. <a href="https://arxiv.org/abs/1610.07015">arXiv:1610.07015</a>, <a href="https://arxiv.org/abs/1703.09721">arXiv:1703.09721</a></td>
</tr>
<tr>
<td>Choked jets</td>
<td>?</td>
<td>Very speculative</td>
</tr>
</tbody>
</table>

- Dominant source class not yet identified?
- Many source classes contribute at similar levels?
- Or just manifestation of what we have seen at the GRB example: efficient neutrino producers (compact) ≠ efficient gamma-ray emitters?
Unconventional possibilities? Ex.: Tidal Disruption Events

- Tidal disruption of a massive star can lead to jet formation
- Can describe/saturate diffuse neutrino flux (spectrum+normalization) for appropriate scaling choice of $\Gamma, t_v$ with black hole mass function
  Lunardini, Winter, arXiv:1612.03160
- However: yet too low TDE statistics for meaningful statements
- Smoking gun signature: muon damping at high energies
Observational search strategies (examples)

- Clustering of signal events? (e.g. in IceCube, Phys. Rev. Lett. 113 (2014) 101101) Anisotropies, point source searches?

- Correlations with known objects/events in gamma-ray catalogues? (e.g. Padovani, Resconi, arXiv:1406.0376; Mertsch, Rameez, Tamborra, arXiv:1612.07311, …)


- Multi-messenger triggers for transients
Neutrinos to test origin of cosmic rays: Theory challenges

- Auger data indicate that cosmic rays at highest energies are not protons. Best fit propagation model.

- Implications for neutrino flux from sources in which a nuclear cascade can develop?

Auger, arXiv:1612.07155

Flavor composition for tests of fundamental physics

(neutrino propagation)
Flavor composition at source from numerical simulations
Example: $p\gamma$, target photons from synchrotron emission of co-accelerated electrons

**Muon beam**
- muon damped

**Pion beam**
$(\nu_e:\nu_\mu:\nu_\tau)=(1:2:0)$

**Undefined**
(mixed source)

Typically $n$ beam for low $E$ (from $p\gamma$)

Parameter space scan of Hillas plot

- All relevant regions recovered
- Some dependence on injection index
- Flavor composition is, in all realistic cases, a function of energy!
- Parameter fit to IC-data:

Measuring flavor? (experimental viewpoint)

> In principle, flavor information can be obtained from different event “topologies“:

- Muon tracks - $\nu_\mu$
- Cascades (showers) – CC: $\nu_e$, $\nu_\tau$, NC: all flavors
- Glashow resonance (6.3 PeV): bar $\nu_e$
- Double bang/lollipop: $\nu_\tau$ (sep. tau track)

(Learned, Pakvasa, 1995; Beacom et al, 2003)

> Early theoretical approaches:

Use flux ratios which take into account detector properties and unknown flux normalization, e.g. muon tracks/cascades:

\[
\hat{R} = \frac{\phi_{\mu}^{\text{Det}}}{\phi_{e}^{\text{Det}} + \phi_{\tau}^{\text{Det}}}
\]

(for flavor mixing and decay only until about 2011: Beacom et al 2002+2003; Farzan and Smirnov, 2002; Kachelriess, Serpico, 2005; Bhattacharjee, Gupta, 2005; Serpico, 2006; Winter, 2006; Majumar and Ghosal, 2006; Rodejohann, 2006; Xing, 2006; Meloni, Ohlsson, 2006; Blum, Nir, Waxman, 2007; Majumar, 2007; Awasthi, Choubey, 2007; Hwang, Siyeon, 2007; Lipari, Lusignoli, Meloni, 2007; Pakvasa, Rodejohann, Weiler, 2007; Quigg, 2008; Maltoni, Winter, 2008; Donini, Yasuda, 2008; Choubey, Niro, Rodejohann, 2008; Xing, Zhou, 2008; Choubey, Rodejohann, 2009; Esmaili, Farzan, 2009; Bustamante, Gago, Pena-Garay, 2010; Mehta, Winter, 2011; many others …)

> IceCube results actually contain more information IceCube, Astrophys. J. 809 (2015) 1, 98

Needs ways to represent all information simultaneously:

Concept of “flavor triangles“ Barenboim, Quigg, 2003
> Flavor triangles

> Measurement

IceCube measurement

> SM expectation

Bustamante, Beacom, Winter,
PRL 115 (2015) 16, 161302

(there is a marginal tension …)
Higher precision from IceCube – Generation Two?

- Plans for upgrade of IceCube experiment
- Instrumented volume $O(10)$ km$^3$, string spacing 240-300m
- Purpose: “deliver substantial increases in the astrophysical neutrino sample for all flavors”
- PINGU-infill for oscillation physics (about 40 strings for lower threshold in DeepCore region). Neutrino mass ordering!
- Similar ideas in sea water (KM3NeT, ORCA)

The future: SM expectations vs. measurement?

(Shaded regions: current 3σ range for mixing params)

Bustamante, Beacom, Winter, PRL 115 (2015) 16, 161302

- IceCube-Gen2 could exclude the current best-fit point
- Allowed regions for specific flavor compositions at source even smaller
What if there is physics beyond the Standard Model?

Effective operators (CPT violation) changing Hamiltonian at high E

Effects leading to *incoherent* superposition of mass eigenstates

Arguelles, Katori, Salvado, PRL 115 (2015) 161303
Bustamante, Beacom, Winter, PRL 115 (2015) 161302

Only $\nu_1$ stable ruled out at $2\sigma$

Same issue!
Neutrino-antineutrino composition, and the Glashow resonance
The “standard” picture: Neutrino production

> Neutrino production in $p\gamma$ interactions:

\[ p + \gamma \rightarrow \Delta^+ \rightarrow \begin{cases} 
\pi^+ + n & \text{1/3 of all cases} \\
\pi^0 + p & \text{2/3 of all cases} 
\end{cases} \]

\[ \pi^+ \rightarrow \mu^+ + \nu_\mu, \]

\[ \mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu \]

\[ (\xi_e, \xi_\mu, \xi_\tau, \bar{\xi}_e, \bar{\xi}_\mu, \bar{\xi}_\tau) = \left( \frac{1}{3}, \frac{1}{3}, 0, 0, \frac{1}{3}, 0 \right) \]

> Neutrino production in $pp$ interactions:

\[ p + p \rightarrow \begin{cases} 
\pi^+ + \text{anything} & \text{1/3 of all cases} \\
\pi^- + \text{anything} & \text{1/3 of all cases} \\
\pi^0 + \text{anything} & \text{1/3 of all cases} 
\end{cases} \]

\[ (\xi_e, \xi_\mu, \xi_\tau, \bar{\xi}_e, \bar{\xi}_\mu, \bar{\xi}_\tau) = \left( \frac{1}{6}, \frac{1}{3}, 0, \frac{1}{6}, \frac{1}{3}, 0 \right) \]
Neutrino detection at the Glashow resonance

- Neutrino detection at Glashow resonance

\[ \bar{\nu}_e + e^- \rightarrow W^- \rightarrow \text{anything} \]

at 6.3 PeV is sensitive to electron antineutrinos

- Neutrino mixing yields an intrinsic “contamination” from muon antineutrinos (TBM approx.):

\[ \xi_f^{\bar{\nu}_e} \approx \frac{5}{9} \xi_{\bar{\nu}_e} + \frac{2}{9} \xi_{\bar{\nu}_\mu} \]

- The \( \pi^- \) decay chain yields about 3.5 as many electron antineutrinos at Earth as the \( \pi^+ \) decay chain

- Potentially dangerous if contamination from \( \pi^- \); such contaminations are expected even in \( p_\gamma \) interactions

## Particle physics caveats

### Kinematics of pion/muon decays

*Deviations depending on spectral index*

<table>
<thead>
<tr>
<th>Production</th>
<th>$\alpha$</th>
<th>$\xi_{\nu_e}$</th>
<th>$\xi_{\nu_\mu}$</th>
<th>$\xi_{\nu_\tau}$</th>
<th>$\bar{\xi}_{\nu_e}$</th>
<th>$\bar{\xi}<em>{\nu</em>\mu}$</th>
<th>$\bar{\xi}<em>{\nu</em>\tau}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference pp</td>
<td>any</td>
<td>0.167</td>
<td>0.333</td>
<td>0</td>
<td>0.167</td>
<td>0.333</td>
<td>0</td>
</tr>
<tr>
<td>Ideal pp</td>
<td>2.0</td>
<td>0.175</td>
<td>0.325</td>
<td>0</td>
<td>0.175</td>
<td>0.325</td>
<td>0</td>
</tr>
<tr>
<td>Ideal pp</td>
<td>2.3</td>
<td>0.179</td>
<td>0.321</td>
<td>0</td>
<td>0.179</td>
<td>0.321</td>
<td>0</td>
</tr>
<tr>
<td>Ideal pp</td>
<td>2.6</td>
<td>0.183</td>
<td>0.317</td>
<td>0</td>
<td>0.183</td>
<td>0.317</td>
<td>0</td>
</tr>
</tbody>
</table>

| Reference p$\gamma$ | any | 0.333 | 0.333 | 0 | 0 | 0.333 | 0 |
| Ideal p$\gamma$ | 2.0 | 0.350 | 0.290 | 0 | 0 | 0.360 | 0 |
| Ideal p$\gamma$ | 2.3 | 0.358 | 0.273 | 0 | 0 | 0.369 | 0 |
| Ideal p$\gamma$ | 2.6 | 0.366 | 0.256 | 0 | 0 | 0.378 | 0 |

### Monte Carlo results

*(Sibyll 2.3, EPOS-LHC and QGSJET-II-04 yield similar results for pp)*

<table>
<thead>
<tr>
<th>Source</th>
<th>$\alpha$</th>
<th>$\xi_{\nu_e}$</th>
<th>$\xi_{\nu_\mu}$</th>
<th>$\xi_{\nu_\tau}$</th>
<th>$\bar{\xi}_{\nu_e}$</th>
<th>$\bar{\xi}<em>{\nu</em>\mu}$</th>
<th>$\bar{\xi}<em>{\nu</em>\tau}$</th>
<th>$\delta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>pp</td>
<td>2.0</td>
<td>0.194</td>
<td>0.321</td>
<td>0</td>
<td>0.156</td>
<td>0.329</td>
<td>0</td>
<td>16%</td>
</tr>
<tr>
<td>pp</td>
<td>2.3</td>
<td>0.204</td>
<td>0.314</td>
<td>0</td>
<td>0.153</td>
<td>0.329</td>
<td>0</td>
<td>22%</td>
</tr>
<tr>
<td>pp</td>
<td>2.6</td>
<td>0.217</td>
<td>0.305</td>
<td>0</td>
<td>0.149</td>
<td>0.329</td>
<td>0</td>
<td>30%</td>
</tr>
</tbody>
</table>

Biehl, Fedynitch, Palladino, Weiler, Winter, JCAP 1701 (2017) 033
Source discrimination: pp versus $p\gamma$ (optimistic case $\alpha \sim 2$)

**Ideal picture**

- **Monte Carlo results**

- Discrimination in IceCube
- No discrimination in IC-Gen2
Glashow resonance as smoking gun signature for nuclei?

- Neutrons produce more $\pi^-$ than $\pi^+$, and primary nuclei are neutron-rich:

- Discrimination $\rho\gamma$ from $A\gamma$ in IC-Gen2?
So what can we learn?

> Scenario discrimination

IceCube-Gen2 can possibly discriminate among scenarios (numbers: IC-86 equivalent years for 90% CL discrimination)

<table>
<thead>
<tr>
<th>Data → Theory ↓</th>
<th>Ideal $p\gamma$</th>
<th>$p\gamma$</th>
<th>pp</th>
<th>$Fe\gamma$</th>
<th>Damped $\mu$</th>
<th>Opt. thick</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ideal $p\gamma$</td>
<td>\cdot</td>
<td>81</td>
<td>32</td>
<td>26</td>
<td>$\infty$</td>
<td>55</td>
</tr>
<tr>
<td>$p\gamma$</td>
<td>53</td>
<td>\cdot</td>
<td>156</td>
<td>93</td>
<td>144</td>
<td>$\infty$</td>
</tr>
<tr>
<td>pp</td>
<td>16</td>
<td>121</td>
<td>\cdot</td>
<td>$\infty$</td>
<td>28</td>
<td>$\infty$</td>
</tr>
<tr>
<td>$Fe\gamma$</td>
<td>12</td>
<td>66</td>
<td>$\infty$</td>
<td>\cdot</td>
<td>20</td>
<td>122</td>
</tr>
<tr>
<td>Damped $\mu$</td>
<td>$\infty$</td>
<td>$\infty$</td>
<td>48</td>
<td>37</td>
<td>\cdot</td>
<td>104</td>
</tr>
<tr>
<td>Opt. thick</td>
<td>33</td>
<td>$\infty$</td>
<td>$\infty$</td>
<td>162</td>
<td>72</td>
<td>\cdot</td>
</tr>
</tbody>
</table>

> After what exposure do we expect to see Glashow events? (90% CL)

<table>
<thead>
<tr>
<th>Dataset</th>
<th>Spectral index</th>
<th>Ideal $p\gamma$</th>
<th>$p\gamma$</th>
<th>pp</th>
<th>$Fe\gamma$</th>
<th>Damped $\mu$</th>
<th>Optically thick</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global fit [10]</td>
<td>$\alpha = 2.5$</td>
<td>33</td>
<td>22</td>
<td>18</td>
<td>16</td>
<td>32</td>
<td>20</td>
</tr>
<tr>
<td>Through-going muons [9, 11]</td>
<td>$\alpha \simeq 2$</td>
<td>15</td>
<td>9.7</td>
<td>7.6</td>
<td>7.1</td>
<td>12</td>
<td>8.9</td>
</tr>
</tbody>
</table>

“$Fe\gamma$ is the first scenario to be tested

Biehl, Fedynitch, Palladino, Weiler, Winter, JCAP 1701 (2017) 033
Summary and conclusions

- The discovery of astrophysical (PeV) neutrinos offers a new perspective of the high-energy universe.

- The origin of these neutrinos is yet unclear and requires further study both from experiment and theory.

- Conceptual arguments can help to identify the sources (multiplet searches, flux and flavor composition, sky distribution, Glashow resonance etc).

- An emergent discipline is multi-messenger (neutrinos, cosmic rays, gravitational waves, gamma-rays) astronomy to identify the origin of the cosmic rays and neutrinos.

- Challenge for neutrino production to test the origin of cosmic rays: what if the primaries are not protons but heavier?

- Astrophysical neutrinos may be also good to test physics beyond the SM in extreme environments, and at extreme distances and energies.