ALP Physics and the Associated Generator

Wolfgang Altmannshofer
waltmann@ucsc.edu

PIONEER Collaboration Meeting

CENPA, Jun 19 - 22, 2024

“Exotics” at PIONEER

- 2-body decays: $\pi \to eN$, $\pi \to \mu N$
- N is a neutral spin 1/2 fermion, a.k.a. sterile neutrino
- In the relevant region of parameter space, N lifetime is macroscopic $\Rightarrow$ decays outside the detector

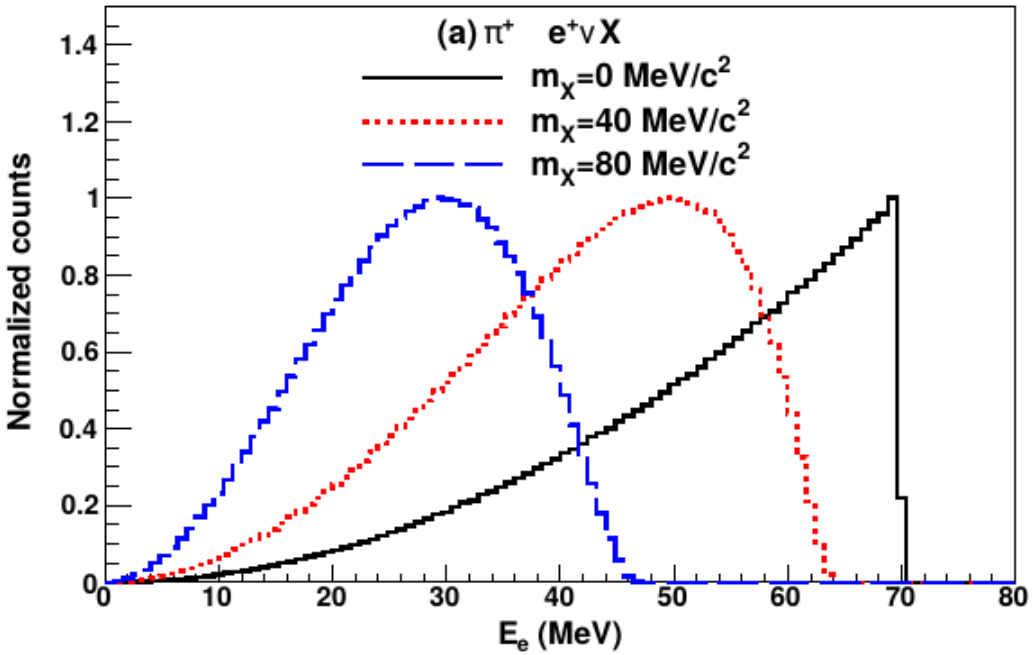
“Exotics” at PIONEER

- 2-body decays: $\pi \to eN$, $\pi \to \mu N$
- N is a neutral spin 1/2 fermion, a.k.a. sterile neutrino
- In the relevant region of parameter space, N lifetime is macroscopic $\Rightarrow$ decays outside the detector

- 3-body decays: $\pi \to e\nu X$, $\pi \to \mu\nu X$
- X could be a scalar, axion like particle, vector, ...
- possible decay modes:
  $X \to e^+e^-$, $X \to \gamma\gamma$, $X \to$ invisible (or X is stable)
- X decay could be prompt or displaced
  (interesting range mm - cm ?)

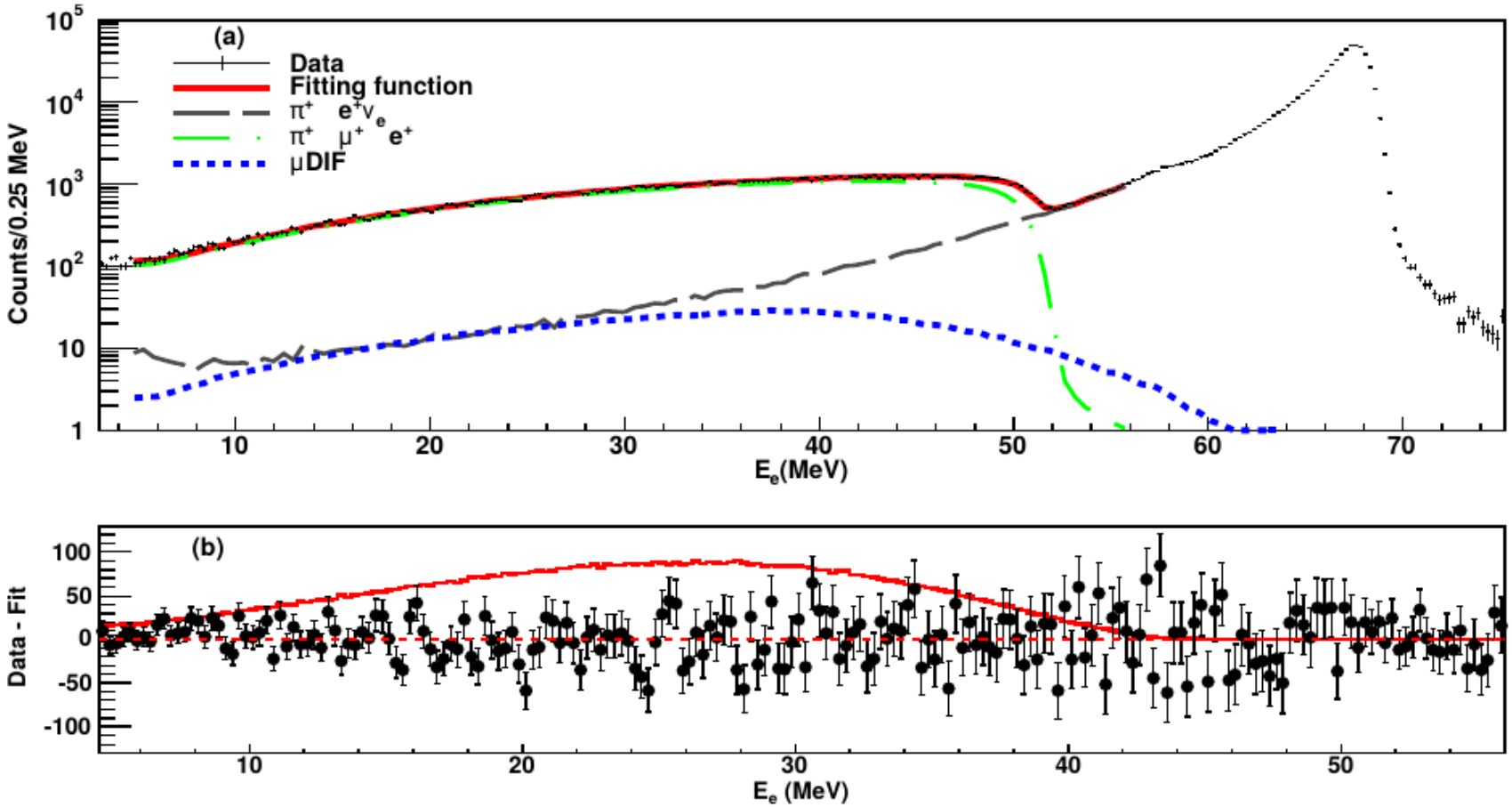
Search for $\pi \to \ell\nu X$ at PIENU

PIENU 2101.07381



- Positron energy in the 3-body decay is not fixed.
- E_e follows a characteristic distribution depending on the mass of X and the way X couples to the Standard Model.
- The chosen model for X was introduced in Batell et al. 1709.07001; it gives the same energy spectrum as the "weak violating ALP" from WA, Dror, Gori 2209.00665.

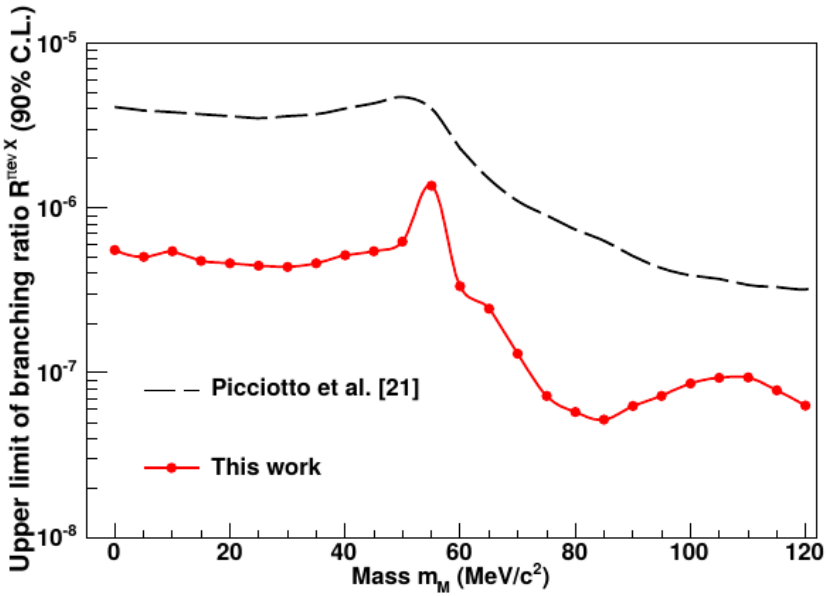
Search for $\pi \to \ell\nu X$ at PIENU



PIENU 2101.07381

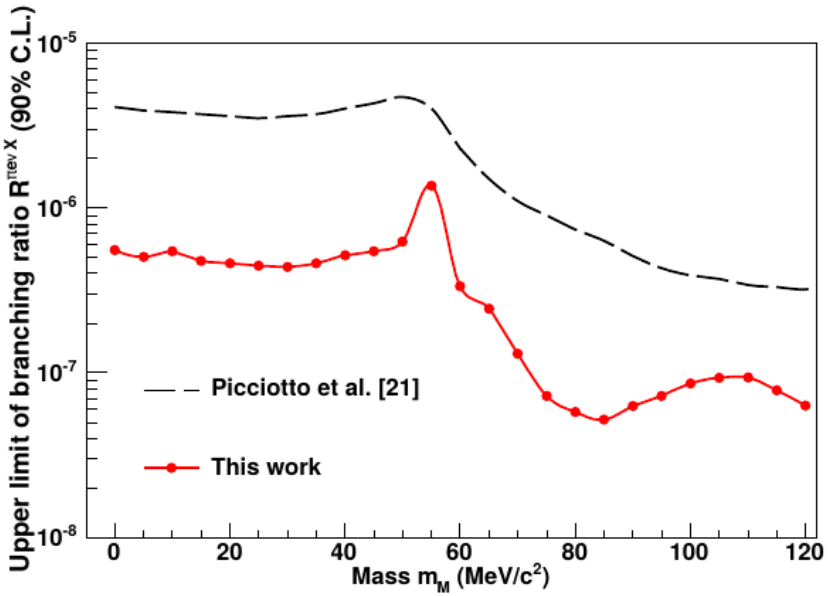
Result from PIENU and Our Recast

PIENU 2101.07381



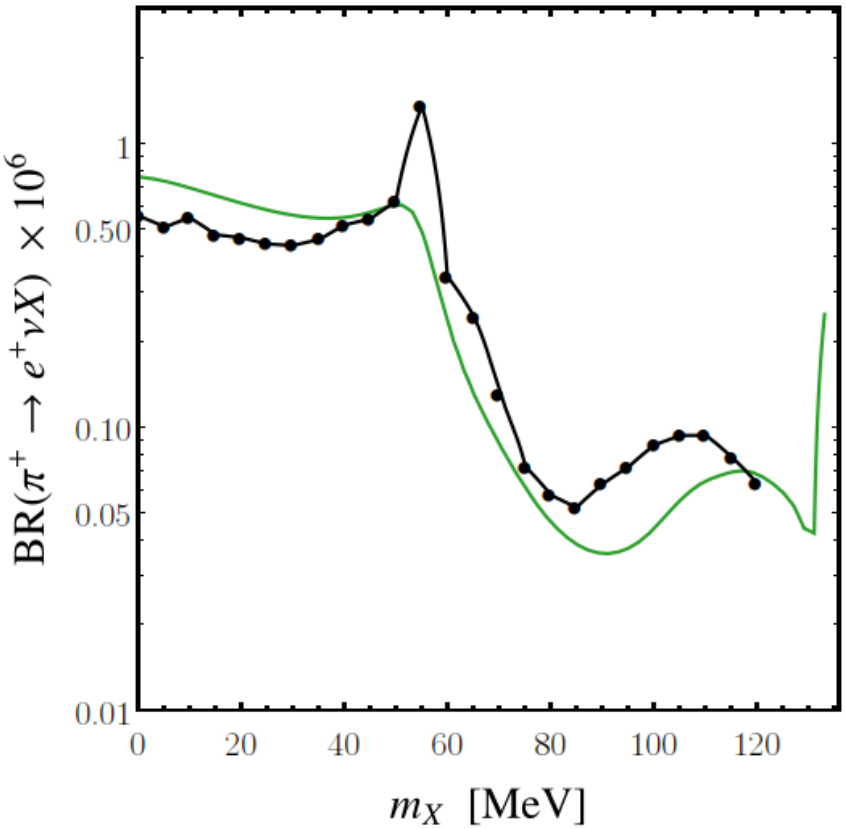
Result from PIENU and Our Recast

PIENU 2101.07381



WA, Giffin, Gori, Jackson, Luong, Seo

work in progress



- Refitting the published data points with the signal and background components we can reasonably reproduce the official PIENU result.

More Models

- 3-body decay $\pi \to e\nu X$ is fully characterized by a double differential decay distribution in the positron energy and the X energy.

$$\frac{d\Gamma(\pi \to e\nu X)}{dE_e dE_X}$$

- We have expressions for a long list of models:
  - scalar with couplings to electrons,
  - axion like particles coupled in various ways to electrons and neutrinos (from WA, Dror, Gori 2209.00665),
  - spin-1 particles with vector or axial vector couplings to electrons and neutrinos,
  - spin-1 particles with dipole couplings to electrons.

Some Examples

scalar

$$\frac{d\mathrm{BR}(\pi^+ \to \ell^+ \nu_\ell\, s)}{\mathrm{BR}(\pi^+ \to \ell^+ \nu_\ell)} = \frac{g_s^2}{4\pi^2}\frac{dE_\ell dE_s}{m_\pi^2} \times \frac{1}{(1-x_\ell)^2}\left[\frac{x_{\ell\nu}x_{\ell s}}{x_\ell(x_{\ell s}-x_\ell)} + \frac{x_{\ell s}(3+x_s-4x_{\ell s})-x_s+x_\ell}{(x_{\ell s}-x_\ell)^2}\right] . \quad (5.7)$$

ALP

$$\frac{d\mathrm{BR}(\pi^+ \to \ell^+ \nu_\ell\, a)}{\mathrm{BR}(\pi^+ \to \ell^+ \nu_\ell)} = \frac{1}{4\pi^2}\frac{dE_\ell dE_a}{m_\pi^2} \times \frac{1}{x_\ell(1-x_\ell)^2}\left[g^2\frac{x_{\ell a}x_a(x_{\ell a}-1)}{(x_{\ell a}-x_\ell)^2} + g(\bar{g}-g_\nu)\frac{x_{\ell a}(x_{\ell\nu}-x_a)+x_a-x_\ell}{x_{\ell a}-x_\ell} + (g-\bar{g}+g_\nu)^2\frac{1}{4x_\ell}\left(x_{\ell a}(x_{\nu a}-x_\ell)-x_a+x_\ell\right)\right] . \quad (5.8)$$

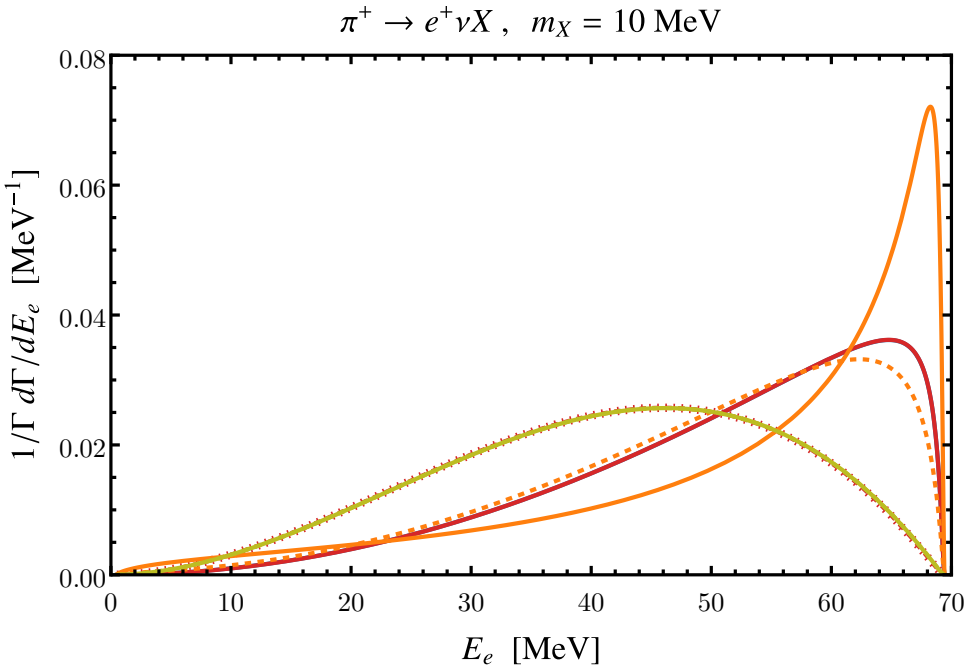
vector

$$\begin{aligned}\frac{d\mathrm{BR}(\pi^+ \to \ell^+ \nu_\ell\, V)}{\mathrm{BR}(\pi^+ \to \ell^+ \nu_\ell)} = \frac{1}{2\pi^2}\frac{dE_\ell dE_V}{m_\pi^2}\frac{1}{x_\ell(1-x_\ell)^2}\Bigg[&g_V^2\left(2+\frac{x_{\ell V}-2+x_\ell}{x_{\nu V}} - \frac{x_V(1-x_\ell)}{x_{\nu V}^2} + \frac{2(1-x_\ell)^2+2x_\ell x_V}{(x_{\ell V}-x_\ell)x_{\nu V}} - \frac{2(1-x_\ell)-x_{\nu V}}{x_{\ell V}-x_\ell} + \frac{2x_\ell+x_V}{(x_{\ell V}-x_\ell)^2}\right)\\ &+ g_A^2\left(\frac{x_{\ell V}+2-3x_\ell}{x_{\nu V}} - \frac{2(x_{\ell V}-1+x_{\nu V})}{x_V} - \frac{(1-x_\ell)x_V}{x_{\nu V}^2} + \frac{2x_\ell}{x_{\ell V}-x_\ell}\left(\frac{x_V}{x_{\nu V}}-\frac{x_{\nu V}}{x_V}\right) - \frac{2(1-x_\ell)^2}{(x_{\ell V}-x_\ell)x_{\nu V}} + \frac{2-x_{\nu V}+6x_\ell}{x_{\ell V}-x_\ell} - \frac{(1-x_\ell)(x_V-4x_\ell)}{(x_{\ell V}-x_\ell)^2}\right)\\ &- 2g_V g_A\left(\frac{x_{\ell V}-x_\ell}{x_{\nu V}} - \frac{x_V(1-x_\ell)}{x_{\nu V}^2} - \frac{x_{\nu V}+2x_\ell}{x_{\ell V}-x_\ell} + \frac{2x_\ell x_V}{(x_{\ell V}-x_\ell)x_{\nu V}} + \frac{x_V(1+x_\ell)-2x_\ell x_{\nu V}}{(x_{\ell V}-x_\ell)^2}\right)\Bigg] . \quad (5.9)\end{aligned}$$

Positron Spectra

The positron energy spectrum depends on the model.

WA, Giffin, Gori, Jackson, Luong, Seo work in progress

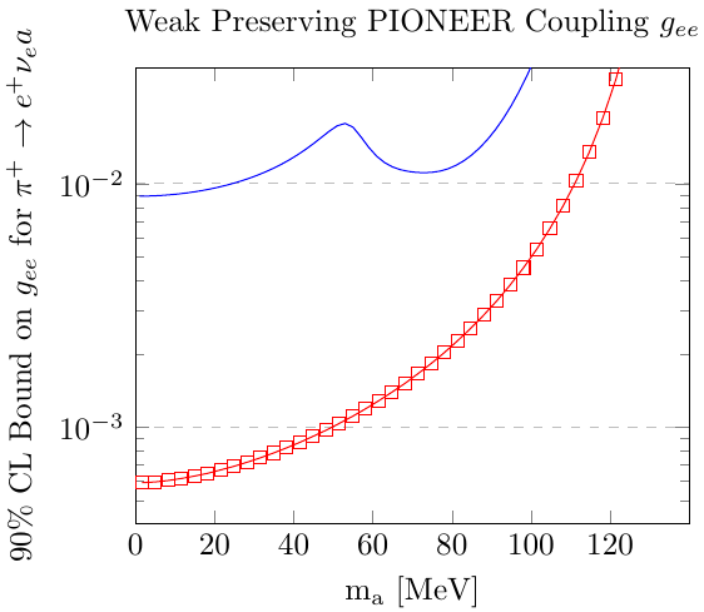


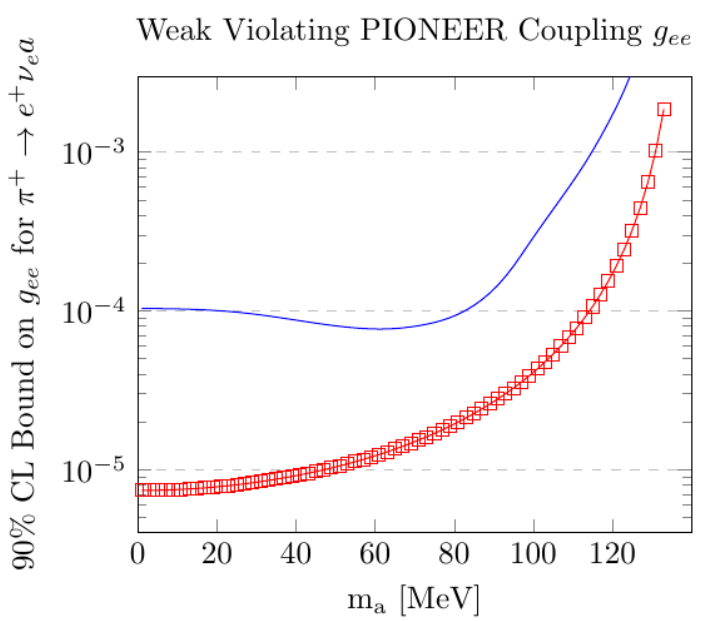
- solid orange: vector
- dashed orange: axial-vector
- solid red: axion
- dotted red: weak violating axion
- yellow: vector with dipole interaction

- Can use these shapes and refit the PIENU data to obtain constraints on other models.
- Want to use some of those shapes to make sensitivity projections of PIONEER (ALPs probably the most popular nowadays).

ALP Interpretation

Ollie Jackson, senior thesis at UCSC





- blue: reinterpretation of PIENU result as constraint on different types of ALP couplings to electrons.
- red: sensitivity estimate for PIONEER (taking the E_e spectrum of $\pi \to e\nu$ from the whitepaper, adding statistical uncertainty and checking how much of an ALP signal can fit in.)

Event Generator

- Work has begun on an event generator of $\pi \to e\nu a$ (a = ALP)
- Option 1: directly integrated into PIONEER simulation infrastructure.
- Option 2: stand alone generator producing event files.
- Both options are pursued.

Event Generator

- Work has begun on an event generator of $\pi \to e\nu a$ (a = ALP)
- Option 1: directly integrated into PIONEER simulation infrastructure.
- Option 2: stand alone generator producing event files.
- Both options are pursued.

- for the moment, fix the model to a "standard" ALP that couples to electrons (and electron neutrinos)

$$\frac{\partial_\mu a}{f_a}\left(\bar{e}\gamma^\mu\gamma_5 e + \bar{\nu}_e\gamma^\mu P_L\nu_e\right)$$

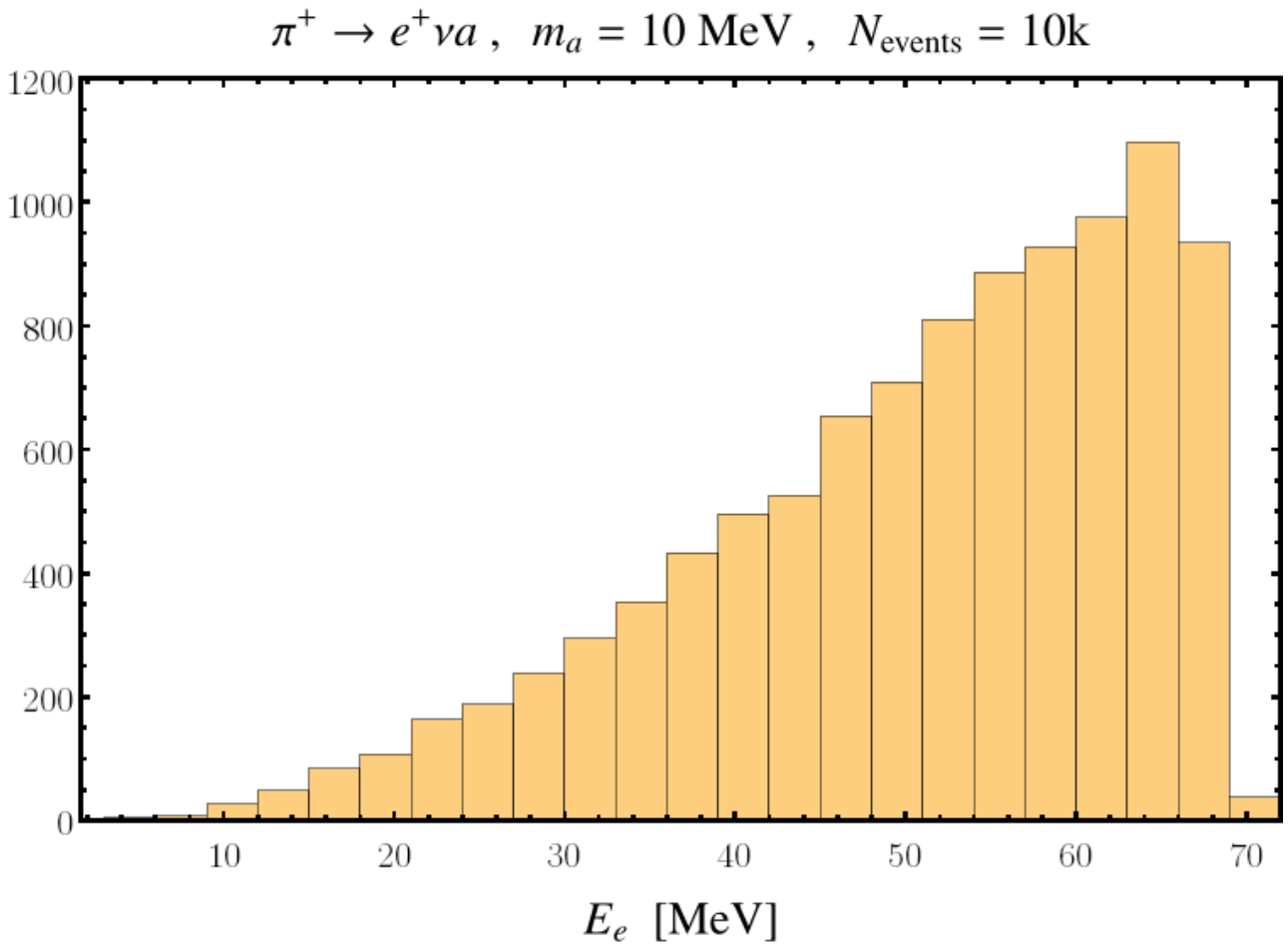
- Free parameters: ALP mass and ALP lifetime.
- Can keep the ALP invisible or let it decay into e^+e^- or $\gamma\gamma$.
- Should be straight forward to implement other models as well.

Example Output of the Stand-Alone Generator

```
<event>
211 -1 0 0 0 0.13957  0.13957
-11 1 -0.0031609 -0.00897826 0.00263702 0.00989017  0.000510999
12 1 0.0655151 0.00983869 -0.00534817 0.0664652  0.
51 1 -0.0623542 -0.000860431 0.00271115 0.063215  0.01
-2.72392 -0.0375876 0.118435
11 1 -0.0531542 -0.00207181 0.00557985 0.0534889  0.000510999
-11 1 -0.00919996 0.00121138 -0.0028687 0.00972611  0.000510999
</event>
<event>
211 -1 0 0 0 0.13957  0.13957
-11 1 -0.00044688 0.000678534 -0.0134726 0.0135067  0.000510999
12 1 0.00840347 -0.0464075 0.0480488 0.0673273  0.
51 1 -0.00795659 0.045729 -0.0345762 0.0587364  0.01
-0.910864 5.23501 -3.95826
11 1 -0.00273127 0.011965 -0.00409821 0.012949  0.000510999
-11 1 -0.00522532 0.033764 -0.030478 0.0457873  0.000510999
</event>
```

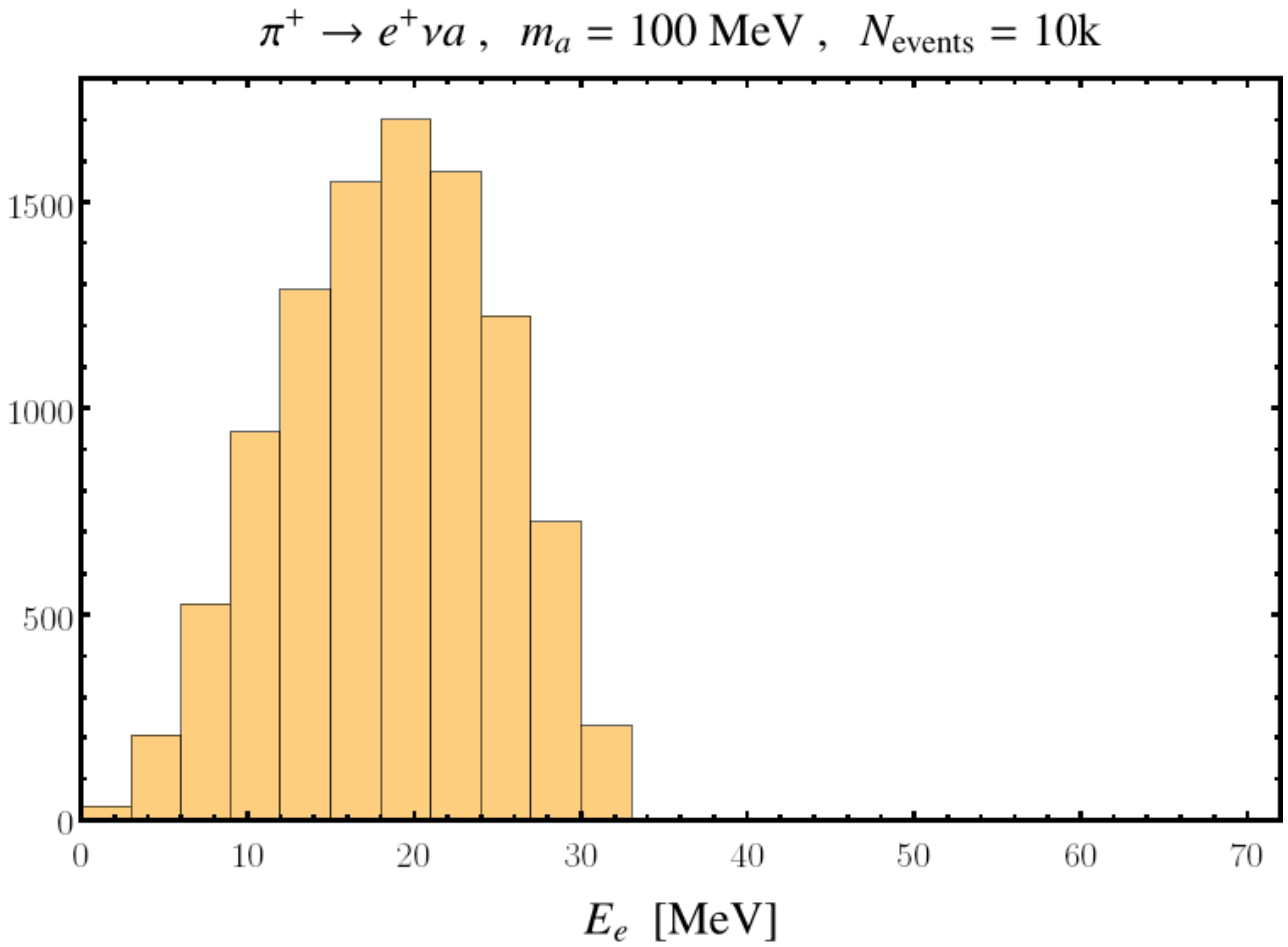
- For the moment my own made-up file structure produced by a mathematica code.
- Will switch to C++ and HepMC output format.

Distributions



Still preliminary; seems to work but needs cross checks.

Distributions



Still preliminary; seems to work but needs cross checks.