TECHNISCHE UNIVERSITÄT DRESDEN

SHERPA

Antonia Bähr

Simulation of Heavy Neutral Lepton (HNL) production and decays with the Sherpa Event generator

DPG Göttingen // 31st of March 2025

Neutrinos are not fully understood yet.

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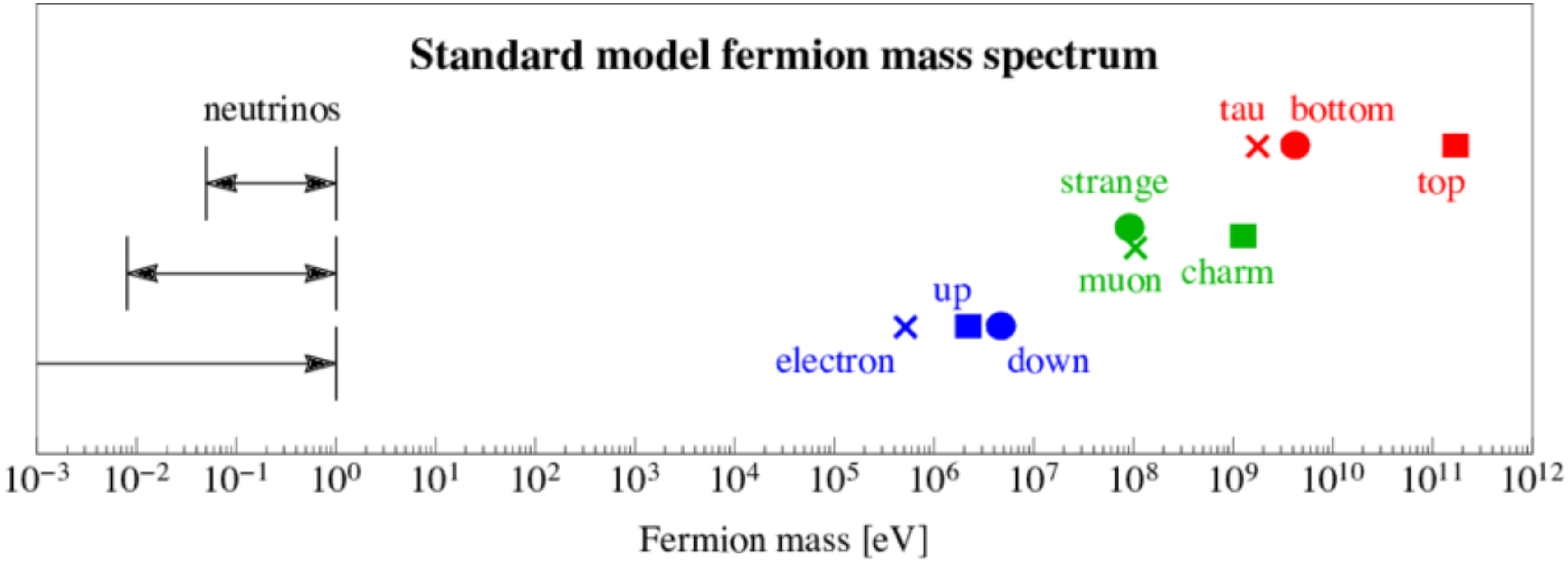
- Neutrinos are not massless (see neutrino oscillation experiments)
- **But** they are very light ($m_\nu \ll 0.45\,\mathrm{eV}$ [KATRIN 2024])



- According to Standard Model (SM): **Only left-handed neutrinos** (& right-handed antineutrinos) exist.

Heavy Neutral Leptons (HNLs) could explain the small neutrino masses.

https://www.symmetrymagazine.org/article/neutrinos-on-a-seesaw

Heavy Neutral Leptons (HNLs) could explain the small neutrino masses.

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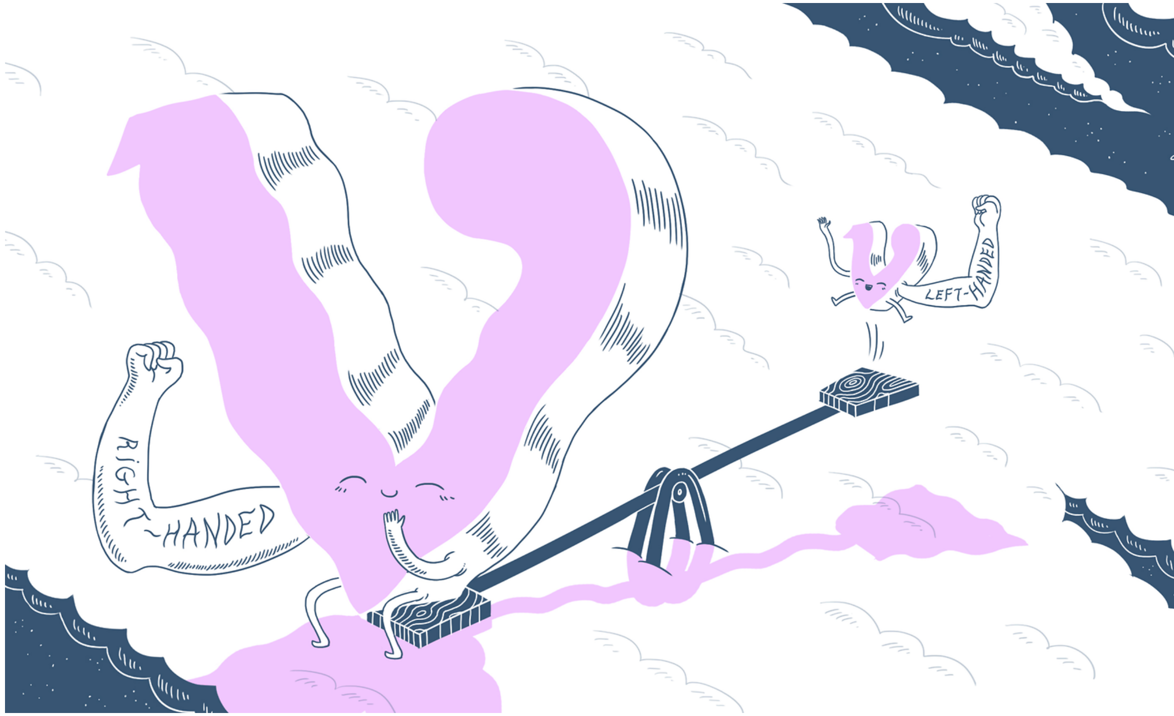
- **Type 1 Seesaw mechanism:**
  - Neutrinos are their own antiparticle (Majorana particle)
  - Introducing heavy right-handed neutrinos (HNLs)

$$\mathscr{L}_{DM} = -\frac{1}{2}\left(\overline{\nu_L}\,\overline{\nu_R{}^c}\right)\begin{pmatrix} 0 & m_D \\ m_D & M \end{pmatrix}\begin{pmatrix} \nu_L{}^c \\ \nu_R \end{pmatrix} + h.c.$$

$$\overset{M \gg m_D}{\hookrightarrow} \quad m_{\nu/N} \approx \frac{1}{2}M \pm \frac{1}{2}\left(M + \frac{2m_D^2}{M}\right)$$

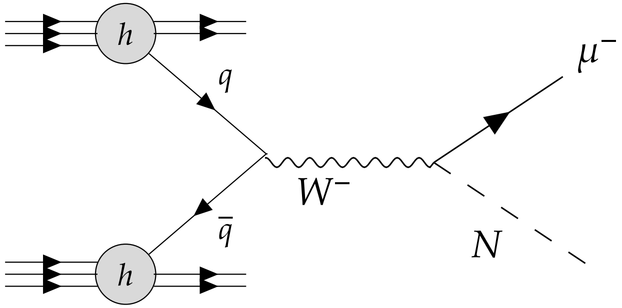
$$|m_\nu| \approx \frac{m_D^2}{M} \text{ and } m_N \approx M$$

  - Heavier $m_N \Rightarrow$ lighter m_ν (observed ligth neutrinos)



- HNLs explain **neutrino lightness, lepton asymmetry** & are **dark matter candidates**

HNL decays: leptonic or semileptonic.



(Drell-Yan process)

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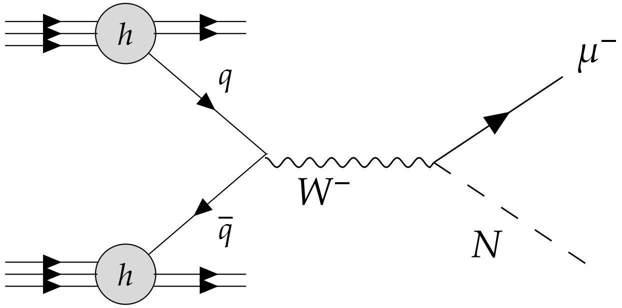

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Semileptonic:

Leptonic:

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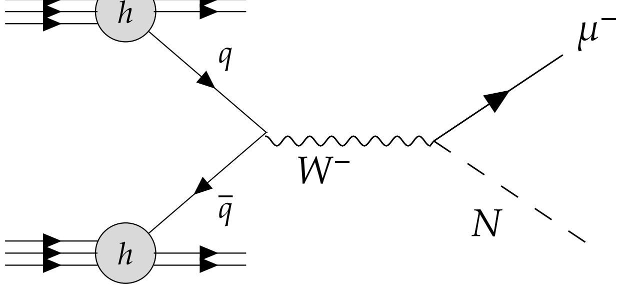

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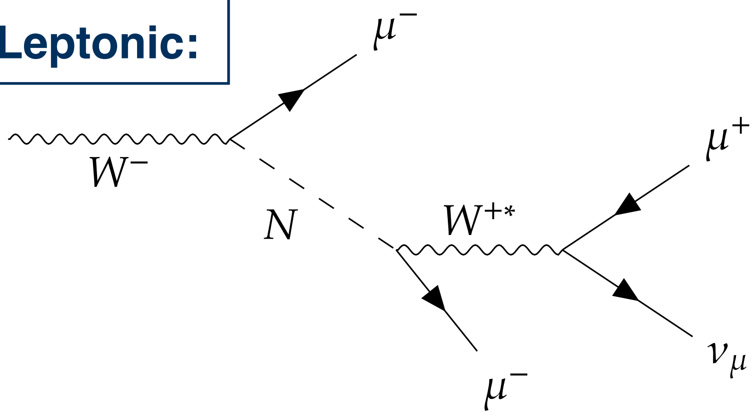

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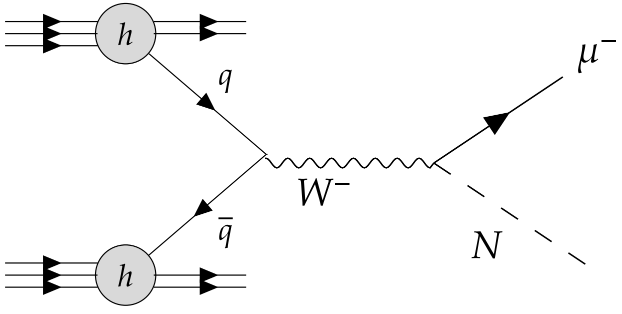

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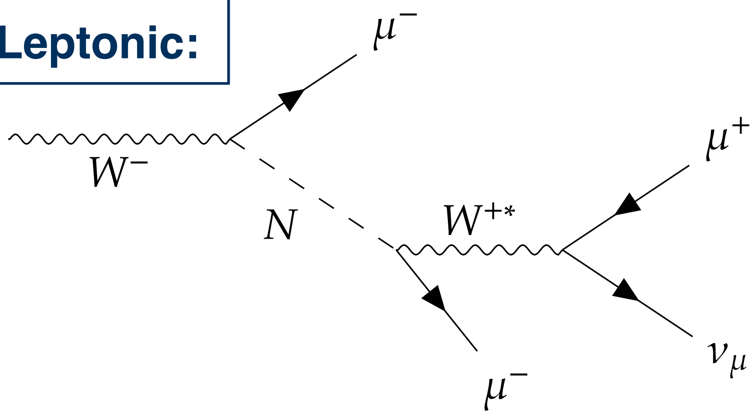
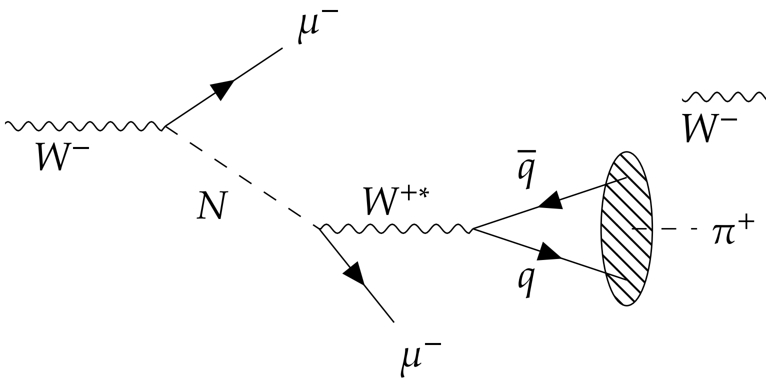
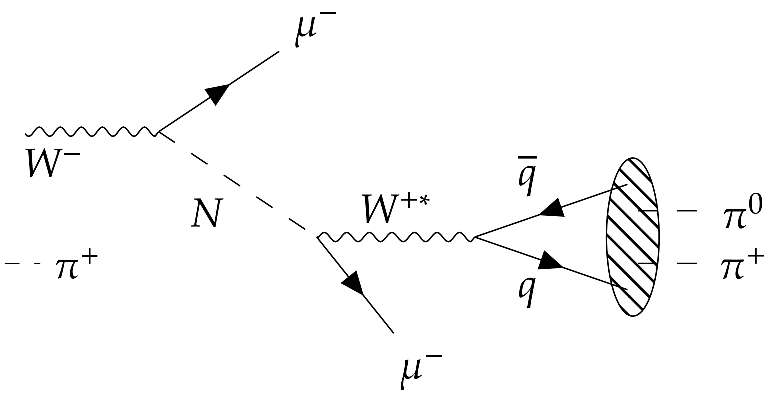


Semileptonic:

π^+



$\pi^+\pi^0$



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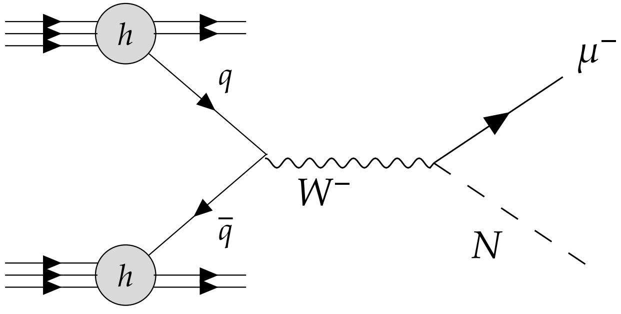
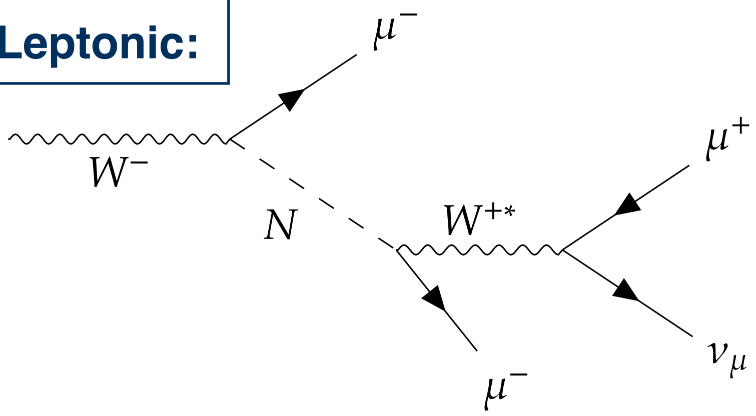


(Drell-Yan process)

Leptonic:



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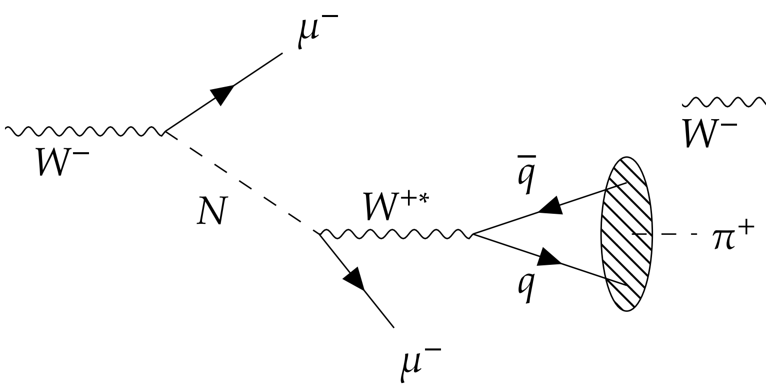
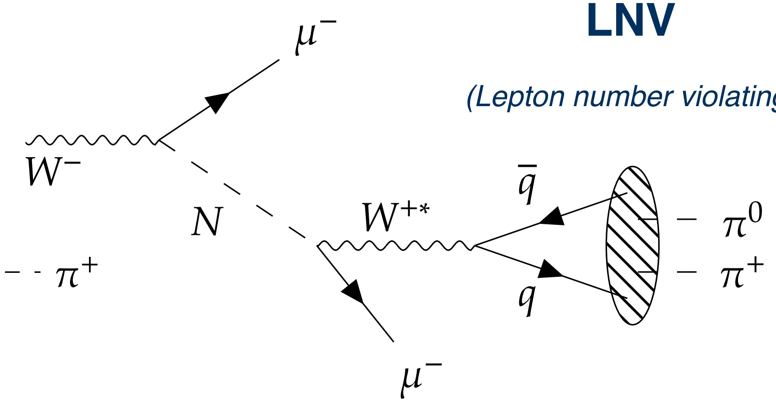


$\underline{\pi^+\pi^0}$

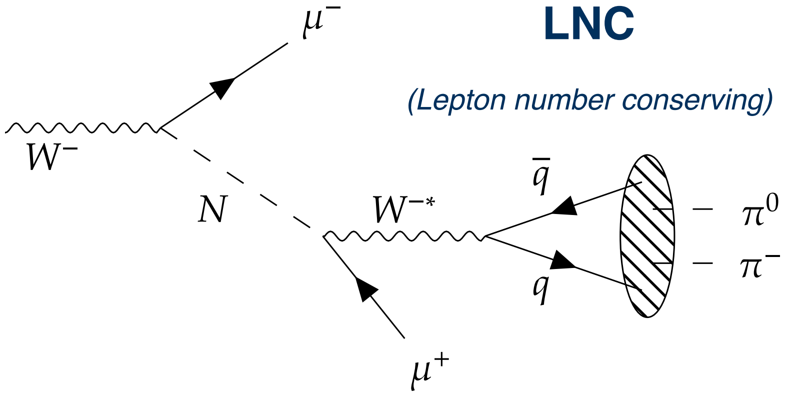
LNV

(Lepton number violating)



LNC

(Lepton number conserving)



HNL decays: leptonic or semileptonic.

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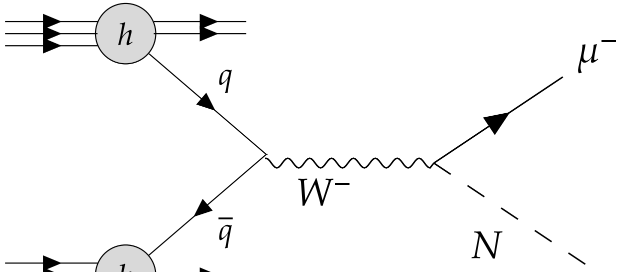
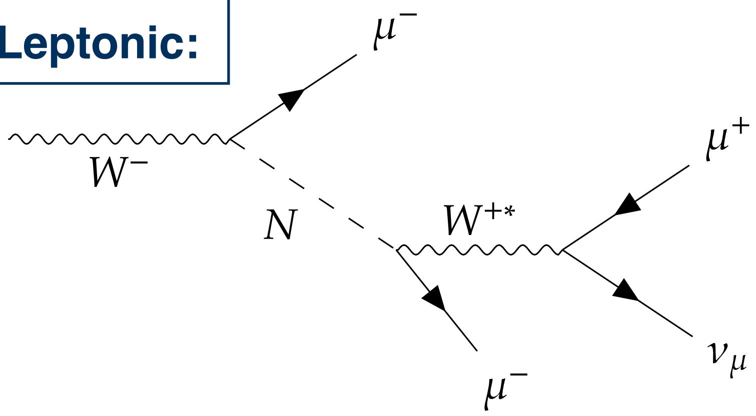


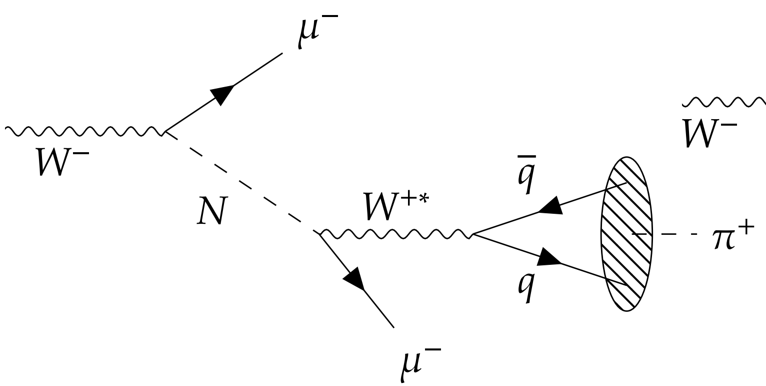
(Drell-Yan process)

Leptonic:



Semileptonic:

π^+



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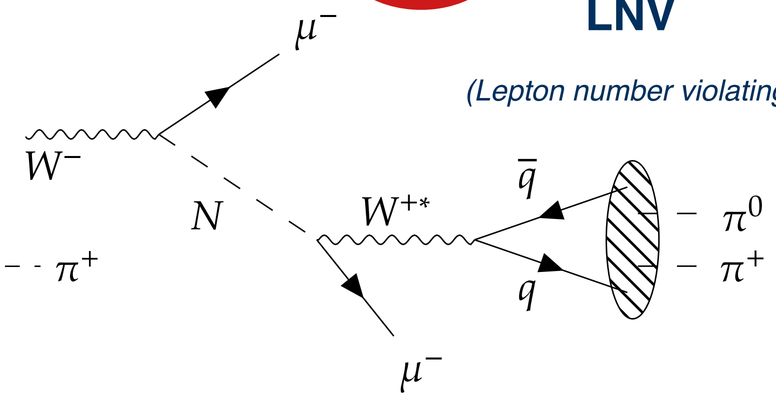

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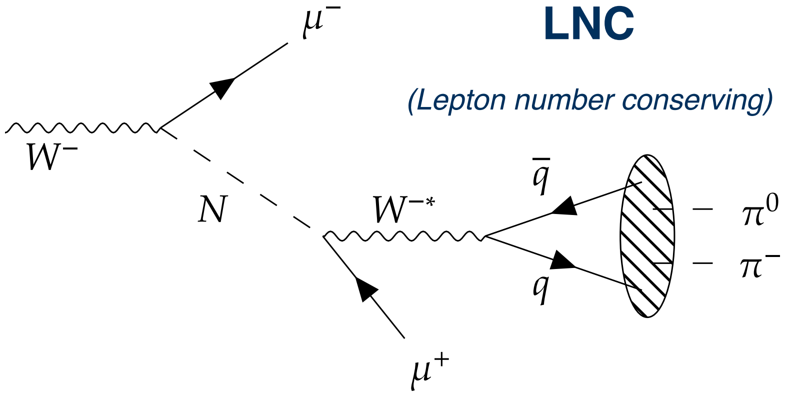


Sherpa is a highly modular Monte Carlo Event generator.

↳ **S**imulation for **H**igh **E**nergy **R**eaction of **PA**rticles

…

SHERPA

Perturbative methods

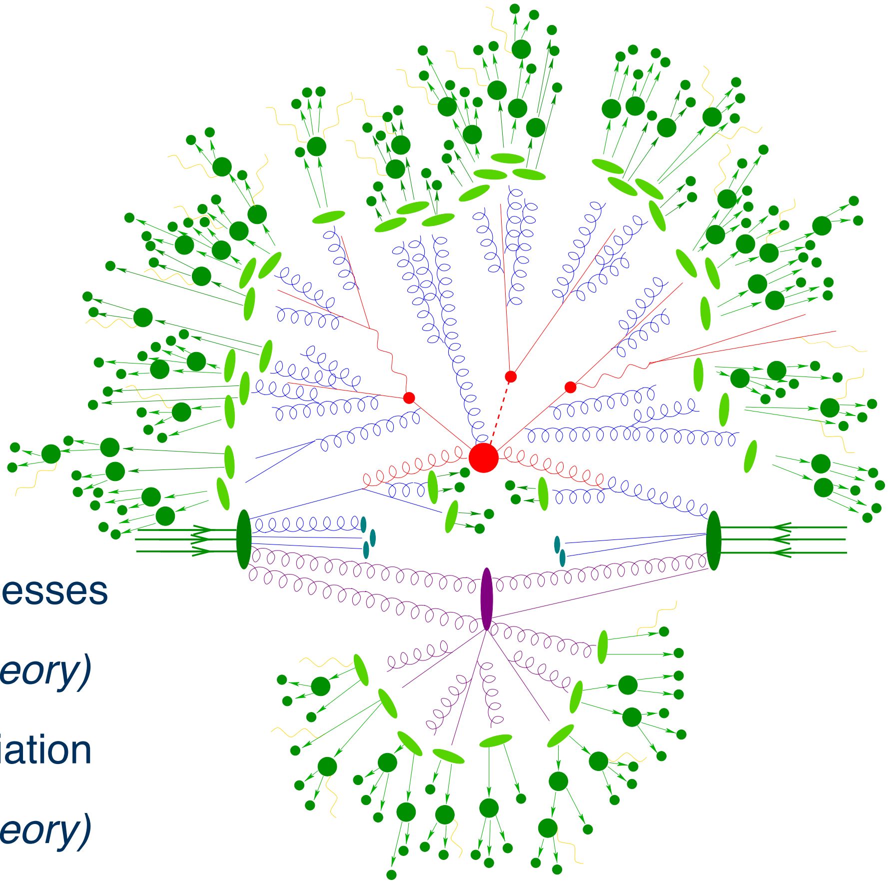
(Parton shower, Matrix Element Generator, …)

Model

(SM, Seesaw, …)

Non-perturbative methods

(HADRONS++, …)



Red: Hard processes *(perturbation theory)*

Blue: QCD radiation (*perturbation theory)*

Light Green: Hadronisation *(phenomenological)*

Dark Green: Hadron decay into other particles

HNLs are implemented using existing models from tau-decays.

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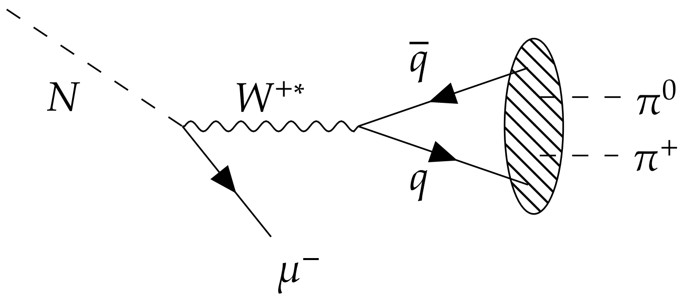
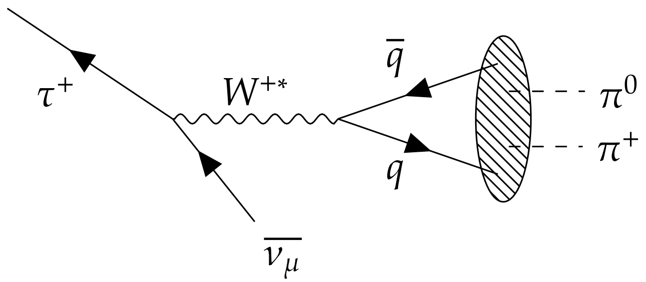
HNL



Tau



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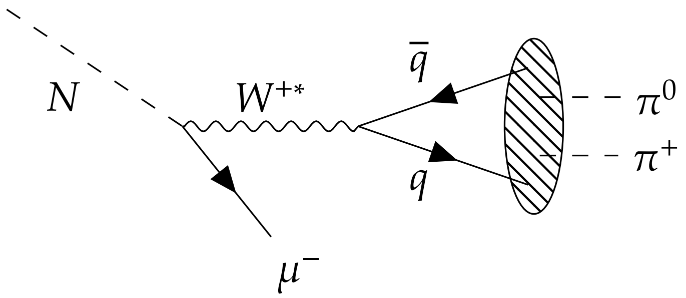
SHERPA

HNL



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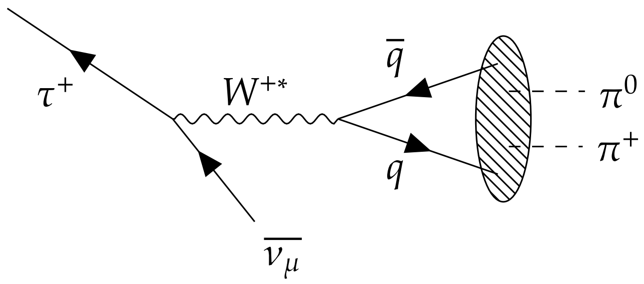
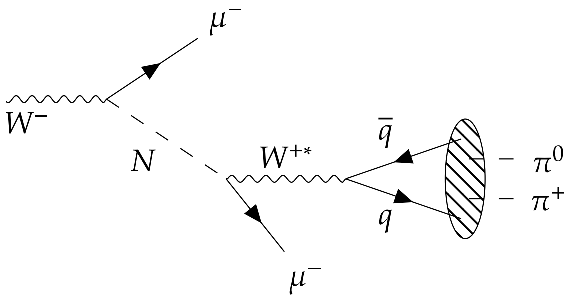


Leptonic decays are easier

(No QCD)



Semileptonic decays

(With QCD-effects)

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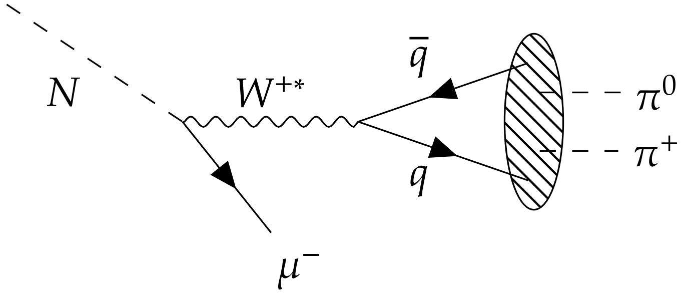
SHERPA

HNL



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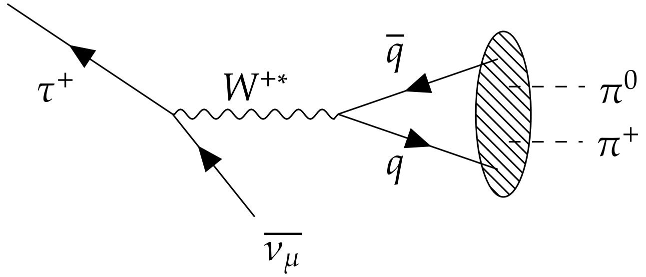

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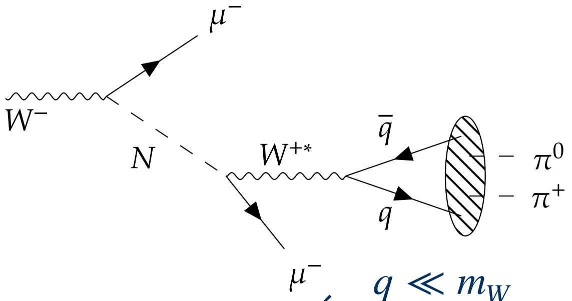
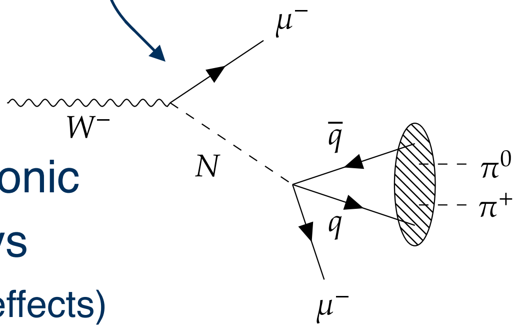


$q \ll m_W$

(Fermi's point-like interaction)



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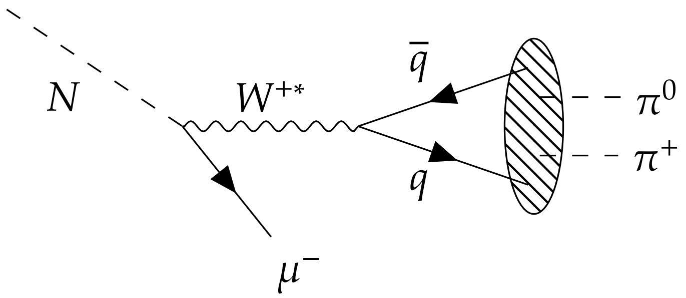

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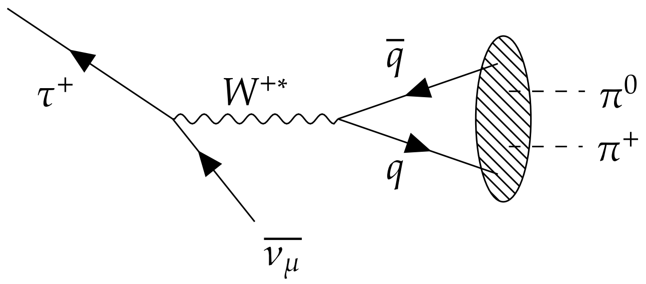

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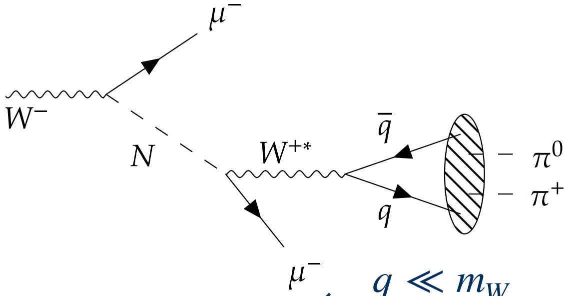

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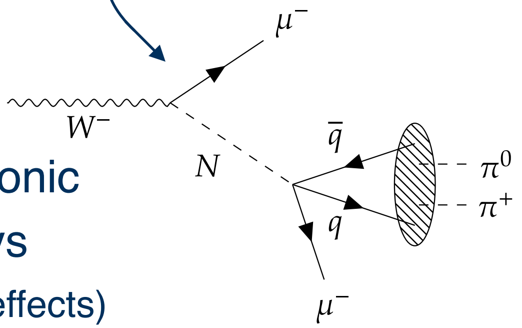


Semileptonic decays

(With QCD-effects)

(G_F = Fermis constant)

$$\mathcal{M} = \frac{G_F}{\sqrt{2}} L^\mu H_\mu$$

$$L^\mu = \langle \mu^- | \underbrace{\gamma^\mu \left((1 - \gamma^5 \right)}_{\text{vector-current}} | \mathrm{N} \rangle$$

axial-current

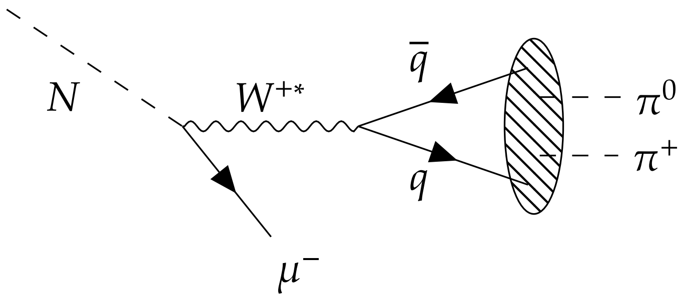
$$H^\mu = V_{\mathrm{CKM}} \times \langle \pi^+ \pi^0 | \overbrace{V_\mu} - \overbrace{A_\mu} | 0 \rangle$$

Implementation of τ-lepton Decays into the Event-Generator Sherpa, Laubrich, 2006

HNLs are implemented using existing models from tau-decays.

SHERPA

HNL



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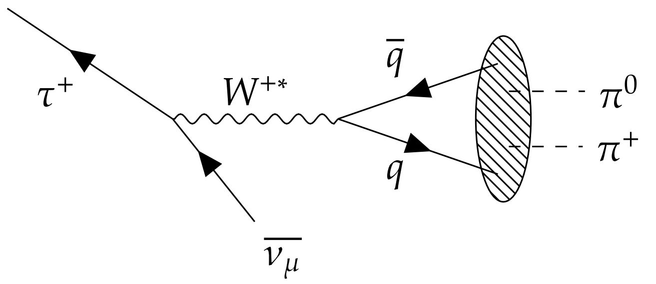

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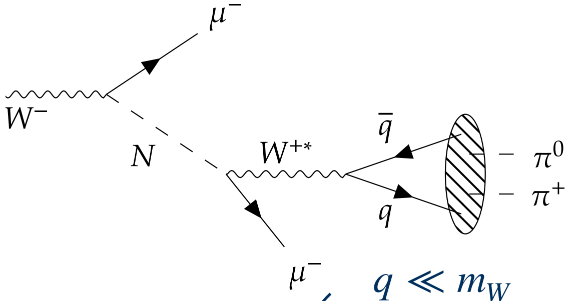

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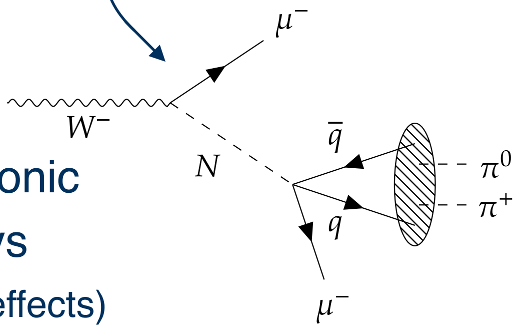

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$$\Downarrow$$

H^μ calculated using non-perturbative form factor models

→ treat HNLs as HADRONS

How to simulate HNL production and decay with SHERPA?

- SHERPA has UFO interface, where BSM Model can be implemented

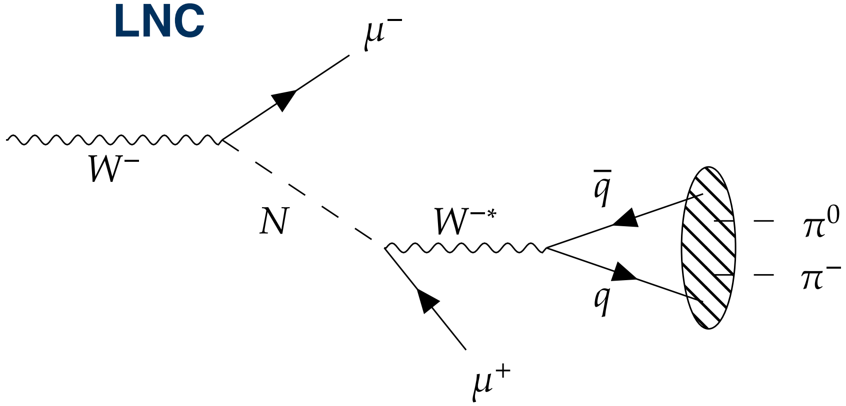
Model introduced in:
Fully Automated Precision Predictions for Heavy Neutrino Production Mechanisms at Hadron Colliders, 2016

Model downloaded from:
https://gitlab.cern.ch/atlas-generators-team/MadGraphModels/-/tree/main/Neutrinos/SM_HeavyN_NLO

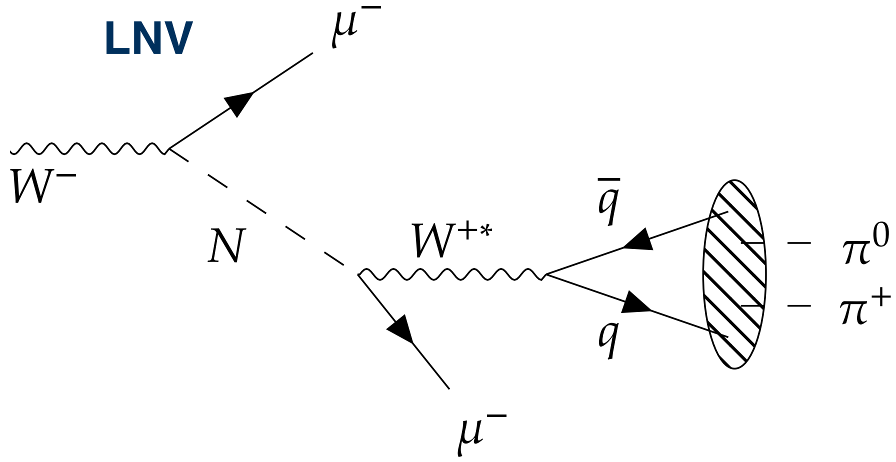
How to simulate HNL production and decay with SHERPA?

- SHERPA has UFO interface, where BSM Model can be implemented
- Parameters for Sherpa Run:
  - Model: SM_HeavyN_NLO,
  - $m_{HNL} = 2\,\mathrm{GeV}$ & $\mathrm{lifetime}_{HNL} = 10\,\mathrm{mm}$
    ➡ influenced by what LHC can detect
  - HNL decay:
    - semileptonic $\left(\pi^+ \pi^0\right)$
    - only muons
    - equal parts LNC and LNV

LNC



LNV



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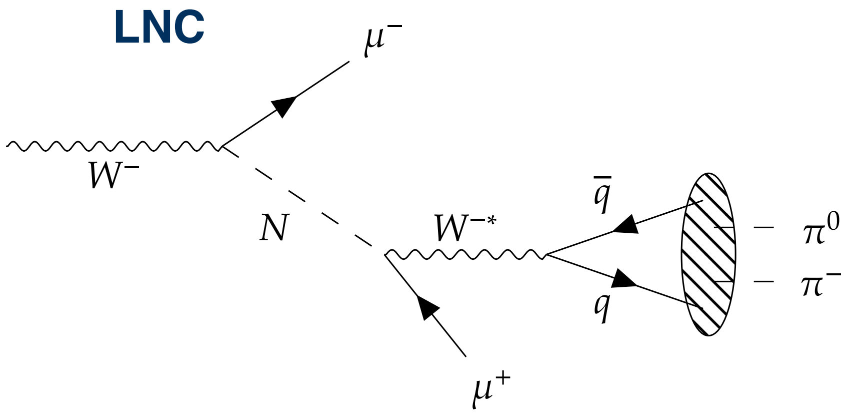
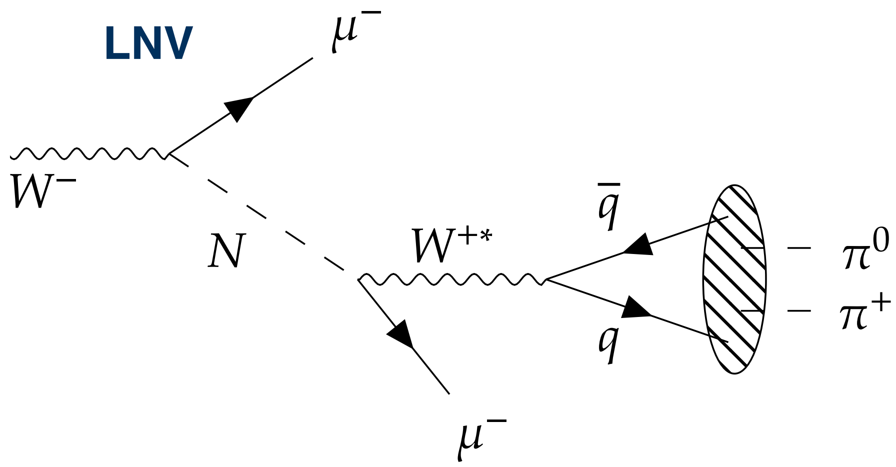
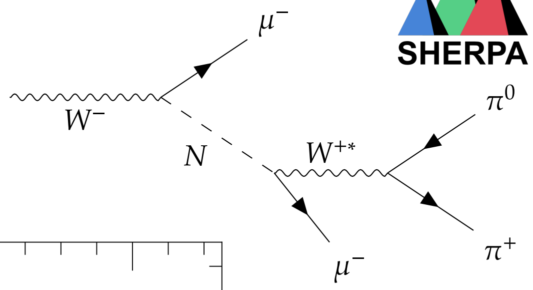
⇒ Comparison to MadGraph data *(HU Berlin, Marzieh Bahmani)*

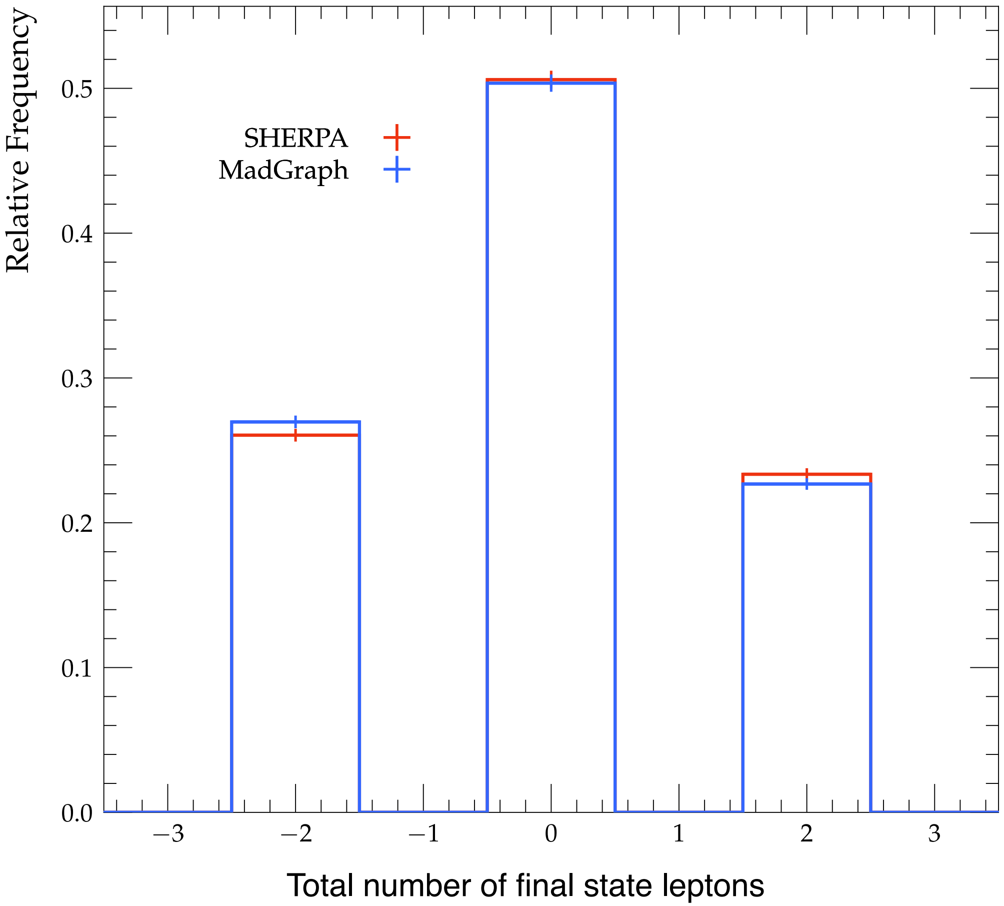




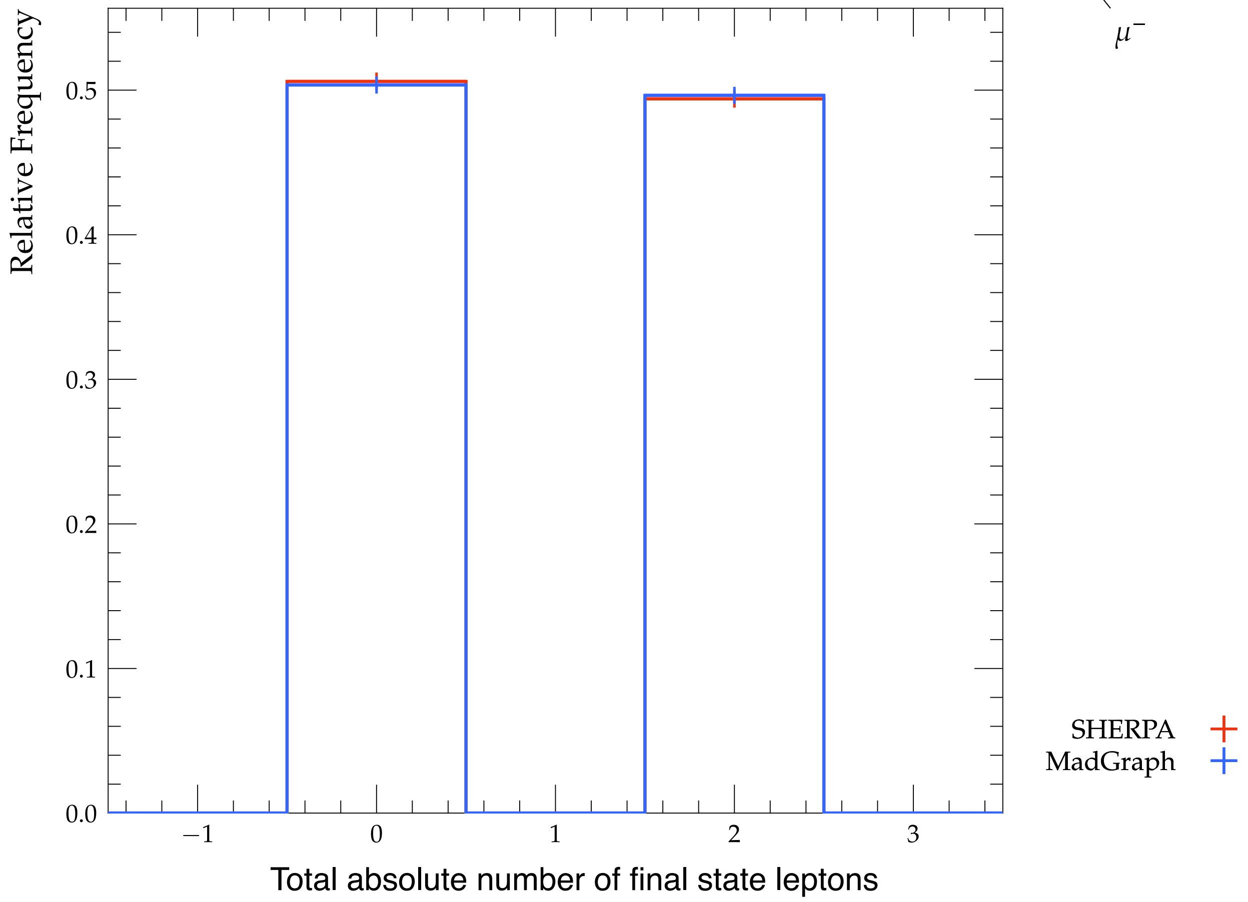
Lepton number violations fit to input conditions.



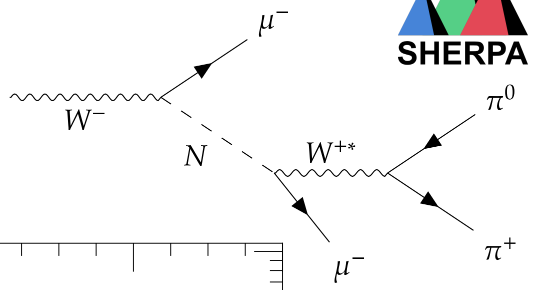
Lepton number violation:



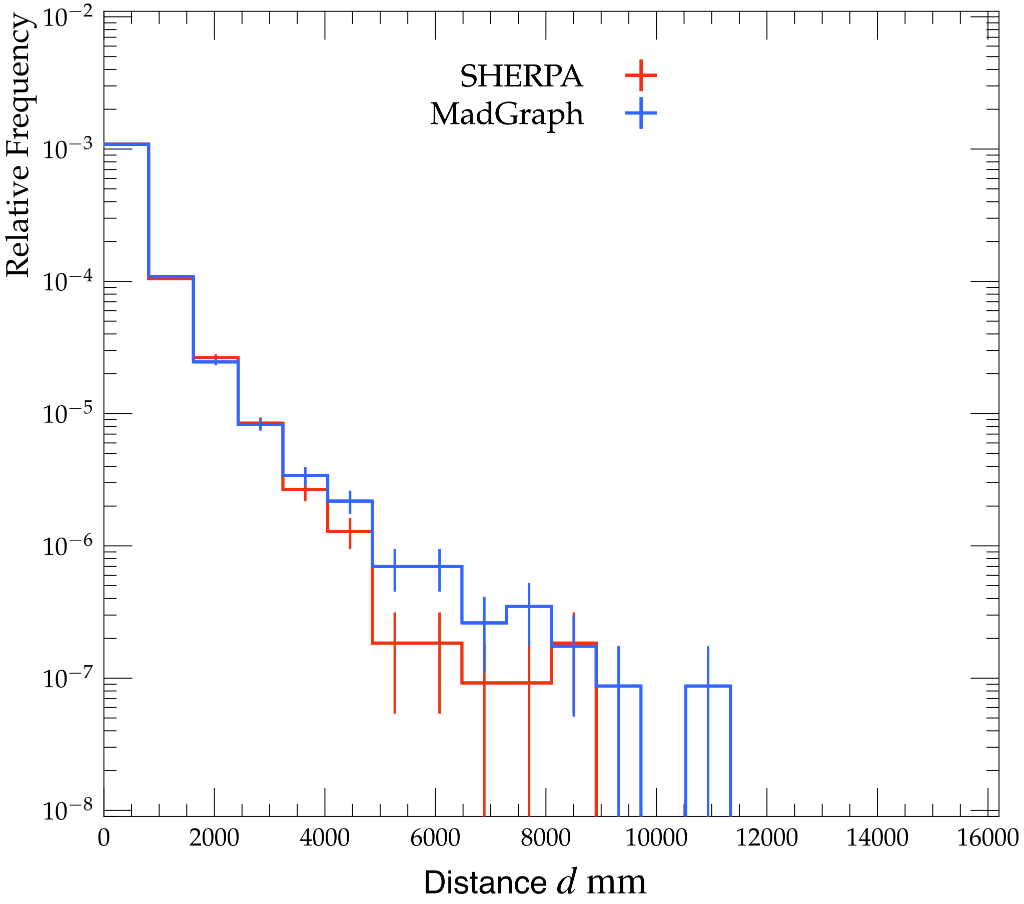
Absolute Lepton number violation:



HNL Lifetime fits to exponential decay.

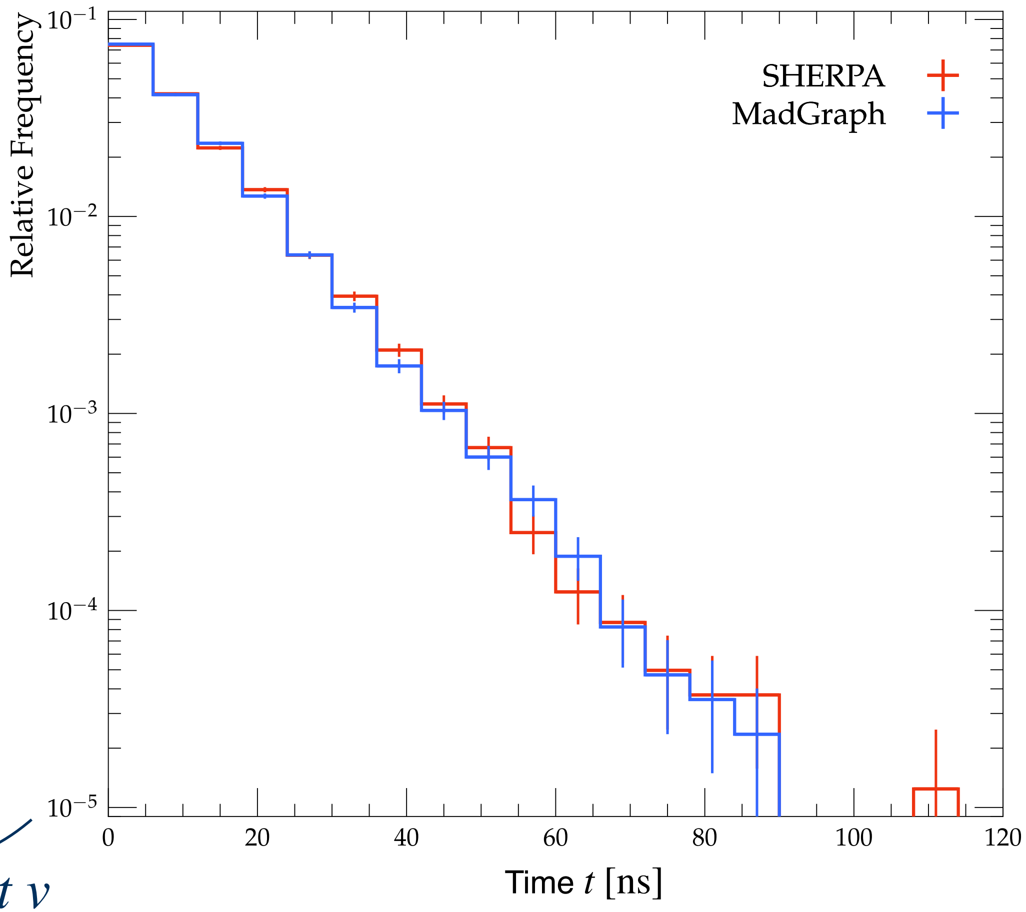


Vertex Offset in Lab frame:



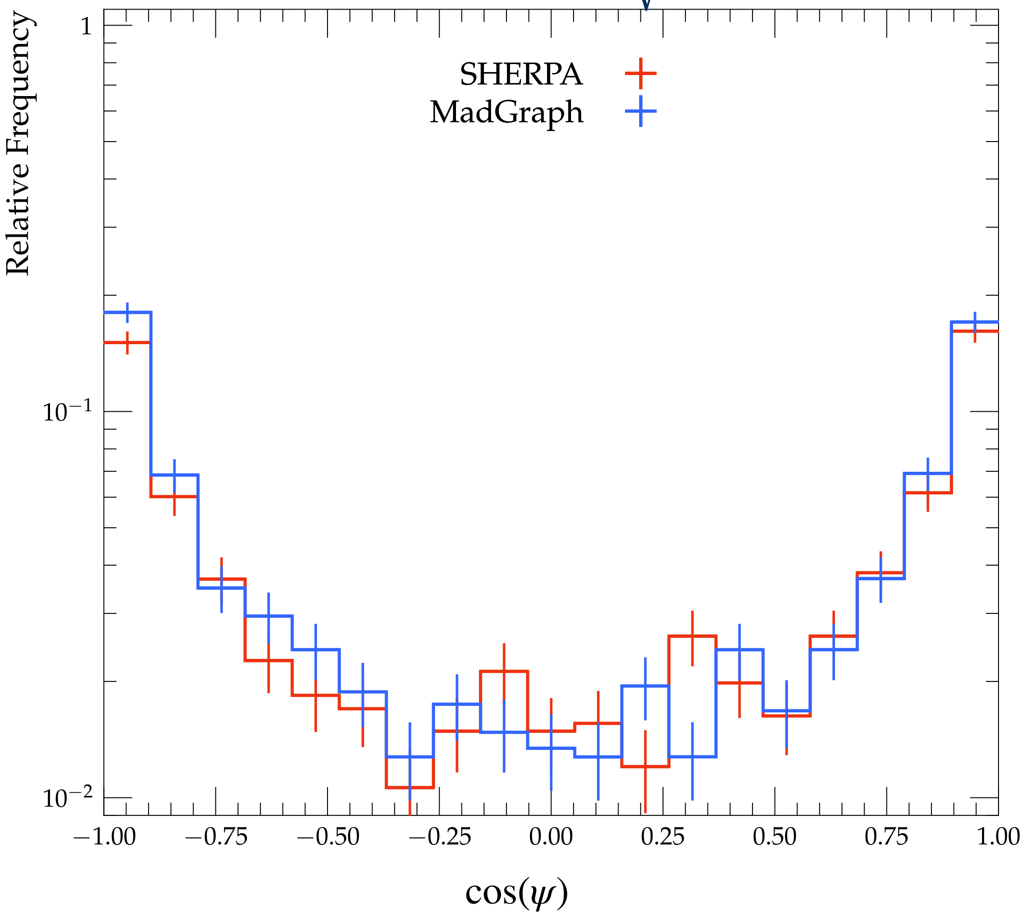
$$d = \gamma\, t\, v$$

Lifetime in Rest frame:

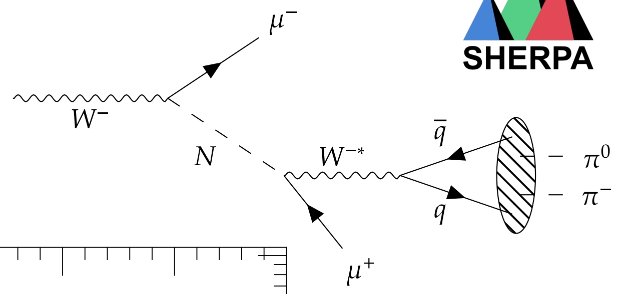


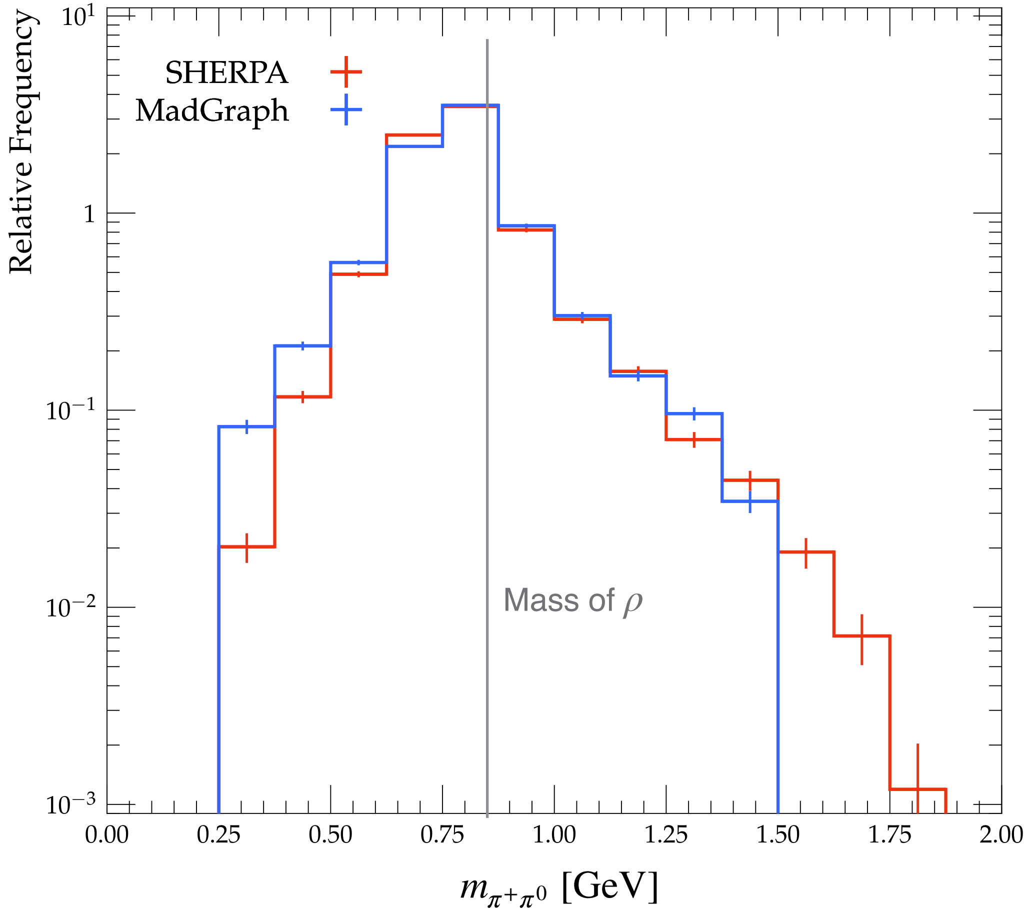
Spin correlation and invariant masses of pions.

Spin correlation: $\cos(\psi) = \frac{m_\rho}{\sqrt{m_\rho^2 - 4\,m_\pi^2}} \cdot \frac{E_{\pi^+} - E_{\pi^0}}{(P_{\pi^+} - P_{\pi^0})}$



Invariant mass of pions:

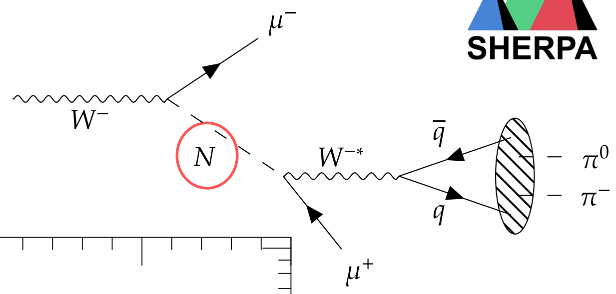




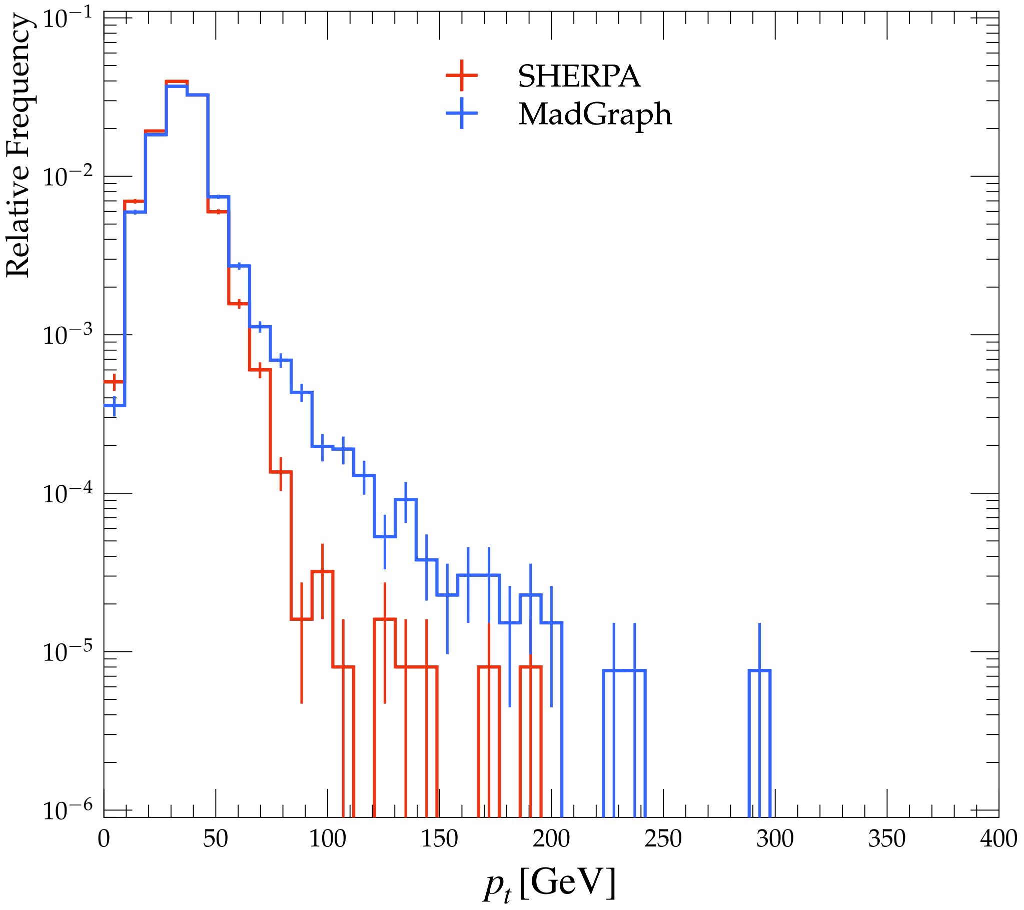
Analysis with: Robust Independent Validation of Experiment and Theory Rivet version 3, 2019

Spin correlation variable from: Tau decays as polarization analysers Andre Rouge, 1990

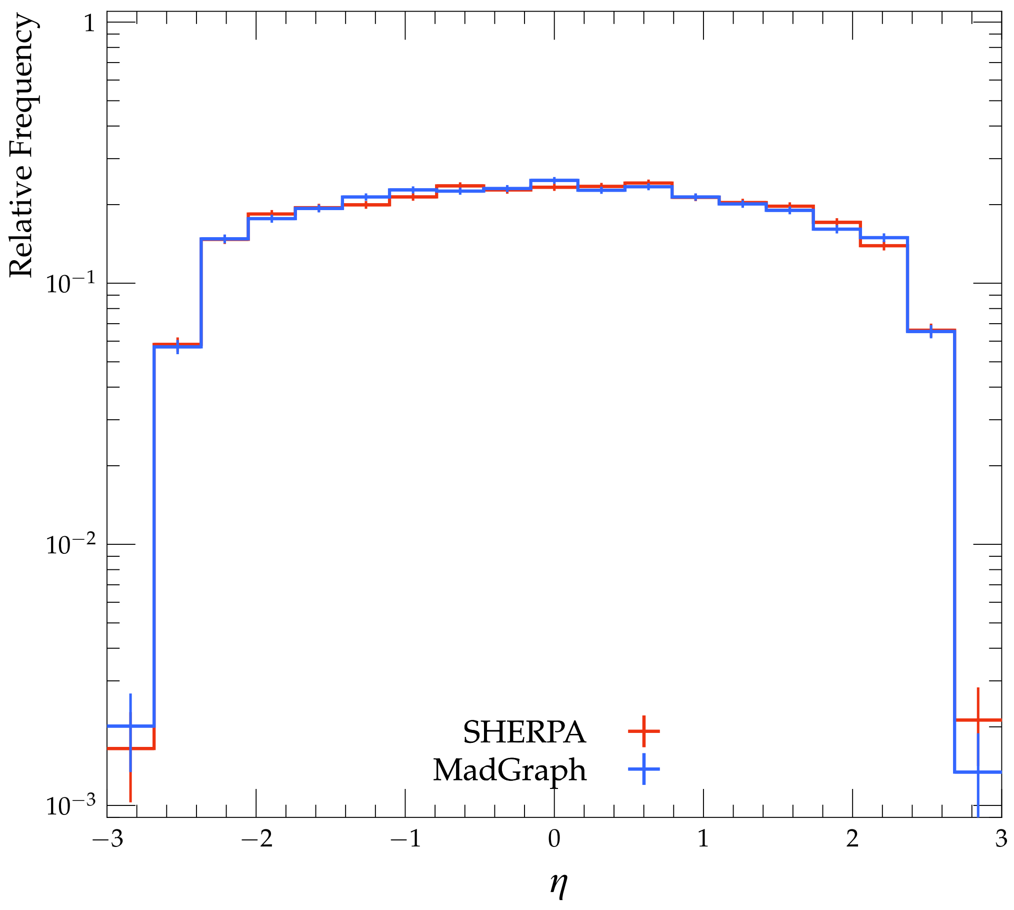
Kinematics: HNL



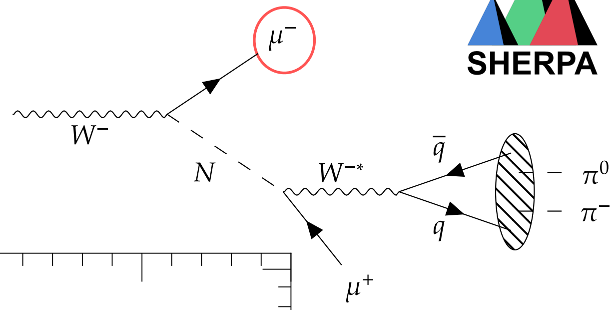
Transverse momentumg p_T:



Pseudorapidity η:



Kinematics: Prompt Lepton: $\mu^{\pm}$



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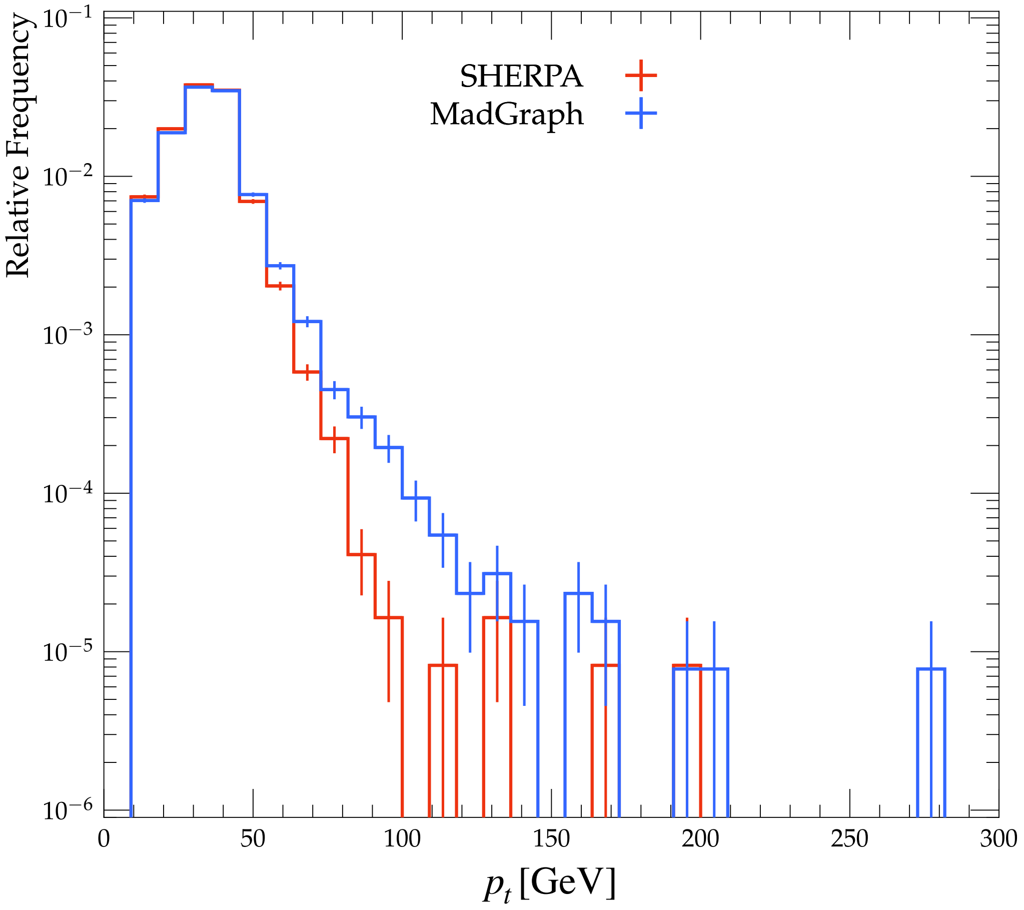
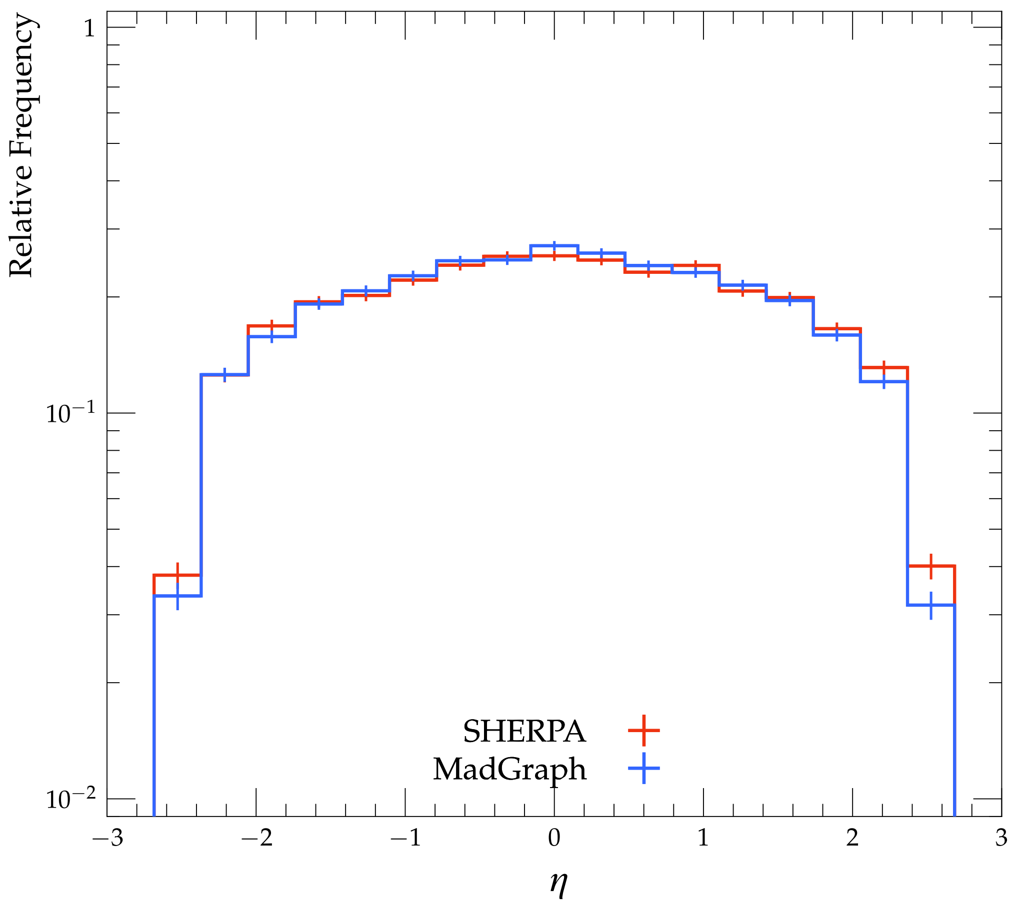
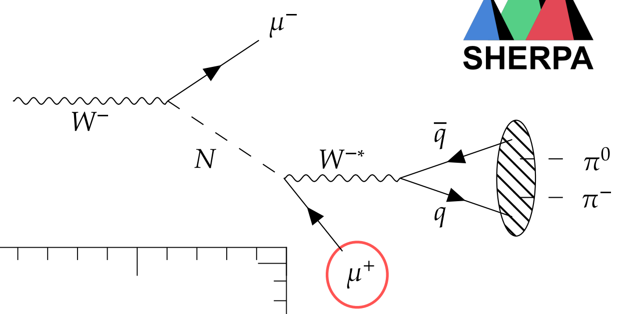


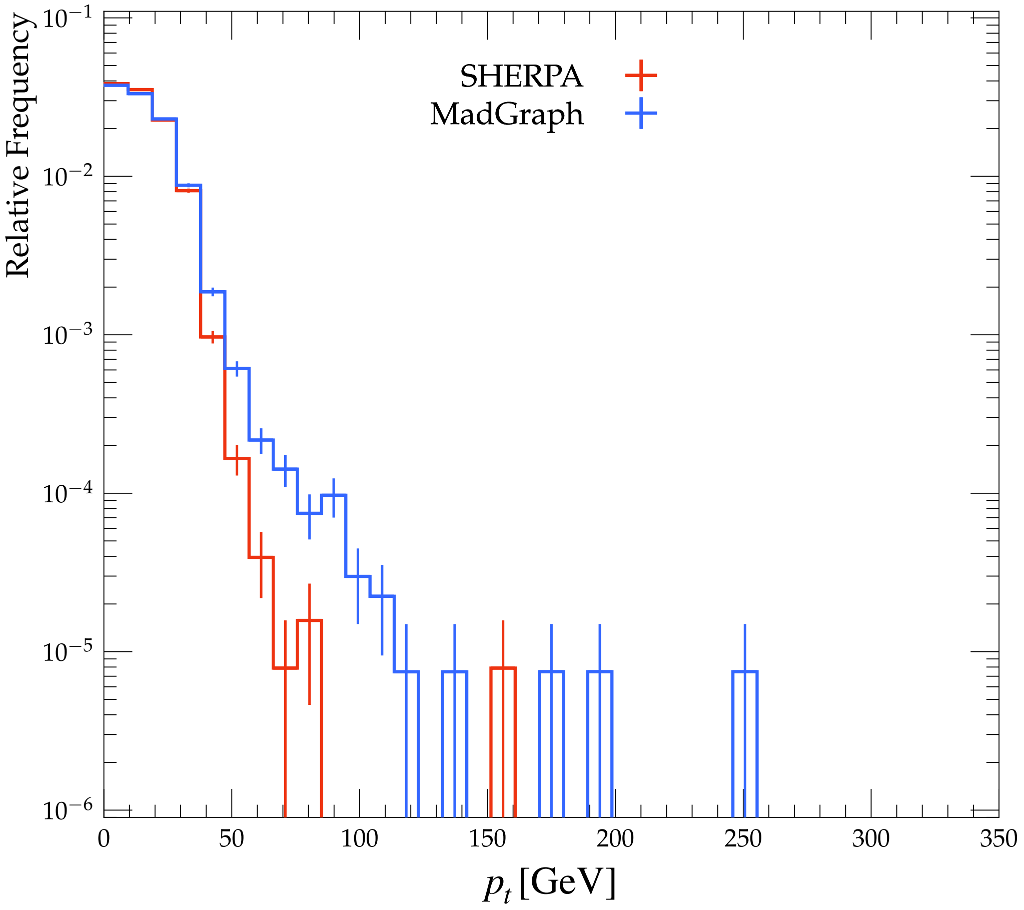
Pseudorapidity η:



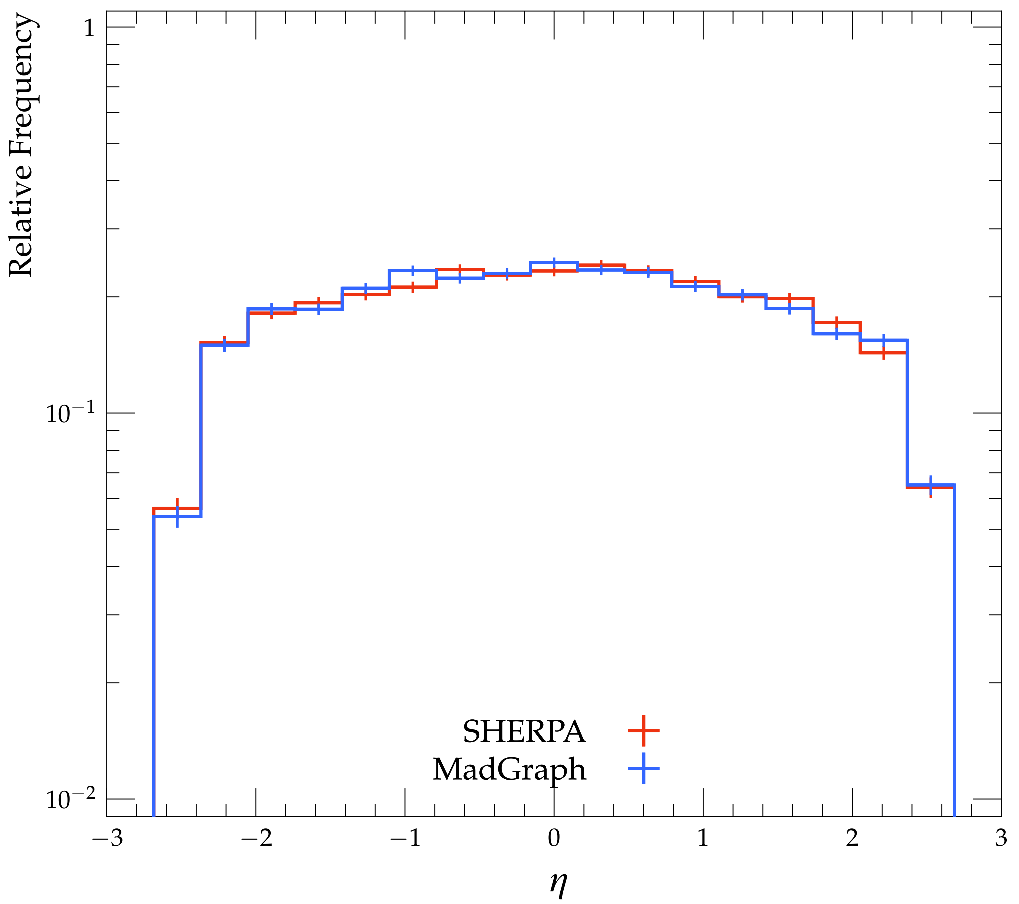
Kinematics: Secondary Lepton: $\mu^\pm$



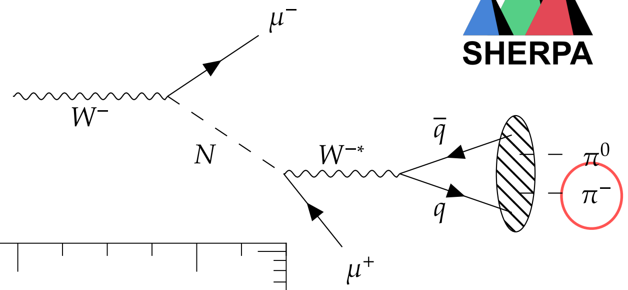
Transverse momentumg p_T:



Pseudorapidity η:

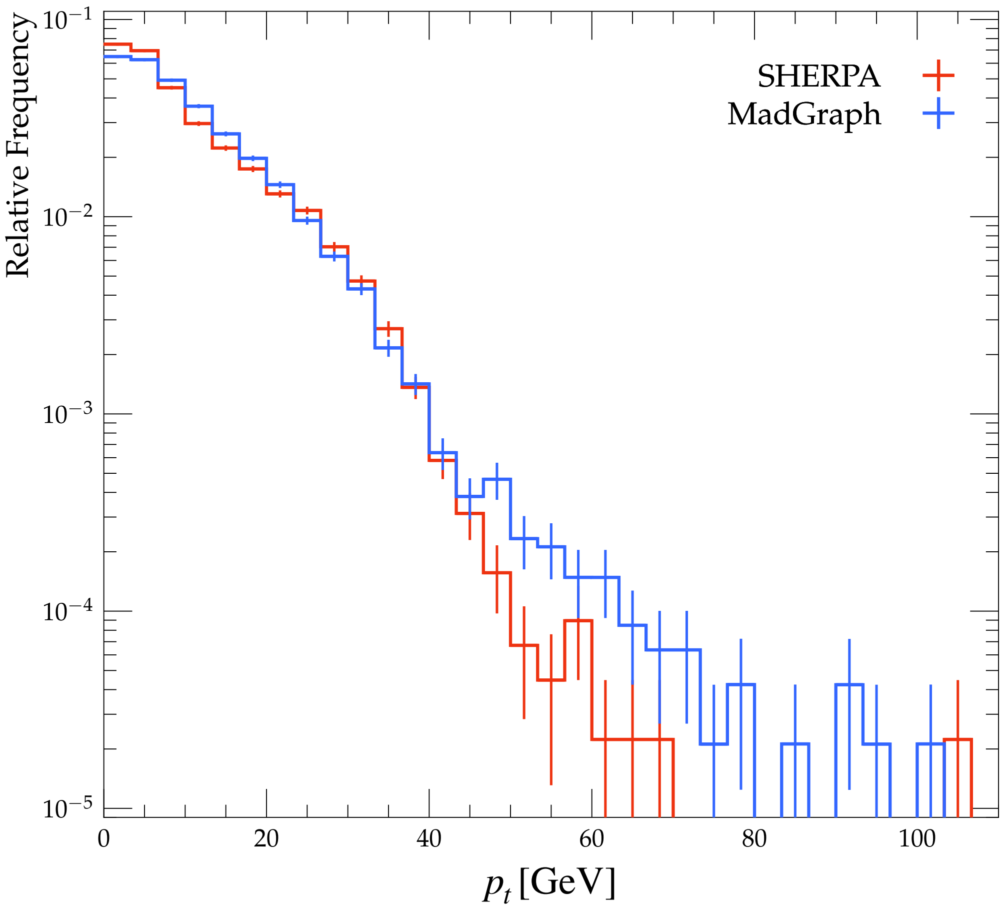


Kinematics: Pions: $\pi^{\pm}$

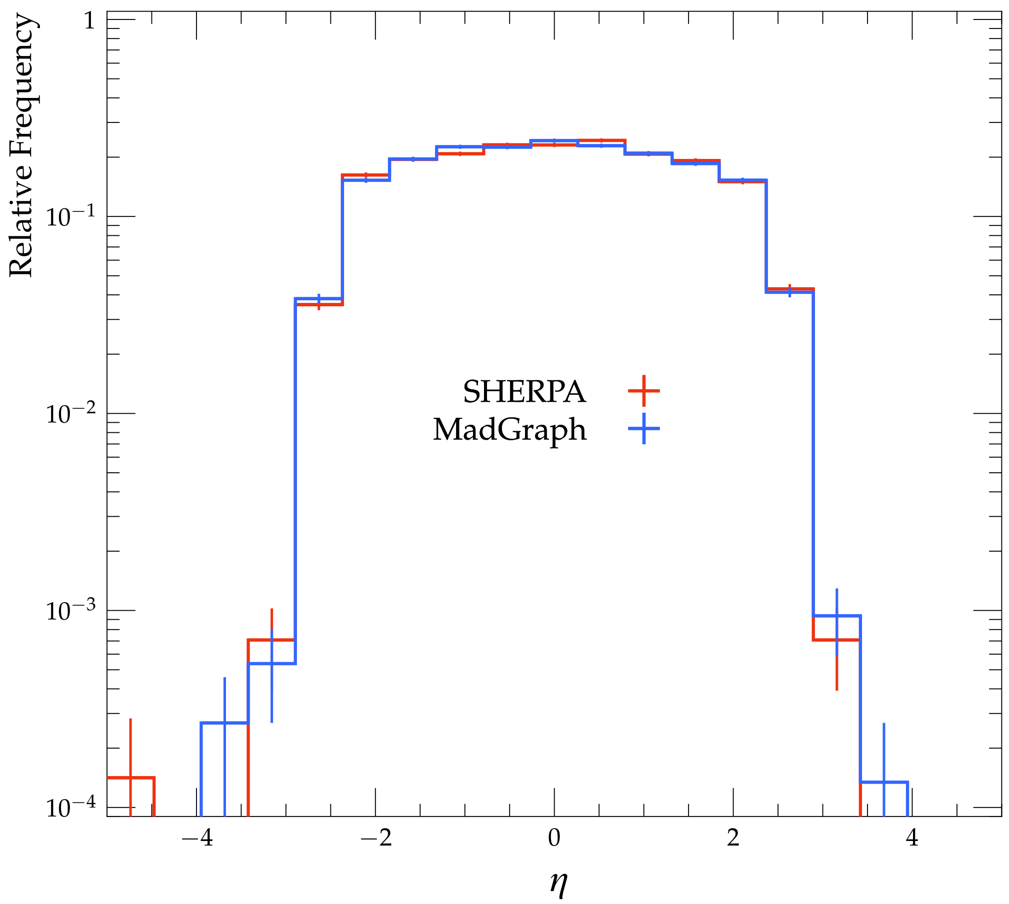


SHERPA

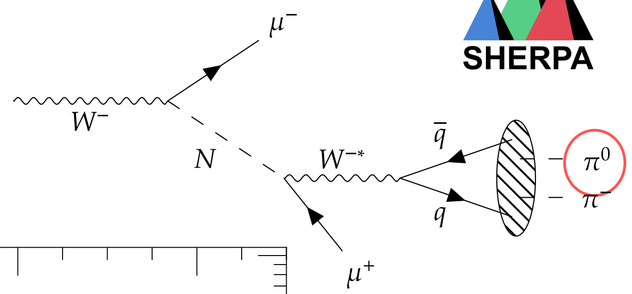
Transverse momentumg p_T:



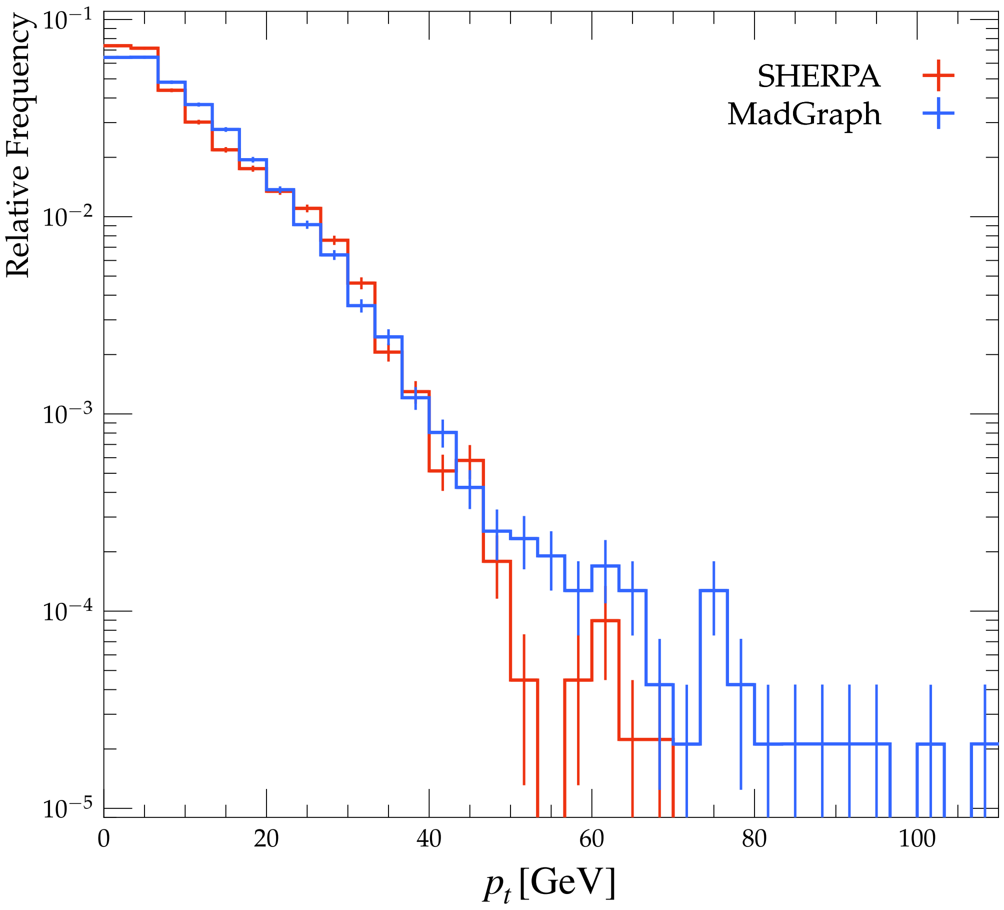
Pseudorapidity η:



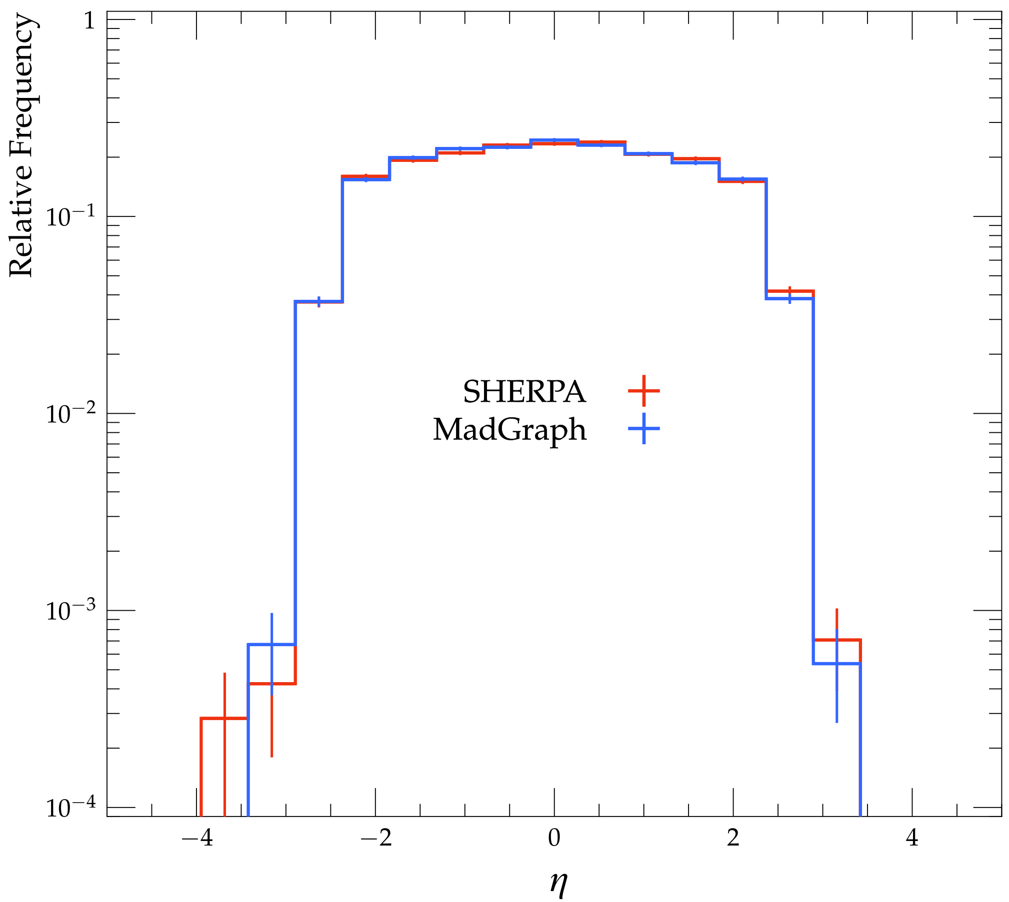
Kinematics: Pion: π^0



Transverse momentumg p_T:



Pseudorapidity η:



Summary

- HNL production and decay can be simulated with the Monte Carlo Event Generator SHERPA.
- Comparison with MadGraph data shows similar results. However, the transverse momentum differs between the two.

Next Steps

- **Analyse:** where do the different transverse momenta come from?
- **Generalise:** include other leptons and (semi-)leptonic decay channels & compare to MadGraph
- Implement higher order QCD corrections in Sherpa
- **Sherpa-development:**
  - Implement fixed target experiments (SHiP)

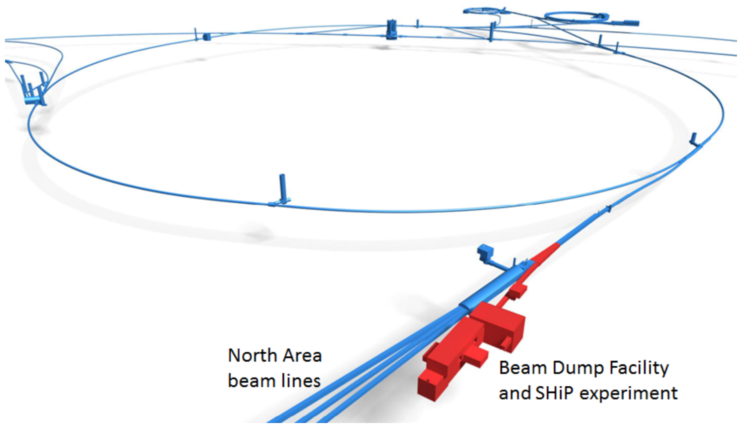


Figure from:
SHiP experiment progress report2019

Thank you for your attention!

Input Parameters for SHERPA and RIVET

- Parameters for SHERPA-Run:
  - Run 2 (Collsion energy 13 TeV)
  - Sherpa-Events (after Filtering): 24 524
  - MadGraph-Events (after Filtering): 18 701
  - Model for V-A implementation: Resonance Chiral Theory
  - Model: SM_HeavyN_NLO, considering only one HNL
  - $m_{HNL} = 2\,\mathrm{GeV}$ & $\mathrm{lifetime}_{HNL} = 10\,\mathrm{mm}$

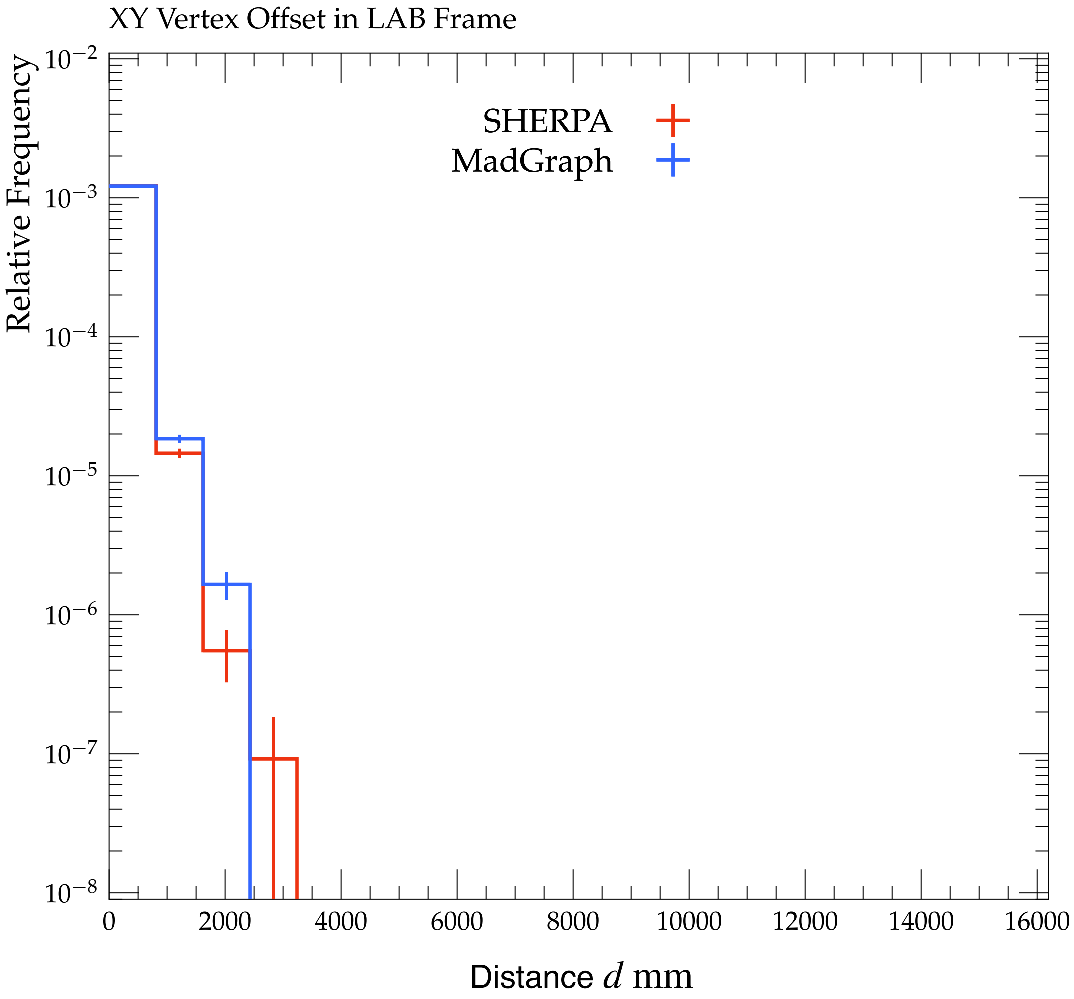
    ➡ influenced by what LHC can detect
  - HNL decay: semileptonic, only muons, equal parts LNC and LNV
- Cuts in RIVET-Analysis:
  - prompt lepton: $\eta < 2.5, p_T > 10\,\mathrm{GeV}$
  - Secondary lepton: $\eta < 2.5$

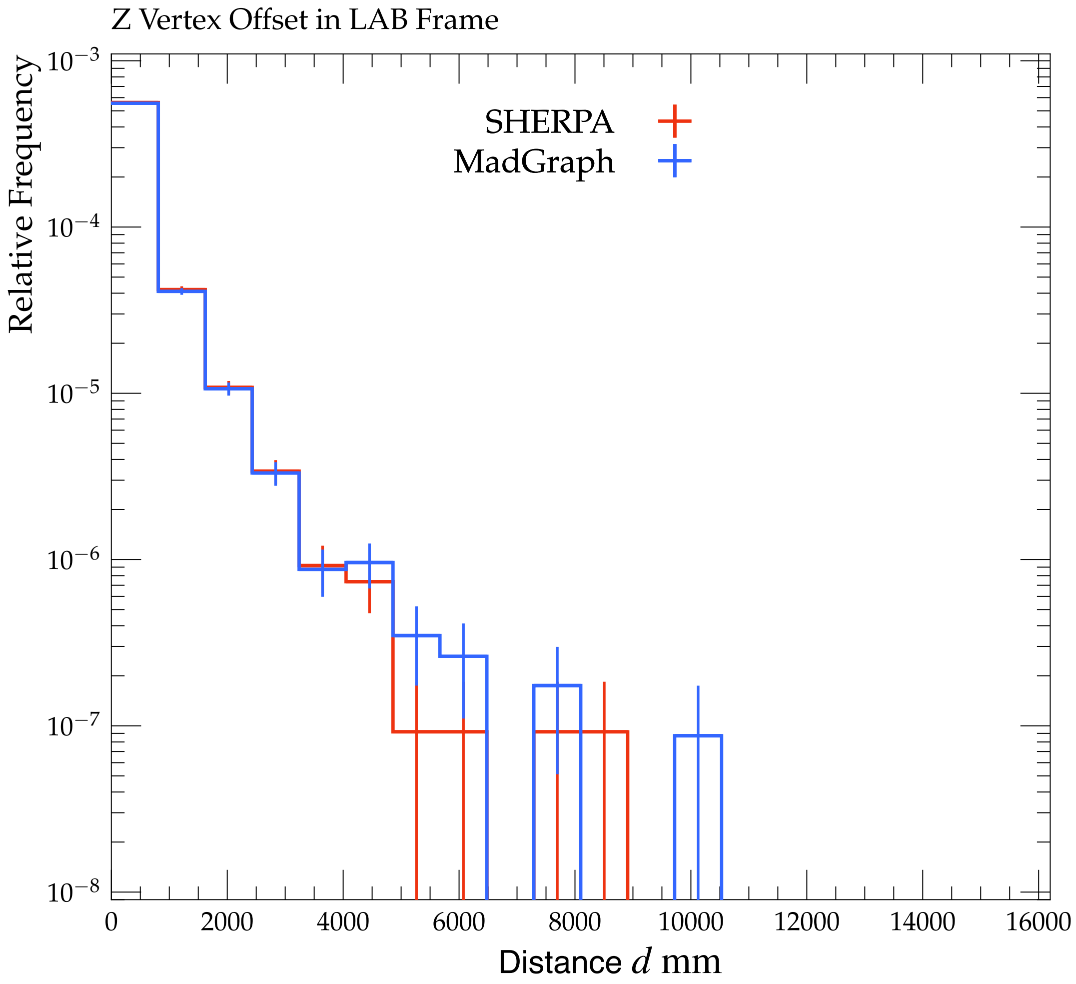
Command to implement model: */path_to_sherpa/sherpa/build/bin/Sherpa-generate-model /path_to_Model/SM_HeavyN_NLO*

Model introduced in:
Fully Automated Precision Predictions for Heavy Neutrino Production Mechanisms at Hadron Colliders, 2016

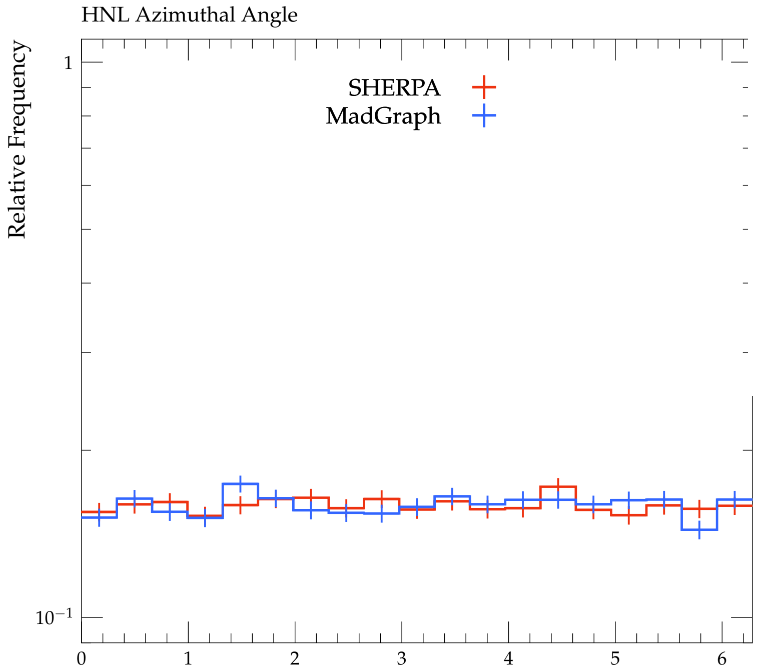
Model downloaded from:
https://gitlab.cern.ch/atlas-generators-team/MadGraphModels/-/tree/main/Neutrinos/SM_HeavyN_NLO

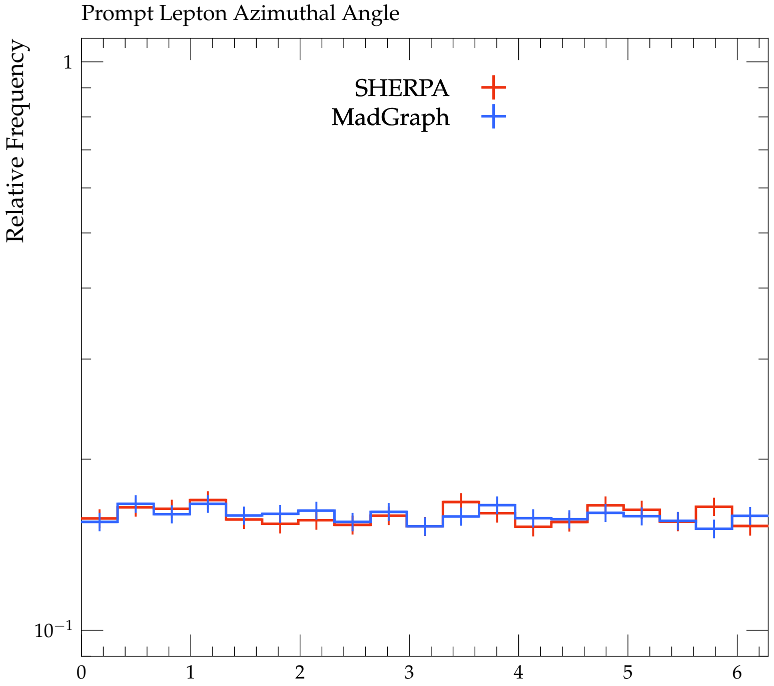
The Vertex offsets mainly stem from the z-axis.

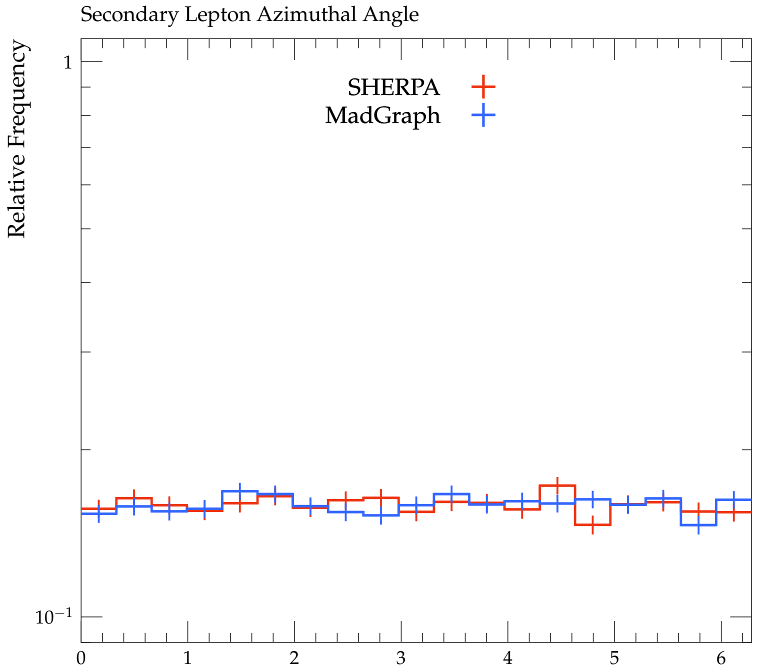


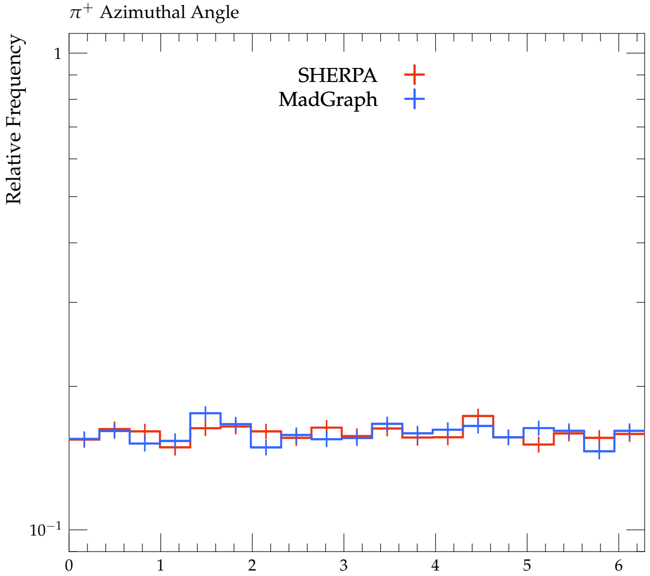


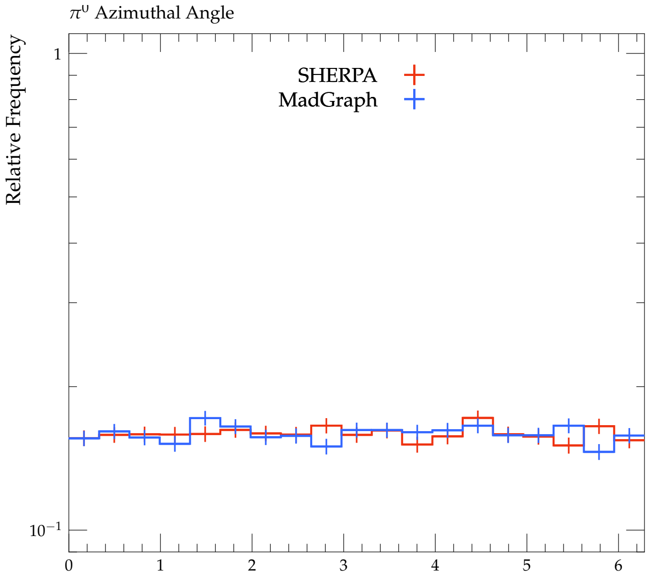
Kinematics: Phi











Sherpa finds the HNL several times, MadGraph finds rho several times