Dresden University of Technology

SHERPA

Antonia Bähr, Marzieh Bahmani, Michael Kobel, Frank Siegert

Institue of Nuclear and Particle Physics – TU Dresden

Simulation of Heavy Neutral Lepton production and decay with the Sherpa event generator

DPG Spring Meeting - Erlangen // 20.03.2026

INSTITUTE OF NUCLEAR AND PARTICLE PHYSICS

Neutrinos are not fully understood yet.

Neutrino oscillation experiment → Neutrinos are not massless! ≠ SM

Why are Neutrinos so light?

$$m_{e_\nu} < 0.45\,\mathrm{eV} \ll m_e \approx 10^6\mathrm{eV}$$

[KATRIN 2024]

Neutrinos are not fully understood yet.

Neutrino oscillation experiment → Neutrinos are not massless! ≠ SM

Why are Neutrinos so light?

$$m_{e_\nu} < 0.45\,\mathrm{eV} \ll m_e \approx 10^6\mathrm{eV}$$

[KATRIN 2024]

How do neutrinos get their mass?

Higgs? Something new?

Neutrinos are not fully understood yet.

Neutrino oscillation experiment → Neutrinos are not massless! ≠ SM

Why are Neutrinos so light?

$m_{e_\nu} < 0.45\,\mathrm{eV} \ll m_e \approx 10^6\mathrm{eV}$

[KATRIN 2024]

How do neutrinos get their mass?

Higgs? Something new?

Are neutrinos their own antiparticles?

Majorana or Dirac?

Neutrinos are not fully understood yet.

Neutrino oscillation experiment → Neutrinos are not massless! ≠ SM

Why are Neutrinos so light?

$m_{e_\nu} < 0.45\,\mathrm{eV} \ll m_e \approx 10^6 \mathrm{eV}$

[KATRIN 2024]

How do neutrinos get their mass?
Higgs? Something new?

Are neutrinos their own antiparticles?
Majorana or Dirac?

Are there right-chiral neutrinos?

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

Type 1 Seesaw mechanism:

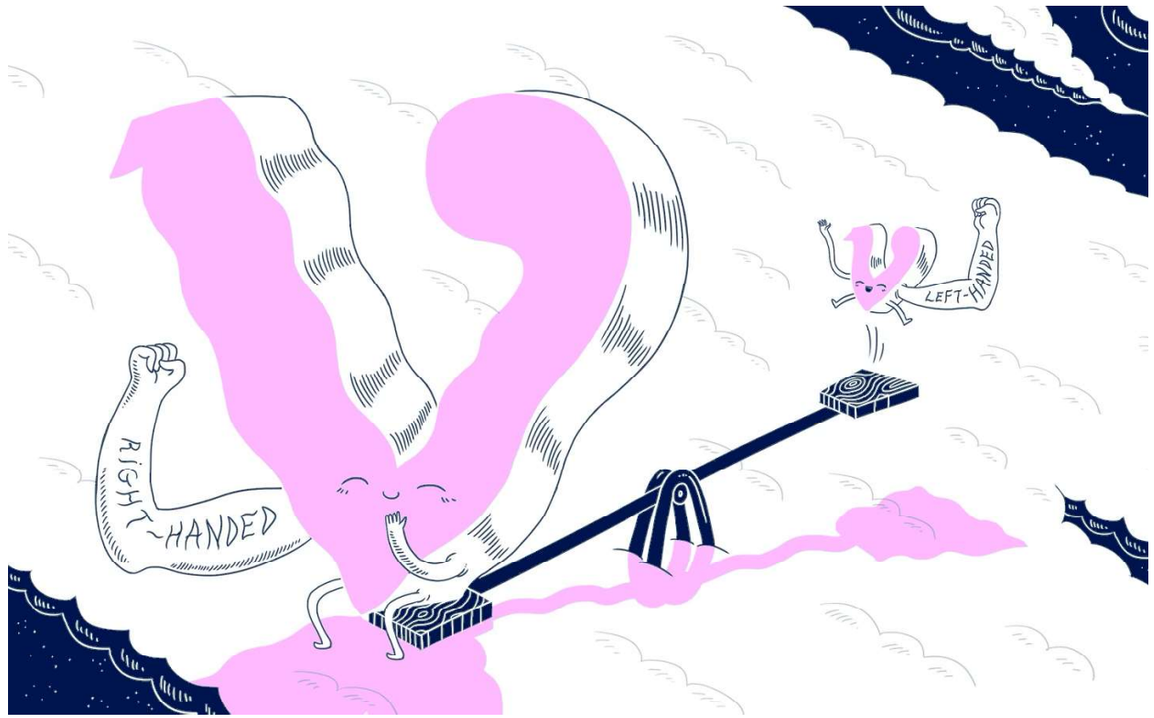
Introducing right-chiral neutrino field
& new kinds of mass terms in Lagrangian

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

$M \gg m_D$

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

→ Neutrino mass eigenstates are their own antiparticle (Majorana)

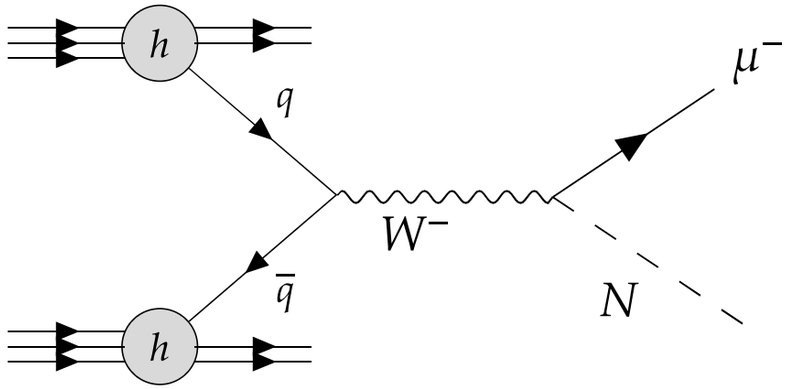


https://www.symmetrymagazine.org/article/neutrinos-on-a-seesaw

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

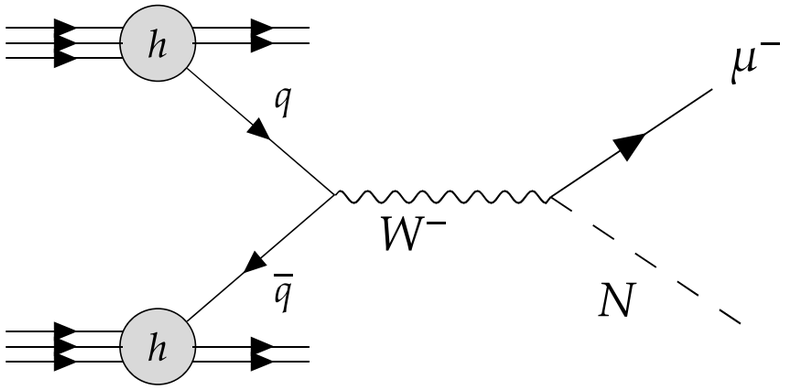
Semileptonic HNL decays

Production (Drell-Yan process)

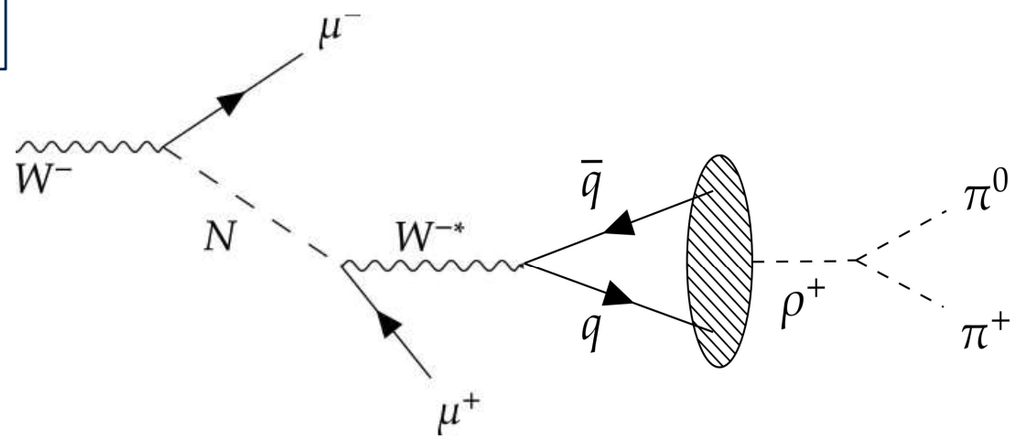


Semileptonic HNL decays

Production (Drell-Yan process)

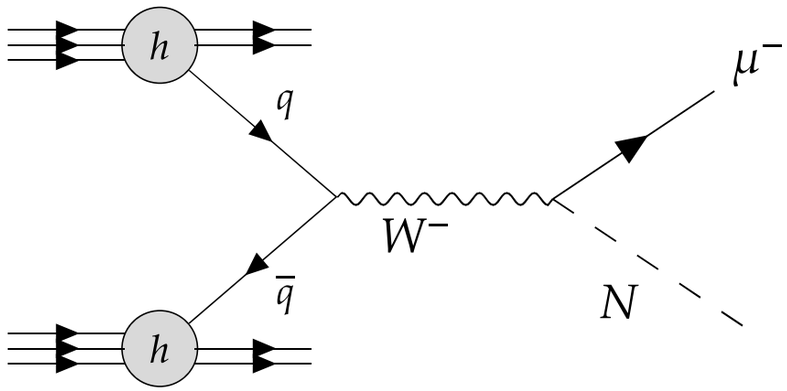


Decay



Semileptonic HNL decays

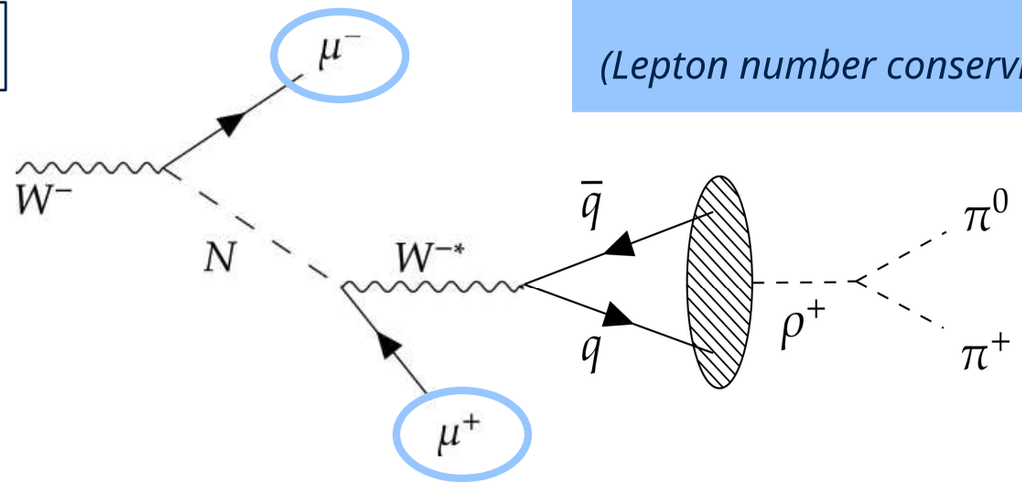
Production (Drell-Yan process)



Decay

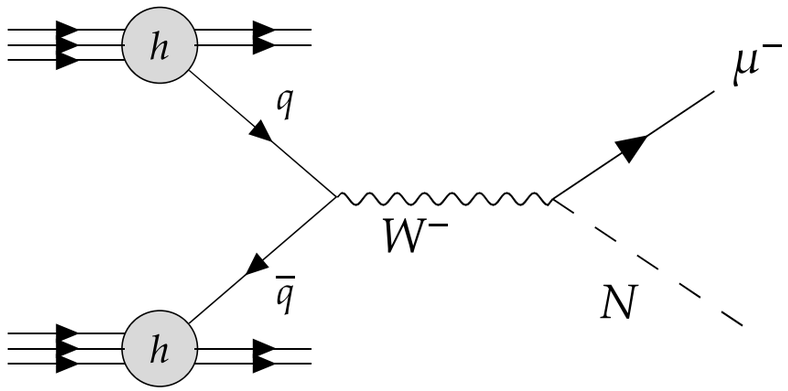
LNC

(Lepton number conserving)



Semileptonic HNL decays

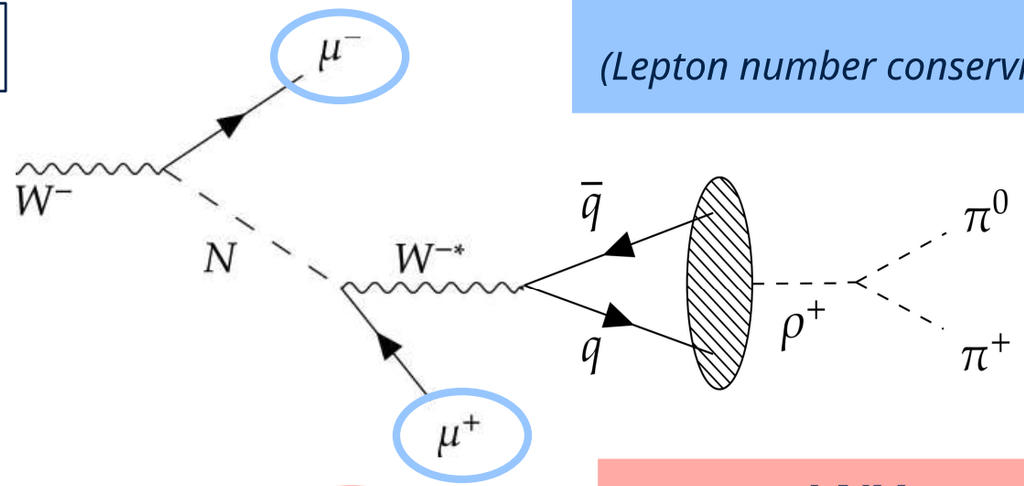
Production (Drell-Yan process)



Decay

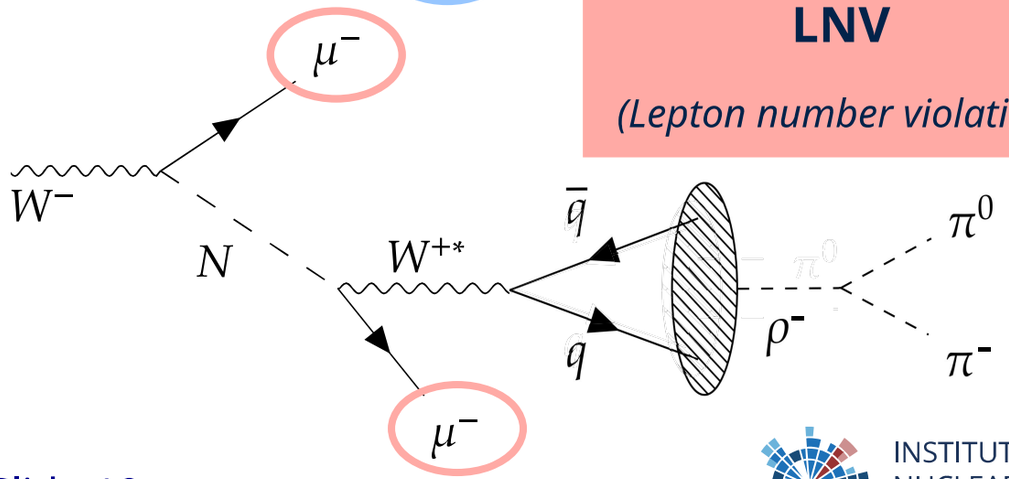
LNC

(Lepton number conserving)



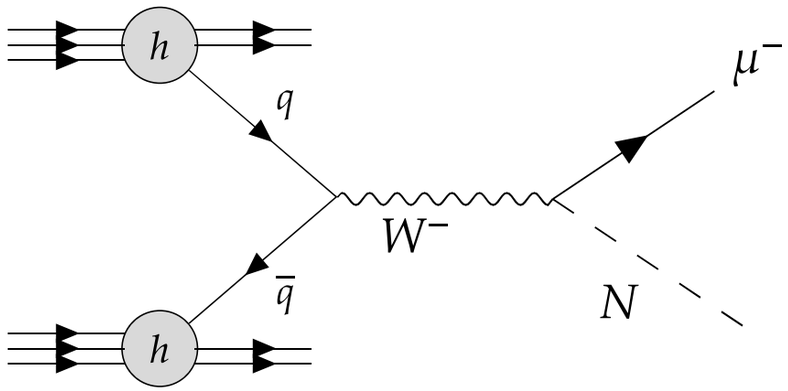
LNV

(Lepton number violating)



Semileptonic HNL decays

Production (Drell-Yan process)

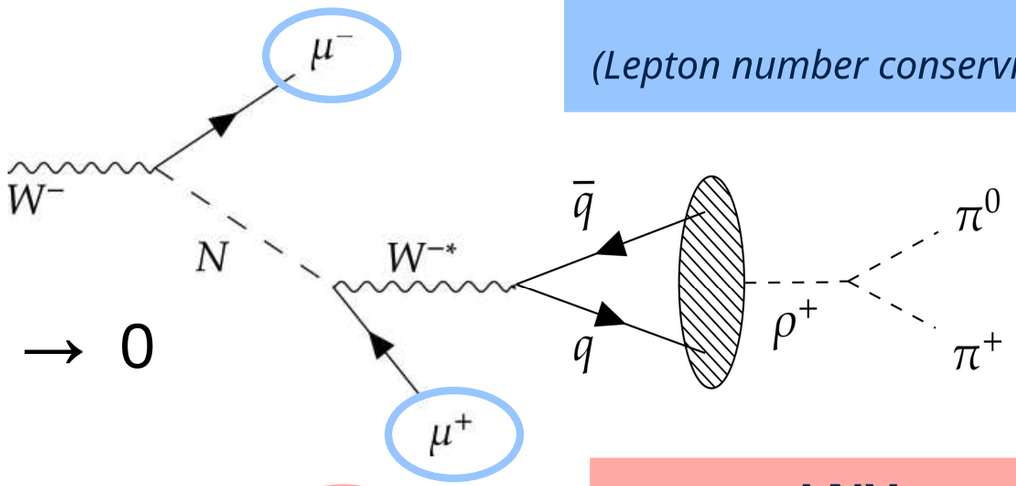


Decay

LN: 0 → 0

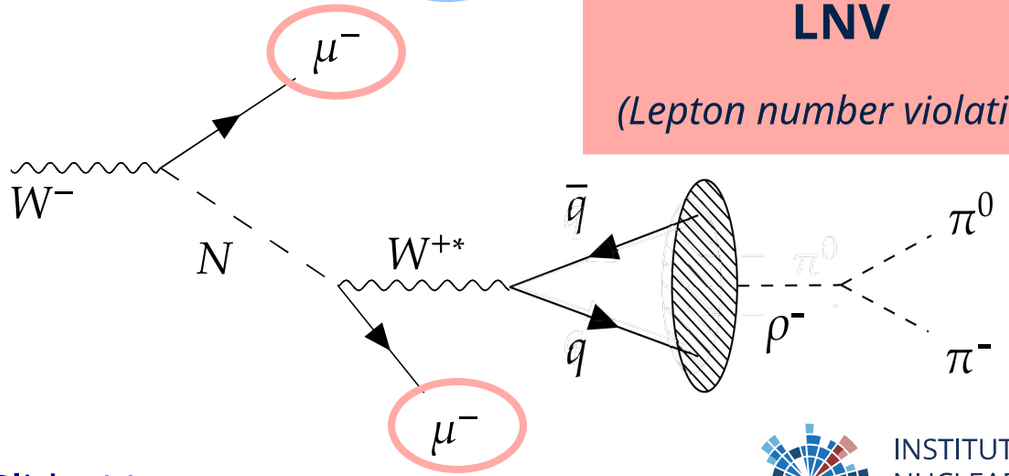
LNC

(Lepton number conserving)



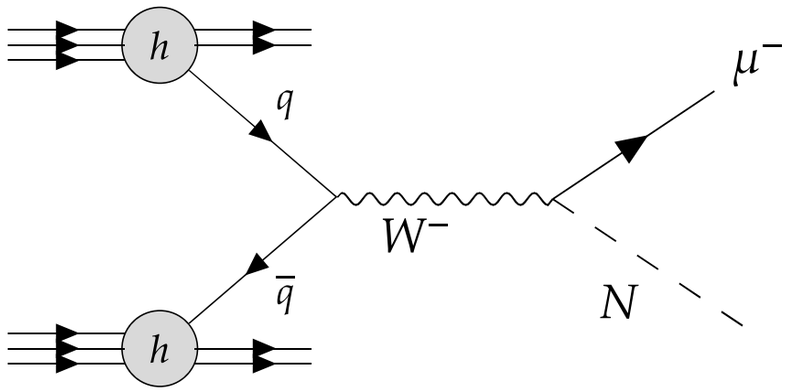
LNV

(Lepton number violating)



Semileptonic HNL decays

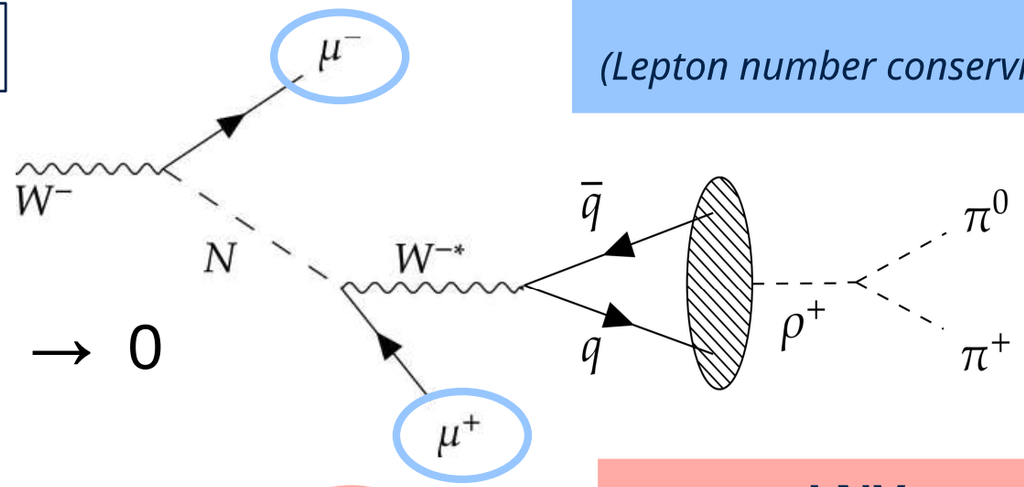
Production (Drell-Yan process)



Decay

LNC

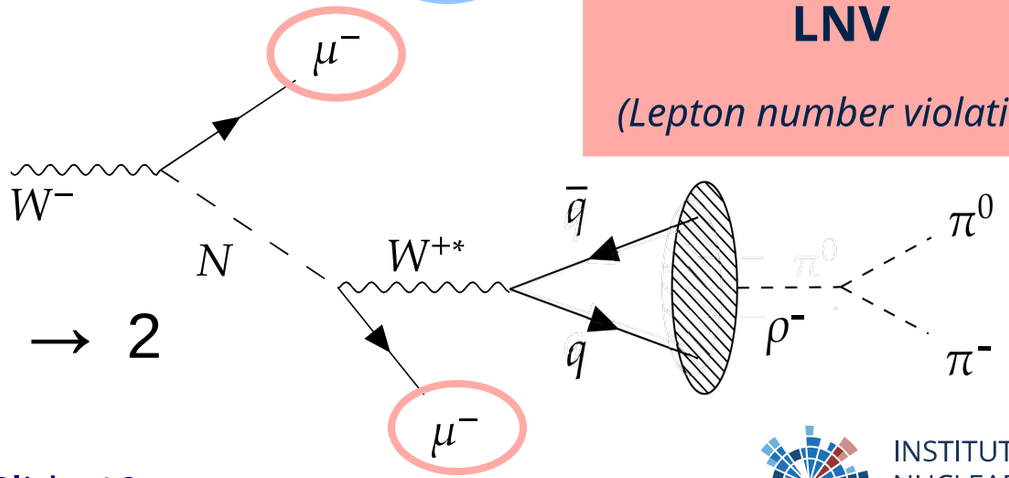
(Lepton number conserving)



LN: 0 → 0

LNV

(Lepton number violating)



LN: 0 → 2

INSTITUTE OF NUCLEAR AND PARTICLE PHYSICS

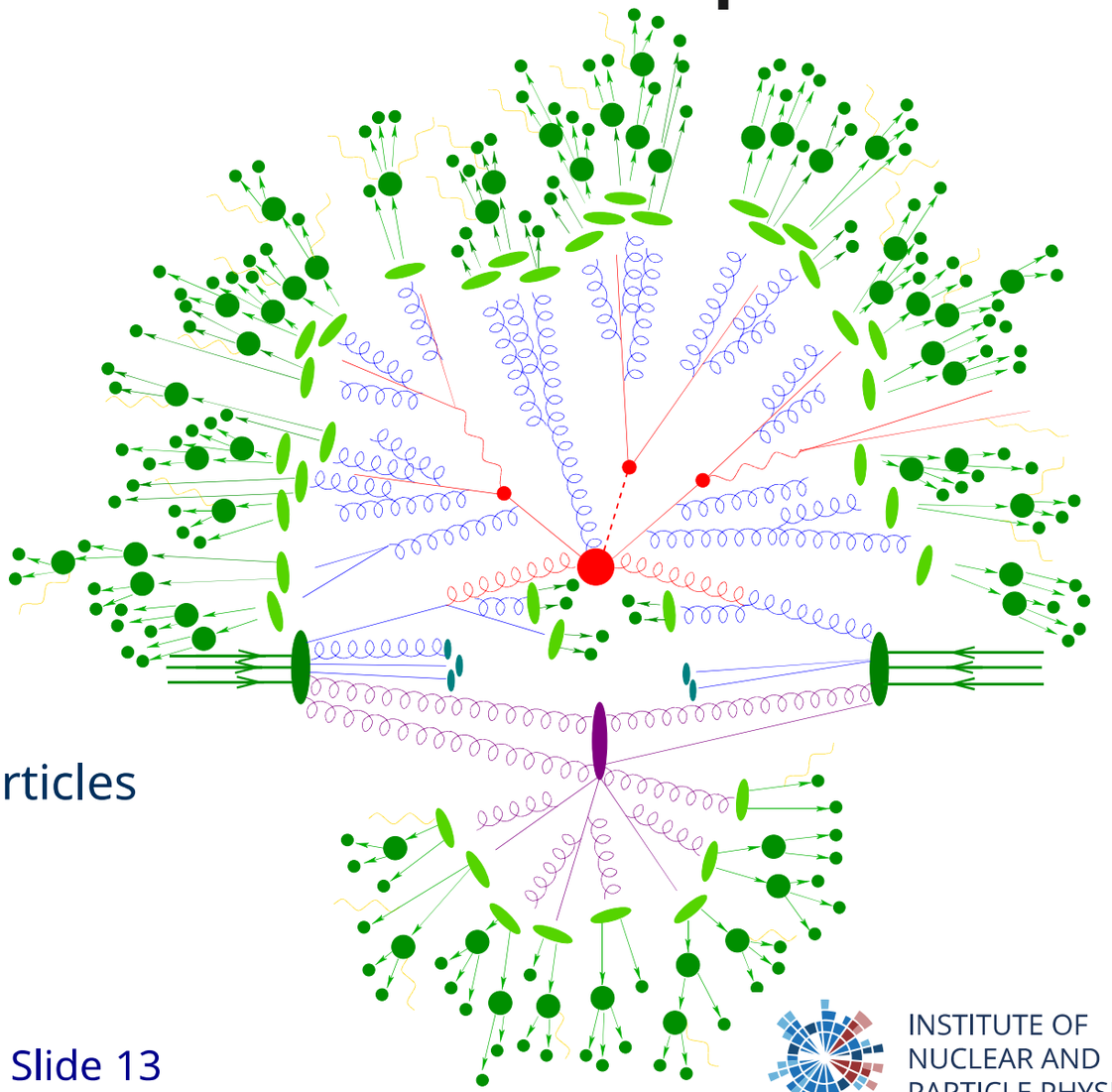
Monte Carlo Event generators split events into substeps.

Red: Hard processes
(perturbation theory)

Blue: QCD radiation
(*perturbation theory)*

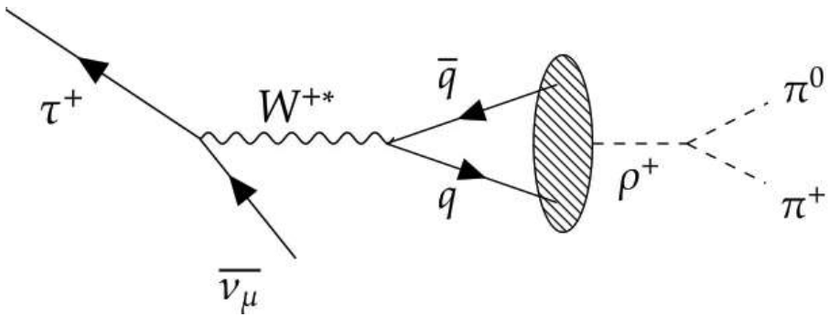
Light Green: Hadronisation
(phenomenological)

Dark Green: Hadron decay into other particles
(phenomenological)



HNLs are implemented using existing models from τ-decays.

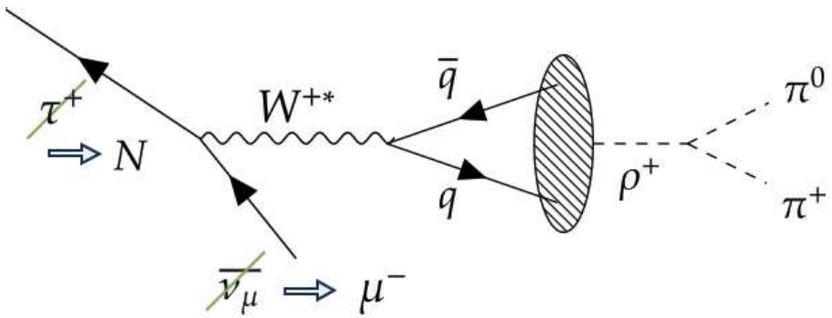
τ



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

HNLs are implemented using existing models from τ-decays.

τ ⟶ HNL



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

INSTITUTE OF NUCLEAR AND PARTICLE PHYSICS

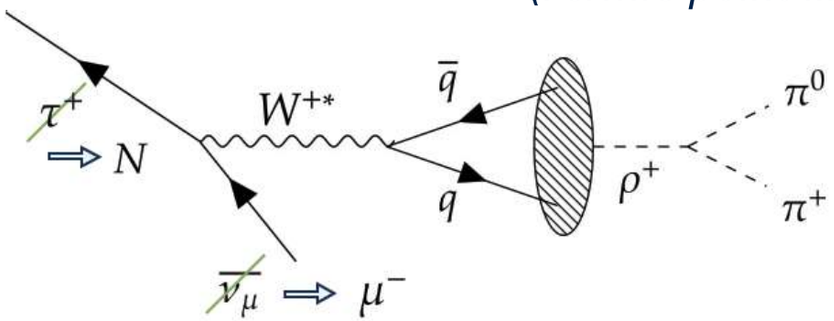
HNLs are implemented using existing models from τ-decays.

τ ➞ HNL

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

G_F = Fermis constant

(Fermi's point-like interaction)



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

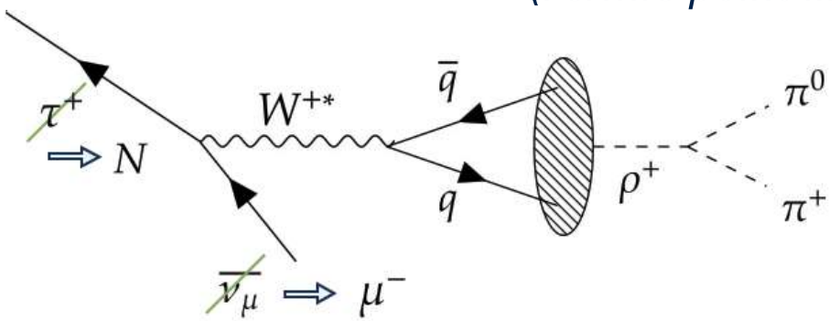
HNLs are implemented using existing models from τ-decays.

τ ➞ HNL

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

(Fermi's point-like interaction)

G_F = Fermis constant



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

➞ calculated using non-perturbative form factor models

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

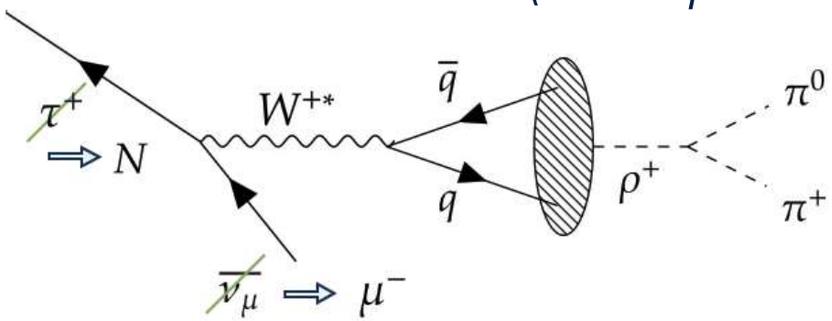
HNLs are implemented using existing models from τ-decays.

τ ➡ HNL

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

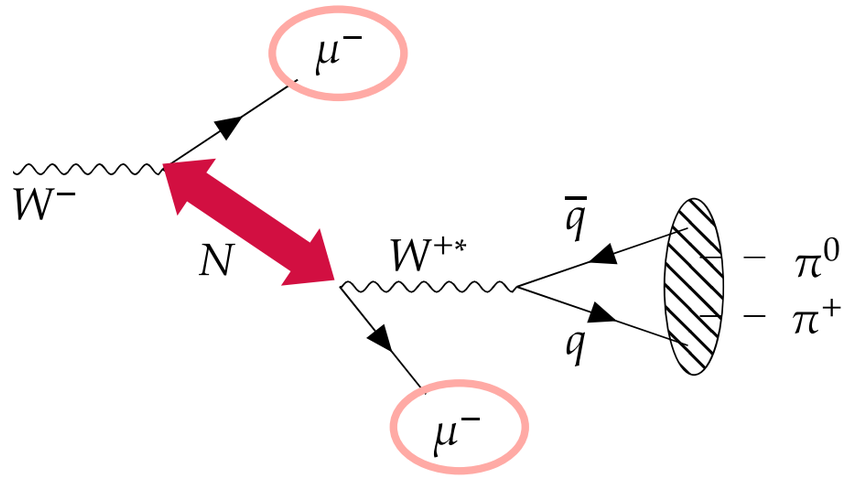
(Fermi's point-like interaction)

G_F = Fermis constant



+

Feynman rules for Majorana Particles



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

➡ calculated using non-perturbative form factor models

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

Feynman rules for fermion-number-violating interactions, Denner et al., 1992

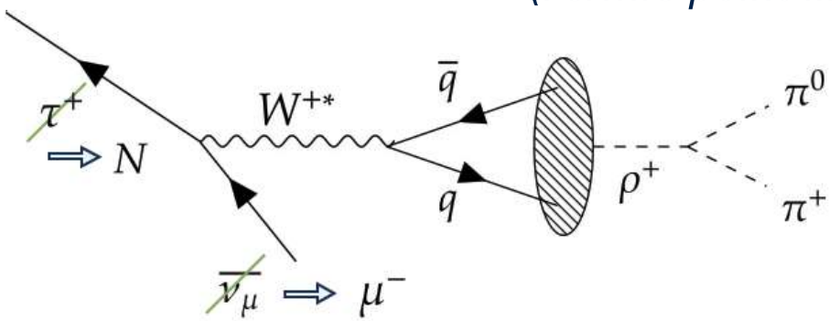
HNLs are implemented using existing models from τ-decays.

τ ➡ HNL

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

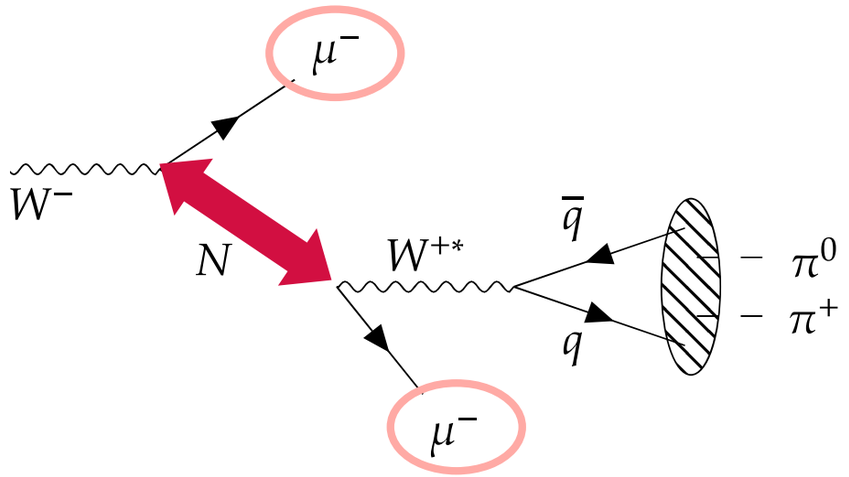
(Fermi's point-like interaction)

G_F = Fermis constant



+

Feynman rules for Majorana Particles



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

$$L^\mu = \langle \mu^- | \gamma^\mu - \gamma^\mu \gamma^5 | \mathrm{N} \rangle$$

➡ calculated using non-perturbative form factor models

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

Feynman rules for fermion-number-violating interactions, Denner et al., 1992

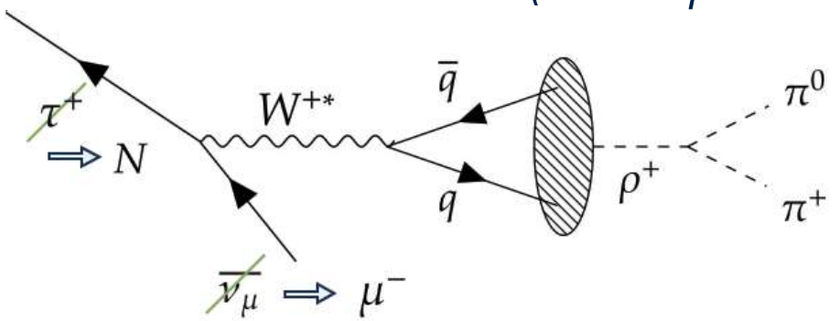
HNLs are implemented using existing models from τ-decays.

τ ➡ HNL

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

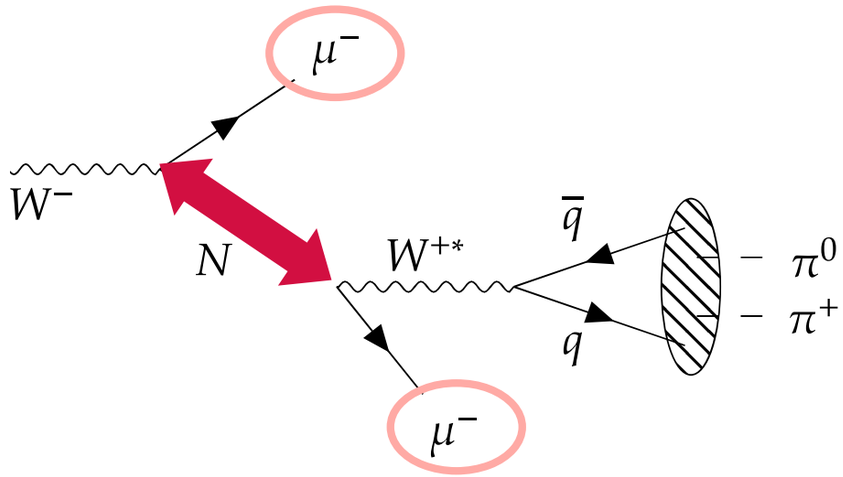
(Fermi's point-like interaction)

G_F = Fermis constant



+

Feynman rules for Majorana Particles



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

$$L^\mu = \langle \mu^- | \gamma^\mu \pm \gamma^\mu \gamma^5 | \mathrm{N} \rangle$$

calculated using non-perturbative form factor models

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

Feynman rules for fermion-number-violating interactions, Denner et al., 1992

INSTITUTE OF NUCLEAR AND PARTICLE PHYSICS

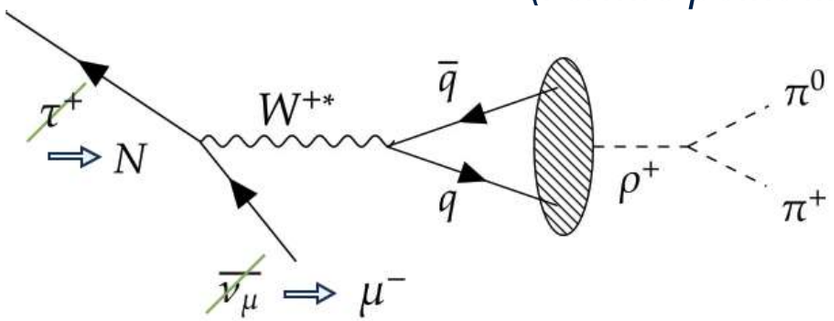
HNLs are implemented using existing models from τ-decays.

τ ➡ HNL

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

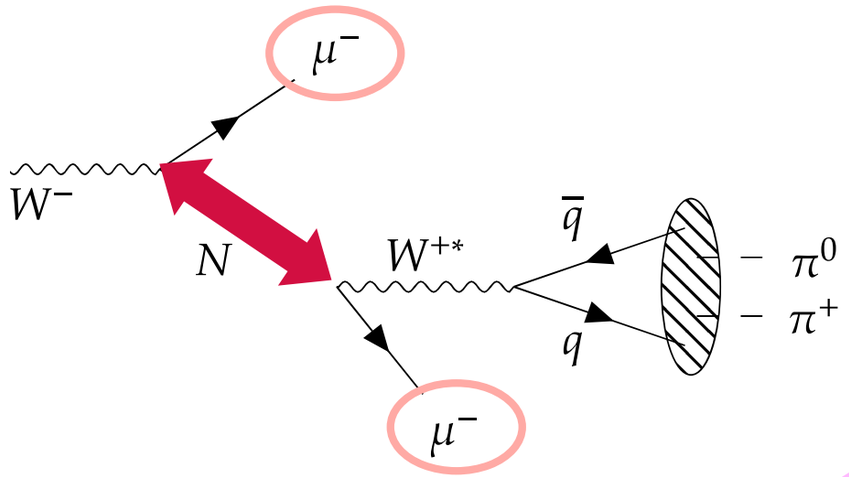
(Fermi's point-like interaction)

G_F = Fermis constant



+

Feynman rules for Majorana Particles



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

$$L^\mu = \langle \mu^- | \gamma^\mu \pm \gamma^\mu \gamma^5 | \mathrm{N} \rangle$$

No New W boson!

calculated using non-perturbative form factor models

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

Feynman rules for fermion-number-viola… …tions, Denner et al., 1992

INSTITUTE OF NUCLEAR AND PARTICLE PHYSICS

Input Parameters for SHERPA

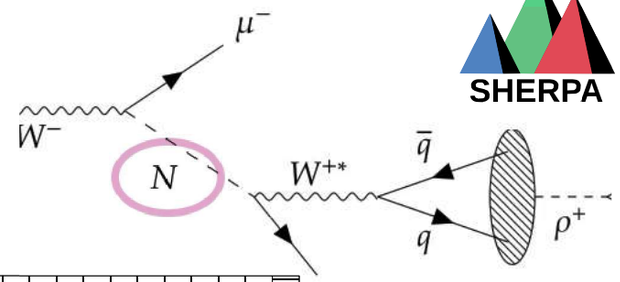
- SHERPA has **UFO interface**, where BSMs can be implemented
- Parameters for SHERPA Run:
  → model: SM_HeavyN_Meson_NLO
  → HNL **mass 2 GeV**
  → HNL **lifetime 10 mm**
  → Run 2 (collision energy 13 TeV)
  → equal parts lepton number conserving (LNC) and violating (LNV) decays

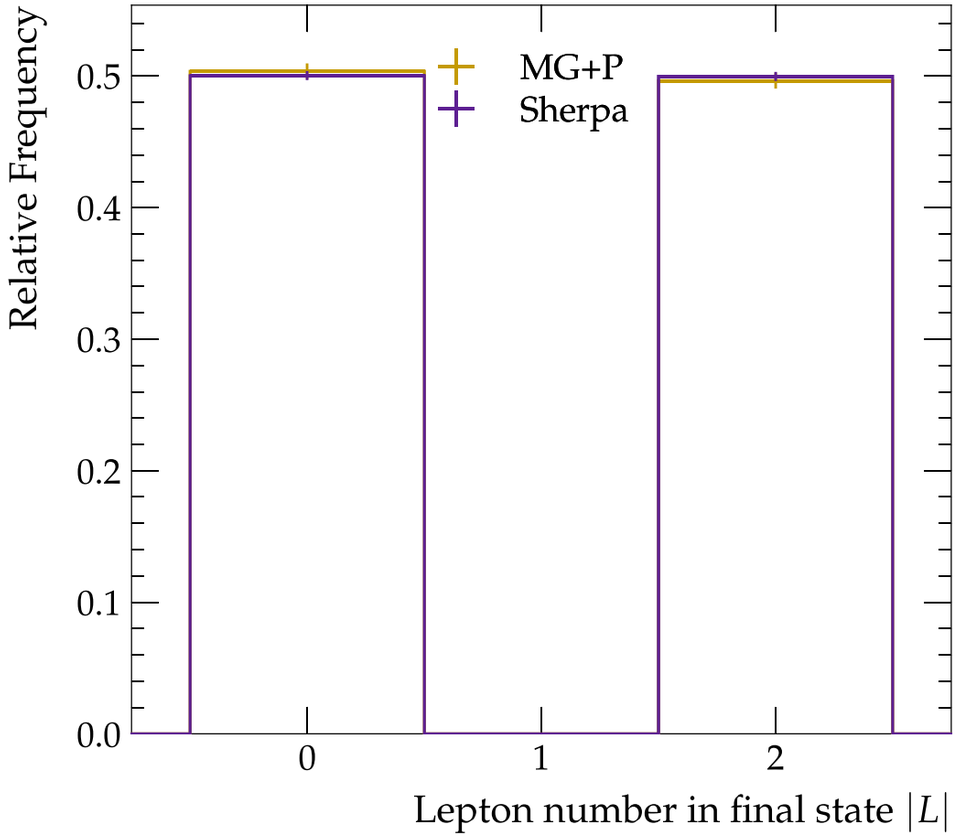
Kinematics of the Semileptonic HNL Decays

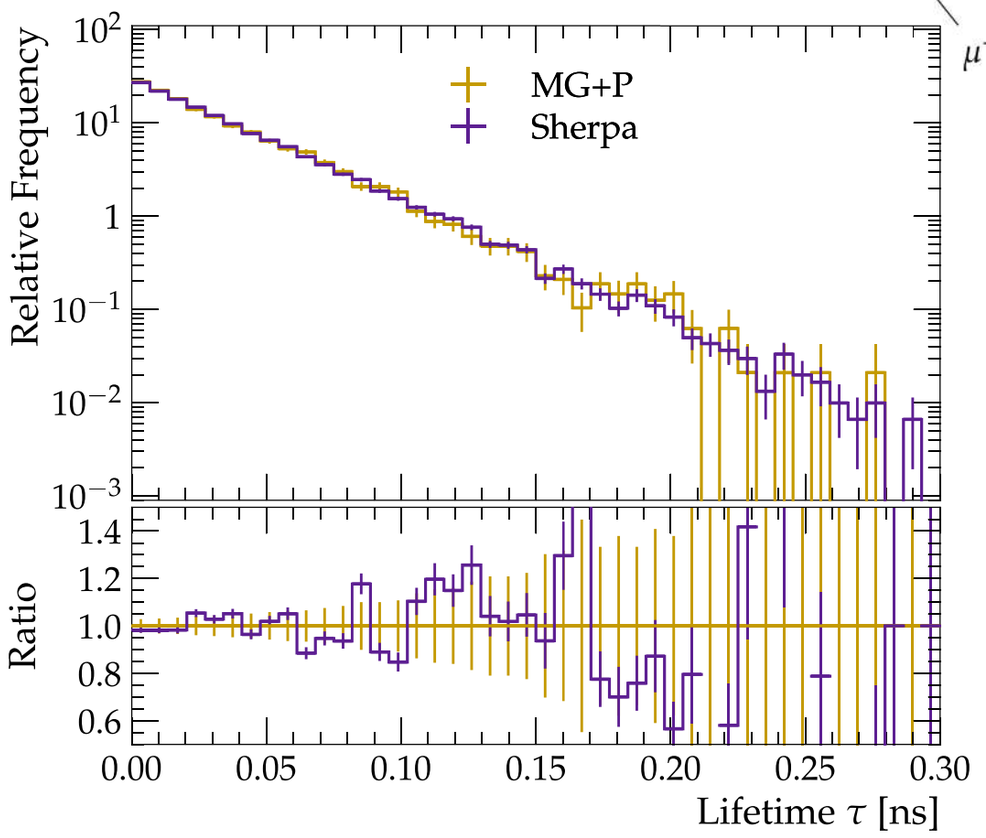
Comparison Sherpa and MadGraph+Pythia (HU Berlin)

ATLAS 2025: Search for heavy neutral leptons in decays of W bosons using leptonic and semi-leptonic displaced vertices in $\sqrt{s}$ =13 TeV pp collisions with the ATLAS detector

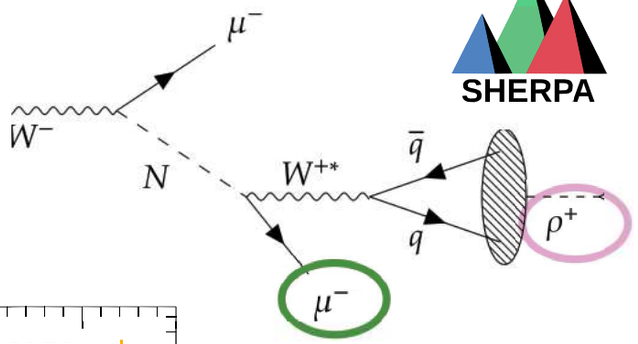
HNL has Nonzero Lifetime



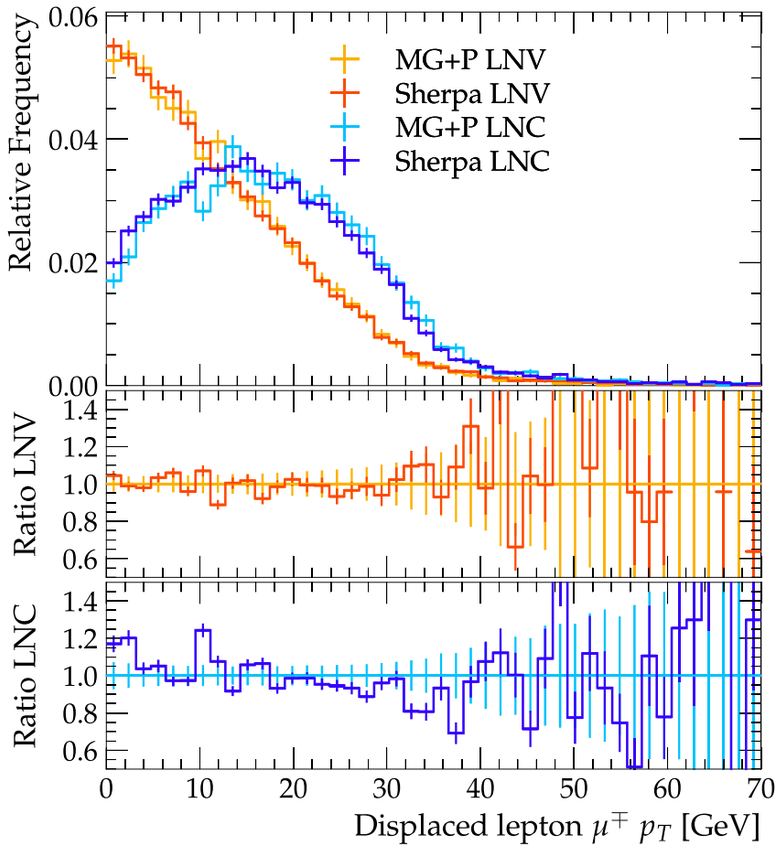




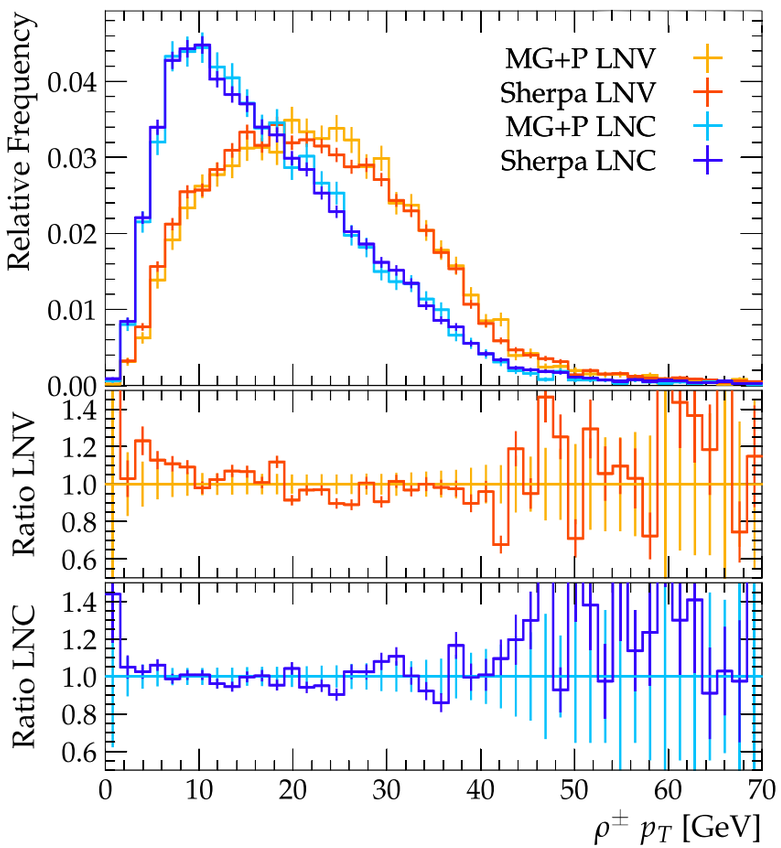
LNC and LNV decays behave differently



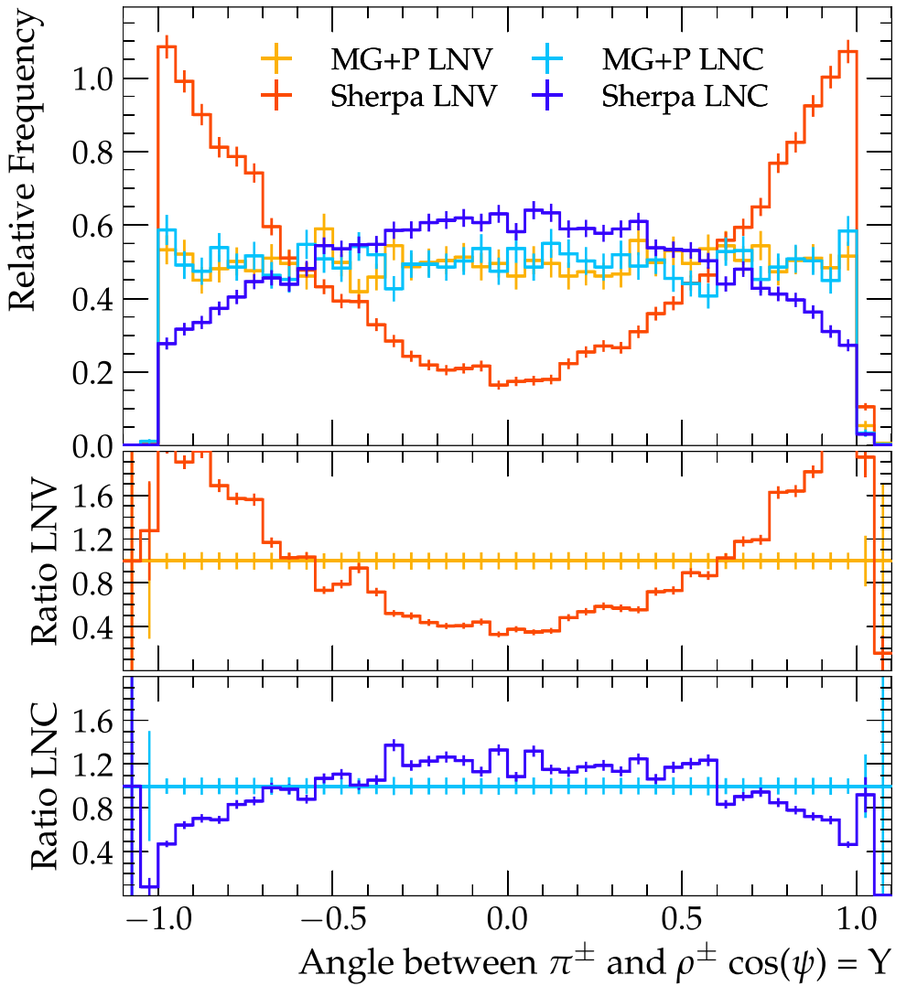
Displaced Lepton



ρ - meson



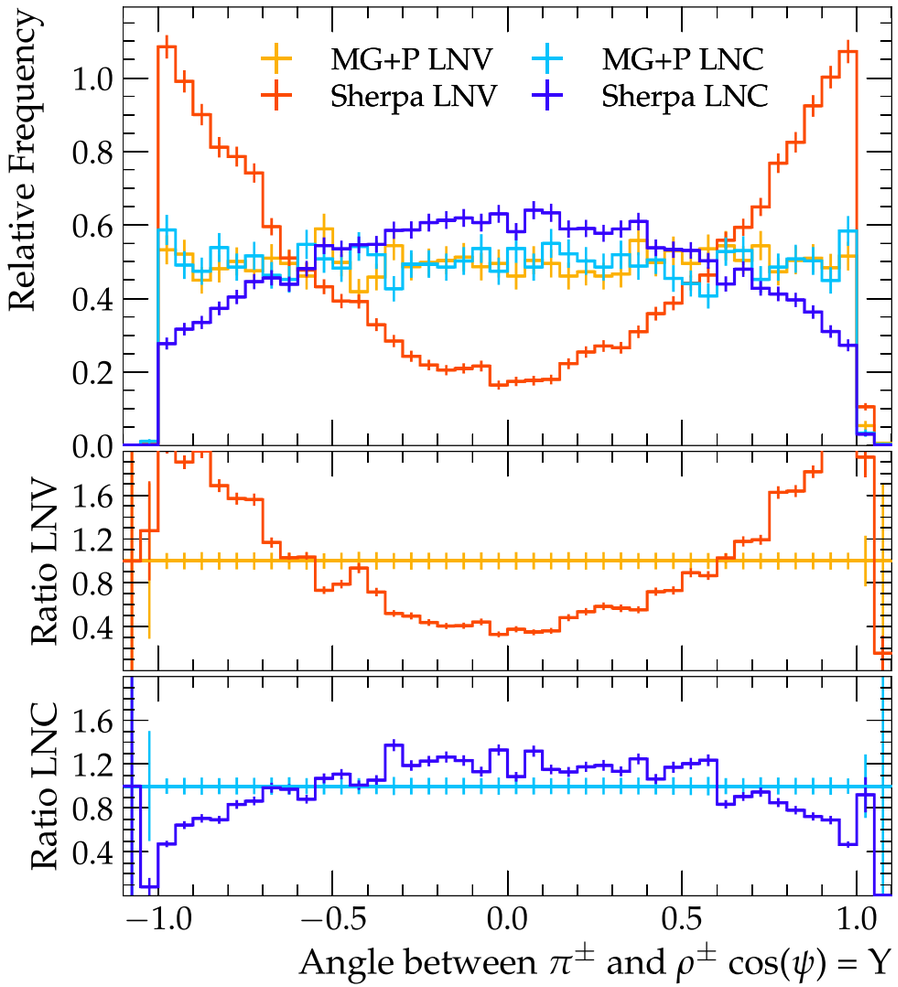
Sherpa is able to Simulate Spin Correlation correctly.



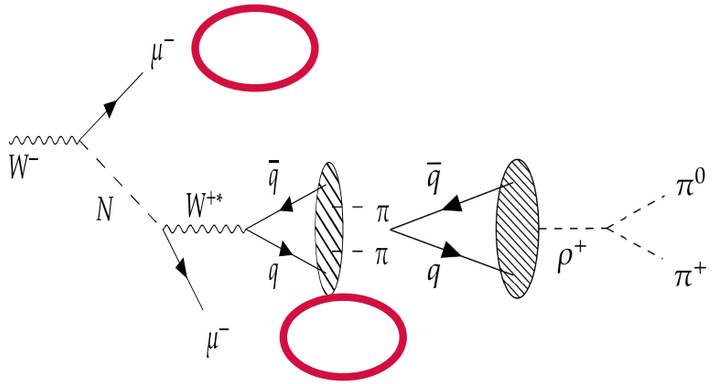
Tau polarization and its correlations as a probe of new physics, Bullock et al., 1993

INSTITUTE OF NUCLEAR AND PARTICLE PHYSICS

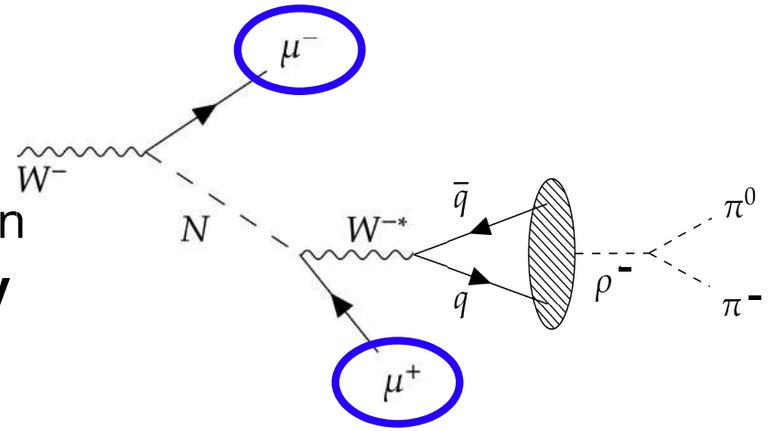
Sherpa is able to Simulate Spin Correlation correctly.



Peak at cos(ψ) = |1|
→ Longitudinal ρ – meson
→ Decay of **right-helicity** HNL (LNV)



Peak at cos(ψ) = 0
→ **Transverse ρ** - meson
→ Decay of **left-helicity** HNL (LNC)



Tau polarization and its correlations as a probe of new physics, Bullock et al., 1993

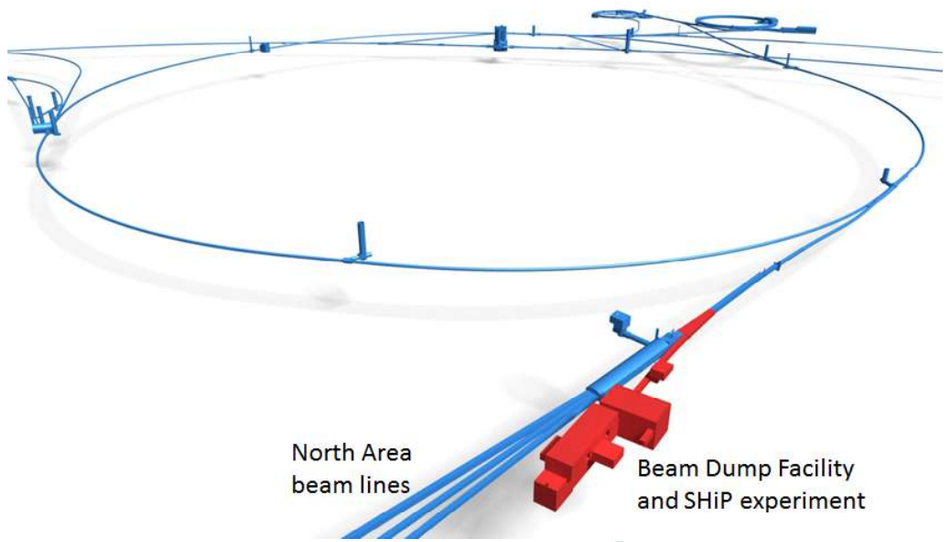
Summary

- **HNL** production and decay can be **simulated** with the Monte Carlo Event Generator **SHERPA**.
- **Comparison** with **MadGraph+PYTHIA** data shows **same results**
- **Additional:** Ability to simulate **semileptonic decays** (with taus) & preserve **spin-correlation**

Next Steps

- Preparation for Atlas central MC Production Chain
- Sherpa-development:

  Implement fixed target experiments (SHiP)



SHiP experiment progress report 2019

INSTITUTE OF NUCLEAR AND PARTICLE PHYSICS

SHERPA

Thanks to my research group & supervisors

Marzieh Bahmani

HUMBOLDT-UNIVERSITÄT ZU BERLIN

HUMBOLDT-UNIVERSITÄT ZU BERLIN

Frank Siegert

Technische Universität Dresden

Thank you for your attention!

TUD

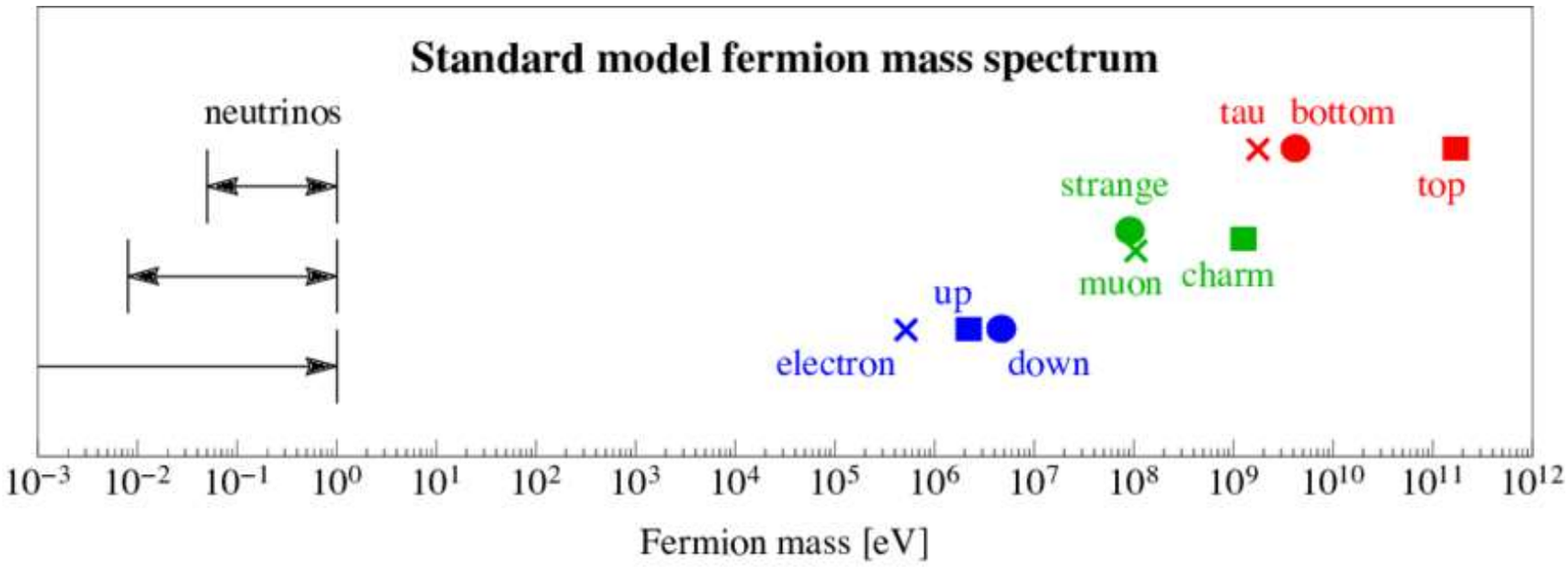
✉ Antonia.baehr@mailbox.tu-dresden.de

INSTITUTE OF NUCLEAR AND PARTICLE PHYSICS

Neutrinos are not fully understood yet.

Neutrinos are not massless (see neutrino oscillation experiments)

But they are very light ([KATRIN 2024])



According to Standard Model (SM): **Only left-chiral neutrinos** exist.

Sherpa is a highly modular Monte Carlo Event generator.

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

Perturbative methods

(Parton shower, Matrix Element

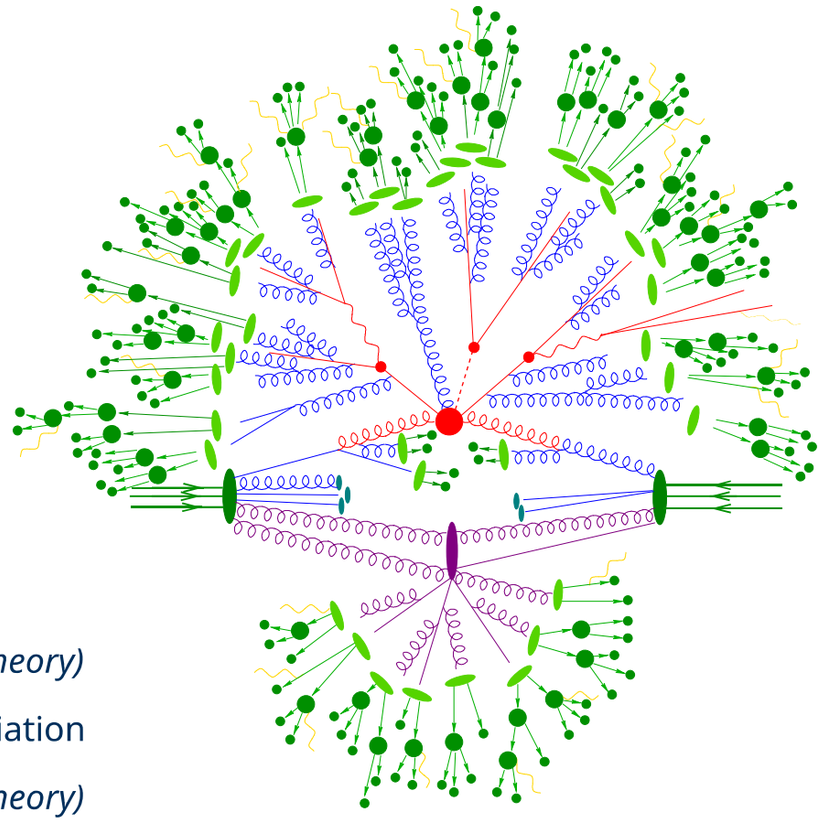
Generator, ...)

Model

(SM, Seesaw, ...)

Non-perturbative methods

(HADRONS++, ...)



Red: Hard processes

(perturbation theory)

Blue: QCD radiation

(*perturbation theory)*

Light Green: Hadronisation *(phenomenological)*

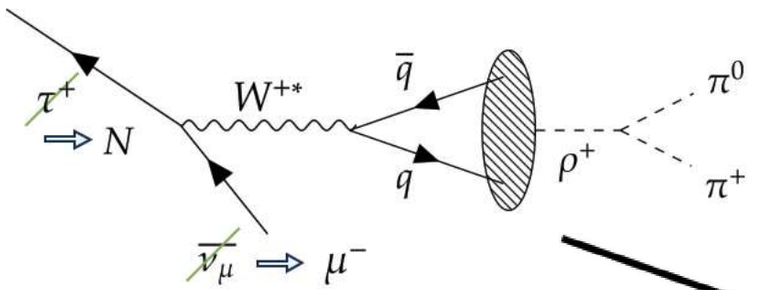
Dark Green: Hadron decay into other particles

Source

HNLs are implemented using existing models from tau-decays.

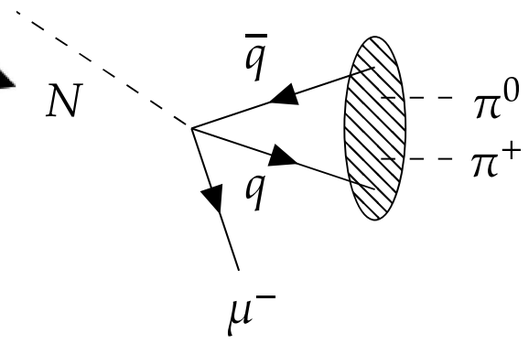
Leptonic decays are easier
(No QCD)

Tau ⇨ HNL



Semileptonic decays
(With QCD-effects)

$q \ll m_W$
(Fermi's point-like interaction)



G_F = Fermis constant

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

$$L^\mu = \langle \mu^- | \gamma^\mu - \gamma^\mu \gamma^5 | \mathrm{N} \rangle$$

vector-current axial-current

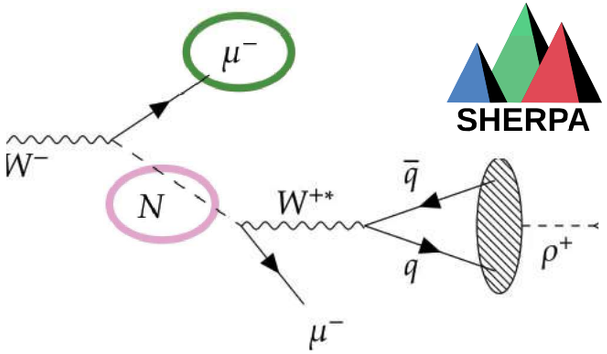
$$H^\mu = V_{\mathrm{CKM}} \times \langle \pi^+ \pi^0 | V_\mu - A_\mu | 0 \rangle$$

⇓

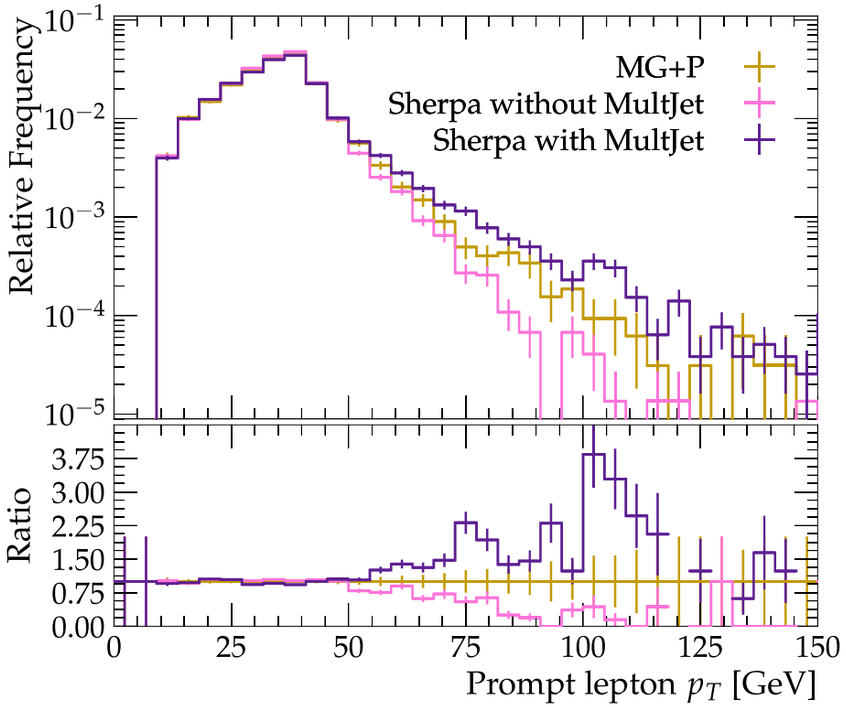
calculated using non-perturbative form factor models

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

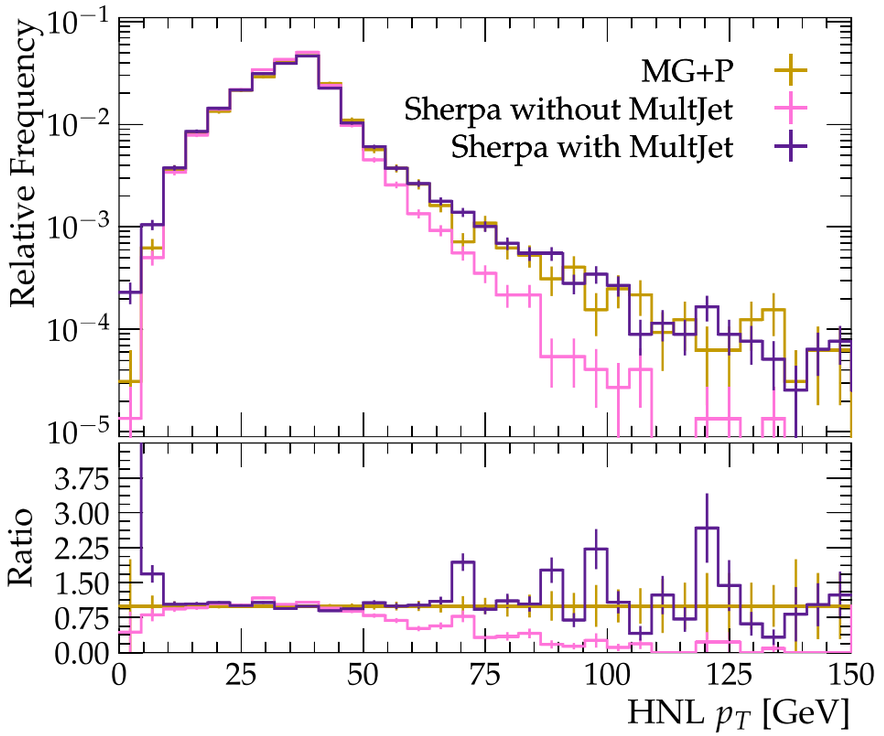
MuliJet merging improves Sherpa simulation OBJ



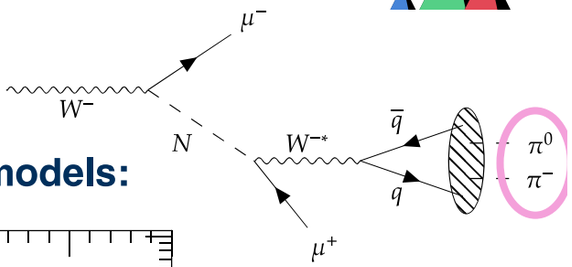
Prompt Lepton



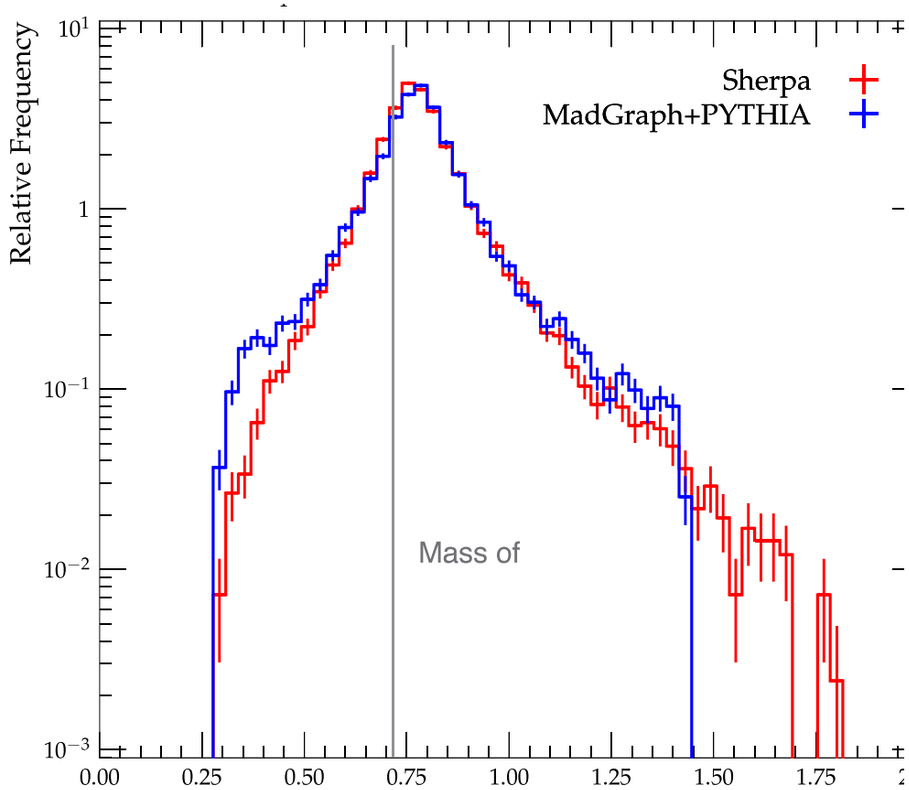
HNL



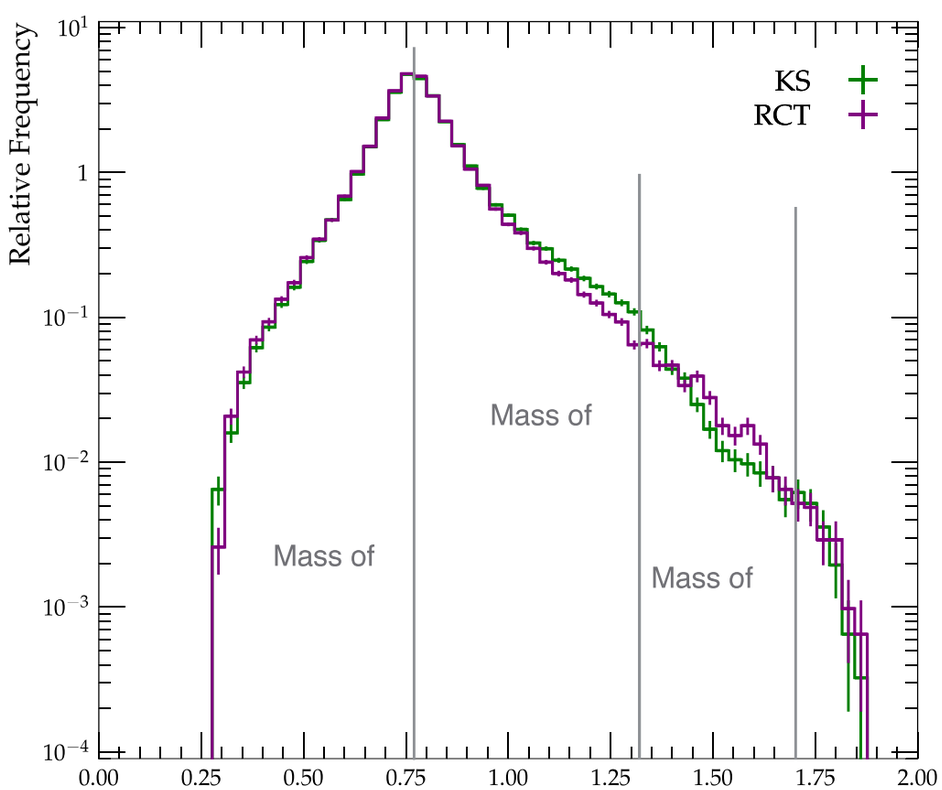
Invariant masses of the pions



Comparison of Event Generators:

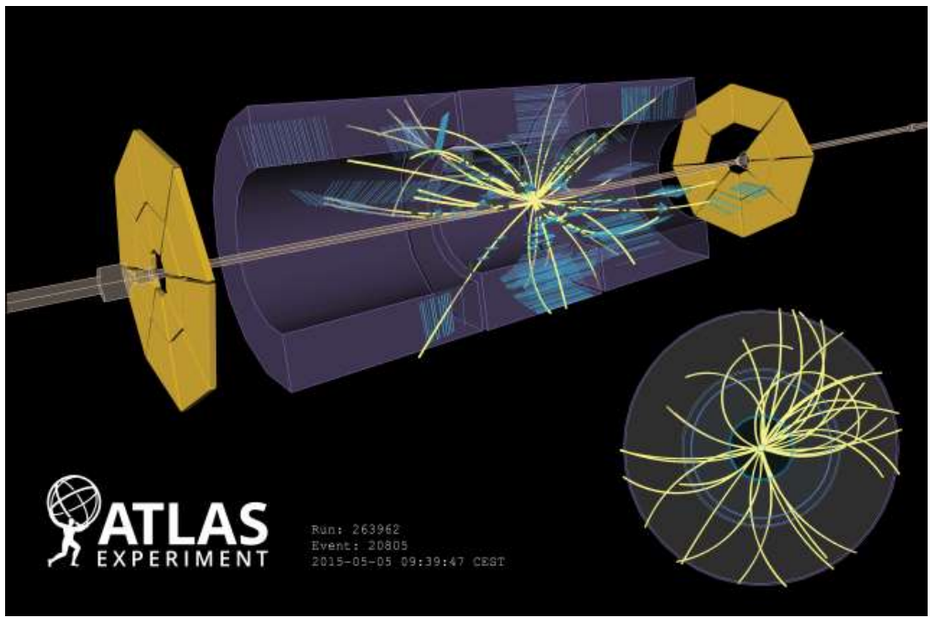


Comparison of Sherpa form factor models:

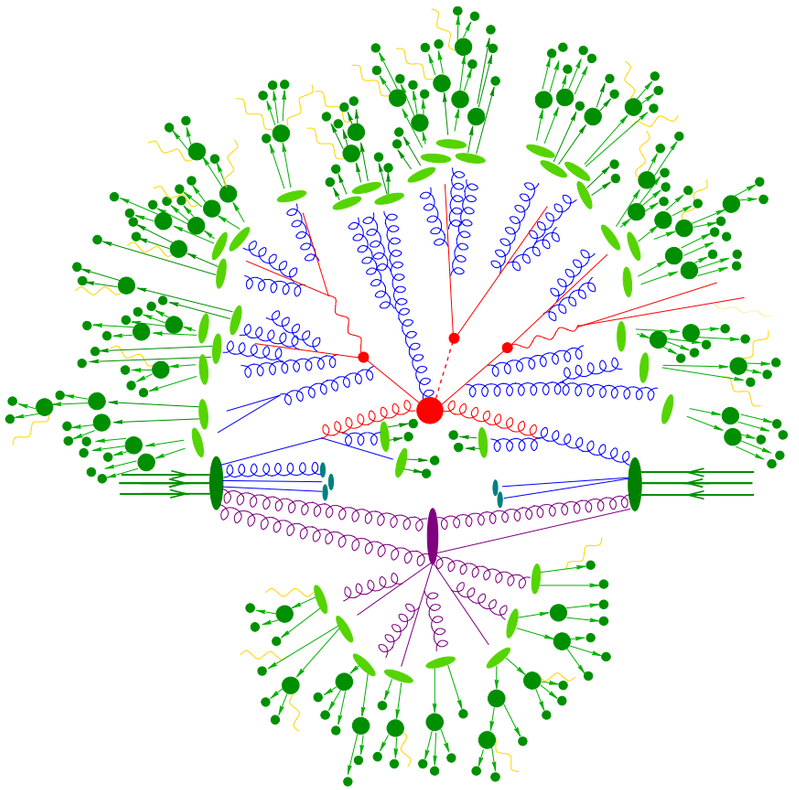


$$H^{\mu} = V_{\mathrm{CKM}} \times \langle \pi^+ \pi^0 \,|\, V_{\mu} - A_{\mu} \,|\, 0 \rangle$$

Comparison of Measurement and Simulation is needed to probe new theories.

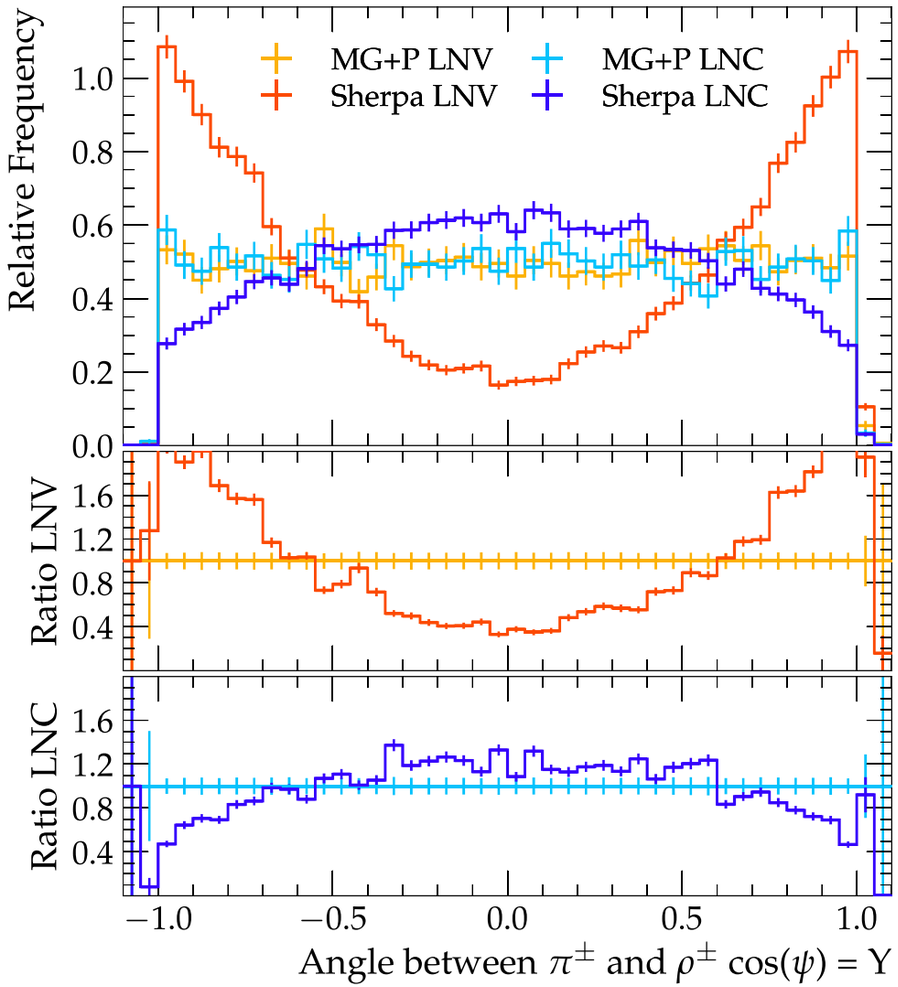


Measurement

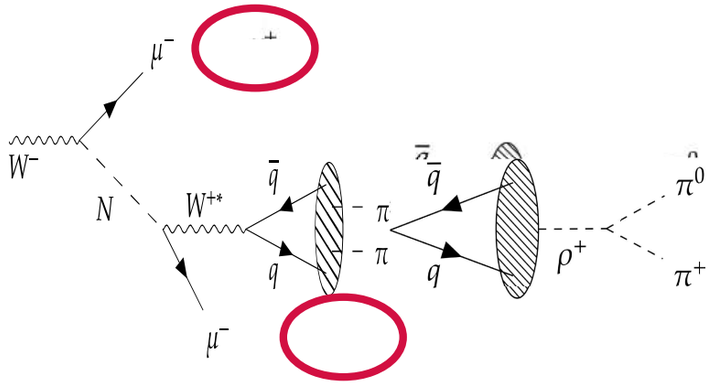


Simulation

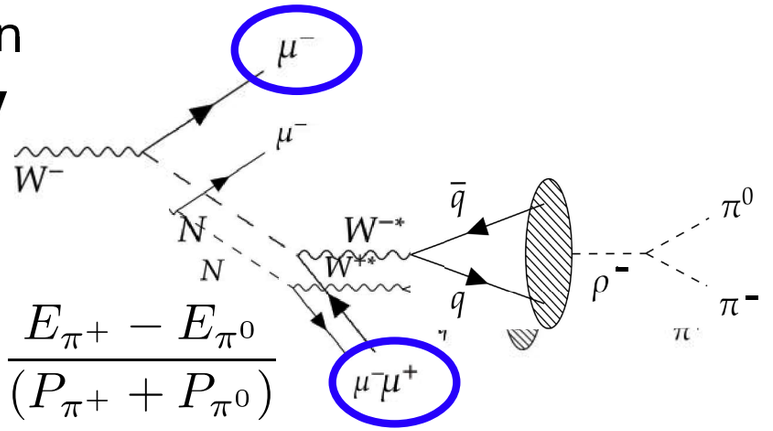
Sherpa is able to Simulate Spin Correlation correctly.



Peak at cos(ψ) = |1|
→ Longitudinal ρ – meson
→ Decay of **right-helicity** HNL (LNV)



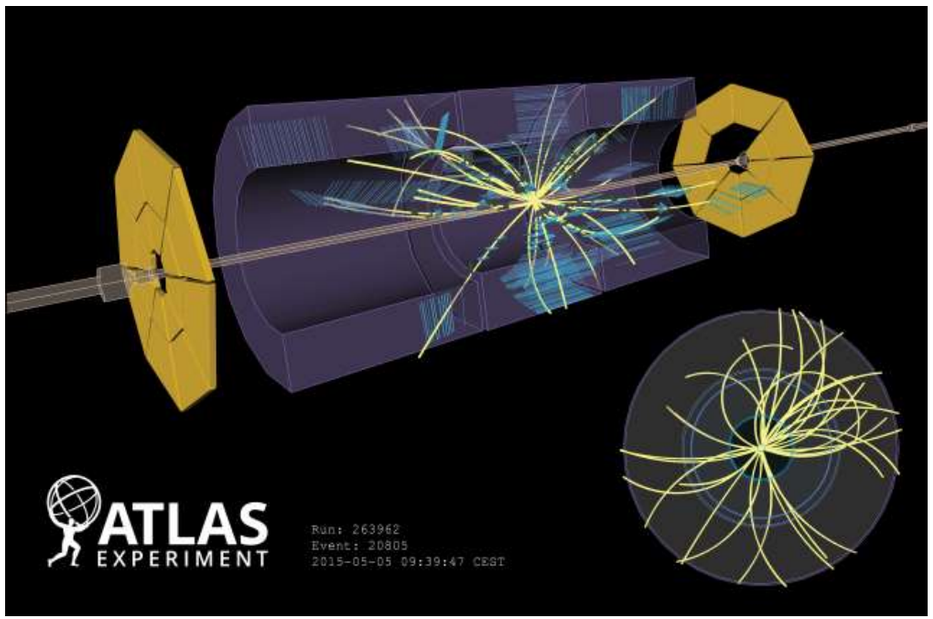
Peak at cos(ψ) = 0
→ **Transverse ρ** - meson
→ Decay of **left-helicity** HNL (LNC)



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

Tau decays as polarization analysers
Andre Rouge, 1990

Comparison of Measurement and Simulation is needed to probe new theories.

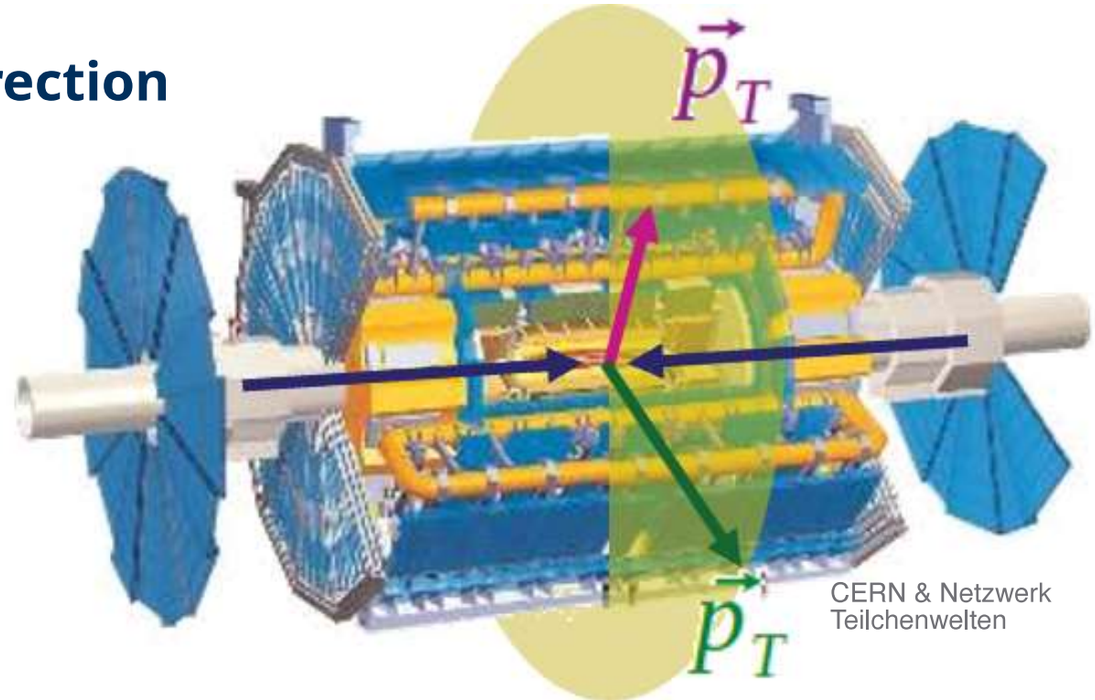


Measurement

Simulation

Comparing Kinematics: Transverse Momentum - Why?

↳ Momentum perpendicular to **Beam Direction**



Originates from physics at vertex

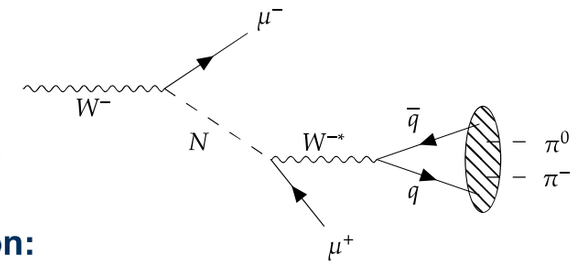
(not beam remnant)

Visible differences between

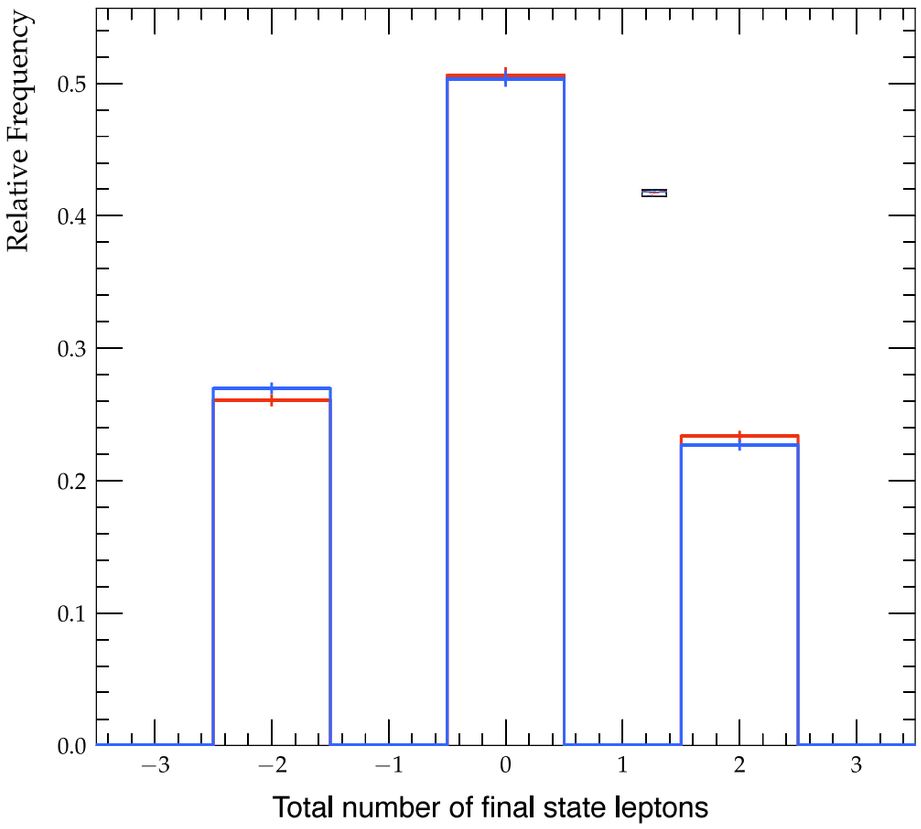
lepton number conserving and violating processes (LNC vs LNV)

$$\sum P_T = 0$$

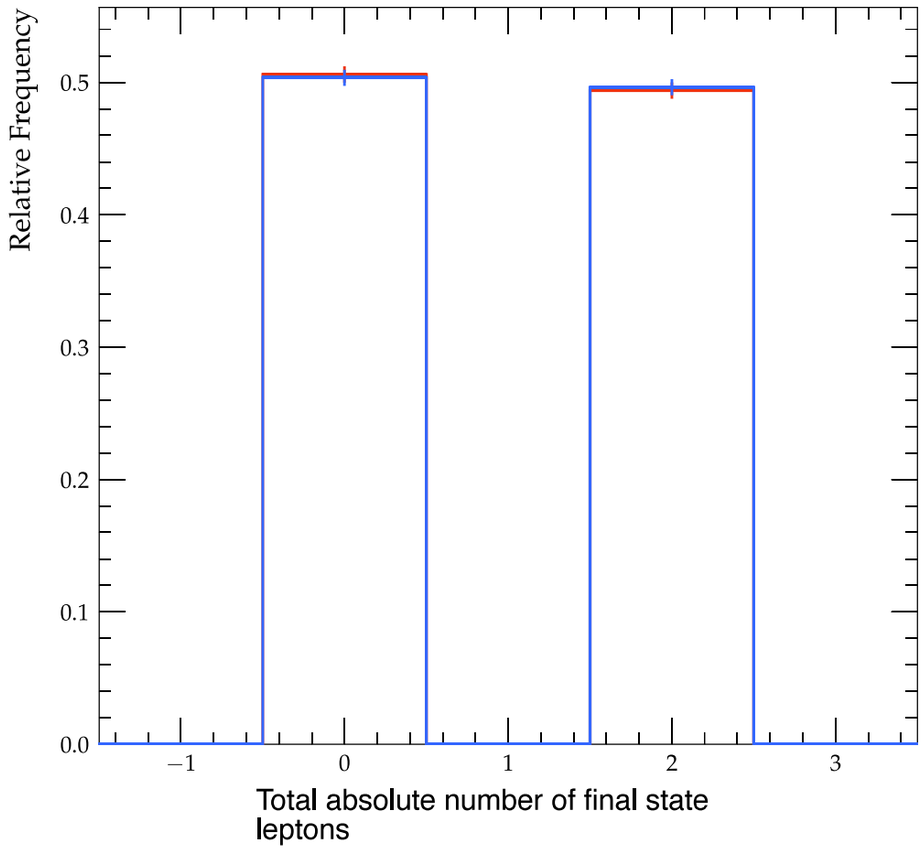
Lepton number violations fit to input conditions.



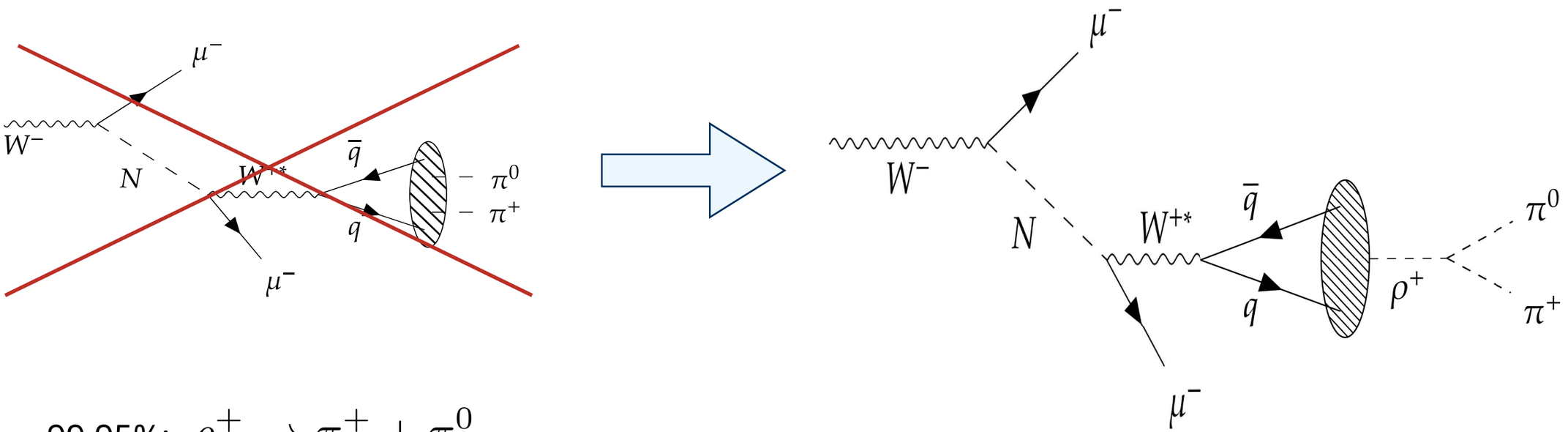
Lepton number violation:



Absolute Lepton number violation:



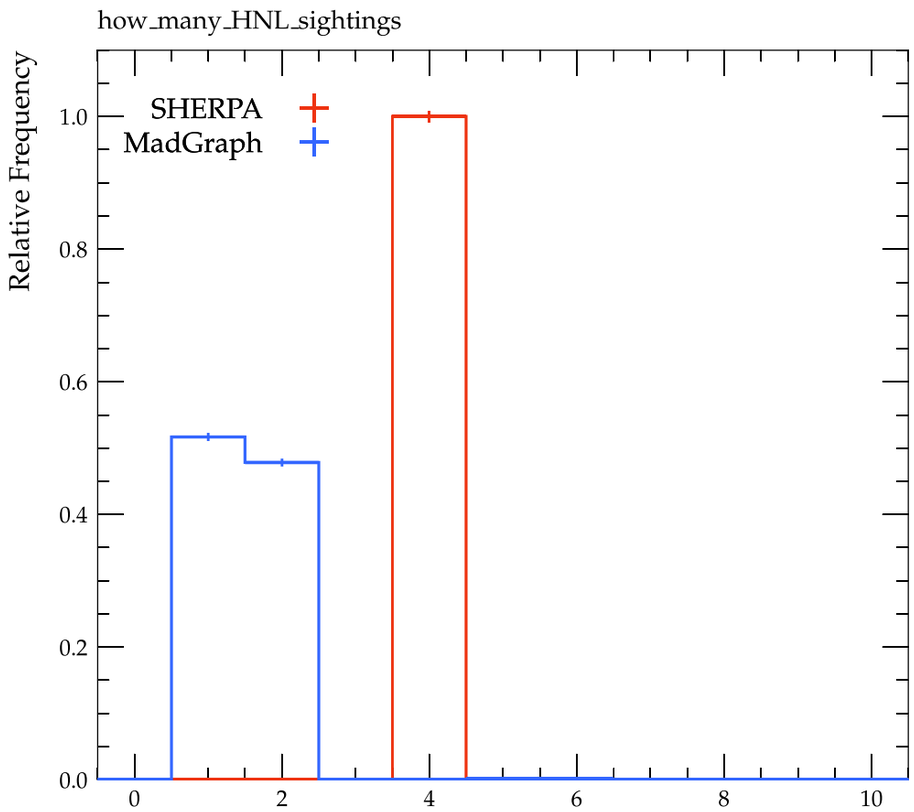
Intermediate step: ρ-mesons decay into pions.

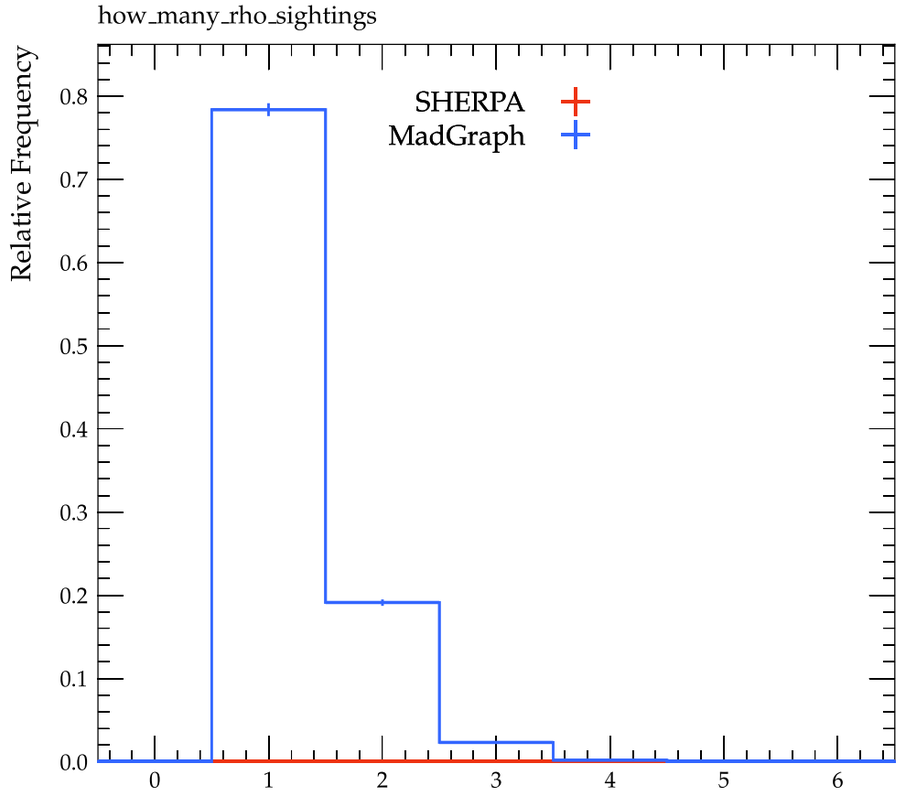


99,95%: $\rho^+ \rightarrow \pi^+ + \pi^0$

Pions & ρ-mesons have **same constituents** (up & down quark) but **different spin**

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





Thank you for your attention!

✉ Antonia.baehr@mailbox.tu-dresden.de