Discovery in Drell-Yan at the LHC

Neil Christensen
University of Wisconsin - Madison
in collaboration with Cheng-Wei Chiang, Gui-Jun Ding and Tao Han
to be published soon!
Figure 2: Transverse mass distributions for all estimated standard model backgrounds and for CMS data. Here, other backgrounds also includes $W \rightarrow \tau \nu$, in addition to the combined "other" backgrounds in Table 1. The hashed lines represent the expected $M_T$ distributions for a $W'$ signal with three different $W'$ masses.
Figure 2: Transverse mass distributions for all estimated standard model backgrounds and for CMS data. Here, other backgrounds also includes $W \rightarrow \tau \nu$, in addition to the combined "other" backgrounds in Table 1. The hashed lines represent the expected $M_T$ distributions for a $W'$ signal with three different $W'$ masses.
Figure 8 - The $M_T$ distribution after all the selection steps in the data and in the simulation. A $W'$ signal with two different hypothetical masses is shown, calculated as

$$M_T = 9 \cdot p_T \cdot E_{\text{miss}} \cdot (8 - \cos \Delta \phi_{\mu 3\nu})$$

where $\Delta \phi_{\mu 3\nu}$ is the opening azimuthal angle between the muon and the direction of $E_{\text{miss}}$ measured in radians. The two-body decay kinematics is exploited to further select events with signal-like topology where the muon and $E_{\text{miss}}$ are expected to be nearly back-to-back in the transverse plane and also balanced in transverse energy. A selection on the ratio of the muon $p_T$ and $E_{\text{miss}}$ is then applied. Further, the angular difference is required to be $\Delta \phi_{\mu 3\nu} > 95.5 \, \text{rad}$. After this selection, the $W'$ signal efficiency for the explored $W'$ mass range is found to be between $\% w$ and $-95.8 \, \%$ within the muon acceptance of $|\eta| < 0.85$.

Estimated SM backgrounds based on MC simulations are shown in Fig. 8 separately for $W$ bosons and for smaller contributions due to QCD, Drell-Yan, and diboson production. The dominant background up to high transverse masses is the $W \rightarrow \mu \nu$ contribution, which is difficult to suppress as it also decays to a muon and a neutrino. The data are also shown in Fig. 8 in agreement with the SM expectation. The background in the signal region is estimated using the lower $8-7 < M_T < 0.7$ GeV side band region of the high $M_T$ part of the spectrum. A relativistic Breit-Wigner function is used as an ad-hoc empirical shape to fit the $M_T$ distribution in the side band, both in the simulation and the data. The parameters of the fitting function are then used to calculate the number of expected background events in the different bins of $M_T$ outside the side band. The choice of the side band lower and upper limits is made in order to minimize the contribution from a hypothetical $W'$ signal and find a region that gives reliable extrapolations of the background in the signal region, based on simulation studies. According to the simulation, $18 \pm 7$ events are expected in the side band region for the combination of all SM backgrounds for an integrated luminosity of 3.6 pb$^{-1}$. The signal contamination would be $85.0 \pm 75.7$ or $75.8 \pm 75.7$ $W'$ events for a mass of 85.7 and 85.8 TeV, respectively. In the data, this region contains 19 events.
The muon channel exhibits slightly higher sensitivity due to the larger efficiency of about 96.8% compared to 96% in the electron channel. In either channel, no events are seen at high transverse masses. Identical NNLO signal cross sections with the same $k_f$ factors and the same PDF uncertainties are used for both channels under the assumption of lepton universality. The search windows are optimized individually for each channel based on the best expected limit. The search windows for both channels can be found in Table 1. For each channel, the likelihood function is determined, and the two likelihood functions are combined.

Theoretical Cross Section

Theoretical Cross Section

The systematic uncertainties for resolution, trigger, and lepton identification efficiencies are assumed to be fully uncorrelated between both channels. The uncertainty on the luminosity is taken as fully correlated, as well as the $k_f$ factors and PDF uncertainties on the theoretical cross section. When all background uncertainties are assumed to be fully correlated between the two channels, the combined limit remains unchanged. From this combination, a $W'$ with SM-like couplings and with mass below 8 TeV is excluded at the 95% confidence level.
This channel is very simple.

A model independent analysis can be done.
FIG 8: The parton-level Feynman diagrams responsible for $pp \rightarrow \nu \bar{\nu} X$, where $k = p_1 n = p_2 n = p_3 n = p_4 q$ and $W$ shows the $W$ boson contribution in the SM, $S$ shows a new scalar resonance contribution, $V$ shows a new vector resonance contribution, and $T$ shows a new tensor resonance contribution.

FIG 9: Transverse mass distribution for the process $d \bar{u} \rightarrow e^+ \bar{\nu} e q$. The energy is set at $\sqrt{s} = 9 TeV$ and the CTEQ6L pdf sets are used. The solid black curve is for the SM, the dot-dashed green curve includes the scalar field, the dotted red curve includes the vector field, and the dashed blue curve includes the tensor field. The scalar and tensor curves are right on top of each other. The mass of the new particle is taken to be $9 TeV$ while the width is taken to be $8 GeV$. The horizontal axis runs from $9xs GeV$ to $9xs GeV$. The vertical axis is the differential cross section in arbitrary units. For this illustration, the couplings are taken to be real and nonzero only for the up quark and electron. The row and column headers refer to the amount of parity violation in each coupling. The scalar fields have an accompanying $\gamma^5$.

By comparing the expected number of events from new physics interactions and the CMS data [8], one can impose constraints on the resonance mass and its couplings to fermions. We show the 95% C.L. bound for the three cases in Figure 11. We then took our estimate of the significance as the square root of this log likelihood and plotted the 95% confidence level for each spin in Figure 11.
FIG 8: The parton-level Feynman diagrams responsible for $pp \rightarrow \nu \bar{\nu} X$ where $k = p_1 n = p_2$.

$W_L^q$ shows the $W$ boson contribution in the SM, $S_L$ shows a new scalar resonance contribution, $V_L$ shows a new vector resonance contribution, and $T_L$ shows a new tensor resonance contribution.

$g \propto t$, $g \propto \gamma^5 nt$, $g \propto \gamma^5 g \propto \gamma^5 - t$.

FIG 9: Transverse mass distribution for the process $d \bar{u} \rightarrow e^- \bar{\nu} e$.

The energy is set at $\sqrt{s} = 1$ TeV, and the CTEQ6L pdf sets are used. The solid black curve is for the SM, the dot-dashed green curve includes the scalar field, the dotted red curve includes the vector field, and the dashed blue curve includes the tensor field. The scalar and tensor curves are right on top of each other. The mass of the new particle is taken to be 1 TeV while the width is taken to be 3 GeV. The horizontal axis runs from $9\times s$ GeV to $13\times s$ GeV. The vertical axis is the differential cross section in arbitrary units.

For this illustration, the couplings are taken to be real and nonzero only for the up quark and electron. The row and column headers refer to the amount of parity violation in each coupling. The scalar fields have an accompanying $\gamma^5$.

$L = 2 \times \ln \left( N_{\nu} - N_{\nu_0} \right)$, where $N_{\nu}$ was the number expected in the SM and $N_{\nu_0}$ was the number expected with the SM plus the new boson. We then took our estimate of the significance as the square root of this log likelihood and plotted the 95% confidence level for each spin in Figure 11.

By comparing the expected number of events from new physics interactions and the CMS data [8], one can impose constraints on the resonance mass and its couplings to fermions. We show the 95% C.L. bound for the three cases in Figure 11.
The most general Lagrangian for the neutral vector boson is

\[ \mathcal{L}_{\text{scalar}} = \bar{u}_i \left( h^q_{Sij} + i h^q_{Pij} \gamma_5 \right) d_j V' + \text{h.c.} \]

\[ + \bar{\nu}_i \left( h^\ell_{Sij} + i h^\ell_{Pij} \gamma_5 \right) \ell_j V' + \text{h.c.} \]
FIG 8: The parton-level Feynman diagrams responsible for $pp \to \nu \bar{\nu} X$ where $k = p_1 n p_2 = p_3 n p_4$.

$W$ boson contribution in the SM, $S$ shows a new scalar resonance contribution, $V$ shows a new vector resonance contribution, and $T$ shows a new tensor resonance contribution.

FIG 9: Transverse mass distribution for the process $d \bar{u} \to e^- \bar{\nu} e$. The energy is set at $\sqrt{s} = z T e V o$ and the CTEQ6L pdf sets are used. The solid black curve is for the SM, the dot-dashed green curve includes the scalar field, the dotted red curve includes the vector field, and the dashed blue curve includes the tensor field. The scalar and tensor curves are right on top of each other. The mass of the new particle is taken to be $t T e V$ while the width is taken to be $u G e V$. The horizontal axis runs from $9 x s G e V$ to $t s x s G e V$. The vertical axis is the differential cross section in arbitrary units. For this illustration, the couplings are taken to be real and nonzero only for the up quark and electron. The row and column headers refer to the amount of parity violation in each coupling. The scalar fields have an accompanying $\gamma^5$.

By comparing the expected number of events from new physics interactions and the CMS data [8], one can impose constraints on the resonance mass and its couplings to fermions. We show the 95% C.L. bound for the three cases in Figure 11.
most general Lagrangian for the neutral vector boson is

\[ \mathcal{L} = \overline{u}_i \gamma^\mu \left( h^q_{V_{ij}} + h^q_{A_{ij}} \gamma^5 \right) d_j V'_\mu + \text{h.c.} \]

\[ + \overline{\nu}_i \gamma^\mu \left( h^\ell_{V_{ij}} + h^\ell_{A_{ij}} \gamma^5 \right) \ell_j V'_\mu + \text{h.c.} \]
FIG 8: The parton-level Feynman diagrams responsible for $pp \rightarrow \nu \bar{\nu} X$ where $k = p_1 n p_2 = p_3 n p_4$. $W$ shows the $W$ boson contribution in the SM, $S$ shows a new scalar resonance contribution, $V$ shows a new vector resonance contribution, and $T$ shows a new tensor resonance contribution.

$g \propto t g \propto \gamma^5 t g \propto t g \propto \gamma^5 - t g \propto - t$

FIG 9: Transverse mass distribution for the process $\bar{u}_i \rightarrow e^- \bar{\nu}_e q$. The energy is set at $\sqrt{s} = ZeV$, and the CTEQ pdf sets are used. The solid (black) curve is for the SM, the dot-dashed (green) curve includes the scalar field, the dotted (red) curve includes the vector field, and the dashed (blue) curve includes the tensor field. The scalar and tensor curves are right on top of each other. The mass of the new particle is taken to be $t TeV$ while the width is taken to be $u GeV$. The horizontal axis runs from $9xs GeV$ to $tsxs GeV$. The vertical axis is the differential cross section in arbitrary unit. For this illustration, the couplings are taken to be real and nonzero only for the up quark and electron. The row and column headers refer to the amount of parity violation in each coupling. The scalar fields have an accompanying $\gamma^5$ and background events as in $LL = 2NlnN\nu - Nv - N\bar{q}$ where $N$ was the number expected in the SM and $\nu$ was the number expected with the SM plus the new boson. We then took our estimate of the significance as the square root of this log likelihood and plotted the 95% confidence level for each spin in Figure 11. By comparing the expected number of events from new physics interactions and the CMS data [8], one can impose constraints on the resonance mass and its couplings to fermions. We show the 95% C.L. bound for the three cases in Figure 11.
\[
\mathcal{L}_{V}^{\text{tensor}} = \frac{i}{\Lambda} \left[ \bar{u}_i \left( h^q_{Ti j} - h^q_{ATi j} \gamma_5 \right) \left( \gamma^\mu \partial^\nu d_j + \gamma^\nu \partial^\mu d_j \right) V^\mu_\nu - \left( \partial^\mu \bar{u}_i \gamma^\nu + \partial^\nu \bar{u}_i \gamma^\mu \right) \left( \tilde{h}^q_{Ti j} + \tilde{h}^q_{ATi j} \gamma_5 \right) d_j V^\mu_\nu \right] \\
+ \frac{i}{\Lambda} \left[ \bar{\nu}_i \left( h^\ell_{Ti j} - h^\ell_{ATi j} \gamma_5 \right) \left( \gamma^\mu \partial^\nu \ell_j + \gamma^\nu \partial^\mu \ell_j \right) V^\mu_\nu - \left( \partial^\mu \bar{\nu}_i \gamma^\nu + \partial^\nu \bar{\nu}_i \gamma^\mu \right) \left( \tilde{h}^\ell_{Ti j} + \tilde{h}^\ell_{ATi j} \gamma_5 \right) \ell_j V^\mu_\nu \right] \\
+ \text{h.c.}
\]
Figure 2: Transverse mass distributions for all estimated standard model backgrounds and for CMS data. Here, other backgrounds also includes W→τν, in addition to the combined "other" backgrounds in Table 1. The hashed lines represent the expected M_T distributions for a W′ signal with three different W′ masses.
The muon channel exhibits slightly higher sensitivity due to the larger efficiency of about 96% compared to 86% in the electron channel. In either channel, no events are seen at high transverse masses. Identical NNLO signal cross sections with the same $k_f$ factors and the same PDF uncertainties are used for both channels under the assumption of lepton universality. The search windows are optimized individually for each channel based on the best expected limit. The search windows for both channels can be found in Table 1. For each channel, the likelihood function is determined and the two likelihood functions are combined.

![Graph showing the relationship between $\sigma \cdot BR(W' \rightarrow e/\mu + \nu)$ and $W'$ mass.](image)

- 95% observed limit Muon
- 95% observed limit Electron
- 95% observed limit Combined
- 95% expected limit Combined
- Theoretical Cross Section

The systematic uncertainties for resolution, trigger, and lepton identification efficiencies are assumed to be fully uncorrelated between both channels. The uncertainty on the luminosity is taken as fully correlated, as well as the $k_f$ factors and PDF uncertainties on the theoretical cross section. When all background uncertainties are assumed to be fully correlated between the two channels, the combined limit remains unchanged. From this combination, a $W'$ with SM-like couplings and with mass below 7.8 TeV is excluded at the 95% confidence level.
What if we actually find a $M_T$ peak?

Can we determine the spin of the resonance?

Can we determine the parity violation?
\[(\lambda, -\lambda) \rightarrow (\lambda', -\lambda')\]

\[
\mathcal{M}_{W}^{\lambda\lambda'} = C_{W}^{\lambda\lambda'} \delta_{\lambda',-1} d_{1,1}^{1} \\
\mathcal{M}_{V}^{\lambda\lambda'} = C_{V}^{\lambda\lambda'} d_{1,\lambda\lambda'}^{1} \\
\mathcal{M}_{T}^{\lambda\lambda'} = C_{T2}^{\lambda\lambda'} d_{1,\lambda\lambda'}^{2} + C_{T1}^{\lambda\lambda'} d_{1,\lambda\lambda'}^{1} \\
\mathcal{M}_{S}^{\lambda\lambda'} = C_{S}^{\lambda\lambda'} d_{0,0}^{0}
\]

\[
\begin{align*}
    d_{0,0} & = 1 \\
    d_{1,\pm1} & = \frac{1}{2} (1 \pm \cos \theta) \\
    d_{1,\pm1}^2 & = \frac{1}{2} (1 \pm \cos \theta) (2 \cos \theta \mp 1) \\
    d_{2,\pm1} & = -\frac{1}{2} (1 \pm \cos \theta) \sin \theta
\end{align*}
\]
What if I knew the full momentum of the neutrino?

Let’s concentrate on the signal for now. But, we will include the pdfs.
But, we don’t know the full momentum of the neutrino!

There is a well-known two-fold ambiguity in the z-component of the neutrino momentum.
\[ s = (E_\ell + E_\nu)^2 - (p_{z\ell} + p_{z\nu})^2 \]
\[ s = (E_\ell + E_\nu)^2 - (p_{z\ell} + p_{z\nu})^2 \]

\[ p_{z\nu} = p_{z\ell} \left( \frac{\hat{s}}{2p_{T\ell}^2} - 1 \right) \pm \frac{E_\ell \sqrt{\hat{s}}}{p_{T\ell}} \sqrt{\frac{\hat{s}}{4p_{T\ell}^2}} - 1 \]
Usually, we try to find a cut that improves our chances of guessing the right solution.

These cuts tend to reduce the signal rate and they tend to modify the angular distribution.
Can we do better?
Can we do better?

Yes!
\[
\cos \theta_S = -\sqrt{1 - \frac{4p_T^2}{M^2}} \ \text{sign} \left( \frac{M}{2} - E_l \right)
\]

\[
\cos \theta_L = -\sqrt{1 - \frac{4p_T^2}{M^2}}
\]
Let’s look at the Large solution first:

We can reconstruct the spin.
FIG. 13: Angular distribution of the negatively charged lepton when only the large solution of the neutrino is taken. Each row lists a case of distinct spin and parity violation. Each plot on the left gives the angular distribution directly obtained from the large solution. On the right, the dashed curve is the angular distributions with full momentum information of the neutrino. The solid curve is the angular distribution obtained from the corresponding distribution on the left by following the procedure explained in the main text.

FIG. 14: Angular distribution of the negatively charged lepton when only the small solution of the neutrino is taken. Each row lists a case of distinct spin and parity violation. Each plot on the left gives the angular distribution directly obtained from the small solution. On the right, the dashed curve is the angular distributions with full momentum information of the neutrino. The solid curve is the angular distribution obtained from the corresponding distribution on the left by following the procedure explained in the main text.

FIG. 13: Angular distribution of the negatively charged lepton when only the large solution of the neutrino is taken. Each row lists a case of distinct spin and parity violation. Each plot on the left gives the angular distribution directly obtained from the large solution. On the right, the dashed curve is the angular distributions with full momentum information of the neutrino. The solid curve is the angular distribution obtained from the corresponding distribution on the left by following the procedure explained in the main text.

FIG. 14: Angular distribution of the negatively charged lepton when only the small solution of the neutrino is taken. Each row lists a case of distinct spin and parity violation. Each plot on the left gives the angular distribution directly obtained from the small solution. On the right, the dashed curve is the angular distributions with full momentum information of the neutrino. The solid curve is the angular distribution obtained from the corresponding distribution on the left by following the procedure explained in the main text.
FIG. 13: Angular distribution of the negatively charged lepton when only the large solution of the neutrino is taken. Each row lists a case of distinct spin and parity violation. Each plot on the left gives the angular distribution directly obtained from the large solution. On the right, the dashed curve is the angular distributions with full momentum information of the neutrino. The solid curve is the angular distribution obtained from the corresponding distribution on the left by following the procedure explained in the main text.

FIG. 14: Angular distribution of the negatively charged lepton when only the small solution of the neutrino is taken. Each row lists a case of distinct spin and parity violation. Each plot on the left gives the angular distribution directly obtained from the small solution. On the right, the dashed curve is the angular distributions with full momentum information of the neutrino. The solid curve is the angular distribution obtained from the corresponding distribution on the left by following the procedure explained in the main text.
FIG. 13: Angular distribution of the negatively charged lepton when only the large solution of the neutrino is taken. Each row lists a case of distinct spin and parity violation. Each plot on the left gives the angular distribution directly obtained from the large solution. On the right, the dashed curve is the angular distributions with full momentum information of the neutrino. The solid curve is the angular distribution obtained from the corresponding distribution on the left by following the procedure explained in the main text.

FIG. 14: Angular distribution of the negatively charged lepton when only the small solution of the neutrino is taken. Each row lists a case of distinct spin and parity violation. Each plot on the left gives the angular distribution directly obtained from the small solution. On the right, the dashed (blue) curve is the angular distributions with full momentum information of the neutrino. The solid (black) curve is the angular distribution obtained from the corresponding distribution on the left by following the procedure explained in the main text.
FIG. 13: Angular distribution of the negatively charged lepton when only the large solution of the neutrino is taken. Each row lists a case of distinct spin and parity violation. Each plot on the left gives the angular distribution directly obtained from the large solution. On the right, the dashed curve is the angular distributions with full momentum information of the neutrino. The solid curve is the angular distribution obtained from the corresponding distribution on the left by following the procedure explained in the main text.

FIG. 14: Angular distribution of the negatively charged lepton when only the small solution of the neutrino is taken. Each row lists a case of distinct spin and parity violation. Each plot on the left gives the angular distribution directly obtained from the small solution. On the right, the dashed curve is the angular distributions with full momentum information of the neutrino. The solid curve is the angular distribution obtained from the corresponding distribution on the left by following the procedure explained in the main text.
FIG. 13: Angular distribution of the negatively charged lepton when only the large solution of the neutrino \( \mathbf{p}_z \) is taken. Each row lists a case of distinct spin and parity violation. Each plot on the left gives the angular distribution directly obtained from the large solution. On the right, the dashed curve is the angular distributions with full momentum information of the neutrino. The solid curve is the angular distribution obtained from the corresponding distribution on the left by following the procedure explained in the main text.

mirror image bin on the \( \cos \theta < 0 \) side. We have applied this procedure to all the cases in the left column of Figure 14, and obtain the corresponding plots on the right. In each plot on the right, the dashed (blue) curve is the
Let’s look at the small solution next:

We can also reconstruct the parity violation. (Look in our paper for the details.)
FIG. 13: Angular distribution of the negatively charged lepton when only the large solution of the neutrino $p_z$ is taken. Each row lists a case of distinct spin and parity violation. Each plot on the left gives the angular distribution directly obtained from the large solution. On the right, the dashed (blue) curve is the angular distributions with full momentum information of the neutrino. The solid (black) curve is the angular distribution obtained from the corresponding distribution on the left by following the procedure explained in the main text.

FIG. 14: Angular distribution of the negatively charged lepton when only the small solution of the neutrino $p_z$ is taken. Each row lists a case of distinct spin and parity violation. Each plot on the left gives the angular distribution directly obtained from the small solution. On the right, the dashed (blue) curve is the angular distributions with full momentum information of the neutrino. The solid (black) curve is the angular distribution obtained from the corresponding distribution on the left by following the procedure explained in the main text.
FIG. 13: Angular distribution of the negatively charged lepton when only the large solution of the neutrino is taken. Each row lists a case of distinct spin and parity violation. Each plot on the left gives the angular distribution directly obtained from the large solution. On the right, the dashed curve is the angular distributions with full momentum information of the neutrino. The solid curve is the angular distribution obtained from the corresponding distribution on the left by following the procedure explained in the main text.

In each plot on the right, the dashed (blue) curve is the mirror image bin on the $\cos \theta < 0$ side. We have applied this procedure to all the cases in the left column of Figure 14, and obtain the corresponding plots on the right.

FIG. 14: Angular distribution of the negatively charged lepton when only the small solution of the neutrino is taken. Each row lists a case of distinct spin and parity violation. Each plot on the left gives the angular distribution directly obtained from the small solution. On the right, the dashed (blue) curve is the mirror image bin on the $\cos \theta < 0$ side.
FIG. 13: Angular distribution of the negatively charged lepton when only the large solution of the neutrino $p^z$ is taken. Each row lists a case of distinct spin and parity violation. Each plot on the left gives the angular distribution directly obtained from the large solution. On the right, the dashed curve is the angular distributions with full momentum information of the neutrino. The solid curve is the angular distribution obtained from the corresponding distribution on the left by following the procedure explained in the main text.

We multiply the number of events in each bin by the fraction for the corresponding bin given in Figure 15. One then subtracts this number from that bin and adds it to the mirror image bin on the $\cos \theta > 0$ side. We have applied this procedure to all the cases in the left column of Figure 14, and obtain the corresponding plots on the right. In each plot on the right, the dashed (blue) curve is the

FIG. 14: Angular distribution of the negatively charged lepton when only the small solution of the neutrino $p^z$ is taken. Each row lists a case of distinct spin and parity violation. Each plot on the left gives the angular distribution directly obtained from the small solution. On the right, the dashed curve is the angular distributions with full momentum information of the neutrino. The solid curve is the angular distribution obtained from the corresponding distribution on the left by following the procedure explained in the main text.
FIG. 13: Angular distribution of the negatively charged lepton when only the large solution of the neutrino is taken. Each row lists a case of distinct spin and parity violation. Each plot on the left gives the angular distribution directly obtained from the large solution. On the right, the dashed curve is the angular distributions with full momentum information of the neutrino. The solid curve is the angular distribution obtained from the corresponding distribution on the left by following the procedure explained in the main text.

FIG. 14: Angular distribution of the negatively charged lepton when only the small solution of the neutrino is taken. Each row lists a case of distinct spin and parity violation. Each plot on the left gives the angular distribution directly obtained from the small solution. On the right, the dashed curve is the angular distributions with full momentum information of the neutrino. The solid curve is the angular distribution obtained from the corresponding distribution on the left by following the procedure explained in the main text.
FIG. 13: Angular distribution of the negatively charged lepton when only the large solution of the neutrino is taken. Each row lists a case of distinct spin and parity violation. Each plot on the left gives the angular distribution directly obtained from the large solution. On the right, the dashed curve is the angular distributions with full momentum information of the neutrino. The solid curve is the angular distribution obtained from the corresponding distribution on the left by following the procedure explained in the main text.

In each plot on the right, the dashed (blue) curve is the angular distribution obtained from the corresponding distribution on the left by dividing each bin by the fraction given in Figure 15. One then subtracts this number from that bin and adds it to the mirror image bin on the \( \cos \theta < 0 \) side. We have applied this procedure to all the cases in the left column of Figure 14, and obtain the corresponding plots on the right.

FIG. 14: Angular distribution of the negatively charged lepton when only the small solution of the neutrino is taken. Each row lists a case of distinct spin and parity violation. Each plot on the left gives the angular distribution directly obtained from the small solution. On the right, the dashed curve is the angular distributions with full momentum information of the neutrino. The solid curve is the angular distribution obtained from the corresponding distribution on the left by following the procedure explained in the main text.
FIG. 13: Angular distribution of the negatively charged lepton when only the large solution of the neutrino \( p_z \) is taken. Each row lists a case of distinct spin and parity violation. Each plot on the left gives the angular distribution directly obtained from the large solution. On the right, the dashed curve is the angular distributions with full momentum information of the neutrino. The solid curve is the angular distribution obtained from the corresponding distribution on the left by following the procedure explained in the main text.

mirror image bin on the \( \cos \theta < 0 \) side. We have applied this procedure to all the cases in the left column of Figure 14, and obtain the corresponding plots on the right. In each plot on the right, the dashed (blue) curve is the...
To summarize:
$pp \rightarrow e\nu$
FIG. 13: Angular distribution of the negatively charged lepton when only the large solution of the neutrino is taken. Each row lists a case of distinct spin and parity violation. Each plot on the left gives the angular distribution directly obtained from the large solution. On the right, the dashed curve is the angular distributions with full momentum information of the neutrino. The solid curve is the angular distribution obtained from the corresponding distribution on the left by following the procedure explained in the main text.

FIG. 14: Angular distribution of the negatively charged lepton when only the small solution of the neutrino is taken. Each row lists a case of distinct spin and parity violation. Each plot on the left gives the angular distribution directly obtained from the small solution. On the right, the dashed curve is the angular distributions with full momentum information of the neutrino. The solid curve is the angular distribution obtained from the corresponding distribution on the left by following the procedure explained in the main text.