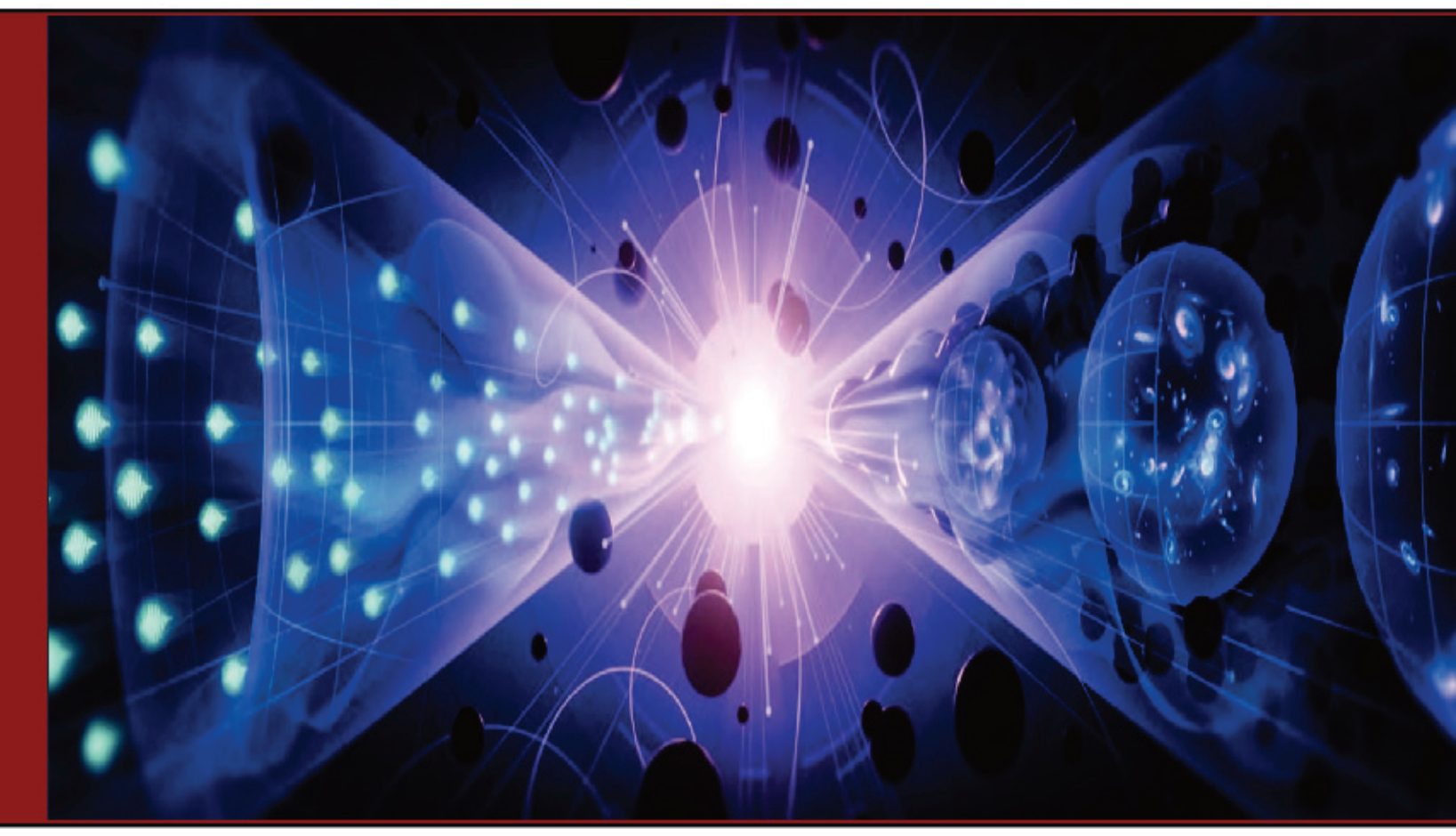




Searching for New Physics at the Future Collider
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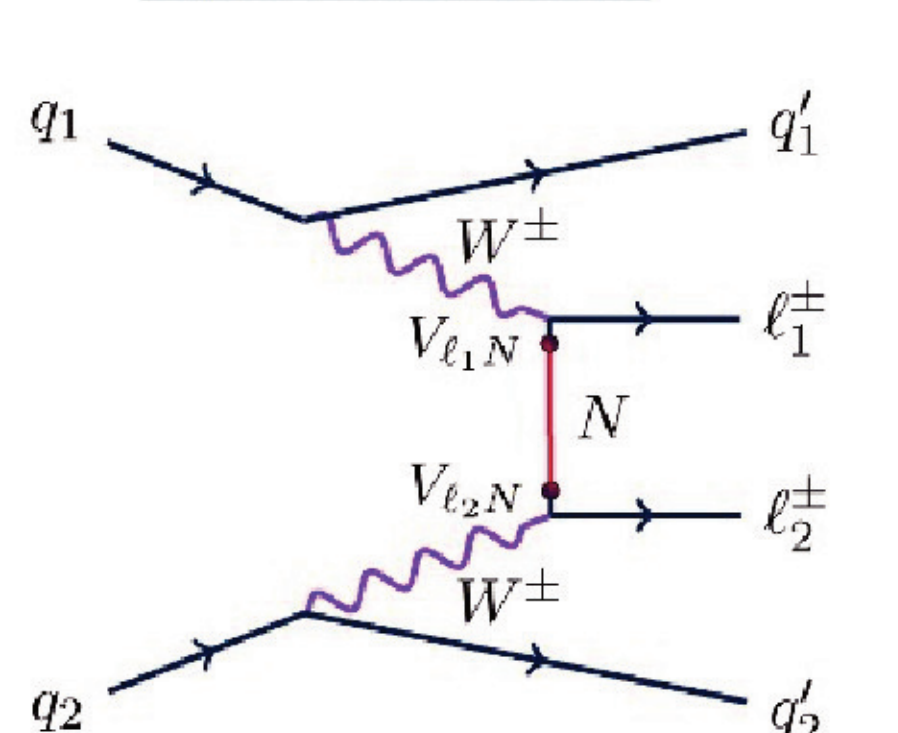


Searching for Majorana neutrinos at a same-sign muon collider

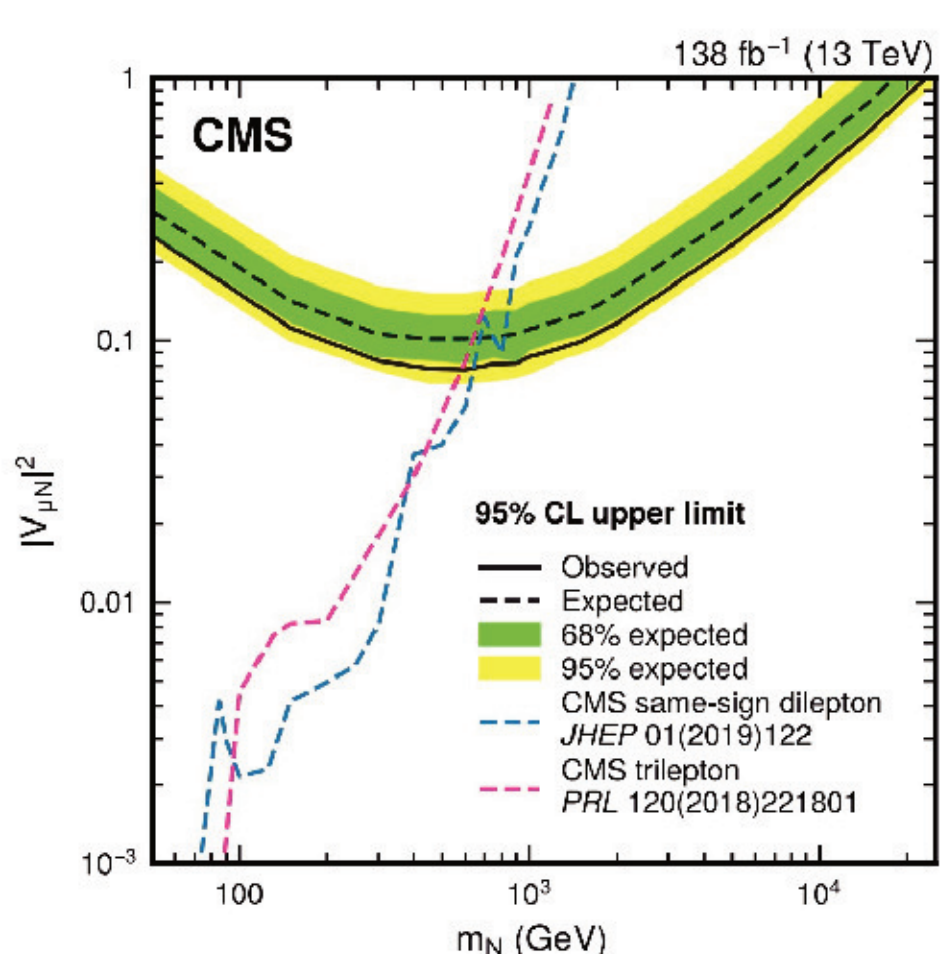
DOI: 10.1103/PhysRevD.109.035020

Searching for Majorana Neutrinos in CMS

PhysRevLett.131.011803



- same-sign WW \rightarrow same-sign $\ell\ell$ through Majorana neutrinos (lepton number violation)
- t-channel processes is less sensitive to the mass of the intermediate particle
- the cross section of VBF(Vector Boson Fusion) process at the TeV mass scale decreases more slowly with increasing N than s-channel



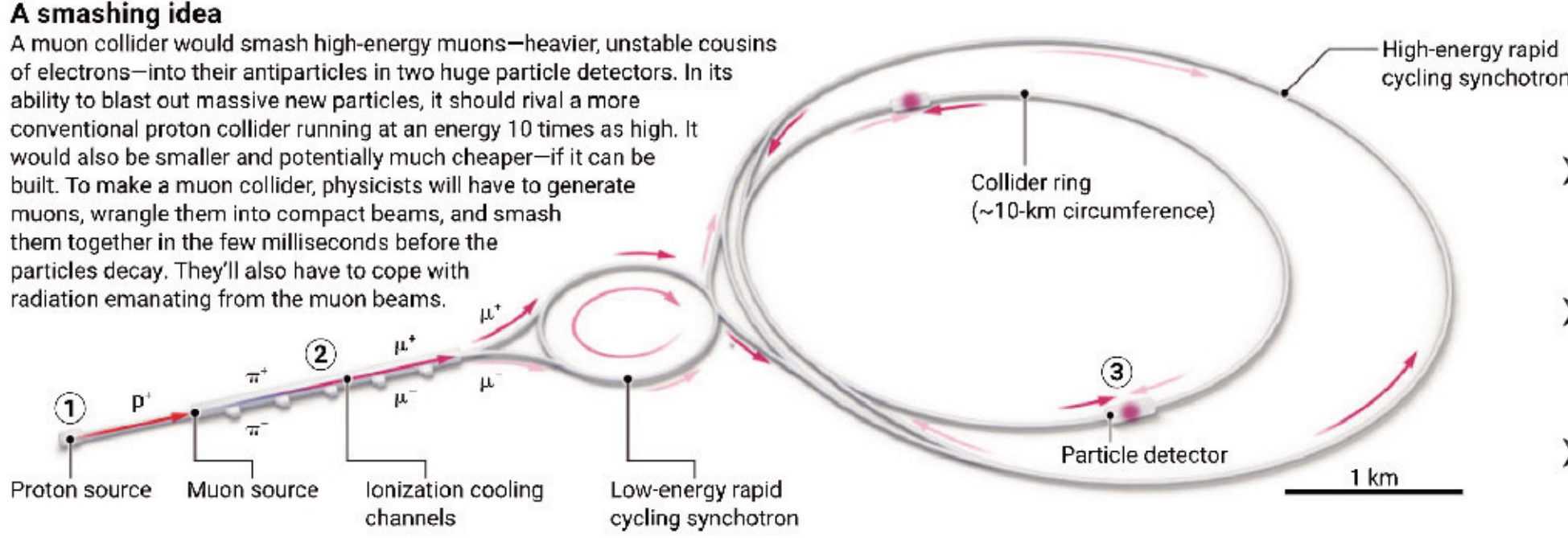
- This is the current CMS measurement of upper limits on the heavy neutrino mixing element $|V_{\mu N}|^2$ at the 95% C.L. as a function of the heavy neutrino mass m_N .

Muon Collider



A smashing idea

A muon collider would smash high-energy muons—heavier, unstable cousins of electrons—into their antiparticles in two huge particle detectors. In its ability to blast out massive new particles, it should rival a more conventional proton collider running at an energy 10 times as high. It would also be smaller and potentially much cheaper—if it can be built. To make a muon collider, physicists will have to generate muons, wrangle them into compact beams, and smash them together in the few milliseconds before the particles decay. They'll also have to cope with radiation emanating from the muon beams.



From Science

The challenge, if you want to capture it in one word, is that the muon is unstable.

Cooling, BIB.....

From US PS report

Muon Collider @MuonCollider - 13m
 THIS IS OUR MUON SHOT!

2.3 The Path to a 10 TeV pCM

Realization of a future collider will require resources at a global scale and will be built through a world-wide collaborative effort where resources will be shared between the countries that provide the particles. The dream from current and past international projects in particle physics, where individual laboratories shared projects that were then shared by other laboratories. The proposed program aligns with the long-term vision of having a major international collider facility in the US, leading the global effort to understand the fundamental nature of the universe.

- Muons are one of the most basic building blocks of the Universe, but they have never been used in a particle collider
- muon-muon collisions are cleaner than proton-proton collisions and thus can lead to higher effective c.m. energy.
- muon collider could be much smaller and cheaper than a functionally equivalent proton collider.
- massive muons emit much less synchrotron radiation than electrons, muons can be accelerated in a circular collider to higher energies with a much smaller circumference.

Majorana Neutrinos Study at Same-Sign Muon Collider

- In type-I seesaw model, the small masses of SM neutrinos can be explained by a suppression due to the high mass of new particle (Majorana neutrino).

- Dirac mass and Majorana mass are defined by the Lagrangian:

$$-L_D = y_{\alpha i} \bar{L}_i \bar{\nu}_{R\alpha} + H.c.$$

$$-L_M = \frac{1}{2} (M_N)_{\alpha\beta} \bar{\nu}_{R\alpha} \nu_{R\beta} + H.c.$$

- The two Lagrangians together lead to the neutrino mass matrix:

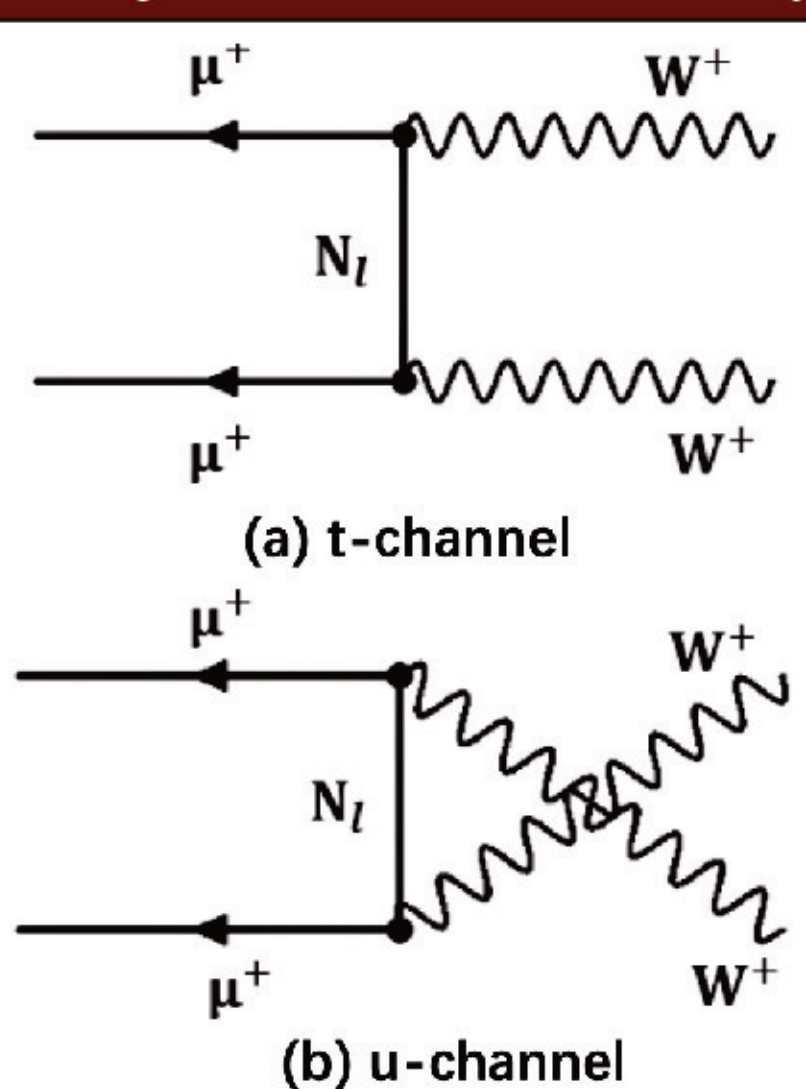
$$\begin{bmatrix} 0 & M_D \\ M_D^T & M_N \end{bmatrix}$$

- The light neutrino masses and mixing element:

$$M_\nu \simeq M_D M_N^{-1} M_D^T, \quad V_{\ell N} \sim M_D M_N^{-1}$$

- Majorana neutrinos couple to the SM through mixing with SM neutrinos:

$$m_\nu = y_{\ell\alpha}^2 v^2 / m_N \Rightarrow \text{Type-I Seesaw Model}$$



- These are (t,u)-channel Feynman diagrams of same-sign muon collider with Majorana Neutrinos generation.

Model: SM HeavyN NLO

$$\sqrt{s} = 1 \text{ TeV and } \mathcal{L} = 1 \text{ ab}^{-1}$$

$$\sqrt{s} = 10 \text{ TeV and } \mathcal{L} = 1 \text{ ab}^{-1}$$

- This process is a typical LNV process.
- This process related to the mediation by Majorana neutrinos.
- This t(u)-channel process is less kinematically suppressed.
- The final states of this process are not complicated.

Backgrounds of this process:

- $\mu^+ \mu^+ \rightarrow W^+ W^+ \bar{\nu}_\mu \bar{\nu}_\mu$
- $\mu^+ \mu^+ \rightarrow Z W^+ \mu^+ \bar{\nu}_\mu$
- $\mu^+ \mu^+ \rightarrow W^+ W^+ \bar{\nu}_\mu \bar{\nu}_\mu$
- $\mu^+ \mu^+ \rightarrow W^+ \mu^+ \bar{\nu}_\mu \bar{\nu}_\mu$
- $\mu^+ \mu^+ \rightarrow Z \mu^+ \mu^+$
- $\mu^+ \mu^+ \rightarrow Z Z \mu^+ \mu^+$
- $\mu^+ \mu^+ \rightarrow W^+ W^+ \mu^+ \mu^+$
- $\gamma \gamma \rightarrow W^+ W^-$

Simulation Results

Three final states:

- Pure-leptonic final states channel: $\mu^+ \mu^+ \rightarrow W^+ W^+ \rightarrow 2\ell + E_T$
- Pure-hadronic final states channel: $\mu^+ \mu^+ \rightarrow W^+ W^+ \rightarrow 4j$
- Semi-leptonic final states channel: $\mu^+ \mu^+ \rightarrow W^+ W^+ \rightarrow \ell^+ 2j + E_T$

Fast Simulation:

- Both signal and background are simulated with MadGraph5_aMC@NLO.
- Showed and hadronized by PYTHIA8.
- Use DELPHES version 3.0 to simulate detector effects with the default card for muon collider detector.

Full Simulation:

- Research full simulation through Muonc software.
- Generate input particles through MadGraph5_aMC@NLO then do parton shower through PYTHIA8.
- The interaction of particles with detector material is simulated by GEANT4 software.
- Both simulation and reconstruction are done within a single framework (such as Marlin framework).

- Pure leptonic channel: $\sqrt{s} = 1 \text{ TeV and } \mathcal{L} = 1 \text{ ab}^{-1}$

Pre-selections:

- the events must include exactly two leptons.
- $p_{T,\ell} > 20 \text{ GeV}, |\eta_\ell| < 2.5, \Delta R_{\ell\ell} > 0.4$

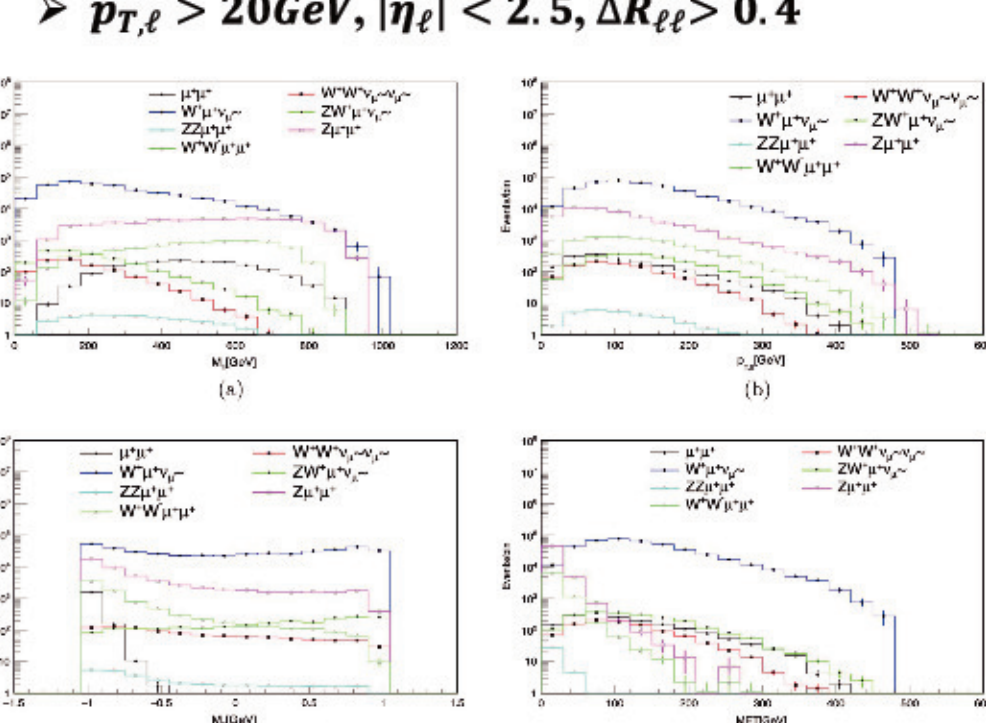


TABLE I. The cut-flow table in the pure leptonic channel.

Variables	Limits
$M_{\ell\ell}$	$> 100.0 \text{ GeV}$
$p_{T,\ell\ell}$	$> 120.0 \text{ GeV}$
E_T	$> 100.0 \text{ GeV}$
$\cos\theta_{\ell\ell}$	< -0.95
$ \eta_\ell $	< 2.5

- Pure semi-leptonic channel: $\sqrt{s} = 1 \text{ TeV and } \mathcal{L} = 1 \text{ ab}^{-1}$

Pre-selections:

- the events must include exactly one lepton+2 jets.
- $p_{T,\ell(j)} > 20 \text{ GeV}, |\eta_\ell| < 2.5, \Delta R_{\ell(j)} > 0.4, |\eta_j| < 4.7$

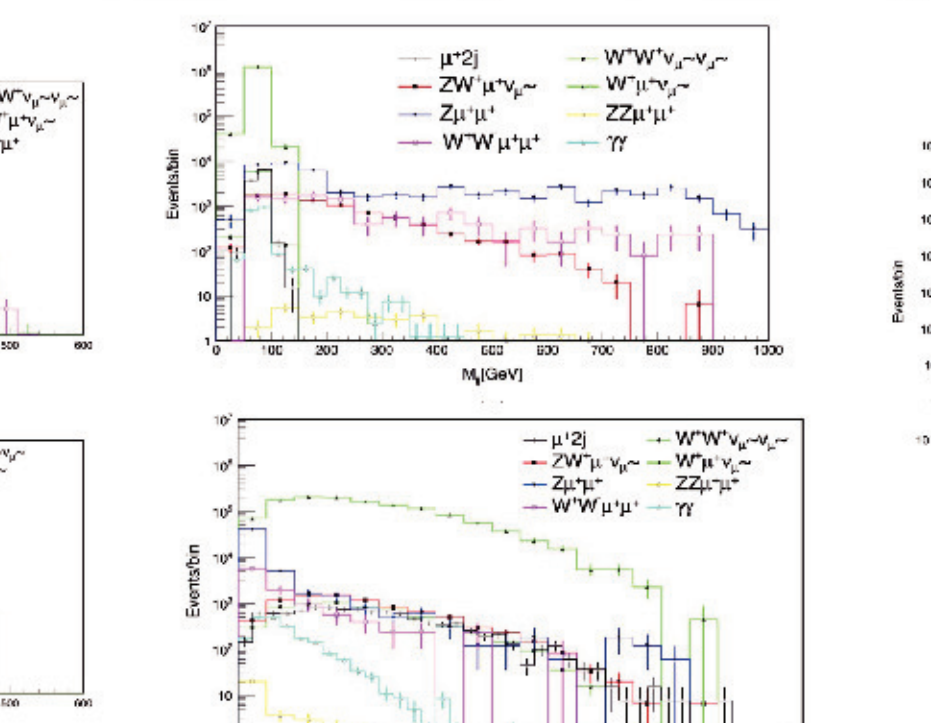


TABLE II. The cut-flow table in the semi-leptonic channel.

Variables	Limits
$M_{j\ell}$	$< 140.0 \text{ GeV}$
$p_{T,j\ell}$	$> 200 \text{ GeV}$
$p_{T,\ell}$	$> 70 \text{ GeV}$
$ \eta_\ell $	< 4.7
$ \eta_j $	< 5.0
E_T	$< 400.0 \text{ GeV}$
Lepton veto	1

- Hadronic resolved channel: $\sqrt{s} = 1 \text{ TeV and } \mathcal{L} = 1 \text{ ab}^{-1}$

Pre-selections:

- Classify four jets in final states into two reconstructed "W bosons".
- the events must include exactly 4 jets.
- $p_{T,j} > 20 \text{ GeV}, |\eta_j| < 4.7, \Delta R_{jj} > 0.4$

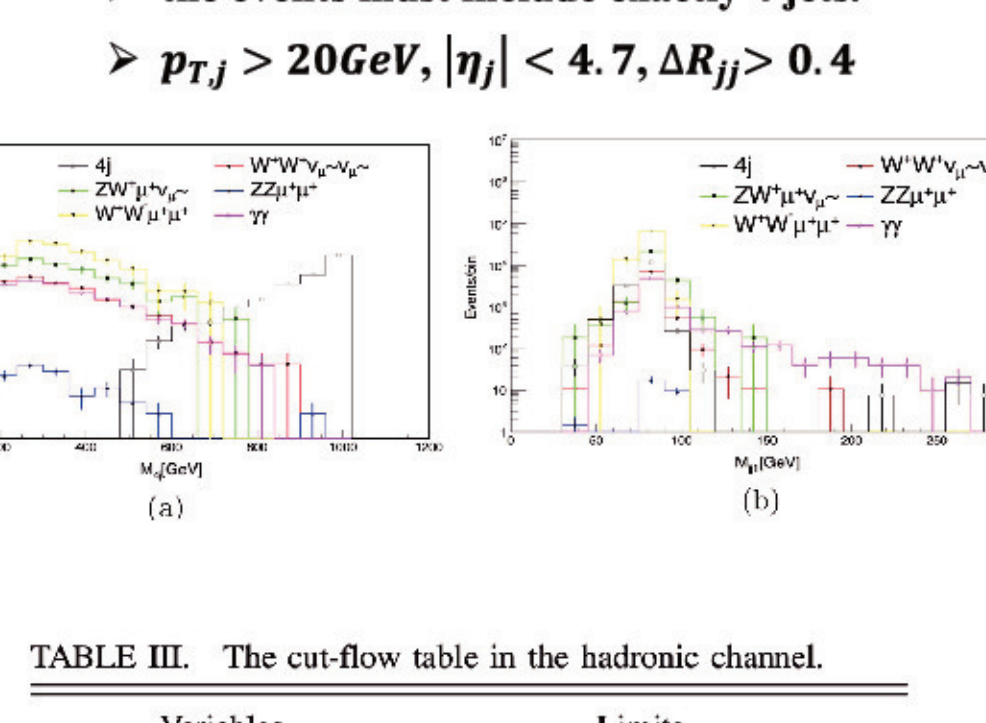


TABLE III. The cut-flow table in the hadronic channel.

Variables	Limits
M_{jj}	$> 750.0 \text{ GeV}$
$p_{T,jj1,2}$	$> 50.0 \text{ GeV}$
$p_{T,jj3,4}$	$> 100.0 \text{ GeV}$
$p_{T,jj}$	$> 1000.0 \text{ GeV}$
E_T	$> 5.0 \text{ GeV}$
$M_{jj1,2}$	$[50 \text{ GeV}, 110 \text{ GeV}]$
$M_{jj3,4}$	$[10 \text{ GeV}, 110 \text{ GeV}]$
$ \eta_j $	< 7.0
$ \eta_j $	< 4.7
Lepton veto	0

- Hadronic merged channel: $\sqrt{s} = 10 \text{ TeV and } \mathcal{L} = 1 \text{ ab}^{-1}$

- we must consider the boost effect when the two quarks from W_j decay merged into a single fatjet with a mass around M_{W_j} .

Pre-selections:

- the events must include exactly 4 jets.

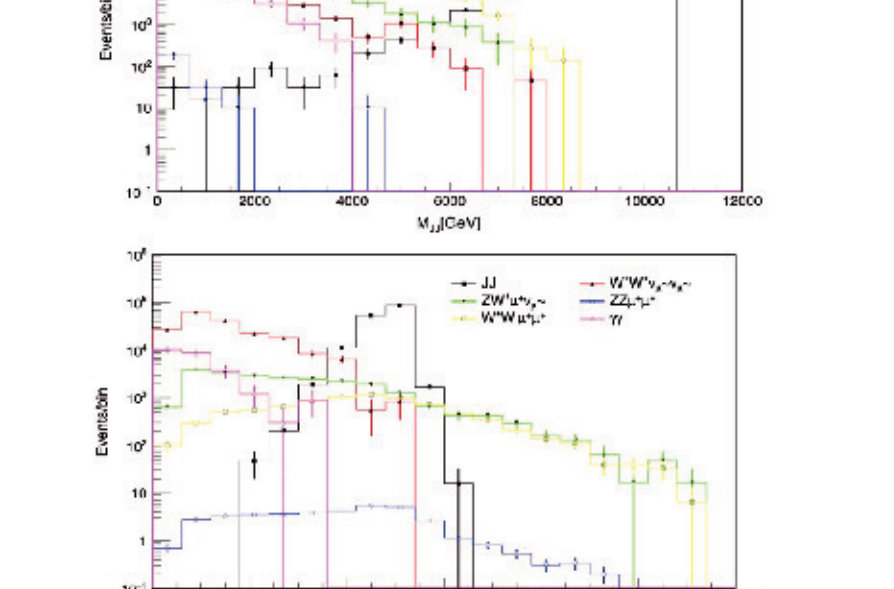
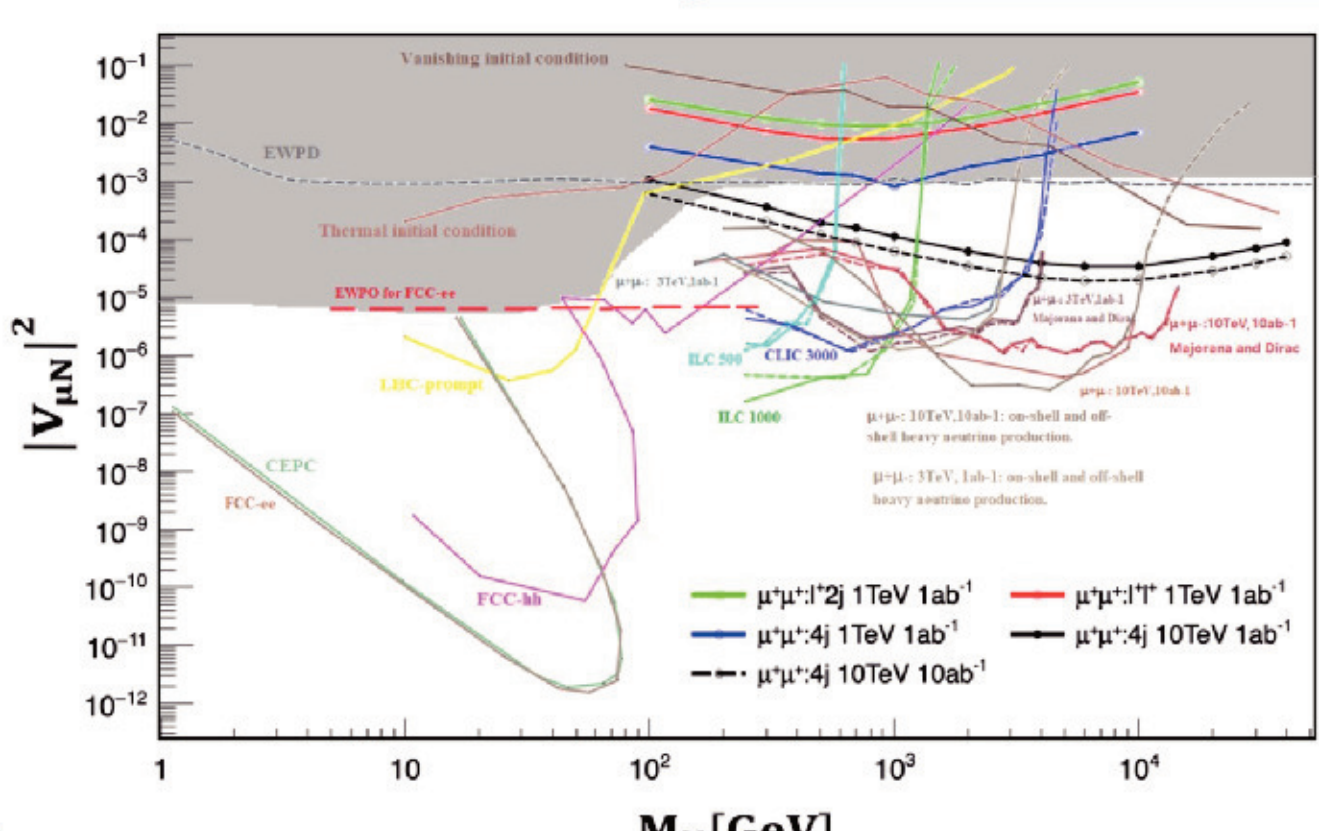


TABLE IV. The cut-flow table in the hadronic channel, with $\sqrt{s} = 10 \text{ TeV}$.

Variables	Limits
Energy	$[2000.0 \text{ GeV}, 4000.0 \text{ GeV}]$
E_T	$[100 \text{ GeV}, 5000 \text{ GeV}]$
$p_{T,j}$	$> 5.0 \text{ GeV}$
$ \eta_j $	$[0.05, 0.95]$
M_{jj}	$[2000 \text{ GeV}, 11000 \text{ GeV}]$
$ \eta_j $	< 7.0
Lepton veto	0

Results—Limit Line

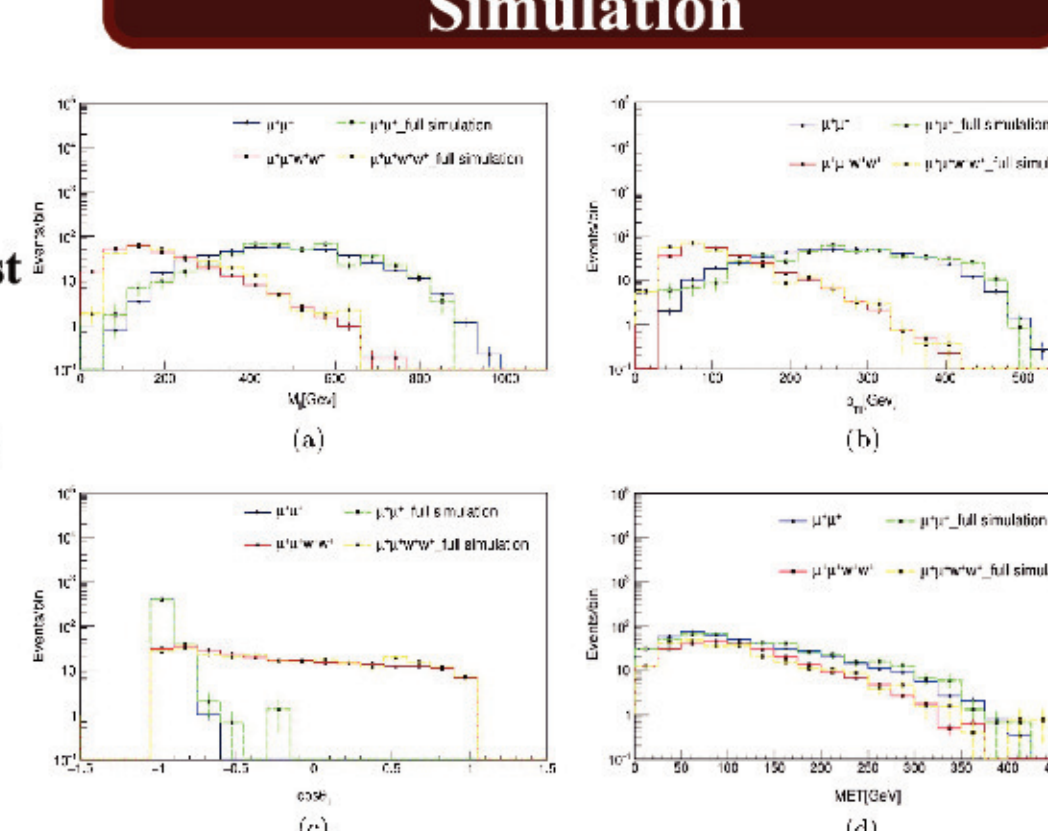


- 2σ exclusion limit of squared mixing element $|V_{\mu N}|^2$ as a function of varying Majorana neutrino mass m_N .
- Our analysis can give the strongest limitation when mass region above 10 TeV.

Future—Improv Full Simulation

Initial results:

- Full simulation can match well with fast simulation.
- Full simulation can reconstruct muons better than fast simulation.



Next:

- Electron ID and photon ID for e/γ reconstruct.
- Add BIB(Beam Induced Background)
- For more simulation: SM, new physics.....