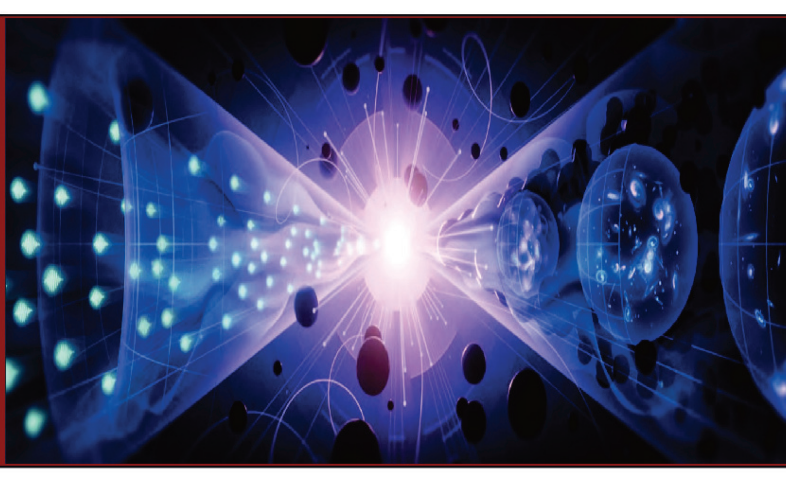
Searching for New Physics at the Future Collider

Ruobing Jiang(蒋若冰) for PKU CMS Group
Supervisor: Qiang Li(李强), Yong Ban(班勇)
Email: ruobing.jiang@cern.ch



Searching for Majorana neutrinos at a same-sign muon collider

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Searching for Majorana Neutrinos in CMS

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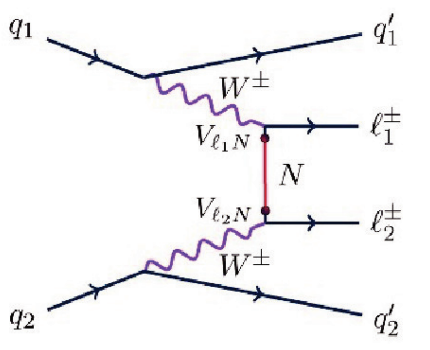
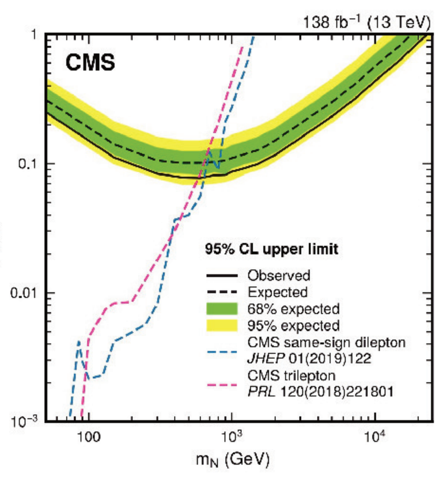


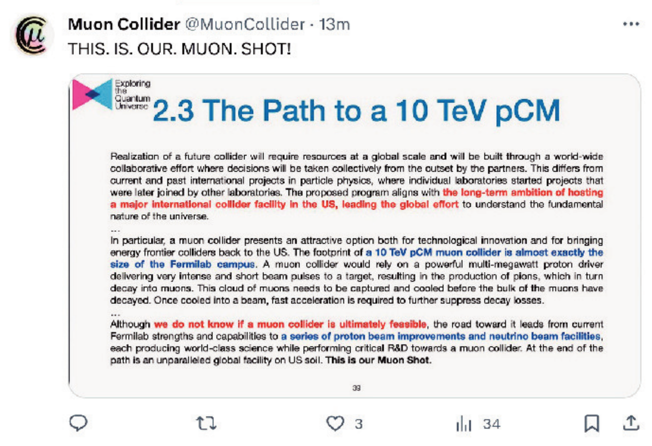
- same-sign WW →same-sign $\ell\ell$ through Majorana neutrinos (lepton number violation)
- t-channel processes is less sensitive to the mass of the intermediate particle
- the cross section of VBF(Vector Boson Fusion) process at the TeV mass scale decreases more slowly with increasing N than s-channel

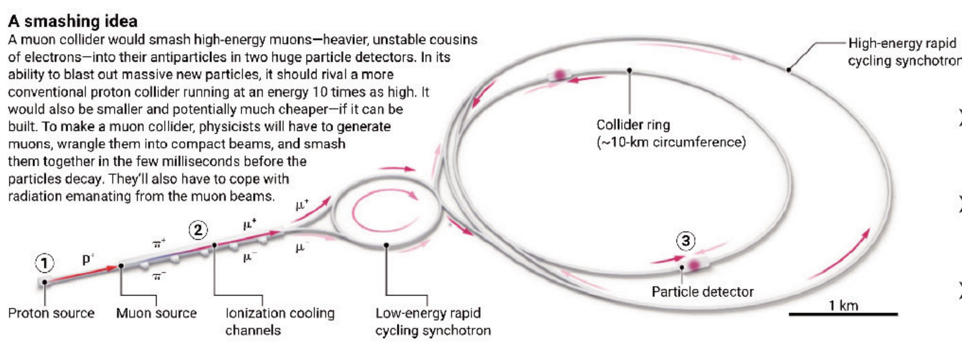


- This is the current CMS measurement of upper limits on the heavy neutrino mixing element $|V_{\mu N}|^2$ at the 95% C.L. as a function of the heavy neutrino mass m_N.

Muon Collider

From US P5 report





From Science

- 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 .

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

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:

$$-L_y = y_{\ell\alpha}\overline{L_\ell}\widetilde{\Phi}\, N_{R\alpha} + \text{H.c.}$$

$$-L_M = \frac{1}{2}(M_N)_{\alpha\beta}\overline{N}^c_{R\alpha}N_{R\beta} + \text{H.c.}$$

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

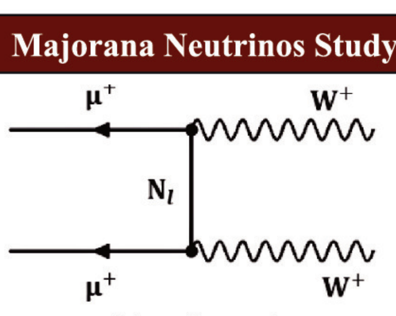
$$\begin{bmatrix} 0 & M_D \\ M_D^T & M_N \end{bmatrix}$$

  - The light neutrino masses and mixing element:

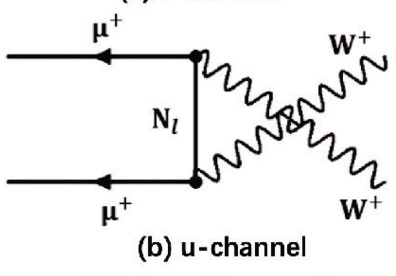
$$M_\nu \simeq M_D M_N^{-1} M_D^T,\ V_{\ell N_\alpha} \sim M_D M_N^{-1}$$

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

$$m_\nu = y^2_{\ell\alpha}\nu^2/m_N$$ → Type-I Seesaw Model



(a) t-channel



(b) u-channel

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

Model:
SM_HeavyN_NLO

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

- 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:

- $\mu^+\mu^+ \to W^+W^+\tilde{\nu}_\mu\tilde{\nu}_\mu$
- $\mu^+\mu^+ \to ZW^+\mu^+\tilde{\nu}_\mu$
- $\mu^+\mu^+ \to W^+\mu^+\tilde{\nu}_\mu\tilde{\nu}_\mu$
- $\mu^+\mu^+ \to Z\mu^+\mu^+$
- $\mu^+\mu^+ \to ZZ\mu^+\mu^+$
- $\mu^+\mu^+ \to W^+W^-\mu^+\mu^+$
- $\gamma\gamma \to W^+W^-$

Simulation Results

Three final states:

- Pure-leptonic final states channel: $\mu^+\mu^+ \to W^+W^+ \to 2\ell + \not{E}_T$
- Pure-hadronic final states channel: $\mu^+\mu^+ \to W^+W^+ \to 4j$
- Semi-leptonic final states channel: $\mu^+\mu^+ \to W^+W^+ \to \ell^+2j + \not{E}_T$

Fast Simulation:

- Both signal and background are simulated with MadGraph5_aMC@NLO.
- Showered 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:**

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

Pre-selections:

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

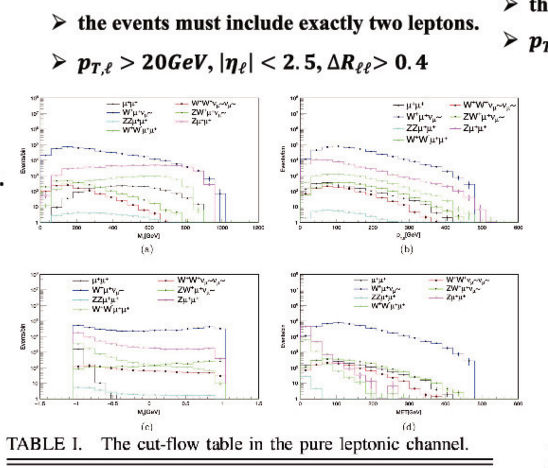


TABLE I. The cut-flow table in the pure leptonic channel.

Variables	Limits
$M_{\ell\ell}$	>100.0 GeV
$p_{T,\ell\ell}$	>120.0 GeV
$\not{E}_T$	>100.0 GeV
$\cos\theta_{\ell\ell}$	< -0.95
$\lvert\eta_\ell\rvert$	< 2.5

- **Pure semi-leptonic channel:**

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

Pre-selections:

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

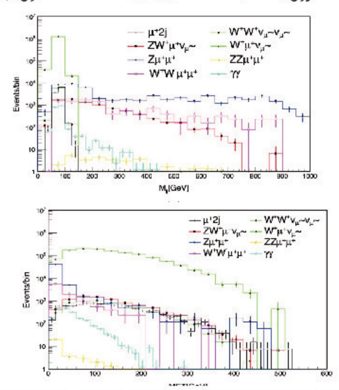


TABLE II. The cut-flow table in the semileptonic channel.

Variables	Limits
M_{jj}	<140.0 GeV
$p_{T,jj}$	>50.0 GeV
$p_{T,\ell}$	>7.0 GeV
$\lvert\eta_j\rvert$	<4.7
$\lvert\eta_\ell\rvert$	<5.0
E_t	<400.0 GeV
Lepton veto	1

- **Hadronic resolved channel:**

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

- Classify four jets in final states into two reconstructed "W bosons" .

Pre-selections:

- the events must include exactly 4 jets.
- $p_{T,j} > 20GeV, |\eta_j| < 4.7, \Delta R_{jj} > 0.4$

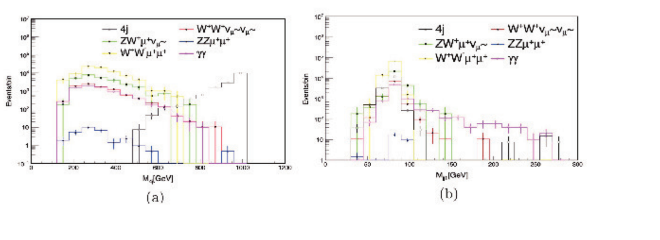


TABLE III. The cut-flow table in the hadronic channel.

Variables	Limits
M_{4j}	>750.0 GeV
$p_{T,j_{1,2,3,4}}$	>50.0 GeV
$p_{T,jj1}$	>100.0 GeV
$p_{T,jj2}$	>100.0 GeV
$p_{T,\ell}$	>5.0 GeV
M_{jj1}	[50 GeV, 110 GeV]
M_{jj2}	[10 GeV, 110 GeV]
$\lvert\eta_\ell\rvert$	<7.0
$\lvert\eta_j\rvert$	<4.7
Lepton veto	0

- **Hadronic merged channel:**

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

- we must consider the boost effect when the two quarks from W_b decay merged into a single fatjet with a mass around M_W.

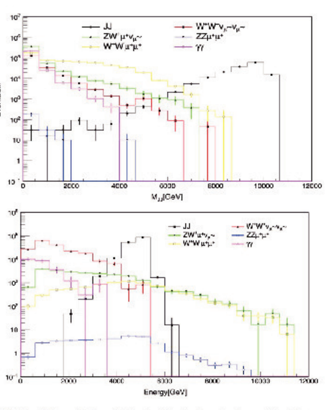
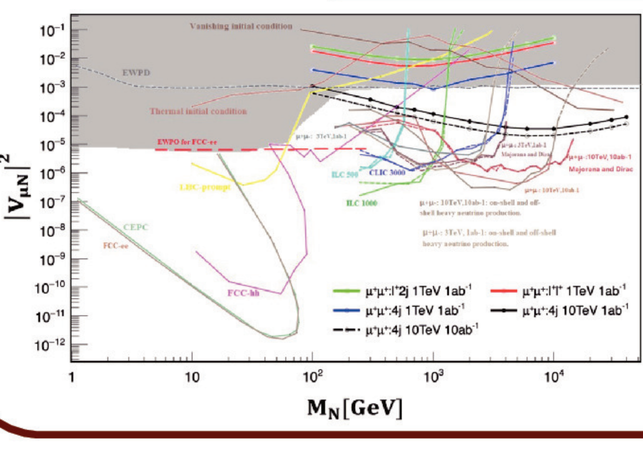


TABLE IV. The cut-flow table in the hadronic channel, with $\sqrt{s} = 10$ TeV.

Variables	Limits
Energy	[2000.0 GeV, 6000.0 GeV]
E_i	[100 GeV, 6000 GeV]
p_T	[100 GeV, 6000 GeV]
$p_{T,\ell}$	> 5.0 GeV
τ_2/τ_1	[0.05, 0.95]
M_{JJ}	[3000 GeV, 11000 GeV]
$\lvert\eta_\ell\rvert$	< 7.0
$\lvert\eta_{FatJet}\rvert$	< 5.0
Lepton veto	0

Results—Limit Line

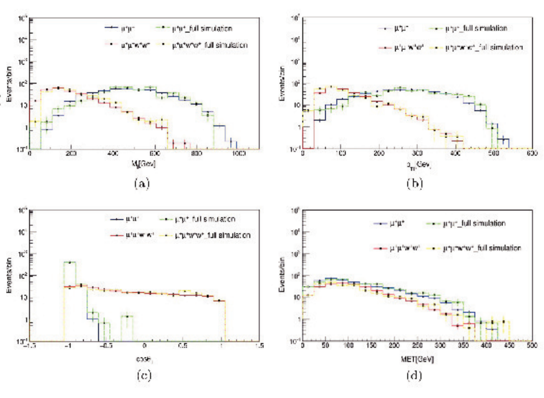


- 2σ exclusion limit of squared mixing element $|V_{\mu N}|^2$ as a function of varying Majorana neutrino mass M_N.
- Our analysis can give the strongest limitation when mass region above 10 TeV.

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......