Searching for Majorana Neutrinos at a Same-Sign Muon Collider

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Detector performance and MDI meeting

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arXiv:2304.04483 [hep-ph]

Majorana neutrinos and type-Ⅰ seesaw model

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:

$$m_\nu = y_{\ell\alpha}^2 \nu^2 / m_N$$

→ Type-Ⅰ Seesaw Model

Recent researches:

at LHC:

[CMS], [arXiv:2206.08956 [hep-ex]]

Electron-positron collider:

arXiv:1805.09520 [hep-ph].

Electron-electron collider:

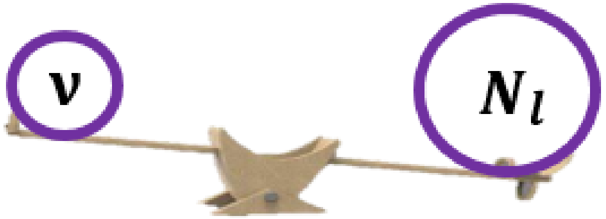
arXiv:1610.02618 [hep-ph]

Muon-muon collider:

arXiv:2302.13247 [hep-ph]

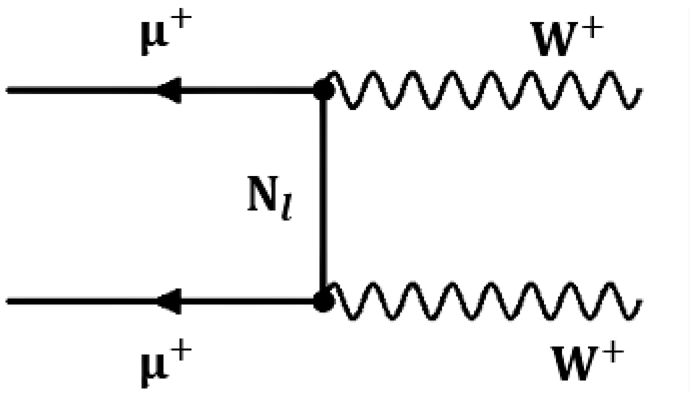
arXiv:2301.05177 [hep-ph]

arXiv:2301.07117 [hep-ph]

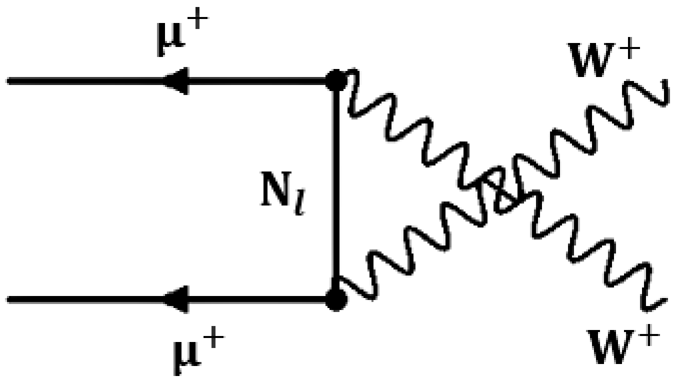


Majorana neutrinos studies at the $\mu^+\mu^+$ collider

Signal process: $\mu^+\mu^+ \to W^+W^+$



(a) t-channel



(b) u-channel

- 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:

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

The results of fast simulation

- Both signal and backgrounds 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.

  (We are currently using CMS card and will switch to muon collider's card for future researches.)

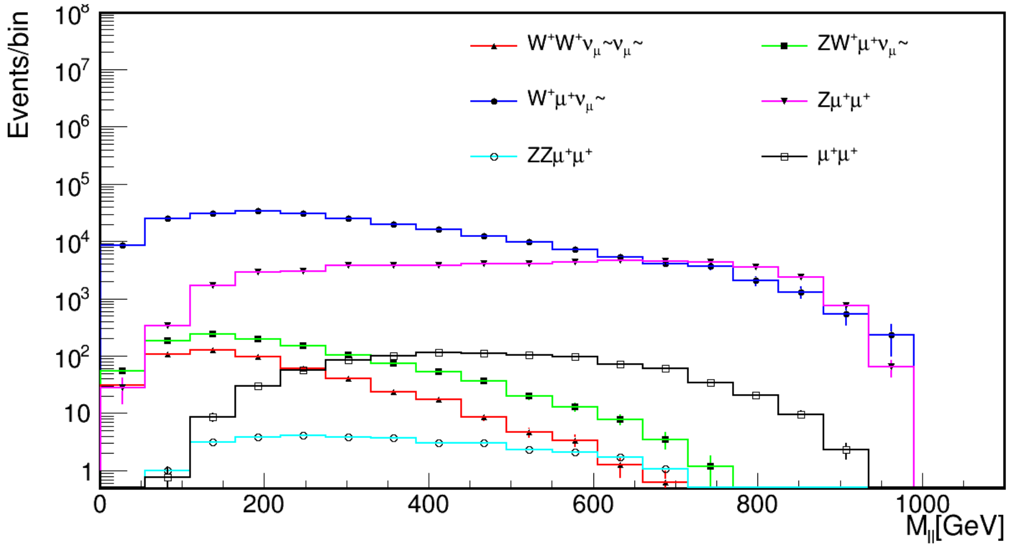
Delphes card

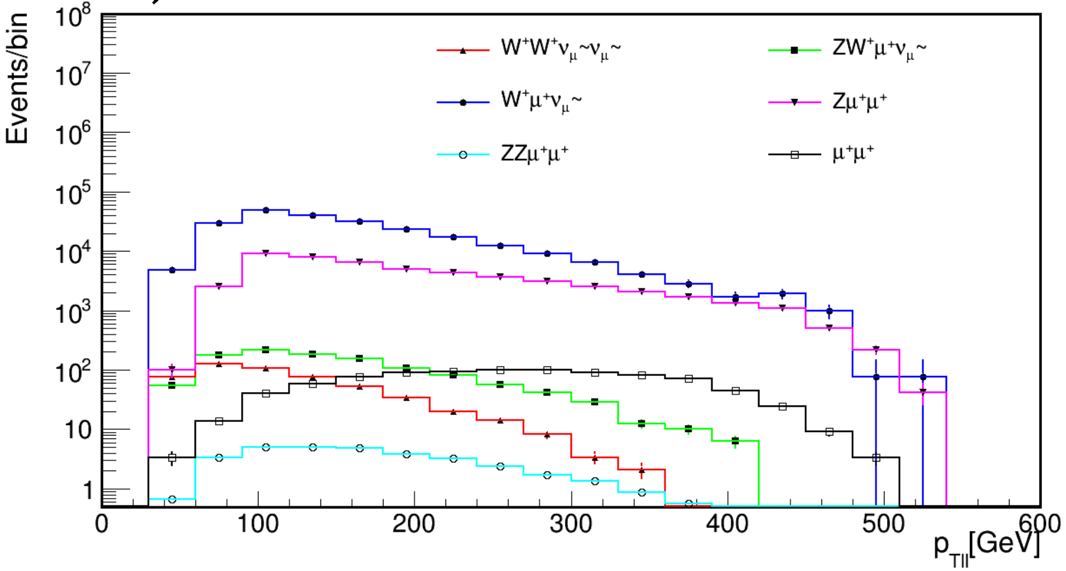
Three final states:

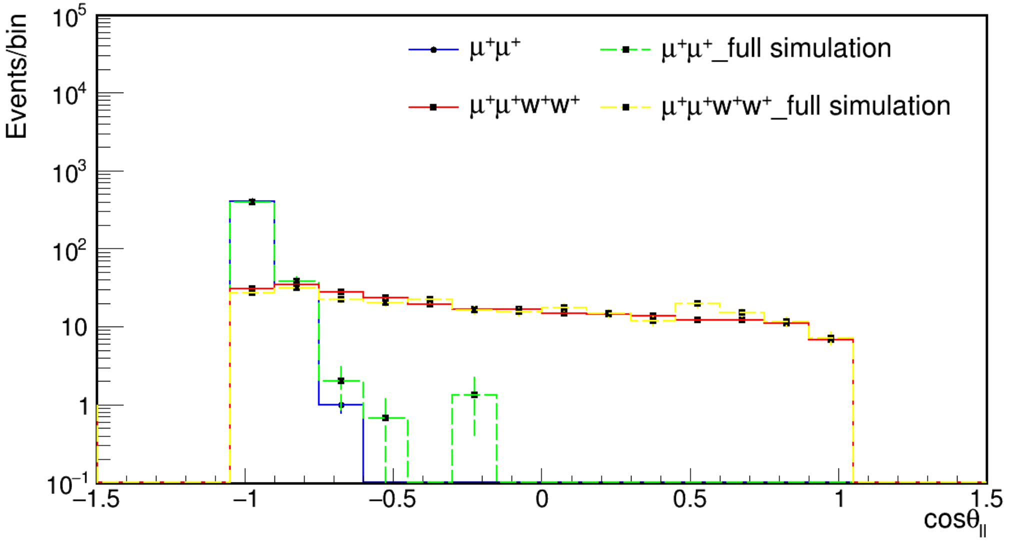
- Pure-leptonic final states channel: $\mu^+\mu^+ \rightarrow W^+W^+ \rightarrow 2\ell + \not{E}_T$
- Pure-hadronic final states channel: $\mu^+\mu^+ \rightarrow W^+W^+ \rightarrow 4j/2J$
- Semi-leptonic final states channel: $\mu^+\mu^+ \rightarrow W^+W^+ \rightarrow \ell^+2j + \not{E}_T$

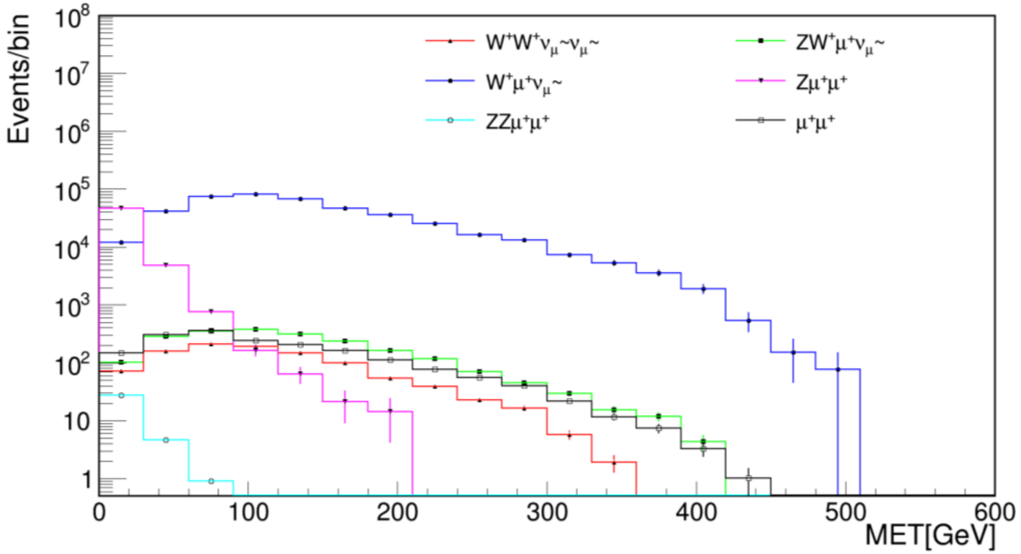
The distributions of variables through fast simulation

- Pure-leptonic channel: $\sqrt{s} = \mathbf{1TeV}, \mathbf{L} = \mathbf{1000fb^{-1}}$







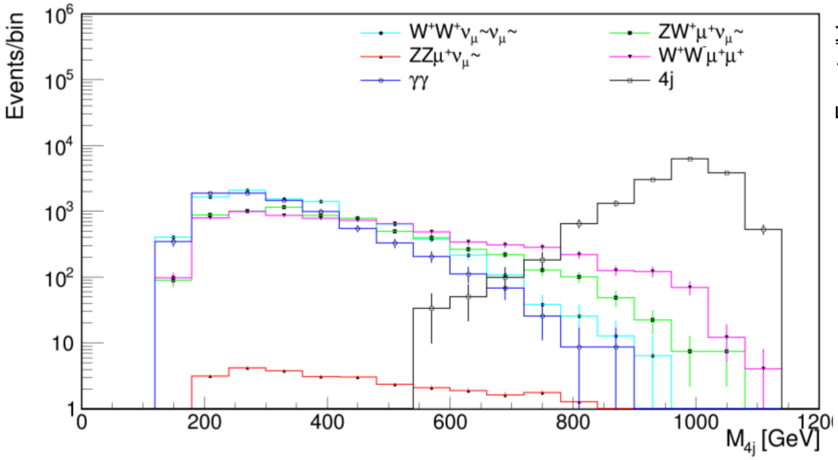


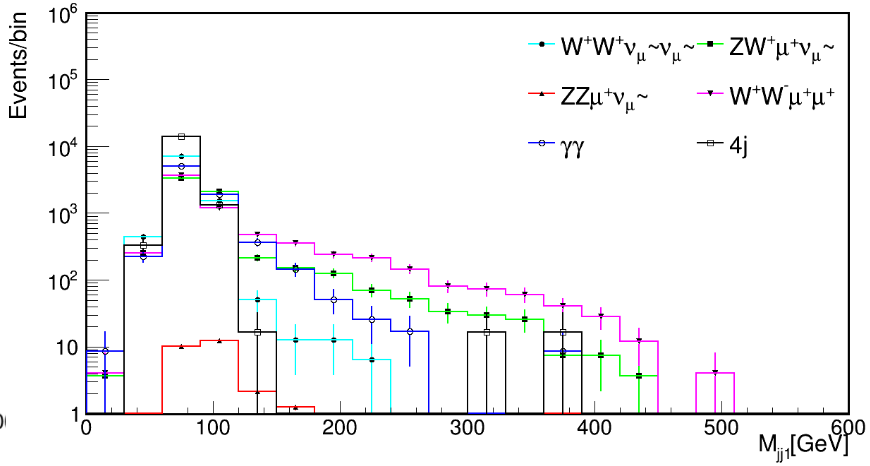
◆ Pure-hadronic channel:

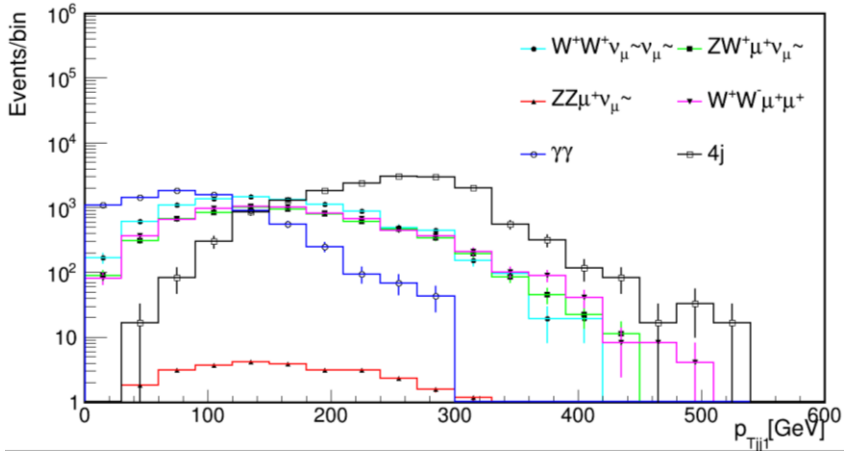
A. Hadronic resolved channel: $\sqrt{s} = 1\mathrm{TeV}, \mathrm{L} = 1000\mathrm{fb}^{-1}$

Classify four jets in final states into two reconstructed "bosons" (W_1, W_2):

- Construct all possible jet pairs candidates: $(j_1 j_2, j_3 j_4)$, $(j_1 j_3, j_2 j_4)$, $(j_1 j_4, j_2 j_3)$,
- Calculate the corresponding mass difference: $\Delta M^2 = (M_1 - M_W)^2 + (M_2 - M_W)^2$,
- Choose the minimum ΔM^2 as the targeted jet pairs.

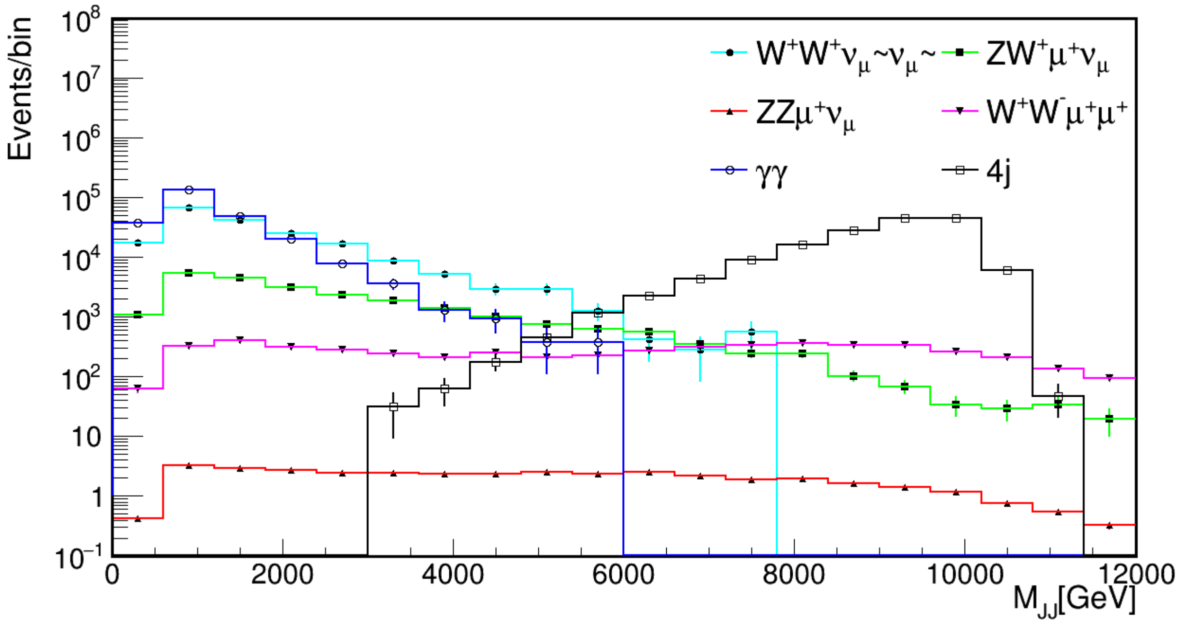


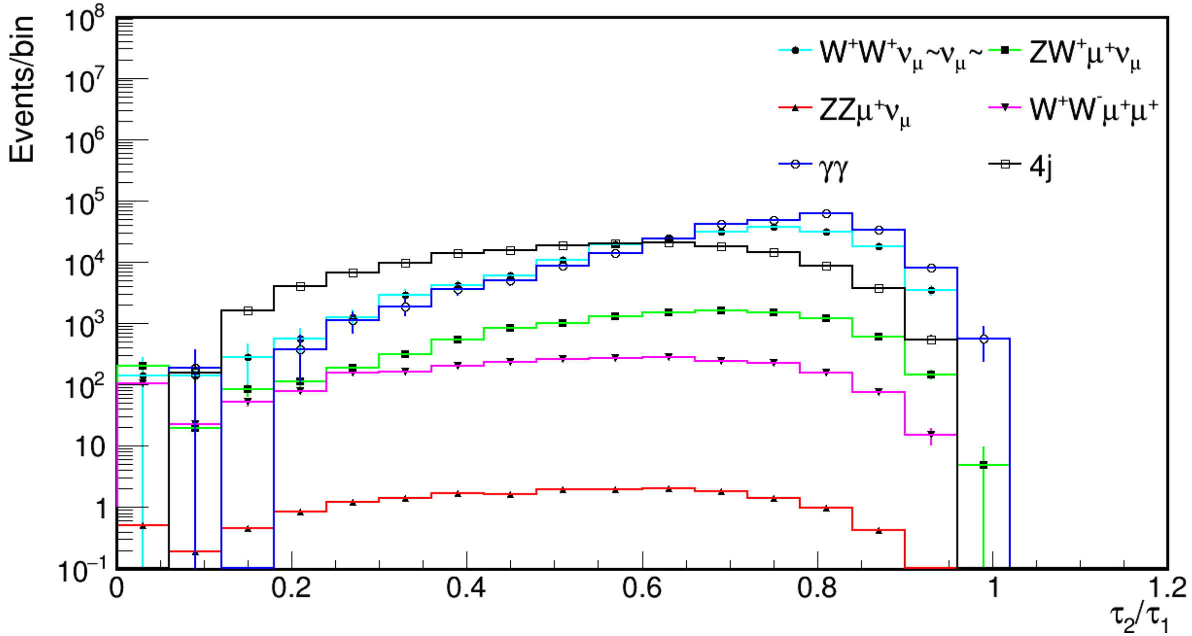




B. Hadronic merged channel: $\sqrt{s} = 10\text{TeV}, \text{L} = 1000\text{fb}^{-1}$

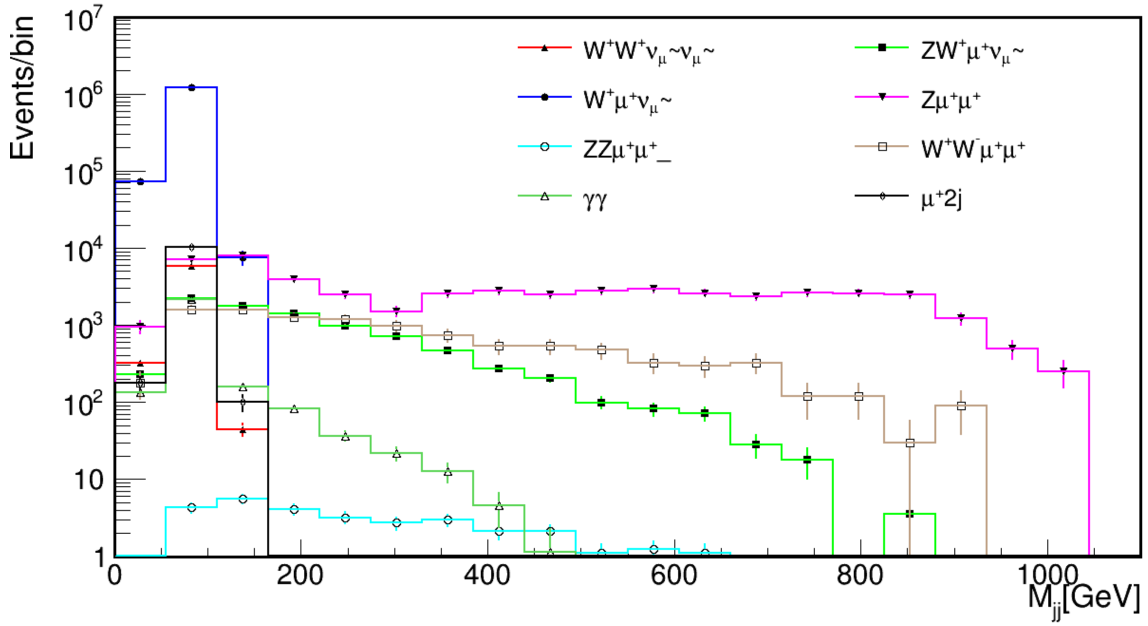
When c.m. energy is several TeV, the influence of fatjet should be considered.

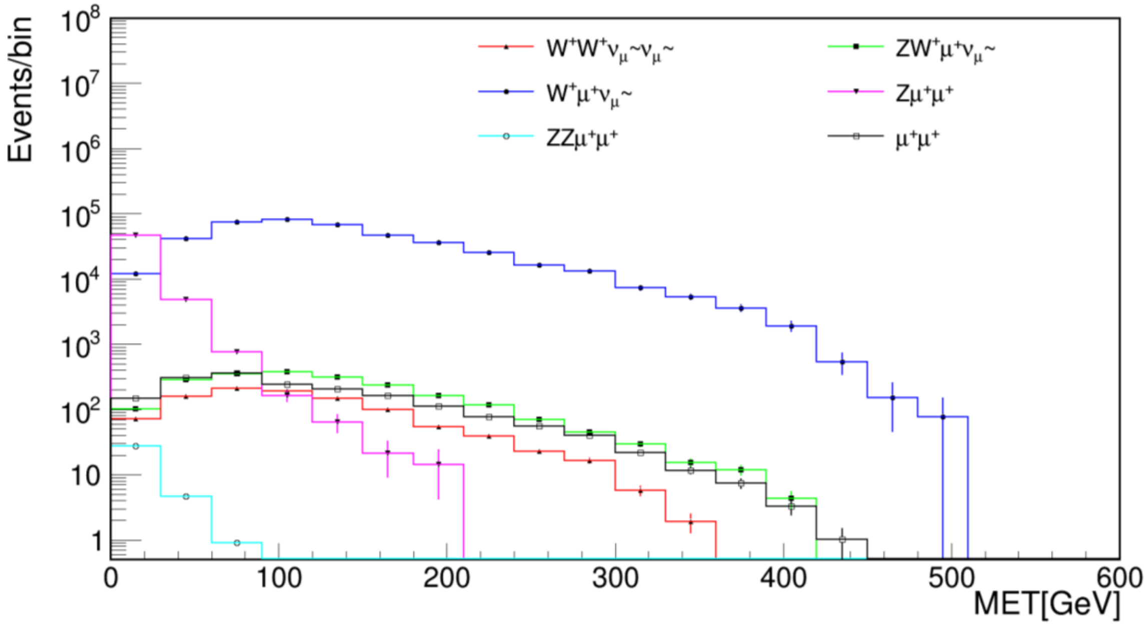




◆ Semi-leptonic channel: $\sqrt{s} = 1\mathrm{TeV}, \mathrm{L} = 1000\mathrm{fb}^{-1}$

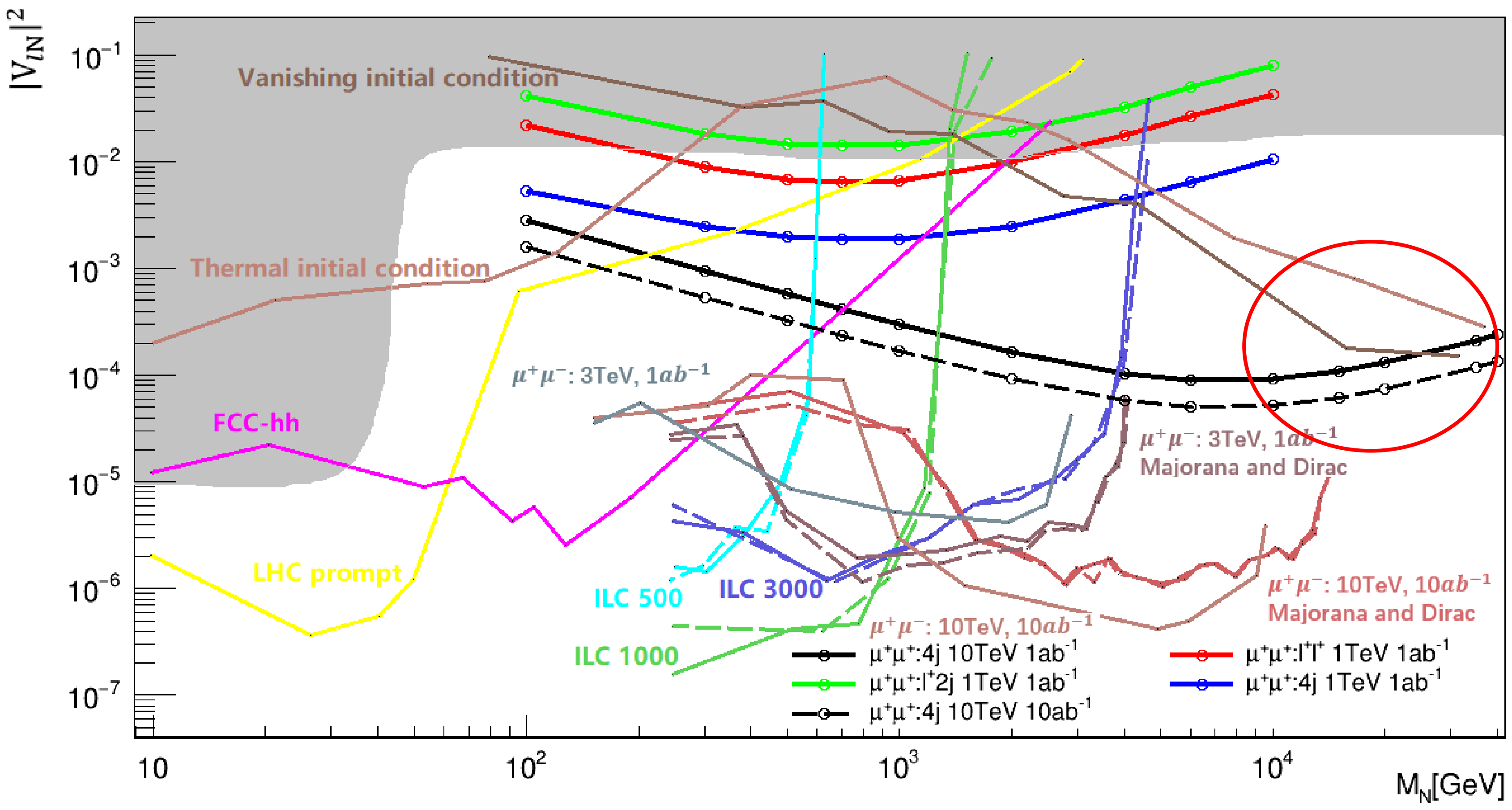
$\mathbf{M_{jj}}$ can be used to reconstruct $\mathbf{W^+}$ boson.





Summary

CL=95% exclusion limit of squared mixing element $|V_{\mu N}|^2$ as a function of varying Majorana neutrino mass M_N.



The results of full simulation

Research full simulation through Muonc software:

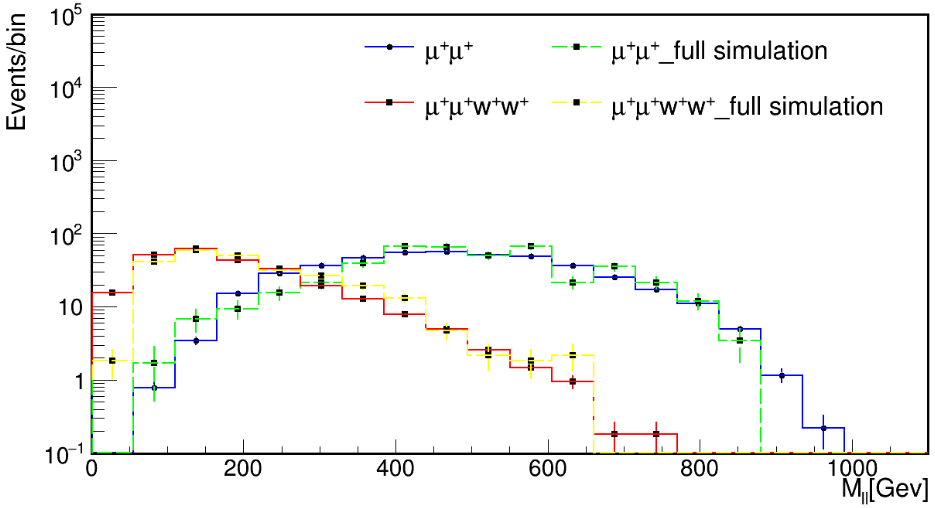
- Generate input particles through MadGraph5_aMC@NLO(MG5_aMC_v3_4_0) then do parton shower through PYTHIA8.
- The interaction of particles with detector material is simulated by GEANT4 software.
- Both simulation and reconstruction are done within a single framework (such as Marlin framework).

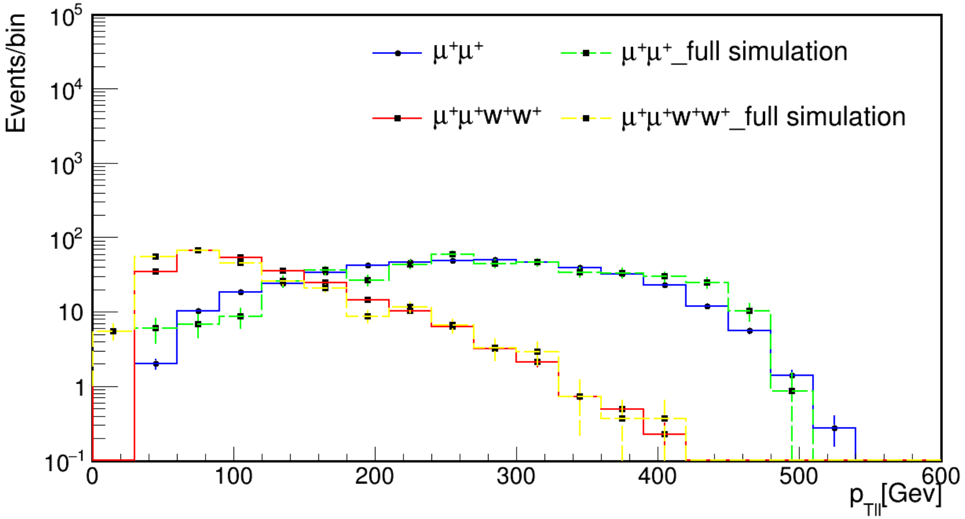
Use signal process and one background in pure-leptonic final states channel:

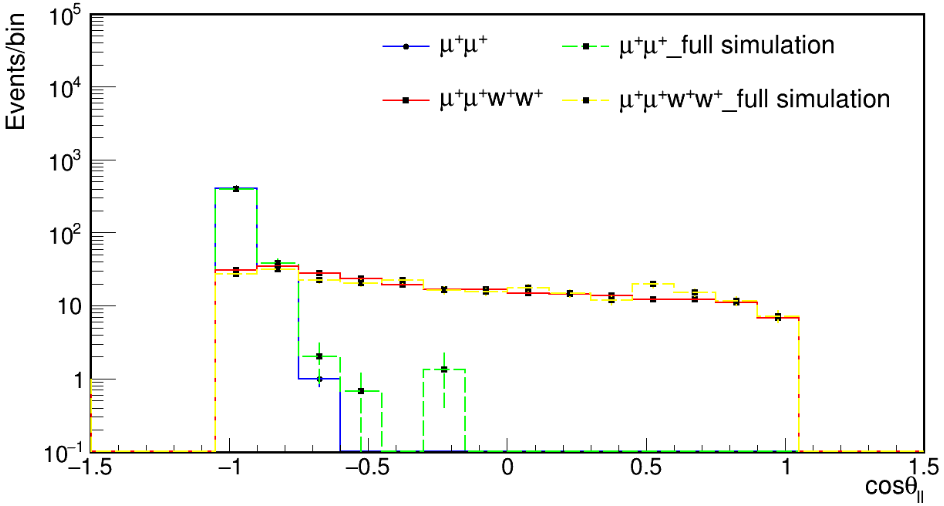
- Signal: $\mu^+\mu^+ \to W^+W^+, W^+ \to \mu^+\nu_\mu, W^+ \to \mu^+\nu_\mu$.
- Background: $\mu^+\mu^+ \to W^+W^+\bar{\nu}_\mu\bar{\nu}_\mu, W^+ \to \mu^+ + \nu_\mu, W^+ \to \mu^+\nu_\mu$.

Fast vs Full simulation for di-muon channel

- **Variables distributions of fast simulation is roughly close to full simulation.**
- **Select μ^+: rctyp==-13&&nrec==2.**

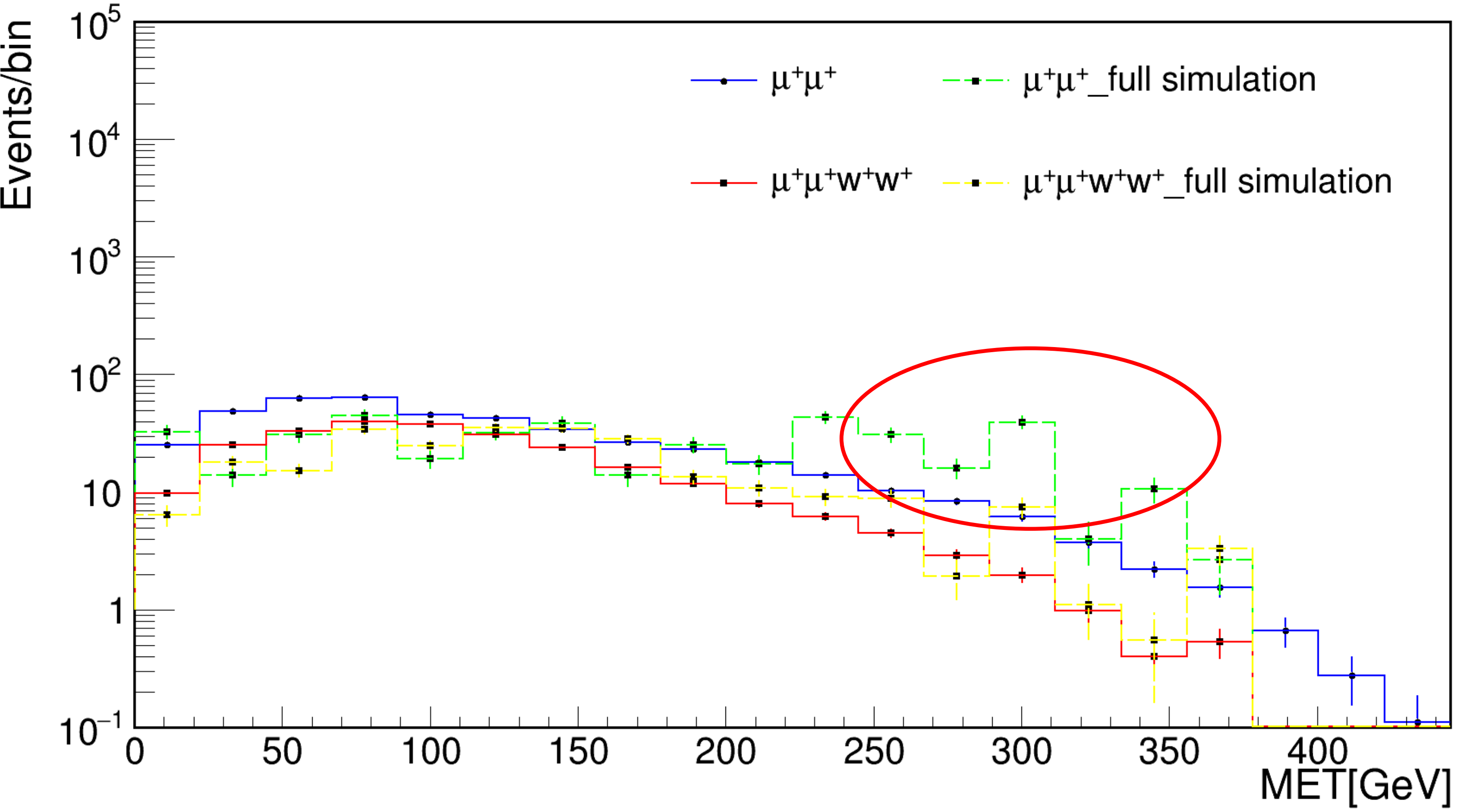






For the Missing transverse energy MET: we calculated as:

$MET \propto \left|\sum_k \vec{P}_{T,k}\right|$ (the parameter k corresponds to all muons and all photons in final states.)



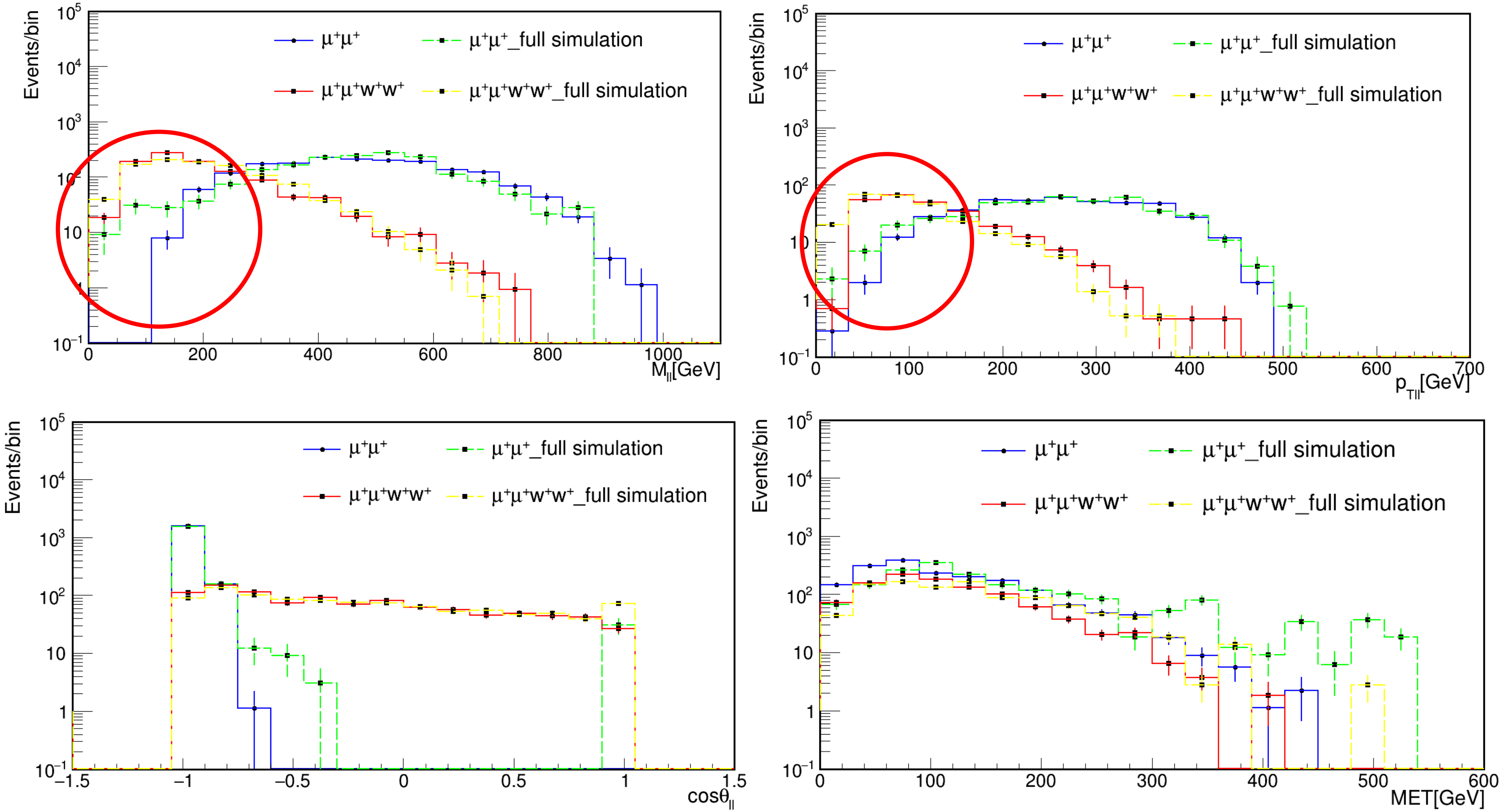
It's complicate to calculate all particles (especially jet) in final states to obtain more accurate MET in full simulation.

We will discuss more later.

If final states only include positrons:

Simply using rctyp==-11&&nrec==2 to select e^{+}. No further ID requirements based on the information from tracking and calorimeter. Any suggestion here?

Fast vs Full simulation for di-electron channel



Conclusions and Outlook

- **We have finished a complete fast simulation analysis about searching for Majorana neutrinos at $\mu^+\mu^+$ collider through $\mu^+\mu^+ \rightarrow W^+W^+$:**
  - Considered three final states and corresponding backgrounds.
  - Obtain variables distributions of different final states for further optimization.
  - Our analysis can give the strongest limitation of mixing element $|V_{\mu N}|^2$ for mass above 10 TeV.
- **We performed full vs fast simulation checks for di-muon and di-electron channels:**
  - Several typical distributions show reasonable agreement.
  - MET variable to be further examined.

Two problems:

1. Currently we use two different configuration xml files for reconstructions, one with jet and the other not. The resulting lctuples contain either jet variables or Pandora reco information (e.g. rcxxxx), but not at the same time. This may bring trouble to calculate MET or missing energy. Is there any recommendated configuration file for more general usage? Our steps of full simulation present in Back Up)

2. How to improve the speed of simulation? It takes me more than 10 hours to obtain 5000 simulation events in the pure-leptonic process. Notice I generate hepmc file first from MadGraph and Pythia8, then transfer this single big file to computing farm for later steps on simulation and reconstructions. (Now we are trying these running on batch systems)

Thanks for your attention!

Back Up

Steps of full simulation:

1. Computing setup:

1) singularity run --bind `echo $HOME` --bind /data/pku/home/rjiang/pku/home/rjiang:/data /cvmfs/unpack ed.cern.ch/registry.hub.docker.com/infnpd/mucoll-ilc-framework:1.6-centos8

(use pwd to view your own path.)

2) Source /opt/ilcsoft/muonc/init_ilcsoft.sh

3) in singularity: git clone https://github.com/MuonColliderSoft/MuC-Tutorial.git

```
jrb@DESKTOP-BG3MH3R:~$ ssh rjiang@hepfarm02.phy.pku.edu.cn
Last login: Thu Mar 30 20:14:19 2023 from 10.4.16.95
==============================================================
 - Welcome to farm.phy.pku.edu.cn
 - User Manual : http://wiki.hep.pku.edu.cn/zh-hans/computing
==============================================================
 - CPU Usage               :  38.30, 37.00, 41.51 (1, 5, 15 min)
 - Memory Usage            :  26023 MB / 128676 MB
 - Disk Usage /data/pku    :  73T / 73T
 - Disk Usage /data/pubfs  :  63T / 107T
 - Disk Usage /data/bond   :  13T / 98T
 - Users Logged on         :  18 user(s)
==============================================================
Note: Port 9001 has now been directed to "farm" instead of "atlas" node.
Reminder: Use `ssh atlas`, `ssh node01`, ..., `ssh node06` to switch nodes.
[ 20:44:48 rjiang@farm ~] (0) $ singularity run --bind `echo $HOME` --bind /data/pku/home/rjiang/pku/home/rjiang:/data /
cvmfs/unpacked.cern.ch/registry.hub.docker.com/infnpd/mucoll-ilc-framework:1.6-centos8
Singularity>
```

git clone https://github.com/MuonColliderSoft/MuC-Tutorial.git

1.simulation:

1) Some settings in xxxx.py:

- the path of xml file, the path of input file(xxxx.hepmc).
- set the number of simulation events.
- the output file: xxxx.slcio.

2) ddsim --steeringFile steer_sim_mumu.py > sim.log 2>&1

```
## The compact XML file
SIM.compactFile = "/opt/ilcsoft/muonc/detector-simulation/geometries/MuColl_v1/MuColl_v1.xml"
```

```
SIM.inputFiles = ["/data/MuC-Tutorial/simulation/d1TeV.hepmc"]
## Macro file to execute for runType 'run' or 'vis'
SIM.macroFile = ""
## number of events to simulate, used in batch mode. -1 all
SIM.numberOfEvents = 10000
## Outputfile from the simulation,only lcio output is supported
SIM.outputFile = "d1TeV.slcio"
```

3. Reconstruction: input file is xxxx.slcio.

1) If jet reconstruction is needed:

- /data/MuC-Tutorial/reconstruction/advanced/jet_reco/jet_reco.xml
- Marlin --global.LCIOInputFiles=xxxx.slcio jet_reco.xml
- Output: Output_REC.slcio , lctuple_jets.root (histograms)

2) If there is no jet reconstruction:

- /data/MuC-Tutorial/reconstruction/steer_reco_mumu.xml(set input file: xxxx.slcio)

```
<global>
  <parameter name="LCIOInputFiles">back5.slcio</parameter>
  <!-- Limit the number of processed records (run+evt): -->
  <parameter name="MaxRecordNumber" value="-1" />
  <parameter name="SkipNEvents" value="0" />
  <parameter name="SupressCheck" value="false" />
  <parameter name="Verbosity" options="DEBUG0-9,MESSAGE0-9,WARNING0-9,ERROR0-9,SILENT">MESSAGE </parameter>
  <parameter name="RandomSeed" value="1234567890" />
</global>
```

- Marlin steer_reco_mumu.xml > reco.log 2>&1
- Output: Output_DST.slcio (it can be used for analysis), Output_REC.000.slcio, histograms.root

4. Analysis:

1) If jet reconstruction is needed:

- /data/MuC-Tutorial/reconstruction/advanced/alternative/lctuple_steer.xml(set input file from reconstruction: Output_REC.slcio)

```xml
<global>
  <parameter name="LCIOInputFiles">
    Output_REC.slcio
  </parameter>
  <parameter name="SkipNEvents" value="0" />
  <parameter name="SupressCheck" value="false" />
  <parameter name="Verbosity" options="DEBUG0-4,MESSAGE0-4,WARNING0-4,ERROR0-4,SILENT"> MESSAGE  </parameter>
</global>
```

- Marlin lctuple_steer.xml > ntuples.out 2>&1
- Output: xxxx.root(include the variables of jets)

```
njet              = 5
jmox              = -3.46141,
                   38.8436, -11.8719, -1.1188, 5.94236
jmoy              = -78.5506,
                   8.86343, -14.8886, 7.36721, 1.54263
jmoz              = 104.097,
                   66.4019, -17.8511, 14.2471, -2.98806
jmas              = 8.65817,
                   5.62509, 0.105817, 2.39232, 1.3889
jene              = 130.741,
                   77.6417, 26.1014, 16.2552, 6.9677
```

```
jevis             = 257.707
jPxvis            = 28.3339
jPyvis            = -75.6659
jPzvis            = 163.906
jmom              = 130.454,
                   77.4377, 26.1012, 16.0781, 6.82787
jcost             = 0.797956,
                   0.857488, -0.683918, 0.886114, -0.437627
jcosTheta         = 0.896944
jTheta            = 0.457988
jPtvis            = 80.7969
jmvis             = 181.713
jmmax             = 130.454
jEmiss            = -257.707
jMmissq           = 33019.5
jMmiss            = 181.713
```

2) There is no jet reconstruction:

- /data/MuC-Tutorial/MuC-Tutorial/analysis/lctuple/ lctuple_steer.xml
- Marlin --global.LCIOInputFiles=Output_DST.slcio --MyAIDAProcessor.FileName=lctuple_example lctuple_steer.xml
- Output: xxxx.root (include variables about reconstruction, mc,……)

The meaning of each branch: https://github.com/iLCSoft/LCTuple/tree/master/src

```
nrec             = 8
rcori            = 0,
                  0, 0, 0, 0, 0, 0, 0
rccid            = 0,
                  0, 0, 0, 0, 0, 0, 0
rctyp            = -211,
                  211, 22, 22, 22, 22, -13, -13
rccov            = 0,
                  0, 0, 0, 0, 0,
                  0, 0, 0, 0, 0,
                  0, 0, 0, 0, 0,
                  0, 0, 0, 0
rcrpx            = 25.854,
                  37.8772, 1324.65, 1267.72, 1305.51, 1291.46,
                  -9.10409, 35.5533
rcrpy            = -16.8058,
                  -11.3637, -810.404, -875.862, -867.772, -846.997,
                  28.8793, 3.74549
rcrpz            = 39.7769,
                  120.14, 2031.5, 1934.85, 1949.54, 1935.01,
                  10.9688, 80.14
```

```
rcmox            = 26.0539,
                  0.873903, 11.3577, 2.98798, 19.3792, 4.38371,
                  -31.4725, 46.5799
rcmoy            = -16.9459,
                  -0.239515, -6.96526, -2.06438, -12.9043, -2.87503,
                  99.6751, 4.93579
rcmoz            = 40.0999,
                  2.7577, 17.3899, 4.56037, 29.0315, 6.56816,
                  37.8711, 105.035
rcmas            = 0.13957,
                  0.13957, 0, 0, 0, 0,
                  0.105658, 0.105658
rcene            = 50.7345,
                  2.90611, 21.907, 5.8298, 37.2143, 8.40377,
                  111.175, 115.006
```