Feasibility Study of Measuring the Higgs Self-coupling Using the Muon Collider

Kenny Jia

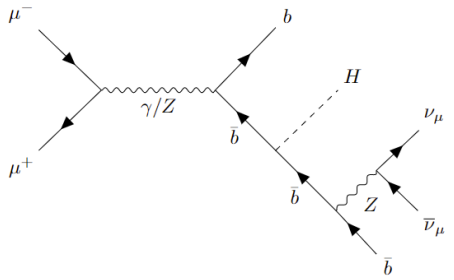
Apr 15th, 2022

Rethinking about sig and bkg

- Signal: $\mu^-\mu^+ \to v_\mu \bar{v}_\mu HH$
  - Dominated by WW fusion mode, sub-dominate by Double Higgs-strahlung ZHH.
- Background, (b-Tag>=3 is effective!):
  - $\mu^-\mu^+ \to v_\mu \bar{v}_\mu q\bar{q}q\bar{q}$, following should be included (but MadGraph Don't):
    - $\mu^-\mu^+ \to v_\mu \bar{v}_\mu q\bar{q}H$, How to avoid double counting with $\mu^-\mu^+ \to ZHH$?
    - $\mu^-\mu^+ \to v_\mu \bar{v}_\mu ZH$, notice that this is NOT included in $v_\mu \bar{v}_\mu q\bar{q}H$ (why?).
    - $\mu^-\mu^+ \to v_\mu \bar{v}_\mu q\bar{q}Z$, dominate by $\mu^-\mu^+ \to v_\mu \bar{v}_\mu ZZ$. By assigning a very high mass to Higgs, we avoid double counting with $v_\mu \bar{v}_\mu ZH$.
    - $\mu^-\mu^+ \to v_\mu \bar{v}_\mu W^+ W^-$, should be easily-distinguishable from signal?
    - Other QCD process, negligible with less than 4 anti-kT jets.
    - Other QED process, with QED=6 neglected by MadGraph (should we include it?).
  - $\mu^-\mu^+ \to q\bar{q}q\bar{q}$, very high cross section, but should be easy to deal with using a cut on Missing ET>0:
    - Dominate by $\mu^-\mu^+ \to W^+ W^-, \mu^-\mu^+ \to ZZ, \mu^-\mu^+ \to Z/a \to W^+ W^-$
  - $\mu^-\mu^+ \to v_\mu lq\bar{q}q\bar{q}$, should be negligible with cut on lepton existence.

Current choices

- Signal: $\mu^-\mu^+ \to v_\mu \bar{v}_\mu \, HH$:
  - Dominated by WW fusion mode, sub-dominate by Double Higgs-strahlung ZHH.
- Background, $\mu^-\mu^+ \to v_\mu \bar{v}_\mu q\bar{q}q\bar{q}$:
  - $\mu^-\mu^+ \to v_\mu \bar{v}_\mu q\bar{q}H$, which too quarks are not decay from one Z boson.
  - $\mu^-\mu^+ \to v_\mu \bar{v}_\mu ZH$.
  - $\mu^-\mu^+ \to v_\mu \bar{v}_\mu q\bar{q}Z$, this channel includes $\mu^-\mu^+ \to v_\mu \bar{v}_\mu ZZ$.
  - Other QCD process with final state $v_\mu \bar{v}_\mu q\bar{q}q\bar{q}$.



Cross section comparison with CLICdp (3TeV)

Process	σ/fb	$\varepsilon_{\text{presel}}$ (%)	ε_{BDT} (%)	N_{BDT}
$HH\nu_e\bar{\nu}_e$; $HH \to b\bar{b}b\bar{b}$	0.19	66	24	61
$HH\nu_e\bar{\nu}_e$; $HH \to$ other	0.40	5.4	3.2	1
$e^+e^- \to q\bar{q}q\bar{q}$	547	0.16	0.16	3
$e^+e^- \to q\bar{q}q\bar{q}\nu\bar{\nu}$	72	1.8	0.68	17
$e^+e^- \to q\bar{q}q\bar{q}l\nu$	107	1.8	0.15	6
$e^+e^- \to q\bar{q}H\nu\bar{\nu}$	4.7	18	3.0	50
$e^\pm\gamma \to \nu q\bar{q}q\bar{q}$	523	1.2	0.09	11
$e^\pm\gamma \to qqH\nu$	116	2.7	0.14	9

Process	σ/fb
$\nu_\mu\bar{\nu}_\mu HH$	0.84
$\mu^+\mu^- \to \nu_\mu\bar{\nu}_\mu q\bar{q}Z$	69
$\mu^+\mu^- \to \nu_\mu\bar{\nu}_\mu HZ$	9.8
$\mu^+\mu^- \to \nu_\mu\bar{\nu}_\mu q\bar{q}q\bar{q}$	1.9
$\mu^+\mu^- \to \nu_\mu\bar{\nu}_\mu q\bar{q}H$	6.6

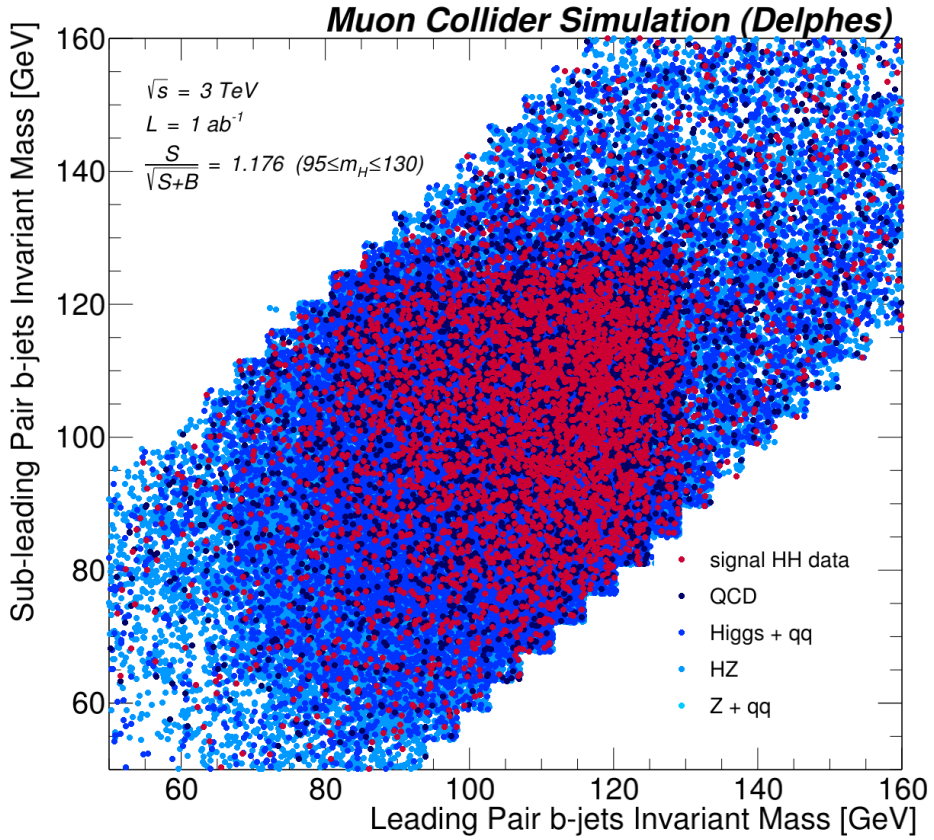
doi :10.1140/epjc/s10052-017-4968-5

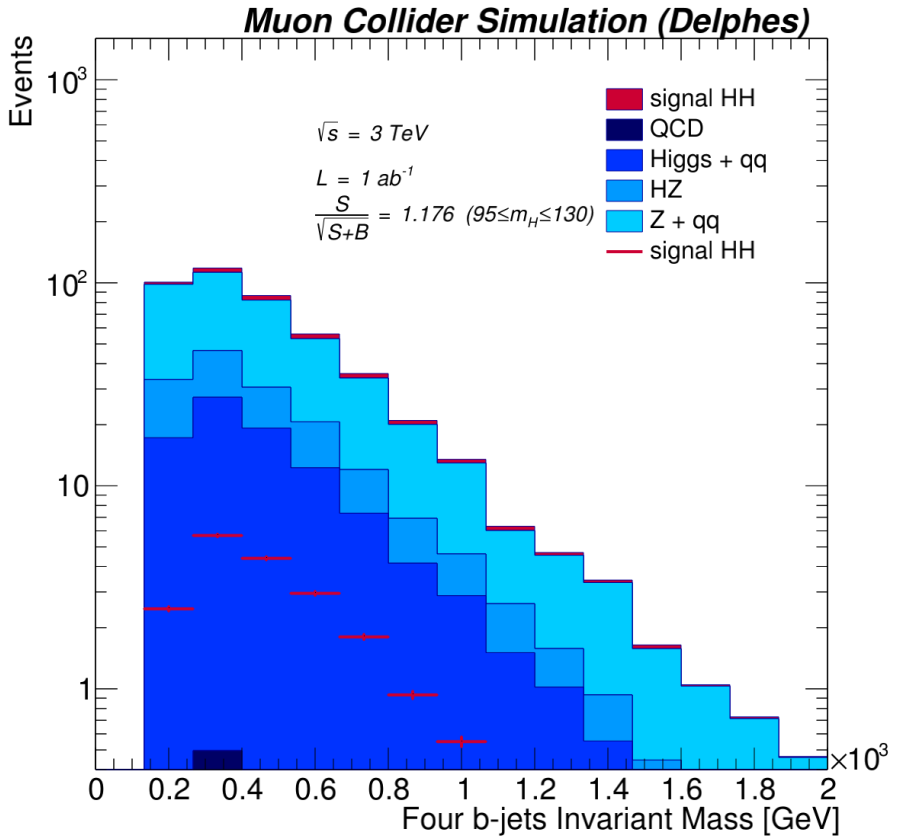
Comparing with CLICdp result at 3 TeV

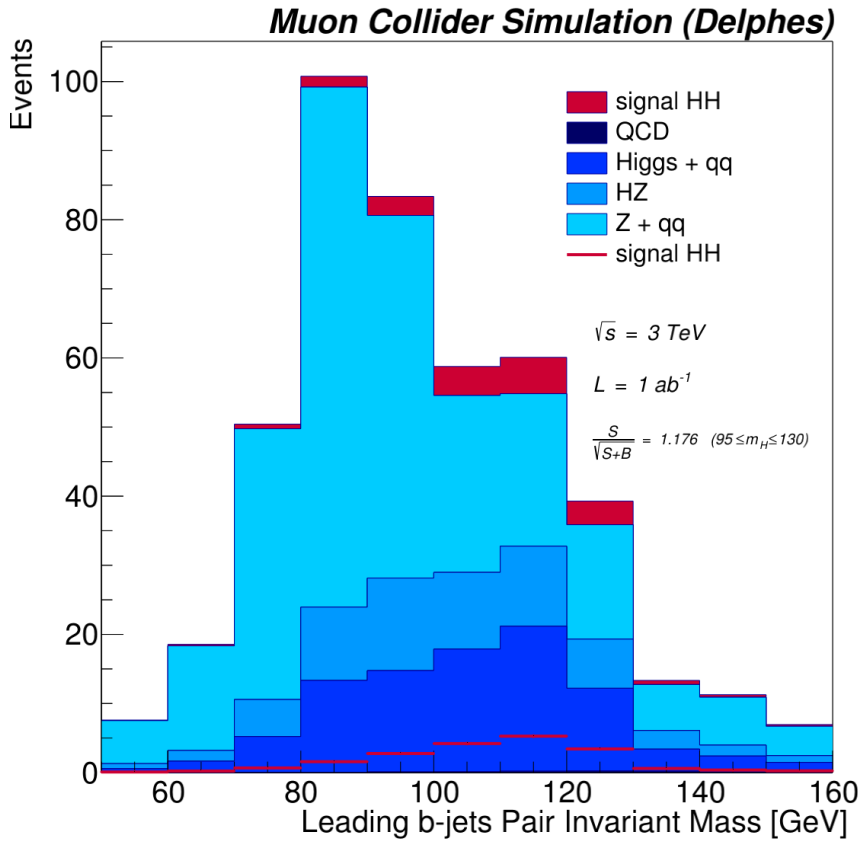
We are not sure which specific Feynman diagram is included in their expression, but it seems that the results matches well.

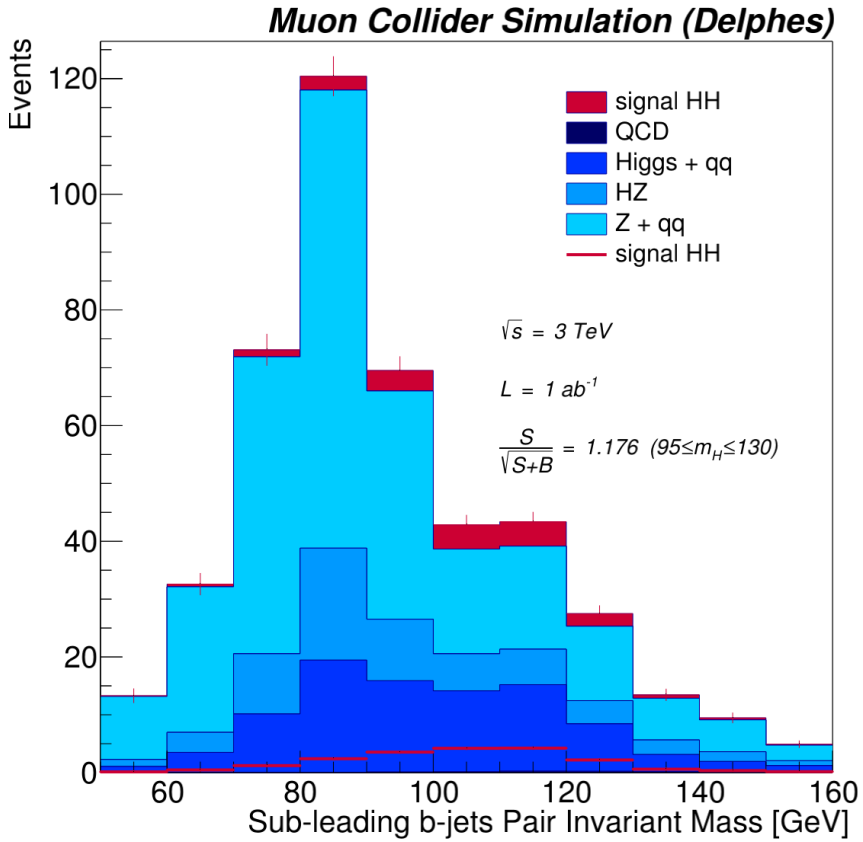
MuCol Process	σ/fb	CLICdp Process	σ/fb	Ratio μ/e
$\nu_\mu\bar{\nu}_\mu HH$	0.84	$\nu_e\bar{e}_\mu HH$	0.69	1.22
$\mu^+\mu^- \to \nu_\mu\bar{\nu}_\mu q\bar{q}q\bar{q}$ (qqZ,ZZ,HZ,qqH)	87.3	$e^+e^- \to \nu_e\bar{\nu}_e q\bar{q}q\bar{q}$	72	1.21
$\mu^+\mu^- \to \nu_\mu\bar{\nu}_\mu q\bar{q}q\bar{q}$ (qqZ,ZZ,HZ*,qqH)	80.1	$e^+e^- \to \nu_e\bar{\nu}_e q\bar{q}q\bar{q}$	72	1.11
$\mu^+\mu^- \to \nu_\mu\bar{\nu}_\mu q\bar{q}q\bar{q}$ (qqZ,ZZ)	70.9	$e^+e^- \to \nu_e\bar{\nu}_e q\bar{q}q\bar{q}$	72	0.98
$\mu^+\mu^- \to \nu_\mu\bar{\nu}_\mu q\bar{q}H$ (w/o HZ)	6.6	$e^+e^- \to \nu_e\bar{\nu}_e q\bar{q}H$	4.7	1.4
$\mu^+\mu^- \to \nu_\mu\bar{\nu}_\mu q\bar{q}H$ (w/ HZ)	16.4	$e^+e^- \to \nu_e\bar{\nu}_e q\bar{q}H$	4.7	3.49
$\mu^+\mu^- \to \nu_\mu\bar{\nu}_\mu q\bar{q}H$ (w/ HZ*)	9.2	$e^+e^- \to \nu_e\bar{\nu}_e q\bar{q}H$	4.7	1.97

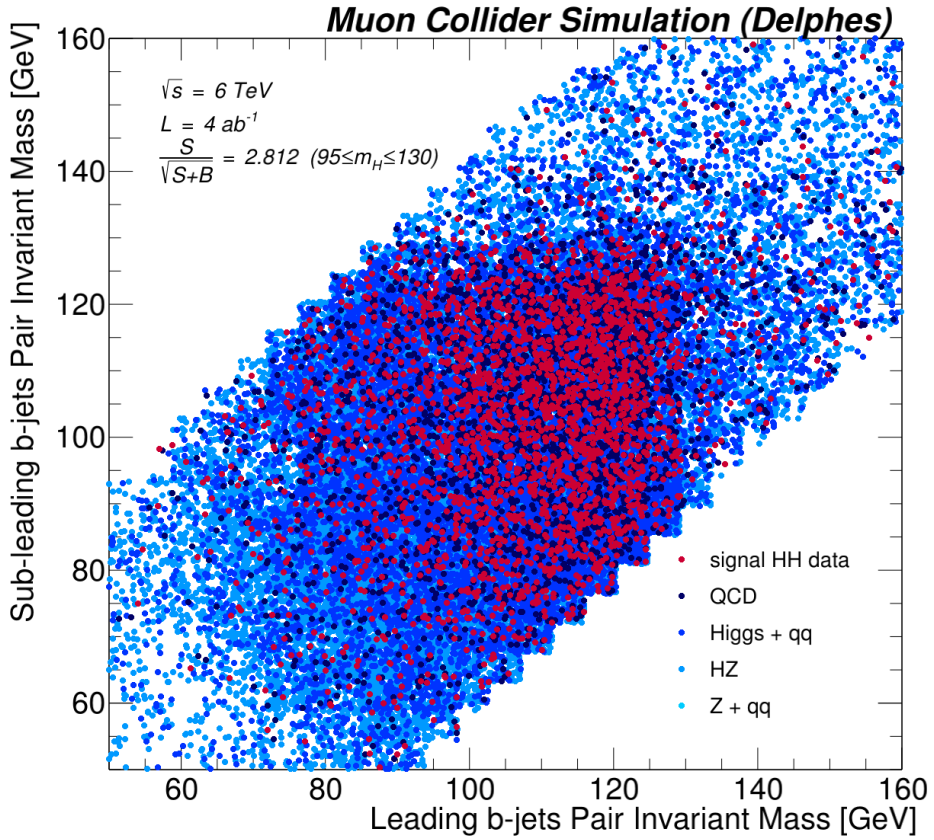
HZ*: With BR($Z \to q\bar{q}$)$\approx 69\%$, we estimated $\sigma(HZ, Z \to q\bar{q}) = 6.7$fb.

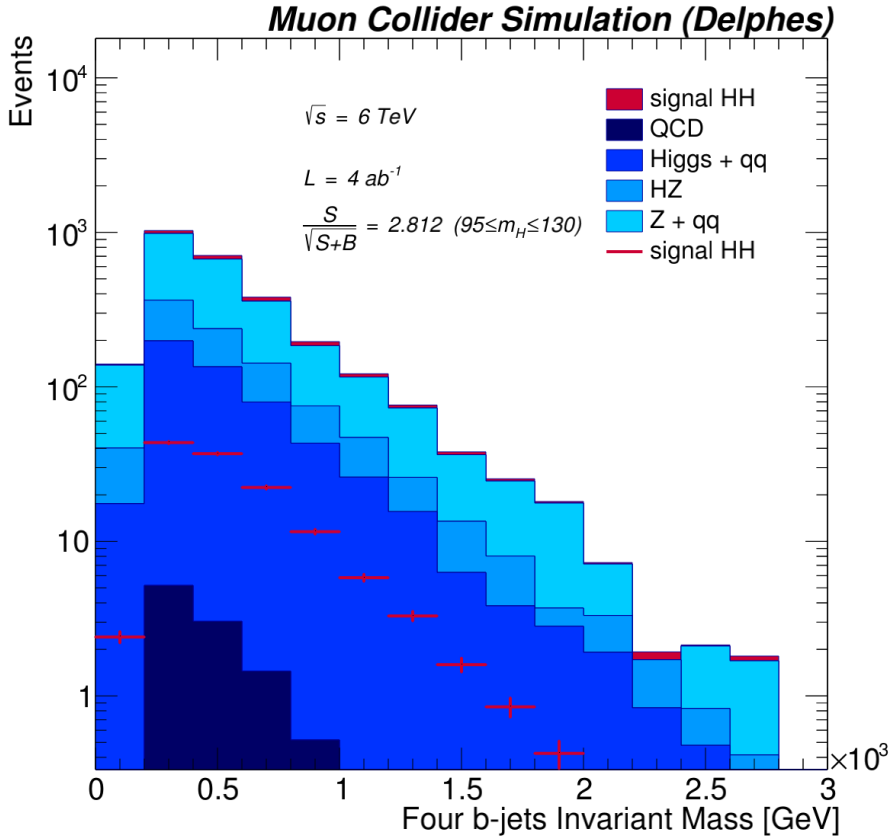

Muon Collider Simulation (Delphes)
$\sqrt{s}$ = 3 TeV
L = 1 ab^{-1}
$\frac{S}{\sqrt{S+B}}$ = 1.176 (95≤m_H≤130)
signal HH data
QCD
Higgs + qq
HZ
Z + qq
Sub-leading Pair b-jets Invariant Mass [GeV]
Leading Pair b-jets Invariant Mass [GeV]
60
80
100
120
140
160

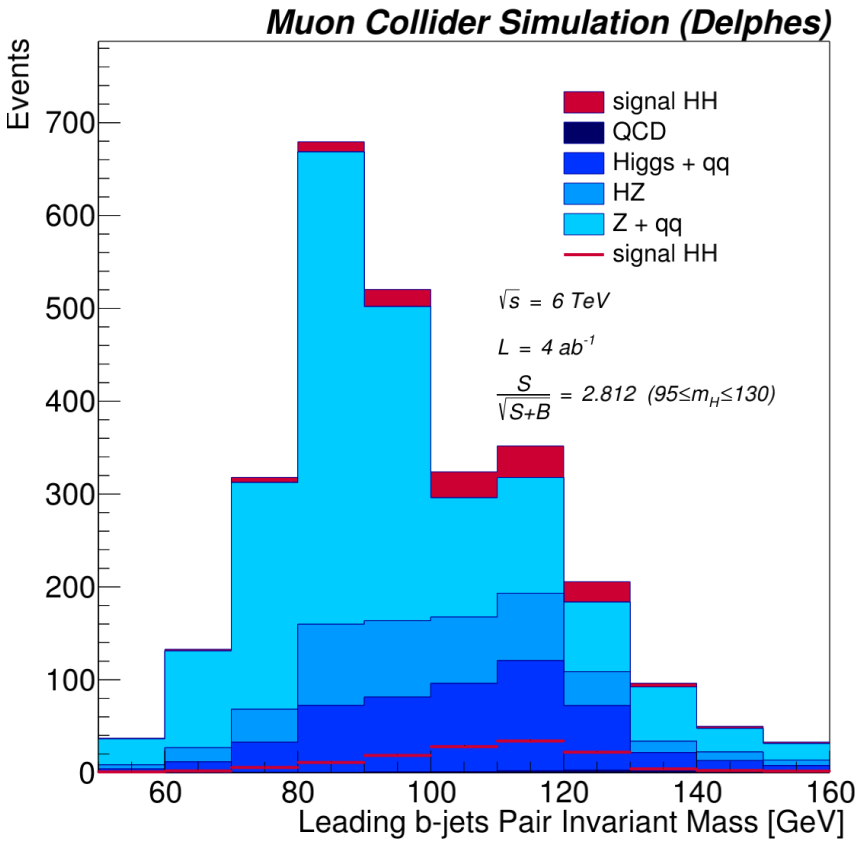

Muon Collider Simulation (Delphes)
$\sqrt{s}$ = 3 TeV
L = 1 ab^{-1}
$\frac{S}{\sqrt{S+B}}$ = 1.176 (95≤m_H≤130)
signal HH
QCD
Higgs + qq
HZ
Z + qq
signal HH
Events
Four b-jets Invariant Mass [GeV]
×10^3
1
10
10^2
10^3
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2

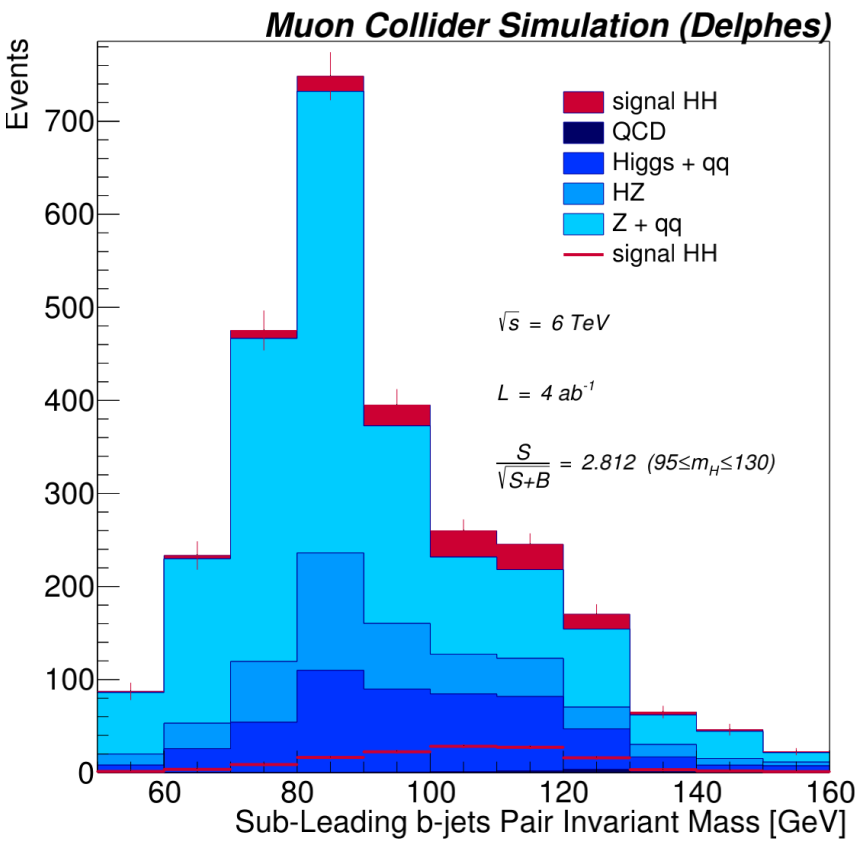

Muon Collider Simulation (Delphes)
Events
signal HH
QCD
Higgs + qq
HZ
Z + qq
signal HH
$\sqrt{s}$ = 3 TeV
L = 1 ab^{-1}
$\frac{S}{\sqrt{S+B}}$ = 1.176 (95≤m_H≤130)
Leading b-jets Pair Invariant Mass [GeV]

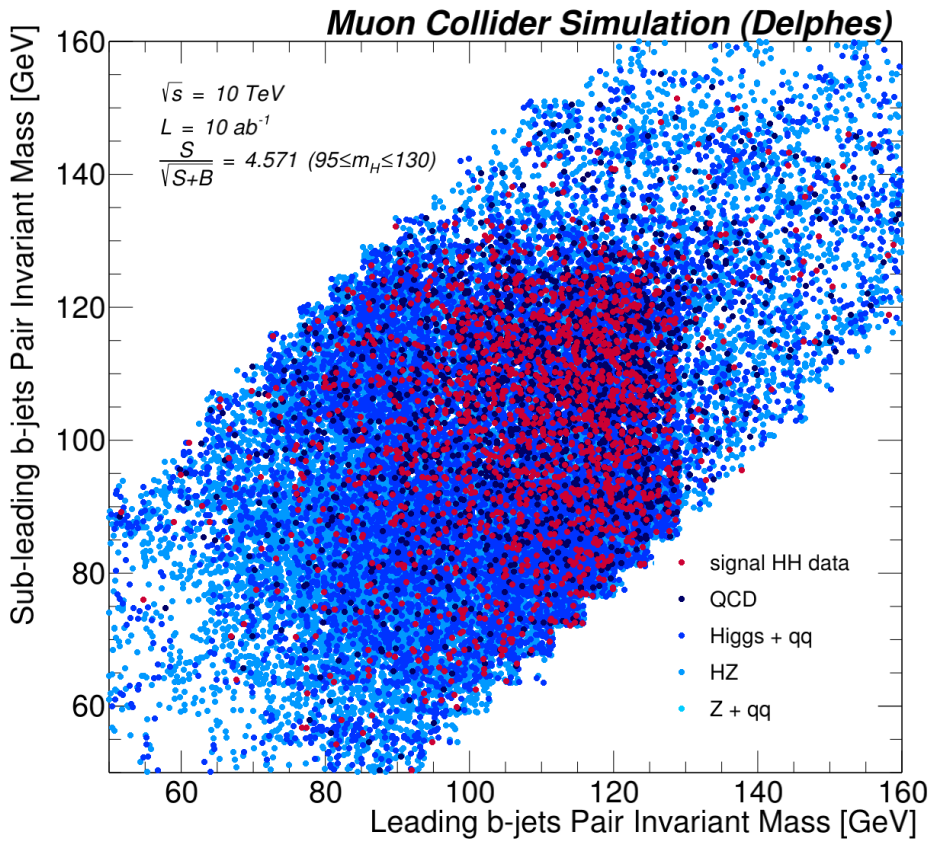

Muon Collider Simulation (Delphes)
Events
signal HH
QCD
Higgs + qq
HZ
Z + qq
signal HH
$\sqrt{s}$ = 3 TeV
L = 1 ab^{-1}
$\frac{S}{\sqrt{S+B}}$ = 1.176 (95≤m_H≤130)
Sub-leading b-jets Pair Invariant Mass [GeV]

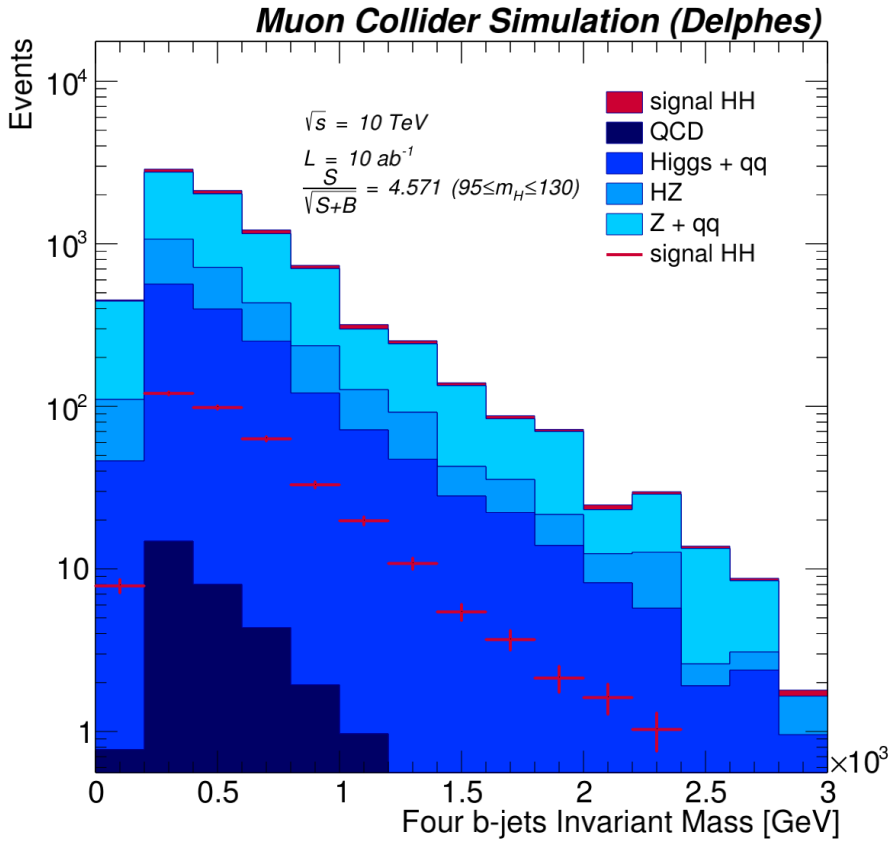

Muon Collider Simulation (Delphes)
$\sqrt{s}$ = 6 TeV
L = 4 ab^{-1}
$\frac{S}{\sqrt{S+B}}$ = 2.812 (95≤m_H≤130)
signal HH data
QCD
Higgs + qq
HZ
Z + qq
Sub-leading b-jets Pair Invariant Mass [GeV]
Leading b-jets Pair Invariant Mass [GeV]
60
80
100
120
140
160

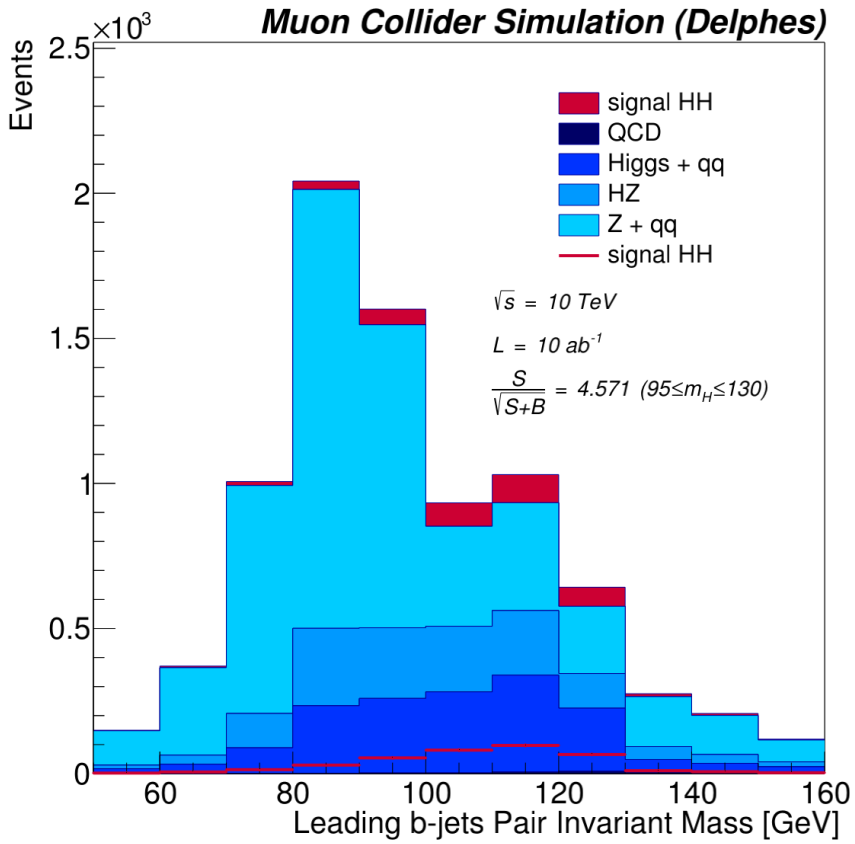

Muon Collider Simulation (Delphes)
$\sqrt{s}$ = 6 TeV
L = 4 ab^{-1}
$\frac{S}{\sqrt{S+B}}$ = 2.812 (95≤m_H≤130)
signal HH
QCD
Higgs + qq
HZ
Z + qq
signal HH
Events
Four b-jets Invariant Mass [GeV]
×10^3
1
10
10^2
10^3
10^4
0
0.5
1
1.5
2
2.5
3

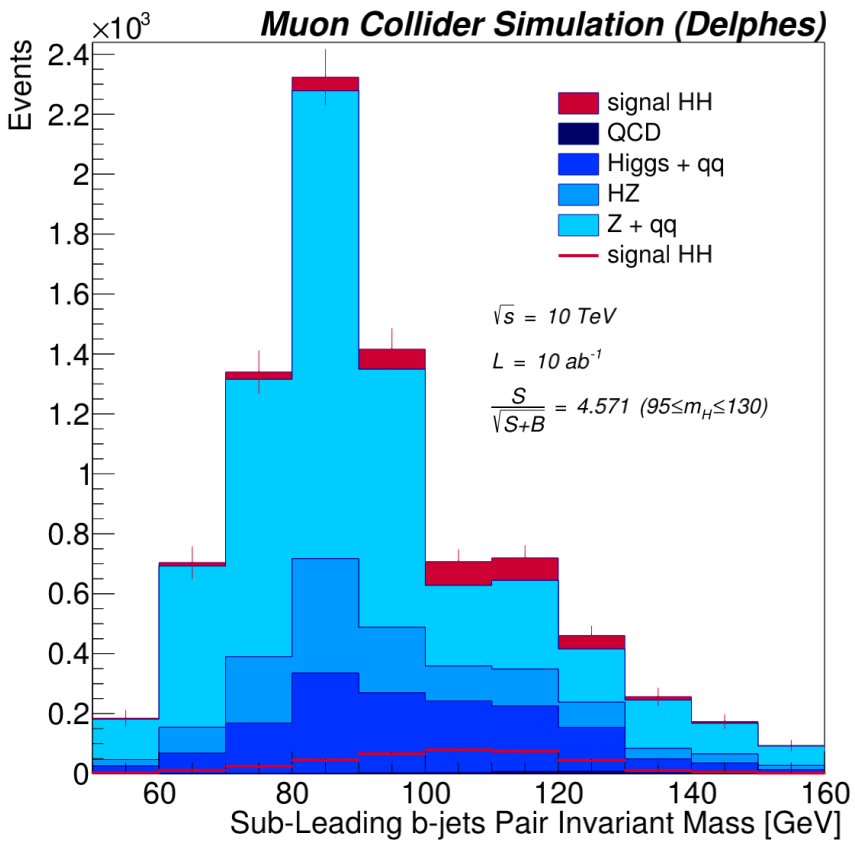

Muon Collider Simulation (Delphes)
Events
signal HH
QCD
Higgs + qq
HZ
Z + qq
signal HH
$\sqrt{s}$ = 6 TeV
L = 4 ab^{-1}
$\frac{S}{\sqrt{S+B}}$ = 2.812 (95≤m_H≤130)
Leading b-jets Pair Invariant Mass [GeV]

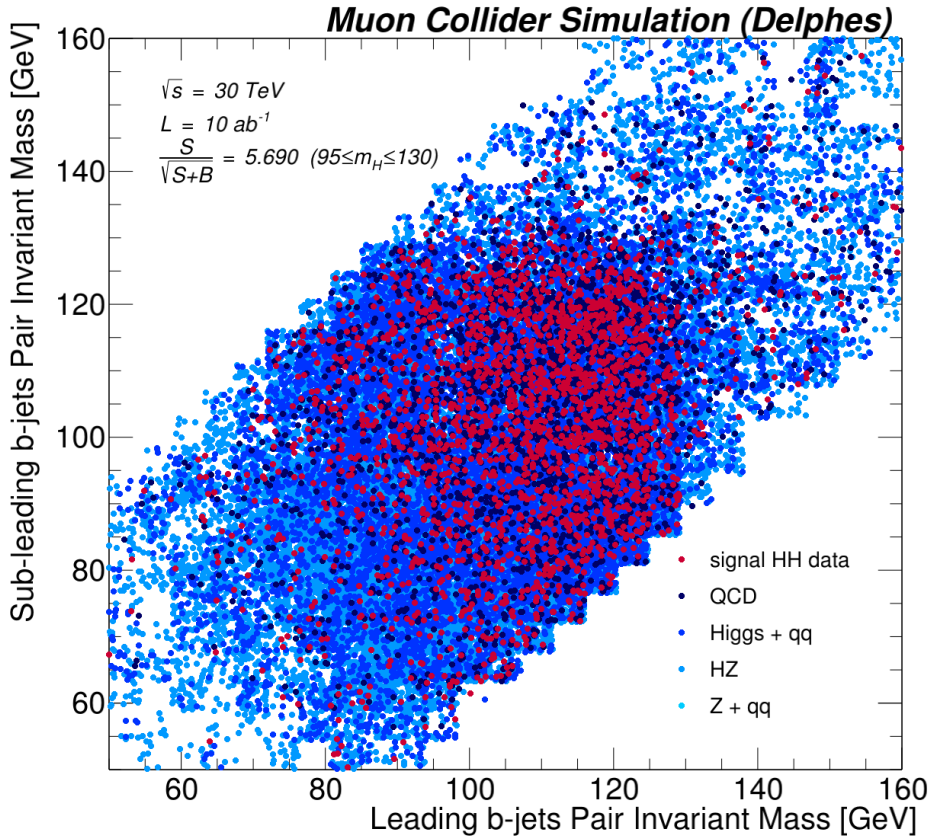

Muon Collider Simulation (Delphes)
Events
signal HH
QCD
Higgs + qq
HZ
Z + qq
signal HH
$\sqrt{s}$ = 6 TeV
L = 4 ab^{-1}
$\frac{S}{\sqrt{S+B}}$ = 2.812 (95≤m_H≤130)
Sub-Leading b-jets Pair Invariant Mass [GeV]

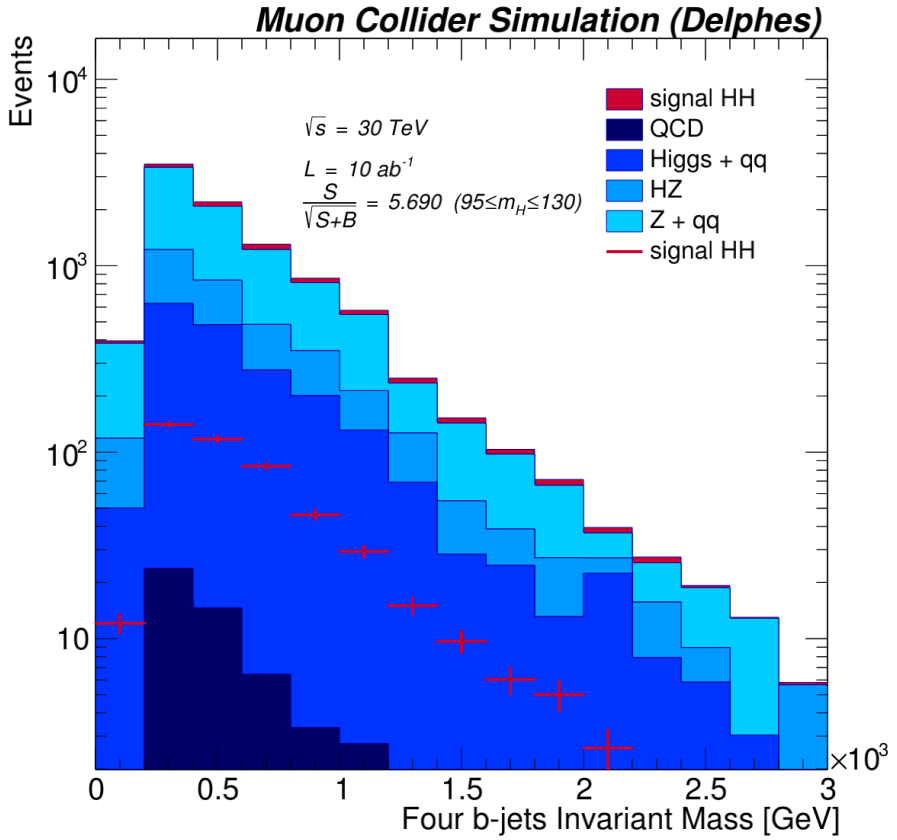

Muon Collider Simulation (Delphes)
$\sqrt{s}$ = 10 TeV
L = 10 ab^{-1}
$\frac{S}{\sqrt{S+B}}$ = 4.571 (95≤m_H≤130)
signal HH data
QCD
Higgs + qq
HZ
Z + qq
Sub-leading b-jets Pair Invariant Mass [GeV]
Leading b-jets Pair Invariant Mass [GeV]
60
80
100
120
140
160

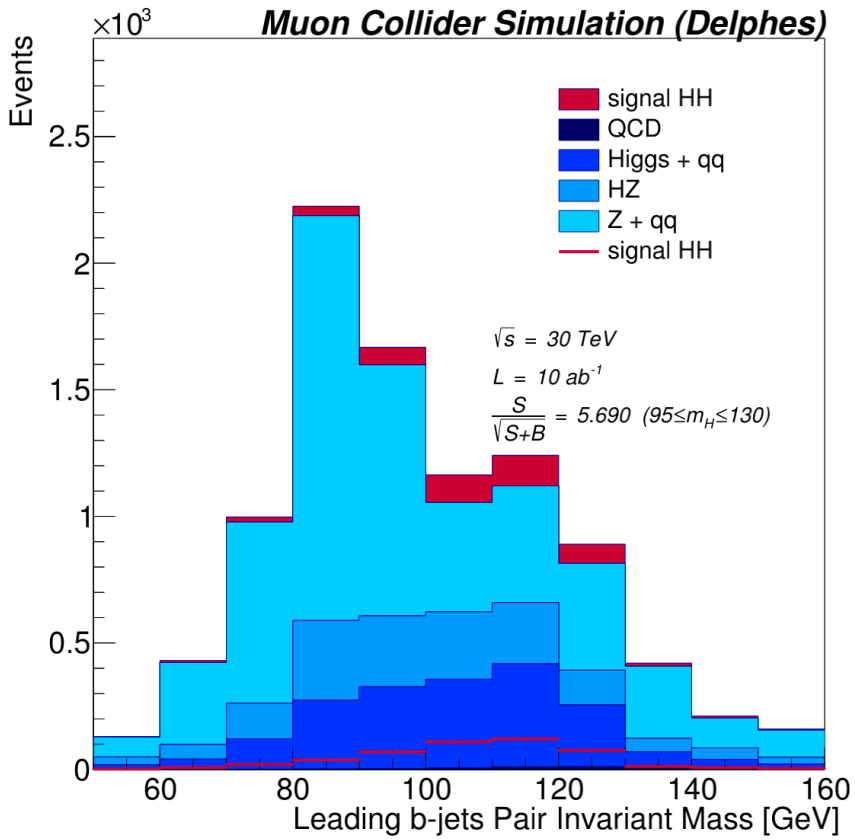

Muon Collider Simulation (Delphes)
$\sqrt{s}$ = 10 TeV
L = 10 ab^{-1}
$\frac{S}{\sqrt{S+B}}$ = 4.571 (95≤m_H≤130)
signal HH
QCD
Higgs + qq
HZ
Z + qq
signal HH
Events
Four b-jets Invariant Mass [GeV]
$\times 10^3$
10^4
10^3
10^2
10
1
0
0.5
1
1.5
2
2.5
3

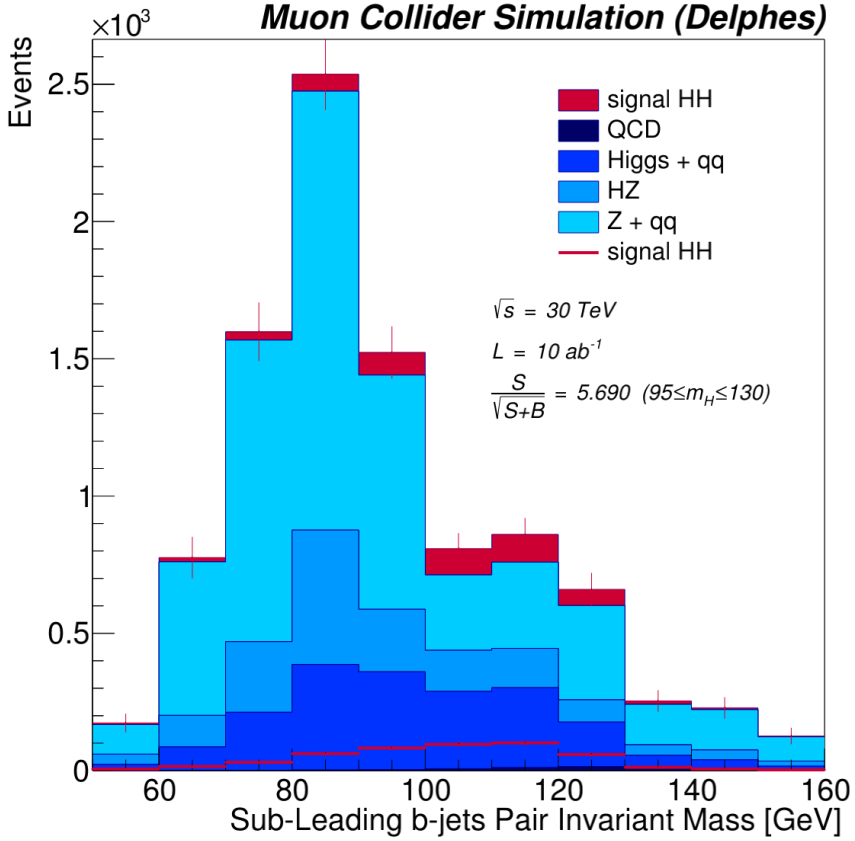

Muon Collider Simulation (Delphes)
Events
×10^3
2.5
2
1.5
1
0.5
0
60
80
100
120
140
160
Leading b-jets Pair Invariant Mass [GeV]
signal HH
QCD
Higgs + qq
HZ
Z + qq
signal HH
√s = 10 TeV
L = 10 ab^-1
S/√(S+B) = 4.571 (95≤m_H≤130)


Muon Collider Simulation (Delphes)
Events
×10^3
2.4
2.2
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
60
80
100
120
140
160
Sub-Leading b-jets Pair Invariant Mass [GeV]
signal HH
QCD
Higgs + qq
HZ
Z + qq
signal HH
√s = 10 TeV
L = 10 ab^-1
S/√(S+B) = 4.571 (95≤m_H≤130)


Muon Collider Simulation (Delphes)
√s = 30 TeV
L = 10 ab-1
S/√S+B = 5.690 (95≤mH≤130)
signal HH data
QCD
Higgs + qq
HZ
Z + qq
Sub-leading b-jets Pair Invariant Mass [GeV]
Leading b-jets Pair Invariant Mass [GeV]
60
80
100
120
140
160


Muon Collider Simulation (Delphes)
√s = 30 TeV
L = 10 ab-1
S/√S+B = 5.690 (95≤mH≤130)
signal HH
QCD
Higgs + qq
HZ
Z + qq
signal HH
Events
Four b-jets Invariant Mass [GeV]
×10^3
10^4
10^3
10^2
10
0
0.5
1
1.5
2
2.5
3


Muon Collider Simulation (Delphes)
×10^3
Events
signal HH
QCD
Higgs + qq
HZ
Z + qq
signal HH
√s = 30 TeV
L = 10 ab^-1
S/√(S+B) = 5.690 (95≤m_H≤130)
Leading b-jets Pair Invariant Mass [GeV]


Muon Collider Simulation (Delphes)
×10^3
Events
signal HH
QCD
Higgs + qq
HZ
Z + qq
signal HH
√s = 30 TeV
L = 10 ab^-1
S/√(S+B) = 5.690 (95≤m_H≤130)
Sub-Leading b-jets Pair Invariant Mass [GeV]

Next step

- Fit
  - An idea is to fit all background to a curve (like MC in real analysis), then we fit the S+B with the curve + a gaussian. But it seems to me that the signal strength is so weak that the gaussian will just have zero amplitude.
- BDT
- DNN later
- Most paper are using BDT(FCC, CLIC, CMS, ATLAS), some are exploring DNN

Appendix: How does MadGraph select which diagrams to include

- By coupling order:
  - Weight assign as QED*2+QCD.
  - Quote from MadGraph authors: “So, the rule for the SM/MSSM is in fact very simple, we take the order having the LOWEST QED order resulting to a nonzero contribution. The motivation for such a rule (besides the fact that, in general, the QED part is sub-dominant) is for the matching procedure (for multi-jet production) where it's important that the multi-jet part is ONLY QCD.”
- With same weight? Why are some diagrams neglected?
  - For example, $\mu^-\mu^+ \to \nu_\mu \bar{\nu}_\mu q\bar{q}H$ does not include $\mu^-\mu^+ \to \nu_\mu \bar{\nu}_\mu ZH$.

Appendix: From CLICdp

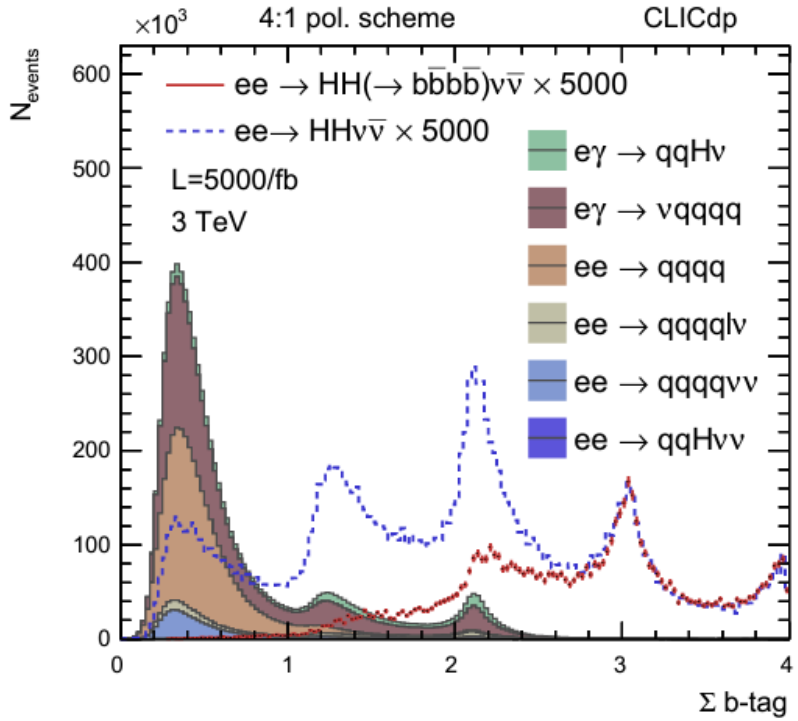


Fig. 4 Distribution of the sum of the *b*-tag values for the inclusive $HH\nu\bar{\nu}$ and the $HH\nu\bar{\nu} \to b\bar{b}b\bar{b}\nu\bar{\nu}$ channel, both scaled by a factor 5000 for better visibility, and for the background processes. No selection is applied

Process	σ/fb	$\epsilon_{\text{looseBDT}}$ (%)	N_{looseBDT}	$\epsilon_{\text{tightBDT}}$ (%)	N_{tightBDT}
$e^+e^- \to HH\nu\bar{\nu}$	0.59	17.6	766	8.43	367
Only HH→ $b\bar{b}b\bar{b}$	0.19	53.4	734	26.3	361
Only HH→ other	0.40	1.1	32	0.2	6
$e^+e^- \to q\bar{q}q\bar{q}$	547	0.0065	259	0.00033	13
$e^+e^- \to q\bar{q}q\bar{q}\nu\bar{\nu}$	72	0.17	876	0.017	90
$e^+e^- \to q\bar{q}q\bar{q}l\bar{\nu}$	107	0.053	421	0.0029	23
$e^+e^- \to q\bar{q}H\nu\bar{\nu}$	4.7	3.8	1171	0.56	174
$e^\pm\gamma \to \nu q\bar{q}q\bar{q}$	523	0.023	821	0.0014	52
$e^\pm\gamma \to q\bar{q}H\nu$	116	0.12	979	0.0026	21