PEKING UNIVERSITY

Longitudinally polarized ZZ scattering at the Muon Collider

Tianyi Yang,[1] Sitian Qian,[1] Congqiao Li,[1] Zhe Guan,[1]
Fanqiang Meng,[1] Jie Xiao,[1] Meng Lu,[2] and Qiang Li[1]

[1] *Department of Physics and State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, 100871, China*

[2] *School of Physics, Sun Yat-Sen University, Guangzhou 510275, China*

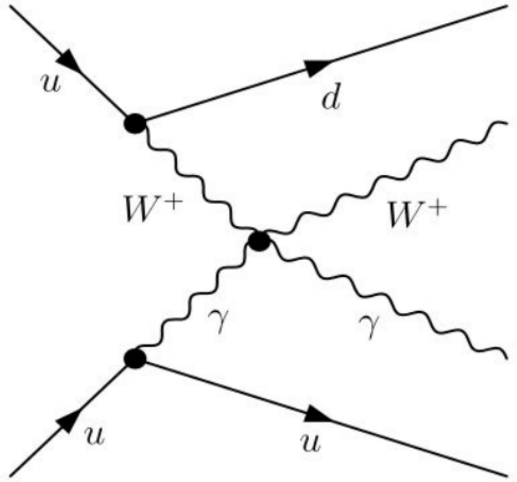
tyyang99@pku.edu.cn

https://doi.org/10.1103/PhysRevD.104.093003

Contents

VBS and longitudinal polarization

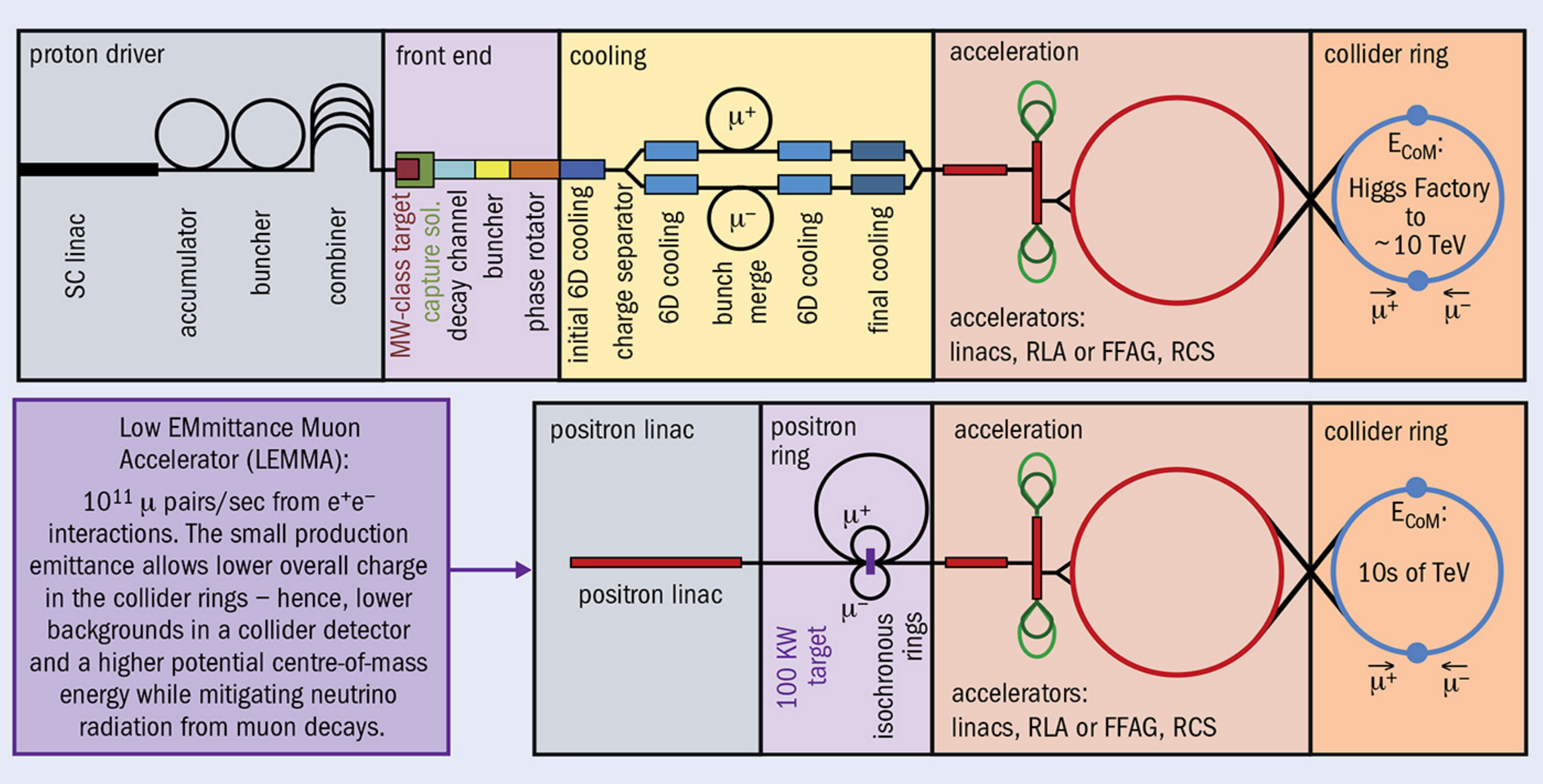
- VBS: scattering between two vector bosons radiated from incoming partons.
  - At the LHC:
    - Two very forward jets, with large eta separation and invariant mass
    - Low hadronic activity in central region
- longitudinal polarization
  - Closely related to the important theoretical property of unitarity restoration through Higgs and possible new physics
  - Below 10% of the total VBS
  - Needs long time to reach 5σ(same-sign WW at the CMS)
    - full simulation: 2.7σ at the 14TeV HL_LHC
    - full Run II: about 1σ



An example Feynman diagram of VBS at the LHC

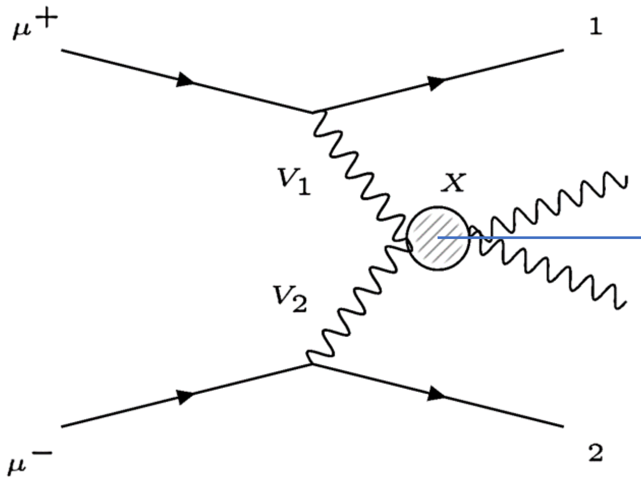
Why we choose the Muon Collider?

- High collision energy
  - Fundamental particle
    - more effective than LHC
  - $m_\mu \approx 207 m_e$
    - Reduced synchrotron radiation
- High luminosity
- More details:
  https://muoncollider.web.cern.ch/



Physics processes at the Muon Collider

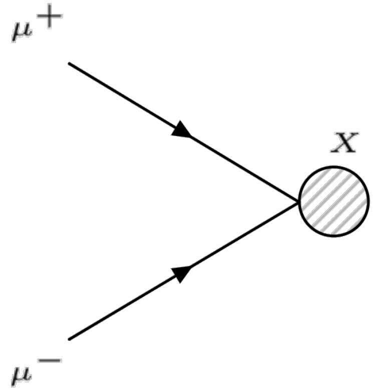
- VBS processes



$$X = nt\bar{t} + mV + kH$$

$$\begin{cases} \mu^+\mu^- \to X\,\nu_\mu\bar{\nu}_\mu & \text{(WW\_VBS)} \\ \mu^+\mu^- \to X\,\mu^+\mu^- & \text{(ZZ\_VBS)} \\ \mu^+\mu^- \to X\,\mu^\pm \overset{(-)}{\nu_\mu} & \text{(WZ\_VBS)} \end{cases}$$

- s-channel



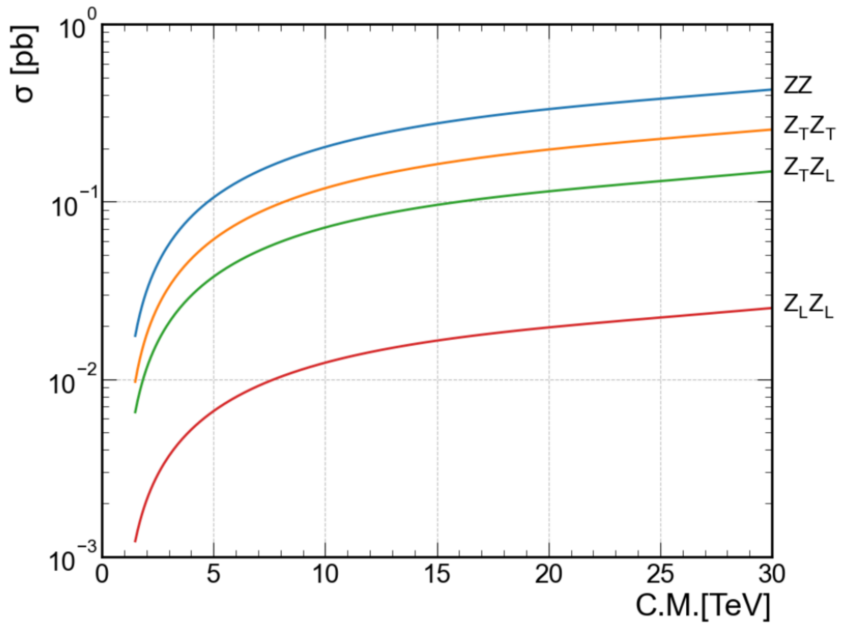
Simpler than the LHC, can be expressed as a "high-luminosity weak boson collider"

Signal and backgrounds processes selection

- Signal:
  - $Z_L Z_L \rightarrow 4l$ in WW_VBS
- 14 TeV, $L = 20\text{ab}^{-1}$; 6TeV, $L = 4\text{ab}^{-1}$, using

$$L = 10\text{ab}^{-1} \times \left(\frac{E_{\text{cm}}}{10\text{TeV}}\right)^2$$

- Backgrounds:
  - Have sufficiently large cross section
  - Exist the possibility of decaying to 4 leptons



SM process type	Selected background
WW_VBS	$H, HZ, HZZ, HWW, HH, WWZ, ZZZ, Z_TZ_T, Z_TZ_L, t\bar{t}Z$
ZZ_VBS	$H, WW, t\bar{t}, 4e, 2e2\mu, 4\mu$
WZ_VBS	WZ, WZH, WH, WWW, WZZ
s-channel	ZZ, WWZ

Analysis steps

- 1.Events generation

MadGraph 2.9.X $\xrightarrow{\text{.lhe}}$ Pythia8 $\xrightarrow{\text{.hepmc}}$ Delphes 3.5.0

- 2.Initial selection
  - select events using root file generated by delphes.
- 3.Use Boosted Decision Tree(BDT) algorithm to distinguish between signals and backgrounds.

Initial events selection

- 4 pt > 20GeV leptons
  - 2muons 2electrons
    - ——charge(l1)*charge(l2)==-1 and charge(l3)*charge(l4)==-1
  - 4muons or 4electrons
    - ——sum(charge(4l))==0 and $\prod$ charge(4l)==1
- delta_r(Ktjets, leptons)
  - clean leptons ——$\Delta R < 0.5$
  - if no jets left ——select
- separate 4 leptons to 2 "Z bosons"

$p_{T_{Z1}} > p_{T_{Z2}}$

  - $l_1^+ l_2^+ l_3^- l_4^- \rightarrow l_1 l_3, l_2 l_4; l_1 l_4, l_2 l_3$
  - $\Delta M^2 = \left(M_{Z_1'} - M_Z\right)^2 + \left(M_{Z_2'} - M_Z\right)^2$
  - $\Delta M^2_{13,24} > \Delta M^2_{14,23} \rightarrow$ choose 14,23, vice versa
  - $2e2\mu$: $Z_1 \rightarrow e^+ e^-, Z_2 \rightarrow \mu^+ \mu^-$

4 $p_t > 20$GeV leptons

↓

The type of leptons is one of $(4e, 4\mu, 2e2\mu)$, satisfying charge conservation

↓

no jets: no component in kt-jet tree have $\Delta R > 0.5$ with all the 4 leptons

↓

reconstruct 4 leptons to 2 "Z bosons"

BDT parameters setting

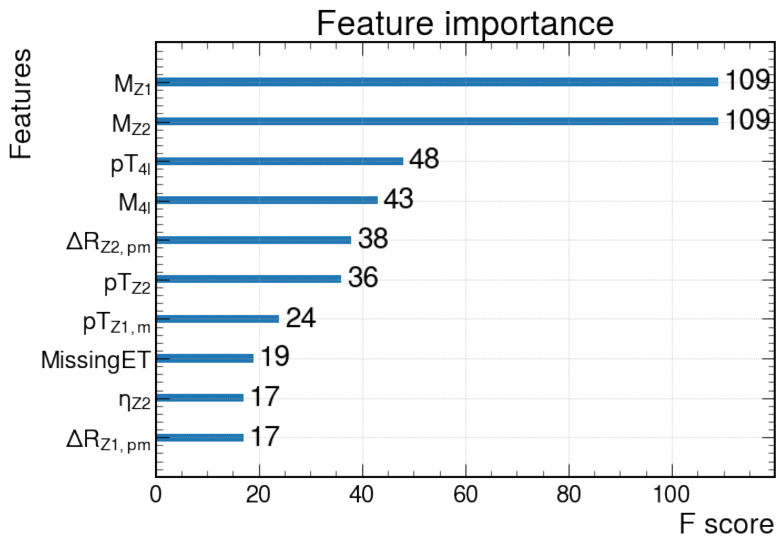
- Shuffle the signal and background events and define the training and test sets with the event ratio of 2 : 1.
- num of trees=200, max depth=5
- apply the per-event weight to account for the cross-section difference among the processes. The weight is defined by:

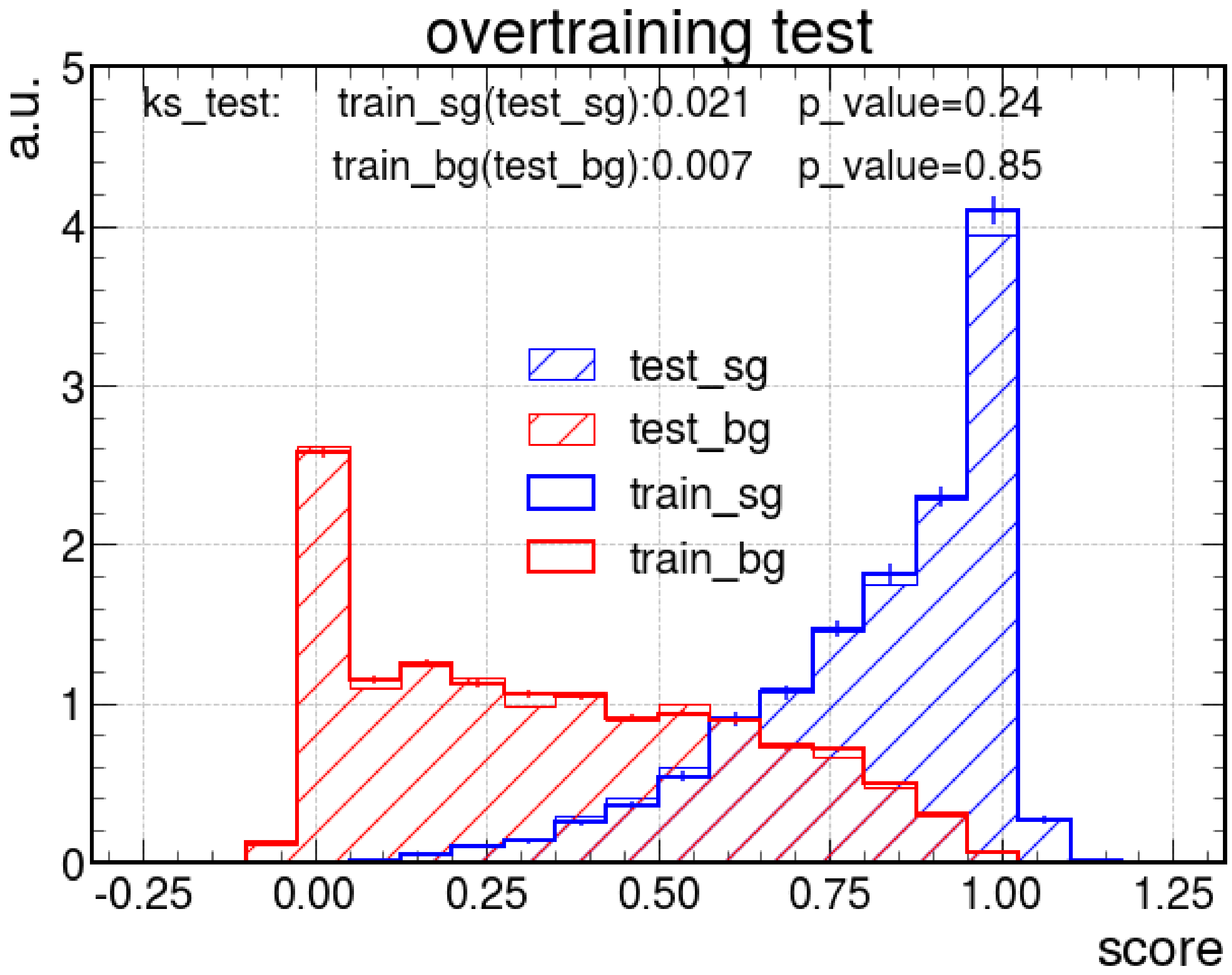
$$n_L = \sigma_X L / N_{G_X}$$

BDT training results—— $\sqrt{S} = 14\text{TeV}$

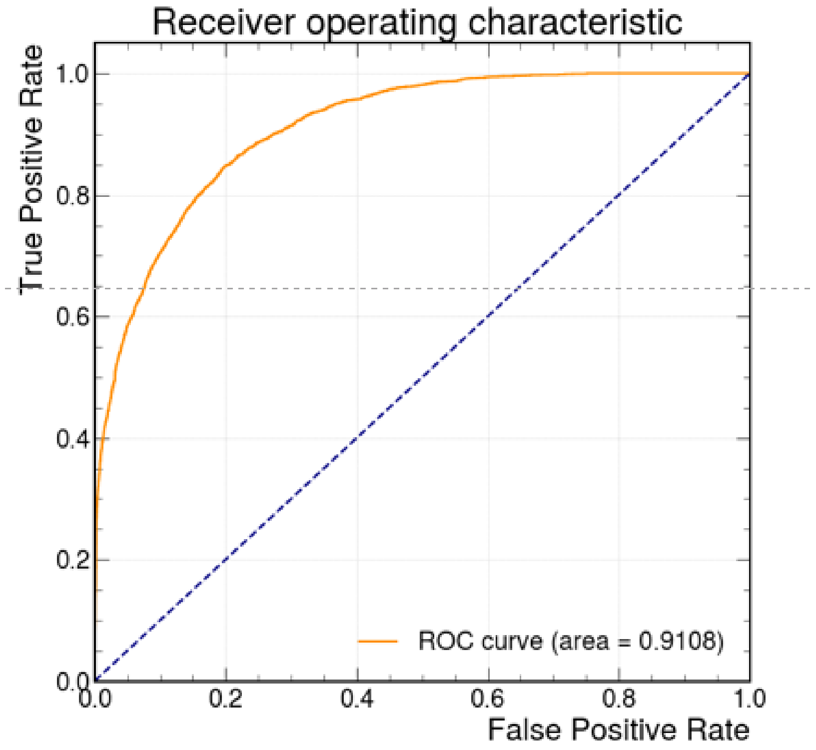
Objective	Features	Number of features
Each lepton	$(p_{\mathrm{T}},\ \eta,\ \phi)$	12
Each "Z boson"	$(p_{\mathrm{T}},\ \eta,\ \phi,\ m_{\mathrm{inv}})$	8
Four leptons combined	$(p_{\mathrm{T},4\ell},\ \eta_{4l},\ \phi_{4l},\ m_{4l})$	4
$\not{E}$	$(p_{\mathrm{T}},\ \eta,\ \phi)$	3
Between two Z bosons	$(\Delta\eta,\ \Delta\phi,\ \Delta R)$	3
Between 2ℓ of Z_1	$(\Delta\eta,\ \Delta\phi,\ \Delta R)$	3
Between 2ℓ of Z_2	$(\Delta\eta,\ \Delta\phi,\ \Delta R)$	3
Lepton flavor type	$(1,\ -1,\ 0)$ for $(4e,\ 4\mu,\ 2e2\mu)$	1
Total:		37

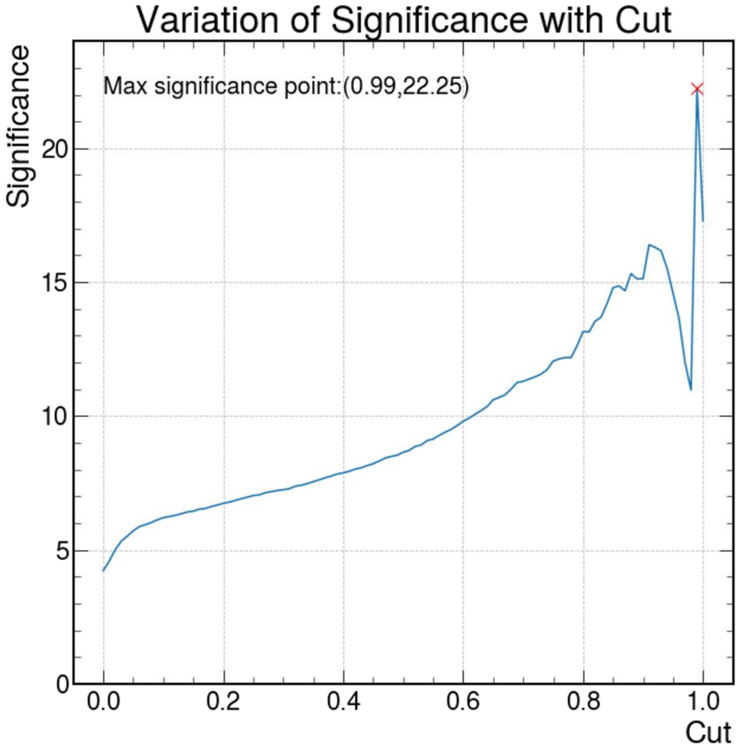
Summary of features used for training BDT model





BDT training results

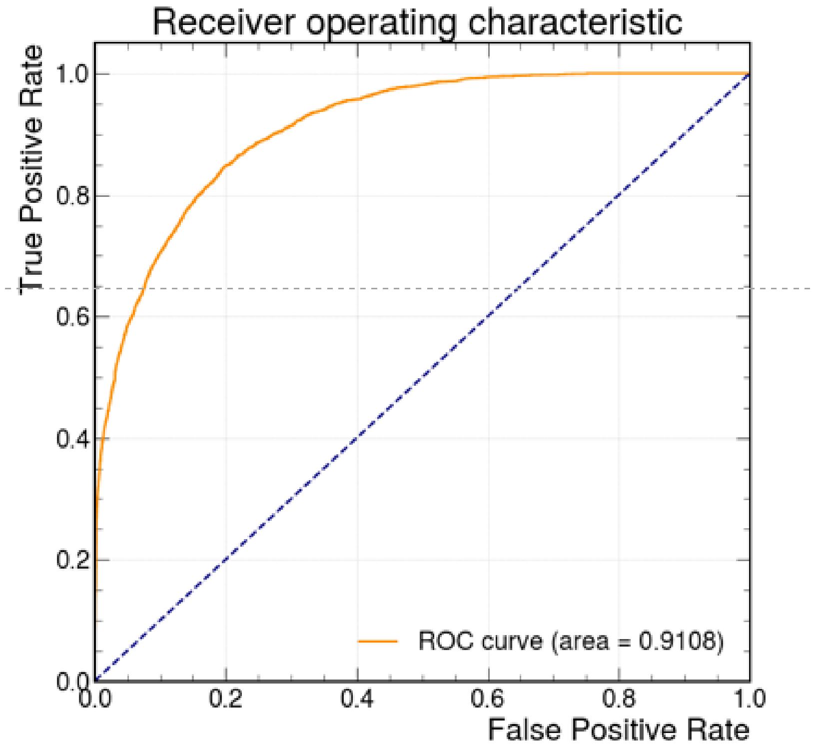


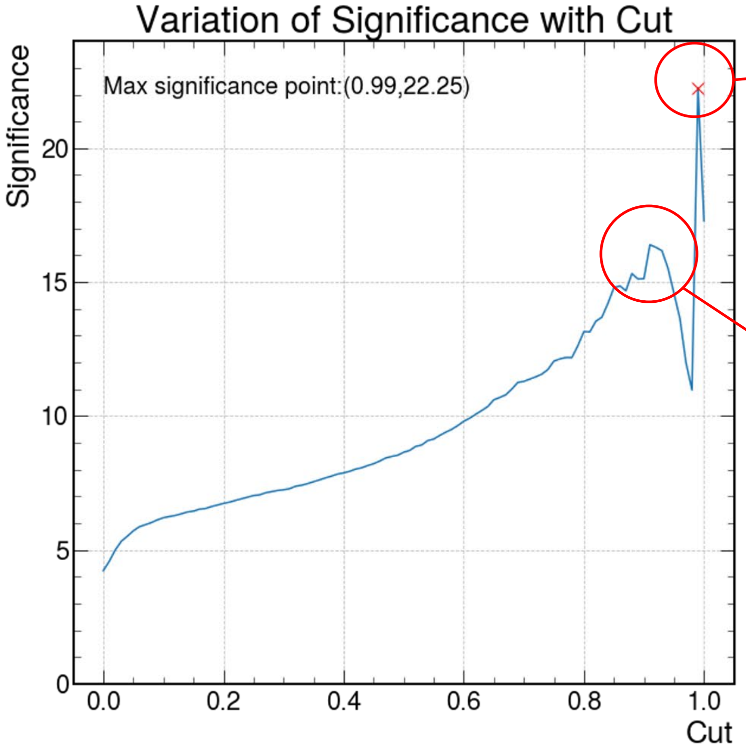


$$S = \sqrt{2(s+b)\ln\left(1+\frac{s}{b}\right) - 2s}$$

$s(b)$ means the weighted number of signal(background) events

BDT training results





Invalid! Mainly due to the events with big n_{L_X} from 1 to 0

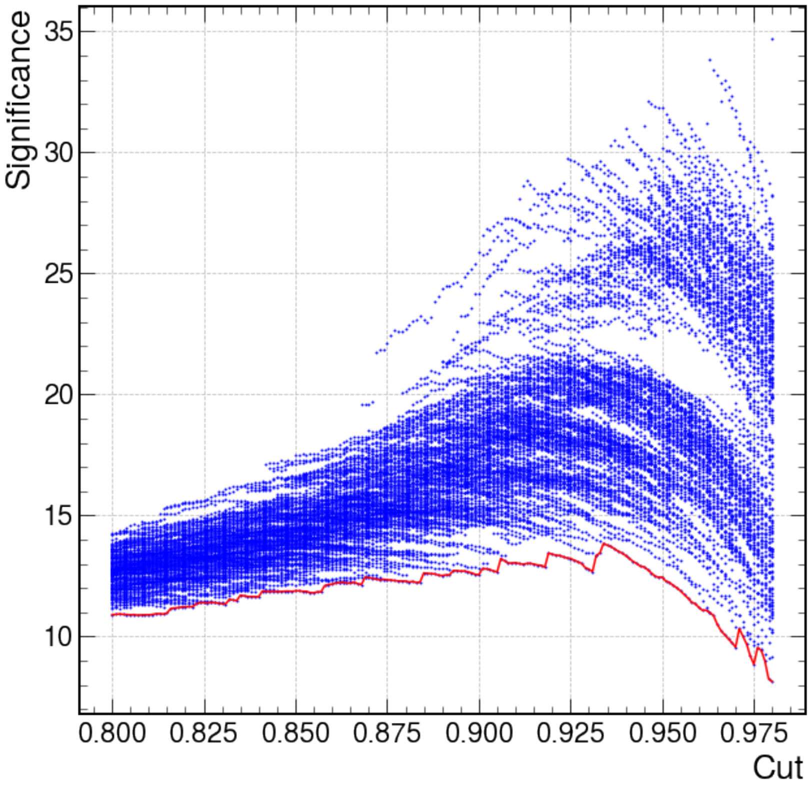
More reliable

$$S = \sqrt{2(s+b)\ln\left(1+\frac{s}{b}\right) - 2s}$$

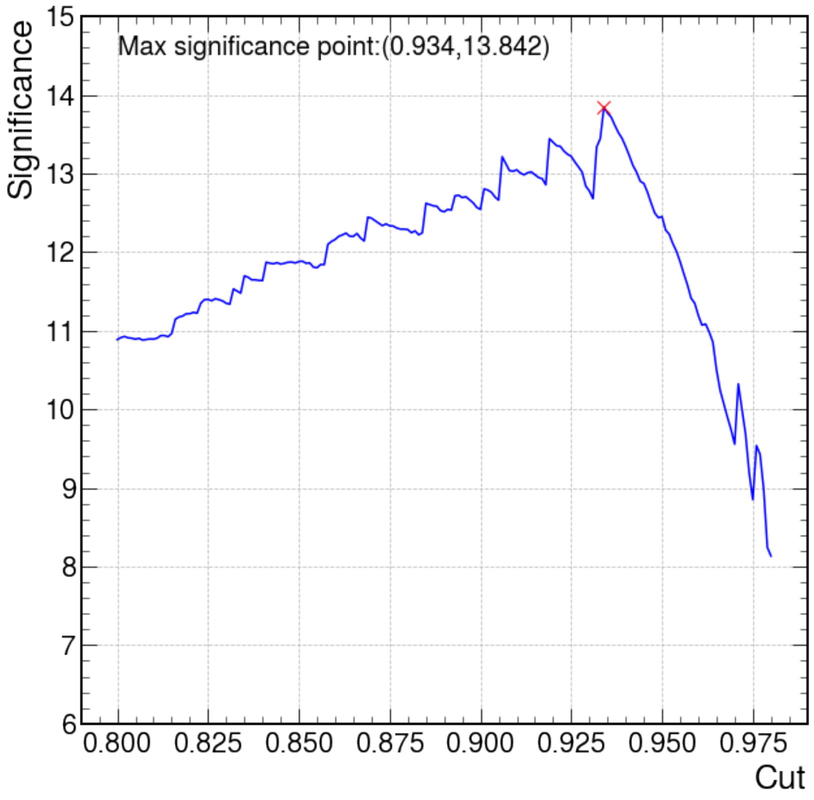
pause the scanning of threshold at 0.95

BDT training results

➢split the training and test sets with 150 different random configurations:



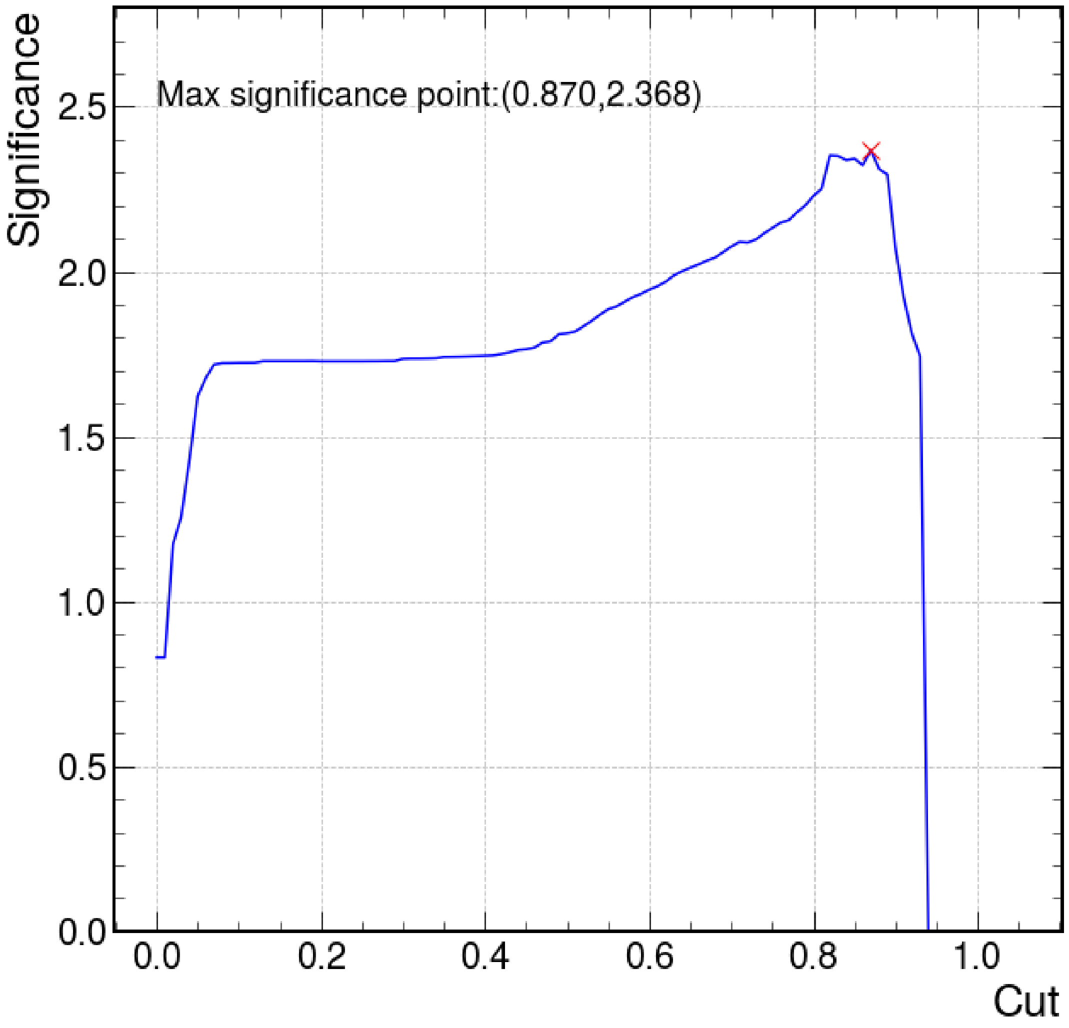
extract the Lower envelope



Optimal cut value ≈ 0.93, Significance ≈ 14σ

Comparison between $\sqrt{S} = 14\text{TeV}\&6\text{TeV}$

- Same analysis frame, but get $S_{\max} \approx 2.4\sigma$
- Three main reasons
  - 1. Smaller cross-section of signal, larger cross-section of some backgrounds
  - 2. Fewer events after initial selection (1/10 of signal)
  - 3. Harder to distinguish between signal and backgrounds——mainly between different polarization fraction



Outlook and conclusions

- $\sqrt{s} = 14\text{TeV}$
  - $S \approx 14\sigma$ when $L = 20\text{ab}^{-1}$, to reach 5σ, $L' \approx 3000\text{fb}^{-1}$
  - For the muon collider, such luminosity will take less than 5 years
- $\sqrt{s} = 6\text{TeV}$
  - $S \approx 2.4\sigma$ when $L = 4\text{ab}^{-1}$

THANKS!

BACKUP

Comparison between BDT and cut-based method

➢cut-flow table and the corresponding significance:

cuts	s	b	$S\,[\sigma]$
$70\text{GeV} < M_{Z1},\ M_{Z2} < 140\text{GeV}$	476.5	6592.1	5.8
$70\text{GeV} < M_{Z1},\ M_{Z2} < 140\text{GeV},\ \Delta R_{Z2,pm} < 0.4$	238.1	1165.9	6.8
$70\text{GeV} < M_{Z1},\ M_{Z2} < 140\text{GeV},\ \Delta R_{Z2,pm} < 0.4,$ $p_{\mathrm{T},4\ell} < 300\text{GeV}$	213.5	424.9	9.6
$70\text{GeV} < M_{Z1}, M_{Z2} < 140\text{GeV},\ \Delta R_{Z2,pm} < 0.4,$ $p_{\mathrm{T},4\ell} < 300\text{GeV},\ \not{E} < 140\text{GeV}$	147.8	158.1	10.4

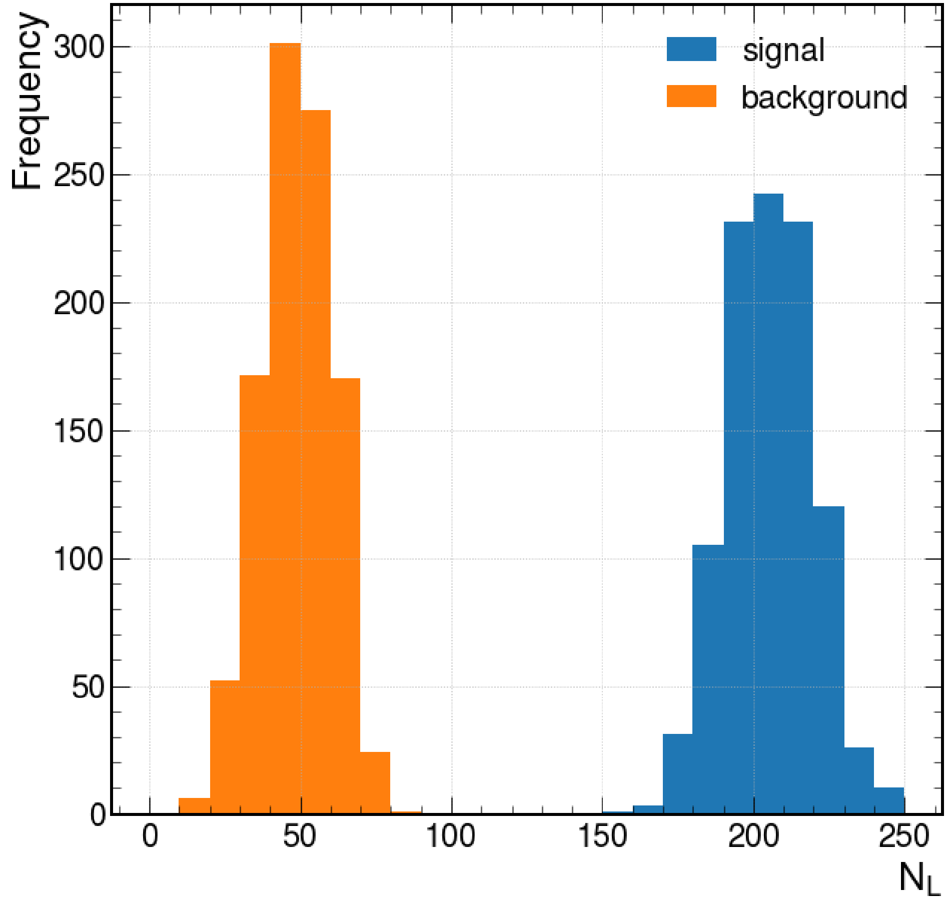
$\Delta R_{Z2,pm}$: ΔR between the two leptons forming Z_2

$$L'' = \frac{5^2}{10^2} L \approx 5\text{ab}^{-1} = 5000\text{fb}^{-1}$$

Comparison between BDT and cut-based method

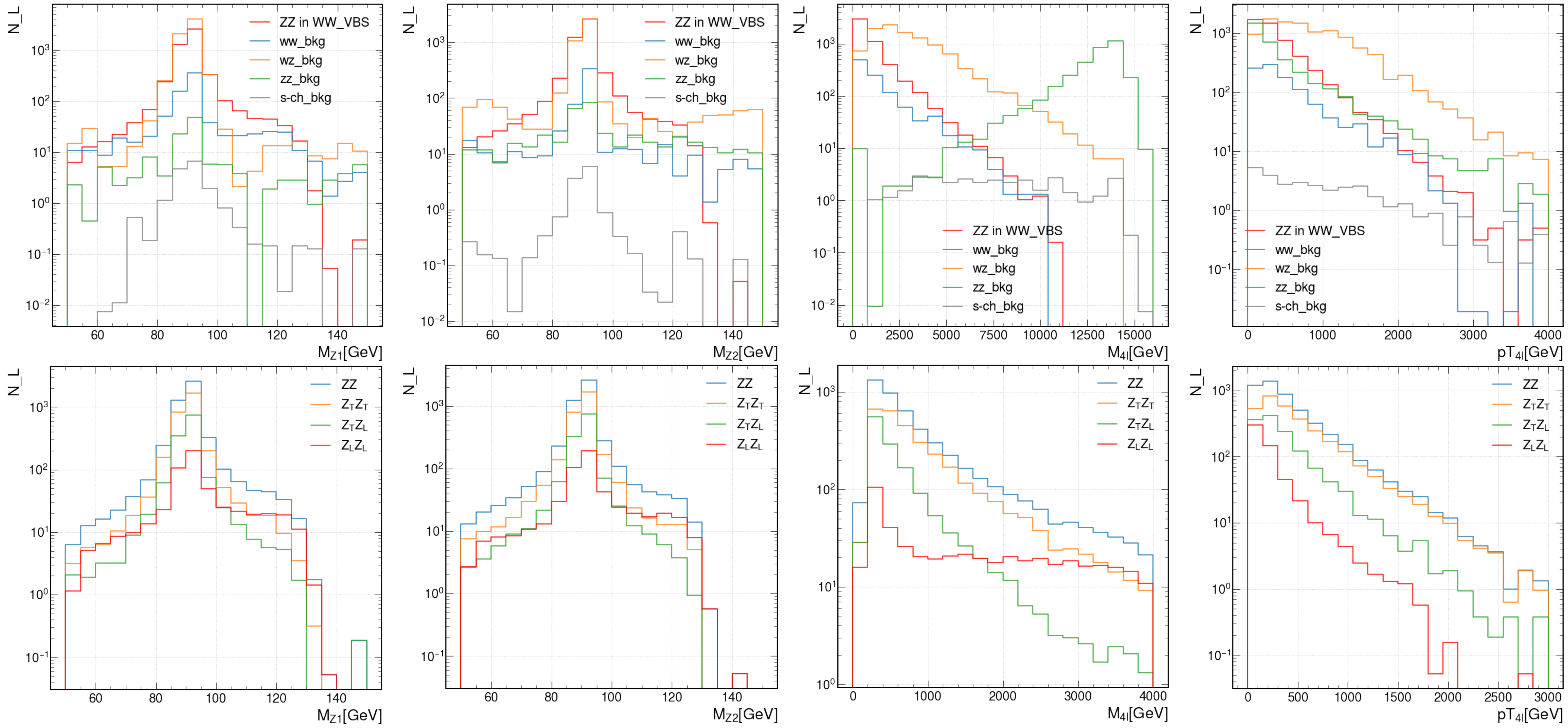
- set cut=0.93, get distribution of N_L of signal and backgrounds in 1000 randomly selected cases
  - $\bar{s} = 205.7, \bar{b} = 49.2$
  - $\hat{\sigma}_s = 14.1, \hat{\sigma}_b = 11.7$
- using $S = \sqrt{2(s+b)\ln\left(1+\frac{s}{b}\right) - 2s}$
  - $s = \bar{s}, b = \bar{b}, S = 20.67$
  - $s = \bar{s} - 3\hat{\sigma}_s, b = \bar{b} + 3\hat{\sigma}_b, S = 14.38$

$$L' = \frac{5^2}{14^2} L \approx 3\text{ab}^{-1} = 3000\text{fb}^{-1}$$



Comparison between BDT and cut-based method

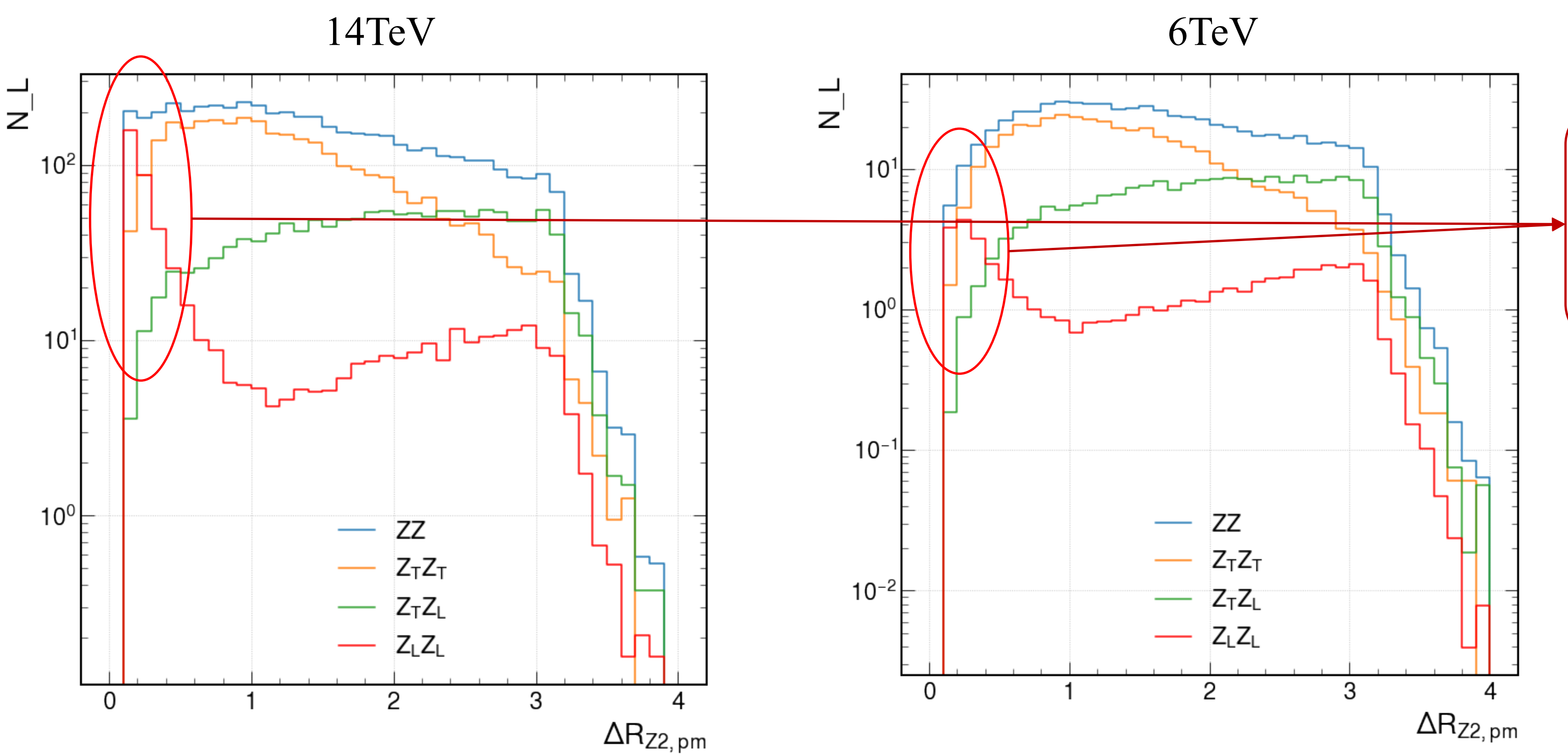
- Consider the top 10 features:



● ● ● ● ● ●

Comparison between $\sqrt{S} = 14\text{TeV}\&6\text{TeV}$

➢Evidence of the 3rd reason



signal stands out at $\Delta R_{Z2,pm} \approx 0$

Discussion about the evidence

- Why exists a peak at $\Delta R_{Z2,pm} \approx 0$?
  - MG run_card: no cut decay

```
#*********************************************************************
# Apply pt/E/eta/dr/mij/kt_durham cuts on decay products or not
# (note that etmiss/ptll/ptheavy/ht/sorted cuts always apply)
#*********************************************************************
 False = cut_decays ! Cut decay products
```

  - delphes muon_collider_card: $\Delta R_{\max} = 0.1$——$\Delta R_{\max} = 0.5$ in CMS_card

```
module Isolation MuonIsolation {
    set CandidateInputArray MuonEfficiency/muons
    set IsolationInputArray EFlowMerger/eflow

    set OutputArray muons

    set DeltaRMax 0.1

    set PTMin 0.5

    set PTRatioMax 0.2
}
```

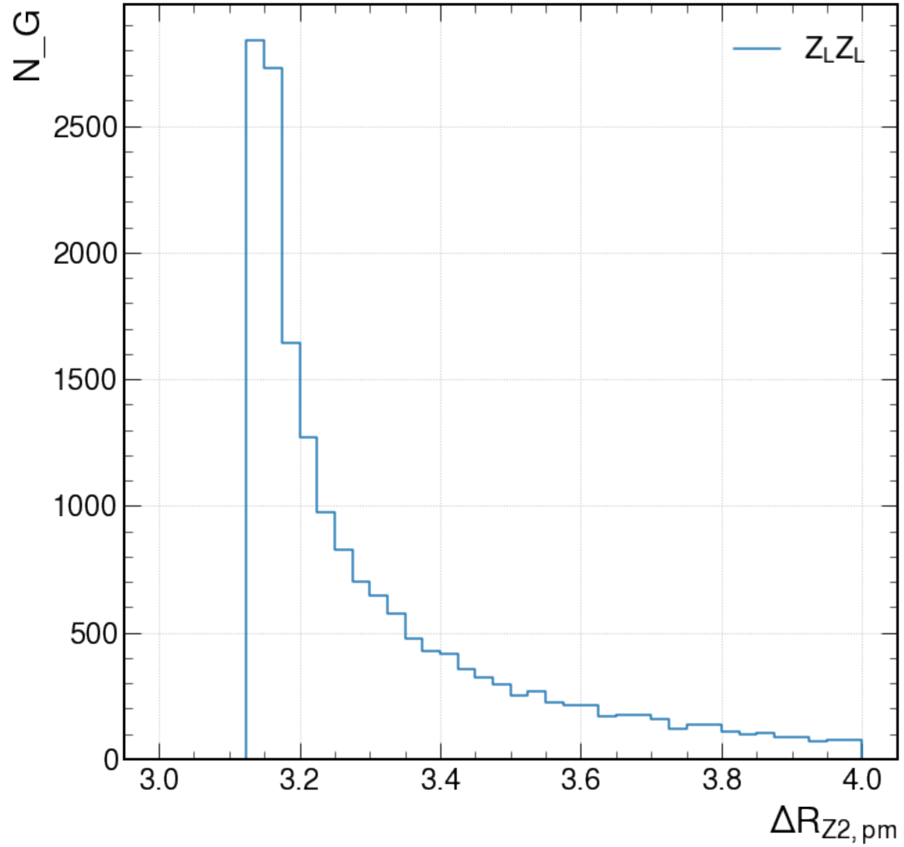
muon_collider_card

```
module Isolation MuonIsolation {
  set CandidateInputArray MuonEfficiency/muons
  set IsolationInputArray EFlowFilter/eflow

  set OutputArray muons

  set DeltaRMax 0.5

  set PTMin 0.5

  set PTRatioMax 0.25
}
```

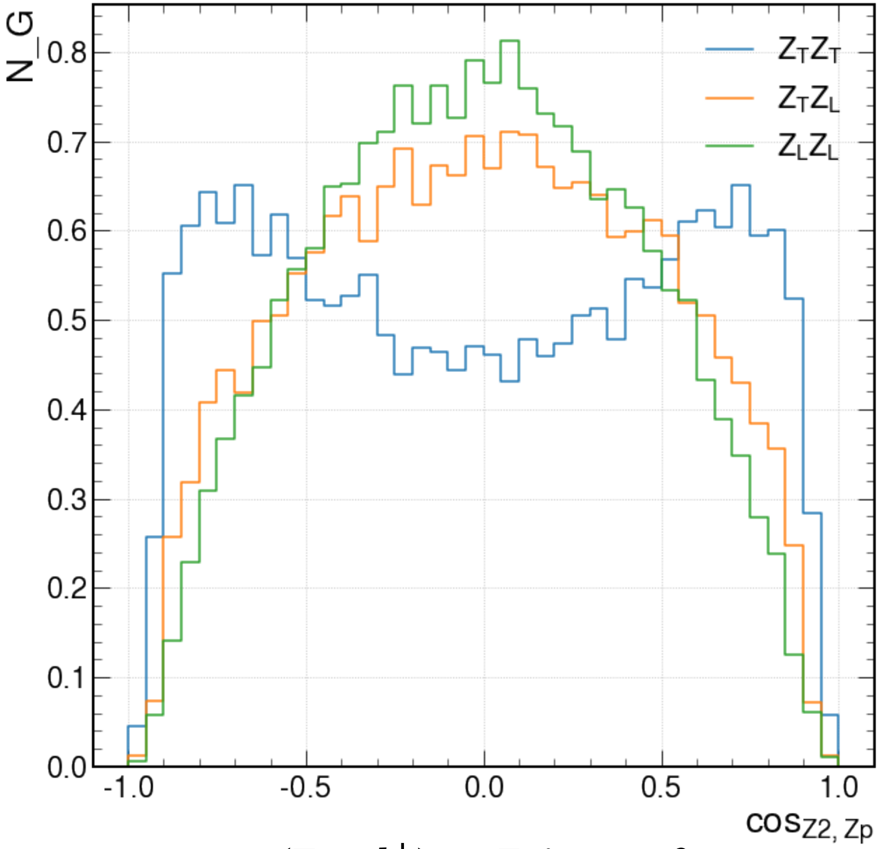
CMS_card

Verify the correctness of MC simulation

- Check two variables at the Z boson's rest frame



$\Delta R_{Z2,pm} > \pi$



$\cos(\mathrm{Z}_2, l^+)$ at Z_2's rest frame

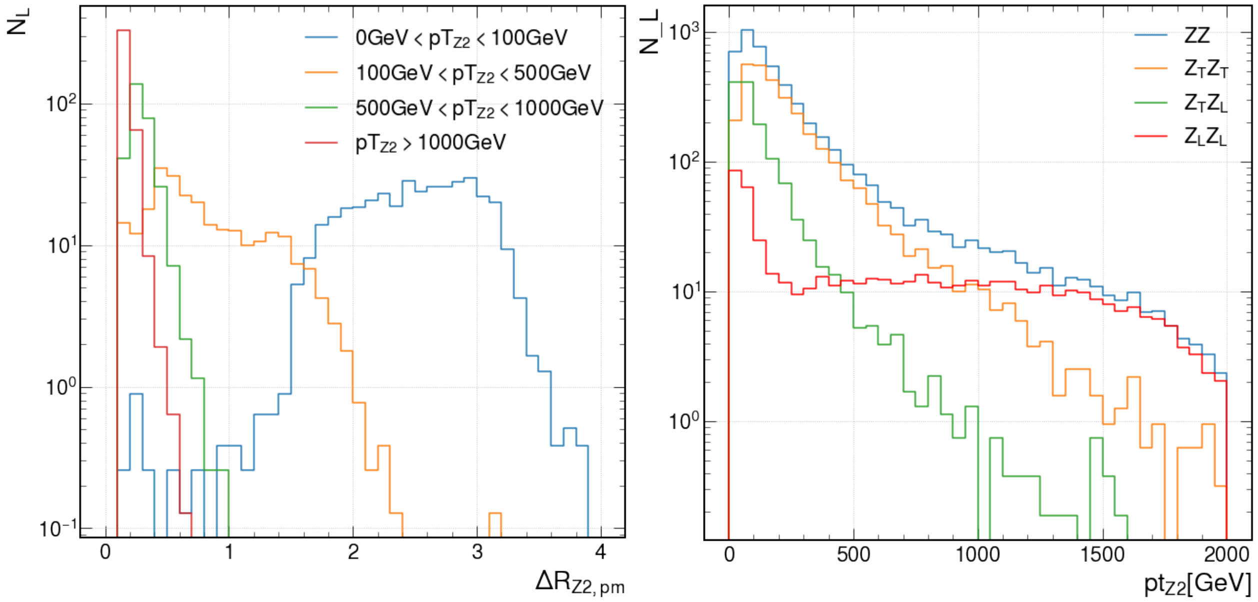
Cut-flow table and the corresponding S when $\Delta R_{Z_{1,2},pm} > 0.2$

cuts	s	b	$S\,[\sigma]$
$\Delta R_{Z_{1,2},pm} > 0.2$	334.3	14331.2	2.8
$0.2 < \Delta R_{Z_1,pm} < 0.8$, $0.2 < \Delta R_{Z_2,pm} < 0.5$	108.7	1007.6	3.4
$0.2 < \Delta R_{Z_1,pm} < 0.8$, $0.2 < \Delta R_{Z_2,pm} < 0.5$, $60\text{GeV} < M_{Z1}, M_{Z2} < 130\text{GeV}$	100.0	695.4	3.7
$0.2 < \Delta R_{Z_1,pm} < 0.8$, $0.2 < \Delta R_{Z_2,pm} < 0.5$, $60\text{GeV} < M_{Z1}, M_{Z2} < 130\text{GeV}$, $p_{\mathrm{T},4\ell} < 500\text{GeV}$	97.0	400.7	4.7
$0.2 < \Delta R_{Z_1,pm} < 0.8$, $0.2 < \Delta R_{Z_2,pm} < 0.5$, $60\text{GeV} < M_{Z1}, M_{Z2} < 130\text{GeV}$, $p_{\mathrm{T},4\ell} < 500\text{GeV}$, $M_{4l} < 3000\text{GeV}$, $\not{E} < 180\text{GeV}$	61.7	90.2	5.9

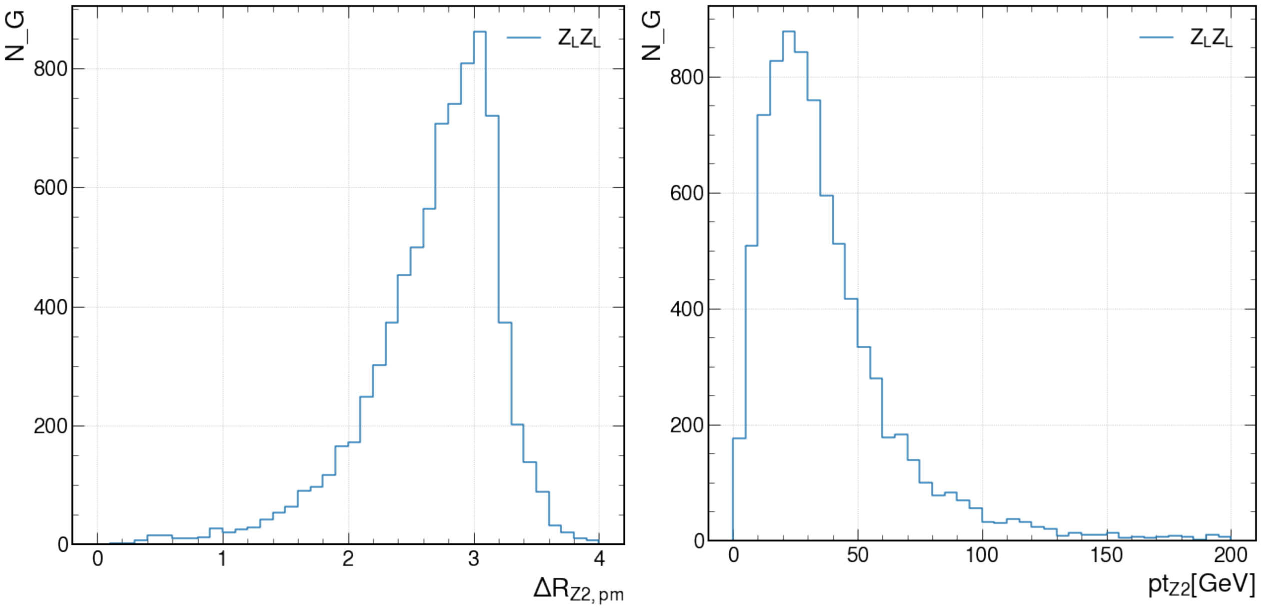
- $\Delta R_{Z_{1,2},pm}$ has a significant impact on the results, require better detector resolution

Comparison between the Muon Collider and the LHC

pp > ZZjj, Z > l+l-



Distributions of $\Delta R_{Z2,pm}$ in different $p_{T_{Z2}}$ intervals at the Muon Collider



Distributions of $\Delta R_{Z2,pm}$ and $p_{T_{Z2}}$ at the LHC