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Testing the standard model and searching for new physics at the Future Collider

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  - https://doi.org/10.1103/PhysRevD.104.093003
- The physics case for a **neutrino lepton collider** in light of the CDF W mass measurement
  - https://arxiv.org/abs/2204.11871

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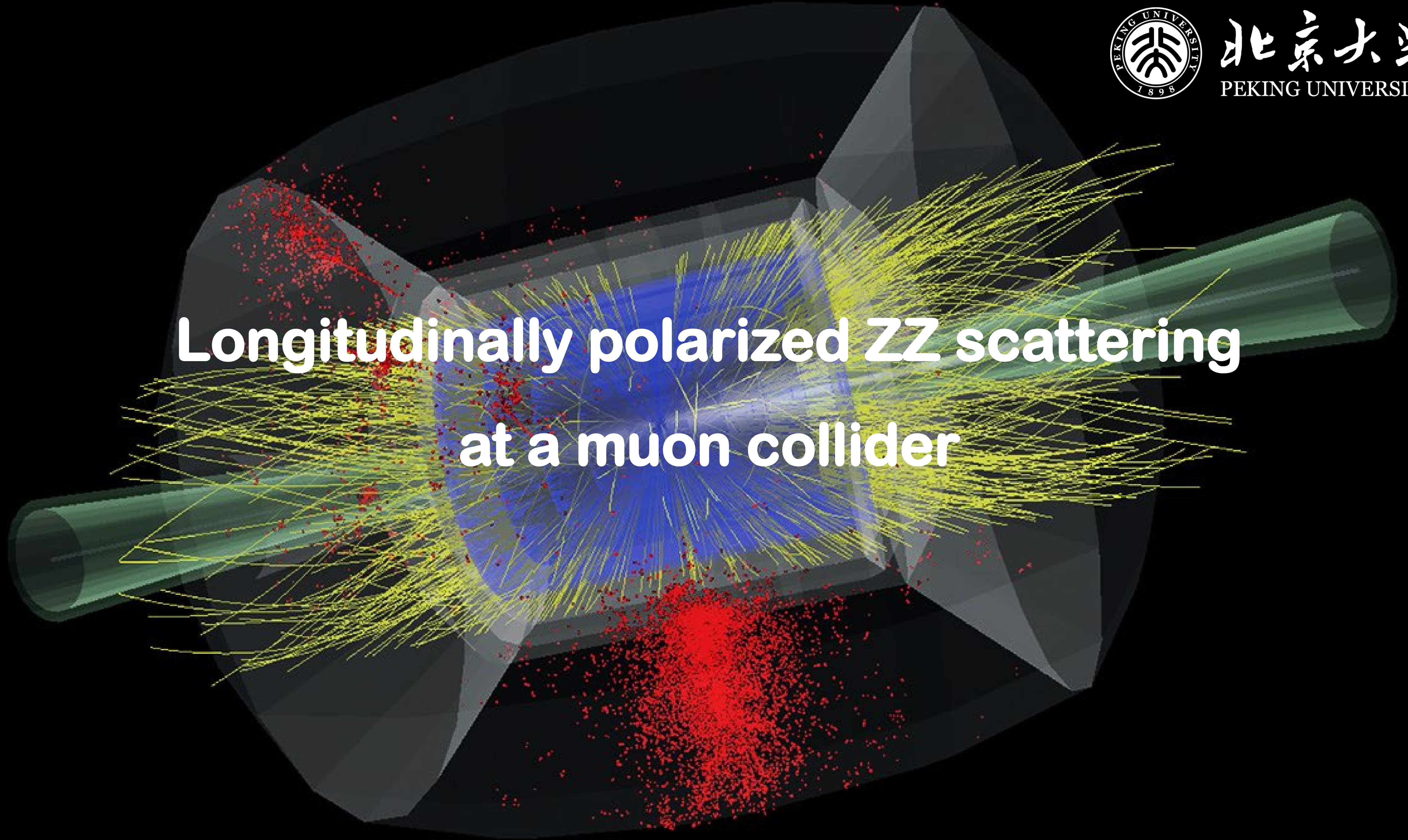
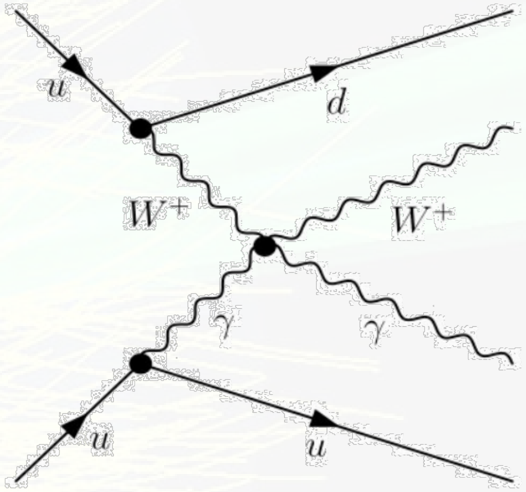


Longitudinally polarized ZZ scattering at a muon collider

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

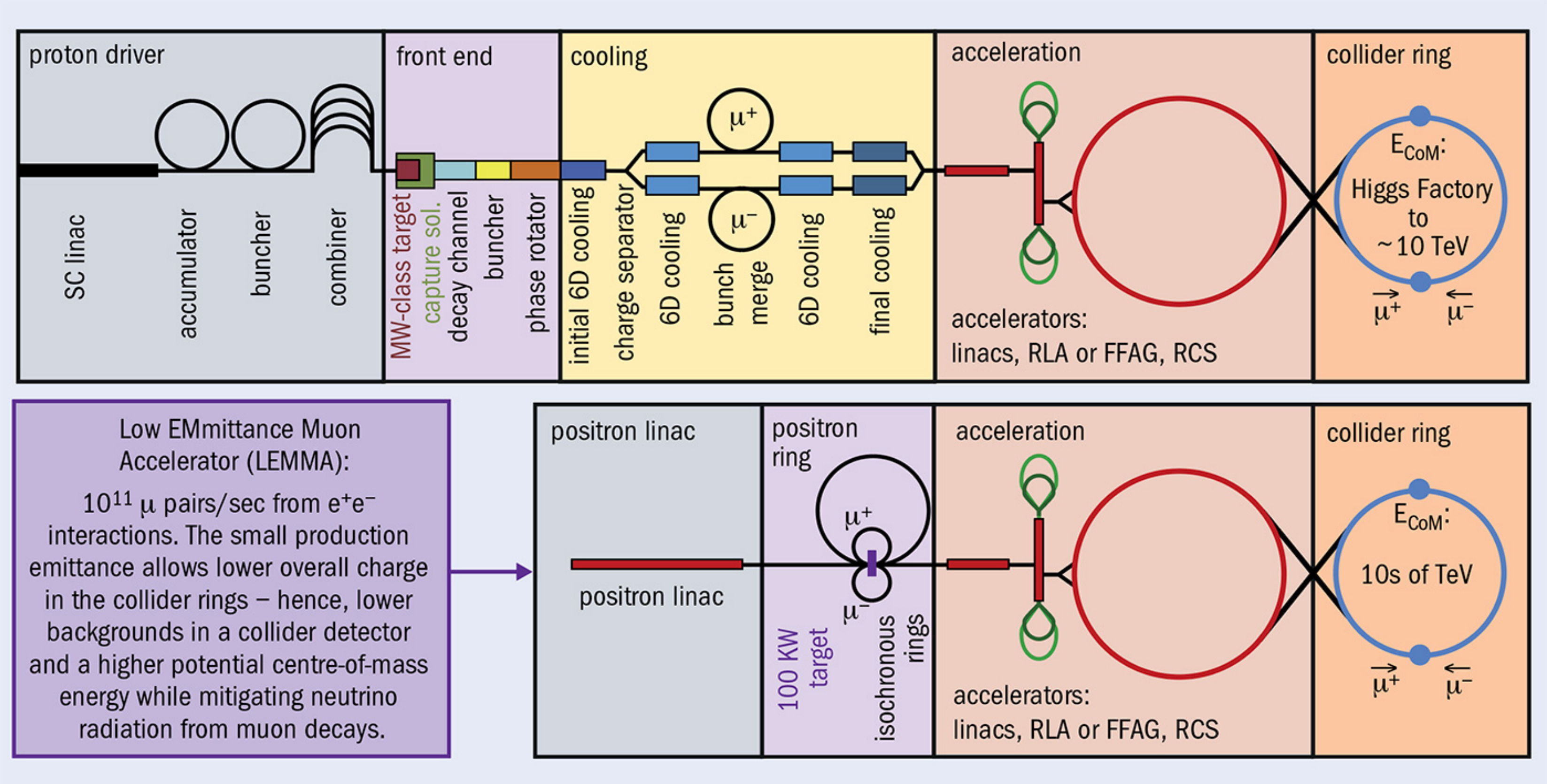


An example Feynman diagram of VBS at the LHC

- 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

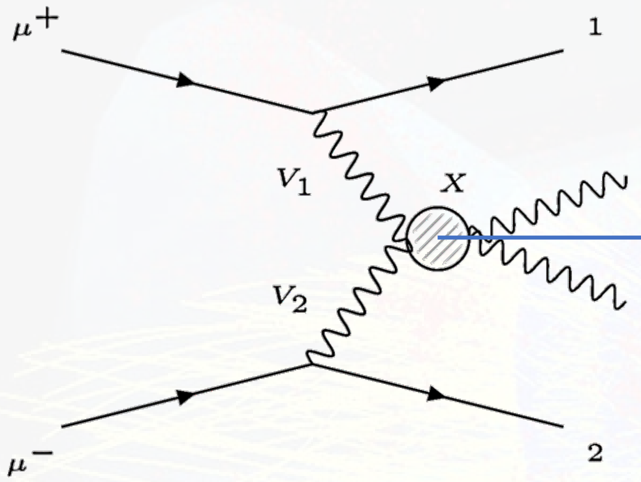
Why we choose the Muon Collider?

- 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

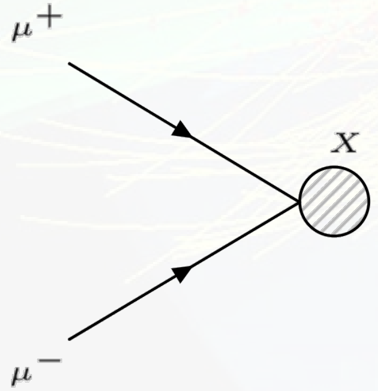
- VBS processes



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

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

- s-channel



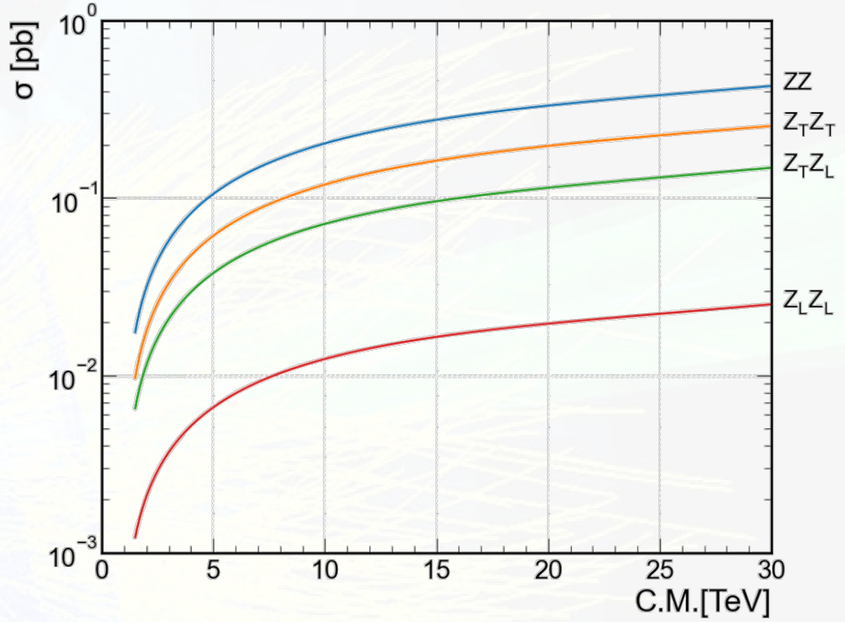
Simpler than the LHC, can be expressed as a "high-luminosity weak boson collider"

Signal and backgrounds processes selection

- Signal:
  - $Z_L Z_L \to 4l$ 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 → .lhe → Pythia8 → .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 ∏ 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” → $p_{T_{Z1}} > p_{T_{Z2}}$
  - $l_1^+ l_2^+ l_3^- l_4^- \rightarrow l_1 l_3, l_2 l_4; l_1 l_4, l_2 l_3$
  - $\Delta M^2 = \left(M_{Z_1'} - M_Z\right)^2 + \left(M_{Z_2'} - M_Z\right)^2$
  - $\Delta M_{13,24}^2 > \Delta M_{14,23}^2 \rightarrow$ 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

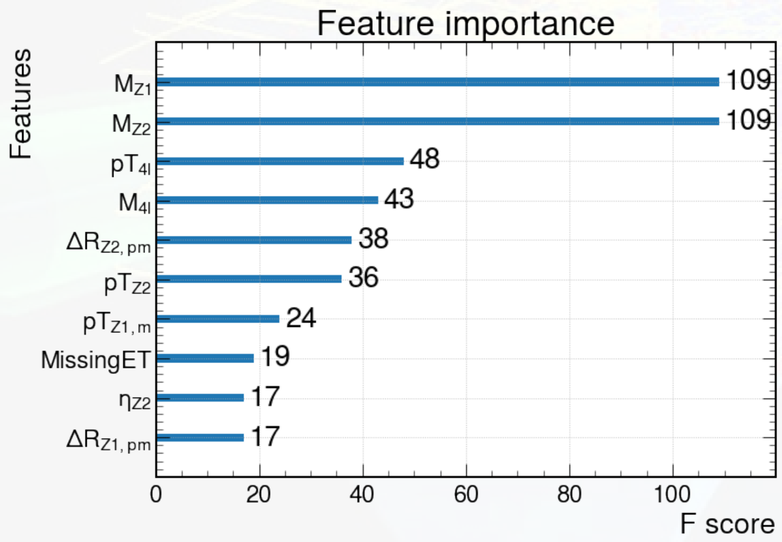
- Shuffle the signal and background events and define the training and test sets with the event ratio of 2 : 1.
- num of trees=200, max depth=5
- apply the per-event weight to account for the cross-section difference among the processes. The weight is defined by:

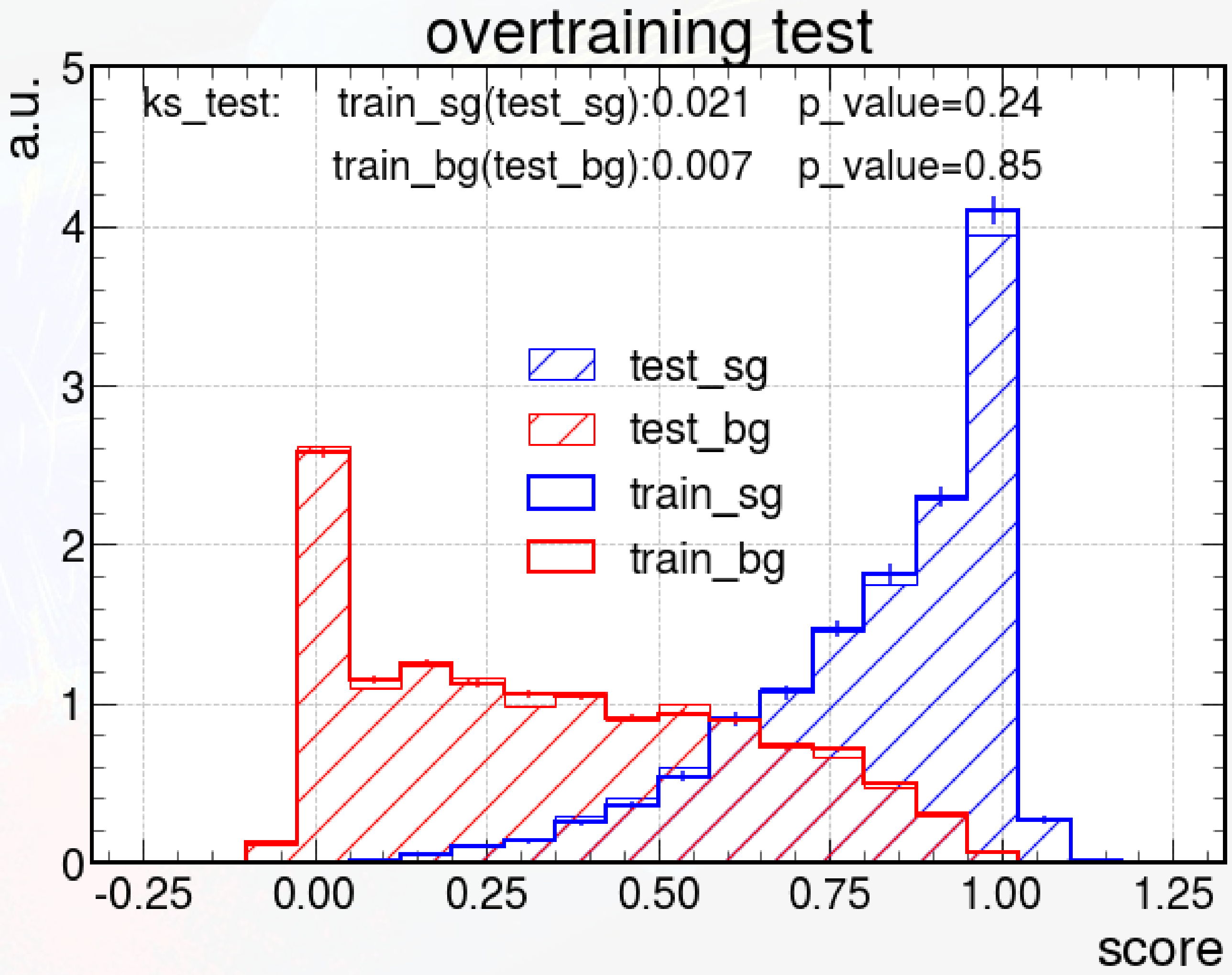
$$n_L = \sigma_X L / N_{G_X}$$

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

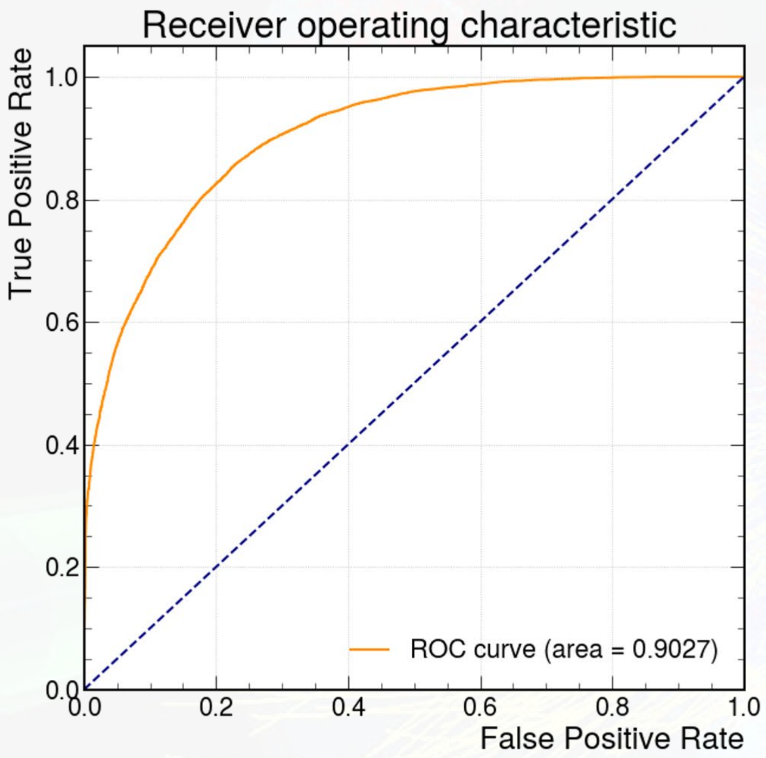
Objective	Features	Number of features
Each lepton	(p_T, η, ϕ)	12
Each "Z boson"	$(p_T, \eta, \phi, m_{inv})$	8
Four leptons combined	$(p_{T,4\ell}, \eta_{4l}, \phi_{4l}, m_{4l})$	4
$\not{E}$	(p_T, η, ϕ)	3
Between two Z bosons	$(\Delta\eta, \Delta\phi, \Delta R)$	3
Between 2ℓ of Z_1	$(\Delta\eta, \Delta\phi, \Delta R)$	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

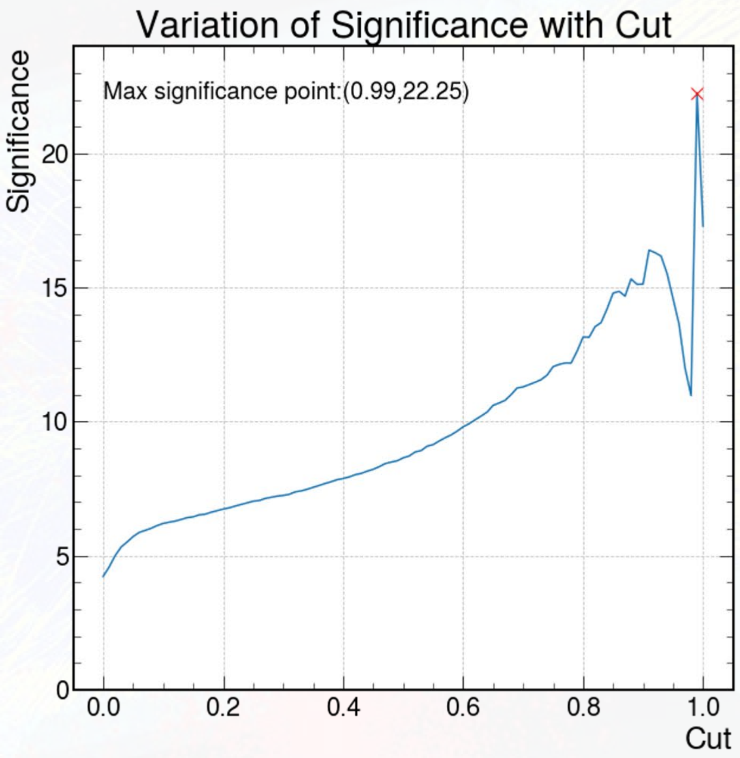
Summary of features used for training BDT model





BDT training results

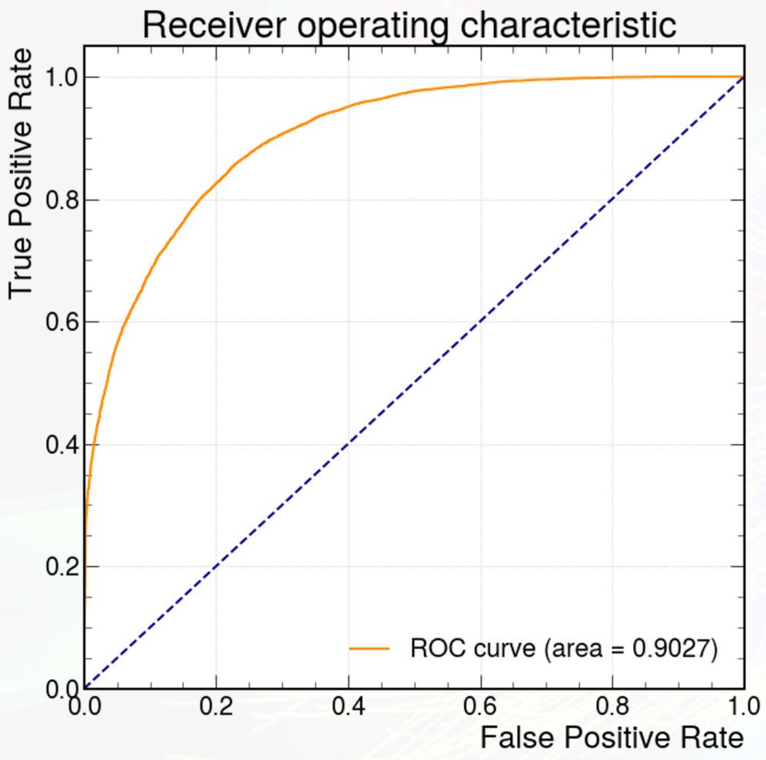


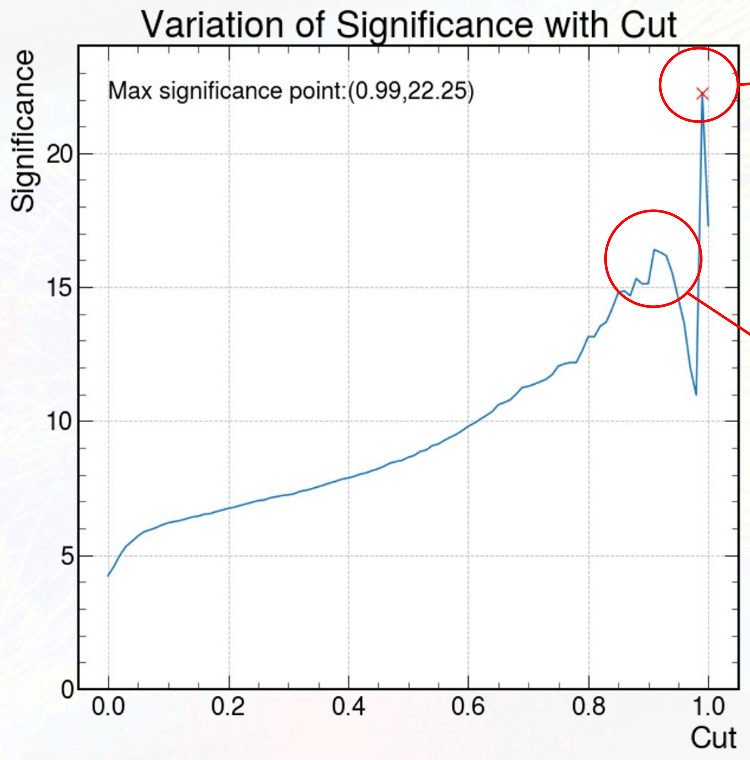


$$S = \sqrt{2(s+b)\ln\left(1+\frac{s}{b}\right) - 2s}$$

$s(b)$ 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

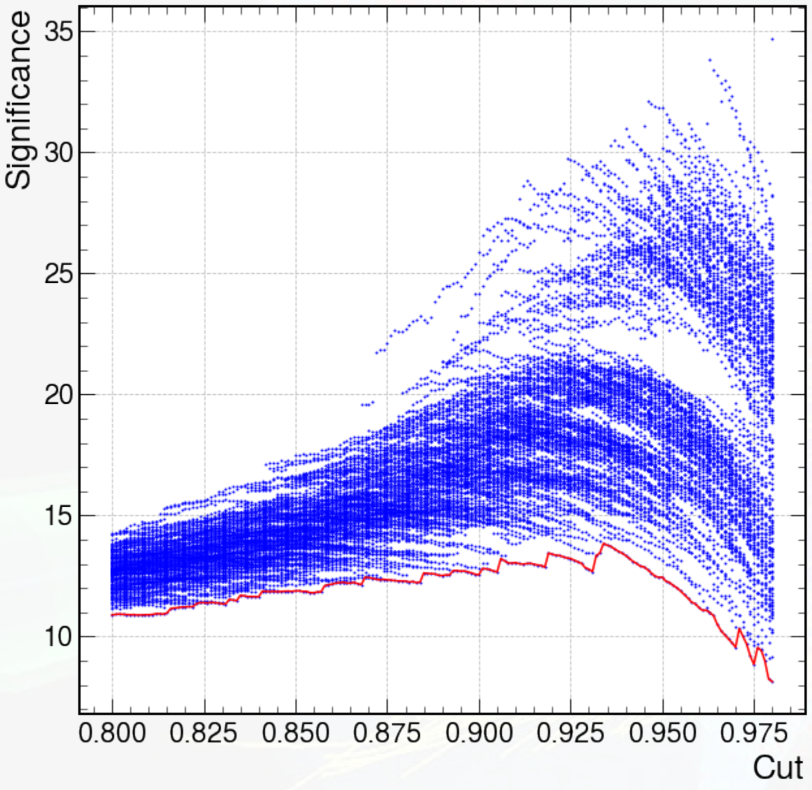
More reliable

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

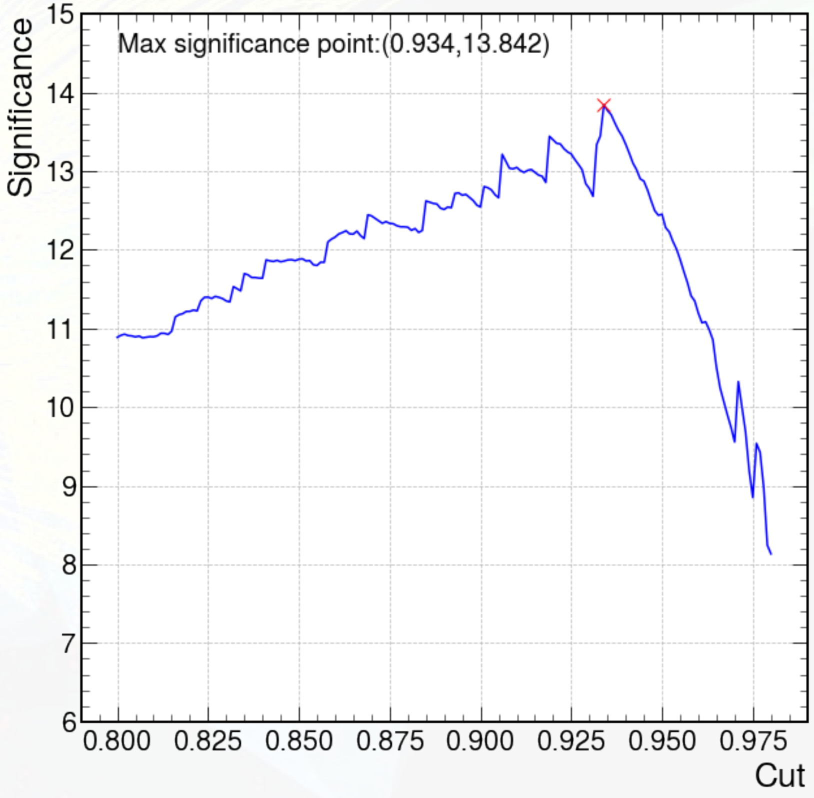
pause the scanning of threshold at 0.95

BDT training results

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



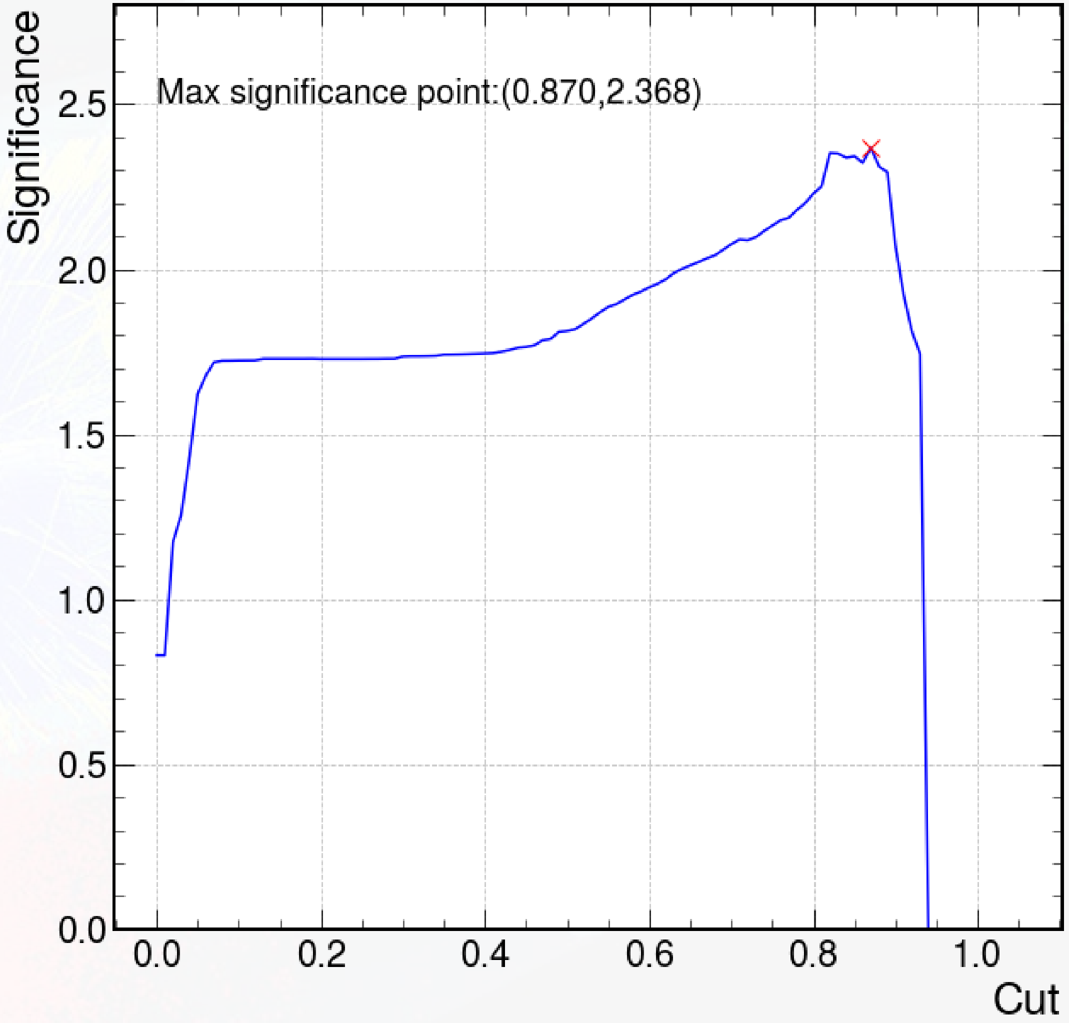
extract the Lower envelope



Optimal cut value ≈ 0.93, Significance $\approx 14\sigma$

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



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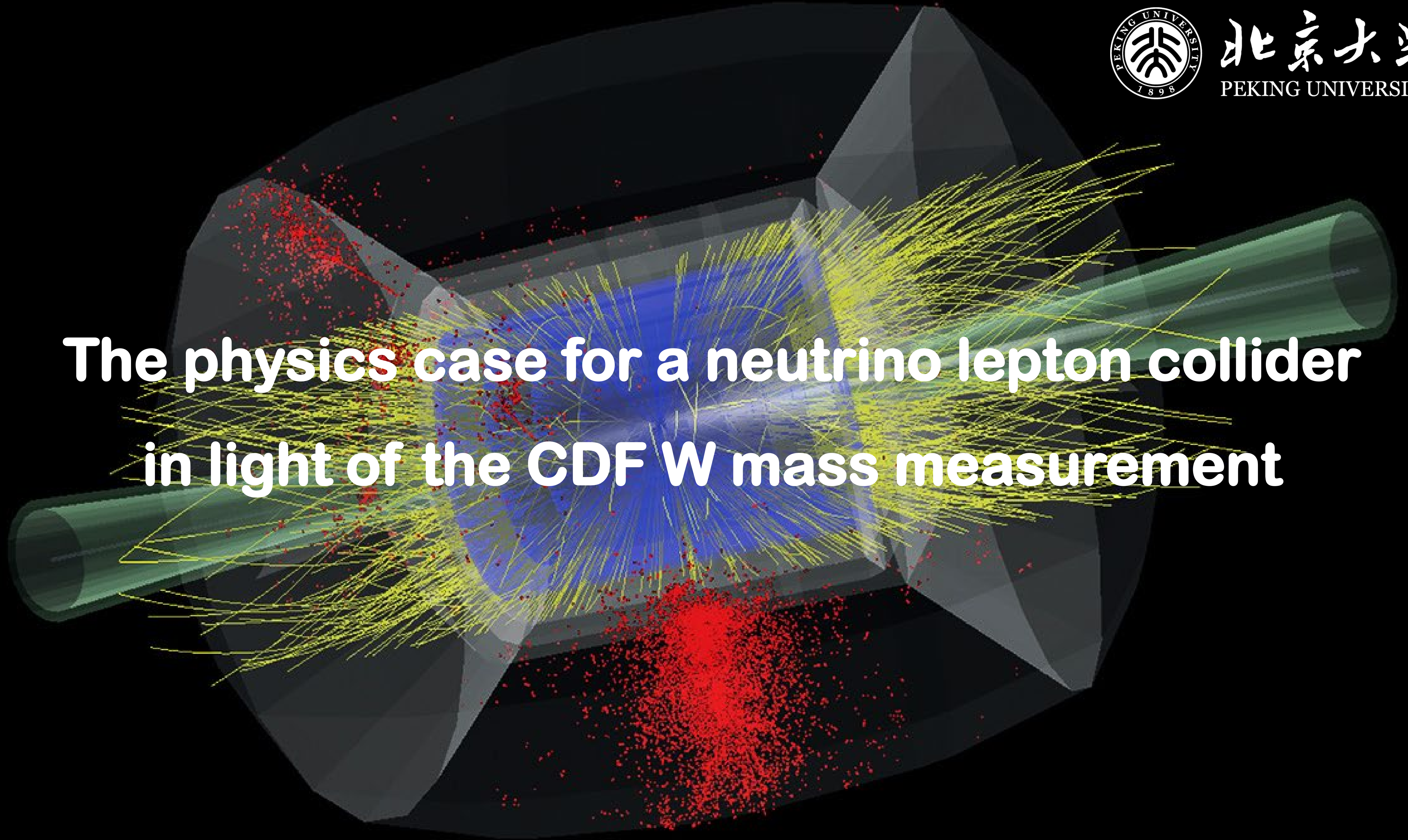
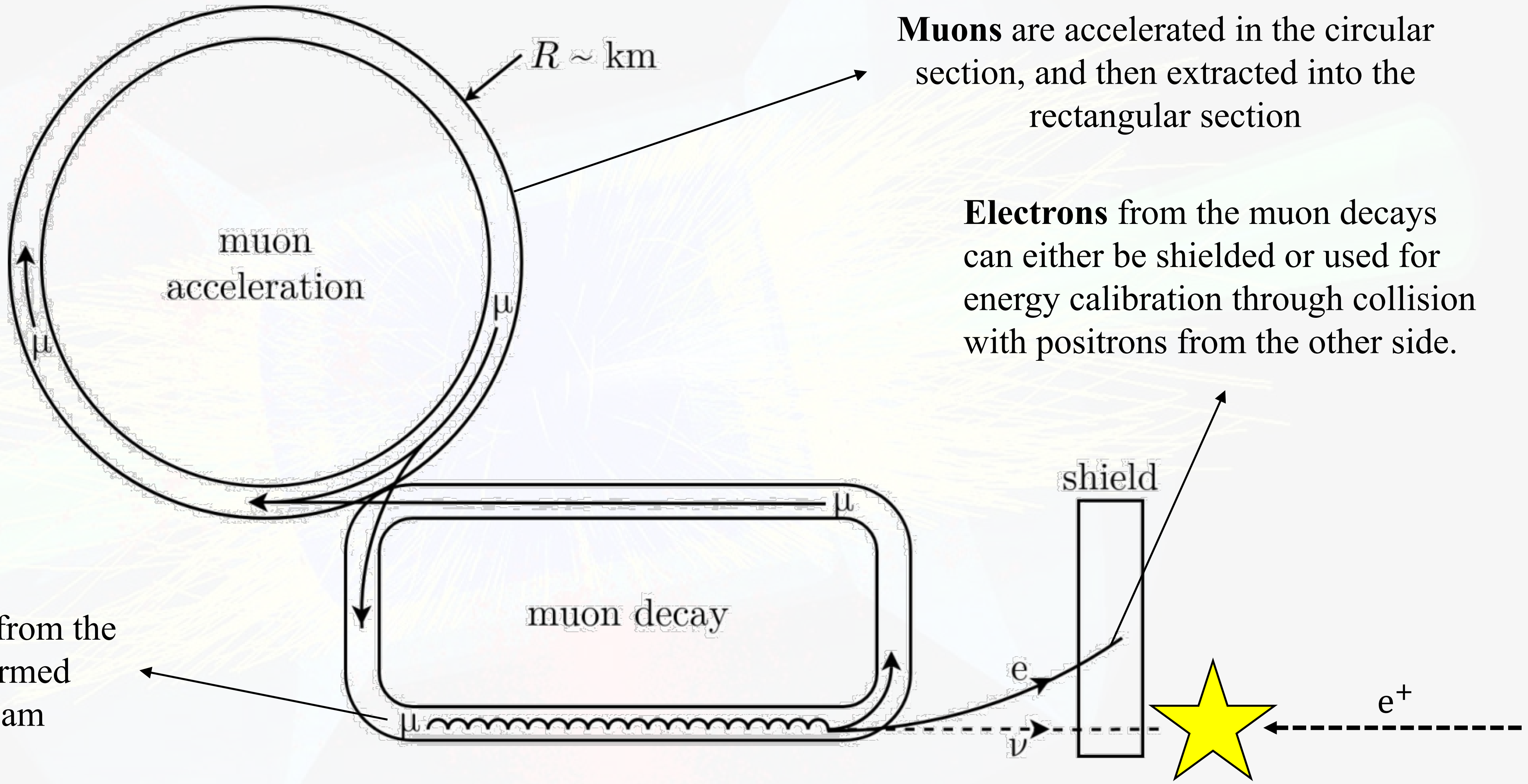


The physics case for a neutrino lepton collider in light of the CDF W mass measurement

An illustration of the proposed neutrino beam and collider



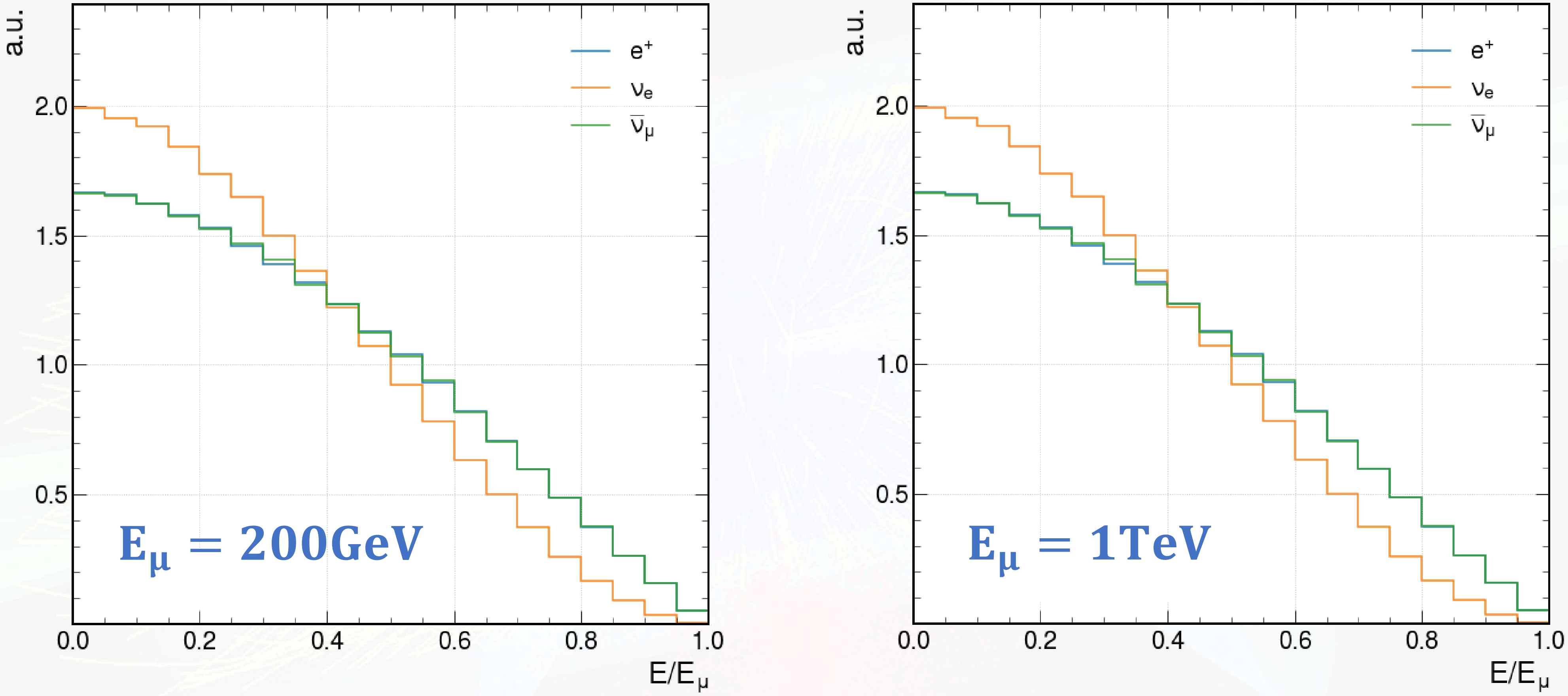
Muons are accelerated in the circular section, and then extracted into the rectangular section

Electrons from the muon decays can either be shielded or used for energy calibration through collision with positrons from the other side.

Neutrinos emitted from the muon decays are formed into a collimated beam

Energy distributions of muon decay products

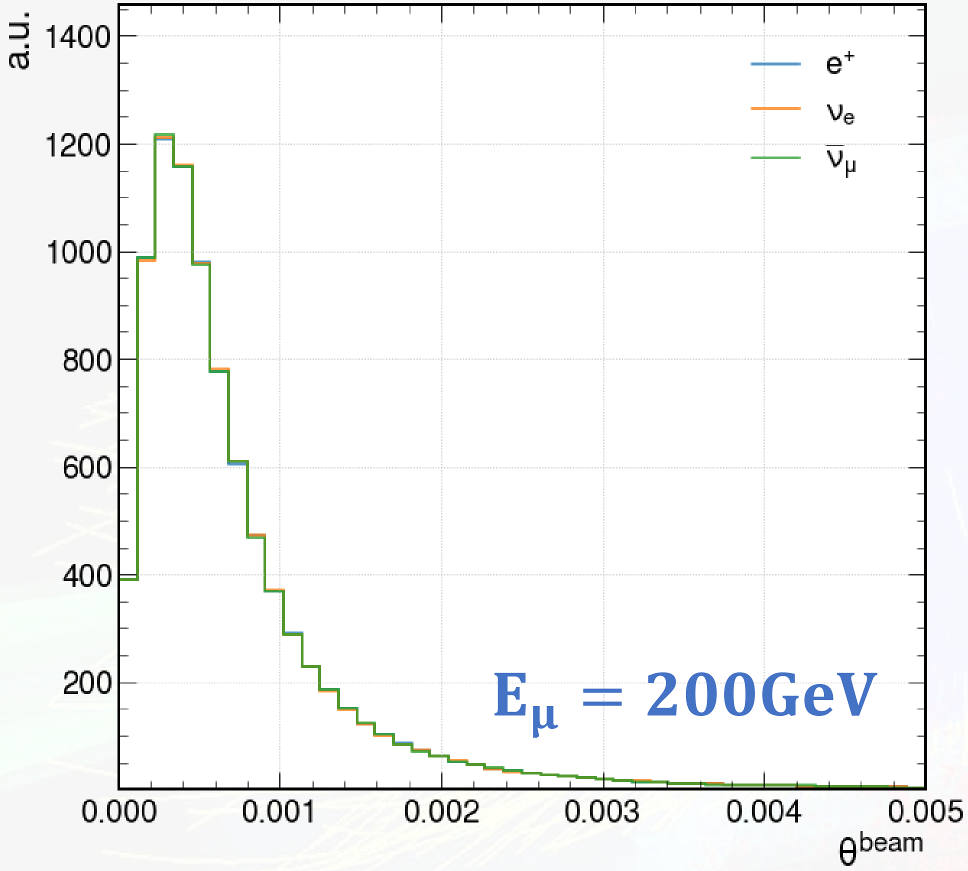
- $\mu^+ \to e^+ \nu_e \overline{\nu_\mu}$

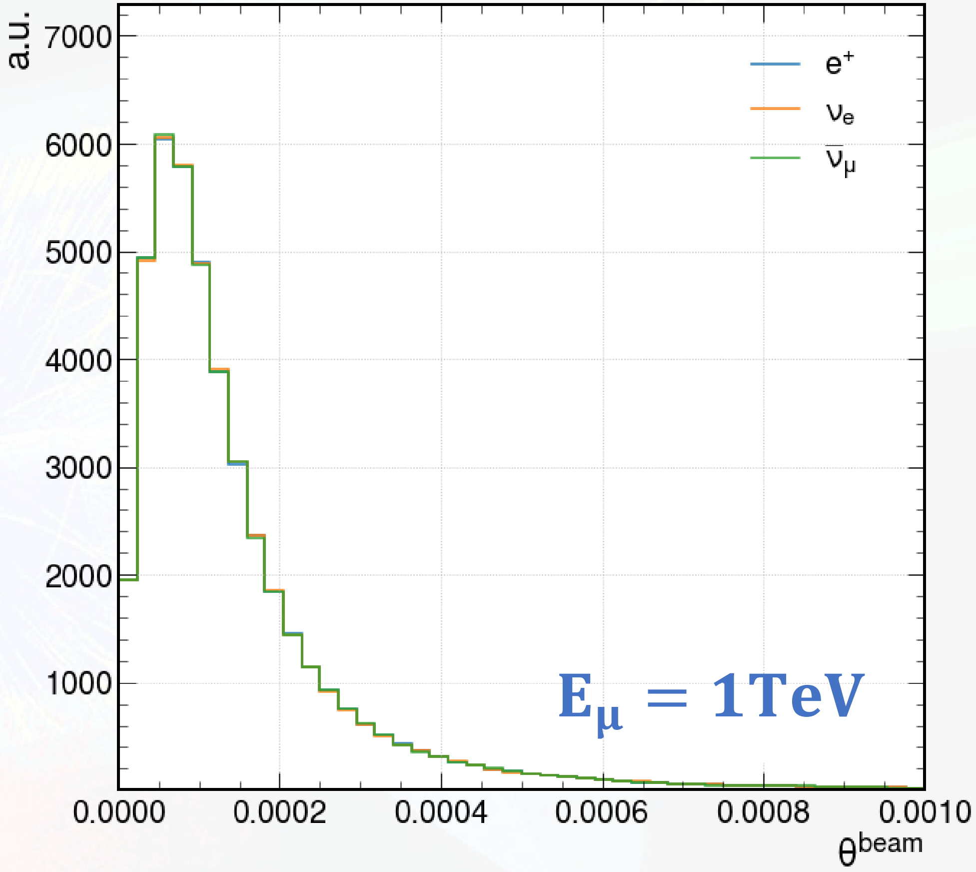


- There is not much difference between the distributions of products emitted from **200 GeV** and **1 TeV** muon beams.

Decay angles distribution of muon decay products

- $\mu^+ \to e^+ \nu_e \overline{\nu_\mu}$



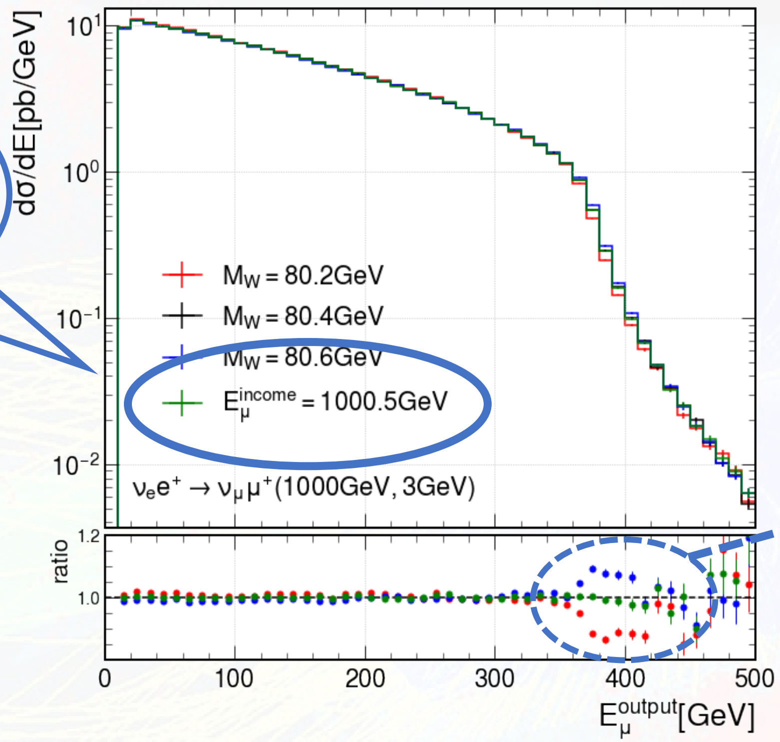


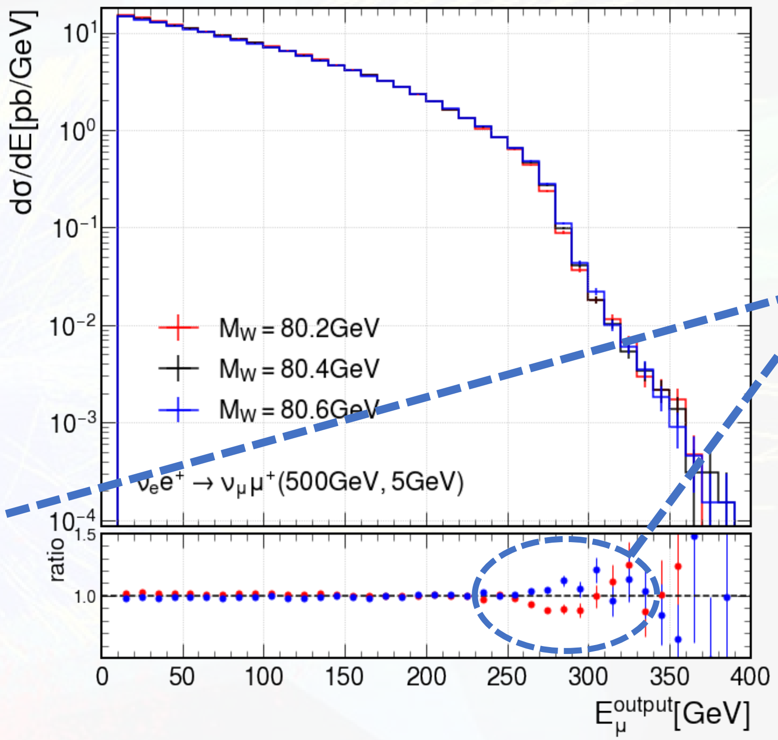
- As the decay angle θ goes like $\theta \sim 10^{-4}/\mathrm{E(TeV)}$, the muon decay products will be more collimated with **increasing beam energy**.

Results for W boson mass accurate measurement

- Simulate $\nu_e e^+ \to W^{+(*)} \to \nu_\mu \mu^+$ for two beam energy scenarios: a neutrino beam arising from a **1000 (500) GeV** muon beam, and a **3 (5) GeV** positron beam.

To test the uncertainty of beam energy, shift the E_μ^{income} by 0.5 GeV





Significant Discrepancy!

- Only considering W decays into muon, at the **[1000, 3] GeV** neutrino positron collider, cross-section = **166.2 (167.6) pb** when M_W = **80.4 (80.41) GeV.**

—— A **10 MeV** accuracy on M_W can be achieved with an integrated luminosity of only **$0.1\ fb^{-1}$**!

Conclusion

- At a **14 TeV** muon collider, a **5σ** discovery of longitudinal polarization can be achieved, with $\mathbf{L = 3000fb^{-1}}$.
- At a **[1000, 3] GeV** neutrino positron collider, a **10 MeV** accuracy on M_W can be achieved, with $\mathbf{L = 0.1fb^{-1}}$.
- Now we come to a **conclusion**:

The future collider has unique advantages over the LHC!

Thanks for listening!

——From Tianyi Yang

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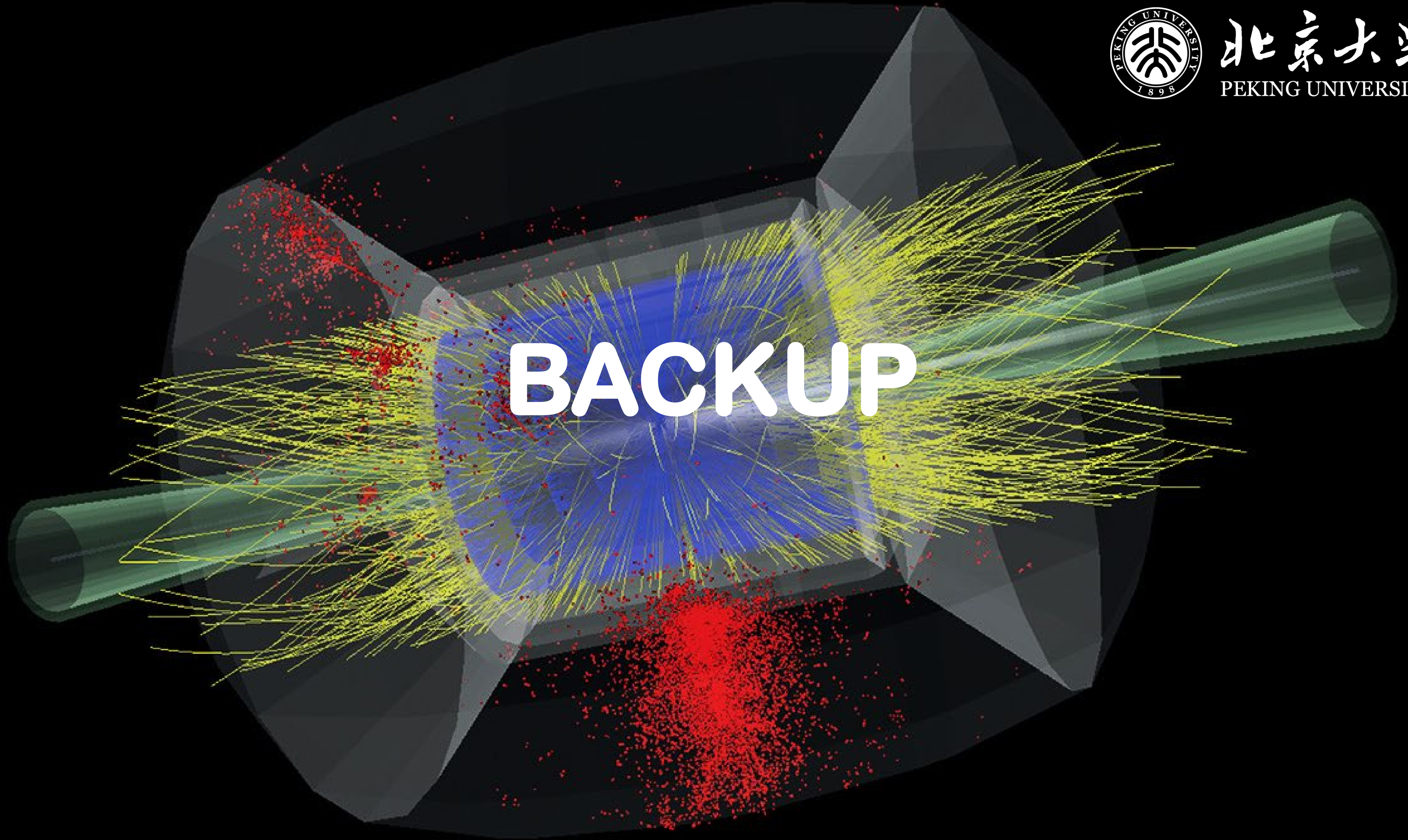


BACKUP

经过初次筛选后的剩余事例数和加权事例数

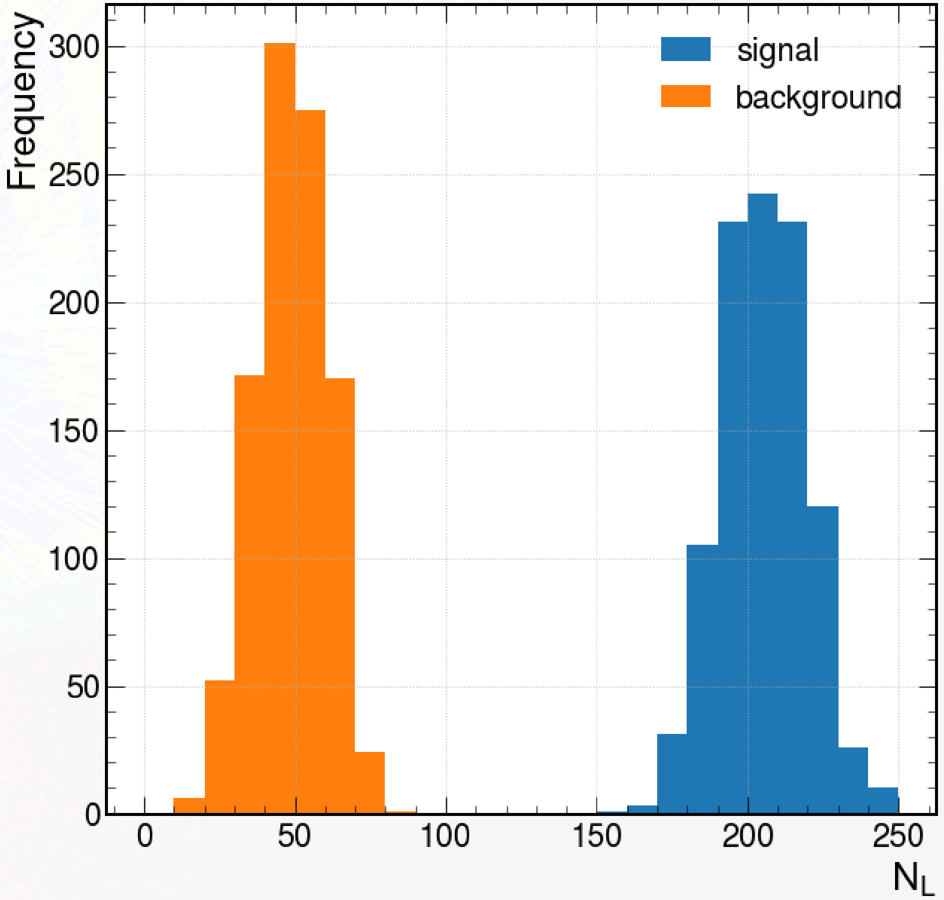
type	N_G	N_L
ww_vbf H_zll_4l:	2862	85.38
ww_vbf HWW:	7	6.57
ww_vbf HZ:	11	100.86
ww_vbf HH:	2	1.79
ww_vbf HZZ:	30	9.56
ww_vbf WWZ_ww2l:	443	584.72
ww_vbf ZTZT:	9759	3073.69
ww_vbf ZTZ0:	7047	1320.44
ww_vbf Z0Z0:	10381	541.10
ww_vbf ZZZ:	104	256.71
ww_vbf ttbarZ_ttbarll:	163	3.11

type	N_G	N_L
zz_vbf H_zll_4l:	3189	9.84
zz_vbf WW_dfc:	1168	2182.27
zz_vbf ttbar:	156	1.57
wz_vbf WZ_dfc:	304	1594.53
wz_vbf WZH:	**623**	**5594.87**
wz_vbf WH:	4	23.72
wz_vbf WWW_dfc:	153	315.85
wz_vbf WZZ:	**324**	**2808.77**
s_ch ZZ_4l:	1019	3.77
s_ch WWZ_ww2l:	237	30.24

Comparison between BDT and cut-based method

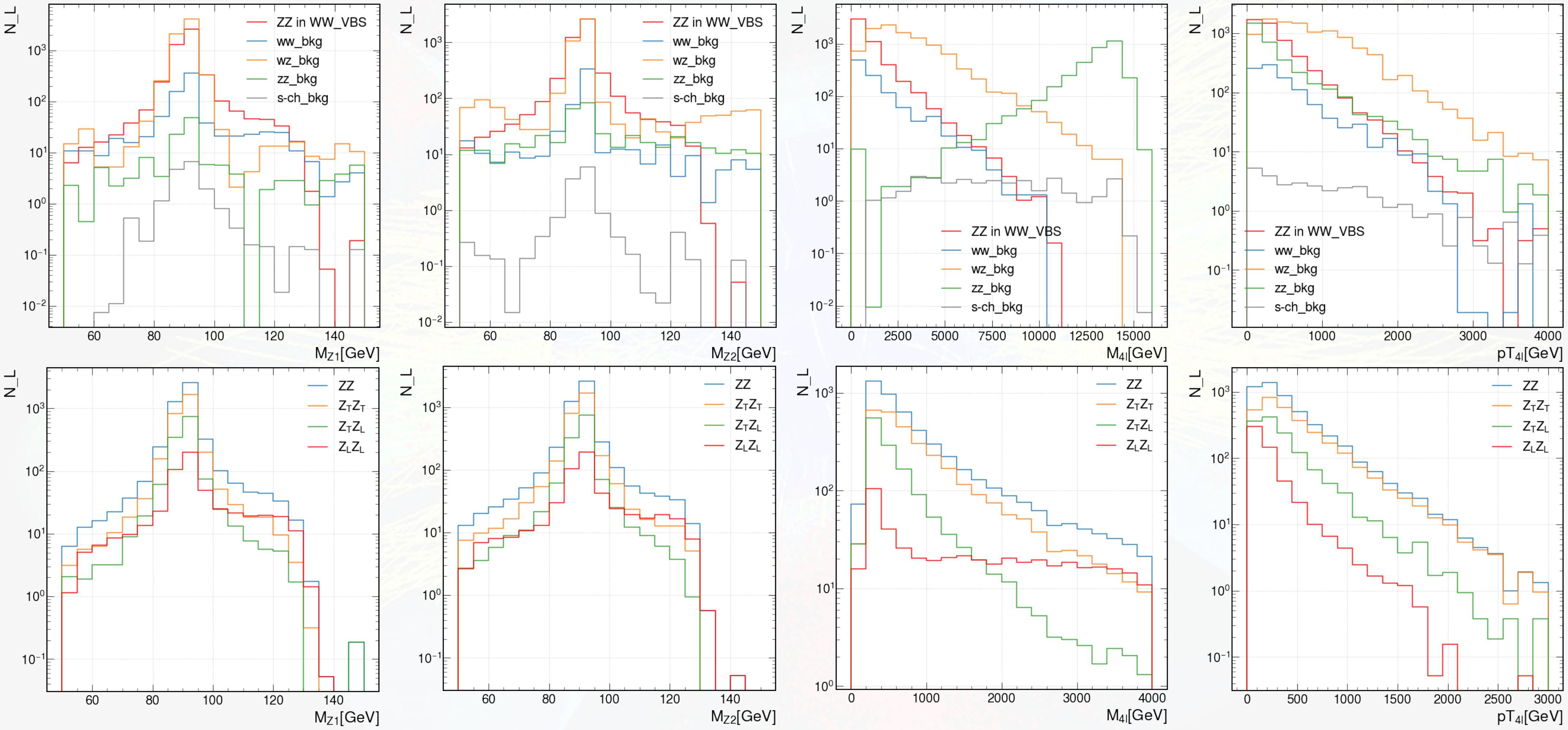
- set cut=0.93, get distribution of N_L of signal and backgrounds in 1000 randomly selected cases
  - $\bar{s} = 205.7, \bar{b} = 49.2$
  - $\hat{\sigma}_s = 14.1, \hat{\sigma}_b = 11.7$
- using $S = \sqrt{2(s+b)\ln\left(1+\frac{s}{b}\right) - 2s}$
  - $s = \bar{s}, b = \bar{b}, S = 20.67$
  - $s = \bar{s}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

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



Comparison between BDT and cut-based method

- Consider the top 10 features:



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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
$70\text{GeV} < M_{Z1},\ M_{Z2} < 140\text{GeV},\ \Delta R_{Z2,pm} < 0.4,$ $p_{\text{T},4\ell} < 300\text{GeV}$	213.5	424.9	9.6
$70\text{GeV} < M_{Z1}, M_{Z2} < 140\text{GeV},\ \Delta R_{Z2,pm} < 0.4,$ $p_{\text{T},4\ell} < 300\text{GeV},\ \not{E} < 140\text{GeV}$	147.8	158.1	10.4

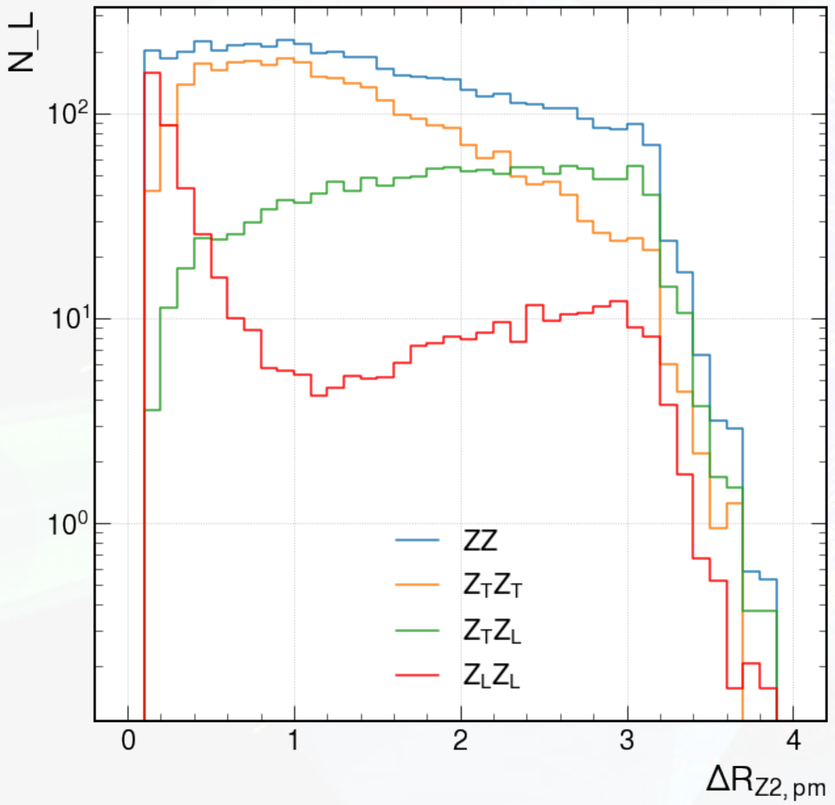
$\Delta R_{Z2,pm}$: ΔR between the two leptons forming Z_2

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

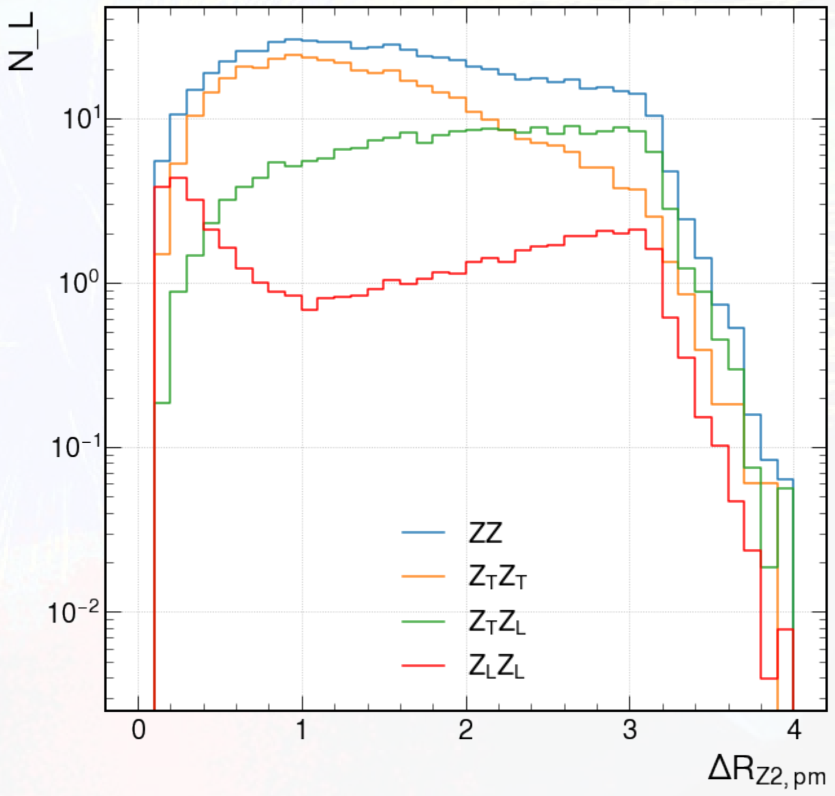
Comparison between $\sqrt{S} = 14TeV\&6TeV$

➢Evidence of the 3rd reason

14TeV

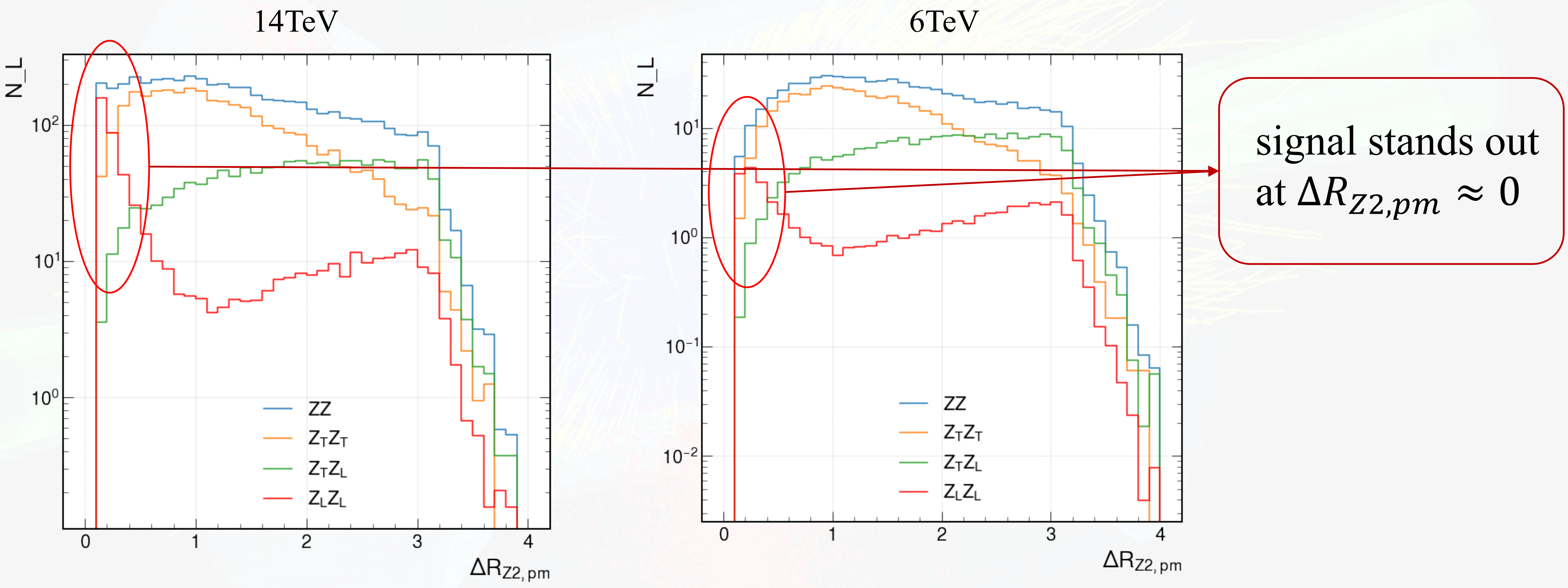


6TeV



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

➢Evidence of the 3rd reason



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
}
```

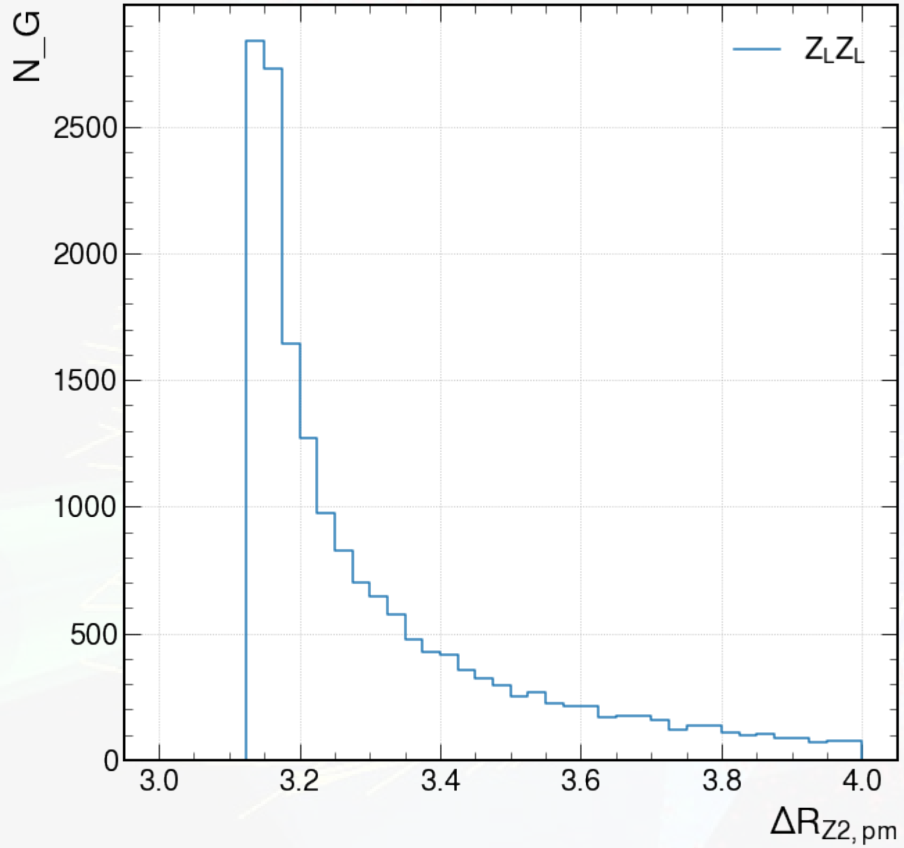
muon_collider_card

```
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
}
```

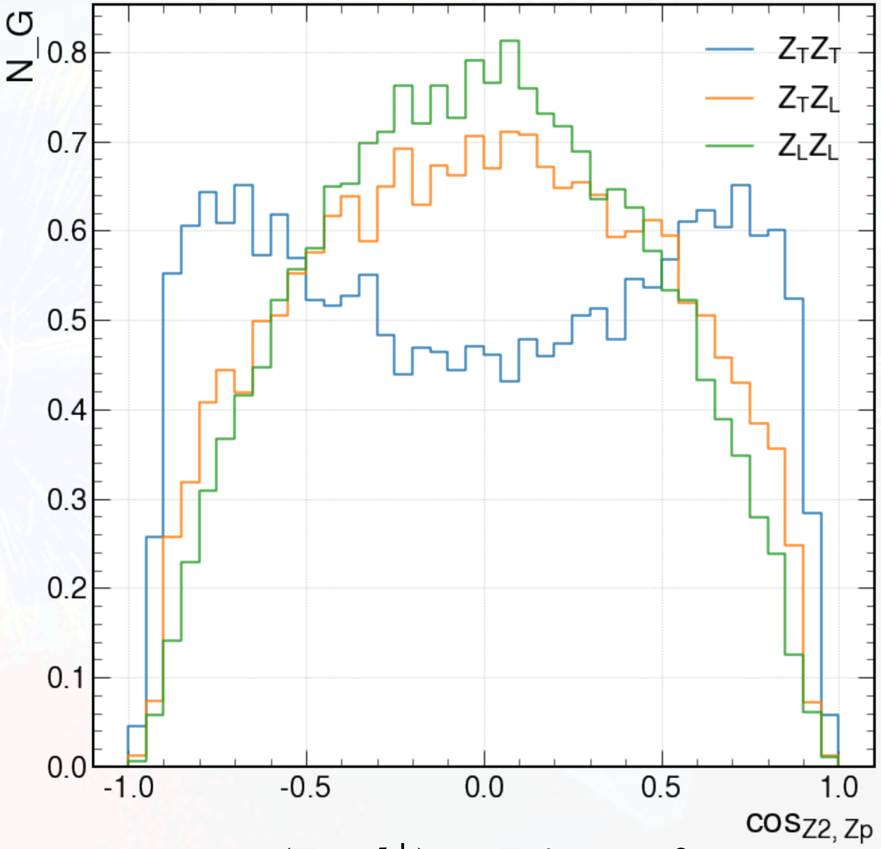
CMS_card

Verify the correctness of MC simulation

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



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



cos(Z_2, l^+) at Z_2's rest frame

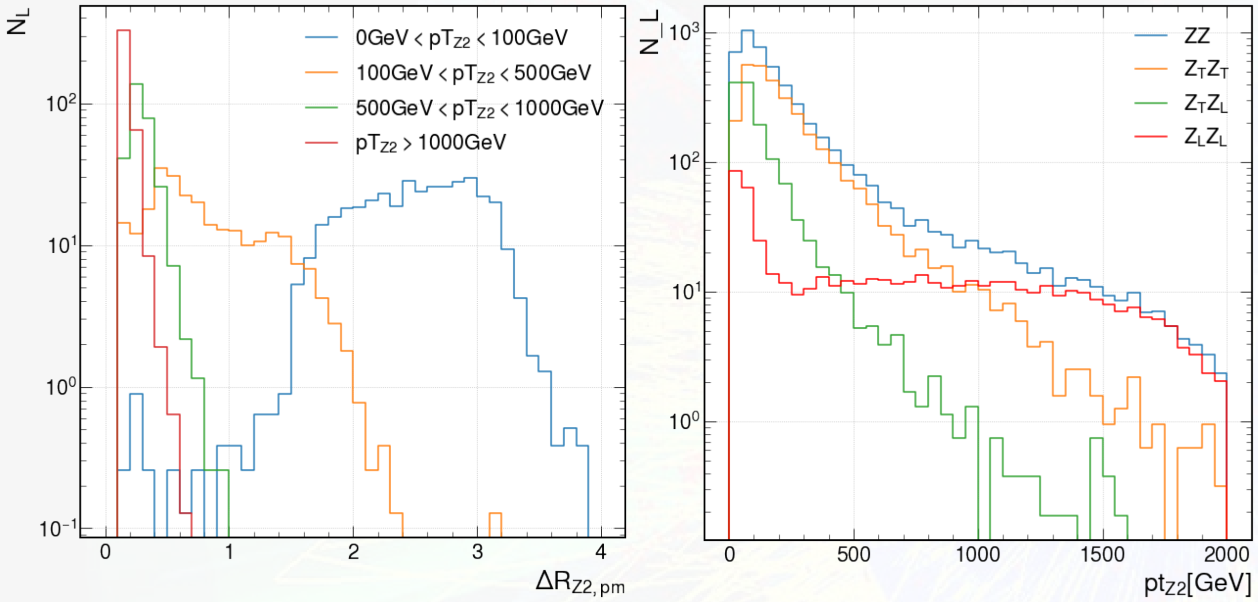
Cut-flow table and the corresponding S when $\Delta R_{Z_{1,2},pm} > 0.2$

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

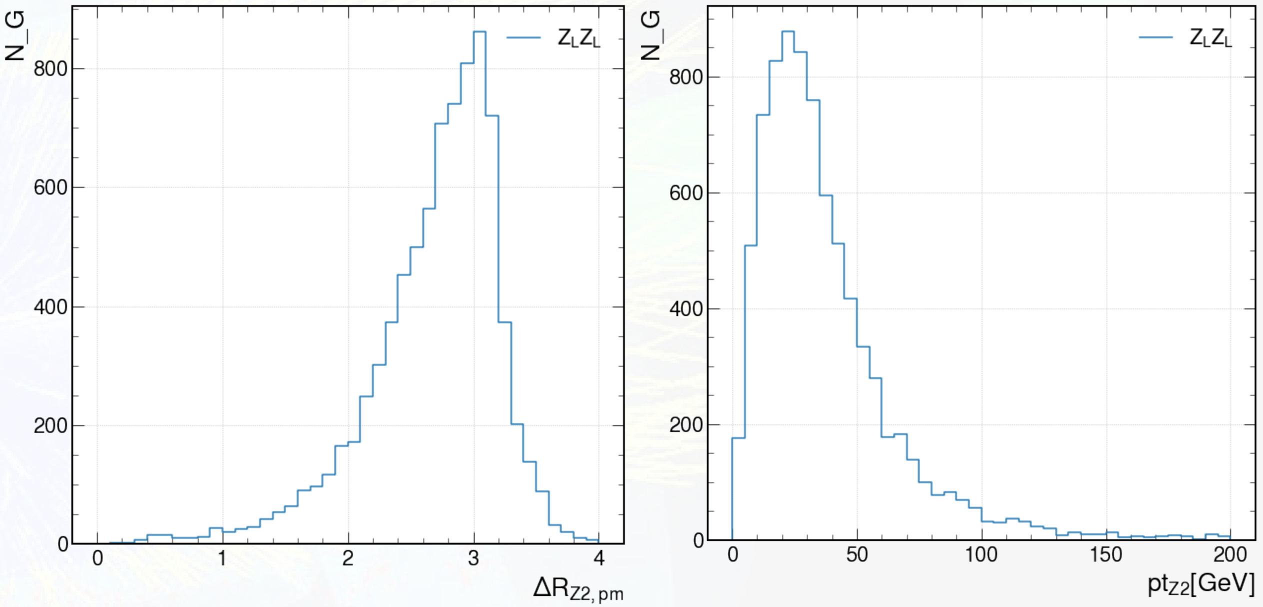
- $\Delta R_{Z_{1,2},pm}$ has a significant impact on the results, require better detector resolution

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