The 5th China LHC Physics Workshop

Longitudinal polarization fraction measurement for same-sign WW and VBS ZZ at CMS

arXiv:1812.07591, arXiv:1908.05196

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Outline

- 1. Higgs and vector boson
- 2. Vector boson scattering (VBS)
- 3. Polarization fraction measurement in VBS same-sign WW
- 4. Polarization fraction measurement in VBS ZZ
- 5. Conclusion

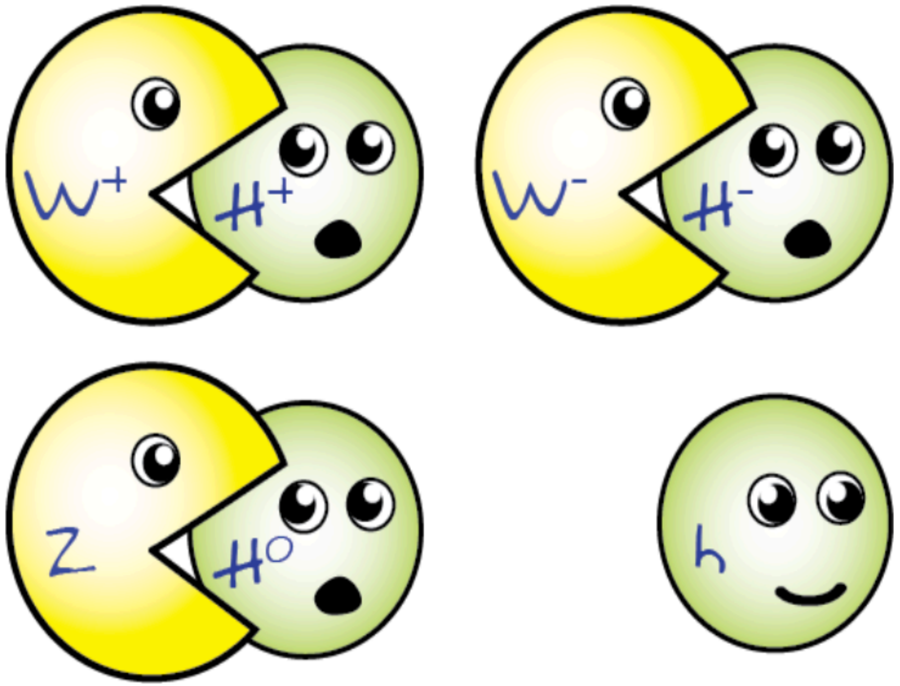
Higgs and longitudinal fraction of vector boson

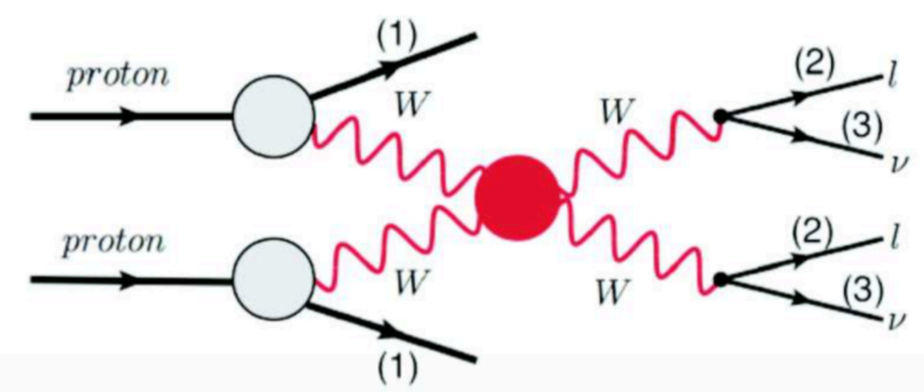
- Without Higgs, gauge bosons are massless in Standard Model (SM) with gauge symmetry.

- Higgs mechanism put forward
  - Breaking gauge symmetry, generating mass of gauge bosons.

  - For Electroweak sector, Electroweak symmetry breaking
    - Massive vector bosons (W^+, W^-, and Z boson)
    - Transverse and longitudinal polarization fraction

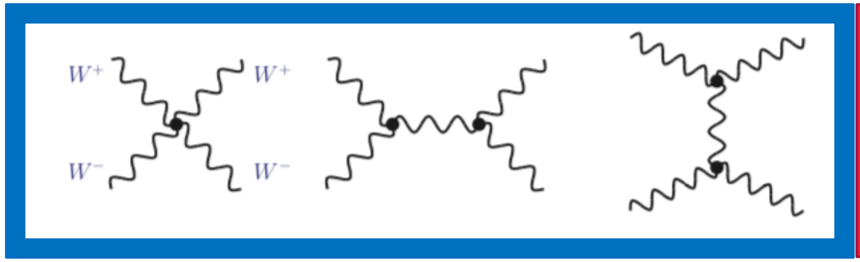
    - Additional massive scalar boson : Higgs boson.

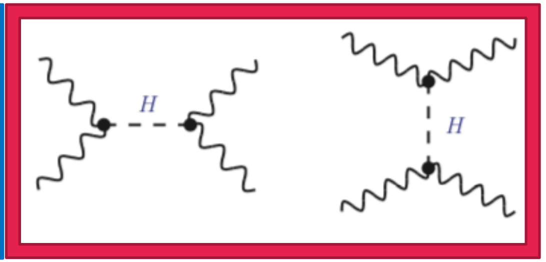




Vector boson scattering and Unitarity violation

- If there is no Higgs boson
  → Cross-section of vector boson scattering (VBS) diverges.



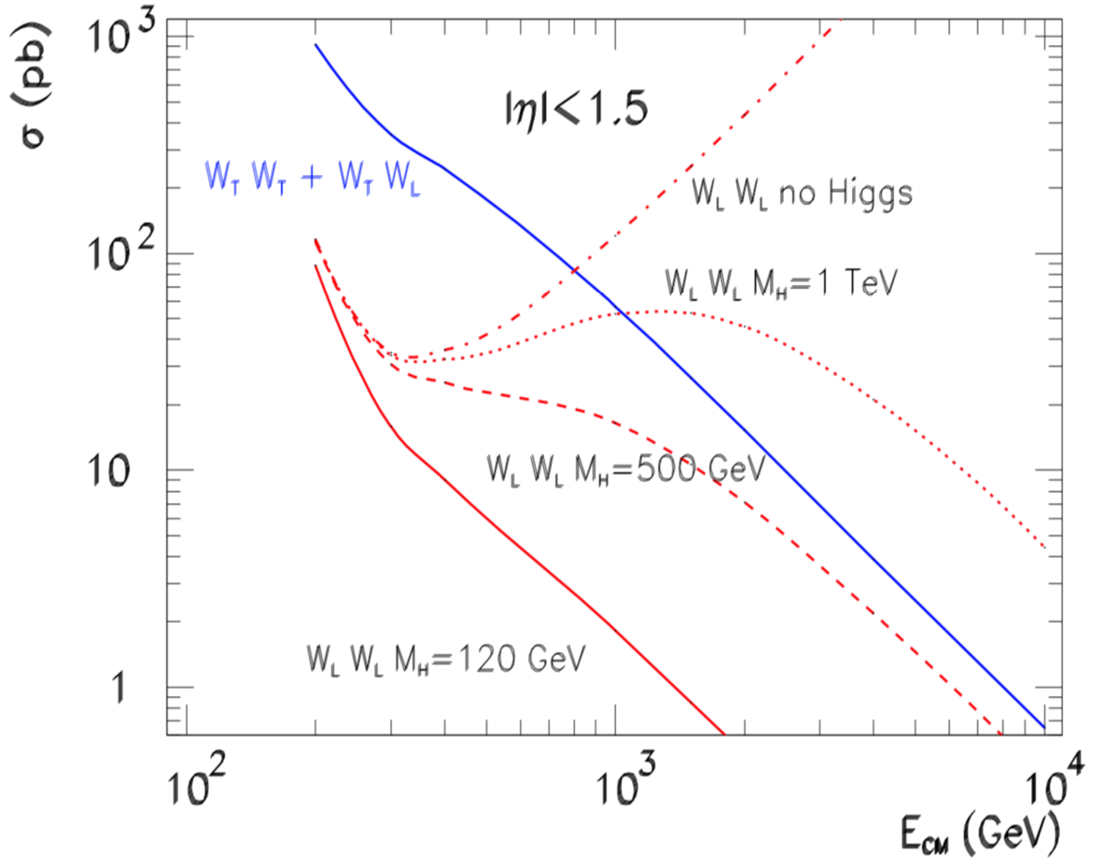


- If Higgs boson is too heavy (> 1 TeV)
  → Diverge

→ Unitarity violation

- $V_L V_L$ -> $V_L V_L$ scattering is crucial.

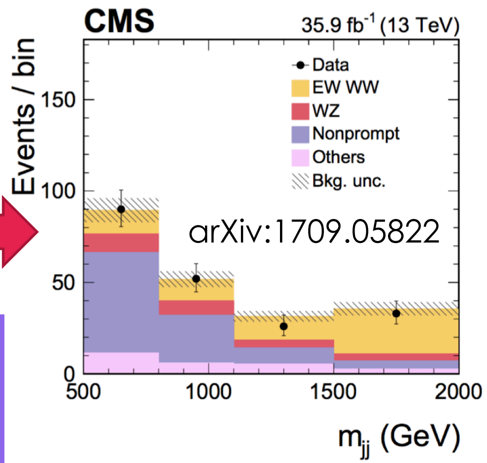
$W^+W^+ \rightarrow W^+W^+$

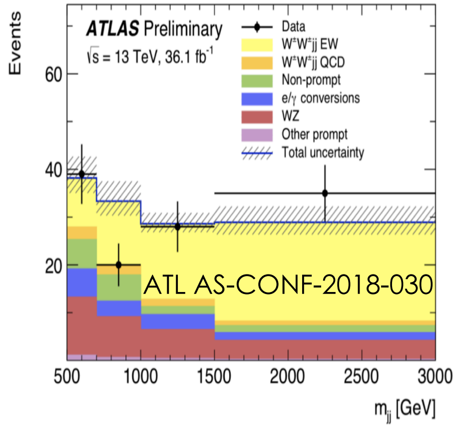


arXiv:1412.8367

Same-sign WW scattering

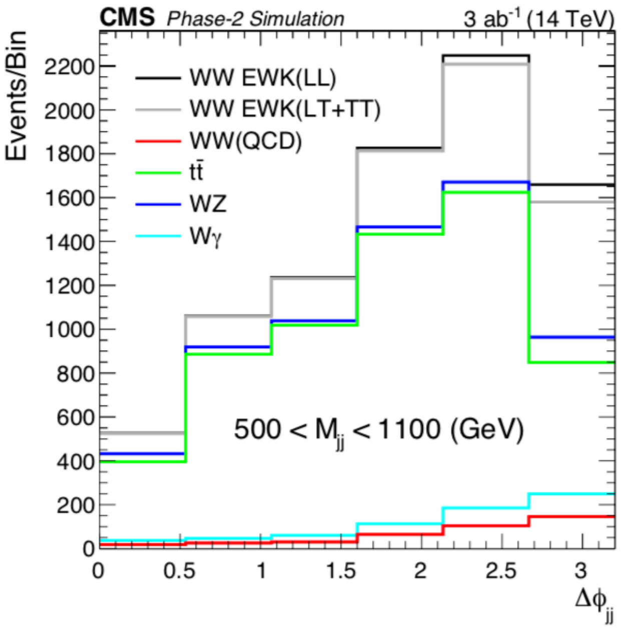
- The process (WW -> WW) has been observed by both ATLAS and CMS with luminosity of ~$36fb^{-1}$, at $\sqrt{s}$ = $13\ TeV$.

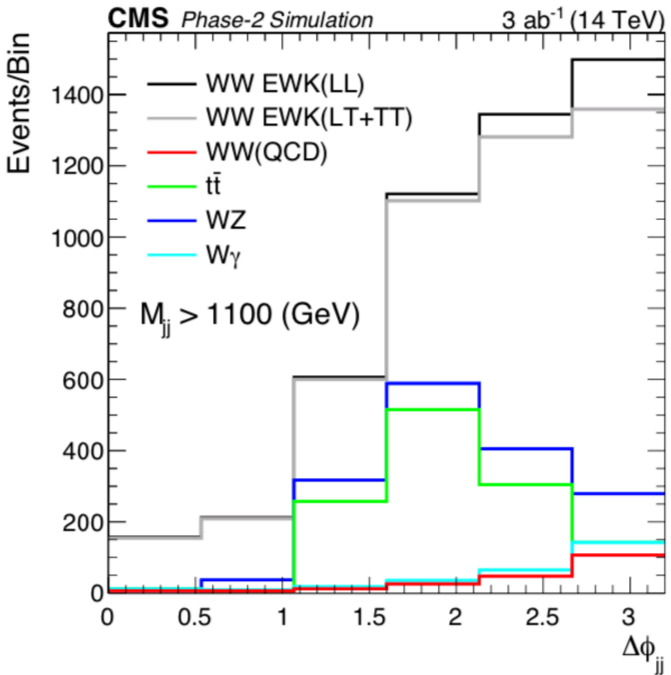


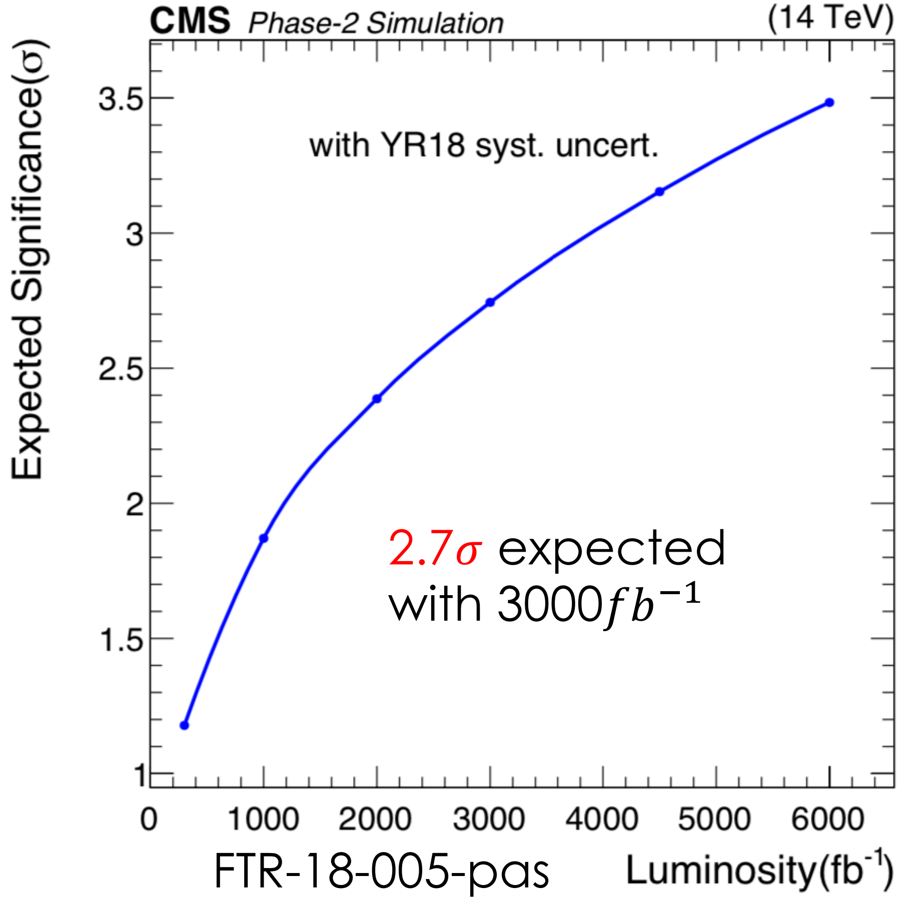


- Longitudinal fraction of vector boson only takes ~6%
  - →Not enough data for measuring W_LW_L -> W_LW_L with current Data.
  - →High Luminosity LHC, prediction on W_LW_L -> W_LW_L
    - $\sqrt{s} = 14\ TeV$
    - Lumi = $3000fb^{-1}$

Multivariate analysis







VBS Same-sign WW analysis setup

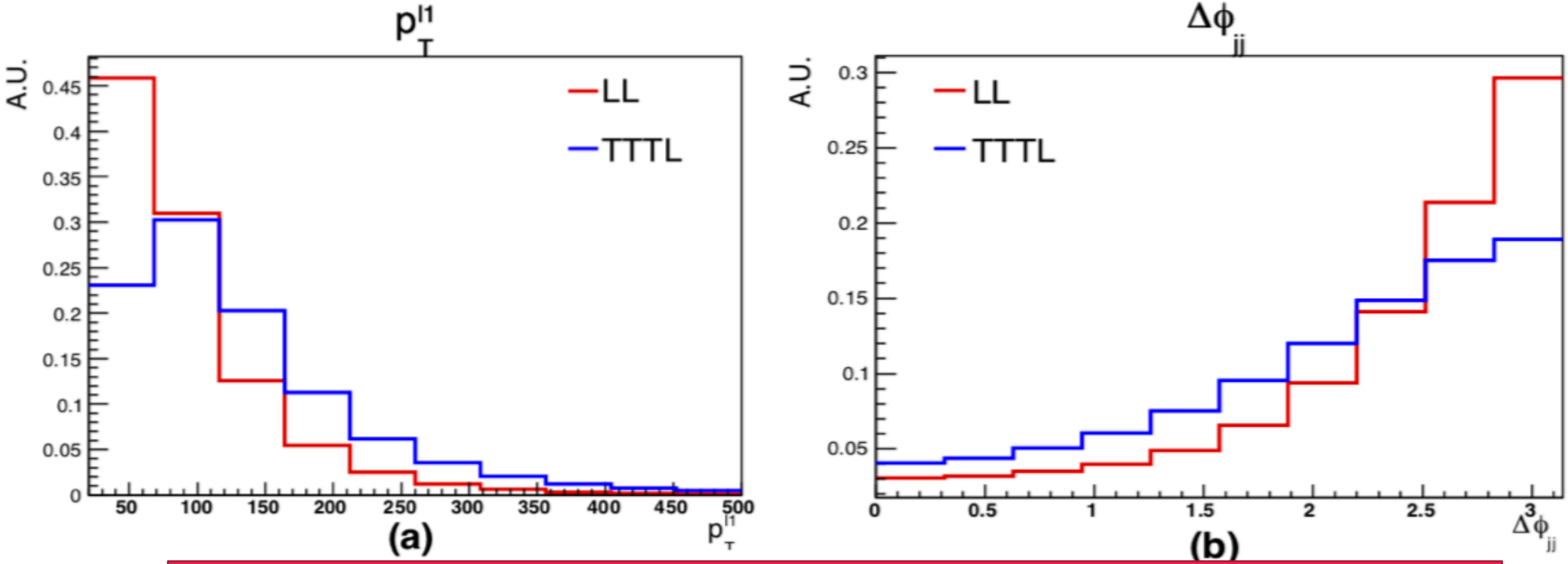
MC production pipe line

MadGraph5_ aMC@NLO → **DECAY** → **Pythia & Delphes** → **Event selection**

- Charged lepton
  - Charged lepton number ≥ 2
  - Same electrical charge
  - P_T > 20 GeV
  - $|\eta|$ < 2.4
  - Z veto (40 < M_{ll} < 70, or M_{ll} > 110)
  - $\Delta\eta_{ll}$ < 2.0
- Missing transverse momentum
  - P_T > 40 GeV
- Jet
  - Jet number ≥ 2
  - P_T > 30 GeV
  - $|\eta|$ < 4.7
  - M_{jj} > 850 GeV
  - $\Delta\eta_{jj}$ > 2.5
- Other
  - B jet veto

Typical kinematic distribution : P_T^{l1}, $\Delta\phi_{jj}$

- $V_L V_L$ -> $V_L V_L$ → ***LL***
- "$V_T V_T$ -> $V_T V_T$" & "$V_T V_L$ -> $V_T V_L$" → ***TTTL***



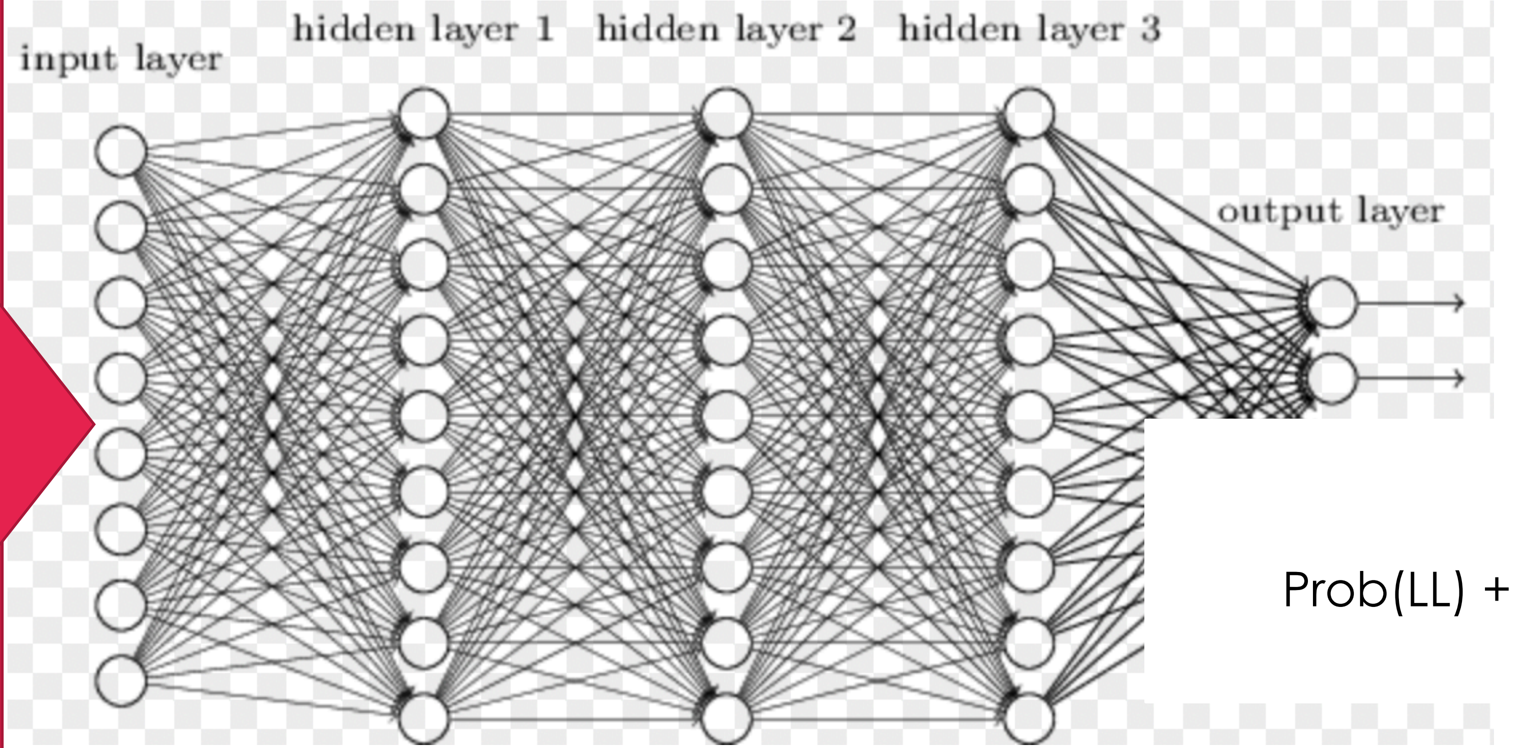
Not enough discriminating power → Idea :: Go for ***multivariate classification***

DNN dense model

Dataset
- Train Dataset → Obtain Trained DNN model
  → LL and TTTL classifier
- Test Dataset → Test performance of the model

Low level:
lep1pt,
lep1eta,
lep1phi,
lep2pt,
lep2eta,
lep2phi,
jet1pt,
jet1eta,
jet1phi.,
jet1M
jet2pt,
jet2eta,
Jet2phi,
jet2M,
MET,
METphi

High level:
dr_ll_jj,
dphijj,
detajj,
Zeppen_lep1,
Zeppen_lep2



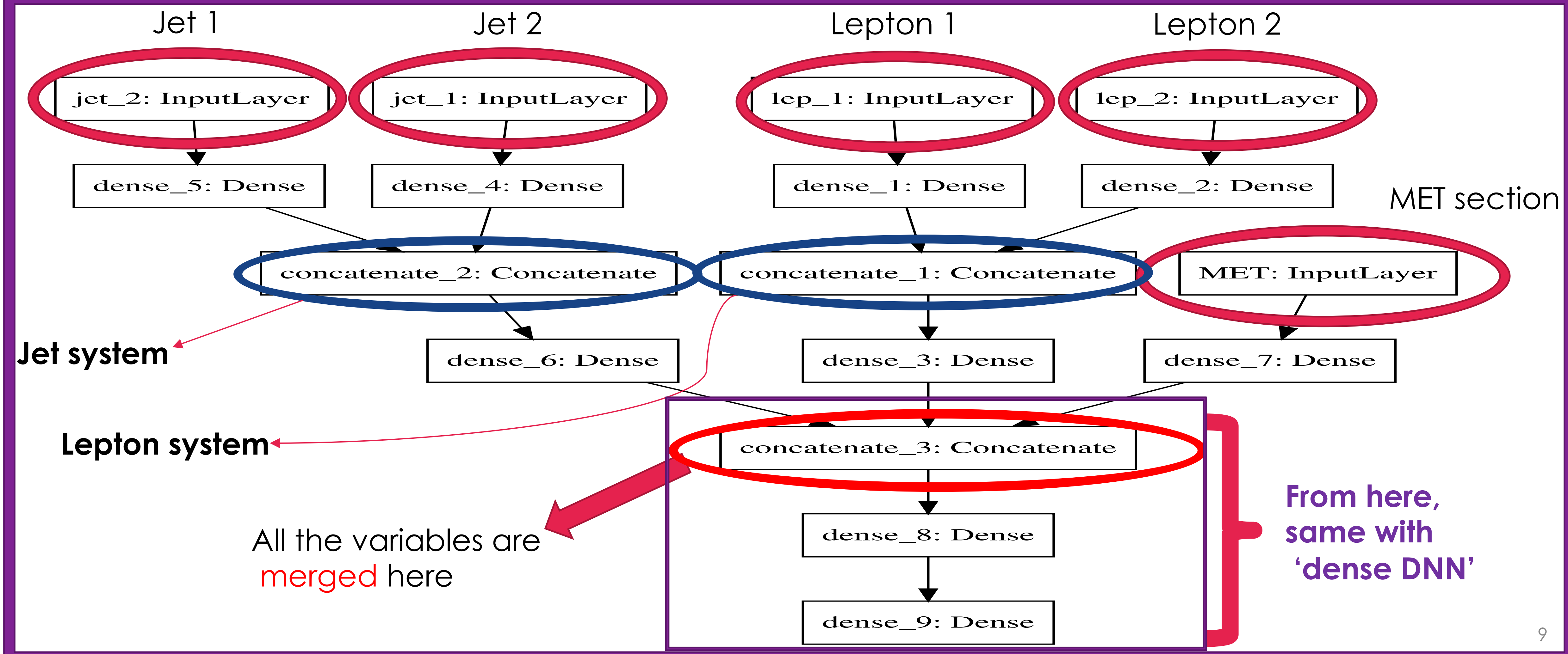
Prob(LL)
Prob(TTTL)

Prob(LL) + Prob(TTTL) = 1

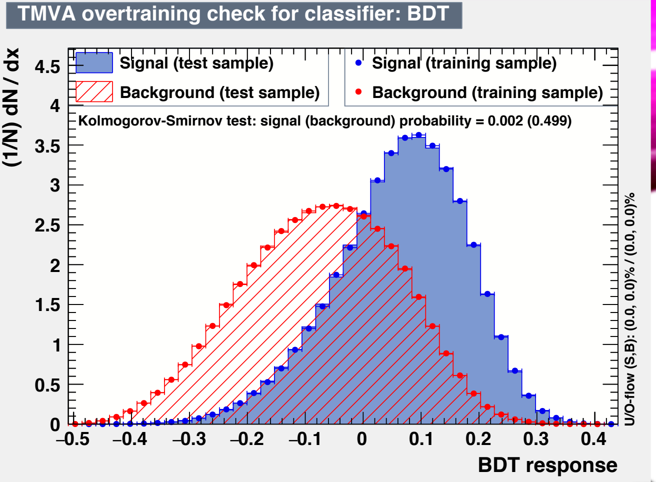
New idea: DNN particle-based model

Polarization might be highly correlated with angular variable of **each particle**

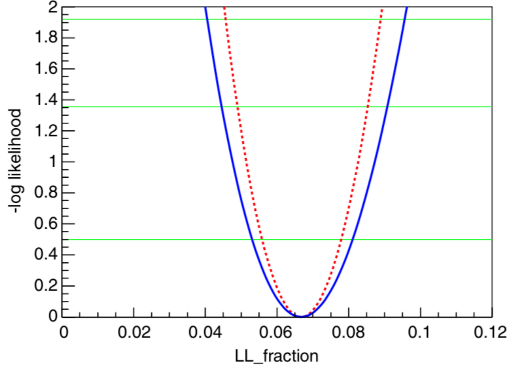
Group each particle features



DNN performance

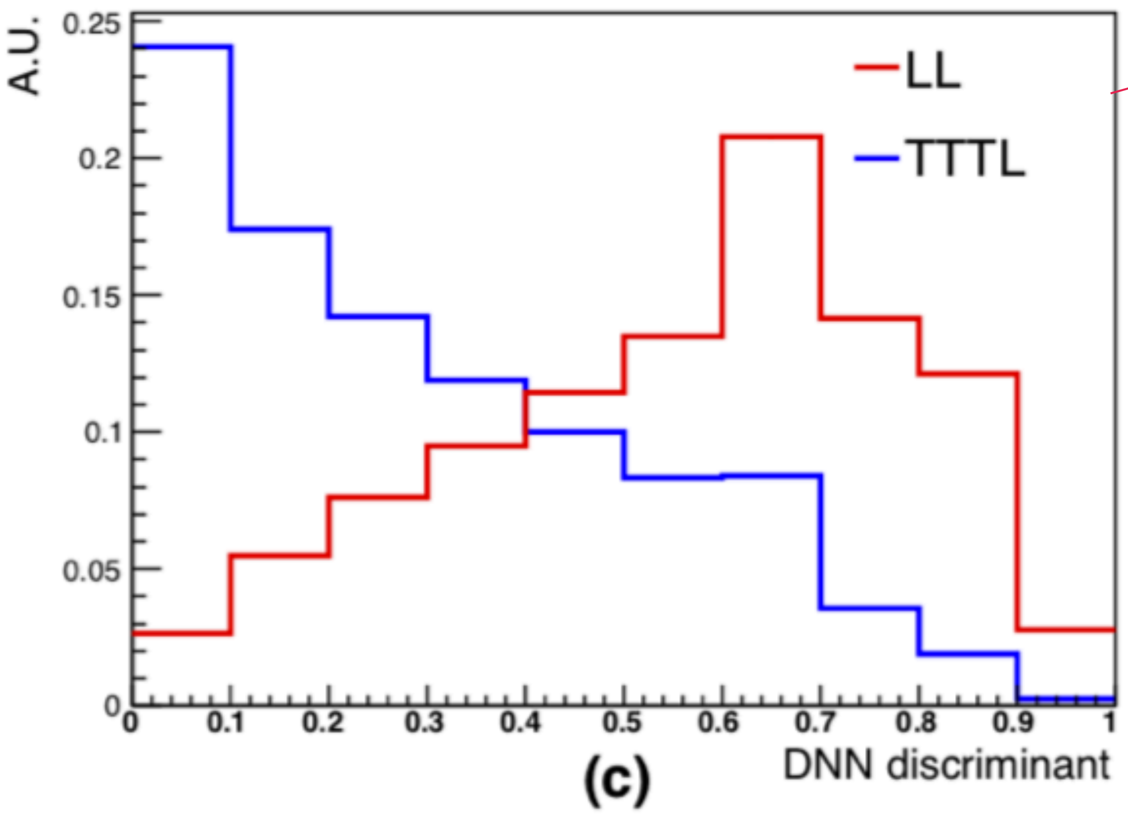


BDT

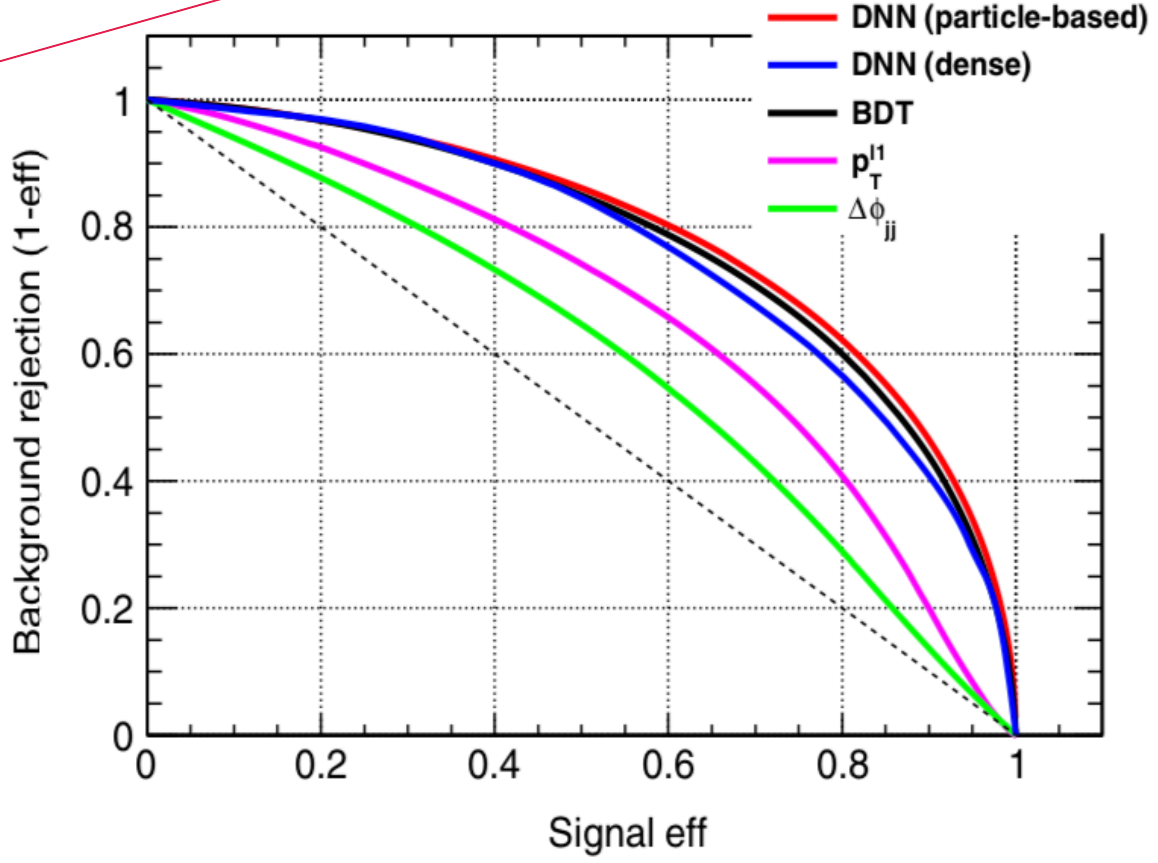


fitting $(M_{jj} > 1.5\ GeV)$

DNN

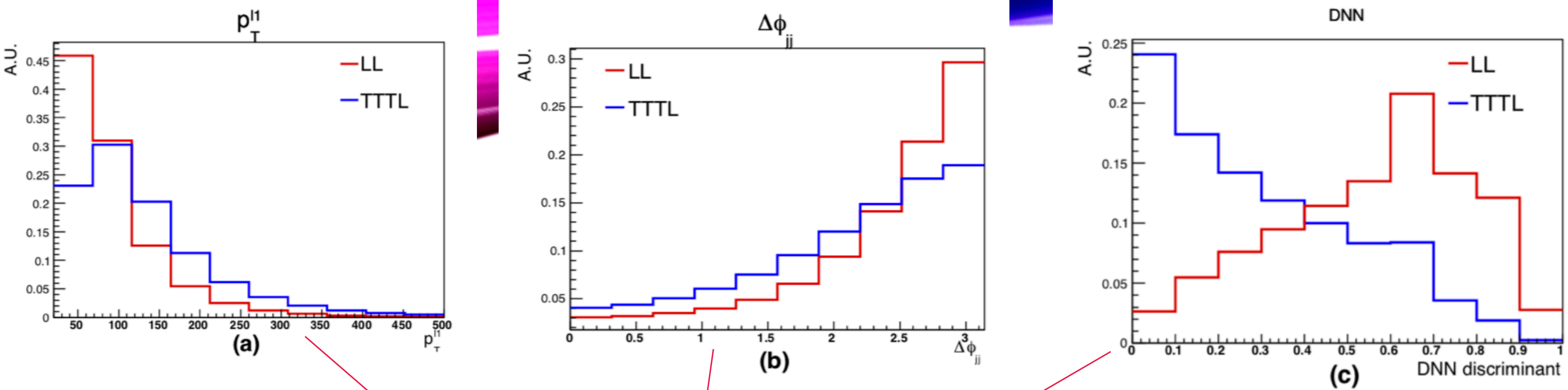


ROC curve

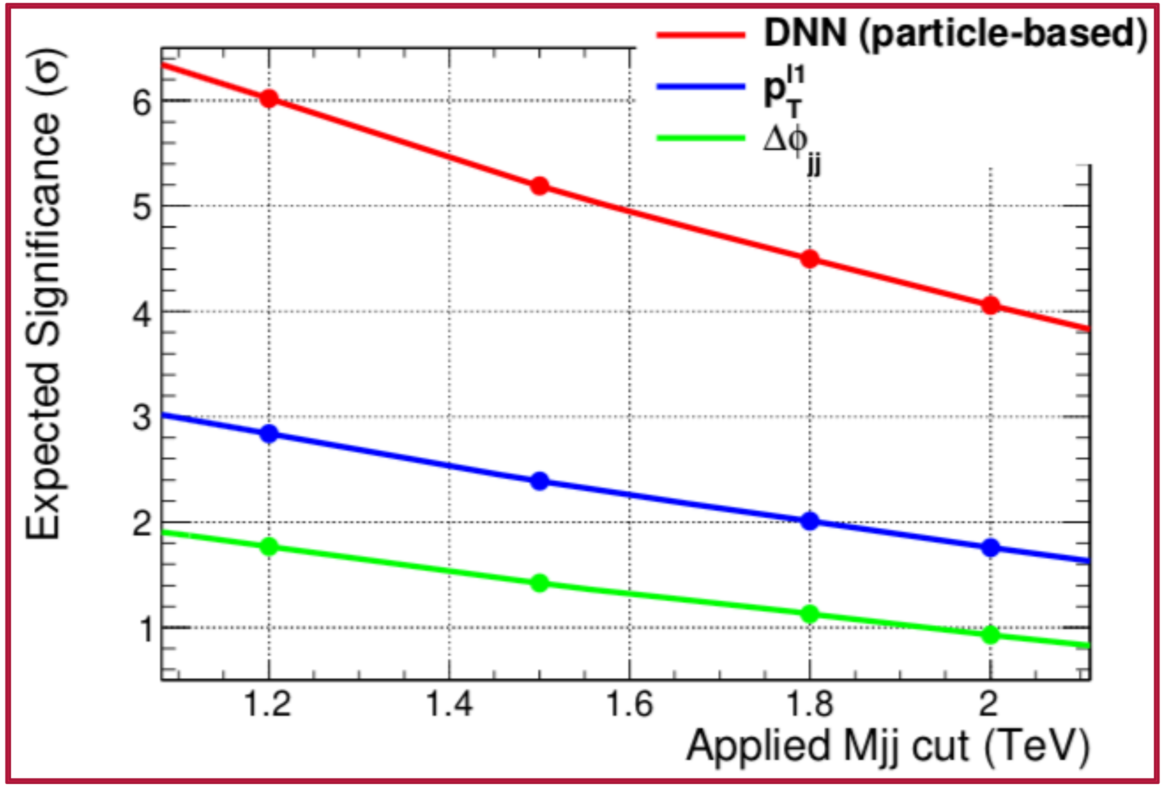


VBS-SSWW Results

arXiv:1812.07591

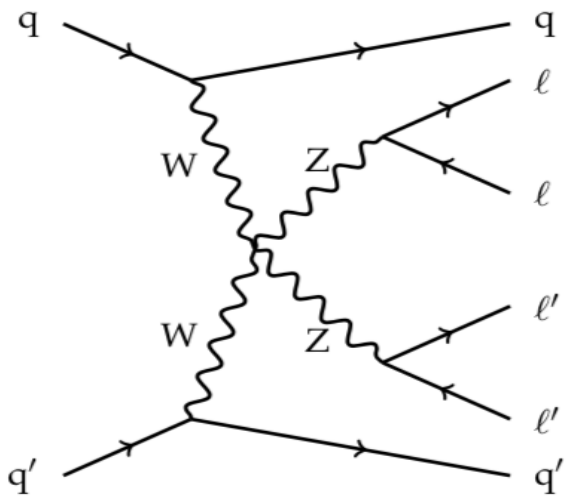


m_{jj} cut	True Fraction	$p_T^{l_1}$	$\Delta\phi_{jj}$	DNN
> 850 GeV	6.66%	$6.67\%^{+1.95\%}_{-1.90\%}$	$6.67\%^{+2.80\%}_{-2.76\%}$	$6.66\%^{+1.11\%}_{-1.04\%}$
> 1200 GeV	6.68%	$6.70\%^{+2.26\%}_{-2.22\%}$	$6.70\%^{+3.29\%}_{-3.25\%}$	$6.68\%^{+1.26\%}_{-1.20\%}$
> 1500 GeV	6.67%	$6.71\%^{+2.62\%}_{-2.57\%}$	$6.68\%^{+3.85\%}_{-3.80\%}$	$6.67\%^{+1.44\%}_{-1.37\%}$
> 1800 GeV	6.69%	$6.70\%^{+3.02\%}_{-2.96\%}$	$6.68\%^{+4.48\%}_{-4.42\%}$	$6.69\%^{+1.63\%}_{-1.56\%}$
> 2000 GeV	6.66%	$6.67\%^{+3.34\%}_{-3.27\%}$	$6.66\%^{+4.98\%}_{-4.93\%}$	$6.66\%^{+1.79\%}_{-1.71\%}$



Higher significance achievable!

Polarization Fraction Measurement in ZZ scattering

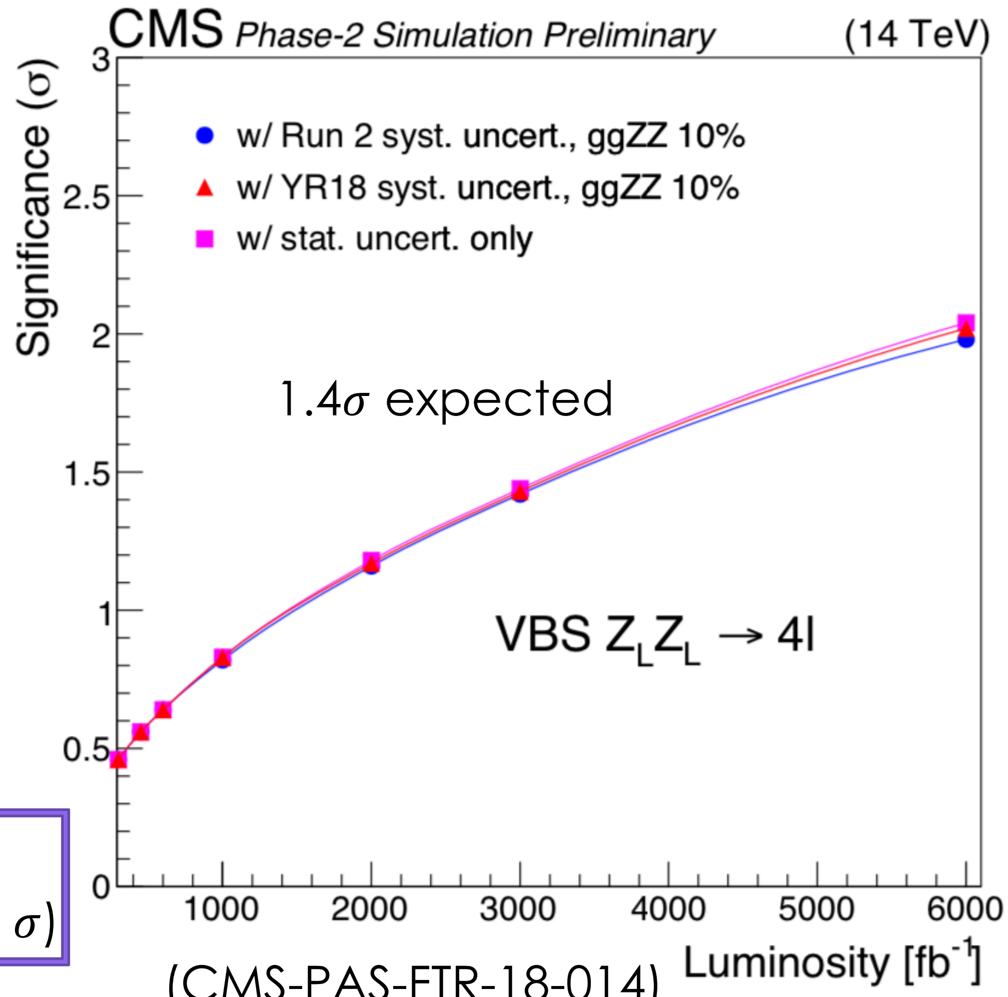


Advantages comparing with VBS Same-sign WW:

- No missing transverse momenta
  → Particle-based DNN
- Easy to modeling background from other process

Disadvantage :

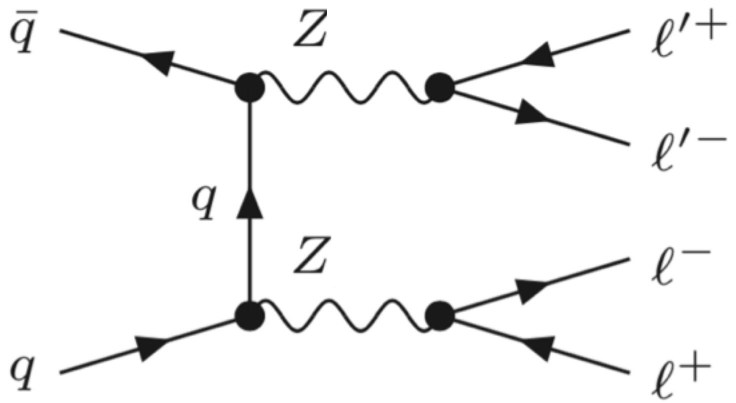
- Low cross-section
  → Lower yield for signal MC

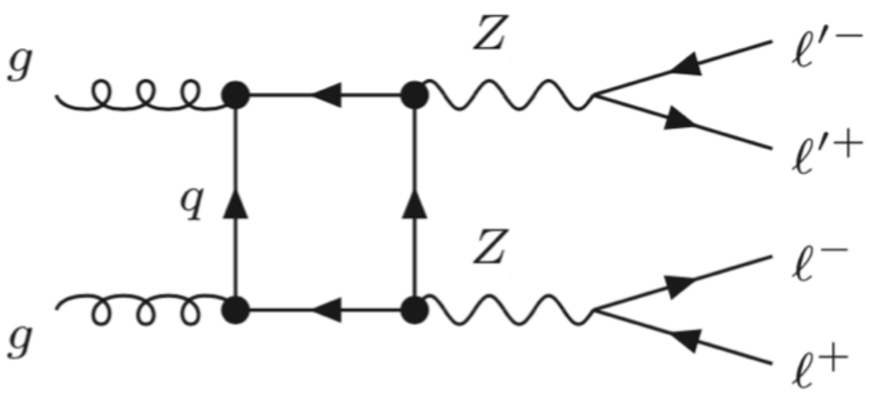


(CMS-PAS-FTR-18-014)

The process is observed using 139 fb^{-1} of pp collision data at $\sqrt{s}$ = 13 TeV collected by the ATLAS detector at the LHC. (5.5 σ)

(ATLAS-CONF-2019-033)

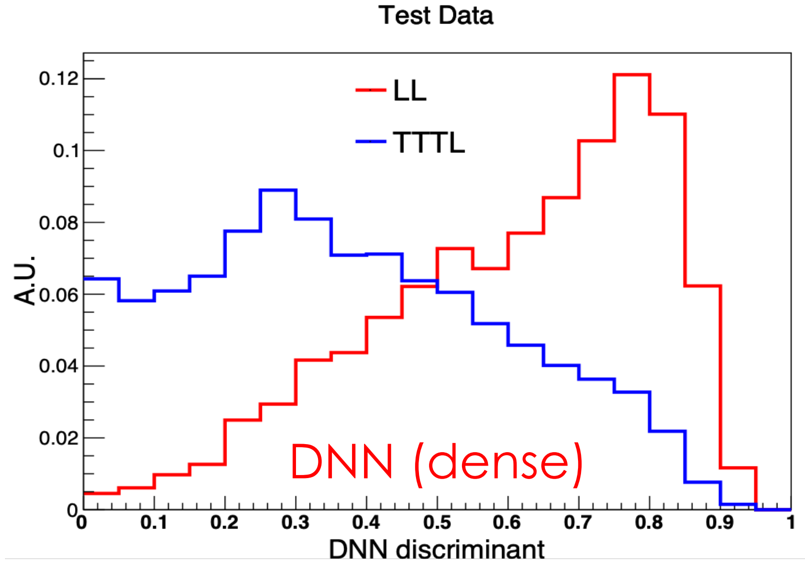


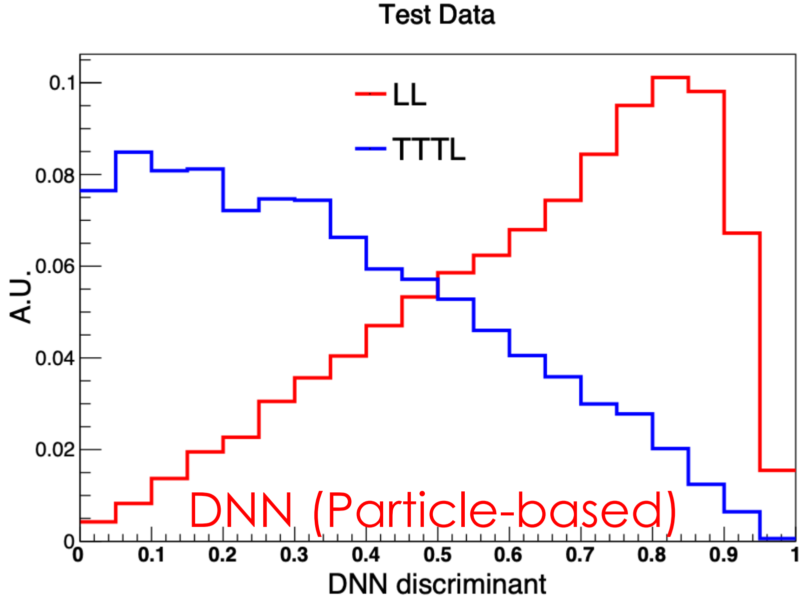


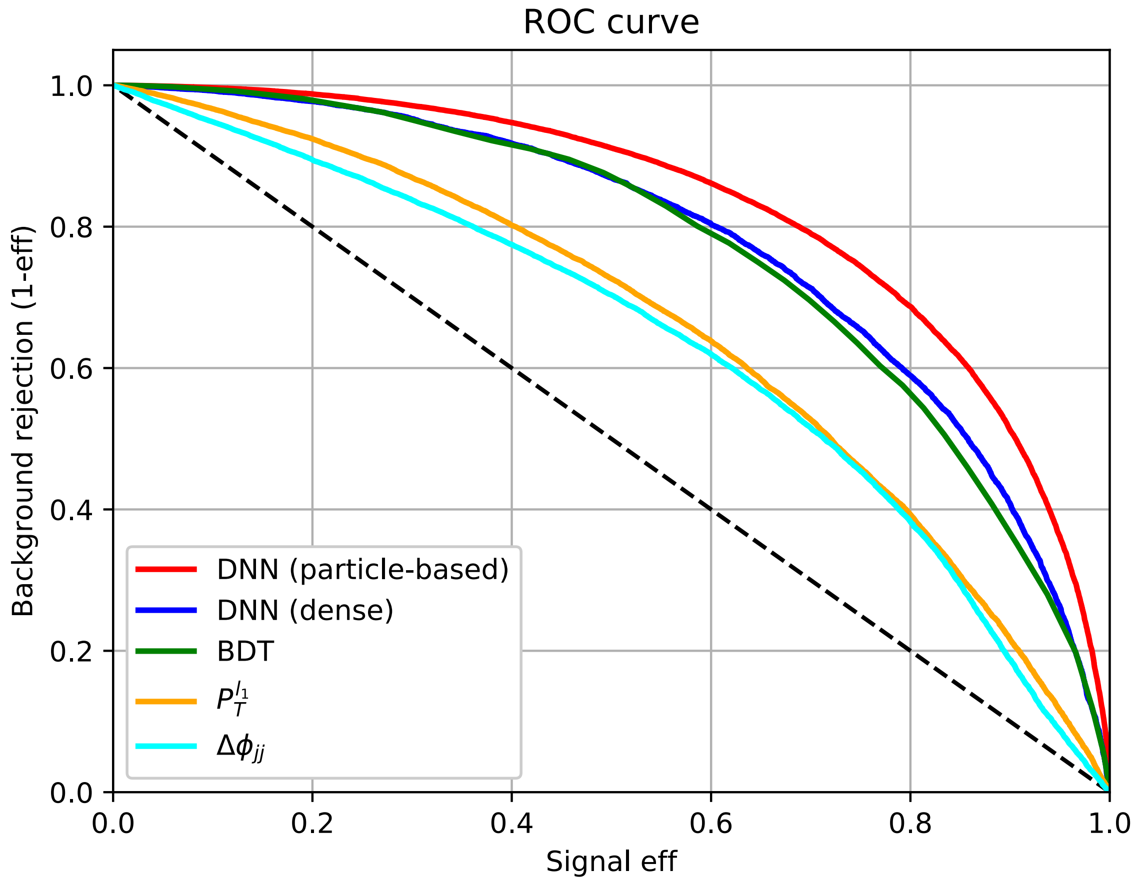
Event Selection

- Lepton
  - More than 4 leptons
  - At least two pair of +,- (same generation of leptons)
  - $P_T^{l_1}$ > 20 GeV
  - $P_T^{l_2}$ > 10 GeV
  - $P_T^{l_4}$ > 5 GeV
- Jet
  - More than 2 jets
  - $P_T^{j_1}$ & $P_T^{j_2}$ > 25 GeV
  - $|\ \eta^{j_1}\ |$ < 4.7
  - | Jet2eta | < 4.7
  - M_{jj} > 400 GeV
  - $|\Delta\eta_{jj}|$ > 2.4
- Z boson
  - 60 GeV < M_{ll} < 120 GeV
  - minimum $(M_{ll}^1 - M_Z^1)^2 + (M_{ll}^2 - M_Z^2)^2$ case (if more than one scenario of lepton pair combination)
- Others
  - B-jet veto

Pilot study : comparison on LL vs TTTL







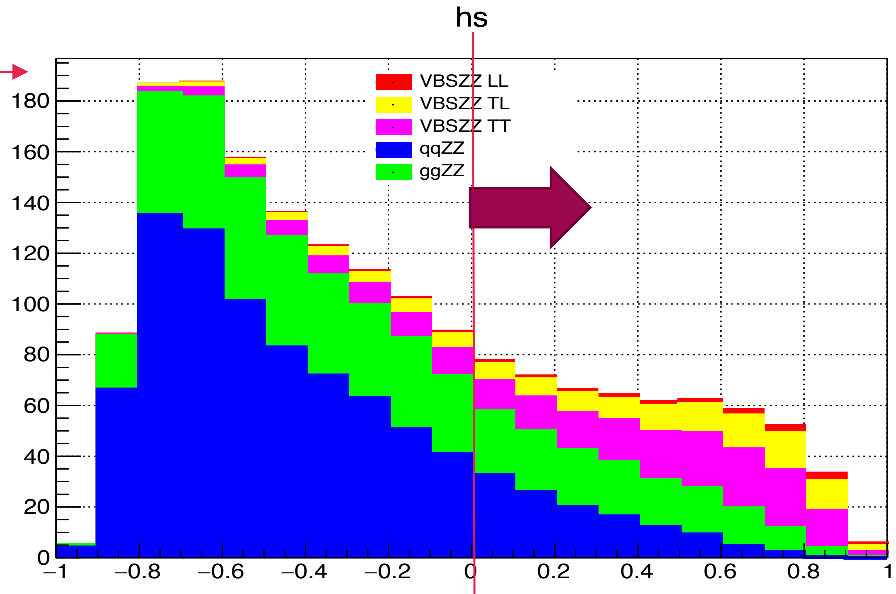
On LL vs TTTL :
Particle-base DNN performs the best
(25,000 events for each LL and TTTL)

Next: Binary classification -> Multi-class classification

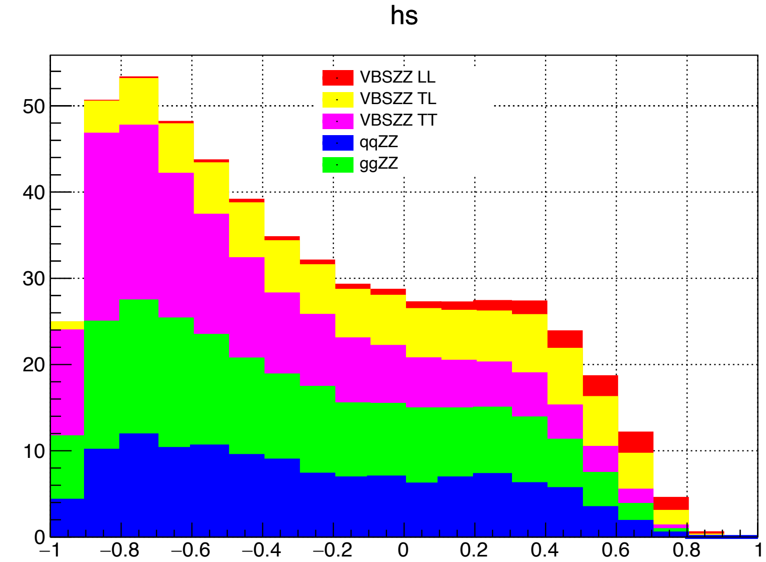
(LL, TTTL) (LL, TT, TL, qqZZ, ggZZ)

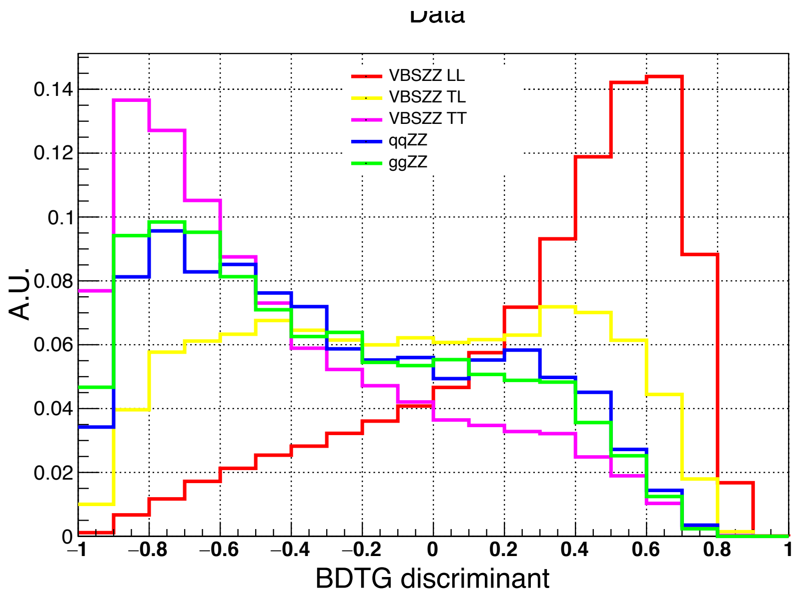
BDT: Two-step BDT

- Similar strategy used in 'CMS-PAS-FTR-18-014'
  - Two BDT models are trained
    - VBS vs QCD (BDT1)
    - LL vs Bkgs (BDT2)



Cut & count on $S/\sqrt{B}$ maximum



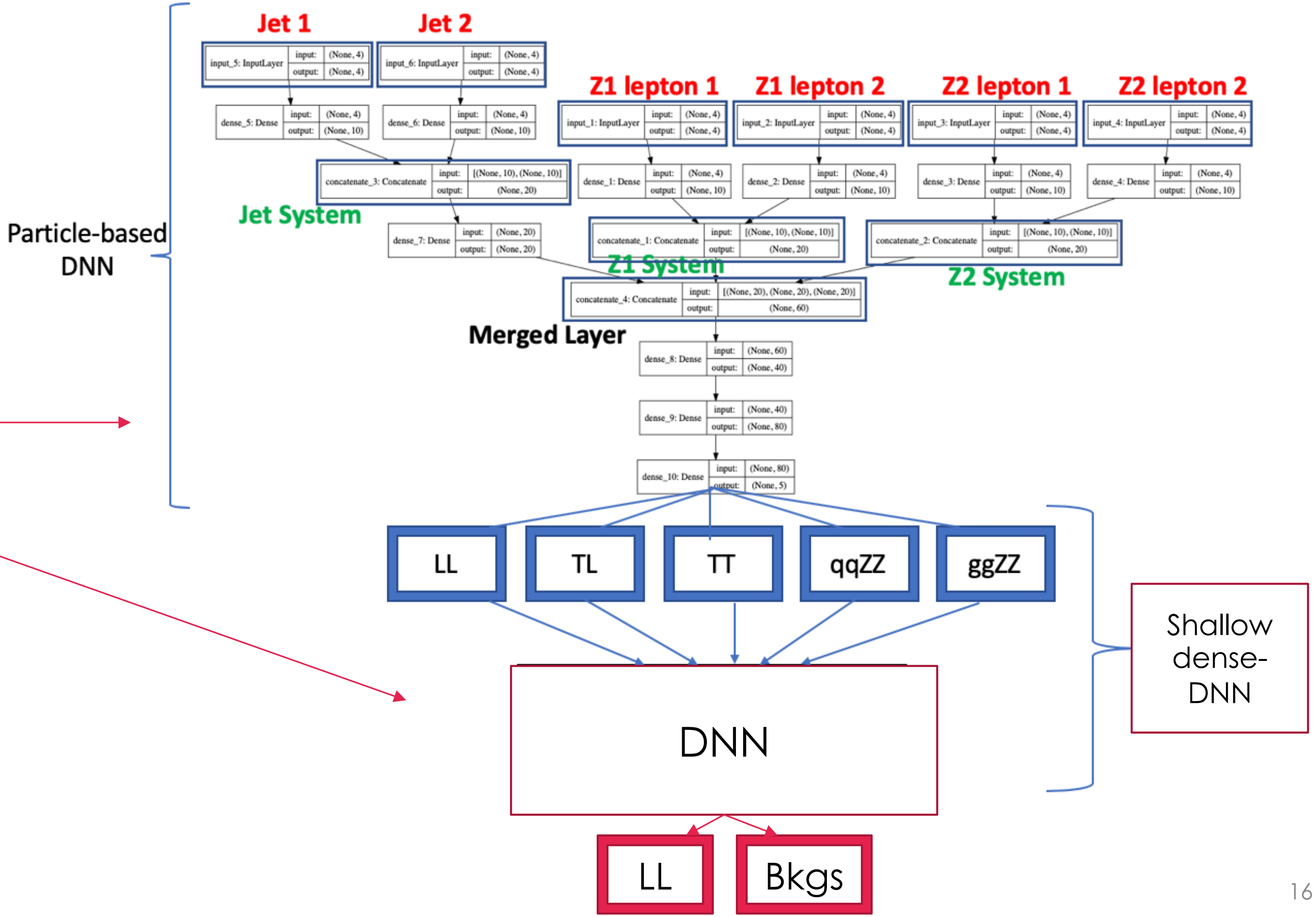


1.41σ (1.23σ)

Statistical uncertainty only (additional 10% uncertainty applied both on signal and background)

DNN: Two-step DNN

- Inspired by two-step BDT ('CMS-PAS-FTR-18-014')
    - Two DNN models are trained
        - Particle-based DNN
        - Shallow dense-NN
- ***1.42σ (1.31σ)***

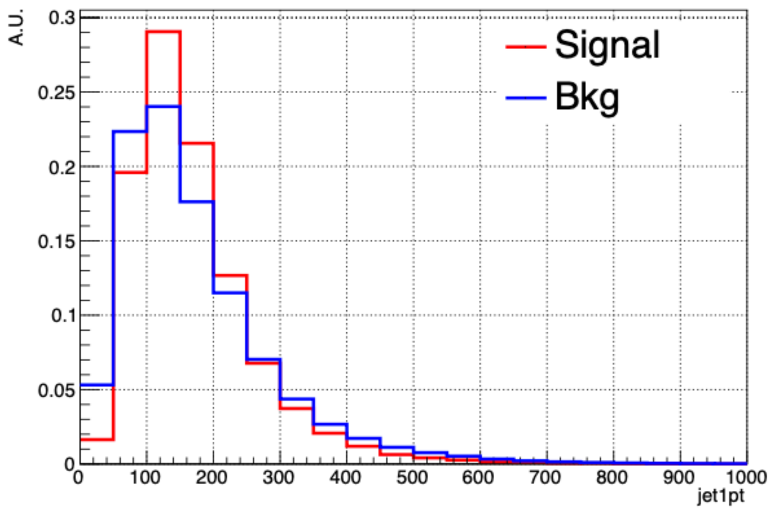


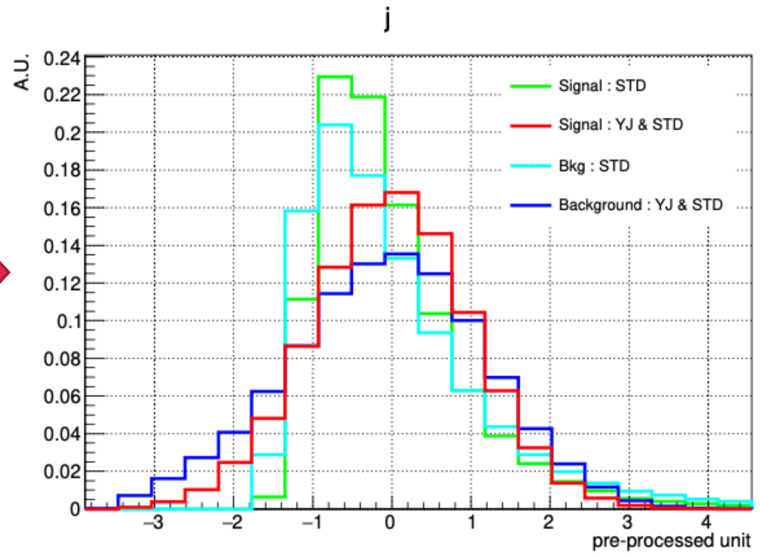
DNN: Data pre-processing effect

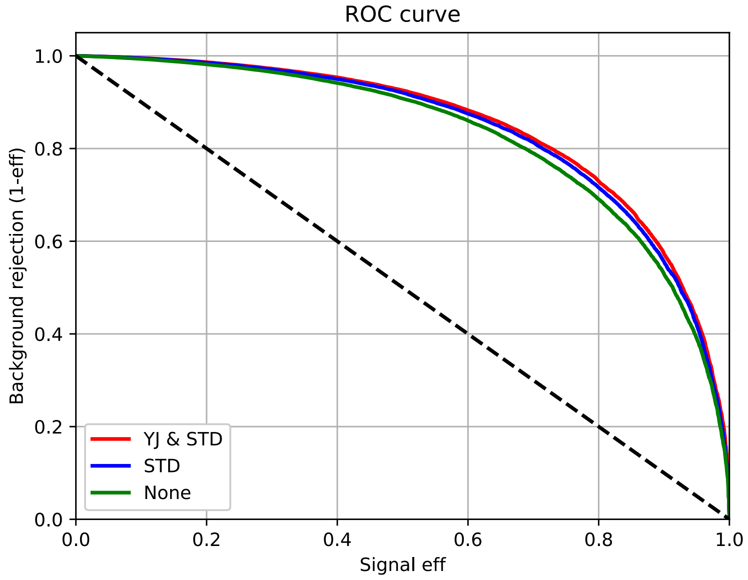
- Two-step DNN
  1. Standardization (STD): shifting
  2. Yeo-Johnson power transformation & Standardization (YJ&STD): make gaussian-like

(Input into two-step DNN)

P_T^{j1} Original distribution → P_T^{j1} transformed distribution → Effect on DNN output



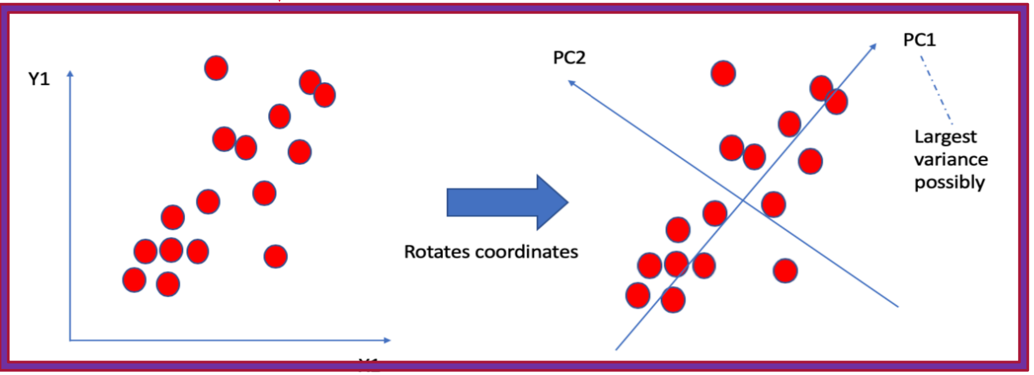


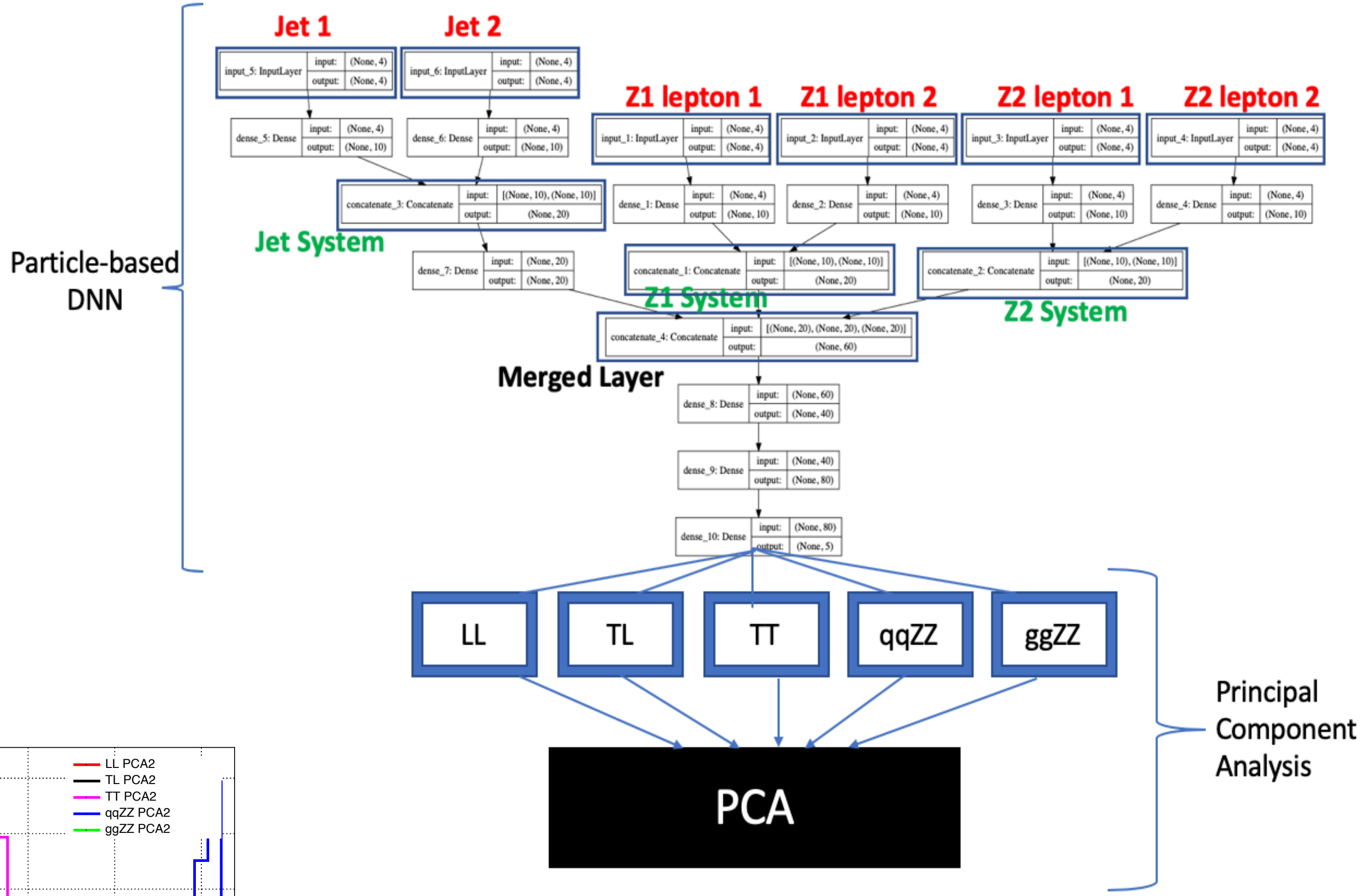


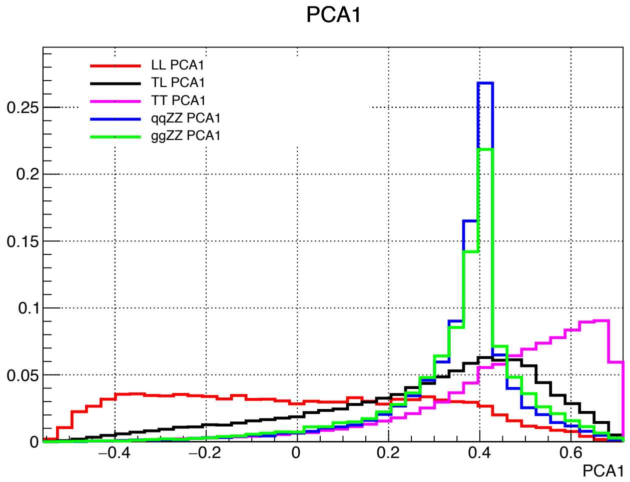
- STD DNN: ***1.43σ (1.33σ)***
- YJ&STD DNN: ***1.47σ (1.38σ)***

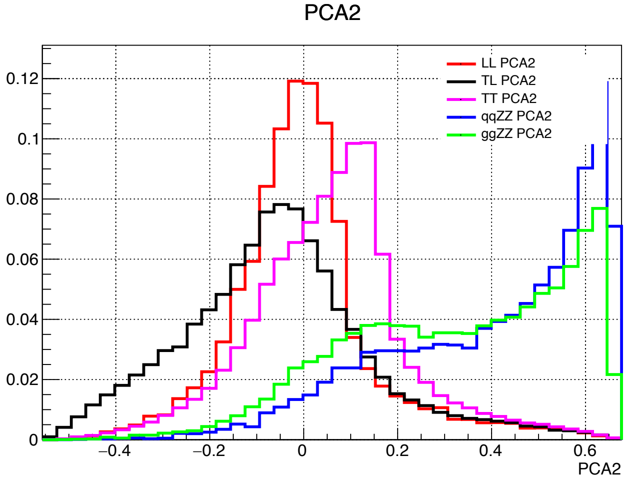
DNN: DNN-PCA

- Particle-based DNN
- PCA







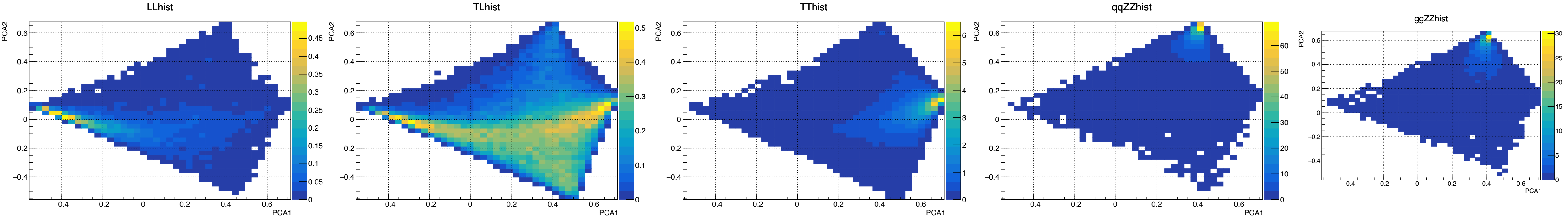


Principle component	PC1	PC2	PC3	PC4	PC5
Explained variance ratio	64.8%	18.1%	13.0%	4.2%	$< 0.1\%$

- ***DNN-PC1*: *1.55σ (1.46σ)***

DNN:
DNN-PCA multi-dimensional fitting

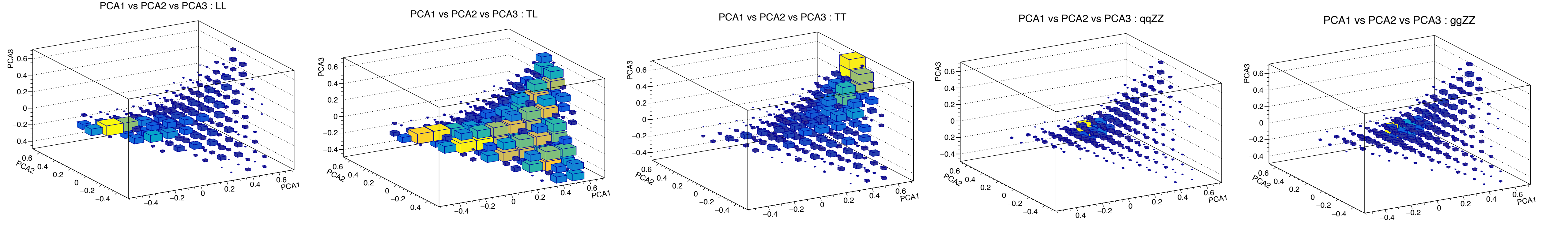
PC1 vs PC2



LL TL TT qqZZ ggZZ

DNN-PC12: 1.65σ (1.57σ)

PC1 vs PC2 vs PC3

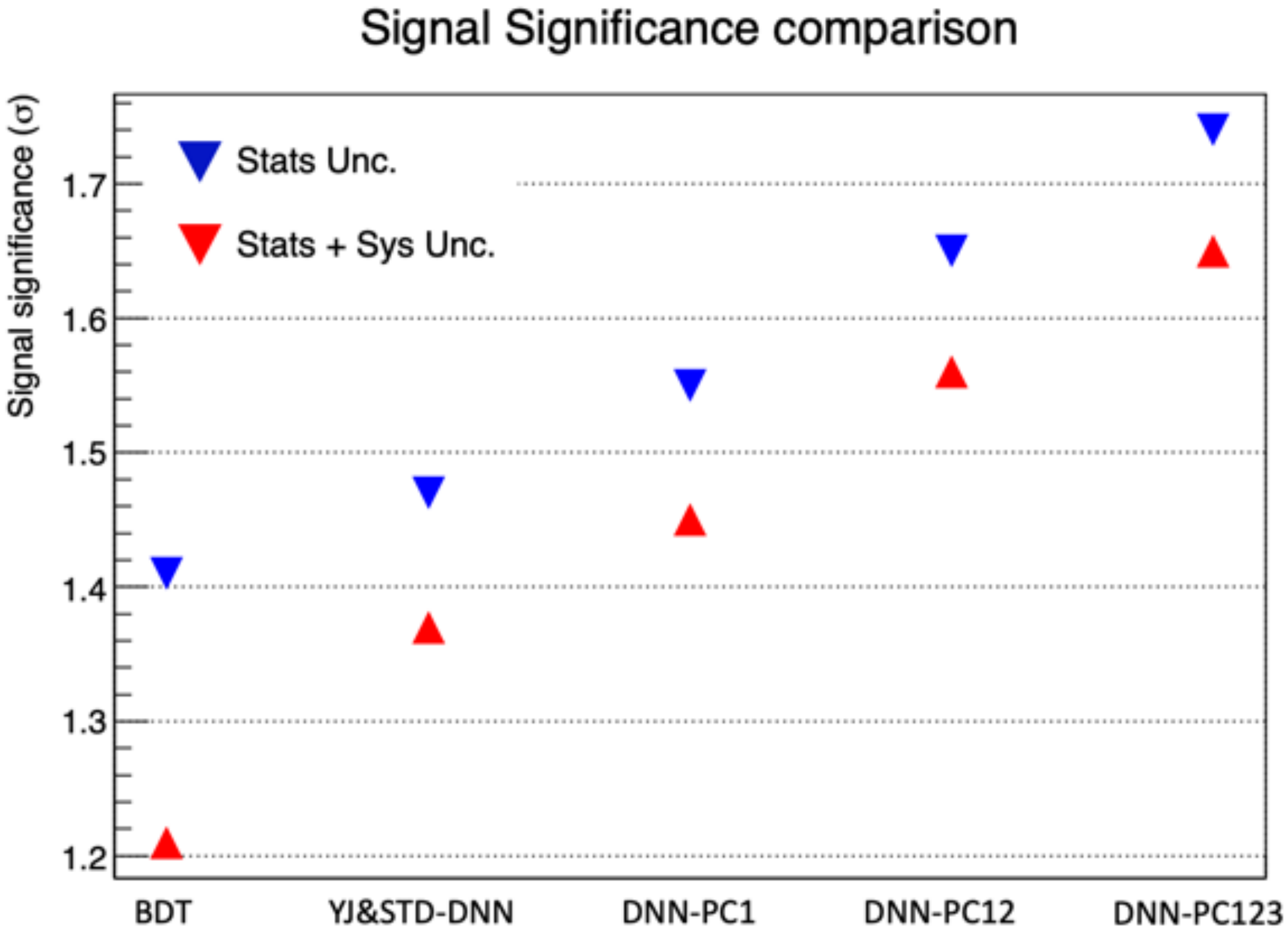


LL TL TT qqZZ ggZZ

DNN-PC123: 1.74σ (1.66σ)

Expected significance on diverse models (VBS ZZ)

arXiv:1908.05196



Summary

- Longitudinally polarized vector boson scattering ($V_L V_L$ -> $V_L V_L$) is crucial for testing Higgs unitarization.

- Within VBS same-sign WW channel, which is one of the most promising VBS channel, we need full HL-LHC data and advanced analysis technique for observing $V_L V_L$ -> $V_L V_L$.

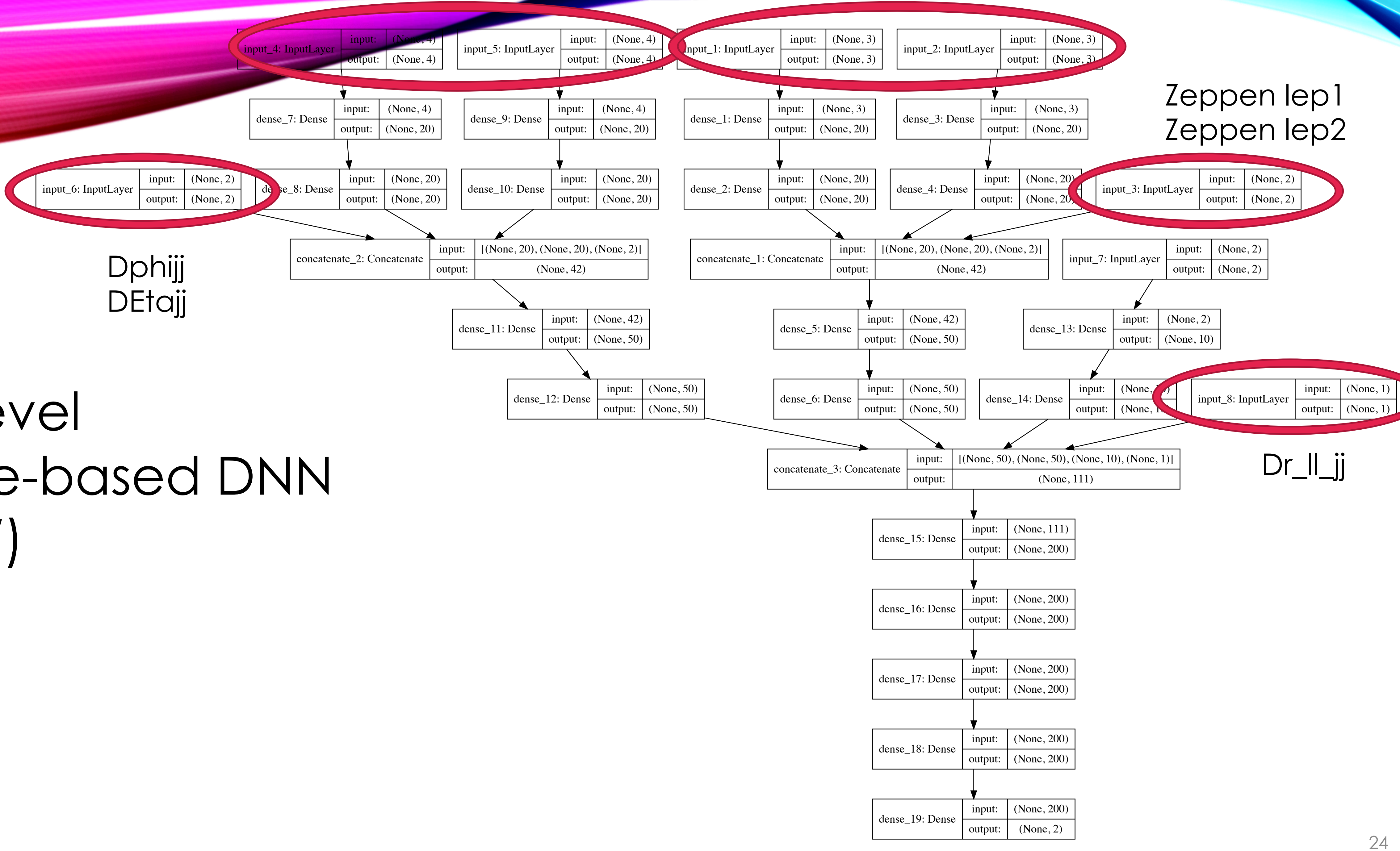
- Deep Neural Network (DNN) can be used to improve sensitivity.
  - Particle-based DNN is an architecture that improves discrimination over dense models.
  - Preliminary studies show greater improvement with ZZ than with WW
  - Hybrid of Particle-based DNN is even more promising.

- Particle-based DNN model might be able to be applied on other analysis.

Thank you!

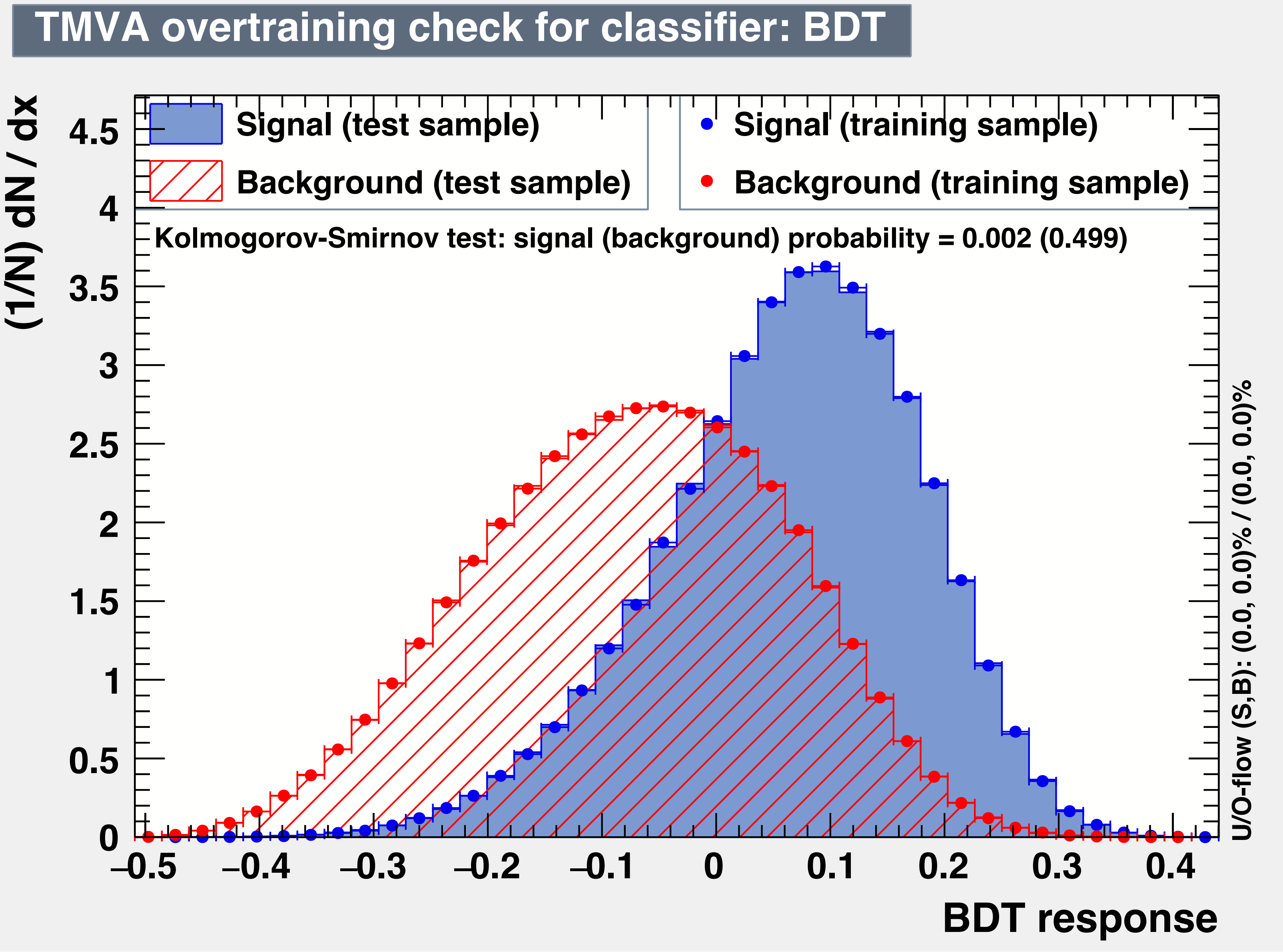
Back-up

High-level Particle-based DNN (SSWW)

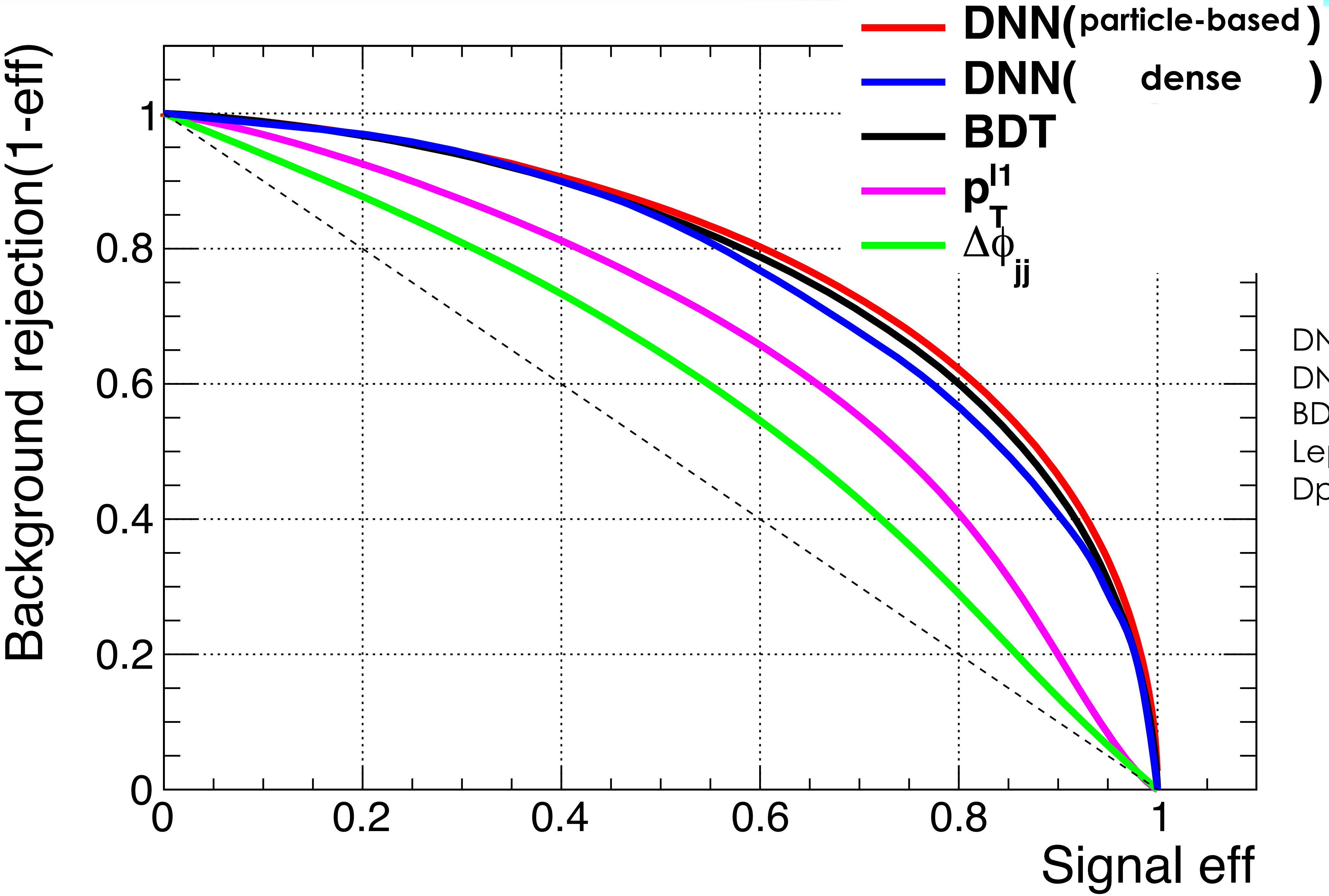


SSWW BDT

1000 trees of 5 maximum depth, 'Adaptive Boost' used for boosting (Gradient optimizer tested as well)



SSWW ROC

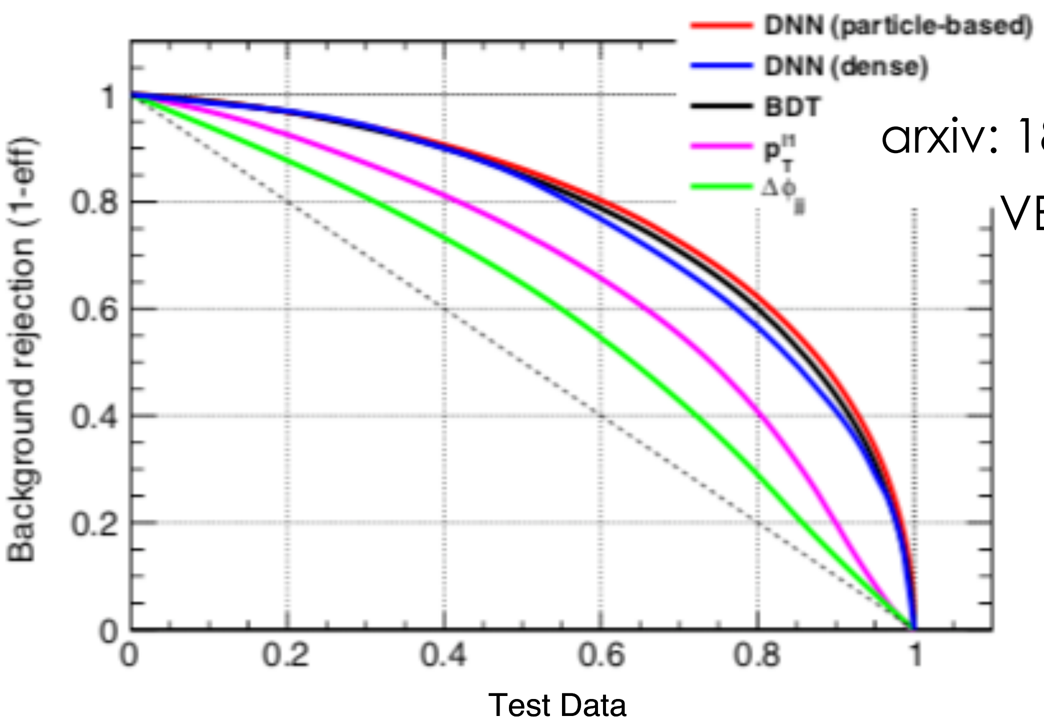


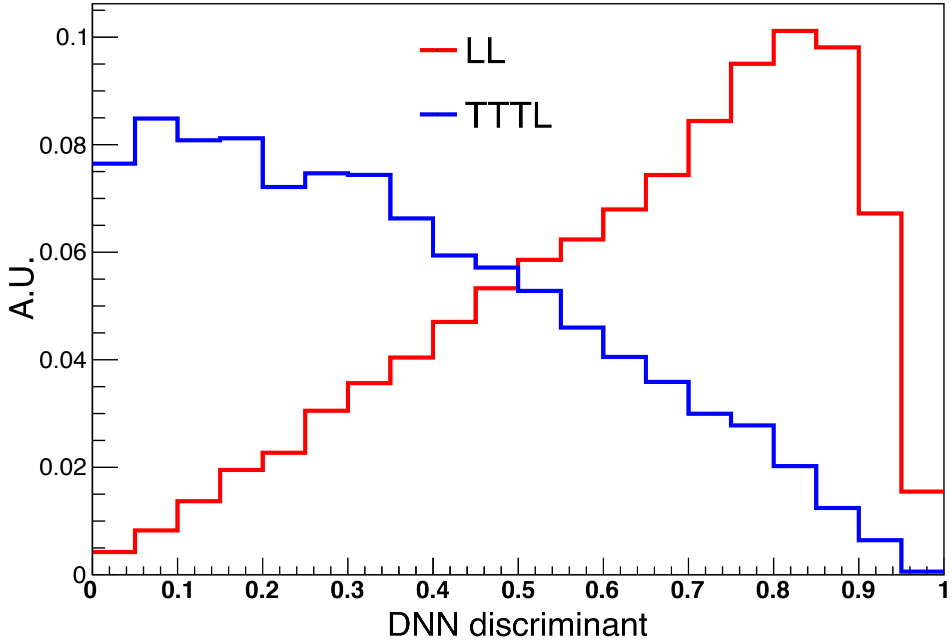
AUC	
DNN Gradual :	0.788
DNN Sequential :	0.762
BDT :	0.776
Lep1pt :	0.666
Dphijj :	0.591

Particle-based DNN

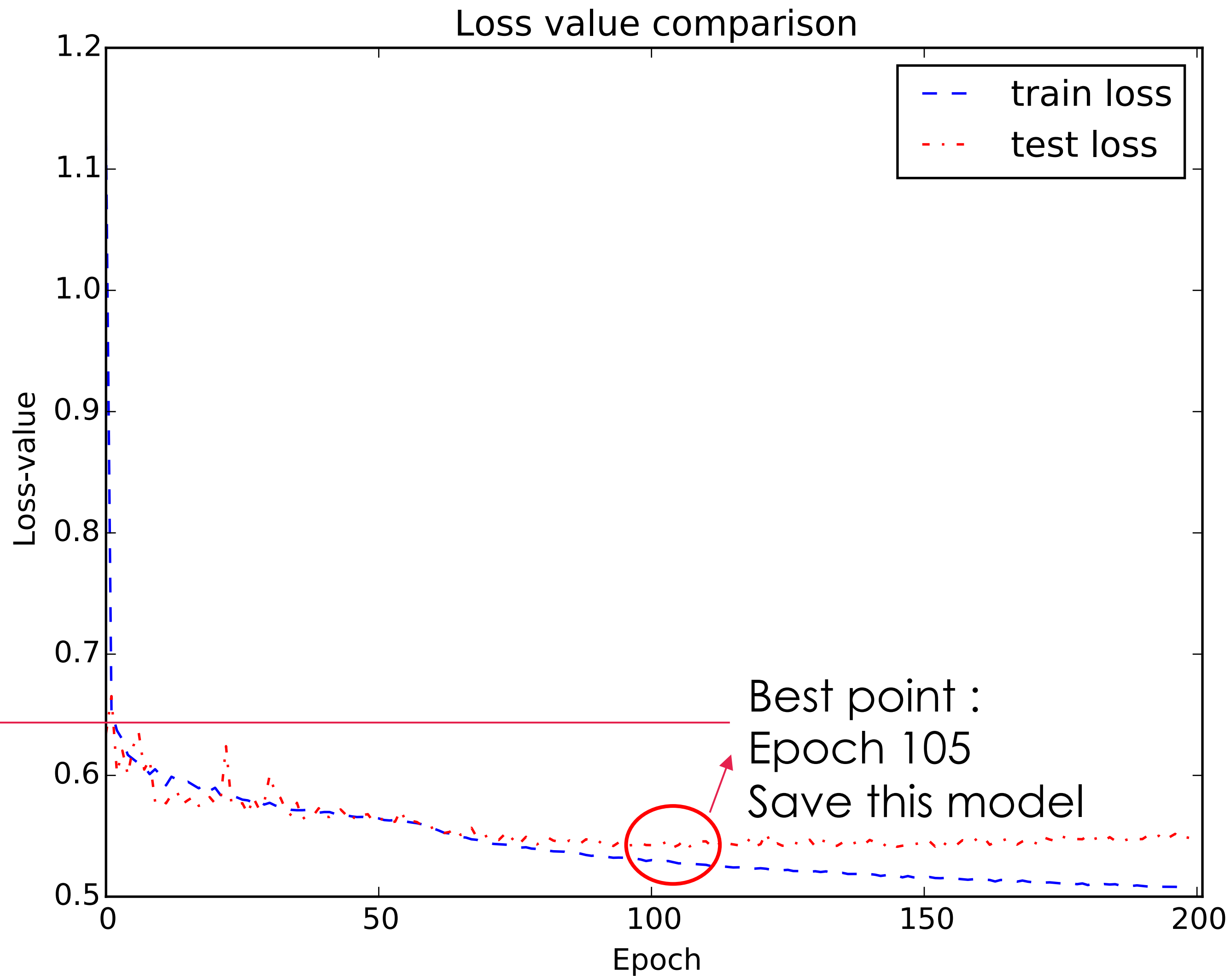
arxiv: 1812.07591

VBS Same-sign WW study



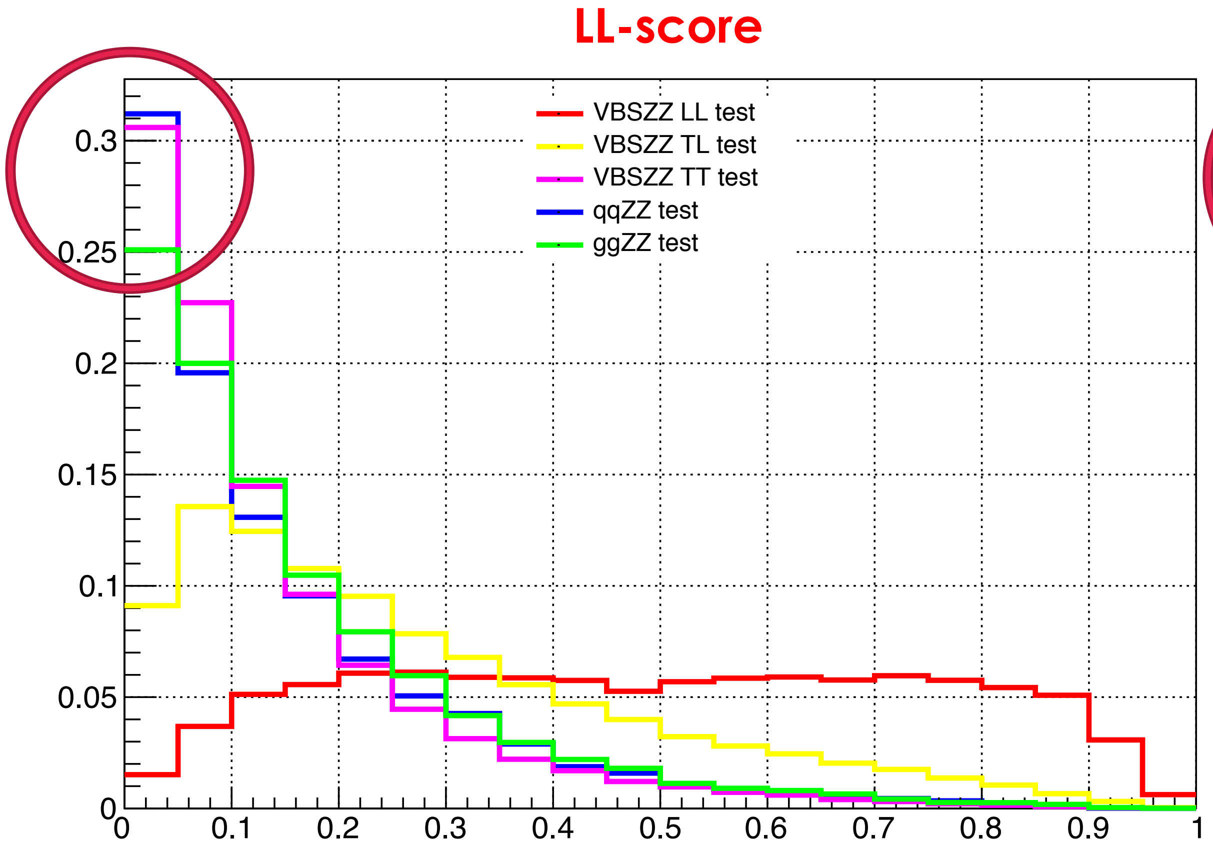


VBS ZZ DNN training

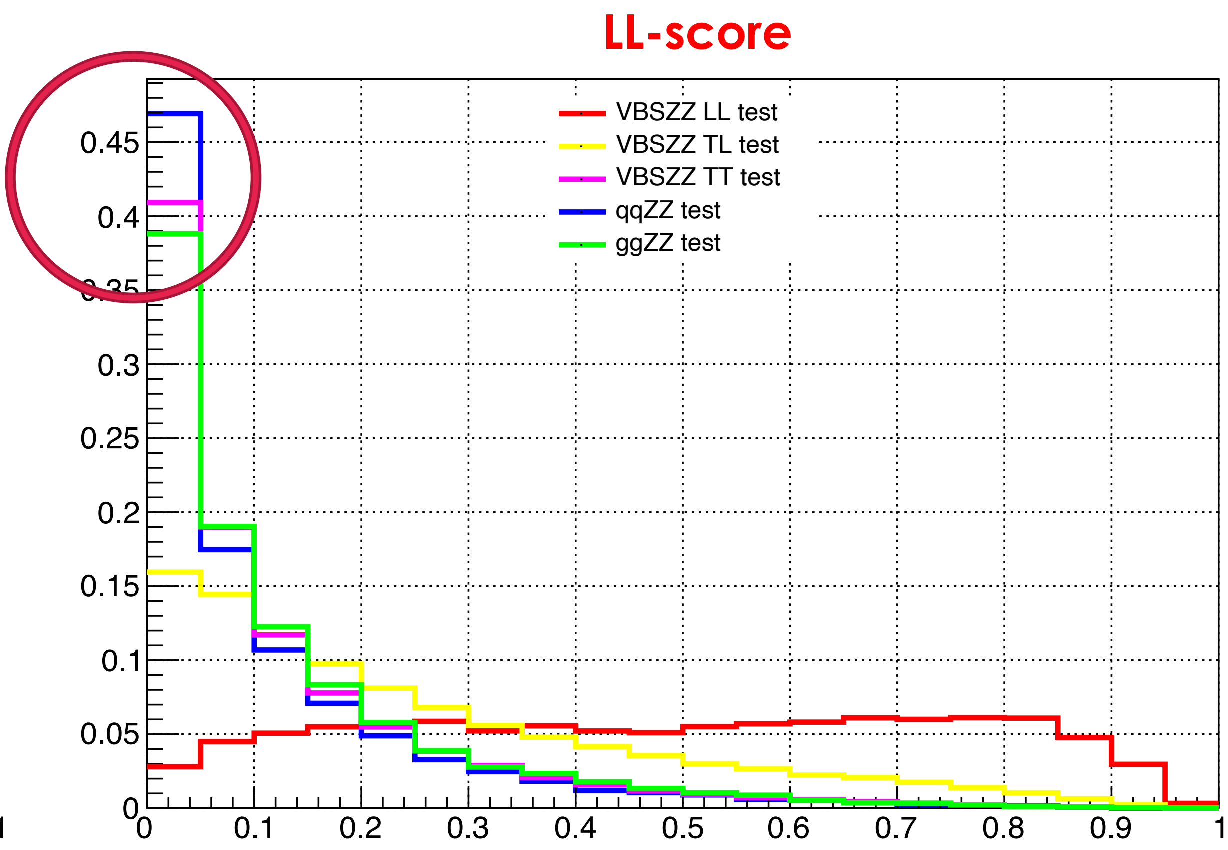


Best point :
Epoch 105
Save this model

Data pre-processing effect comparison



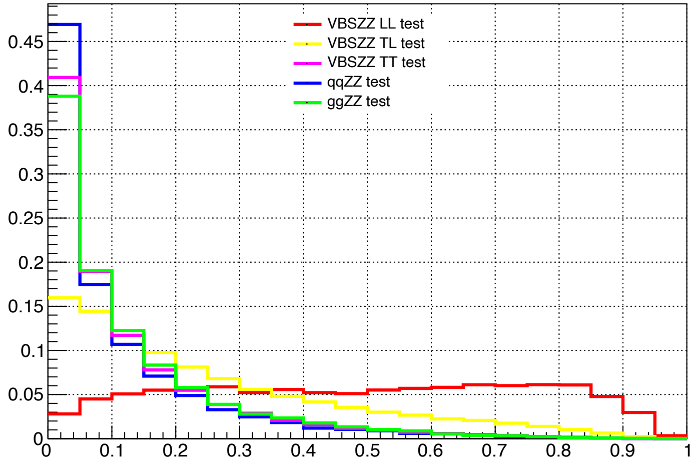
Only 'Standardization' applied



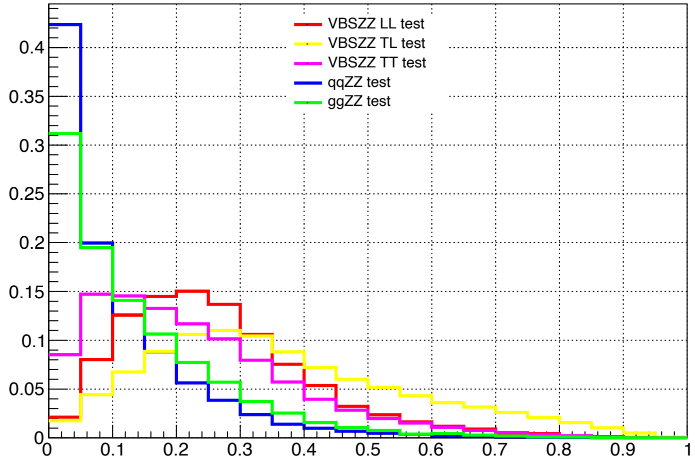
'Yeo-Johnson' & 'Standardization' applied

DNN scores: Two-step DNN

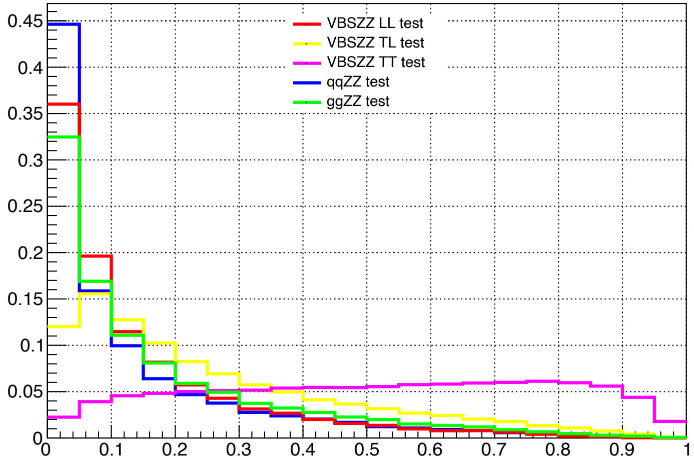
LL-score



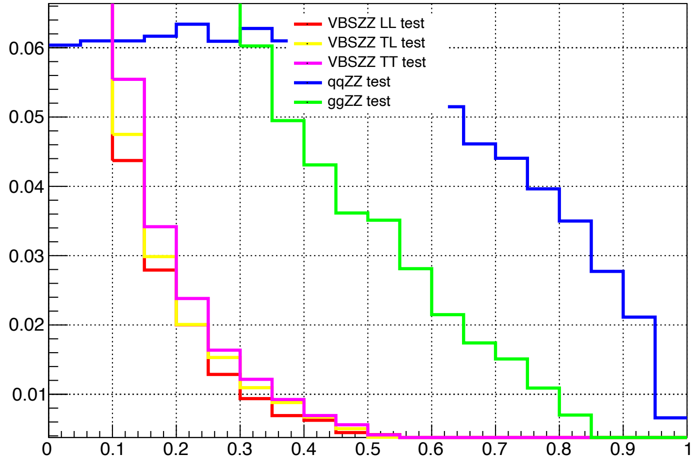
TL-score



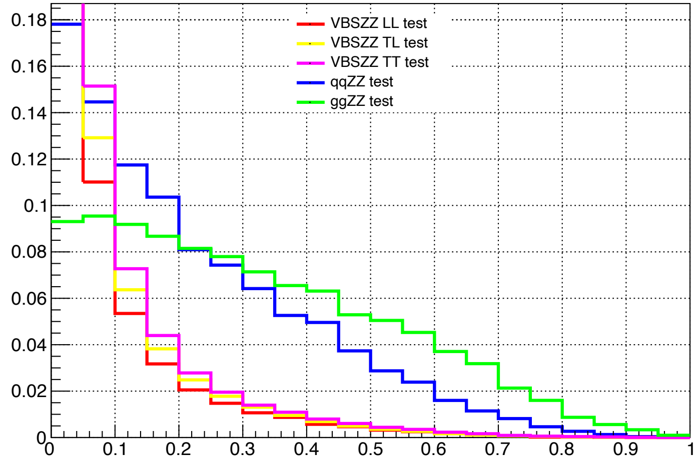
TT-score



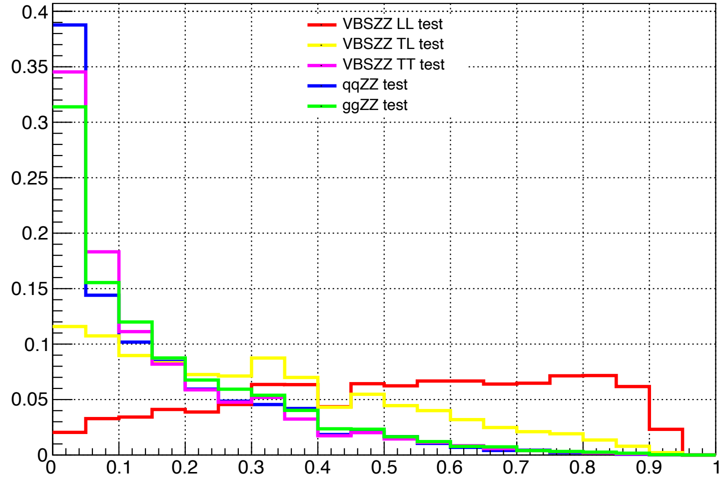
qqZZ-score



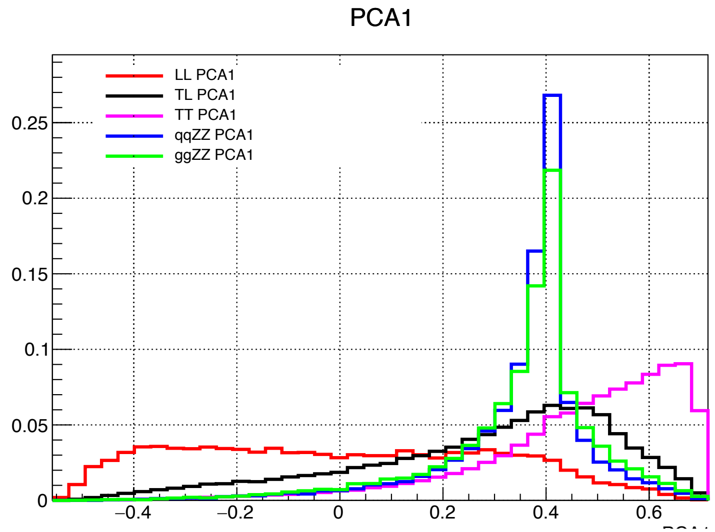
ggZZ-score

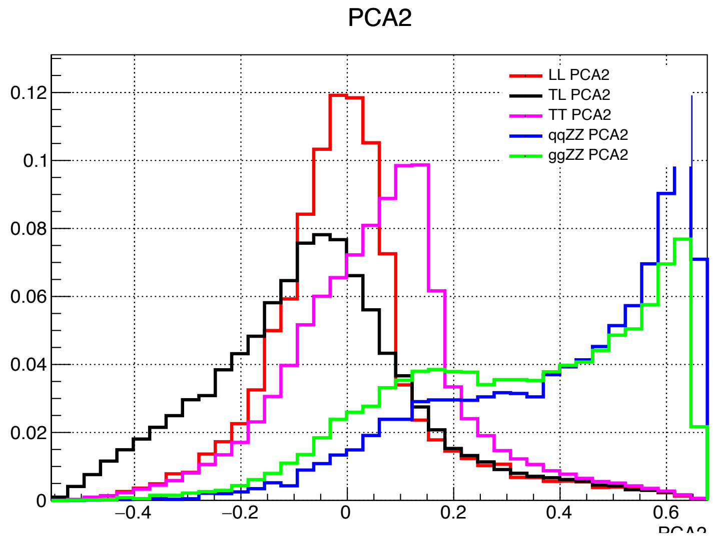


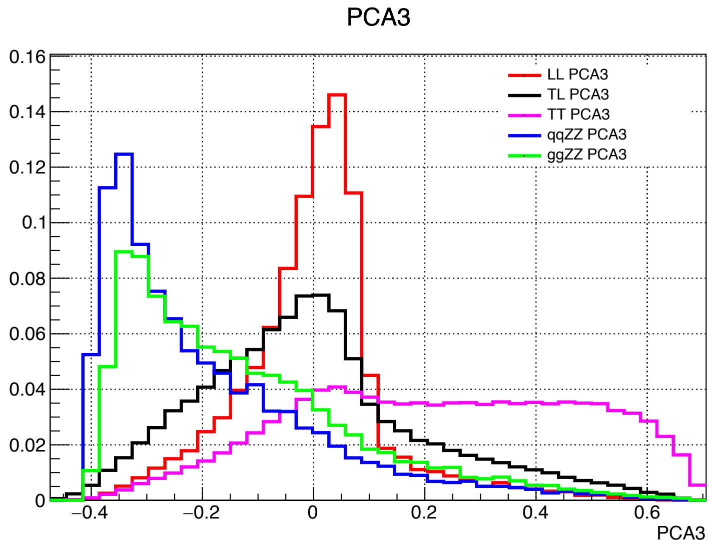
Shallow dense-NN score

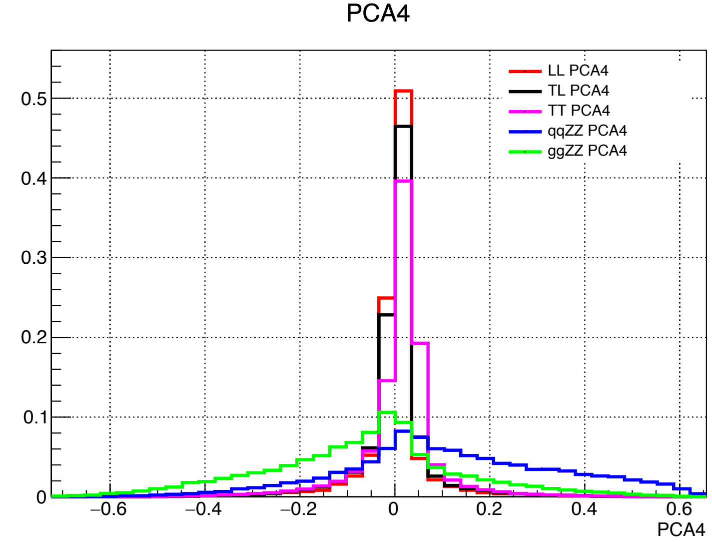


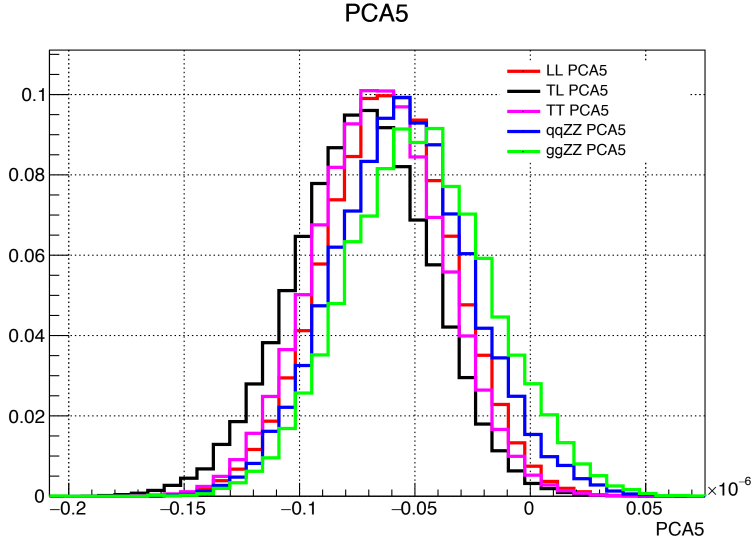
4.1. PC distribution











	PCA1	PCA2	PCA3	PCA4	PCA5
Explained variance ratio	64.8%	18.1%	13.0%	4.2%	<0.1%