$t\bar{t}HH$ channel with 2 leptons in the final state searching

Hanyang University High Energy Physics Laboratory

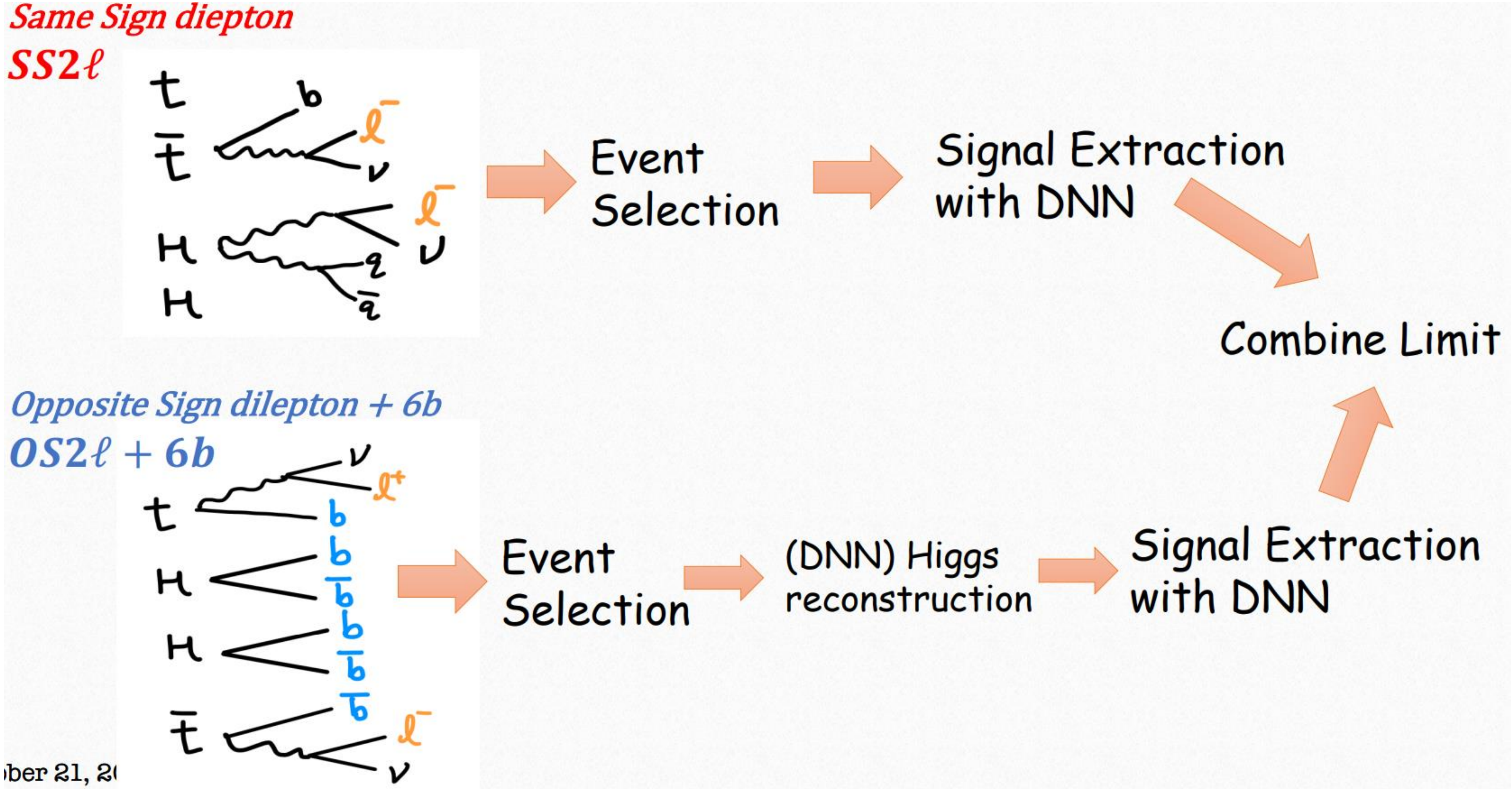
Sungbeom Cho, Taejeong Kim, Yang Tianyi, Yeonsu Ryou

$t\bar{t}HH$ searching

- Sungbeom Cho in our group has been working on the prospective $t\bar{t}HH$ study at the HL-LHC $\sqrt{s} = 14\ \mathrm{TeV},\ 3000\ \mathrm{fb}^{-1}$: AN-2024/209 (draft slides).
- We plan to develop this strategy into an analysis using Run 3 data and CMS Monte Carlo.

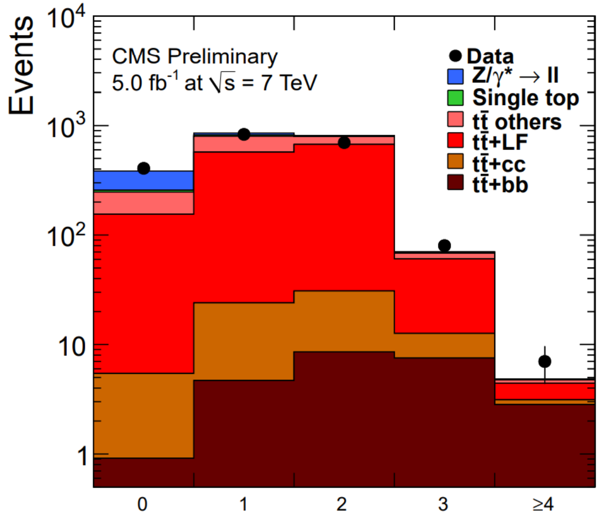
- The characteristic of our analysis is the **two leptons** in the final state:
  - Same-sign two leptons (SS2l)
  - Opposite-sign two leptons with $H \rightarrow b\bar{b}$ (OS2l+6b)
- The analyses in the two channels use the deep neural network (DNN) method to enhance signal-background discriminant.

Analysis strategy



Samples

- Signal: $t\bar{t}HH$ with $t\bar{t}$ single lepton (**SL**) and double lepton (**DL**) decay modes, and Higgs boson pair decay *inclusively*.
- Background:
  - Single Higgs backgrounds: $t\bar{t}H$, $t\bar{t}b\bar{b}H$, $t\bar{t}ZH$
  - Non Higgs backgrounds: $t\bar{t}VV$, $t\bar{t}b\bar{b}V$, $t\bar{t}b\bar{b}$, $t\bar{t}4b$, $t\bar{t}t\bar{t}$
  - Not using inclusive $t\bar{t}$ sample in this study.



  - Run 1 study indicates $t\bar{t}$ + light hardly have high b-Jet multiplicity

- Generator: **MadGraph5aMC@NLO** v 2.9.15 + parton shower using **Pythia 8**
- Detector simulation: **Delphes** v 3.5.0 using *CMS_PhaseII_0PU_v02.tcl* card.
- PDF modeling: **NNPDF 2.3** and **NNPDF 4.0**
- Higgs boson and top quark decay modeled using **MadSpin**.

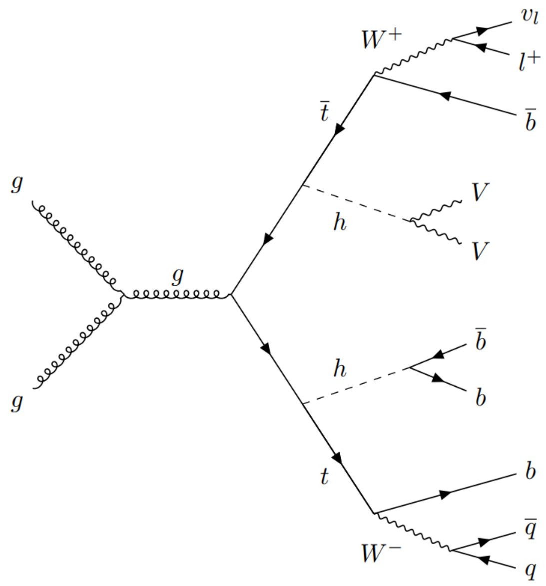
Object selection

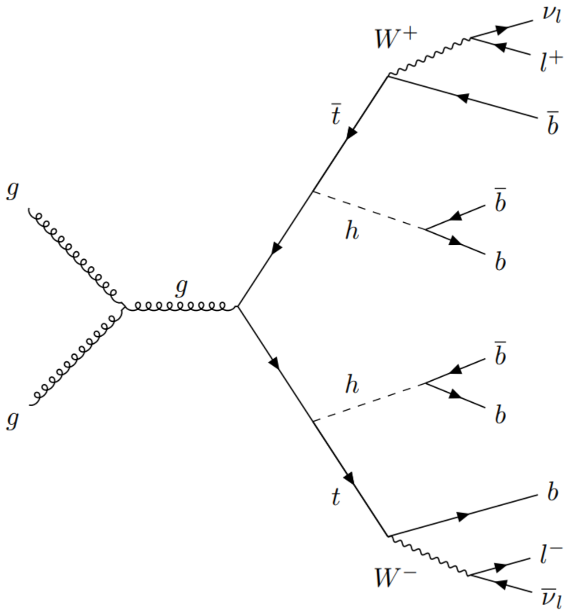
- $e^{\pm}$: $p_T > 23\ \text{GeV}, |\eta| < 3.0$
  - Identification efficiency ~0.97
  - Isolation variable $I_{rel} < 0.3$ for $\Delta R < 0.3$
- $\mu^{\pm}$: $p_T > 17\ \text{GeV}, |\eta| < 2.8$
  - Identification efficiency ~0.97
  - Isolation variable $I_{rel} < 0.3$ for $\Delta R < 0.3$
- Jets: $p_T > 30\ \text{GeV}, |\eta| < 3.0$, using anti-$k_T$ method with $\Delta R = 0.4$.
- B-tagging at *Loose* working point
  - Efficiency=0.85
  - Light flavour mis-tagging rate=0.10

Event selection

- SS2l:
  - $n_{lep} = 2$ (S1), with the **SAME** sign (S2)
  - $MET > 30$ GeV (S3)
  - $n_{B-tag} \geq \mathbf{3}$ (S4), Jets $H_T > \mathbf{300}$ GeV (S5)

- OS2l+6b:
  - $n_{lep} = 2$ (S1), with the **opposite** sign (S2)
  - $MET > 30$ GeV (S3)
  - $n_{B-tag} \geq \mathbf{5}$ (S4), Jets $H_T > \mathbf{500}$ GeV (S5)

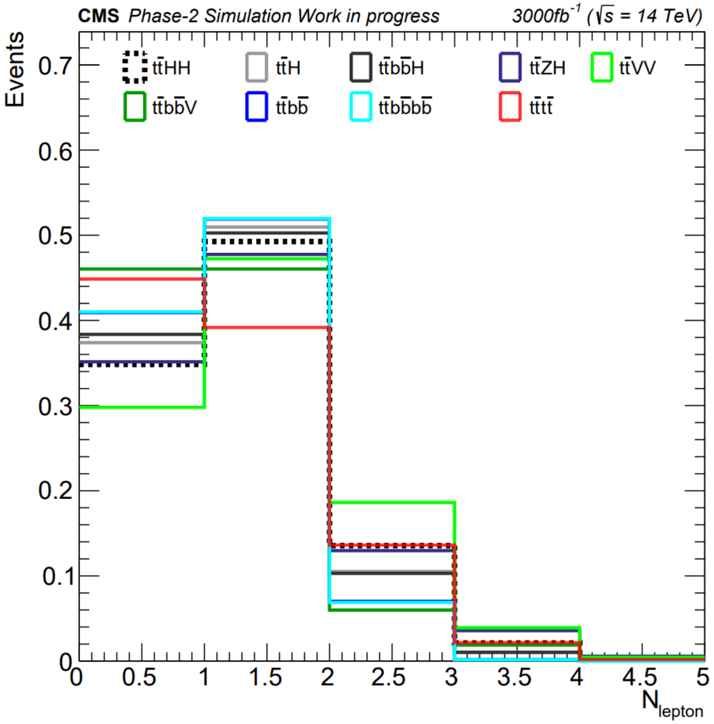




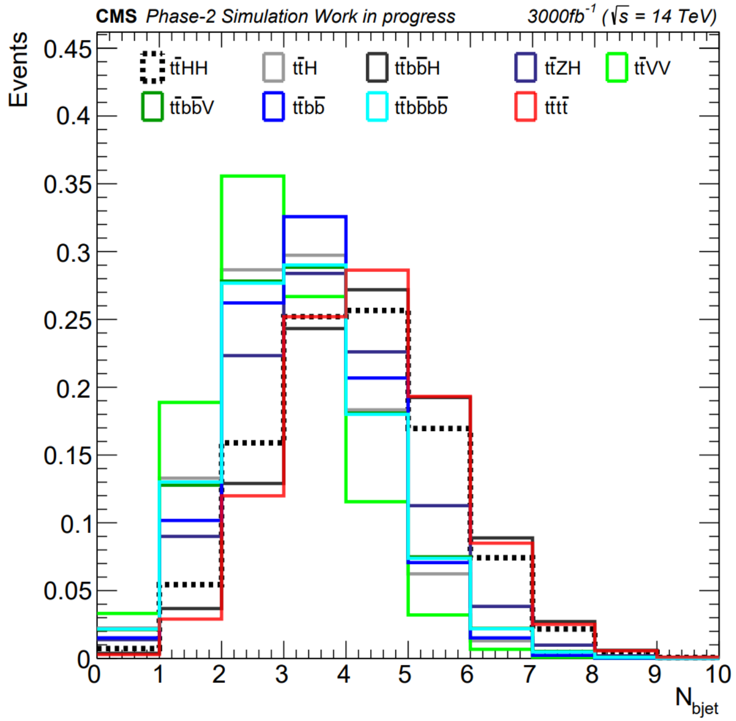
- Later, multiple lepton cases will be considered.

Object multiplicity illustration

Lepton count



B-jet count



- Events with more than 2 jets has a relatively small contribution.
- $t\bar{t}HH$ signal has higher B-jet multiplicity than $t\bar{t}b\bar{b}$ and $t\bar{t}4\bar{b}$, but lower than the $4t$ sample.

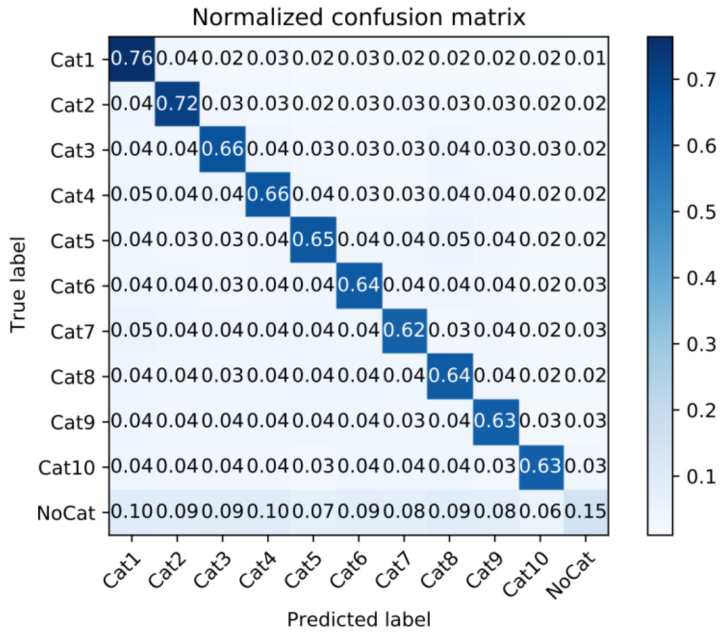
OS2l Higgs boson reconstruction (b-jet pairing)

- Traditional approach:
  - Minimizing $\chi^2 = \left((m_{jj} - m_{\text{Higgs}})/\sigma_{\text{Higgs}}\right)^2$
  - With only 16% accuracy.
- DNN jet matching:
  - Using Keras DNN determine the jet matching category

Matchable

Jet1	Jet2	Jet3	Jet4	Jet5	Category
H	H	0	0	0	1
H	0	H	0	0	2
H	0	0	H	0	3
H	0	0	0	H	4
0	H	H	0	0	5
0	H	0	H	0	6
0	H	0	0	H	7
0	0	H	H	0	8
0	0	H	0	H	9
0	0	0	H	H	10
Not matchable					11

Category definition

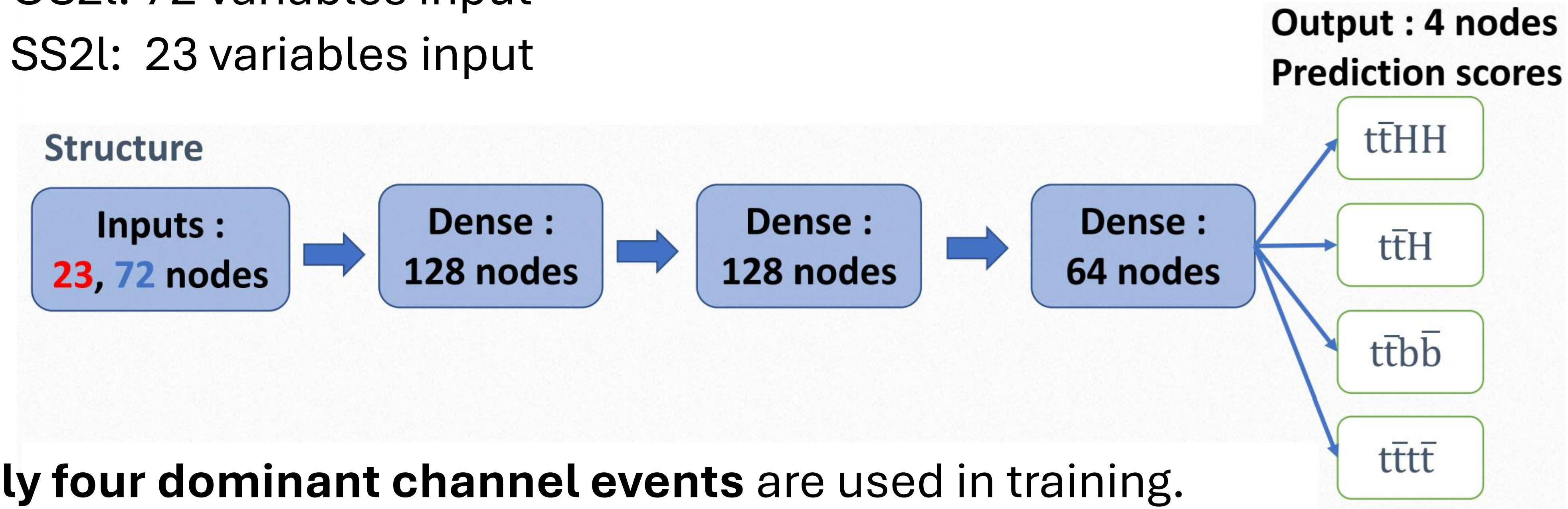


Performance

Better than invariant mass χ^2

DNN analysis

- Both OS2l and SS2l train a signal-background discriminant DNN **respectively**.
  - OS2l: 72 variables input
  - SS2l: 23 variables input



- **Only four dominant channel events** are used in training.
- The response of other backgrounds are also examed.

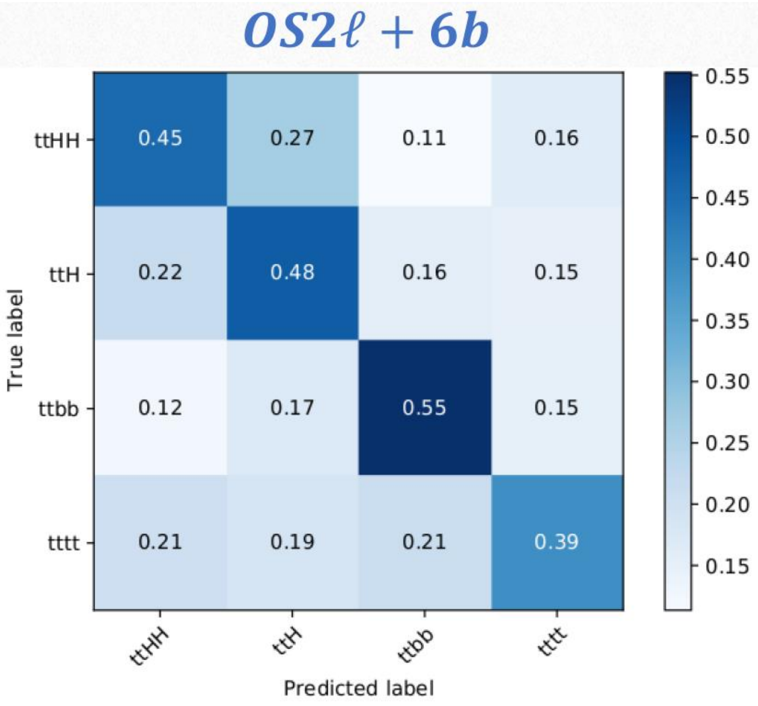
OS2l+6b DNN

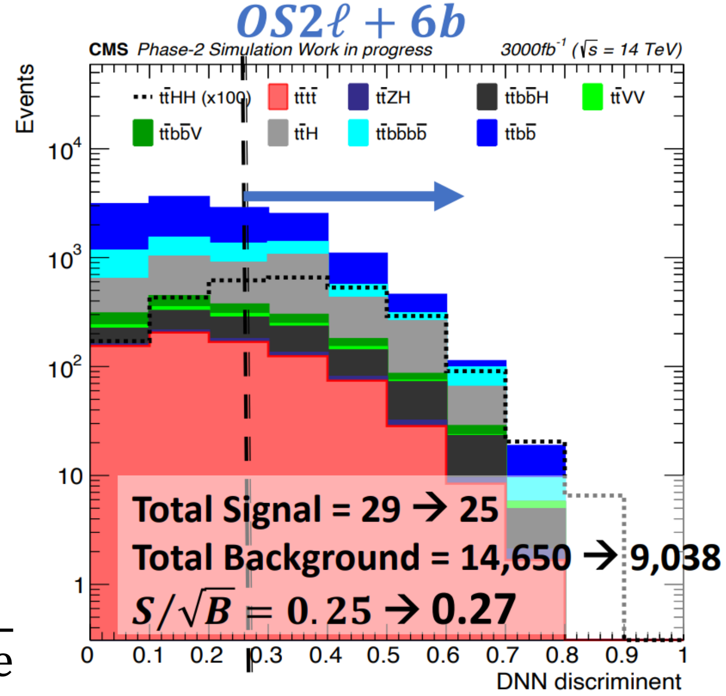
Variables	Description	Objects (x, y)
MET	Missing Transverse Energy	–
N_x	Multiplicity of x	l_1, l_2 (leptons: e or μ), b_1, b_2, b_3, b_4, b_5 (b−tagged jets) b_1, b_2, b_3, b_4, b_5
$p_T(x)$	Transverse momentum of x	
$\eta(x)$	Pseudorapidity of x	
$\phi(x)$	Azimuthal angle of x	
$m(x)$	Mass of x	b_1, b_2, b_3, b_4, b_5
$m_{max}(x, y)$	Maximum mass between x and y	
H_T	Scalar sum of transverse momenta of jets	
H_T^{norm}	H_T normalized to total energy	
$\Delta R(x, y)$	Distance ΔR between x and y	
$\Delta R_{avg}(x, y)$	Average ΔR between x and y	
$\Delta R_{min}(x, y)$	Minimum ΔR between x and y	
$\Delta R_{max}(x, y)$	Maximum ΔR between x and y	
$\tau_{twist}(x, y)$	Twist angle between x and y	
$m_H^1(x)$	Mass of the primary Higgs boson	
$m_H^2(x)$	Mass of the secondary Higgs boson	
$\Delta\eta^{bfh}(x)$	Pseudorapidity difference of x and y from Higgs	
$H_T^{bfh}(x)$	Scalar sum of p_T of b−jets from the primary Higgs	
$\Delta R^{bfh}(x)$	Distance ΔR between b−jet pairs from the primary Higgs	

Table 1: Input variables of the DNN event classifier in OS2l region. The total number of variables is 72. l_i represents leptons and b_i represents b−tagged jets, both ordered by p_T.

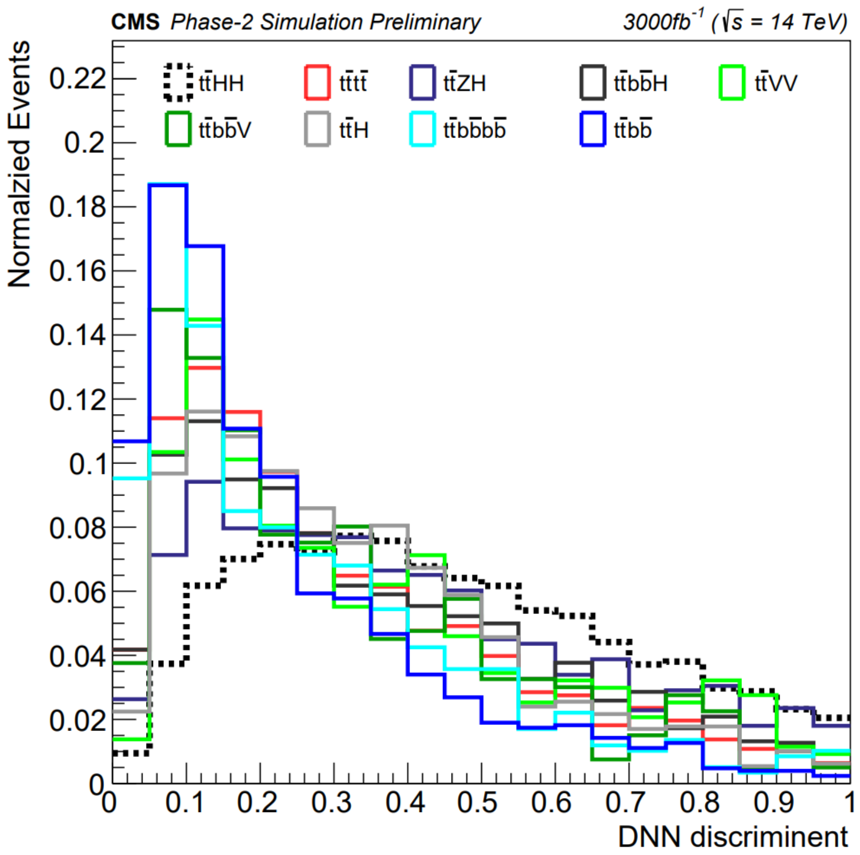
OS2l DNN input variables

$$\text{DNN } discriminant = \frac{t\bar{t}HH \text{ score}}{\sum_{Bkg} Bkg \text{ score}}$$





OS2l+6b DNN



- The DNN performance of all channels including those not used for the train.
- $t\bar{t}4b$ sample behaves similar to $t\bar{t}bb$.
- Other backgrounds also differ from $t\bar{t}HH$ signal.

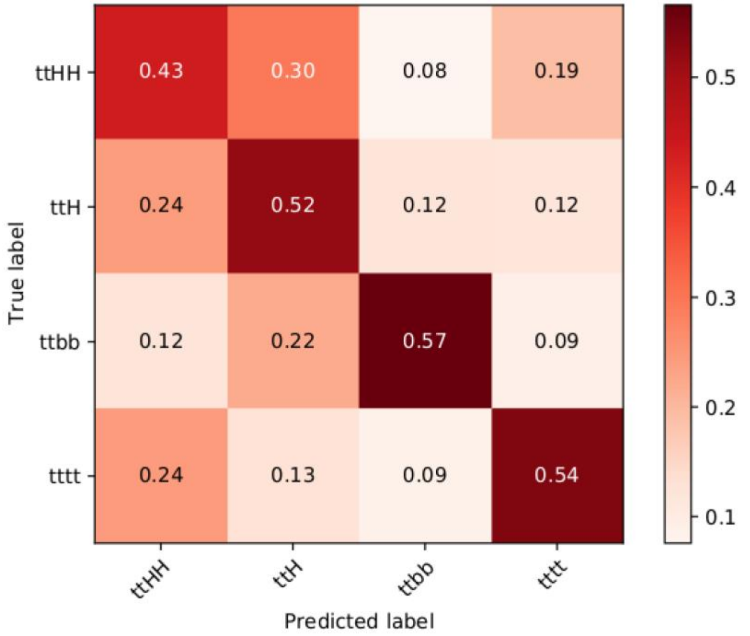
SS2l DNN

Variables	Description	Objects (x, y)
MET	Missing Transverse Energy	–
N_b	Multiplicity of b – jets	–
$p_T(x)$	Transverse momentum of x	l_1, l_2 (leptons), b_1, b_2, b_3 (b–tagged jets)
$\eta(x)$	Pseudorapidity of x	l_1, l_2 (leptons), b_1, b_2, b_3
$\phi(x)$	Azimuthal angle of x	l_1, l_2 (leptons), b_1, b_2, b_3
$m(x)$	Mass of x	b_1, b_2, b_3
$\Delta R(x, y)$	Distance ΔR between x and y	Between b_1, b_2, b_3 pairs

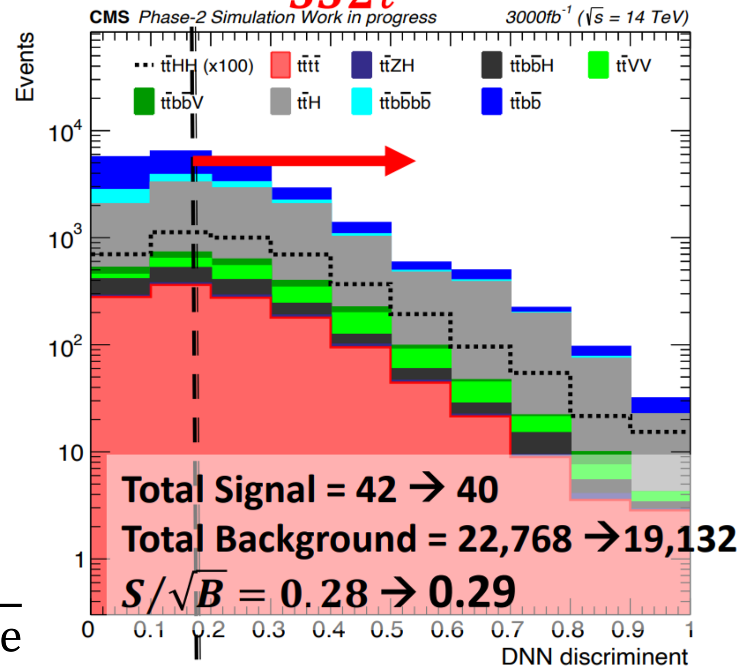
Table 2: Input variables of the DNN event classifier in SS2l region. The total number of variables is 23. l_i represents leptons and b_i represents b–tagged jets, both ordered by p_T.

SS2l DNN input variables

$SS2\ell$

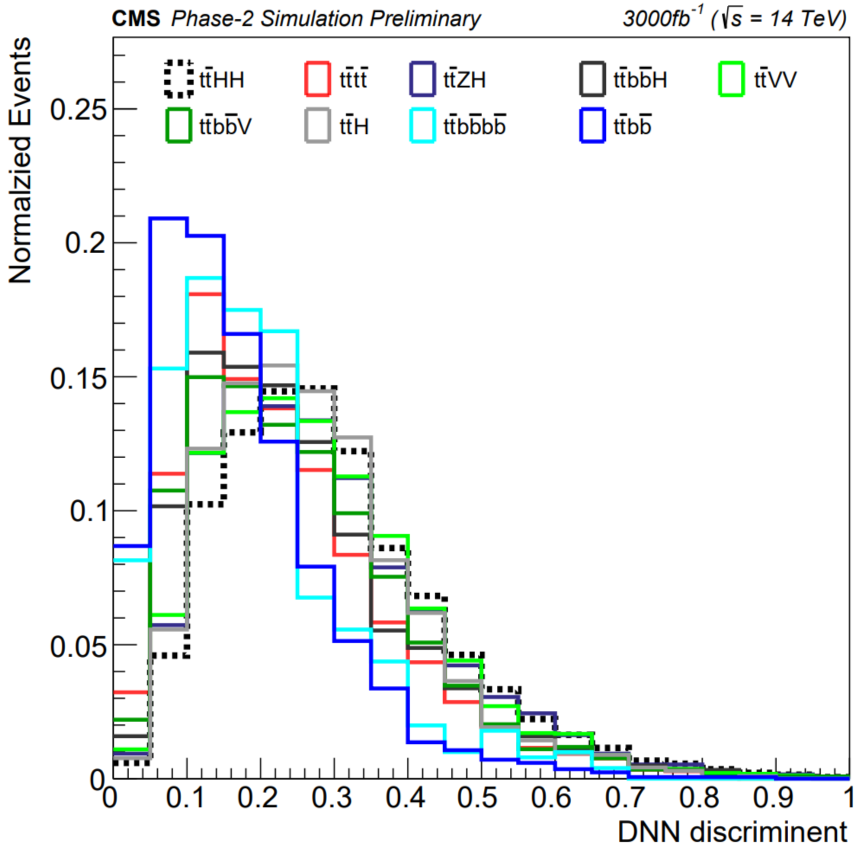


$SS2\ell$



$$\text{Again, DNN } discriminant = \frac{t\bar{t}HH \text{ score}}{\sum_{Bkg} Bkg \text{ score}}$$

SS2*l* DNN



- $t\bar{t}4b$ sample also behaves similar to $t\bar{t}bb$.
- Signal discriminant for $SS2l$ is not higher than other backgrounds.
- Further development on the DNN is needed.

Events cutflow

Sample	S0	S1	S2	S3	S4	S5	S6
TT_SL+DL	None	nLep = 2	Opposite Sign	MET>30	nbJet ≥ 5	Ht > 500	DNN
ttHH	**1000000**	**135564**	**93580**	**84950**	**19356**	**15822**	**12811**
ttH	500000	52586	40037	35520	2076	1341	915
ttbbH	150000	15452	11783	10709	2947	2398	1543
ttZH	150000	19439	14809	13584	1819	1567	1156
ttVV	150000	27914	18448	17143	558	462	310
ttbbV	150000	8977	6381	5546	513	418	248
ttbb	500000	35023	31640	27801	2134	1293	653
ttbbbb	150000	10313	9347	8193	877	610	245
4t	100000	13617	8963	8358	2270	2140	1279

Sample	S0	S1	S2	S3	S4	S5	S6
TT_SL+DL	None	nLep = 2	Same Sign	MET>30	nbJet ≥ 3	Ht > 300	DNN
ttHH	**1000000**	**135564**	**41984**	**37894**	**26225**	**25467**	**22502**
ttH	500000	52586	12549	11003	4679	4061	3536
ttbbH	150000	15452	3669	3302	2576	2461	1903
ttZH	150000	19439	4630	4243	2536	2463	2102
ttVV	150000	27914	9466	8782	3424	3293	2851
ttbbV	150000	8977	2596	2295	1267	1181	916
ttbb	500000	35023	3383	2828	1990	1693	927
ttbbbb	150000	10313	966	843	587	503	353
4t	100000	13617	4654	4344	3578	3567	2664

- Both OS2l+6b and SS2l **DNN** suppress the $t\bar{t}b\bar{b}$ and $t\bar{t}4b$ backgrounds.

- **Same-sign requirement** has a strong suppression of $t\bar{t}b\bar{b}$ and $t\bar{t}4b$ backgrounds.

Results

- Currently results are reported as the exclusion limits of the hypotheses with signal strength $\mu = \sigma_{\text{measure}}/\sigma_{\text{SM}}$.
- Limits from yield-only (DNN shape not included yet) likelihood fit using the Combine tool.
  - **SS2l**: $\mu < 14$ at 95% Confidence Level.
  - **OS2l+6b**: $\mu < 11$ at 95% Confidence Level.
  - **Combined** result: $\mu < 10$ at 95% Confidence Level.

- No pileup, background scaling, or experimental systematic uncertainties considered. Only a 2.5% luminosity uncertainty included.

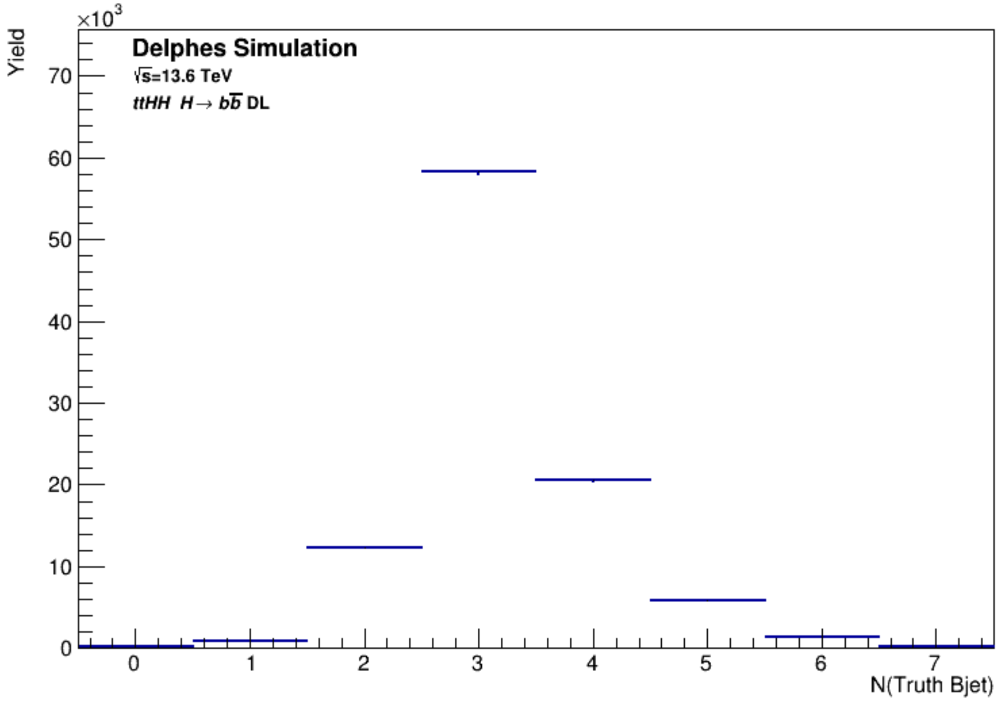
Run 3 proposal

- The two lepton final state framework tends to complete. Pre-study for Run 3 analysis should start.
- Now still using MG5+Delphes sample. *CMS Delphes card* used for the Run 3 detector description.

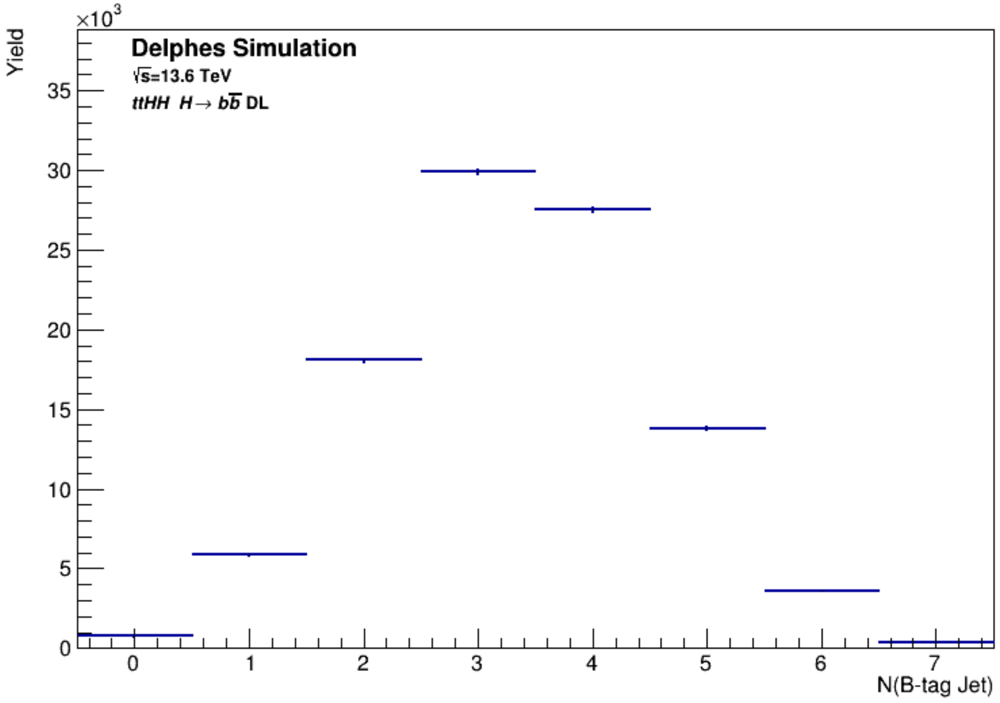
- Currently I started checking from the Truth-level information of the toy sample:
  - $\sqrt{s} = 13.6\ \mathrm{TeV}$ 100k MC events $t\bar{t}HH$, $t\bar{t}$ DL + $HH \rightarrow 4b$
- Meanwhile, the data object multiplicity is also checked.

Truth B-Jet Multiplicity

Truth



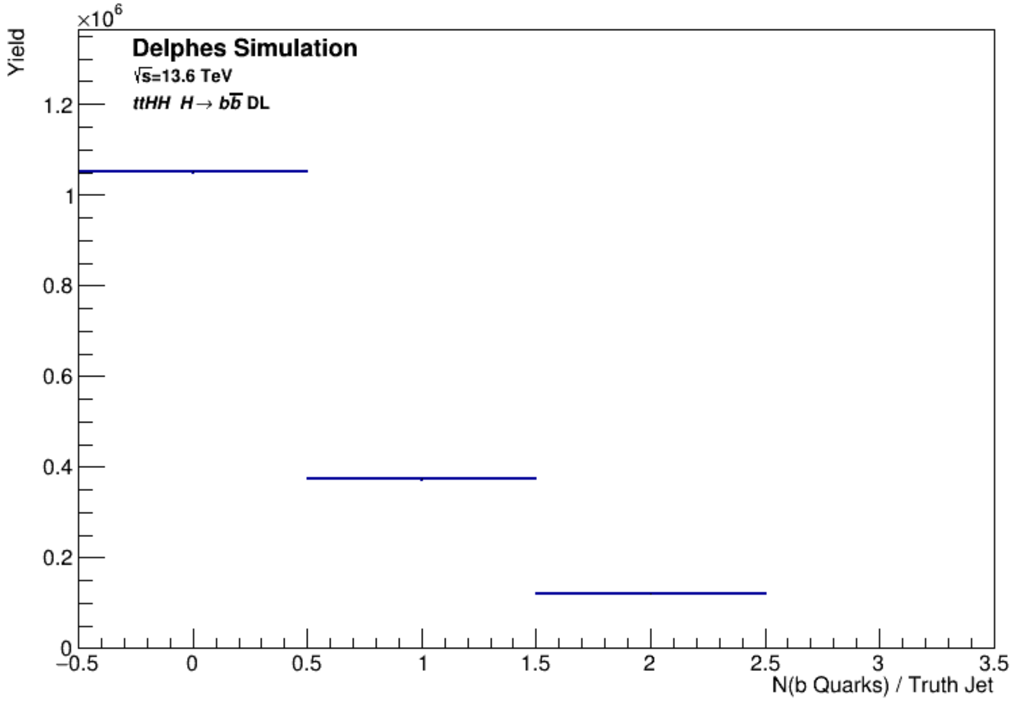
Reco



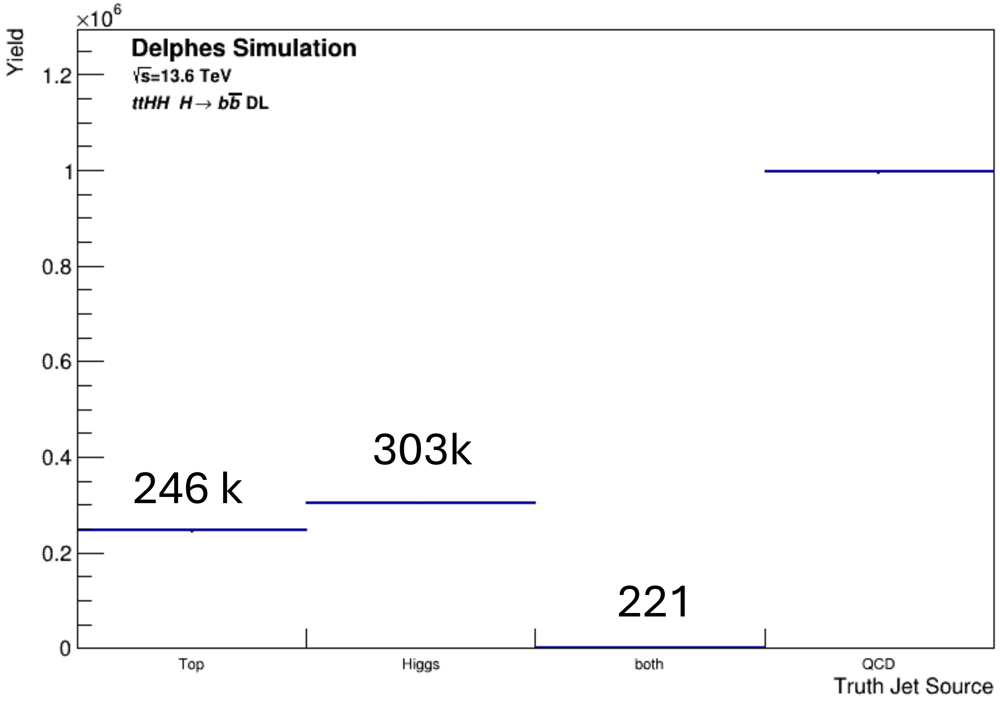
- Truth-level B-jet multiplicity also peaked at 3, even truth hardly reaches 6.

N(b quark) in truth jet

Number of b quarks joining the truth jet hadronization

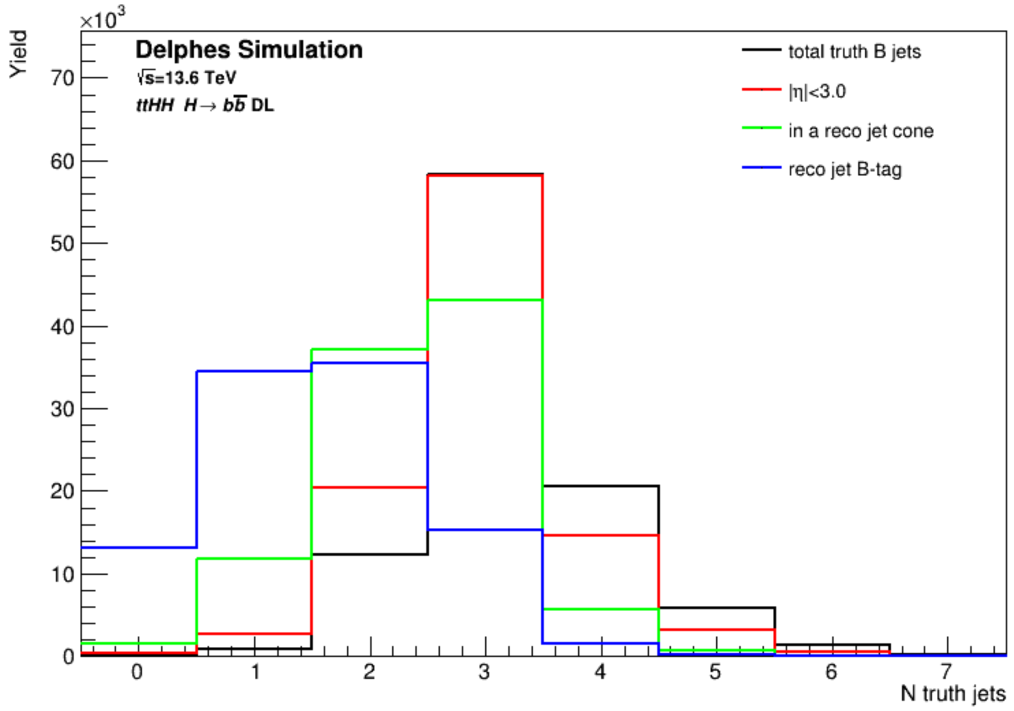


Source of truth jet



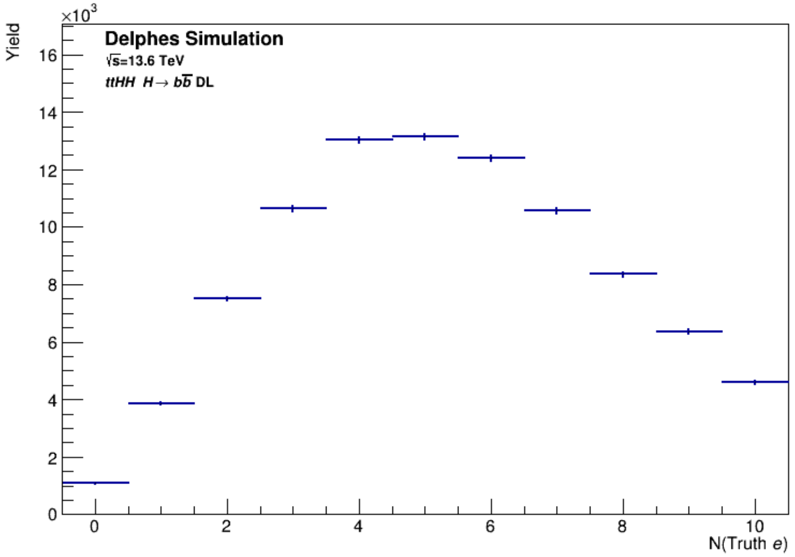
- One B-jet might use 2 b-quarks at a not small rate.
- Most jets come from only top quarks or only Higgs.

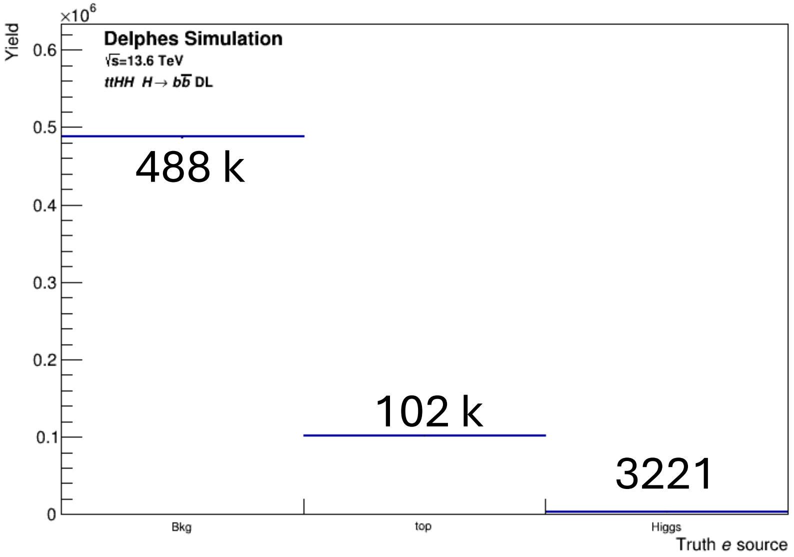
B-jet reconstruction performance

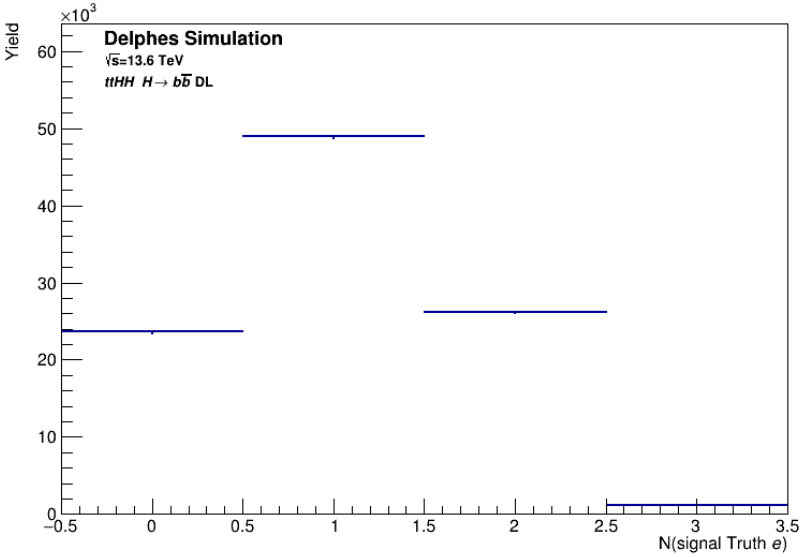


- Run 3 CMS calorimeter only covers $|\eta| < 3.0$ range. Some of the Truth B-jets are not in the detector response regions.
- A large number of truth B-jets are not centered inside a reconstructed jet cone.
- The reconstructed jet containing the truth B jet might not be b-tagged. B-tagging multiplicity is almost 1 less.

Truth Electrons





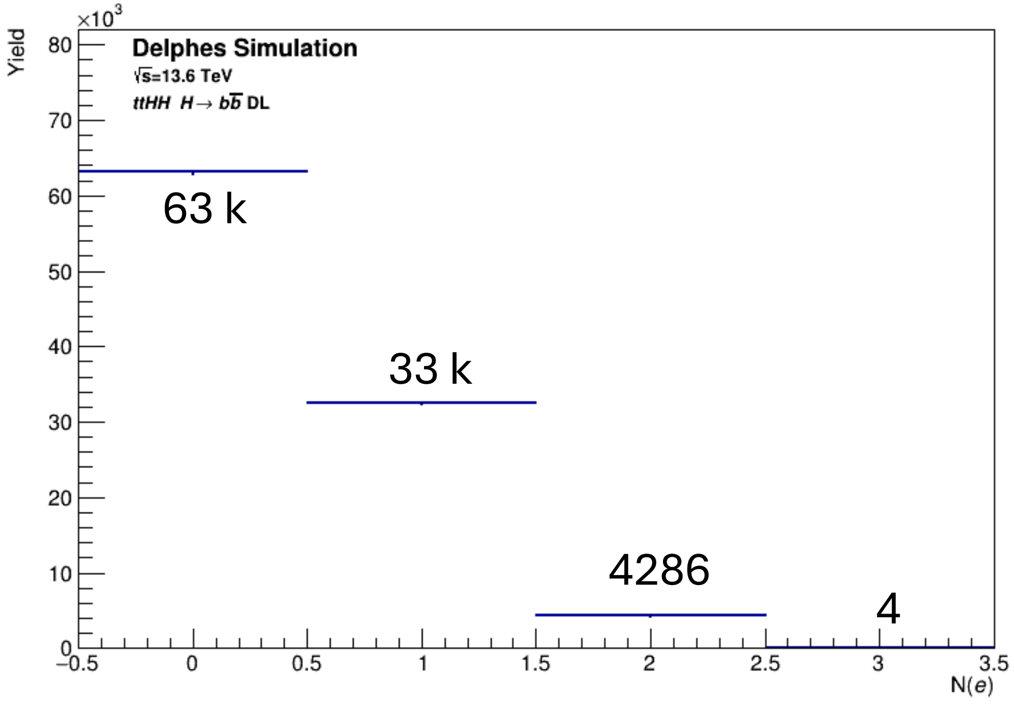


- Truth electron multiplicity peaked at 5.
- Most are non-prompt backgrounds from jets.
- Expected distribution 1:2:1 for $N(e) = 0,1,2$ excluding these jet electrons.

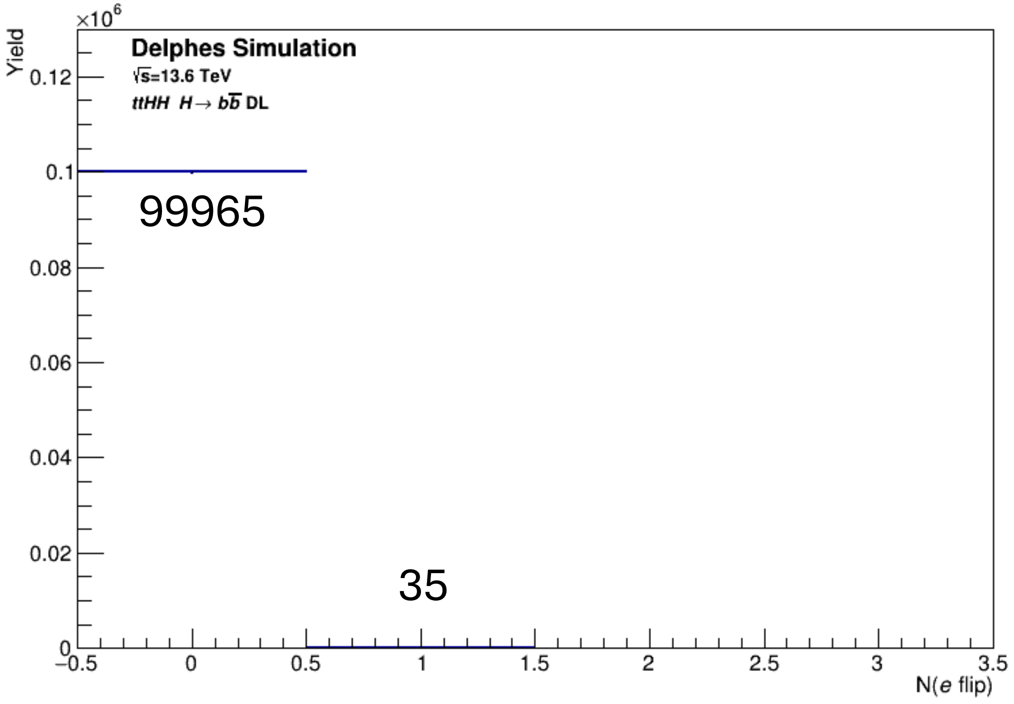
- Some truth electron comes from a Higgs boson.
- Might from b quark decay.

Reconstructed electron multiplicity

Total multiplicity

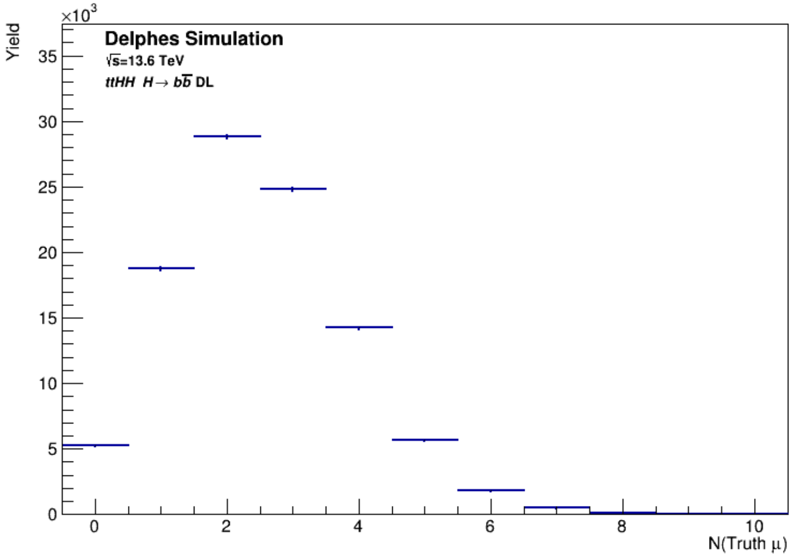


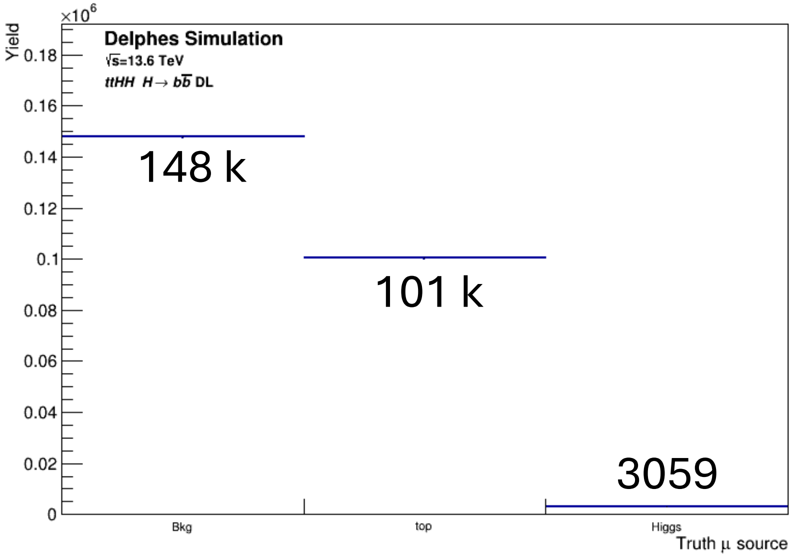
Charge-Flipping multiplicity

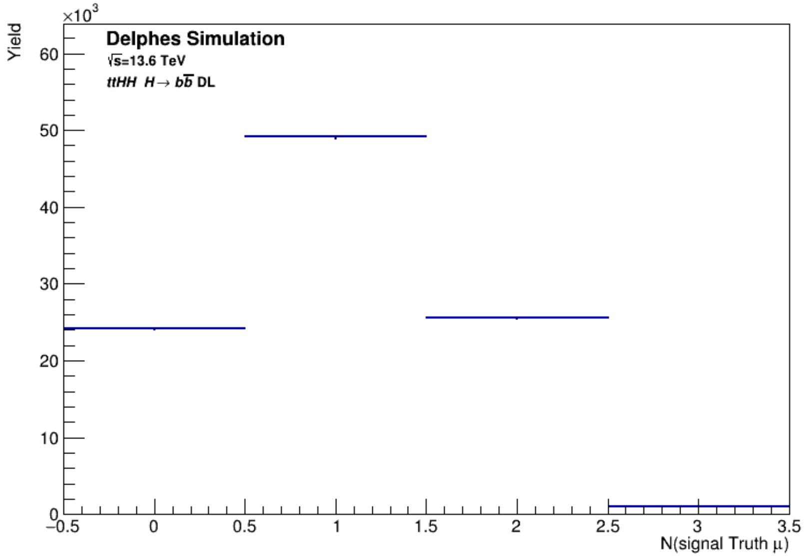


- $N(e)$ distribution after Delphes changes a lot → around 40% simulation & reconstruction rate (including detector response, reconstruction, identification, isolation…).
- 35 events in 100k have reconstruction electron charge flipped, very low rate.

Truth Muons



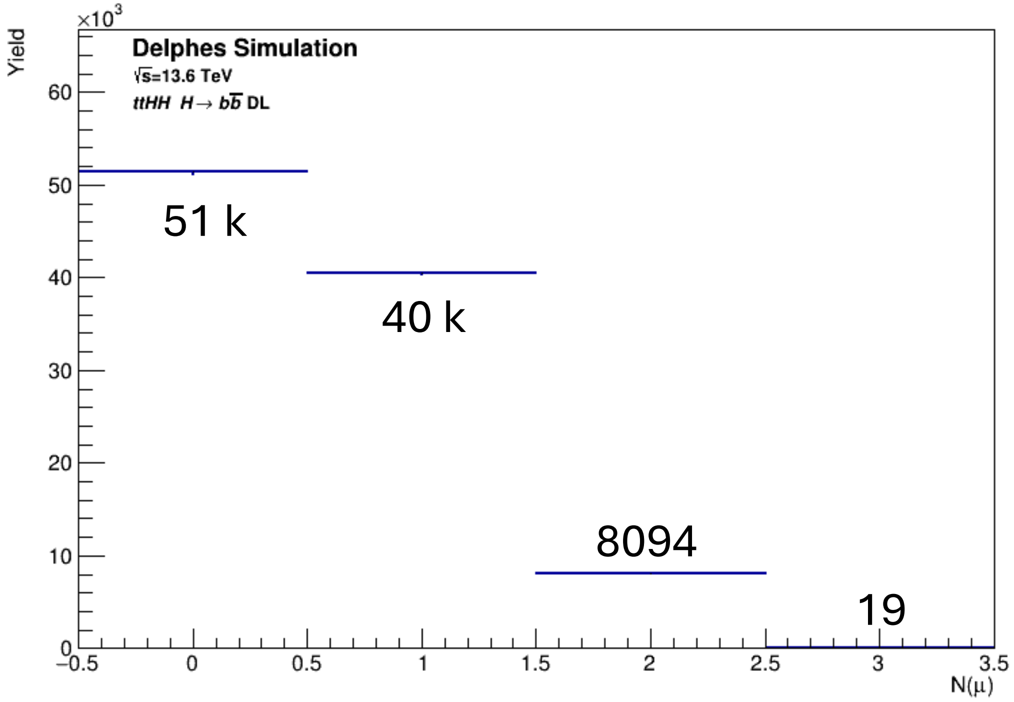




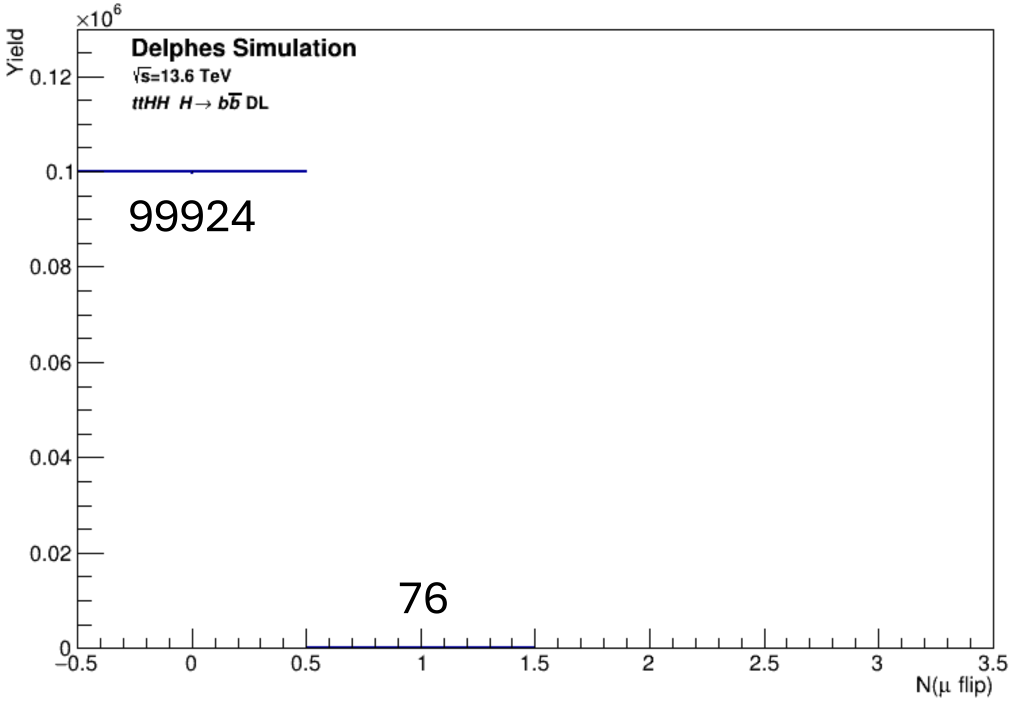
- Truth muon signal behaves similar to Truth electrons.
- The background muons are less than truth electron backgrounds.

Reconstructed muon multiplicity

Total multiplicity



Charge-Flipping multiplicity



- Muon has better total simulation & reconstruction rate, ~55%.
- 76 events in 100k have reconstruction muon charge flipped, **double** the rate of electrons.

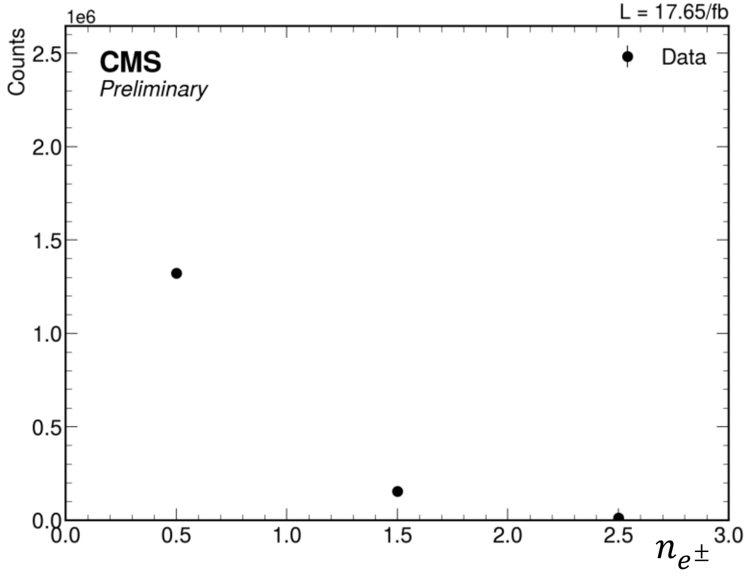
Data samples 2022

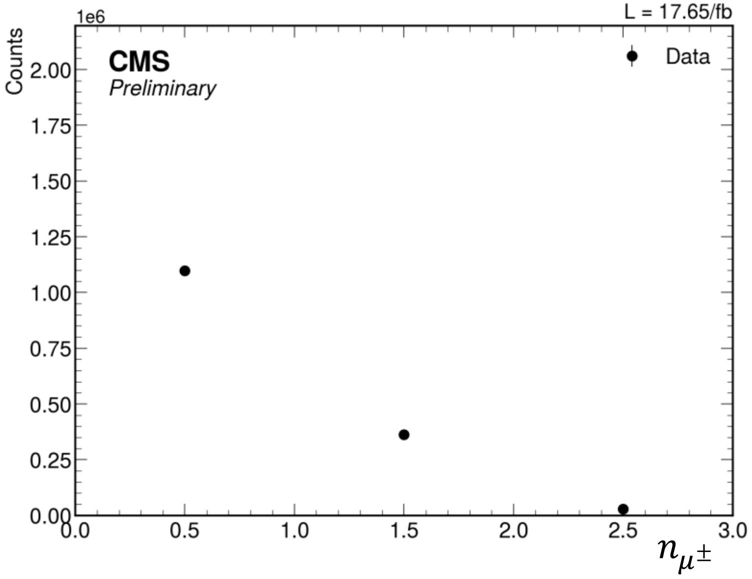
- https://docs.google.com/presentation/d/1F4ndU7DBcyvrEEyLfYqb29NGkBPs20EAnBxe_l7AEIl/edit#slide=id.g289f499aa6b_2_52
- Era C $5.0104\ \mathrm{fb}^{-1}$
  - /{EGamma|Muon|SingleMuon|MuonEG}/Run2022C-22Sep2023-v1/NANOAOD
- Era D $2.9700\ \mathrm{fb}^{-1}$
  - /{EGamma|Muon|MuonEG}/Run2022D-22Sep2023-v1/NANOAOD
- Era E $5.8070\ \mathrm{fb}^{-1}$
  - /{EGamma|Muon|MuonEG}/Run2022E-22Sep2023-v1/NANOAOD
- Era F $17.7819\ \mathrm{fb}^{-1}$
  - /{EGamma|MuonEG}/Run2022F-22Sep2023-v1/NANOAOD
  - /Muon/Run2022F-22Sep2023-v2/NANOAOD
- Era G $3.0828\ \mathrm{fb}^{-1}$
  - /{Muon|MuonEG}/Run2022G-22Sep2023-v1/NANOAOD
  - /EGamma/Run2022G-22Sep2023-v2/NANOAOD

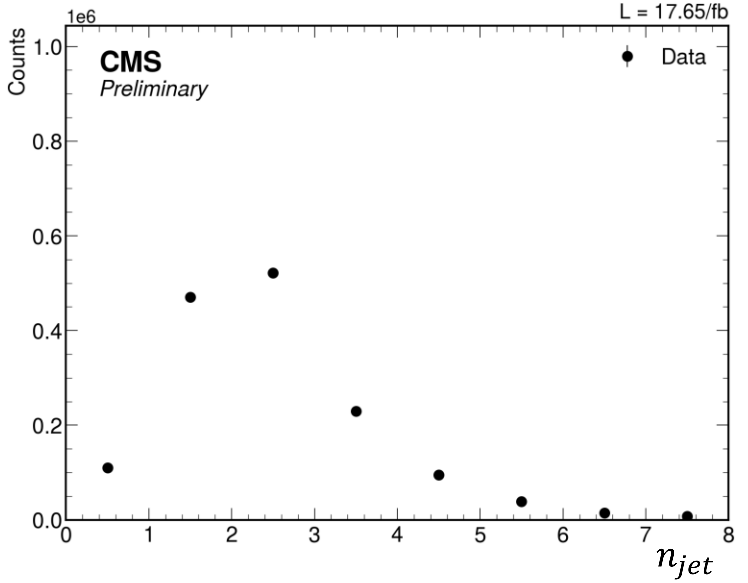
Data samples 2023

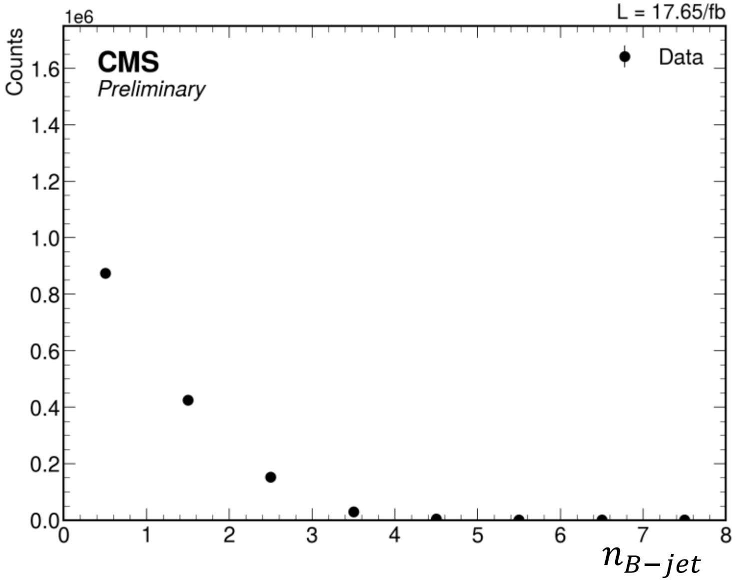
- https://docs.google.com/presentation/d/1TjPem5jX0fzqvTGI271_nQFoVBabsrdrO0i8Qo1uD5E/edit#slide=id.g289f499aa6b_2_58
- Era C $17.794\ \mathrm{fb}^{-1}$
  - /Egamma{0|1}/Run2023C-22Sep2023_v{1|2|3|4}-v1/NANOAOD
  - /Muon0/Run2023C-22Sep2023_v{1|2|3|4}-v1/NANOAOD
  - /Muon1/Run2023C-22Sep2023_v{1|2|3}-v1/NANOAOD
  - /Muon1/Run2023C-22Sep2023_v4-v2/NANOAOD
  - /MuonEG/Run2023C-22Sep2023_v{1|2|3|4}-v1/NANOAOD
- Era D $9.451\ \mathrm{fb}^{-1}$
  - /{Egamma|Muon}{0|1}/Run2023D-22Sep2023_v{1|2}-v1/NANOAOD
  - /MuonEG/Run2023D-22Sep2023_v{1|2}-v1/NANOAOD
- Later into Heavy ion era.

Data 2023 review









- Run2023C v1 as example
- Data:
  - EGamma0/1
  - Muon 0/1
  - MuonEG
- Pre-selection of the lepton and jet objects applied.
- B-tagging uses the 90% efficiency working point in 2022.

Summary

- The HL-LHC study demonstrates the multi-b background suppression and potential of the SS2l channel.
- The advantage and potential of DNN is demonstrated.
- Delphes-based stats-only HL-LHC yield measurement has 14 (11) times SM signal strength limits at 95% CL.

- The Truth-level $t\bar{t}HH$ checking gives hint on the lower B-jet multiplicity, and provides estimation on lepton reconstruction and charge flipping.

- The object multiplicity of Run 3 data has been checked.