

Исследование чувствительности экспериментов на БАК к наблюдению процесса рождения бозона Хиггса в канале $pp \rightarrow tH$

Научный руководитель: Солдатов Е.Ю., к.ф.-м.н.

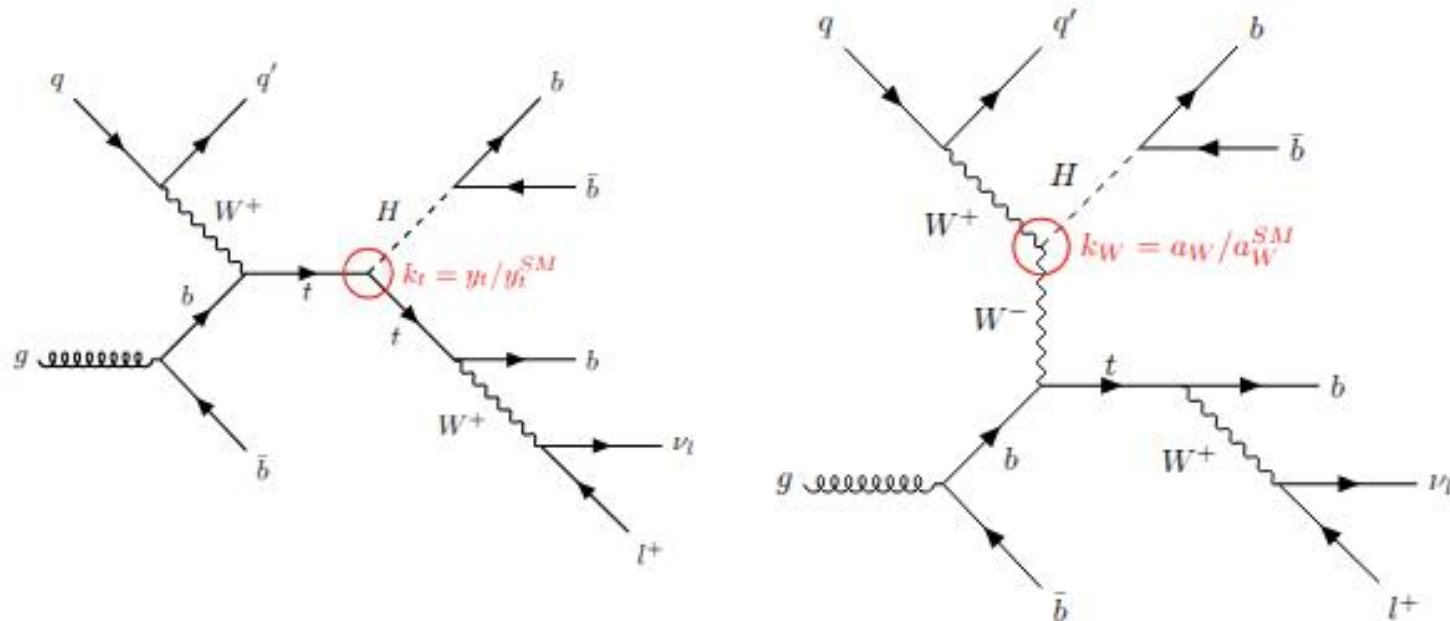
Научные консультанты: Бойко И.Р., к.ф.-м.н., Гусейнов Н.А., к.ф.-м.н.

Студент: Дадашова А.Э.

Мотивация и цели

Цель: исследование методом Монте-Карло событий ассоциативного рождения бозона Хиггса с одиночным топ-кварком в рамках Стандартной Модели и ИВТ/ИТС (Инвертированное Взаимодействие Топ-кварка/Inverted Top Coupling).

Мотивация: поиск редкого процесса $pp \rightarrow tH$ на БАК с целью измерения комплексной фазы константы взаимодействия бозона Хиггса с топ-кварком и ее сравнение с теоретическими предсказаниями Стандартной Модели.



Диаграммы Фейнмана для процесса $pp \rightarrow tH$

Генерации событий

$m(b) = 4.2 \text{ ГэВ}$
 $m(t) = 172.5 \text{ ГэВ}$
 $m(H) = 125 \text{ ГэВ}$
 $Y_b * m(b) = 4.2 \text{ ГэВ}$
 $Y_t * m(t) = 172.5 \text{ ГэВ}$

Генерация: MadGraph5_aMC@NLO, POWHEG (ttbar)
Адронизация: PYTHIA 8, Herwig7 (ttbar)
Реконструкция струй: FastJet
Framework: Rivet

Jets:
anti-KT
 $p_T^{\text{min}} = 20.0 \text{ ГэВ}$
 $|\eta|^{\text{max}} = 5.0$
 $R = 0.5$

Отбор событий: $p_T^{\text{lead}} > 27 \text{ ГэВ}$;
 $p_T^{\text{v, reco}} \geq 10 \text{ ГэВ}$; $|\eta|^{\text{lead}} \leq 2.7$; $3 \leq N^{\text{b-jets}} \leq 4$;
 $|\eta|^{\text{b-jet}} < 2.4$

Информация о сгенерированных событиях

Процесс	N _{events}	Сечение (фб)	N _{weghted}
tHbq (NLO) BSM CP0/CP180	5 497 800	13.29/157.20	842.96/13021.37
tHbq (NLO) SM	8 782 291	13.41	822.26
tt (NLO)	30 000 000	404843.62	526296.71
ttbb (LO)	65 979 470	4807.00	148296.95
ttZ (LO)	22 000 000	34.10	2953.06
ttH (NLO)	2 750 000	128.85	13097.60
tZbq (LO)	22 000 000	31.37	1648.49
ttW (LO)	22 000 000	212.20	791.77

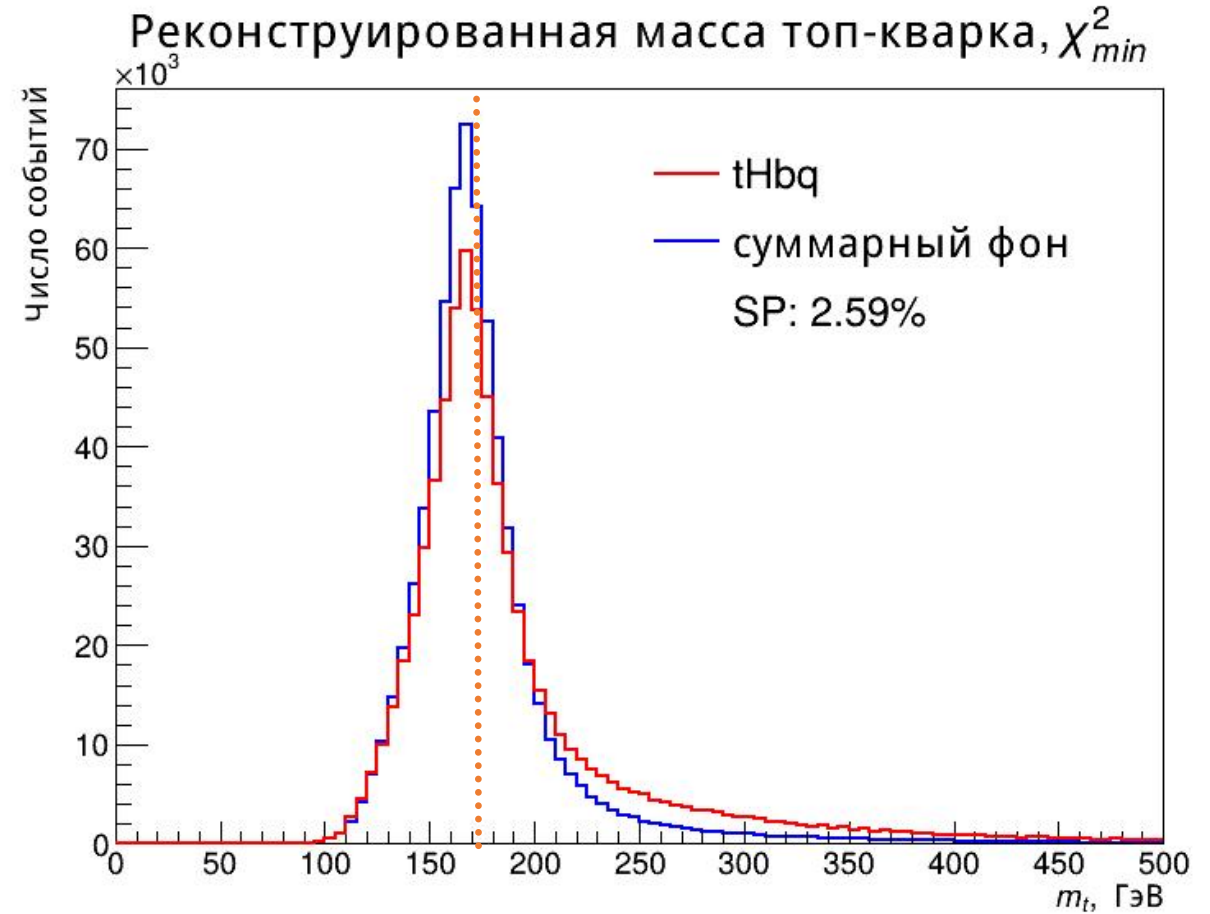
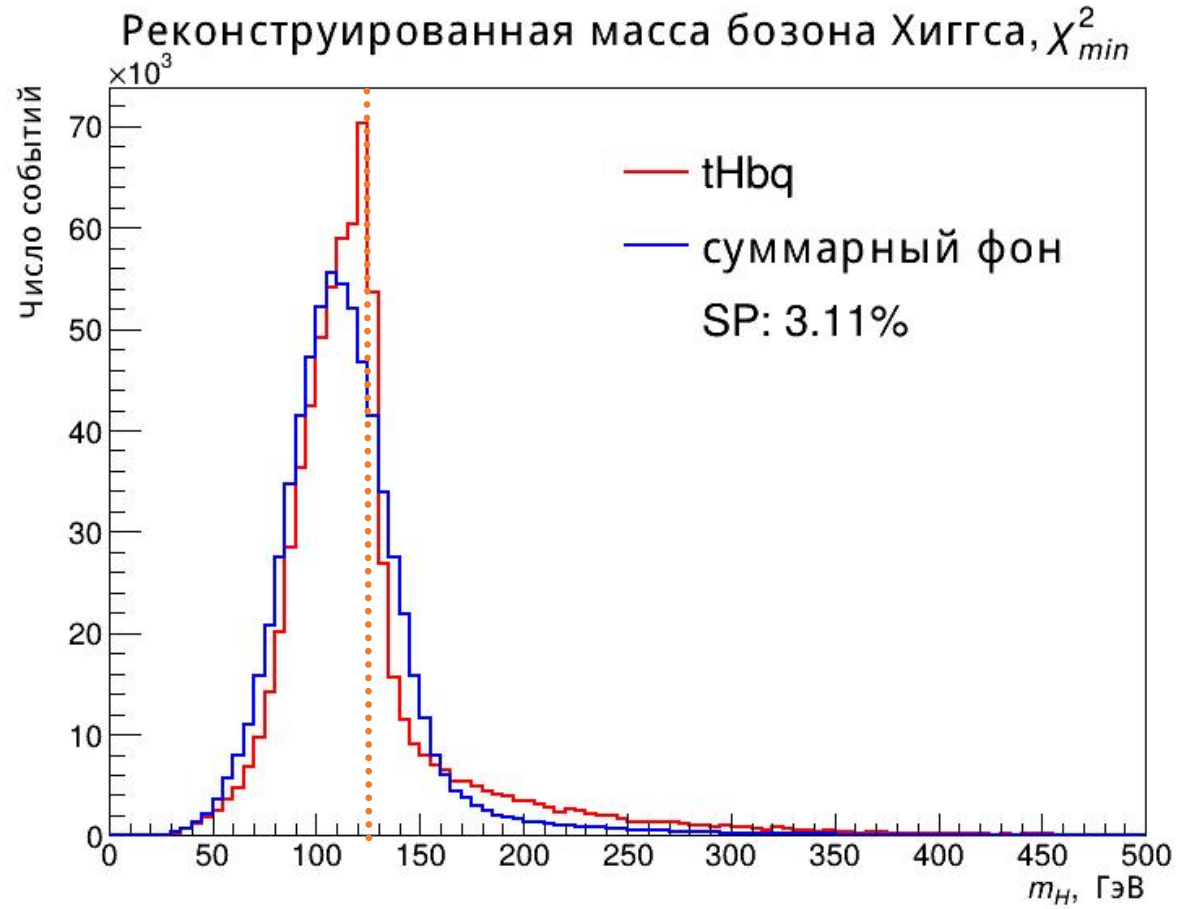
N_{events} - число сгенерированных событий
N_{weghted} - число взвешенных событий, соответствующее ожидаемой статистике Run3 (500 фб⁻¹)

Реконструкция события

- Для всех событий предпринимается попытка реконструкции сигнального процесса:
 $pp \rightarrow tH (H \rightarrow bb, t \rightarrow bl\nu)$
- Струи реконструируются из адронов конечного состояния.
- Поперечный импульс нейтрино реконструируется как недостающий поперечный импульс струй и заряженного лептона.
- Продольная компонента импульса нейтрино восстанавливается из кинематического ограничения : $m_{l\nu} = m_W$.
- b-струи приписываются распаду топ-кварка или бозона Хиггса путем перебора всех комбинаций и выбора той из них, что дает массы m_t и m_H , ближайшие к номинальным.

В рамках гипотезы о том, что все события соответствуют сигнальному процессу, реконструированы 51 кинематических переменных. Эти переменные были переданы нейронной сети, разделяющей сигнальный и фоновые процессы.

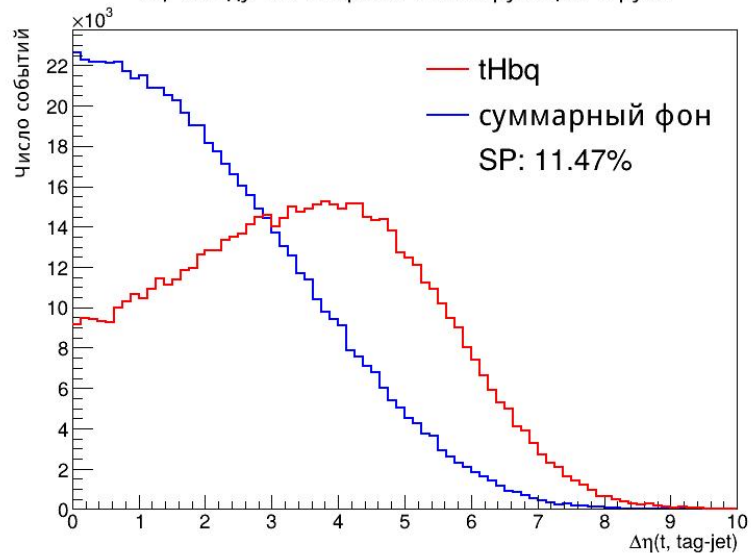
Инвариантная масса реконструированного бозона Хиггса и топ-кварка для сигнального и фоновых процессов



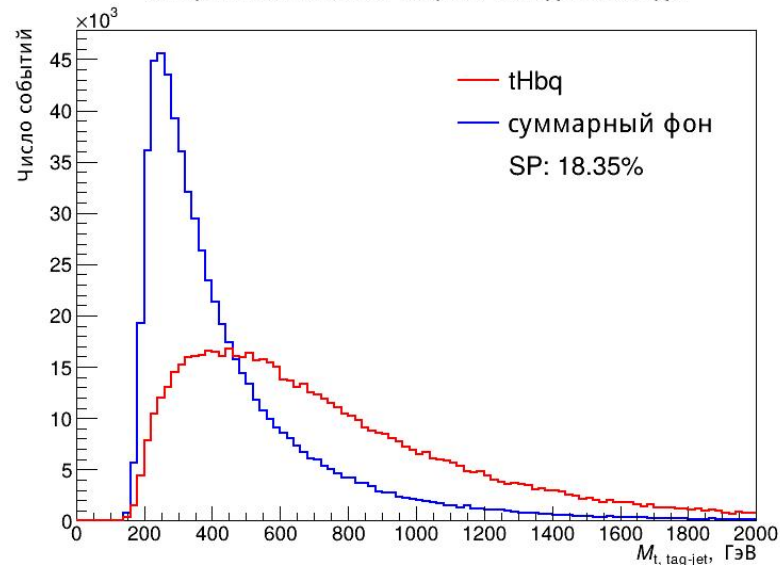
*суммарный фон = tt, ttH, ttZ, ttbb, tZbq, ttW

Распределения переменных с высокой разделительной способностью сигнал/фон

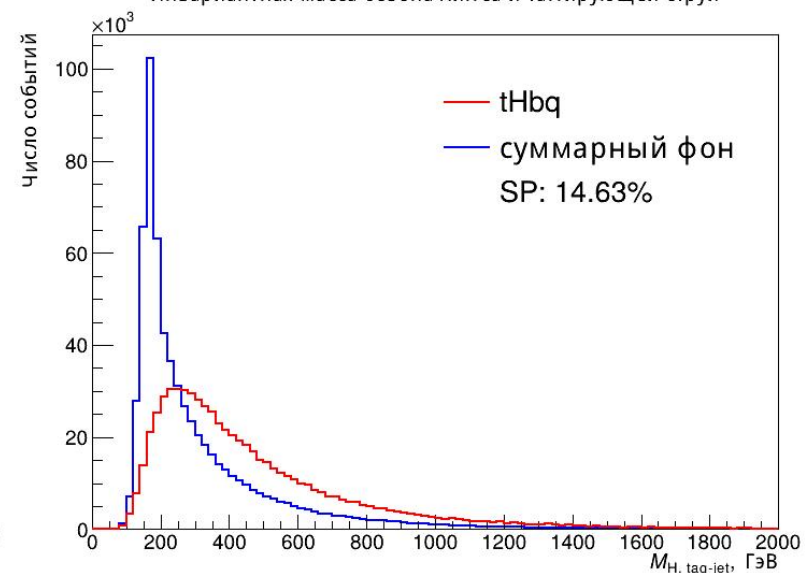
$\Delta\eta$ между топ-кварком и тагирующей струей



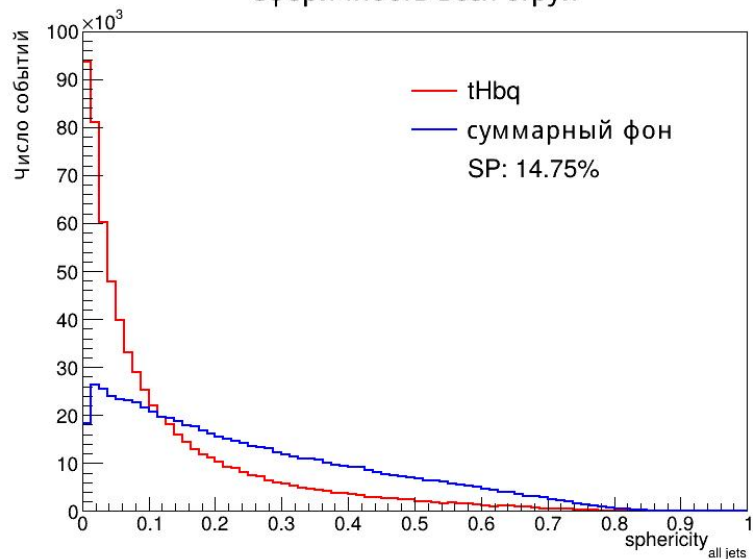
Инвариантная масса топ-кварка и тагирующей струи



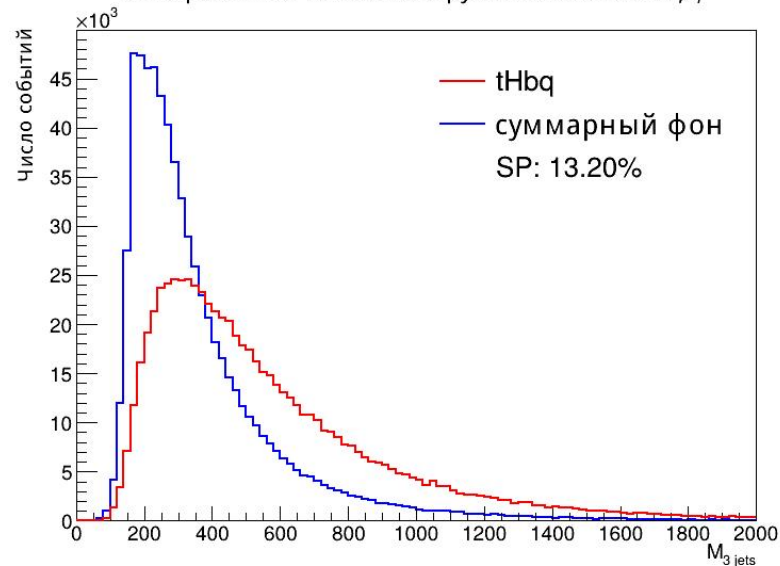
Инвариантная масса бозона Хиггса и тагирующей струи



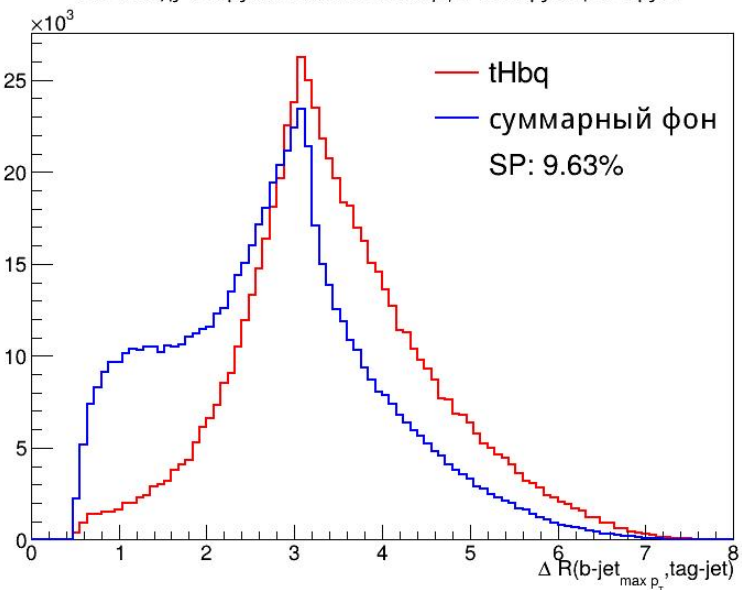
Сферичность всех струй



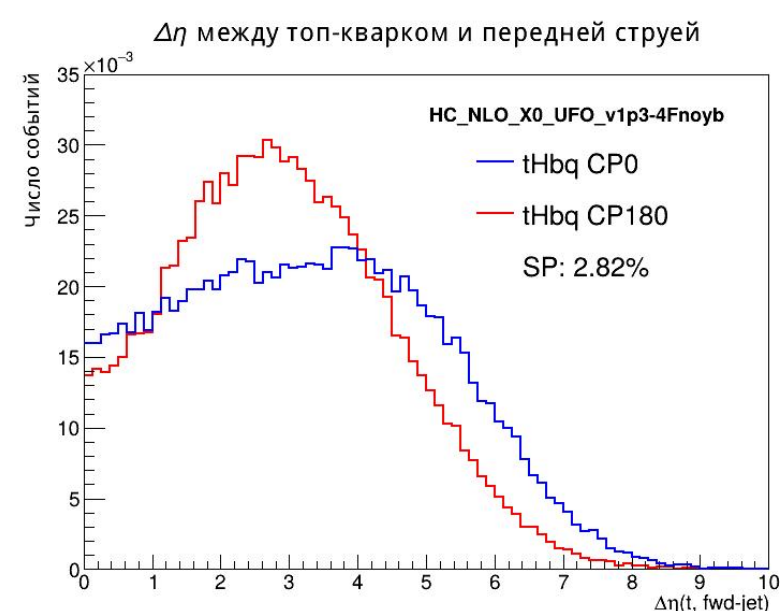
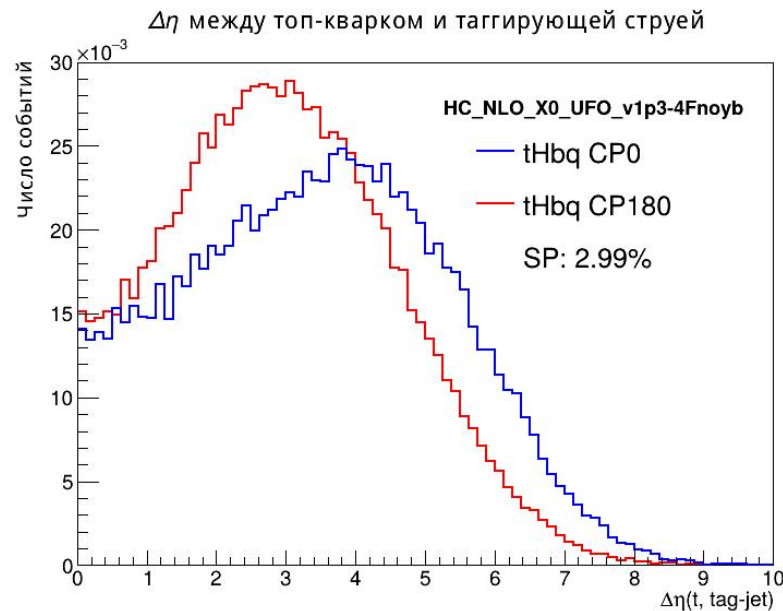
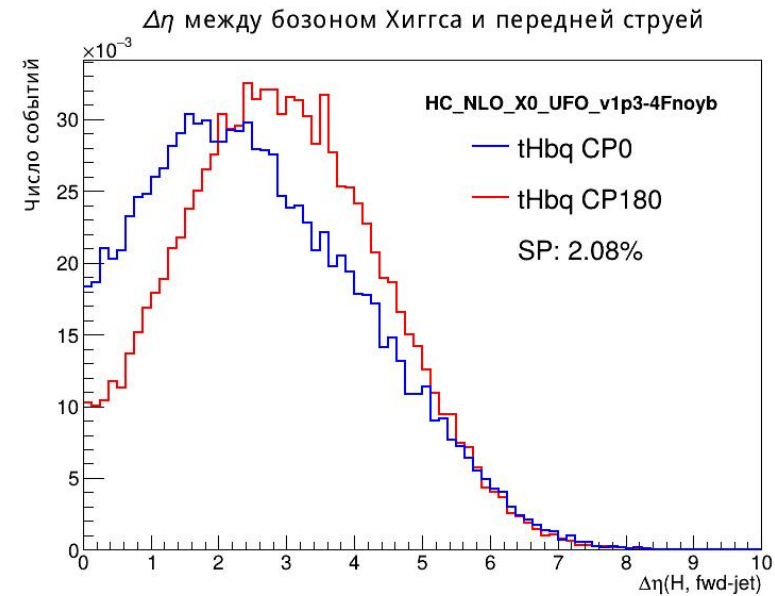
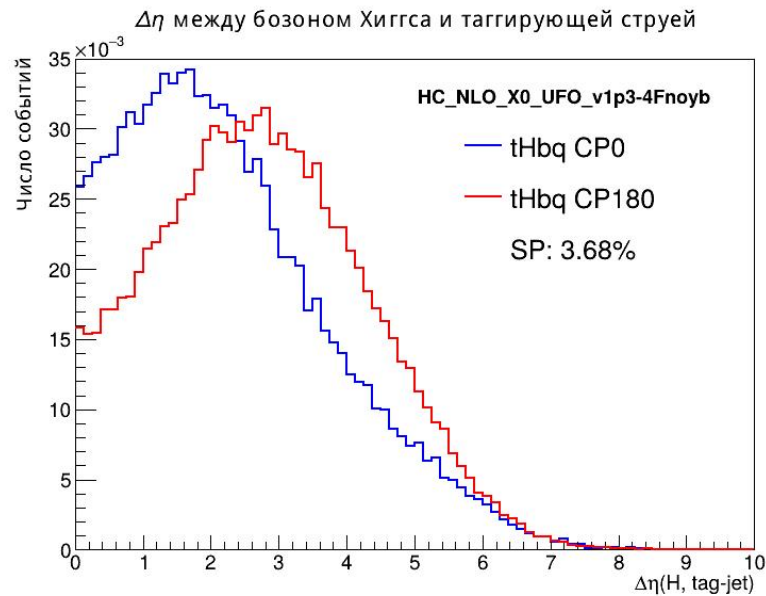
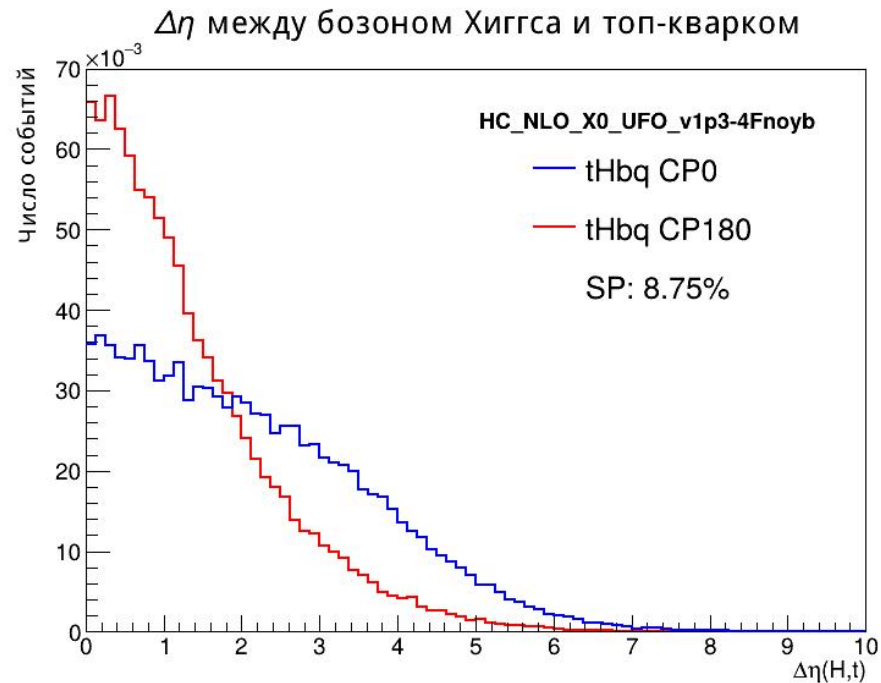
Инвариантная масса 3-х струй с наибольшим p_T



ΔR между b-струей с наибольшим p_T и тагирующей струей

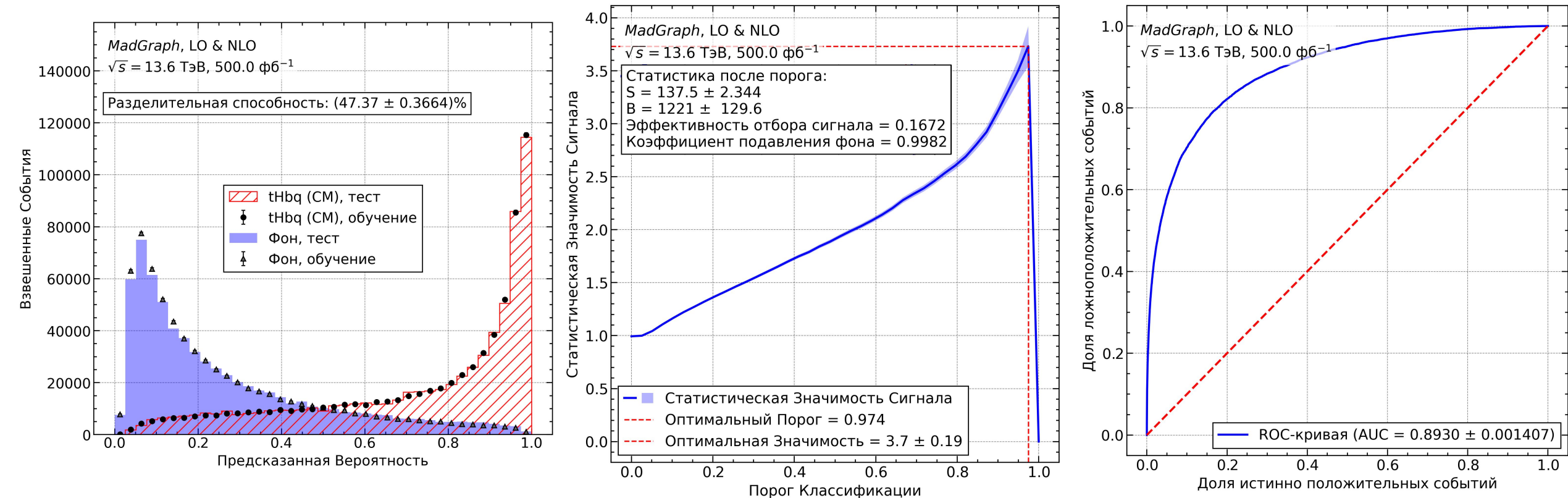


Разделительная способность сигнала СМ и ИВТ



ИВТ: <https://arxiv.org/pdf/1306.6464>

Оценка чувствительности экспериментов на БАК к процессу $t\bar{t}H$ в рамках СМ



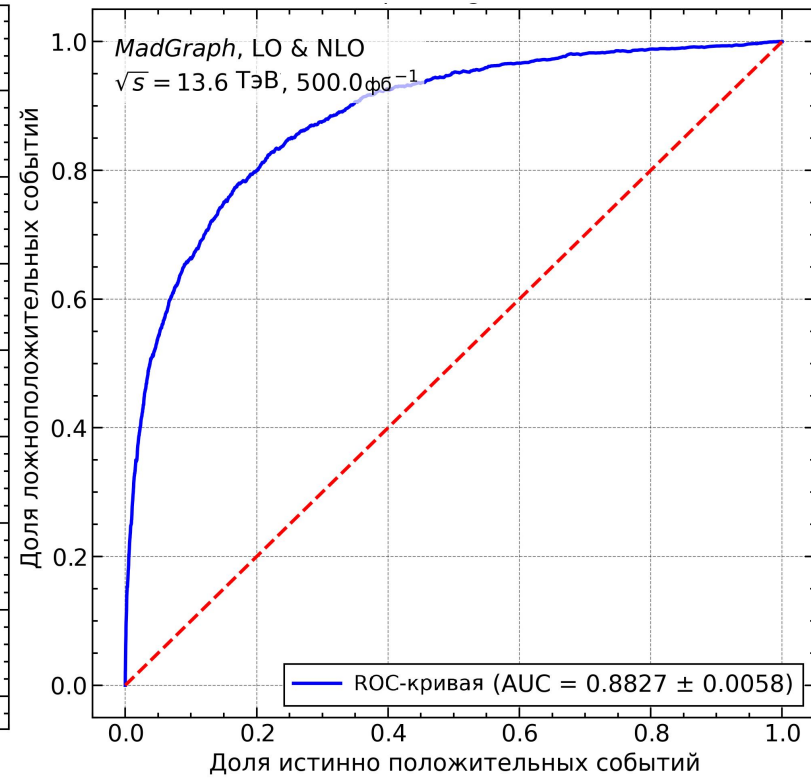
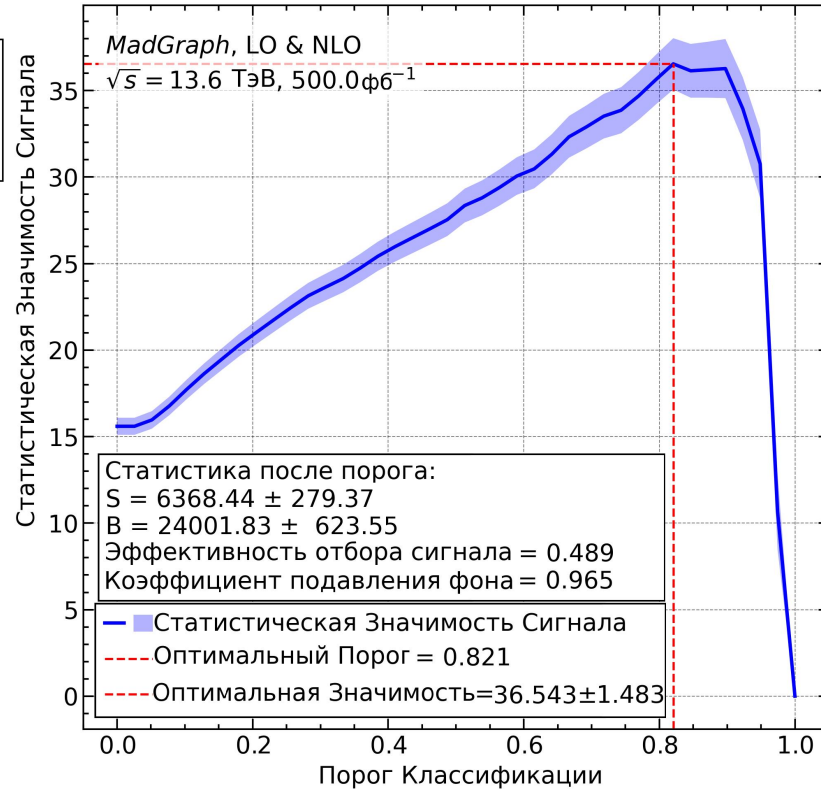
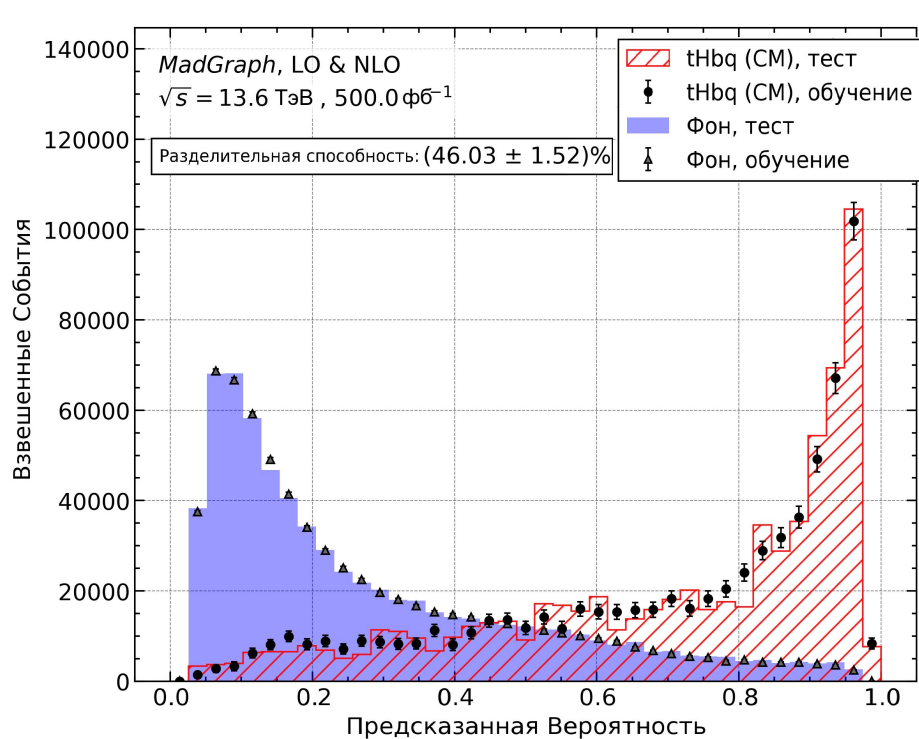
$$Z = \frac{S}{\sqrt{S + B}}$$

Значимость сигнального процесса:

$(3.70 \pm 0.19 \pm 0.12)\sigma$ для светимости 500 fb^{-1}

$(9.06 \pm 0.47 \pm 0.30)\sigma$ для светимости 3000 fb^{-1}

Оценка чувствительности экспериментов на БАК к процессу $t\bar{t}H$ в рамках модели ИВТ



$$Z = \frac{S}{\sqrt{S + B}}$$

Значимость сигнального процесса:

$(36.50 \pm 1.50 \pm 1.07)\sigma$ для светимости 500 фб^{-1}

$(89.4 \pm 3.7 \pm 2.6)\sigma$ для светимости 3000 фб^{-1}

Заключение

- Смоделирован сигнальный процесс ассоциативного рождения бозона Хиггса с одиночным t -кварком (процесс tH), а также соответствующие фоновые процессы в приближении NLO для энергии столкновений 13.6 ТэВ в системе центра масс в рамках Стандартной Модели и ИВТ.
- Реконструированы и проанализированы кинематические переменные, отобраны наиболее важные из них для выделения сигнального процесса от основных фоновых процессов.
- Проведена оценка чувствительности экспериментов БАК к сигнальному процессу (tH) для Run2+Run3 и предстоящего High-Luminosity Run.
- Полученные результаты указывают на то, что сигнальный процесс tH в рамках СМ может быть обнаружен только на High-Luminosity Run, при этом с высокой вероятностью сигнальный процесс tH в рамках ИВТ модели, если он существует, может быть обнаружен на скомбинированных данных Run2+Run3

Спасибо за внимание!

BACK-UP

Process	N _{events}	Сечение (фб)	N _{sel}	N _{weght}
tt (NLO)	30 000 000	404843.62	174 976	526296.71
tt (LO)	220 000 000	367015.60	1 010 650	843009.81
ttbb (LO)	65 979 470	4807.00	4 069 410	148296.95
ttZ (LO)	22 000 000	34.10	3 809 967	2953.06
ttH (NLO)	2 750 000	128.85	559 133	13098.96
ttH (LO)	22 000 000	103.40	4 100 869	9637.04
tZbq (LO)	22 000 000	31.37	2 313 062	1648.49
ttW (LO)	22 000 000	212.20	164 175	791.77

$tt(NLO) = total * k\text{-factor} * semileptonic = 811(pb) * 1.138546122 * 0.4384373$

$tt(LO) = sigma_semileptonic * (total_official/total_madgraph) = 194.6(pb) * (923.6/489.6)$

total_oficial (13.6 TeV) = 923.6 pb : <https://twiki.cern.ch/twiki/bin/view/LHCPhysics/TtbarNNLO>

$ttH(NLO) = total * (tt \rightarrow semileptonic) * (H \rightarrow bb) = 507.2(fb) * 0.438 * 0.58$

Model	Order	N _{events}	σ total (fb)	σ (fb)	N _{sel}	N _{weighted}
SM	NLO	8 782 291	69.66	13.41	1 077 004	822.03
SM	LO	22 000 000	-	12.45	2 613 269	739.44
HC_NLO_X0 CP0	NLO	5 497 800	69.04	13.29	700 892	842.96
HC_NLO_X0 CP180 (ITC)	NLO	5 497 800	816.6	157.20	910 801	13021.37

H→bb = 0.58 : <https://pdg.lbl.gov/2024/reviews/rpp2024-rev-higgs-boson.pdf>

t→1l = 0.332 : http://pdg.ihep.su/listings/particle_properties.html

tt→semileptonic: <https://pdg.lbl.gov/2023/reviews/rpp2023-rev-top-quark.pdf>

Предыдущий анализ

Исследование рождения бозона Хиггса совместно с
одиноким топ-кварком методом Монте-Карло

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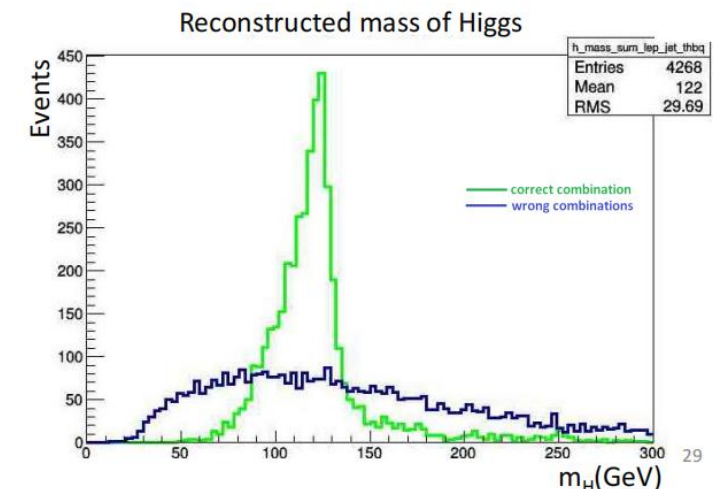
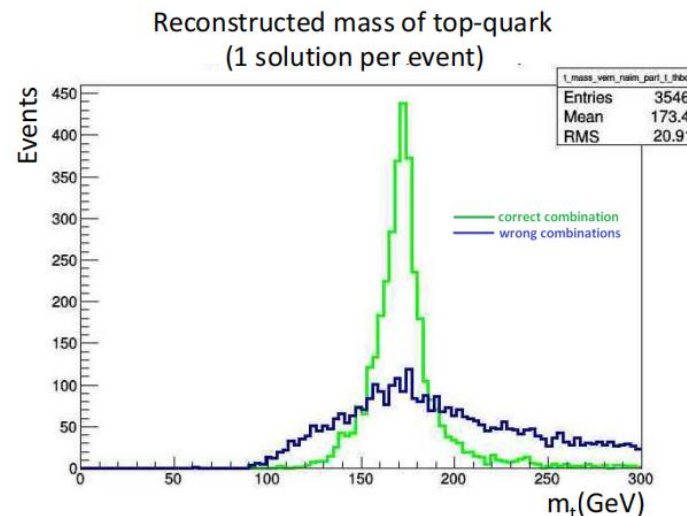
²Институт физики НАНА, Баку

5 сентября 2021 г.

- MadGraph MG5_aMC_v2_6_3_2 (last version)
- LHAPDF-6.1.6 (last version)
- ExRootAnalysis: A package to convert the various output (LHE) in a ROOT format.
- Pythia 8.2: A package containing Pythia6 and PGS. Pythia6 is able to shower and to hadronize your events and is able to perform the matching for multi-jet production. PGS is a fast detector simulation package. or Pythia 8.
- Delphes: A package allowing to have a fast detector simulation, in replacement of PGS.

- PDF set: CT10; $m(b)$: 4.2 GeV; $m(t)$: 172.5 GeV
- $m(H)$: 125 GeV; $Y_b \cdot m(b)$: 4.2 GeV; $Y_t \cdot m(t)$: (+1) * 172.5 GeV (SM) and (-1) * 172.5 GeV (BSM)
- Number of generator events = 34119 (as in ATLAS Ntuples)
- $p p > tt h bb q, h > b b \sim, (t > w+ b, w+ > \text{all all}), (t \sim > w- b \sim, w- > \text{all all})$

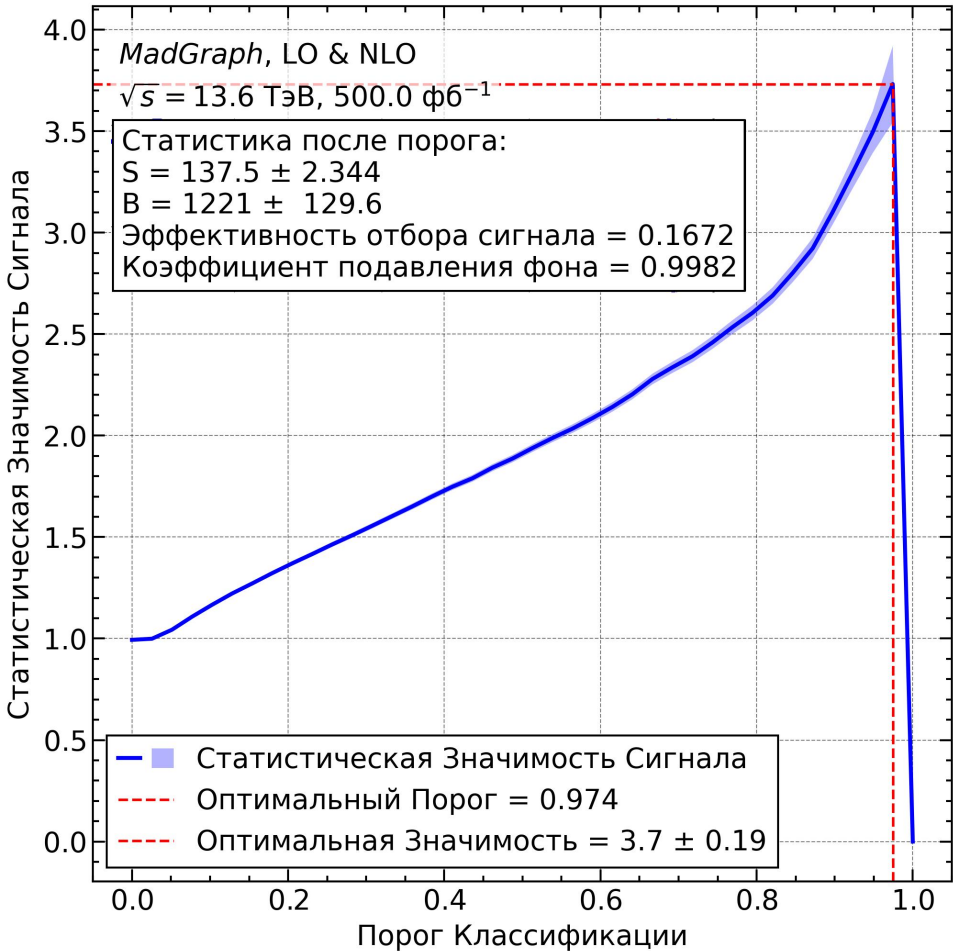
	Cross Section MadGraph, pb	Cross Section ATLAS MC (for Nevents 300k), pb
SM	$0.03205 \pm 6.9e-05$	0.031216
BSM	0.4135 ± 0.00078	0.422364



Information about the neural network SM

Architecture			
Layer	Neurons Number	Activation Function	Normalization
Input Layer	47	-	-
Hidden Layer 1	160	swish	BatchNormalization, Dropout (0.5)
Hidden Layer 2	160	tanh	BatchNormalization, Dropout (0.5)
Hidden Layer 3	96	swish	BatchNormalization, Dropout (0.3)
Output Layer	1	Sigmoid	-

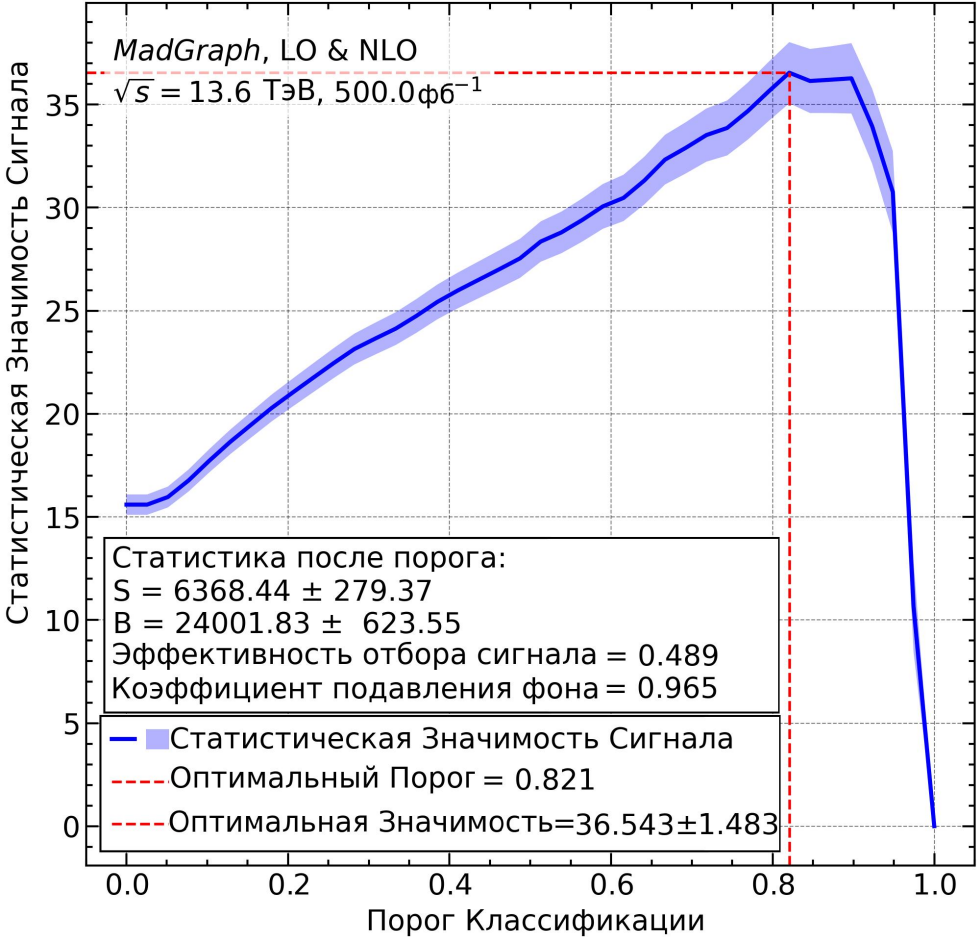
Training setting					
Parameter	Optimizer	Learning rate	Batch size	Loss function	Number of epochs
Value	Adam	0.0004	512	Binary Crossentropy	5000



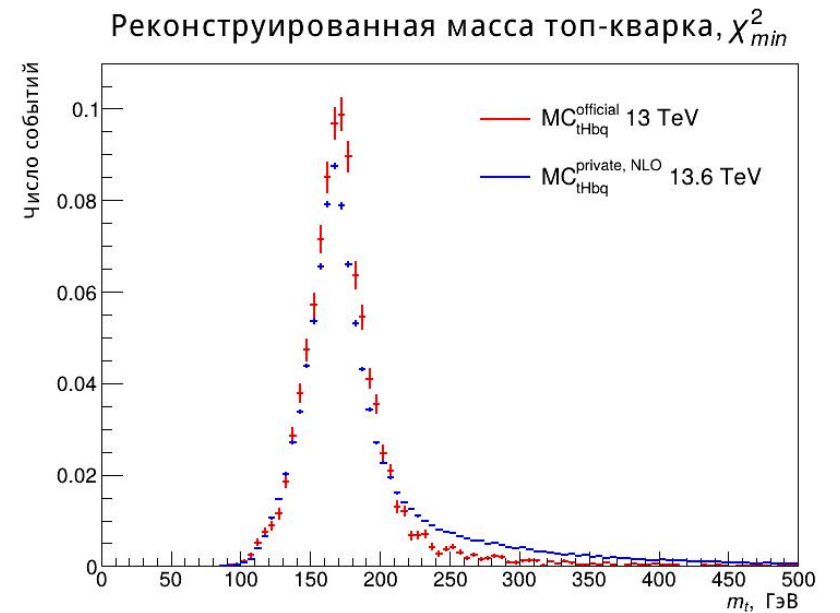
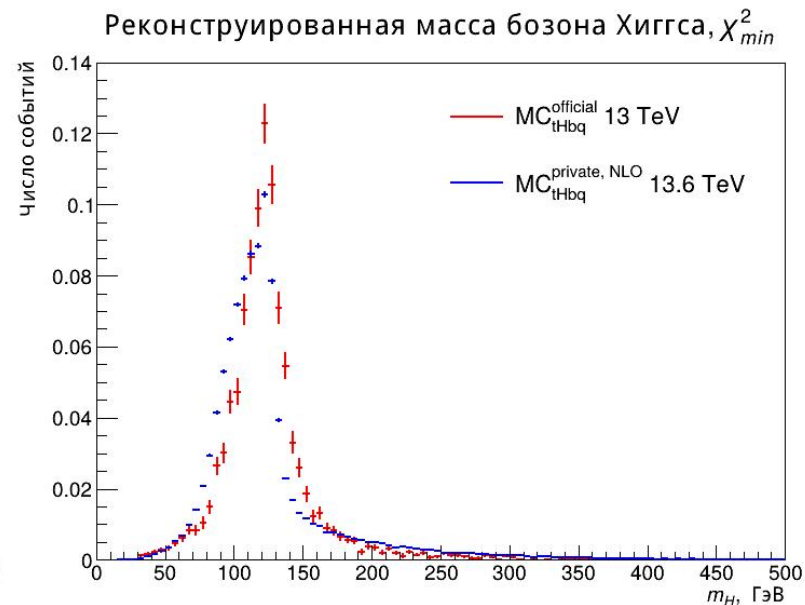
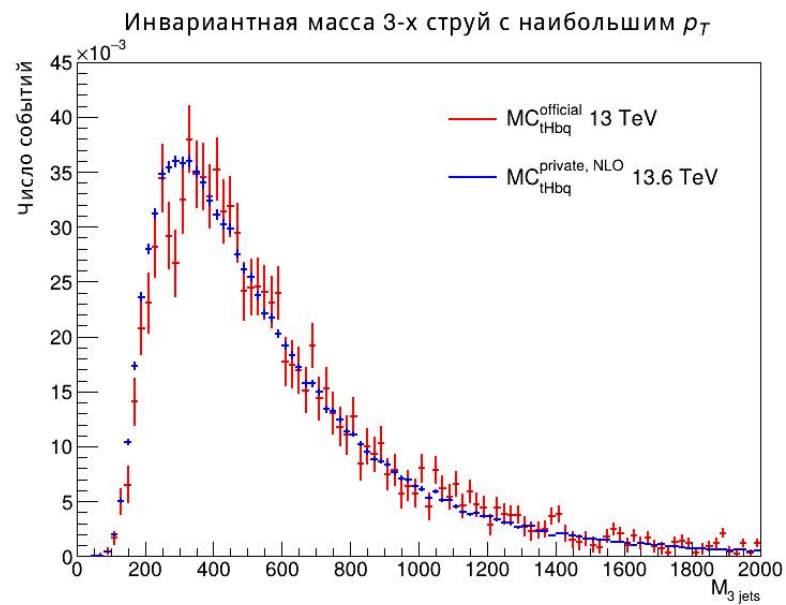
Information about the neural network ITC

Architecture			
Layer	Neurons Number	Activation Function	Normalization
Input Layer	47	-	-
Hidden Layer 1	160	swish	BatchNormalization, Dropout (0.5)
Hidden Layer 2	160	tanh	BatchNormalization, Dropout (0.5)
Hidden Layer 3	96	swish	BatchNormalization, Dropout (0.3)
Output Layer	1	Sigmoid	-

Training setting					
Parameter	Optimizer	Learning rate	Batch size	Loss function	Number of epochs
Value	Adam	0.0004	512	Binary Crossentropy	5000



Validation of the signal process



$$m_W^2 = (p_{lead} + p_\nu)^2 \leftarrow \begin{array}{l} \text{the four-momentum} \\ \text{conservation law of the} \\ \text{W-boson} \end{array}$$

$$P_{Z,\nu}^\pm = \frac{1}{P_{T,l}^2} \left(\mu P_{Z,l} \pm E_l \sqrt{\mu^2 - P_{T,l}^2 (E_T^{miss})^2} \right)$$

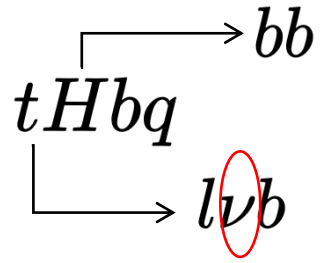
$$\mu = \frac{m_W^2}{2} + P_{X,l} E_T^{miss,x} + P_{Y,l} E_T^{miss,y}; \quad m_W = 80.35 \text{ GeV}$$

$$E_T^{miss,x} = - \sum p_{\text{charged lepton}}^x - \sum p_{\text{jet}}^x \quad E_T^{miss,y} = - \sum p_{\text{charged lepton}}^y - \sum p_{\text{jet}}^y$$

$$E_T^{miss} = \sqrt{E_T^{miss,x2} + E_T^{miss,y2}} \leftarrow \text{neutrino momentum}$$

$$\left. \begin{aligned} p_{\nu,1} &= Vec4(E_T^{miss,x}, E_T^{miss,y}, p_{z,\nu}^+, \sqrt{E_T^{miss2} + p_{z,\nu}^{+2}}) \\ p_{\nu,2} &= Vec4(E_T^{miss,x}, E_T^{miss,y}, p_{z,\nu}^-, \sqrt{E_T^{miss2} + p_{z,\nu}^{-2}}) \end{aligned} \right\} \begin{array}{l} \text{two solutions for the} \\ \text{neutrino momentum} \end{array}$$

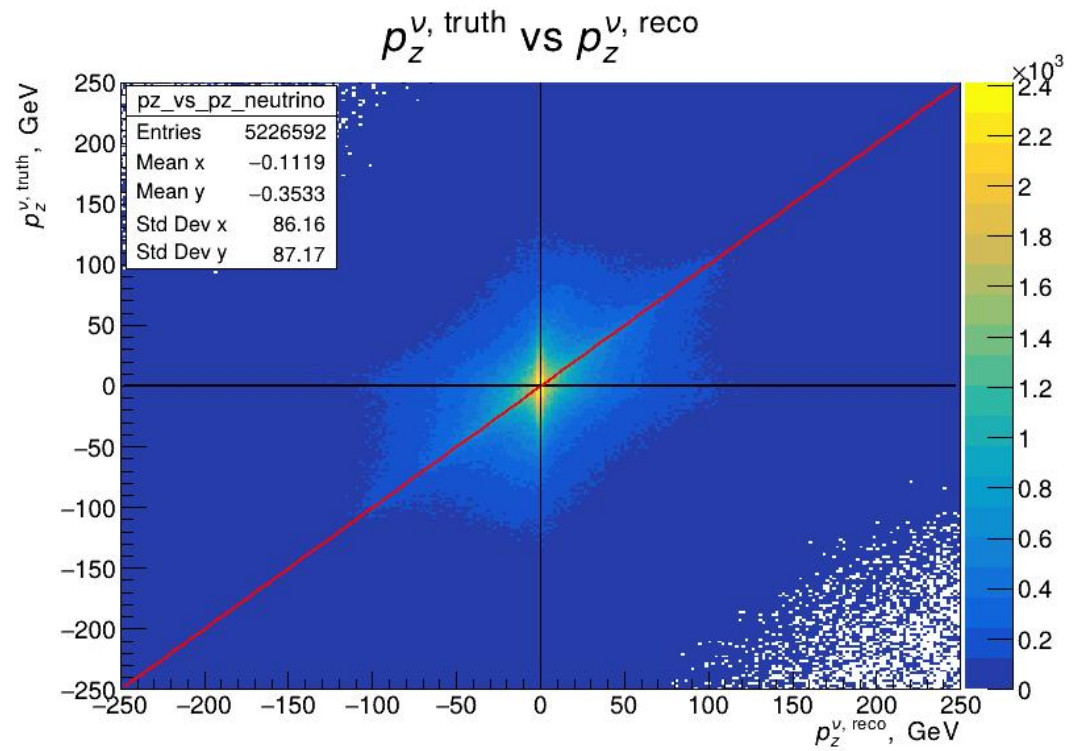
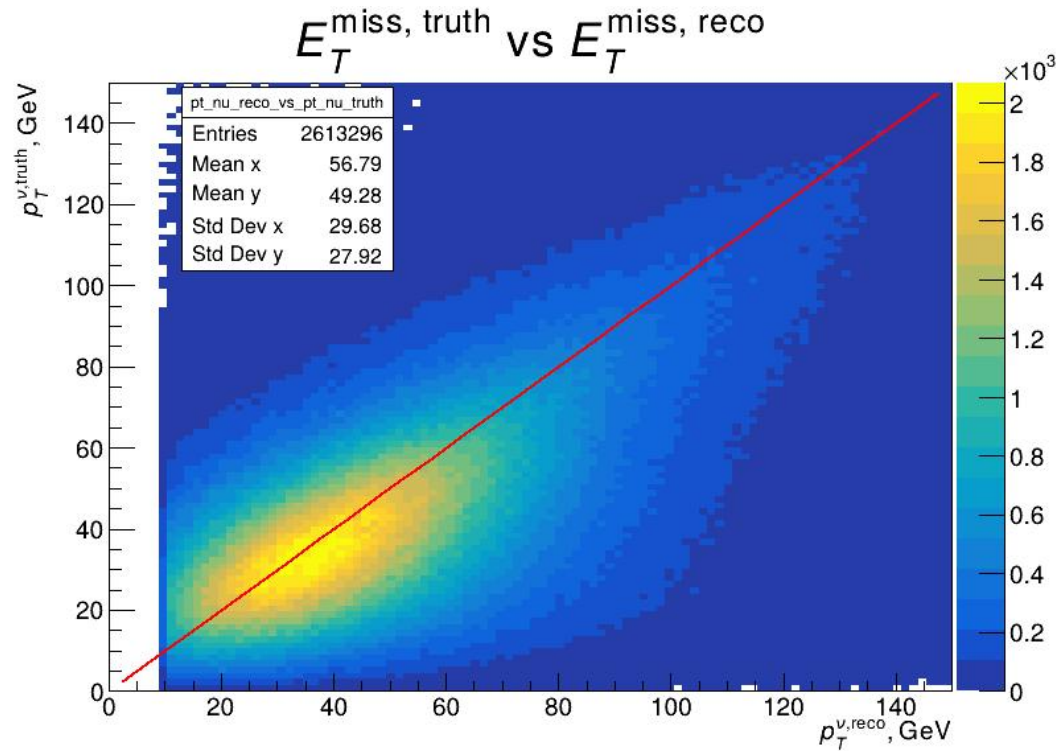
Neutrino reconstruction



Formula for calculating the z-component of neutrino momentum:

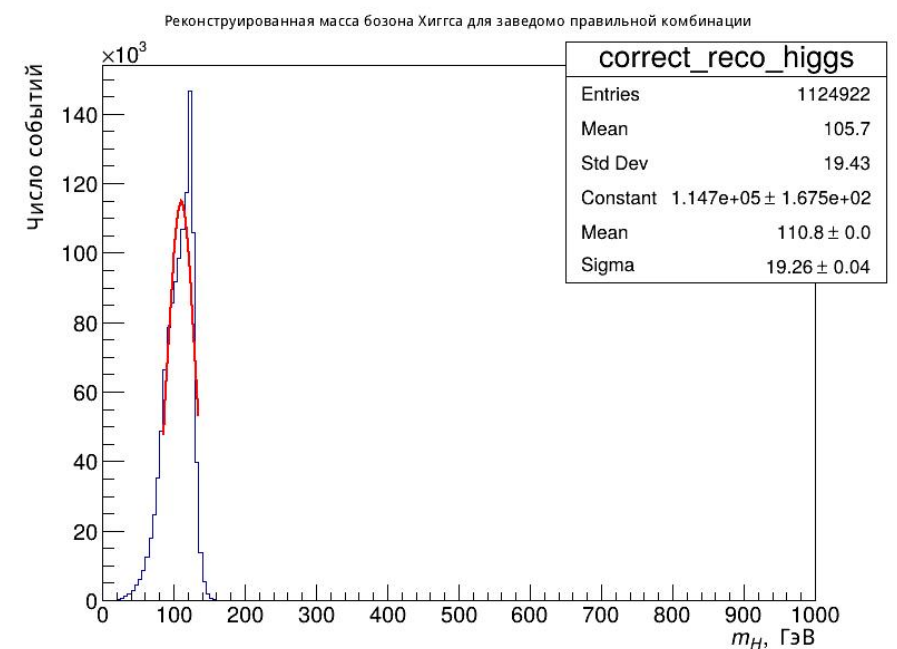
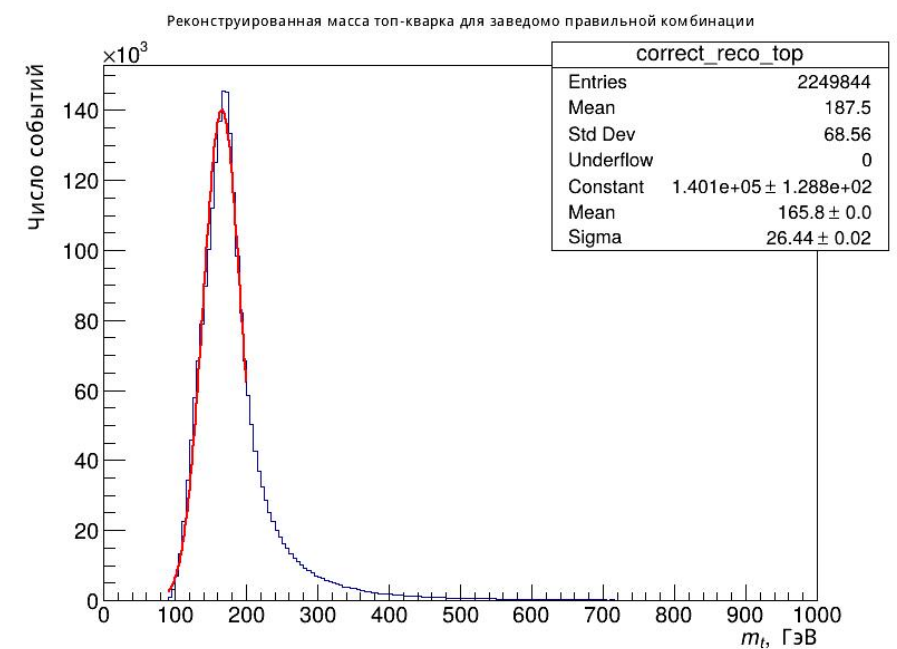
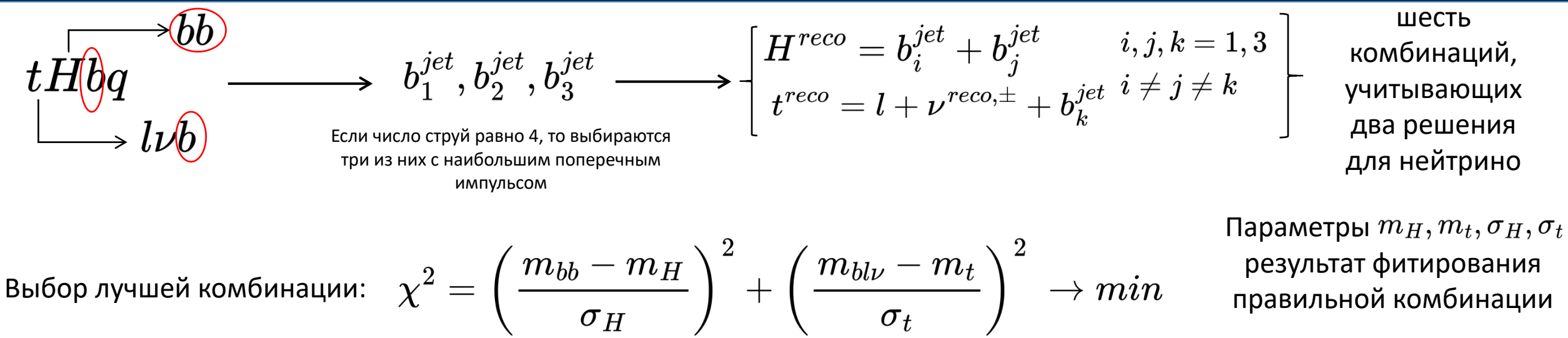
$$P_{Z,\nu}^{\pm} = \frac{1}{P_{T,l}^2} \left(\mu P_{Z,l} \pm E_l \sqrt{\mu^2 - P_{T,l}^2 (E_T^{miss})^2} \right),$$

where $\mu = \frac{m_W^2}{2} + P_{X,l} E_T^{miss,x} + P_{Y,l} E_T^{miss,y}$; $m_W = 80.35$ GeV

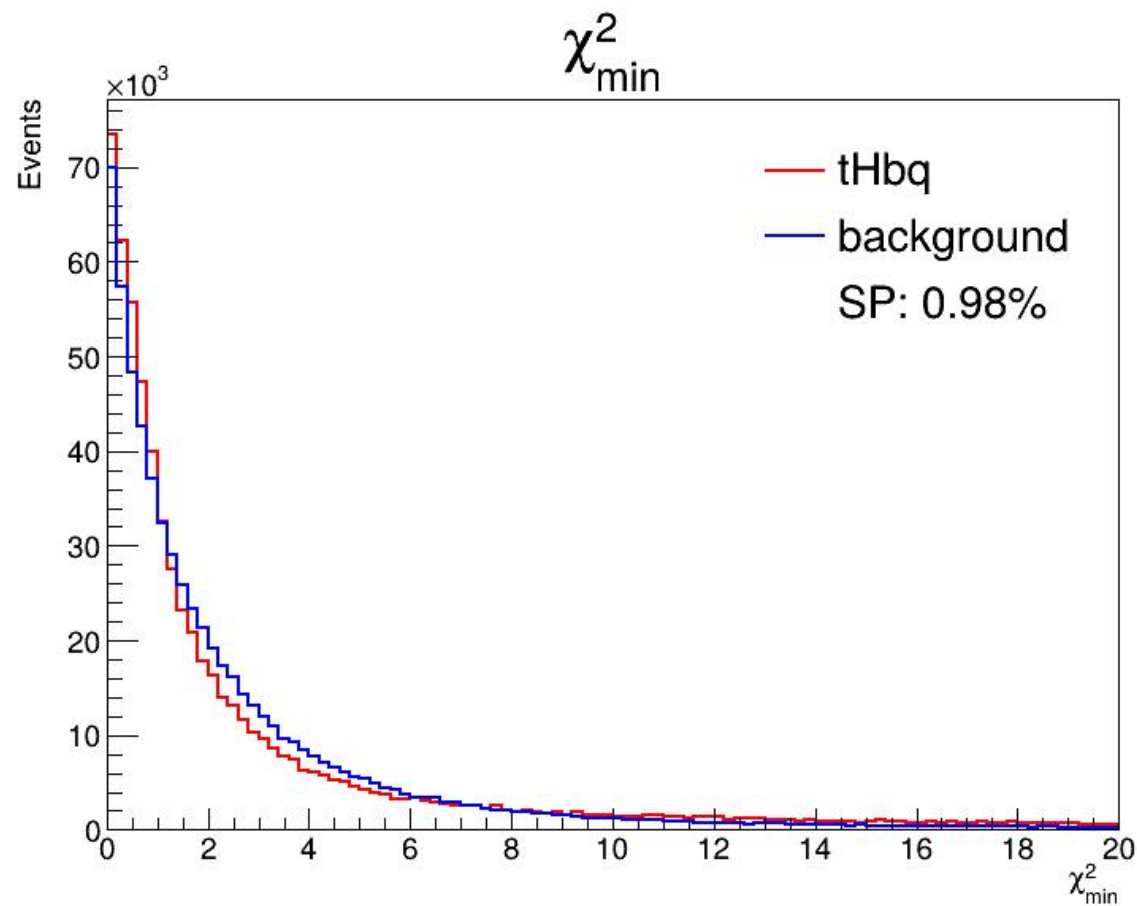
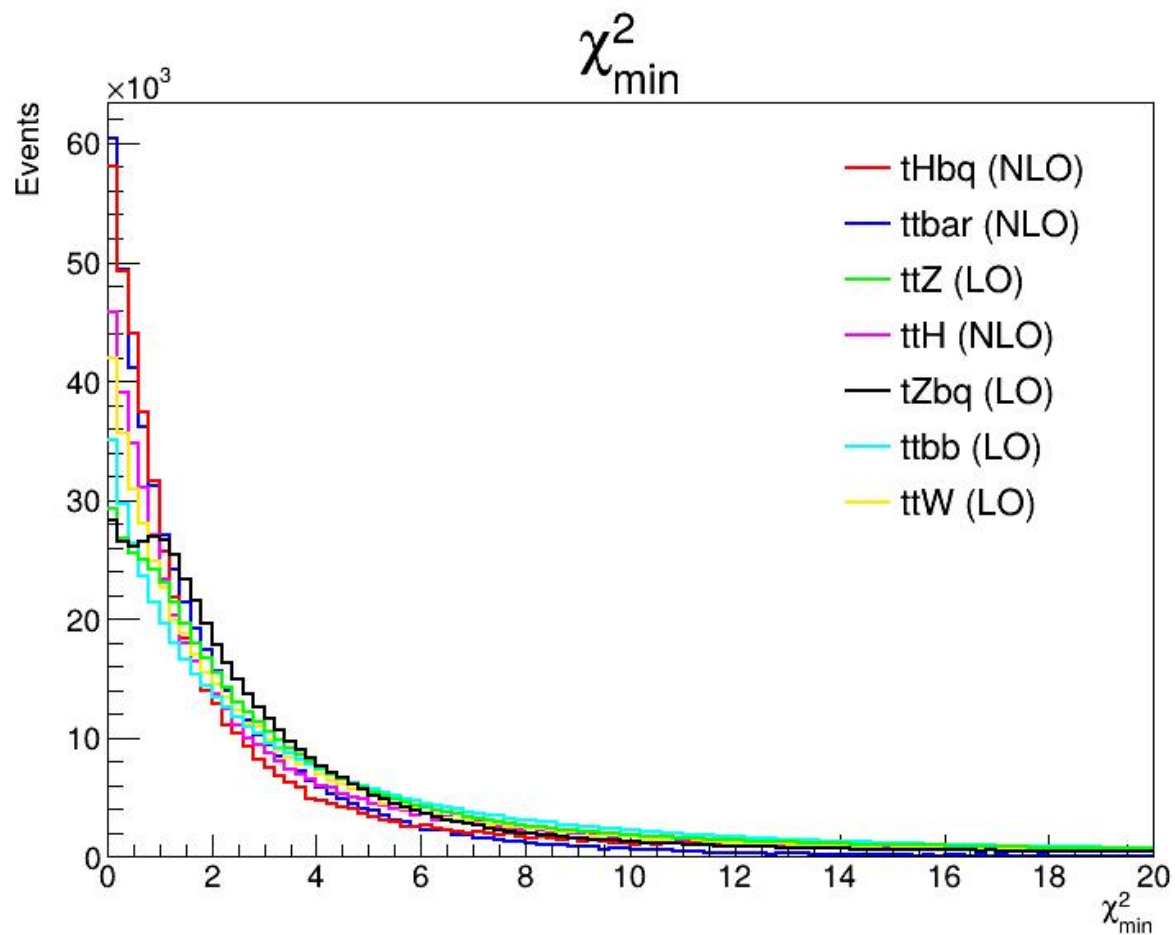


each event gives 2 entries: correct solution and wrong solution

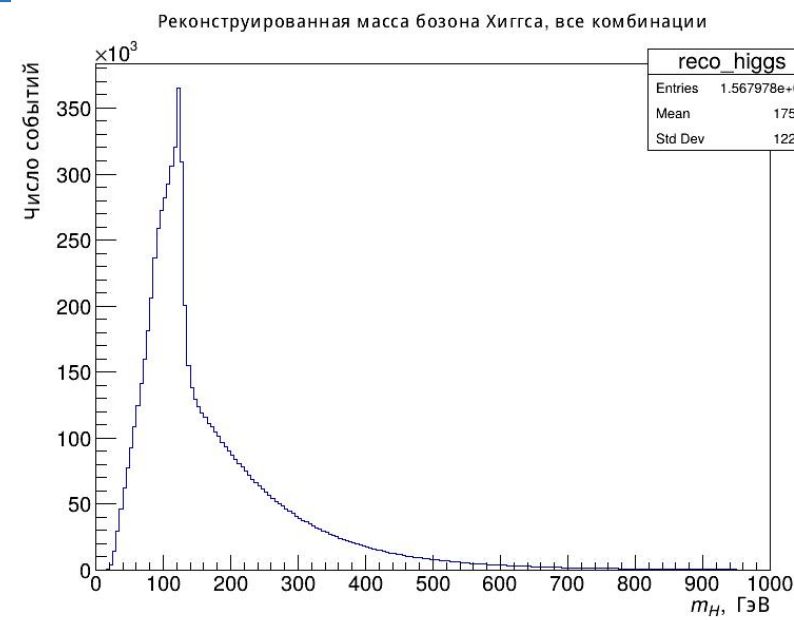
Алгоритм реконструкции топ-кварка и бозона Хиггса



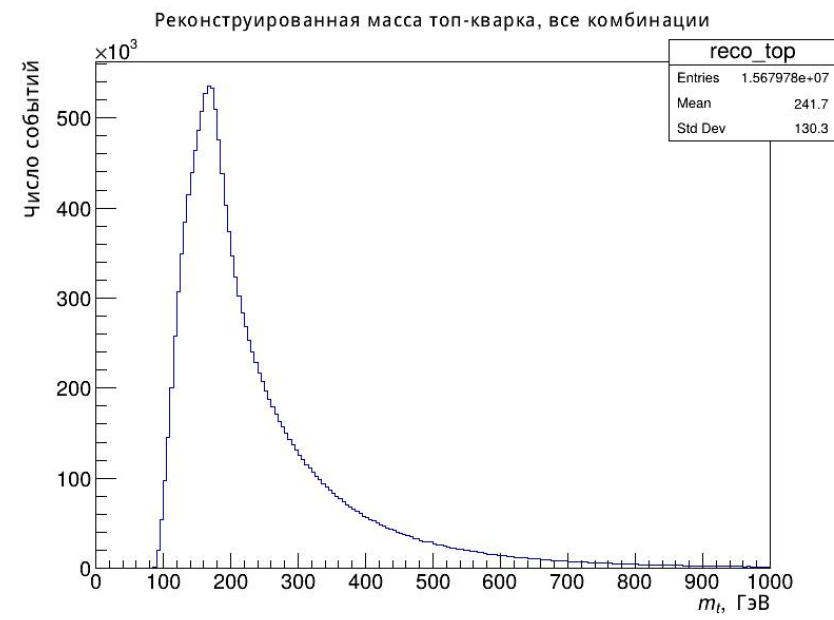
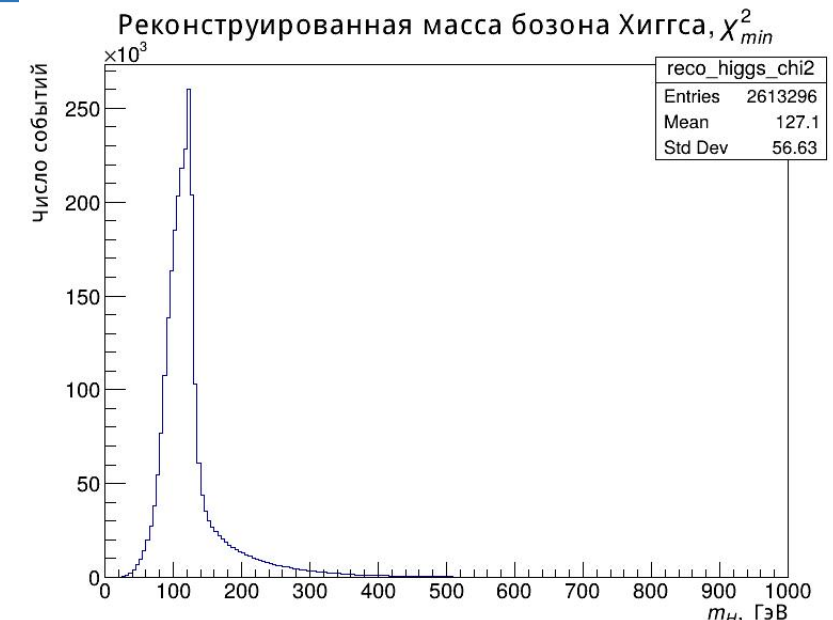
χ^2 for the signal and background processes



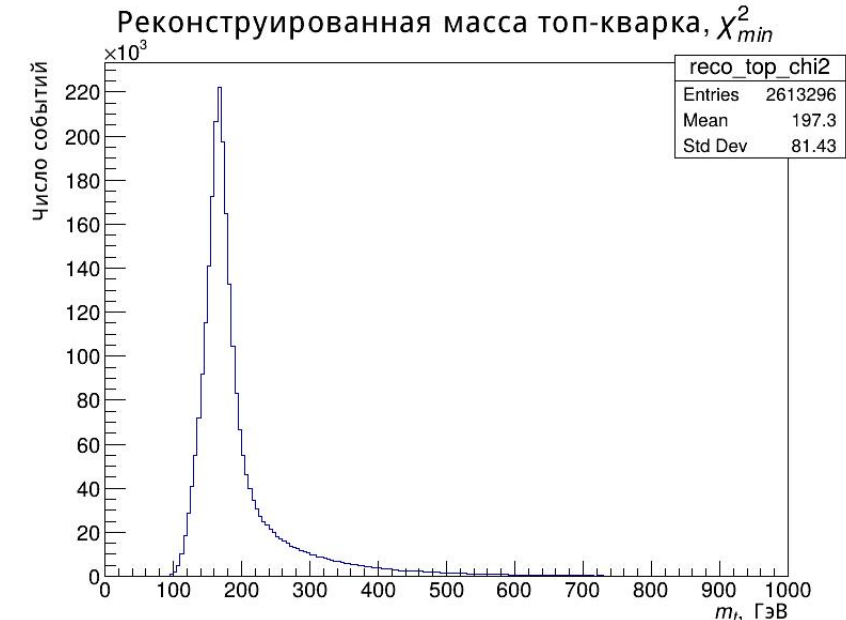
Реконструированные массы бозона Хиггса и топ-кварка для сигнального процесса



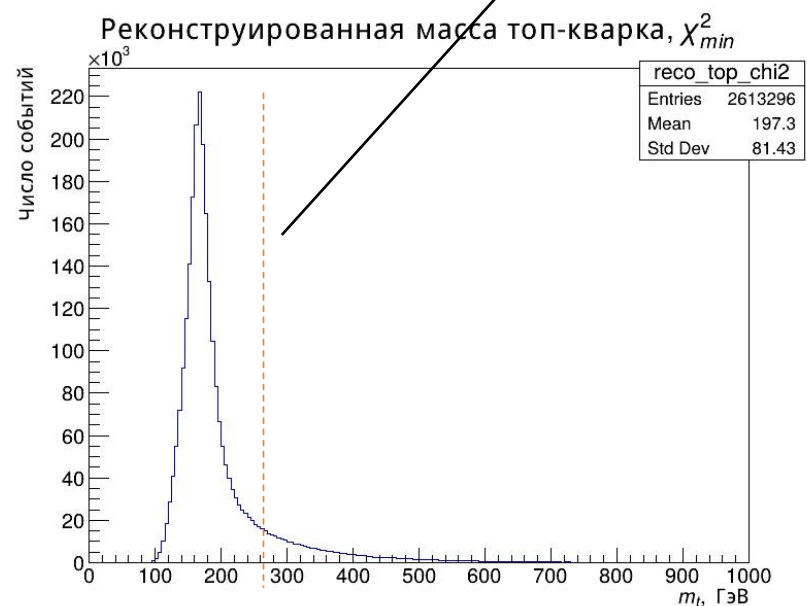
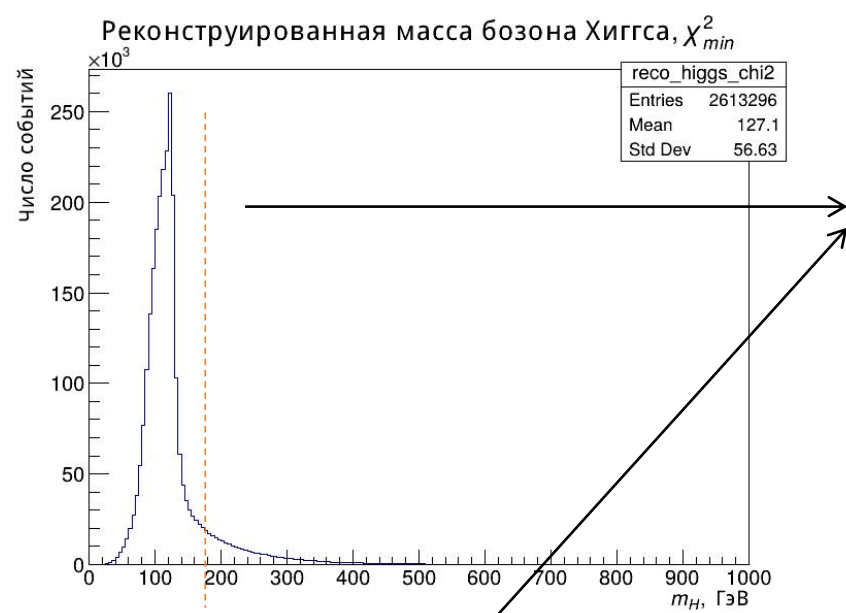
χ^2_{min}



χ^2_{min}



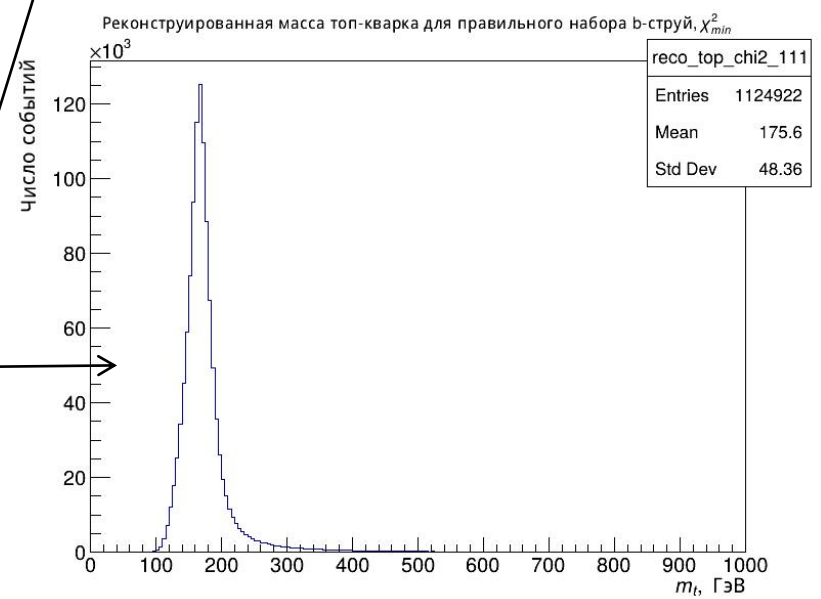
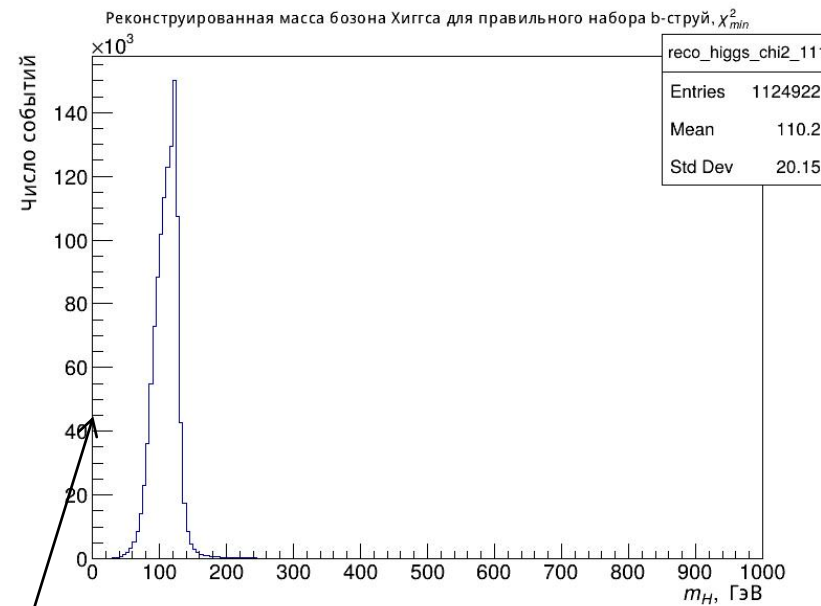
Tails in distributions of reconstructed Higgs boson and top-quark masses for the signal process



Откуда берутся
«хвосты»?

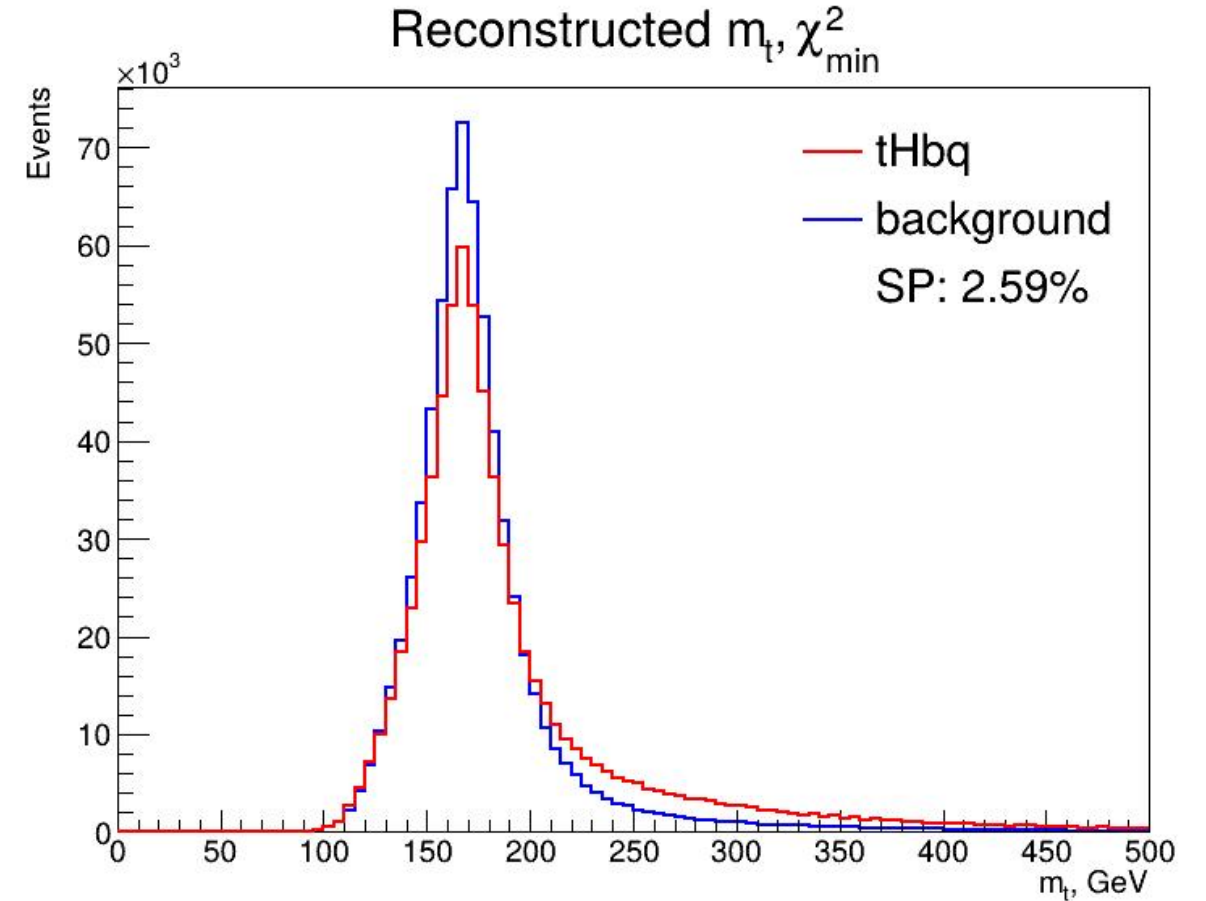
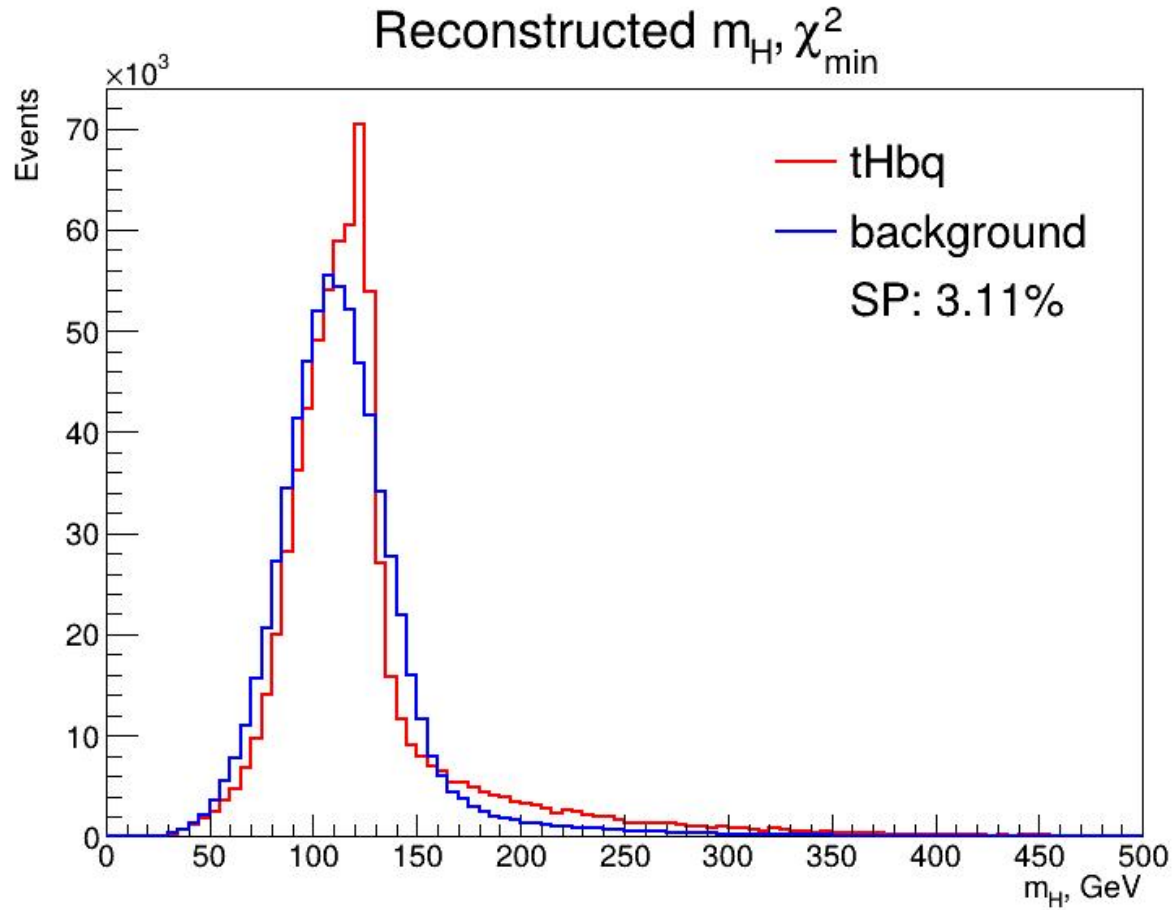
Примерно в половине
отобранных событий
набор из трех b-струй, из
которых извлекаются
массы бозона Хиггса и
топ-кварка, содержит b-
струю от кварка-
наблюдателя

Что произойдет, если
рассмотреть набор
«правильных» b-
струй



В этом случае
критерий χ^2 не
выбирает
неправильные
массы

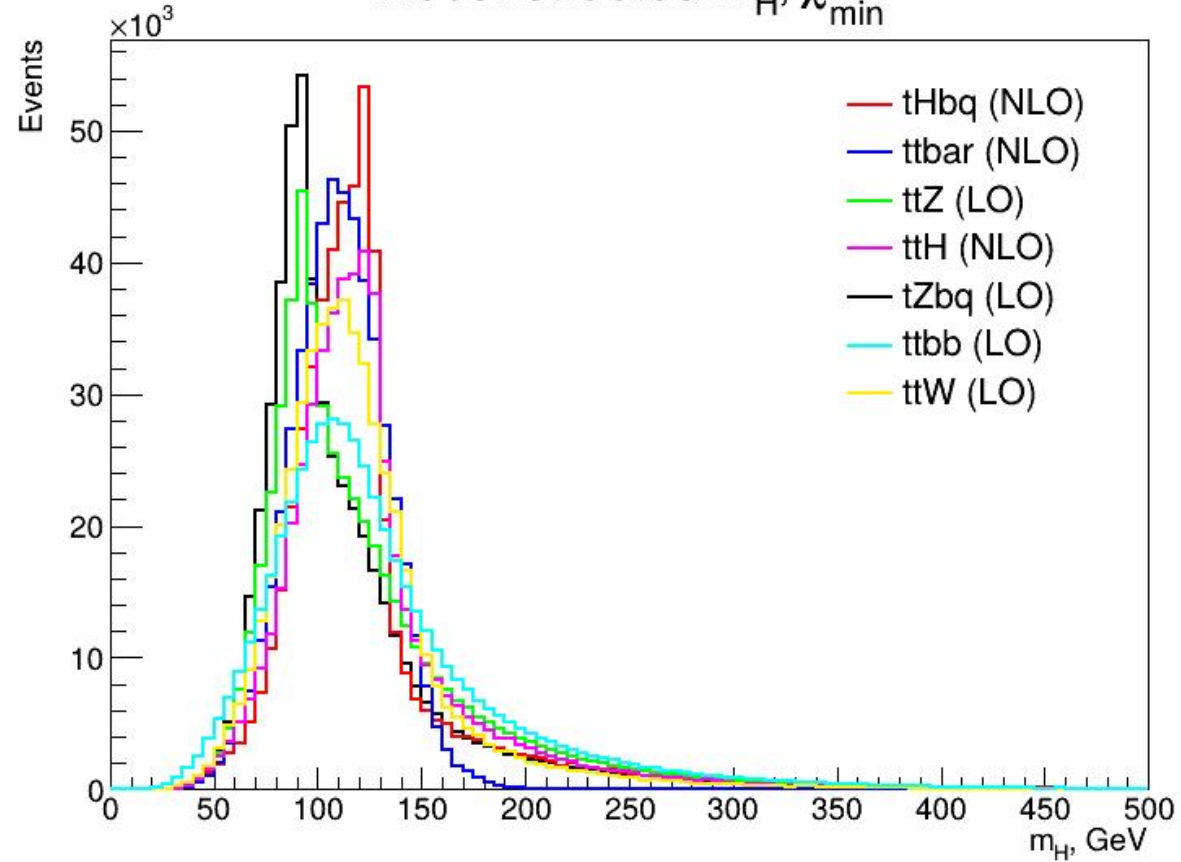
Reconstructed masses of the top quark and Higgs boson for background processes



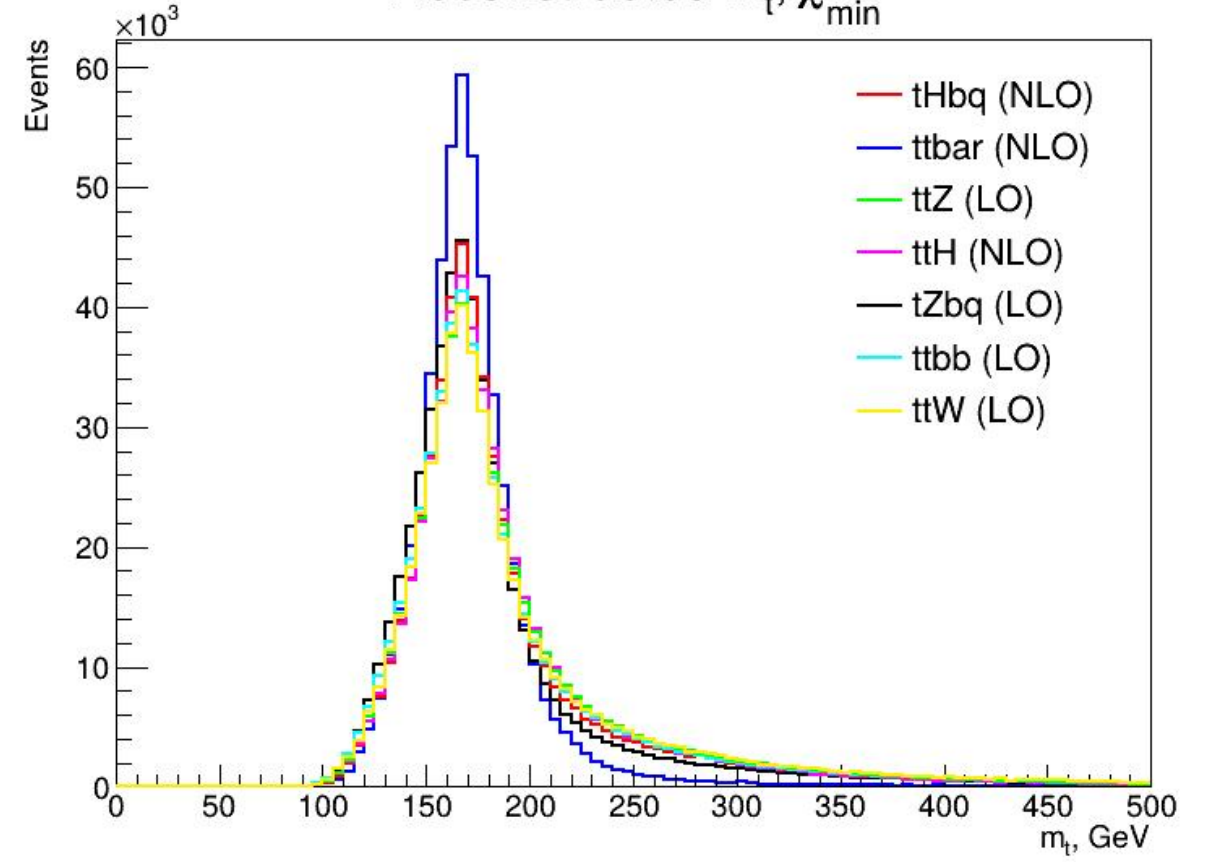
*background = tt , ttH , ttZ , $ttbb$, $tZbq$, ttW

Reconstructed masses of the top quark and Higgs boson for background processes

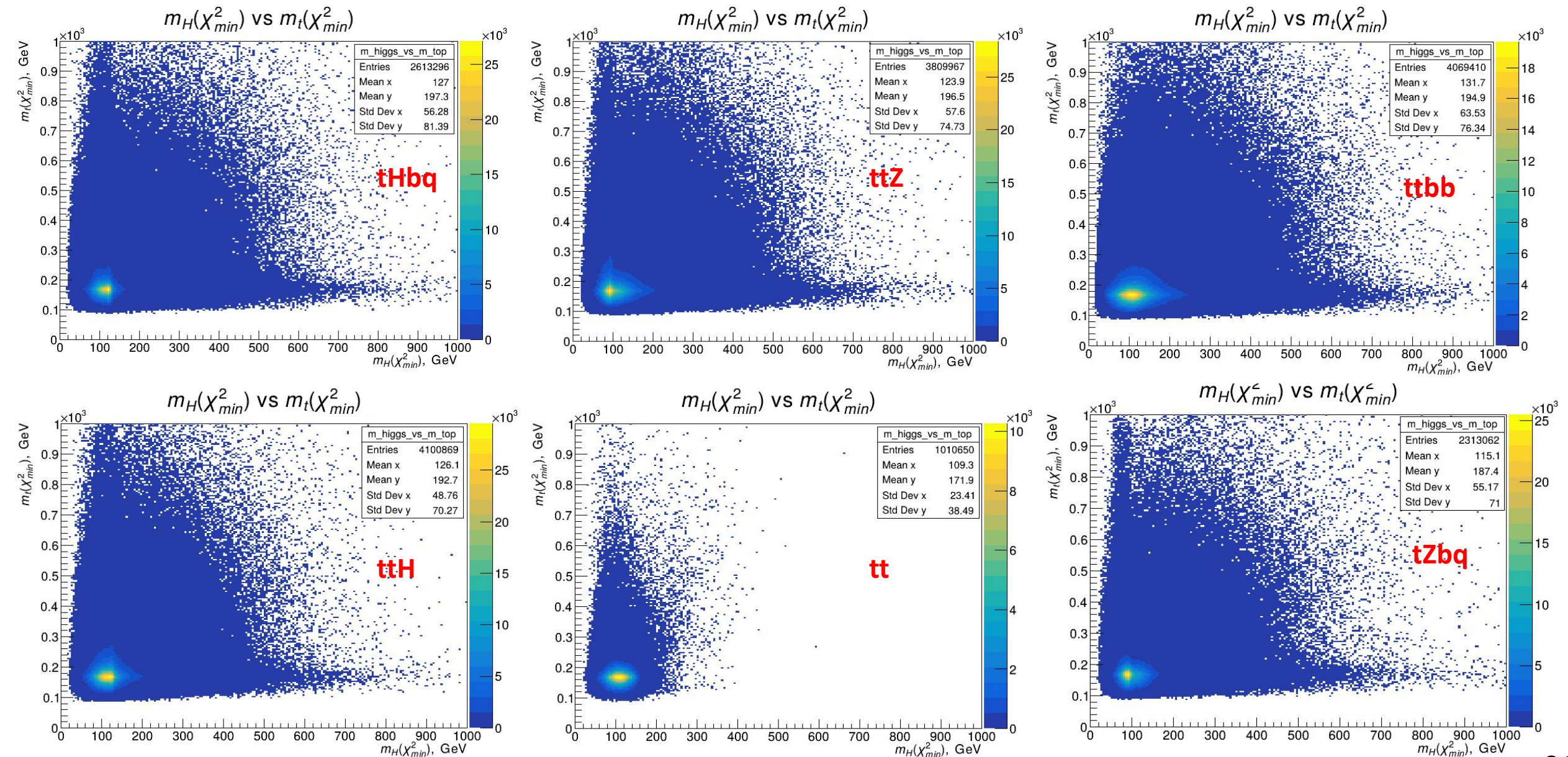
Reconstructed $m_H, \chi^2_{\min}$



Reconstructed $m_t, \chi^2_{\min}$

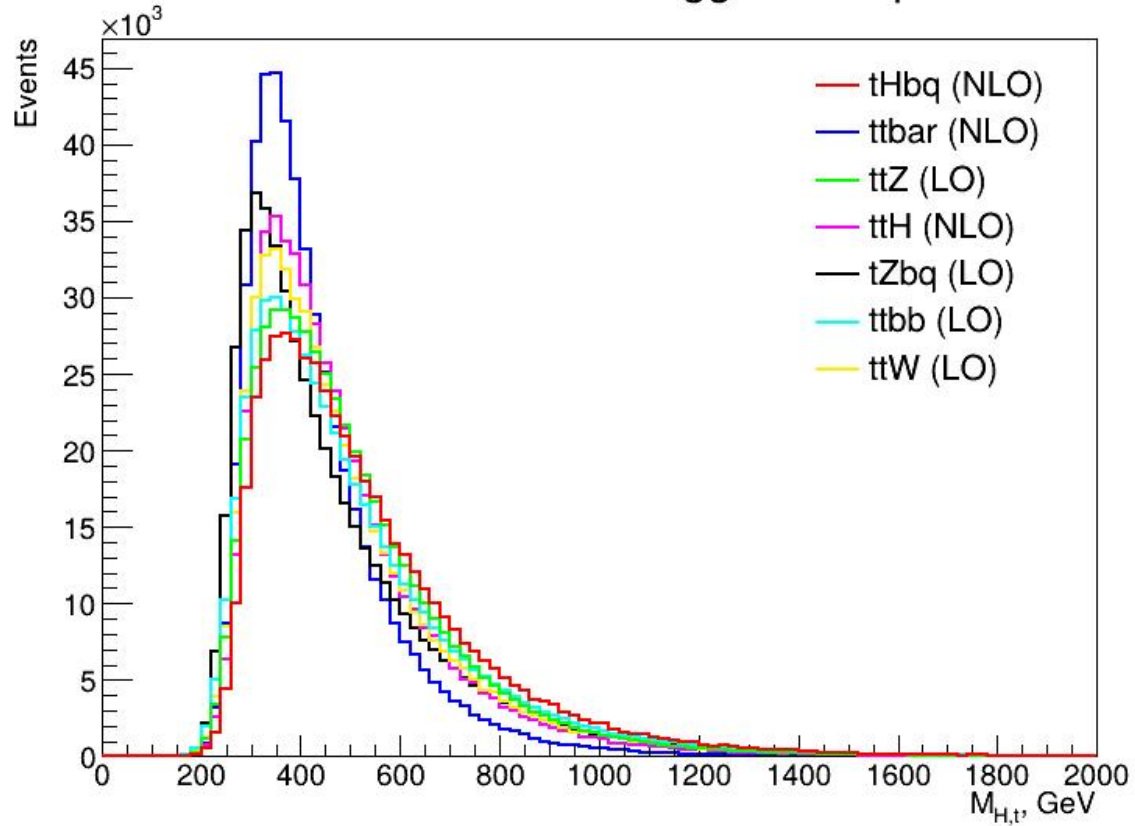


Two-dimensional distributions on the reconstructed Higgs boson and top-quark masses

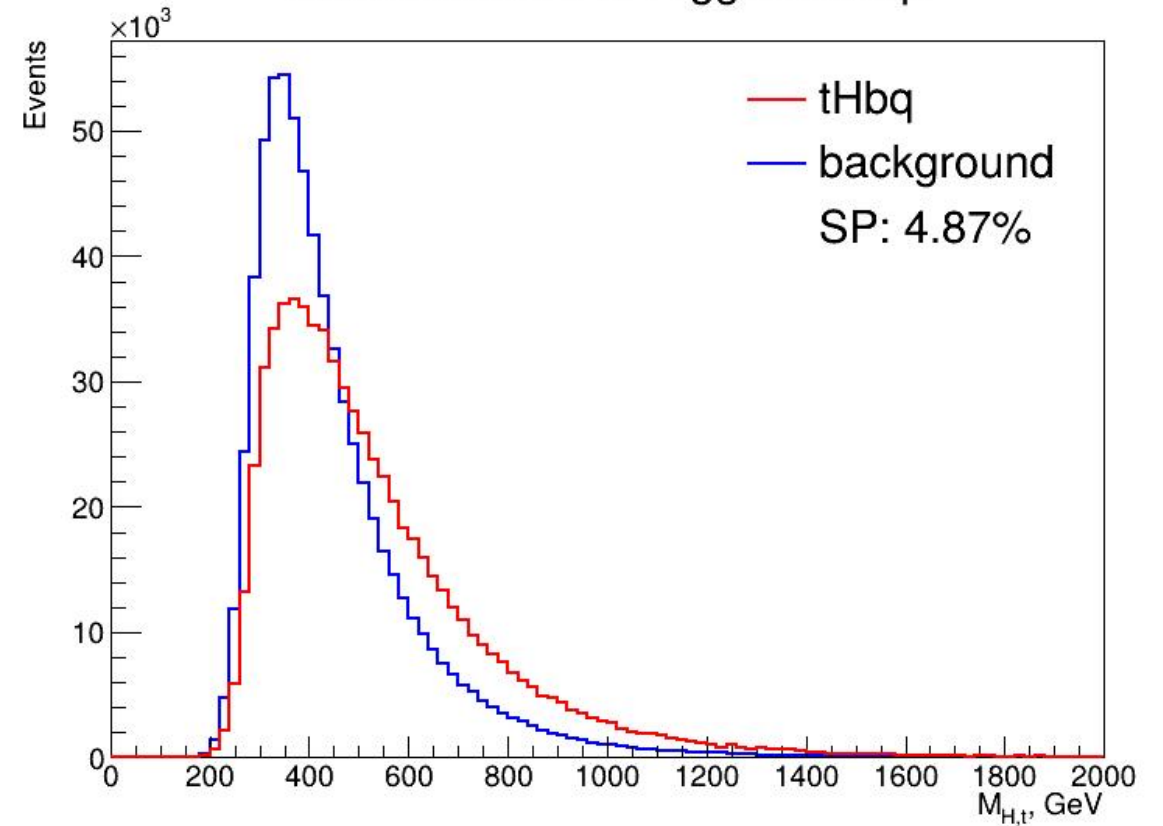


Invariant mass of the top quark and Higgs boson system for the signal and background processes

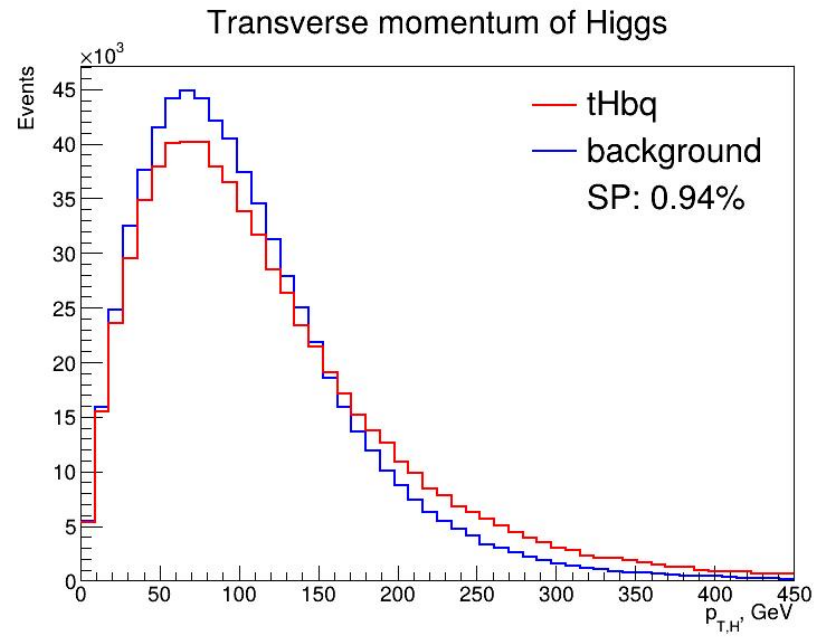
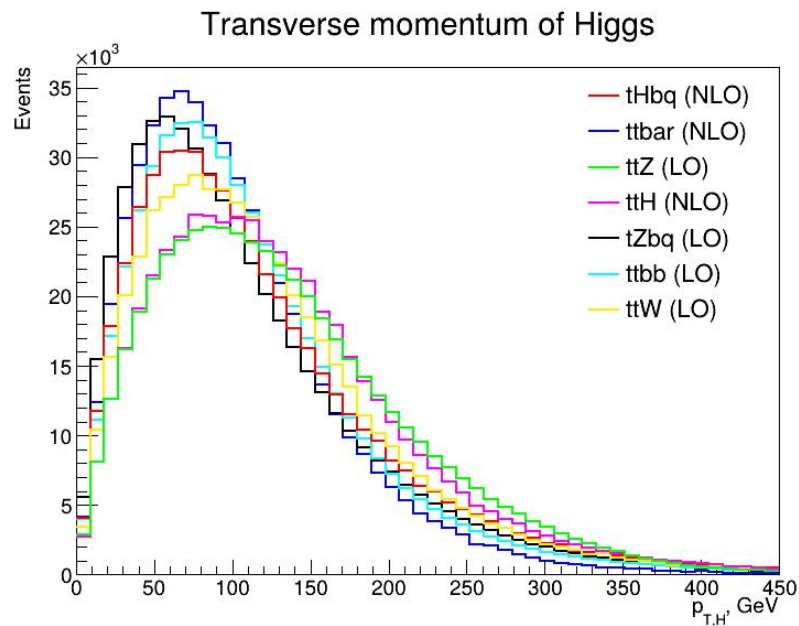
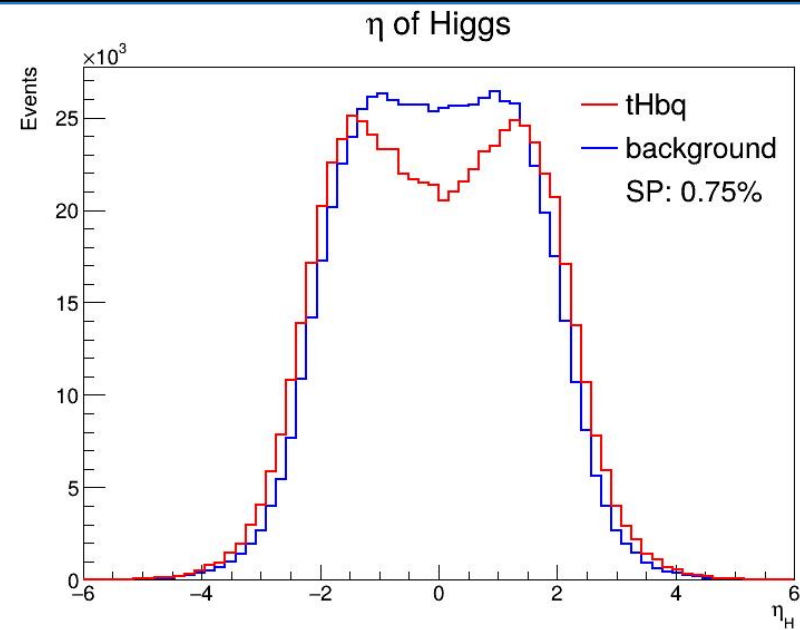
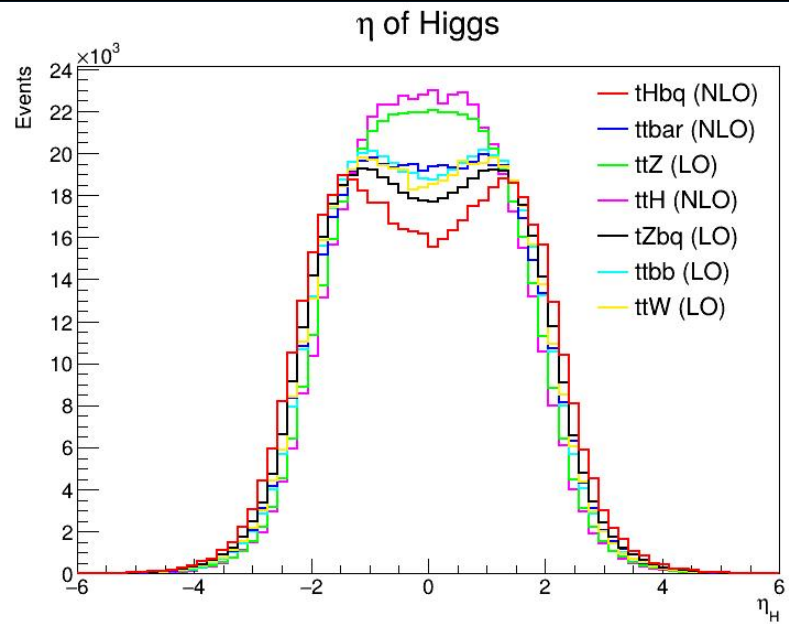
Invariant mass of Higgs and top



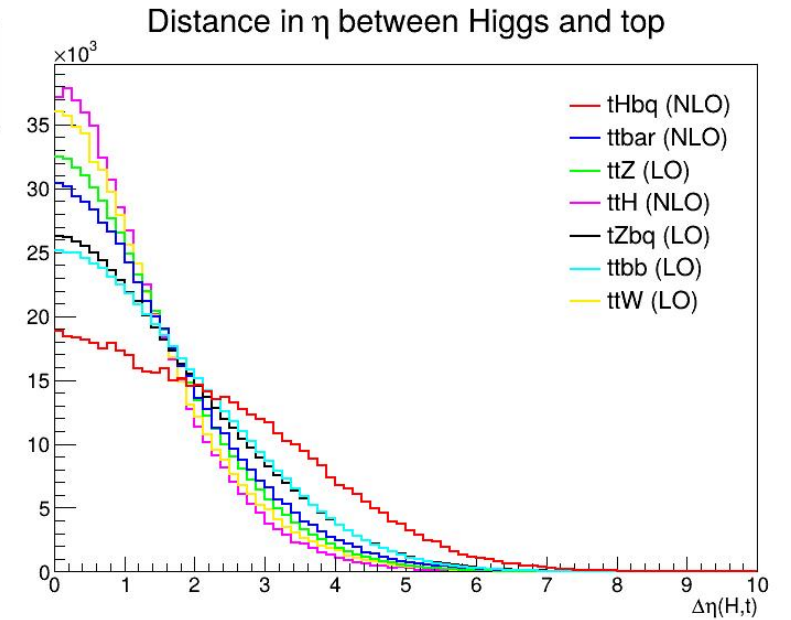
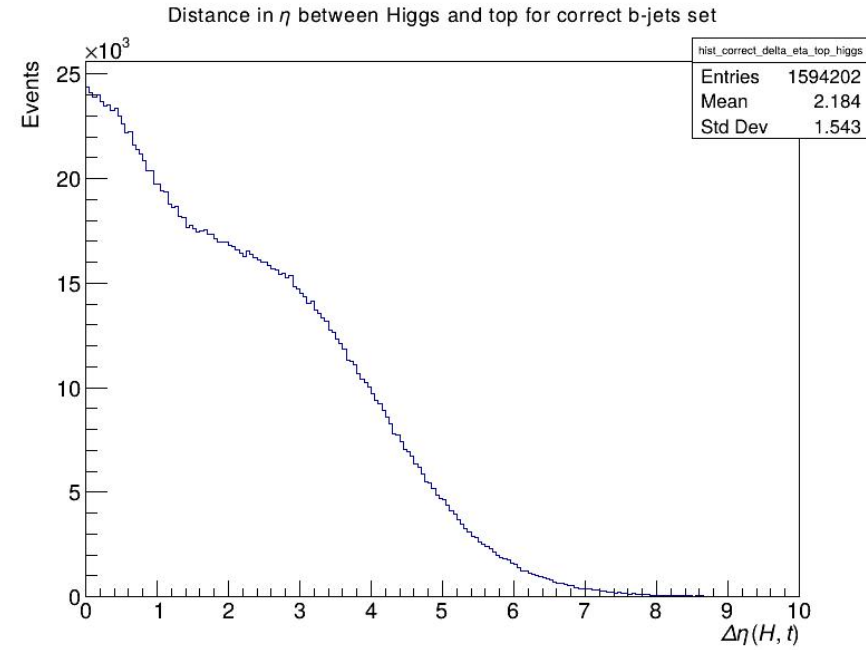
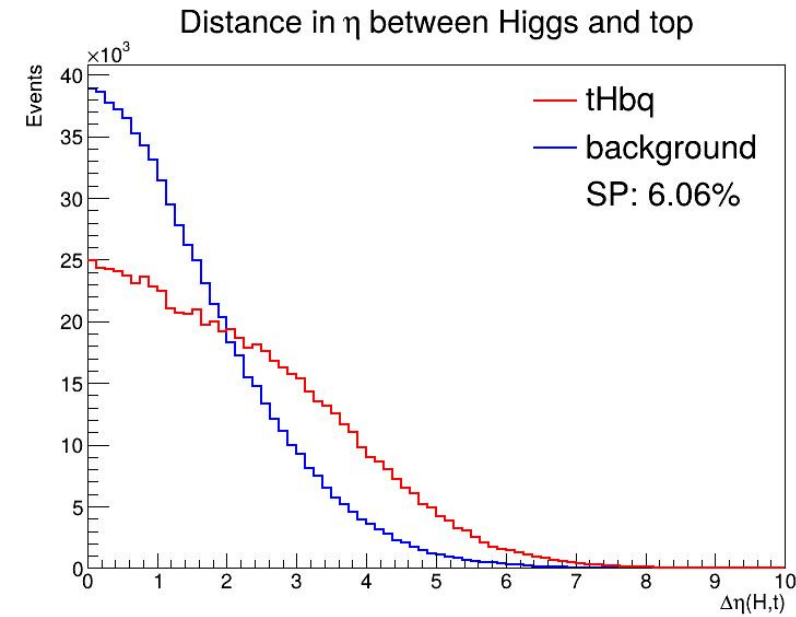
Invariant mass of Higgs and top



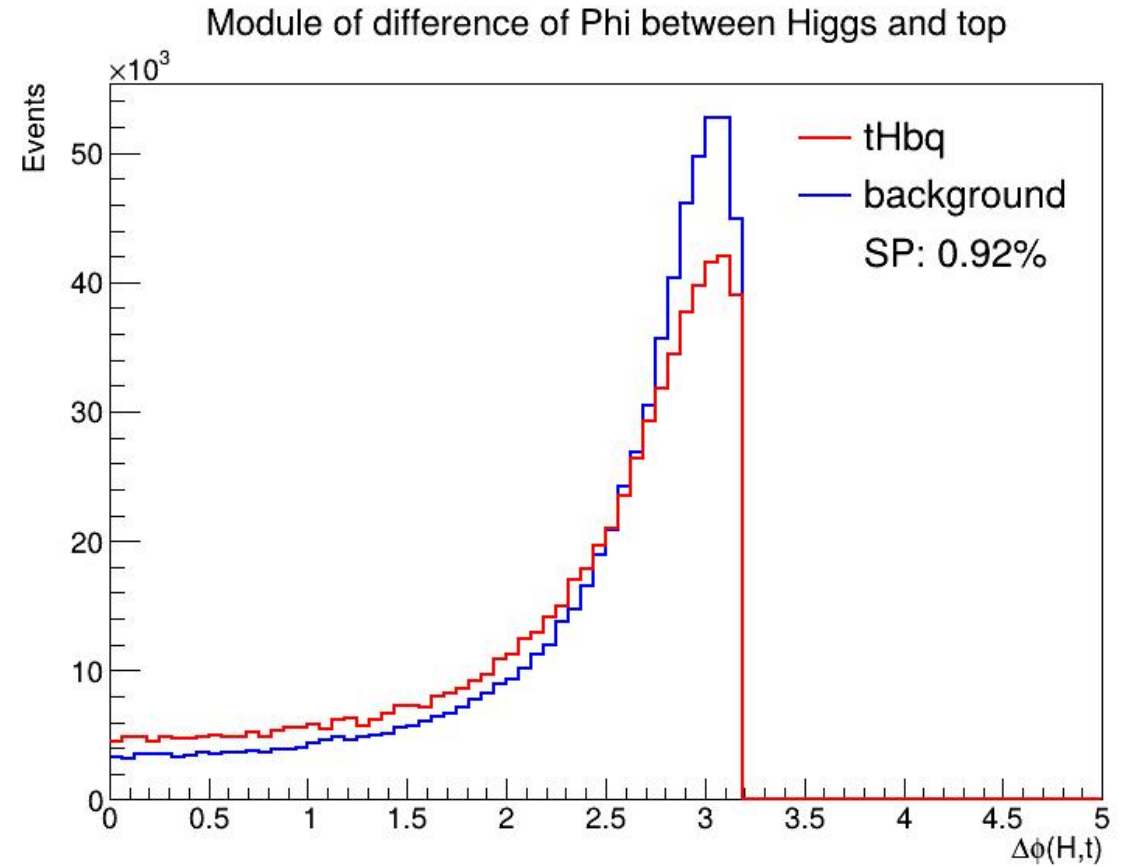
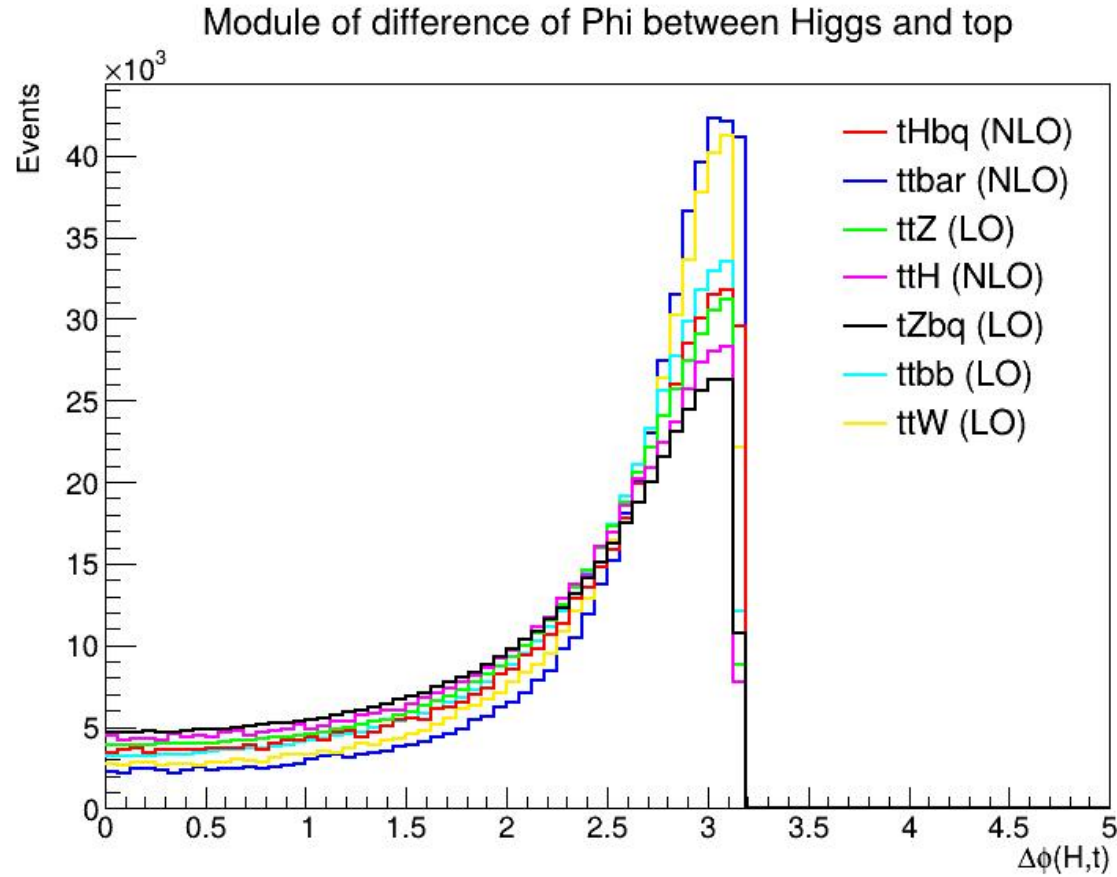
η and p_T Higgs boson for the signal and background processes



Distance η between top quark and Higgs boson for the signal and background processes



$|\Delta\phi|$ between top quark and Higgs boson for the signal and background processes



Forward and Tagging jet

$tHbq$

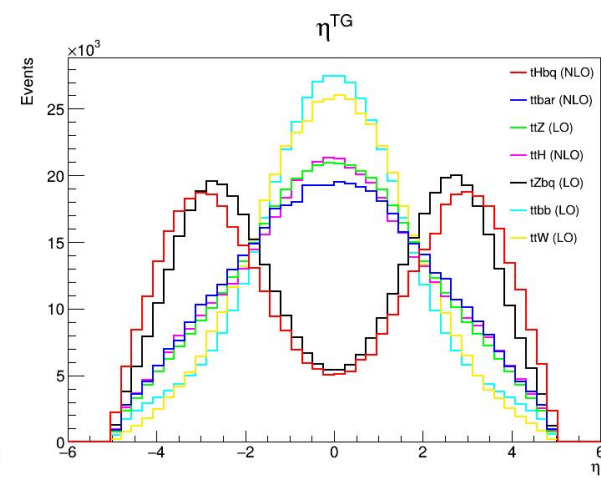
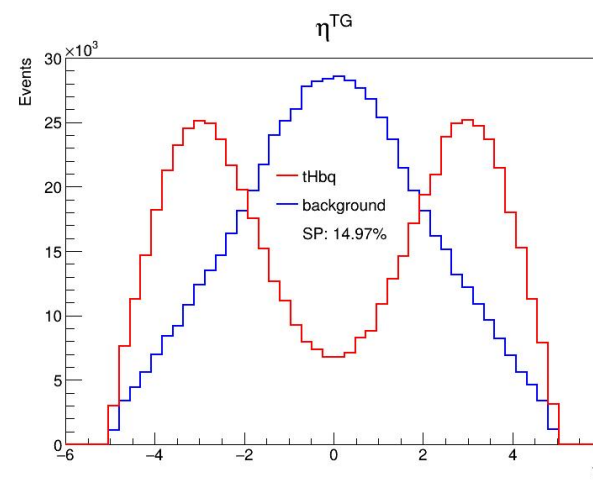
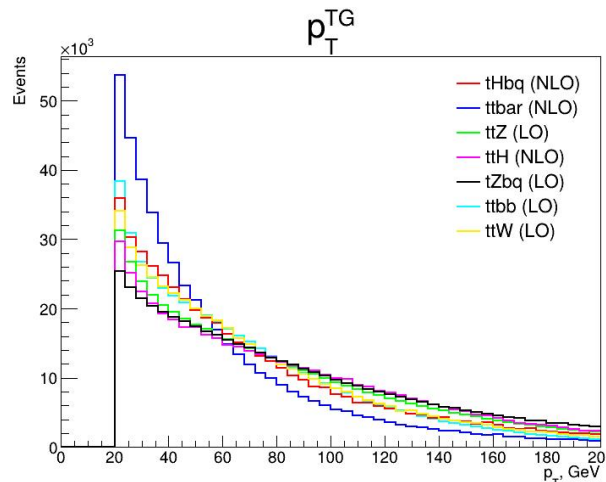
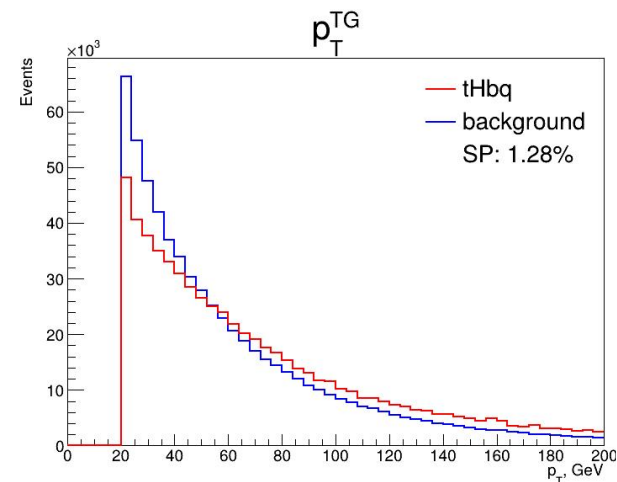
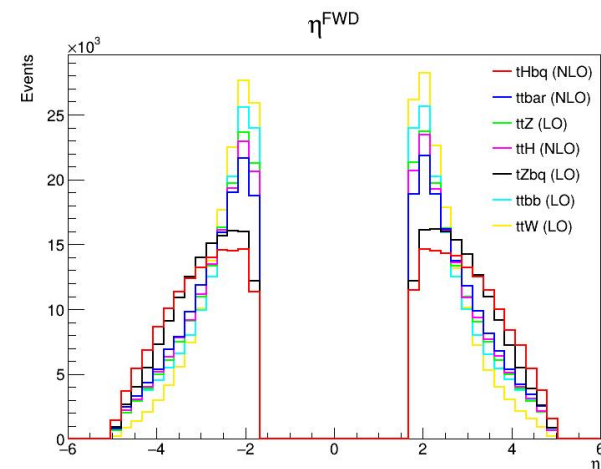
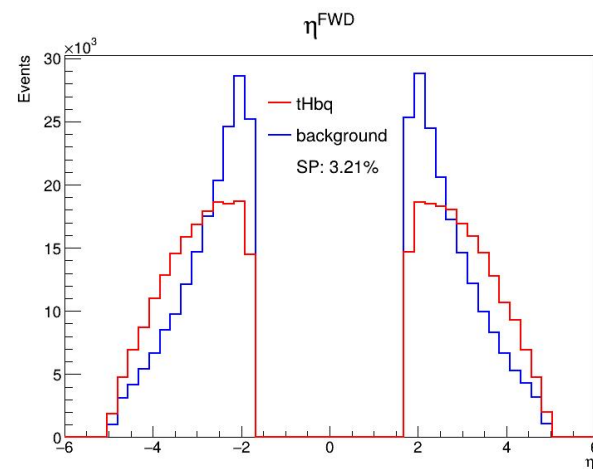
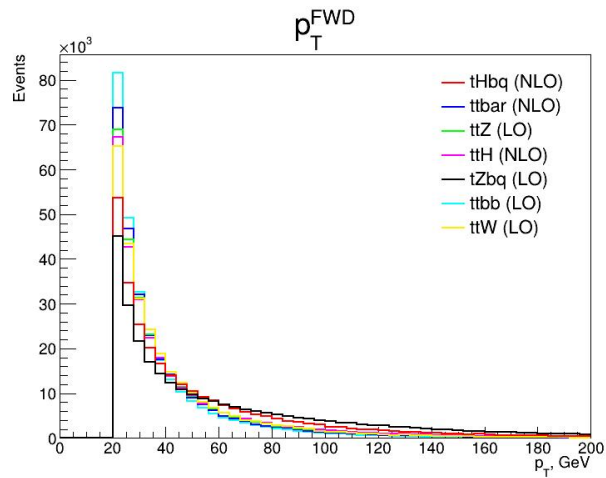
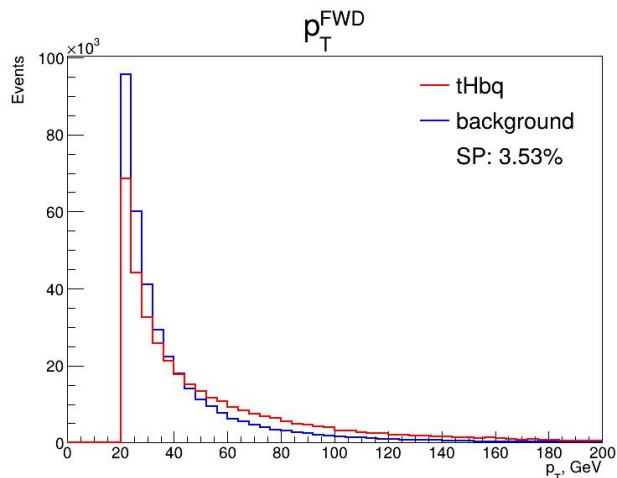
The jet generated by the quark-spectator can be used to extract the signalling process

$$1) p_T^{FWD} > 30 \text{ GeV}, |\eta^{FWD}| > 1.74$$

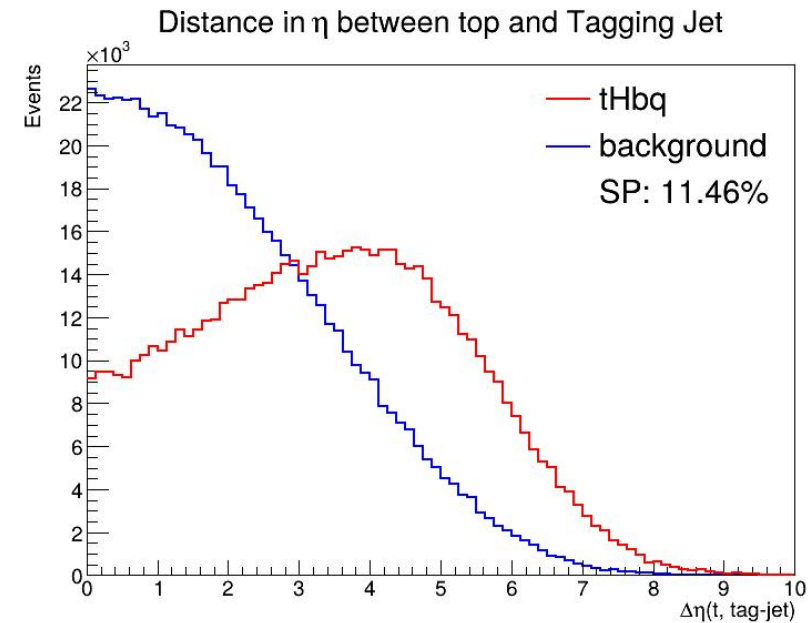
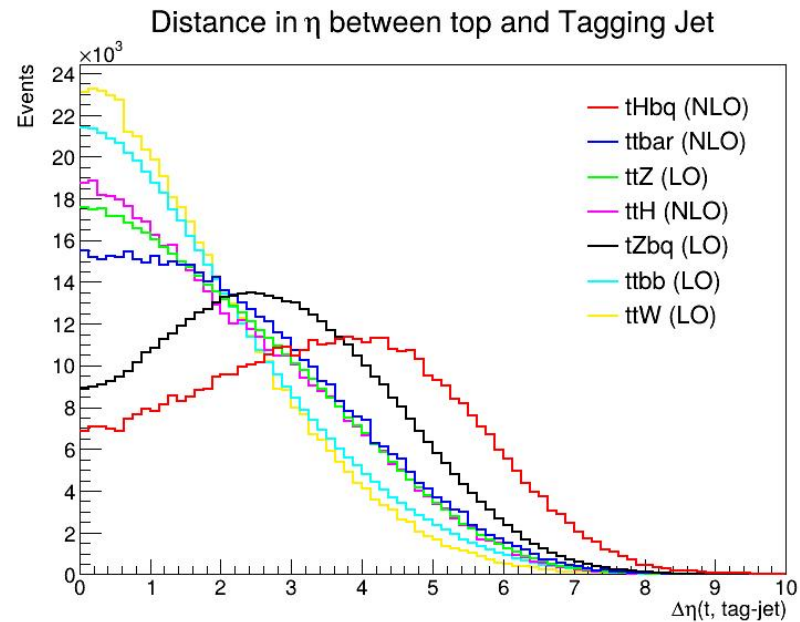
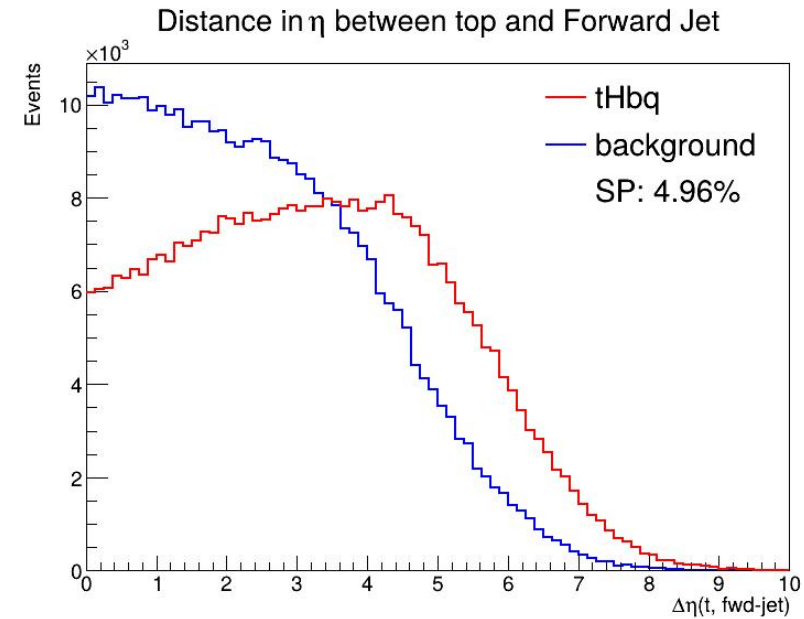
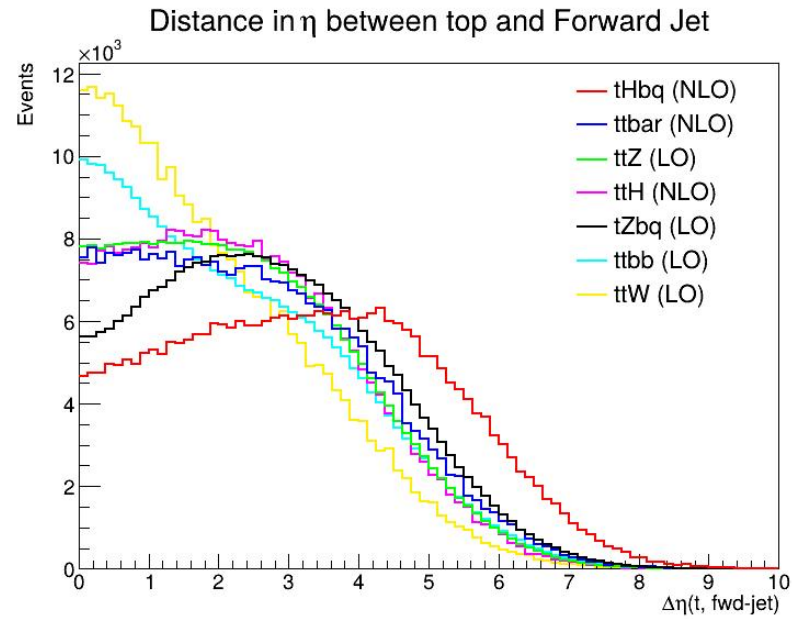
← Classical search algorithm
(Forward Jet)

$$2) m(bjet^{lep. top}, non-bjet)^{max}$$

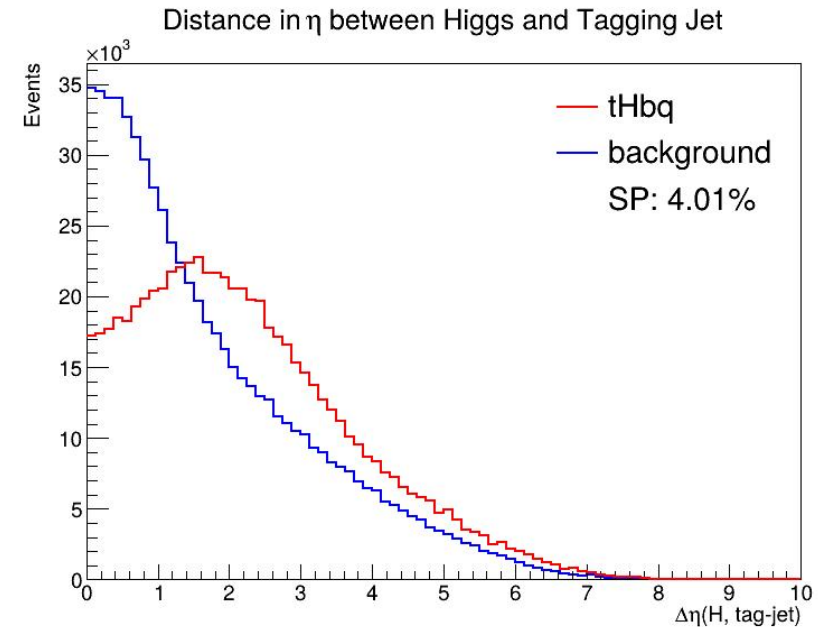
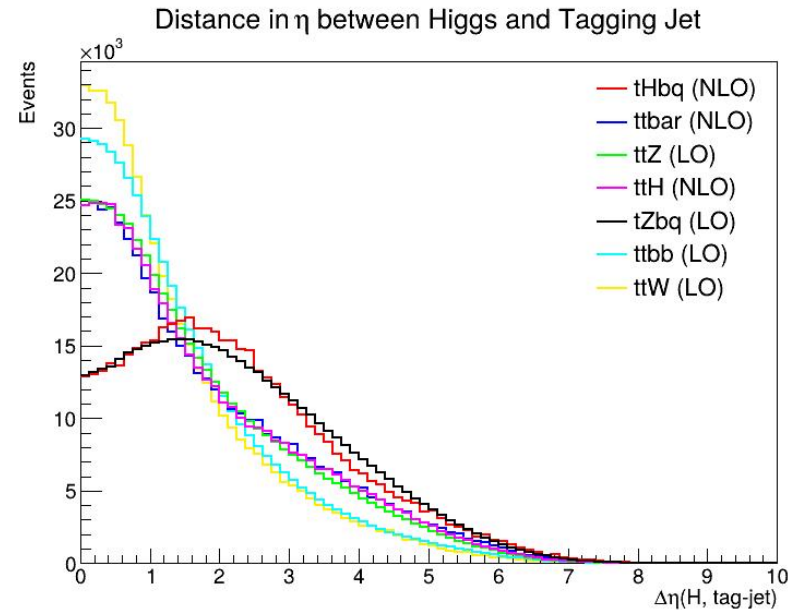
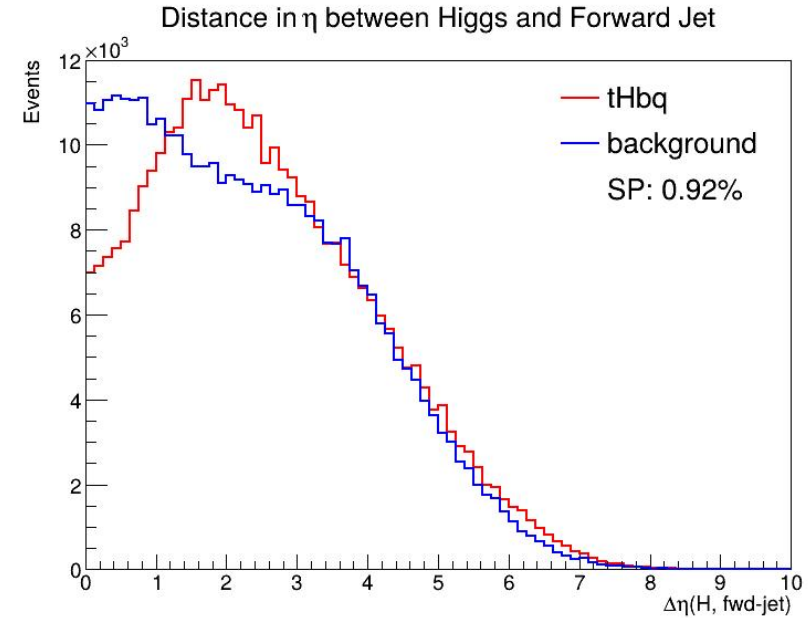
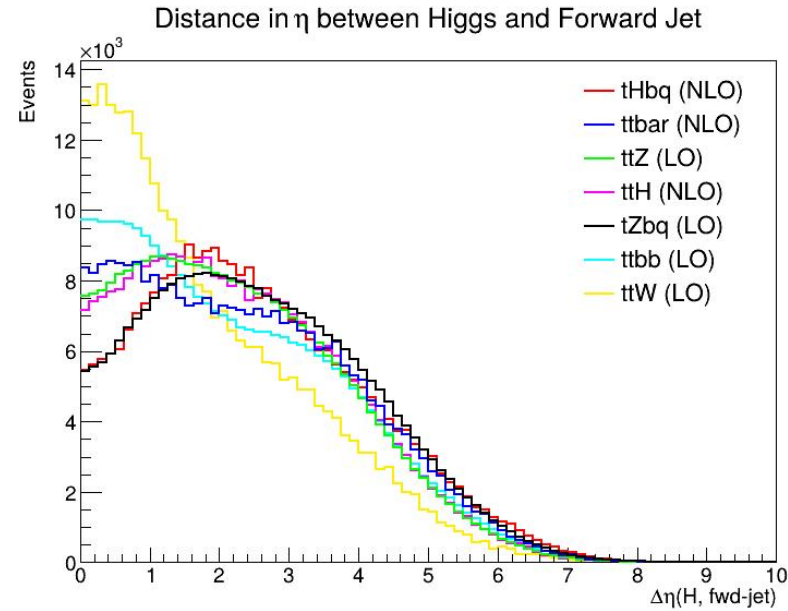
← Alternative search algorithm
(Tagging jet)



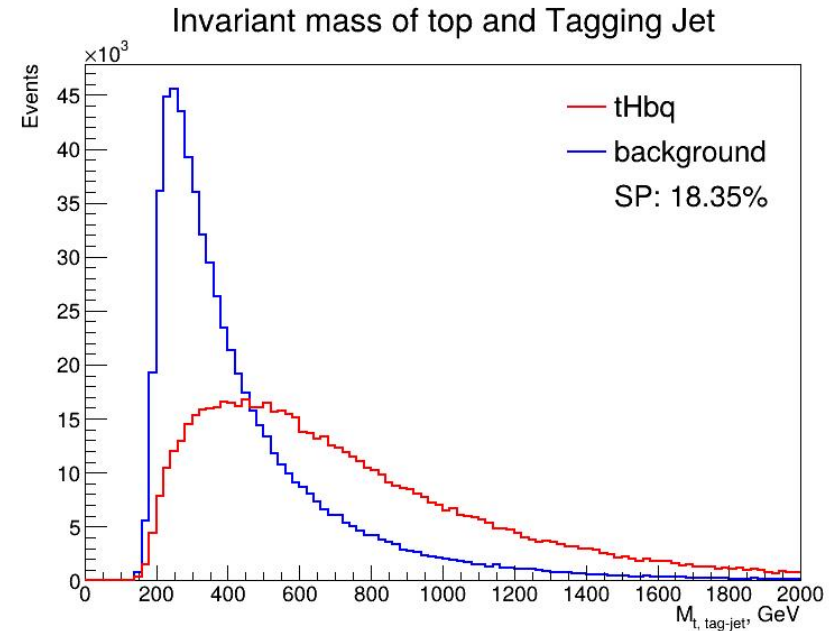
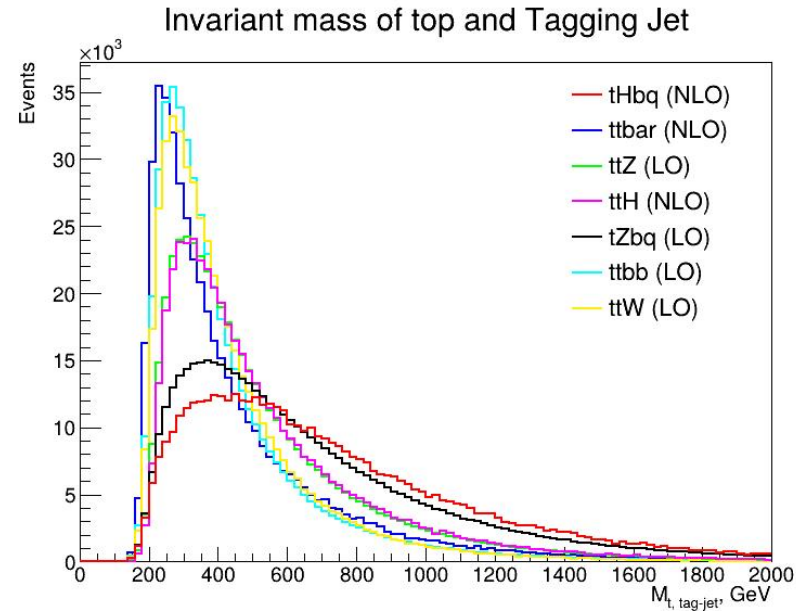
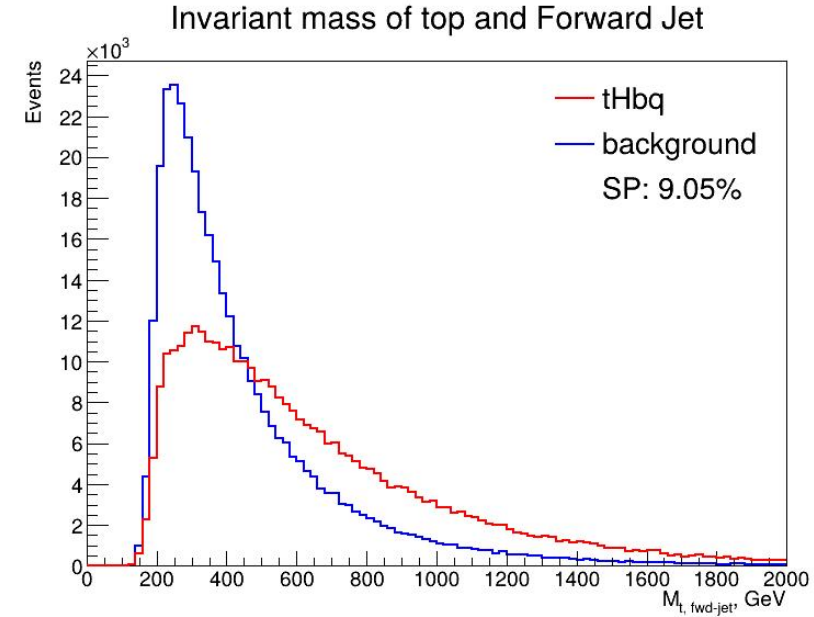
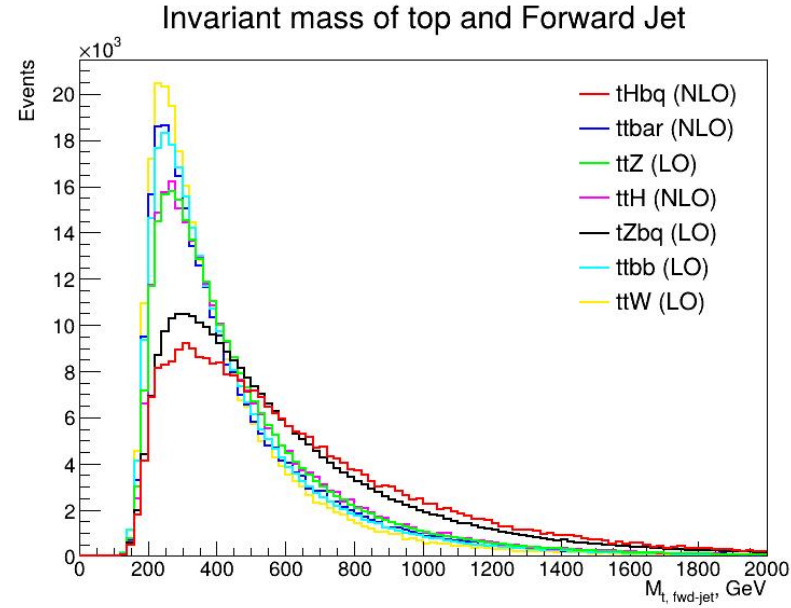
$|\Delta\eta|$ between top quark and Forward (Tagging) Jet for the signal and background processes



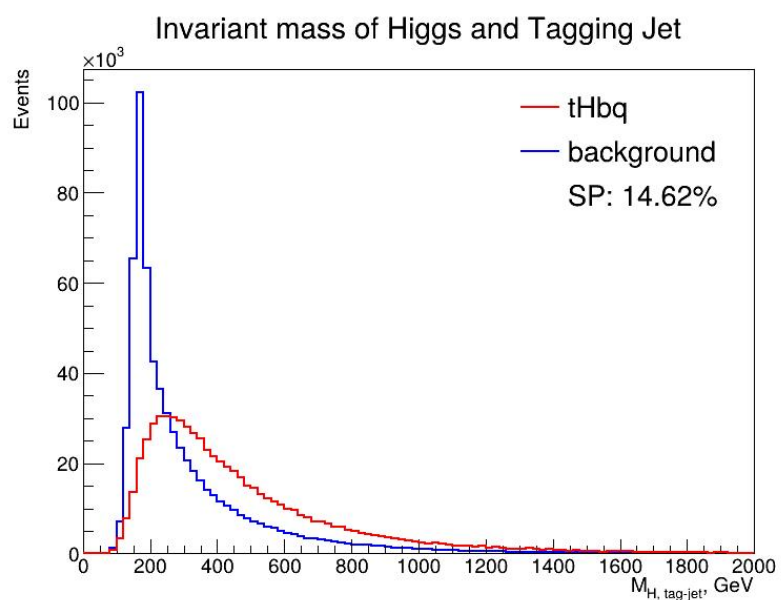
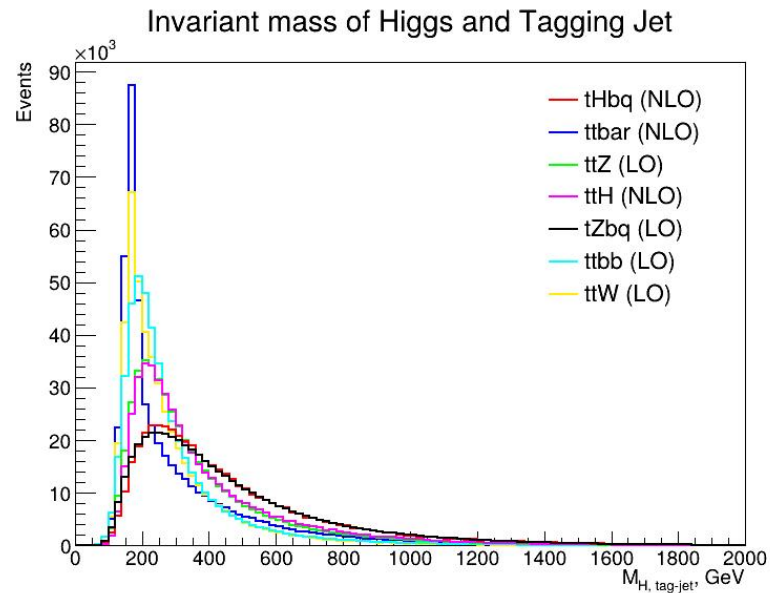
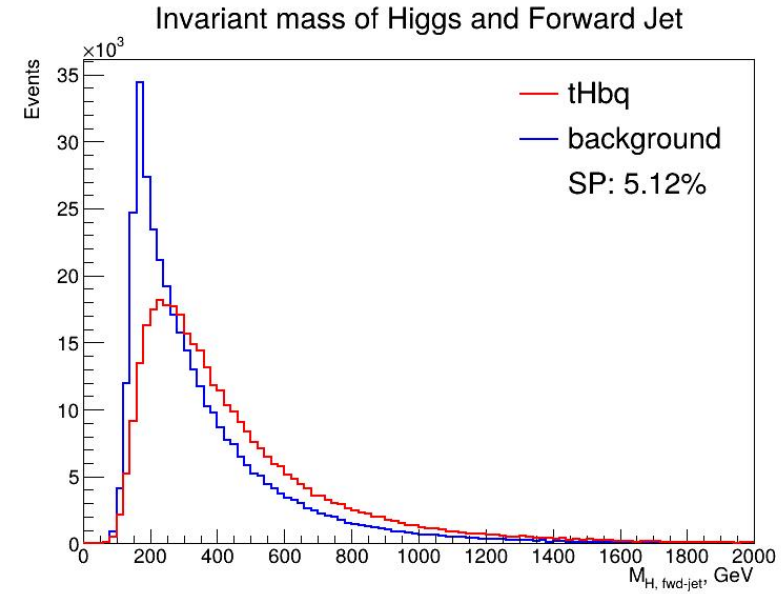
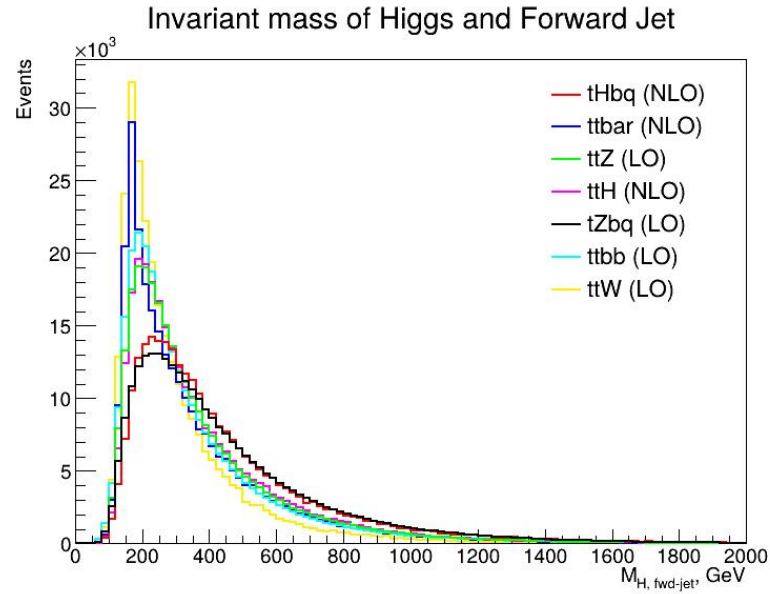
Distance in η between Higgs and Forward (Tagging) Jet for the signal and background processes



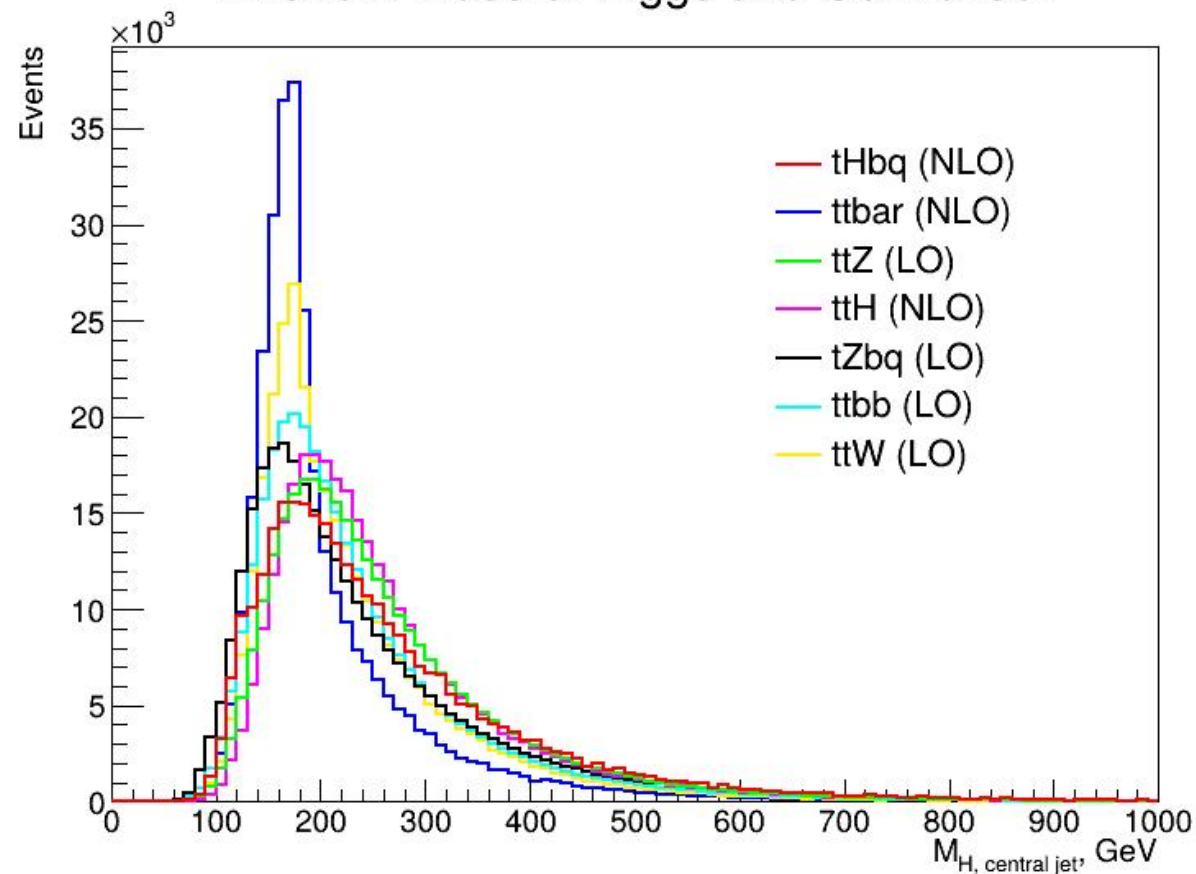
Invariant mass of Top-quark and Forward (Tagging) Jet for the signal and background processes



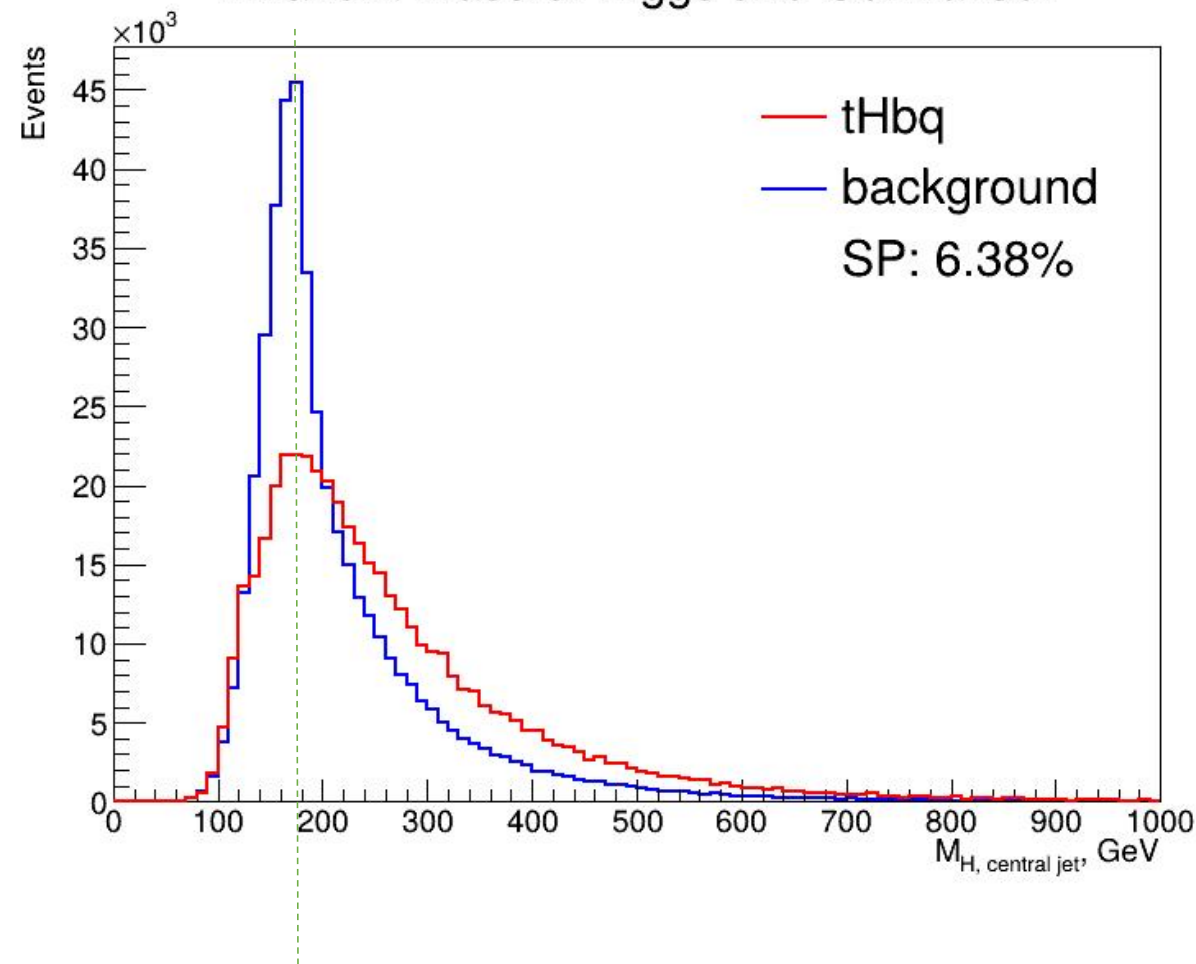
Invariant mass of Higgs and Forward (Tagging) Jet for the signal and background processes



Invariant mass of Higgs and Central Jet

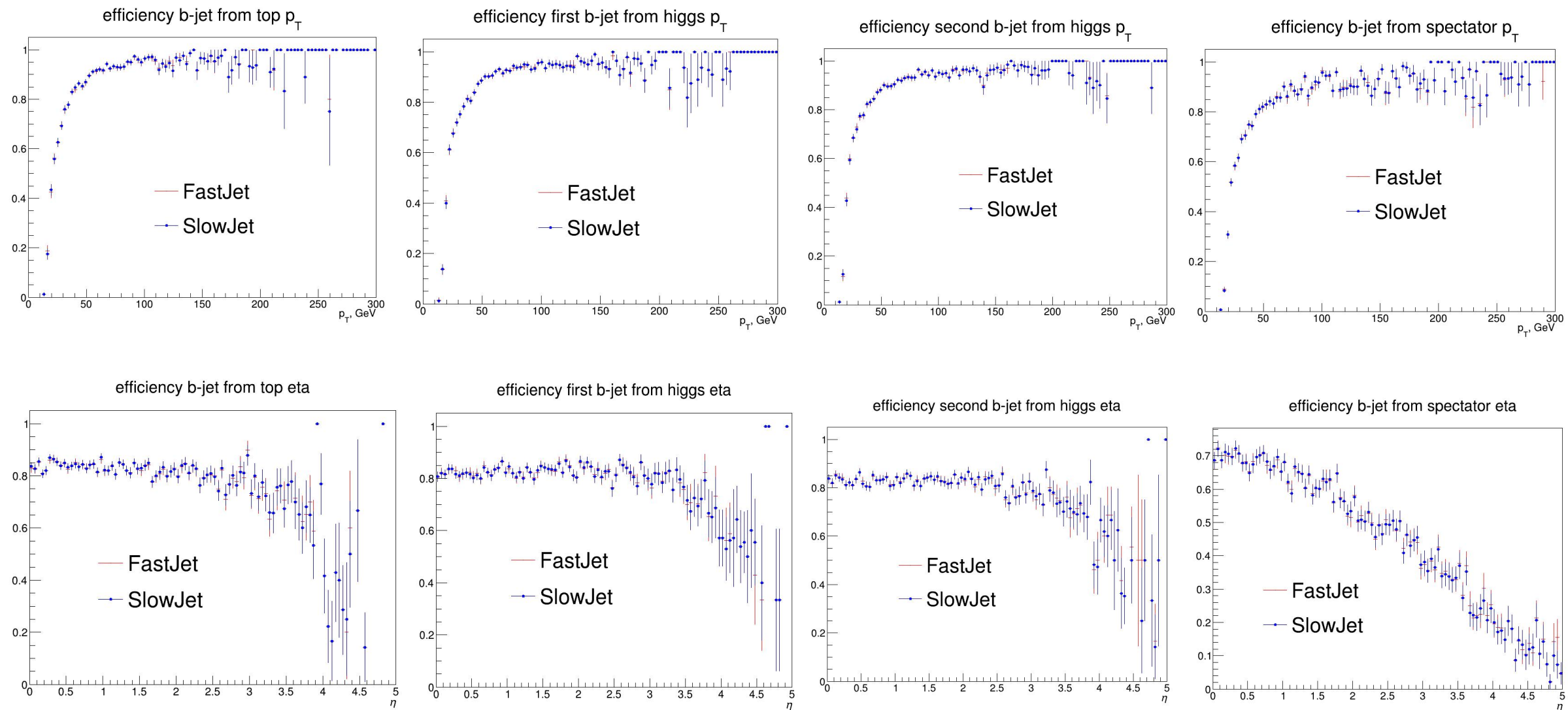


Invariant mass of Higgs and Central Jet

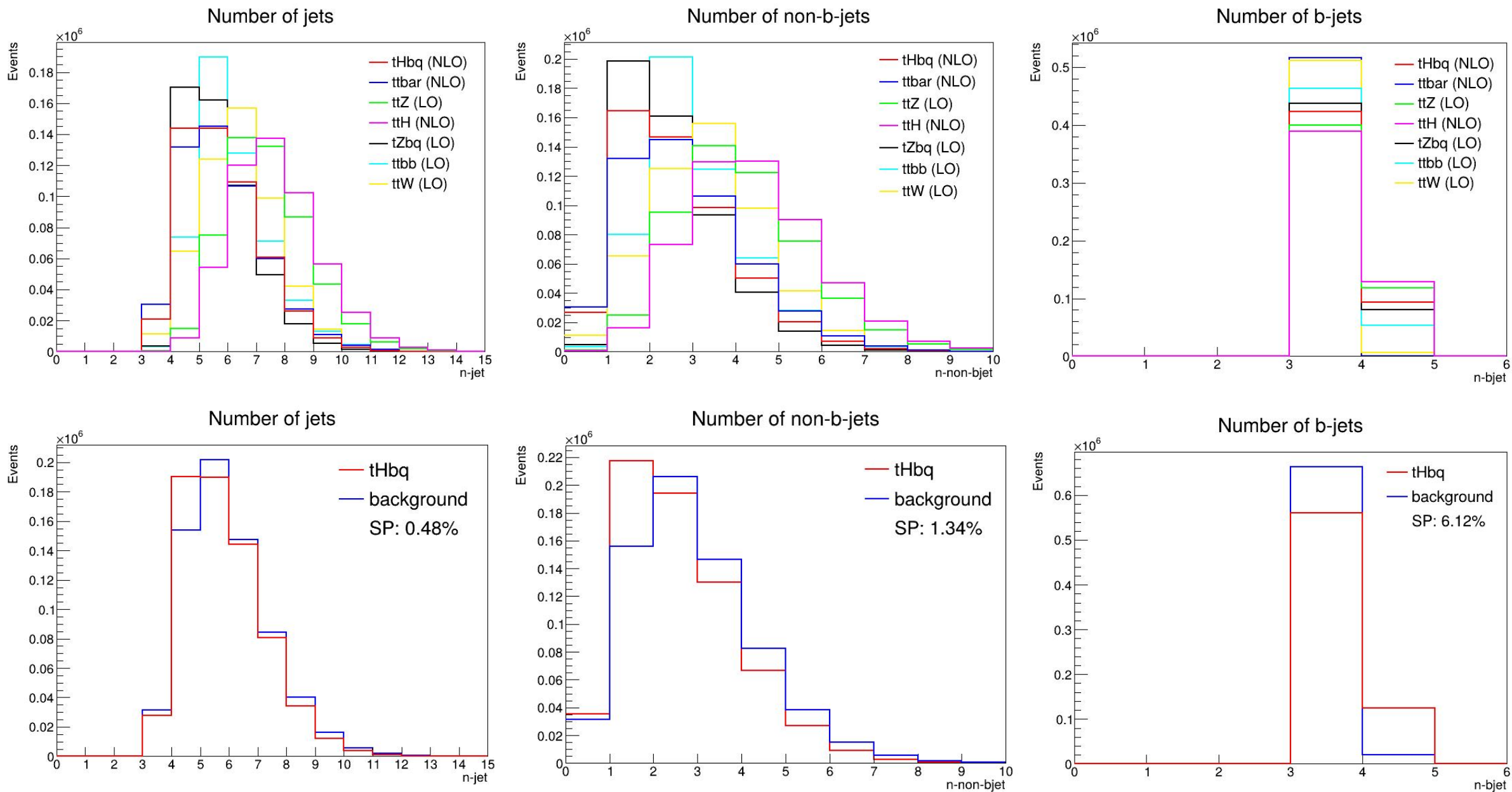


3) $|\eta^{\text{central jet}}| \leq 1.74$ with $\max p_T$

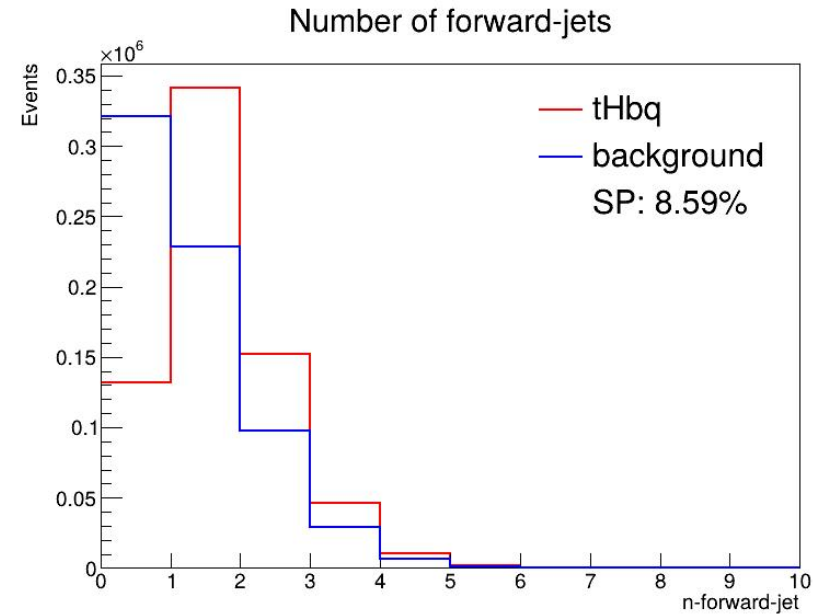
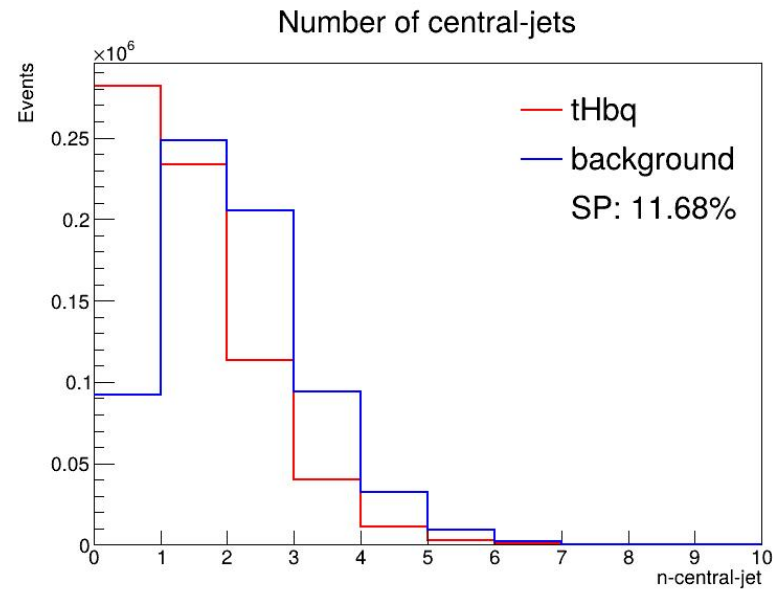
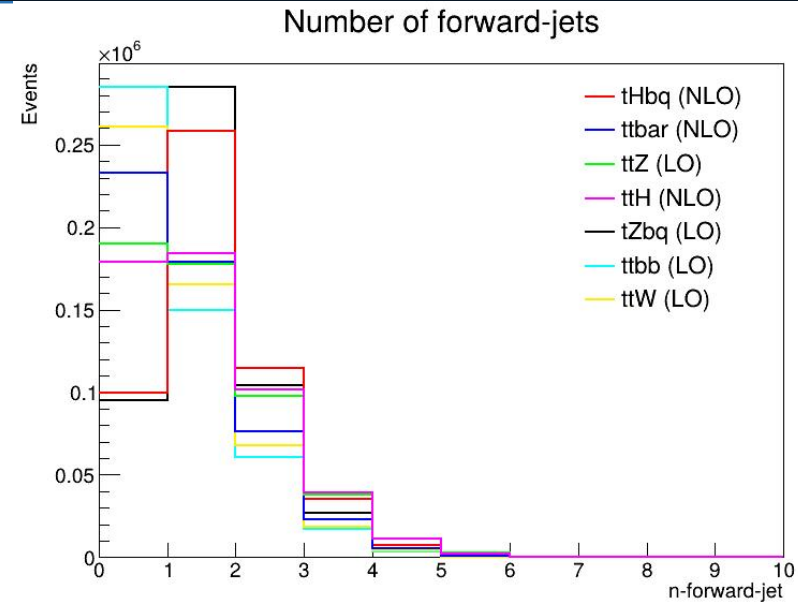
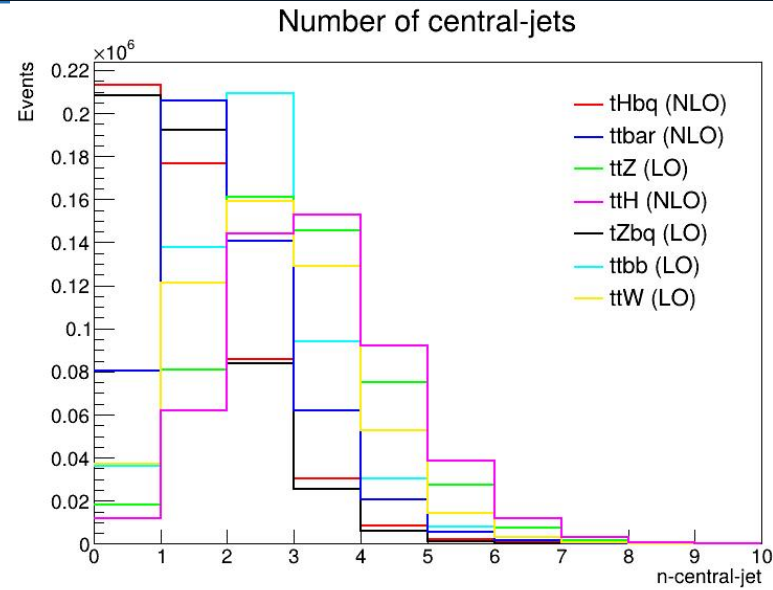
FastJet vs SlowJet



Number of jets for the signal and background processes



Number of central and forward jets



Aplanarity, spherisity and Fox-Wolfram Moments

$$M_{xyz} = \begin{pmatrix} p_{xi}^2 & p_{xi}p_{yi} & p_{xi}p_{zi} \\ p_{yi}p_{xi} & p_{yi}^2 & p_{yi}p_{zi} \\ p_{zi}p_{xi} & p_{zi}p_{yi} & p_{zi}^2 \end{pmatrix}$$

full momentum tensor

The individual eigenvalues are normalized and ordered such that

$$\lambda_1 > \lambda_2 > \lambda_3$$
$$\sum_i \lambda_i = 1$$

Fox-Wolfram Moments:

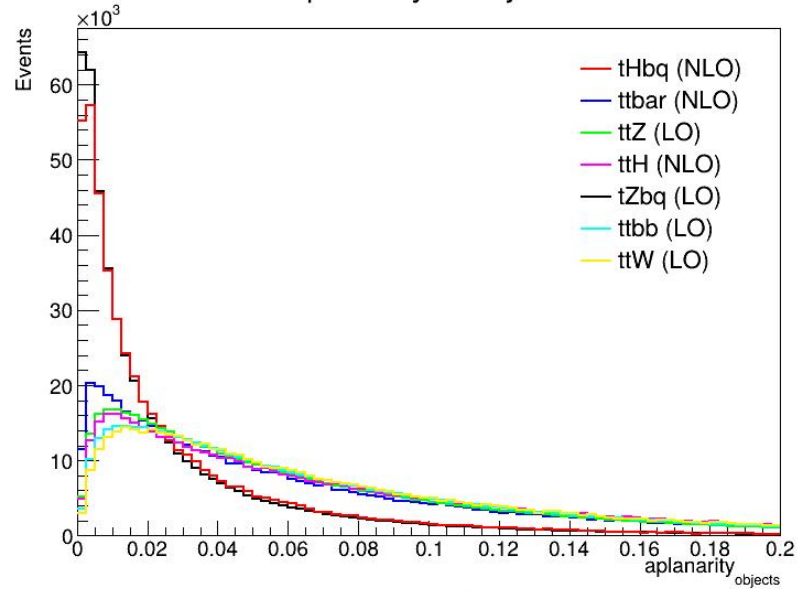
$$H_l = \frac{\sum_{ij} p_T^i p_T^j P_l(\cos \theta_{ij})}{(\sum_i p_T^i)^2}$$

$$\text{Spherisity: } S = \frac{3}{2}(\lambda_2 + \lambda_3)$$

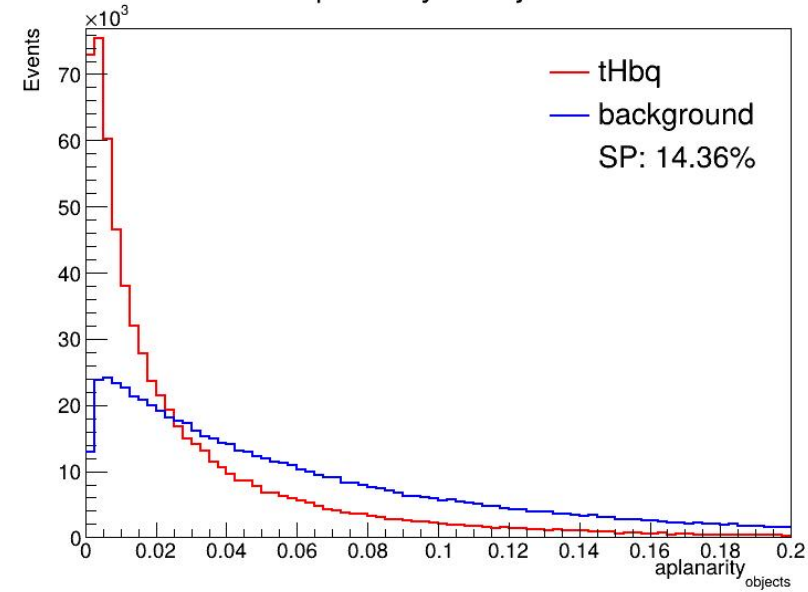
$$\text{Aplanarity: } A = \frac{3}{2}\lambda_3$$

Aplanarity for the signal and background processes

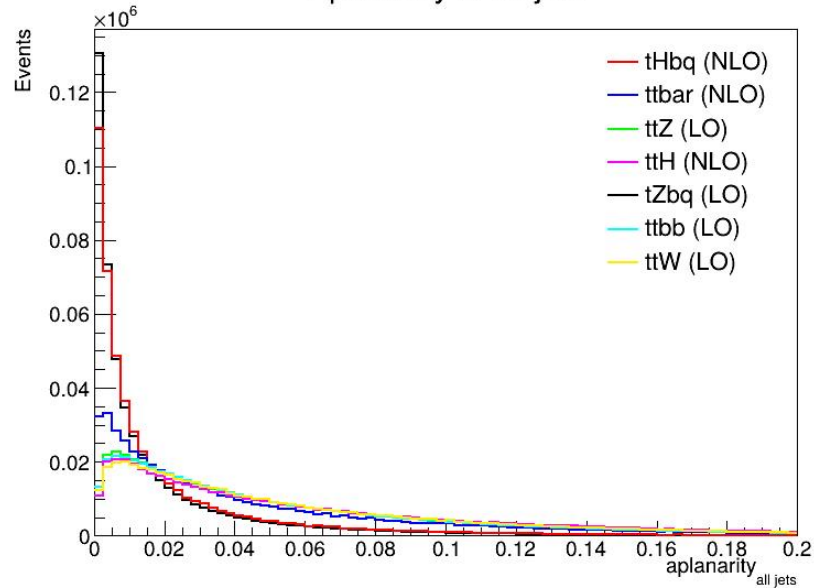
Aplanarity of objects



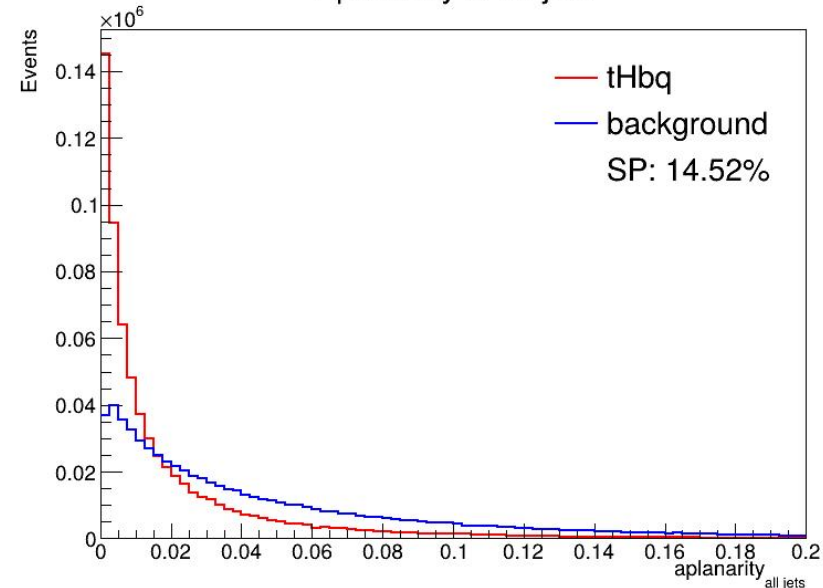
Aplanarity of objects



Aplanarity of all jets

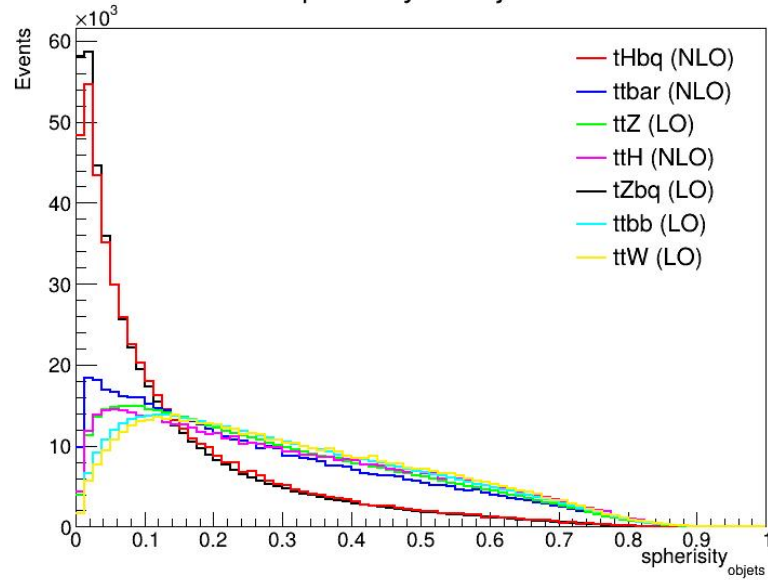


Aplanarity of all jets

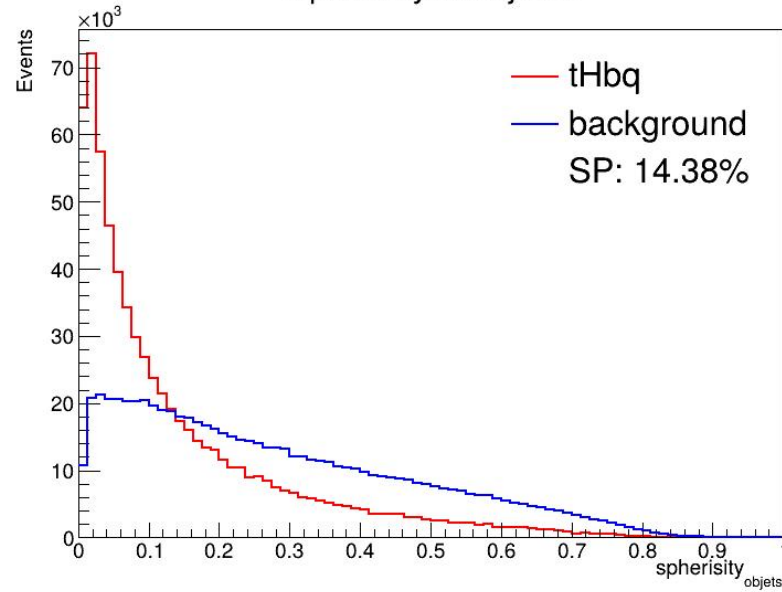


Sphericity for the signal and background processes

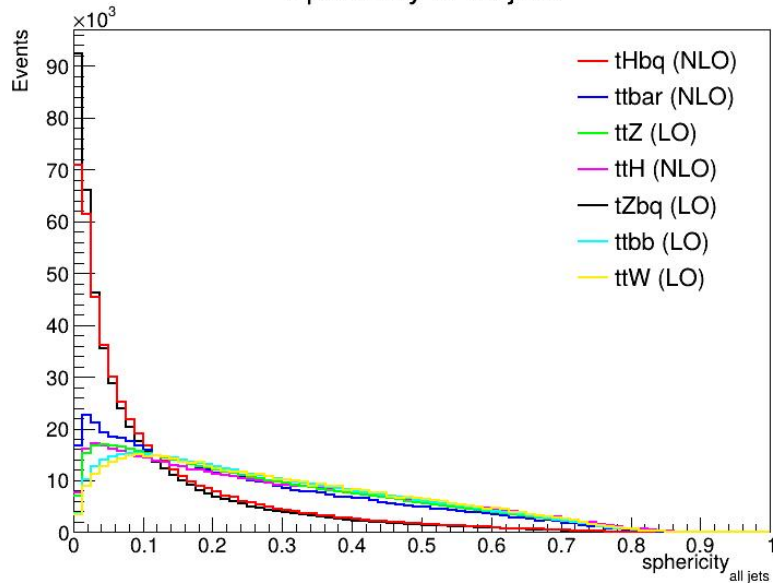
Sphericity of objects



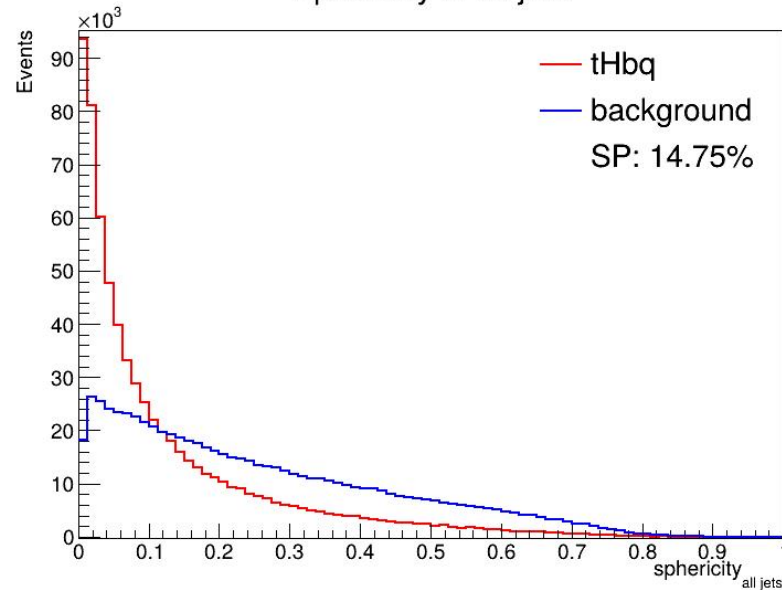
Sphericity of objects



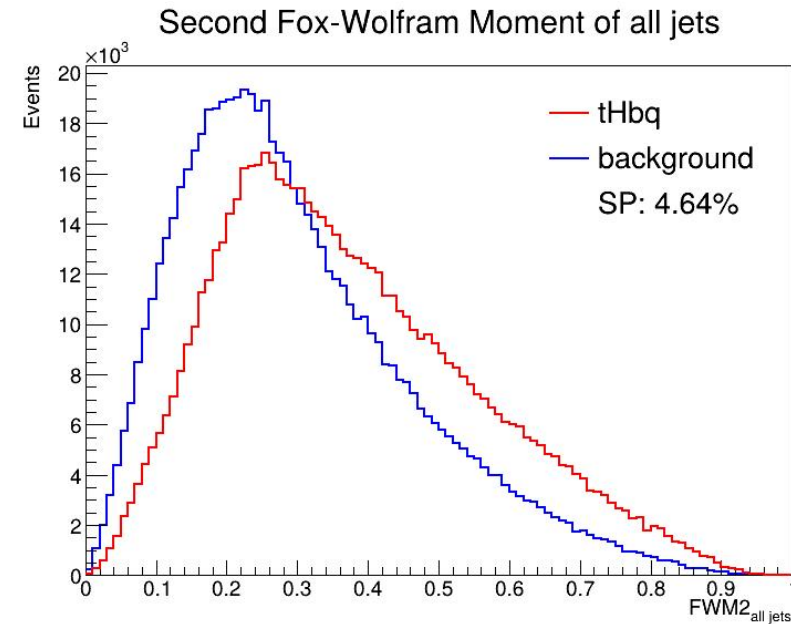
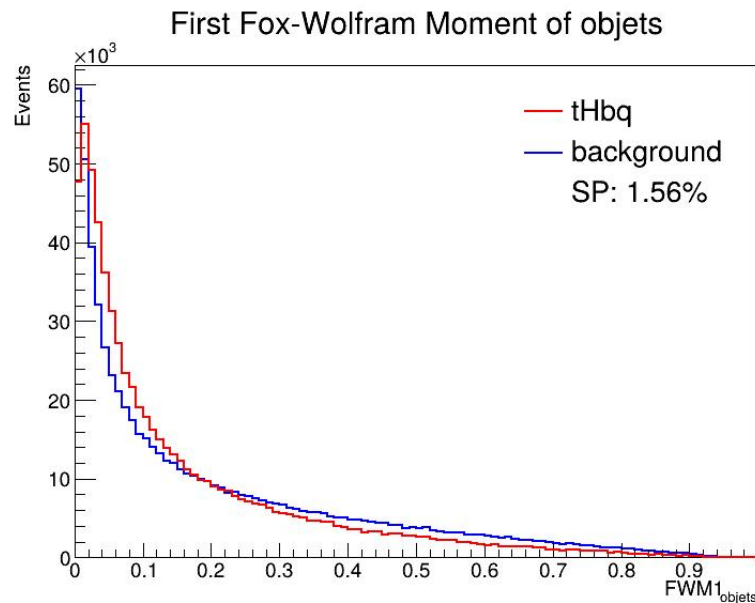
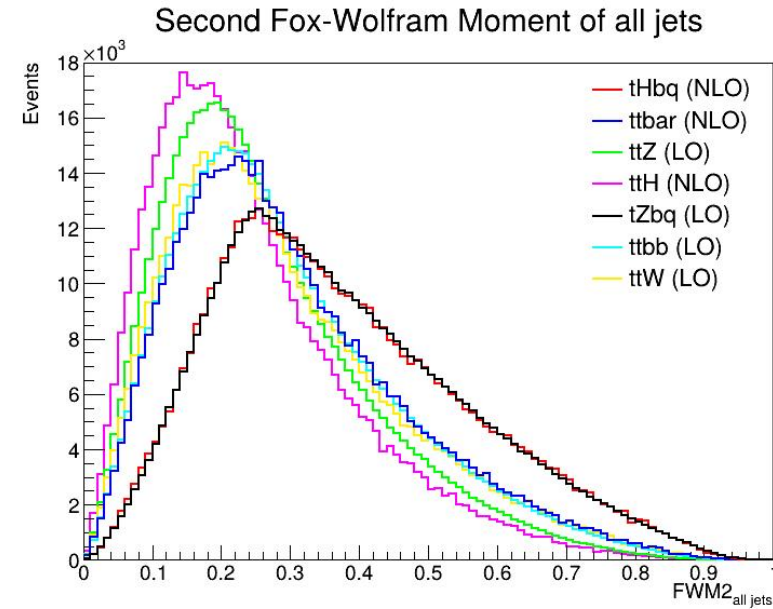
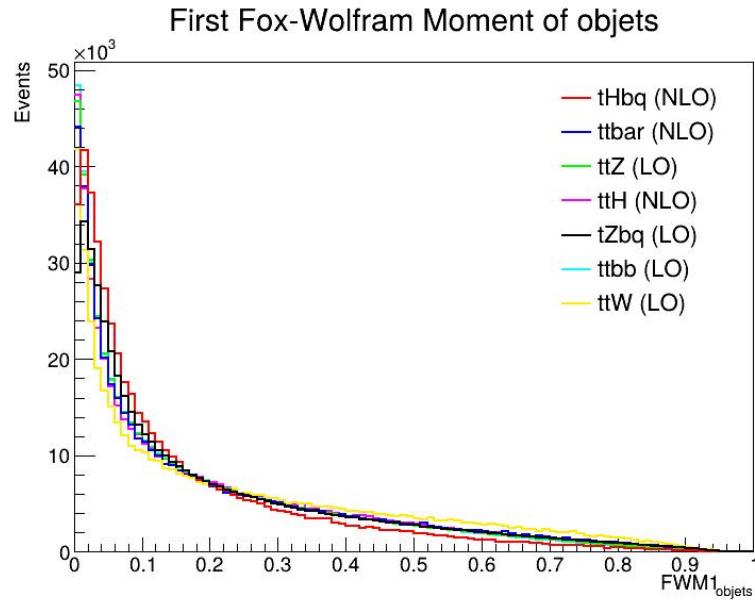
Sphericity of all jets



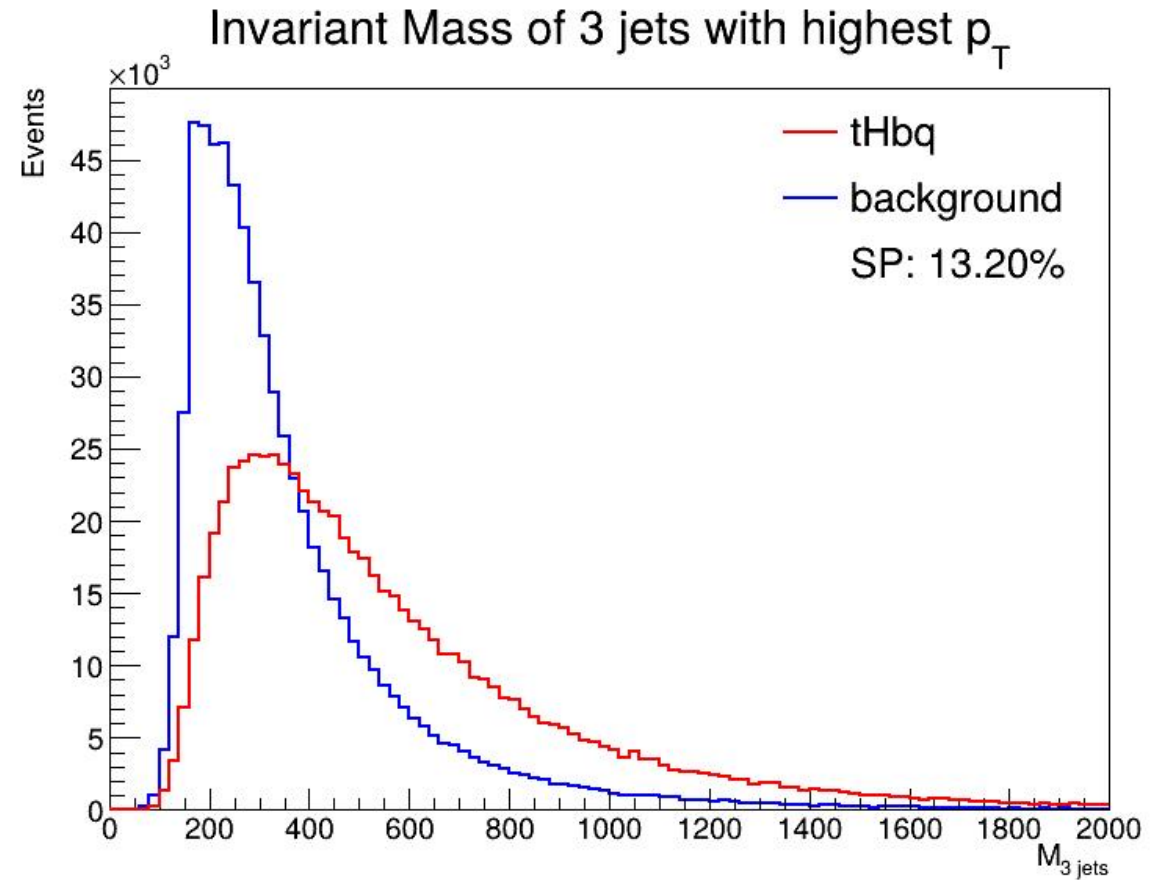
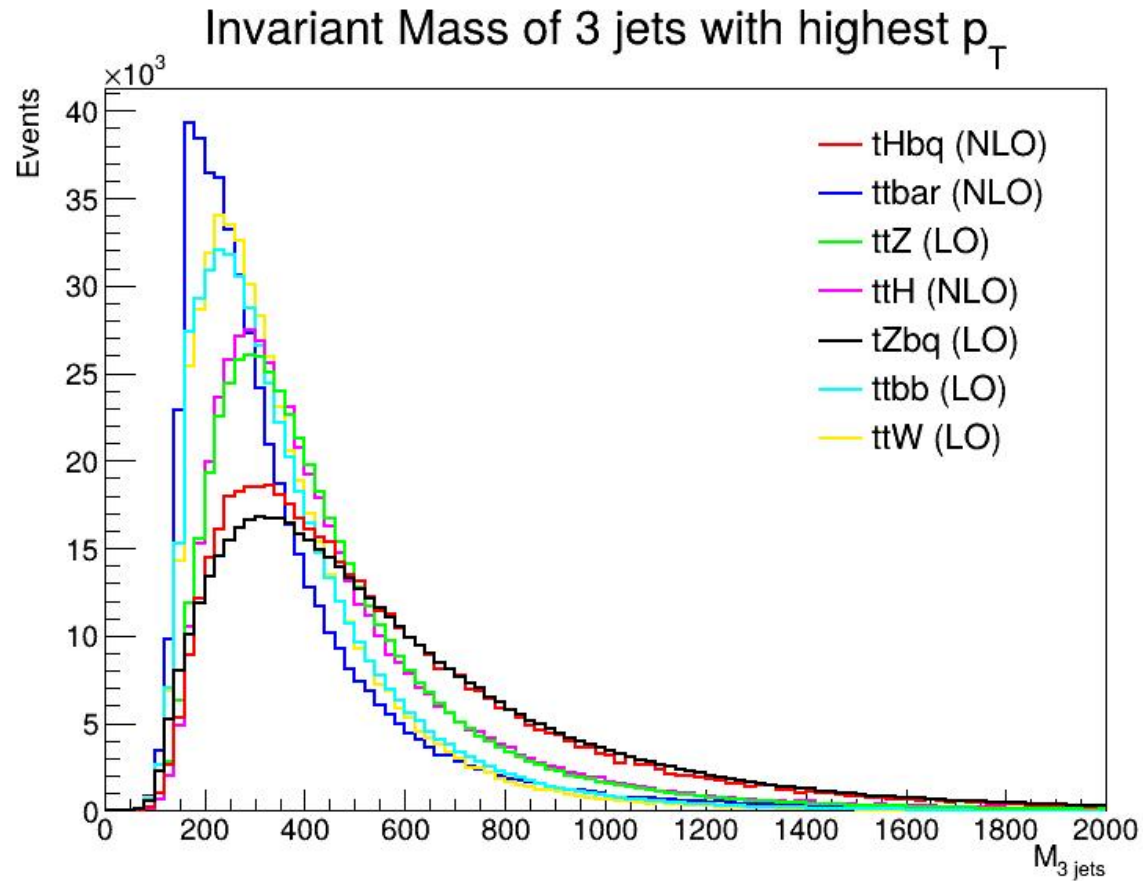
Sphericity of all jets



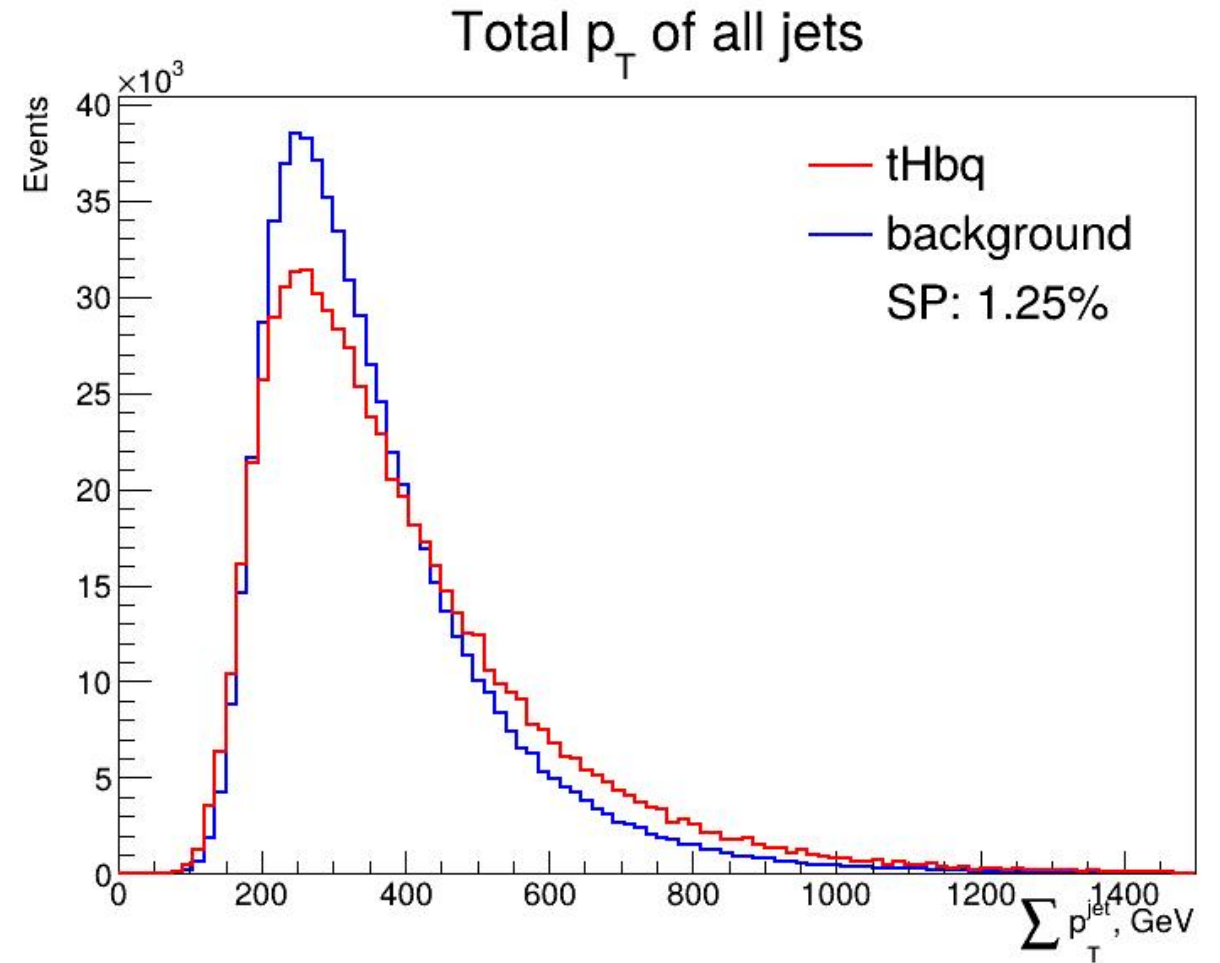
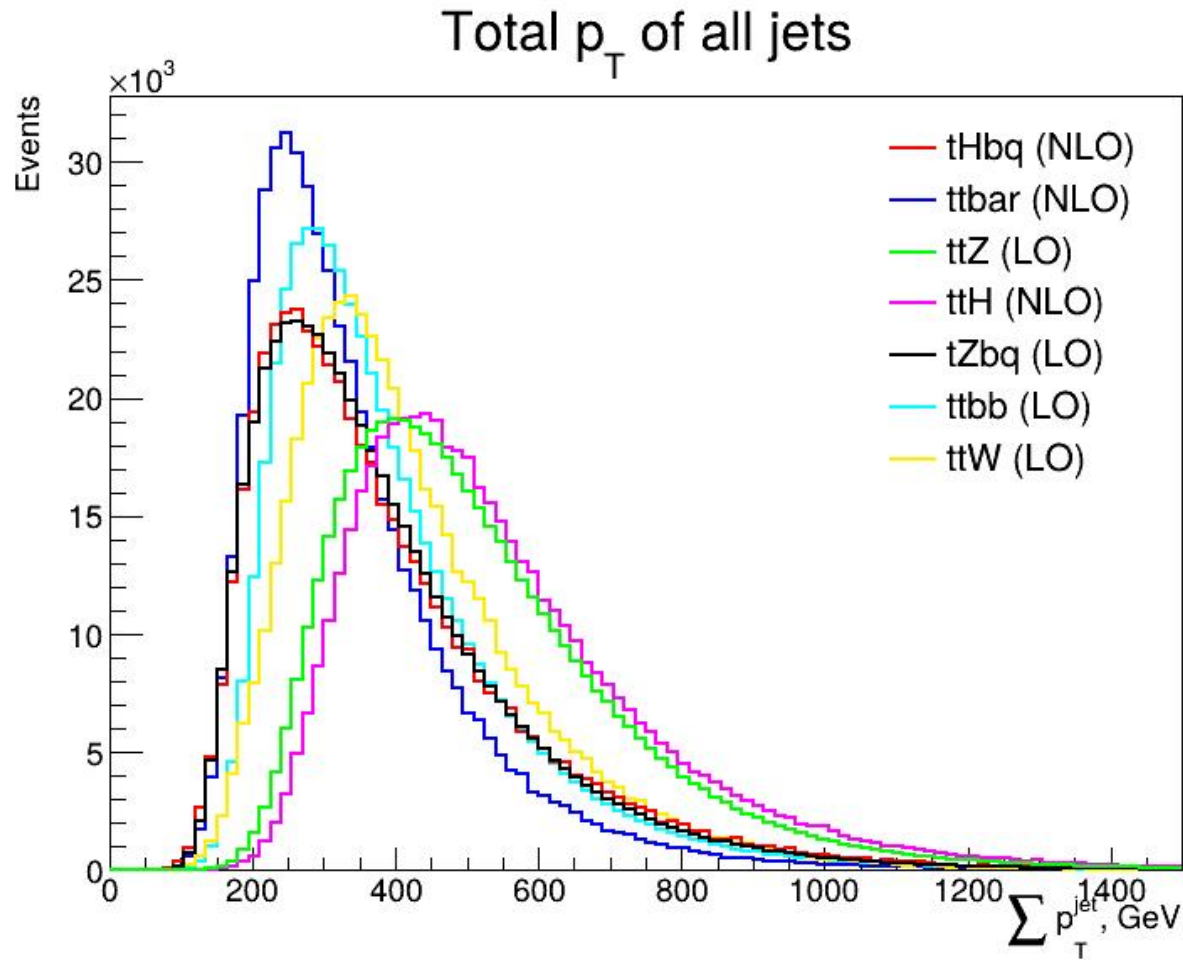
First and Second Fox-Wolfram moment for the signal and background processes



Invariant mass of 3 jets with highest p_T for the signal and background processes

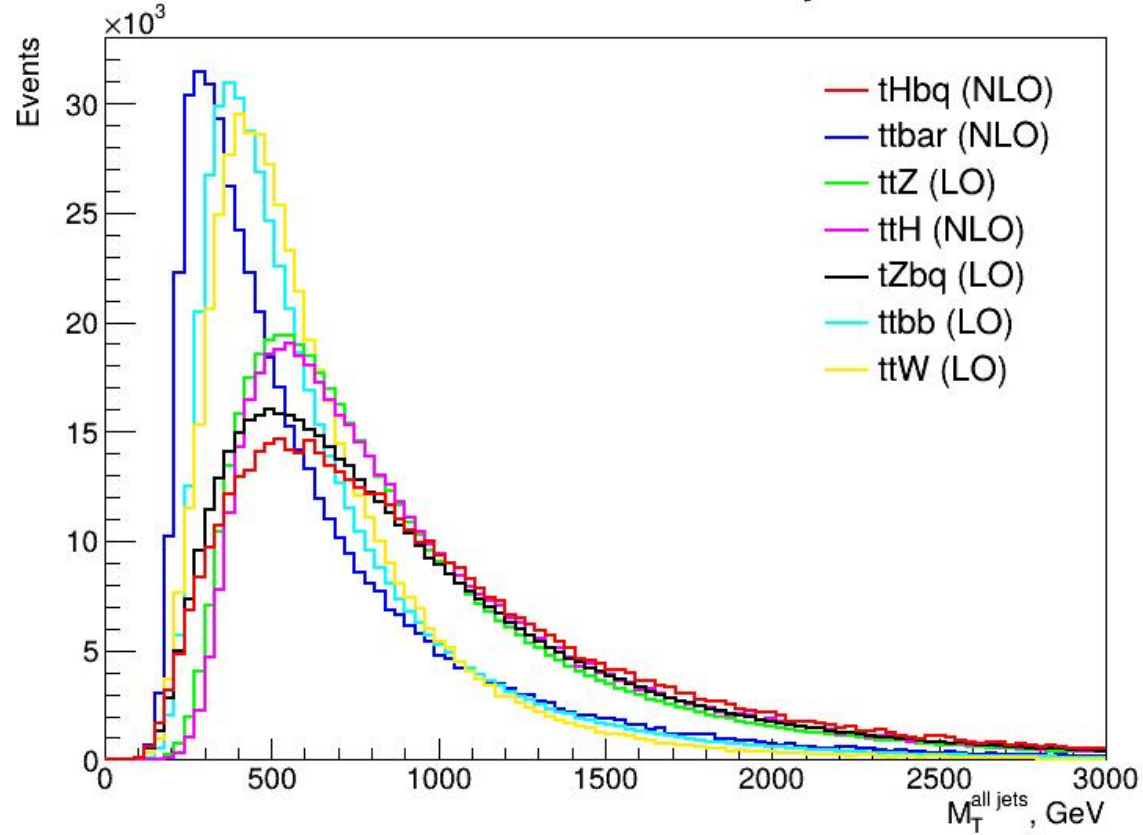


Total p_T of all jets for the signal and background processes

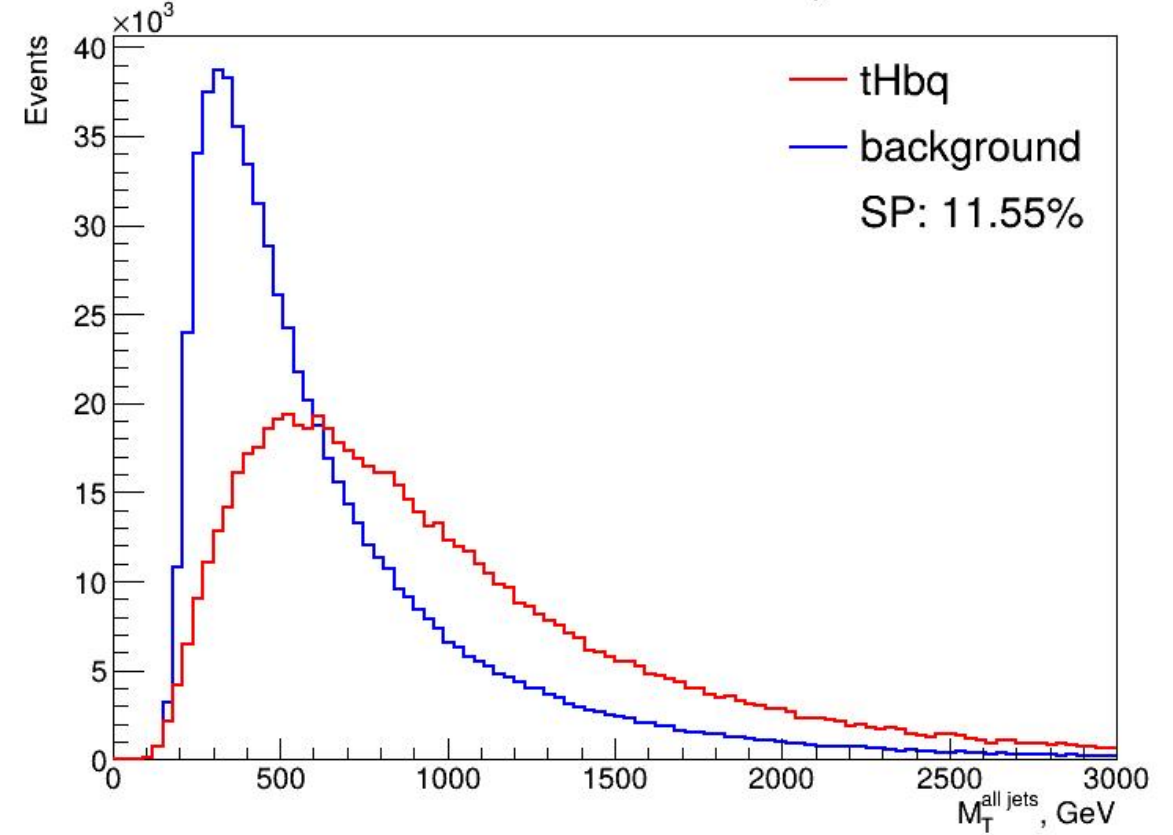


Transverse mass of all jets for the signal and background processes

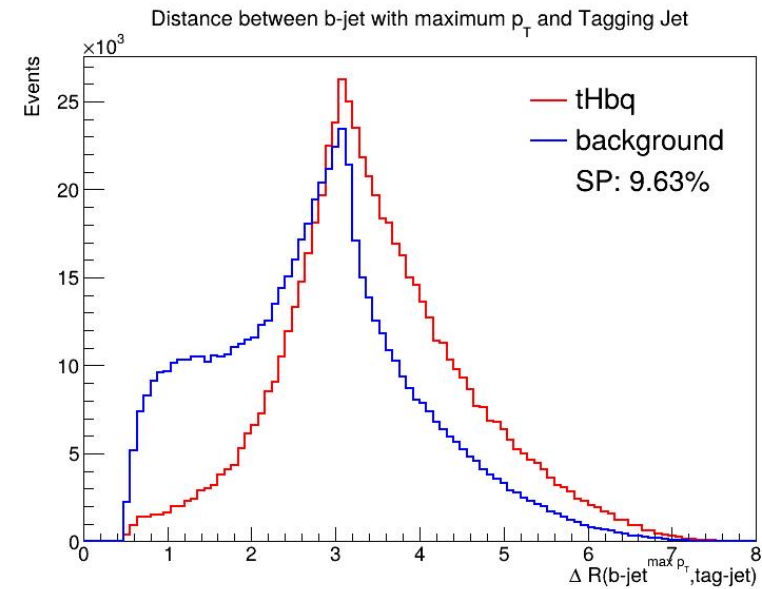
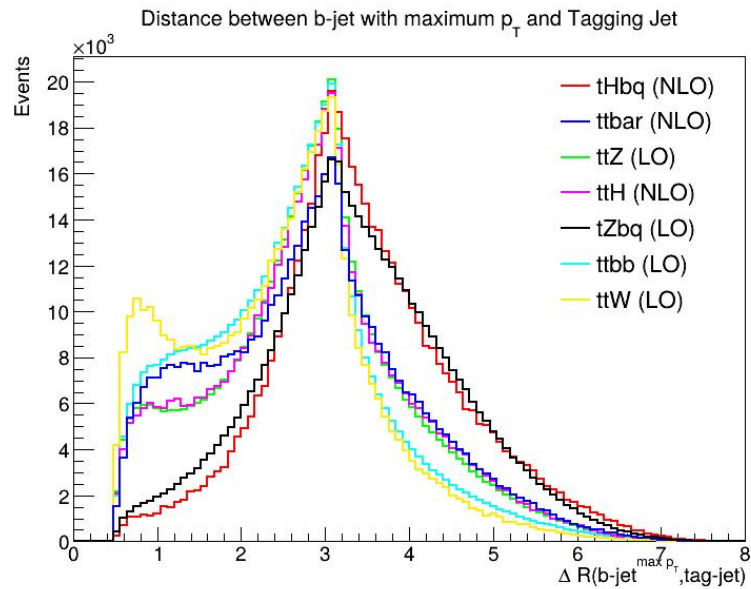
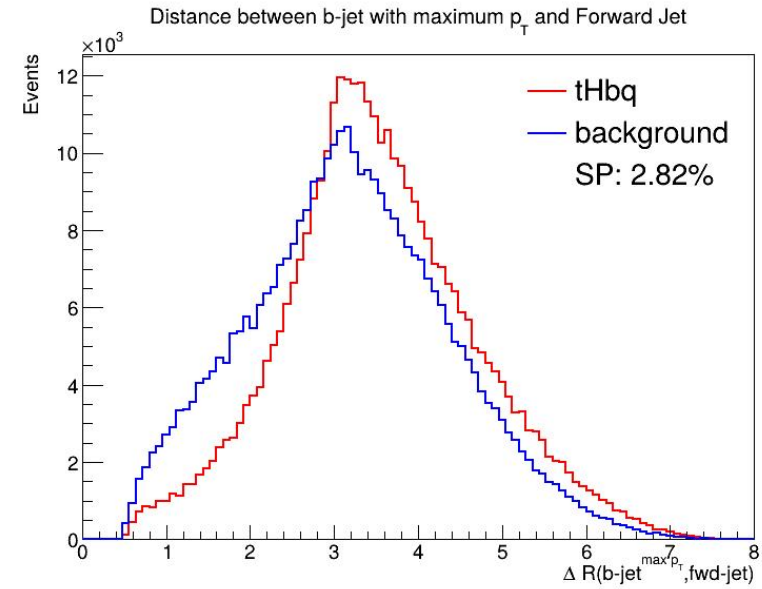
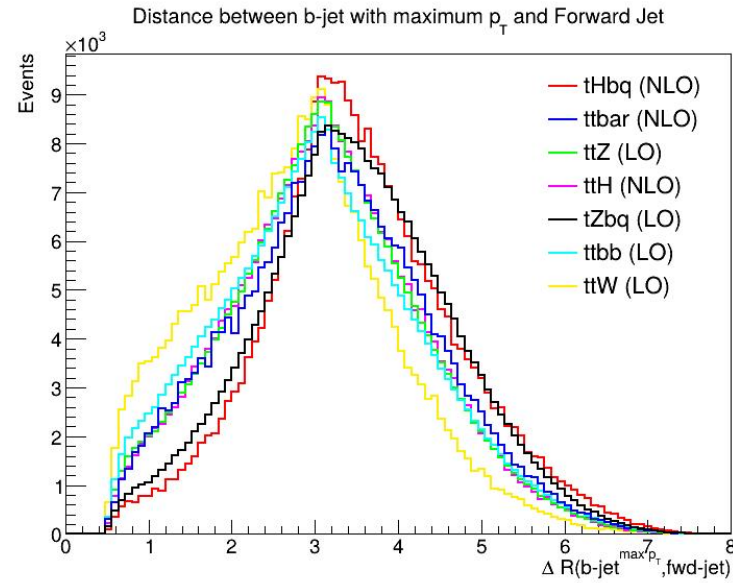
Transverse mass of all jets



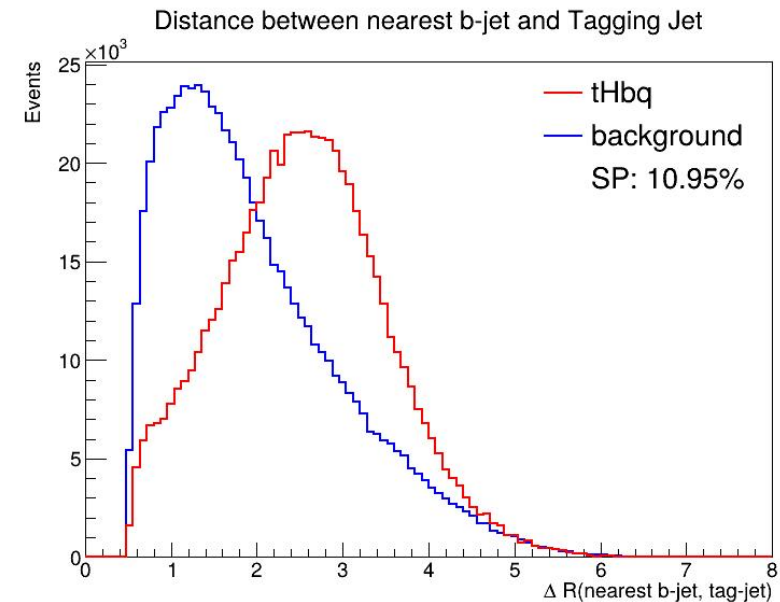
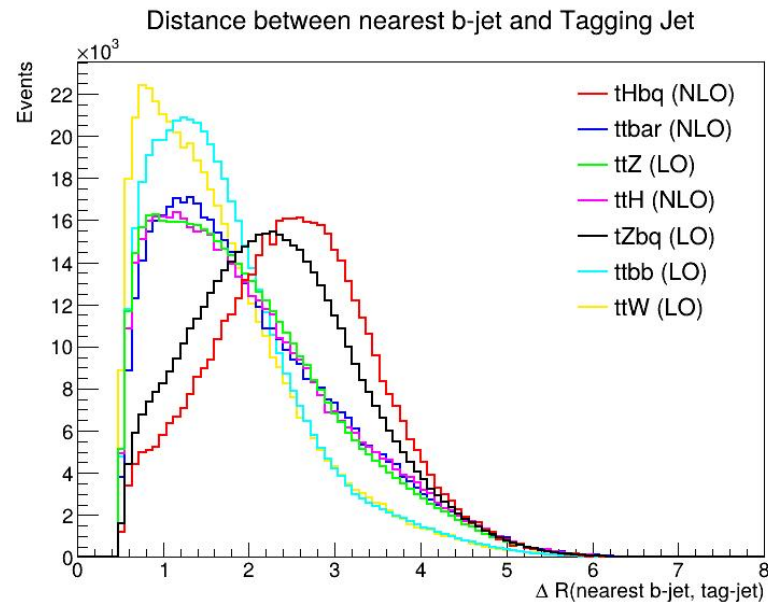
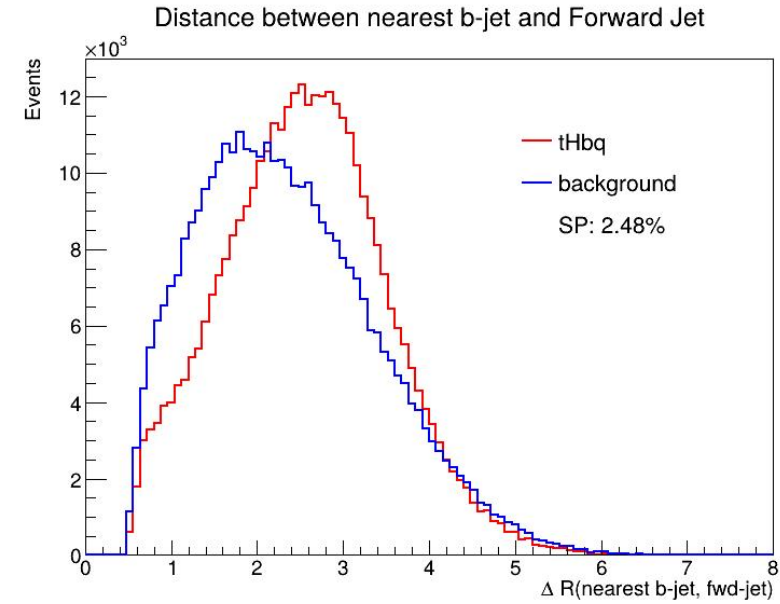
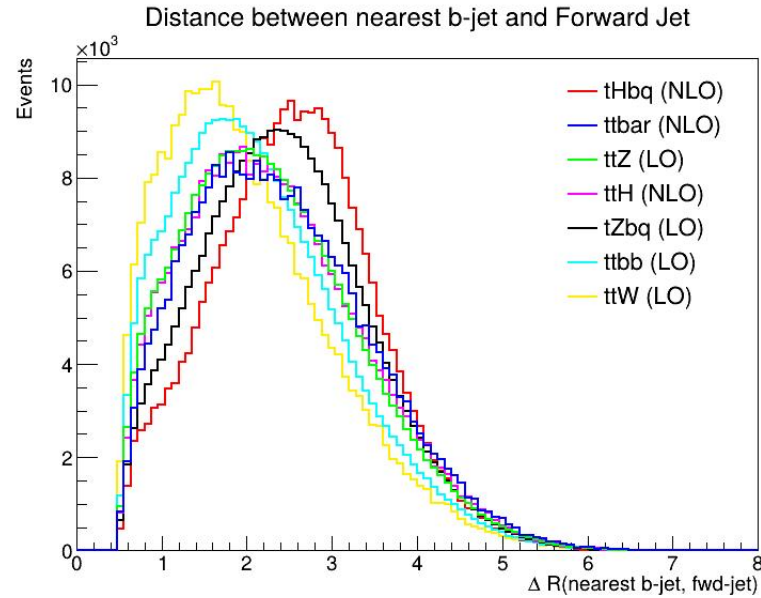
Transverse mass of all jets



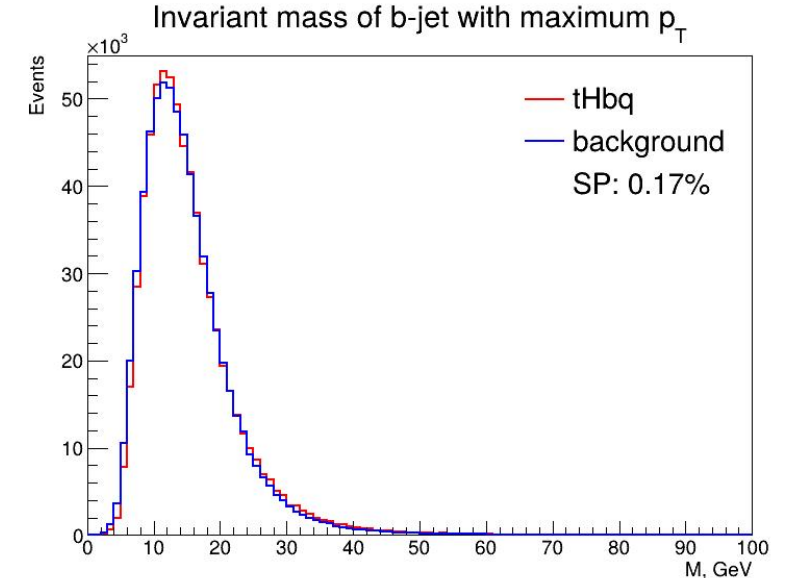
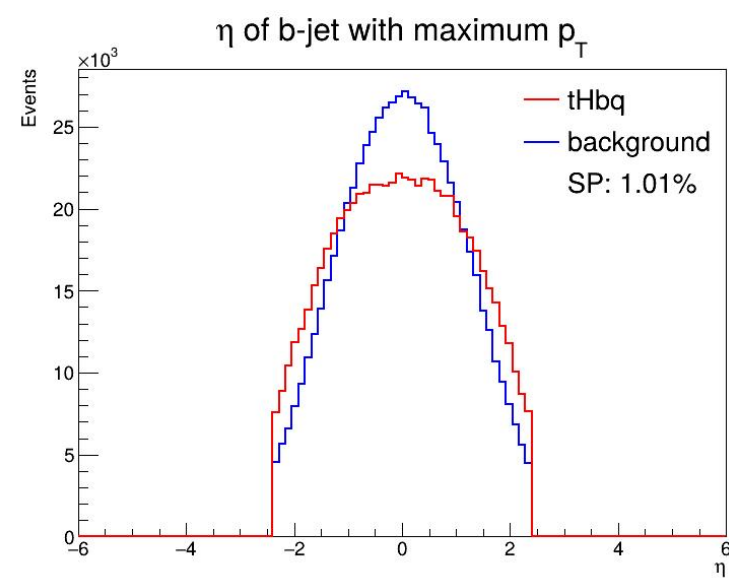
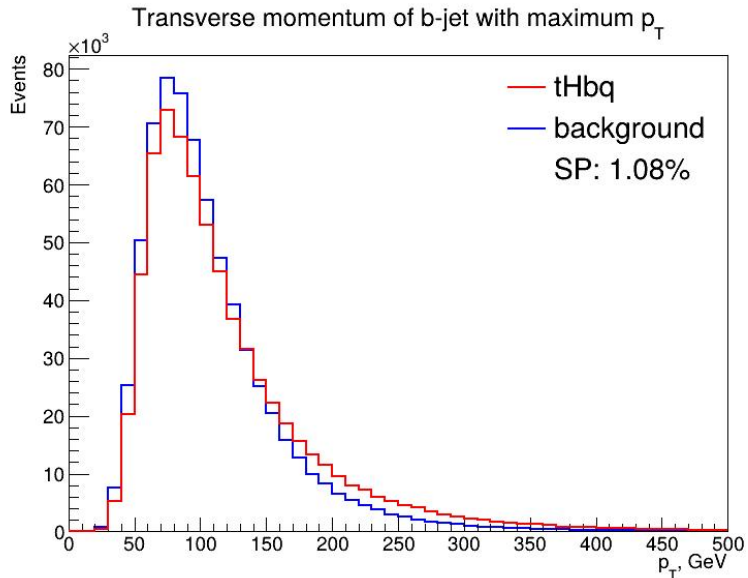
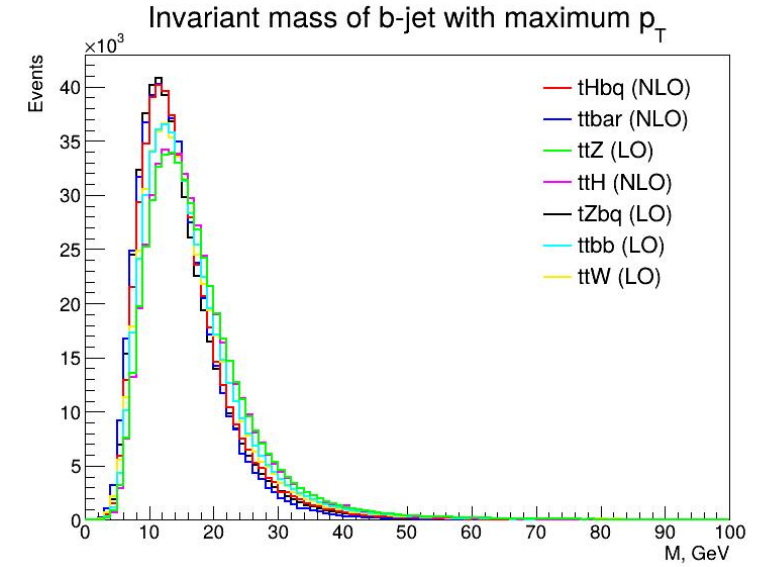
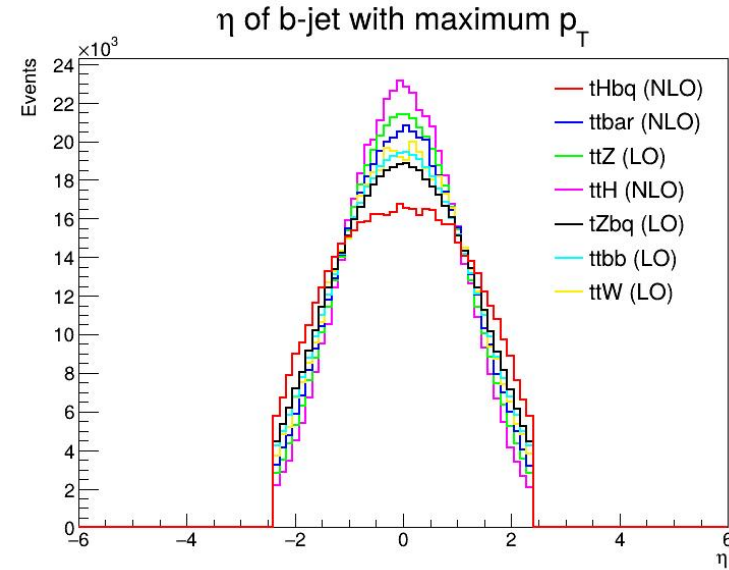
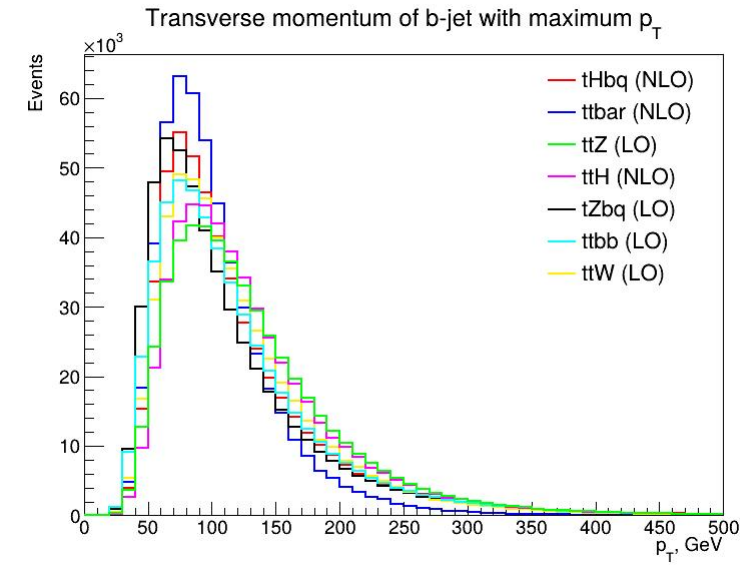
Distance between b-jet with maximum p_T and Forward (Tagging) Jet for the signal and background processes



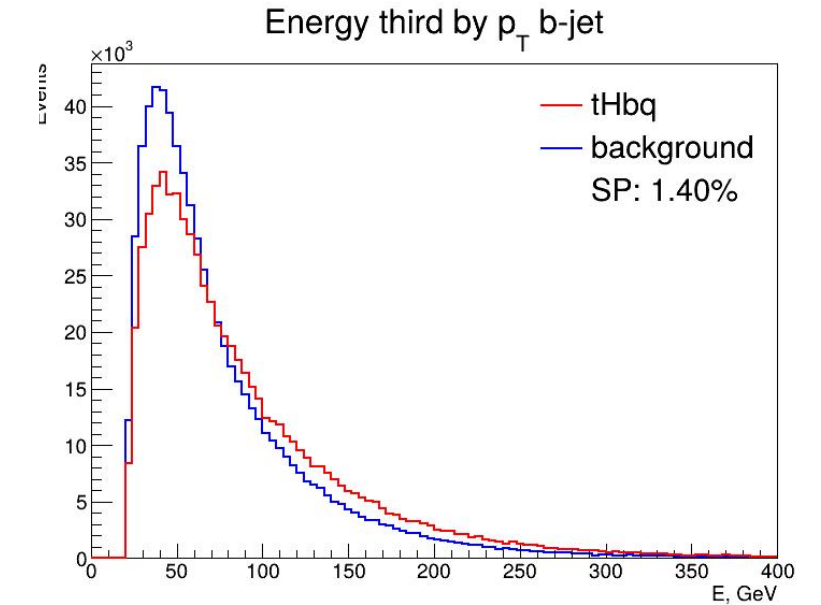
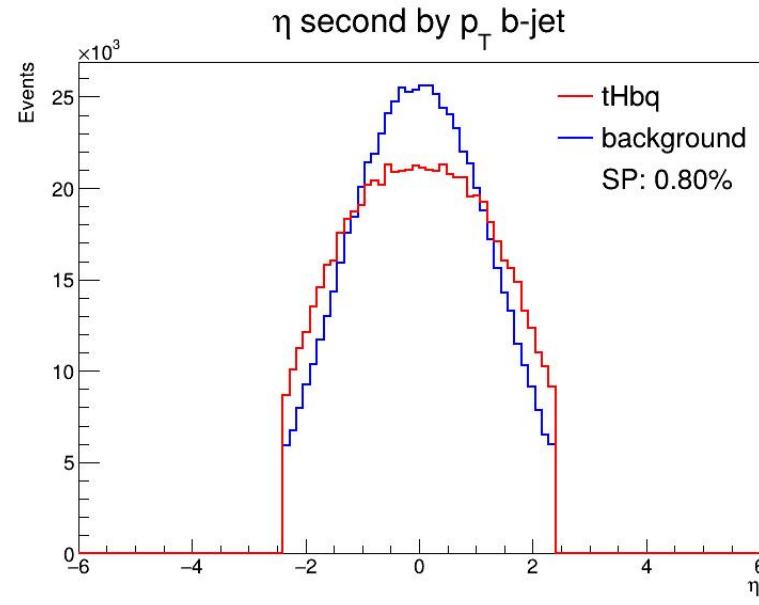
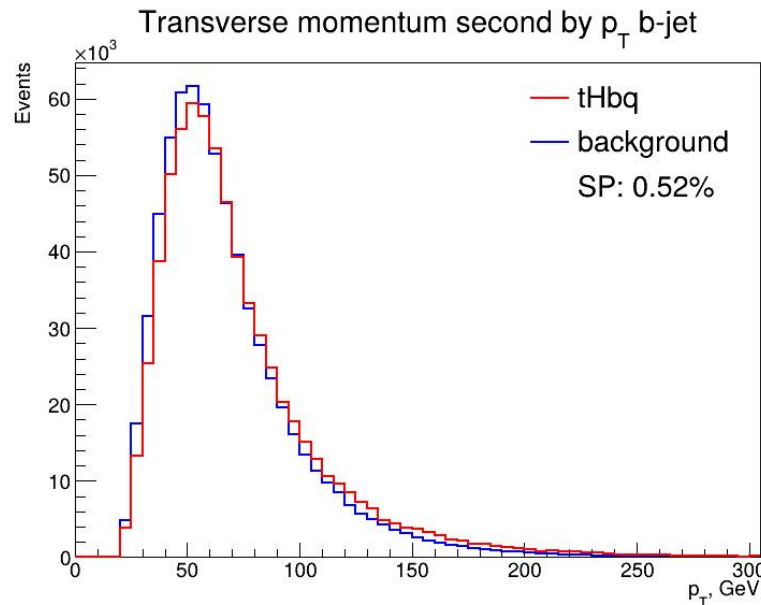
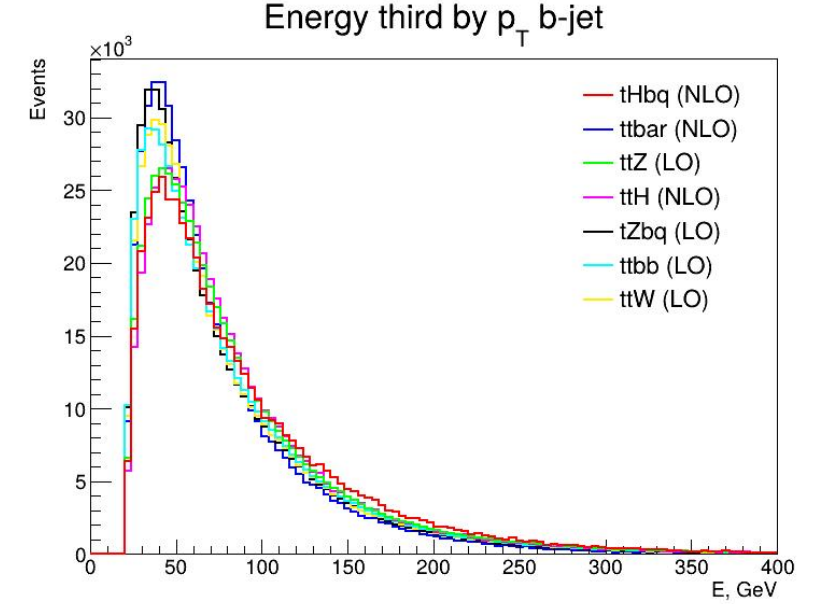
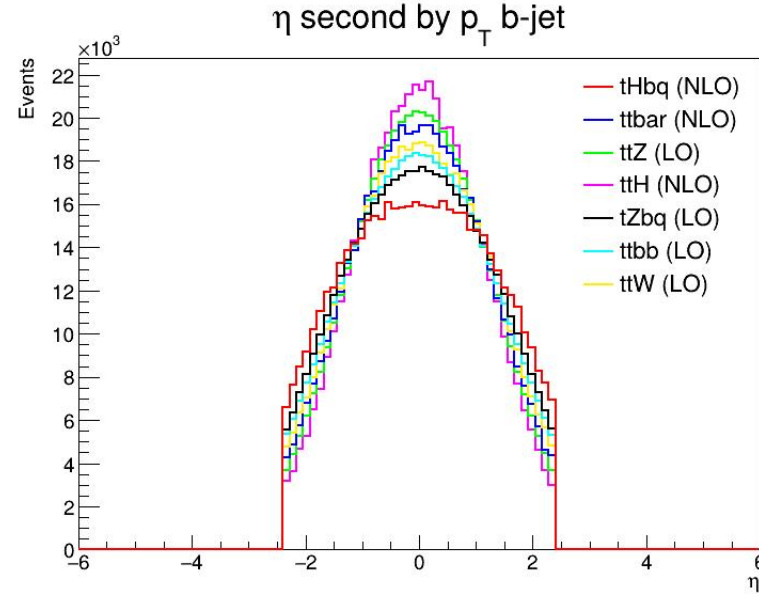
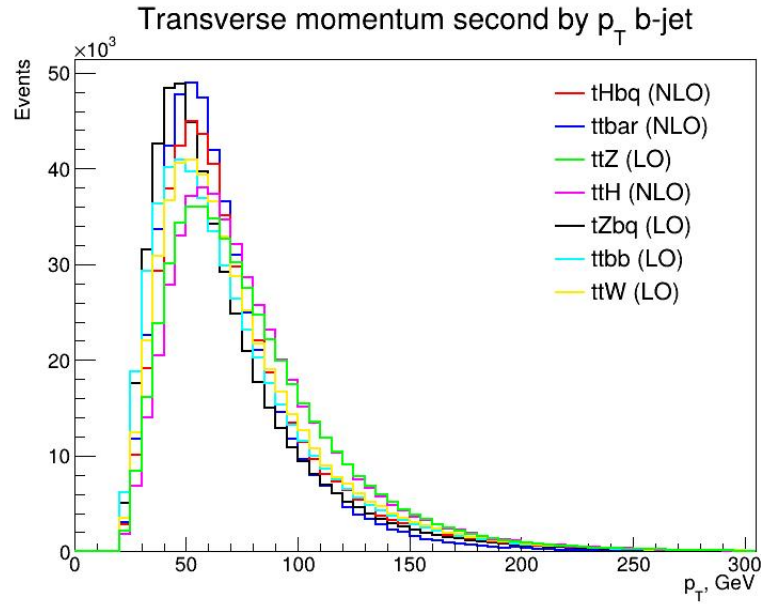
Distance between nearest b-jet and Forward (Tagging) Jet for the signal and background processes



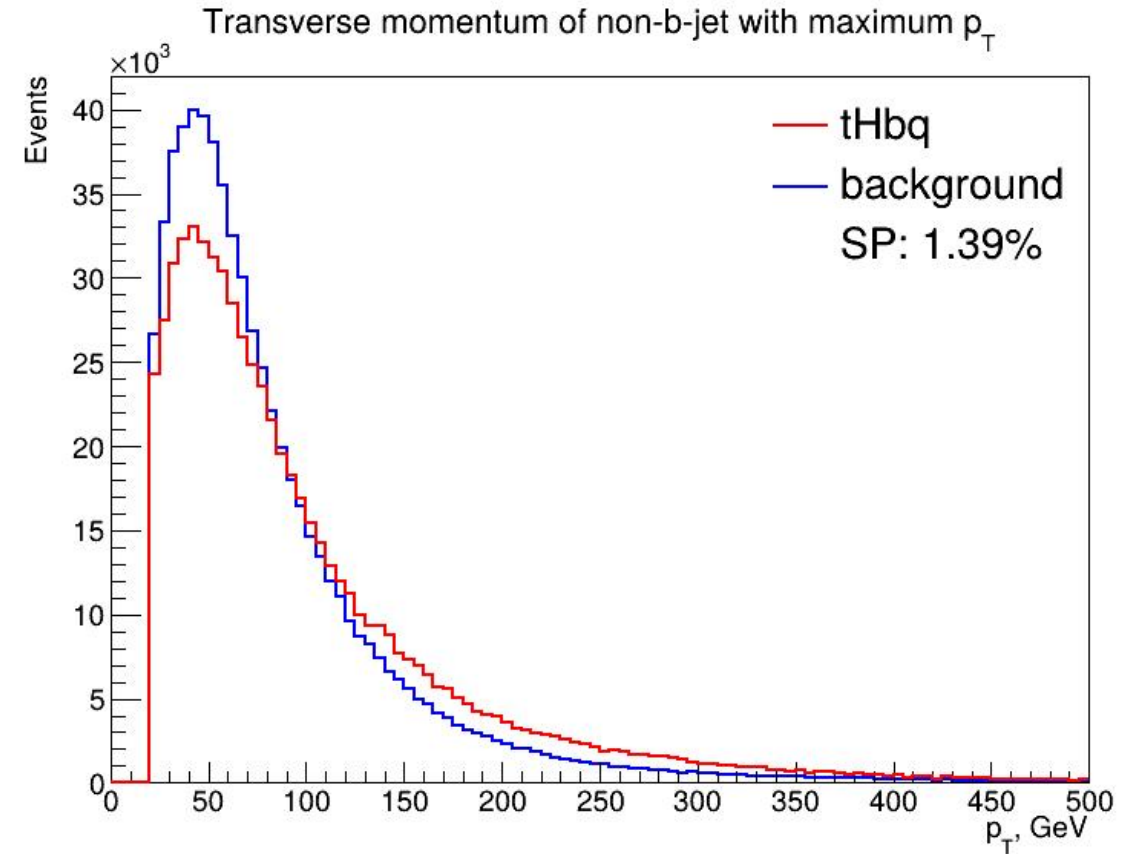
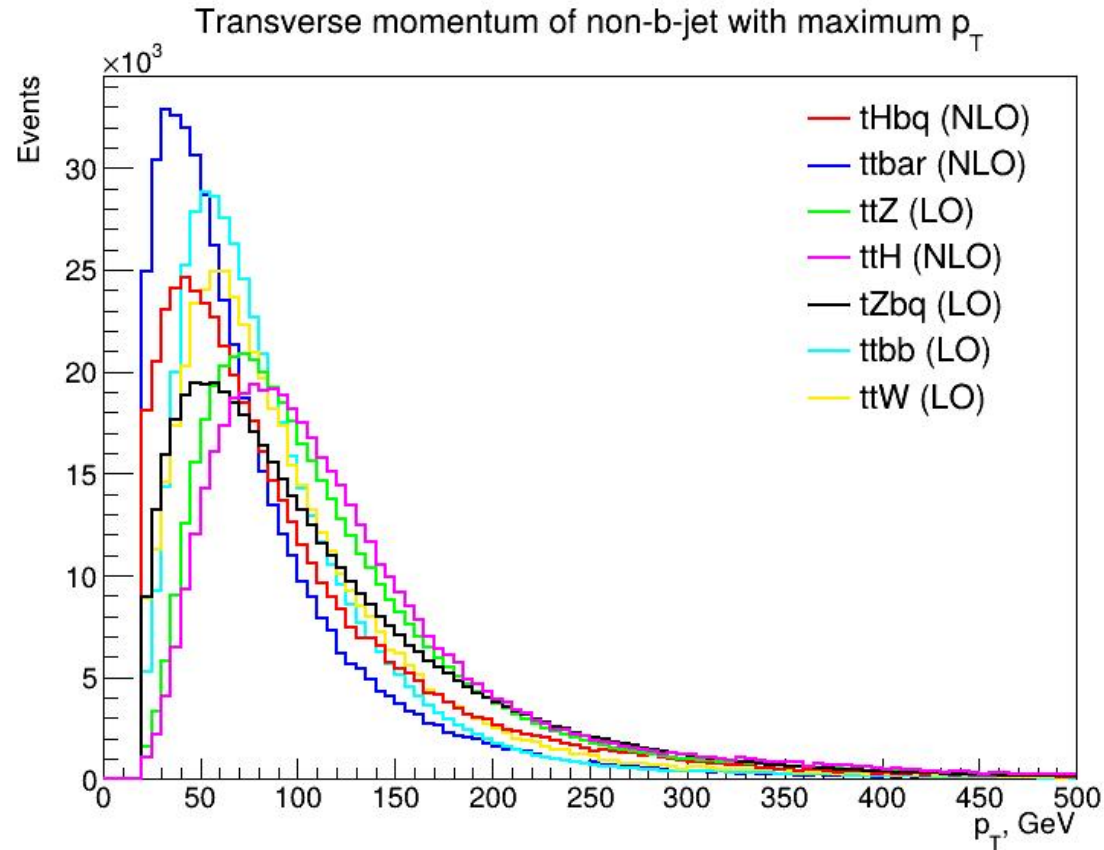
Characteristics b-jet with maximum p_T for the signal and background processes



Characteristics other b-jets for the signal and background processes

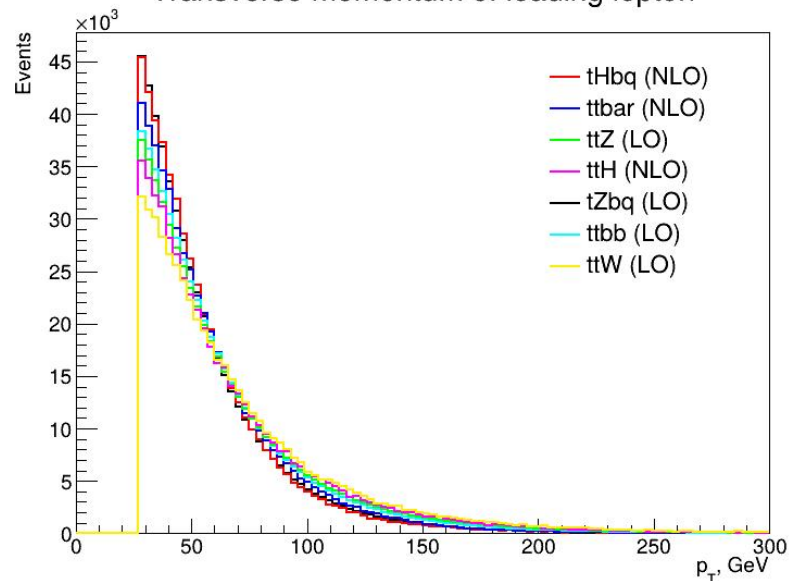


Transverse momentum non-b-jet with maximum p_T for the signal and background processes

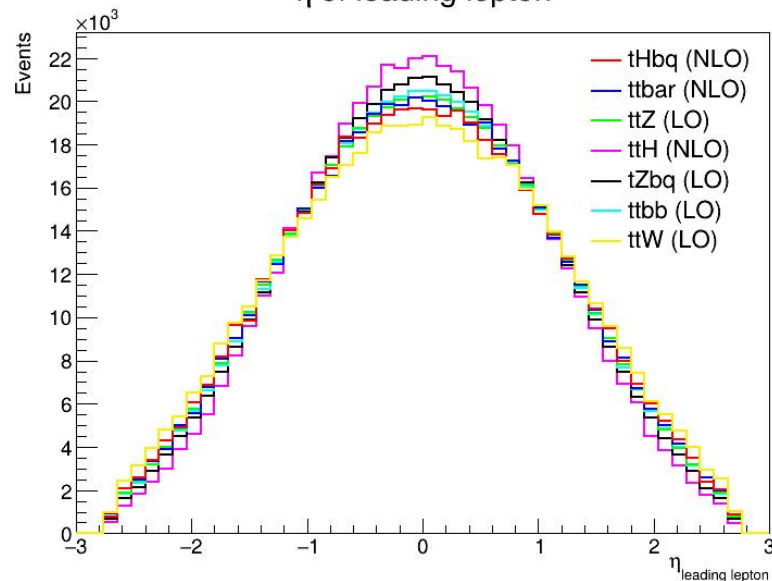


Leading lepton

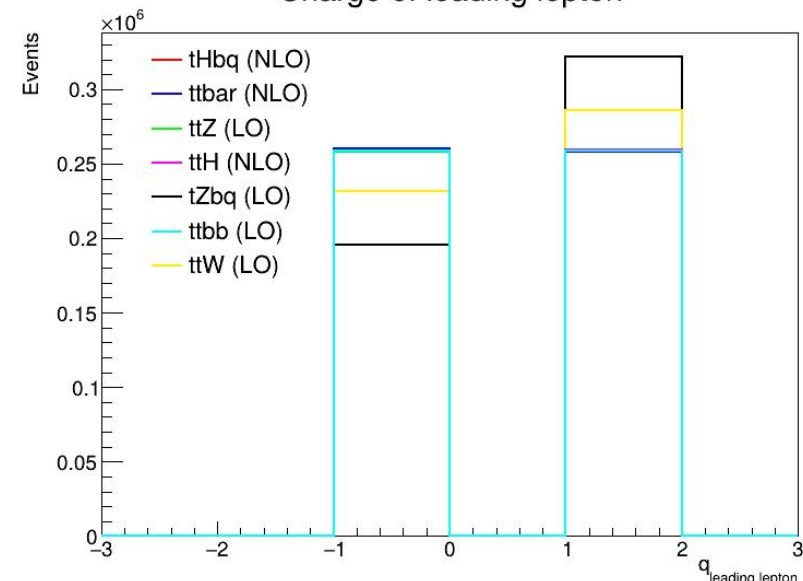
Transverse momentum of leading lepton



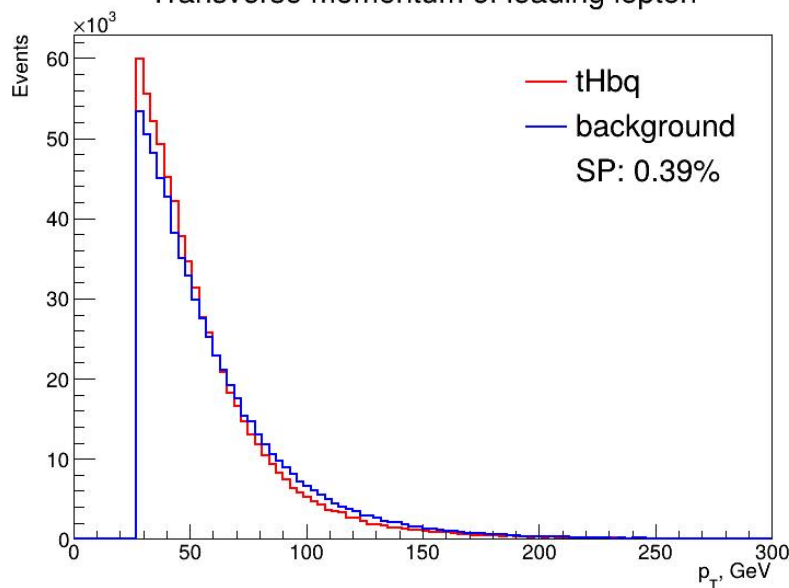
η of leading lepton



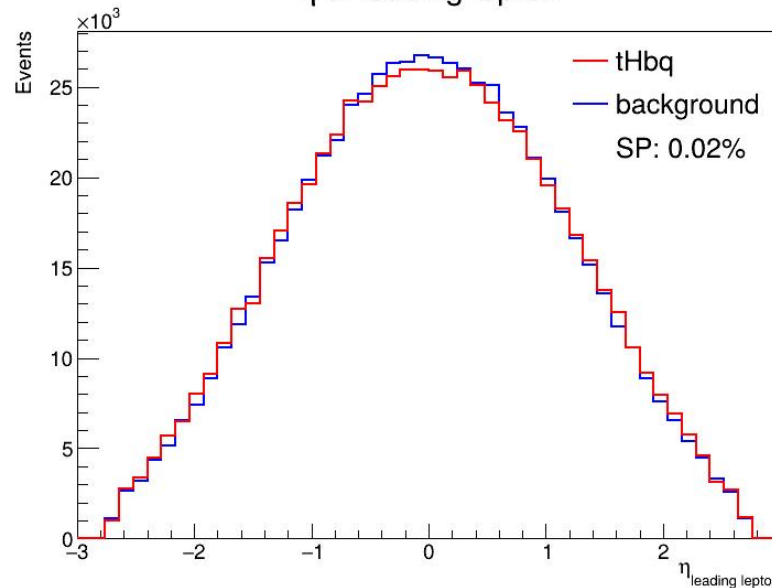
Charge of leading lepton



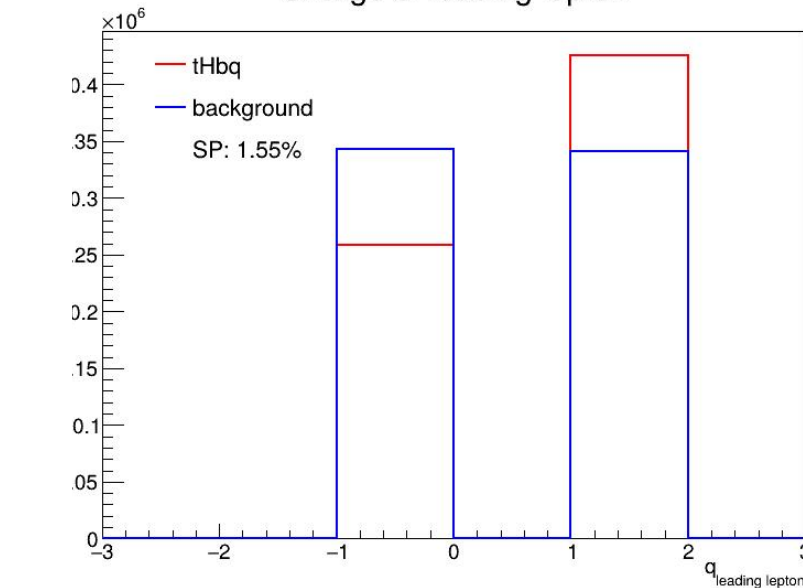
Transverse momentum of leading lepton



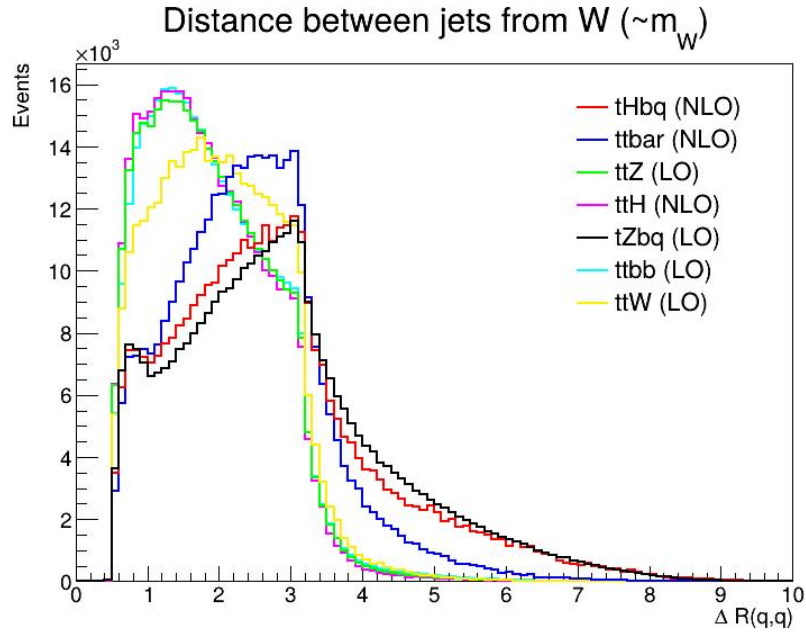
η of leading lepton



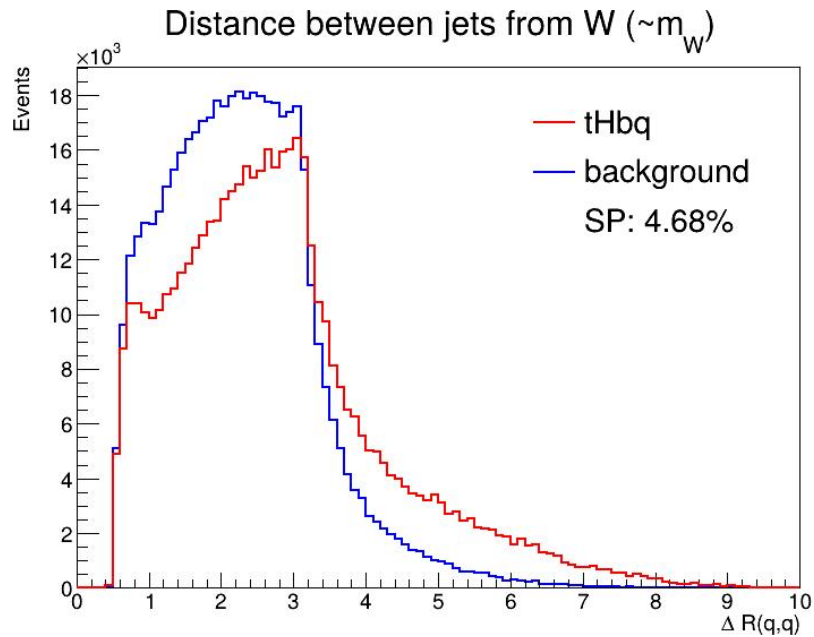
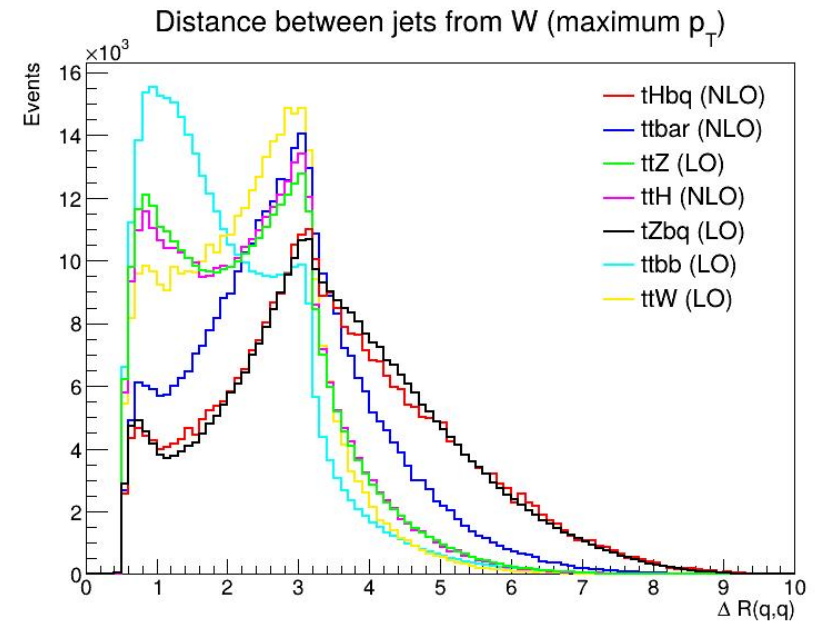
Charge of leading lepton



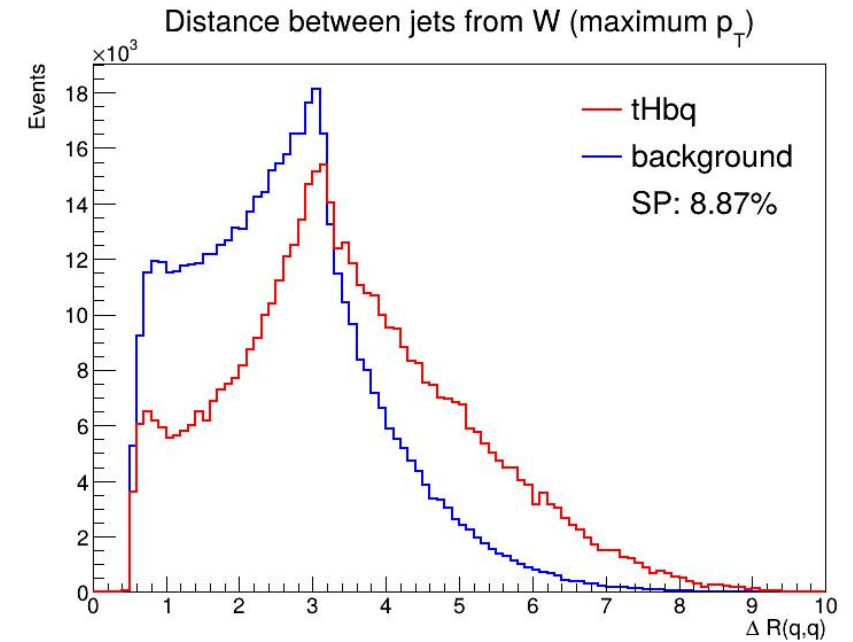
Distance between jets from W-bozon for the signal and background processes



$p_T^{max} (non - bjet)$

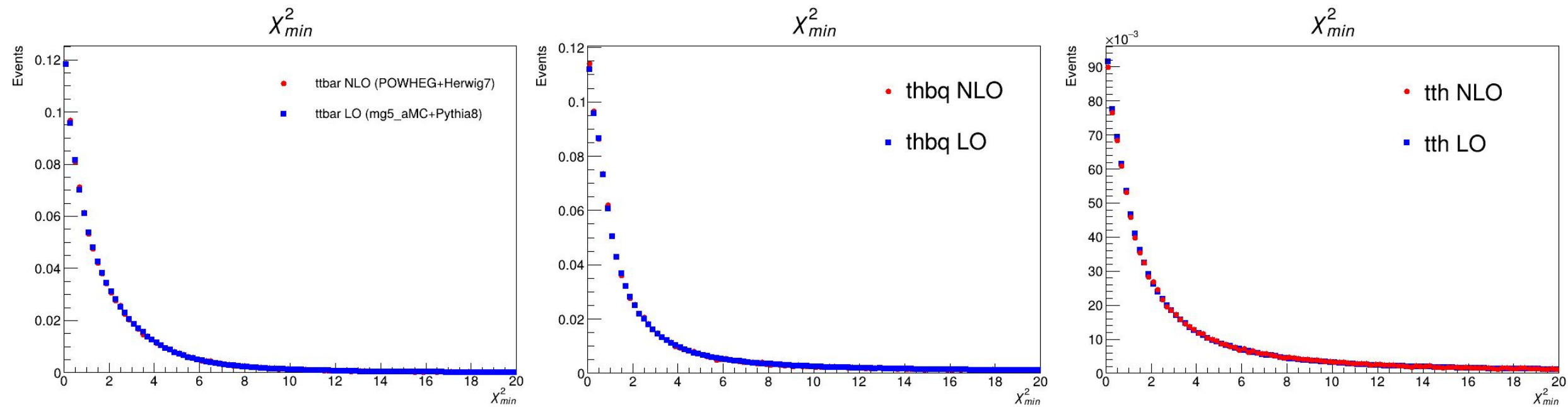


$m^{non-bjets} \sim 80.4 \text{ GeV}$

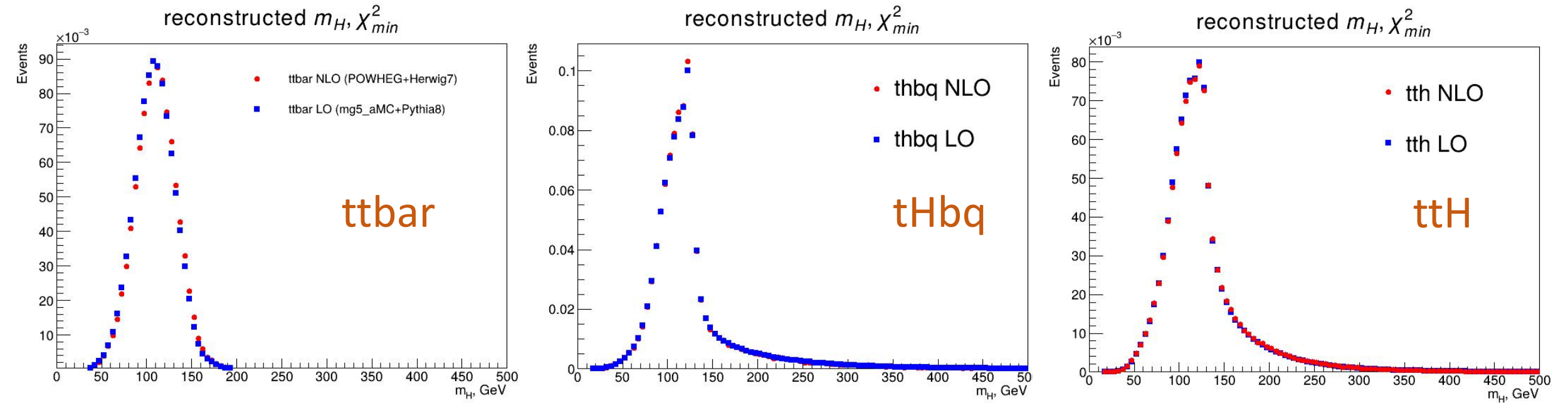


NLO vs LO

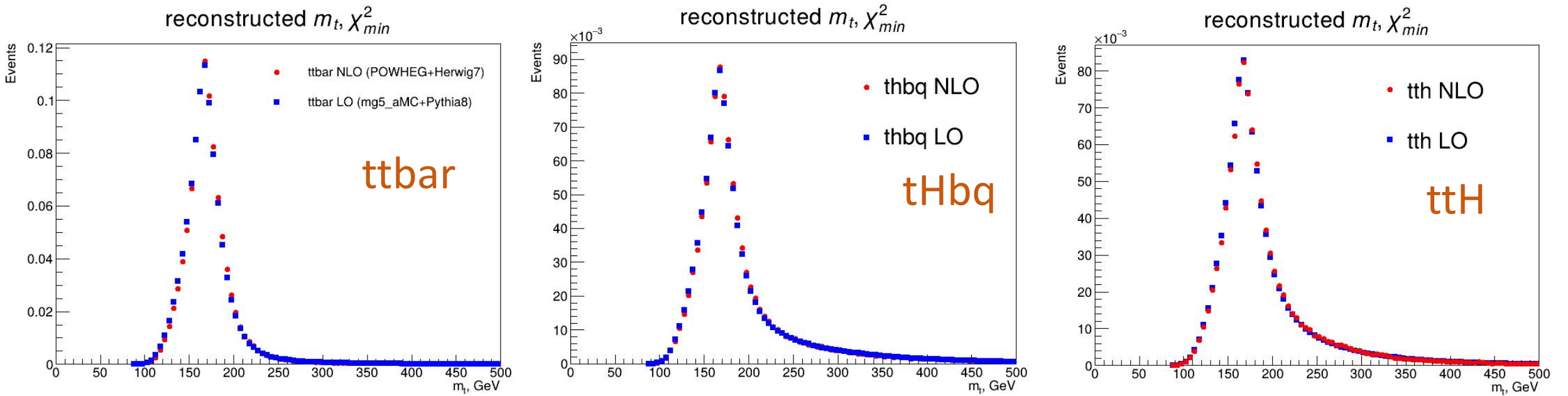
χ^2 for the signal and background processes



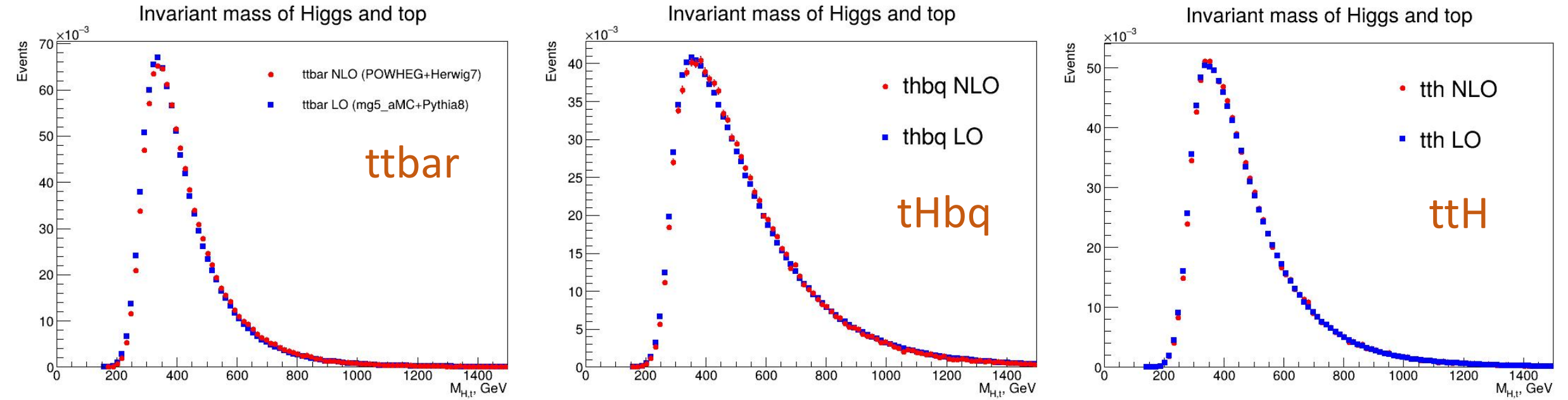
Reconstructed masses of the Higgs boson for the signal process and background processes



Reconstructed masses of the top quark for the signal process and background processes

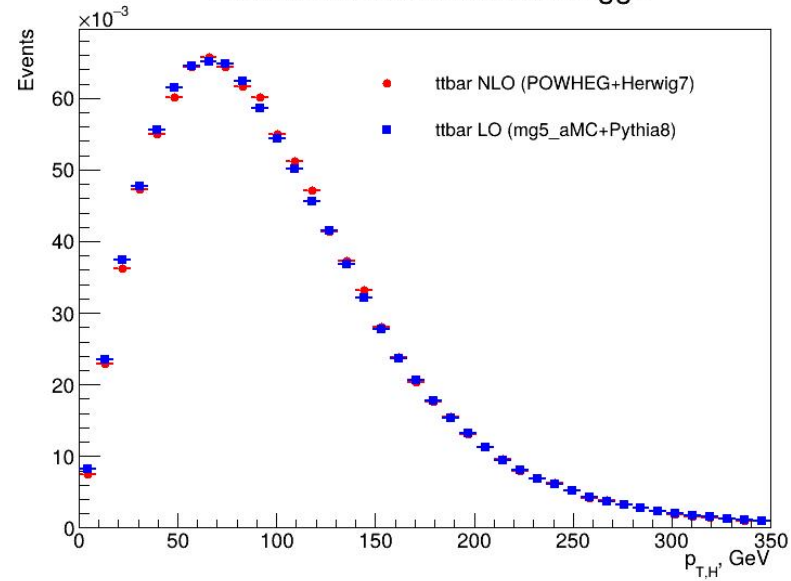


Invariant mass of the top quark and Higgs boson system for the signal and background processes

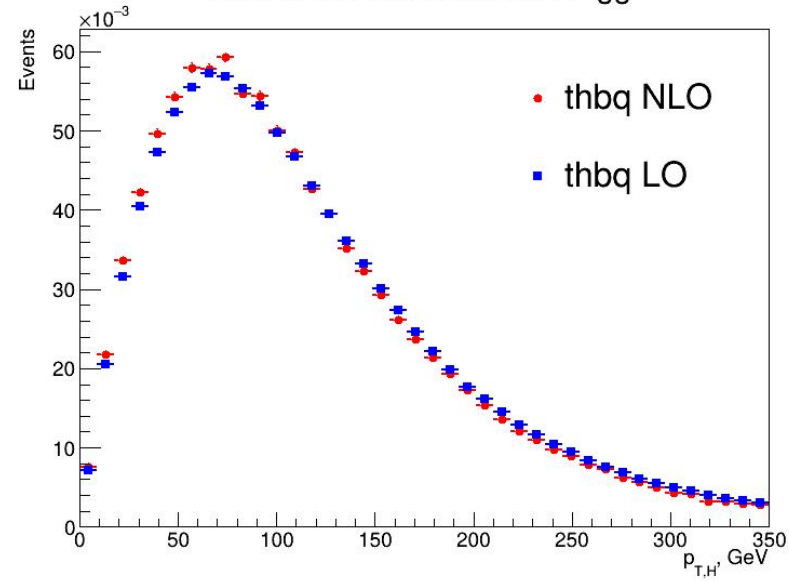


η and p_T Higgs boson for the signal and background processes

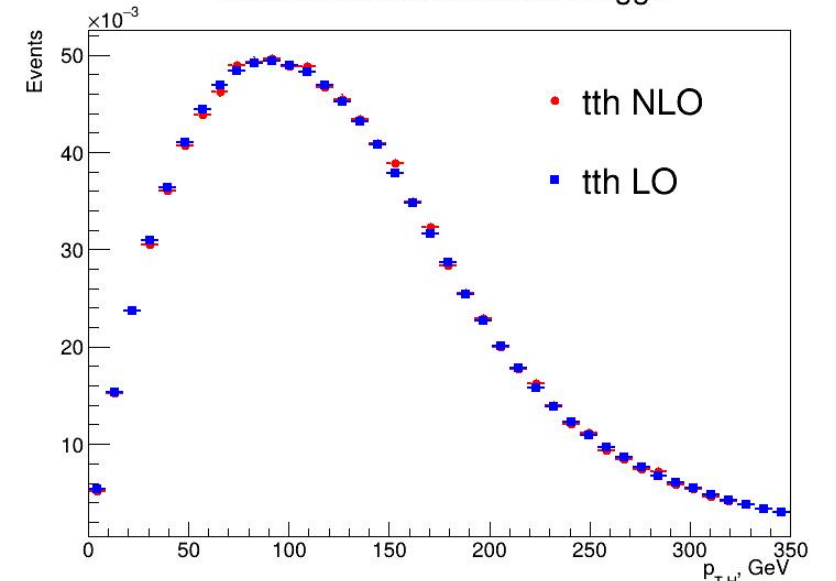
Transverse momentum of Higgs



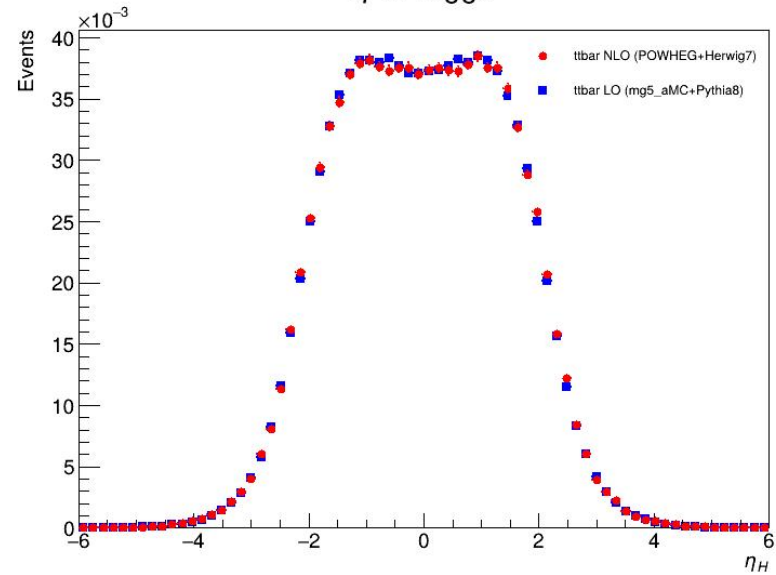
Transverse momentum of Higgs



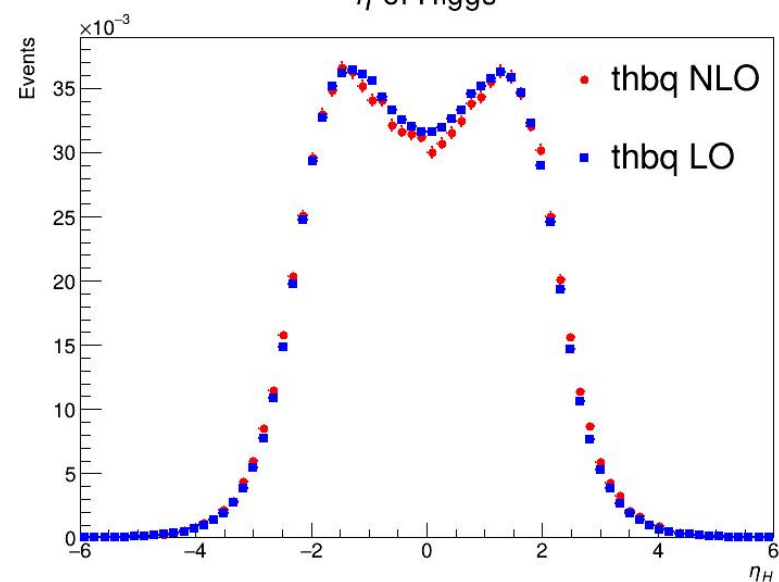
Transverse momentum of Higgs



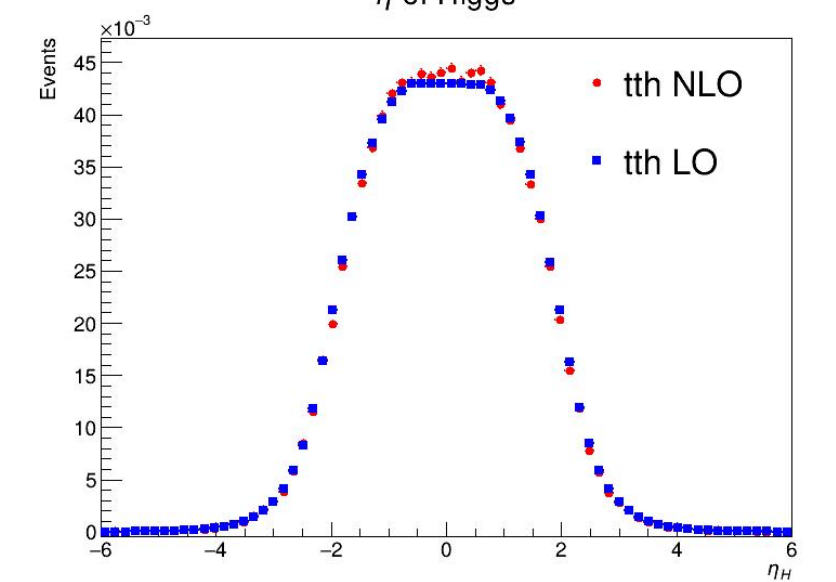
η of Higgs



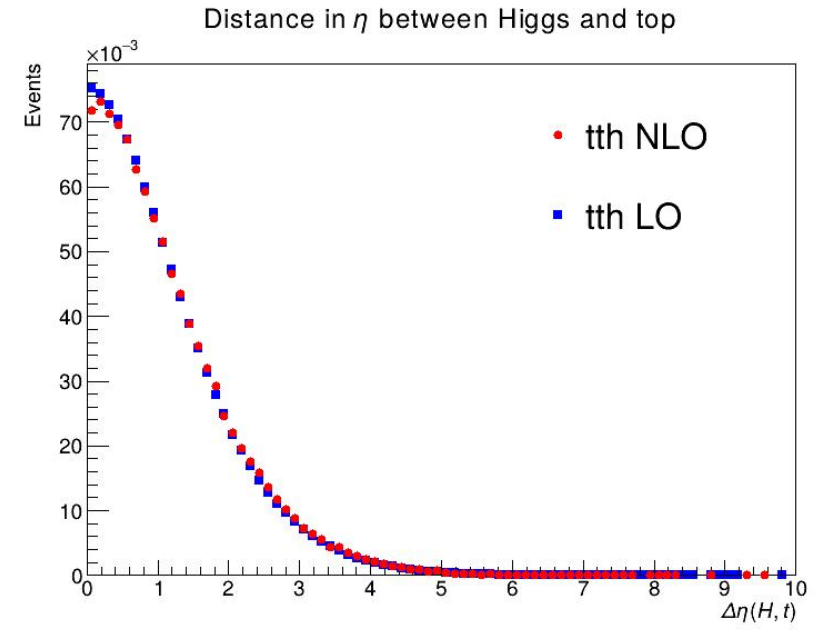
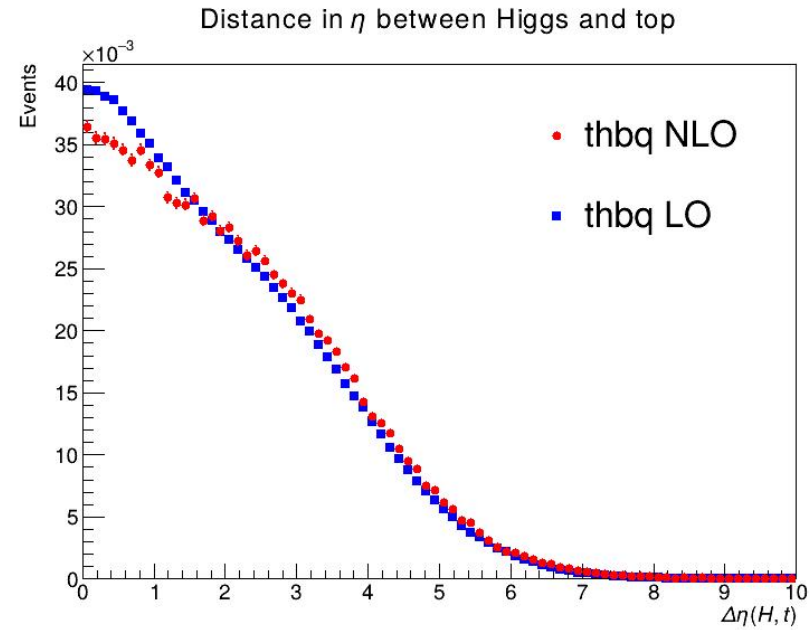
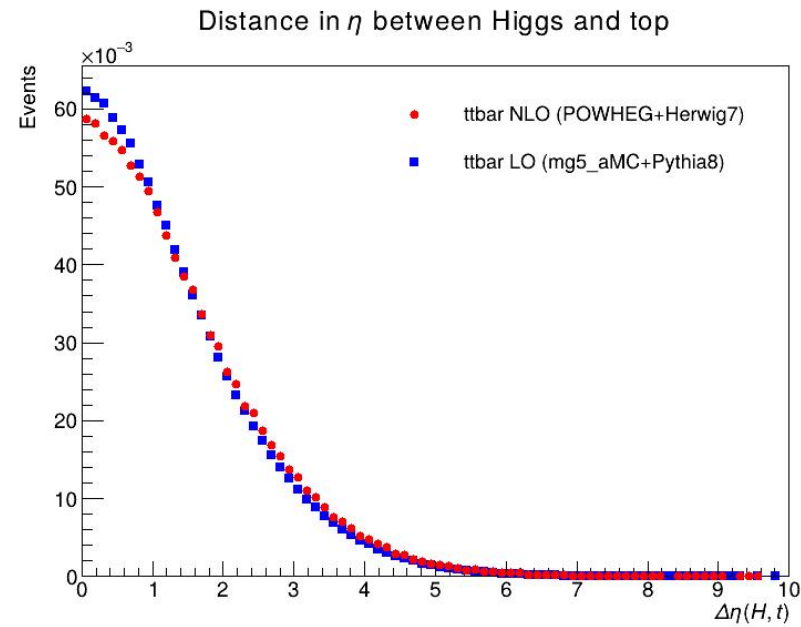
η of Higgs



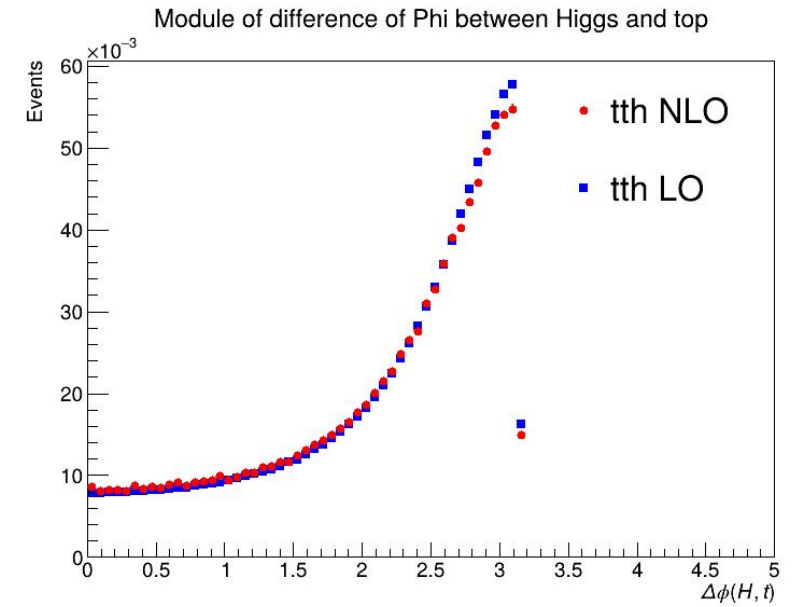
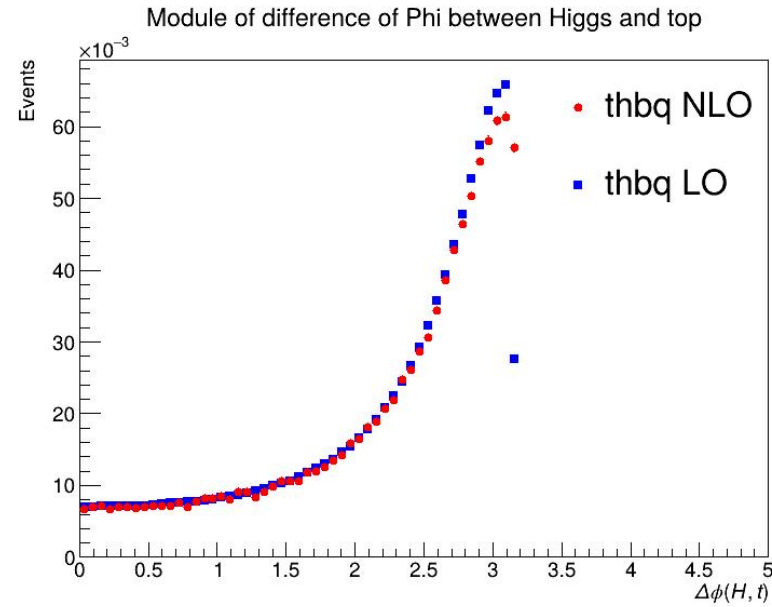
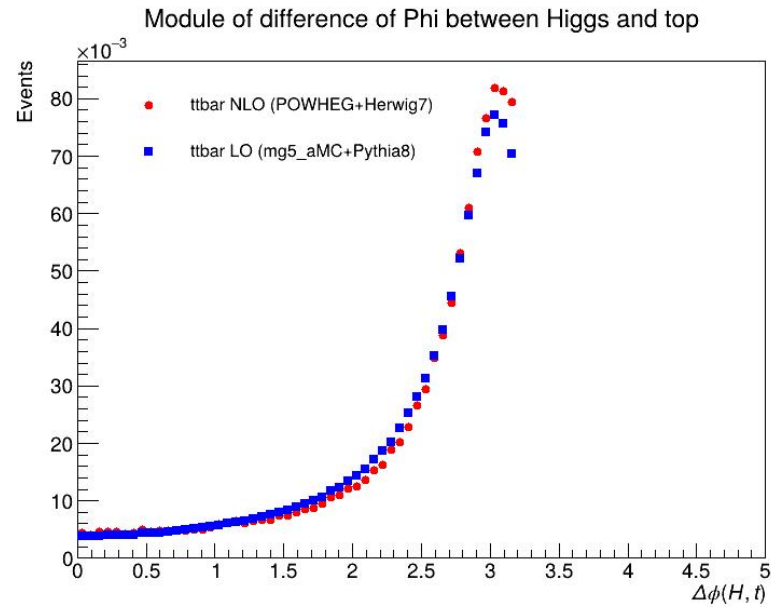
η of Higgs



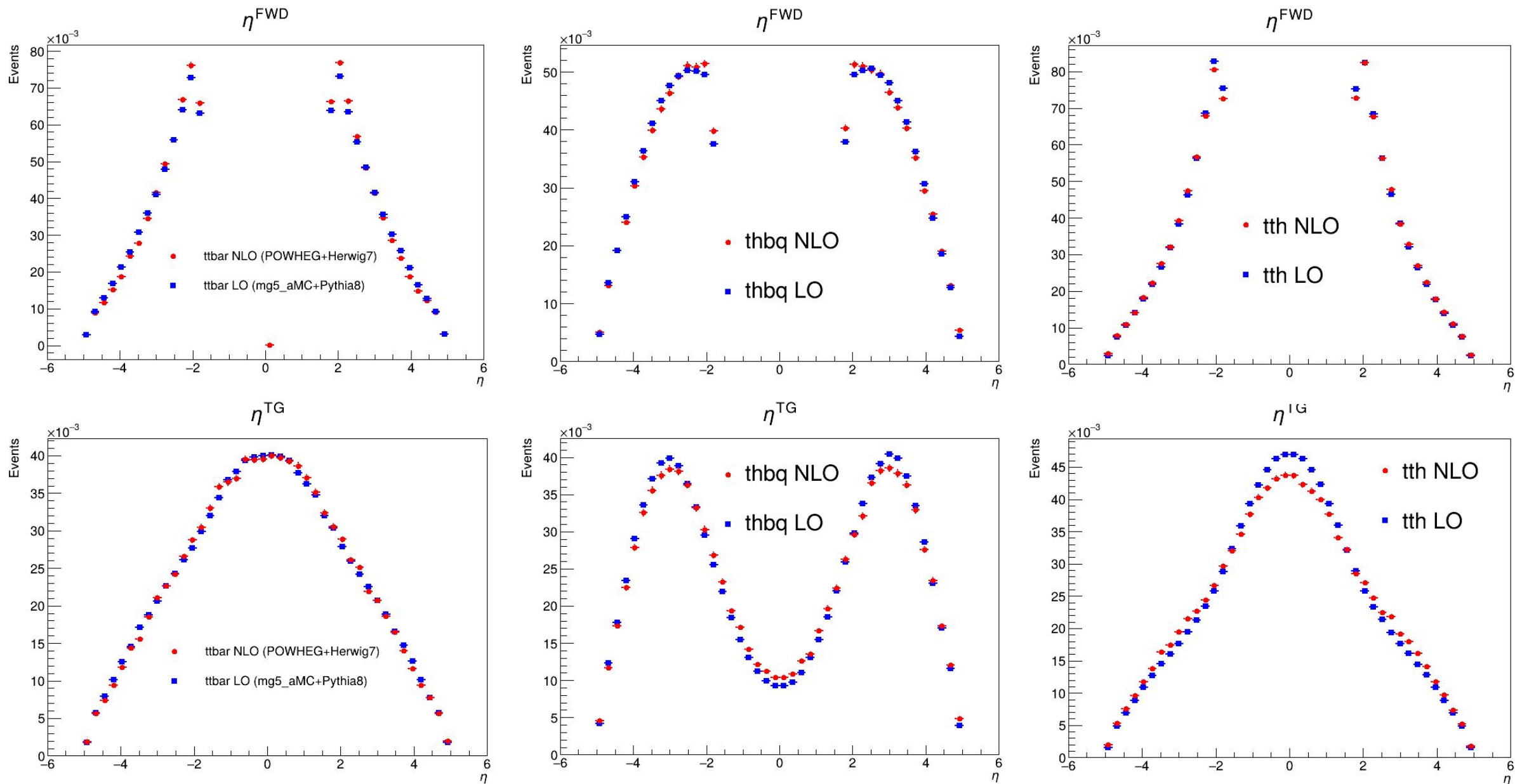
Distance η between top quark and Higgs boson for the signal and background processes



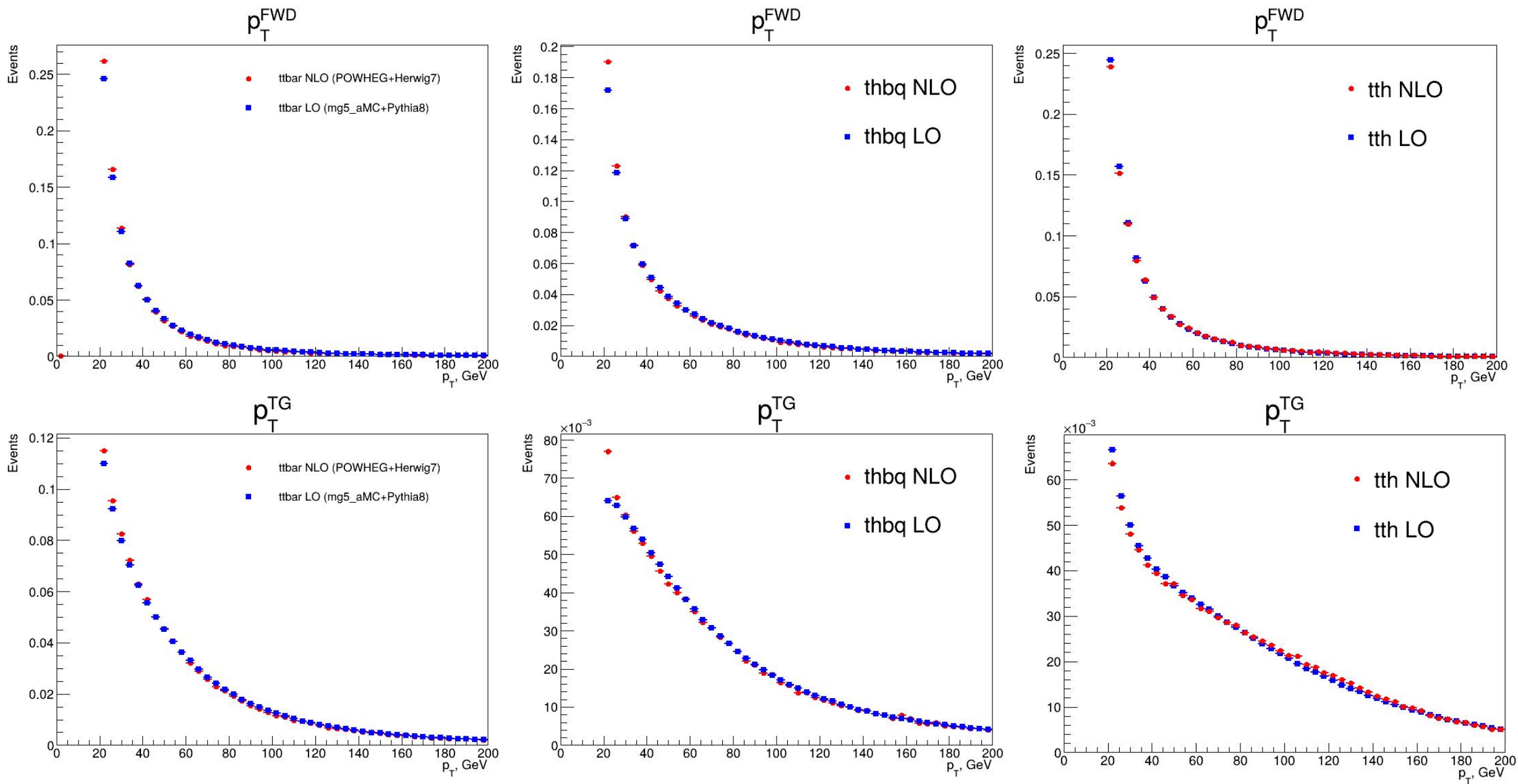
$|\Delta\phi|$ between top quark and Higgs boson for the signal and background processes



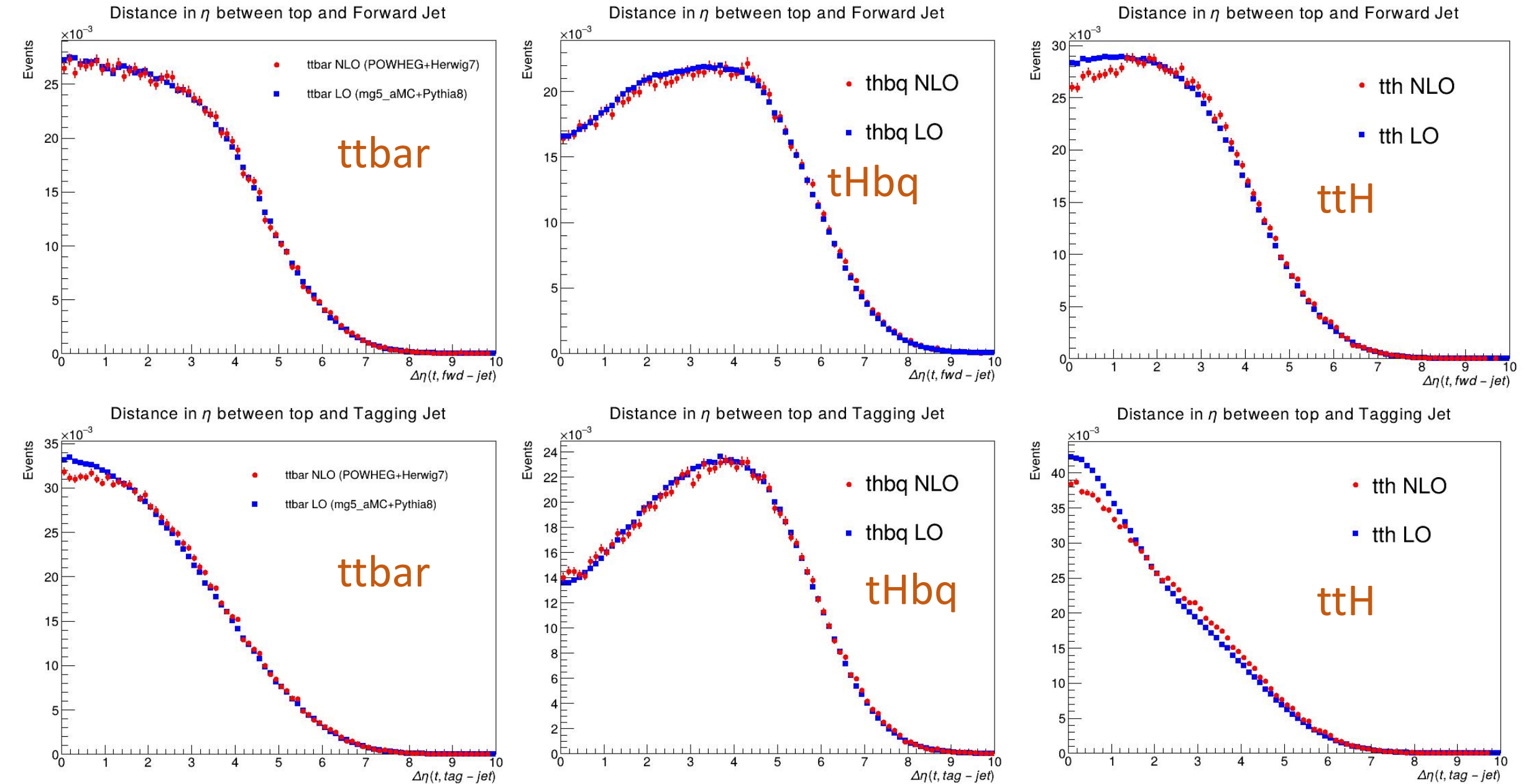
Forward and Tagging jet



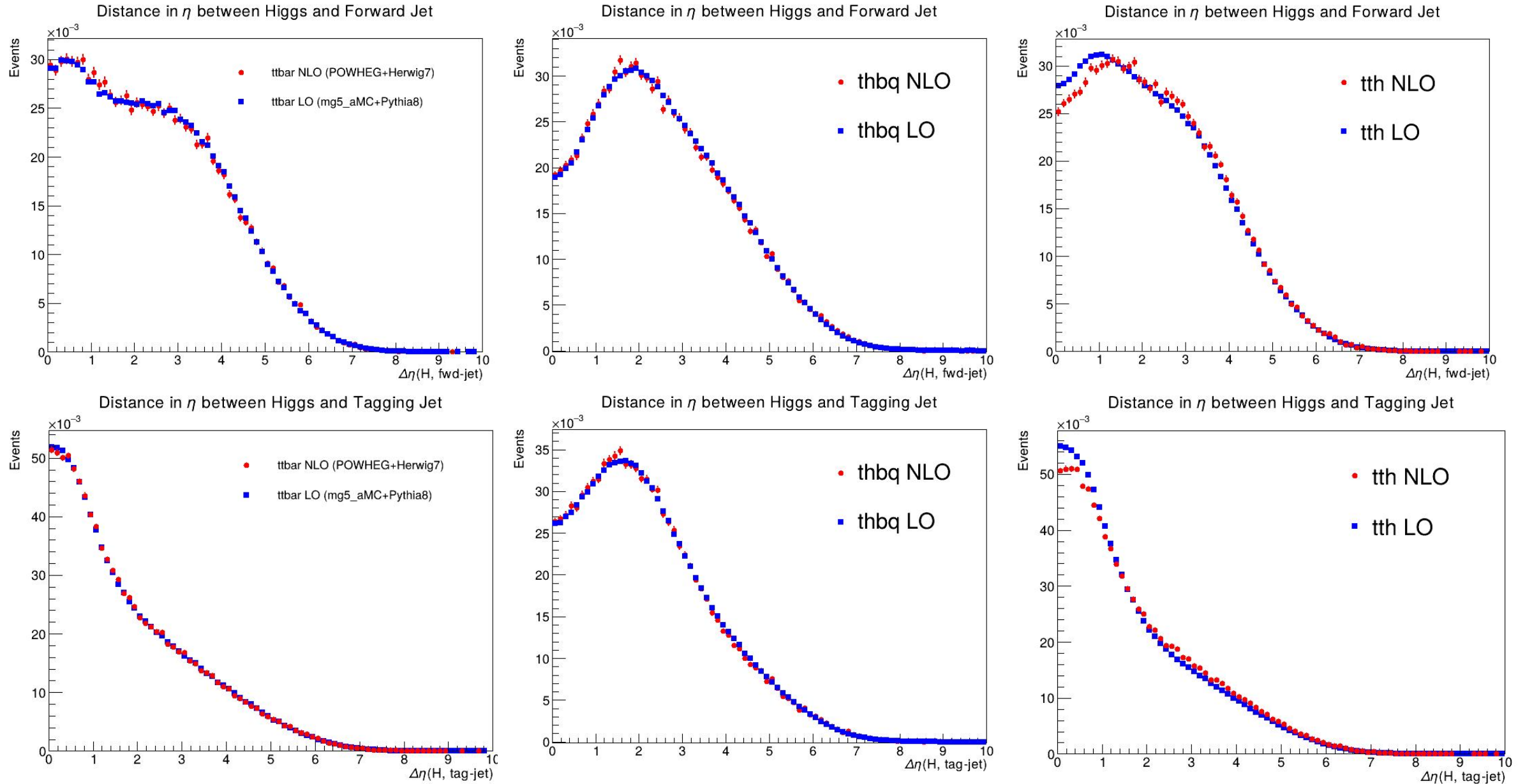
Forward and Tagging jet



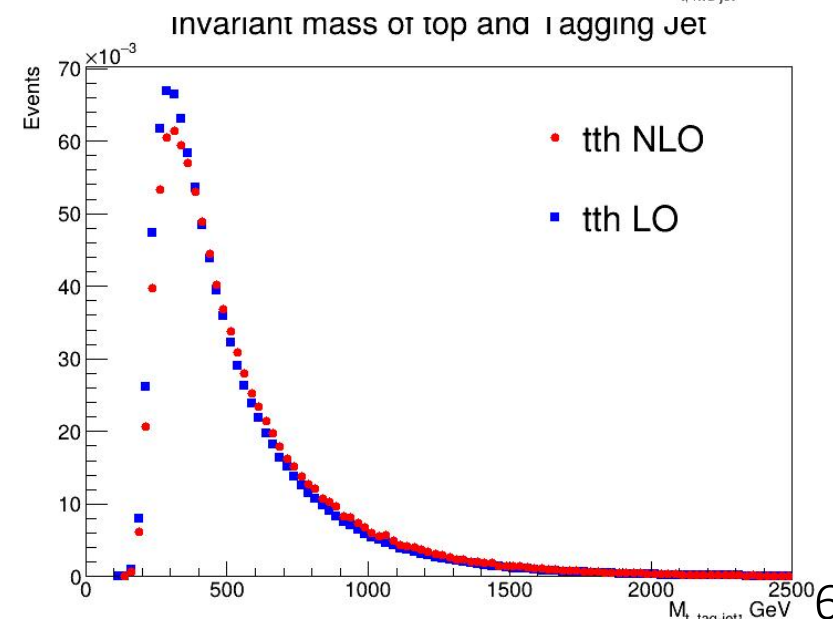
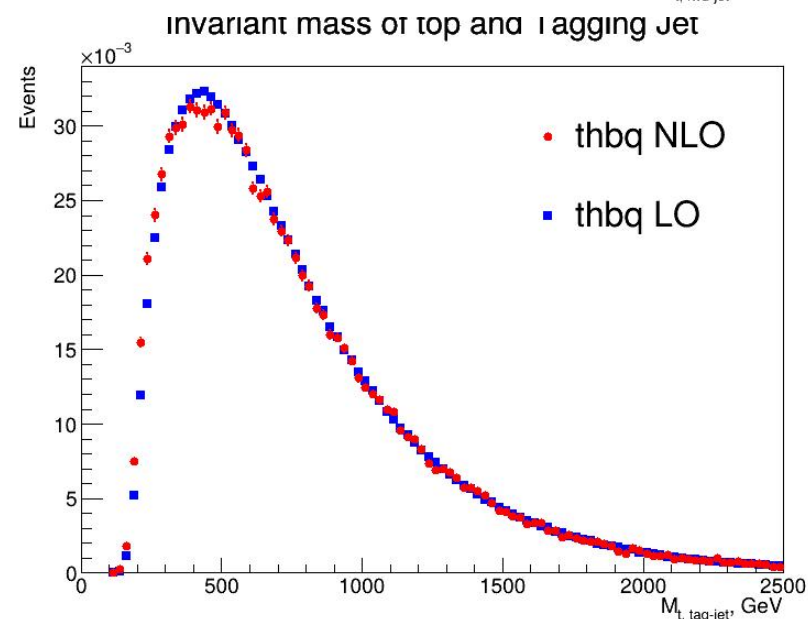
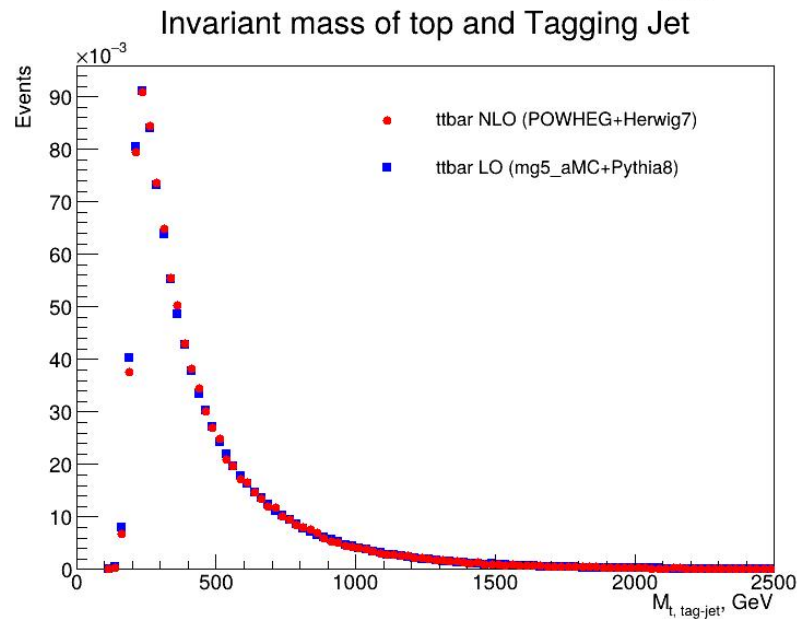
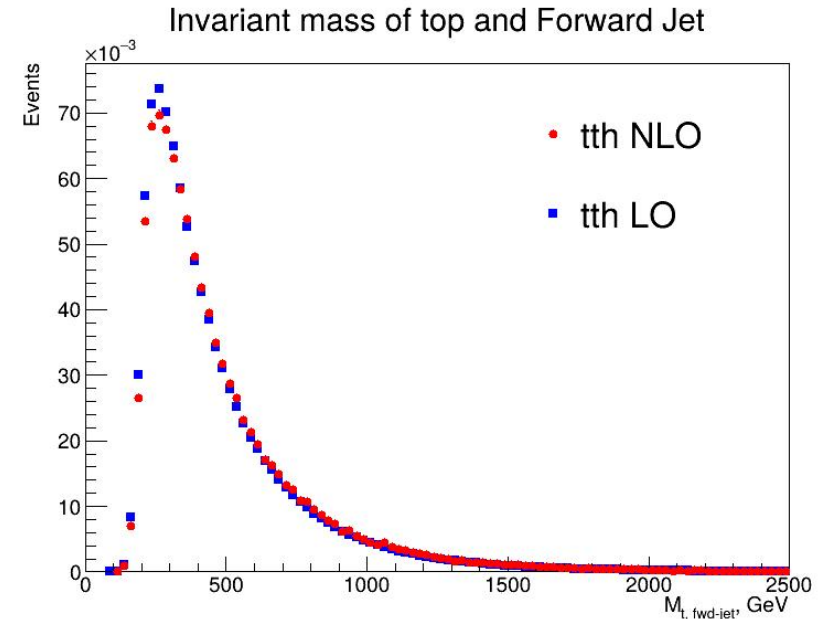
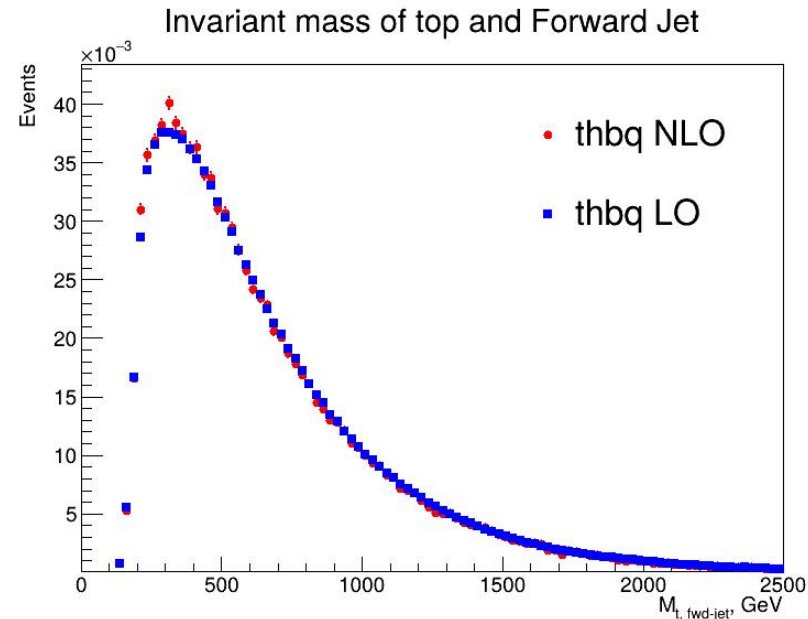
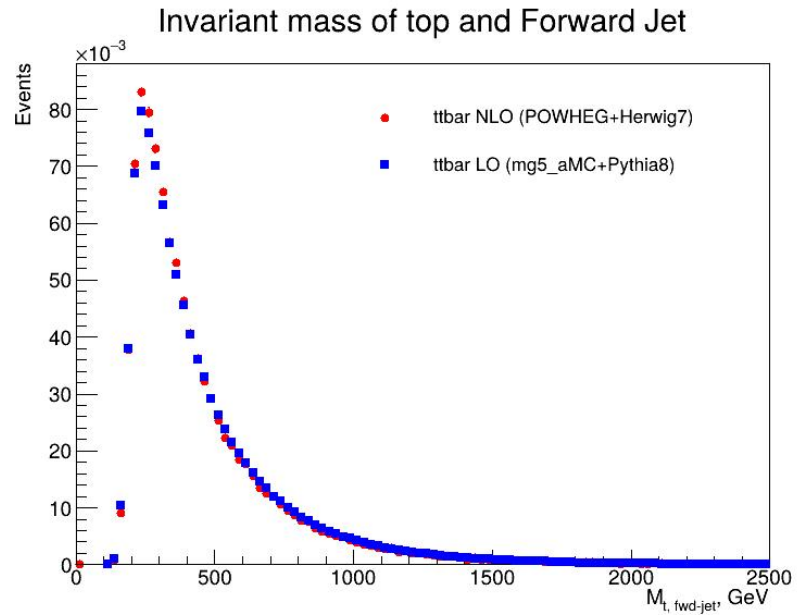
$|\Delta\eta|$ between top quark and Forward (Tagging) Jet for the signal and background processes



Distance in η between Higgs and Forward (Tagging) Jet for the signal and background processes

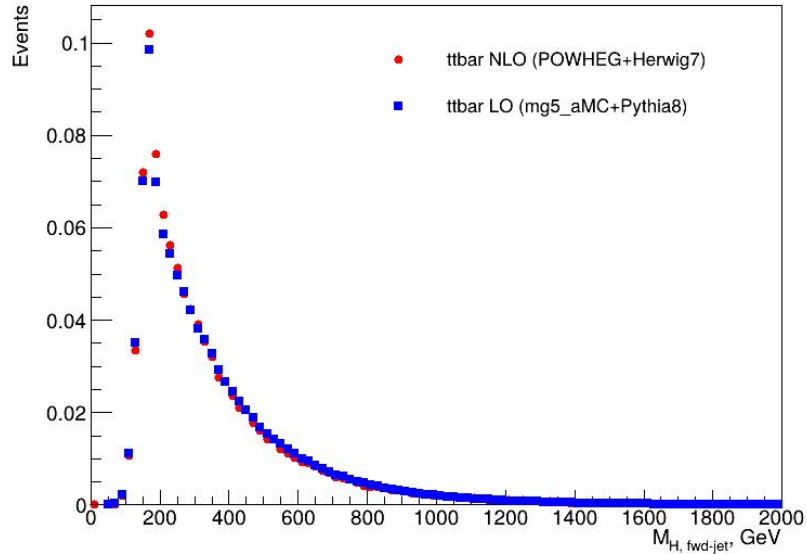


Invariant mass of Top-quark and Forward (Tagging) Jet for the signal and background processes

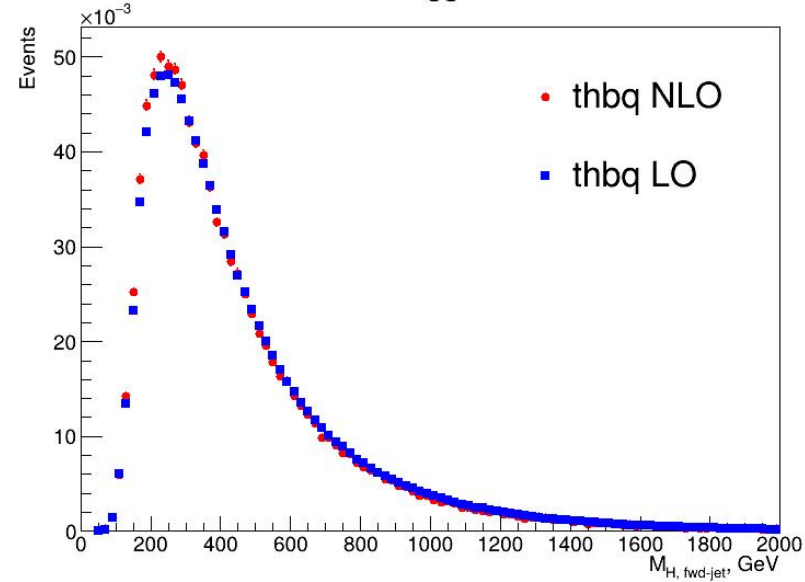


Invariant mass of Higgs and Forward (Tagging) Jet for the signal and background processes

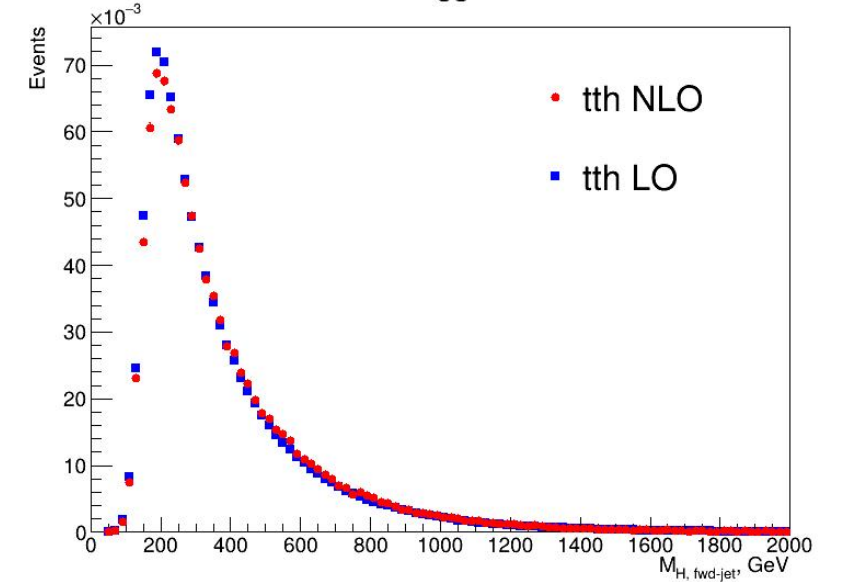
Invariant mass of Higgs and Forward Jet



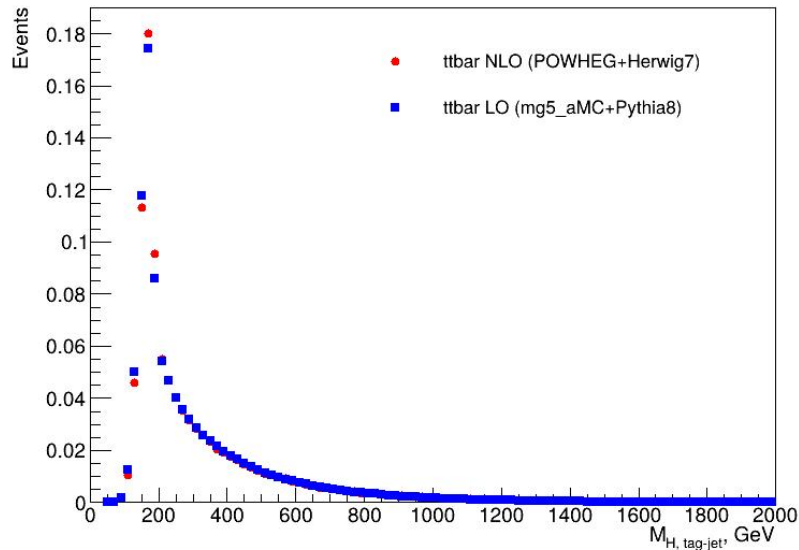
Invariant mass of Higgs and Forward Jet



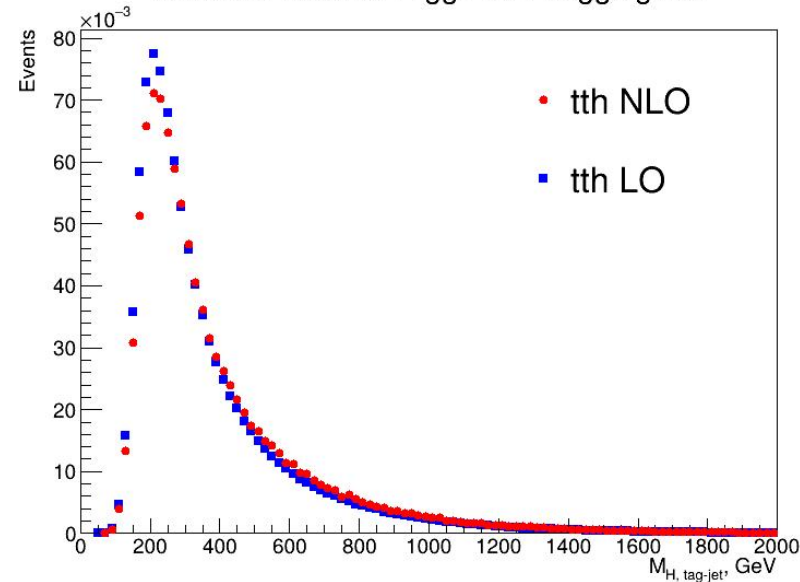
Invariant mass of Higgs and Forward Jet



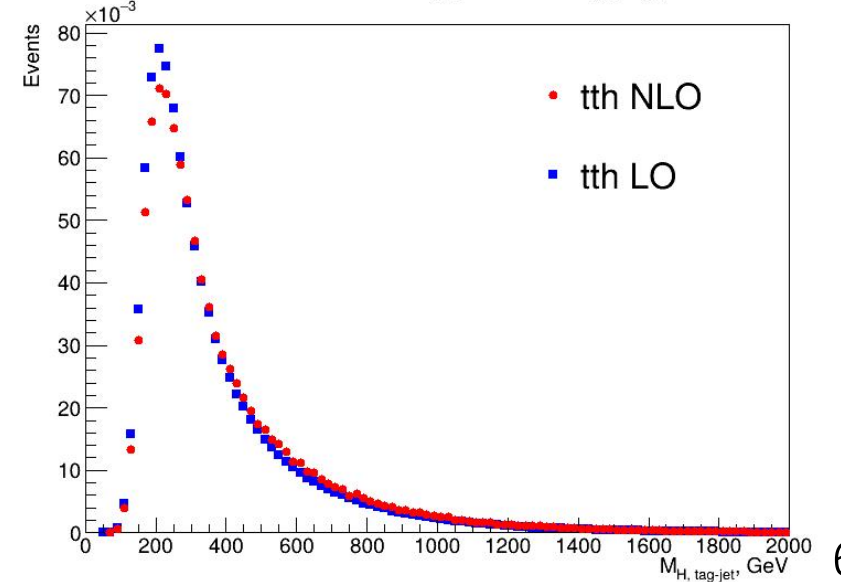
Invariant mass of Higgs and Tagging Jet



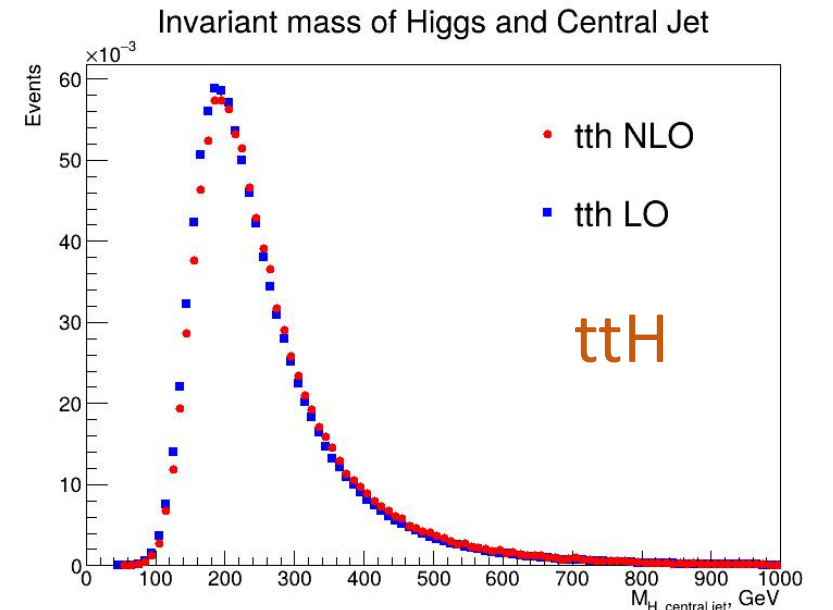
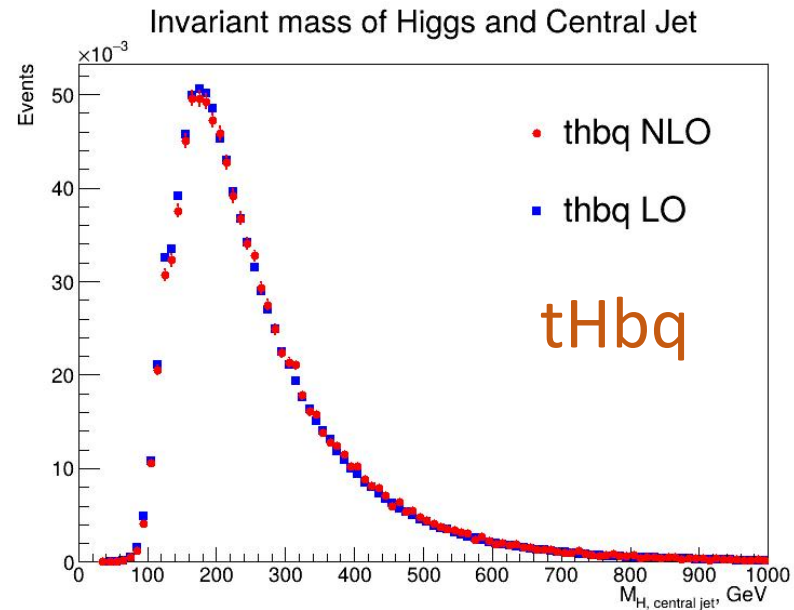
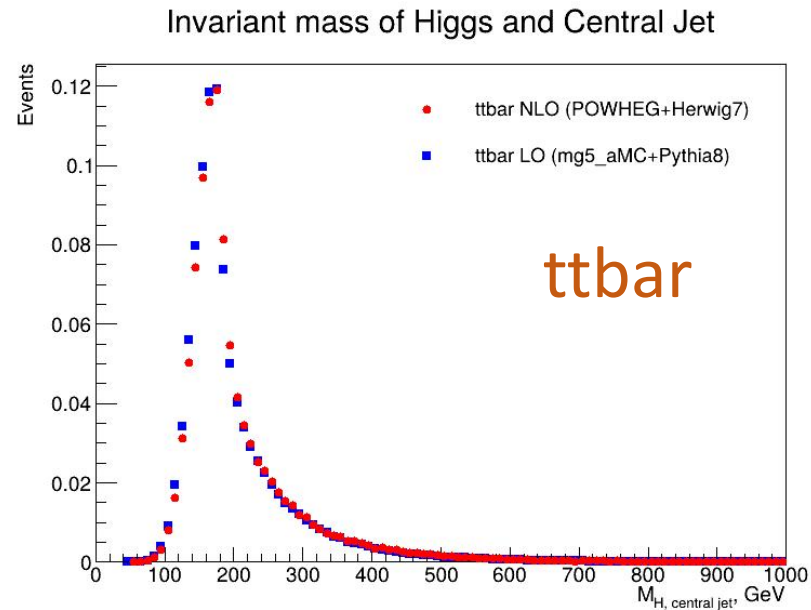
Invariant mass of Higgs and Tagging Jet



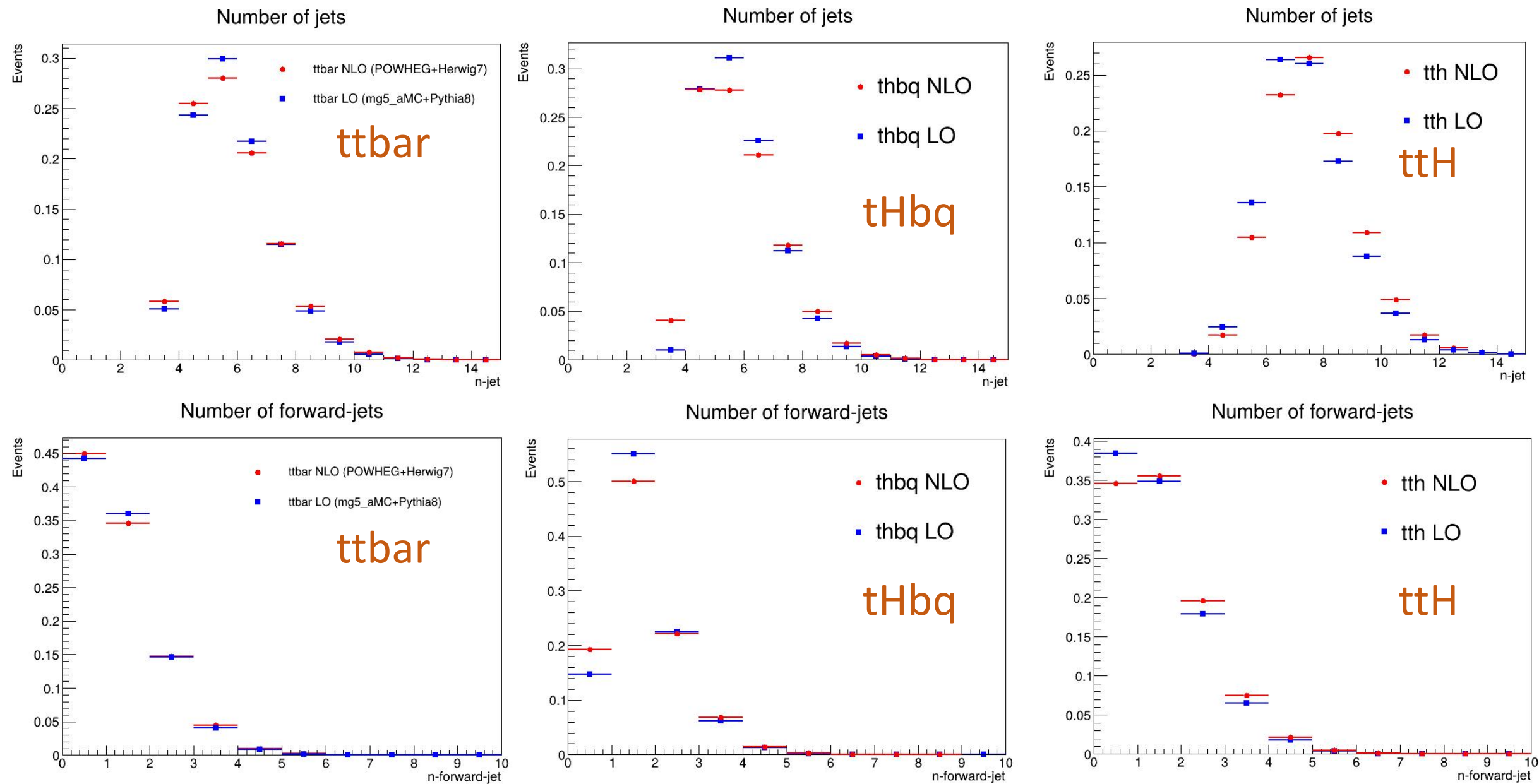
Invariant mass of Higgs and Tagging Jet



Invariant mass Higgs and Central Jet for the signal and background processes

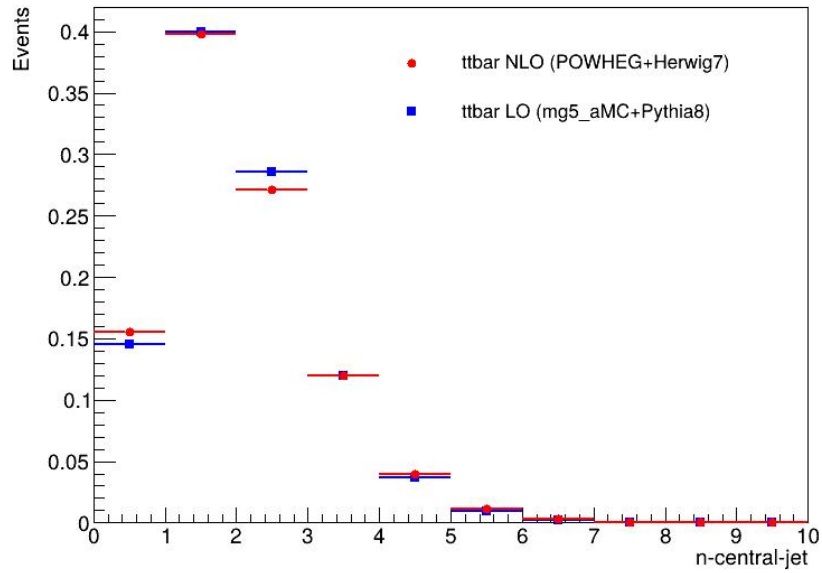


Number of jets

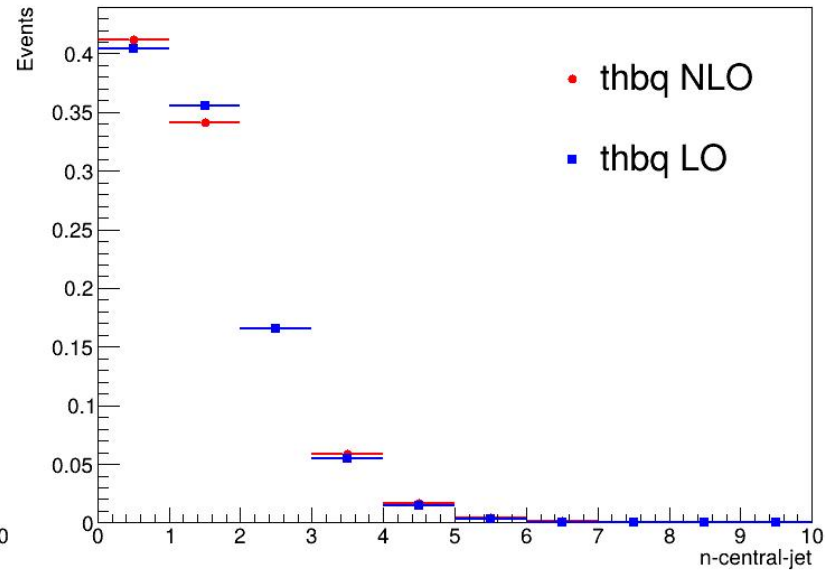


Number of central jets

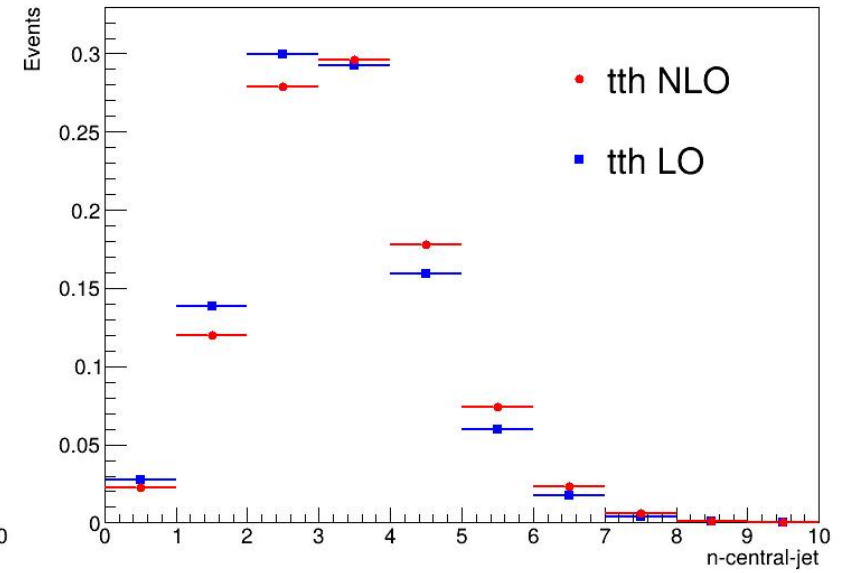
Number of central-jets



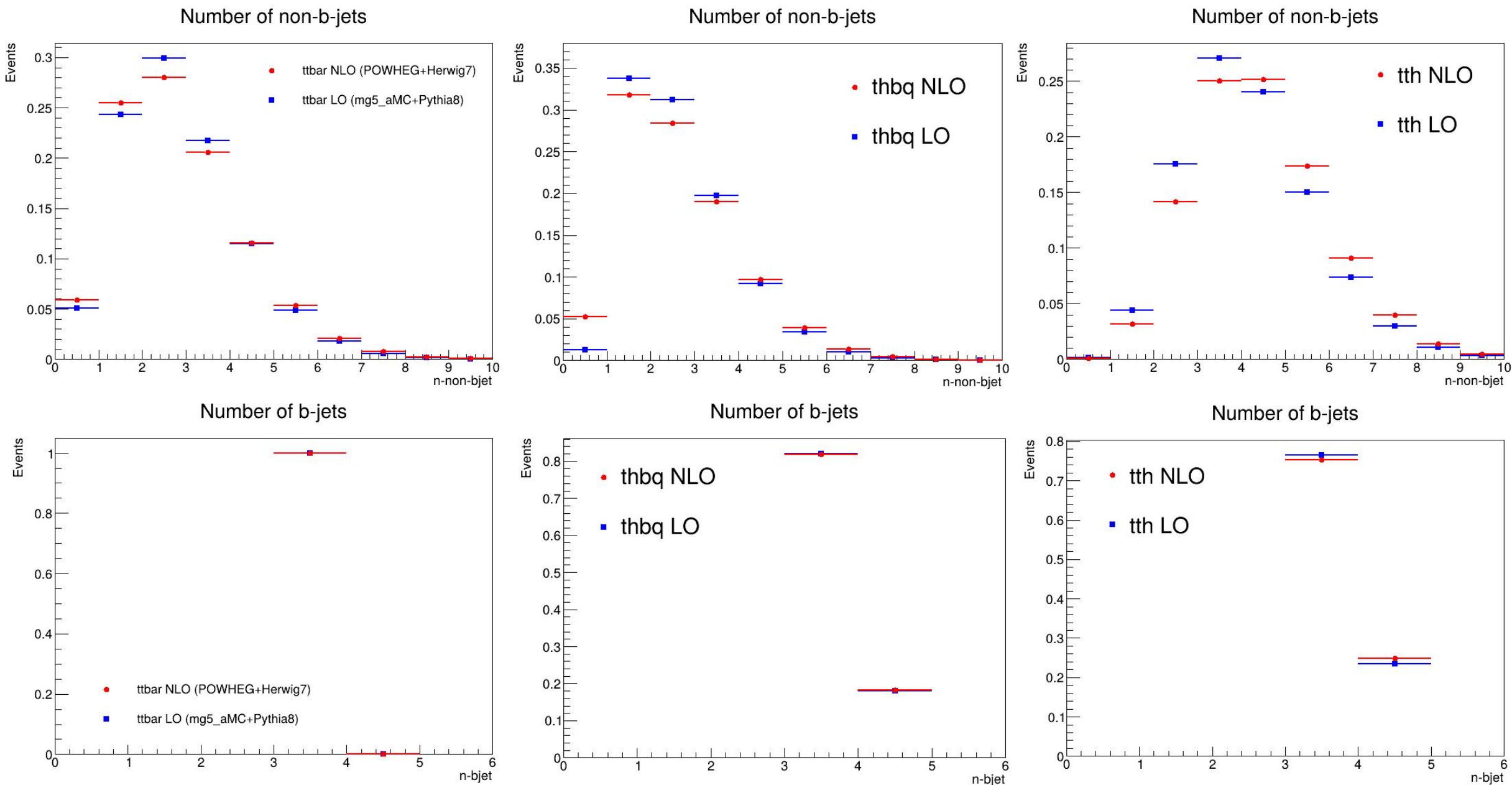
Number of central-jets



Number of central-jets

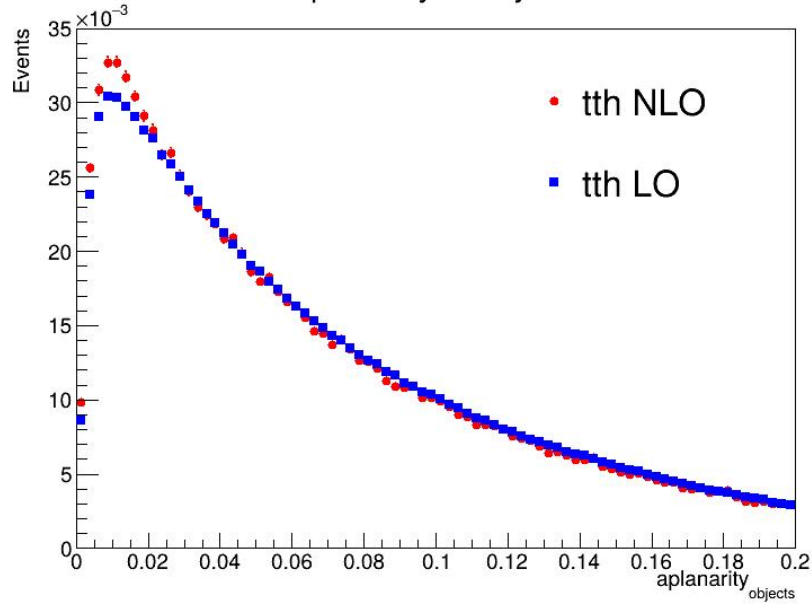


Number of b-jets and non-b-jets

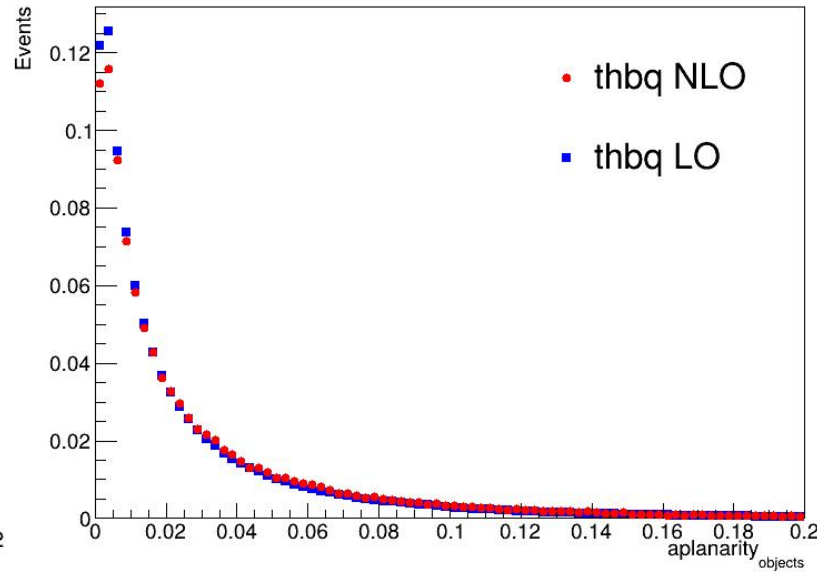


Aplanarity for the signal and background processes

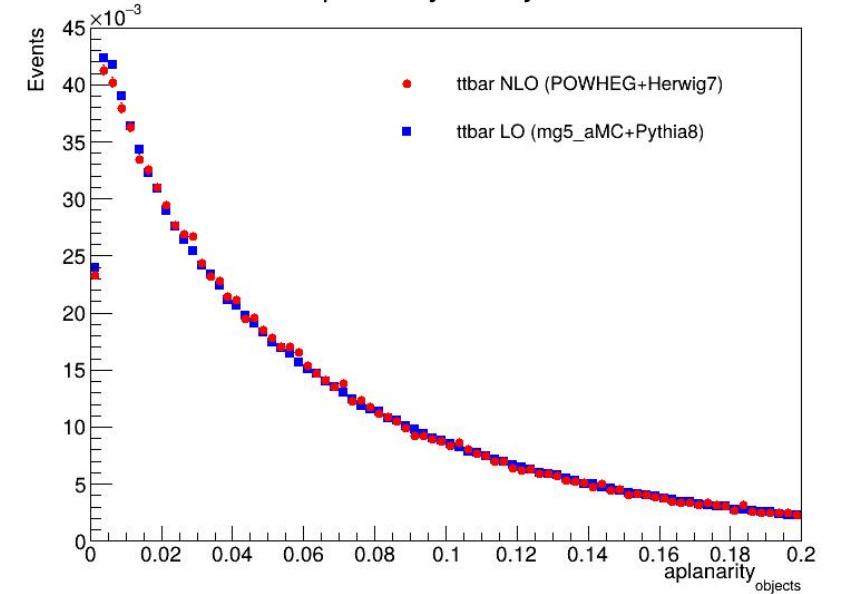
Aplanarity of objects



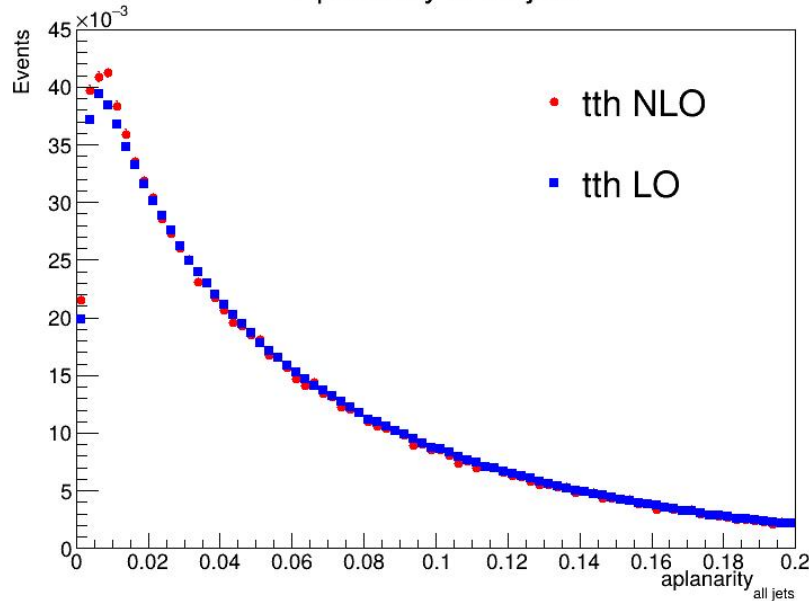
Aplanarity of objects



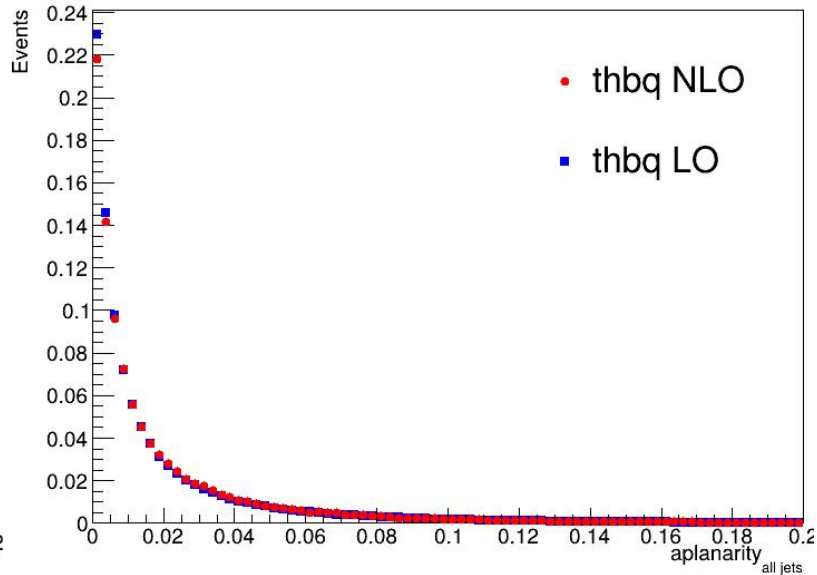
Aplanarity of objects



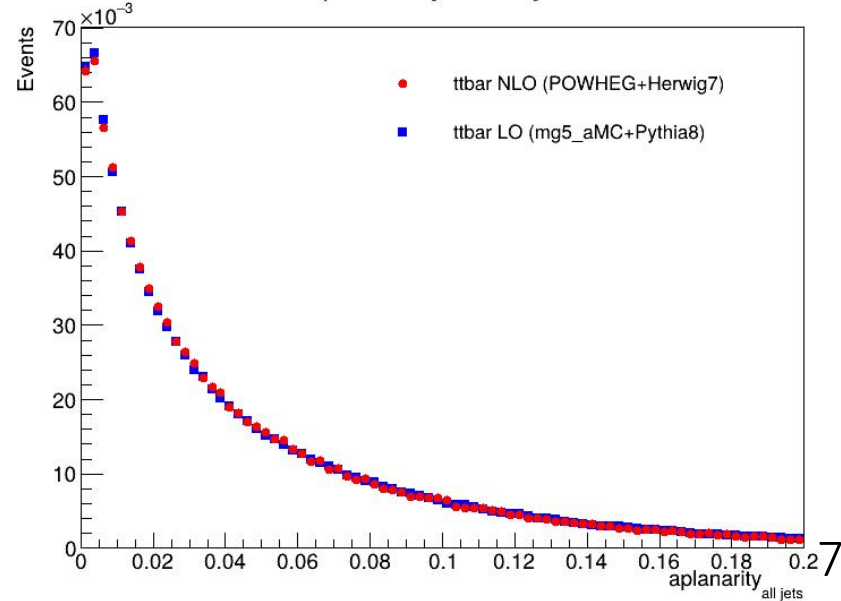
Aplanarity of all jets



Aplanarity of all jets

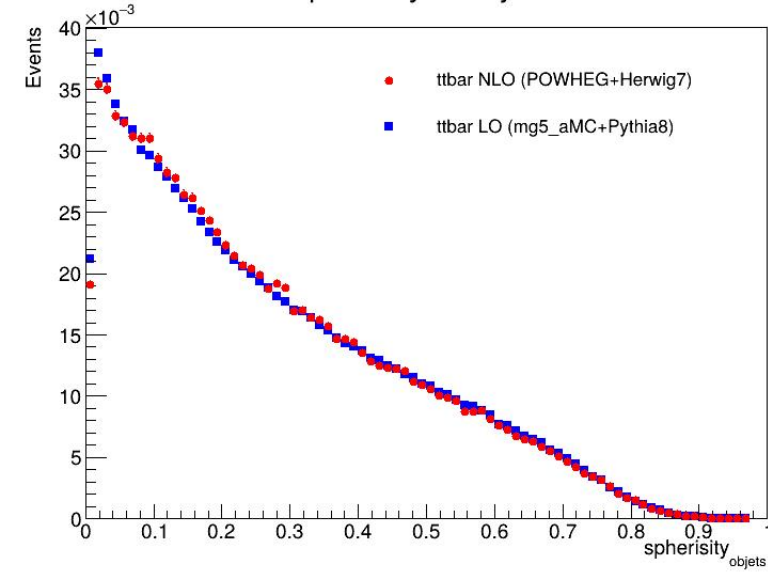


Aplanarity of all jets

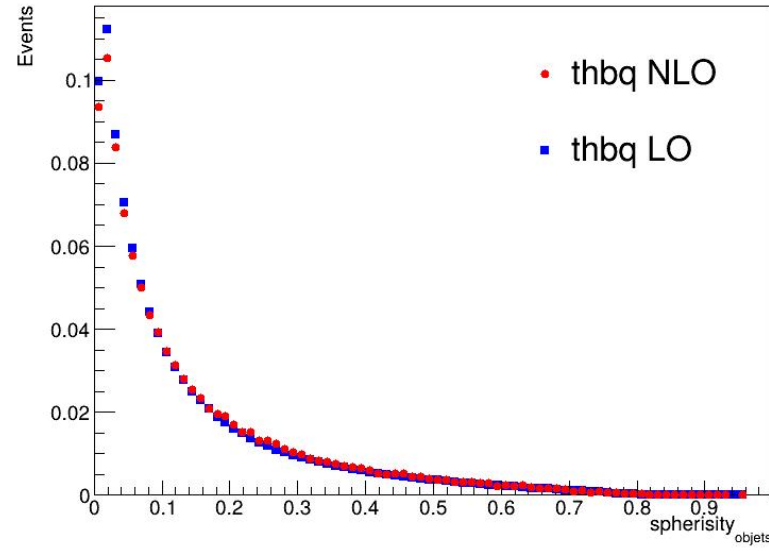


Sphericity for the signal and background processes

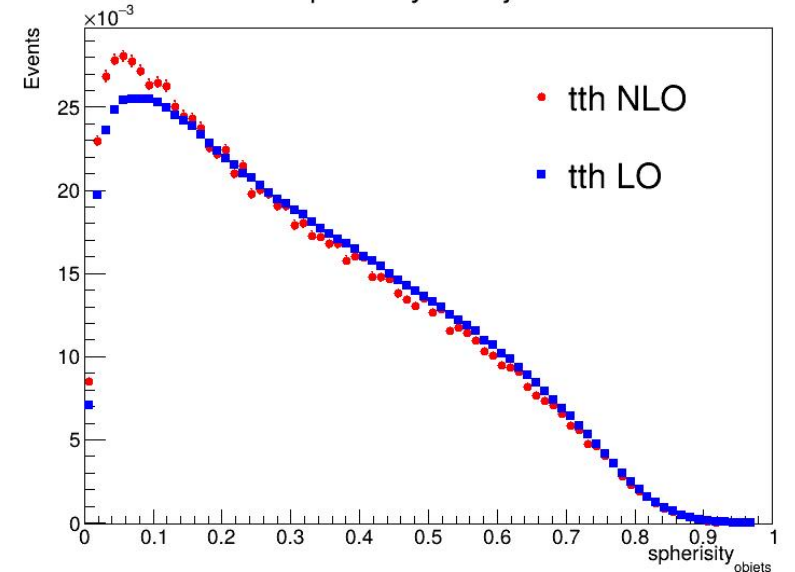
Sphericity of objects



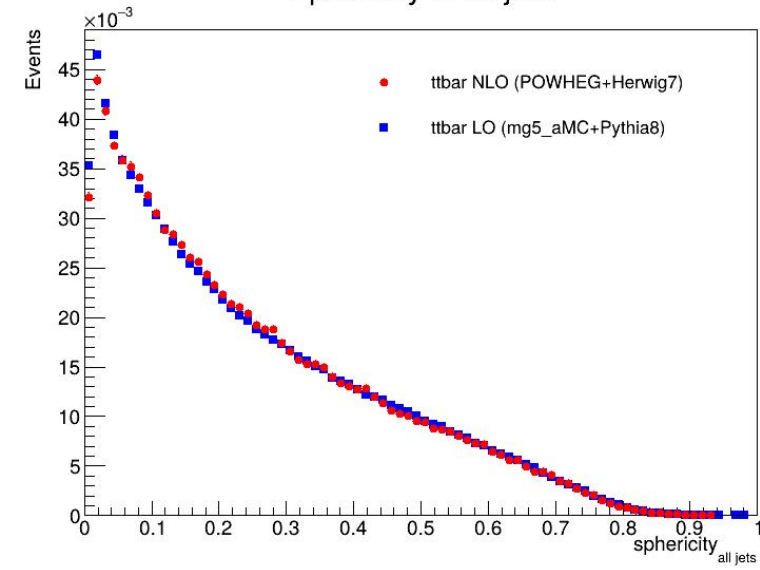
Sphericity of objects



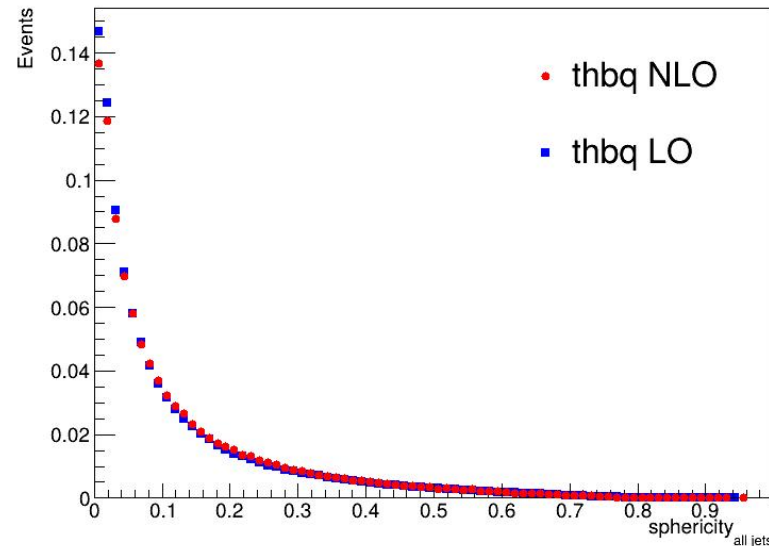
Sphericity of objects



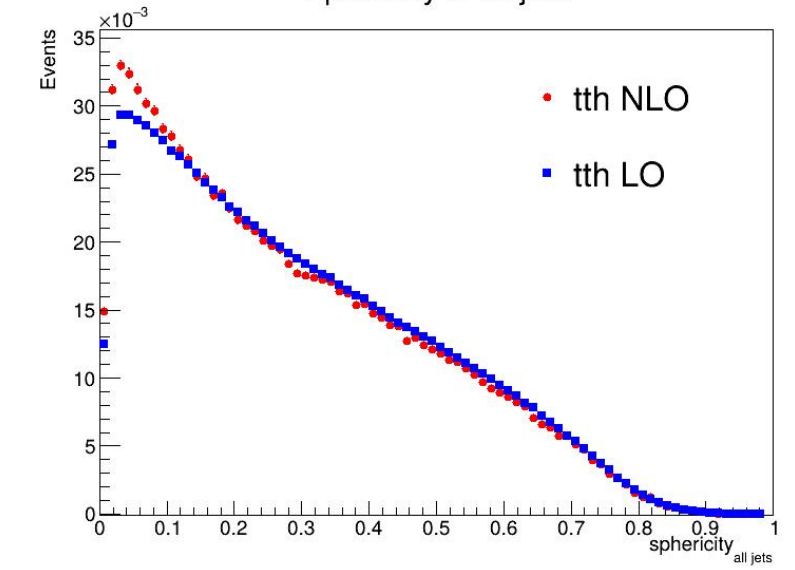
Sphericity of all jets



Sphericity of all jets

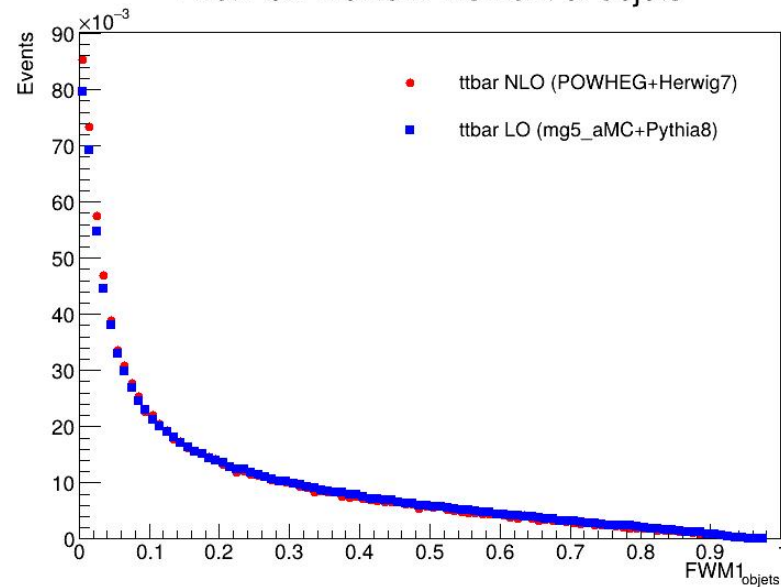


Sphericity of all jets

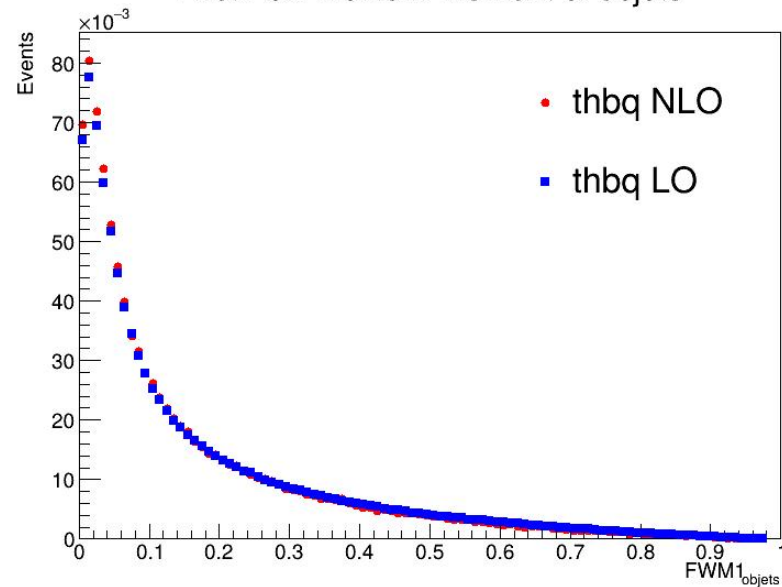


First and Second Fox-Wolfram moment for the signal and background processes

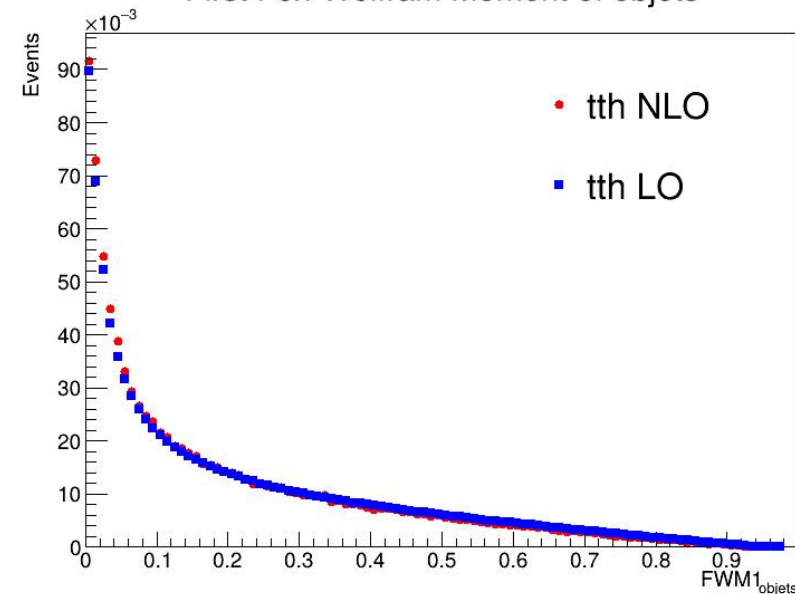
First Fox-Wolfram Moment of objets



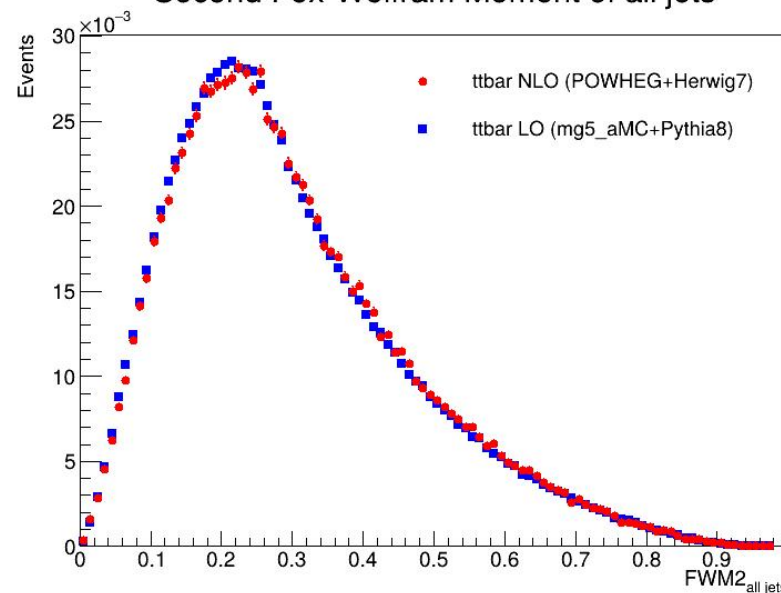
First Fox-Wolfram Moment of objets



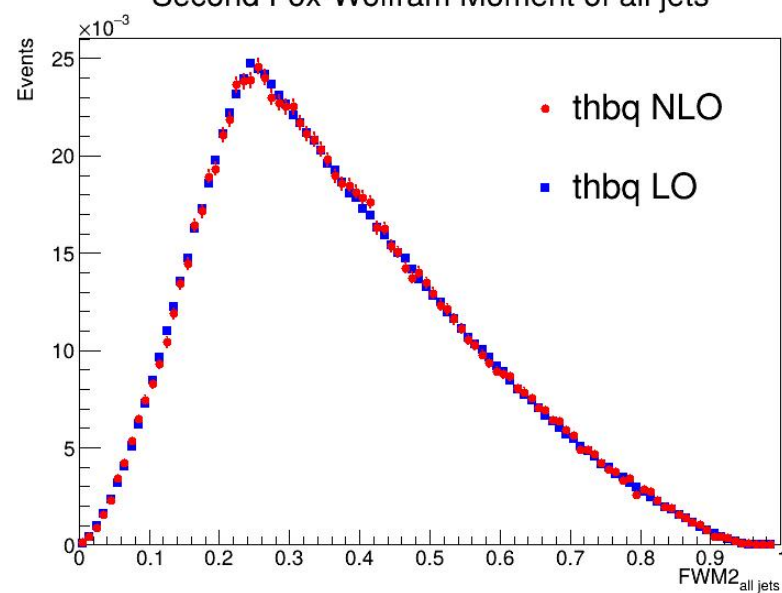
First Fox-Wolfram Moment of objets



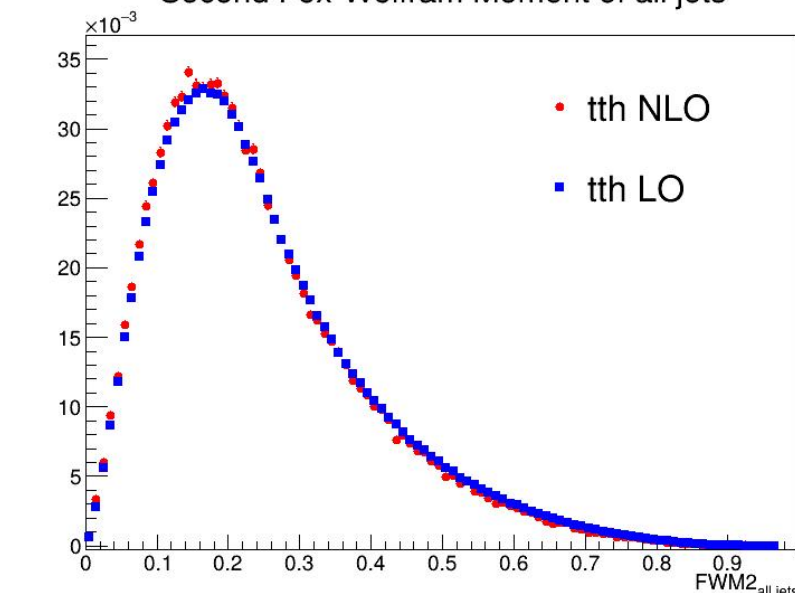
Second Fox-Wolfram Moment of all jets



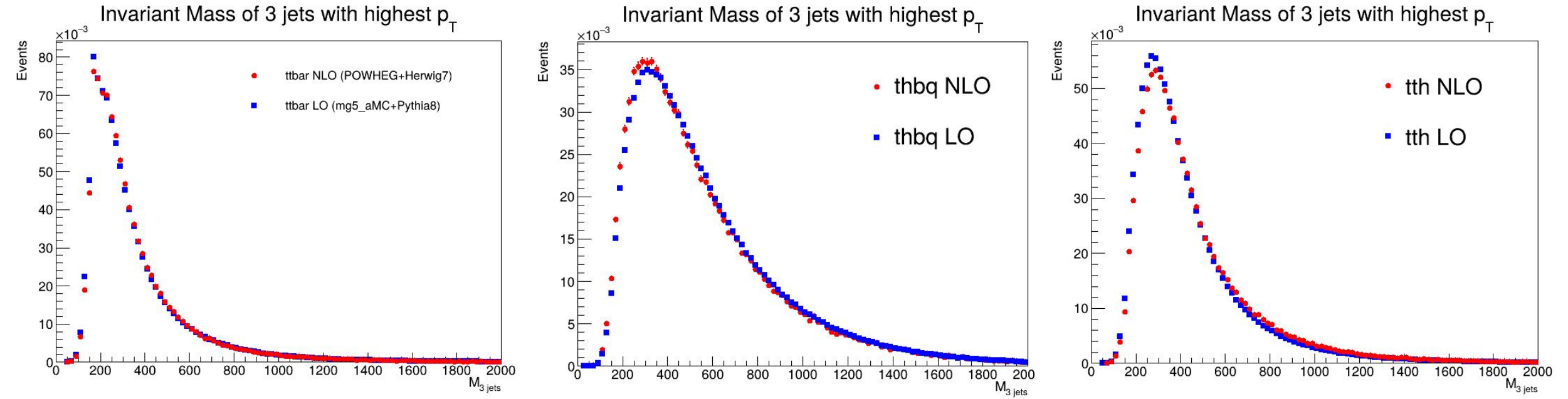
Second Fox-Wolfram Moment of all jets



Second Fox-Wolfram Moment of all jets

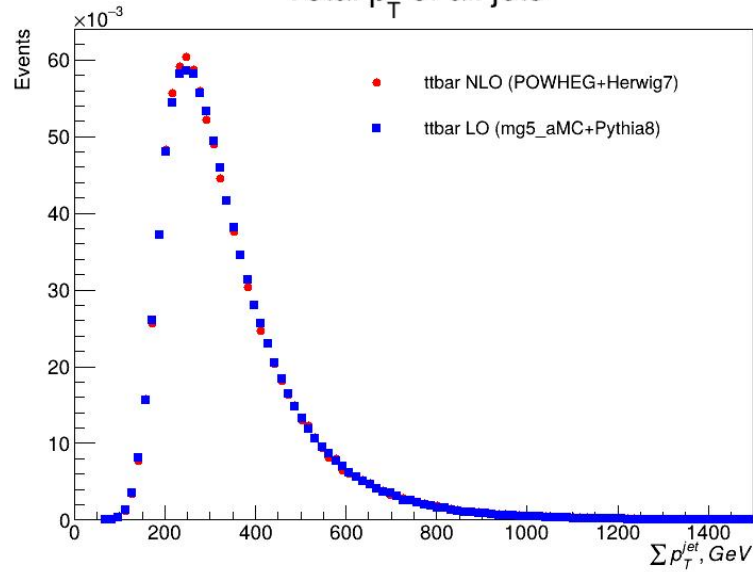


Invariant mass of 3 jets with highest p_T for the signal and background processes

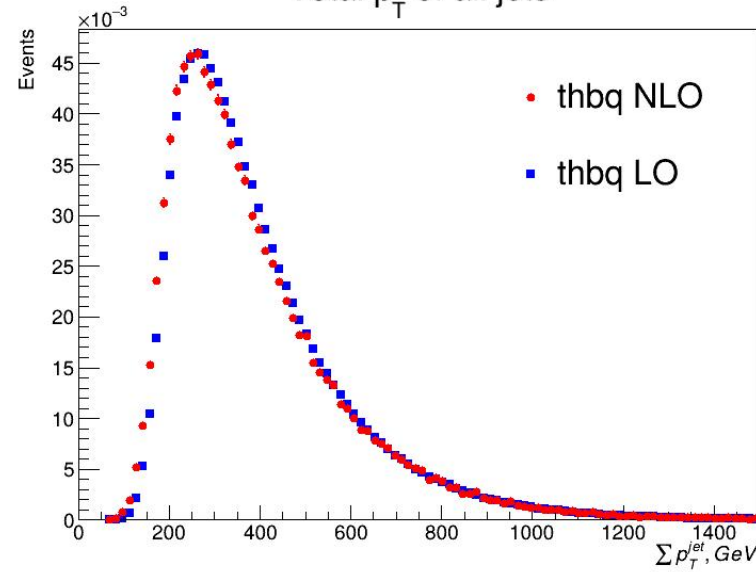


Total p_T and transverse mass of all jets for the signal and background processes

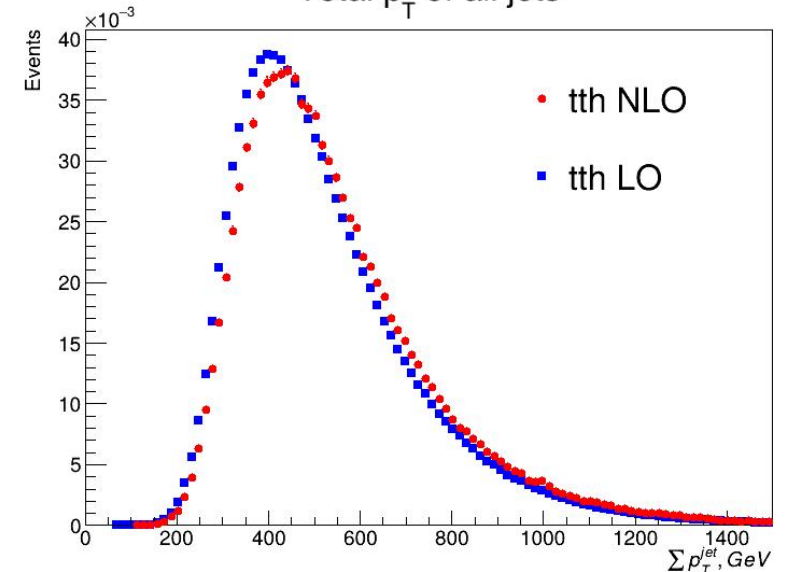
Total p_T of all jets



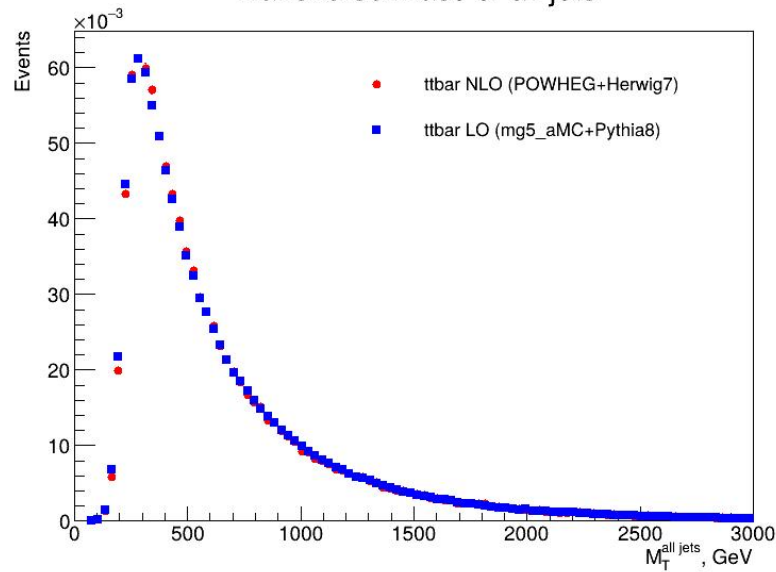
Total p_T of all jets



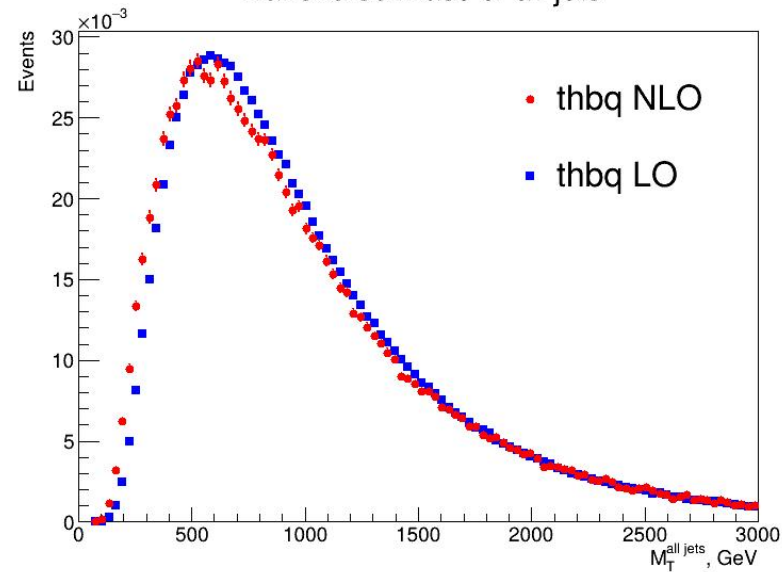
Total p_T of all jets



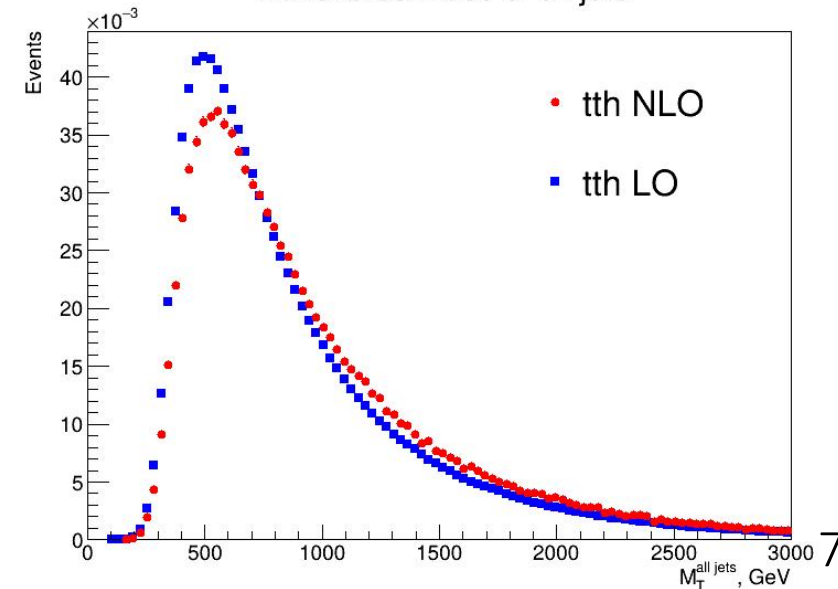
Transverse mass of all jets



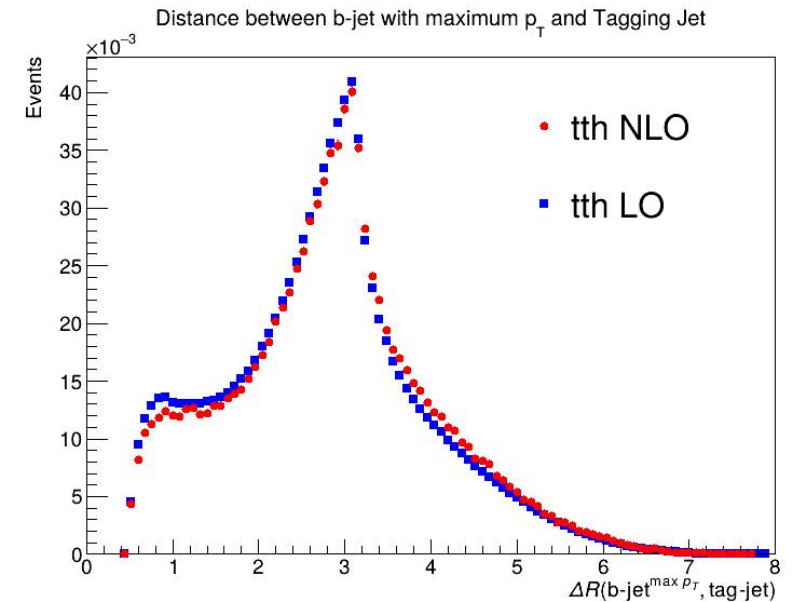
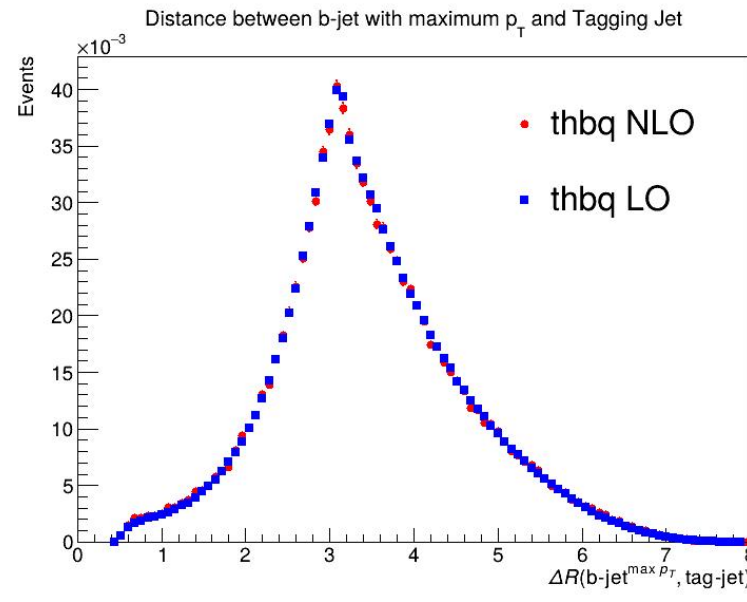
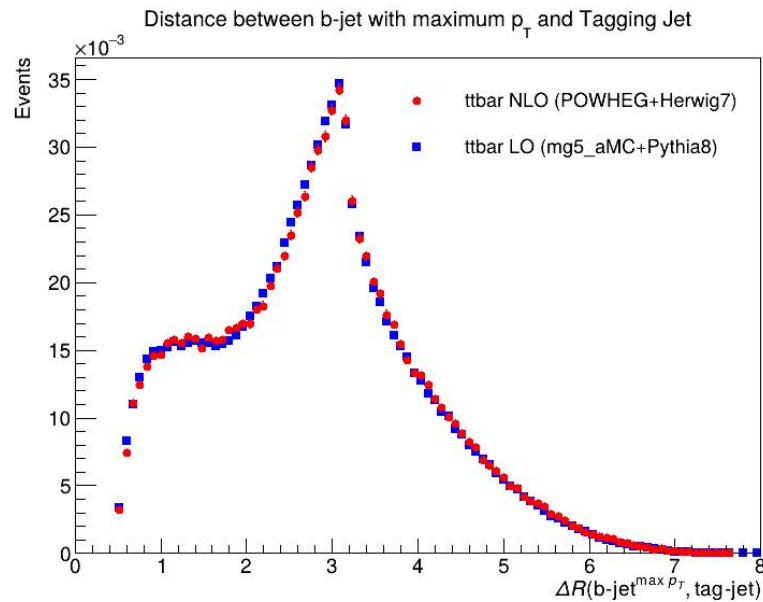
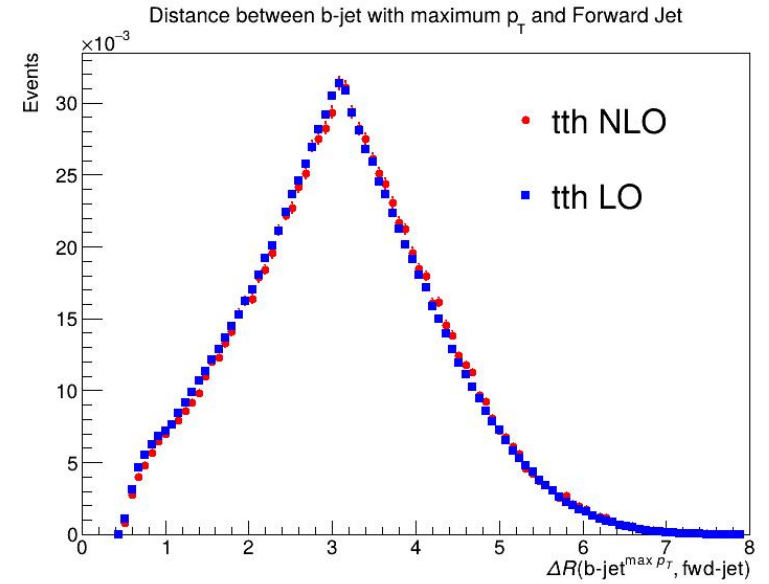
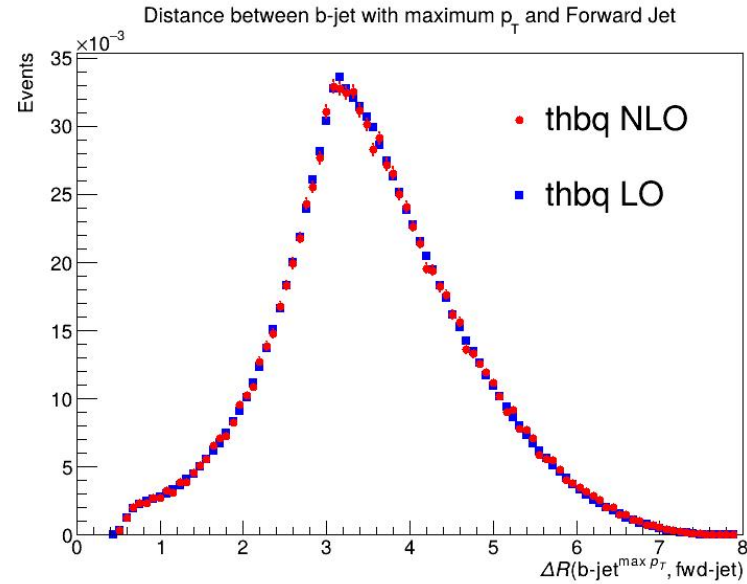
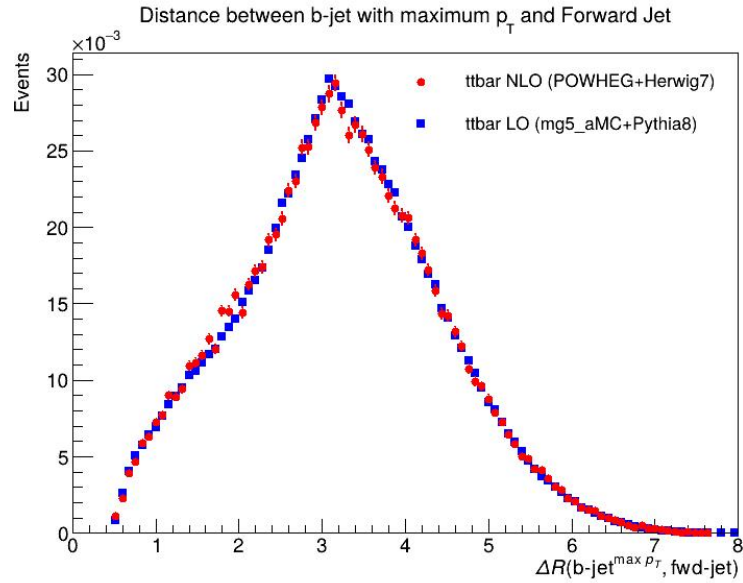
Transverse mass of all jets



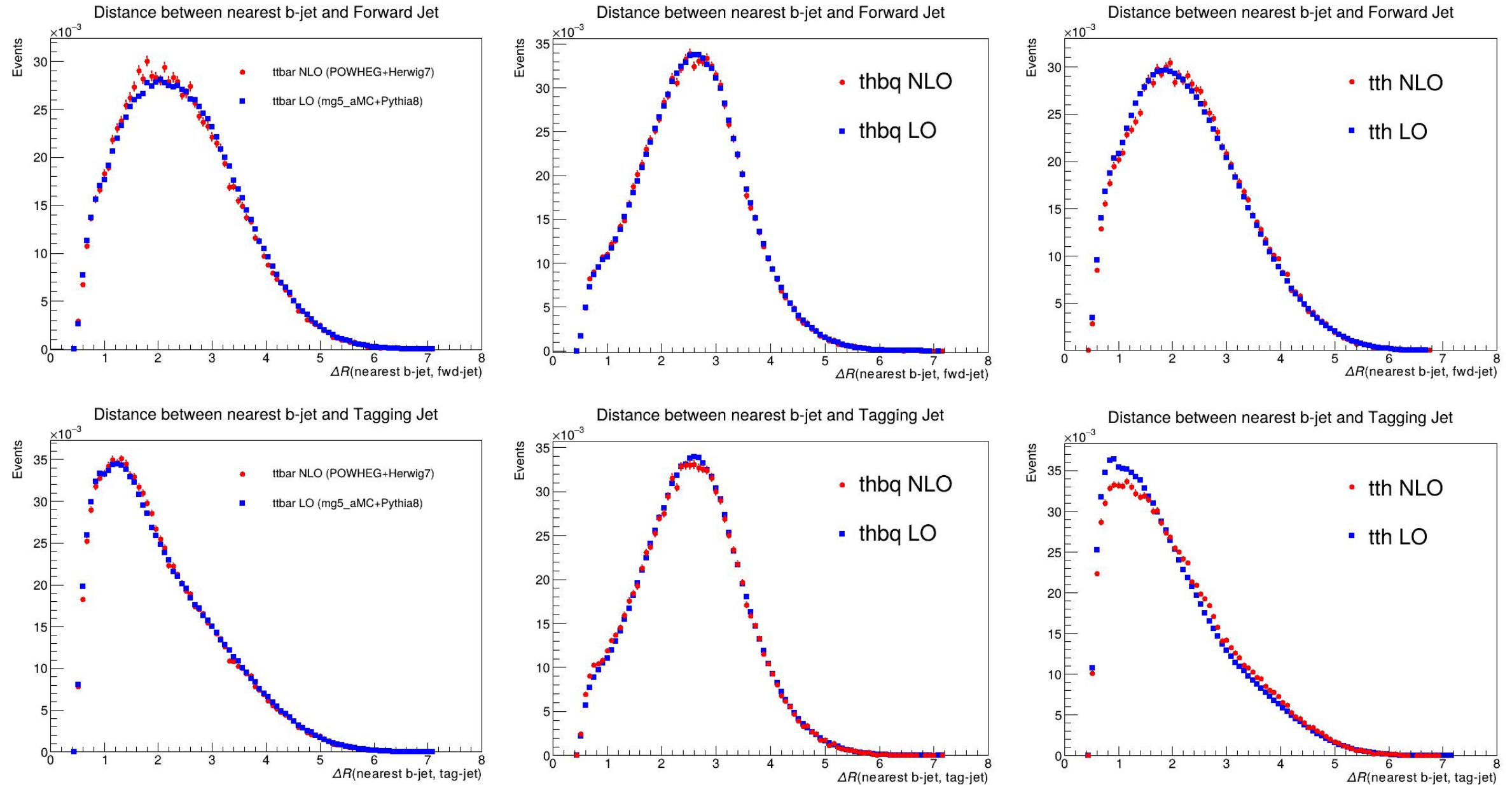
Transverse mass of all jets



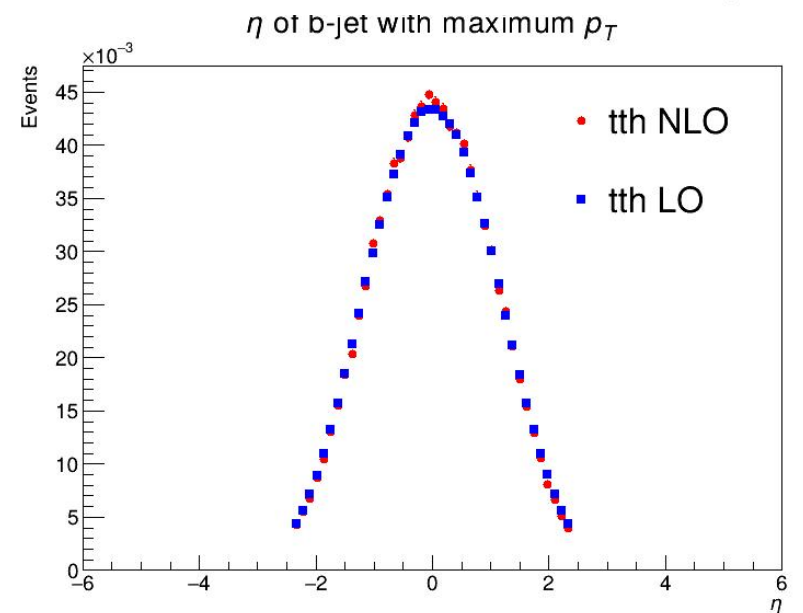
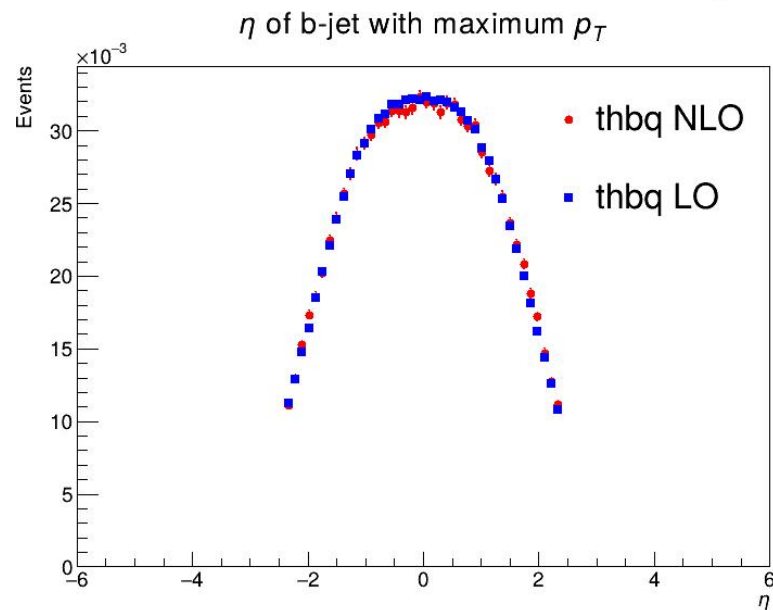
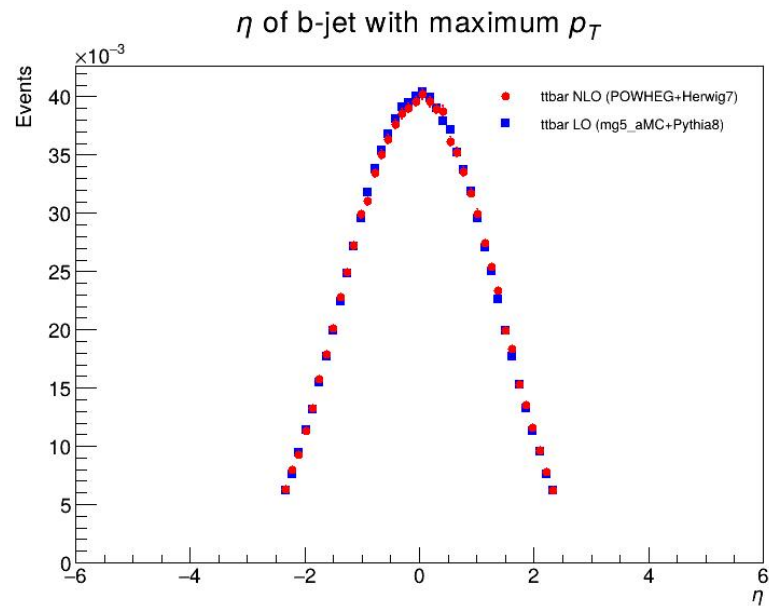
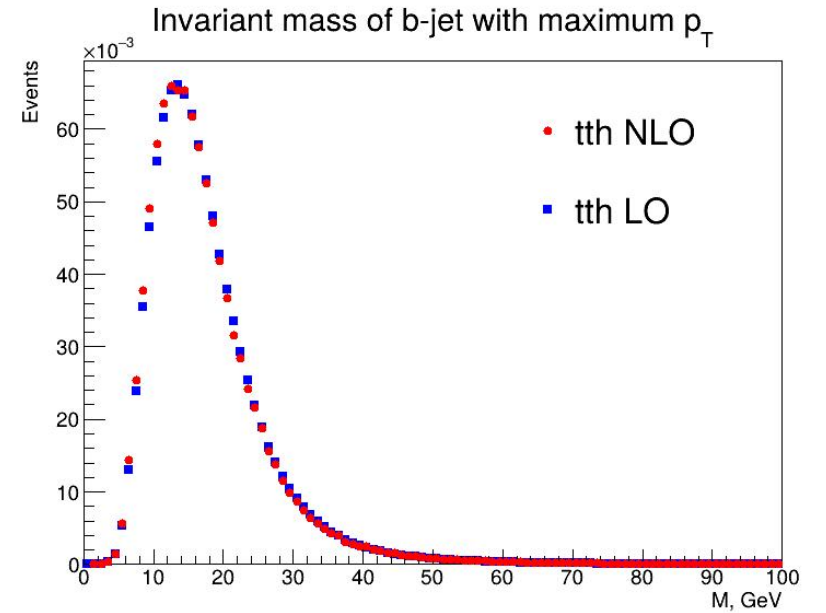
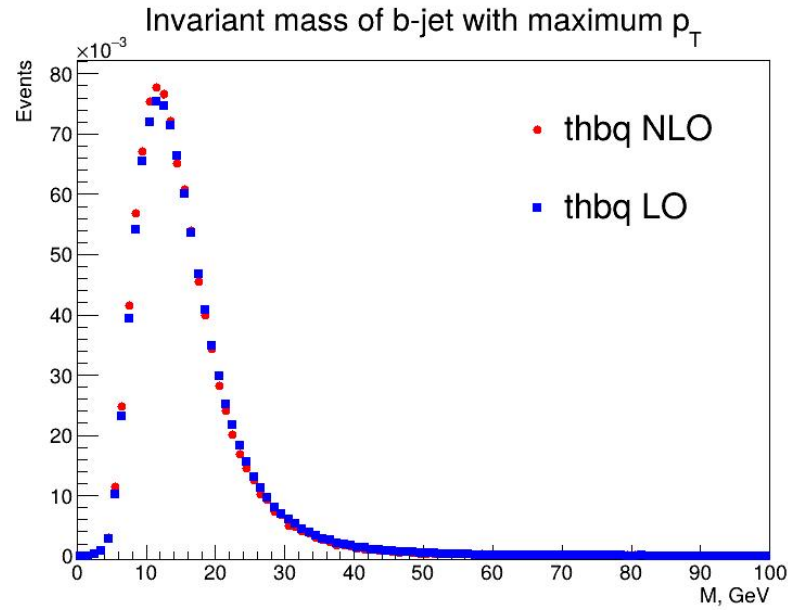
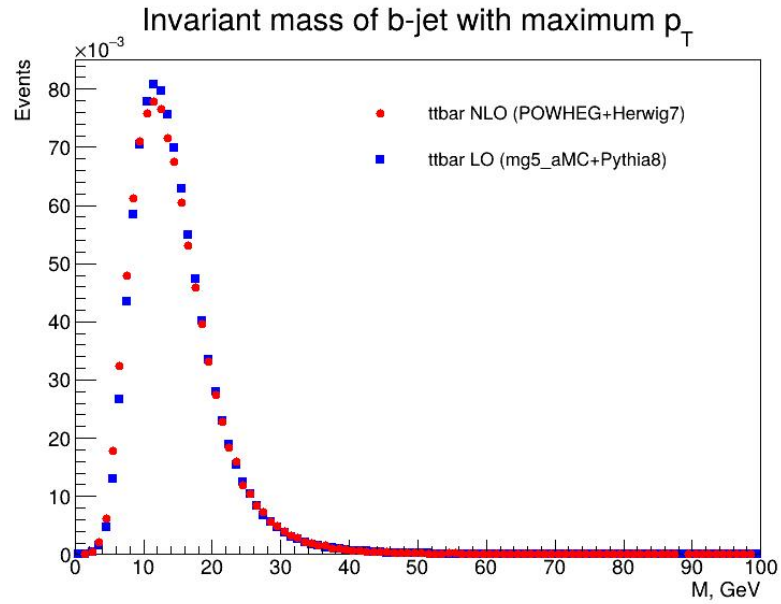
Distance between b-jet with maximum p_T and Forward (Tagging) Jet for the signal and background processes



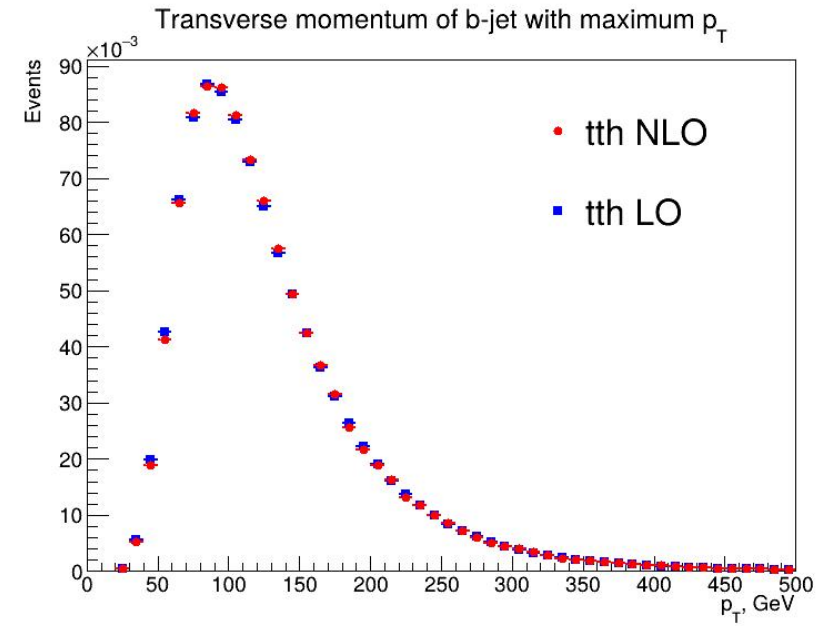
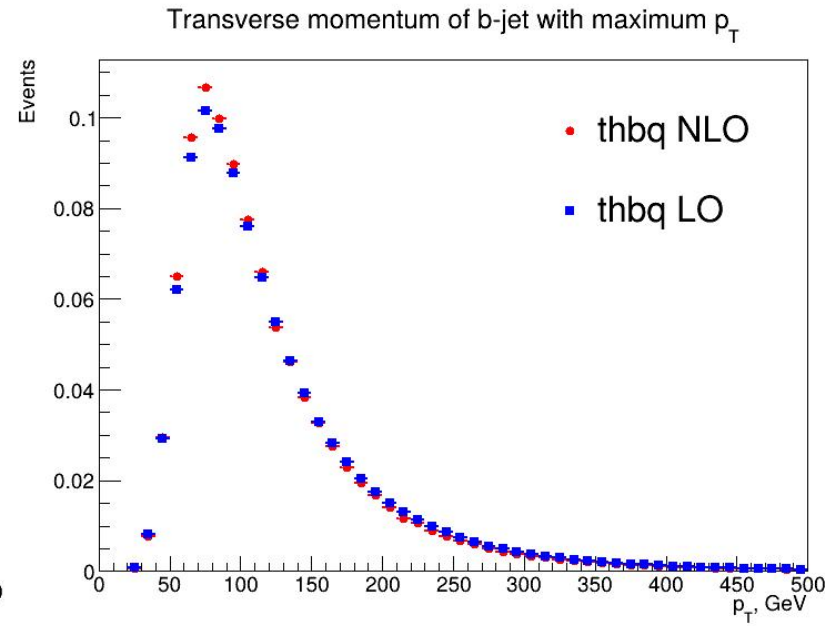
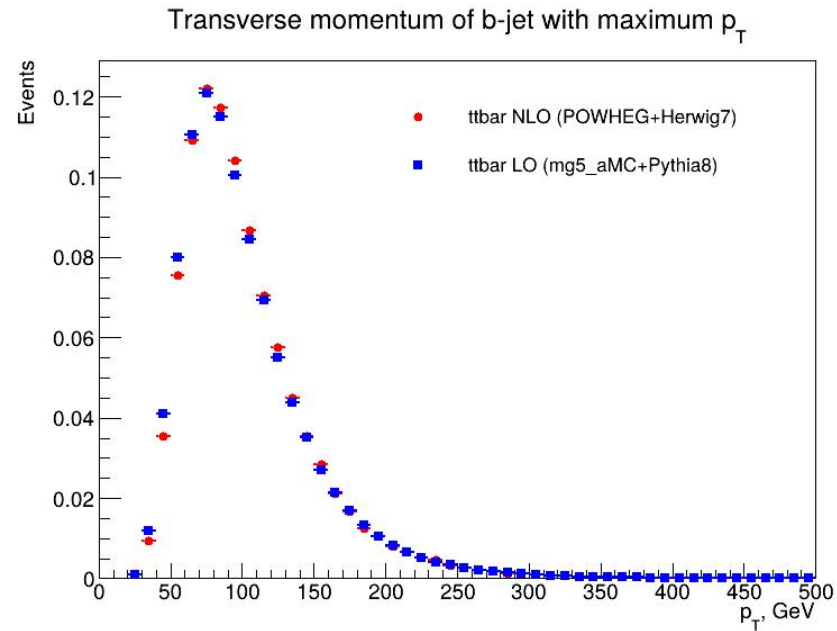
Distance between nearest b-jet and Forward (Tagging) Jet for the signal and background processes



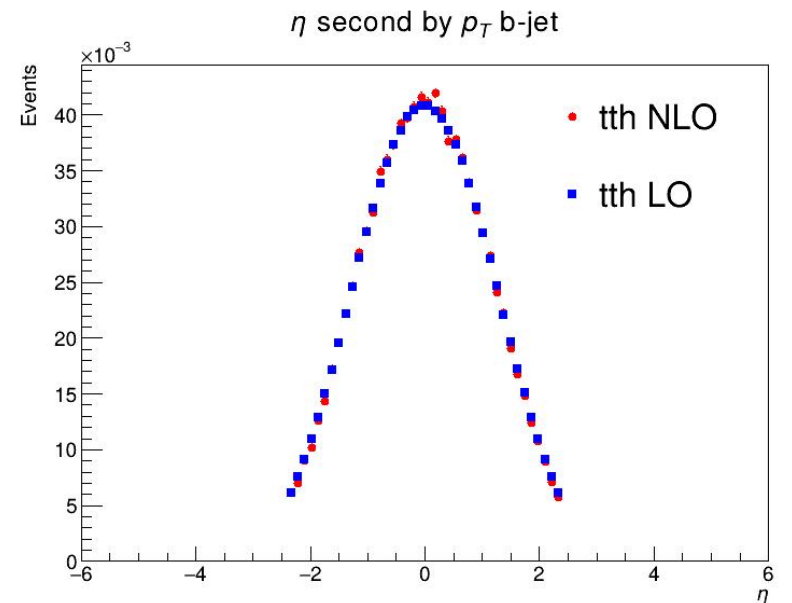
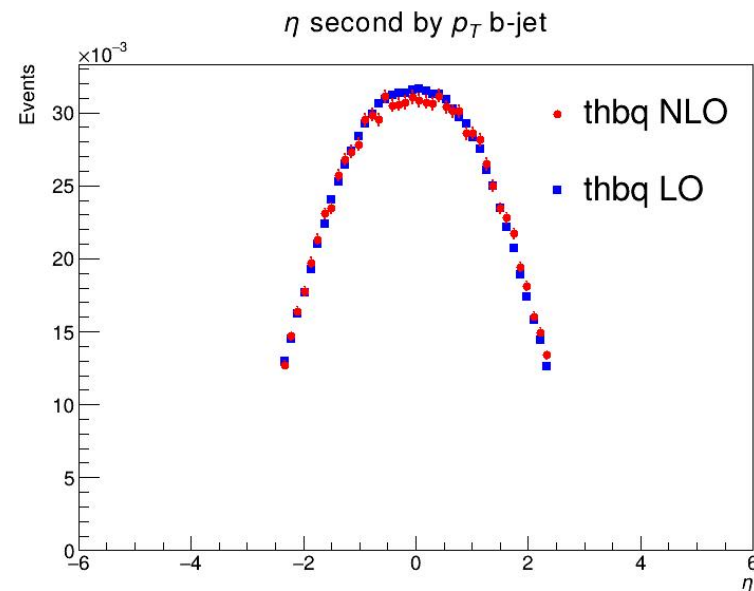
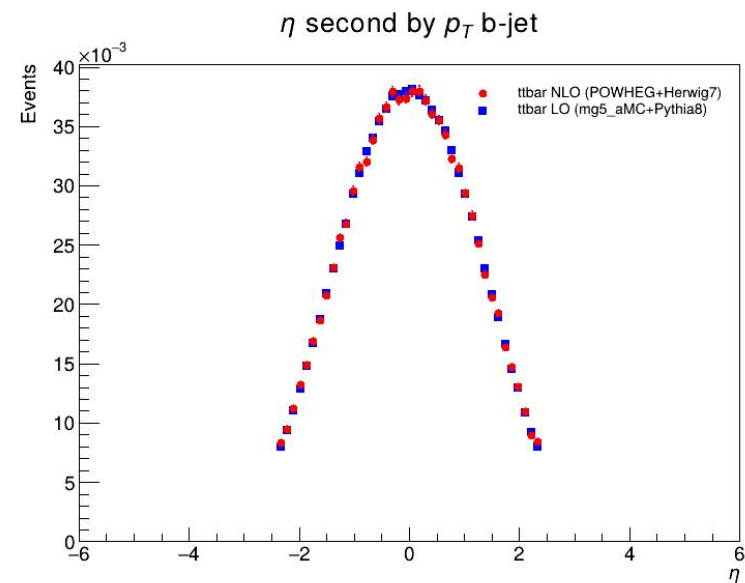
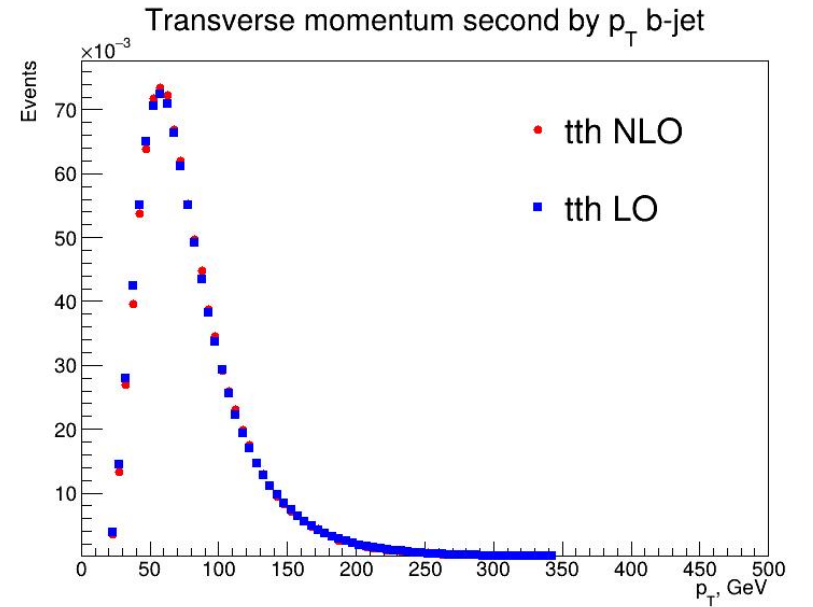
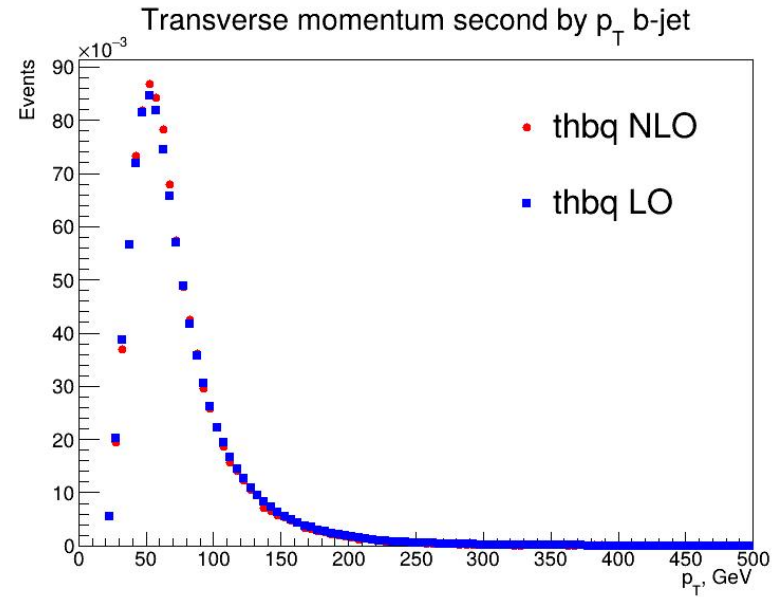
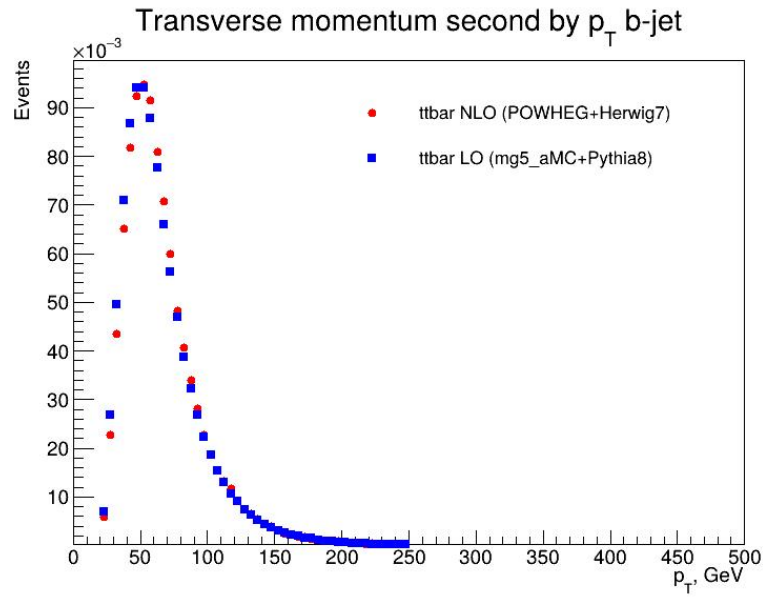
Characteristics b-jet with maximum p_T for the signal and background processes



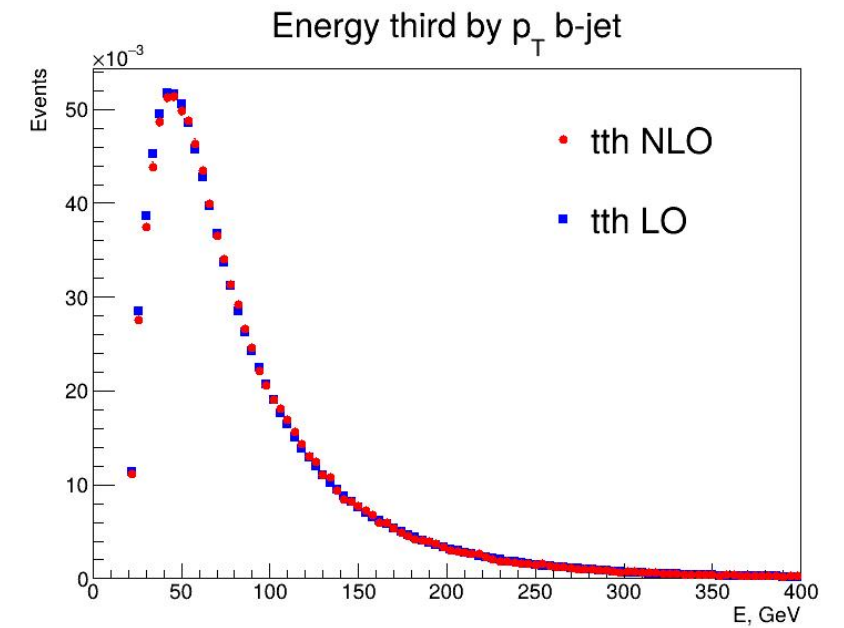
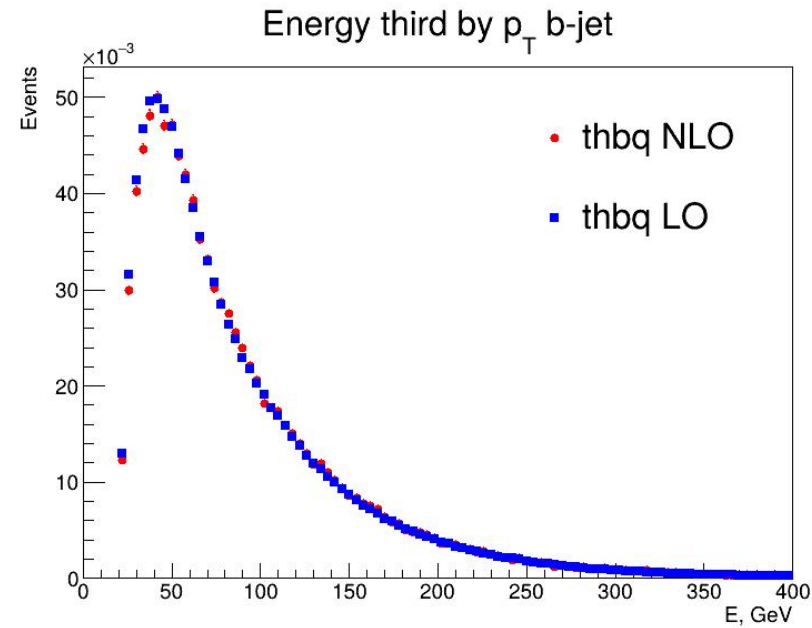
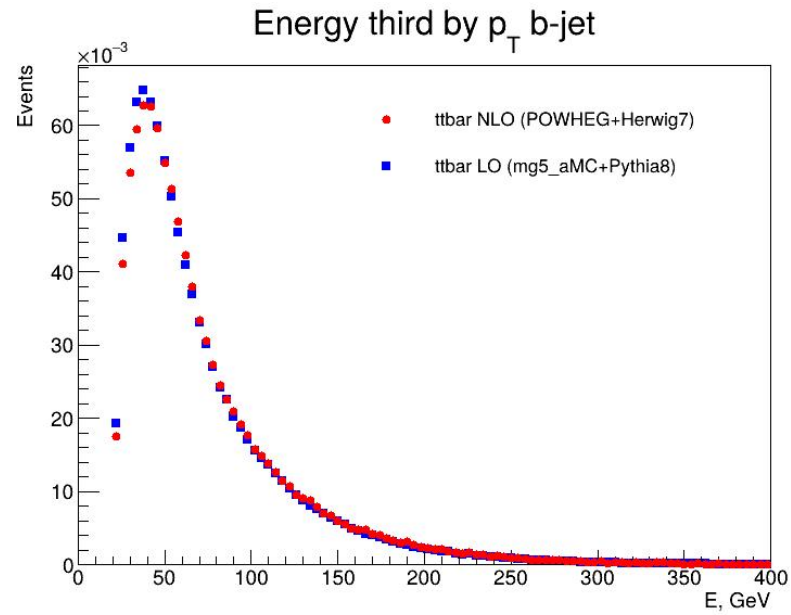
Characteristics b-jet with maximum p_T for the signal and background processes



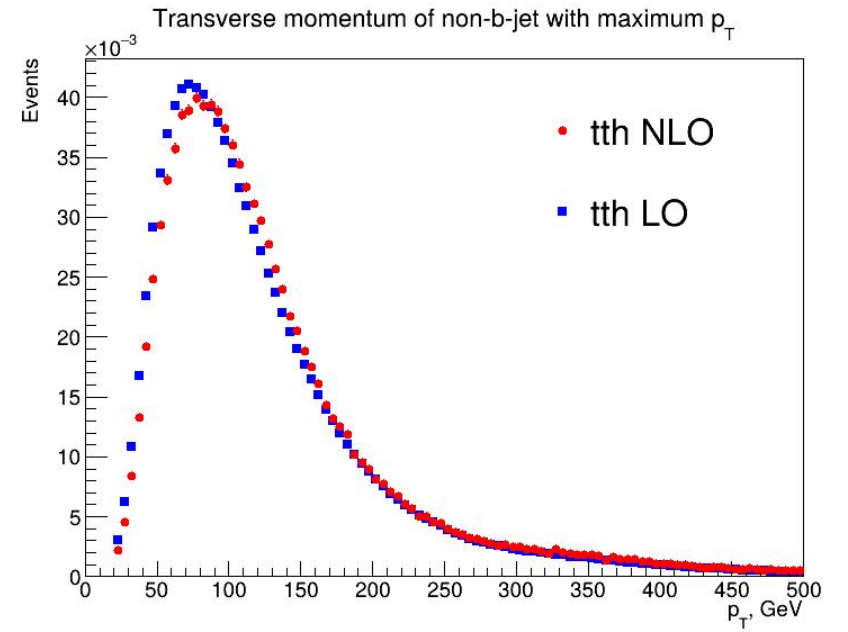
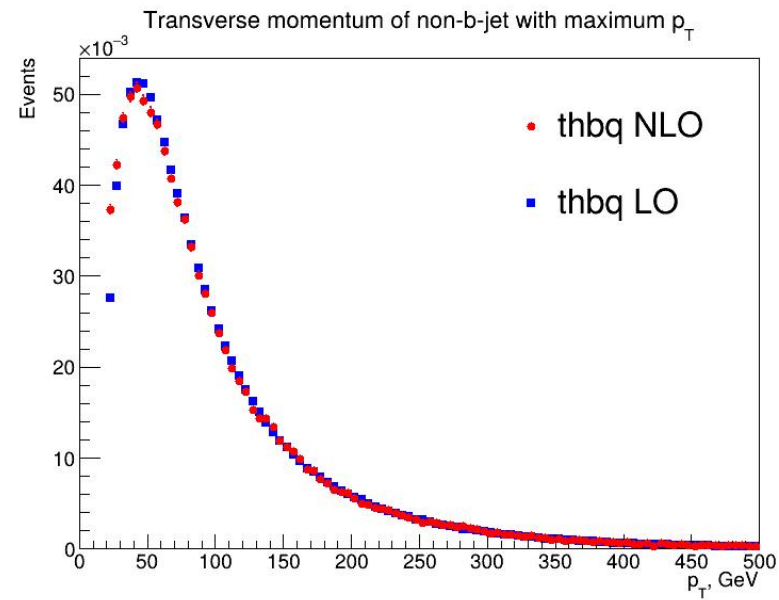
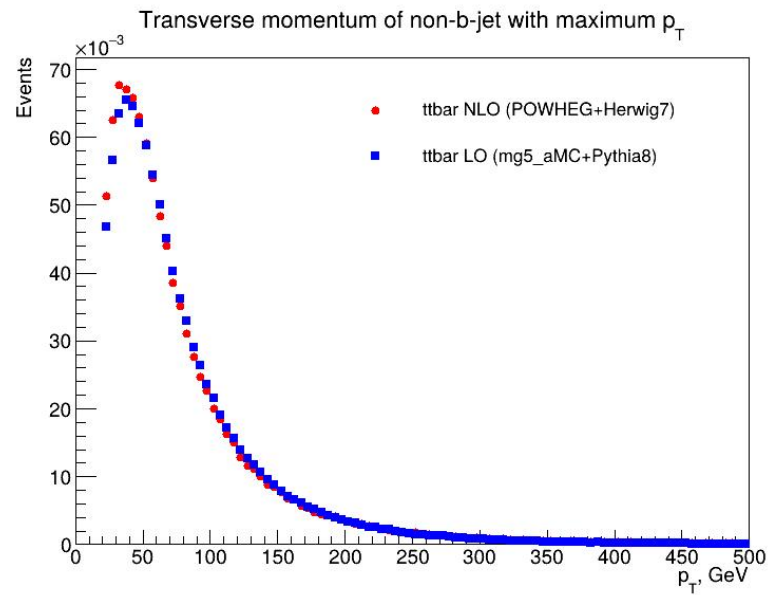
Characteristics other b-jets for the signal and background processes



Characteristics other b-jets for the signal and background processes

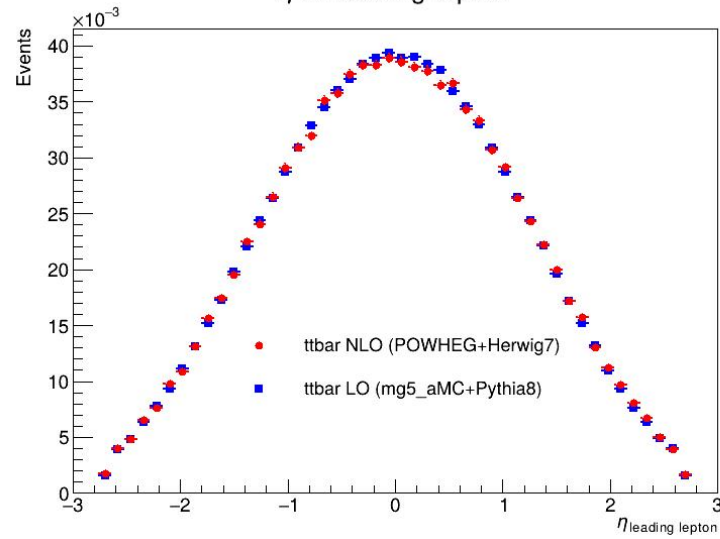


Transverse momentum non-b-jet with maximum p_T for the signal and background processes

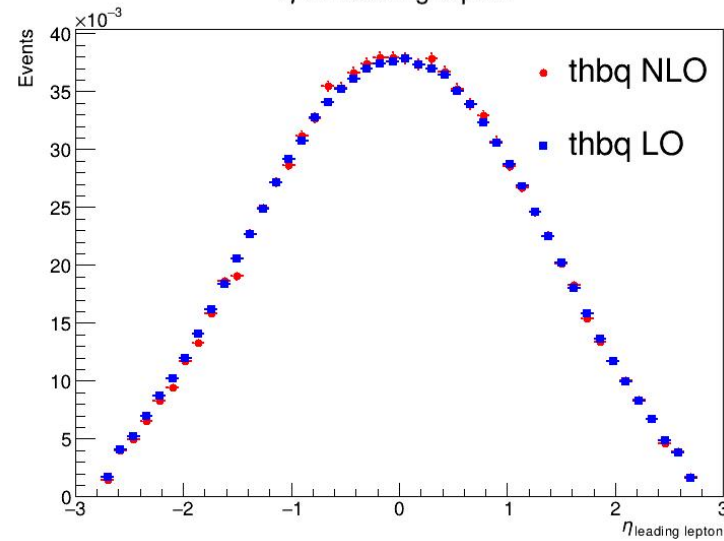


Leading lepton

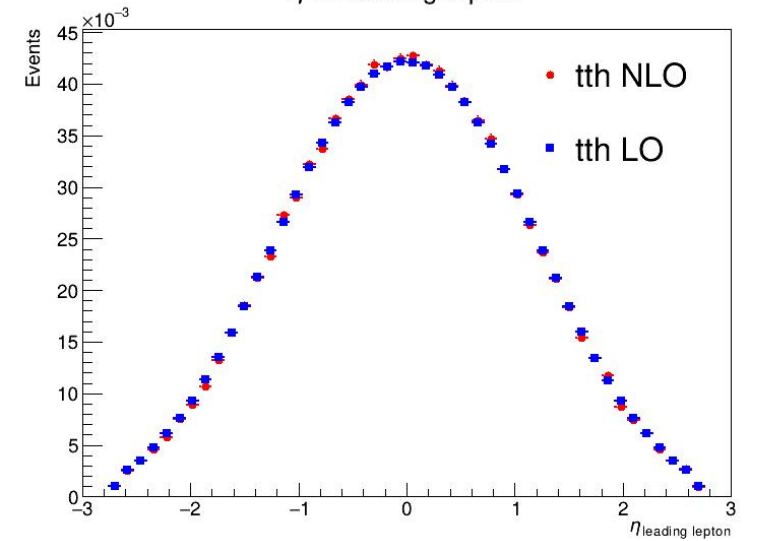
η of leading lepton



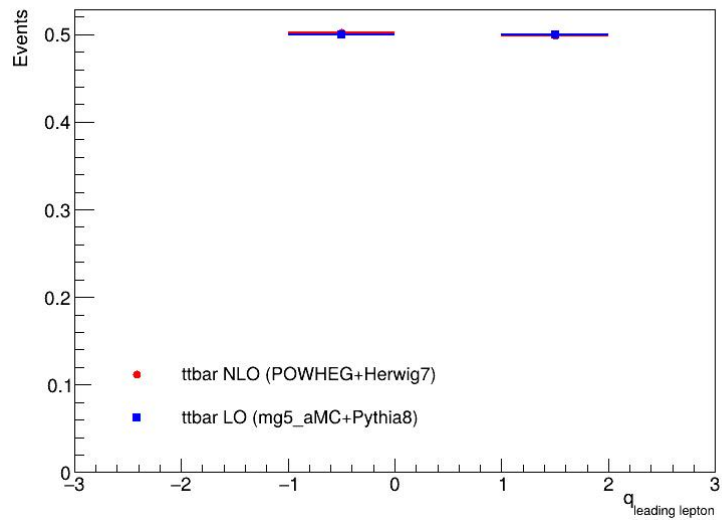
η of leading lepton



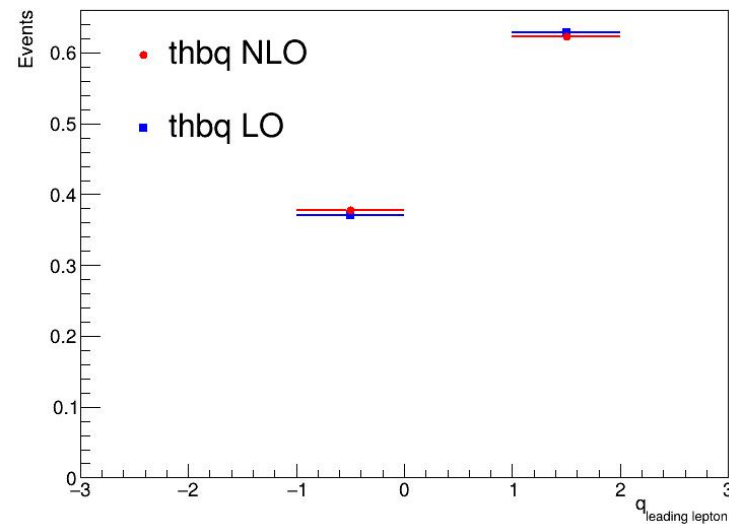
η of leading lepton



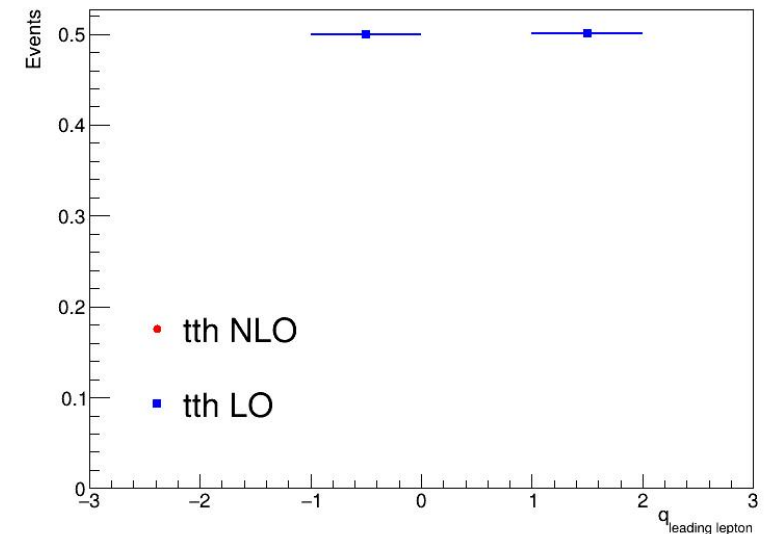
Charge of leading lepton



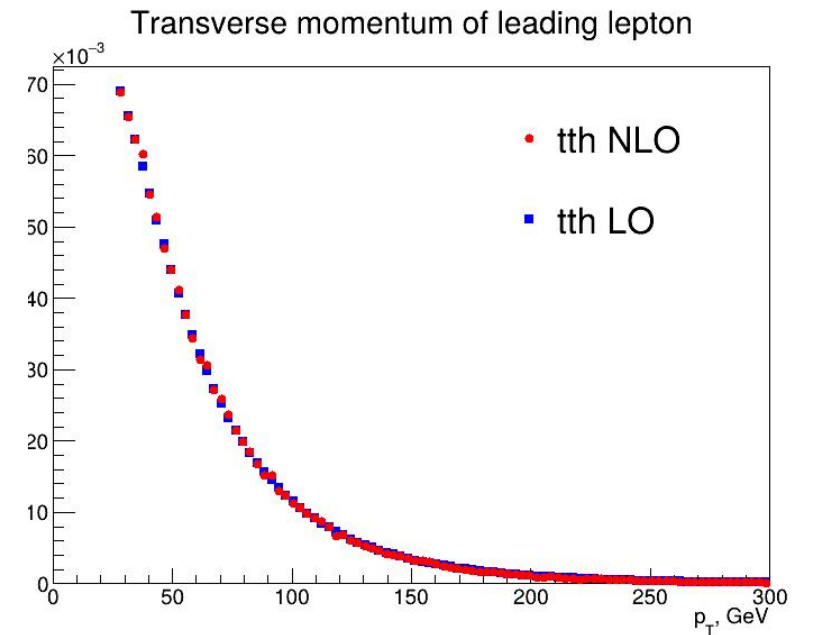
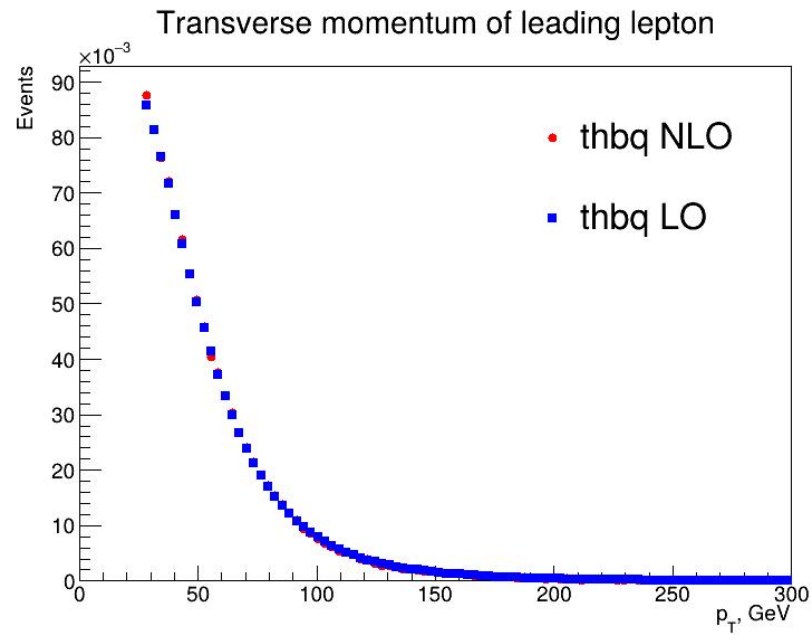
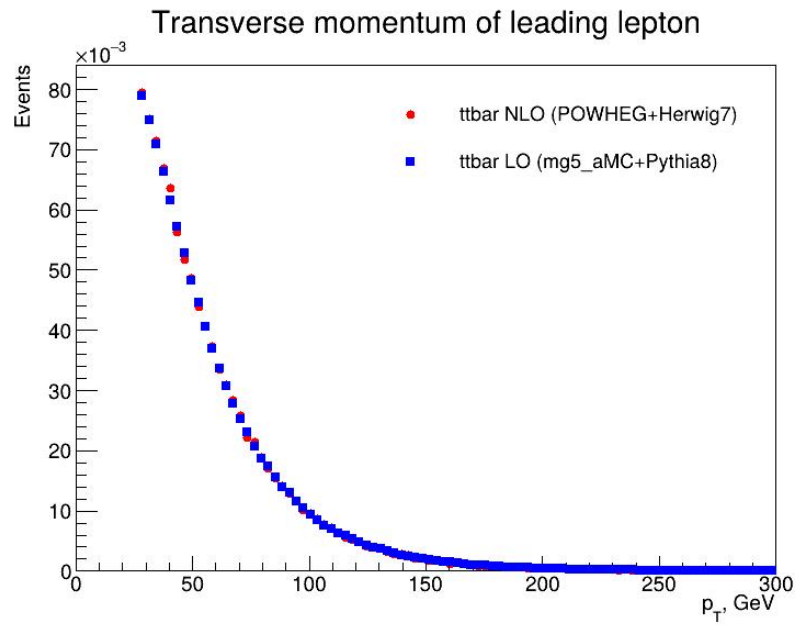
Charge of leading lepton



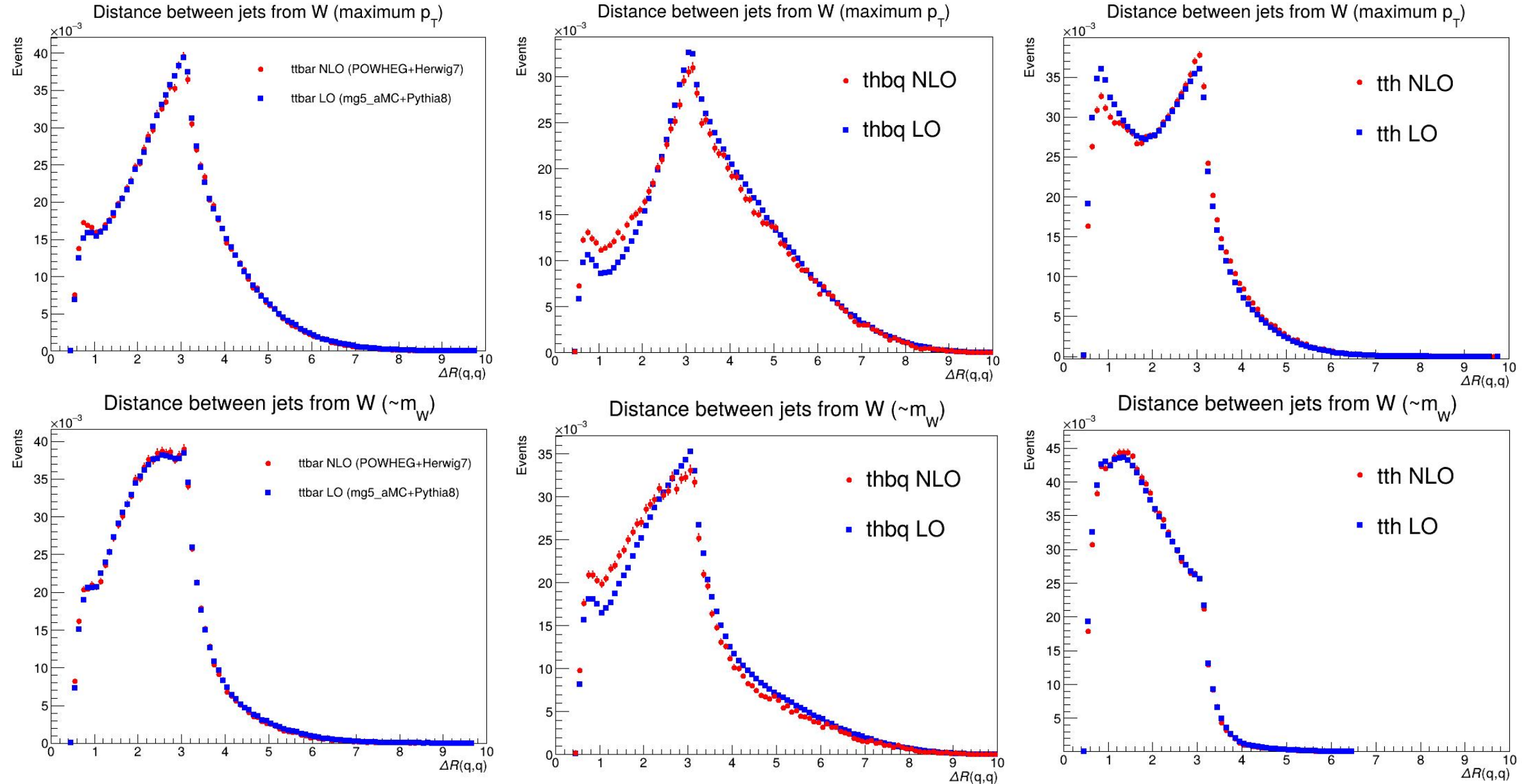
Charge of leading lepton



Leading lepton

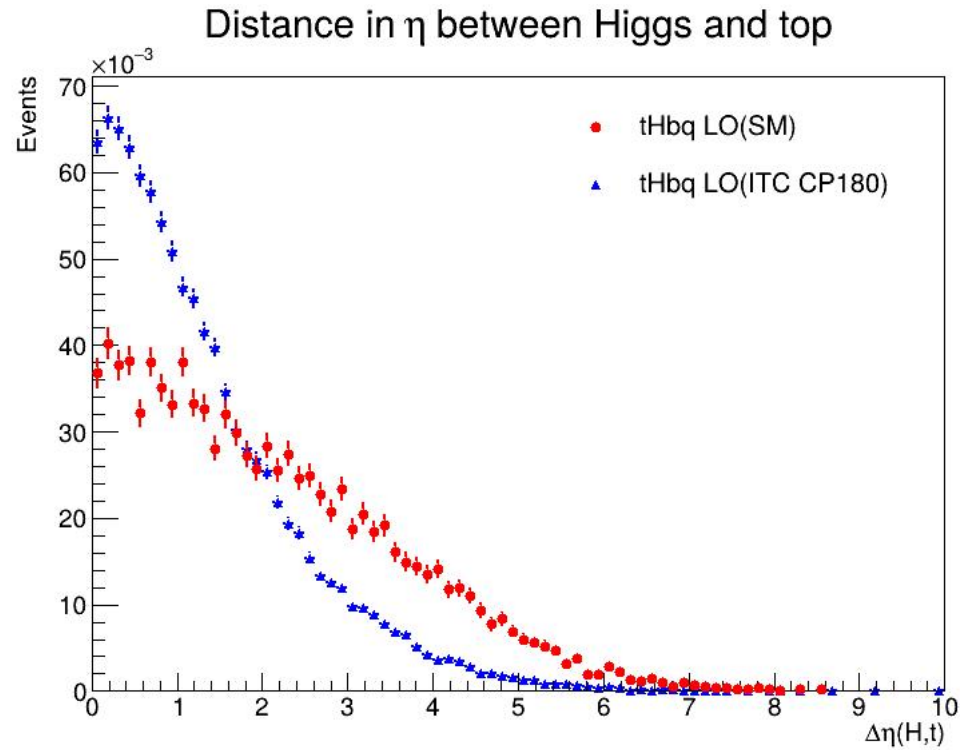


Distance between jets from W-bozon for the signal and background processes

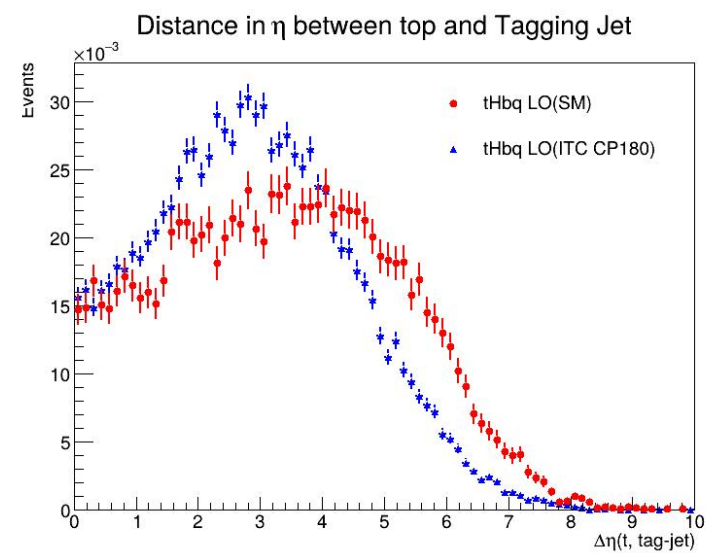
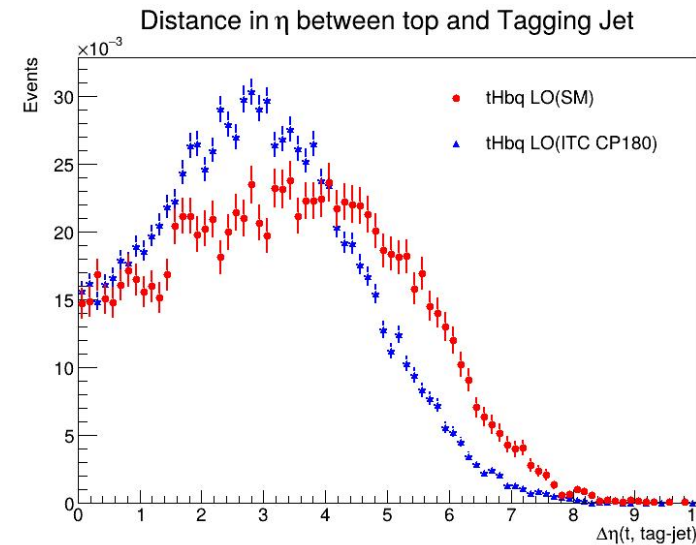
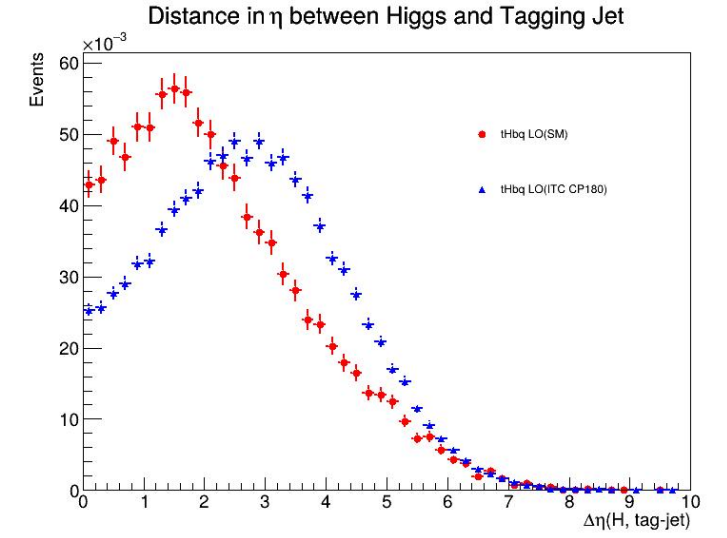
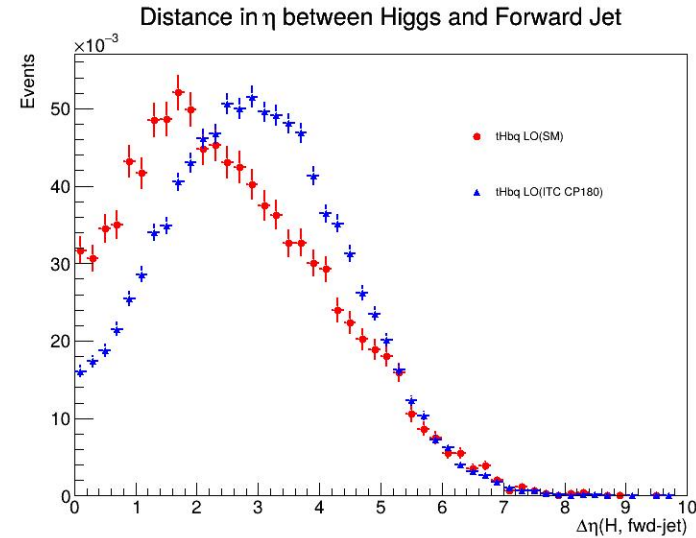


ITC

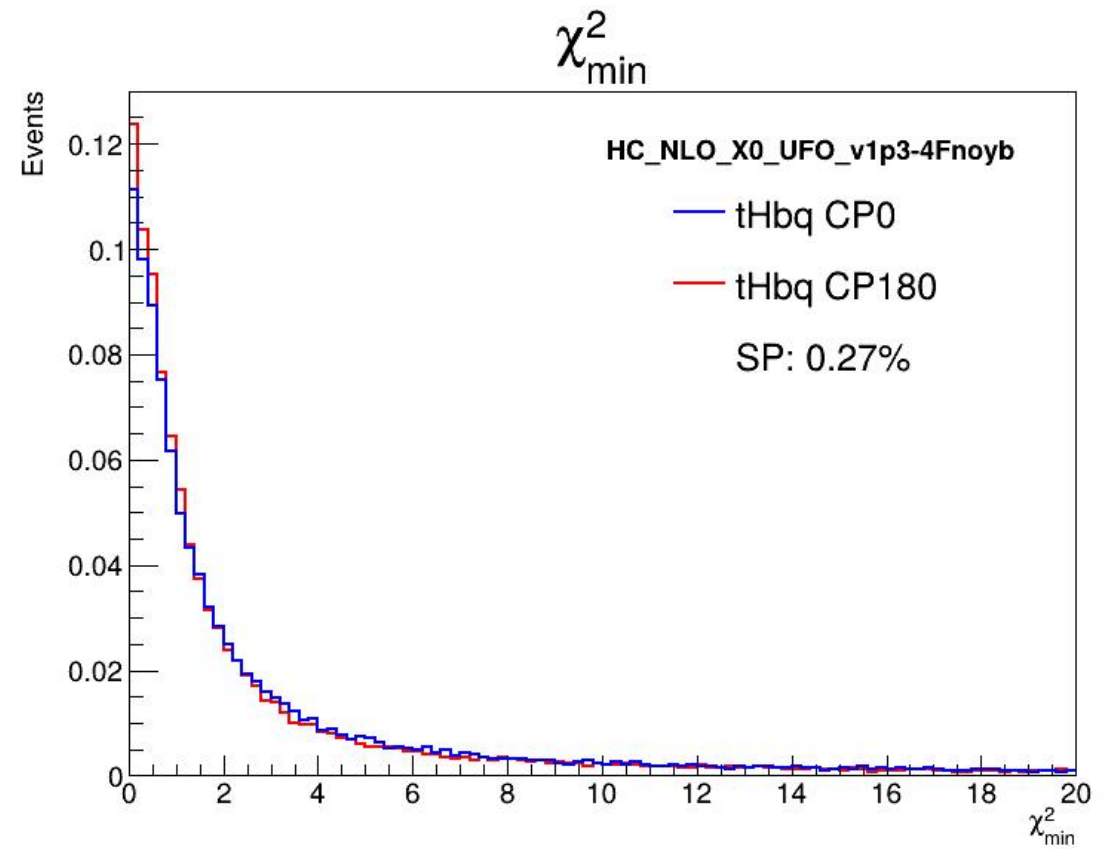
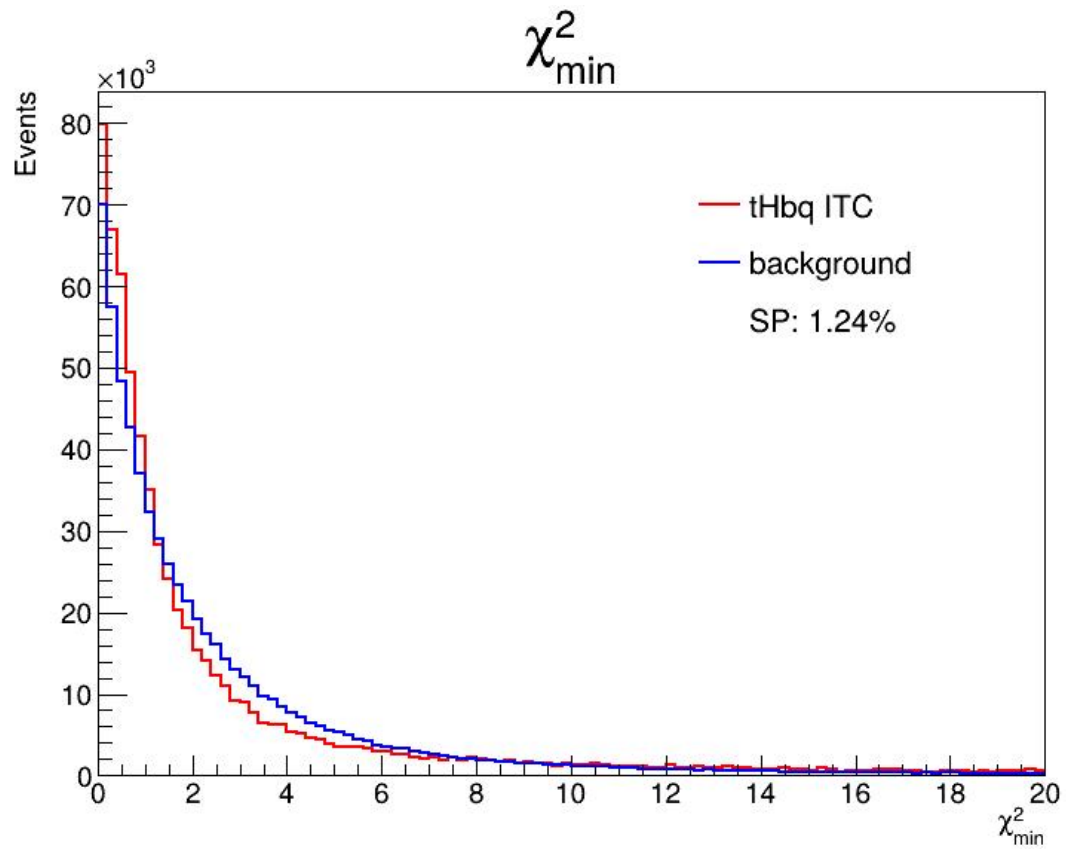
Inverted Top Coupling (ITC)



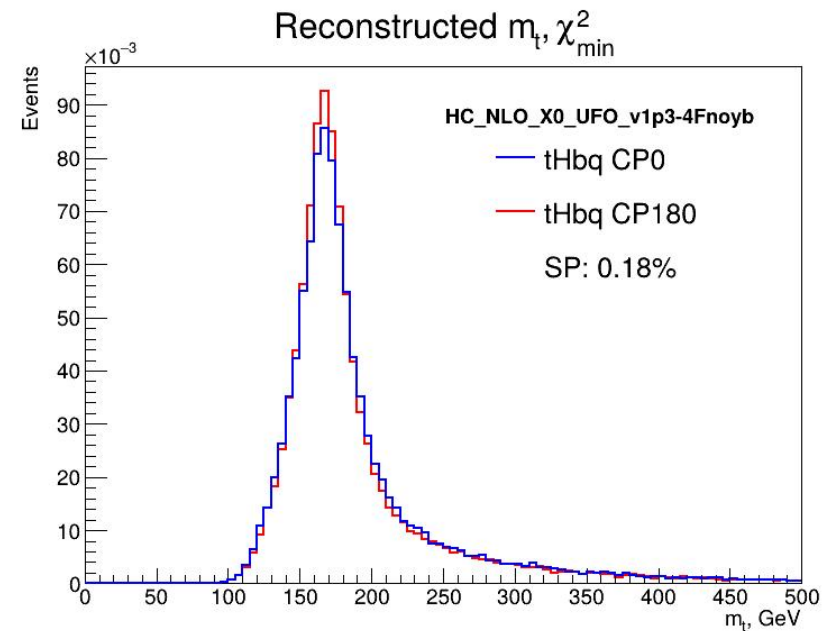
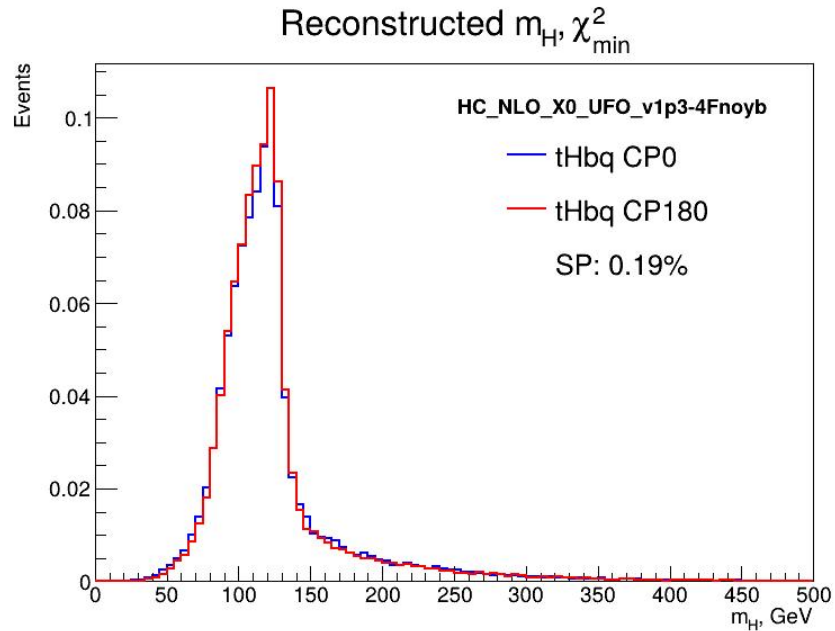
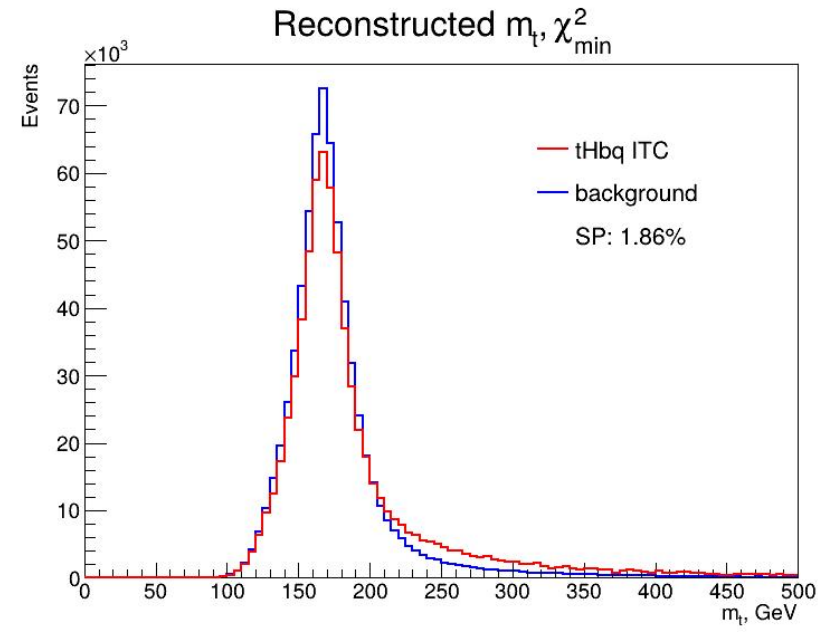
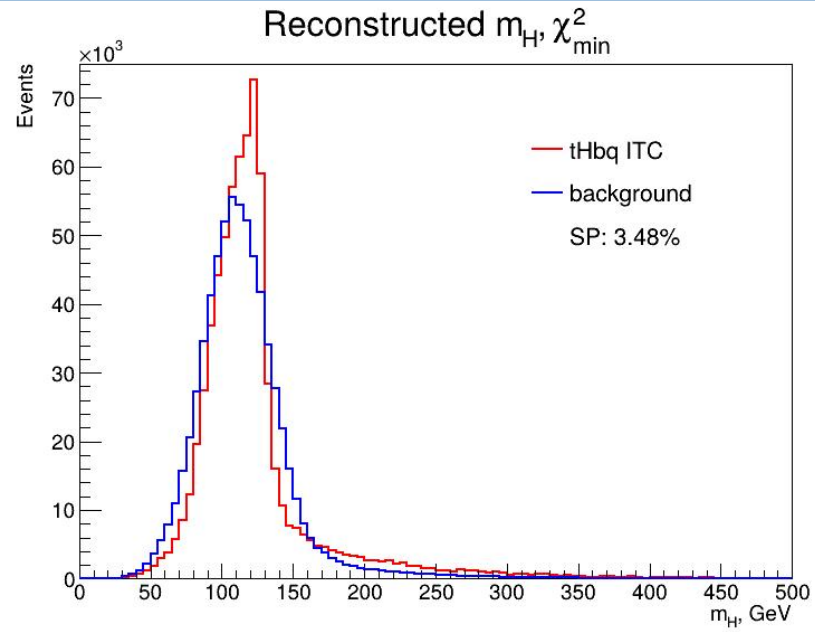
<https://arxiv.org/pdf/1306.6464>



χ^2 for the signal and background processes

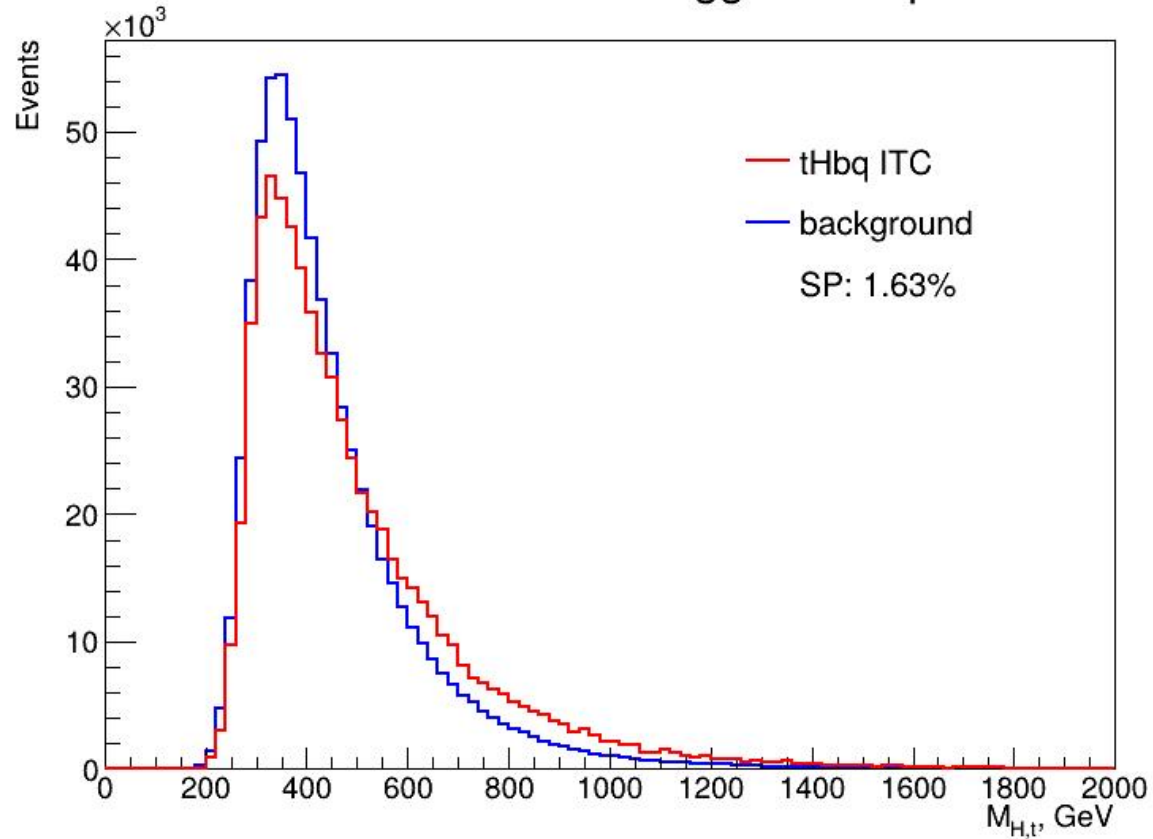


Reconstructed masses of the top quark and Higgs boson for background processes

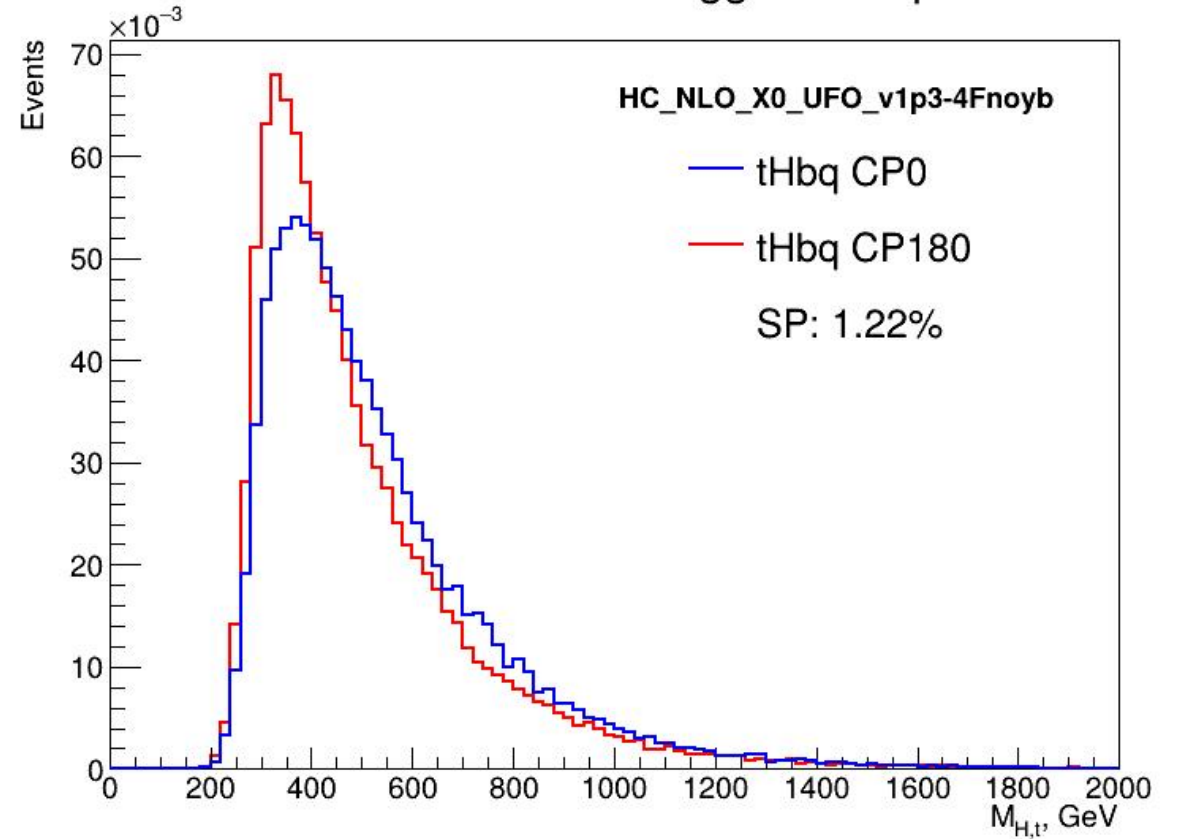


Invariant mass of the top quark and Higgs boson system for the signal and background processes

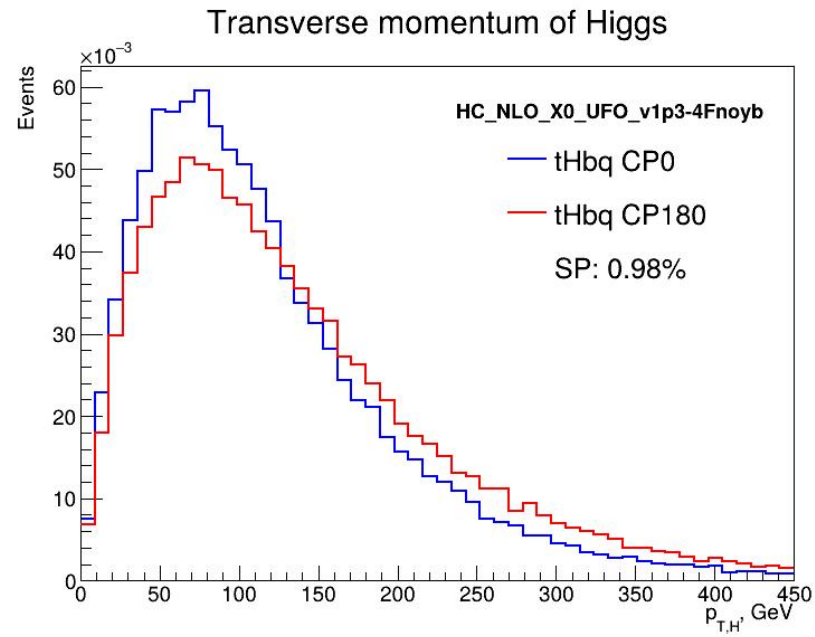
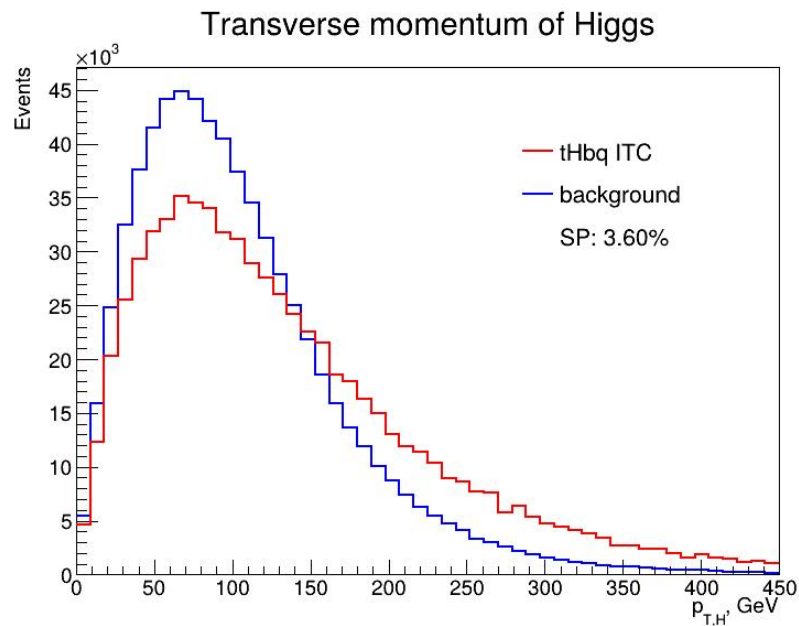
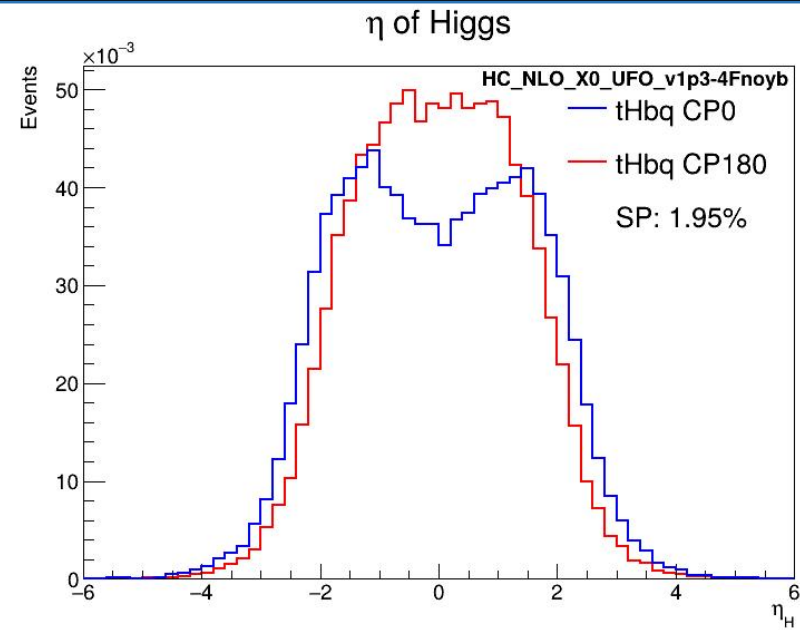
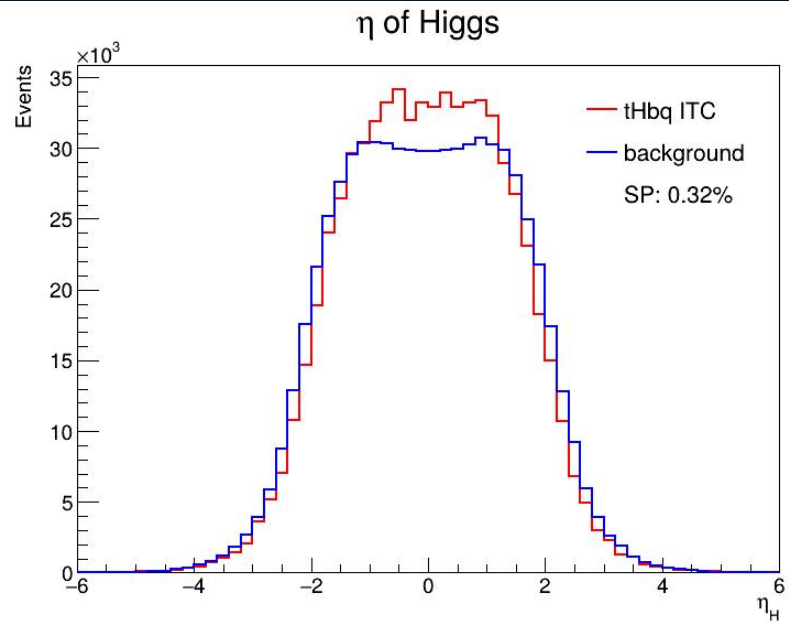
Invariant mass of Higgs and top



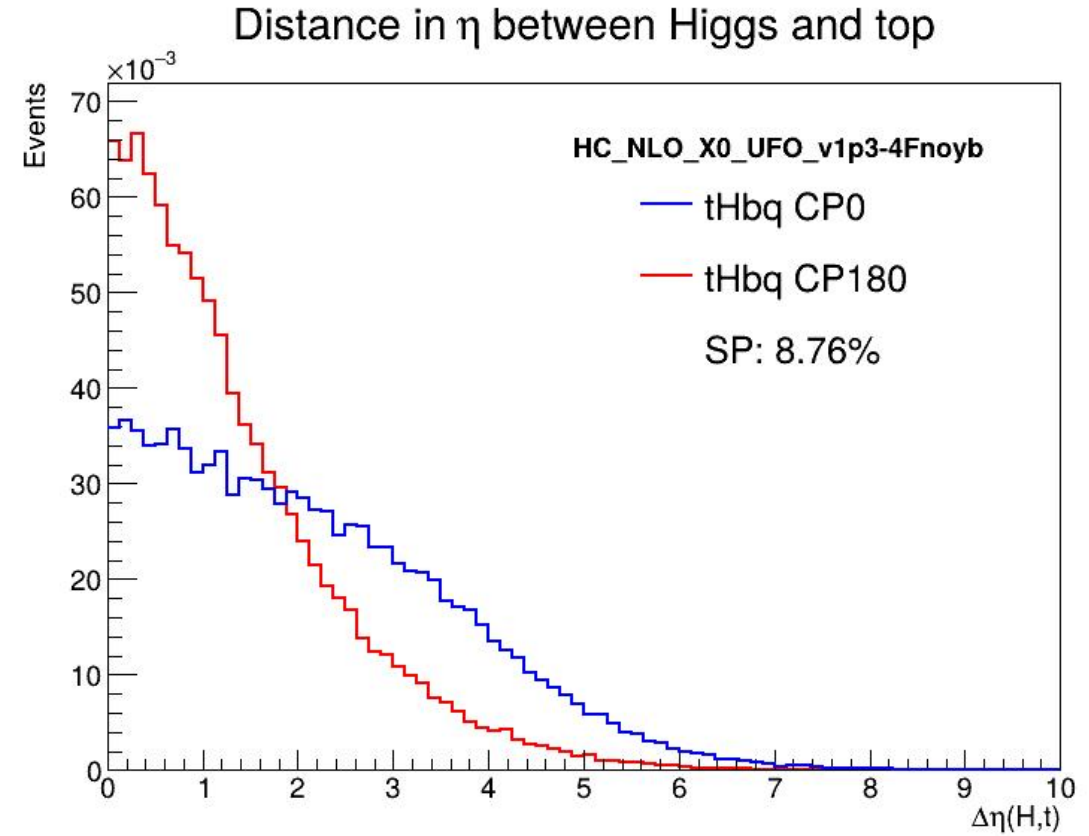
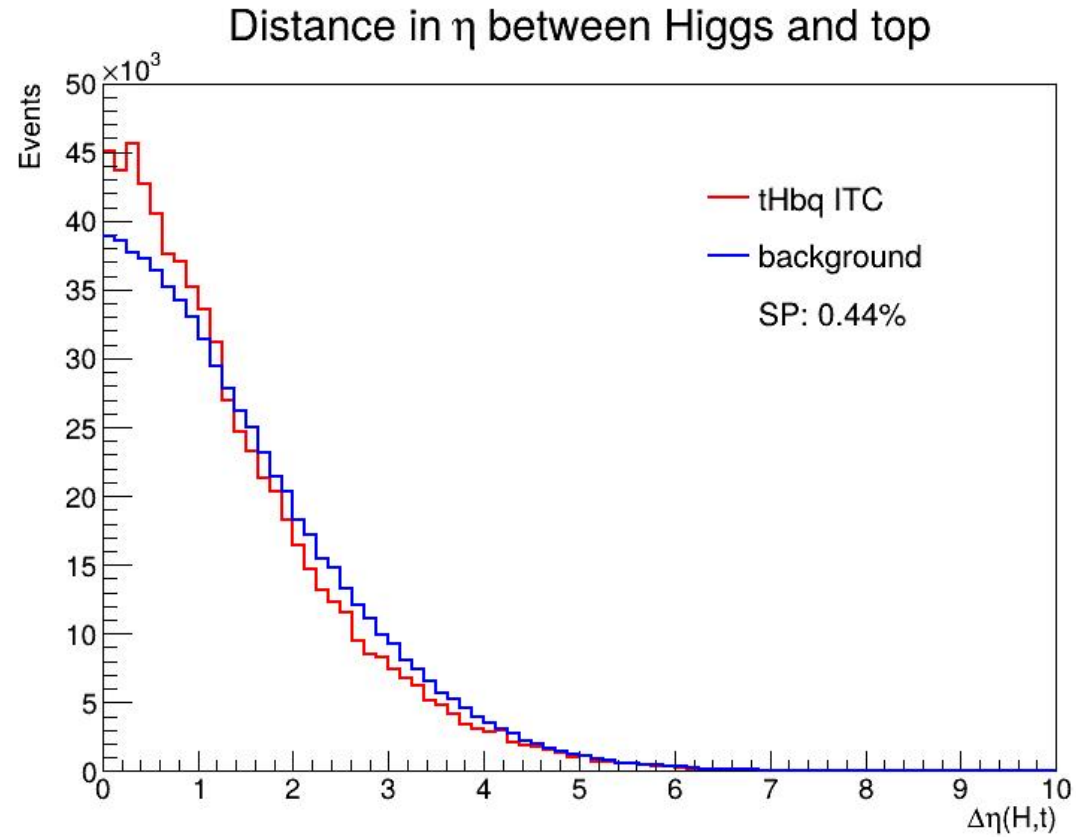
Invariant mass of Higgs and top



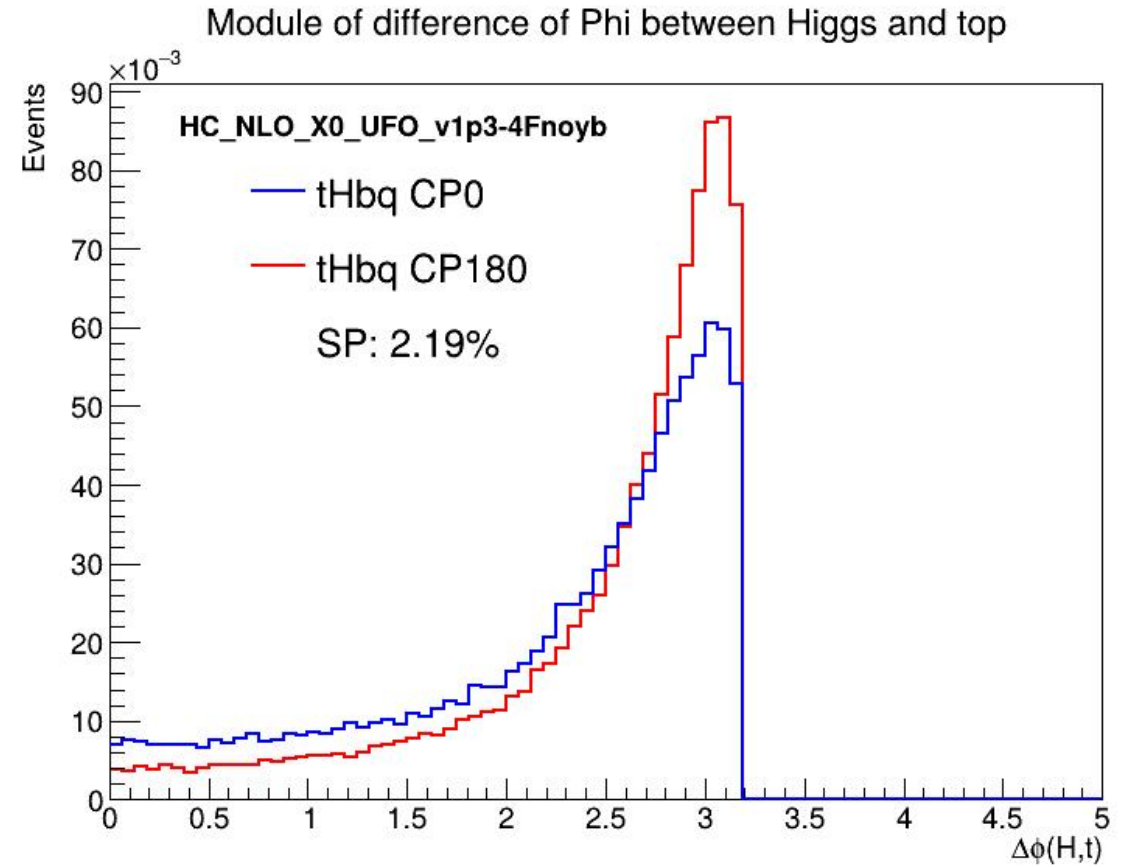
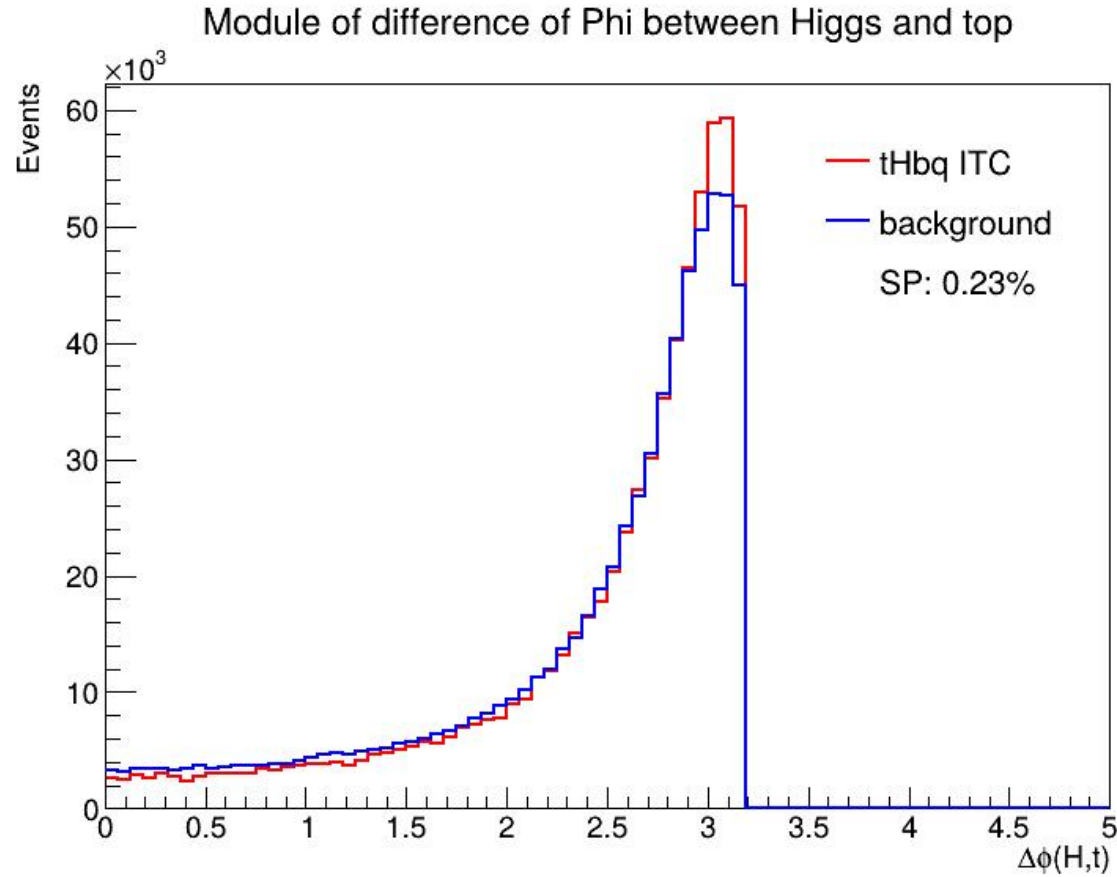
η and p_T Higgs boson for the signal and background processes



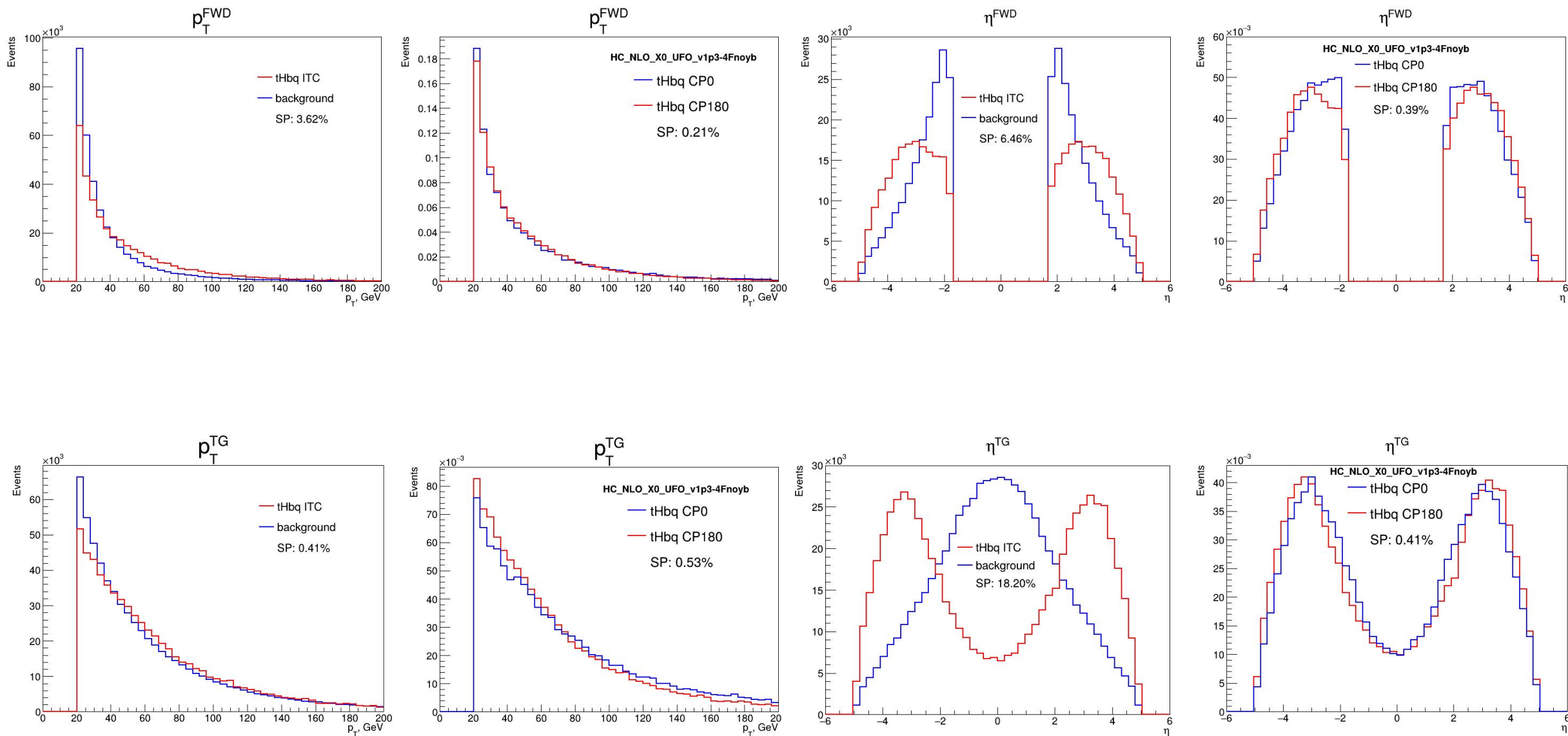
Distance η between top quark and Higgs boson for the signal and background processes



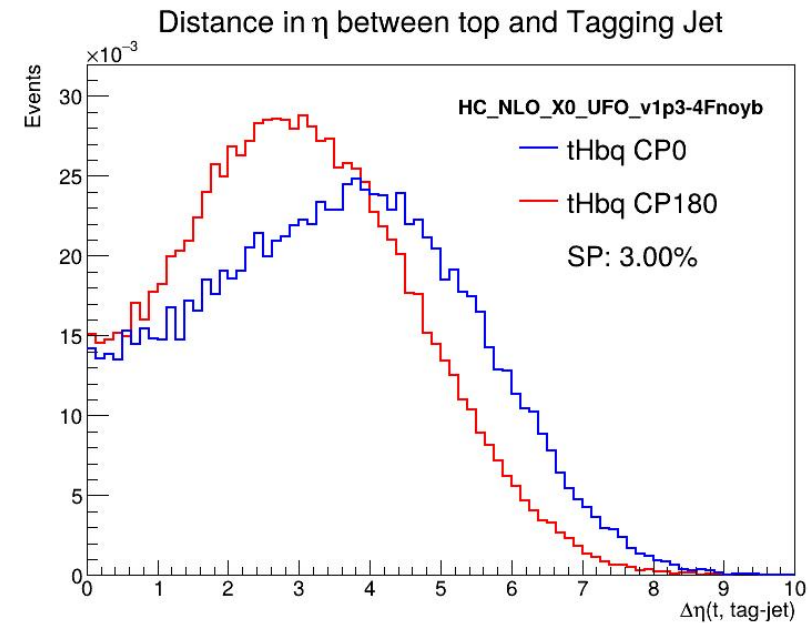
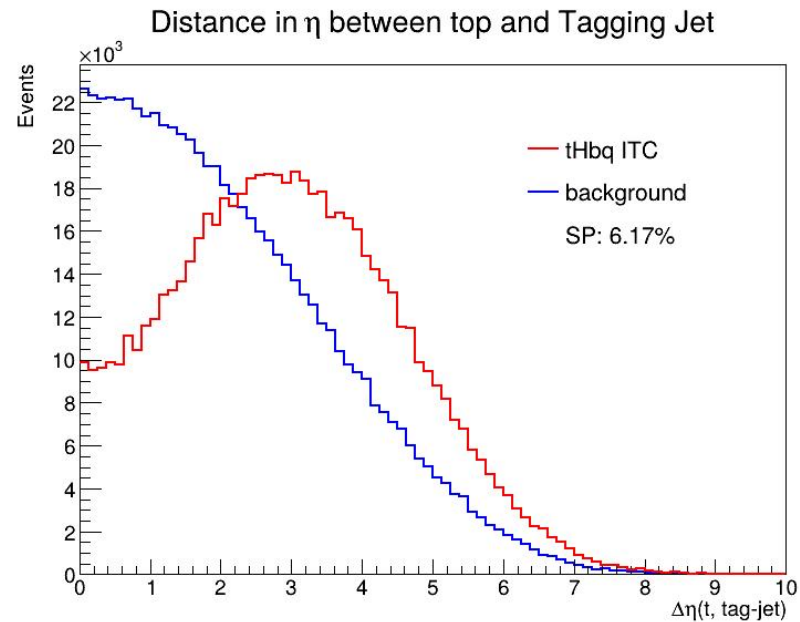
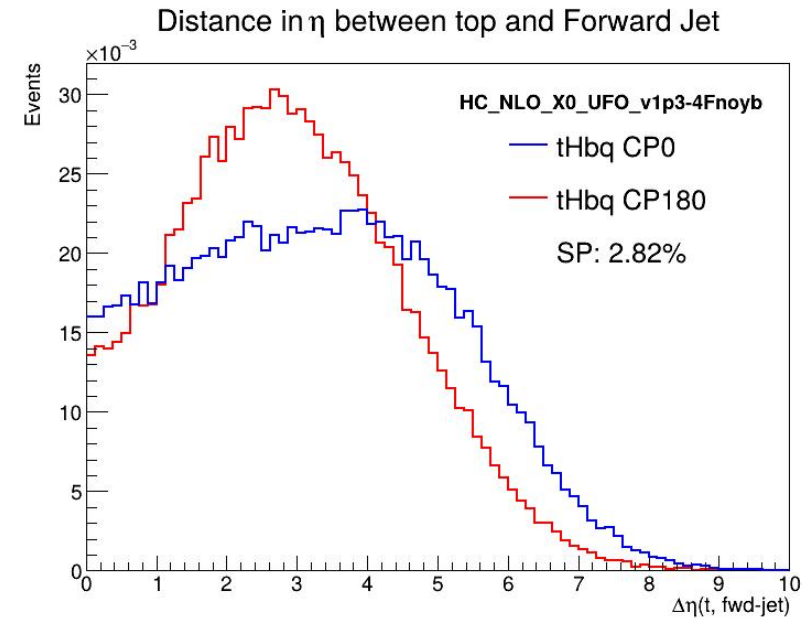
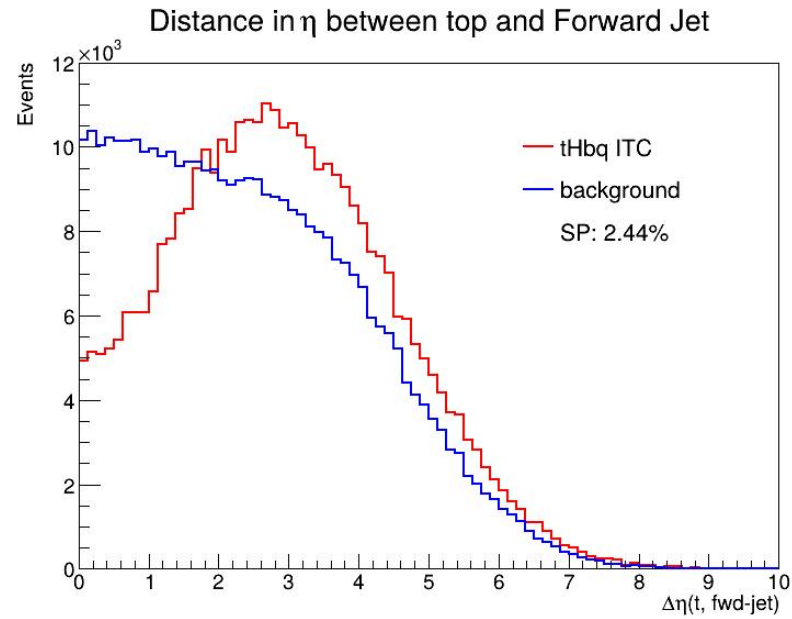
$|\Delta\phi|$ between top quark and Higgs boson for the signal and background processes



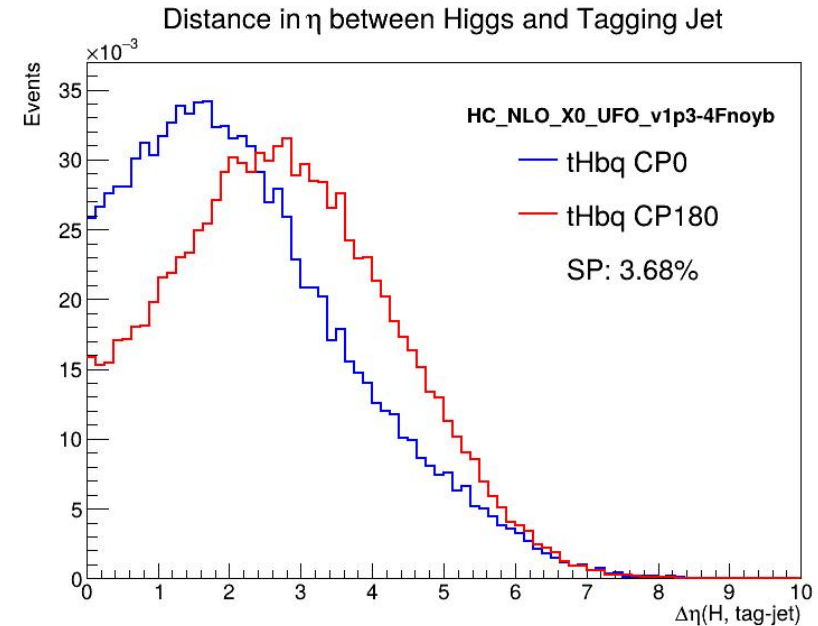
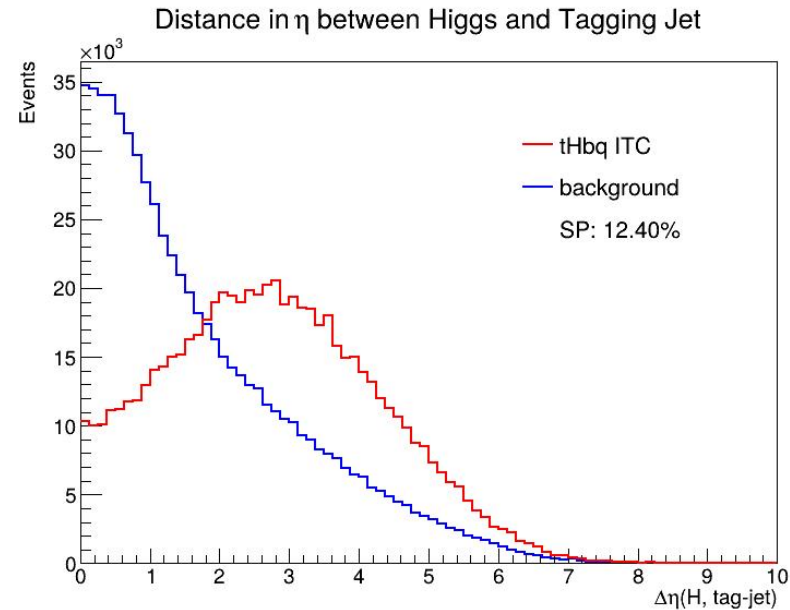
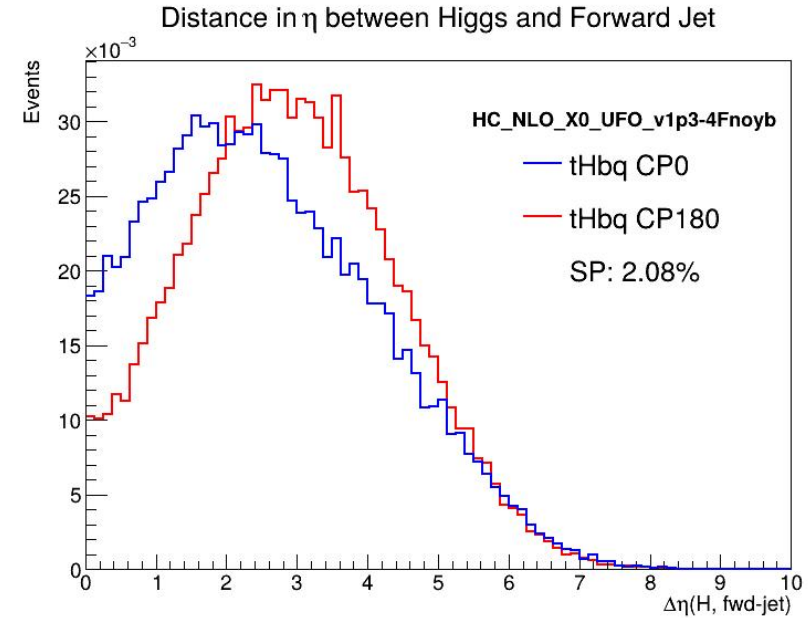
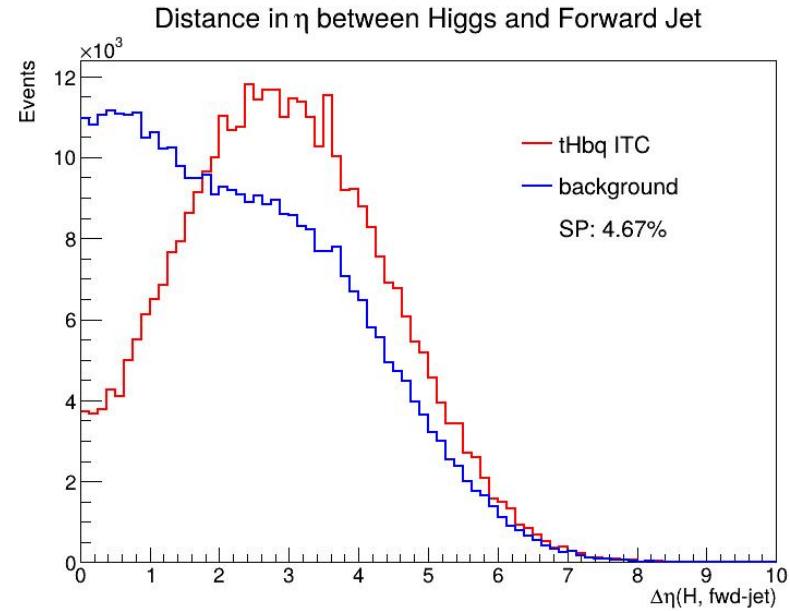
Forward and Tagging jet



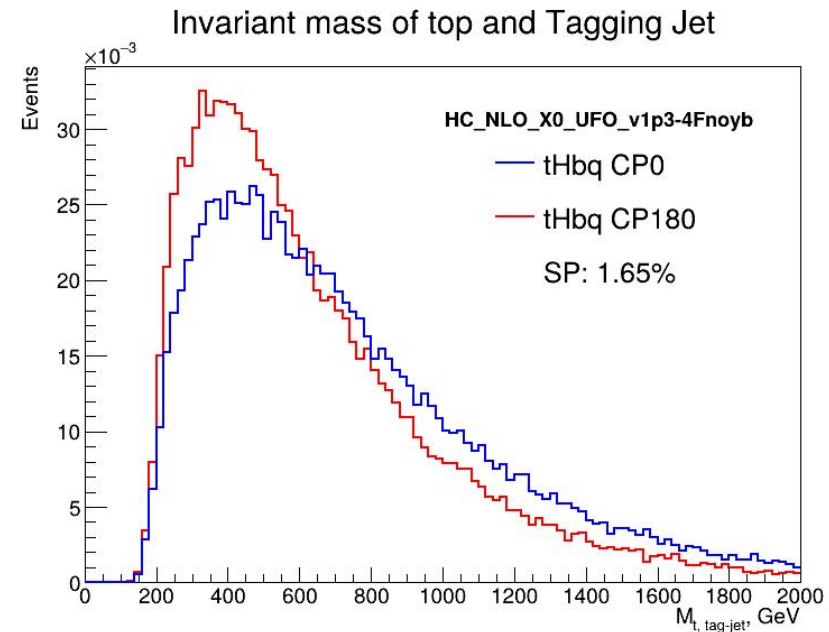
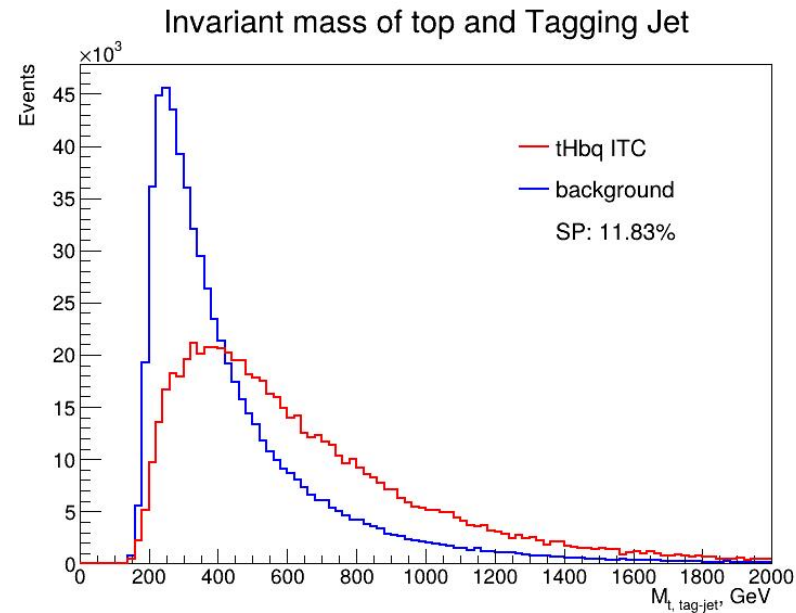
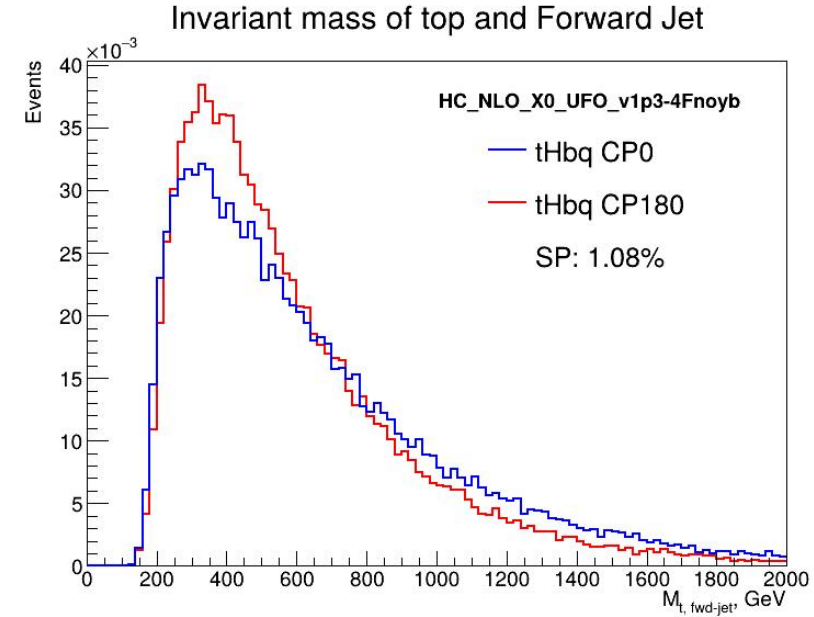
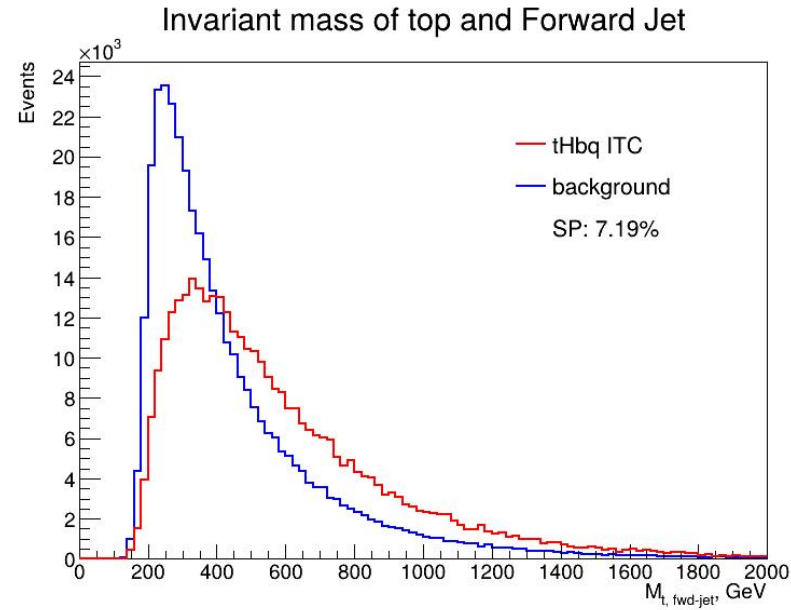
$|\Delta\eta|$ between top quark and Forward (Tagging) Jet for the signal and background processes



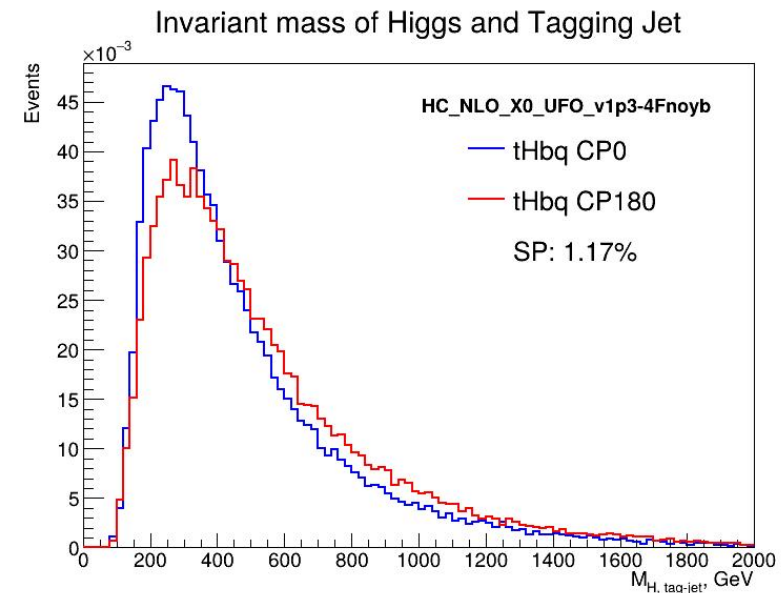
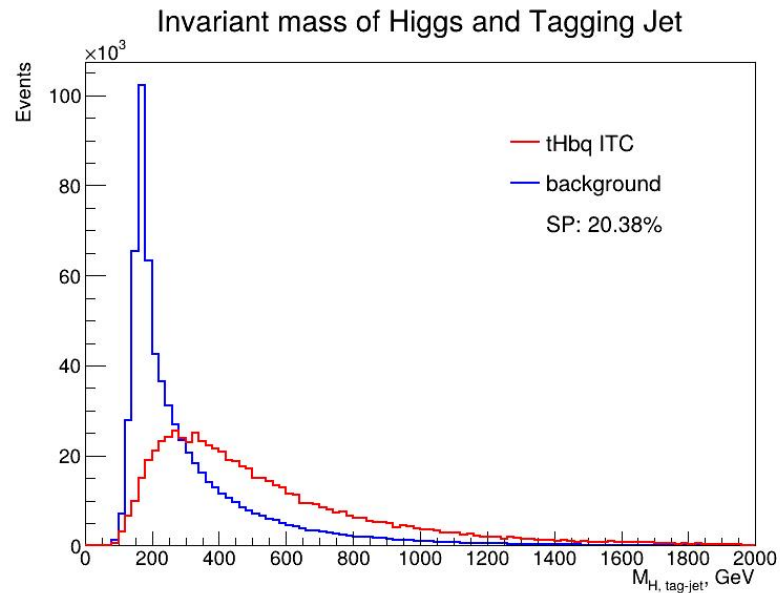
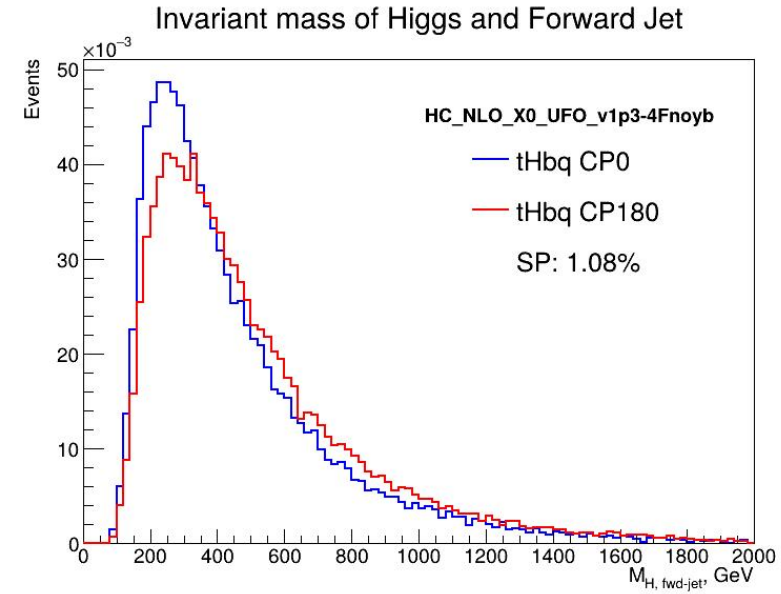
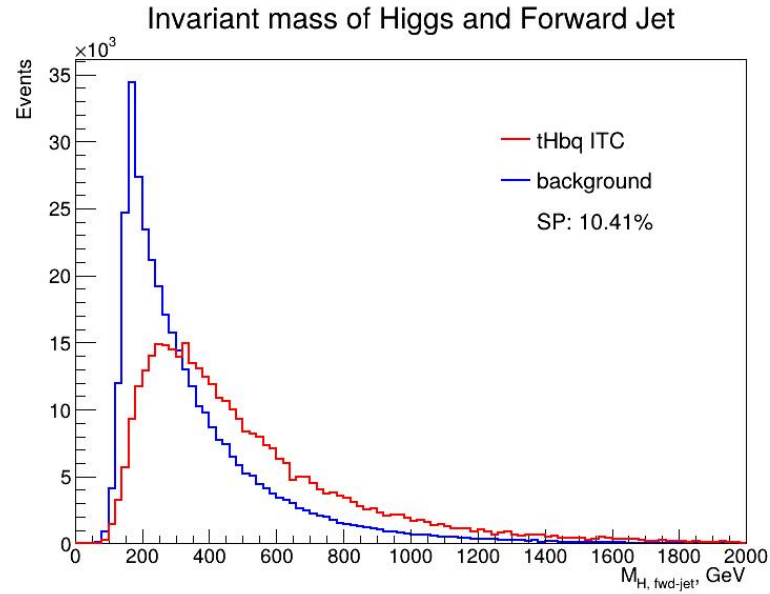
Distance in η between Higgs and Forward (Tagging) Jet for the signal and background processes



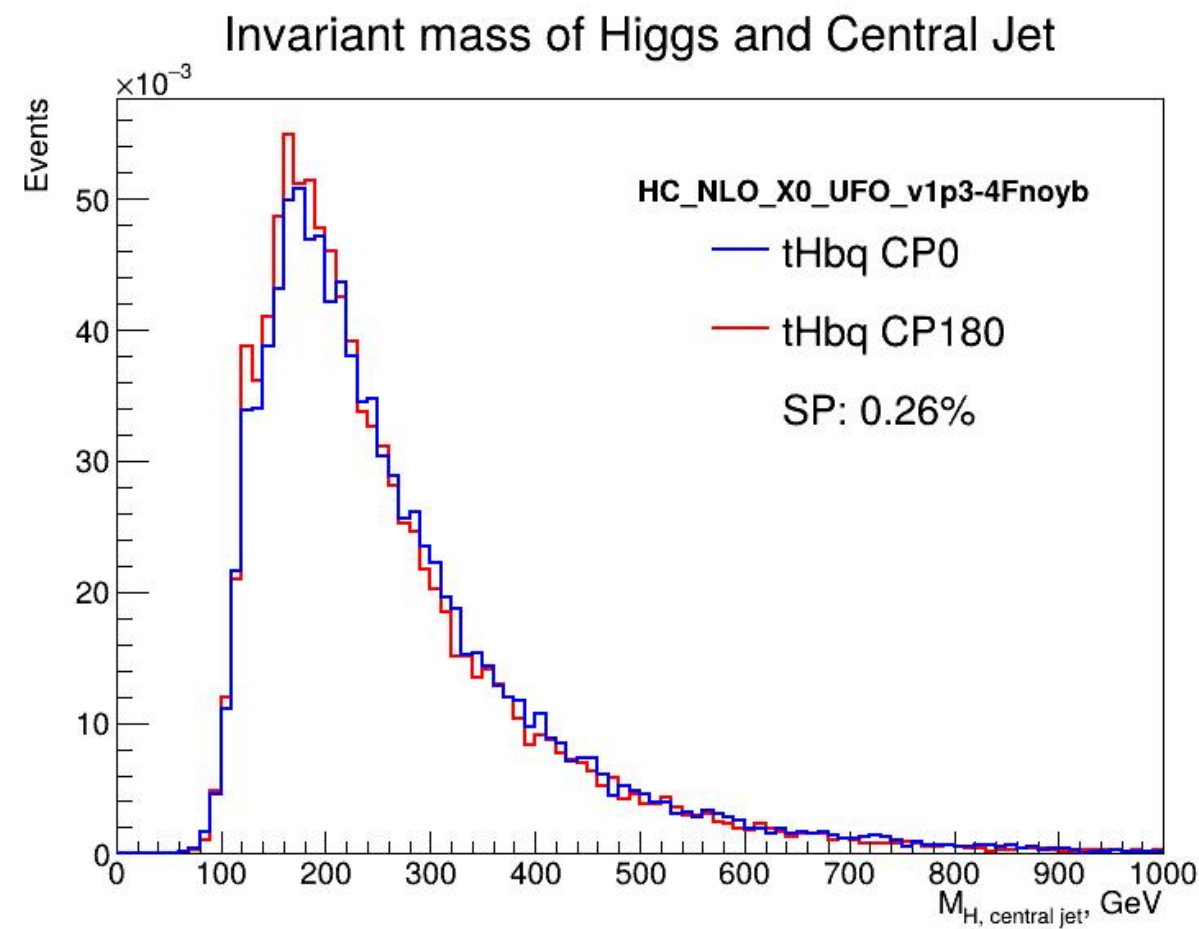
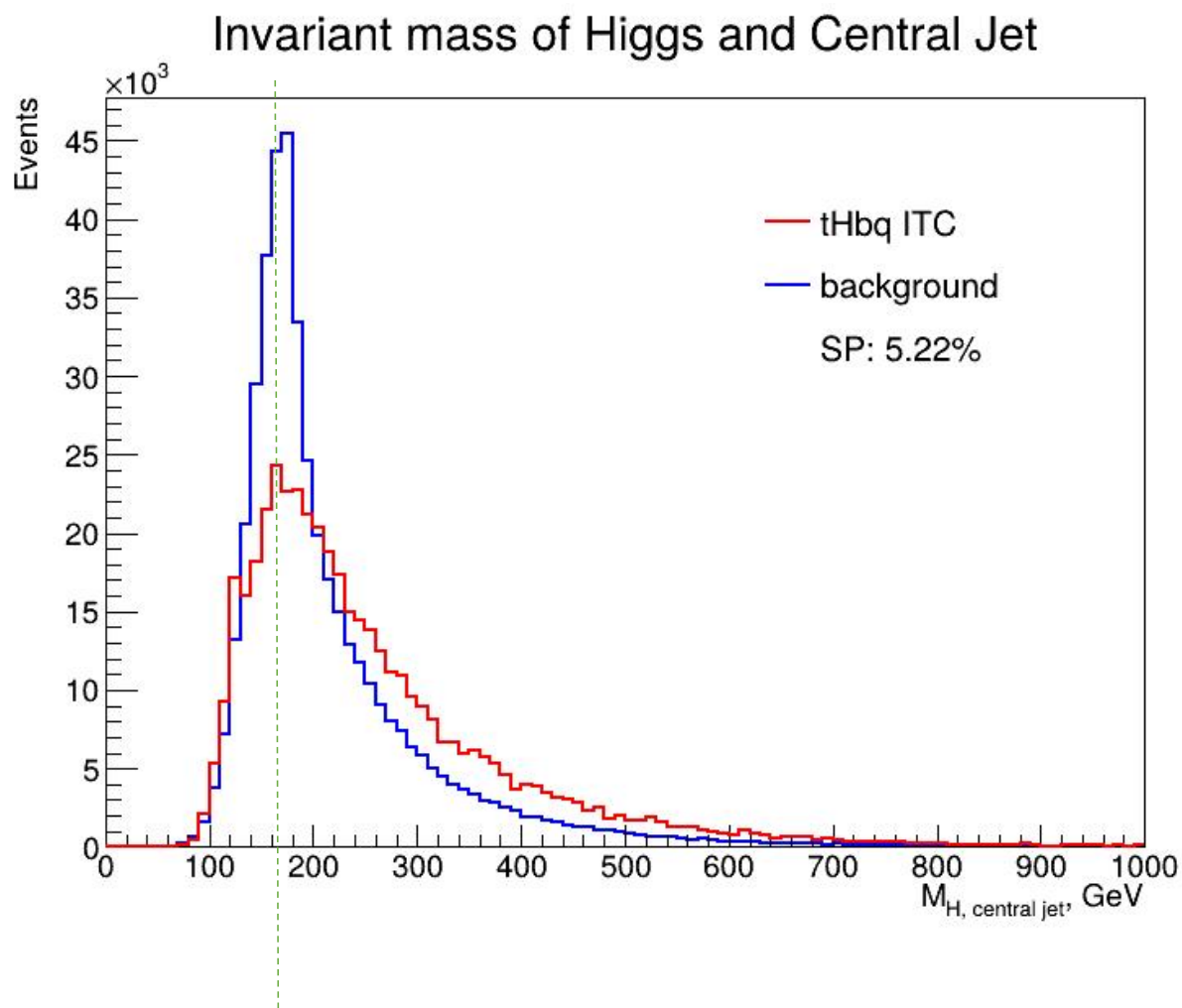
Invariant mass of Top-quark and Forward (Tagging) Jet for the signal and background processes



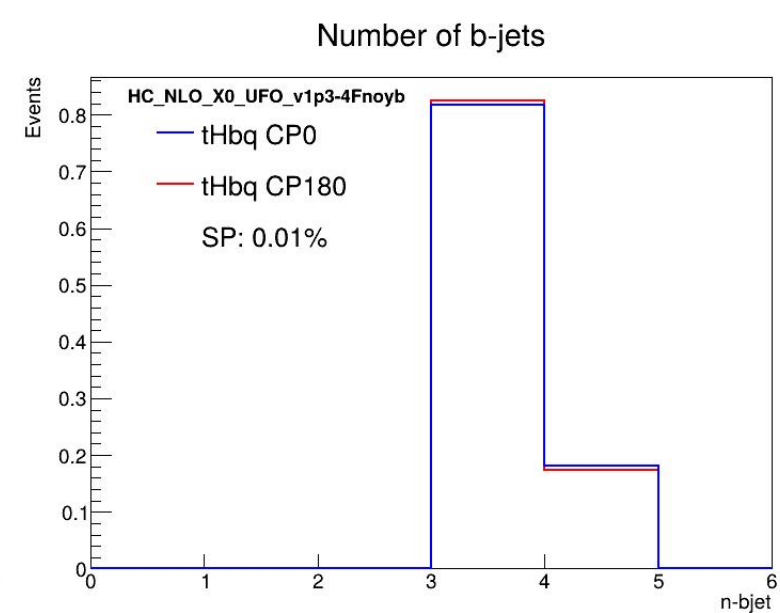
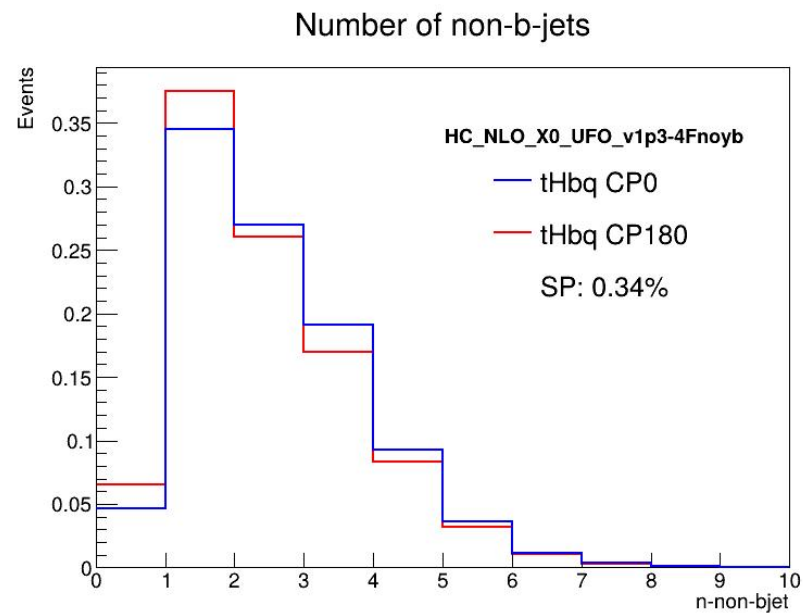
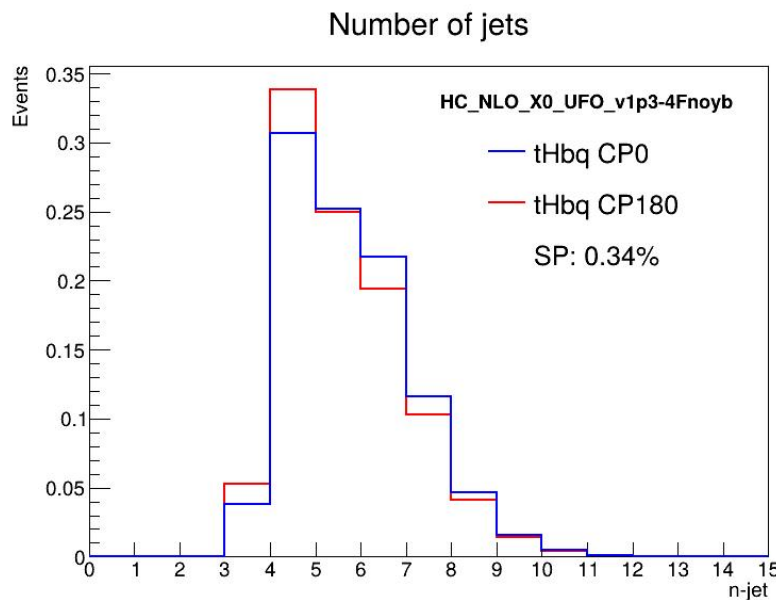
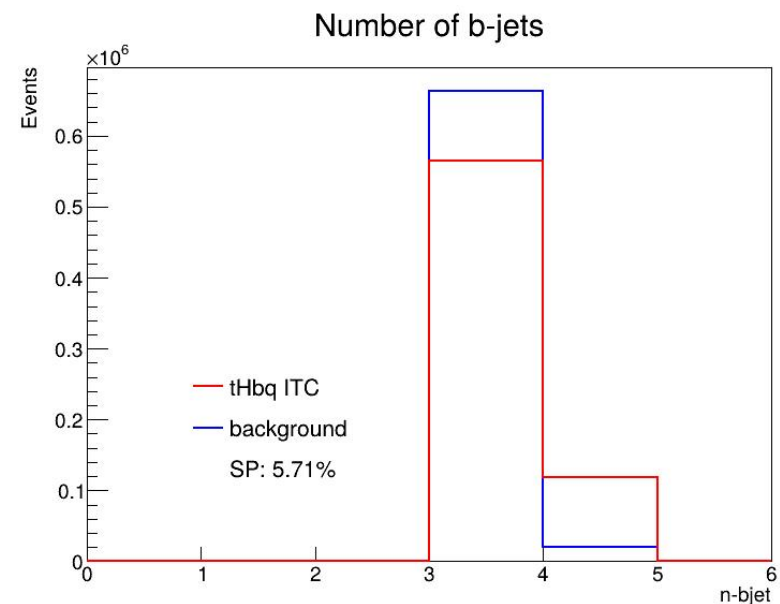
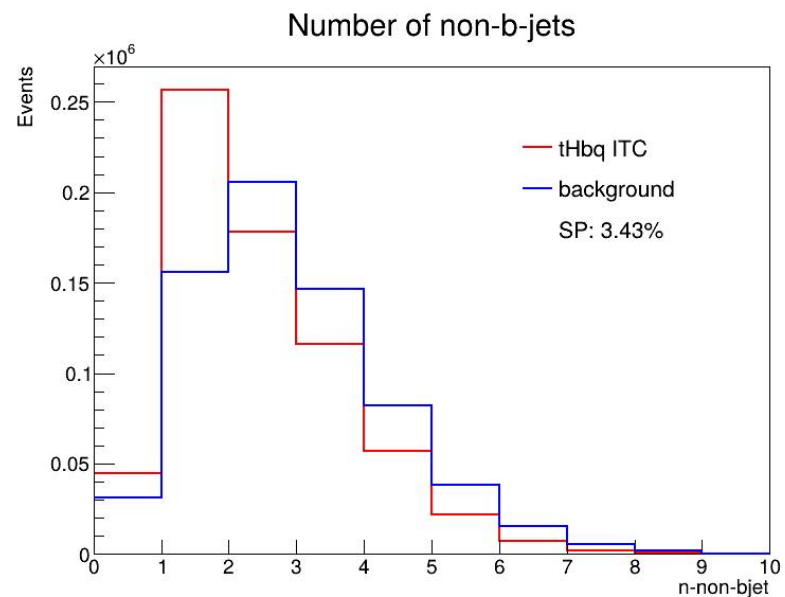
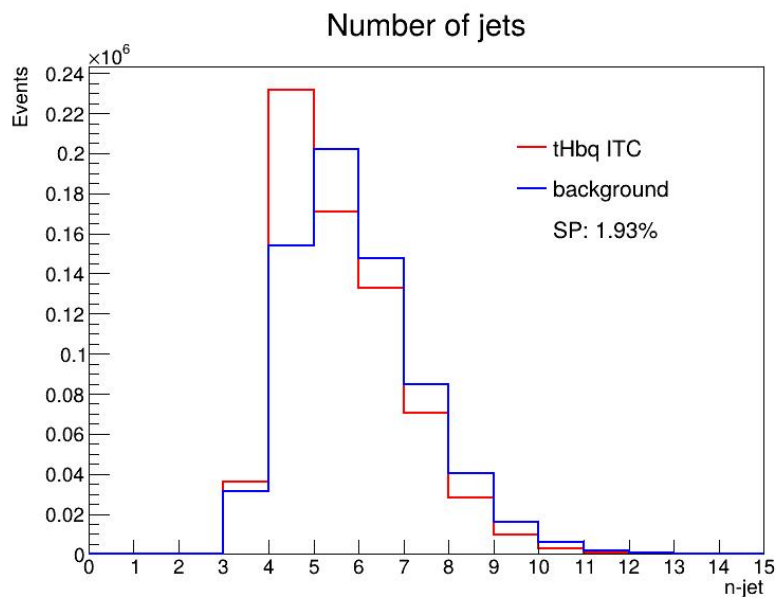
Invariant mass of Higgs and Forward (Tagging) Jet for the signal and background processes



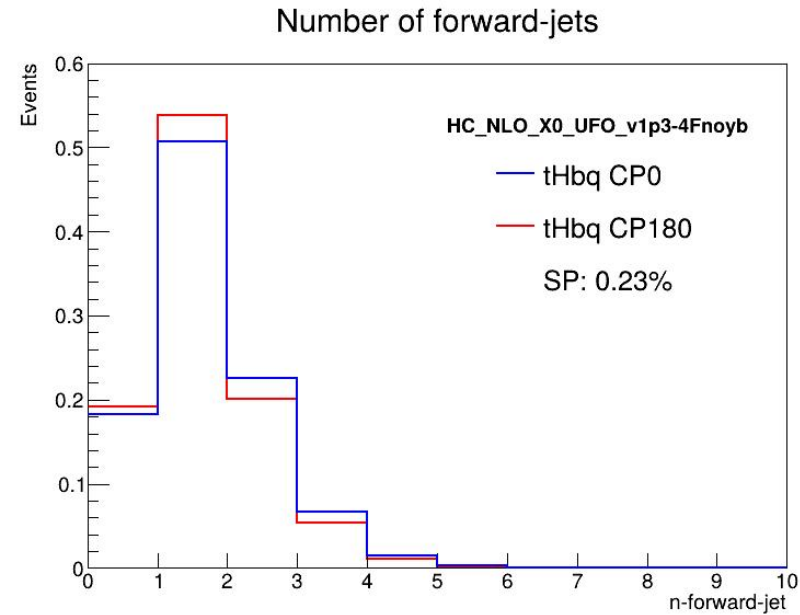
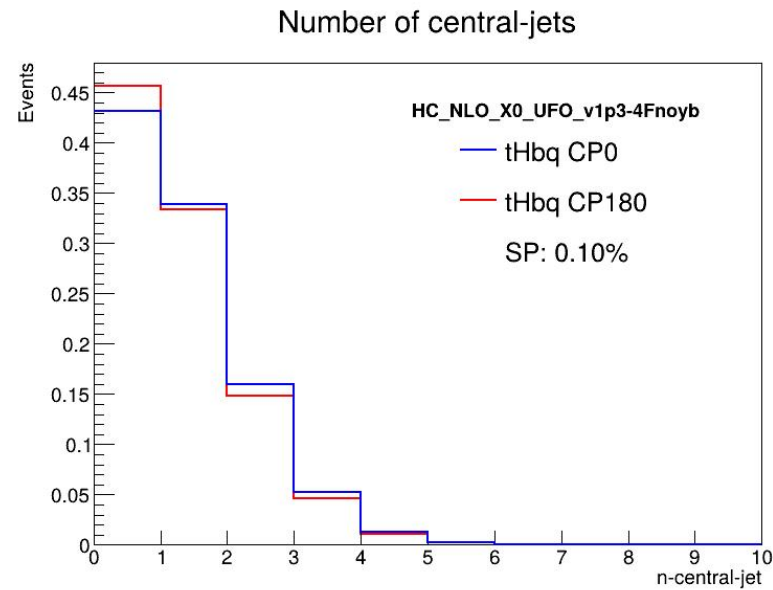
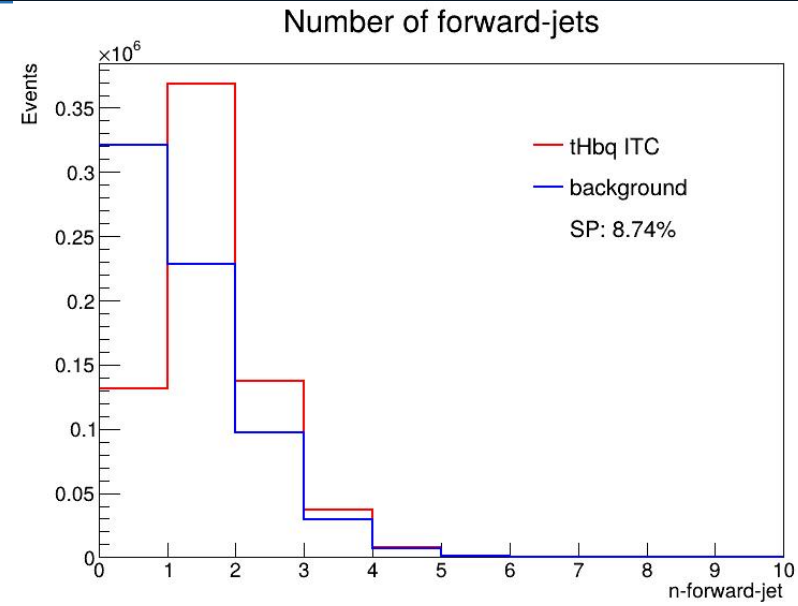
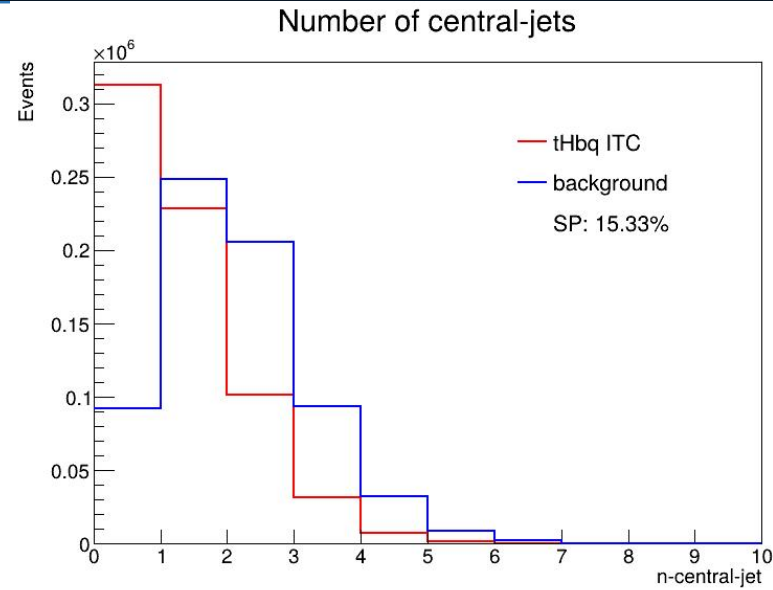
Invariant mass Higgs and Central Jet for the signal and background processes



Number of jets for the signal and background processes

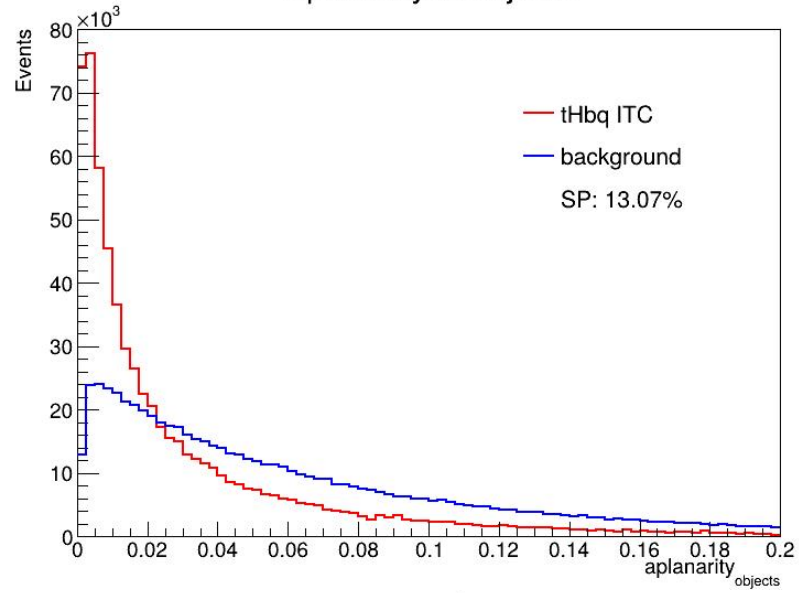


Number of central and forward jets

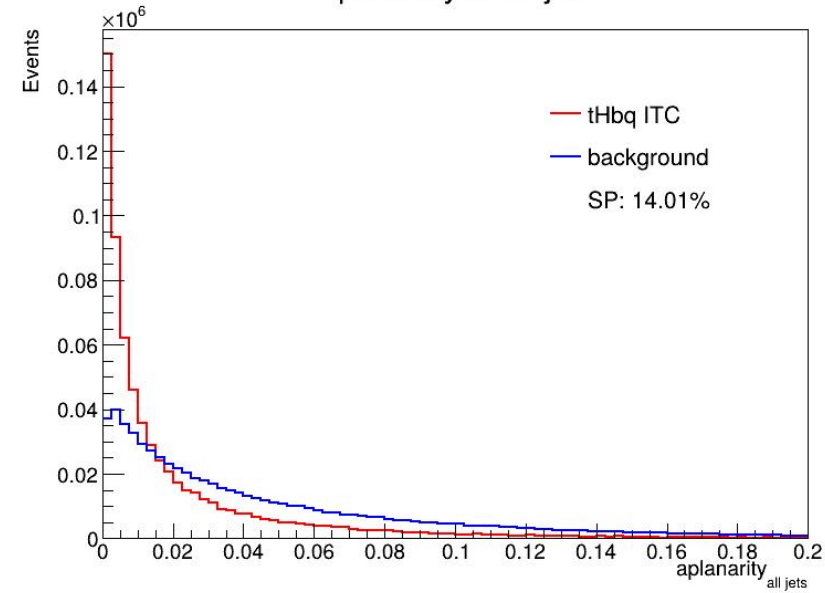


Aplanarity for the signal and background processes

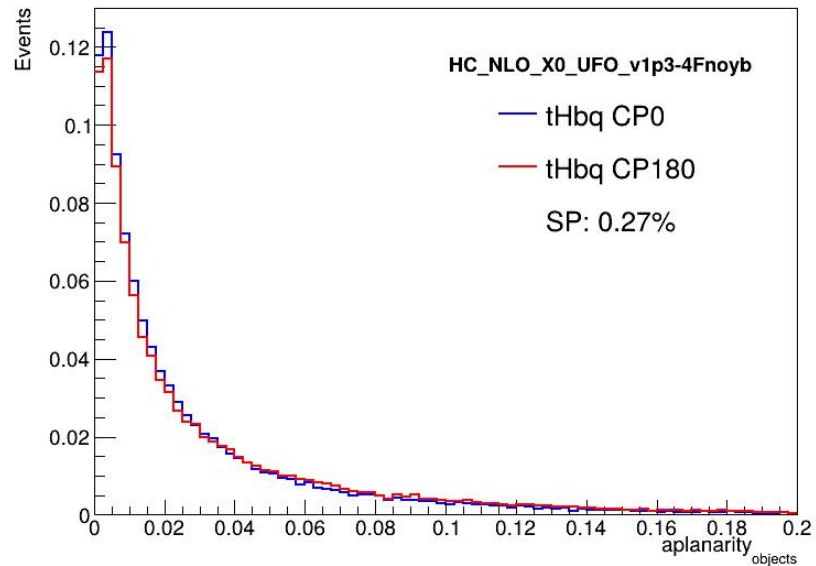
Aplanarity of objects



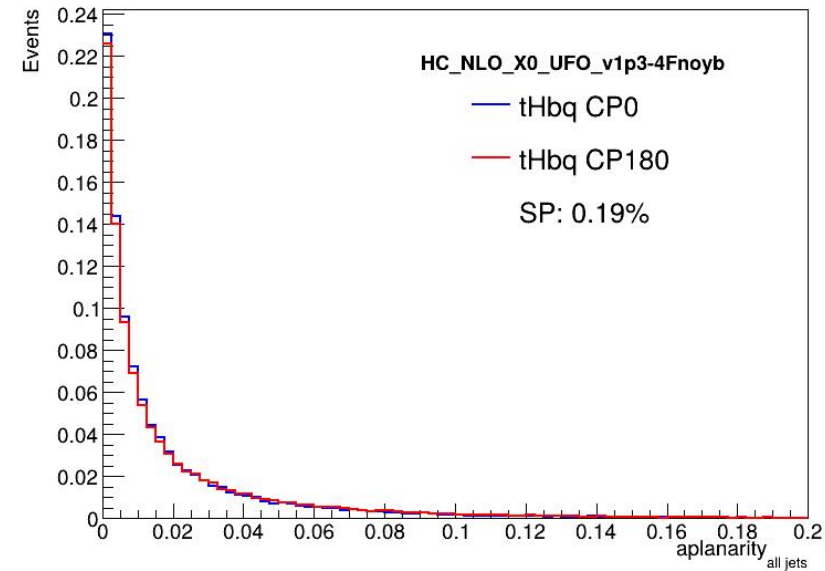
Aplanarity of all jets



Aplanarity of objects

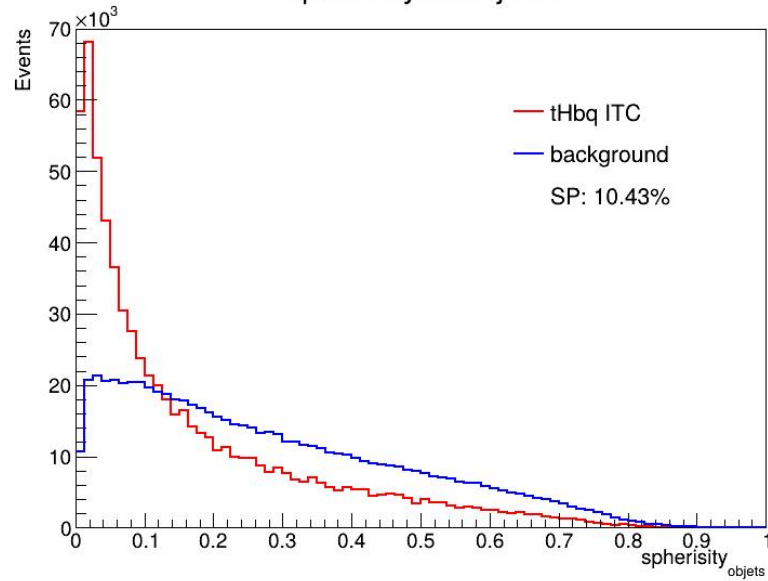


Aplanarity of all jets

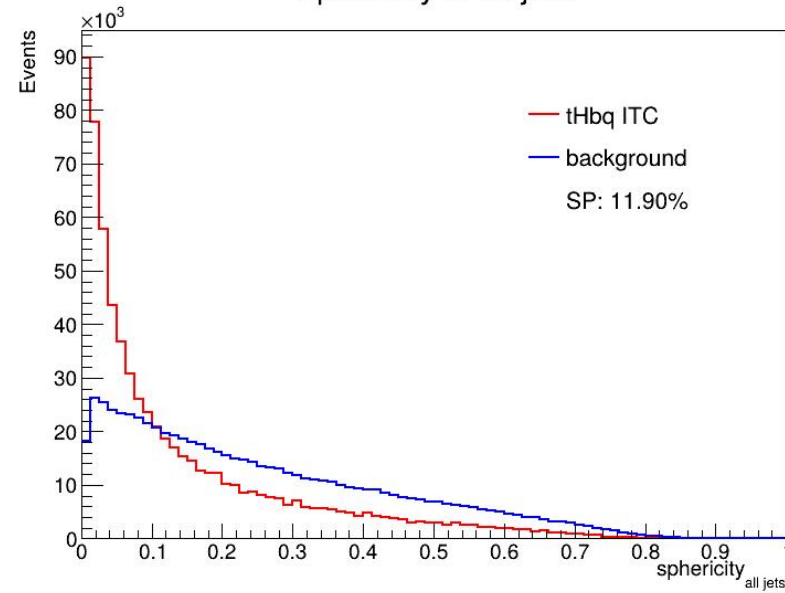


Sphericity for the signal and background processes

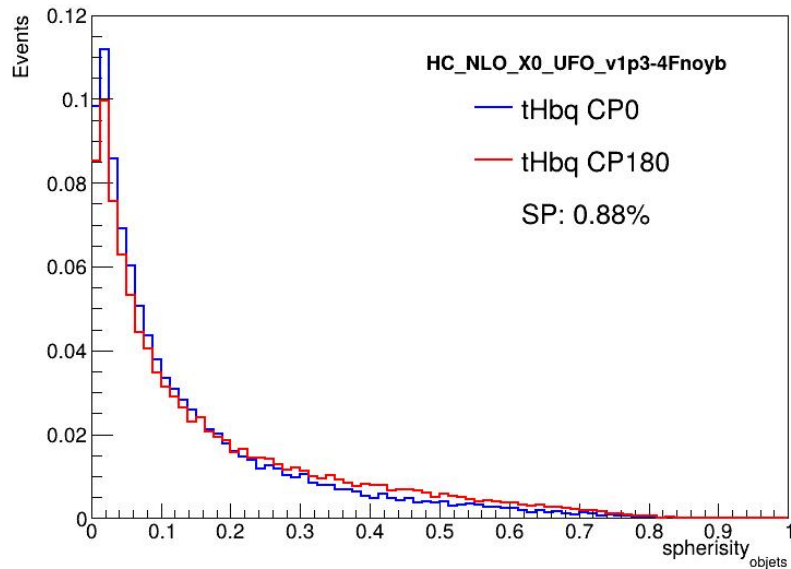
Sphericity of objets



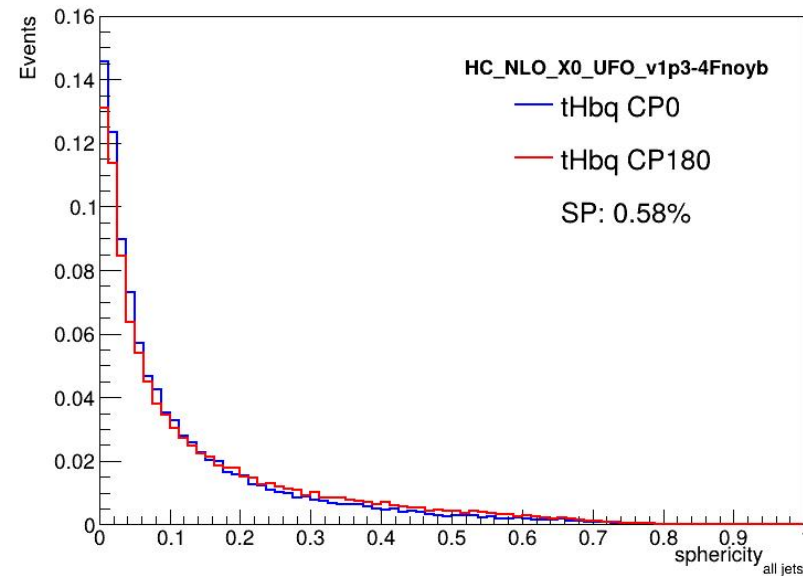
Sphericity of all jets



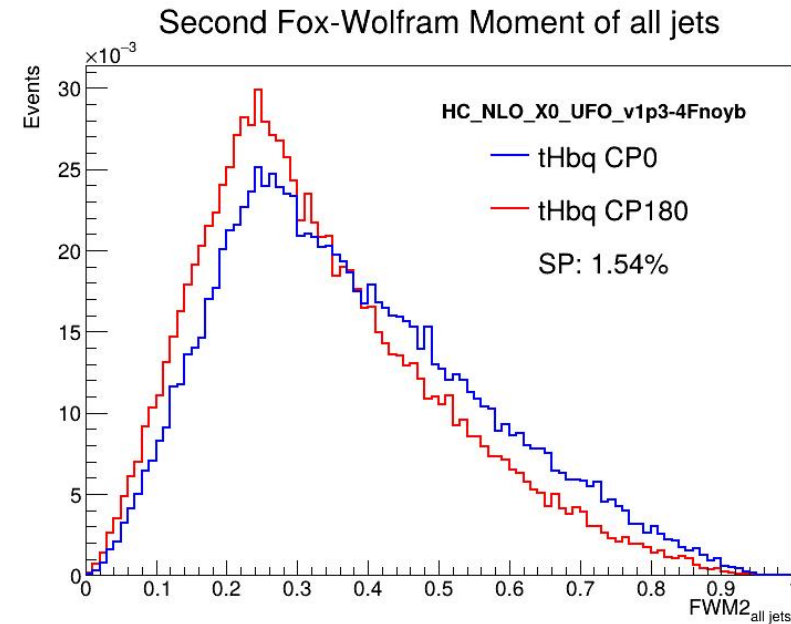
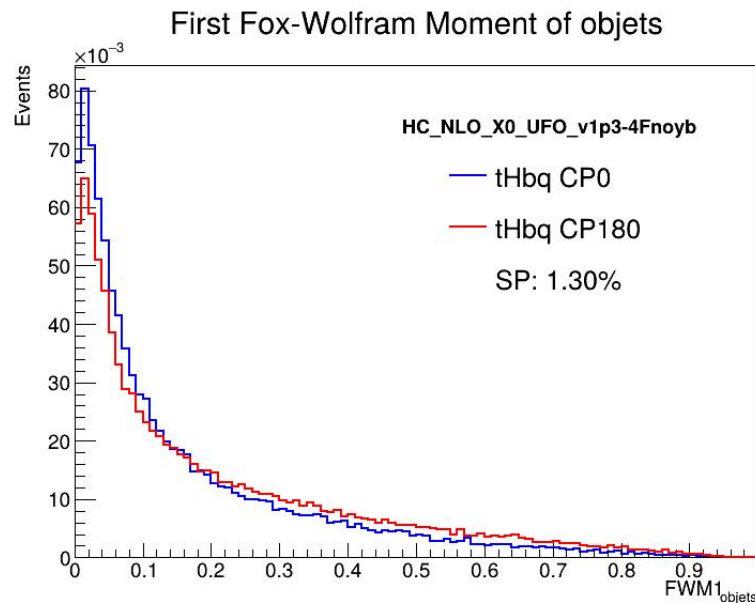
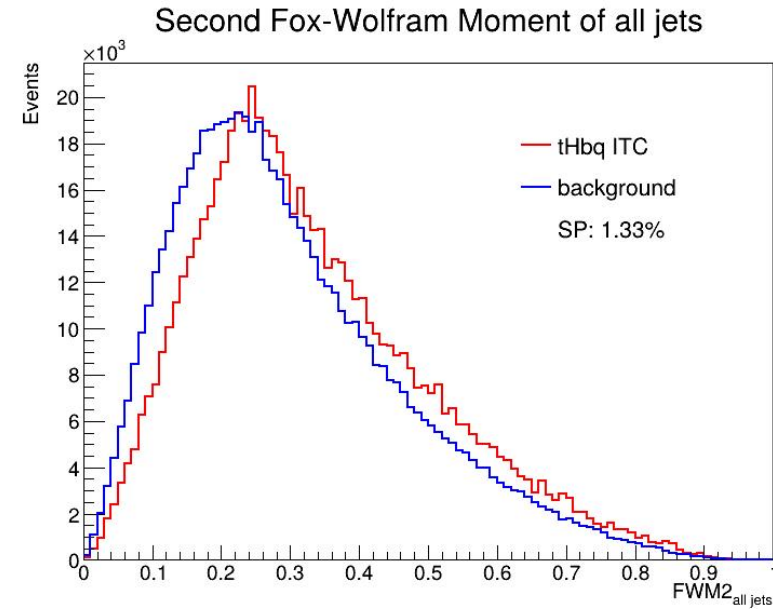
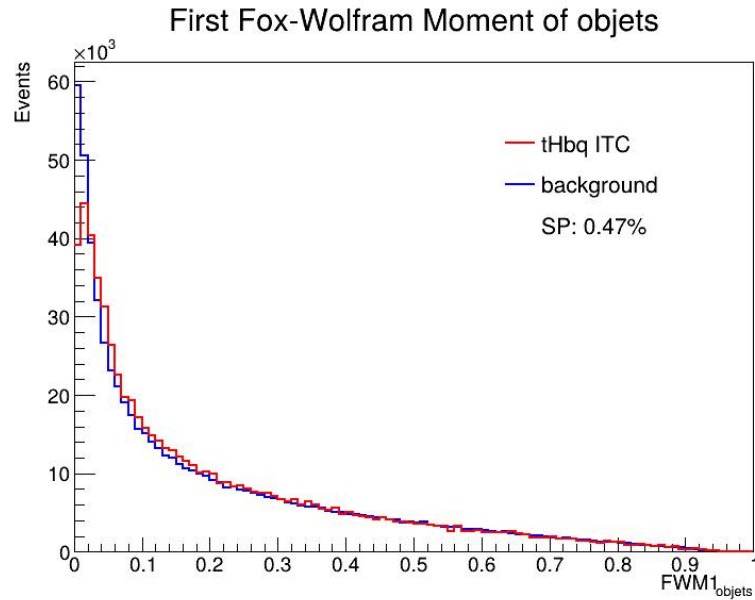
Sphericity of objets



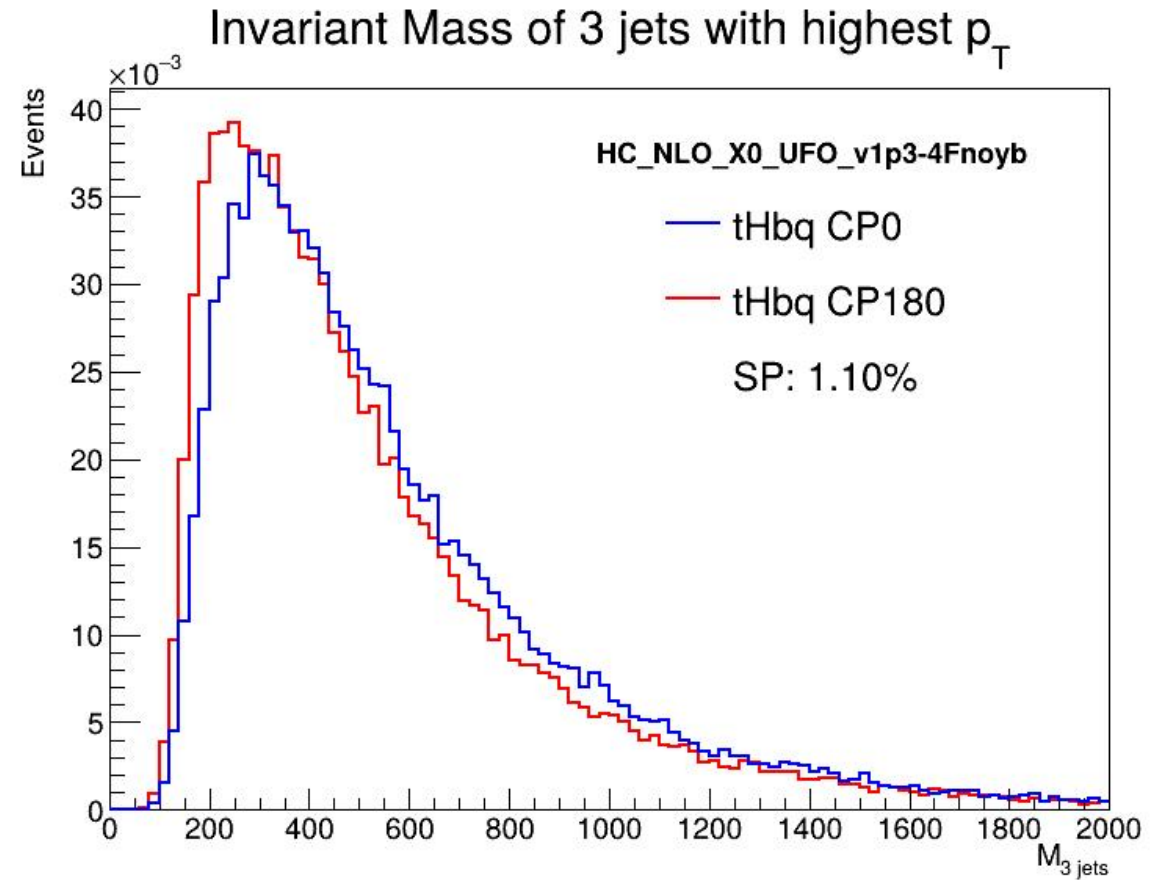
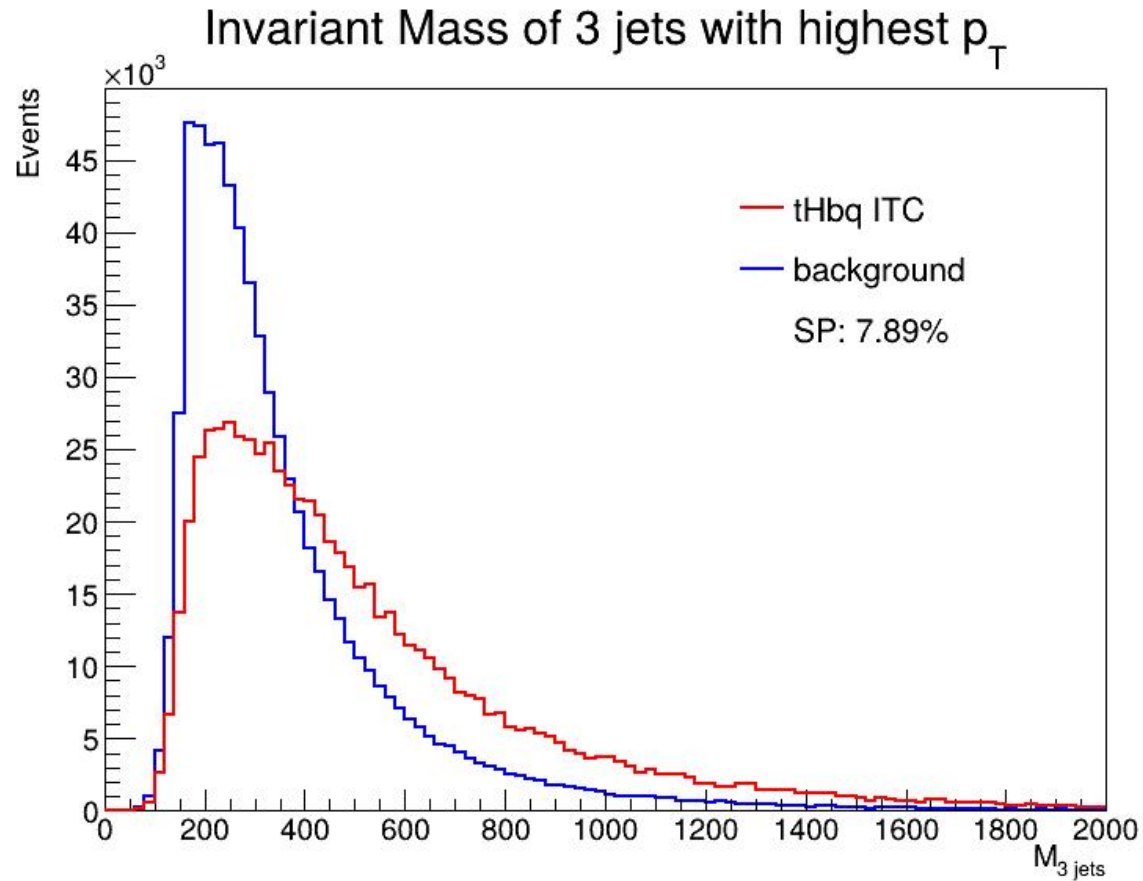
Sphericity of all jets



First and Second Fox-Wolfram moment for the signal and background processes

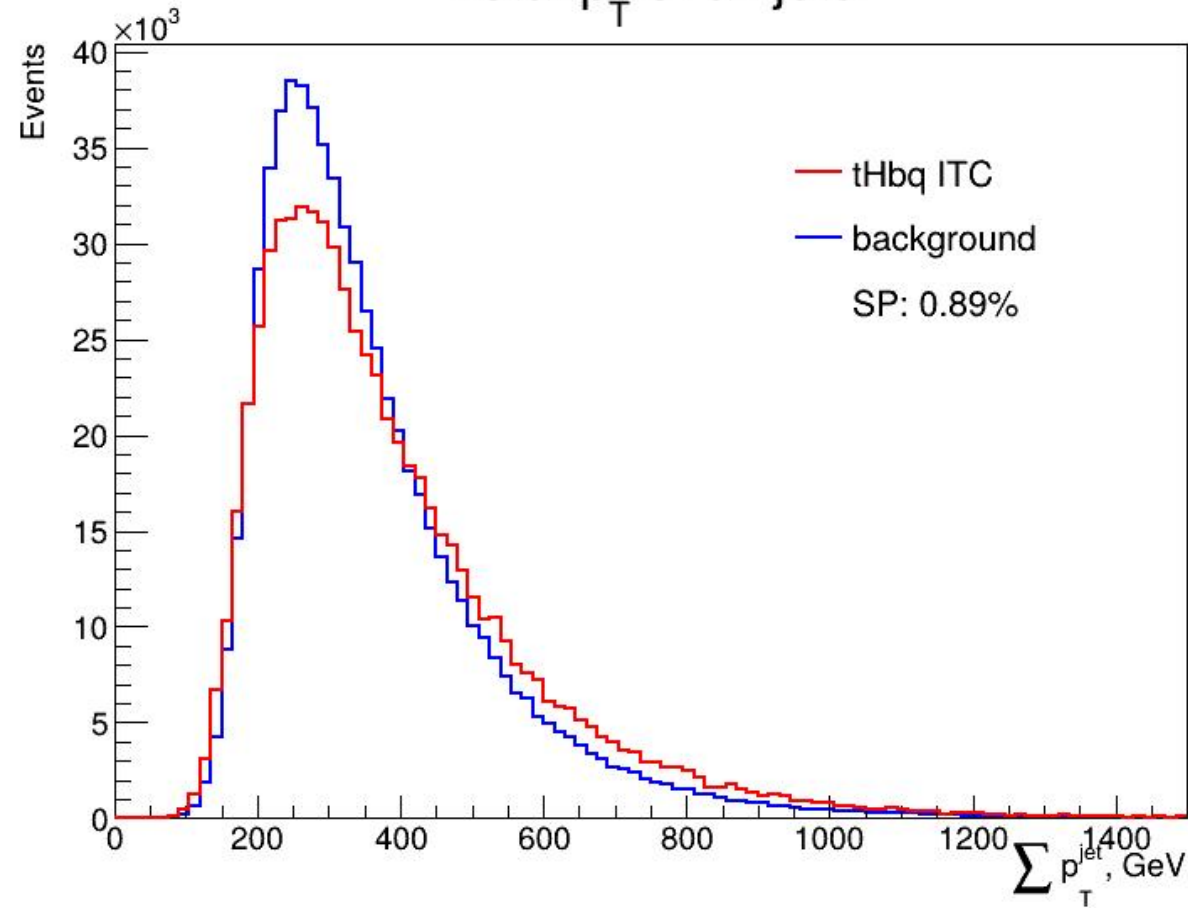


Invariant mass of 3 jets with highest p_T for the signal and background processes

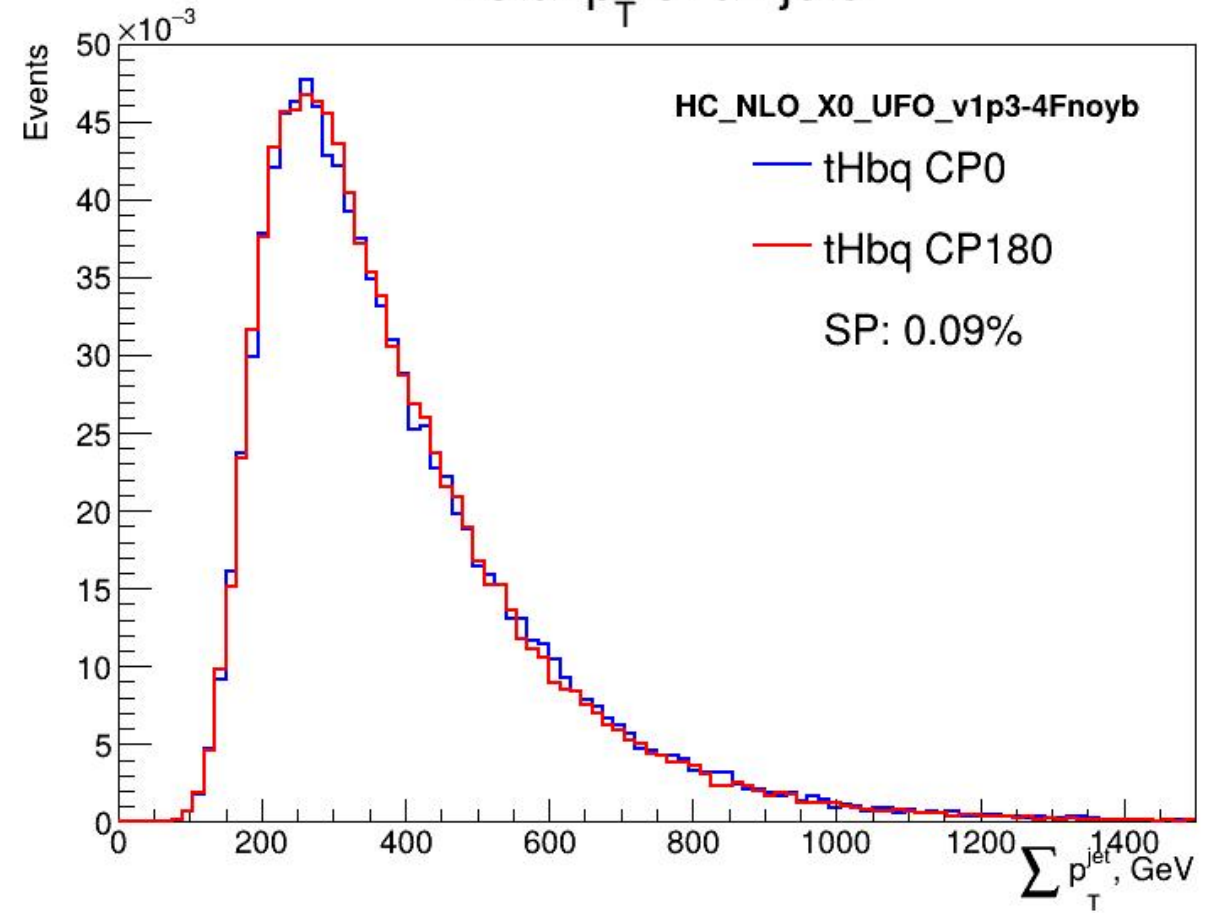


Total p_T of all jets for the signal and background processes

Total p_T of all jets

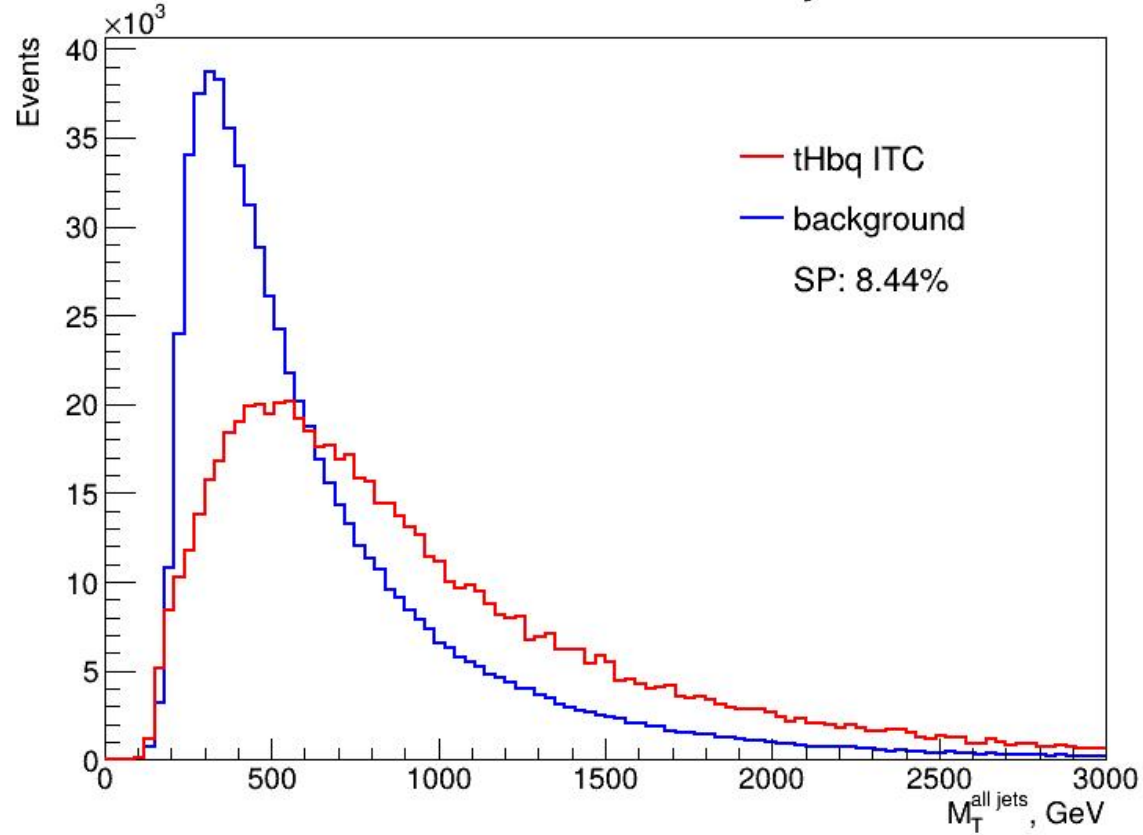


Total p_T of all jets

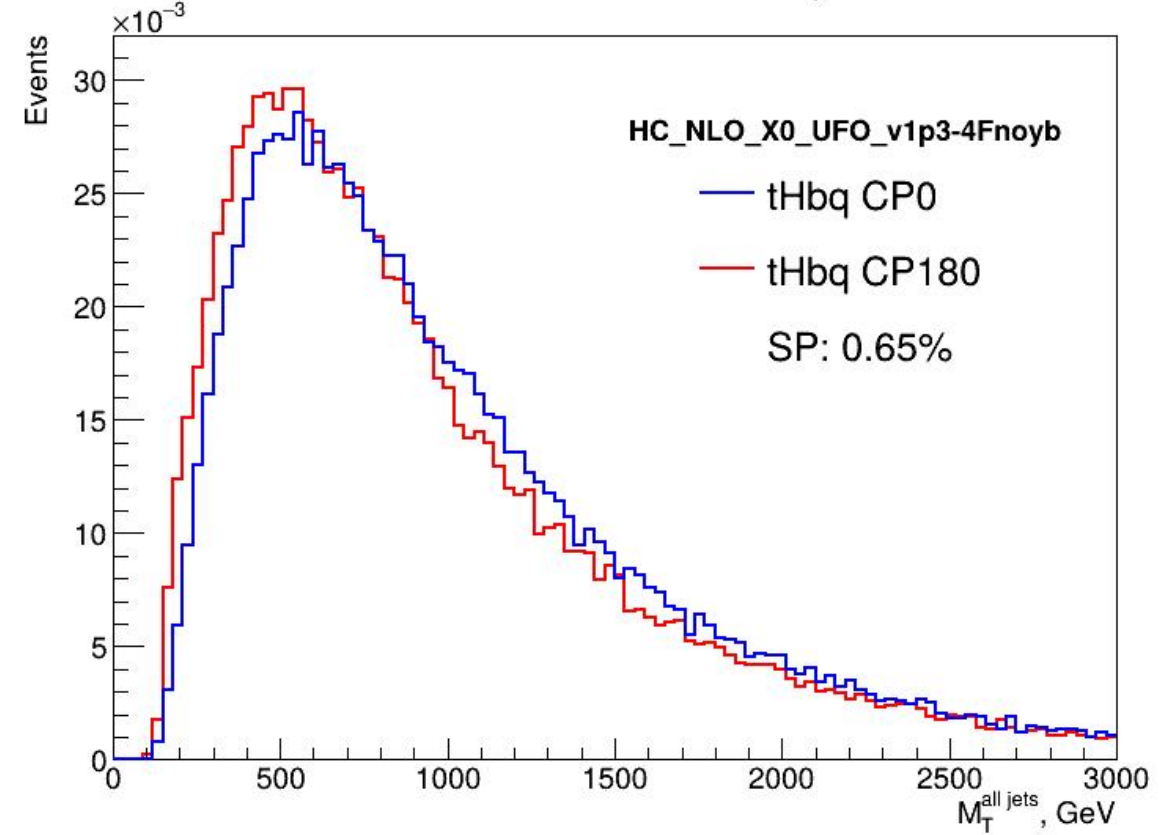


Transverse mass of all jets for the signal and background processes

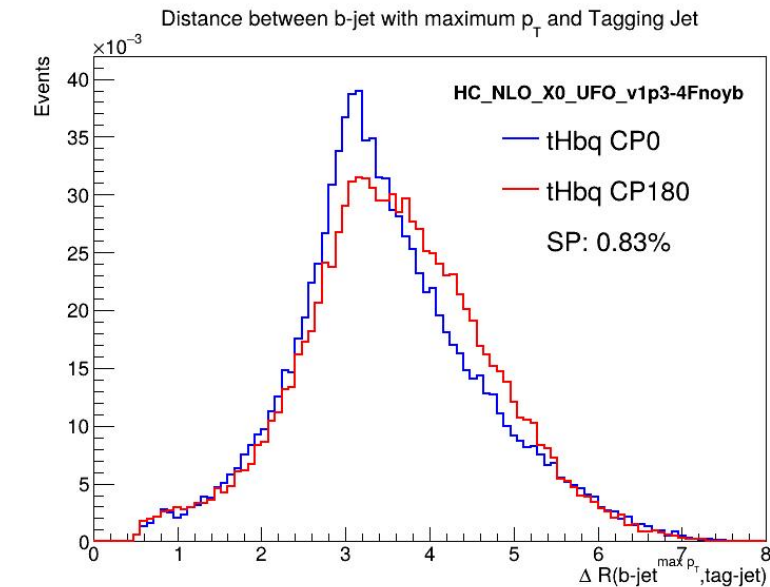
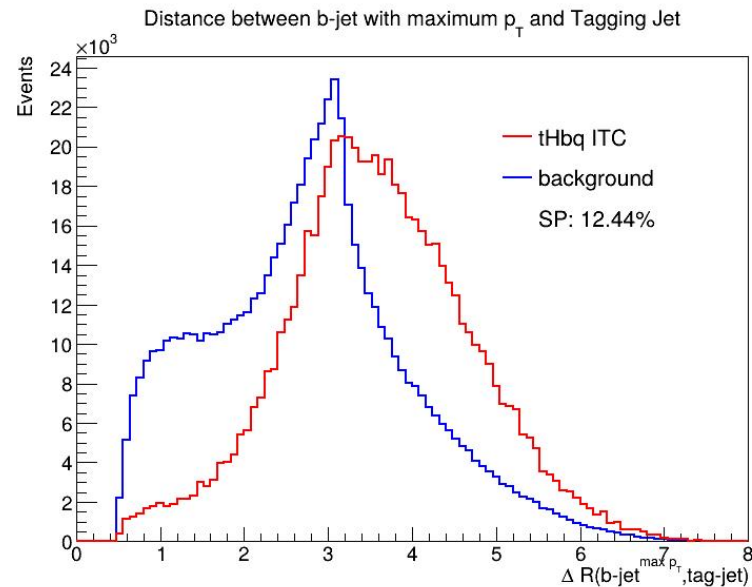
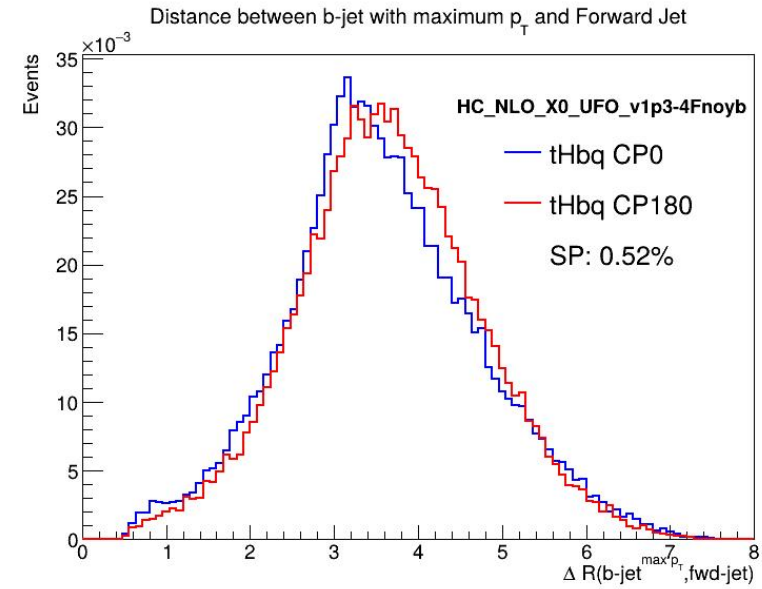
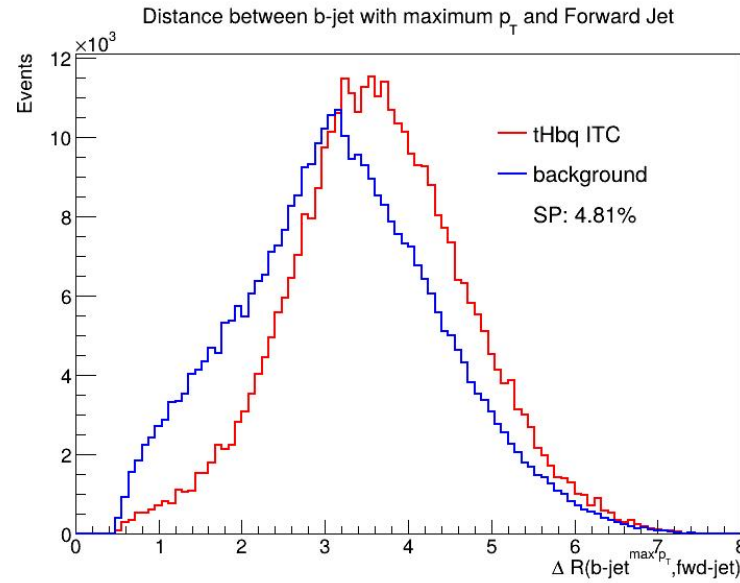
Transverse mass of all jets



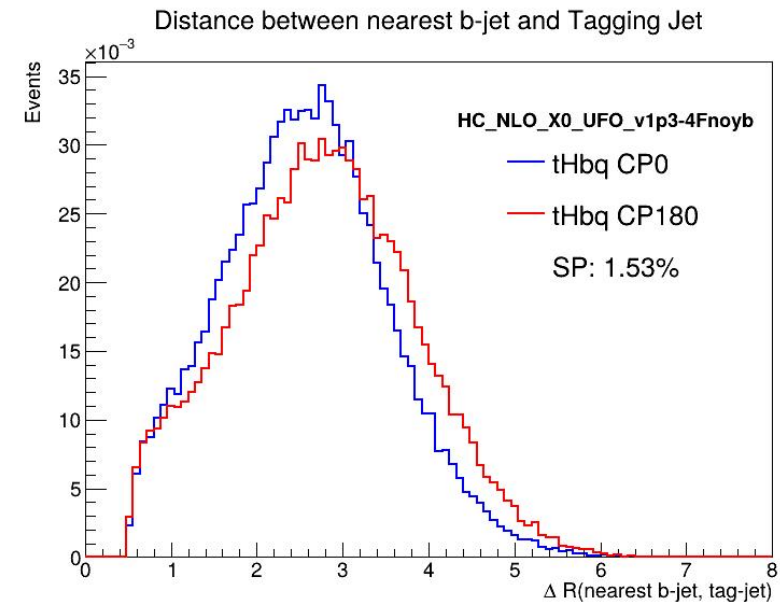
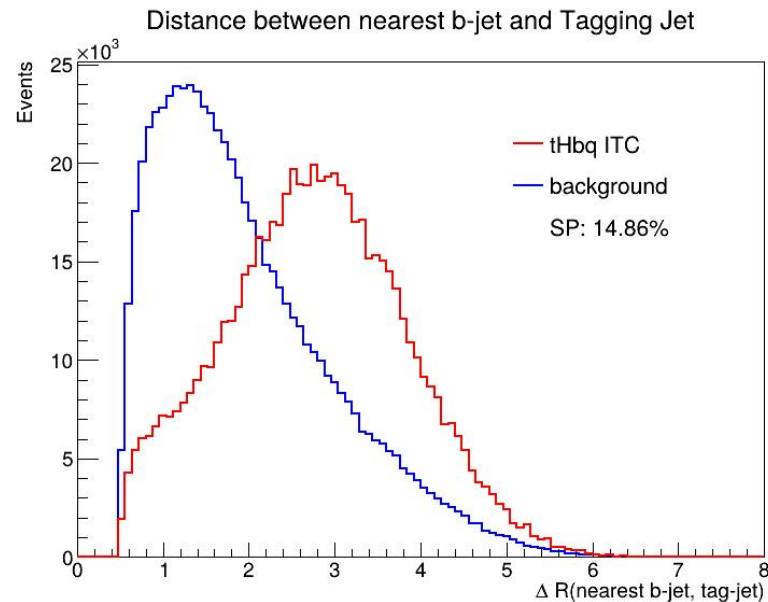
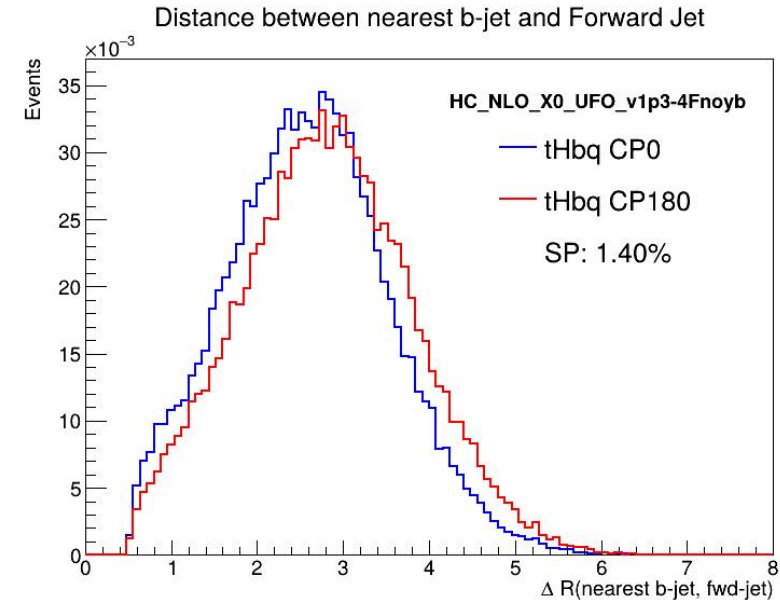
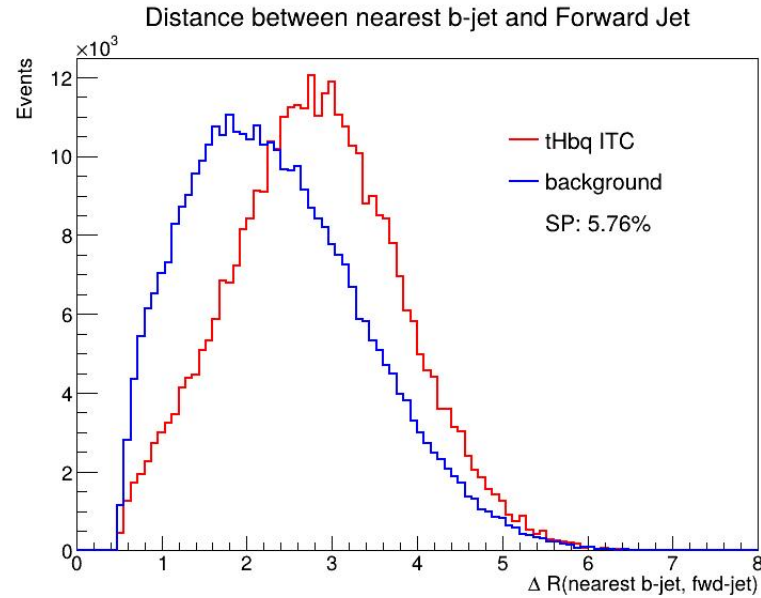
Transverse mass of all jets



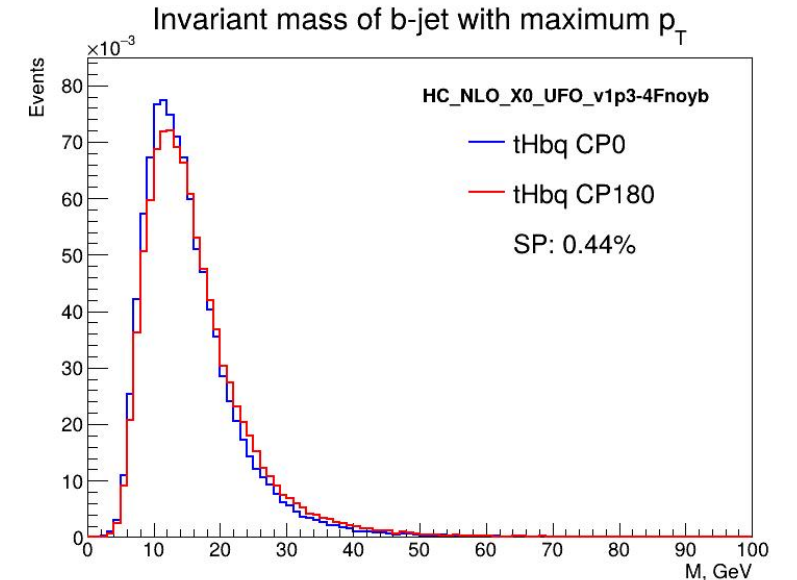
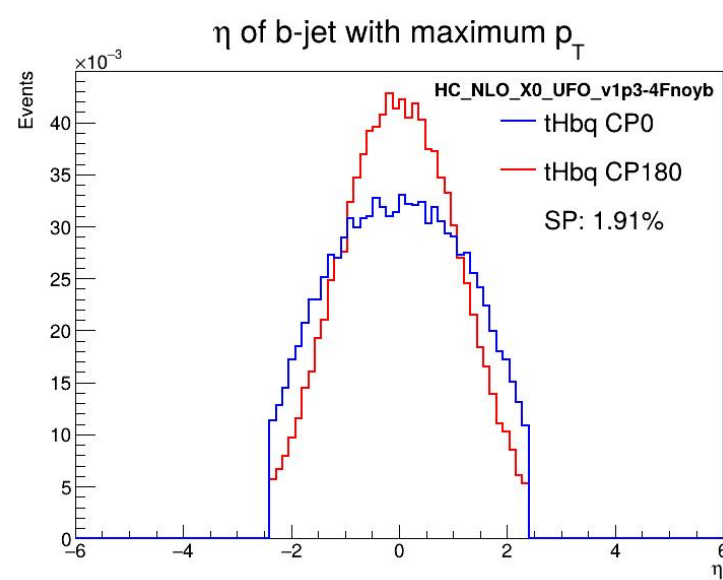
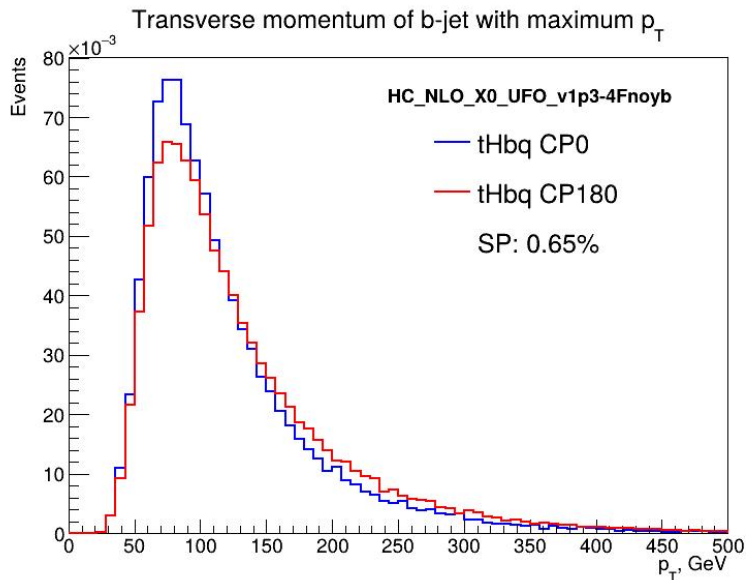
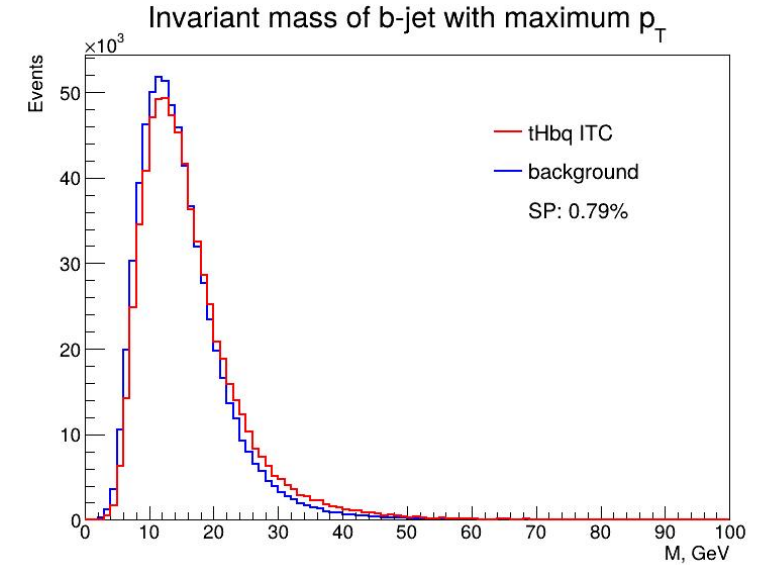
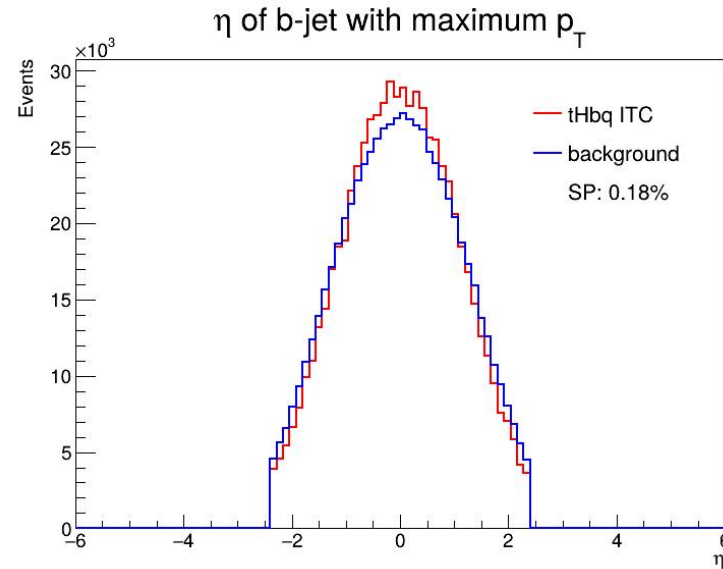
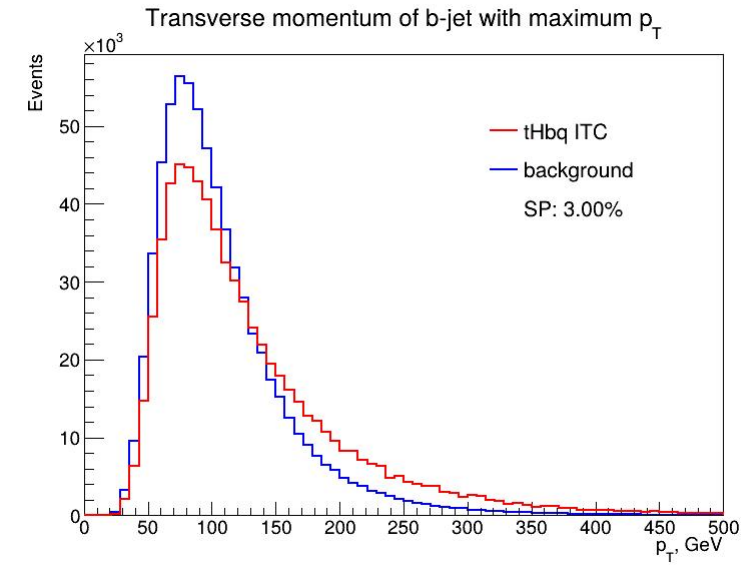
Distance between b-jet with maximum p_T and Forward (Tagging) Jet for the signal and background processes



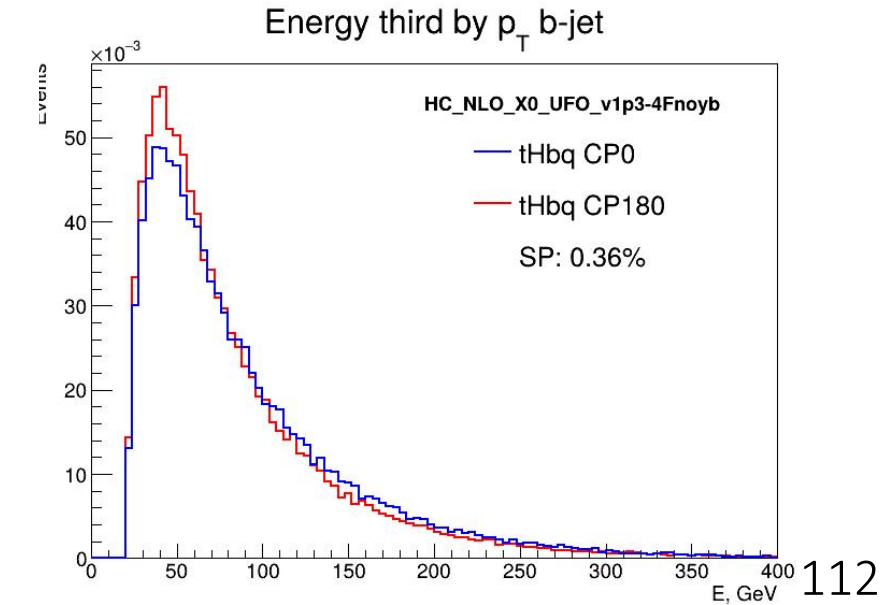
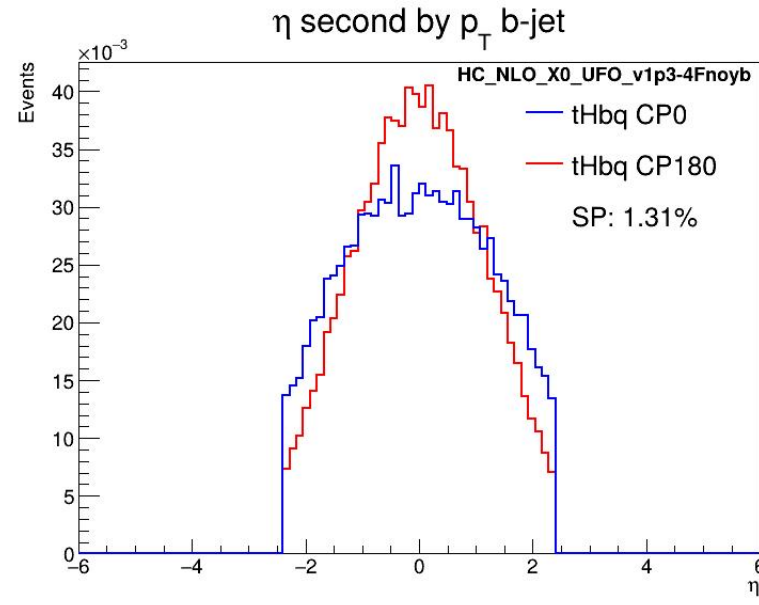
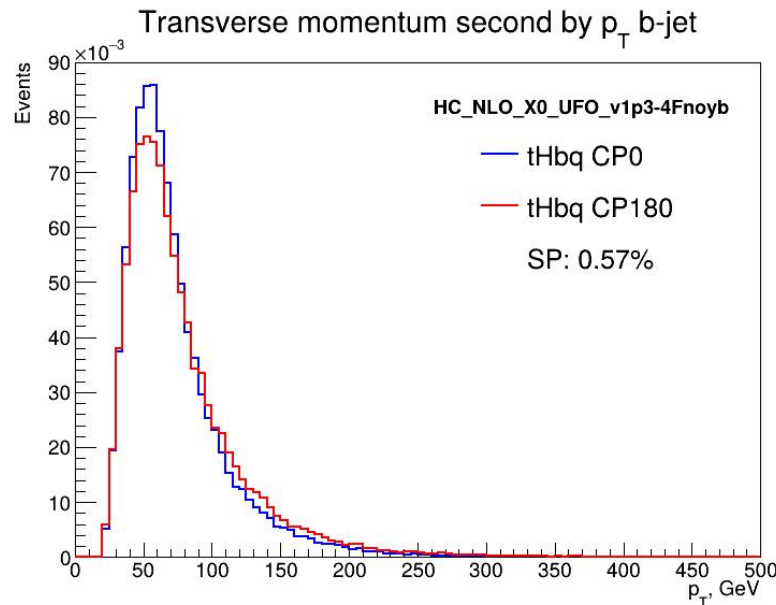
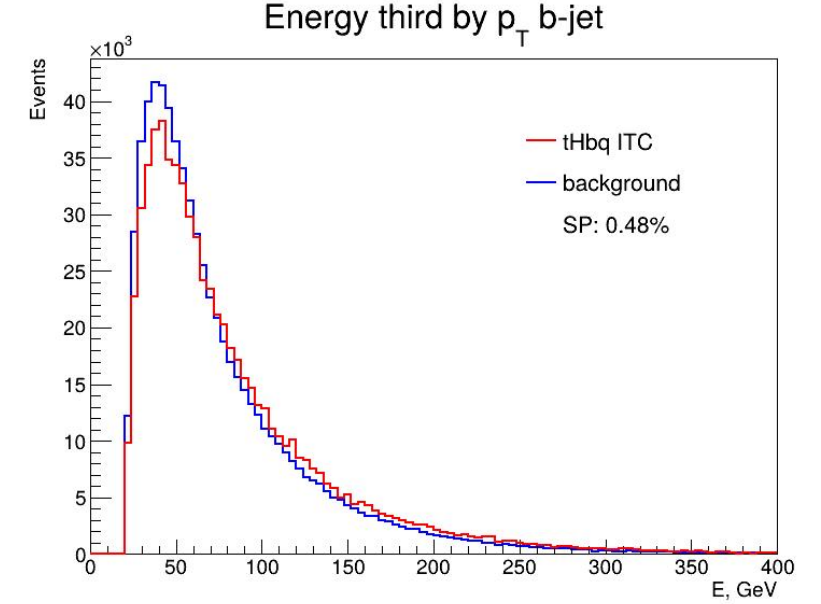
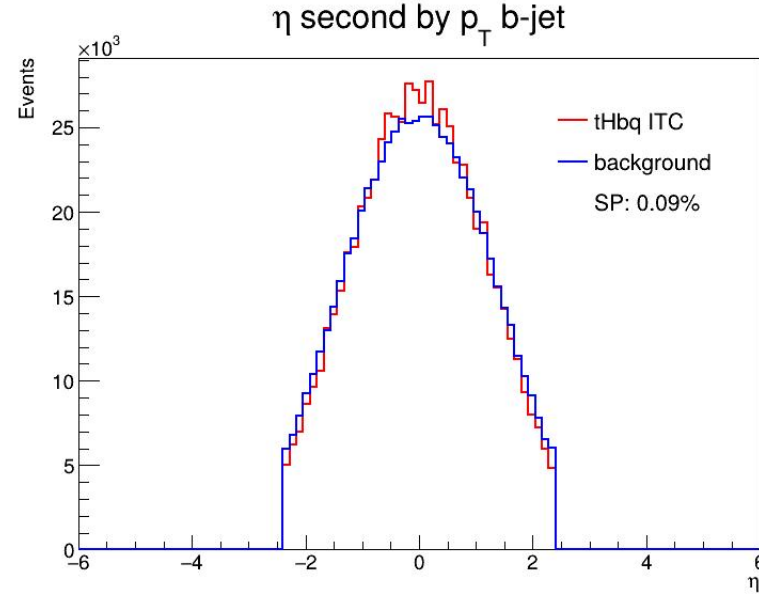
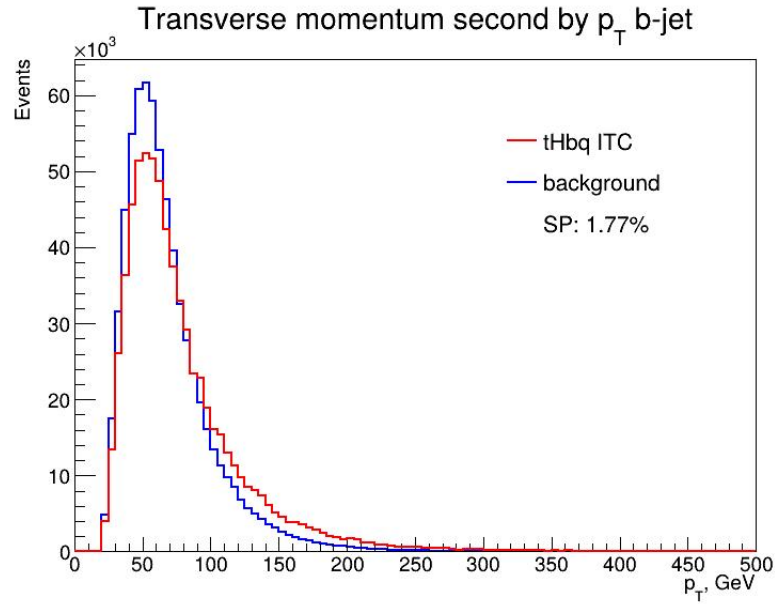
Distance between nearest b-jet and Forward (Tagging) Jet for the signal and background processes



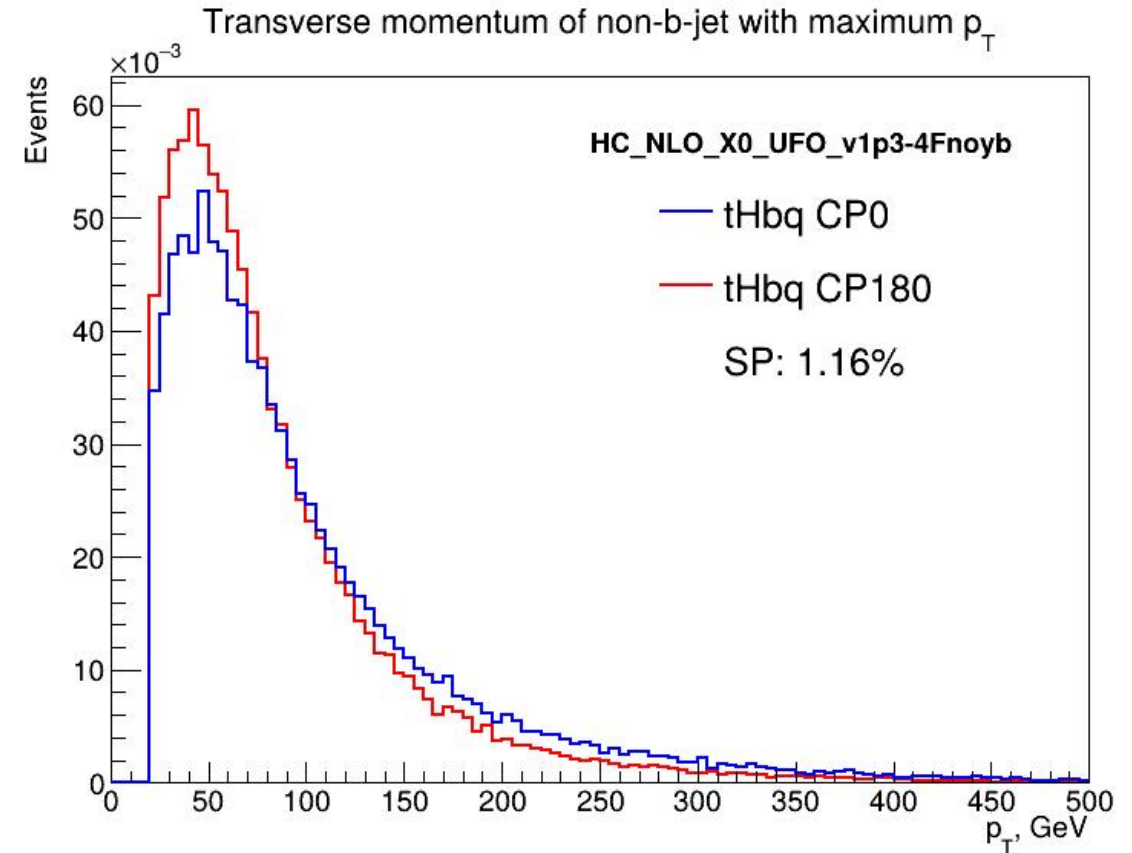
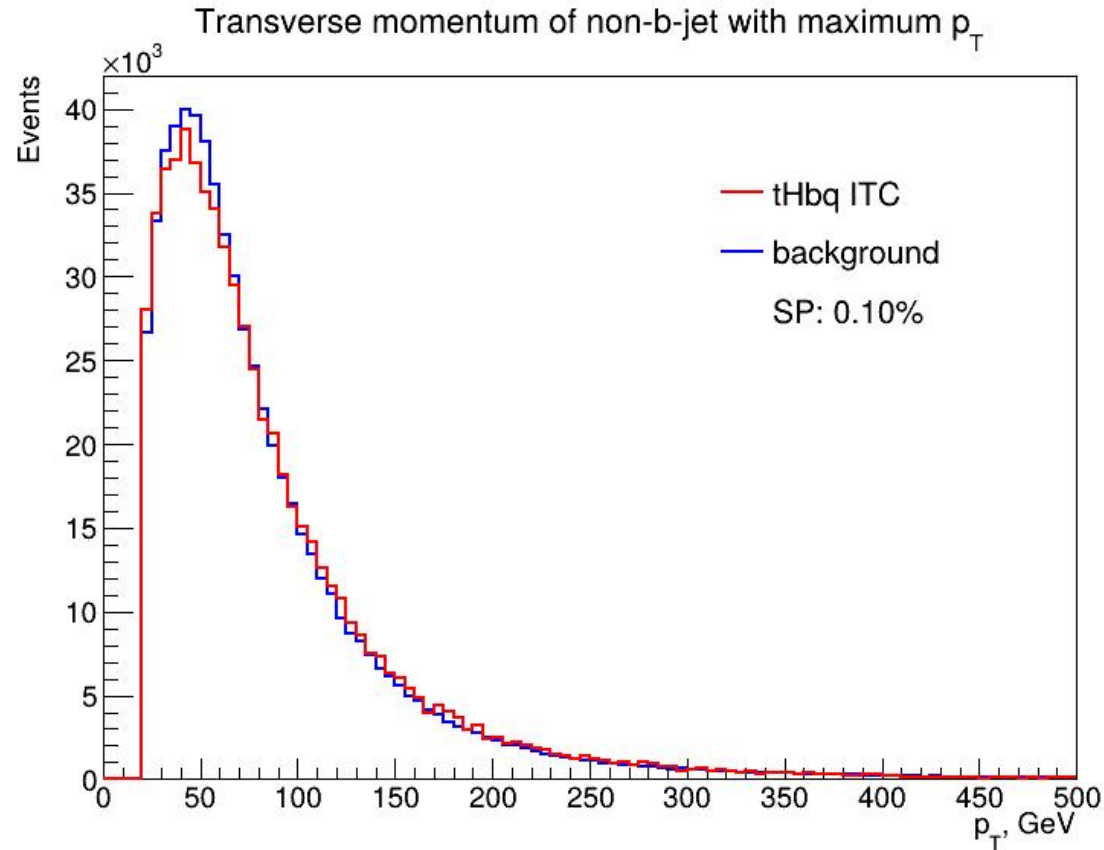
Characteristics b-jet with maximum p_T for the signal and background processes



Characteristics other b-jets for the signal and background processes

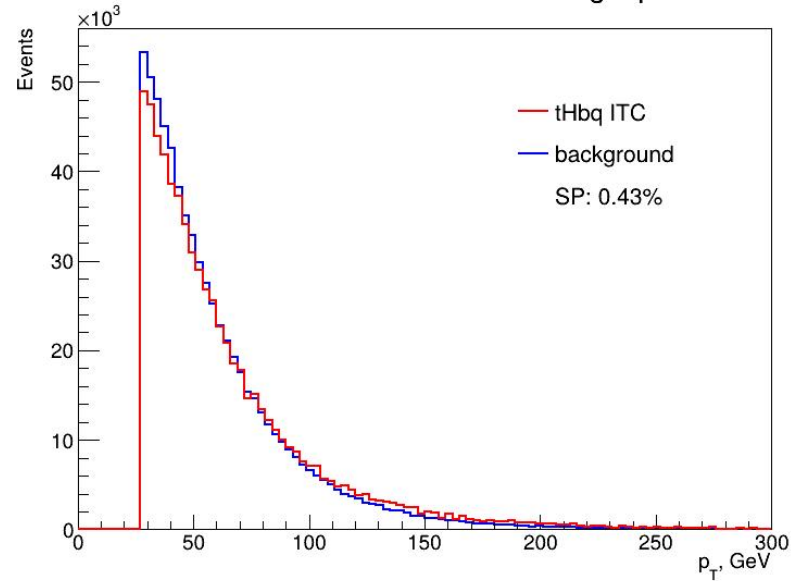


Transverse momentum non-b-jet with maximum p_T for the signal and background processes

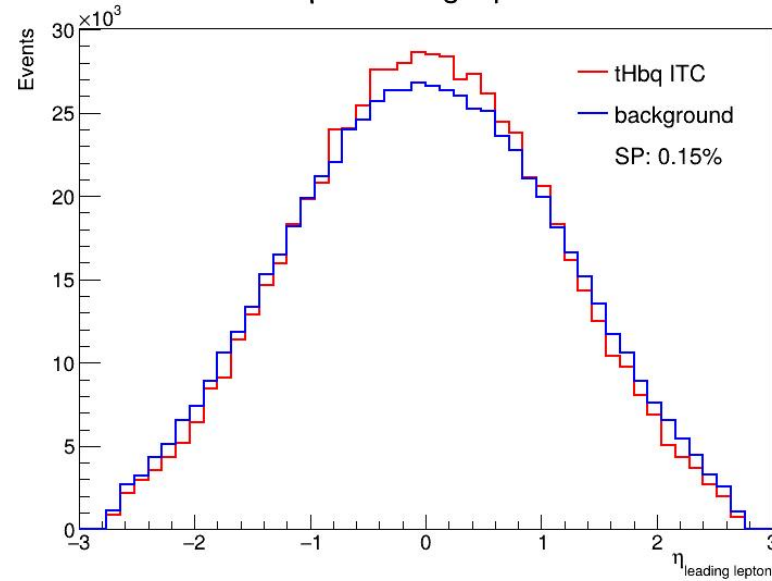


Leading lepton

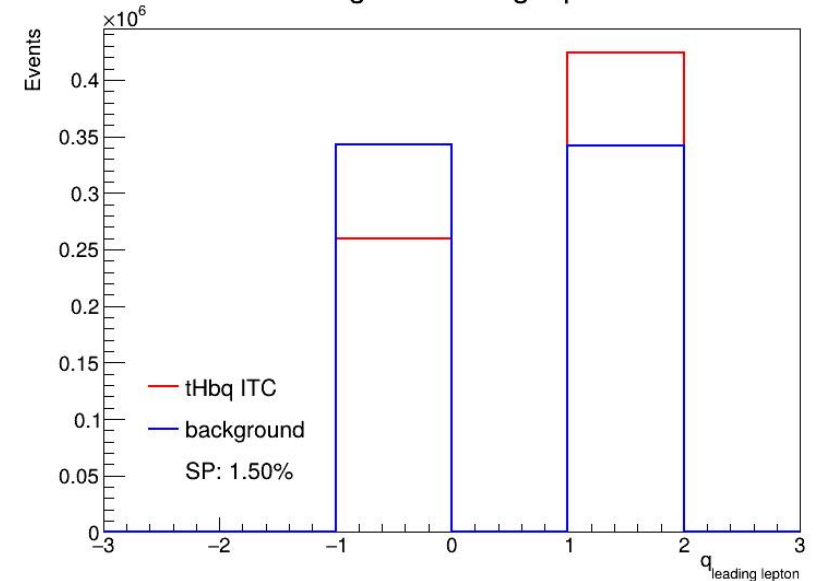
Transverse momentum of leading lepton



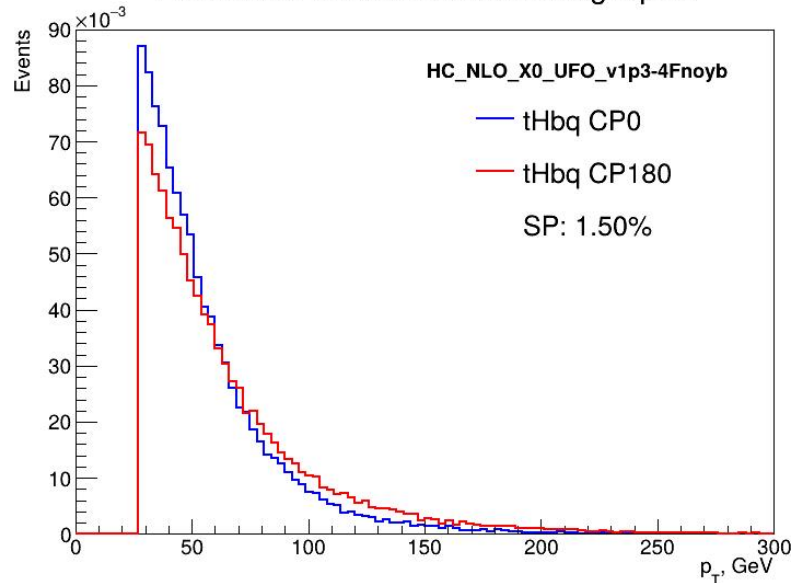
η of leading lepton



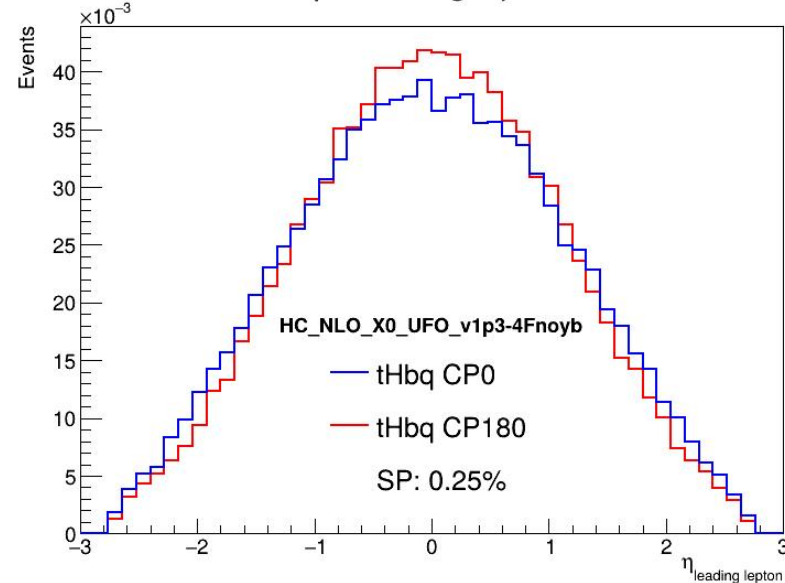
Charge of leading lepton



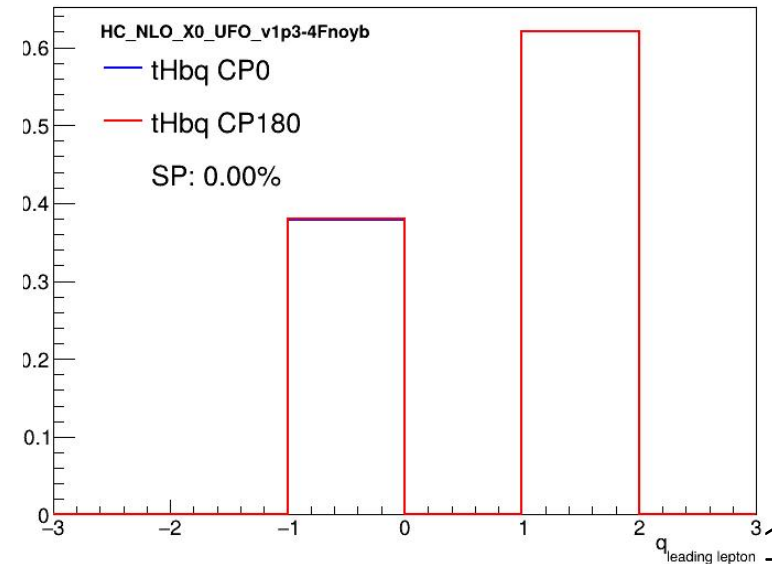
Transverse momentum of leading lepton



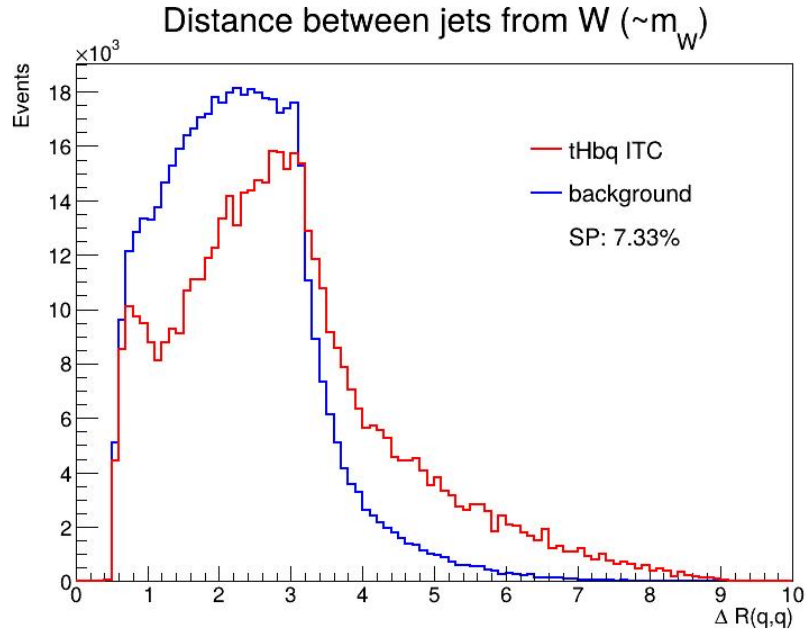
η of leading lepton



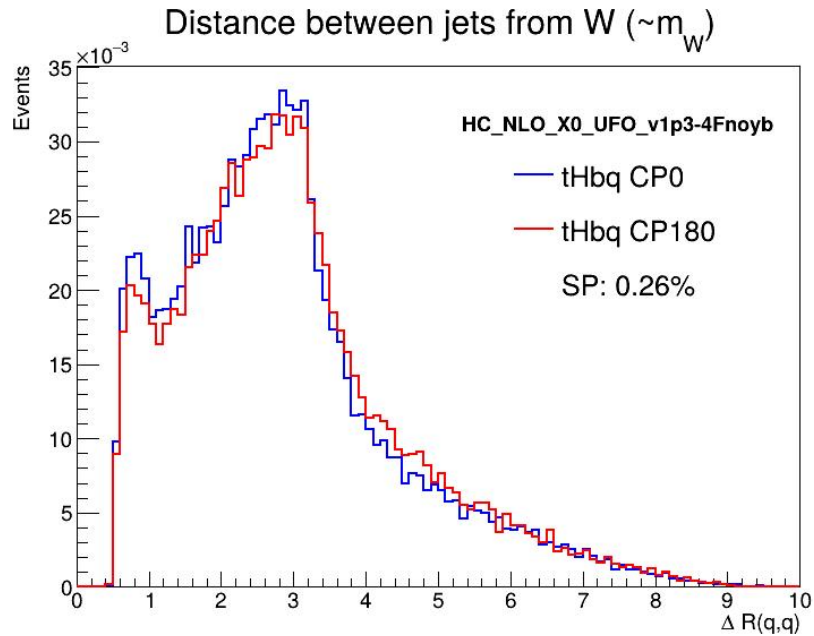
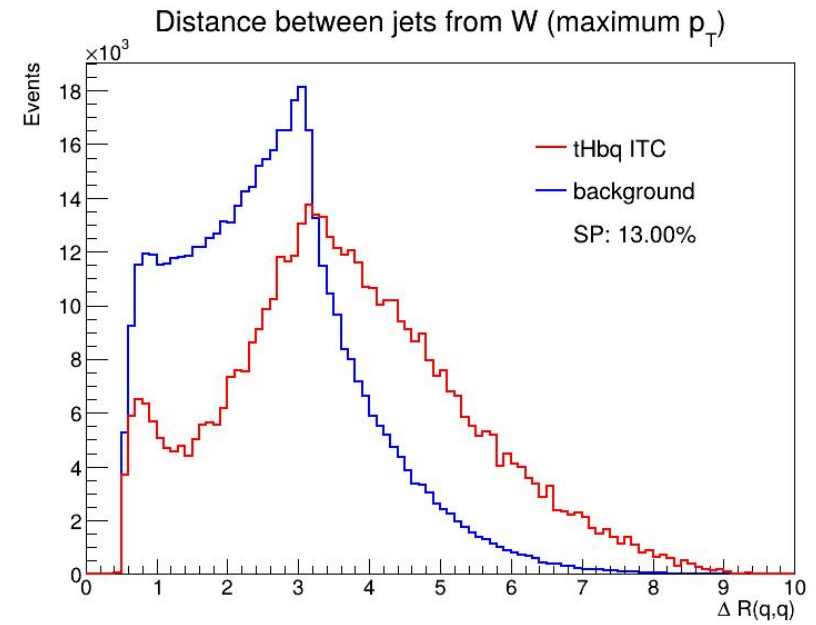
Charge of leading lepton



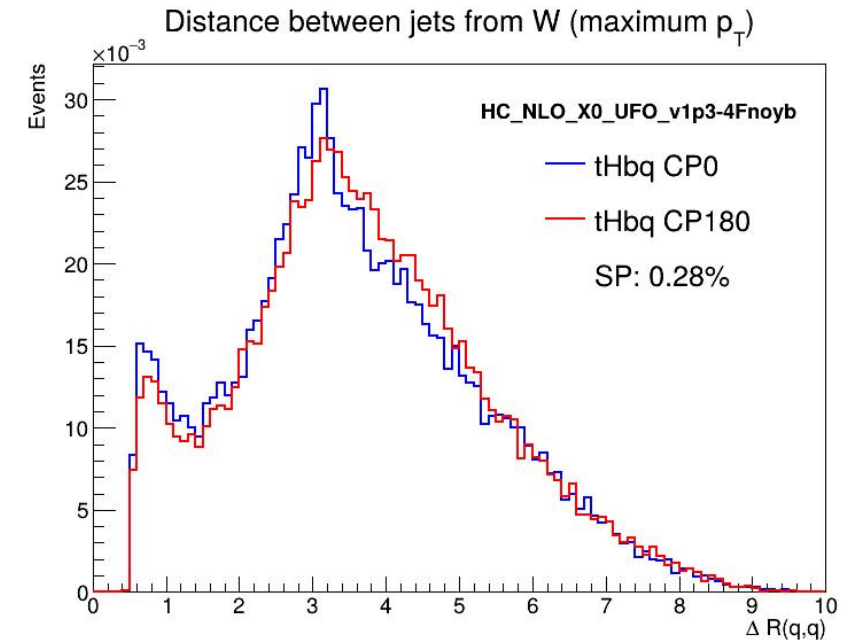
Distance between jets from W-bozon for the signal and background processes



$p_T^{max} (non - bjet)$



$m^{non-bjets} \sim 80.4 \text{ GeV}$



A set of variables most sensitive to the selection of signalling process events

Название	Определение
M_{3J}	Инвариантная масса трех струй с наибольшим p_T
N_b	Количество струй, порожденных b-кварками
$Sphresity_{all\ jets}$	Мера равномерности распределения струй в пространстве
$Sphresity_{lnu}$	Мера равномерности распределения объектов в пространстве
$Aplanarity_{all\ jets}$	Мера отклонения струй от одной общей плоскости
$\Delta(\eta_{t,FWD})$	Разность псевдобыстрот топ-кварка и передней струи
$Aplanarity_{lnu}$	Мера отклонения объектов от одной общей плоскости
$\Delta(\eta_{t,H})$	Разность псевдобыстрот топ-кварка и бозона Хиггса
$M_{t,H}$	Восстановленная масса топ-кварка и бозона Хиггса
M_H	Восстановленная масса бозона Хиггса
$fwm_{lnu}jet1$	Первый момент Фокса-Вольфрама, составленный из импульсов объектов
P_t^{FWD}	Поперечный импульс передней струи
$M_{H,FWD}$	Инвариантная масса бозона Хиггса и передней струи
$M_{H, cen. jet}$	Инвариантная масса бозона Хиггса и центральной легкой струи
η^{FWD}	Псевдобыстрота передней струи
χ^{min}	Качество (критерий χ^2) определения масс бозона Хиггса и топ-кварка
M_t	Восстановленная масса топ-кварка

Q_{lep}	Заряд лептона с наибольшим p_T
$\Delta(R_{qqW})$	Угол между струями от адронного распада W -бозона
N_{nonb}	Количество струй, порожденных кварками, отличных от b-кварка
$fwm2$	Второй момент Фокса-Вольфрама, составленный из импульсов струй
RapGap_maxptb	Разность псевдобыстрот передней струи и b-струи с наибольшим p_T
RapGap_closetb	Разность псевдобыстрот передней струи и ближайшей к ней b-струи
$P_{nonb\ max}^t$	Наибольший поперечный импульс среди легких струй
W_T_m	Поперечная масса всех струй
M_{FWD}	Инвариантная масса передней струи и топ-кварка
η_{lep}	Псевдобыстрота лептона с наибольшим p_T
E_{b2}	Энергия третьей по поперечному импульсу b-струи
$\Delta(\phi_{t,H})$	Разность азимутальных углов топ-кварка и бозона Хиггса
HT_alljets	Алгебраическая сумма поперечных импульсов всех струй
$\Delta(\eta_{H,FWD})$	Разность псевдобыстрот бозона Хиггса и передней струи
P_H^t	Восстановленный поперечный импульс бозона Хиггса
P_{b0}^t	Поперечный импульс b-струи с наибольшим p_T
P_{b1}^t	Поперечный импульс второй по p_T b-струи
η_H	Восстановленная псевдобыстрота бозона Хиггса
η_{b1}	Псевдобыстрота второй по p_T b-струи
M_{b0}	Инвариантная масса передней струи и b-струи с наибольшим p_T

Variables descriptions

Encoding	Definition	SP SM %	SP ITC %
mass_3jet	Invariant mass of three jets with the largest p_T	13.20	7.89
sphericity_all_jets	Measure of uniformity of the distribution of jets in the space	14.75	11.90
aplanarity_all_jets	Measure of deviation of the jets from the common plane	14.52	14.01
delta_eta_top_higgs	Difference of pseudorapidities from the top quark and Higgs boson	6.06	0.44
delta_eta_top_fwd	Difference of pseudorapidities of the top quark forward jet	4.96	2.44
delta_eta_top_tag	Difference of pseudorapidities of the top quark tagging jet	11.47	6.17
mass_th	Invariant mass of top quark and Higgs boson	4.87	1.63
mass_higgs	Reconstructed mass of Higgs boson	3.11	3.48
mass_top	Reconstructed mass of the top quark	2.59	1.86
pt_fwd	Transverse momentum of the forward jet	3.53	3.62
max_pt_nonbjet	Largest transverse momentum among light jets	1.39	0.10
eta_tag	Tagging jet pseudorapidity	14.97	18.20
mass_higgs_fwd	Invariant mass of Higgs boson and forward jet	5.12	10.41
mass_higgs_tag	Invariant mass of Higgs boson and tagging jet	14.63	20.38
mass_top_fwd	Invariant mass of the top quark and forward jet	9.05	7.19
mass_top_tag	Invariant mass of the top quark and tagging jet	18.35	11.83
q_lead	Charge of the lepton with the largest p_T	1.55	1.50
n_nonbjet	Number of jets produced by quarks other than a b quark	1.34	3.43
fwjets2	Second Fox–Wolfram moment composed of the momenta of jets	4.64	1.33
fwlnujet1	First Fox–Wolfram moment composed of the momenta of objects	1.56	0.47
deltaR_bjetmax_fwd	Difference between the pseudorapidities of the forward jet and the b jet with the largest p_T	2.82	4.81
deltaR_bjetmax_tag	Difference between the pseudorapidities of the tagging jet and the b jet with the largest p_T	9.63	12.44
deltaR_nearest_bjet_fwd	Difference between the rapidities of the forward jet and the b jet closest to it	2.48	5.76
deltaR_nearest_bjet_tag	Difference between the rapidities of the tagging jet and the b jet closest to it	10.95	14.86
mT_all_jets	Transverse mass of all jets	11.55	8.44
eta_lead	Pseudorapidity of the lepton with the largest p_T	0.02	0.15
sum_pt_jets	Algebraic sum of transverse momenta of all jets	1.25	0.89
energy_third_bjet	Energy of the b jet third in its transverse momentum	1.40	0.48
delta_phi_higgs_top	Difference between the azimuthal angles of the top quark and Higgs boson	0.92	0.23
delta_eta_higgs_fwd	Difference between the pseudorapidities of Higgs boson and for-ward jet	0.92	4.67
delta_eta_higgs_tag	Difference between the pseudorapidities of Higgs boson and tagging jet	4.01	12.40
max_pt_bjet	Transverse momentum of the b jet with the largest p_T	1.08	3.00
pt_second_bjet	Transverse momentum of the b jet second in its p_T value	0.52	1.77

Encoding	Definition	SP SM %	SP ITC %
eta_higgs	Reconstructed pseudorapidity of Higgs boson	0.75	0.32
eta_second_bjet	Pseudorapidity of the b jet second in its p_T value	0.80	0.09
m_max_bjet	Invariant mass of the b jet with the largest p_T	0.17	0.79
eta_max_bjet	Pseudorapidity of the b jet with the largest p_T	1.01	0.18
mass_higgs_central_jet	Invariant mass of Higgs boson and central light jet	6.38	5.22
n_forward_jet	Number of forward light jets	8.59	8.74
n_central_jet	Number of central light jets	11.68	15.39
chi2_min	Quality (χ^2 criterion) of determining the masses of Higgs boson and top quark	0.98	1.24
deltaR_qq_W_max_pt	Difference between the rapidities of the light jets with the largest p_T	8.87	13.00
deltaR_qq_W_nearest_mass_W	Difference between the rapidities of the light jets whose masses are closest to the mass of the W boson	4.68	7.33
pt_lead	Largest transverse momentum among leptons	0.39	0.43
has_tag_jet	Binary mask for the presence or absence of a tagging jet	-	-
has_fwd_jet	Binary mask for the presence or absence of a forward jet	-	-
has_central_jet	Binary mask for the presence or absence of a central jet	-	-
n_bjet	Number of jets produced by b quarks	6.12	5.71
n_jet*	Number of jets	0.48	1.93
sphericity_Inu*	Measure of uniformity of the distribution of objects in the space	14.38	10.43
pt_tag*	Transverse momentum of the tagging jet	1.28	0.41
aplanarity_Inu*	Measure of deviation of objects from the common plane	14.36	13.07
pt_higgs*	Reconstructed transverse momentum of Higgs boson	0.94	3.60
eta_fwd	Forward jet pseudorapidity	3.21	6.46

Variable1	Variable2	Pearson coefficient
n_nonbjet	n_jet*	0.971
sphericity_all_jets	sphericity_all_Inu*	0.879
pt_tag*	max_pt_nonbjet	0.866
aplanarity_all_jets	aplanarity_Inu*	0.812
pt_higgs*	max_pt_bjet	0.807

Additional information

Processes	Pre-selection
tH	73.80 ± 0.15
tWH	49.62 ± 0.04
tt + $\geq 1b$	60170 ± 50
tt + $\geq 1c$	33585 ± 29
tt + light	106290 ± 90
ttH	1676.9 ± 1.4
ttZ	891.0 ± 0.8
ttW	362.01 ± 0.31
tZq	170.54 ± 0.25
tWZ	2.2157 ± 0.0019
Wt channel	5849 ± 5
t channel	3223 ± 4
s channel	259.71 ± 0.22
W + jets	4072 ± 4
Z + jets	609.5 ± 0.6
VV	291.79 ± 0.26
other Higgs	25.054 ± 0.023
Rare top	8.936 ± 0.008
Fakes	8028 ± 7
Total	225640 ± 190
Data	244167

Process	Generator	Order (scheme)	PDF set	Parton shower	PDF set (tune)
Signal					
<i>tHq</i>	MADGRAPH5_AMC@NLO 2.6.2	NLO (4FS)	NNPDF3.0NLO nf4	PYTHIA 8.230	NNPDF2.3Lo (A14 tune)
Backgrounds					
$\bar{t}\bar{t}$	POWHEG Box v2	NLO (5FS)	NNPDF3.0NLO	PYTHIA 8.230	NNPDF2.3Lo (A14 tune)
V+jets	SHERPA 2.2.1	NLO+LO	NNPDF3.0NNLO	-	-
Diboson	SHERPA 2.2.1-2	NLO+LO	NNPDF3.0NNLO	-	-
Triboson	SHERPA 2.2.2	NLO+LO	NNPDF3.0NNLO	-	-
$\bar{t}\bar{t}Z$	MADGRAPH5_AMC@NLO 2.3.3	NLO	NNPDF3.0NLO	PYTHIA 8.210	NNPDF2.3Lo (A14 tune)
$\bar{t}\bar{t}W$	SHERPA 2.2.10	NLO	NNPDF3.0NNLO	-	-
$\bar{t}\bar{t}H$	POWHEG Box v2	NLO (5FS)	NNPDF3.0NLO	PYTHIA 8.230	NNPDF2.3Lo (A14 tune)
<i>t</i> -channel	POWHEG Box v2	NLO (4FS)	NNPDF3.0NLO nf4	PYTHIA 8.230	NNPDF2.3Lo (A14 tune)
<i>t</i> W	POWHEG Box v2	NLO (5FS, DR)	NNPDF3.0NLO	PYTHIA 8.230	NNPDF2.3Lo (A14 tune)
<i>s</i> -channel	POWHEG Box v2	NLO	NNPDF3.0NLO	PYTHIA 8.230	NNPDF2.3Lo (A14 tune)
<i>t</i> Zq	MADGRAPH5_AMC@NLO 2.3.3	NLO	NNPDF3.0NLO	PYTHIA 8.230	NNPDF2.3Lo (A14 tune)
<i>t</i> WH	MADGRAPH5_AMC@NLO 2.8.1	NLO (5FS, DR)	NNPDF3.0NLO	PYTHIA 8.245p3	NNPDF2.3Lo (A14 tune)
<i>t</i> WZ	MADGRAPH5_AMC@NLO 2.3.3	NLO	NNPDF3.0NLO	PYTHIA 8.212	NNPDF2.3Lo (A14 tune)
<i>ttt</i>	MADGRAPH5_AMC@NLO 2.2.2	NLO	NNPDF3.1NLO	PYTHIA 8.186	NNPDF2.3Lo (A14 tune)
$\bar{t}\bar{t}\bar{t}$	MADGRAPH5_AMC@NLO 2.3.3	NLO	NNPDF3.1NLO	PYTHIA 8.230	NNPDF2.3Lo (A14 tune)
<i>gg</i> H	POWHEG Box v2	NLO	CT10	PYTHIA 8.210	CTEQ6L1 (AZNLO tune)
<i>qq</i> H	POWHEG Box v1	NLO	CT10	PYTHIA 8.186	CTEQ6L1 (AZNLO tune)
WH	PYTHIA 8.186	LO	NNPDF2.3Lo	-	-
ZH	PYTHIA 8.186	LO	NNPDF2.3Lo	-	-

