Updates on hh → VVbb decay channels

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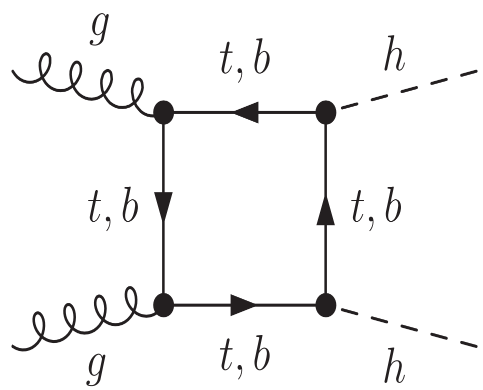
for the R&D for Future Accelerator WG1 of I.N.F.N

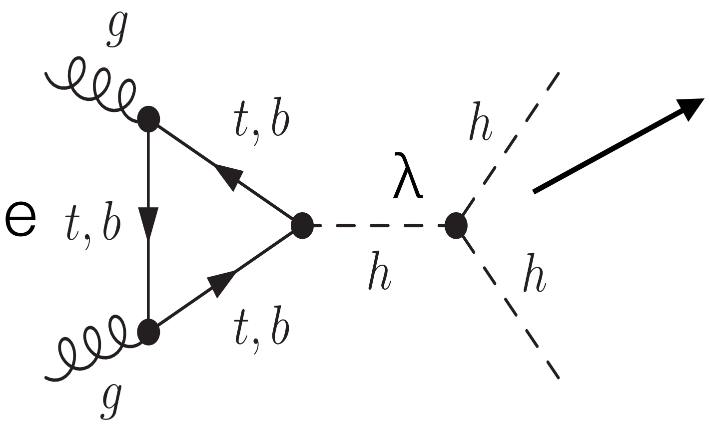
hh production and signal model

hh production mechanism

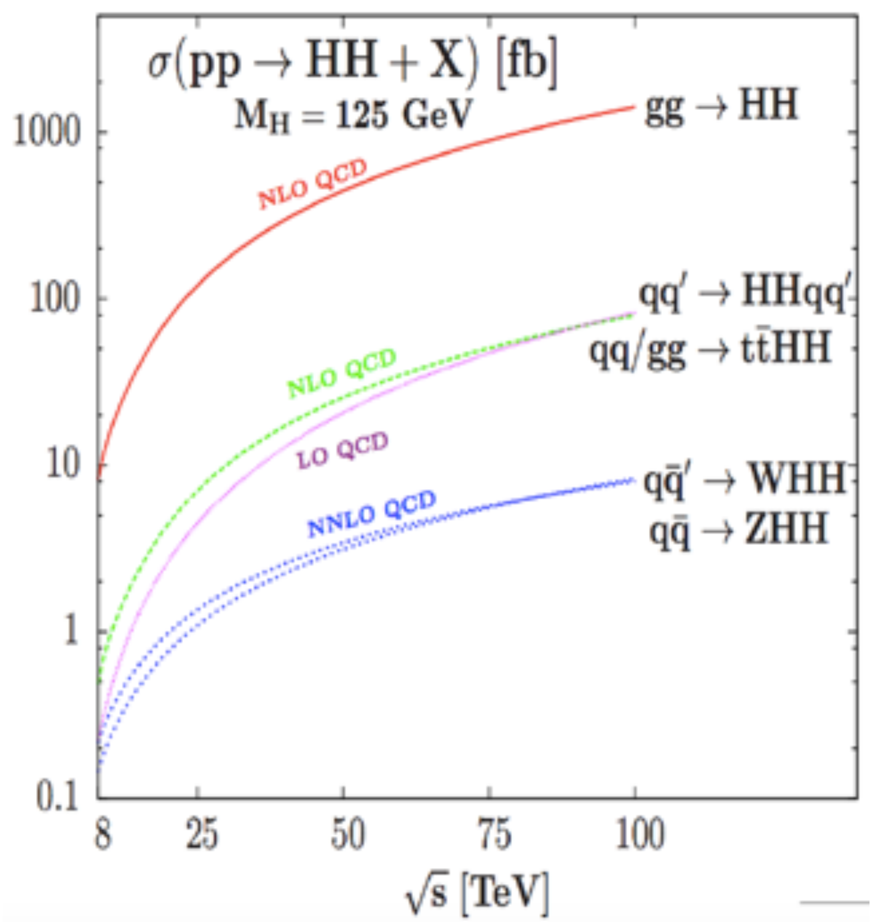
box



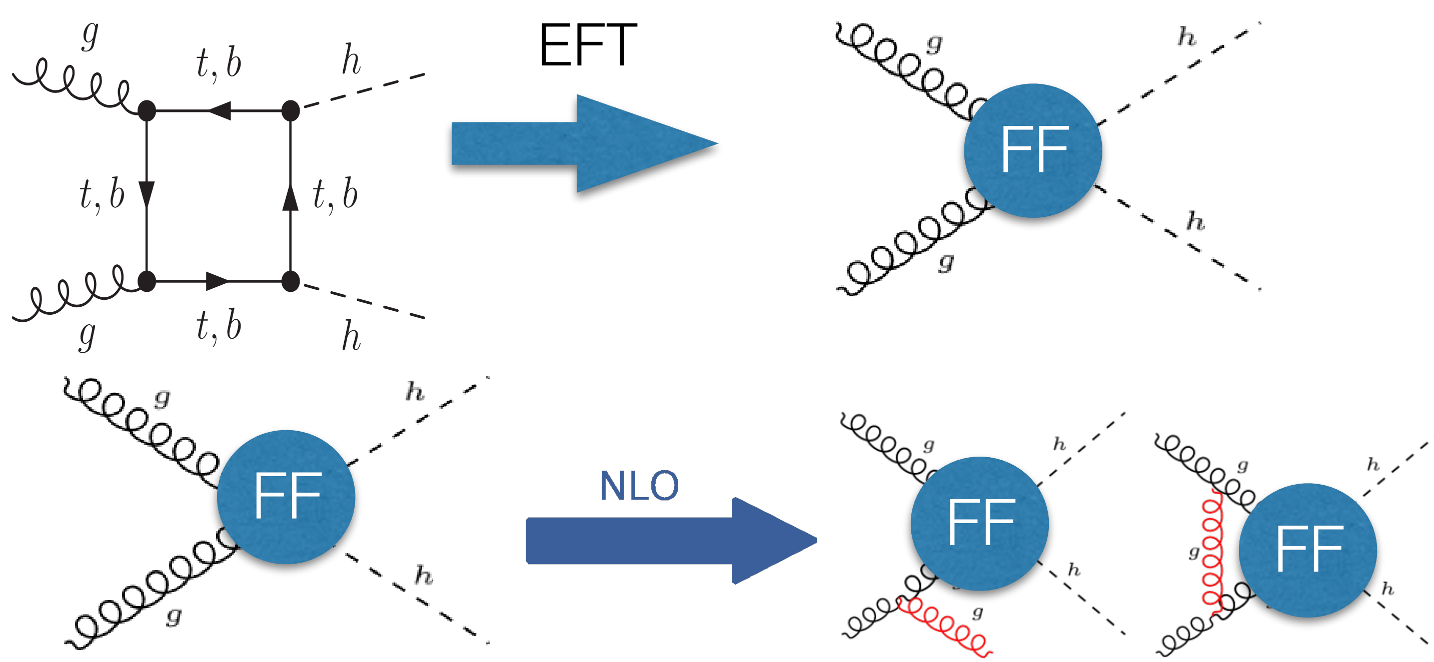
triangle



self-coupling

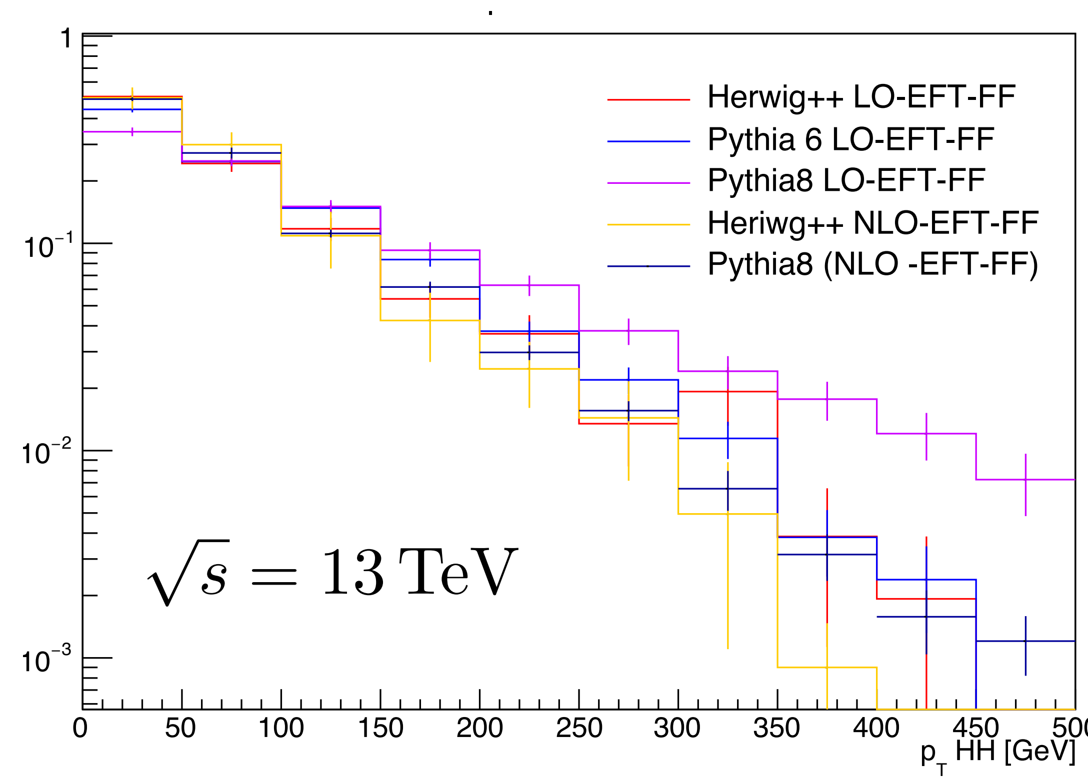


- dominant production through gluon-gluon fusion;
- signal model simulated using Madgraph5_aMC@NLO, using NLO reweighting with finite top mass effect correction implemented through Form Factor *R. Frederix et al.*, Phys. Lett. B732 (2014) 142

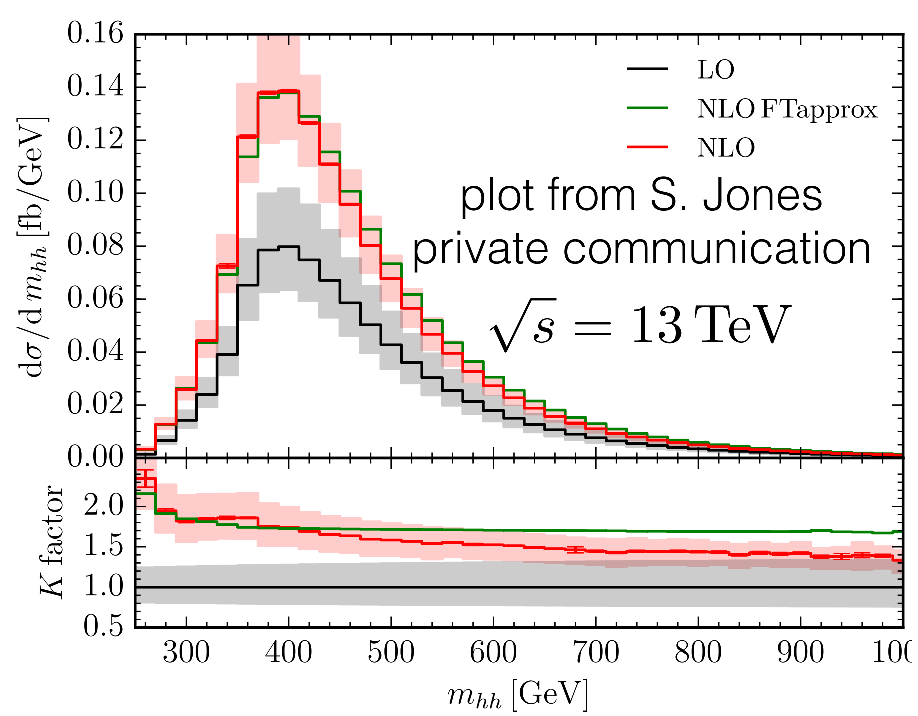


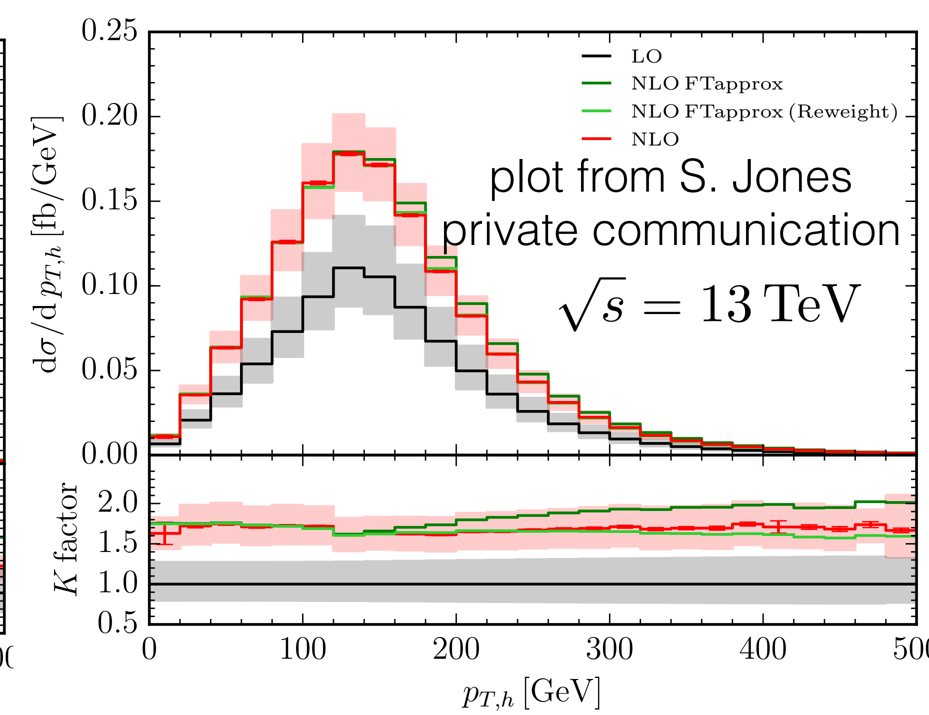
Parton shower choice and EFT approx validation

- Comparison between LO calculations with finite top mass correction with NLO ones for different Parton Showers
- Pythia8 shows an hard p_T^{hh} spectrum when using LO simulation not shown by the other Parton Showers
- Prefer to use Herwig++ for signal simulation

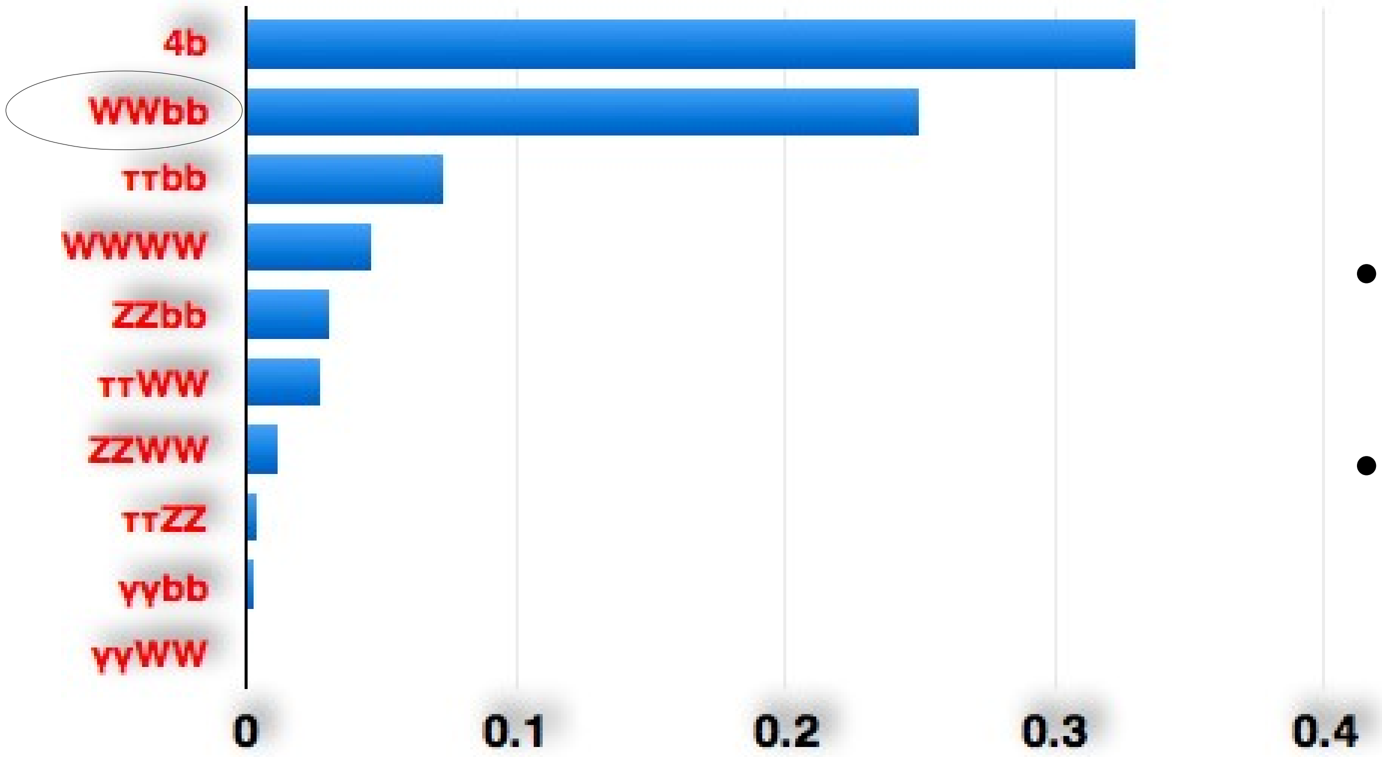


- full NLO computation with finite top mass effect available [S. **Borowka et al. JHEP 1610 (2016) 107]**
- our approximation (FTapprox) quite in good agreement with full calculation
- possible to reweight the m_{hh} distribution to reproduce also the p_T^h
- now available in Powheg, aMC@NLO





hh decay channels



The Higgs boson can decay to different final states:

- 4b, WWbb are the dominant ones
- γγbb, ZZbb are the cleanest one

- 4b, γγbb have been already studied in the present physics-report

- For WWbb there is a feno-paper in the 1-lepton final state: PRD87 (2013) 0011301 claiming for 4σ observation with 600 fb^{-1} @14 TeV, preliminary CMS results with 3.2 fb^{-1} of 13 TeV data in the 2-lepton final state find much worse results [CMS-PAS-HIG-16-024]

~ × 40 at 100 TeV wrt to 14 TeV

$\sqrt{s}$ [TeV]	$\sigma^{\rm NLO}$ [fb]
8	8.2
14	33.9
33	207.3
100	1417.8

results from the 2016 FCC physics report

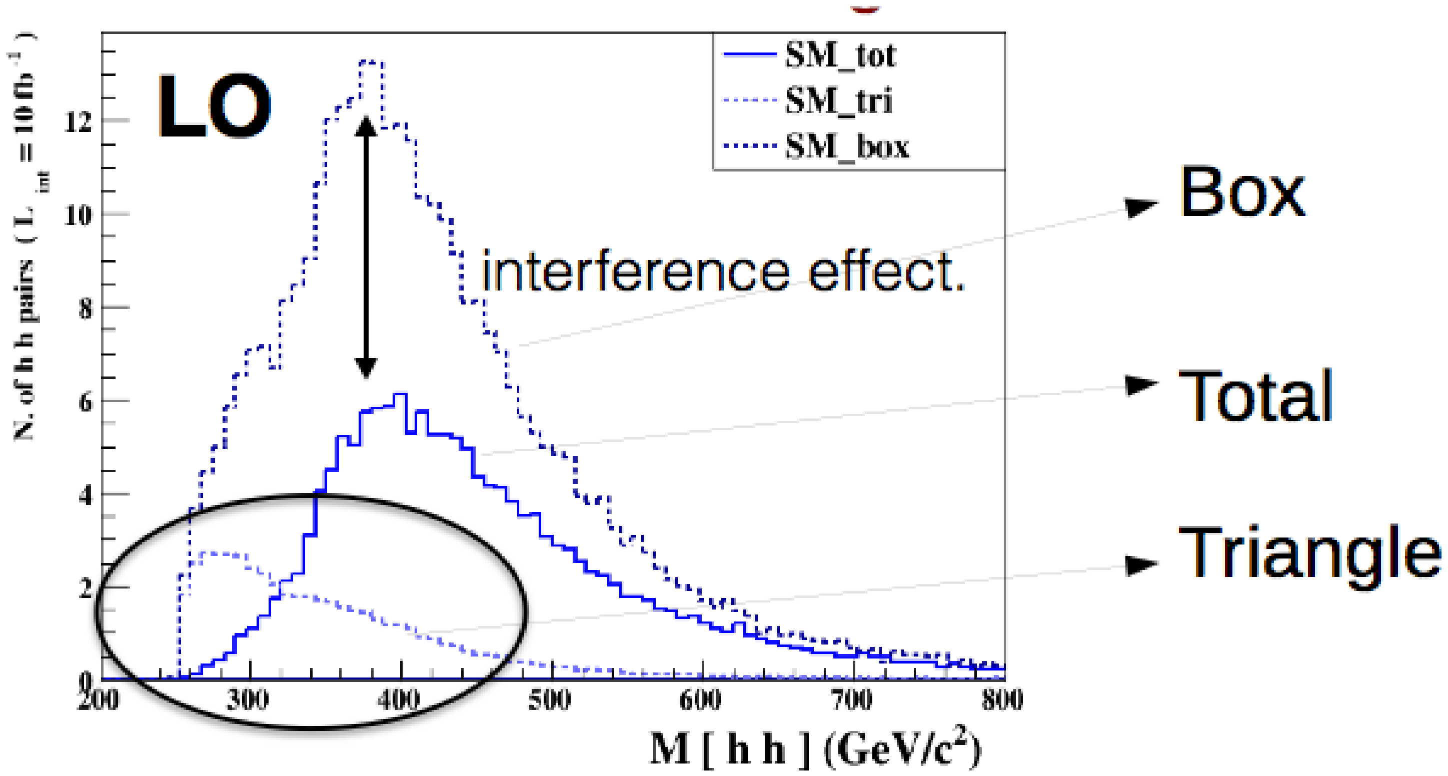
30 ab^{-1}

	Δσ/σ	Δλ/λ
γγbb	1.3%	2.5%
4b	25% (S/B ~2%)	200%
ZZbb, 4l	~30%	~40%

In this presentation, focus on two final states:

WWbb, ZZbb

Sensitivity to λ and MC events simulated?



- **Triangle mainly contributing to very low m_{hh},**
- **but moderate m_{hh} can be sensitive through interference with top-box.**

low m_{hh} feasible for ZZbb, less for WWbb

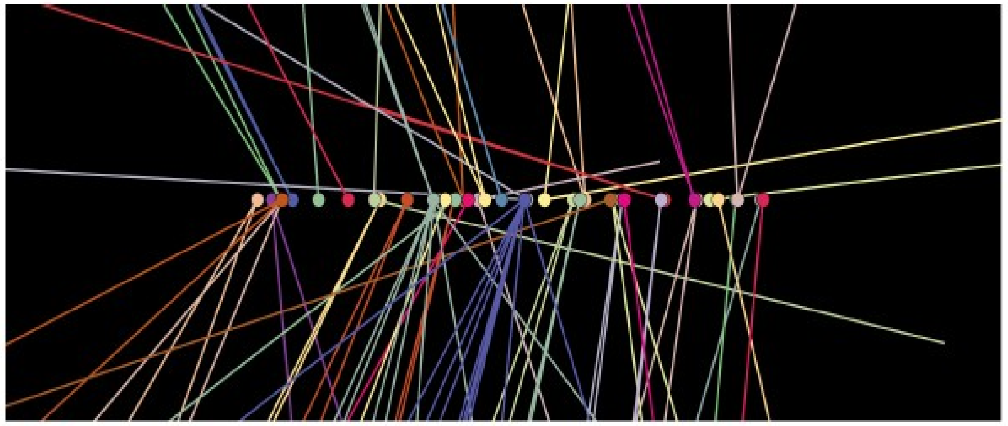
sample	**σ(pb)**	**N_{evts}^{gen}**
hh	1.4	1M
$t\text{-}t_{bar}$		
$l^{\pm}\nu qqbb$	4.1×10^3	10M
$\tau^{\pm}\nu qqbb$	0.2×10^3	2M

Pile-up at FCC-hh

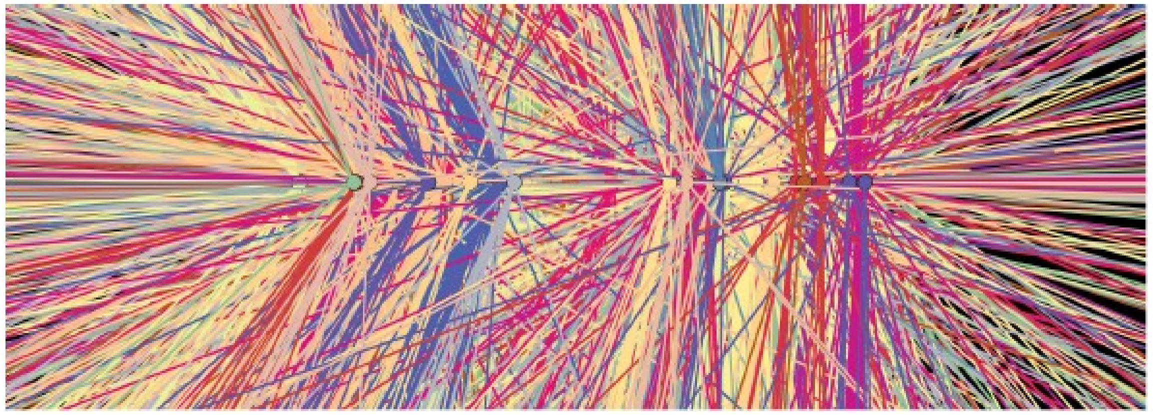
Pile-up simulation

100k Herwig++ 2.7.1 min-bias events overlapped to the hard process using Delphes

LHC condition



FCC-hh condition



Optimizing integrated luminosity of future hadron colliders, M. Benedikt et. al.

For bunch spacing of 25 ns

	FCC Phase 1	FCC Phase 2
Peak pileup	180	940
Peak pileup line density m^{-1}	≤ 3200	≤ 17000
rms bunch length [cm]	8	8

For 5 ns bunch spacing Pile-up → Pileup / 5

Configurations chosen for this study:
Pile-up = 50 ≈ Pile-up at Phase 1 at 5 ns
Pile-up = 200 ≈ Pile-up at Phase 1 at 25 ns OR Phase 2 at 5 ns

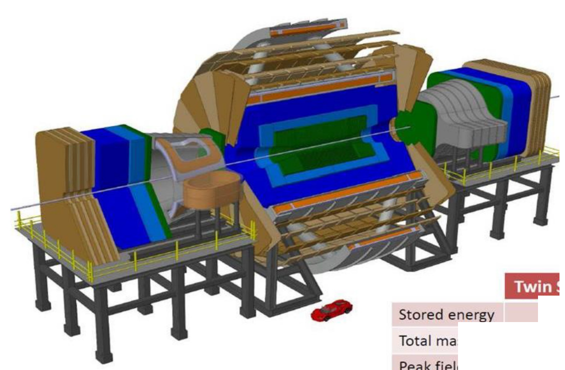
Pile-up conditions and detector simulation

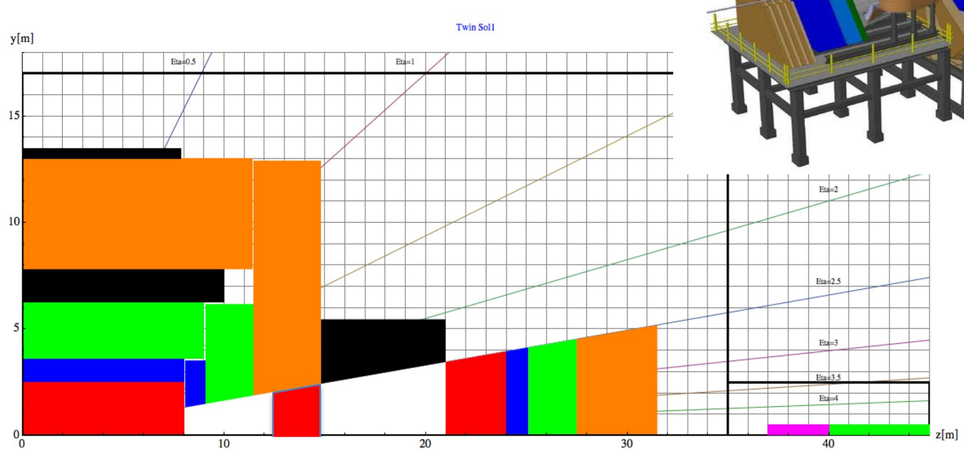
pile-up configuration used in this presentation

- WWbb 50, 200, 900 vertices, ZZbb 1000

Simulation of the 5 ns low and high luminosity phase and of the 25 ns high luminosity phase

Base-line geometry
Twin solenoid +
Dipole magnetic system





ZZbb

Tracker
EMCAL
HCAL
Coil+Cryostat
Muon system

Fwd Tracker
Dipole

Detector simulation with

Delphes git trunk: ZZbb
Delphes 3.3.2: WWbb
Fwd dipole not used in the ZZbb case

Calorimetry

ECAL granularity:
0.0125 x 0.0125 $|\eta| < 2.5$
0.025 x 0.025 $2.5 < |\eta| < 4.0$
0.05 x 0.05 $4.0 < |\eta| < 6.0$

ECAL Energy Resolution:
$\sigma(E)/E = 10\% / \sqrt{E} \oplus 1\%$
$|\eta| < 6.0$

HCAL granularity:
0.05 x 0.05 $|\eta| < 2.5$
0.1 x 0.1 $2.5 < |\eta| < 4.0$
0.2 x 0.2 $4.0 < |\eta| < 6.0$

HCAL Energy Resolution:
$\sigma(E)/E = 50\%/\sqrt{E} \oplus 3\%$ $|\eta| < 4.0$
$\sigma(E)/E = 100\%/\sqrt{E} \oplus 5\%$ $|\eta| < 6.0$

Tracking

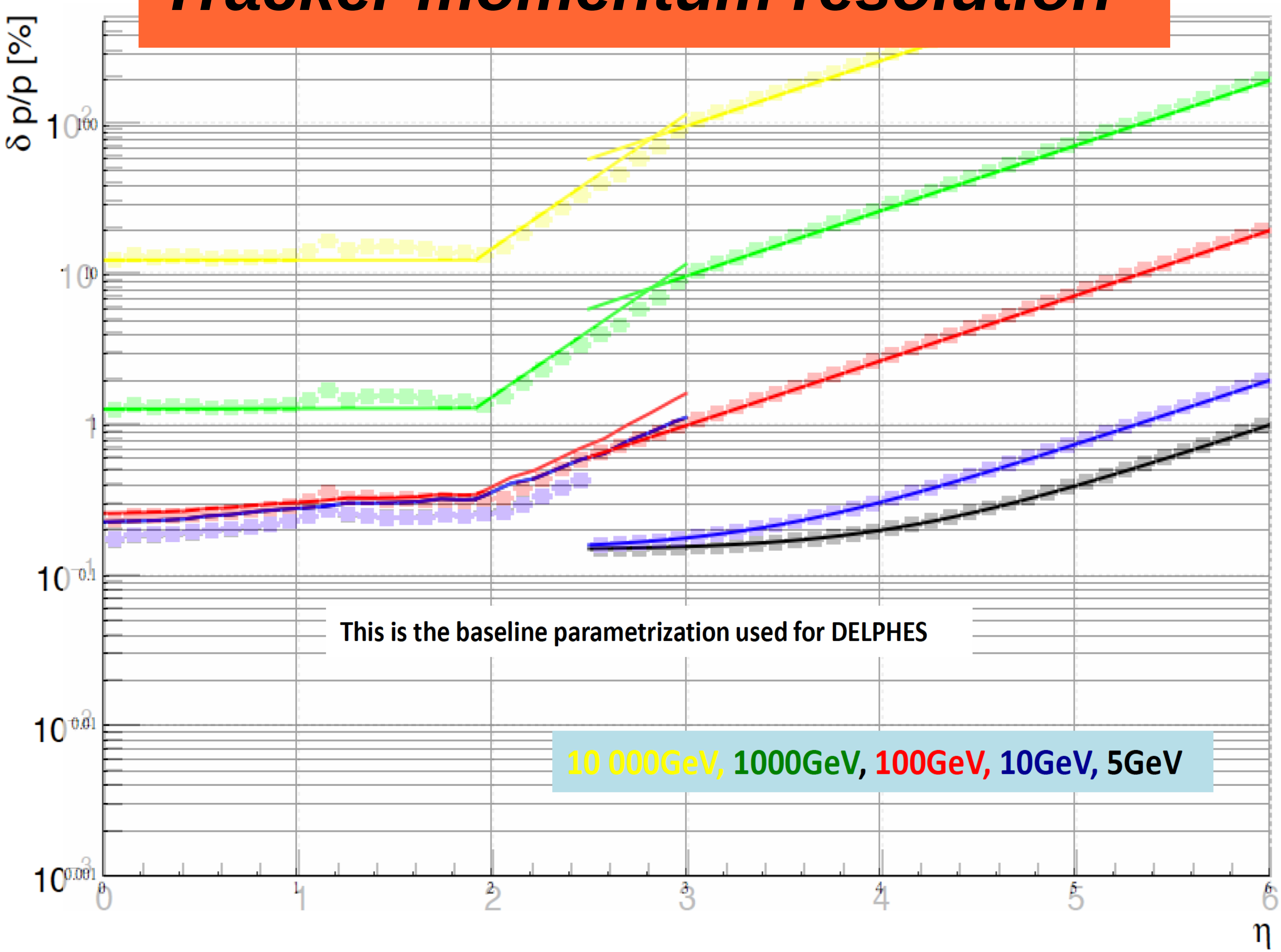
Efficiency c-quark jets:
4 % $|\eta| < 2.5$
3 % $2.5 < |\eta| < 4.0$ ZZbb

Efficiency light-quark jets:
0.1 % $|\eta| < 2.5$
0.075 % $2.5 < |\eta| < 4.0$ ZZbb

Efficiency b-quark jets:
75% WWbb 85 % ZZbb $|\eta| < 2.5$
64% $2.5 < |\eta| < 4.0$ ZZbb

z_0 resolution (*)
- *in $|\eta|<2.5$*
  - **$\sigma(z_0)$= 0.01 mm , p_T<5 GeV**
  - **$\sigma(z_0)$= 0.005 mm , p_T>5 GeV**
- **In $2.5<|\eta|<4$**
  - **$\sigma(z_0)$= 0.1 mm , p_T<5 GeV**
  - **$\sigma(z_0)$= 0.05 mm , p_T>5 GeV**
- **In $4.0<|\eta|<6.0$**
  - **$\sigma(z_0)$= 1.0 mm , p_T<5 GeV**
  - **$\sigma(z_0)$= 0.5 mm , p_T>5 GeV**

Tracker momentum resolution



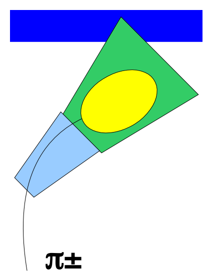
Object reconstruction and performances

✦ Particle Flow Reconstruction

- Using charged hadrons, muons, electrons and calorimeter towers to build particle-flow objects
- Tracks from pile-up are rejected if $|Z_0 - Z_{\rm PV}| > \sqrt{\sigma^2(Z_0) + \sigma^2(Z_{\rm PV})}$

✦ Jets

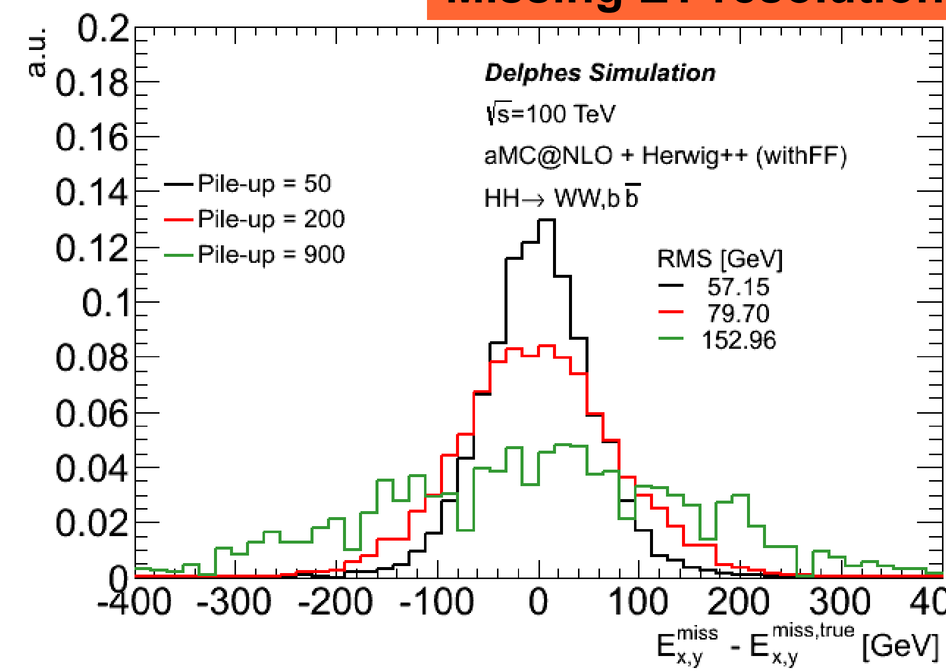
- Anti-Kt (Fast Jet) algorithm
- particle-flow objects as inputs
- R = 0.4
- Jet Area pile-up correction:
- private calibration to particle level $p_T^{\rm corrected} = p_T^{\rm raw} - \rho \cdot {\rm Jet Area}$
- $p_T^{\rm jet} > 20$ GeV



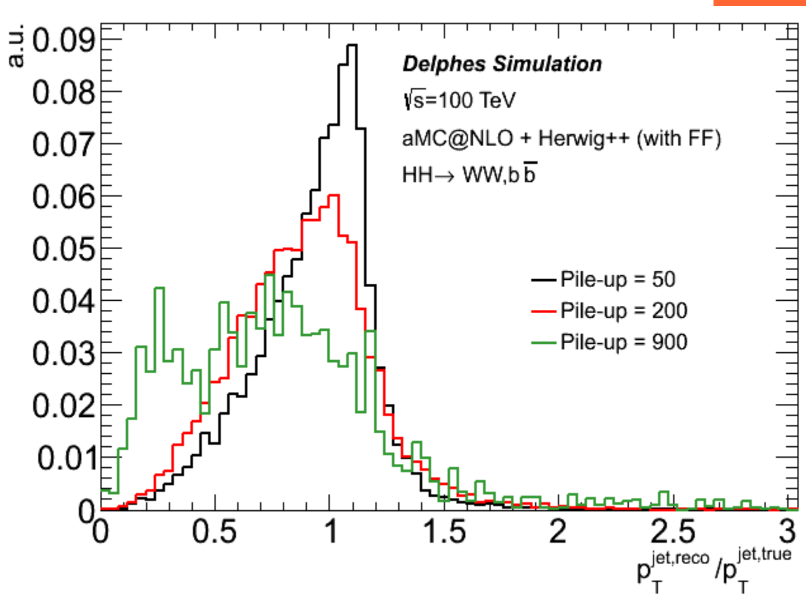
✦ Missing Transverse Energy

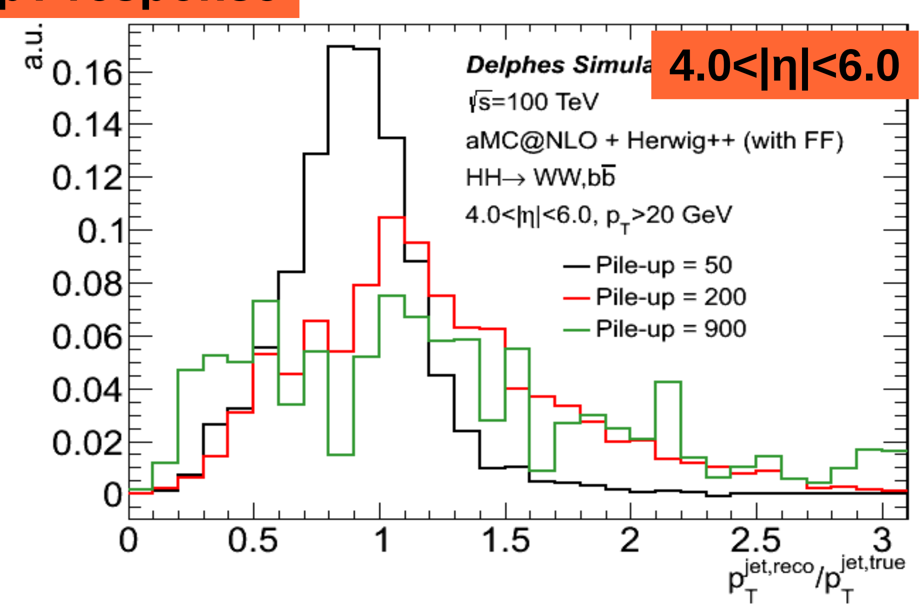
- Anti-Kt (Fast Jet) algorithm
- negative vector sum of Jets, after pile-up correction and calibration

Missing ET resolution

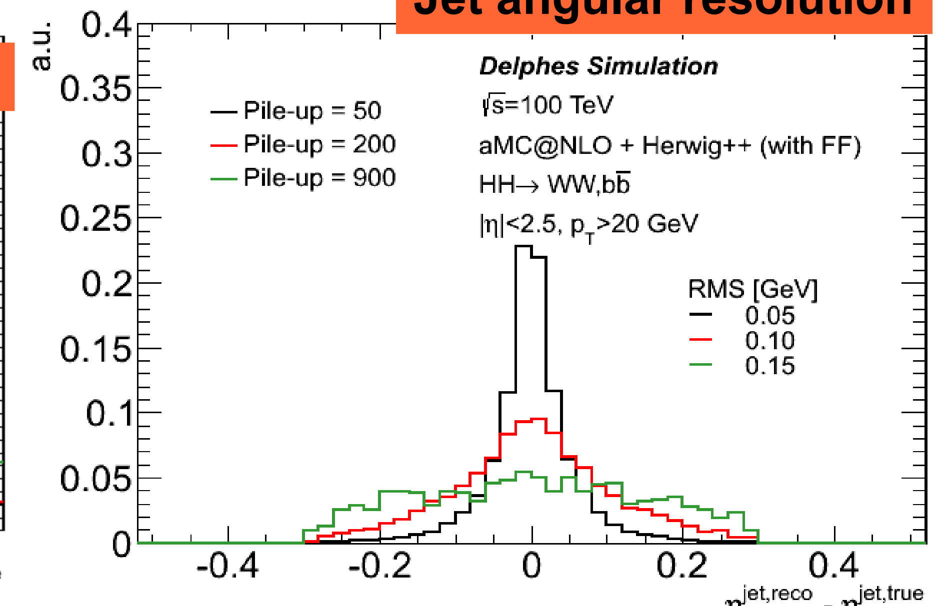


Jet pT response



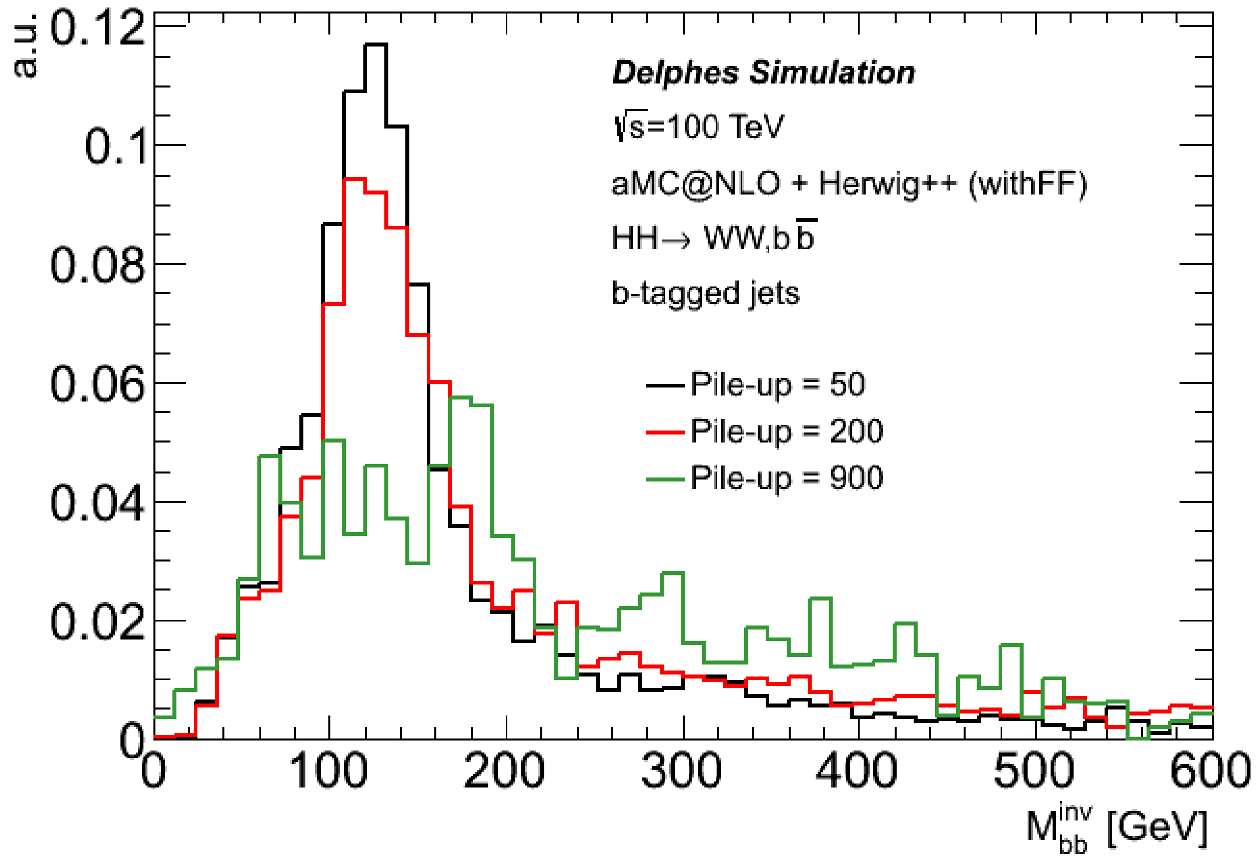


Jet angular resolution

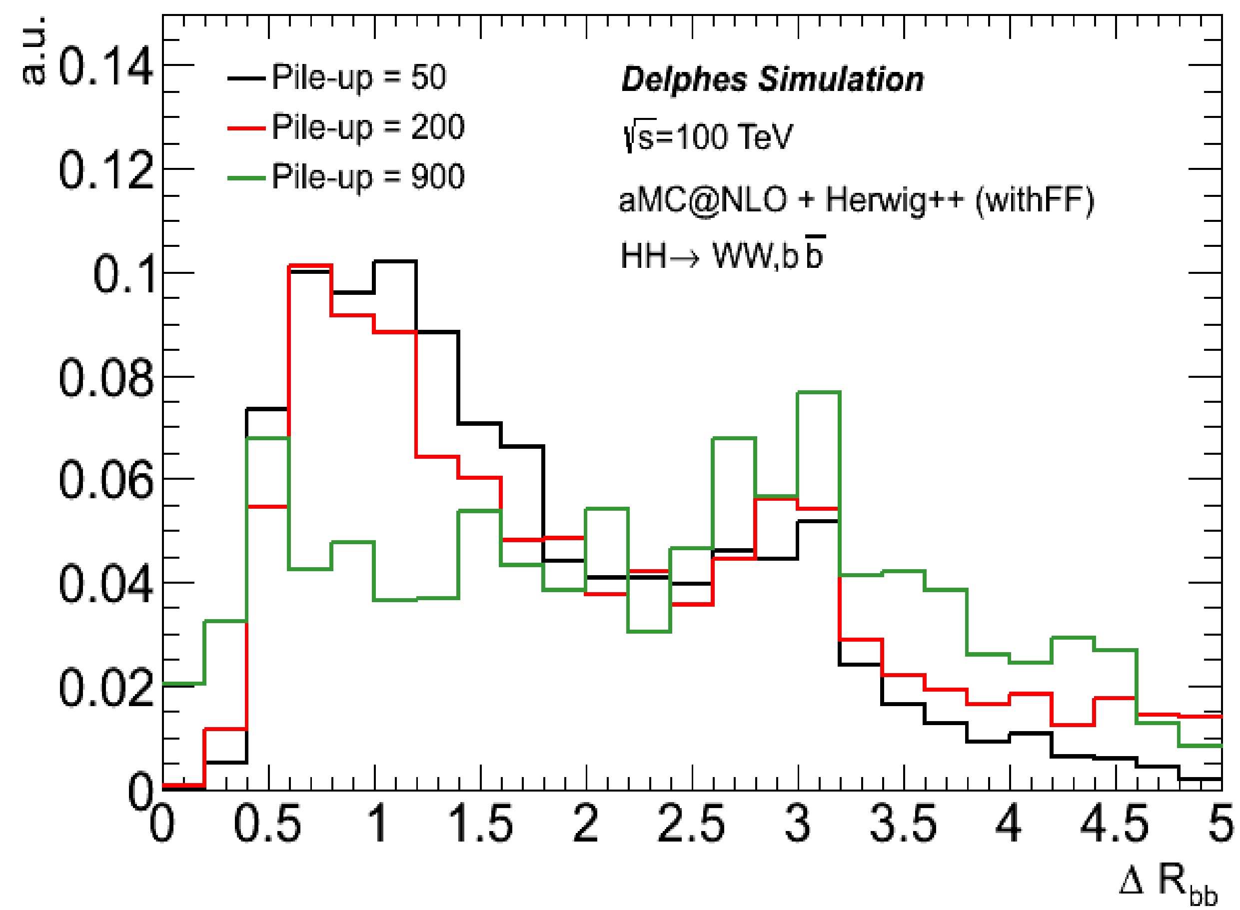


Discriminant variabes at various pile-up conditions

Mbb invariant mass



Rbb invariant mass



Clear deterioration from
Pileup = 50 to 200
Pile-up = 900 seems very difficult

Study of detector parameter variation

Nominal Calorimeter Resolution

ECAL Energy resolution
σ E/E = 10% / √E ⊕ 1%

HCAL Energy resolution
- **σ E/E = 50% / √E ⊕ 3% in |η|<4**
- **σ E/E = 100% / √E ⊕ 5% in 4 < |η|<6**

Calorimeter Resolution "Up"

ECAL Energy resolution
σ E/E = 20% / √E ⊕ 1%

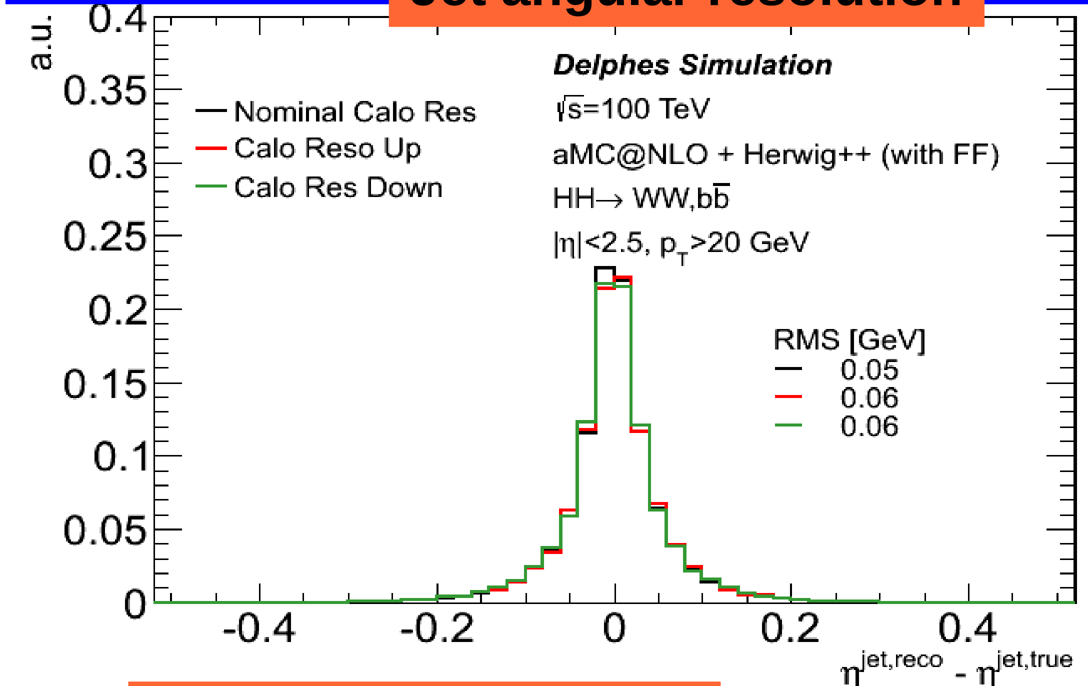
HCAL Energy resolution
- **σ E/E = 50% / √E ⊕ 3% in |η|<4**
- **σ E/E = 100% / √E ⊕ 5% in 4 < |η|<6**

Calorimeter Resolution "Down"

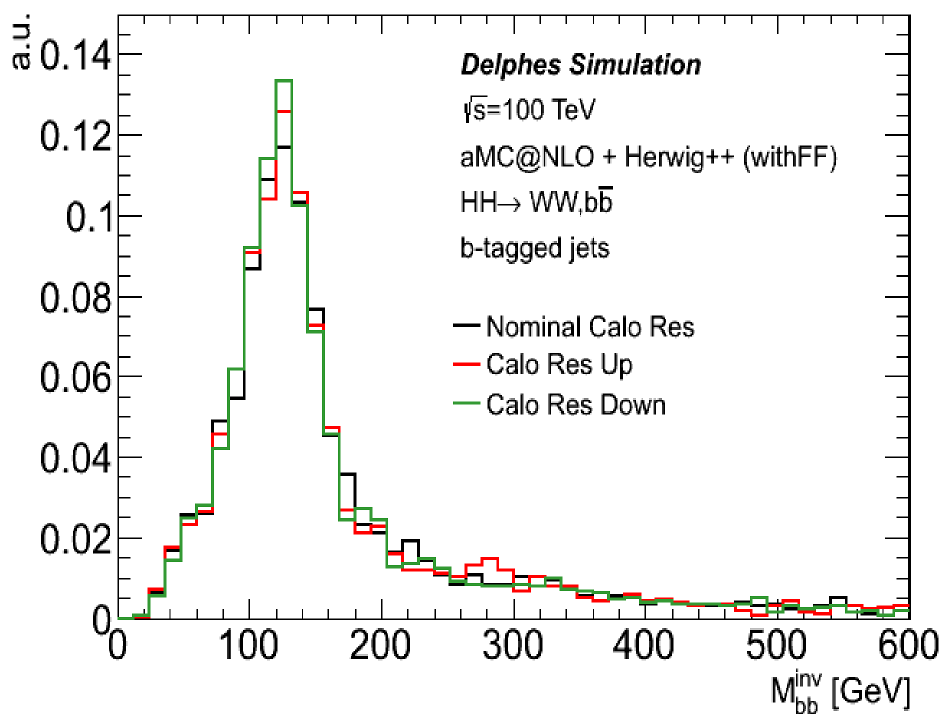
ECAL Energy resolution
σ E/E = 5% / √E ⊕ 1%

HCAL Energy resolution
- **σ E/E = 25% / √E ⊕ 3% in |η|<4**
- **σ E/E = 50% / √E ⊕ 5% in 4 < |η|<6**

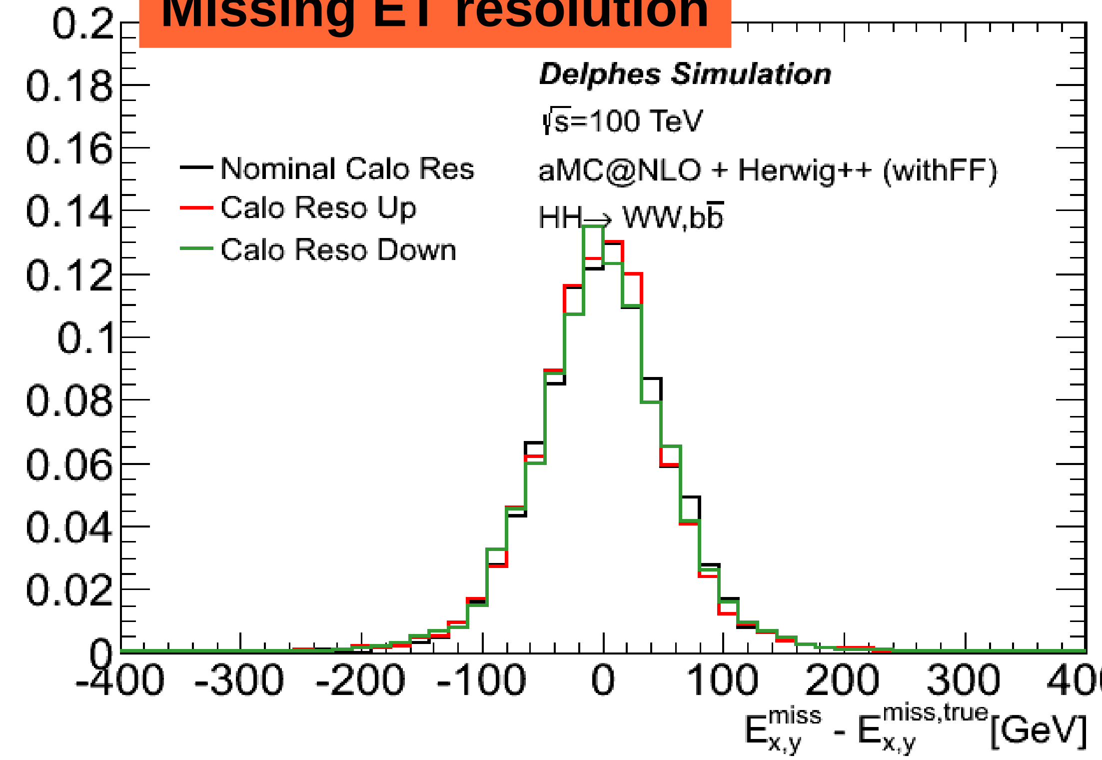
Jet angular resolution



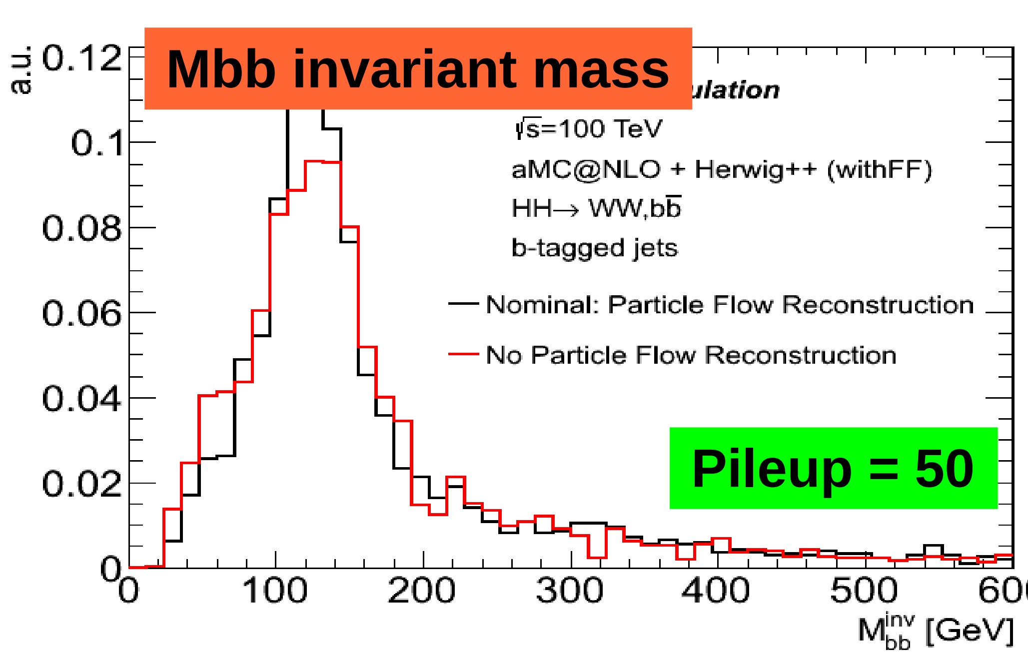
Mbb invariant mass

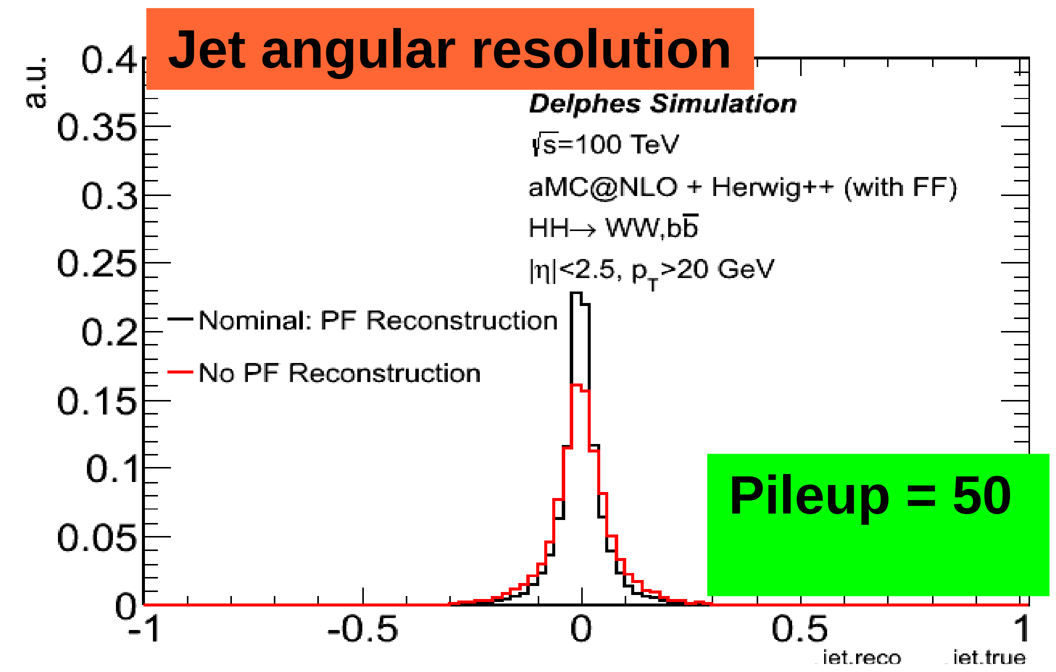


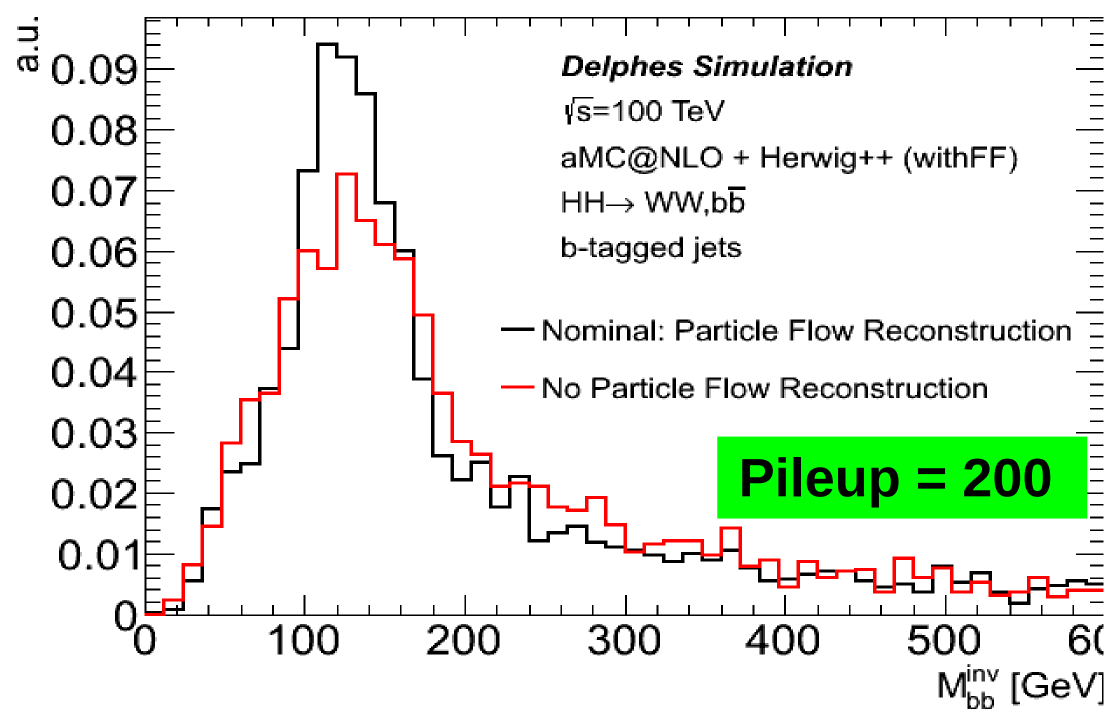
Missing ET resolution

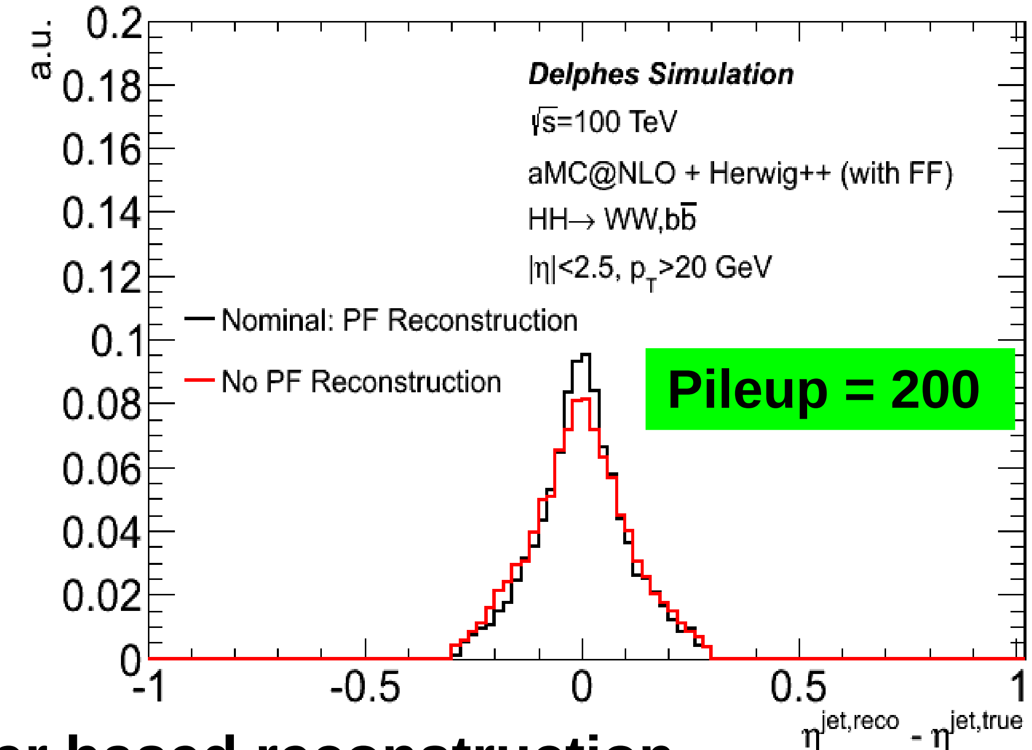


Particle flow versus calorimeter tower jets





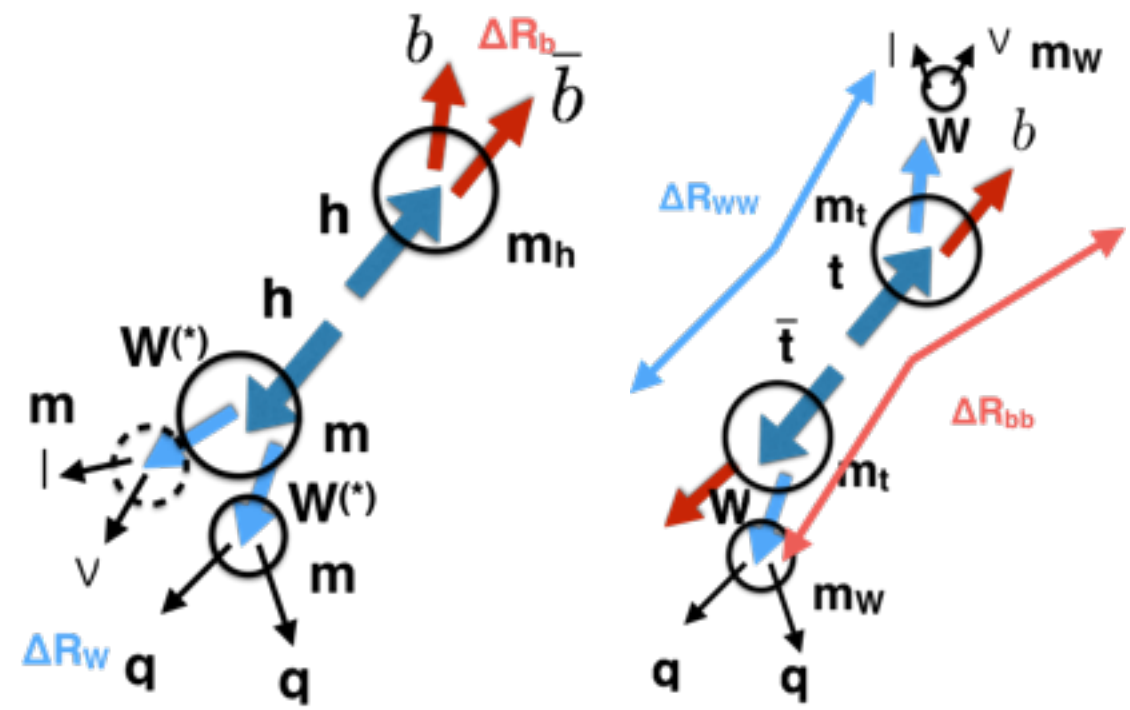


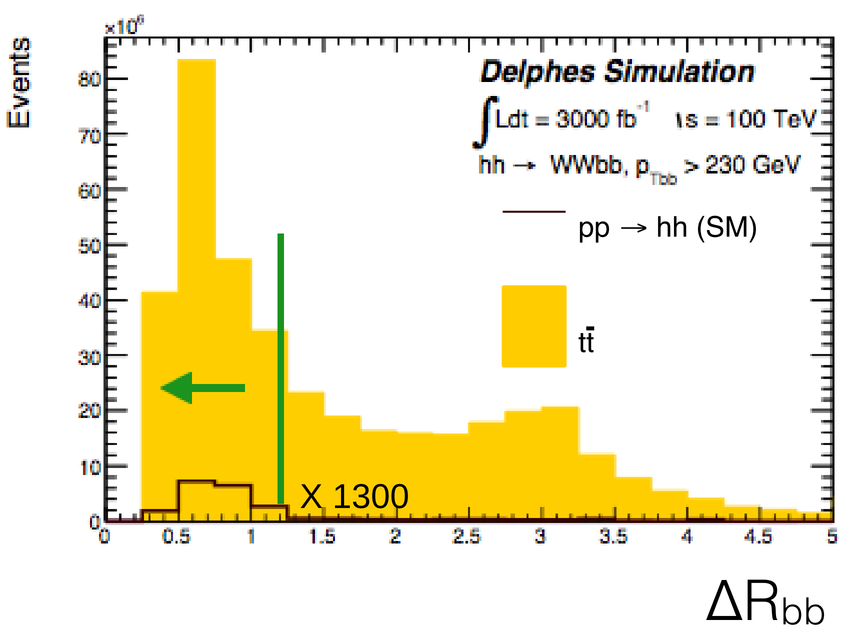


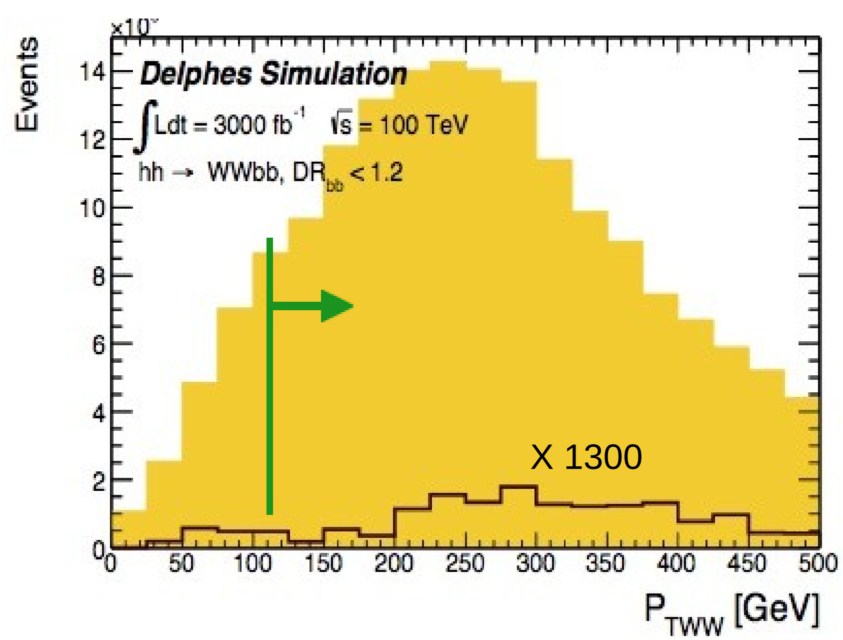
- **Deterioration using calorimeter based reconstruction**

The hh→WWbb→lνbb channel

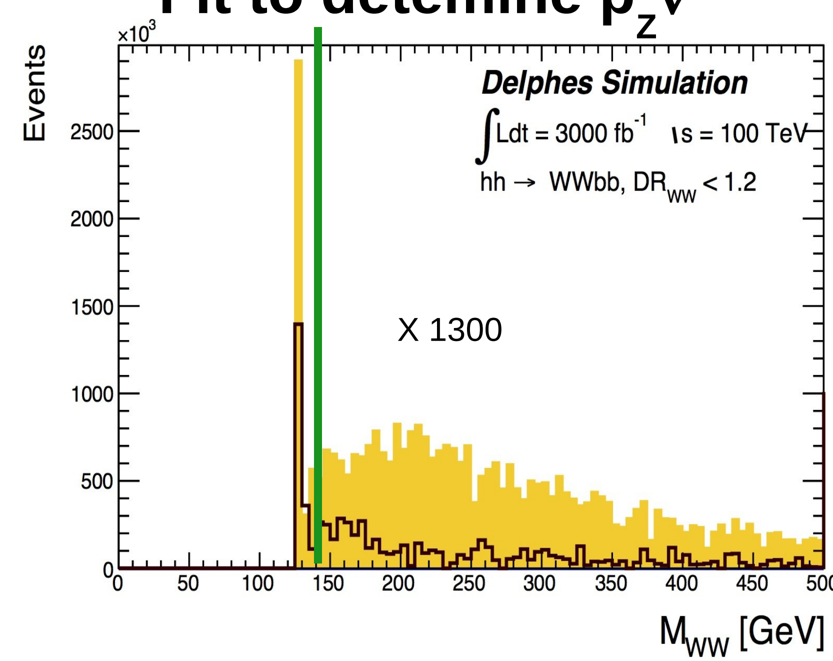
- Final state very close to the ttbar background, possible to disentangle the two only through the use of many variables
- Ideal analysis would exploit all mass constraints through a kinematic fit, profit of different angular and spin correlation through an MVA analysis
- This is just the first attempt, tried to use a simple cut based analysis, to train the machinery
  - at least one isolated lepton with $p_T > 15$ GeV, $|\eta| < 2.5$ use the Higgs mass constraint to compute the neutrino longitudinal momentum
  - at least 4 jets with $p_T > 20$ GeV $|\eta| < 2.5$
  - at least 2 b-jets







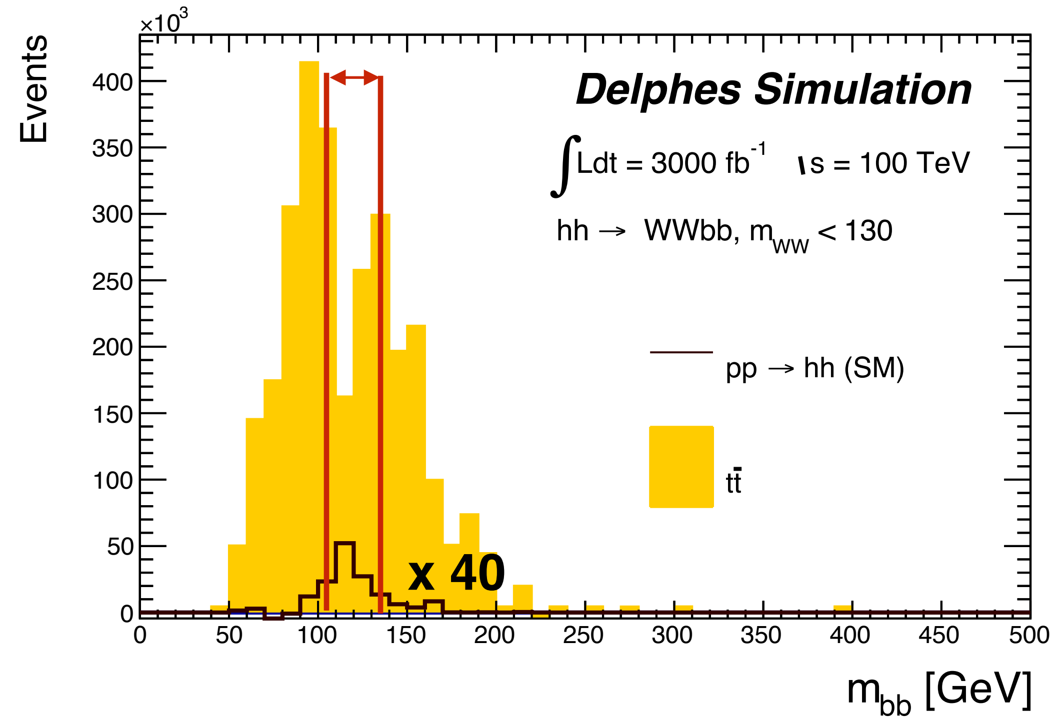
Fit to detemine $p_z\nu$



The hh→WWbb→lvbb channel, analysis cuts and results

Analysis cuts

Variable	Cut
$p_T(bb)$	> 230 GeV
ΔRbb	< 1.2
$p_T(WW)$	> 140 GeV
ΔR_{WW}	< 1.2
m_{WW}	< 130 GeV
m_{bb}	105 – 135 GeV



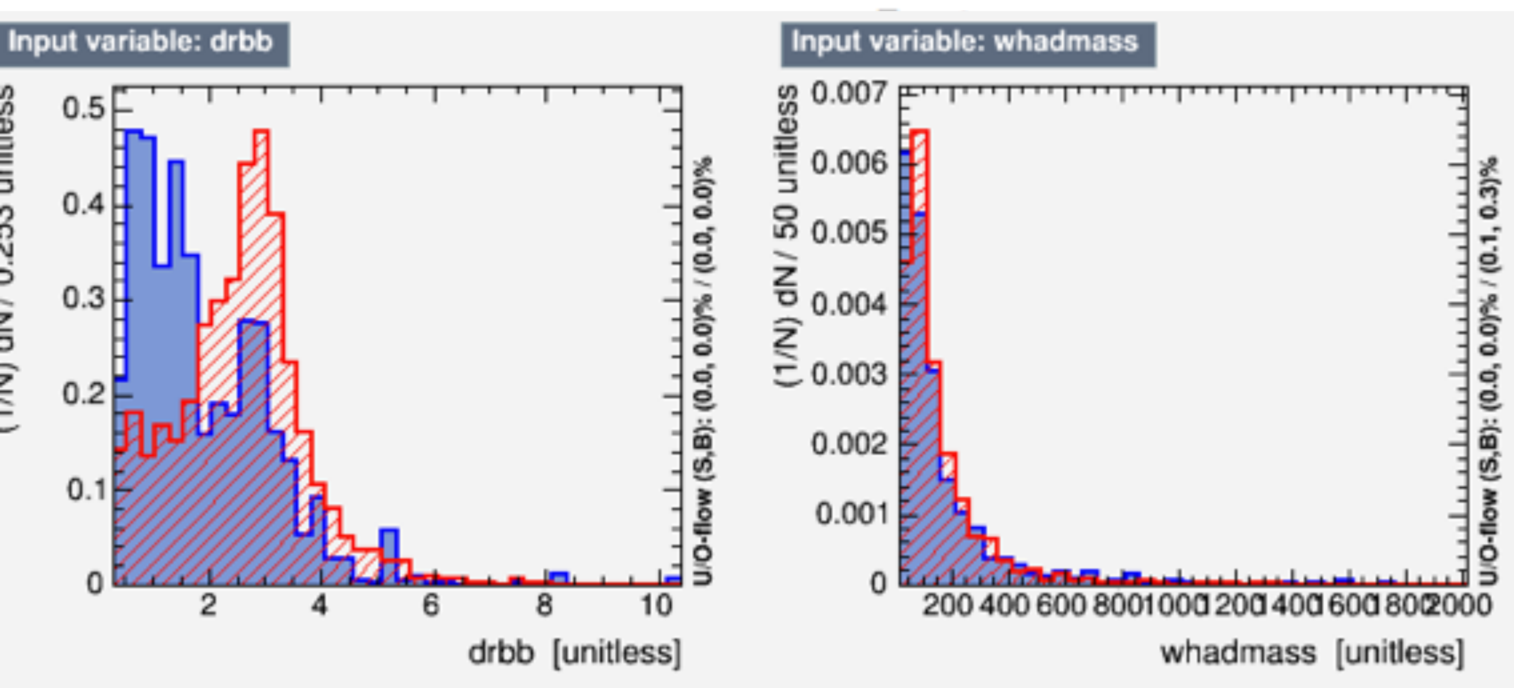
3 ab^{-1} PU 50	Object selection	Final selection	ε
hh-WWbb	7084	803	$2.5 \cdot 10^{-3}$
t-t_{bar}	$5.4 \cdot 10^{9}$	$7.9 \cdot 10^{5}$	
S/B_{kg}	$1.3 \cdot 10^{-6}$	$1.0 \cdot 10^{-3}$	

3 ab^{-1} PU 200	Object selection	Final selection	ε
hh-WWbb	$5.4 \cdot 10^{4}$	273	$8.5 \cdot 10^{-4}$
t-t_{bar}	$3.6 \cdot 10^{9}$	$3.4 \cdot 10^{5}$	
S/B_{kg}	$1.5 \cdot 10^{-5}$	$8.0 \cdot 10^{-4}$	

S/B quite low , need to work more on analysis selection implementing more variables and using a MVA approach.

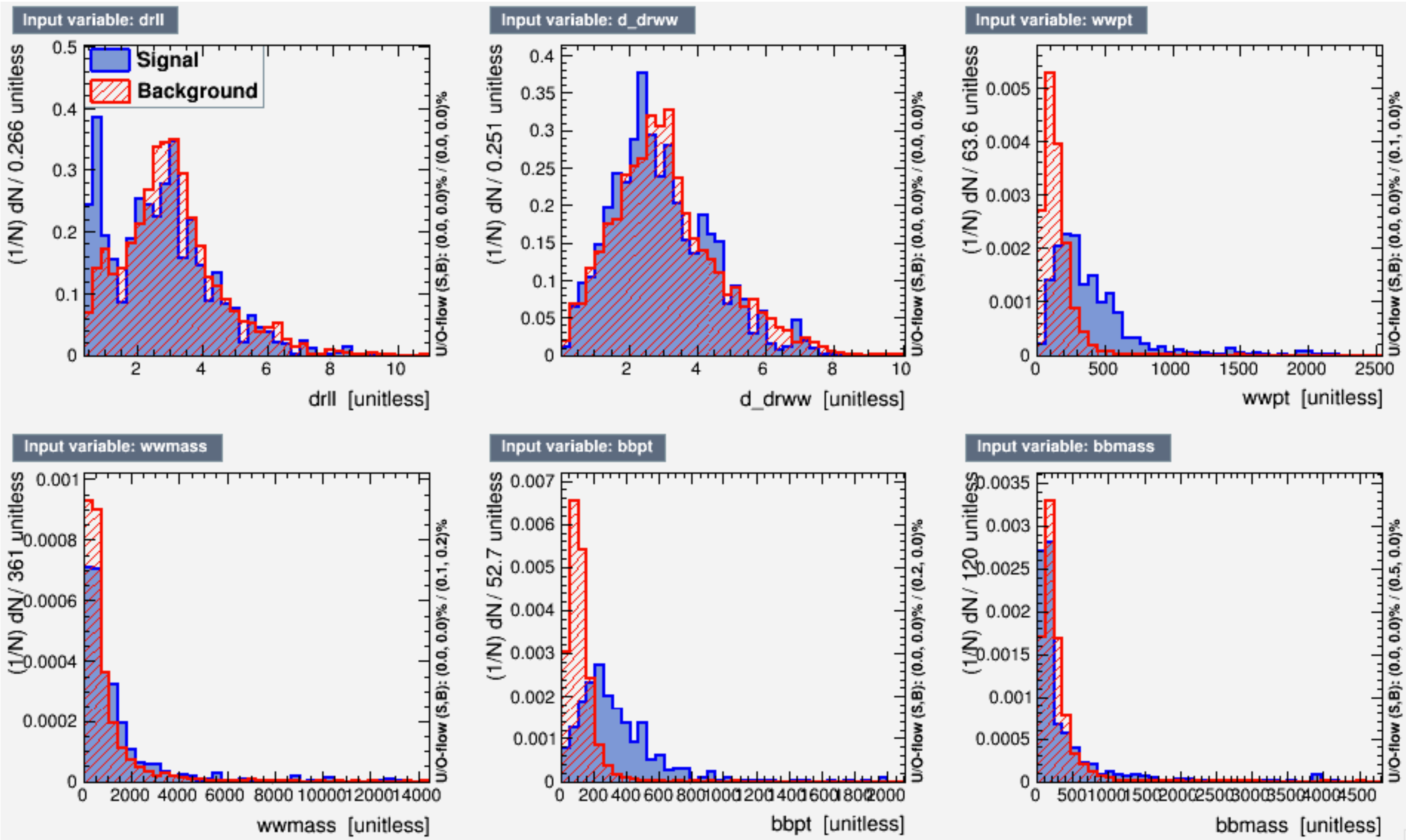
BDT input variables

drll: ΔR_{jj} (j is a light jet)
whadmass: m_{jj}

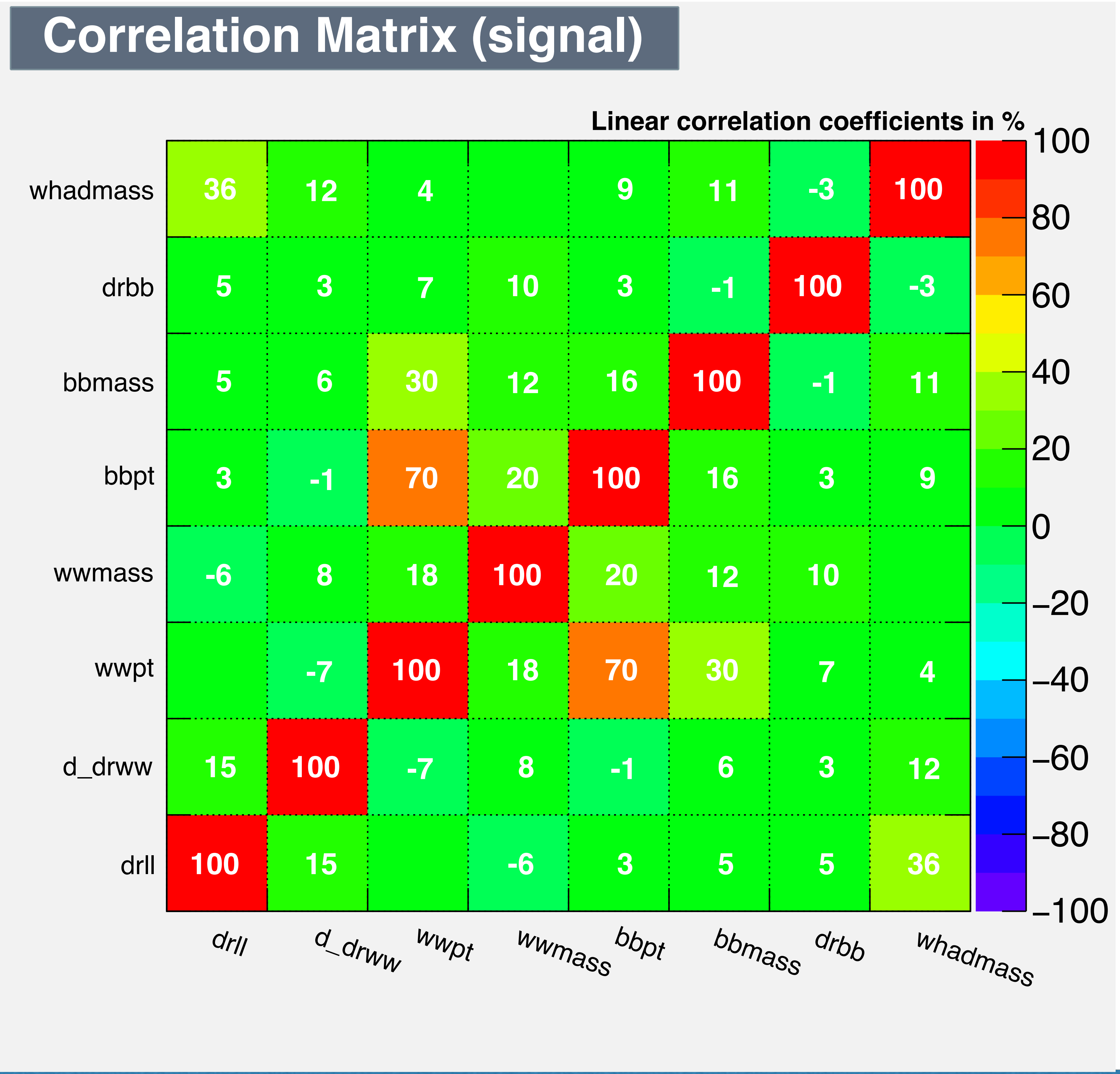



```
: Ranking input variables (method specific)..
: Ranking result (top variable is best ranked
: -----------------------------------------
: Rank : Variable   : Variable Importance
: -----------------------------------------
:    1 : drbb       : 1.820e-01
:    2 : drll       : 1.700e-01
:    3 : d_drww     : 1.415e-01
:    4 : bbpt       : 1.293e-01
:    5 : bbmass     : 1.099e-01
:    6 : wwpt       : 1.022e-01
:    7 : wwmass     : 8.427e-02
:    8 : whadmass   : 8.076e-02
: -----------------------------------------
```

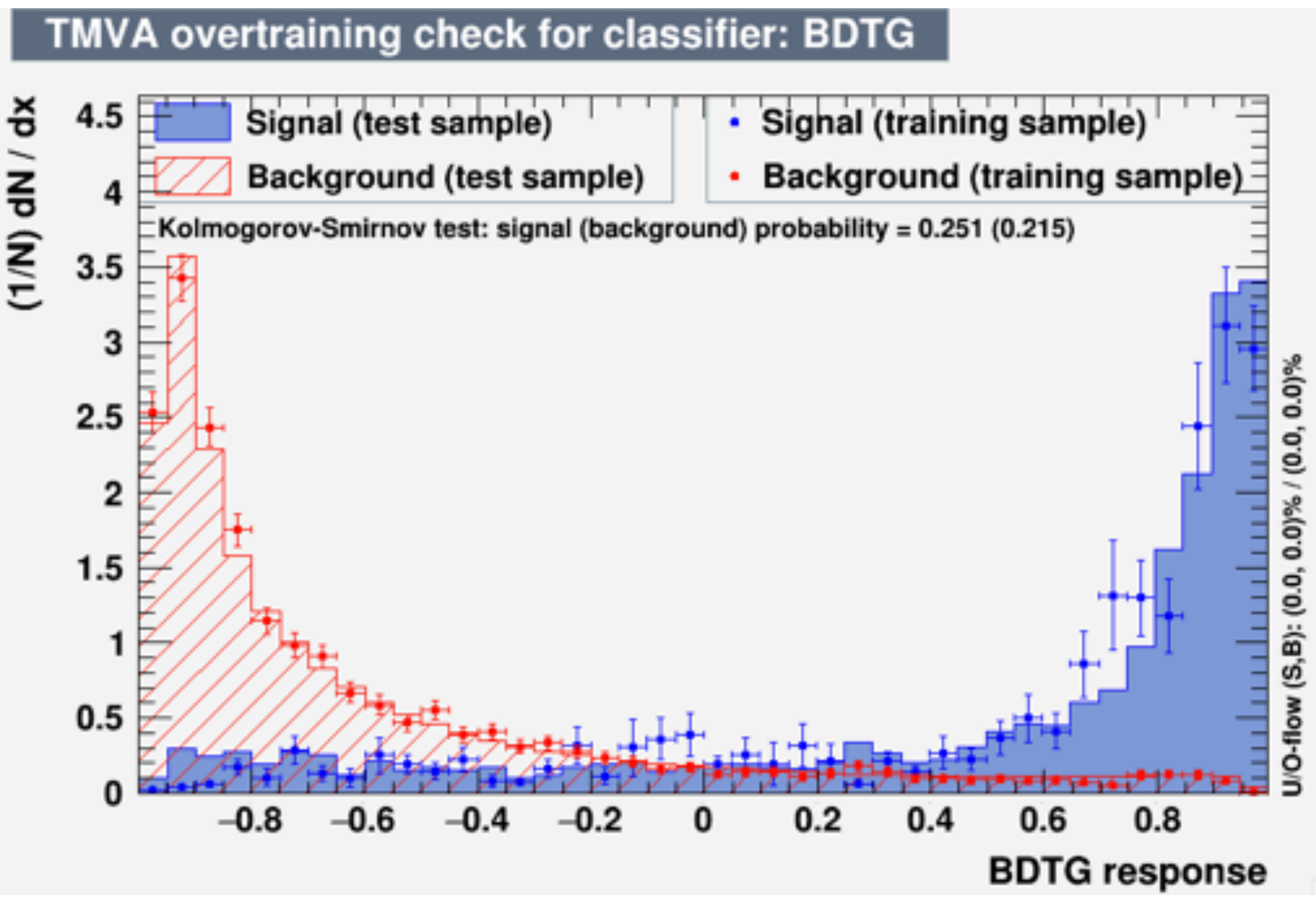
Input variables distributions, second set

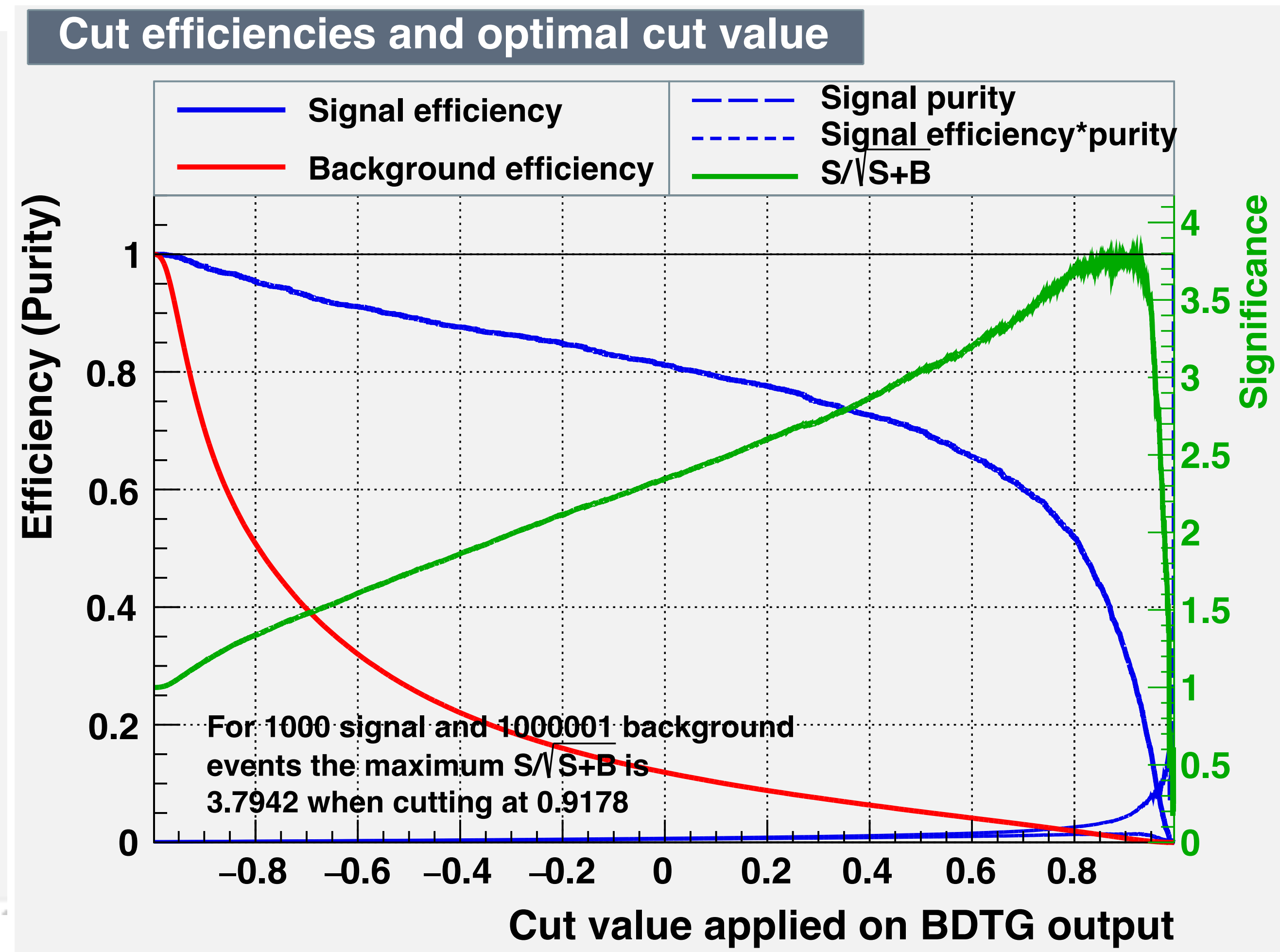


Input variables correlation



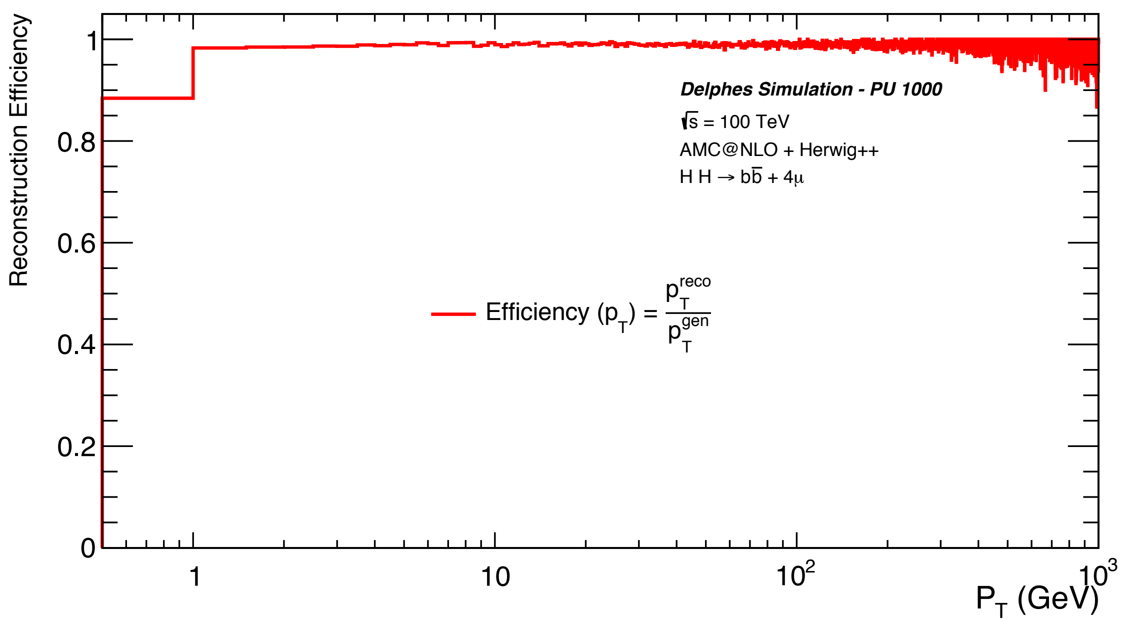
BDT performance

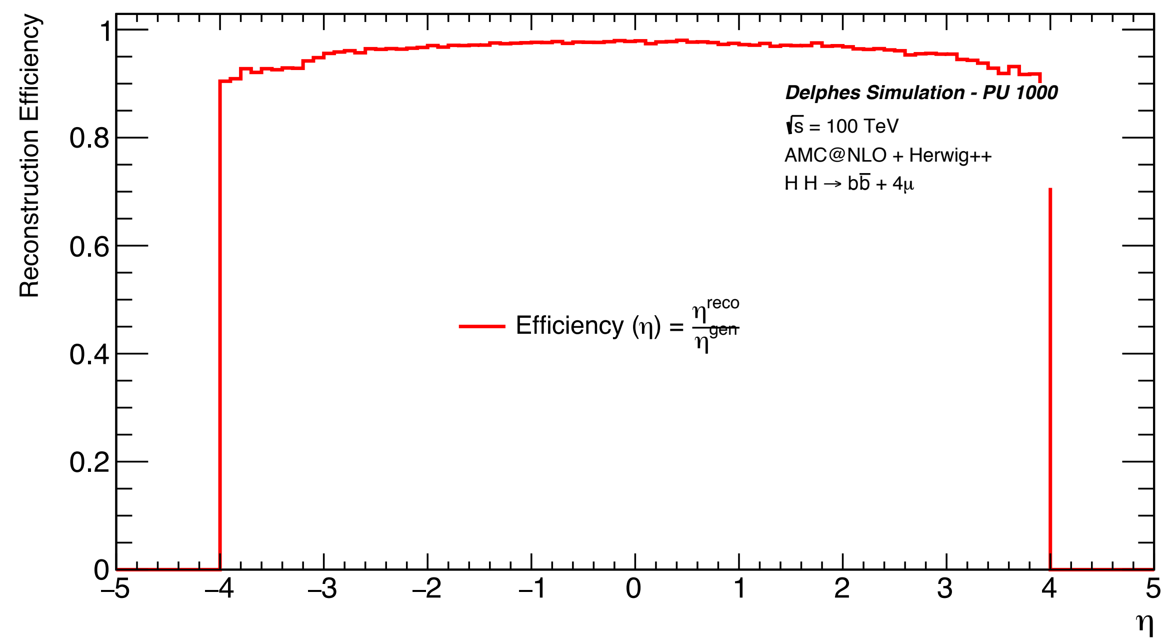


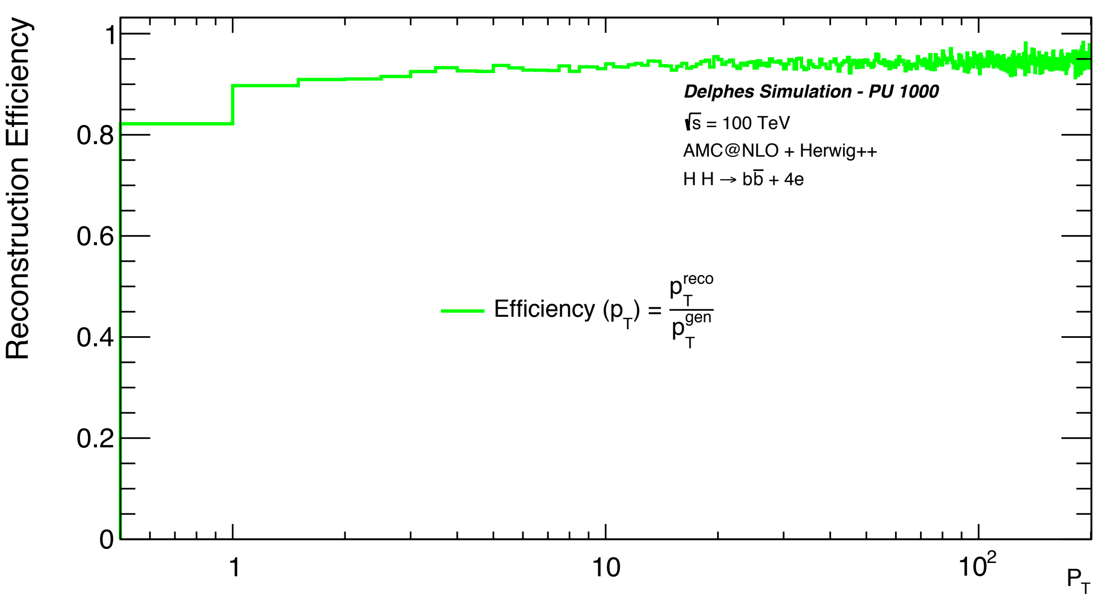


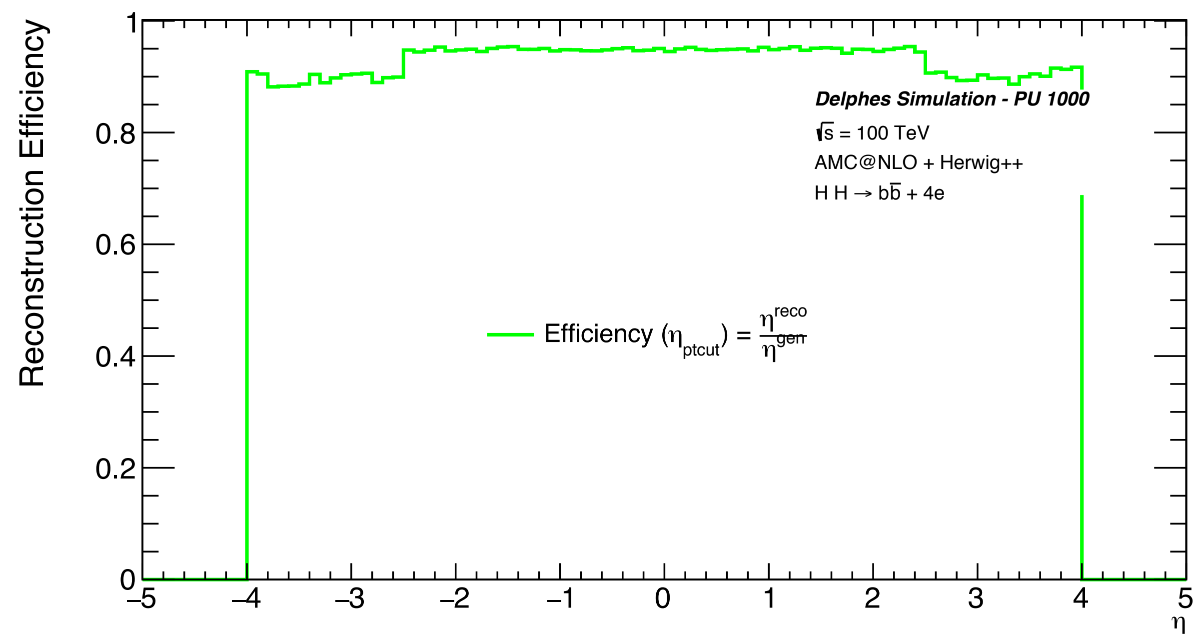
Poor performance at the moment, need to work on adding more variables, include preselection cuts and so on.

Lepton efficiencies in the ZZbb → 4lbb analysis





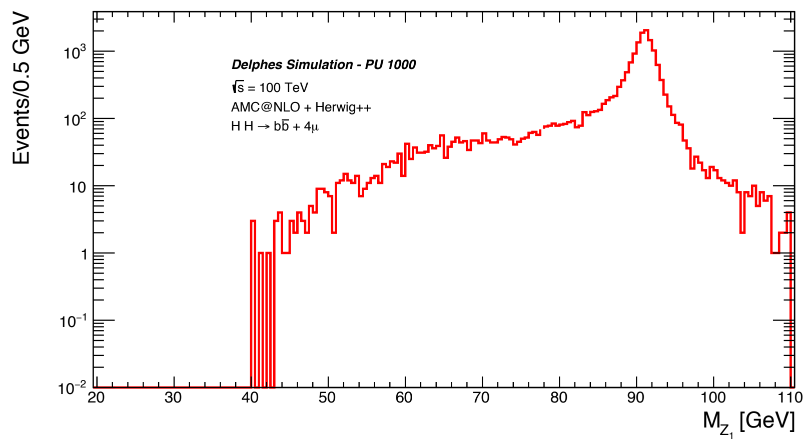


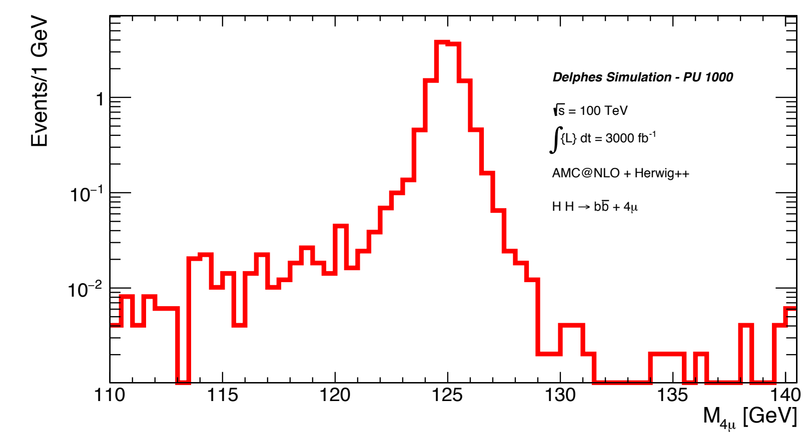


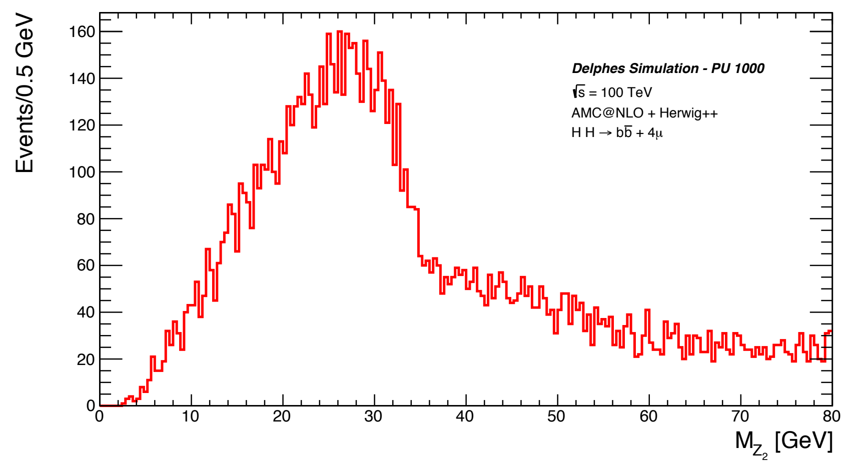
Extremely high tracking efficiencies for muons: need to start to think to trigger and identification efficiencies to have realistic acceptances

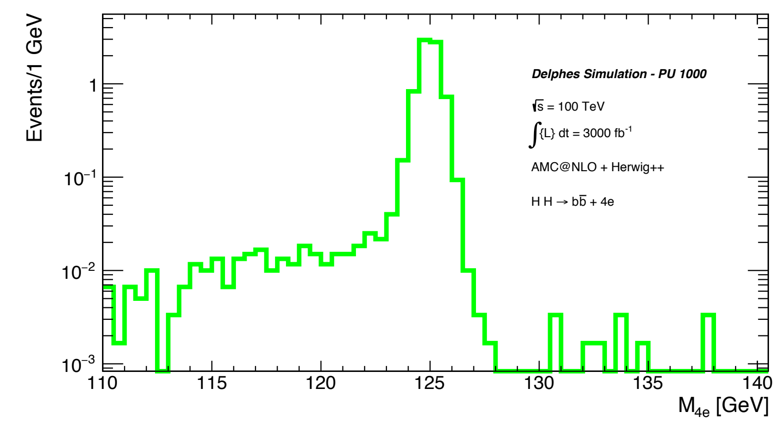
The hh→ZZbb→4lbb channel

- ≥ 4 muons with p_T > 5 GeV, |η| < 4.0
- ≥ 4 electrons with p_T > 7 GeV, |η| < 4.0
- Z_1 selection: $\ell^+\ell^-$ pair with mass closest to the nominal Z boson mass
  40 GeV < m_{Z1} < 120 GeV
- Z_2 selection: second $\ell^+\ell^-$ pair
  12 GeV < m_{Z2} < 120 GeV
- Among the 4 selected leptons: at least one with p_T>20 GeV and one with p_T>10 GeV
- QCD suppression: $m(\ell^+\ell^-)$ > 4 GeV
- Kinematic cuts: $m_{4\ell}$ > 120 GeV, $m_{4\ell}$ < 130 GeV
- At least 2 b-jets with p_T > 30 GeV









$$\mathcal{L} = 3\,\mathrm{ab}^{-1}$$

	σ·L·Br(hh→ZZbb→4lbb	no b-jet req.	with b-jet	ε (no b-jet)	ε (b-jet)
4μ	161	61	12.1	38%	7.4%
4e	161	40	7.7	25%	4.8%
Tot	322	101	20	31%	6.2%

- forward b-tagging can be an important ingredient of the analysis, need to test configuration with fwd dipole
- big impact from lepton isolation cut (not presented here), need to optimise isolation criteria

Conclusions

- WWbb analysis still needs work for optimisation, plan for the workshop is to study jet eta acceptance and improve BDT response

- ZZbb plans: implement some guess on trigger efficiencies and include main backgrounds in the simulation