Study of hh production in the WWbb channel at the FCC-hh

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Motivation: probing the Higgs potential

Very well known (LEP, Flavour factories, Tevatron, LHC)

$$\mathcal{L} = -\frac{1}{4g'^4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4g^2}W^a_{\mu\nu}W^{\mu\nu a} - \frac{1}{4g_s^2}G^a_{\mu\nu}G^{\mu\nu a}$$
$$+\bar{Q}_i i\not{D}Q_i + \bar{u}_i i\not{D}u_i + \bar{d}_i i\not{D}d_i + \bar{L}_i i\not{D}L_i + \bar{\ell} \dots$$
$$+\left(Y_u^{ij}\bar{Q}_i u_j \tilde{H} + Y_d^{ij}\bar{Q}_i d_j H + Y_l^{ij}\bar{L}_i \ell_j H + c.c.\right)$$
$$-\lambda(H^\dagger H)^2 + \lambda v^2 H^\dagger H - (D^\mu H)^\dagger D_\mu H$$
$$-(D^\mu H)^\dagger D_\mu H \to -(\partial^\mu H)^\dagger \partial_\mu H - 2\frac{M_W^2}{v}W^{+\mu}W^-_\mu H - \frac{M_Z^2}{v}Z^\mu Z_\mu H + \dots$$

almost known (LHC)

unknown

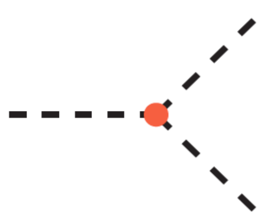
very well known

well known (LHC)

The last missing piece of our (Standard) theory of nature

$$V(H) = \frac{1}{2}M_H^2 H^2 + \frac{1}{2}\frac{M_H^2}{v}H^3 + \frac{1}{8}\frac{M_H^2}{v^2}H^4 + \text{constant}$$

Possible At FCC

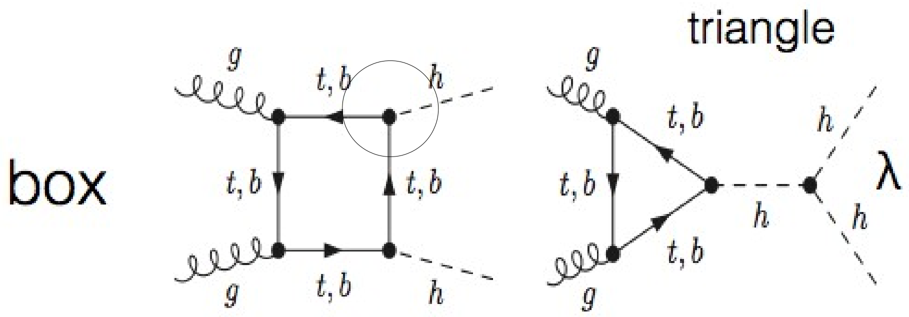


$$\frac{3M_H^2}{v} \times (-\imath)$$

$$\frac{3M_H^2}{v^2} \times (-\imath)$$

Very hard

hh Production mechanism

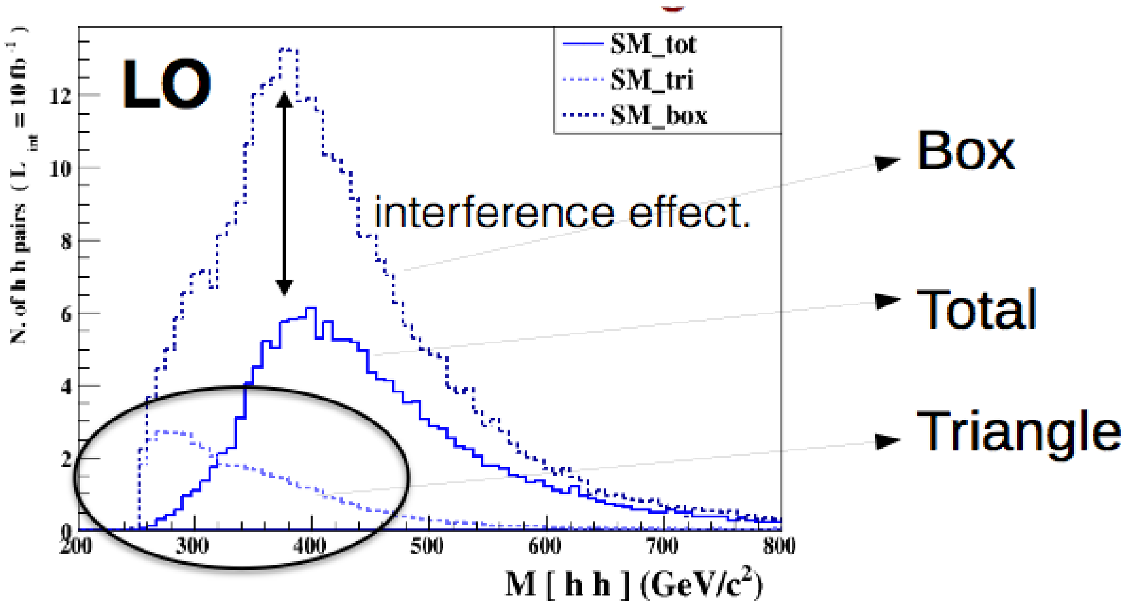


less interesting:
tth, bbh coupling

Interesting:
self-coupling

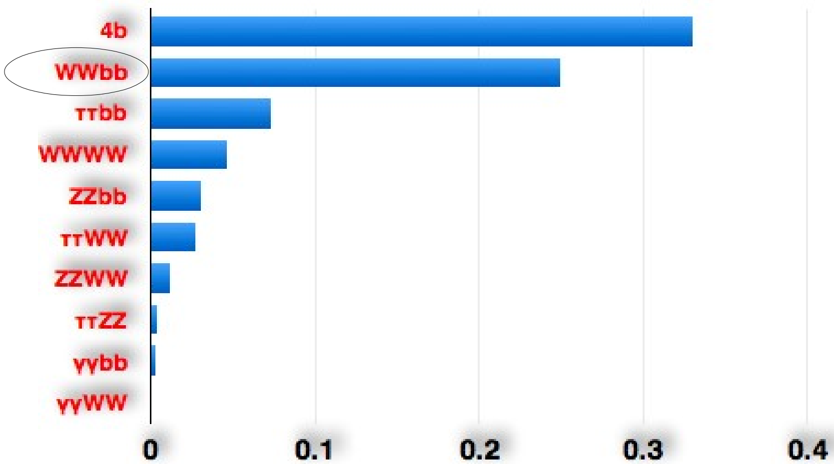
~ × 40 at 100 TeV wrt to 14 TeV

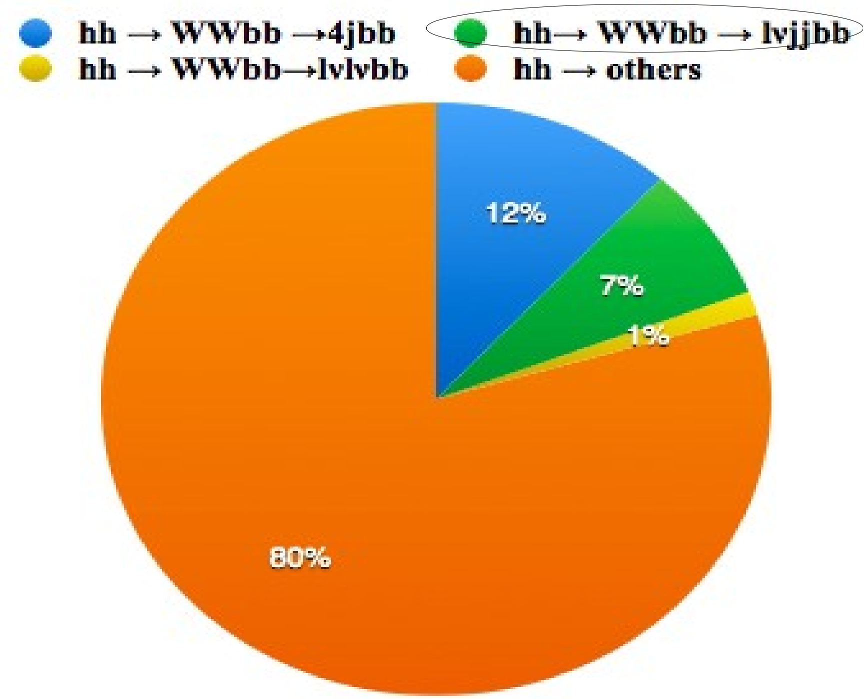
$\sqrt{s}$ [TeV]	σ^{NLO} [fb]
8	8.2
14	33.9
33	207.3
100	1417.8



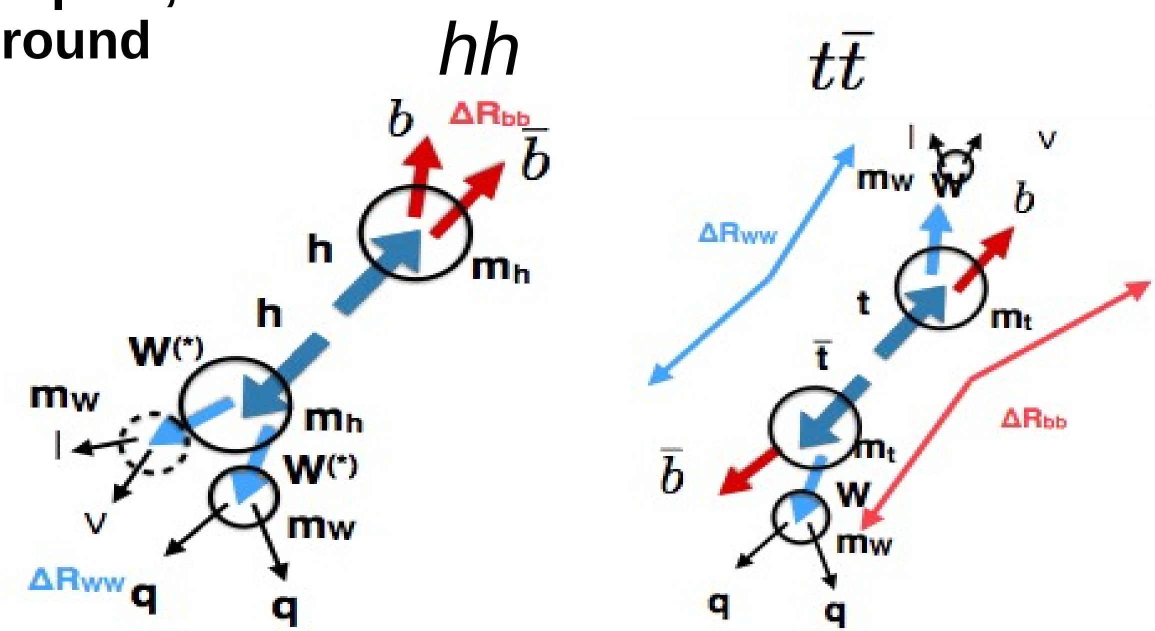
- **Triangle mainly contributing to very low m_{hh},**
- **but moderate m_{hh} can be sensitive through interference with top-box.**

hh decays





- BR lνjj bb ~ 7% of the total
- 4j channel also interesting to exploit, but overwhelming QCD background

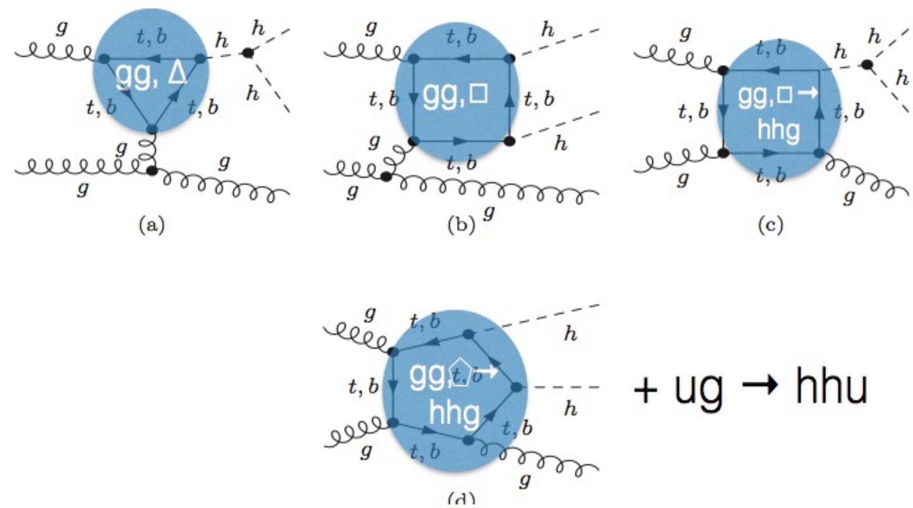


- Main background: $t\bar{t}$ with same final state
- Main discriminant variables: M_{bb}, ΔR_{bb}, ΔR_{WW}
- Kinematics can be closed
- Crucial to have good, E_T^{miss} and jet, p_T and angular resolution
- Challenging in high pile-up environments.

σ(100 TeV) / σ(14 TeV)~ × 40(32) for HH (tt)

Signal and background modeling

- **signal events generated with Madgraph5_aMC@NLO 2.2.3 PDF CT10@NLO**
- **Shower: Herwig++ 2.7.1, PDF cteq6l1**



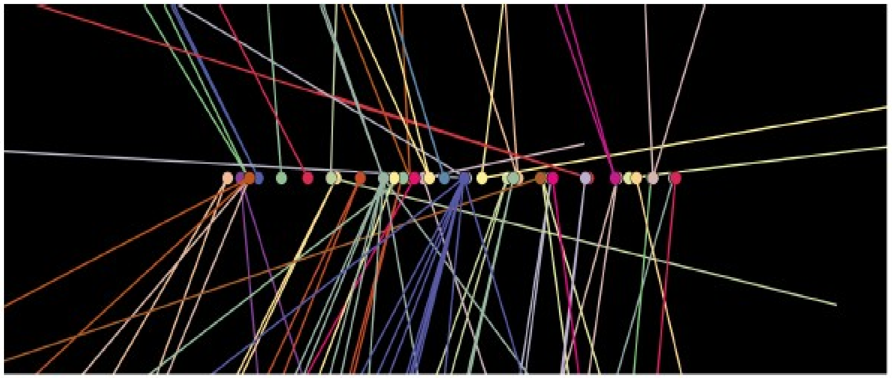
- $t\bar{t}$ **background events simulated with Madgraph5_aMC@NLO,**
- **Decays forced to lνjj using MadSpin (preserving spin correlations in the whole decay chain).**

Sample	σ (πβ)	$N_{evts}^{gen.}$
hh	1.4	1M
$\bar{t}t$		
$l^{\pm}$νφφβ β	4.1 10^3	10M
$\tau^{\pm}$νφφβ β	0.2 10^3	2M

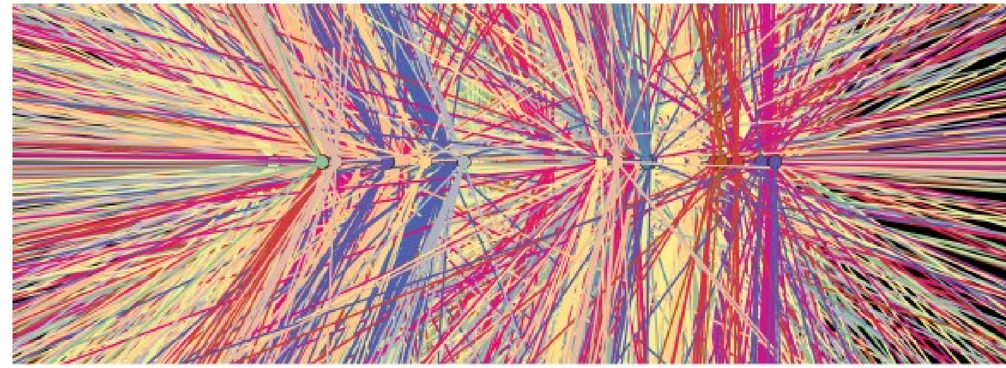
- **100k of Pile-up events simulated with Herwig++ minimum bias simulation**

Pile-up at FCC-hh

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

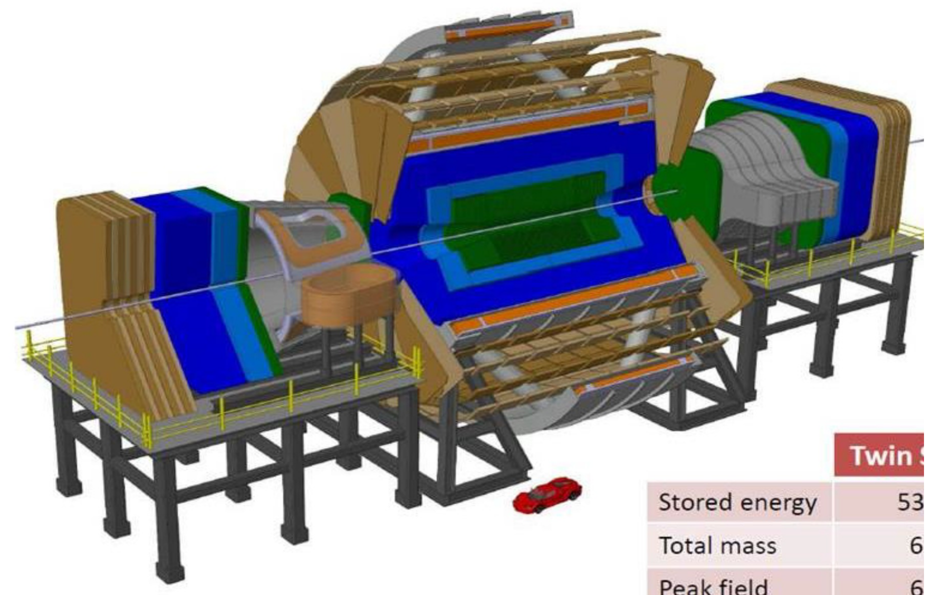
For 5 ns bunch spacing Pile-up → Pileup / 5

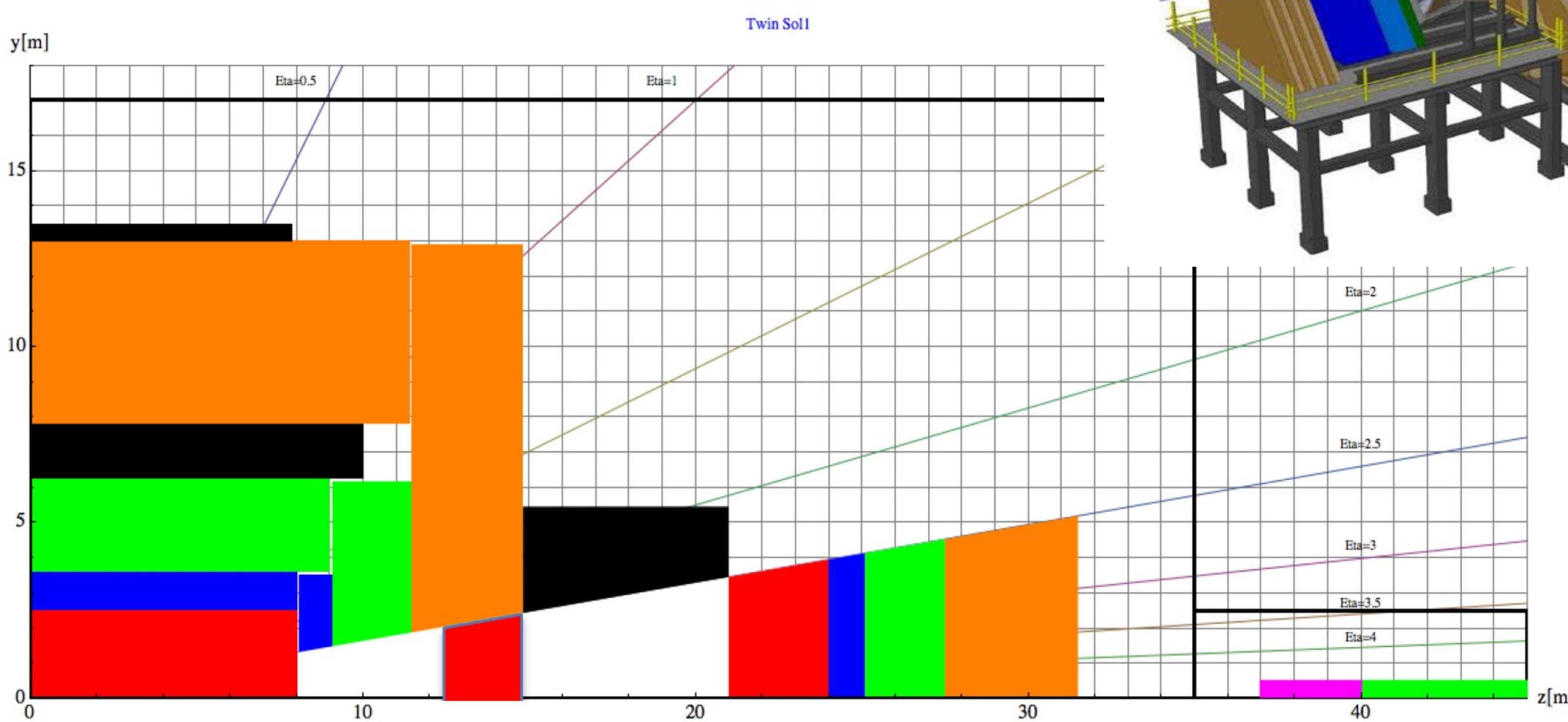
Configurations chosen for this study:

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

Base-line geometry Twin solenoid + Dipole magnetic system





Tracker

Fwd Tracker

EMCAL

Dipole

HCAL

Coil+Cryostat

Muon system

Detector Parametrization - Calorimeters

Based on Delphes card: FCChh_DelphesCard_WithDipole_v00.tcl

ECAL granularity

- **0.0125 x 0.0125 for $|\eta|<2.5$**
- **0.025 x 0.025 for $|\eta|<4.0$**
- **0.05 x 0.05 for $|\eta|<6.0$**

ECAL Energy resolution

$\sigma E/E = 10\% / \sqrt{E} \oplus 1\%$

HCAL granularity

- **0.05 x 0.05 for $|\eta|<2.5$**
- **0.1 x 0.1 for $|\eta|<4.0$**
- **0.2 x 0.2 for $|\eta|<6.0$**

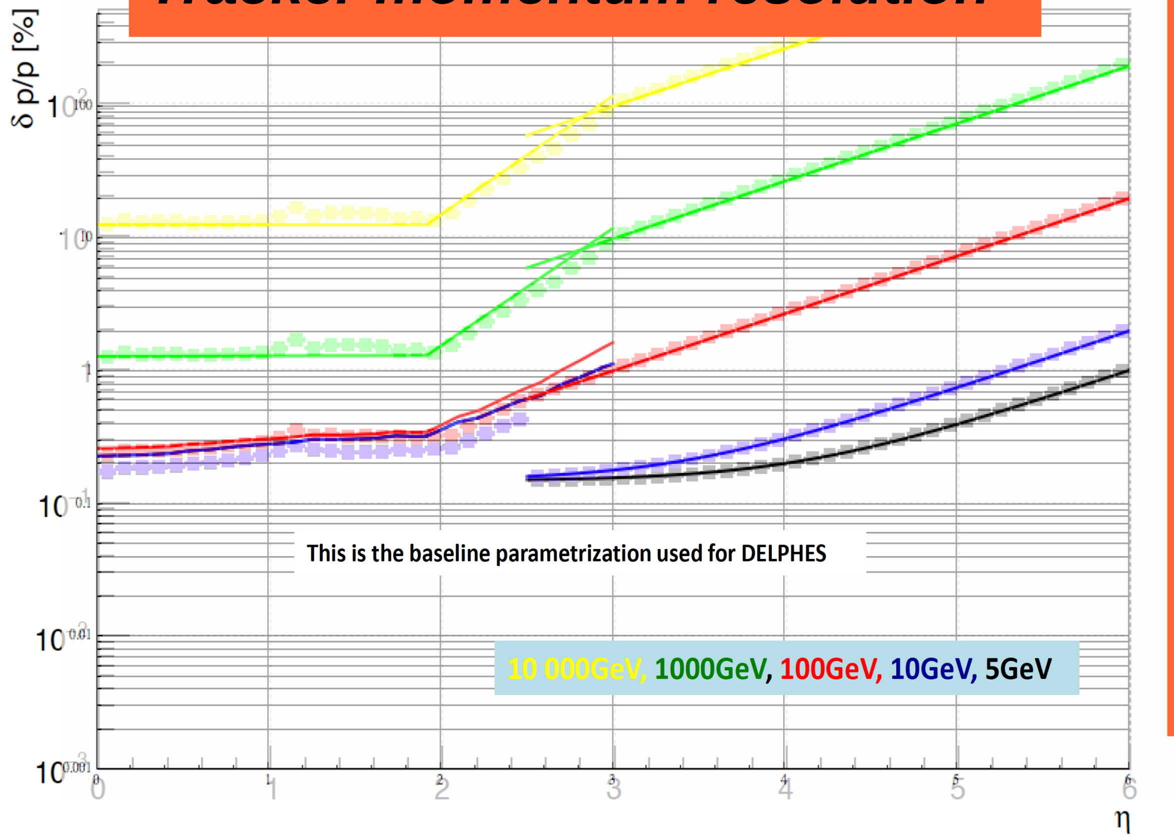
HCAL Energy resolution

- **$\sigma E/E = 50\% / \sqrt{E} \oplus 3\%$ in $|\eta|<4$**
- **$\sigma E/E = 100\% / \sqrt{E} \oplus 5\%$ in $4 < |\eta|<6$**

Show only sub-detector
Most relevant for this study

Detector Parametrization - Tracker

Tracker momentum resolution



z_0 resolution (*)

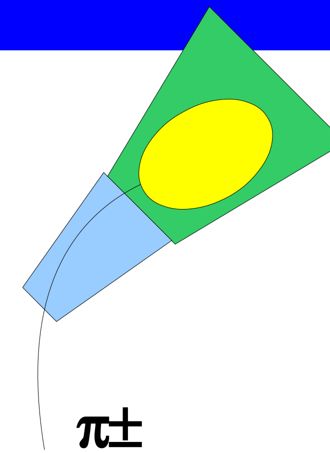
- ***in |η|<2.5***
  σ(z_0)= 0.01 mm , p_T<5 GeV
  σ (z_0)= 0.005 mm , p_T>5 GeV
- **In 2.5<|η|<4**
  σ(z_0)= 0.1 mm , p_T<5 GeV
  σ (z_0)= 0.05 mm , p_T>5 GeV
- **In 4.0<|η|<6.0**
  σ(z_0)= 1.0 mm , p_T<5 GeV
  σ (z_0)= 0.5 mm , p_T>5 GeV

**** in official card***
z_0 resolution constant
for |η|<2.5 for all η

B-tagging
Efficiency for light jets 0.1 %
Efficiency for c-quark jets 4%
Efficiency for b-quark jets 75%

Caveat: same parametrization used for Pile-up 50 and 200

Reconstruction



- ***Particle Flow Reconstruction*:**
  Using charged hadrons, muons and electrons to build
  ***particles flow* objects =**
  Tracks & Calorimeter deposit – charged deposit

- **Tracks from Pileup are rejected if** $| z_0 - z_{PV} | > \sqrt{\sigma^2 (z_0) + \sigma^2 (z_{PV})}$

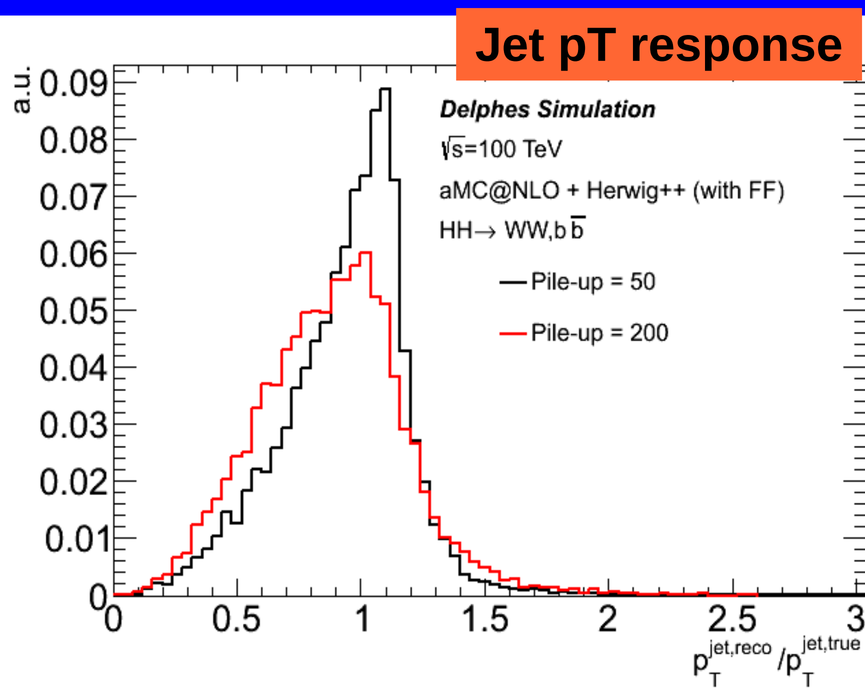
- **Jets**
  - **Anti-Kt (FastJet) JetAlgorithm**
  - **Particle-flow objects as inputs**
  - **cone 0.4**
  - **Jet Area pile-up correction:**
    - $p_T^{jet, corrected} = p_T^{jet,raw} - \rho \quad Areajet$
  - ***Private* calibration to the particle level:**
    - **Evaluate** $< p_T^{reco\ jet} / p_T^{true\ jet} >$ **vs** $p_T^{reco\ jet}, \eta^{reco\ jet}$
    - **Numeral inversion scale:**

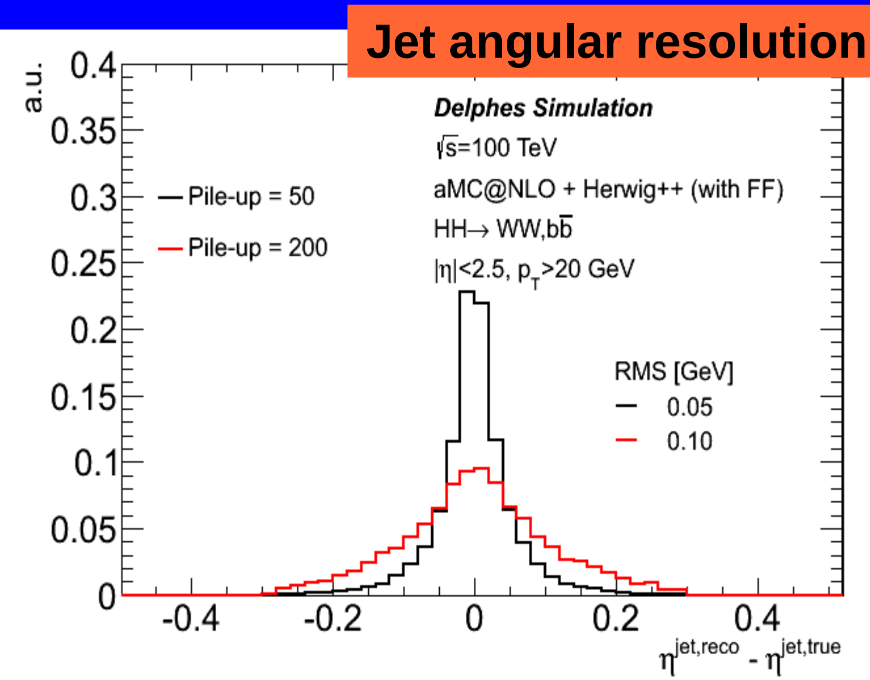
$$p_T^{reco\ jet\ calibrated} = f\left(< p_T^{reco\ jet} / p_T^{true\ jet} >, p_T^{reco\ jet}, \eta^{reco\ jet} p_T \right)$$

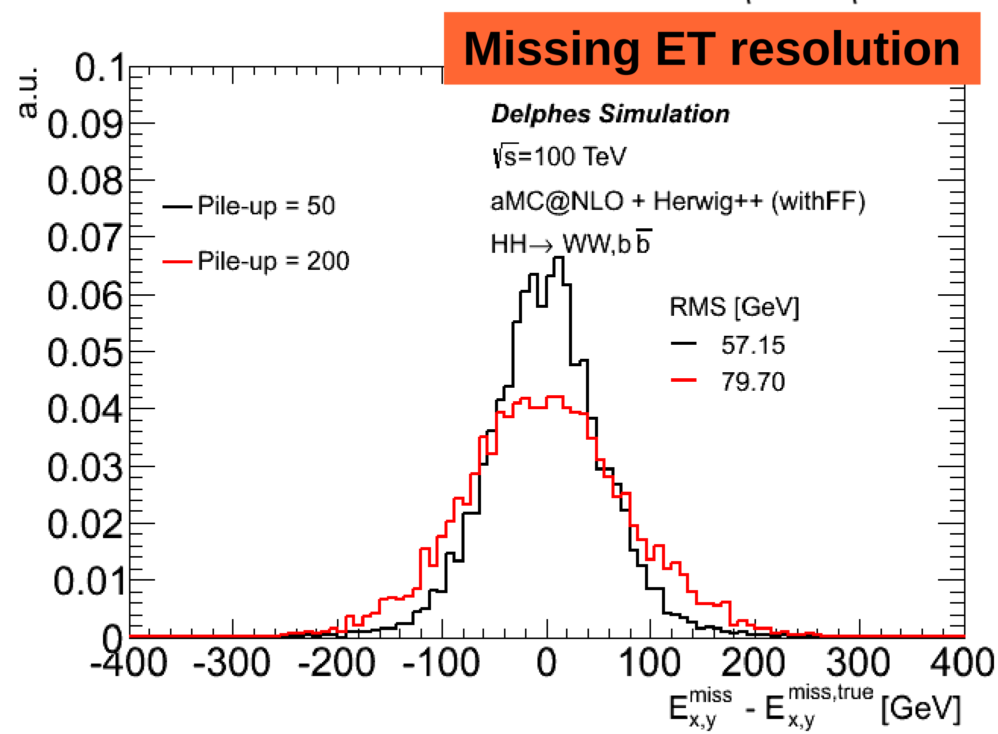
- $p_T^{reco\ jet\ calibrated} > 20$ **GeV**

- **Missing Transverse Energy:**
  Negative vector sum of Jets, after pile-up correction and calibration

Reconstruction Performances of Jets and MET





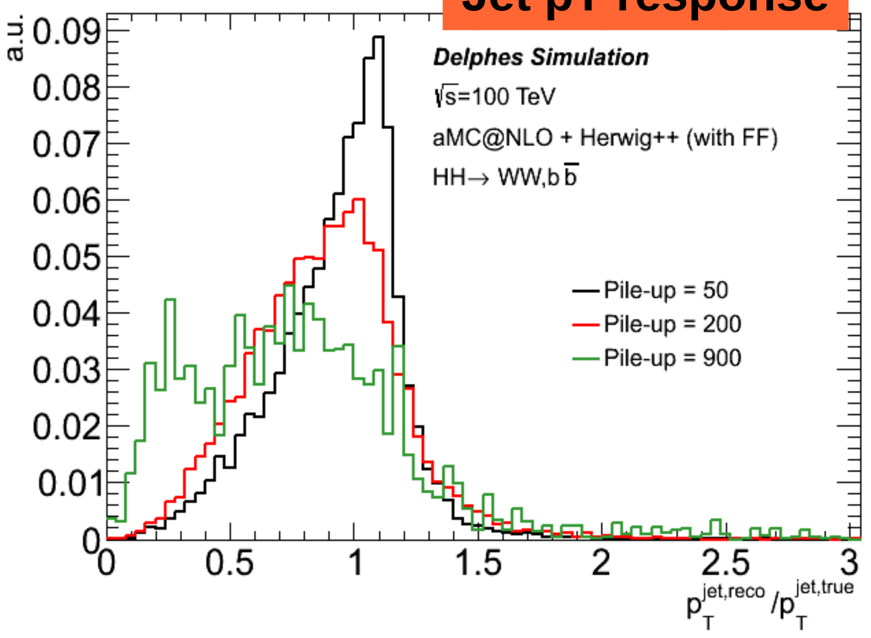


Clear deterioration from Pileup = 50 to 200

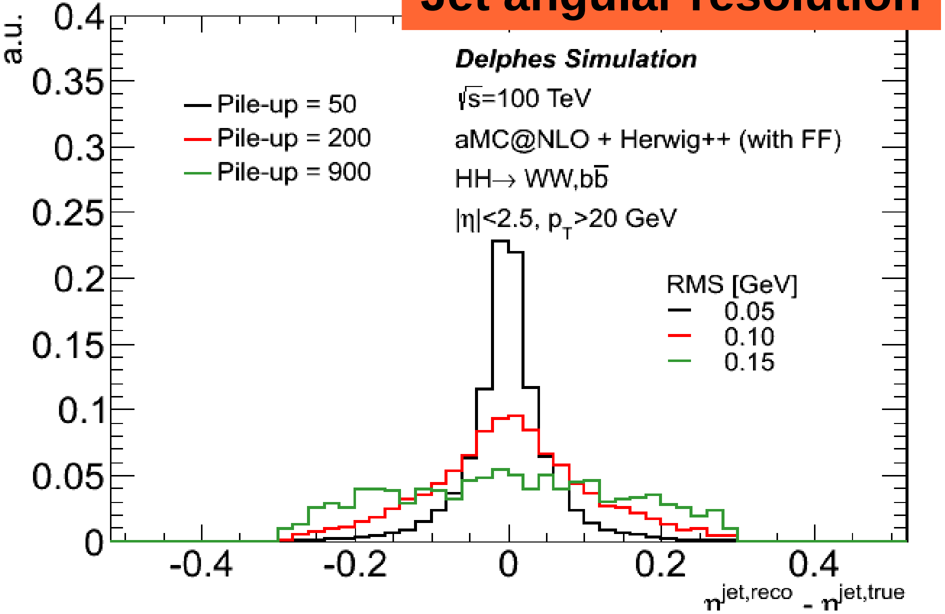
As exercise also tested PU=900 (computing very expensive)...

Reconstruction Performances of Jets and MET

Jet pT response



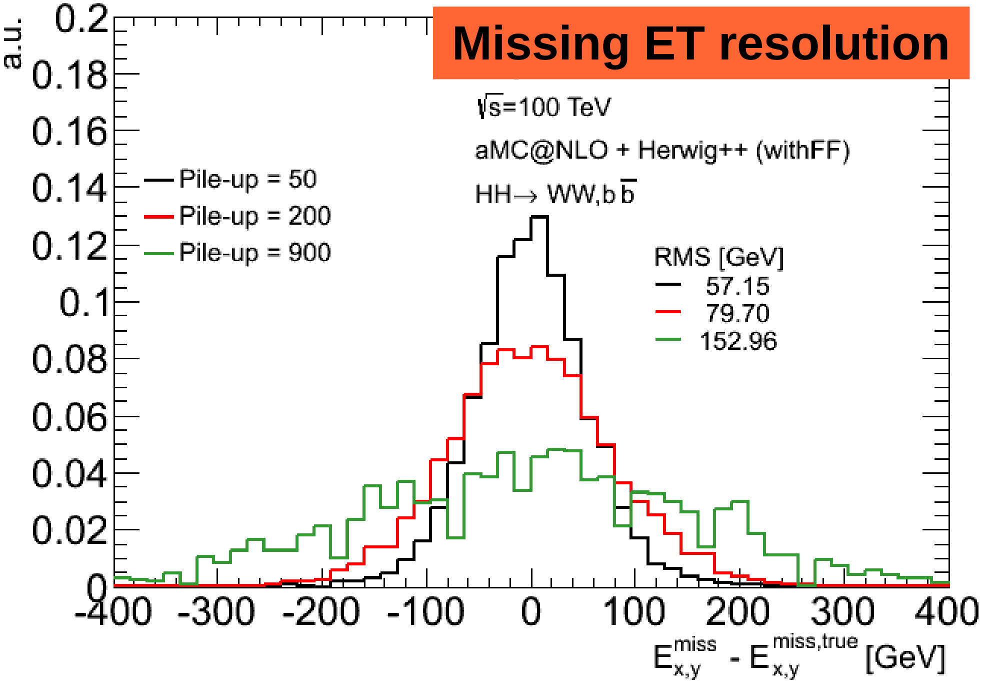
Jet angular resolution



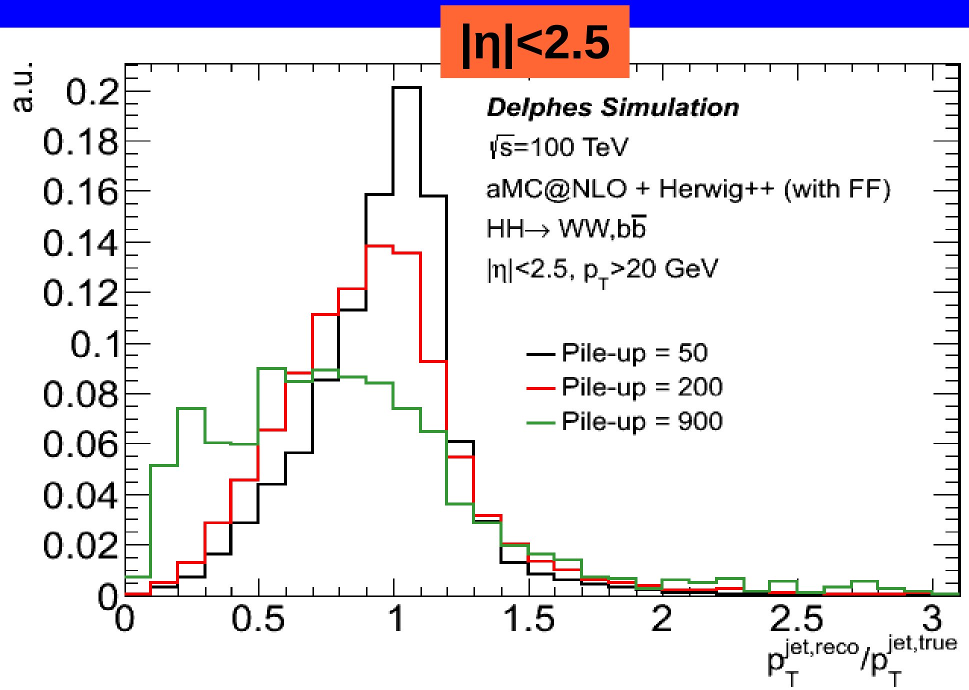
Clear deterioration from Pileup = 50 to 200

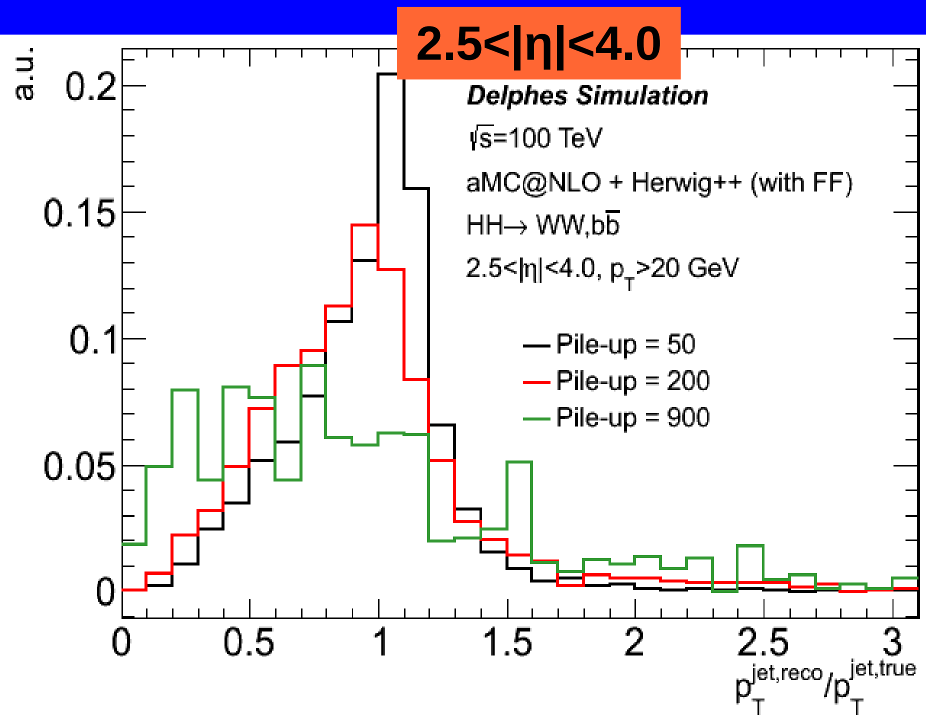
As exercise also tested PU=900 (computing very expensive)...

Missing ET resolution

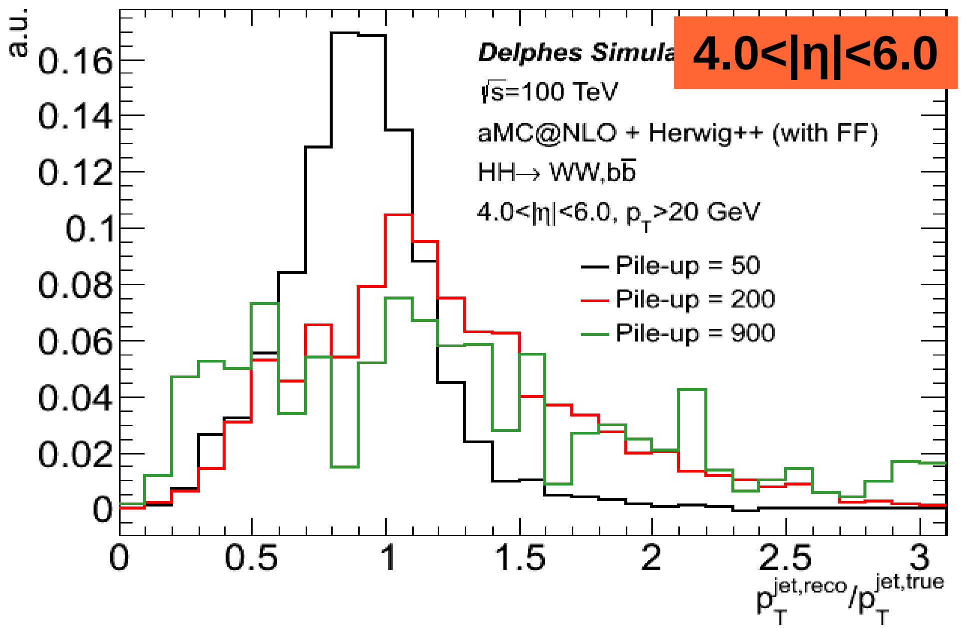


Reconstruction Performances of Jets: η dependence



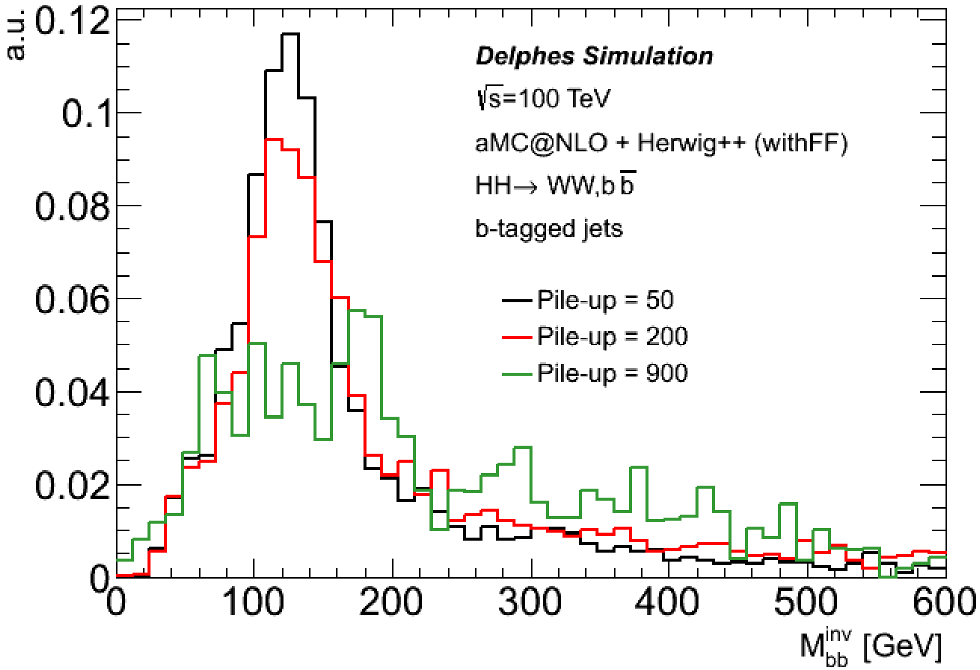


- **Deterioration of jet response resolution with increasing η**
- **Expected due to higher pile-up signals**

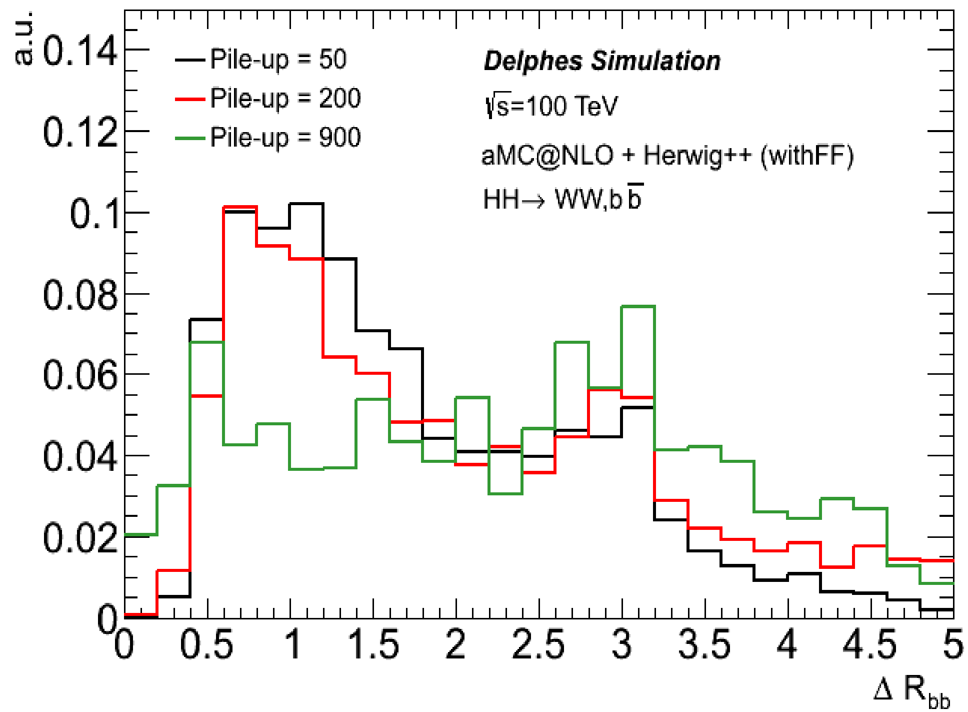


Discriminant variables at various pile-up

Mbb invariant mass



Rbb invariant mass



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

Detector parameter variations: Calorimeter resolution

- **Constant term driven by requirement on Multi-TeV physics**
- **Here stochastic term is varied**
  - **Factor 2 Up and Down, HCal only Down**

Nominal Calorimeter Resolution

ECAL Energy resolution

σ E/E = 10% / $\sqrt{E}$ $\oplus$ 1%

HCAL Energy resolution

- **σ E/E = 50% / $\sqrt{E}$ $\oplus$ 3% in $|\eta|<4$**
- **σ E/E = 100% / $\sqrt{E}$ $\oplus$ 5% in $4 < |\eta|<6$**

Calorimeter Resolution "Up"

ECAL Energy resolution

σ E/E = 20% / $\sqrt{E}$ $\oplus$ 1%

HCAL Energy resolution

- **σ E/E = 50% / $\sqrt{E}$ $\oplus$ 3% in $|\eta|<4$**
- **σ E/E = 100% / $\sqrt{E}$ $\oplus$ 5% in $4 < |\eta|<6$**

Calorimeter Resolution "Down"

ECAL Energy resolution

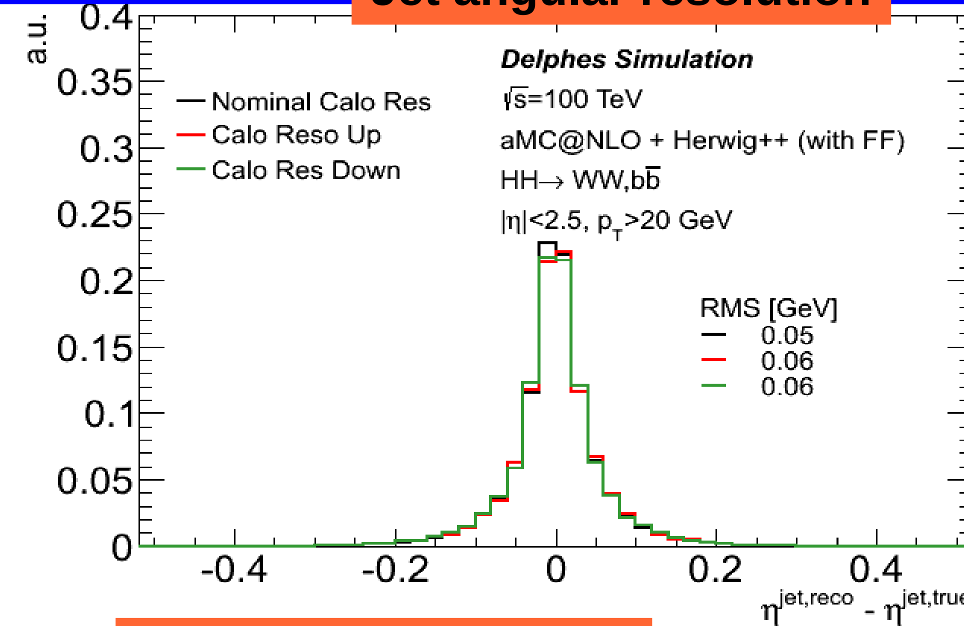
σ E/E = 5% / $\sqrt{E}$ $\oplus$ 1%

HCAL Energy resolution

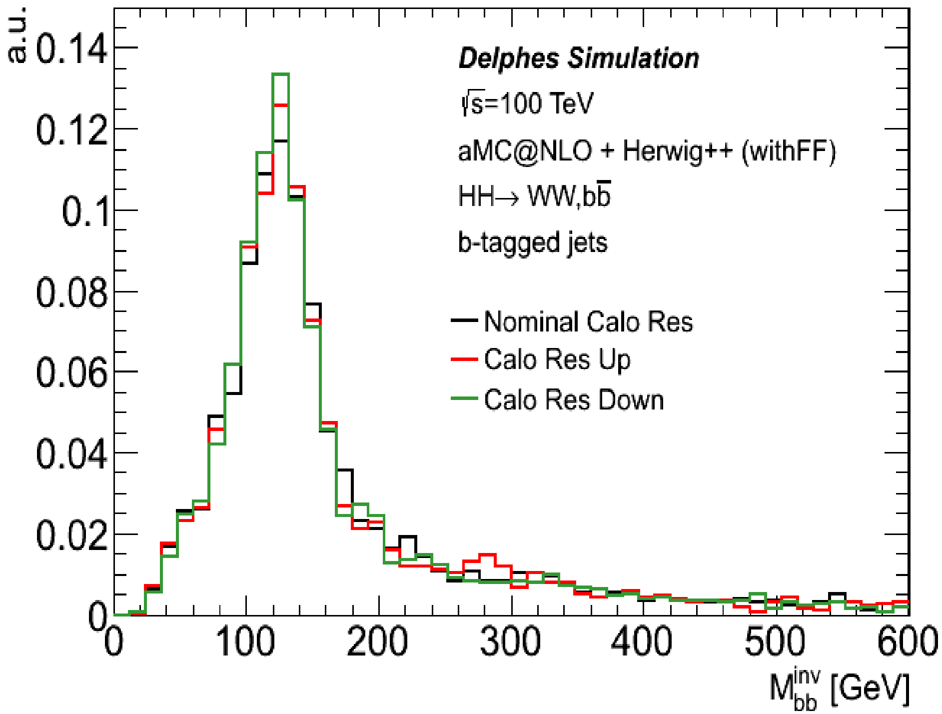
- **σ E/E = 25% / $\sqrt{E}$ $\oplus$ 3% in $|\eta|<4$**
- **σ E/E = 50% / $\sqrt{E}$ $\oplus$ 5% in $4 < |\eta|<6$**

Detector parameter variations: Calorimeter resolution

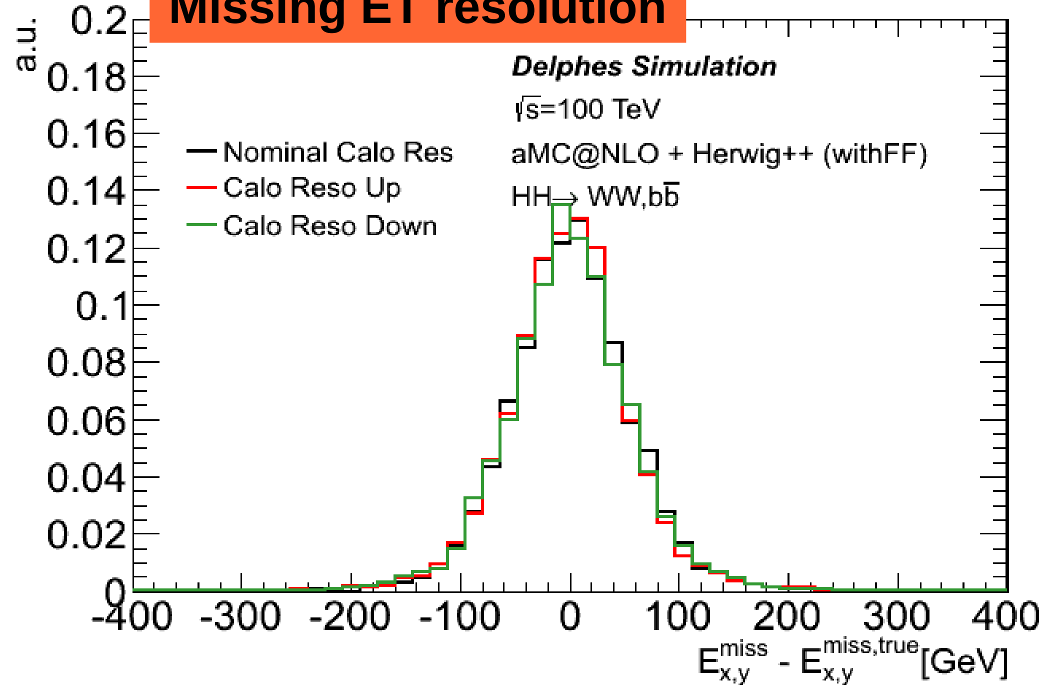
Jet angular resolution



Mbb invariant mass



Missing ET resolution



- **Pile-up = 50 used**
- **Very small differences**
- **Effects likely washed-out by pileup**

Detector parameter variations: z_0 resolution

- **Tracks from Pileup are rejected if $| z_0 - z_{PV} | > \sqrt{\sigma^2(z_0) + \sigma^2(z_{PV})}$**
- **Expect effects on resolution of jets and Missing Transverse energy due to enhanced pile-up contributions**

- **Compare our choice = *z_0 resolution dependent on η***
  vs official card = z_0 resolution constant on η

z_0 resolution

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

z_0 resolution

$\sigma(z_0)$= 0.01 mm , p_T<5 GeV

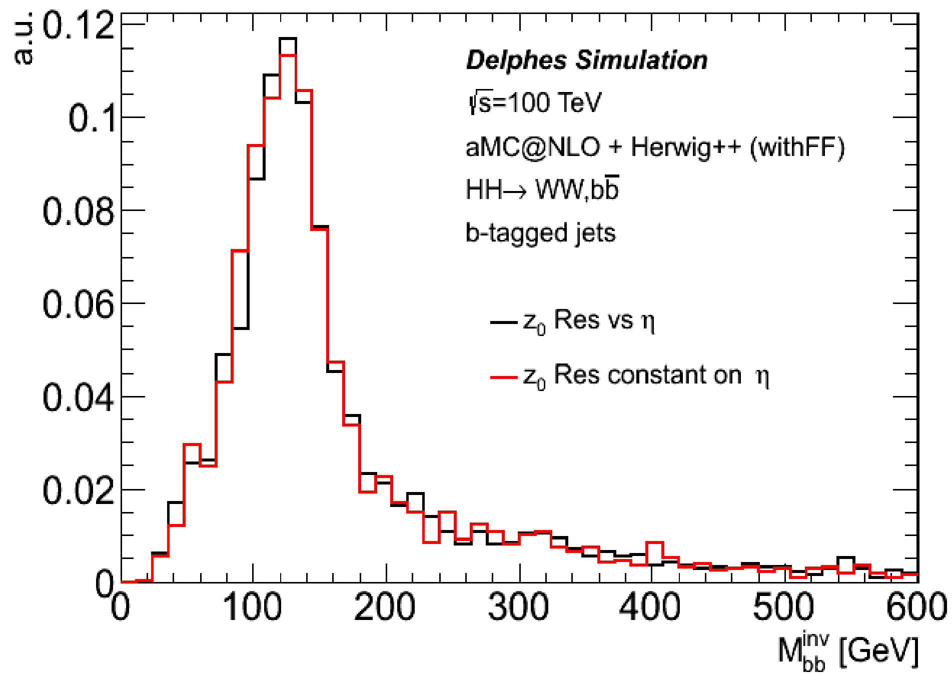
$\sigma(z_0)$= 0.005 mm , p_T>5 GeV

For all η

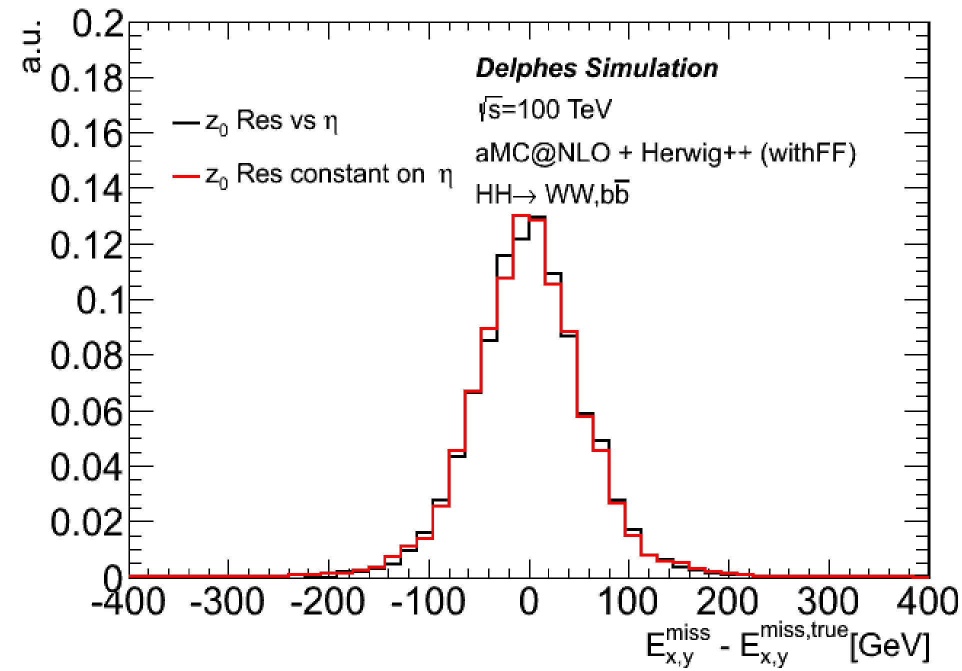
Detector parameter variations: z_0 resolution

Pile-Up = 50

Mbb invariant mass

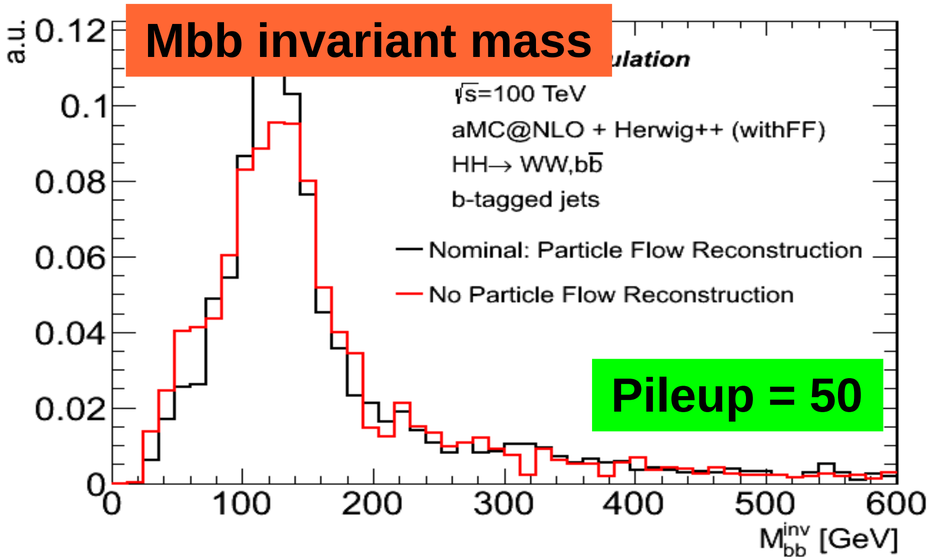


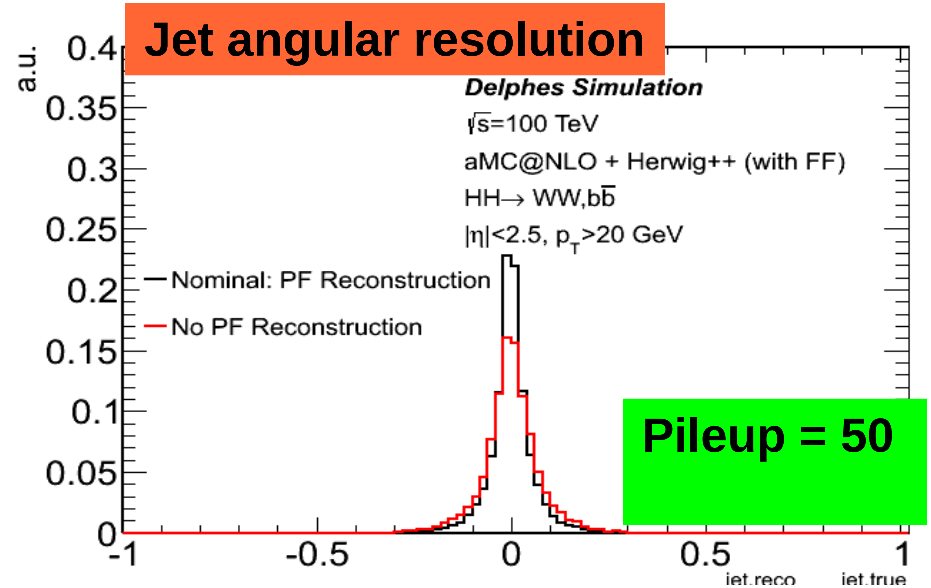
Missing ET resolution

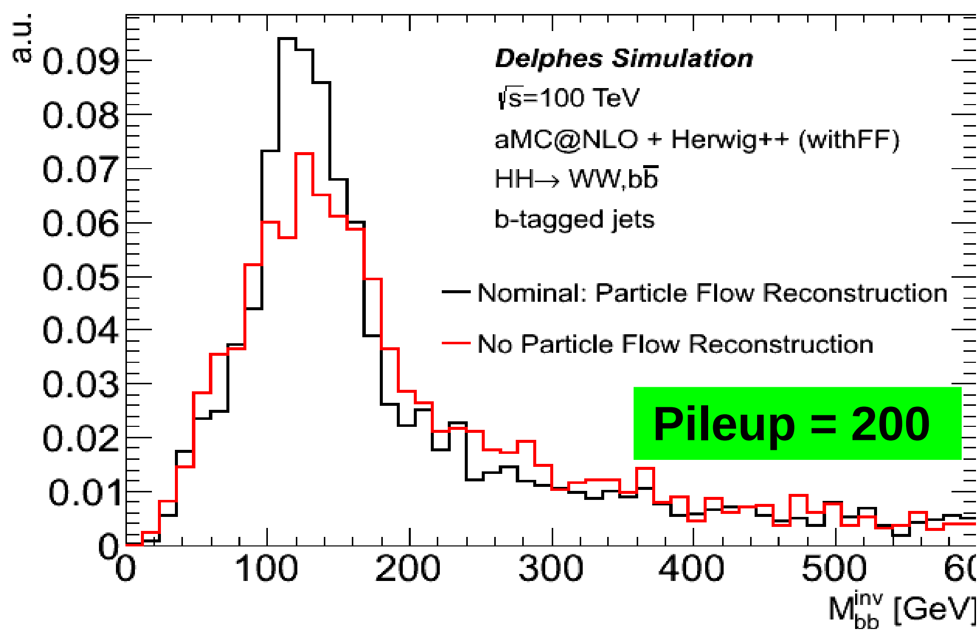


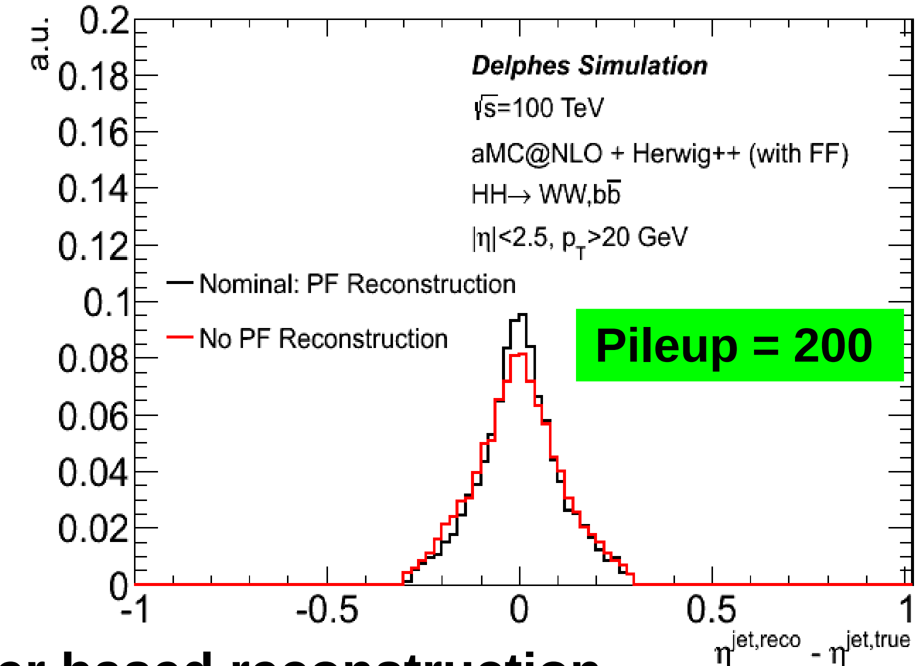
- **Caveat: B-tagging not changed**
- **Mbb ~not sensitive: b-jets are mostly central**
- **MET ~not sensitive: driven by central jets**
- **Caveat: dependence on topology**
  VBF,VBS would be different

Particle Flow vs Calorimeter based Jet reconstruction









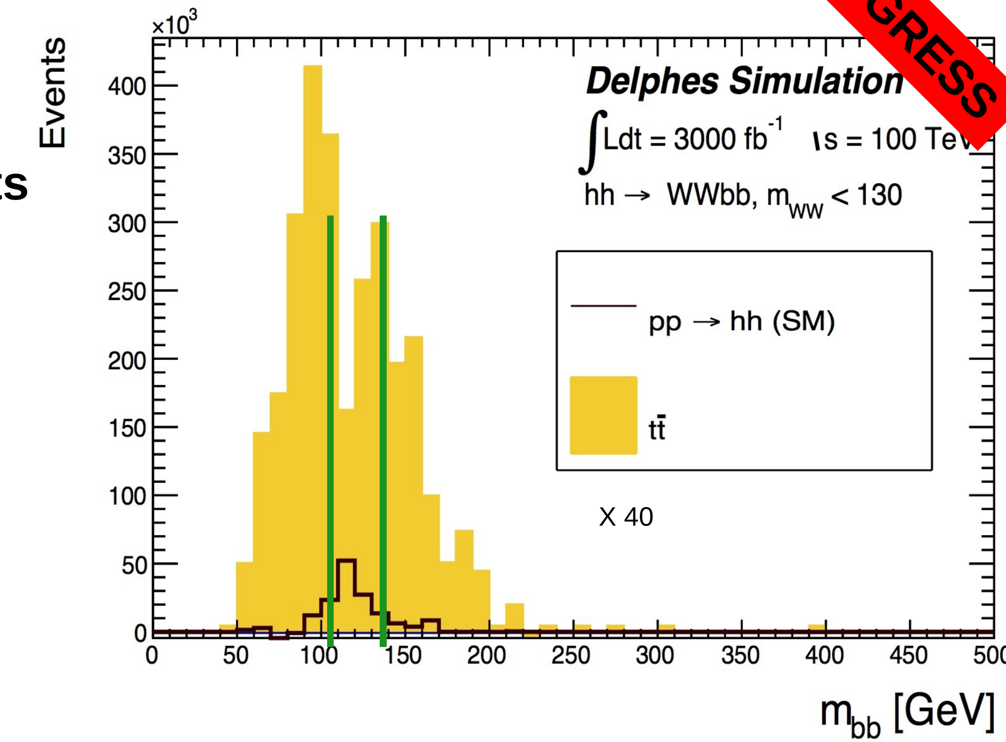
- **Deterioration using calorimeter based reconstruction**

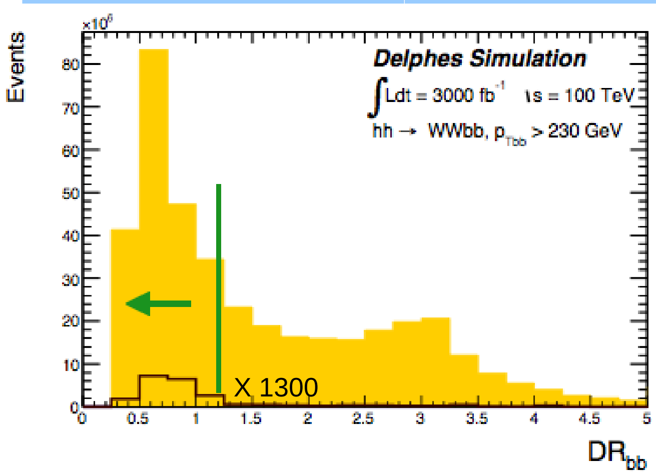
Objects and Event selection

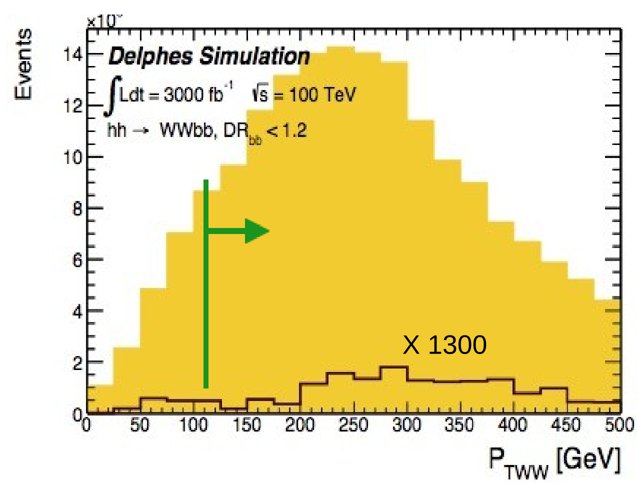
WORK in PROGRESS

- **At least one isolated lepton wit p_T > 15 GeV**
- **4,5 jets with p_T > 20 GeV $|\eta|$ < 2.5, passing a Jet Vertex Fraction selection**
- **Overlap removal between muons,electron,jets**

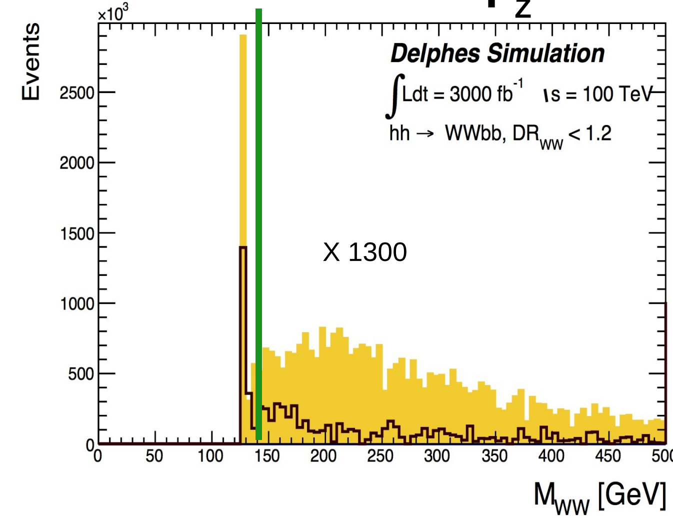
Variable	Cut
$p_T(bb)$	> 230 GeV
ΔRbb	< 1.2
$p_T(WW)$	> 140 GeV
ΔR_{WW}	< 1.2
m_{WW}	< 130 GeV
m_{bb}	105 – 135 GeV







Fit to detemine $p_Z\nu$



Analysis results

WORK in PROGRESS

Need more sophisticated techniques: kinematic fit, MVA analysis to bring S/Top > 10%.

3 ab^{-1},PU 50	Object selection	Final Selection	ε
Signal	7084	803	$2.5\ 10^{-3}$
Top bkg	$5.4\ 10^{9}$	$7.87\ 10^{5}$	
S/Top	$1.31\ 10^{-6}$	$1.02\ 10^{-3}$	

- **PU = 200 configuration not been optimised**
- **20% reduction in S/B**
- **~× 3 reduction in the final signal yield**

3 ab^{-1},PU 200	Preselection	Final Selection	ε
Signal	$5.4\ 10^{4}$	273	$8.5\ 10^{-4}$
Top bkg	$3.6\ 10^{9}$	$3.4\ 10^{5}$	
S/Top	$1.5\ 10^{-5}$	$8.0\ 10^{-4}$	

Conclusions

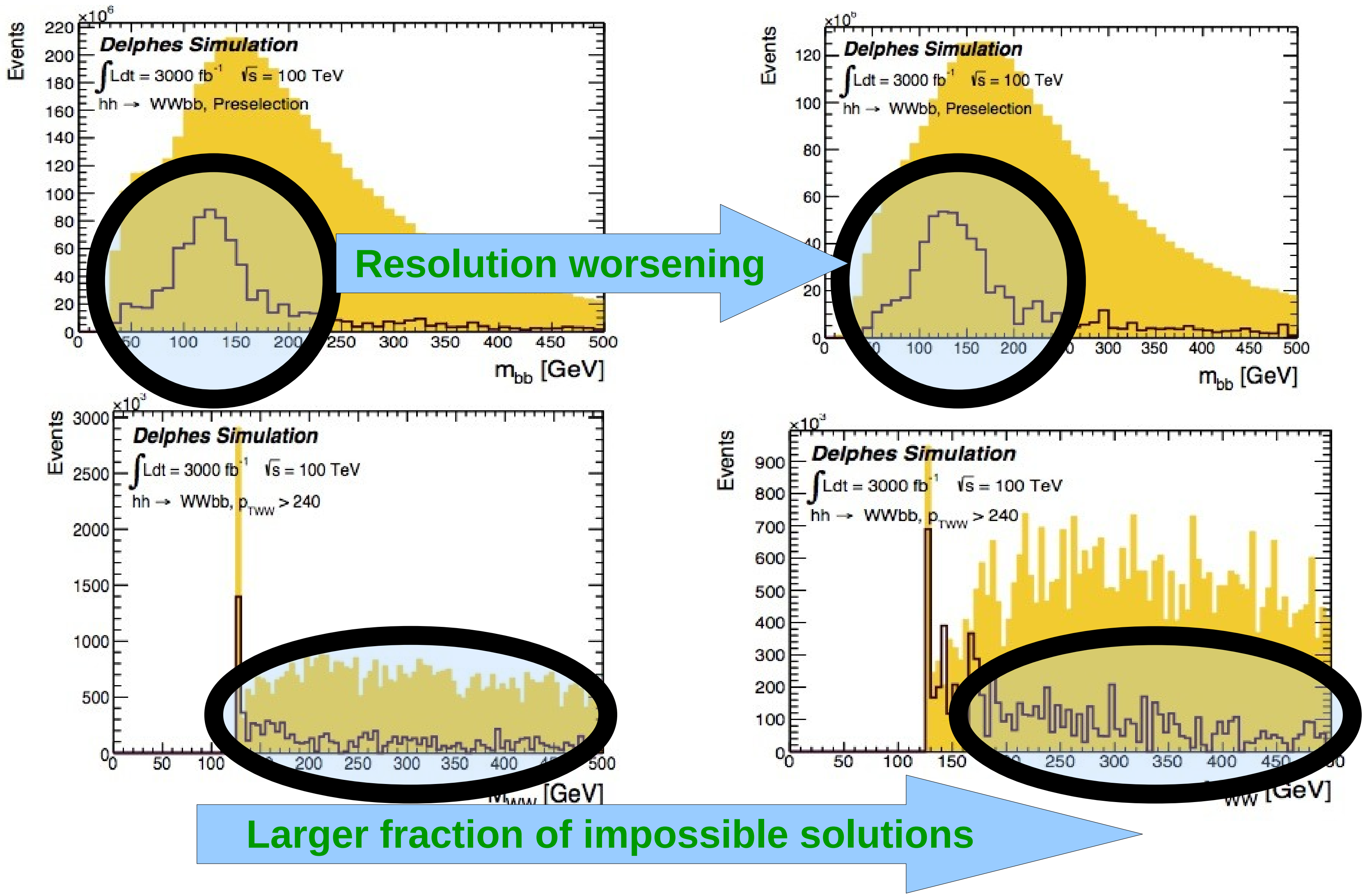
- First studies with realistic pile-up condition have been shown
  - Reconstruction and analysis degradation
  - At Pileup = 900 need smarter reconstruction

- Particle-flow reconstruction likely better for the hh kinematics (low E)

- Still a lot of work to be done:
  - Analysis still far to be sensitive to λ
    - top background difficult to handle
  - Optimization of cuts
    - fat jet and MVA technique
  - Additional pile-up suppression techniques
  - Change of other detector parametrizations
    - b-tagging, track resolution & efficiencies..

backup

50 200



Delphes Simulation
∫Ldt = 3000 fb⁻¹ √s = 100 TeV
hh → WWbb, Preselection
hh → WWbb, p_TWW > 240
Events
m_bb [GeV]
Resolution worsening
Larger fraction of impossible solutions

Objects selection

- At least one isolated lepton wit p_T > 15 GeV (calo isolation corrected for pile-up and track isolation applied);
- 4,5 jets with p_T > 20 GeV $|\eta| < 2.5$, passing a JVF selection:
    - $\Sigma p_T^{PV}/\Sigma p_T > 0.1$ for anti-btag jets, > 0.02 for b-tagged jets)
- Object overlap removal:
    - Leptons: take the highest p_T lepton;
    - preference order: muons, electrons, jets;
    - overlap removal cone: $\Delta R = 0.1$;

m_{WW} distribution

- Neutrino p_z is computed using the relation $m_{WW} = m_h$, that is quadratic in p_z;

- If two real solutions are found, that closest in ΔR to the lepton is taken, in this case $m_{WW} = m_h$ by definition;

- If 2 complex solutions are found only the real part is taken, in thise case $m_{WW} > m_h$;

- The $m_{WW} > m_h$ represents the failure to find a solution consistent with the Higgs mass hypothesis