

Measurement of double Higgs production at CLIC

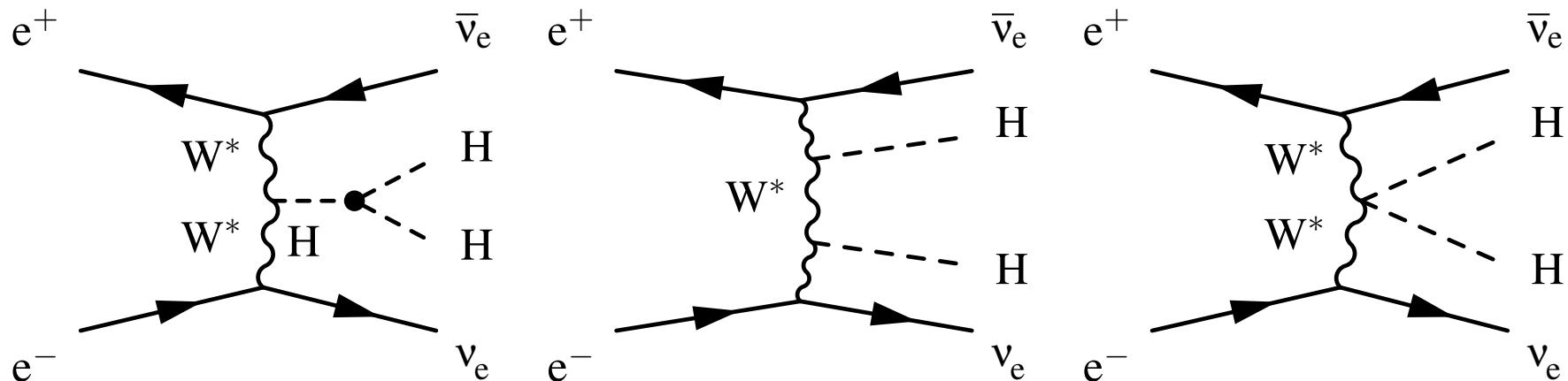
Philipp Roloff*, Rosa Simoniello*, Boruo Xu°
on behalf of the CLICdp collaboration

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November 2-6, 2015

* CERN
° University of Cambridge



Introduction

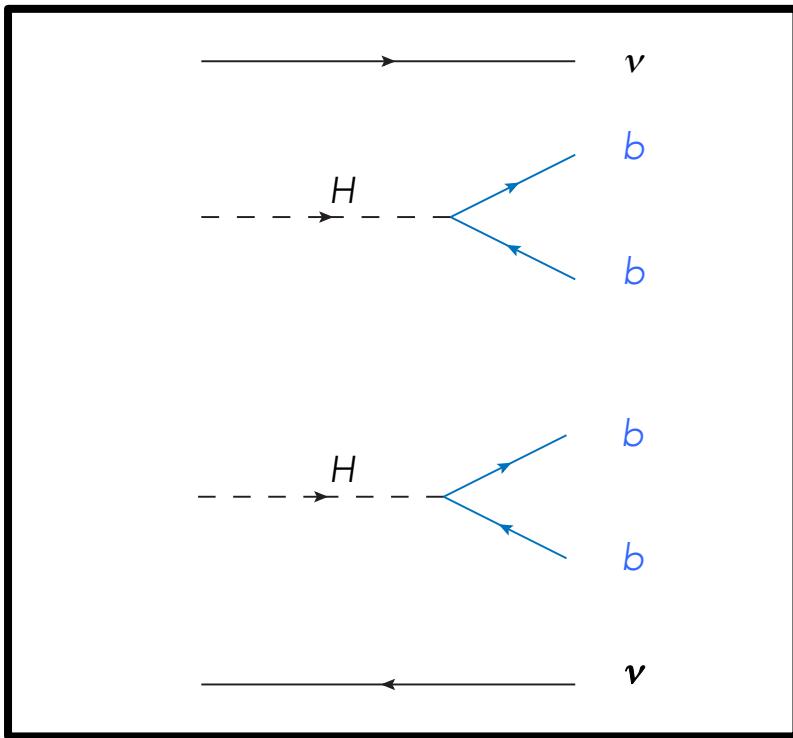


Trilinear Higgs
self coupling, g_{HHH}

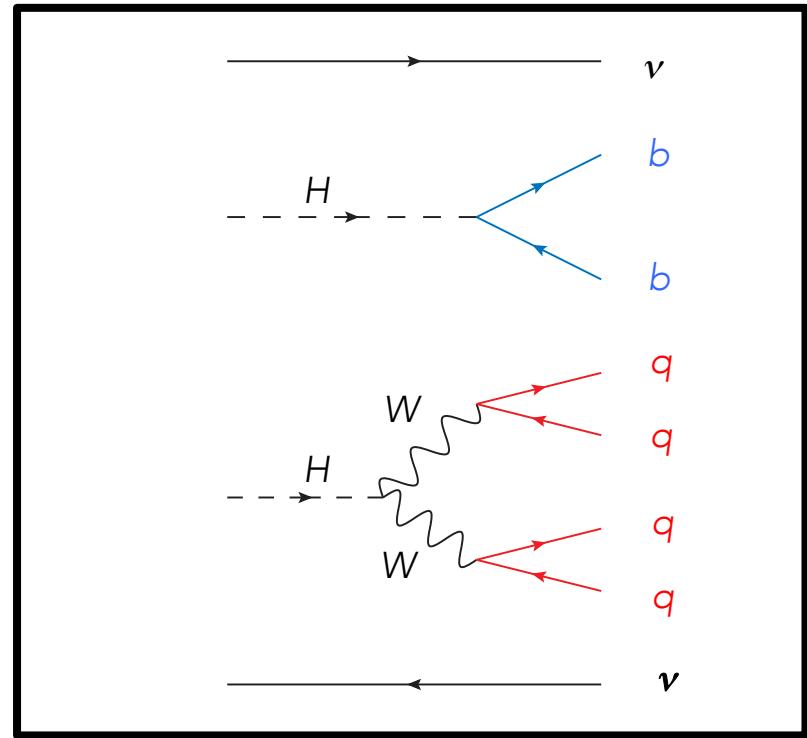
Quartic coupling, g_{HHWW}

- Measurement of g_{HHH} at 3 TeV and 1.4 TeV via double Higgs production → very appealing measurement for its physics discovery potential
- Also sensitive to g_{HHWW} → simultaneous extraction
- Existing results included in the Higgs paper: precision on $g_{\text{HHH}} \sim 10\%$ at 3 TeV
- In this talk, status of the re-analysis:
 - Optimise the analysis chain with a view to the new CLIC detector model
 - Divide analysis in sub-channels to increase significance → target the analysis selection according to specific signal topology and background composition

Sub-channels



$$\text{BR}(m_H=126\text{GeV}) = 0.315$$



$$\text{BR}(m_H=126\text{GeV}) = 0.119$$

- Sub-channels considered:
 - $HH\nu\nu \rightarrow bbbb\nu\nu \rightarrow \sim 371$ events at 3 TeV, ~ 71 events at 1.4 TeV
 - $HH\nu\nu \rightarrow bbWW\nu\nu \rightarrow bbqqqq\nu\nu \rightarrow \sim 140$ events at 3 TeV, ~ 27 events at 1.4 TeV
 - In future: $HH\nu\nu \rightarrow bbWW\nu\nu \rightarrow bbqqql\nu\nu$?
- Try to keep the analyses mutual exclusive for final combination

Analysis strategy

$\text{HH}\nu\nu \rightarrow \text{bbbb}\nu\nu$

Detector model:

- CLIC_SiD

Energy:

- 3 TeV
- 1.4 TeV (to be started)

Rejection of beam background:

- Tight selected PFOs

Preselection:

- e, μ, τ veto (fully optimised)
- Cluster event in 4/5 jets

Classifier for MVA:

- BTD with Gradient Boost

$\text{HH}\nu\nu \rightarrow \text{bbWW}\nu\nu \rightarrow \text{bbqqqq}\nu\nu$

Detector model:

- CLIC_ILD

Energy:

- 3 TeV (to be started)
- 1.4 TeV

Rejection of beam background:

- Selected PFOs

Preselection:

- e, μ, τ veto (to be optimised)
- Cluster event in 6 jets
- χ^2 of mass reconstruction

Classifier for MVA:

- BTD

Higgs mass reconstruction strategy

- $\text{HH}\nu\nu \rightarrow \text{bbbb}\nu\nu$ has 4 jets in the final state
- $\text{HH}\nu\nu \rightarrow \text{bbWW}\nu\nu \rightarrow \text{bbqqqq}\nu\nu$ has 6 jets in the final state

→ *Need to associate the right jets to the right Higgs*

- For $\text{HH}\nu\nu \rightarrow \text{bbbb}\nu\nu$ minimise:

$$\chi^2 = (m_{\alpha,\beta} - m_H)^2 + (m_{\gamma,\delta} - m_H)^2 \quad m_H = 126 \text{ GeV}$$

- For $\text{HH}\nu\nu \rightarrow \text{bbWW}\nu\nu \rightarrow \text{bbqqqq}\nu\nu$ minimise:

$$\chi_6^2 = \frac{(M_{12} - M_{H_{bb}})^2}{\sigma_{H_{bb}}^2} + \frac{(M_{3456} - M_{H_{WW}})^2}{\sigma_{H_{WW}}^2} + \frac{(M_{34} - M_{W^\pm})^2}{\sigma_{W^\pm}^2}$$

Remarks

- Both sub-channels are in a preliminary phase
- Object selection for the $\text{HH}\nu\nu \rightarrow \text{bbWW}\nu\nu \rightarrow \text{bbqqqq}\nu\nu$ has not been fully optimised except for the jet selection
→ *in the next slides the object identification is shown for the $\text{HH}\nu\nu \rightarrow \text{bbbb}\nu\nu$ subchannel*
- **Only few backgrounds are included in the analysis**
→ **very preliminary results**

Lepton and Tau identification

- Isolated lepton and tau identification is applied as a veto
- Identification working point optimised on WWvv sample at 3 TeV

Requirements for isolated leptons (IsolatedLeptonFinder):

- $d_0 < 0.03$ mm, $z_0 < 0.04$ mm, $R_0 < 0.06$ mm
- $0.05 < R_{\text{cal}} < 0.25 \parallel R_{\text{cal}} > 0.9$
- $\cos\theta = 0.995$ (scan in: 0.990, 0.995, 0.999)
- Polynomial isolation: A=0.0, B=5.7, C=-50.
- $E_{\text{track}} > 15$ GeV

- **Fake reconstruction in WWvv: ~1%**
- **Rejected ~77% of WW events with at least 1 lepton (e, μ , τ)**

Requirements for taus (TauFinder):

- $p_T = 1$ GeV: scan in (1, 2)
- $p_T^{\text{seed}} = 10$ GeV: scan in (5, 10)
- Search cone = 0.03: scan in (0.02, 0.03, 0.05, 0.07 ,0.09, 0.11)
- Isolation cone = 0.3: scan in (0.2,0.3,0.4)
- Isolation energy = 3 GeV: scan in (3.,5.,10.)
- Invariant mass = 2 GeV: scan in (1.5,2.,2.5)

- **Purity of ~51%, efficiency of ~25%**
- **Rejected 0.1% of signal events**

Jets optimisation

- 4 jets final state -> gluon radiation may not be completely included in the corresponding jet
→ *investigate clustering the event in 5 jets*
- Jets large enough to capture all energy from physics event without including too much background, especially in the forward region
→ *investigate several jet algorithms with different R parameter*
 - **Exclusive longitudinally invariant k_t :**
Clustering in 3, 4, 5, 6 jets, scan in R
 - **Exclusive Valencia algorithm (VLC) with $\beta = 1$:**
Clustering in 4, 5 jets, scan in R, $\gamma = 1.0, 0.8, 0.5, 1.3$
 - **Inclusive anti- k_t :**
Minimum $p_T = 4, 7, 10, 15$ GeV, scan in R
 - **Inclusive SIScone:**
Minimum $p_T = 4, 7, 10, 15$ GeV, scan in R

VLC algorithm

Longitudinal invariant algorithms:

$$d_{ij} = \min(p_{T,i}^{2n}, p_{T,i}^{2n}) \Delta R_{ij}^{2n} / R^2$$

Use of longitudinal invariant variables p_T , η

$$d_{iB} = p_{T,i}^{2n}$$

for $n = 1 \rightarrow k_t$, for $n = -1 \rightarrow \text{anti-}k_t$

Valencia algorithm:

$$d_{ij} = \min(E_i^{2\beta}, E_i^{2\beta}) (1 - \cos\theta_{ij}) / R^2$$

$$d_{iB} = E^{2\beta} \sin^{2\gamma} \theta_{iB}$$

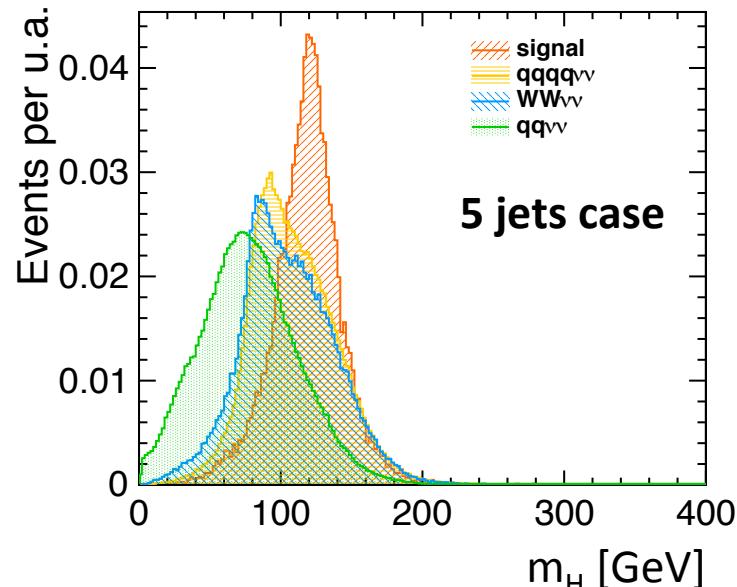
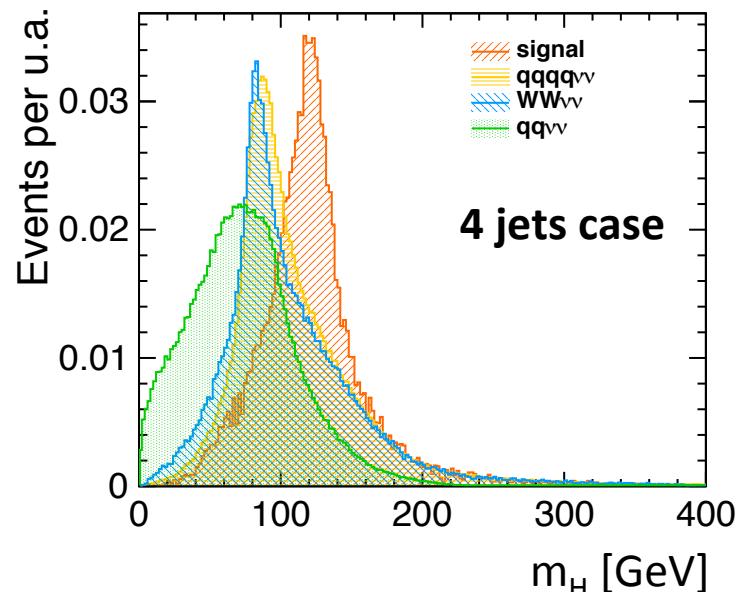
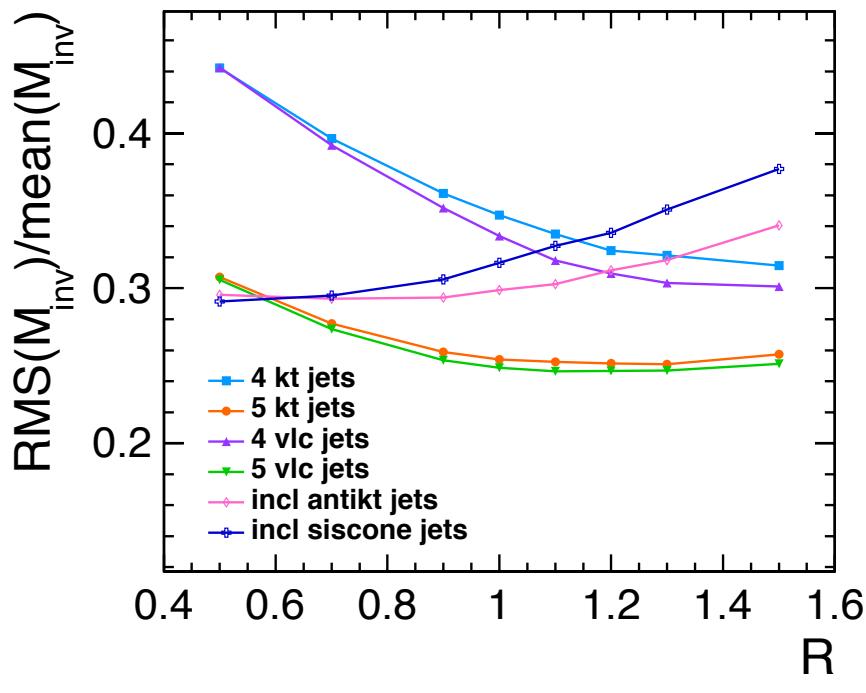
$$\text{for } \beta = \gamma = 1 \rightarrow d_{iB} = p_{T,i}^2$$

*Specific for lepton colliders
→ no need for longitudinal invariant variables
→ E , θ more robust for computing distance in forward regions*

Reference paper: <https://inspirehep.net/record/1291037?ln=en>

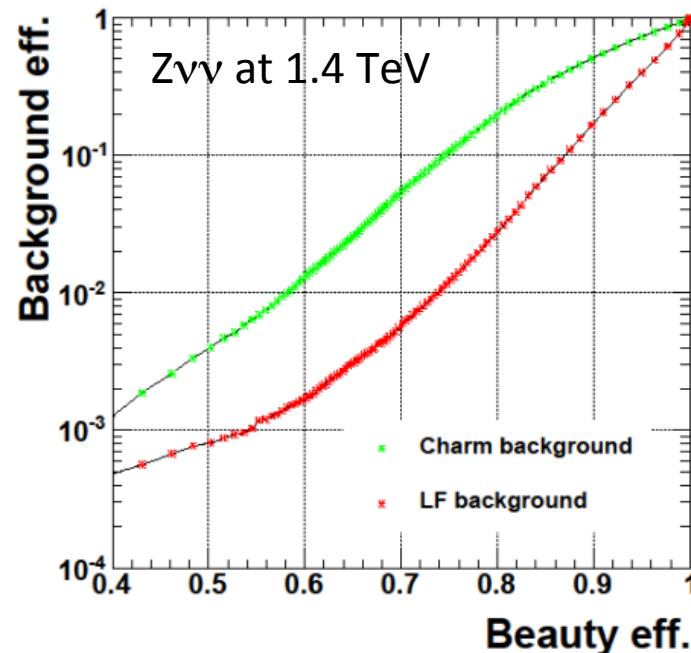
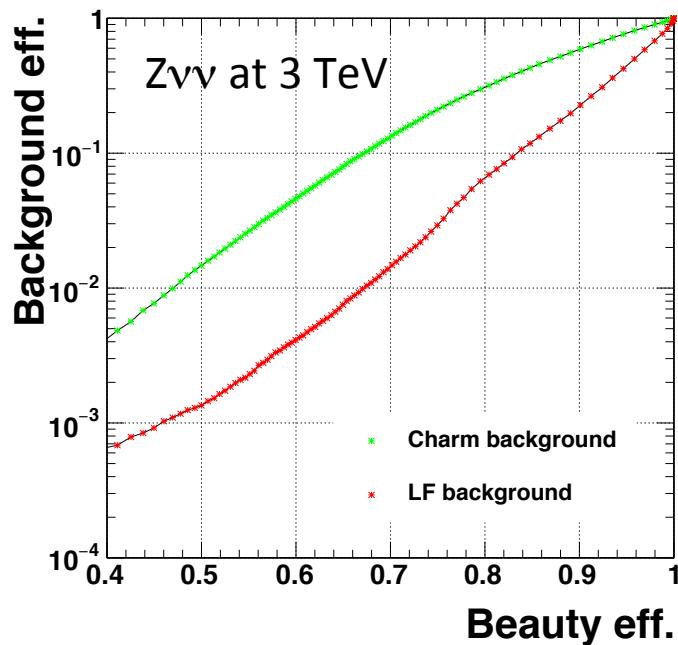
Results

- Based on results on signal sample:
 - $R = 1.1$
 - VLC a bit better than k_t
 - 5 jets better than 4 jets
- 5 jets more bkg in the mass peak



b-tag

- Based on LCFIPlus with root 5.28
 - 1) Jet reconstruction
 - 2) Vertexing
 - 3) Durham algorithm in LCFIPlus
- Vertexing as first step at 3 TeV collect too much background
→ worsening in mass resolution



Discriminating variables for HHvv->bbbbvv

- More background coming soon !

Bkg samples	Cross section at 3 TeV [fb]	Eff for preselection [%]
ee->qqqqvv	74.1	0.97
ee->qqvv	1318.2	0.98

Input variables in MVA:

- jet variables

$$p_T^{j1}, p_T^{j2}, p_T^{j3}, p_T^{j4}$$

$$b\text{-tag}^{j1}, b\text{-tag}^{j2}, b\text{-tag}^{j3}, b\text{-tag}^{j4}$$

$$\max(|\eta|)$$

- di-quark system variables

$$m^{H1}, m^{H2}$$

$$\alpha(H1, H2)$$

- event variables

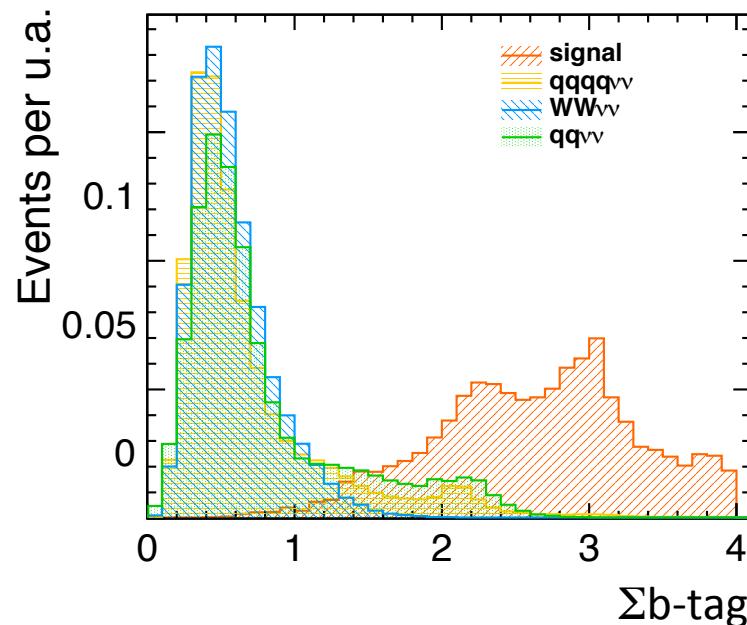
$$\Sigma b\text{-tag}$$

$$\Sigma m^j$$

$$\gamma_{45}, \gamma_{23}, \text{sphericity}$$

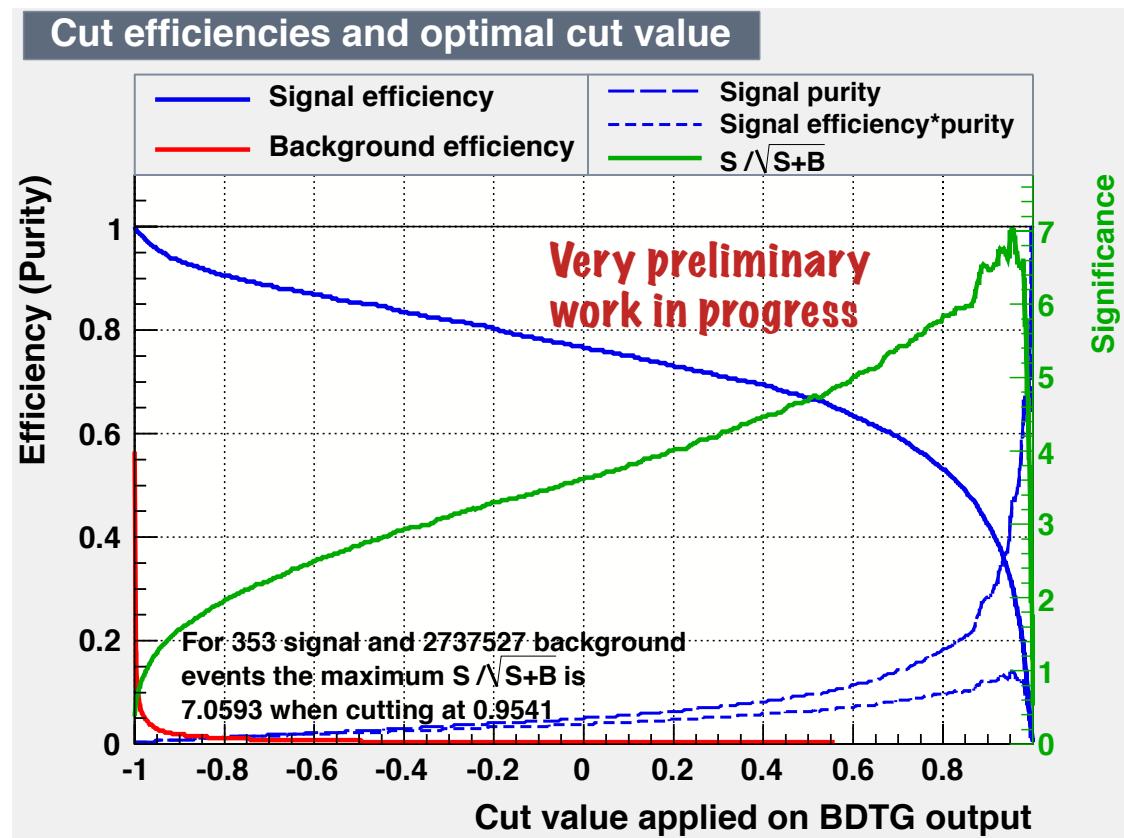
$$p_T^{\text{miss}} \text{ on the } \Sigma p_T^{\text{jet}} \text{ axis}$$

Most powerful discriminating variable



To investigate: the discriminating power of the di-quark angle

Preliminary results for HHvv->bbbbvv at 3 TeV



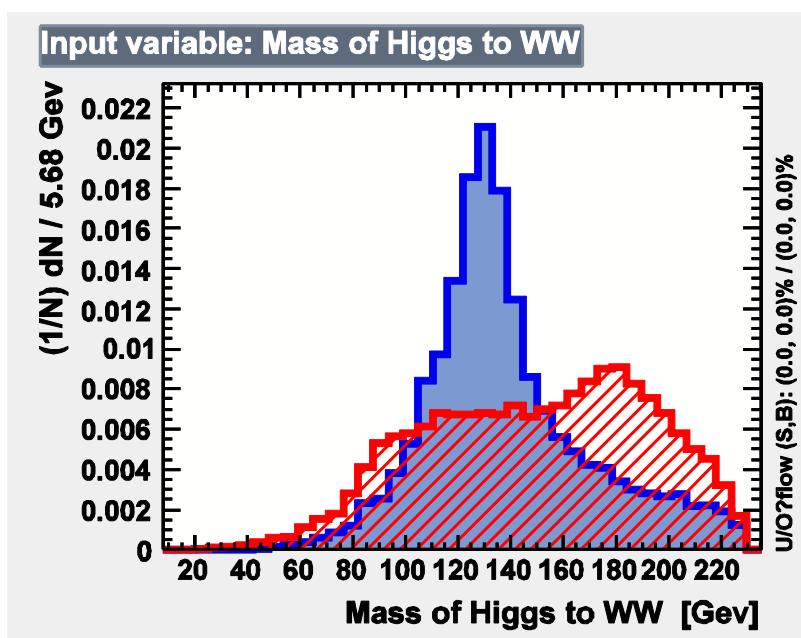
L [ab ⁻¹]	# sig exp	# bkg exp	BDTG cut	S/ $\sqrt{S+B}$	# sig	# bkg	ϵ sig	ϵ bkg
2	353	2737527	0.9541	7.06	108	127	0.31	4.7e-05
3	531	4106189	0.9541	8.66	163	191	0.31	4.7e-05

- Accuracy on the cross section 14.3% (11.5%) for L = 2 ab⁻¹ (3 ab⁻¹)

Discriminating variables for $\text{HH}\nu\nu \rightarrow \text{bbWW}\nu\nu$

- More background to be added !

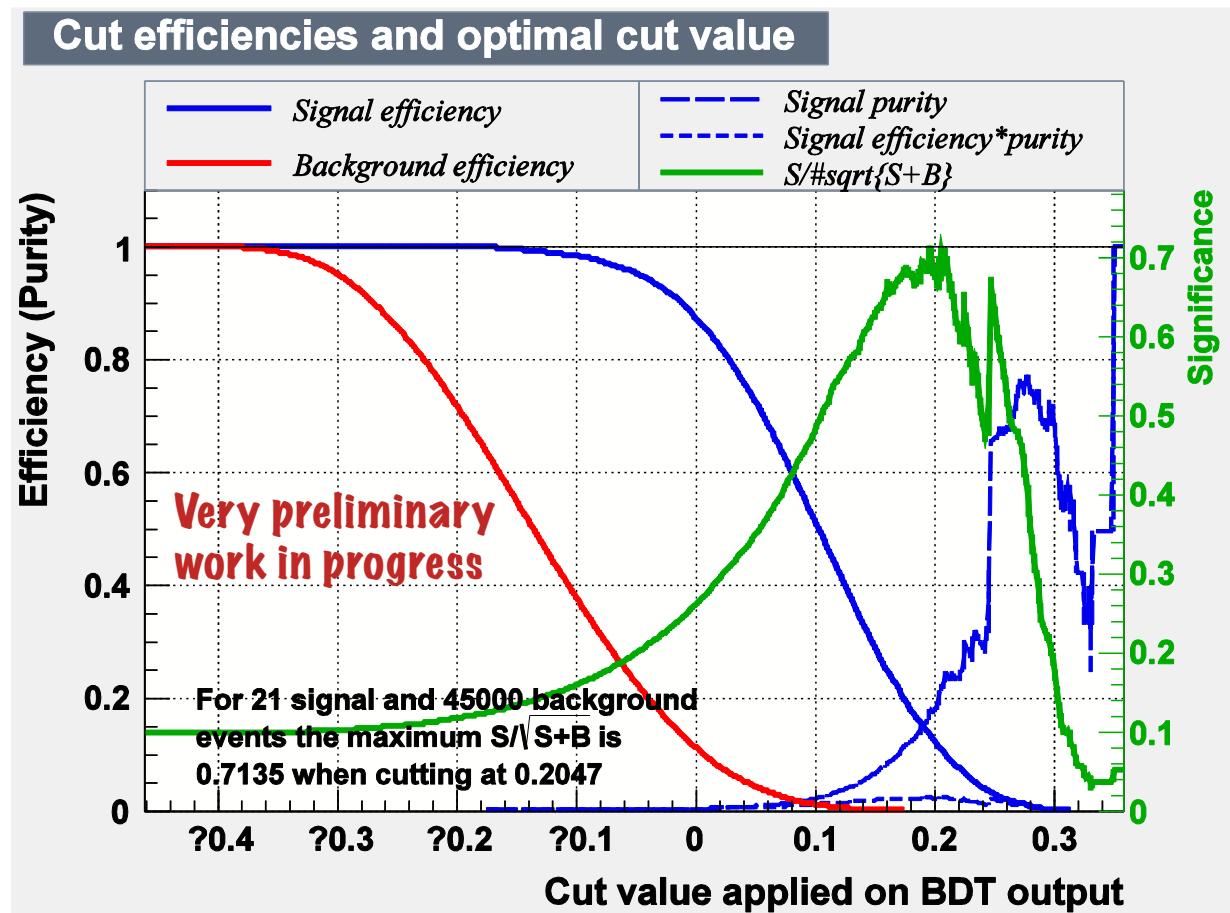
Bkg samples	Cross section at 1.4 TeV [fb]
ee->hhvv->other	0.130
ee->qqqqvv	23.2
ee->qqqqll	62.1
ee->qqqqlv	110.4



Input BDT variables:

- Sum of $\text{H} \rightarrow \text{bb}$ b tag value
- Highest b tag value
- Sum of all b tag value
- P_T visible momentum
- Principle thrust
- Aplanarity, Sphericity
- $\text{H} \rightarrow \text{bb}$ mass, $\text{H} \rightarrow \text{WW}$ mass
- $-\log(y_{45}), -\log(y_{34}), -\log(y_{23}), -\log(y_{67}), -\log(y_{78})$
- Acolinearity of 2 jets forming $\text{H} \rightarrow \text{bb}$
- Visible energy
- Invariant mass of visible momentum
- Recoil mass
- Acolinearity of 2 jets forming $\text{H} \rightarrow \text{WW}$
- Acolinearity of 2 jets forming on-shell W
- χ^2
- On shell W mass
- Acolinearity of 2 H
- Acolinearity of 2 jets forming off-shell W
- Sum of $\text{H} \rightarrow \text{WW}$ b tag value

Preliminary results for HHvv->bbWWvv at 1.4 TeV



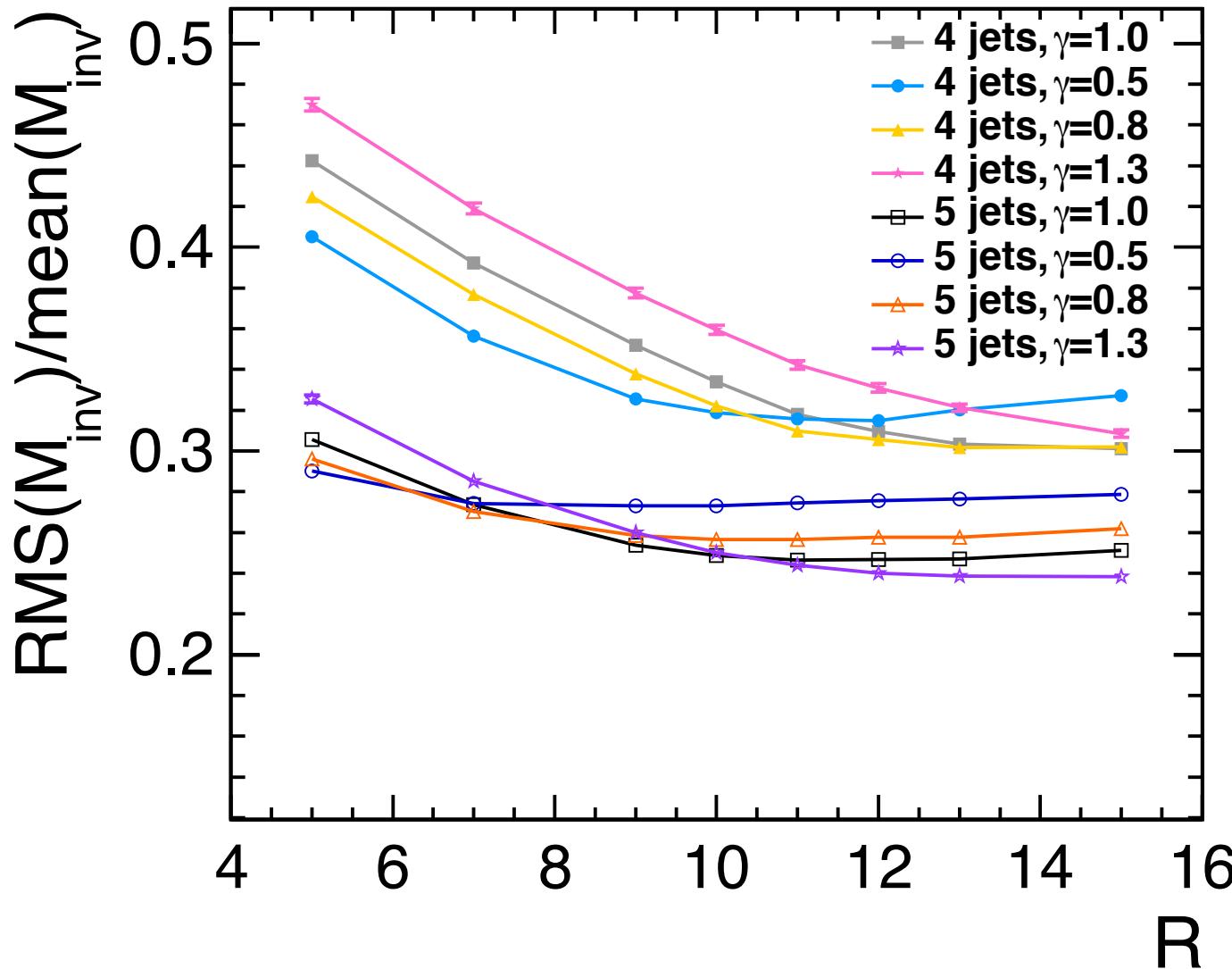
L [ab ⁻¹]	# sig exp	# bkg exp	BDT cut	S/v(S+B)	# sig	# bkg
1.5	21	45000	0.2047	0.71	2	8

Conclusion and next steps

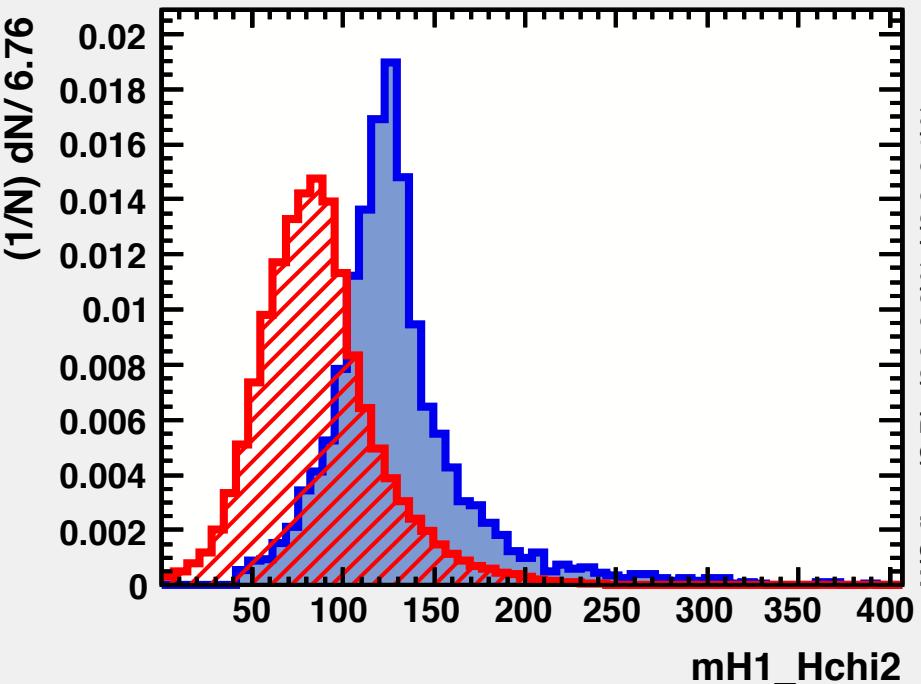
- Re-analysis of the double Higgs production has started
- Divide analysis in sub-channels:
 - $\text{HH}\nu\nu \rightarrow \text{bbbb}\nu\nu$
 - $\text{HH}\nu\nu \rightarrow \text{bbWW}\nu\nu \rightarrow \text{bbqqqq}\nu\nu$
- For both sub-channels the full analysis chain is in place
- Need to add all backgrounds to have final results
- For both sub-channels investigating more discriminating variables
- For the $\text{HH}\nu\nu \rightarrow \text{bbWW}\nu\nu \rightarrow \text{bbqqqq}\nu\nu$ still room for improvement in the object identification
- This analysis will be a test case for the new detector model when available

BACK-UP

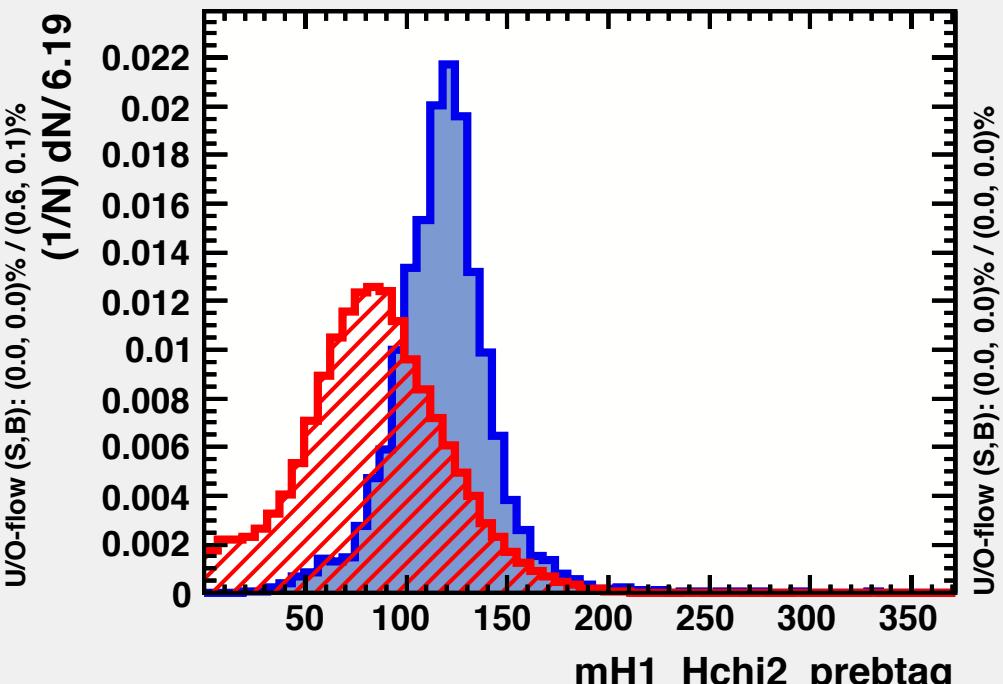
VLC - gamma comparison



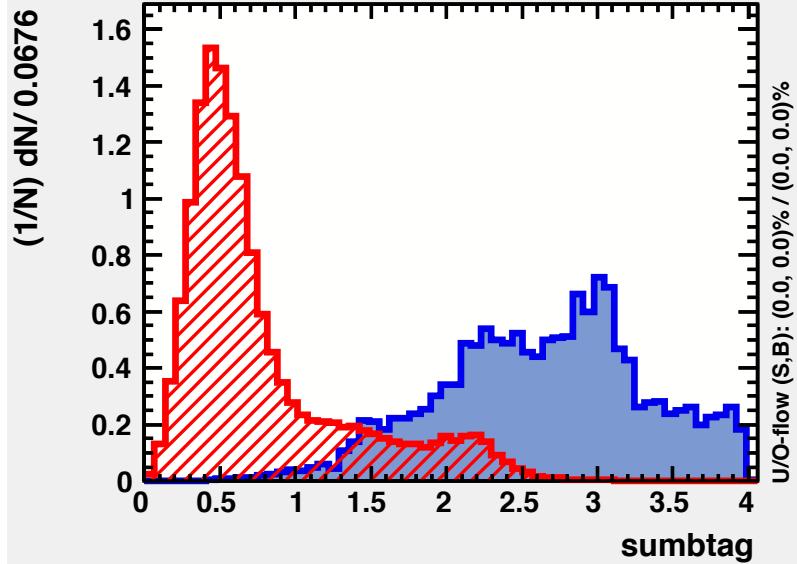
Input variable: mH1_Hchi2



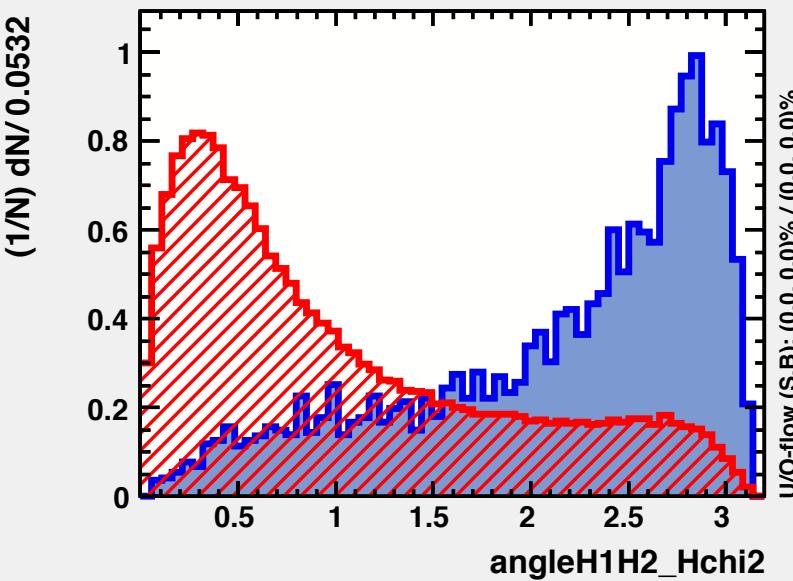
Input variable: mH1_Hchi2_pretag



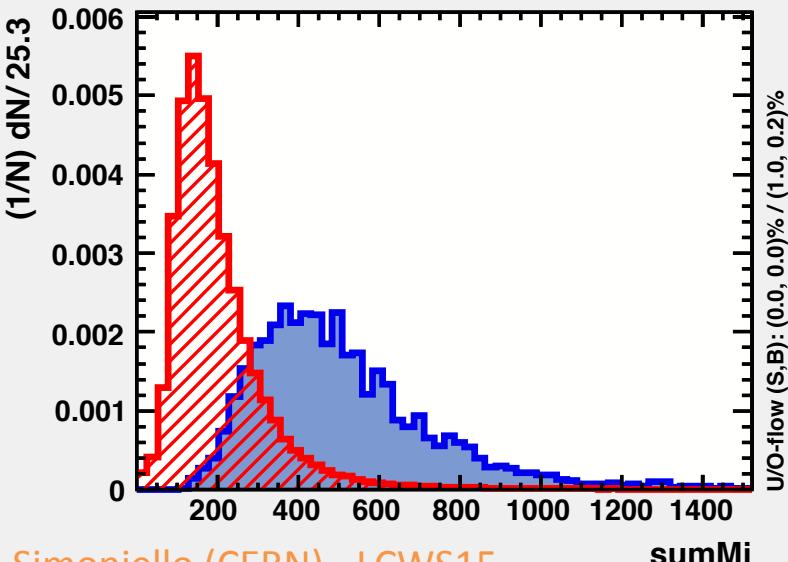
Input variable: sumtag



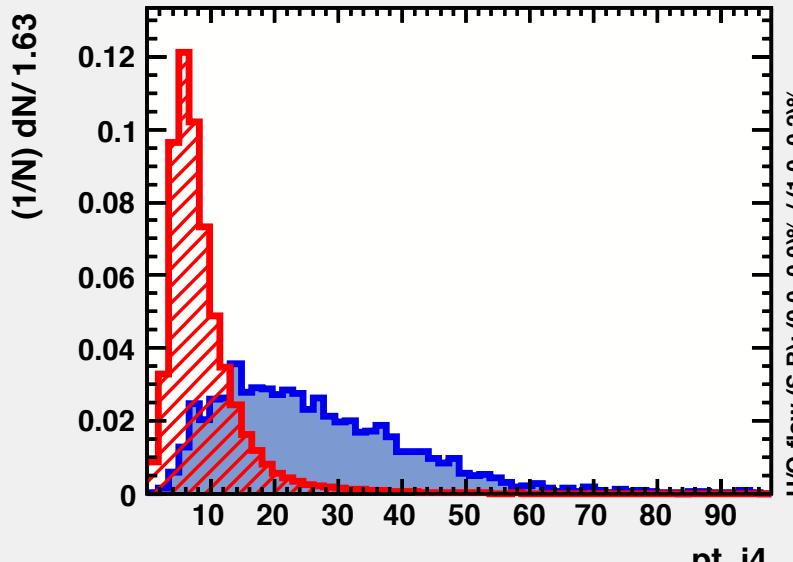
Input variable: angleH1H2_Hchi2



Input variable: sumMj

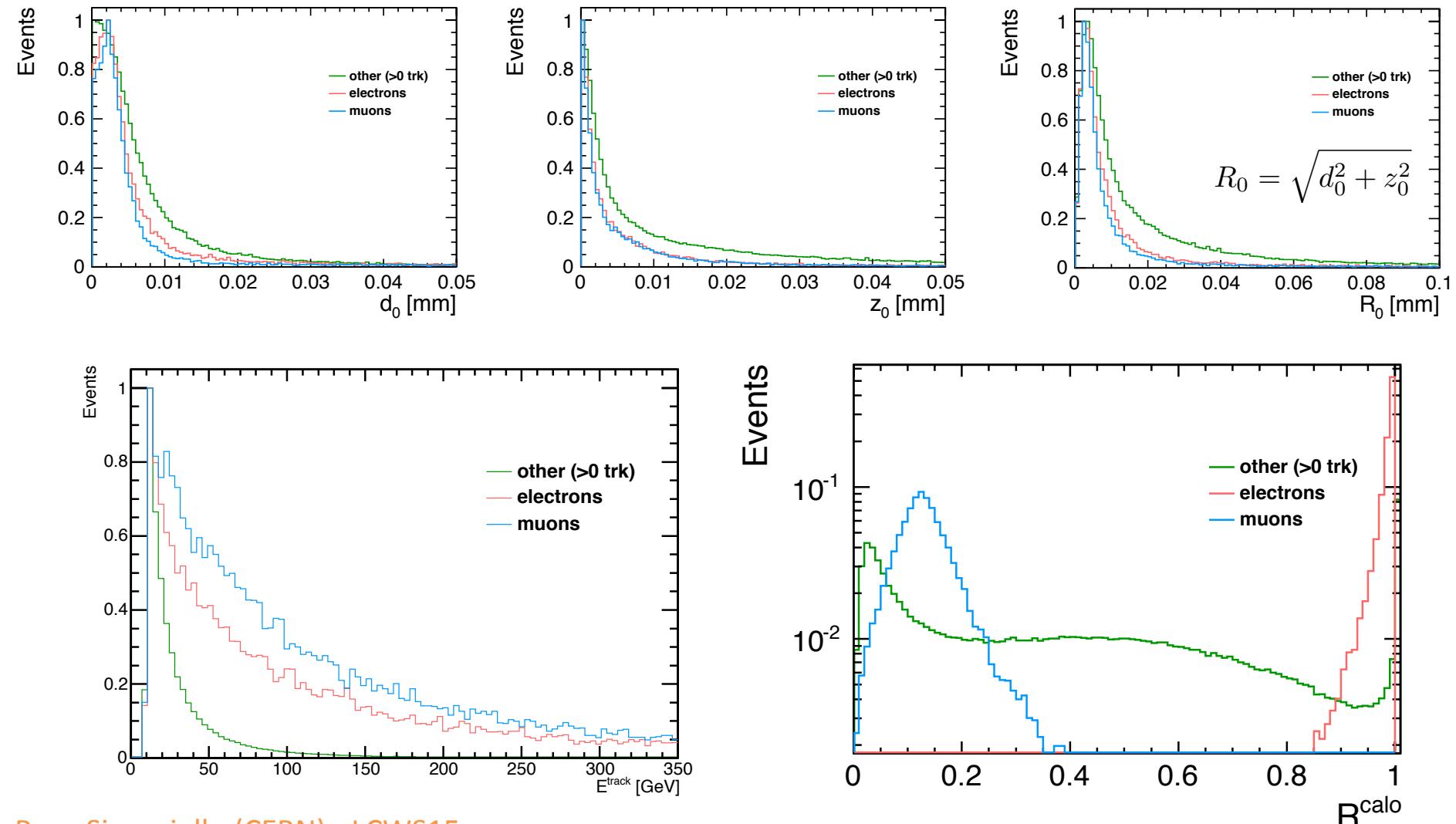


Input variable: pt_j4

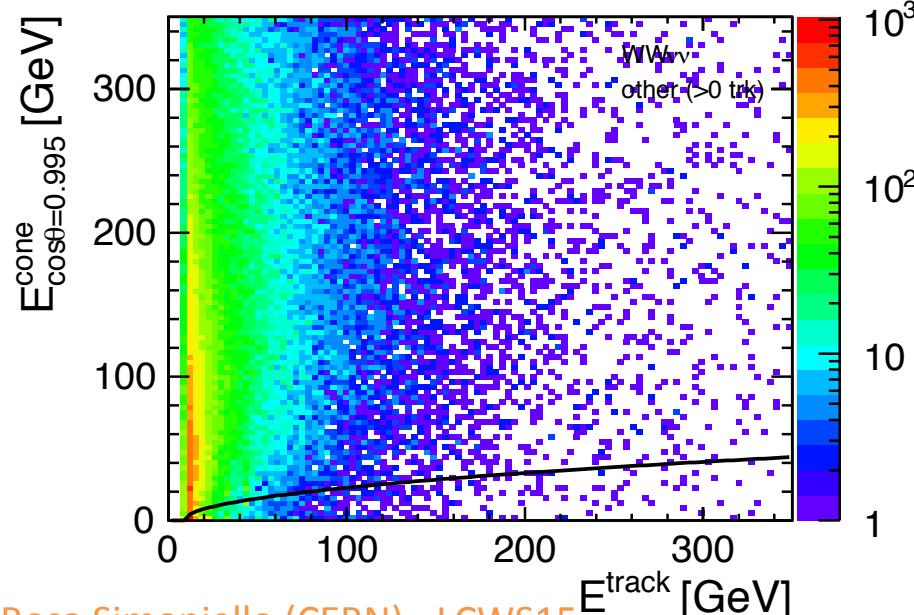
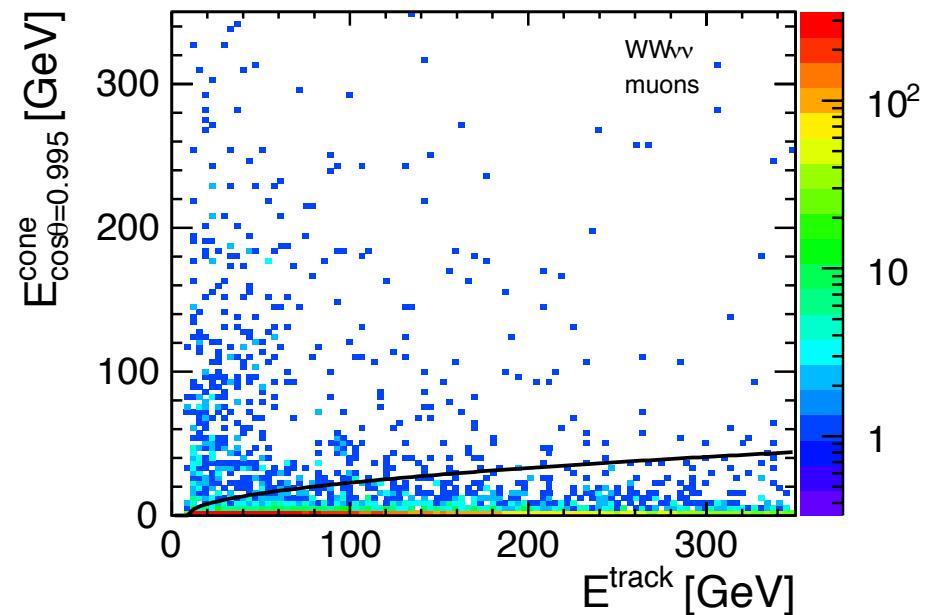
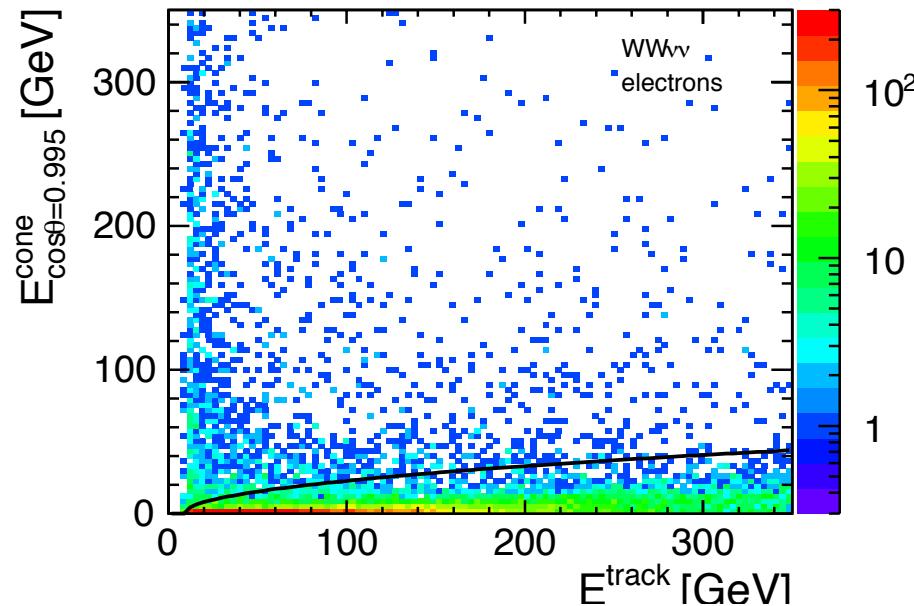


Lep ID – basic variables

- $d_0 < 0.03$, $z_0 < 0.04$, $R_0 < 0.06$
- $0.05 < R_{\text{cal}} < 0.25 \quad \text{||} \quad R_{\text{cal}} > 0.9$



Lep ID – polynomial isolation



In these plots cuts on variable on previous slide are already applied

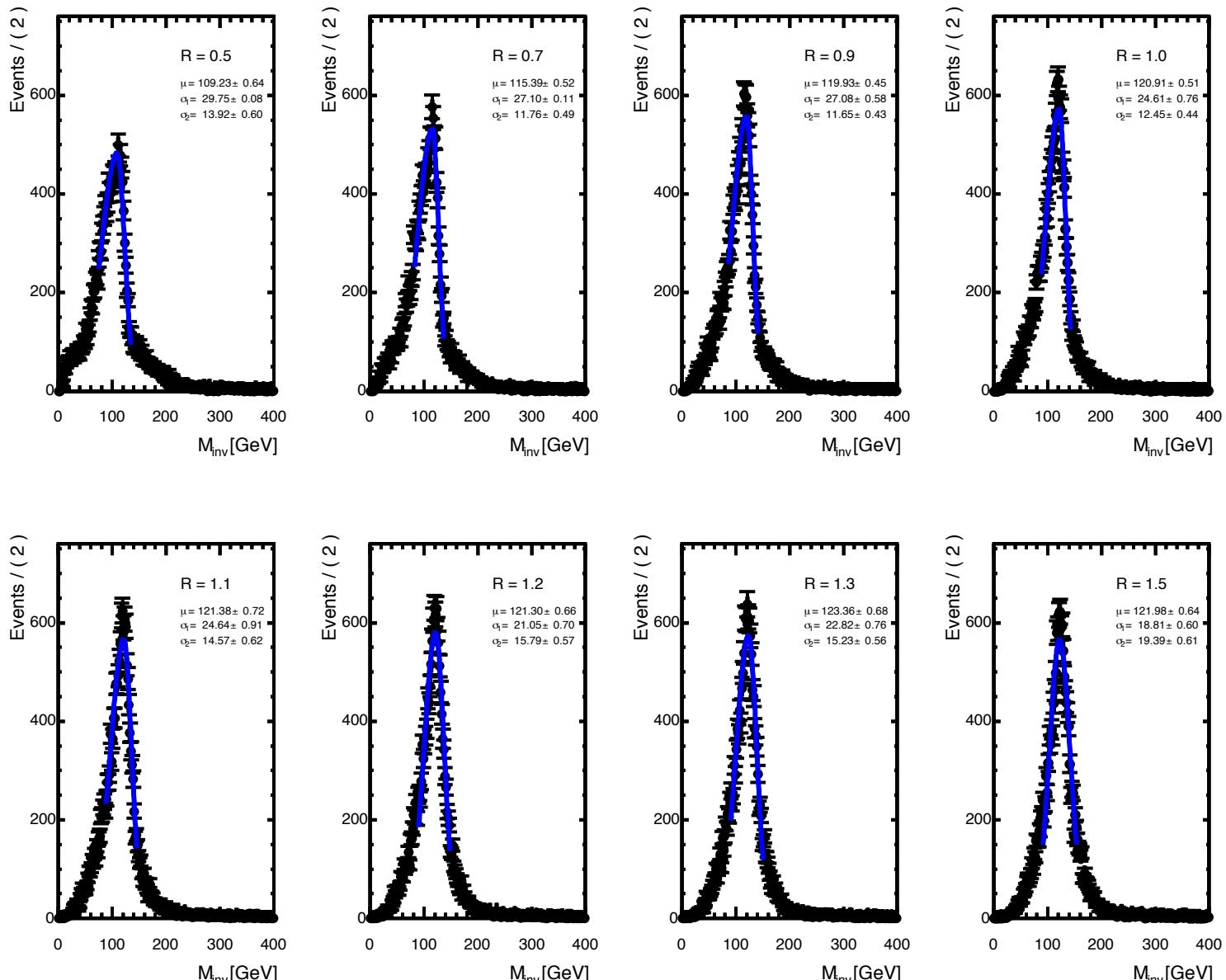
$$A=0.0, B=5.7, C=-50.$$

$$E_{\text{cone}}^2 \leq A * E_{\text{track}}^2 + B * E_{\text{track}} + C$$

energies are in GeV

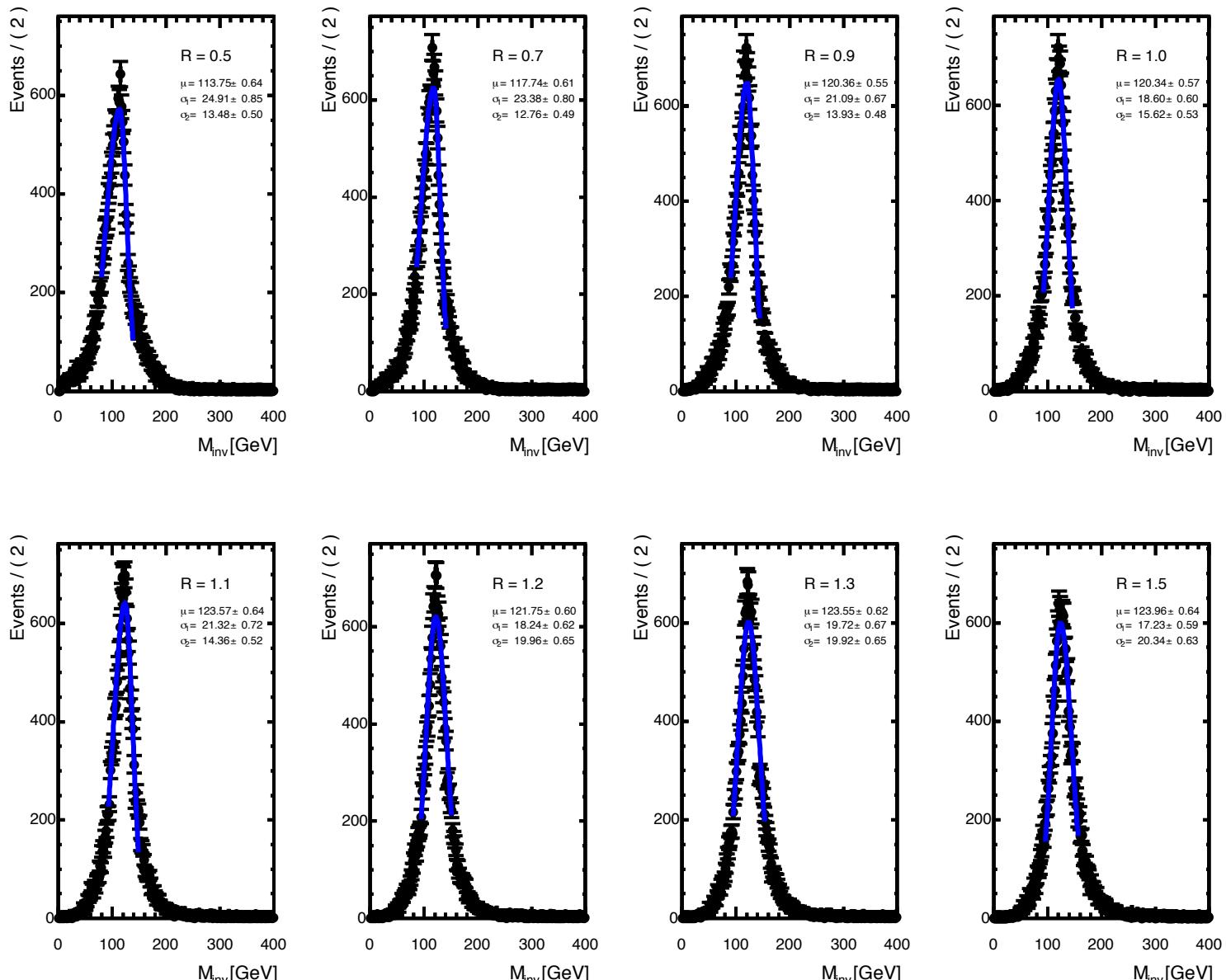
vlc – 4 jets

Asymmetric gaussian fit:
1 common mean, 2 sigmas

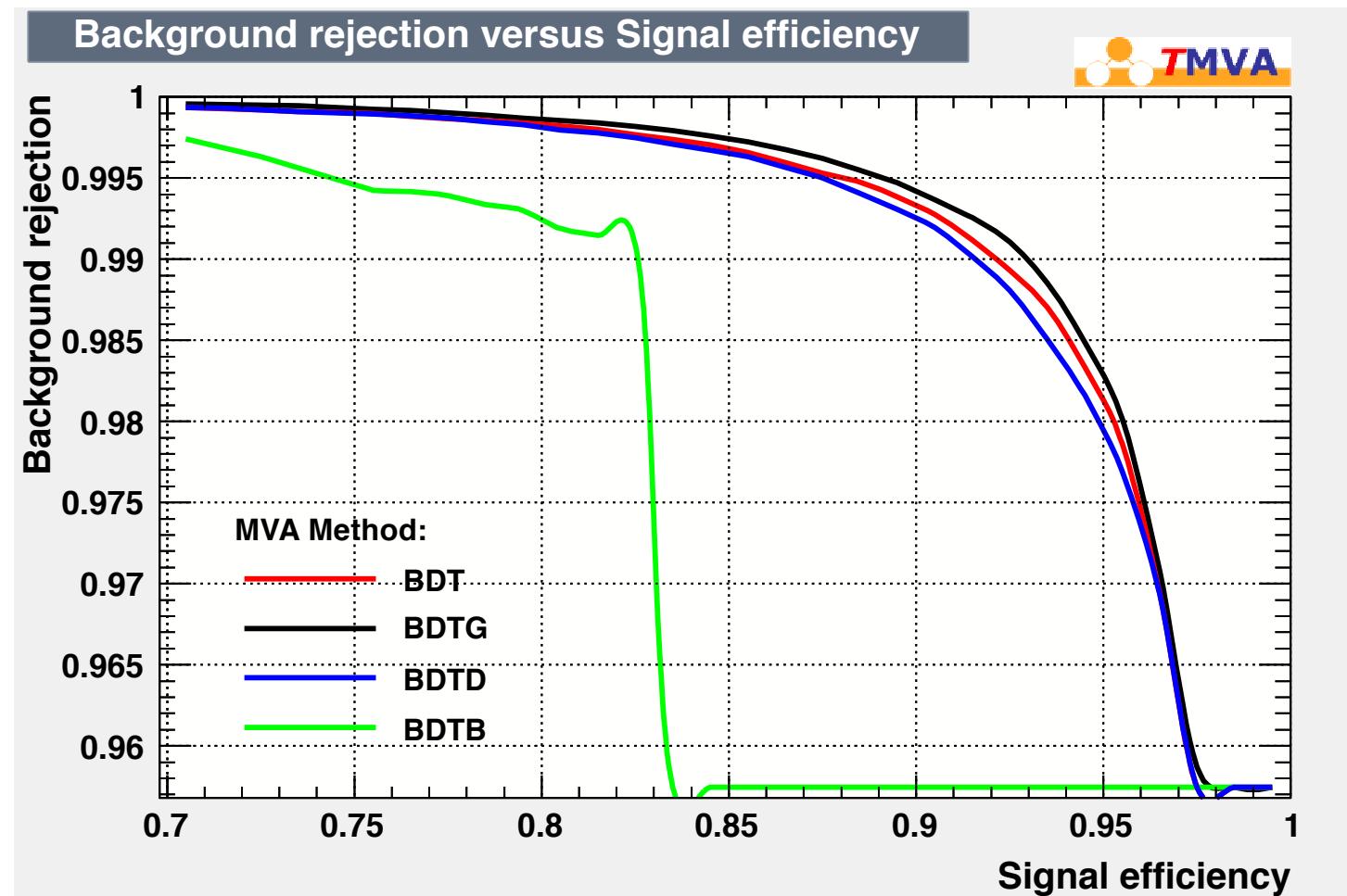


vlc – 5 jets

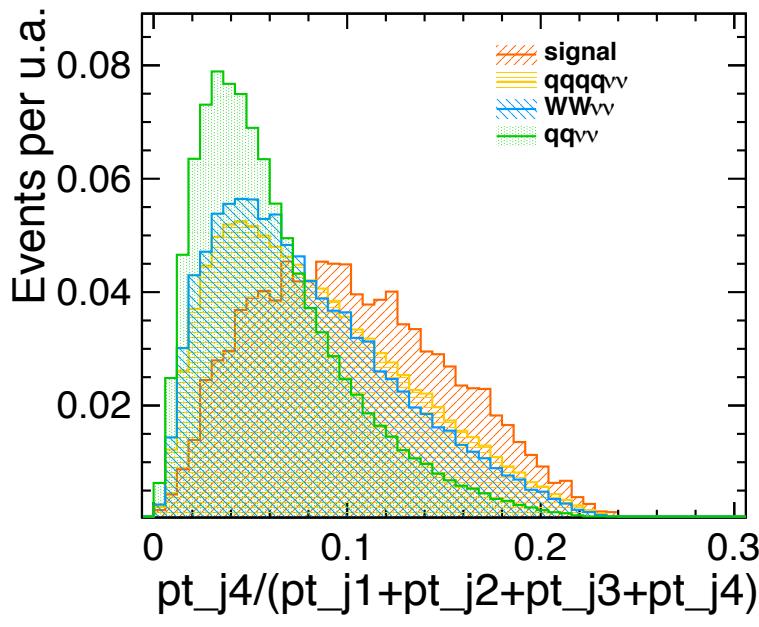
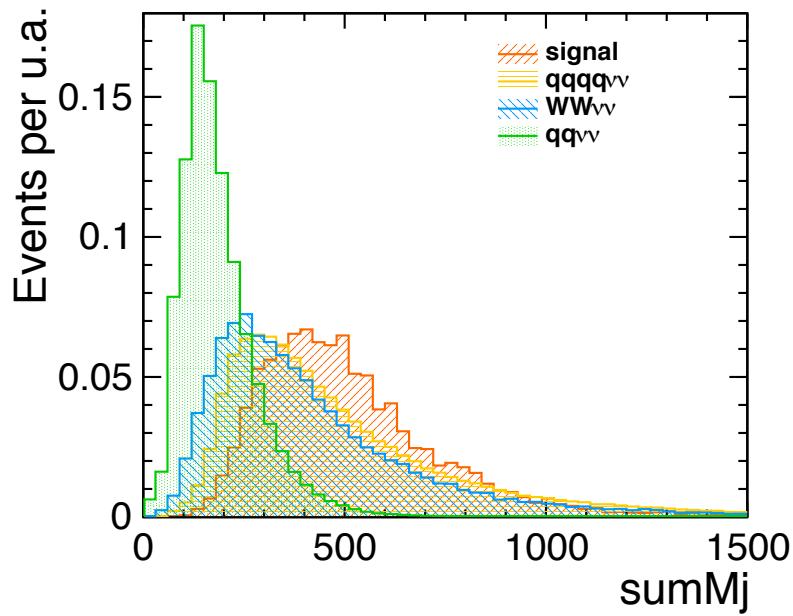
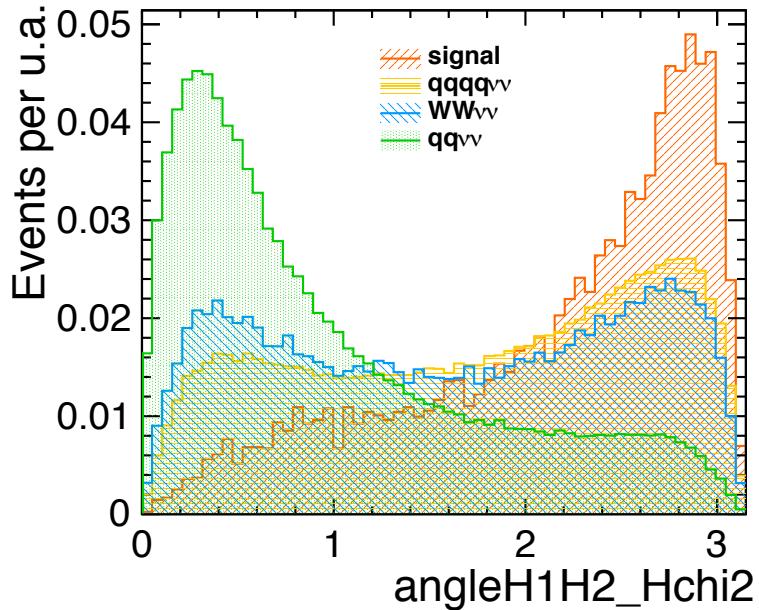
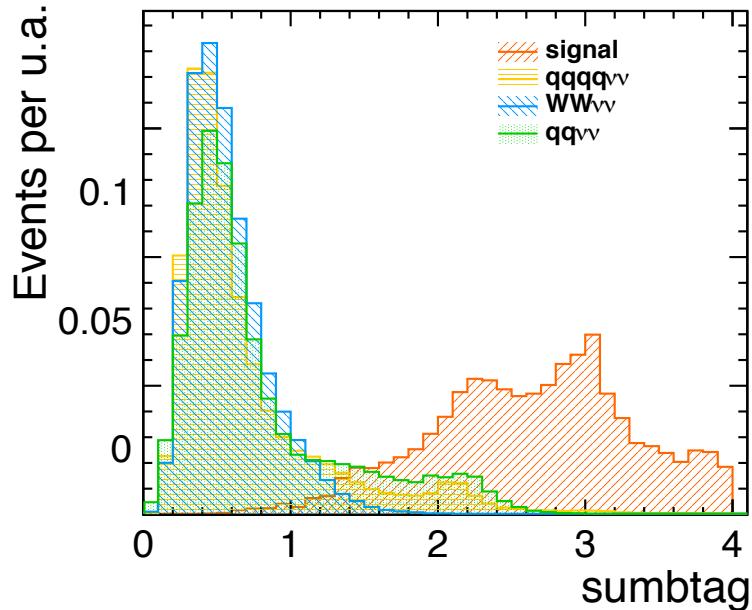
*Asymmetric gaussian fit:
1 common mean, 2 sigmas*



ROC curves



- Choose to work with BDTG



TMVA overtraining check for classifier: BDTG

