Observation of the strongly interacting Higgs sector in the CMS detector

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- problems in the Standard Model for $m_H \geq 700$ GeV

  1. coupling $V_L V_L V_L V_L \sim m_H^2 \Longrightarrow V_L$'s interact strongly (perturbation theory?)
  2. unitarity is broken in $V_L V_L \to V_L V_L$ scattering ($VV \to VV$ scattering dominated by $V_L V_L \to V_L V_L$)
  3. new physics must enter to cure these problems

- **if there is no Higgs boson then what?**

  An alternative is effective theory of strongly coupled Higgs sector (strongly interacting scalar sector breaks EW symmetry)

  As a result V_L's can interact strongly.

  Submodels:

  - models with scalar resonances = SM with heavy Higgs boson and unitarized amplitudes
  - models with vector resonances or without resonances in VV scattering

Higgs mechanism

- Higgs sector lagrangian:

$$\mathcal{L}_{Higgs} = \lambda v h(2w^+w^- + z^2 + h^2) - \frac{1}{4}\lambda(2w^+w^- + z^2 + h^2)^2$$

dla $v^2 = \mu^2/\lambda, 1/v^2 = G_F\sqrt{2}$, $\lambda = \frac{G_F m_h^2}{\sqrt{2}}$, GB: $w^{\pm}$, z

- SSB $\Rightarrow$ GB's appear
- GET: V_L's interact like GB's

Strongly interacting boson sector

- SSB of $SU(2)_L xSU(2)_R \rightarrow SU(2)_C$ triggers $SU(2)_L xU(1)_Y \rightarrow U(1)_Q$ in SM $\Rightarrow$ GB's
- GET: V_L's interact like GB's

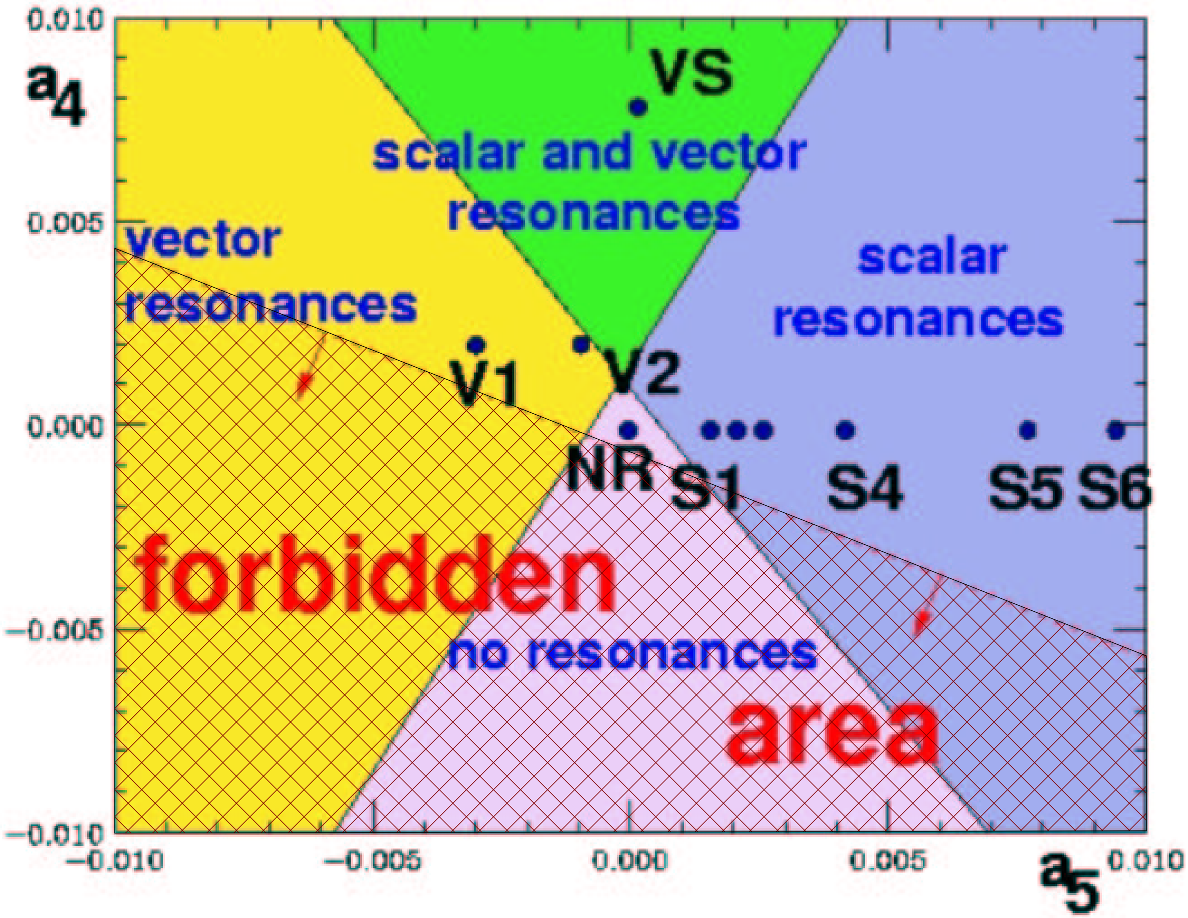
Electro-Weak Chiral Lagrangian (EWChL)

- strong interaction between scalars (GB's) described by effective theory (analogy to interactions of π's)
  $\mathcal{L} = \frac{v^2}{4} < D_\mu U D^\mu U^\dagger > + a_4 (< D_\mu U D^\nu U^\dagger >)^2 + a_5 (< D_\mu U D^\mu U^\dagger >)^2 + \ldots$
  $U = exp(i\frac{\bar{\pi}\bar{\tau}}{v})$, $\bar{\pi}$ – 3 would-be GB, $\bar{\tau}$ – Pauli matrices
- 2 parameters: a_4, a_5 up to order p^4
- various models accesible through a_i parameters choice

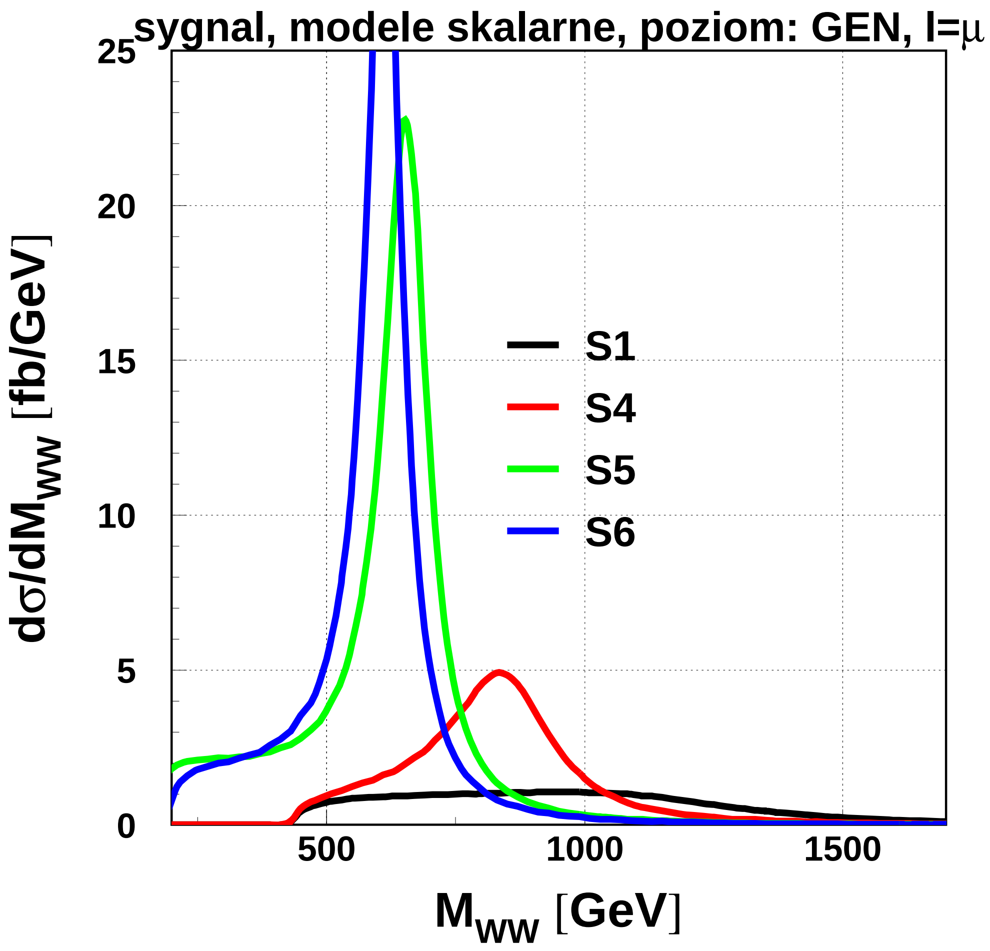
Models obtained from EWChL

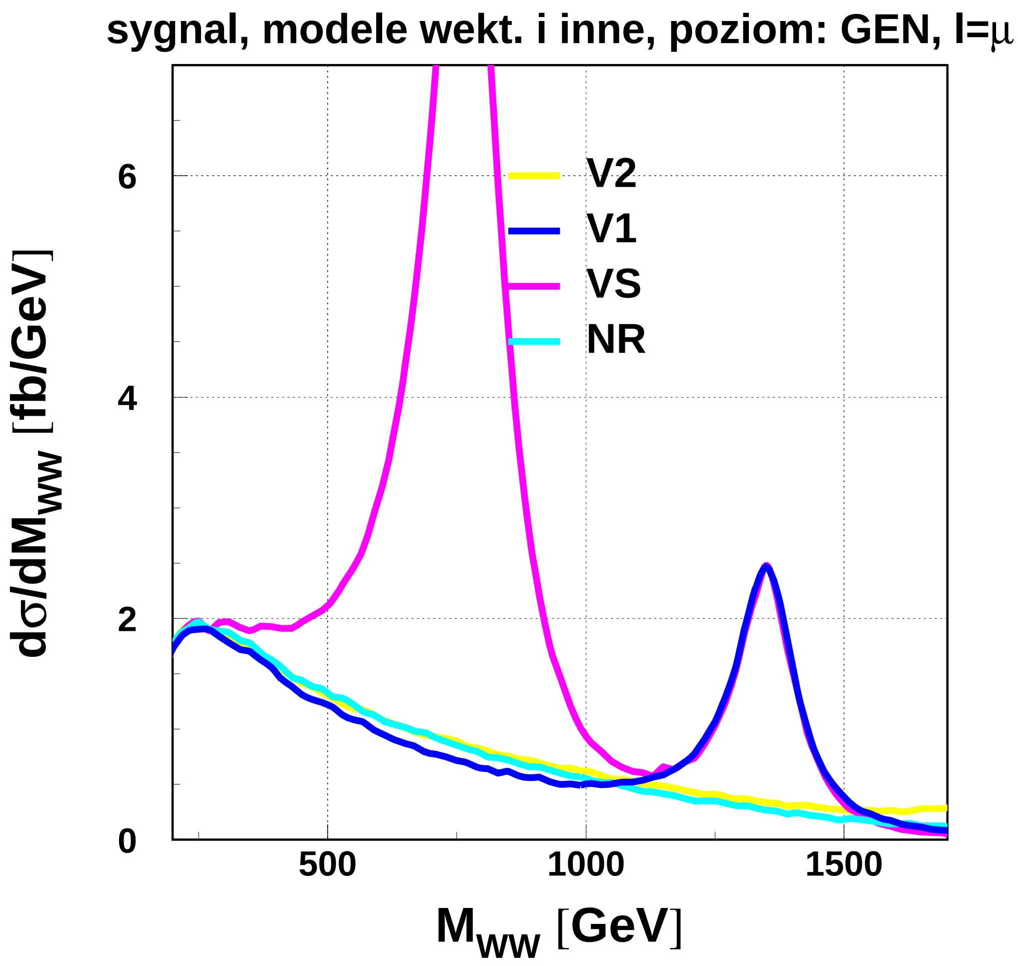
- nonresonant - application limited to $\sqrt{s}$ <1.5 GeV
- resonant (resonances appear after unitarization of partial waves - analogy with $\pi\pi$ scattering):
  - scalar (e.g. SM with higgs)
  - vector
  - scalar+vector
- untarization, e.g.:

$$t_J = t_J^{(2)} + t_J^{(4)} + ... \rightarrow t_J = \frac{t_J^{(2)2}}{t_J^{(s)} - t_J^{(4}}$$



$\frac{d\sigma}{dM_{WW}}$ for $V_LV_L \rightarrow W_LW_L$ in EWChL with unitarization



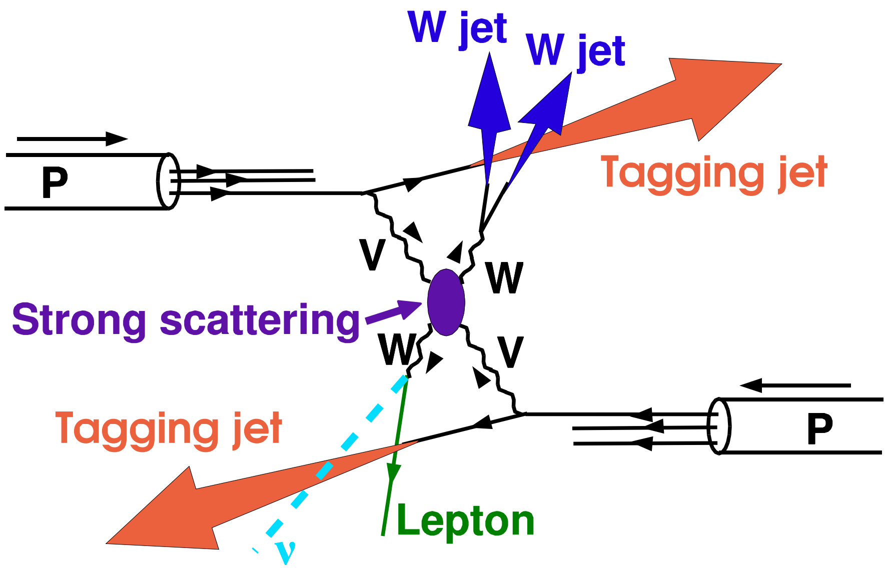


Work objectives

1. preparation of selection procedure
2. determination of CMS detector discovery reach
3. preparation of identification procedure of a particularly realized model of strong scattering:
   - SM with heavy Higgs boson
   - numerous models with/without resonances

Experimental signature of strong VV scattering

strong $V_LV_LV_LV_L$ coupling $\Longrightarrow$ enhanced production of WW final states in VBF (WW/ZZ→WW)



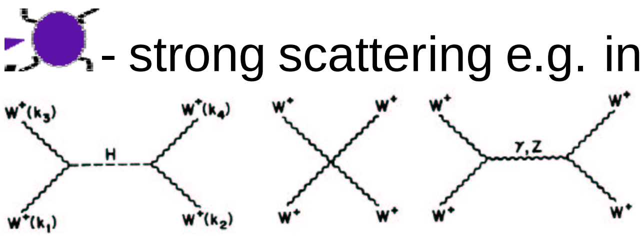
channels of interest:

$$W_LW_L \, / \, Z_LZ_L \rightarrow W^{\pm}_LW^{\pm}_L \rightarrow qql\nu$$

characteristics:

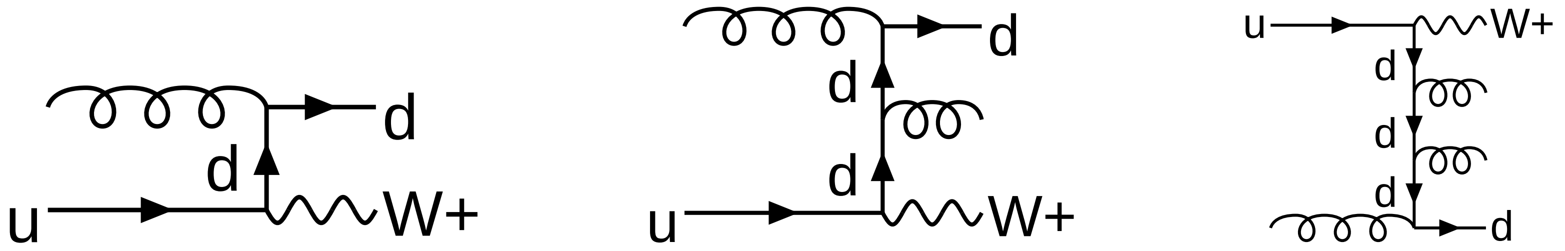
- hard, central and isolated lepton
- hard escaping ν (large MET)
- 2 (1) very hard and central W jets
- 2 very forward tagging jets

- strong scattering e.g. in the SM for $W^{\pm}W^{\pm}$:



Background channels

1. 1 real W + jets: Wj, Wjj, Wjjj (j=u, ū, d, $\bar{d}$, g)



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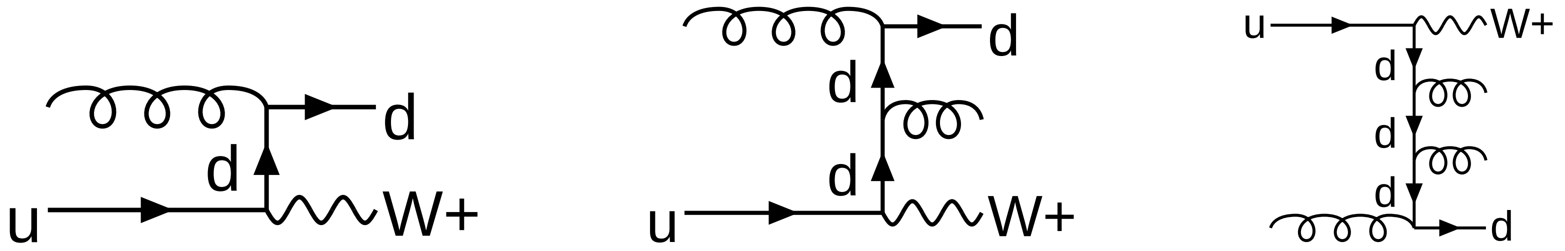
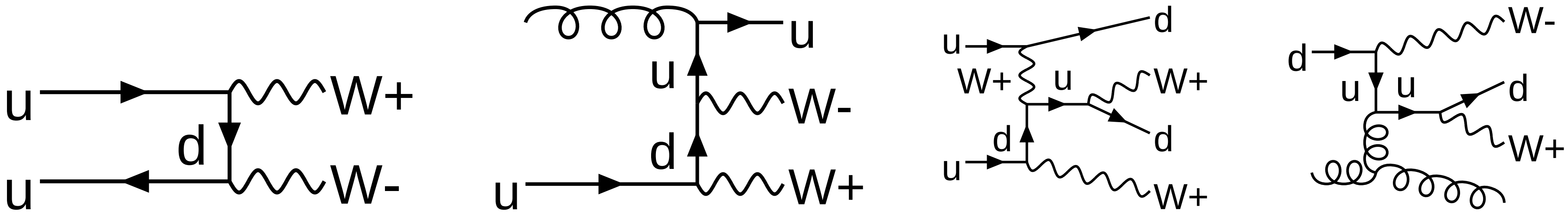


2. 2 real W's + jets: WW, WWj, EW⊕QCD WWjj (j=u, ū, d, $\bar{d}$, g)



Background channels

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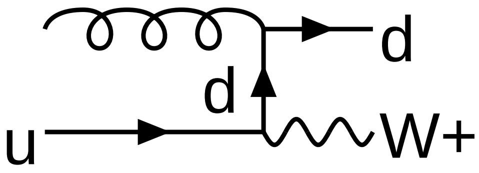

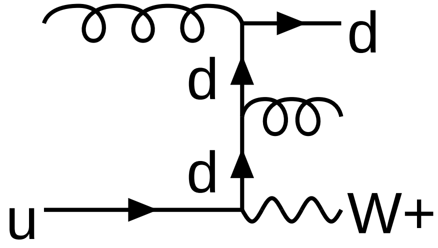

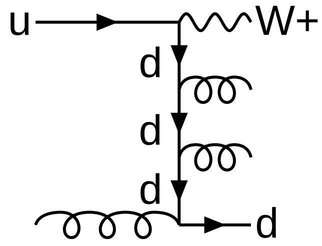

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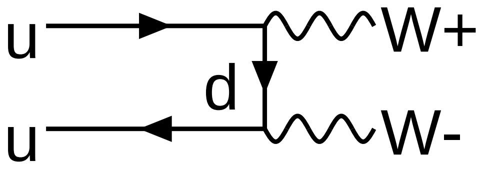
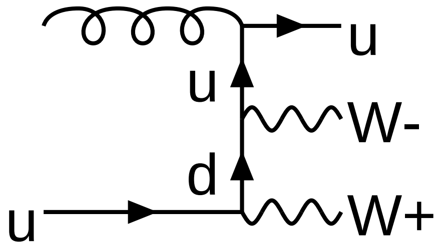
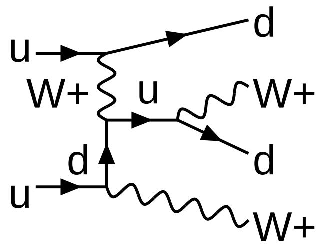
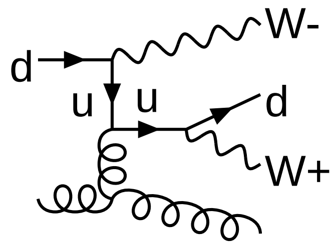


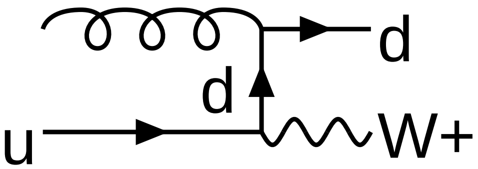


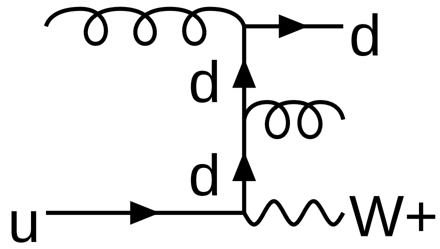


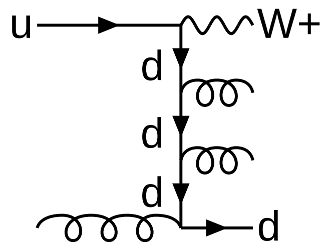


3. VV→W_TW_T, VV→W_LW_T scattering of the order of V_LV_L scattering in SM for $m_H \sim$100 GeV (already included in WWjj)

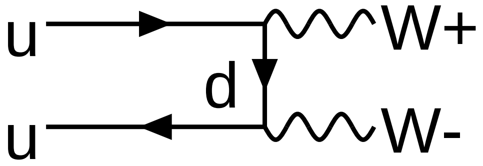
1. 1 real W + jets: Wj, Wjj, Wjjj (j=u, $\bar{u}$, d, $\bar{d}$, g)

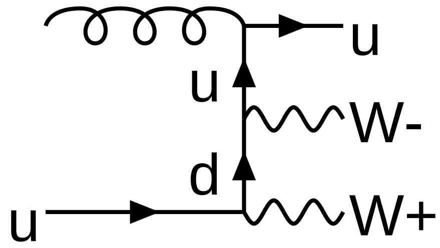


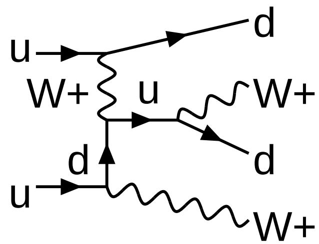


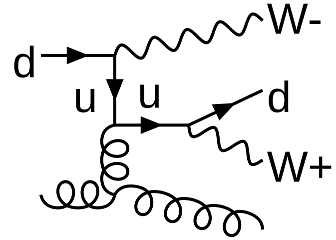


2. 2 real W's + jets: WW, WWj, EW⊕QCD WWjj (j=u, $\bar{u}$, d, $\bar{d}$, g)



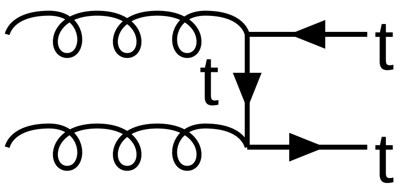


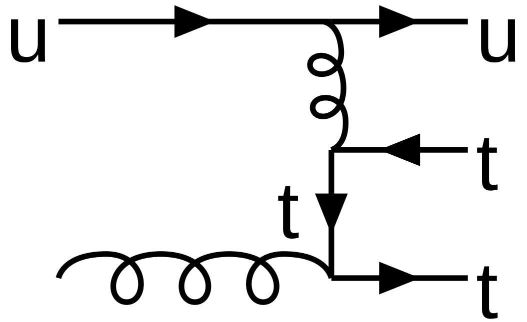


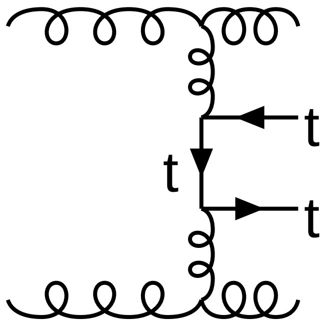


3. VV→W_TW_T, VV→W_LW_T scattering of the order of V_LV_L scattering in SM for m_H~100 GeV (already included in WWjj)

4. $t\bar{t}$+ jets: $t\bar{t}$, $t\bar{t}$j, $t\bar{t}$jj (j=u, $\bar{u}$, d, $\bar{d}$, g)







Generators used

$2 \to 2$ processes

PYTHIA 6.2

- signal $V_L V_L \to V_L V_L$ scattering
- backgrounds: Wj, $t\bar{t}$

$2 \to 3$, $2 \to 4$ processes

COMPHEP 4.2p1

LO matrix element calculation for a given process

- EW$\bigoplus$QCD $pp \to WWjj$
- complicated backgrounds: W+multijets, $t\bar{t}$+multijets

Signal generation

- approximated - currently being used

  approximations:
  1. effective W approx.$\Rightarrow V_L$ pt spectrum
  2. equivalence theorem: V_L's scatters $\sim$ like Goldstone bosons
  3. final V's are on the mass shell

  - $V_L V_L \rightarrow W_L W_L$ in PYTHIA:
    - heavy SM Higgs boson
    - QCD-like models
    - Electro-Weak Chiral Lagrangian (EWChL) - effective theory for strongly interacting bosons (provided by Butterworth, et al. PRev D65, 096014)

- more exact calculation of LO matrix elements in COMPHEP - planned approach
  -  in SM for heavy Higgs boson
  -  in SM for heavy Higgs boson / in EWChL $\oplus$ EW diagrams
  -  $\oplus$ qqqlν diagrams (PHASE)

X-sections, preselection & selection

Cross-sections were calculated in LO in PYTHIA and COMPHEP

process	very loose $\hat{p}_\perp \sim 2$ GeV cuts σ [pb]				
SIGNAL S4	-				
$W^{\pm}j$	38000				
$W^{-}jj$	?				
$W^{\pm}jjj$	11000($W^{+}jjj$)				
$W^{+}W^{-}j$	170				
$W^{+}W^{-}jj$[b]	...				
$t\bar{t}$	630				
$t\bar{t}j$	4400				
$t\bar{t}jj$	14709				

[a] generation is very CPU consuming and enough estatistics has not been generated yet

[b] generated in COMPHEP for m_H=115 GeV for all contributing diagrams (QCD$\bigoplus$EW) excluding virtual γ, s, c, b, t; with virtual light higgs to have well-behaved calculation for large W-pair inv. masses

X-sections, preselection & selection

Cross-sections were calculated in LO in PYTHIA and COMPHEP

process	very loose $\hat{p}_\perp \sim 2$ GeV cuts σ [pb]	after gener. presel. σ [pb]			
SIGNAL S4	-	0.016			
$W^{\pm}j$	38000	22000			
$W^{-}jj$	?	63			
$W^{\pm}jjj$	11000($W^{+}jjj$)	54			
$W^{+}W^{-}j$	170	5.6			
$W^{+}W^{-}jj$[b]	...	3.8			
$t\bar{t}$	630	-			
$t\bar{t}j$	4400	502			
$t\bar{t}jj$	14709	2010			

[a] generation is very CPU consuming and enough estatistics has not been generated yet

[b] generated in COMPHEP for m_H=115 GeV for all contributing diagrams (QCD$\bigoplus$EW) excluding virtual γ, s, c, b, t; with virtual light higgs to have well-behaved calculation for large W-pair inv. masses

- preselection steps:
  1. during generation in PYTHIA&COMPHEP objects: partons and W's cuts on pT & η

X-sections, preselection & selection

Cross-sections were calculated in LO in PYTHIA and COMPHEP

process	very loose $\hat{p}_\perp \sim 2$ GeV cuts σ [pb]	after gener. presel. σ [pb]	after CMKIN presel.*BR σ [fb]		
SIGNAL S4	-	0.016	4.2		
$W^\pm j$	38000	22000	360		
$W^- jj$	?	63	12		
$W^\pm jjj$	11000($W^+ jjj$)	54	42		
$W^+W^- j$	170	5.6	1.7		
$W^+W^- jj^b$	...	3.8	0.02 ± 0.02		
$t\bar{t}$	630	-	133		
$t\bar{t}j$	4400	502	753		
$t\bar{t}jj$	14709	2010	930		

[a] generation is very CPU consuming and enough estatistics has not been generated yet

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- preselection steps:
  1. during generation in PYTHIA&COMPHEP
     objects: partons and W's
     cuts on pT & η
  2. before accepting CMKIN
     objects:leptons & clusters
     cuts on pT & η

Cross-sections were calculated in LO in PYTHIA and COMPHEP

process	very loose $\hat{p}_\perp \sim 2$ GeV cuts σ [pb]	after gener. presel. σ [pb]	after CMKIN presel.*BR σ [fb]	after OFFLINE selection with fast det. simul. (CMSJET) l = e, μ σ [fb]	
SIGNAL S4	-	0.016	4.2	0.8	
$W^\pm j$	38000	22000	360	0.3	
$W^- jj$	?	63	12	0.001	
$W^\pm jjj$	11000($W^+ jjj$)	54	42	<2.2[a]	
$W^+W^- j$	170	5.6	1.7	0.009	
$W^+W^- jj$[b]	...	3.8	0.02 ± 0.02	~ 0	
$t\bar{t}$	630	-	133	0.1	
$t\bar{t}j$	4400	502	753	0.6	
$t\bar{t}jj$	14709	2010	930	<3x2.[a]	

[a] generation is very CPU consuming and enough estatistics has not been generated yet

[b] generated in COMPHEP for m_H=115 GeV for all contributing diagrams (QCD$\bigoplus$EW) excluding virtual γ, s, c, b, t; with virtual light higgs to have well-behaved calculation for large W-pair inv. masses

- preselection steps:
  1. during generation in PYTHIA&COMPHEP objects: partons and W's cuts on pT & η
  2. before accepting CMKIN objects:leptons & clusters cuts on pT & η
- OFFLINE selection:
  - constructed and optimized with fast simul. CMSJET
  - translated and being optimized with full simul. ORCA

Cross-sections were calculated in LO in PYTHIA and COMPHEP

process	very loose $\hat{p}_\perp \sim 2$ GeV cuts σ [pb]	after gener. presel. σ [pb]	after CMKIN presel.*BR σ [fb]	after OFFLINE selection with fast det. simul. (CMSJET) l = e, μ σ [fb]	#/100 fb^{-1}
SIGNAL S4	-	0.016	4.2	0.8	78.2 ± 2.3
$W^\pm j$	38000	22000	360	0.3	28.6 ± 6.1
$W^- jj$	?	63	12	0.001	0.11 ± 0.04
$W^\pm jjj$	11000($W^+ jjj$)	54	42	<2.2[a]	<3x74.[a]
$W^+ W^- j$	170	5.6	1.7	0.009	0.9 ± 0.3
$W^+ W^- jj$[b]	...	3.8	0.02 ± 0.02	~ 0	~ 0
$t\bar{t}$	630	-	133	0.1	10 ± 4
$t\bar{t}j$	4400	502	753	0.6	57 ± 9
$t\bar{t}jj$	14709	2010	930	<3x2.[a]	<3x205[a]

[a] generation is very CPU consuming and enough estatistics has not been generated yet

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- preselection steps:
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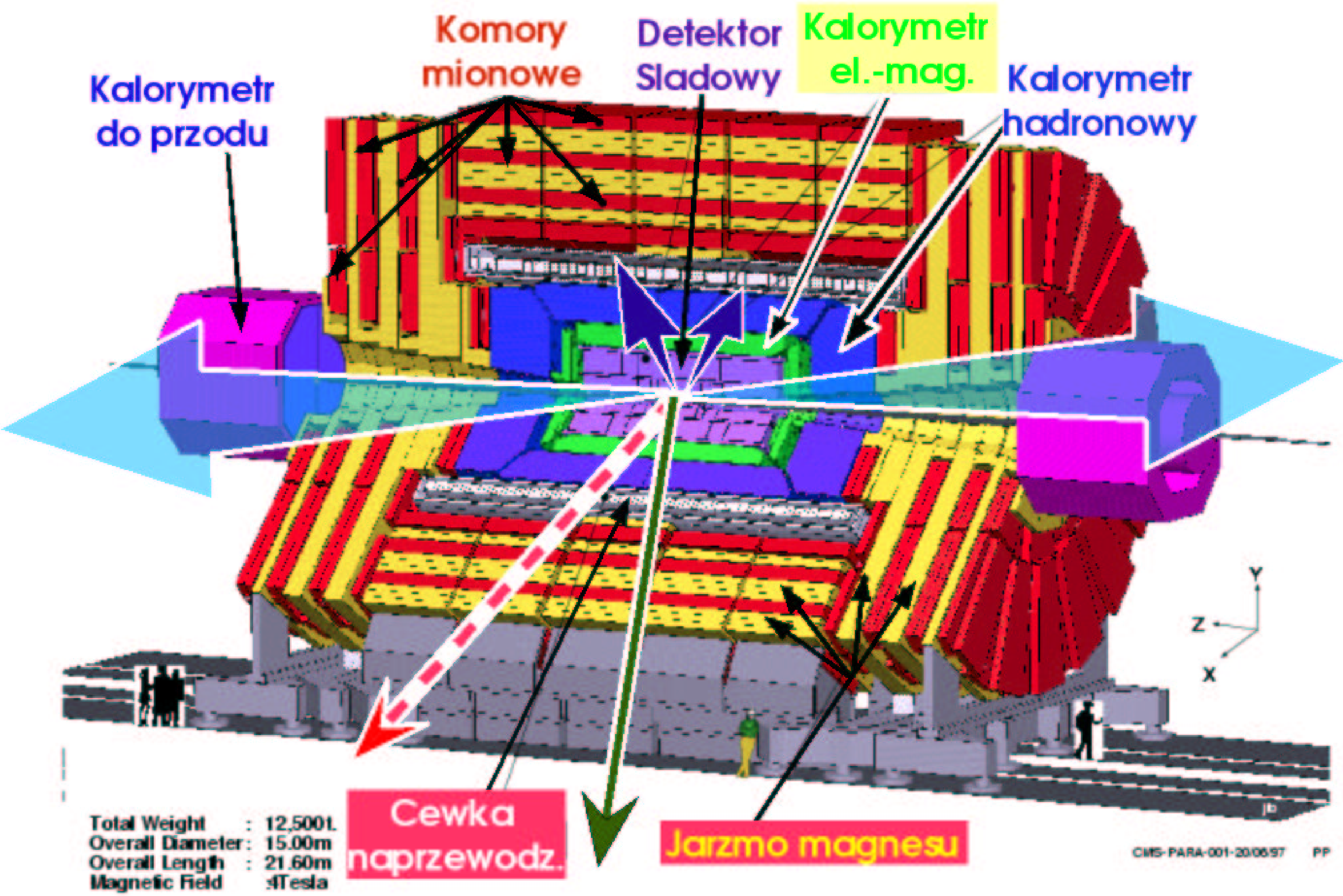


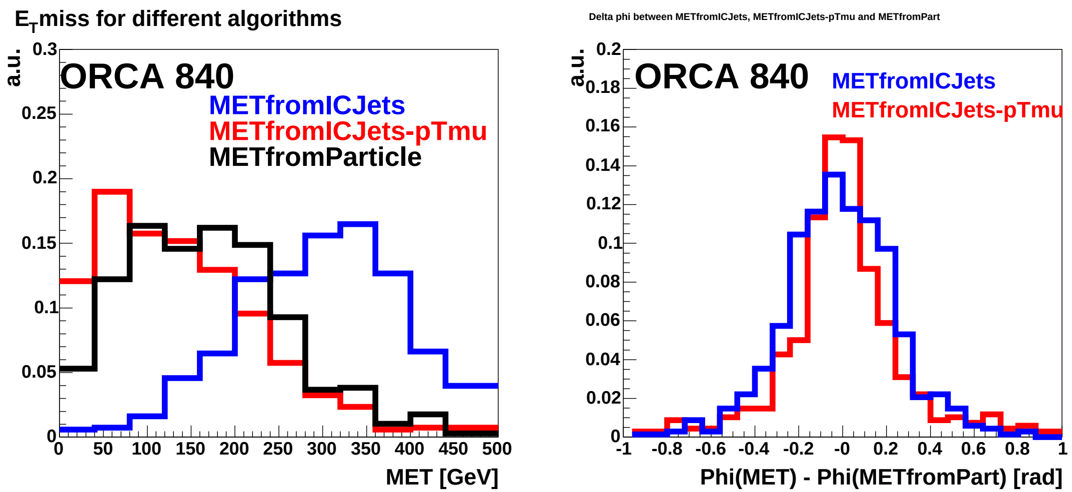
Komory
mionowe
Detektor
Sladowy
Kalorymetr
el.-mag.
Kalorymetr
hadronowy
Kalorymetr
do przodu
Cewka
naprzewodz.
Jarzmo magnesu
Total Weight : 12,500t
Overall Diameter : 15.00m
Overall Length : 21.60m
Magnetic Field : 4Tesla
Y
Z
X

- leptons are isolated in calorimeters and in the tracker (W$\rightarrow$lν)
- p_T^{ν} of ν reconstructed from Missing Transverse Energy (MET).
  Overall transverse momentum is conserved and = $\vec{0}$ $\Rightarrow$

$$\overrightarrow{p_T^{\nu}} = \overrightarrow{MET} = -\sum_{CALO\ towers} (E_i sin\theta_i)\hat{n}^{a}$$

- muons do not interact in calorimeters $\Rightarrow$ MET needs to be corrected:

$$\overrightarrow{MET}_{corr} = \overrightarrow{MET} - p_T^{lept}$$



[a] $\hat{n}$ is transverse unit vector pointing to CALO tower

- leptonic W reconstruction (W_{lept}=l+ν):
  M(l+ν)=M_W $\Rightarrow$ we have p_z^ν if quadratic equation is solved
- very hard W$\rightarrow$q$\bar{q}$ can be reconstructed from a single jet
  (candidate close to M_W is chosen)
  69% of hadronic W's are reconstructed from 1 jet (full simulation)
- tagging very forward jets are detected by forward calorimeters
- transverse momentum is conserved & $W^{lept}W^{hadr}j^{tag}j^{tag}$ is full final state $\Rightarrow$

$$p_T^{WWjj} \approx 0$$

Summary of OFFLINE selection cuts

1. $N_{iso\ lept} = 1$, lept=μ, e
   (efekt. id. = 100%)

2. $N_{jet} \geq 3$

3. $p_T^{lept} > 90$ GeV

4. E_T^{miss}(improved)>50 GeV
   - candidate for ν

5. $W_{lept} = \mu + \nu$: ν reconstructed from E_T^{miss} and $M(W_{lept}) = M_W$

6. W_{lept}: $p_T^{Wlept} > 200$ GeV

7. W_{hadr}: candidate (1 or 2 jets of $|\eta|<2.$) closest to M_W,
   70 GeV<$M(W_{hadr})$<100 GeV
   correction of jets is needed!

8. $p_T^{Whadr} > 150$ GeV

9. W's separated from each other:
   $|\eta_{Wlept} - \eta_{Whadr}| > 0.5$

10. top veto: vetoed events with $M(W_{hadr}+j)$ or $M(W_{lept}+j)$ in (140 GeV, 200 GeV);
    j-any of jets (for W_{lept} also W-jets)

11. 2 tagging jets: a jet very forward and a jet very backward of $2.0<|\eta|<4.5$, E>500 GeV, $p_T > 40$ GeV
    one tagging jet is not enough

12. $p_T^{WWjj} < 50$ GeV

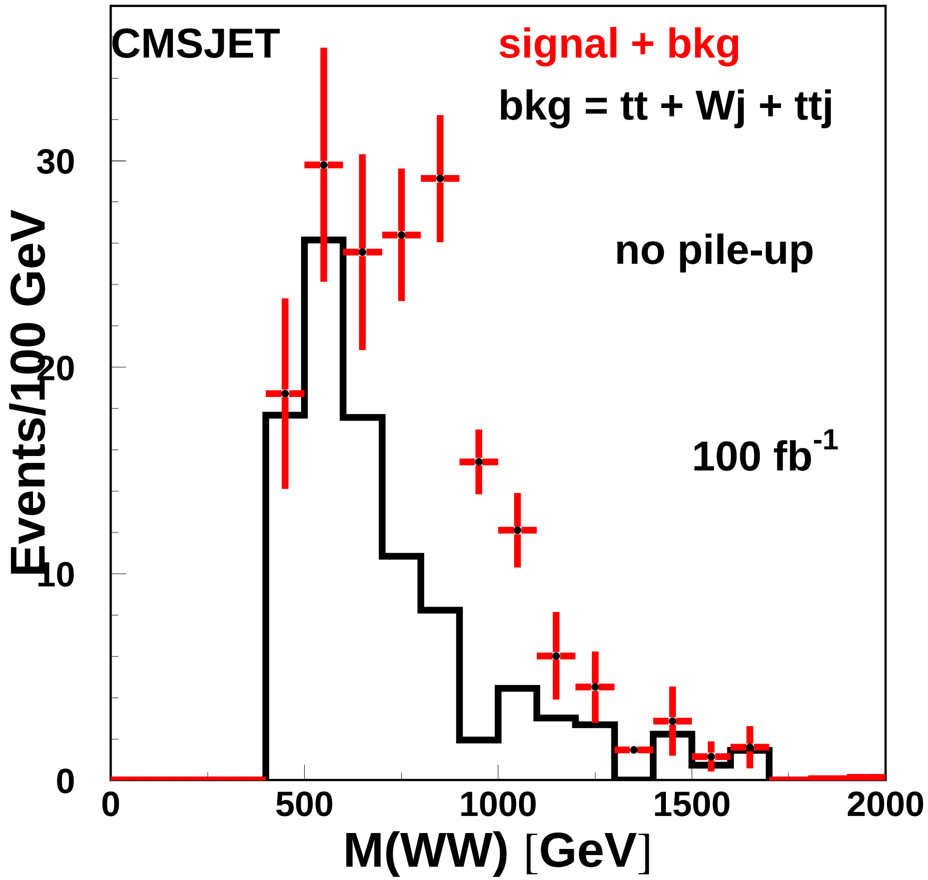
Details on backup slides

selection cut	CMSJET with preselection			
	S4	$t\bar{t}200$	Wj100	$t\bar{t}j$
before presel (μ+e)	16.4 fb	11.3 pb	374 pb	502 pb
preselection	25.6%	0.6%	5.9E-4	1.5E-3
$N_{iso\ lept}$ = 1 & lept.==μ & $N_{jet} \geq 3$	11.1%	2.0E-3	1.9E-4	4.1E-4
p_T(lept) & E_T^{miss} & ν_μ rec. & p_T^{Wlept}	8.1%	7.0E-4	1.0E-5	1.1E-4
$M(W_{hadr})$, p_{TWhadr}>150 GeV	6.6%	2.9E-4	8.2E-7	4.4E-5
top veto	5.3%	3.0E-5	2.8E-7	5.0E-6
tagging jets	2.4%	7.7E-6	2.9E-8	9.0E-7
p_T^{WWjj}<50 GeV	2.3%	3.4E-6	1.9E-8	7.2E-7
# / 100 fb^{-1}	38.2±1.6	3.8±1.3	0.7±0.5	36±7

S4: signal for a_4=0.0, a_5=0.0040

tt200: $t\bar{t}$ with 200< $\hat{p}_\perp$ <400 GeV

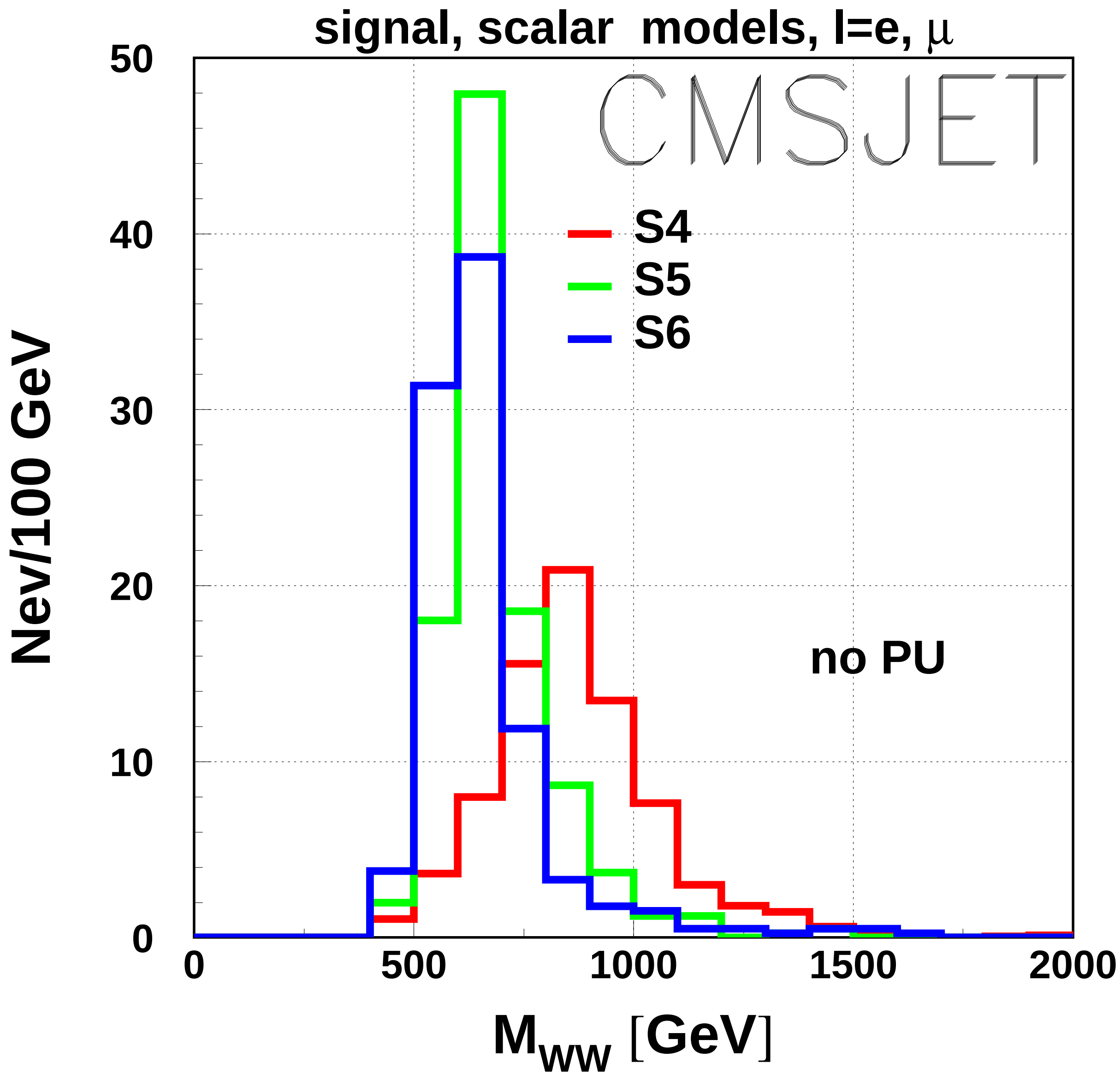
Wj100: Wj with 100< $\hat{p}_\perp$ <200 GeV model S4, a4=0.0, a5=0.0040, WW→qqlν, l=e, μ



fast simulation (CMSJET) for l = e, μ:

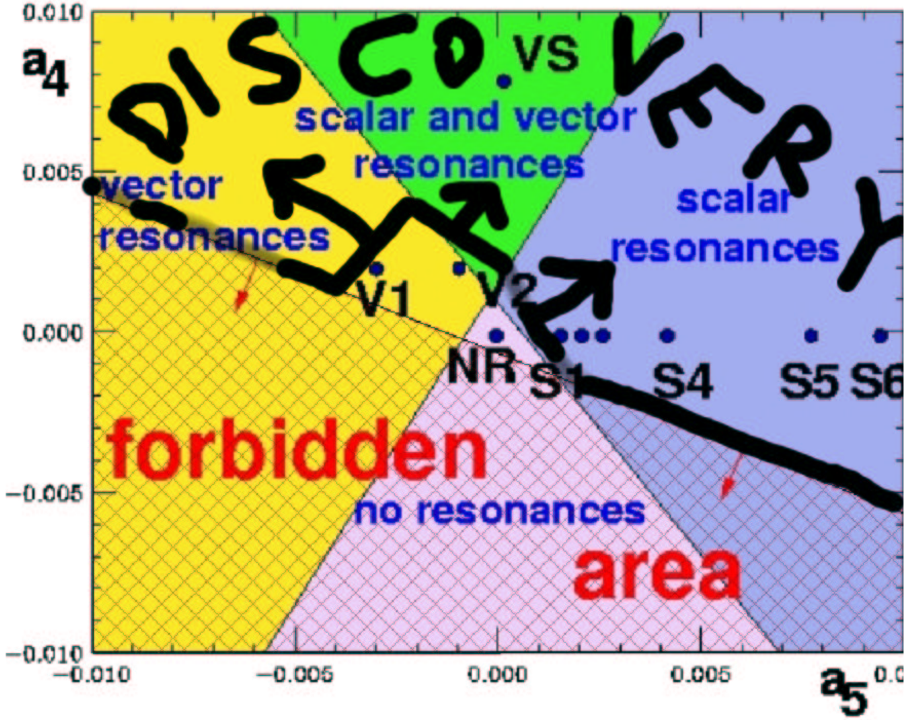
- signal S4: N_{S4} = 78±2
- Wj: N_{Wj} = 29±6
- $t\bar{t}$: N_{tt} = 10±4
- $t\bar{t}j$: $N_{t\bar{t}j}$ = 57±9

N(S4)	N(B)	S=N(S4)/$\sqrt{N(B)}$	disc. prop.
78±2	87±12	8.0±0.5	∼100%



signal, scalar models, l=e, μ
CMSJET
S4
S5
S6
no PU
Nev/100 GeV
M_{WW} [GeV]
0
10
20
30
40
50
0
500
1000
1500
2000

EWChL parameter space:



discovery: $S \geq 5$

$S=5 \Rightarrow$ discovery propability: 50%

model	m[GeV]	a_4	a_5	# / 100 fb^{-1}	$S=NS/\sqrt{NB}$
results with fast simulation (CMSJET)					
S1	1400	0.0	0.0015	52.3 ± 0.3	$5.3 \pm$
S2	1300	0.0	0.0020	61.4 ± 0.8	$6.3 \pm$
S3	1200	0.0	0.0025	68.4 ± 0.3	$7.0 \pm$
S4	900	0.0	0.0040	78 ± 2	8.0 ± 0.5
S5	820	0.0	0.0077	102 ± 5	10.4 ± 0.8
S6	770	0.0	0.0090	95 ± 5	9.7 ± 0.8
V1	1360	0.002	-0.003	44 ± 1	4.4 ± 0.3
V2	1900	0.002	-0.001	31 ± 4	3.2 ± 0.4
VS		0.008	0.0	113 ± 4	11.5 ± 1.4
NR	-	0.0	0.0	32.2 ± 0.3	$3.3 \pm$

Summary

- **there are indications that signal of strong VV scattering could be observed**
- **W+multijets and $t\bar{t}$+multijets are very important sources of background**

already done

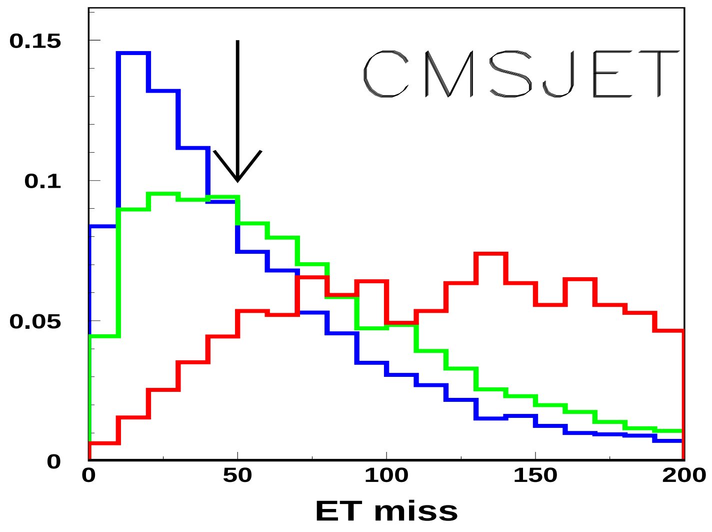
- selection with fast simulation (CMSJET)
- dedicated preselection constructed
- all sources of physics background considered
- expected discovery contours obtained

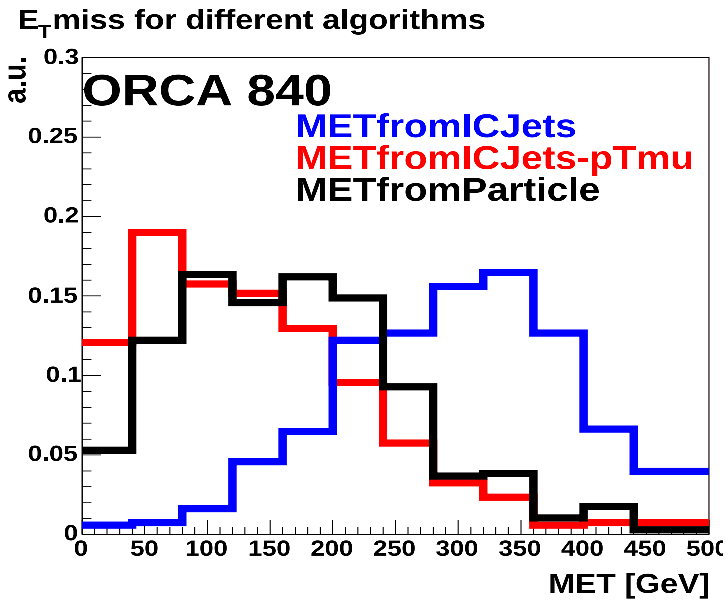
remains to be done

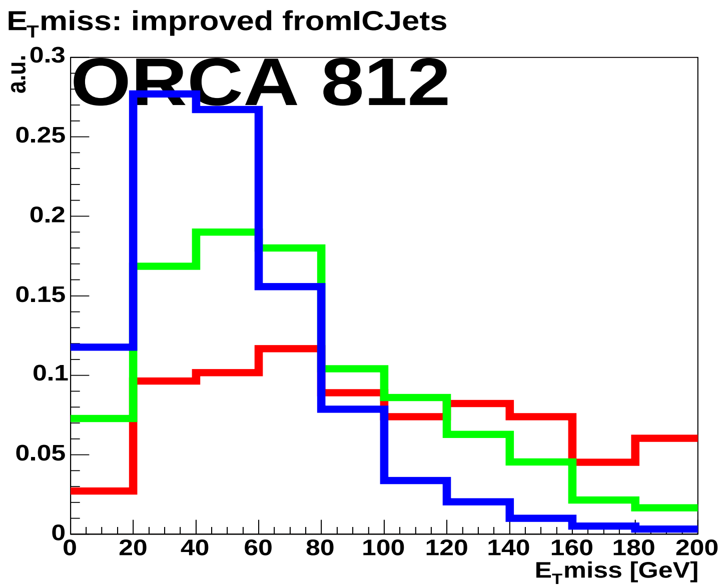
- significance of signal interference with other WWjj diagrams (COMPHEP) and qqqqlν diagrams (PHASE)
- optimization of analysis with full detector simulation and reconstruction
- study on systematic uncertainties: background x-sections, . . .

1. Definitions for preselection (generation level):
   - leptons: pT$>$70 GeV, $|\eta|$ $<$2.5
   - central clusters (CS): pT$>$30 GeV, $|\eta|$ $<$2, (PYCELL clusterisation in PYTHIA)
   - forward/backward clusters: pT>30 GeV, $|\eta|$ $>$1.8, ($|\eta|$+0.3*pT)$>$12.5
2. Preselection cuts (details on back-up slides):
   - number of leptons $N_{lept}\geq$1
   - number of forward clusters: $\geq$1, number of backward clusters: $\geq$1
   - hadronic activity in central region only from hadronic W:
     - $N_{CS}=$1: hard cluster (W jet)
     - $N_{CS}=$2: ($pT_{1.}$+$pT_{2.}$)$>$130 GeV and close to each other (W jets)
     - $N_{CS}\geq$3:
       - 1st and 2nd CS's - hard and close to each other
       - additional softer clusters (CS's 3rd, 4th, . . .) are:
         - either soft or close to 1st $\vee$ 2nd CS or not too central
       - number of separated clusters limited

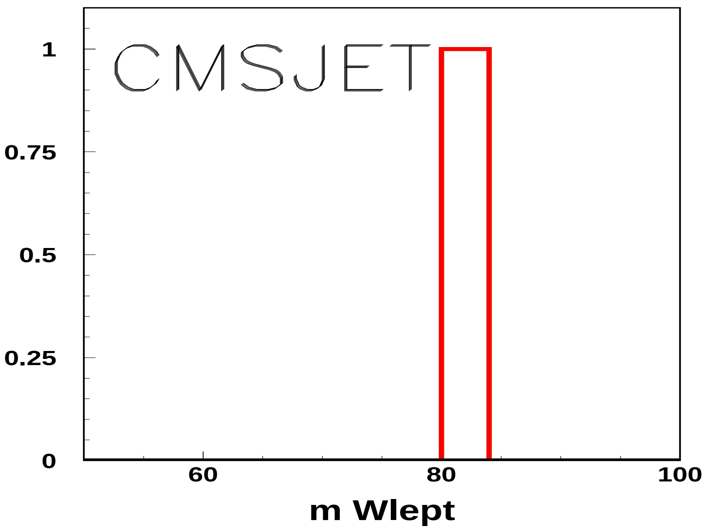
- $N_{iso\ lept}$ = 1, lept=μ, e (efekt. id. = 100%)
- $N_{jet} \geq 3$
- p_T^{lept}>90 GeV
- E_T^{miss}(improved)>50 GeV - candidate for ν

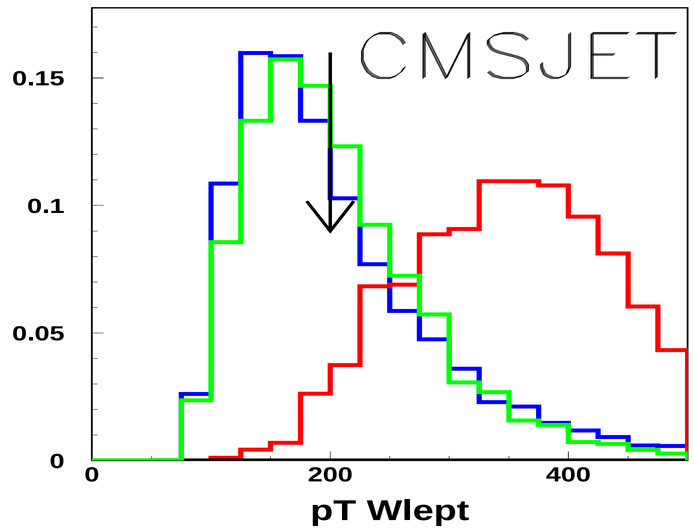


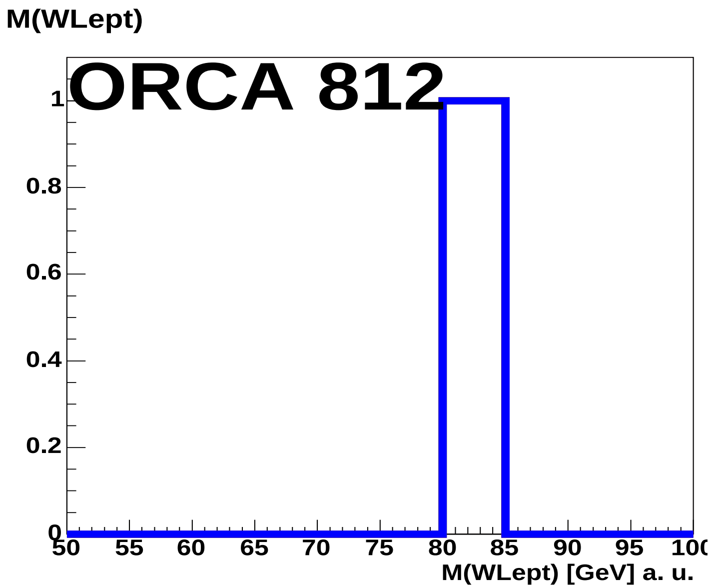


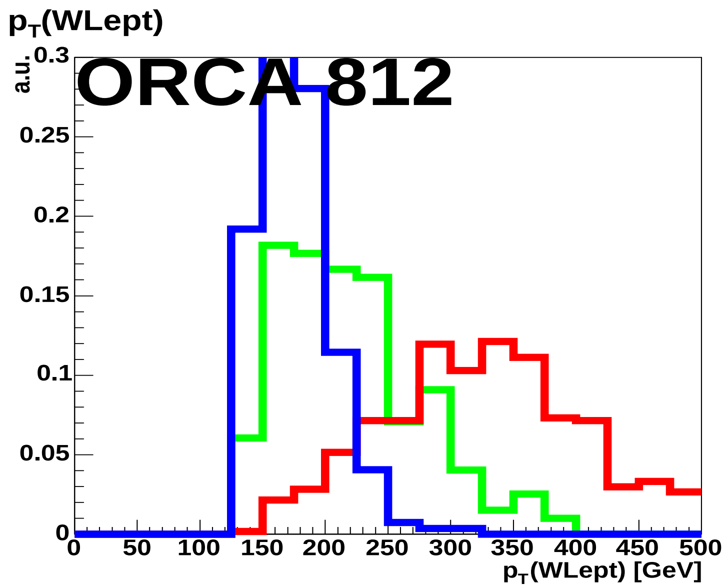


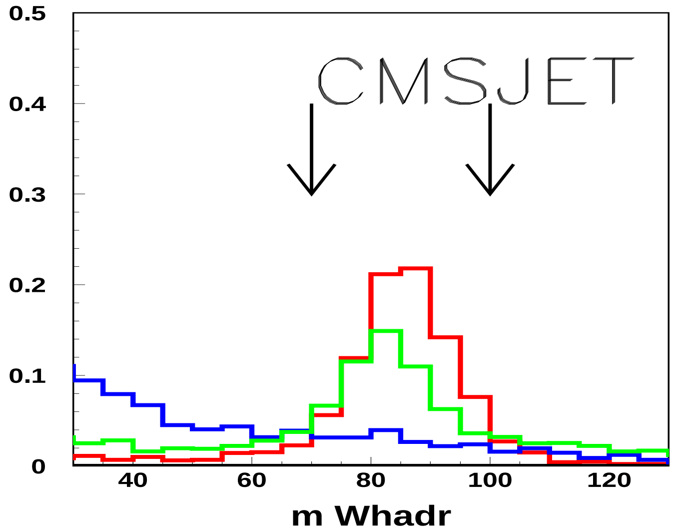
- $W_{lept}=\mu+\nu$: ν reconstructed from E_T^{miss} and $M(W_{lept})=M_W$
- W_{lept}: $p_T^{Wlept}>200$ GeV

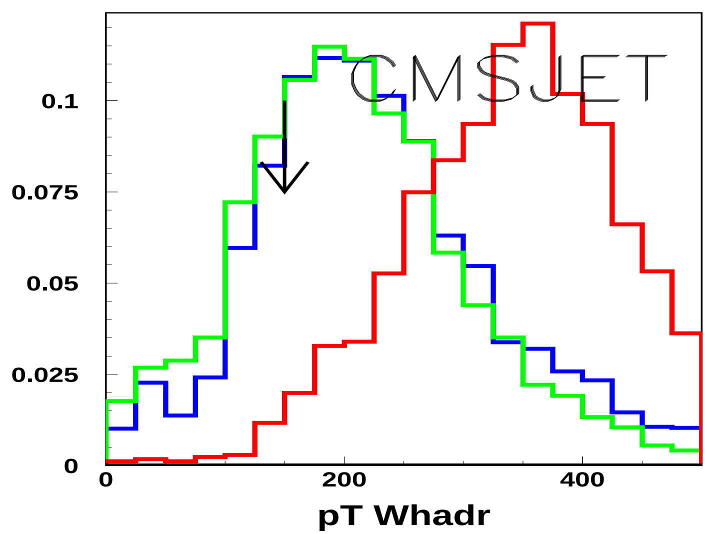




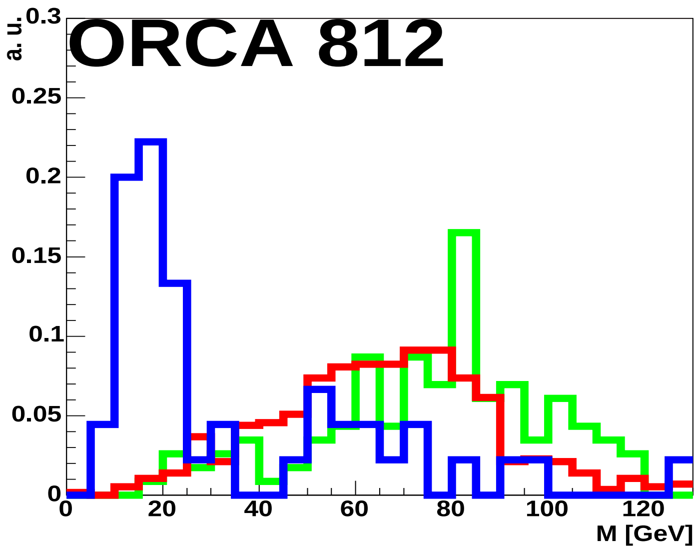




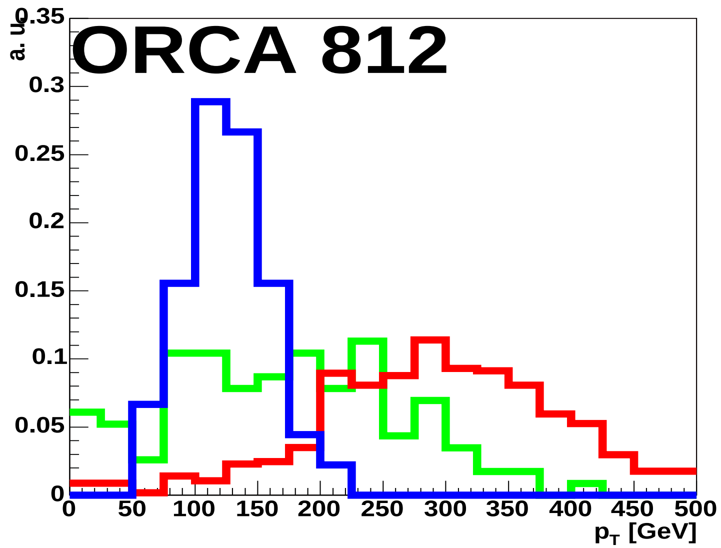




Mass of WHadr recostructed from 1 or 2 jets



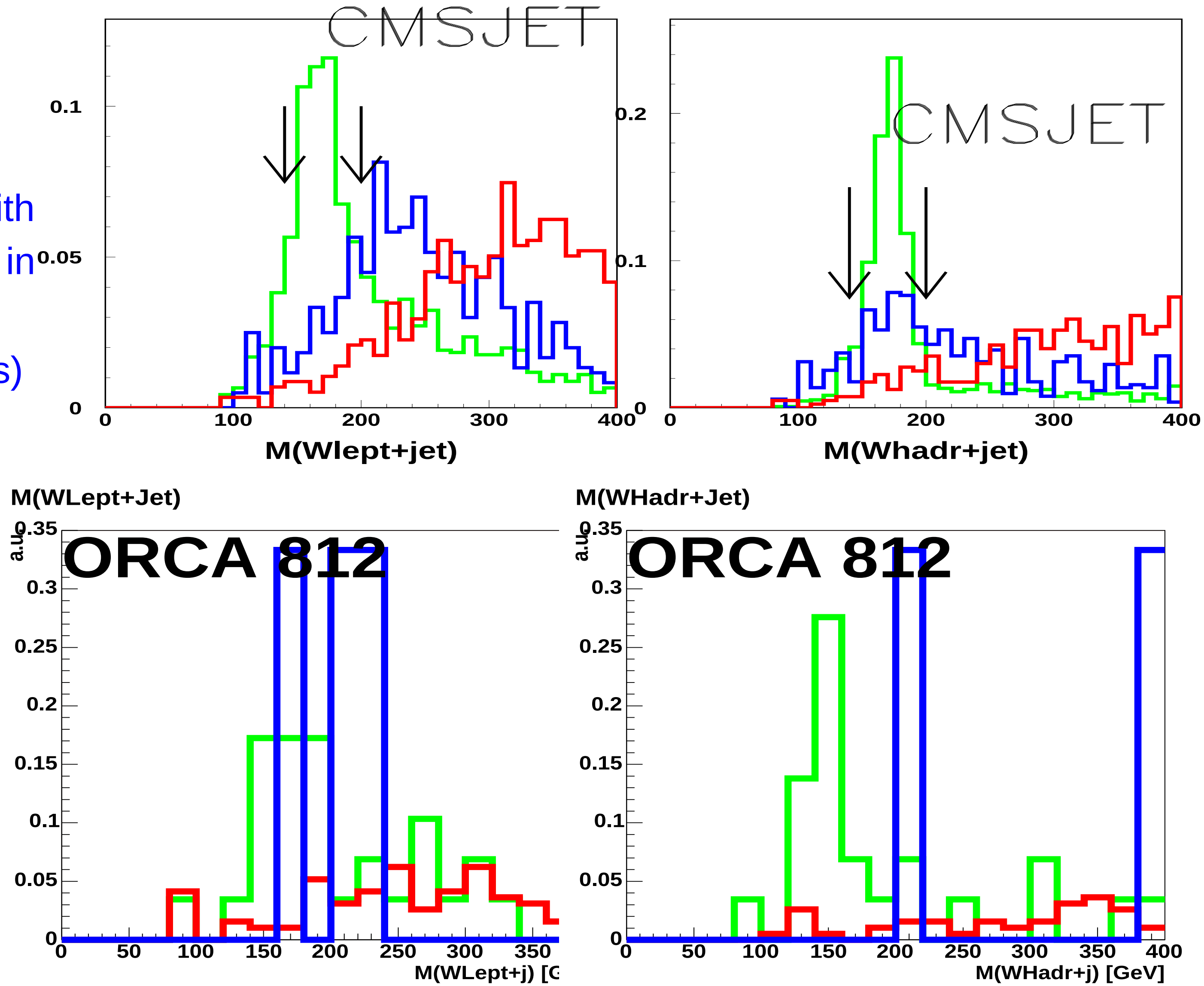
p_T of WHadr recostructed from 1 or 2 jets



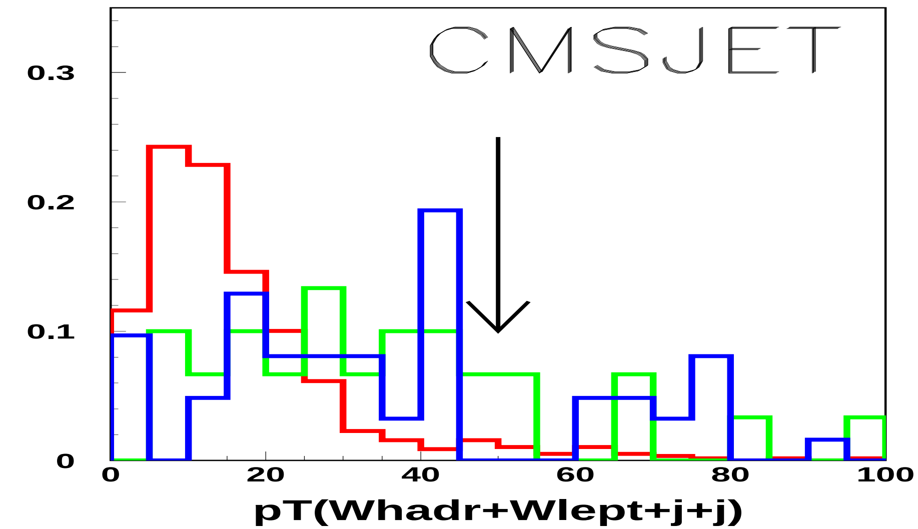
- W_{hadr}: candidate (1 or 2 jets $|\eta|$<2.) closest to M_W, 70 GeV<$M(W_{hadr})$<100 GeV
  correction of jets is needed!
- p_T^{Whadr}>150 GeV

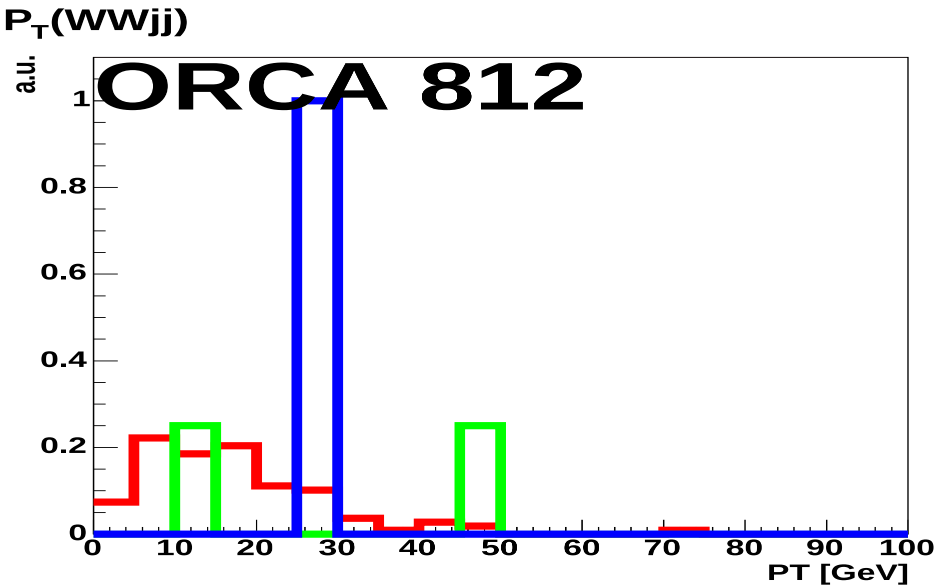
- top veto: vetoed events with $M(W_{hadr}+j)$ or $M(W_{lept}+j)$ in (140 GeV, 200 GeV);

  j-any of jets (for W_{lept} also W-jets)



- 2 tagging jets: a jet very forward and a jet very backward of 2.0<|η|<4.5, E>500 GeV, p_T>40 GeV
  one tagging jet is not enough





- p_T^{WWjj}<50 GeV