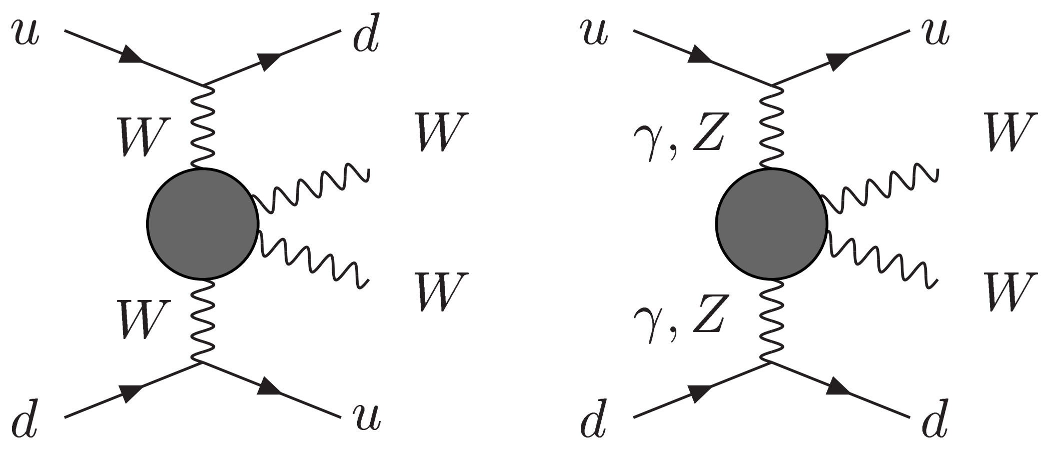
Boson Boson scattering in PHASE

E. Accomando, A. Ballestrero, E. Maina

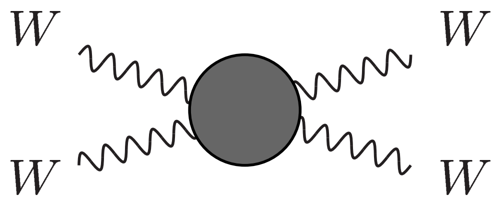
Univ. of Torino and I.N.F.N. Torino



MC4LHC: CERN, July 28, 2003

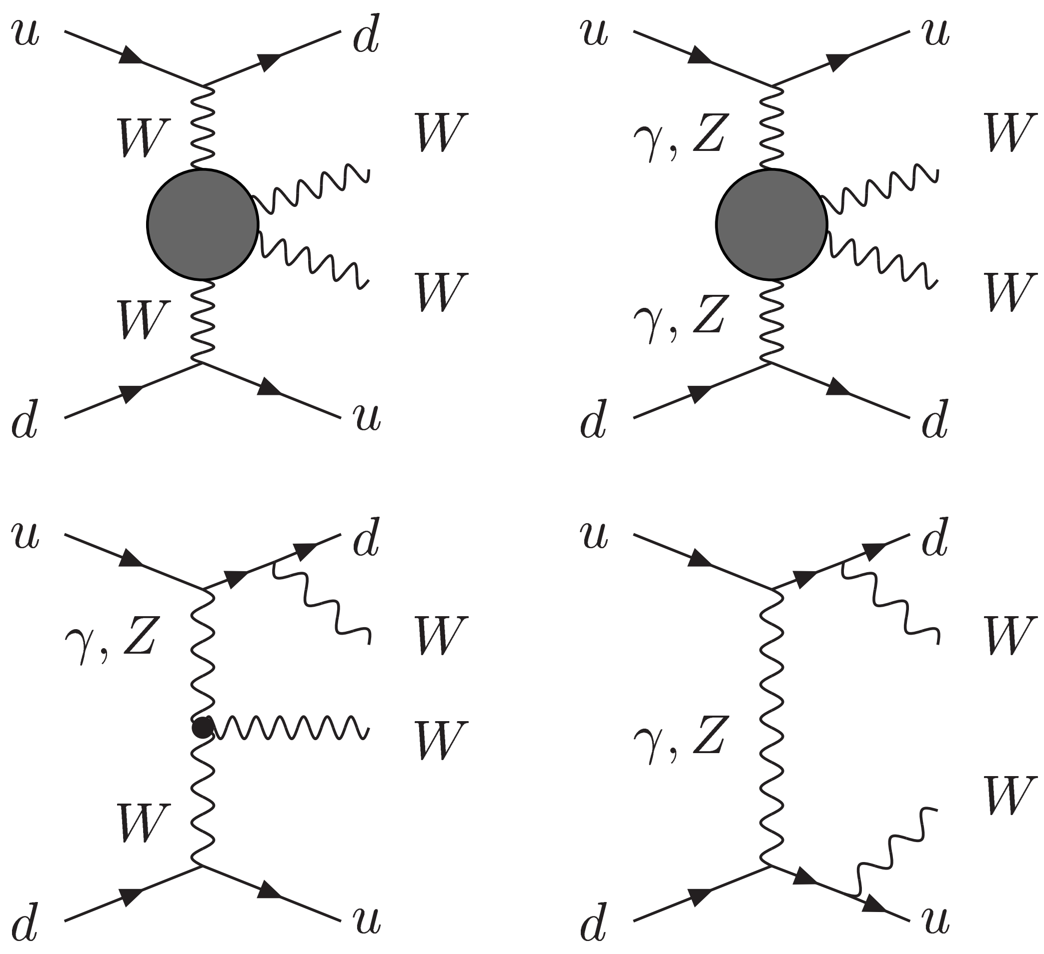
Electroweak symmetry breaking

- $M_W \approx M_h$: Higgs visible
- $M_W \ll M_h \ll \sqrt{s}$: Higgs mechanism works. Partial waves scattering amplitudes $\approx$ const $\propto M_h$. At large M_h the system is strongly interacting.
- $M_W \ll \sqrt{s} \ll M_h$: amplitudes grow with energy. At large s perturbation theory breaks down.



Measure VV scattering!

At the LHC



Signal

- Very energetic isolated leptons in central region
- 2 W, Z-jets + low extra jet activity in central region
- Two highly energetic, low P_T spectator jets, well separated in η

Backgrounds: mainly QCD

- $t\bar{t}$ production
- $W + j$ production
- $WW + j$ production

What if no Higgs: Unitarization

Electroweak Chiral Lagrangian: Expansion in derivatives of the Goldstone fields.

$$\mathcal{L} = \mathcal{L}^{(0)} + \mathcal{L}^{(2)} + \mathcal{L}^{(4)}$$

$$\mathcal{L}^{(0)} = \text{Massless SM}$$

$$\mathcal{L}^{(2)} = \frac{v^2}{4}\langle D_\mu U D^\mu U^\dagger \rangle \qquad \mathcal{L}^{(4)} = a_4(\langle D_\mu U D^\nu U^\dagger \rangle)^2 + a_5(\langle D_\mu U D^\mu U^\dagger \rangle)^2$$

$$U = \exp\left(i\frac{\omega^a \tau^a}{v} \right)$$

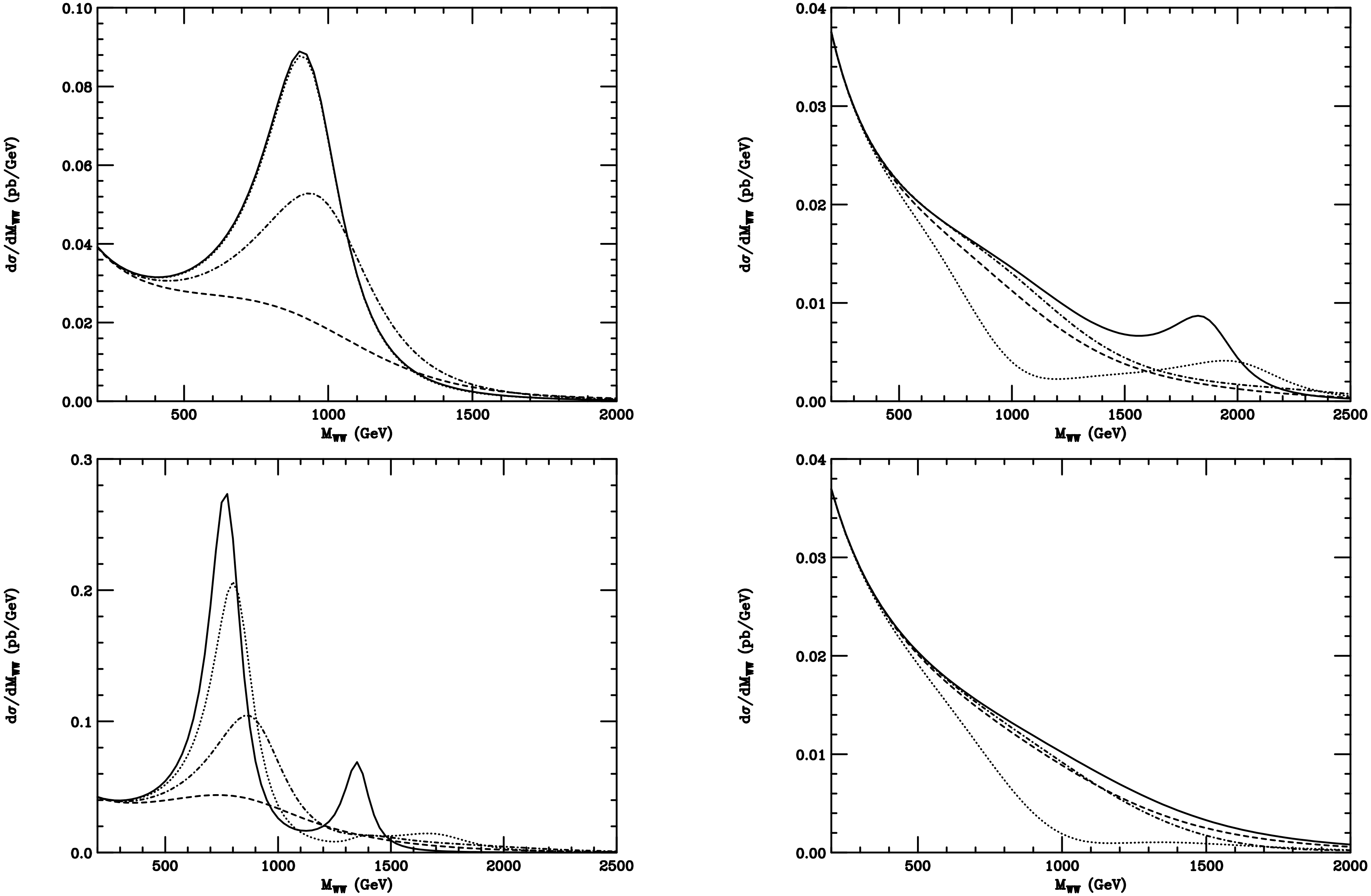
$$\omega^a (a = 1,2,3) = \text{GoldstoneB} \qquad \tau^a = \text{Pauli mat.} \qquad \langle \cdots \rangle = SU(2)\text{ trace}$$

In the SM $v = 246$ GeV, $a_5 = v^2/(8m_H^2)$, $a_4 = 0$.

The partial waves isospin amplitudes t_{IJ} for $W_L W_L \to W_L W_L$ violate unitarity: $t \sim s/v$.

There are different ways of constructing amplitudes which satisfy unitarity constraints from low order amps.

BUTTERWORTH,COX,FORSHAW,PRD65(02)96014



(A4,A5): UL:(0,0.003), UR:(0.002,-0.003), LL:(0.008,0), LR:(0;0)UL=UPLEFT ETC.

PADÈ: CONTINOUS

N/D: $M = 10^3$ DASH, $M = 10^4$ DOTDASH, $M = 10^5$DOT

LARGE INTERFERENCES:

WW SCATTERING AND THE REST

KLEISS-STIRLING,PL182B(86)75

$$V(q_1^2 = m^2 + 4\sqrt{s}\Delta_1)V(q_2^2 = m^2 + 4\sqrt{s}\Delta_2) \to X$$

THE HIGH-ENERGY OFF-SHELL BEHAVIOUR IS WORSE THAN ON-SHELL

PROC	OFF-OFF	ON-OFF	ON-ON
$ZZ \to ee$	$\Delta_1\Delta_2$	$m^2\Delta_1/\sqrt{s}$	m^4/s
$ZZ \to ZZ$	$(m_h^2;\Delta_1\Delta_2)$	m_h^2	m_h^2
$ZZ \to WW$	$\Delta_1\Delta_2 s^2/m^4$	$\Delta_1 s\sqrt{s}/m^2$	$(m_h^2;m^2)$
$WW \to WW$	$\Delta_1\Delta_2 s^2/m^4$	$\Delta_1 s\sqrt{s}/m^2$	$(m_h^2;m^2)$

THE PROBLEM CAN BE TRACED TO TRIPLE AND QUARTIC VERTICES.

WHEN THE INCOMING V'S ARE OFF SHELL VECTOR EMISSION FROM THE FERMION

MUST

BE INCLUDED. DO NOT MAKE APPROXIMATIONS!

AT THE LHC AND LC INCOMING VECTORS ARE BOTH ALWAYS OFF-MASS-SHELL.

LARGE INTERFERENCES:

WW SCATTERING AND THE REST AT LHC

E.ACCOMANDO,A.BALLESTRERO,E.M.

- $ud \rightarrow udW^+W^- \rightarrow ud\mu^-\overline{\nu_\mu}c\overline{s}$
- INITIAL STATE: p_u ALONG z, p_d ALONG $-z$,
- $1 < \eta(d) < 5.5$, $-1 > \eta(u) > -5.5$. SELECTING WW FUSION DIAGRAMS.
- $E(u,d) > 20\,\mathrm{GeV}$, $P_t(u,d) > 10\,\mathrm{GeV}$
- $70 < M(cs, e\nu) < 90\,\mathrm{GeV}$. FINAL STATE W'S CLOSE TO MASS-SHELL.

M_h	WW SIGNAL	TOTAL
120	0.2106672	0.1319138E-02
200	0.2174115	0.7960299E-02
500	0.2114054	0.2804993E-02
2000	0.2100076	0.1490797E-02
NOH	0.2099891	0.1468983E-02

σ (PB)

Status

- Hints of resonance production in WW scattering. Large parameter and model dependence. Control of SM background is essential.
- WW scattering subset totally insufficient. High energy behaviour worsens for off-mass-shell V's.
- CompHEP, ALPGEN have WW scattering in Production$\times$Decay approach. Approximation needs to be checked.
- MADGRAPH, O'MEGA, GRACE, AMEGIC++, HELAC can compute any process.
- No complete MC so far dedicated to WW scattering

Complete calculation of 6f EW production is necessary.

Physics beyond VV scattering

- Higgs of course!
  - VV fusion is one of the main production channels $> 10\%$ for $m_h > 100$ GeV
  - Couplings to VV, e.g. SSVV
  - Self interactions
- VVV production
- (Quartic) anomalous couplings among V's
- $t\bar{t}$: small compared to gg channel. High P_T?

Higgs production at LHC

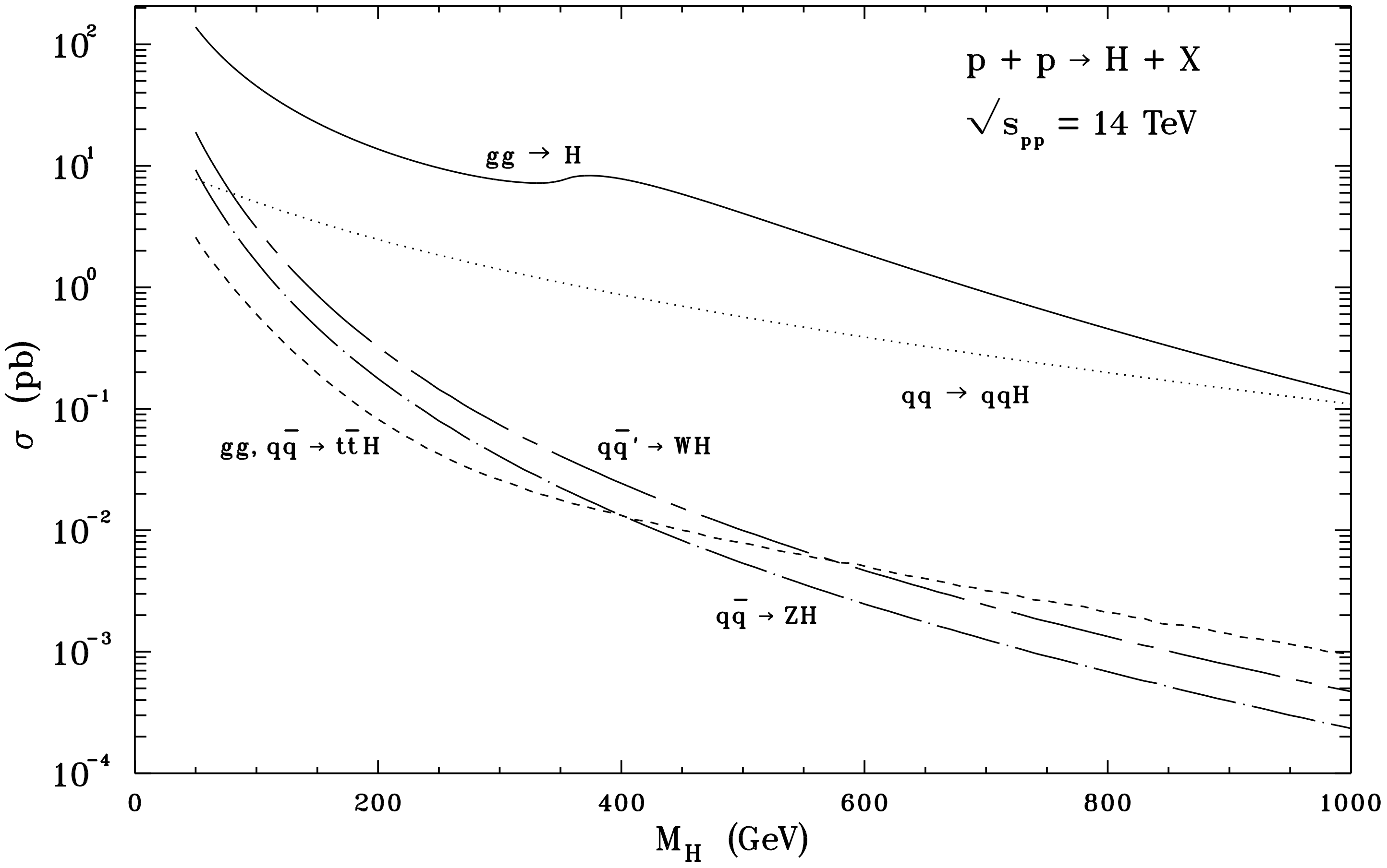


Fig. 5b

PHASE

PHact Adaptive Six-fermion Event-generator

An event generator:

- all $q_1 q_2 \to q_3 q_4 q_5 q_6 l \overline{\nu_l}$ processes at $\mathcal{O}(\alpha_{em}^6)$
  THIS IS WHERE WW SCATTERING IS!
  $q_1 q_2 \to q_3 q_4 q_5 q_6 l \bar{l}$ and $q_1 q_2 \to q_3 q_4 l_1 \overline{\nu_{l_1}} l_2 \overline{\nu_{l_2}}$ also interesting, τ's?
  $qq \to 6q$ have large backgrounds
- one-shot: all processes generated simultaneously.
  Subsets possible.
- over the full phase space: Efficiency
- interfaced with PYTHIA/HERWIG with Les Houches protocol

PROBLEMS

- Large number of processes
- Large number of diagrams/process
- Large number of channels/enhanced regions

Which Processes in $q_1 q_2 \to q_3 q_4 q_5 q_6 \mu \overline{\nu_\mu}$ at $\mathcal{O}(\alpha_{em}^6)$?

- Equivalent processes with all fermions outgoing: $\sum_{i=1}^{8} Q_i = 0$
- Fix one pair to be $c\overline{s}$
- $q_1 q_2 \to q_3 q_4 c\overline{s} \mu \overline{\nu_\mu}$ with $\sum_{i=1}^{4} Q_i = 0$

PROCESSES

Particles	type	diag	#proc(2+1)
$c\bar{s}d\bar{u}c\bar{s}\mu\bar{\nu}$	4W	202	6 + 2
$u\bar{u}u\bar{u}c\bar{s}\mu\bar{\nu}$	2Z2W	422	6 + 2
$u\bar{u}c\bar{c}c\bar{s}\mu\bar{\nu}$	2Z2W	422	10 + 1
$u\bar{u}s\bar{s}c\bar{s}\mu\bar{\nu}$	2Z2W	422	10 + 1
$u\bar{u}b\bar{b}c\bar{s}\mu\bar{\nu}$	2Z2W	233	15 + 0
$d\bar{d}d\bar{d}c\bar{s}\mu\bar{\nu}$	2Z2W	422	6 + 2
$d\bar{d}c\bar{c}c\bar{s}\mu\bar{\nu}$	2Z2W	422	10 + 1
$d\bar{d}s\bar{s}c\bar{s}\mu\bar{\nu}$	2Z2W	422	10 + 1
$d\bar{d}b\bar{b}c\bar{s}\mu\bar{\nu}$	2Z2W	233	15 + 0
$c\bar{c}c\bar{c}c\bar{s}\mu\bar{\nu}$	2Z2W	1266	3 + 2
$c\bar{c}b\bar{b}c\bar{s}\mu\bar{\nu}$	2Z2W	466	10 + 1
$s\bar{s}s\bar{s}c\bar{s}\mu\bar{\nu}$	2Z2W	1266	3 + 2
$s\bar{s}b\bar{b}c\bar{s}\mu\bar{\nu}$	2Z2W	466	10 + 1
$b\bar{b}b\bar{b}c\bar{s}\mu\bar{\nu}$	2Z2W	610	6 + 2
$u\bar{u}d\bar{d}c\bar{s}\mu\bar{\nu}$	2Z2W+4W	312	15 + 0
$c\bar{c}s\bar{s}c\bar{s}\mu\bar{\nu}$	2Z2W+4W	1046	6 + 2
TOTAL			141 + 20

ALL PARTICLES OUTGOING

$(u, d) \leftrightarrow (c, s)$ SYMMETRY

CC SYMMETRY

TRIVIAL $(\mu, \nu_\mu) \leftrightarrow (e, \nu_e)$

How many diagrams are really needed?

- 16 different amplitudes
- Amplitudes with the same number of diagrams can be programmed at the same time, even though they are different
- Numerology:

202 = 101 x 2	233 = 211 + 22	312 = 101 + 211	422 = 211 x 2
466 = 233 x 2	610 = (211 + 94) x 2	1046 = 101 x 2 + 211 x 4	1266 = 422 x 3

We are left with 4 sets with 101, 211, 22 and 94 diagrams

- Computed with PHACT: faster and more easily modified than using a third-party automatic program.
- Amplitude tests completeted!

Processes vs VV scattering: 4W,2W2Z

$d\overline{u}c\overline{s}c\overline{s}\mu\overline{\nu}$ 202 diagrams				
Process	$w^+w^- \to w^+w^-$ 7 diag.	$w^-w^- \to w^-w^-$ 7 diag.	$zw^- \to zw^-$ 4 diag.	$zz \to w^+w^-$ 4 diag.
$\overline{d}u \to c\overline{s}c\overline{s}\mu\overline{\nu}$				
$\overline{d}\overline{c} \to \overline{u}\overline{s}c\overline{s}\mu\overline{\nu}$	x			
$\overline{d}s \to \overline{u}cc\overline{s}\mu\overline{\nu}$	x			
$u\overline{c} \to d\overline{s}c\overline{s}\mu\overline{\nu}$	x			
$us \to dcc\overline{s}\mu\overline{\nu}$	x			
$\overline{c}s \to d\overline{u}c\overline{s}\mu\overline{\nu}$	x			
$\overline{c}\overline{c} \to d\overline{u}\overline{s}\overline{s}\mu\overline{\nu}$		x		
$ss \to d\overline{u}cc\mu\overline{\nu}$		x		
$u\overline{u}u\overline{u}c\overline{s}\mu\overline{\nu}$ 422 diagrams				
$\overline{u}u \to u\overline{u}c\overline{s}\mu\overline{\nu}$				x
$\overline{u}\overline{c} \to \overline{u}u\overline{u}\overline{s}\mu\overline{\nu}$			x	
$\overline{u}s \to \overline{u}u\overline{u}c\mu\overline{\nu}$			x	
$u\overline{c} \to uu\overline{u}\overline{s}\mu\overline{\nu}$			x	
$us \to uu\overline{u}c\mu\overline{\nu}$			x	
$\overline{c}s \to u\overline{u}u\overline{u}\mu\overline{\nu}$				
$\overline{u}\overline{u} \to \overline{u}\overline{u}c\overline{s}\mu\overline{\nu}$				x
$uu \to uuc\overline{s}\mu\overline{\nu}$				x

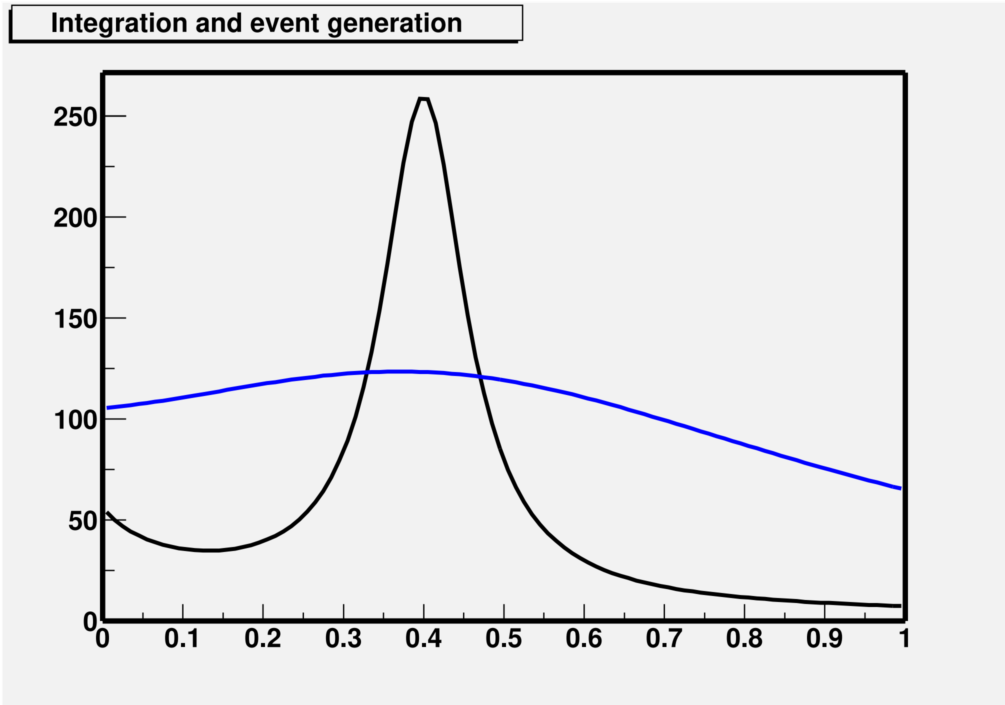
PROCESSES VS VV SCATTERING: 4W + 2W2Z

$u\overline{u}d\overline{d}c\overline{s}\mu\overline{\nu}$ 312 diagrams				
Process	$w^+w^- \to w^+w^-$	$w^-w^- \to w^-w^-$	$zw^- \to zw^-$	$zz \to w^+w^-$
$\overline{u}u \to d\overline{d}c\overline{s}\mu\overline{\nu}$	x			
$\overline{u}\overline{d} \to \overline{u}\overline{d}c\overline{s}\mu\overline{\nu}$	x			x
$\overline{u}d \to \overline{u}dc\overline{s}\mu\overline{\nu}$				x
$\overline{u}c \to \overline{u}d\overline{d}\overline{s}\mu\overline{\nu}$		x	x	
$\overline{u}s \to \overline{u}d\overline{d}c\mu\overline{\nu}$		x	x	
$u\overline{d} \to u\overline{d}c\overline{s}\mu\overline{\nu}$				x
$ud \to udc\overline{s}\mu\overline{\nu}$	x			x
$u\overline{c} \to ud\overline{d}\overline{s}\mu\overline{\nu}$	x		x	
$us \to ud\overline{d}c\mu\overline{\nu}$	x		x	
$\overline{d}d \to u\overline{u}c\overline{s}\mu\overline{\nu}$	x			
$\overline{d}\overline{c} \to u\overline{u}\overline{d}\overline{s}\mu\overline{\nu}$	x		x	
$\overline{d}s \to u\overline{u}\overline{d}c\mu\overline{\nu}$	x		x	
$d\overline{c} \to u\overline{u}d\overline{s}\mu\overline{\nu}$	x	x		
$ds \to u\overline{u}dc\mu\overline{\nu}$	x	x		
$\overline{c}s \to u\overline{u}d\overline{d}\mu\overline{\nu}$				

Integration

It is absolutely necessary to obtain a precise cross section: it ensures that the phase-space parametrization matches reasonably well the behaviour of the amplitude squared.

Otherwise generation efficiency will be extremely poor.



Integration can be used to adapt more closely to the integrand

Possible strategies:

- adaptive integration (Vegas)
  - adapts well to cuts
  - a rough estimate of mapping parameters is usually sufficient
  - fails if several sets of enhancements in $|\, Amp\, |^2$ or not along diagonals ☹
- multichannel
  - requires a large number of channels (easy to add)
  - all channels are integrated over simultaneously
  - sensitive to cuts, efficiency generally small ☹
  - mapping parameters to be determined with high accuracy ☹
- adaptive+multichannel
  - Adapts well to cuts
  - A rough estimate of mapping parameters is usually sufficient
  - All channels have to be integrated separately ☹

Integration in PHASE at present

- All relevant phase space mappings are ready
- Different mappings are combined reducing the number of channels
- Can integrate/generate any single processes with reasonable CPU time (Up to crashes due to numerical accidents)
- Automatic relative weighting of channels still needs effort. It must work for:
  - any process
  - any set of cuts

  NON TRIVIAL!

Usage

- For each M_H generate one grid for each process and store them
- Generate events using grids

Where do we stand?

- PHASE is assembled and running
- Diagrams OK! Fast!
- Integration single process OK! Automatization of multichannel details: testing phase
- Interface to PYTHIA via LesHouches protocol OK! HERWIG?
- One-shot technology not yet in place but borrowed from WPHACT where it worked very well. Started.
- Large scale production of grid files (automatic?): to be done

TECHNICALITIES

- G_F SCHEME: $G_F, M_W, M_Z, M_H \rightarrow$ ALL OTHER PARAMETERS
- d, u, s, c MASSLESS, b MASSIVE
- CKM DIAGONAL
- $\Gamma \neq 0$: $U(1)$ GAUGE INVARIANCE HANDLED WITH $M^2 \rightarrow M^2 - iM\Gamma$.
  IS $SU(2)$ GAUGE INVARIANCE NUMERICALLY RELEVANT?

EXTENSIONS

- EXTRACT $q_1 q_2 \to q_3 q_4 V V' \to q_3 q_4 q_5 q_6 \mu \overline{\nu_\mu}$ SIGNAL
  - ARE THERE LARGE INTERFERENCES? GAUGE CANCELLATIONS?
  - CAN IT BE EXTRACTED WITH APPROPRIATE CUTS?
- $q_1 q_2 \to q_3 q_4 q_5 q_6 l^+ l^-$
  - ESSENTIAL FOR $WW \to ZZ$
  - ADDITIONAL HANDLE ON $WZ \to WZ$
- $q_1 q_2 \to q_3 q_4 q_5 q_6 \mu \overline{\nu_\mu}$ AT $\mathcal{O}(\alpha_s^2 \alpha_{em}^4)$
  $q_1 q_2 \to q_3 q_4 g g l_1 l_2$, $q_1 g \to q_2 q_3 q_4 g l_1 l_2$, $gg \to q_1 q_2 q_3 q_4 l_1 l_2$
  QCD BACKGROUND: CAN IT BE HANDLED?

Conclusions

- WW scattering holds the key to the EWSB mechanism
- Exciting phenomena could take place
- SM predictions not yet accurate enough
- PHASE is (rapidly?) approaching production stage

A LOT MORE WORK LIES AHEAD!