PHANTOM: a Monte Carlo event generator for six parton final states at high energy colliders

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Outline

The PHANTOM project

- An overview of the framework
- Main features for physics studies at ILC

An example of application: EWSB studies at ILC

- A case study: complete results for $e^+e^- \to \nu_e\bar{\nu}_e + 4j$
- Physics interplay with LHC

Processes with six partons in the final state will be central to the physics program at ILC as well as at the upcoming LHC

Some interesting channels accessible at ILC:

- Vector Boson Fusion $e^+e^- \to f\bar{f}H \to f\bar{f}VV \to 6f$
- Higgs-strahlung $e^+e^- \to ZH \to f\bar{f}VV \to 6f$
- triple gauge boson production $e^+e^- \to ZW^+W^-[ZZZ] \to 6f$
- top pair production $e^+e^- \to t\bar{t} \to 6f$

Accurate computational tools are required in the quest of achieving the best possible description of these and other processes in the vast realm of 6f physics

A lot of work has been done since the first complete calculations have started to appear...

Six-fermion tools for ILC

Current status:

General purpose MC tools

- `GRACE`
- `HELAS/MadGraph/MadEvent`
- `Whizard+Omega`
- `Sherpa/AmegiC++`
- `HELAC/PHEGAS`

Dedicated 6f MC tools

- `eett6f` $e^+e^- \to b\bar{b} + 4f$, including QCD
- `Sixfap` $e^+e^- \to 6f$, no QCD
- `Sixphact` $e^+e^- \to 6f$, naive QCD approach (NQCD)
- `Lusifer` $e^+e^- \to 6f$, including one-gluon exchange
- `Sixrad` $e^+e^- \to 6q/4q2g/2q4g$

There is still room for progress in several directions...

- improving efficiency
- extending the coverage of final states with *gluon* jets
- facilitating comparative studies on LHC/ILC sinergy

⇓

Project PHANTOM

$^{(*)}$ PHAct New TOrino Montecarlo

A full-fledged, *dedicated* event generator for complete six-parton studies at Tevatron, LHC and ILC

Profits from the experience obtained with PHASE, specific for $pp \rightarrow 4q + \ell\nu$ Accomando,Ballestrero,Maina

PHANTOM 1.0

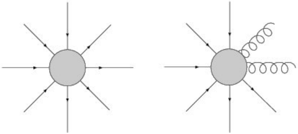
Ballestrero, Belhouari, G.B., Kashkan, Maina

arXiv:0801.3359 [hep-ph]

Event generator dedicated to six-parton physics at pp, $p\bar{p}$ and e^+e^- colliders

- Exact tree-level matrix elements at $\mathcal{O}(\alpha_{EM}^6) + \mathcal{O}(\alpha_{EM}^4 \alpha_S^2)$
- Full coverage of Standard Model processes at fixed order

$$\begin{matrix} pp \\ p\bar{p} \\ e^+e^- \end{matrix} \longrightarrow \begin{cases} 6f \\ 5f + g \\ 4f + 2g \end{cases}$$

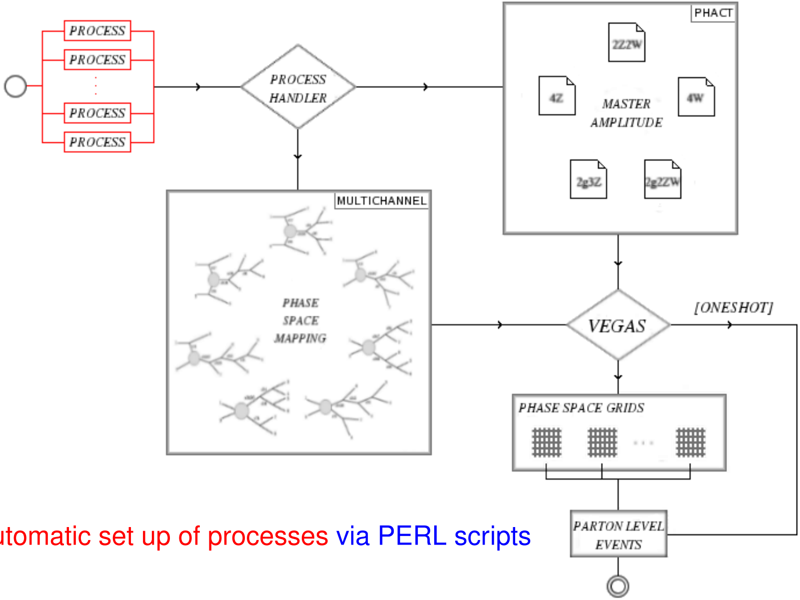


Holds the signal of

- Higgs production via Vector Boson Fusion $ffH \to ffVV$ ...
- Vector Boson Scattering $WW \to WW, WZ \to WZ$ ...
- triple gauge boson production
- $t\bar{t}$ production
- triple/quadruple-vertex EW interactions

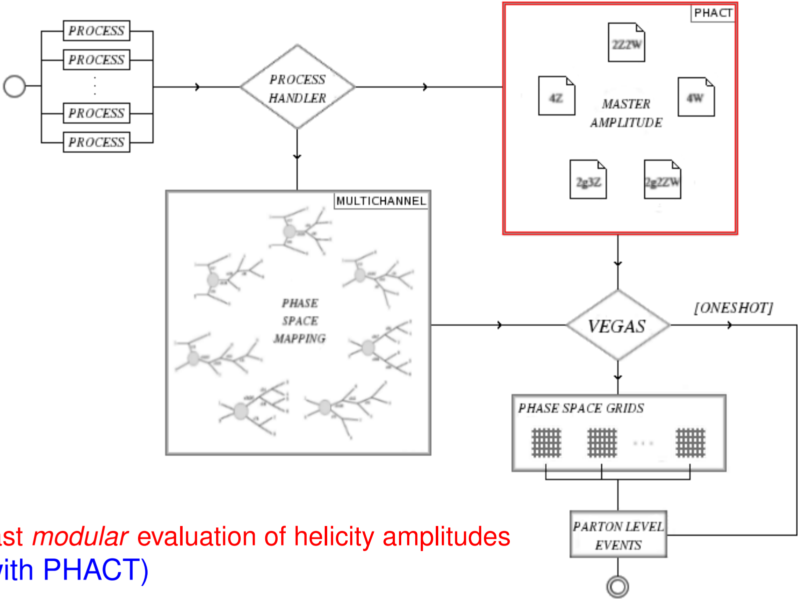
together with all EW+QCD irreducible background at fixed order

An overview of the framework



Automatic set up of processes via PERL scripts

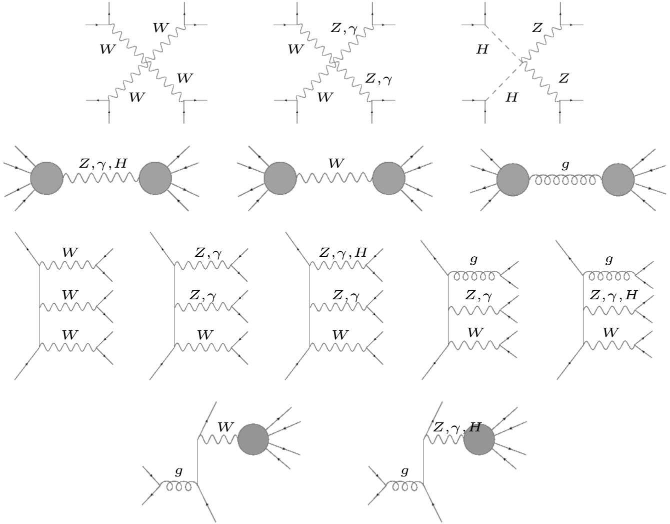
An overview of the framework



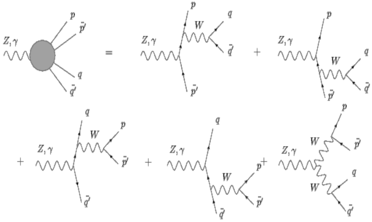
Fast *modular* evaluation of helicity amplitudes
(with PHACT)

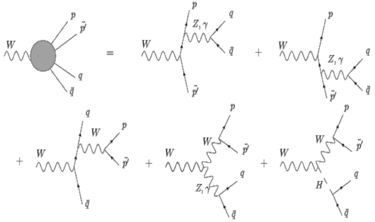
Matrix Element Calculation

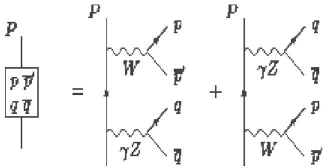
Example: diagrams with 8 external fermions, organized into basic topologies

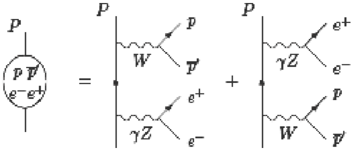


Examples of subdiagrams

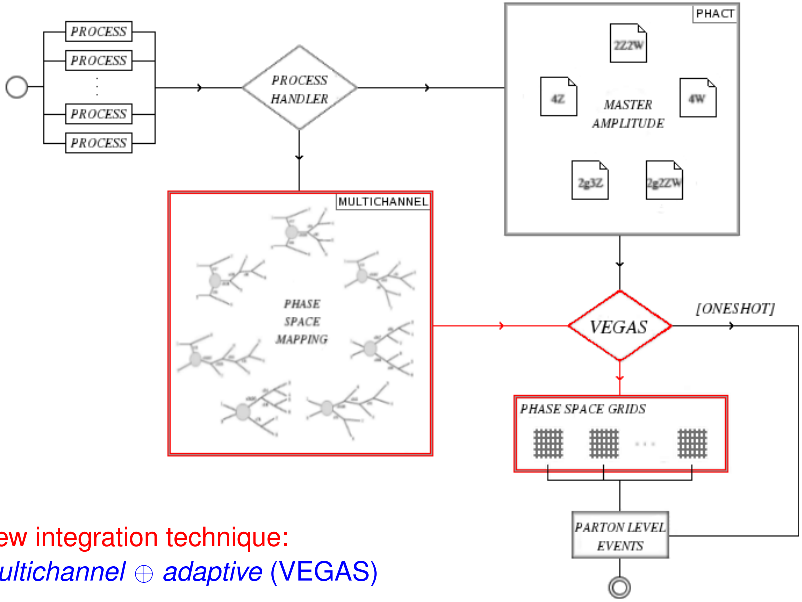






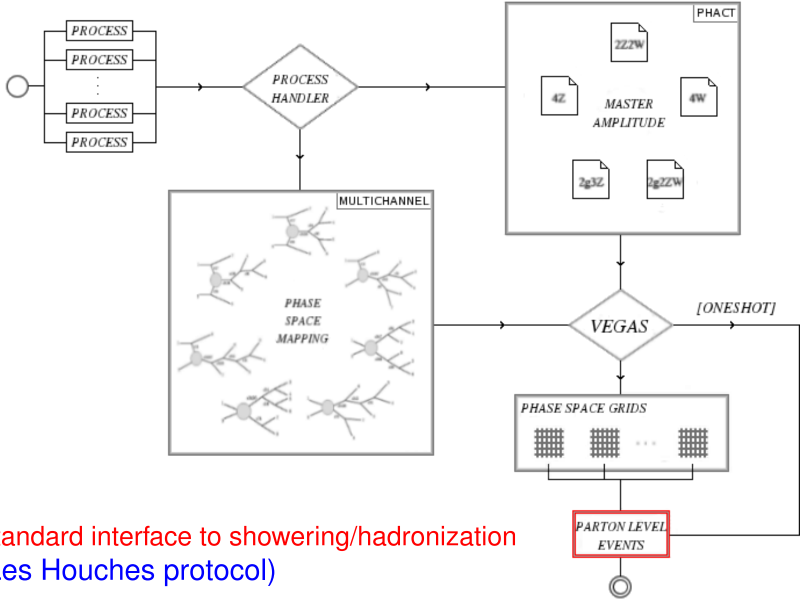


An overview of the framework



New integration technique:
multichannel $\oplus$ *adaptive* (VEGAS)

An overview of the framework



Standard interface to showering/hadronization
(Les Houches protocol)

Phase Space Integration

Given the extremely rich peaking structure of the integrand, it is crucial to minimize variance in order to get a precise cross section and improve the generation efficiency

Iterative-adaptive multichannel

Accomando, Ballestrero, Maina ’04

Merges two complementary approaches

Multichannel

- ad-hoc phase space mappings
- usually sensitive to cuts

Adaptive (VEGAS)

- integrand blind
- fails for complex peaking structures

Adapts to different kinematical cuts with good generation efficiency

Main features for ILC applications

Efficient

- fast evaluation of helicity amplitudes (with PHACT)
- new integration technique: adapts well to different sets of cuts

Complete

- $\mathcal{O}(\alpha_{EM}^6) + \mathcal{O}(\alpha_{EM}^4 \alpha_S^2)$ fully embodies the tree-level irreducible background (and inteferences) for final states with at least two leptons
- Initial State Radiation (ISR) via leading log structure functions
- beamstrahlung via interface to CIRCE library

User friendly

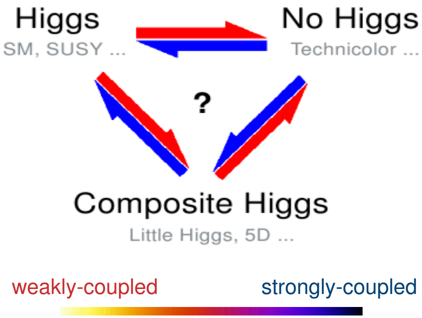
- possibility of unweighted generation of any number of processes at the same time (*oneshot* mode)

All-in-one

- suitable for comparative studies between LHC and ILC physics potential

Example of application: EWSB studies at ILC

Vector Boson Scattering is a *model-independent* probe of the mechanism of Electroweak Symmetry Breaking



In order to understand the nature of the new physics which will manifest at the Terascale, a crucial issue to be settled is whether the EWSB dynamics is weakly or strongly coupled

A case study: $e^+e^- \to \nu_e\bar{\nu}_e\, 4j$

Several studies have already appeared

Barger, Cheung, Han, Phillips '95 ...

W^+W^- fusion is a sensitive probe of the dynamics of EWSB: different models predict different ratios $\sigma(W^+W^- \to W^+W^-)/\sigma(W^+W^- \to ZZ)$

Principal backgrounds:

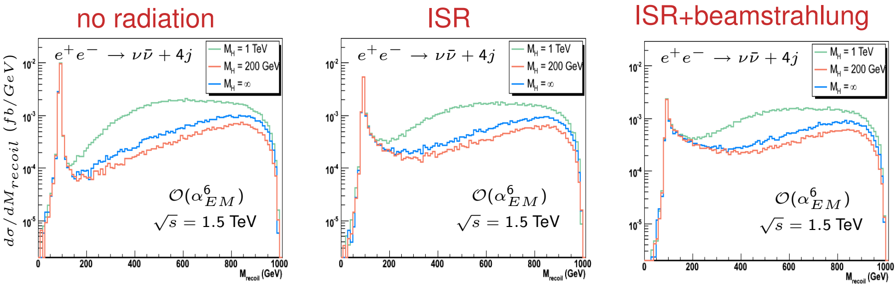
$e^+e^- \to e^+e^-W^+W^-$, e^+e^-ZZ , $e^\pm\nu W^\pm Z$ (with undetected $e^\pm$)
$e^+e^- \to ZW^+W^- \to \nu\bar{\nu}W^+W^-$ (Z-resonant channel)

Some interesting observables:

- four-jet invariant mass (M_{4j}): holds information about M_{VV}
- *recoil* four-jet mass (M_{recoil}): complementary to M_{4j}, related to total missing momentum (neutrinos + initial-state radiation)

First results with PHANTOM

Effect of initial-state radiation and beamstrahlung on the *recoil mass* distribution (for W^+W^- resonant final states)



Selection cuts:

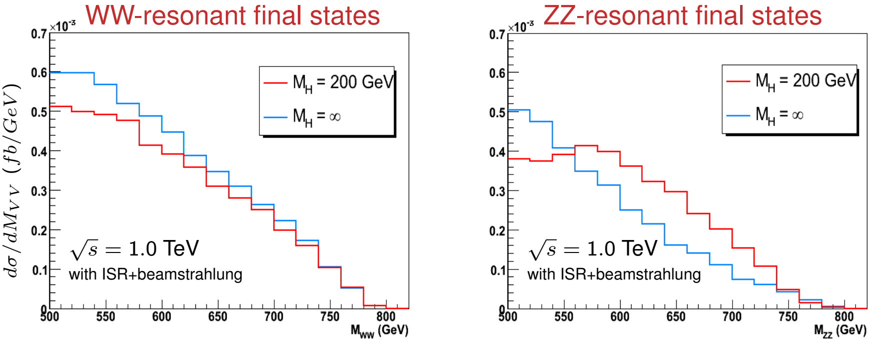
$M_{jj} > 40$ GeV; $M_{VV} > 500$ GeV; $p_T(V) > 150$ GeV; $|\cos\theta_V| < 0.8$;

50 GeV $< p_T(WW) <$ 300 GeV; 20 GeV $< p_T(ZZ) <$ 300 GeV

ISR and beamstrahlung change cross sections up to 20%

Complete $\mathcal{O}(\alpha_{EM}^6) + \mathcal{O}(\alpha_{EM}^4 \alpha_S^2)$ results

$\sqrt{s} = 1.0$ TeV



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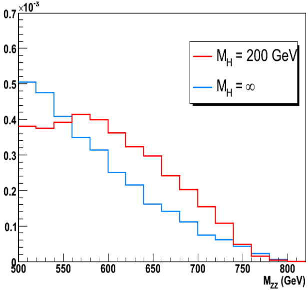
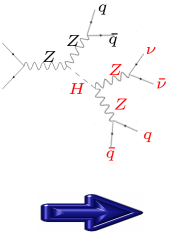
$M_{recoil} > 200$ GeV

Early on-set of EWSB effects is partially masked in the ZZ channel by residual non-scattering contributions. What's going on?

ISR and beamstrahlung limit the validity of the kinematical cut $M_{recoil} > 200$ GeV in suppressing *Higgs-strahlung* contributions

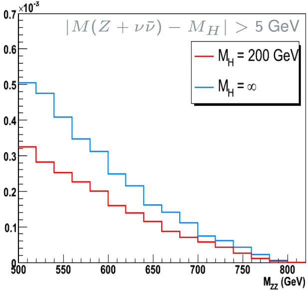
ZZ-resonant final states





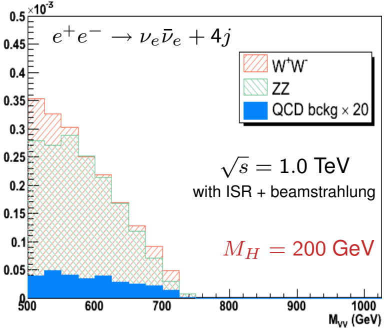
No Higgs-strahlung

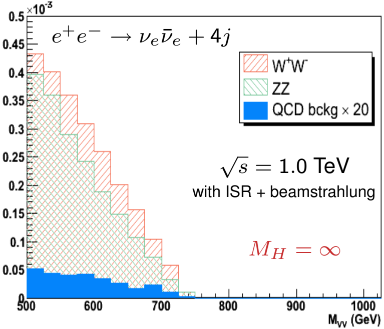
ZZ-resonant final states



Genuine $e^+e^- \to ZH \to jj + \nu\bar{\nu}jj$ events enter the analysis

Complete $\mathcal{O}(\alpha_{EM}^6) + \mathcal{O}(\alpha_{EM}^4\alpha_S^2)$ results





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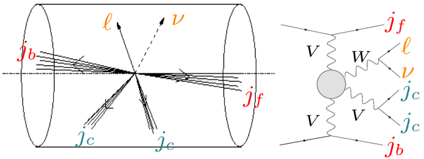
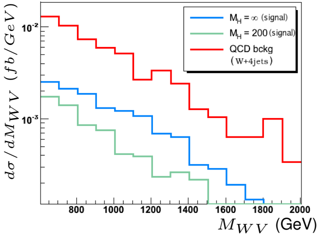
$M_{recoil} > 250$ GeV

A parallel with LHC: $pp \to 4j + \ell\nu$

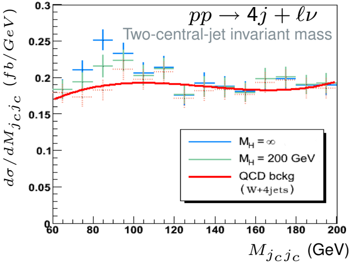
✓ Scattering contributions enhanced via *forward/backward* jet tagging



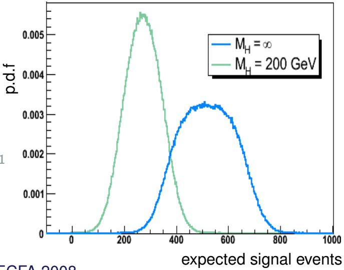
✗ Huge QCD background



Basic idea: background subtraction in the two-central-jet invariant mass

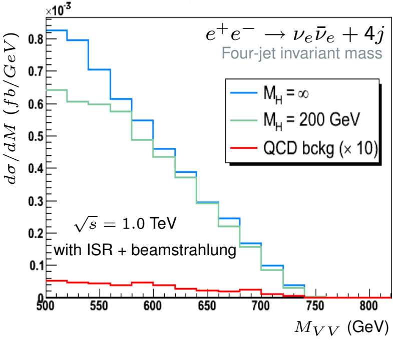


$\mathcal{L} = 100$ fb^{-1}

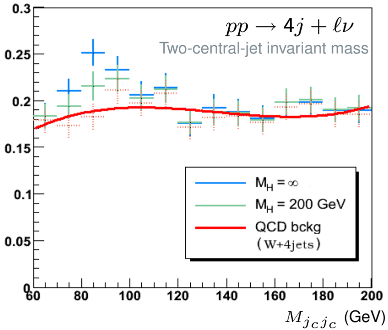


A comparison with LHC results

ILC



LHC



Number of expected scattering events:

ILC ($\sqrt{s} = 1.0$ TeV) $M_{VV} > 400$ GeV $\mathcal{L} = 500$ fb^{-1}		**ILC** ($\sqrt{s} = 1.5$ TeV) $M_{VV} > 500$ GeV $\mathcal{L} = 500$ fb^{-1}		**LHC** ($\ell = e, \mu$) $M_{VV} > 600$ GeV $\mathcal{L} = 100$ fb^{-1}	
$M_H = 200$	$M_H = \infty$	$M_H = 200$	$M_H = \infty$	$M_H = 200$	$M_H = \infty$
102 ± 10	120 ± 11	236 ± 15	393 ± 20	274 ± 69	520 ± 104

Conclusions

PHANTOM is a project dedicated to complete six-parton simulations at hadron and e^+e^- colliders

- It has features and efficiency competitive with the other six fermion MC's for ILC
- It will be particularly suitable for comparative studies between the LHC and ILC physics potential

LHC can reach higher energies for parton interactions

ILC on the other hand has a much lower QCD background

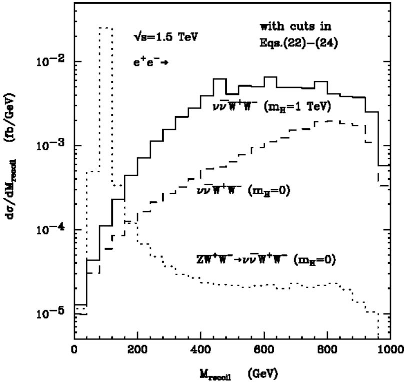
It is interesting to compare the reach of the two colliders in the broad field of six-fermion physics

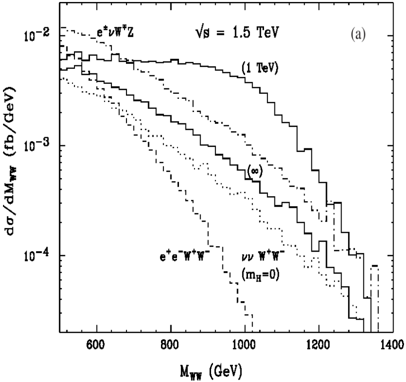
Backup slide

Barger, Cheung, Han, Phillips ’95

$\sqrt{s} = 1.5$ TeV

No ISR/beamstrahlung





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