Physics studies at the LHC with Phantom

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Phantom 1.0 is ready and has been used for the first preliminary analyses

First event generator for complete $\mathcal{O}(\alpha_{EM}^6) + \mathcal{O}(\alpha_{EM}^4 \alpha_S^2)$ six-fermion studies at the LHC

Exact tree-level matrix elements

- no *production* $\times$ *decay* approach
- *pure EW* and *EW+QCD* irreducible background for boson-boson scattering and Higgs search
- complete $6f$ LO predictions for top production

Phantom 1.0

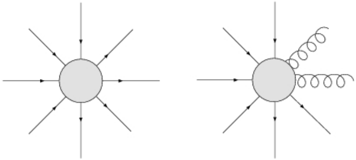
Ballestrero, Belhouari, GB, Maina

Dedicated six-fermion event generator for LHC studies

Extended to p-$\bar{p}$ collisions

All Standard Model processes $\mathcal{O}(\alpha_{EM}^6) + \mathcal{O}(\alpha_{EM}^4 \alpha_S^2)$

- $qq' \rightarrow 6f$
- $qq' \rightarrow 2g\,4f$
- $qg \rightarrow 1g\,5f$
- $gg \rightarrow 6f$



f = *any* fermion $\Rightarrow$ up to 6 quarks in the final state

New Physics (W.I.P.)

- alternative models of Electroweak Symmetry Breaking

Some technical features

User friendly

- Huge set of parton-level processes handled by a PERL script
- *One-shot*: unweighted events for *any number* of processes generated simultaneously

Efficient

- fast *modular* evaluation of amplitudes (PHACT)
- good coverage of phase-space via new *iterative-adaptive multichannel* approach (multichannel $\oplus$ VEGAS), already used in PHASE 1.0 (Accomando, Ballestrero, Maina)

Les Houches ready

- new Les Houches Event File (LHEF) format – MC4LHC-06 [hep-ph/0609017]
- interfaced with pdf's via the Les Houches Accord PDF (LHAPDF) package

Physics potential

$\mathcal{O}(\alpha_{EM}^6)$

Phase 1.0 : $qq' \rightarrow 4q + l\,\nu$

$\hookrightarrow$ Phantom 0.9 : $qq' \rightarrow$ all $6f$

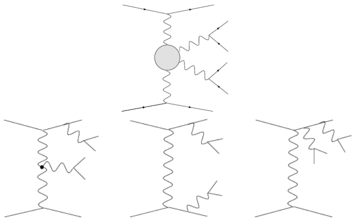
Holds the signal of

- Higgs production via Vector Boson Fusion $qqH \rightarrow qqVV$
- Vector Boson Scattering (VBS) $WW \rightarrow WW, WZ \rightarrow WZ...$
- three-boson production
- triple/quadruple-vertex EW interactions

together with all possible EW irreducible background from a six-fermion point of view.

example: VBS signal

Possible large interferences and gauge cancellations with *pure EW* irreducible background

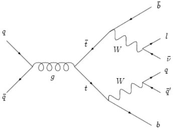


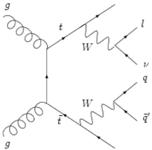
Physics potential

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

Phantom 1.0

Main top channel and $WW + 2$ jets

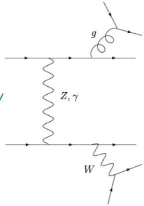




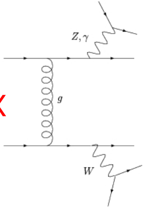
All *EW+QCD irreducible background* to the previous signals with one gluon exchange (and interferences)

Parton Shower MC does not approximate *all* contributions to the amplitude

√

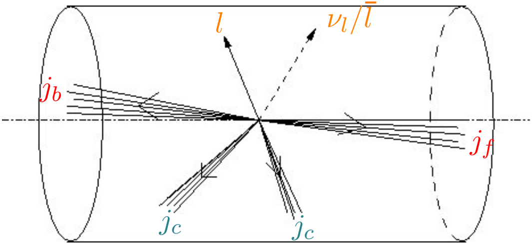


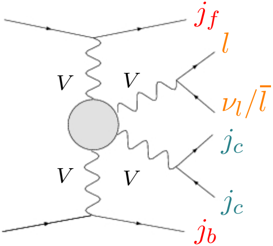
X



Physics studies on Vector Boson Scattering

Typical VBS signature: two forward/backward *tag* jets + two central jets and leptons

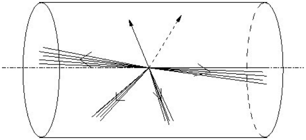




$M_{j_c j_c ll}$ = invariant mass of two most central jets + leptons

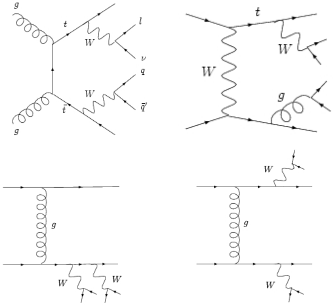
- holds the information about M_{VV}, i.e. the CM energy in VBS
- *light* Higgs $\Rightarrow$ sharp peak in $d\sigma/dM_{j_c j_c ll}$
- *heavy* Higgs or alternative scenario $\Rightarrow$ discrepancies with SM predictions at high $M_{j_c j_c ll}$

Enhance signal



- cut on the pseudorapidity of the two forward/backward jets (η_{j_f}, η_{j_b})
- cut on the invariant mass of the central jets ($M_{j_c j_c}$)

Suppress backgrounds



- exploit *b-tagging* + cuts on invariant mass to avoid top contributions
- cut on p_T and pseudorapidity of the lepton pair ($\eta_{l\nu}$)
- cut on the invariant mass of *leptons + tag jet* ($M_{j_f l\nu}$, $M_{j_b l\nu}$)

Physics analyses

Preliminary parton-level studies available: semi-leptonic 'l^+l^-' and '$l\nu$' final states

- $qq' \to 4q + \mu^+\mu^-$ $\mathcal{O}(\alpha_{EM}^6)$
- $qq' \to 4q + \mu\,\nu_\mu$ $\mathcal{O}(\alpha_{EM}^6)$ and $\mathcal{O}(\alpha_{EM}^6) + \mathcal{O}(\alpha_{EM}^4\alpha_S^2)$

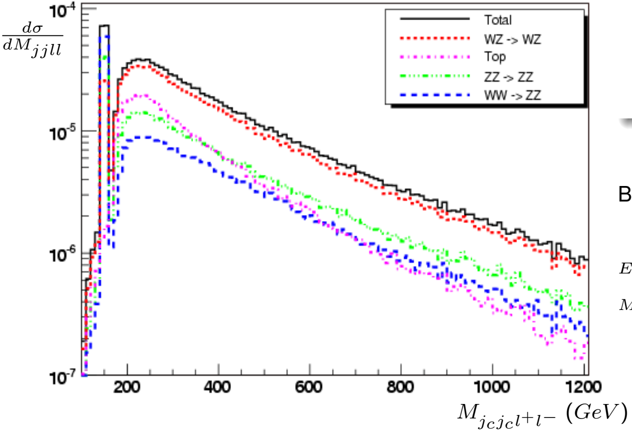
Analysed models

- Standard Model with light Higgs
- Standard Model with no Higgs
  (benchmark scenario for New Physics)

The l^+l^- channel

$$pp \rightarrow qq' \rightarrow 4q + \mu^+ \mu^-$$

$\mathcal{O}(\alpha_{EM}^6)$ invariant mass distribution of $\mu^+\mu^-$ + two most central quarks



$M_H = 150$ GeV

Basic acceptance cuts:

$|\eta_l| < 3 \quad |\eta_j| < 5$

$E(j) > 30\,GeV \quad p_T(j) > 20\,GeV$

$M_{ll} > 20\,GeV \quad M_{jj} > 60\,GeV$

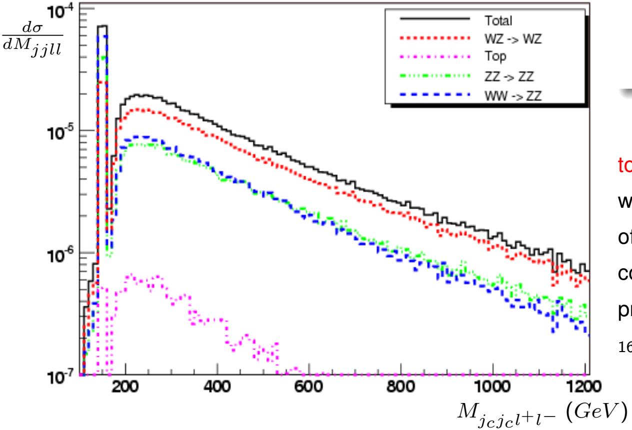
$\Delta\eta_{j_f j_b} > 3.8$

pure EW Higgs irreducible background amounts to $\sim 5 - 10\%$

The l^+l^- channel

$$pp \to qq' \to 4q + \mu^+ \mu^-$$

$\mathcal{O}(\alpha_{EM}^6)$ invariant mass distribution of $\mu^+\mu^-$ + two most central quarks with *top veto*



$M_H = 150$ GeV

top candidates: events with a b and two quarks of the right flavour combination to be produced in a W decay

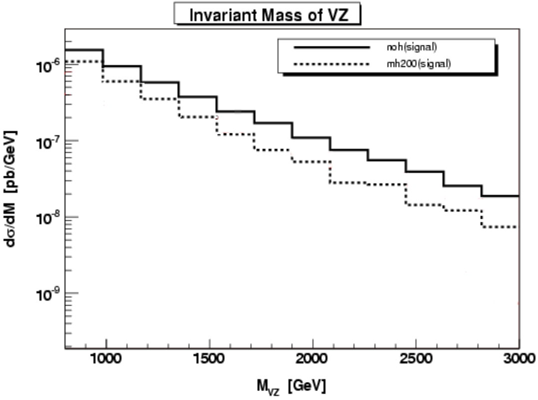
160 $GeV < M_{bqq} <$ 190 GeV

The $WZ \to WZ$ set of diagrams gives the largest contribution

The l^+l^- channel

$$pp \rightarrow qq' \rightarrow 4q + \mu^+ \mu^-$$

$\mathcal{O}(\alpha_{EM}^6)$ predictions in the high-invariant-mass region



no Higgs
vs
$M_H = 200$ GeV

Basic acceptance cuts

Selection cuts:

$81\, GeV < M(ll) < 101\, GeV$

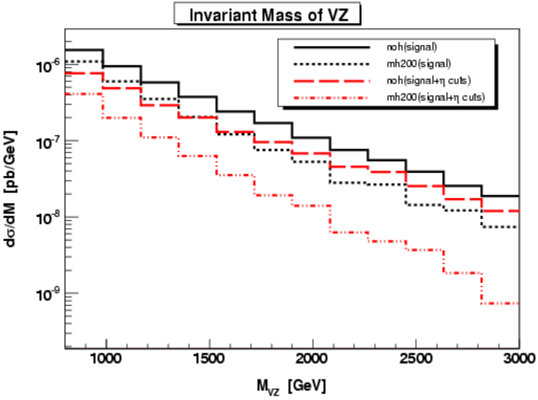
$M(qq) = M_V \pm 10\, GeV$

with flavour information

The l^+l^- channel

$$pp \to qq' \to 4q + \mu^+ \mu^-$$

$\mathcal{O}(\alpha_{EM}^6)$ predictions in the high-invariant-mass region



no Higgs
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$M_H = 200$ GeV

Basic acceptance cuts

Selection cuts:

$81\,GeV < M(ll) < 101\,GeV$

$M(qq) = M_V \pm 10\,GeV$

with flavour information

$|\eta(Z_{ll})| < 2 \quad |\eta(V_{qq})| < 2$

Simple requirements of centrality of the final-state bosons enhance the difference between the two models

The l^+l^- channel

Effect of requiring a minimum ΔR separation among partons on the number of expected events ($\mathcal{L} = 100\,\text{fb}^{-1}$)

M_{cut}	NoHiggs	$M_H = 200\,GeV$	Ratio
800 GeV	40	16	2.50
900 GeV	32	11	2.91
1.0 TeV	25	8	3.13
$\Delta R = 0.4$			
800 GeV	23	12	1.92
900 GeV	15	8	1.88
1.0 TeV	10	5	2.00
$\Delta R = 0.5$			
800 GeV	15	10	1.50
900 GeV	10	6	1.66
1.0 TeV	6	4	1.50

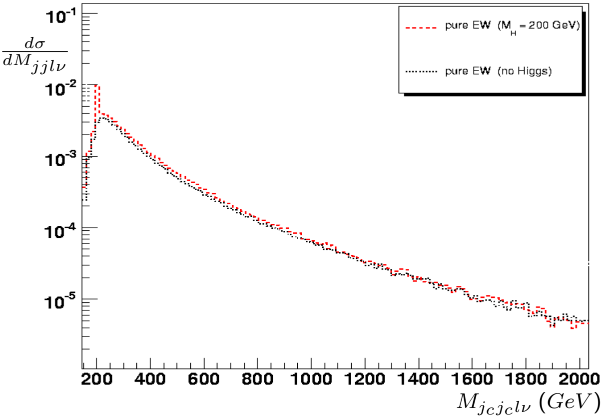
- W's and Z's with high p_T are most likely to merge into one jet
- In case of light Higgs, vector boson distributions are less central

$\hookrightarrow$ A *light Higgs* scenario is less affected by ΔR cuts.
To evidentiate new physics low ΔR cuts should be studied

The $l\nu$ channel

$$pp \longrightarrow qq' \longrightarrow 4q + \mu\,\nu_\mu$$

$\mathcal{O}(\alpha_{EM}^6)$ predictions



no Higgs

vs

$M_H = 200$ GeV

Basic acceptance cuts:

$E(l) > 20\,GeV \quad p_T(l) > 10\,GeV$

$|\eta_l| < 3$

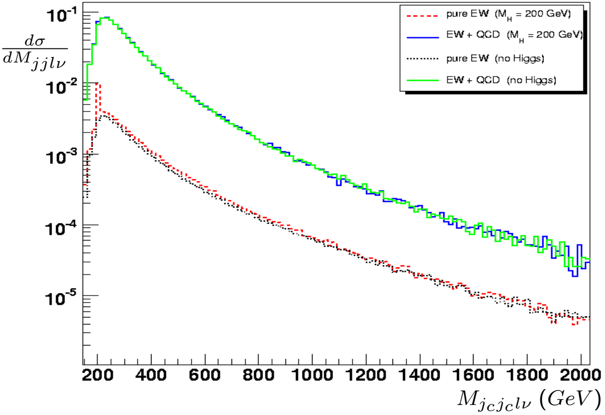
$E(j) > 20\,GeV \quad p_T(j) > 10\,GeV$

$|\eta_j| < 6.5 \quad m_{jj} > 20\,GeV$

The $l\nu$ channel

$$pp \to qq' \to 4q + \mu\,\nu_\mu$$

Comparison between $\mathcal{O}(\alpha_{EM}^6)$ and $\mathcal{O}(\alpha_{EM}^6) + \mathcal{O}(\alpha_{EM}^4 \alpha_S^2)$ predictions



no Higgs
vs
$M_H = 200$ GeV

Basic acceptance cuts:

$E(l) > 20\,GeV \quad p_T(l) > 10\,GeV$

$|\eta_l| < 3$

$E(j) > 20\,GeV \quad p_T(j) > 10\,GeV$

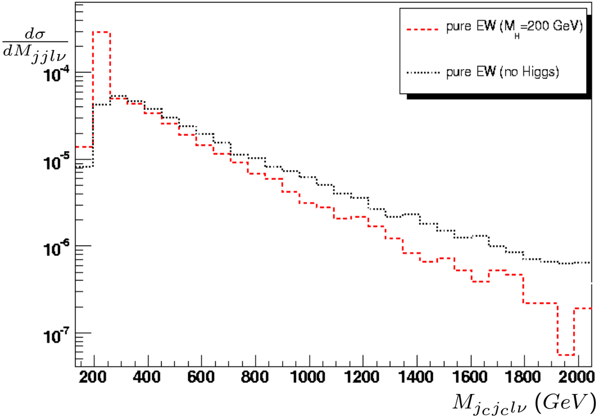
$|\eta_j| < 6.5 \quad m_{jj} > 20\,GeV$

No sensible difference at high $M_{j_c j_c l\nu}$ between the two scenarios without proper selection cuts!

The $l\nu$ channel

$$pp \rightarrow qq' \rightarrow 4q + \mu\,\nu_\mu$$

Final $\mathcal{O}(\alpha_{EM}^6)$ result after applying selection cuts



no Higgs
vs
$M_H = 200$ GeV

events with no *b* quarks

$70\,GeV \leq M_{jcjc} \leq 100\,GeV$

$|\eta_{j_f} - \eta_{j_b}| > 4$

$p_T(\mu\nu) > 100\,GeV$

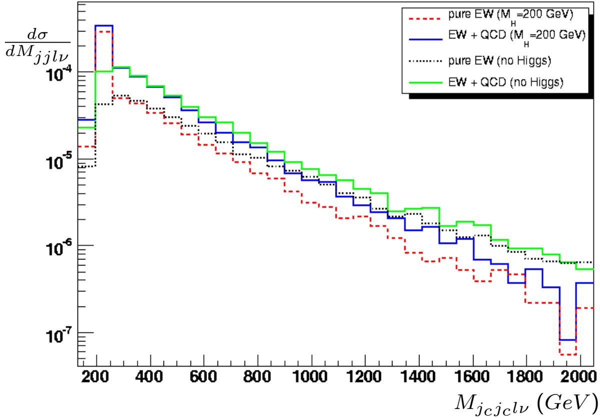
$|\eta(\mu\nu)| \leq 2$

$\min\,(M_{j_f l\nu}\,,\,M_{j_b l\nu}) > 250\,GeV$

The $l\nu$ channel

$$pp \longrightarrow qq' \longrightarrow 4q + \mu\,\nu_\mu$$

Final $\mathcal{O}(\alpha_{EM}^6)$ + $\mathcal{O}(\alpha_{EM}^4\alpha_S^2)$ result after applying selection cuts



no Higgs
vs
$M_H = 200$ GeV

events with no *b* quarks

$70\ GeV \leq M_{j_cj_c} \leq 100\ GeV$

$|\eta_{j_f} - \eta_{j_b}| > 4$

$p_T(\mu\nu) > 100\ GeV$

$|\eta(\mu\nu)| \leq 2$

$\min\left(M_{j_fl\nu}\,,\,M_{j_bl\nu}\right) > 250\ GeV$

Observable difference between no Higgs and $M_H = 200$ GeV:
ratio ~ 1.5 at $M_{j_cj_cl\nu} = 1$ TeV

The $l\nu$ channel

Integrated cross sections in the *high*-$M_{j_c j_c l\nu}$ region

$M_H = 200$ GeV

- $\int_{1\,TeV}^{\infty} dM_{j_c j_c l\nu} \frac{d\sigma}{dM_{j_c j_c l\nu}} \sim$ 2 fb

  $\hookrightarrow \quad \sim 200$ events/year expected at $\mathcal{L} = 100\,\text{fb}^{-1}$

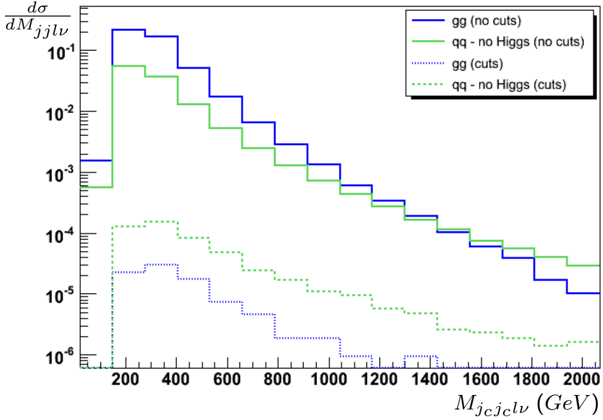
no Higgs

- $\int_{1\,TeV}^{\infty} dM_{j_c j_c l\nu} \frac{d\sigma}{dM_{j_c j_c l\nu}} \sim$ 3 fb

  $\hookrightarrow \quad \sim 300$ events/year expected at $\mathcal{L} = 100\,\text{fb}^{-1}$

The $l\nu$ channel

Comparison between $gg \to 4q + \mu\,\nu_\mu$ and $qq' \to 4q + \mu\,\nu_\mu$
$\mathcal{O}(\alpha_{EM}^6) + \mathcal{O}(\alpha_{EM}^4 \alpha_S^2)$ contributions



Basic acceptance cuts:

$E(l) > 20\ GeV \quad p_T(l) > 10\ GeV$

$|\eta_l| < 3$

$E(j) > 20\ GeV \quad p_T(j) > 10\ GeV$

$|\eta_j| < 6.5 \quad m_{jj} > 20\ GeV$

Selection cuts:

b-tagging for $|\eta| < 1.5$ with

efficiency 0.8

$70\ GeV \leq M_{j_c j_c} \leq 100\ GeV$

$|\eta_{j_f} - \eta_{j_b}| > 4 \quad |\eta(\mu\nu)| \leq 2$

$p_T(\mu\nu) > 100\ GeV$

$\min\,(M_{j_f l\nu}\,,\, M_{j_b l\nu}) > 250\ GeV$

More realistic selection criteria based on *b-tagging* and invariant mass cuts are under study

New Physics

Work in progress

Beyond the Standard Model

Alternative models of Electroweak Symmetry Breaking

Without Higgs, the amplitude for $W_L W_L$ scattering grows indefinitely with CM energy $\rightarrow$ violation of unitarity

Different models of constructing amplitudes which satisfy unitarity constraints from low-order amplitudes have been implemented in Phantom for $W_L W_L$ and are currently under test (Butterworth *et al.*, Chanowitz)

Future projects

Phenomenology

- complete analysis including processes with 2 *external gluons* (Phantom) and *boson + jets* background contribution (AlpGen)
- more realistic studies in CMS accounting for detector simulation and reconstruction (in collaboration with the Torino CMS group)
- beyond the benchmark *no-Higgs* scenario: analysis of alternative models of EWSB

R&D

- Further optimization of the code
- Extension to e^+e^- colliders