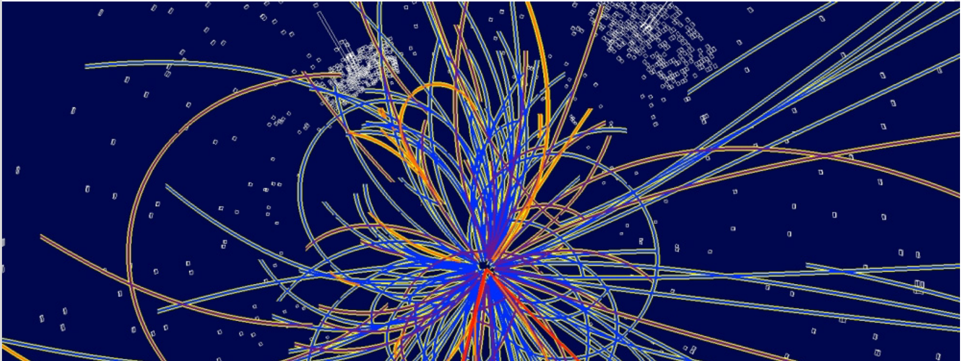
INSTITUTE FOR THEORETICAL PHYSICS, HEIDELBERG UNIVERSITY

BSM searches using weak boson pair production

Christoph Englert | 26.10.2010

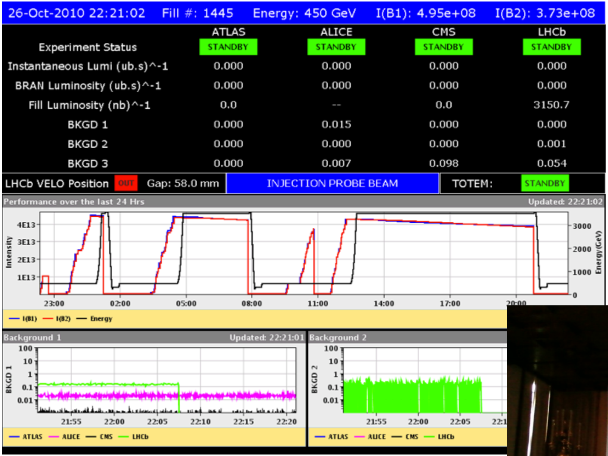
HIGH ENERGY SEMINAR, UC DAVIS



Outline

1. Weak boson pair (+jets) production processes at the LHC
   - unitarizing resonances in weak boson fusion
   - indirect effects in QCD Wγ(+jet) and WZ(+jet) production
2. Unravelling resonance J^{CP} properties from semi-hadronic ZZ decays
   - (sub)jet methods
   - strategy-adapted observables

Expecting data

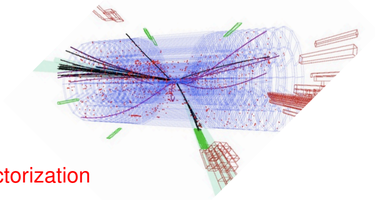


LHC Phenomenology

- need to reliably simulate and interpret (B)SM LHC physics...

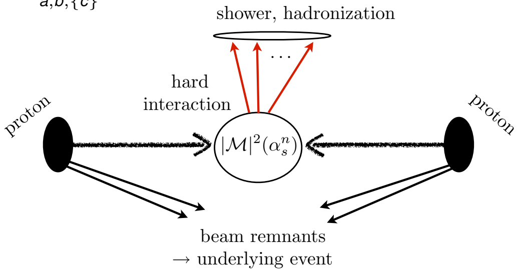
(new, better, beloved, ...) electroweak model
$\otimes$
physics already there
(i.e. QCD, Zs, Ws, ts)

$\overset{?}{\Longrightarrow}$



- apply asymptotic perturbative expansion and factorization

$$\sigma = \sum_{a,b,\{c\}} \int \cdots \int \mathrm{d}x_1\, \mathrm{d}x_2\, \mathrm{dLIPS}\, f_{a/P}(x_1, \mu_F)\, f_{b/P}(x_2, \mu_F)\, |\mathcal{M}^{ab\to\{c\}}(\mu_F, \mu_R)|^2\, \Theta(\text{cuts})\, \mathcal{F}(\text{jets})$$



hard process sets the stage

new particles $\sim$ new large scale

1.) exploit known radiation patterns

2.) assess theoretical uncertainty

3.) improve perturbative precision

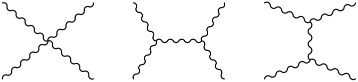
What do we currently know?

no viable test of the Fermi-scale and beyond! But we may expect . . .

$$\mathcal{L} = \mathcal{L}_{\text{SM w/o Higgs}} + \underbrace{\mathcal{L}_{[SU(2)\times U(1)/U(1)]}}_{\text{new resonances?}} + \underbrace{\frac{1}{\Lambda_{UV}^2}\mathcal{L}^{(6)} + \ldots}_{\text{non-SM interactions?}}$$

What can we guess from theory

- Require new propagating degrees of freedom [Cornwall, Levin, Tiktopoulos '73]



$\propto$ (energy)^2

- Higgs mass in the SM is a very relevant operator

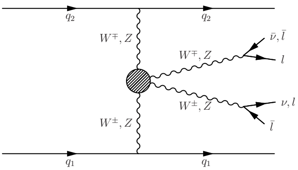
$$\mathcal{L}_{\text{SM}} \supset \Lambda_{\text{UV}}^2 H^\dagger H \qquad \text{EWSB \& } M_{\text{Planck}}, M_{\text{GUT}}, \ldots \to \text{HIERARCHY PROBLEM}$$

- Ameliorate with approx. global symmetries or non-canonical scaling
  [SUSY...] [Agashe, Contino, Pomarol '04] [Luty, Okui '04]
- Framework for fully-computable strong interactions motivated from AdS/CFT
  [Witten '98] [Arkani-Hamed, Porrati, Randall '01] [Rattazzi, Zaffaroni '01] [Csaki, Grojean, Pilo, Terning '04]

Phenomenological aspects of strongly interacting sectors

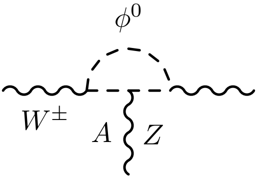
$$\left\langle J_A^\mu(p) J_A^\nu(-p) \right\rangle = (p^2 g^{\mu\nu} - p^\mu p^\nu) \left(\frac{F_\pi^2}{p^2} + \sum_n \frac{F_n^2}{p^2 - m_n^2} \right)$$

['t Hooft '74] [Witten '79]



production of longitudinally polarized gauge bosons in experimentally clean channels

[Bagger *et al.* '95] [CE, Jager, Worek, Zeppenfeld '08]



precise predictions of processes involving trilinear gauge boson couplings

[Baur, Han, Ohnemus '93] [LEPWG '06]

[Campanario, CE, Spannowsky, Zeppenfeld '09 '10]

Indirect searches

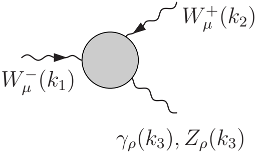
non-standard trilinear couplings

- Integrating out new high-mass degrees of freedom:

  non-SM operators at low scales

- Extend SM Lagrangian by the most general $\mathcal{CP}$-conserving dim ≤ 6 operators modifying the trilinear gauge vertices

$$\begin{aligned}\mathcal{L}_{WW\gamma} &= -ie\big[W^\dagger_{\mu\nu}W^\mu A^\nu - W^\dagger_\mu A_\nu W^{\mu\nu} \\ &\quad + \kappa_\gamma W^\dagger_\mu W_\nu F^{\mu\nu} + \frac{\lambda_\gamma}{m_W^2} W^\dagger_{\lambda\mu} W^\mu_\nu F^{\nu\lambda}\big] \\ \mathcal{L}_{WWZ} &= -ie\cot\theta_w\,\big[g_1^Z\left(W^\dagger_{\mu\nu}W^\mu A^\nu - W^\dagger_\mu A_\nu W^{\mu\nu}\right) \\ &\quad + \kappa_Z W^\dagger_\mu W_\nu Z^{\mu\nu} + \frac{\lambda_Z}{m_W^2} W^\dagger_{\lambda\mu} W^\mu_\nu Z^{\nu\lambda}\big]\end{aligned}$$



- Analysis with $q\bar{q} \to W\gamma$, WZ kinematically favored, but jet emission unsuppressed at the LHC: [Baur, Han, Ohnemus '93] [Baur, Han, Ohnemus '95]

$$\sigma(W\gamma + \text{jet})/\sigma(W\gamma) \sim 3$$

$\rightarrow$ necessary to precisely know anomalous couplings impact on $W\gamma$+jet
NLO QCD precision mandatory

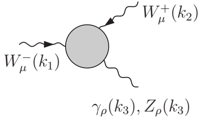
Indirect searches

non-standard trilinear couplings

high-scale unitarity: anomalous parameters should be understood as form factors, e.g.

$$(\Delta g_1^Z, \Delta\kappa_Z, \lambda_Z, \Delta\kappa_\gamma, \lambda_\gamma) = \frac{(\Delta g_1^{Z,0}, \Delta\kappa_Z^0, \lambda_Z^0, \Delta\kappa_\gamma^0, \lambda_\gamma^0)}{(1 + m_{WZ}^2/\Lambda^2)^2},$$

$\Lambda^{\mathrm{LEP}} = 2$ TeV



Bounds from combined LEP data [LEPWG '06]

$g_1^{Z,0} = 0.991^{+0.022}_{-0.021}$ $\kappa_\gamma^0 = 0.984^{+0.042}_{-0.047}$ $\lambda_\gamma^0 = -0.016^{+0.021}_{-0.023}$ 68% CF

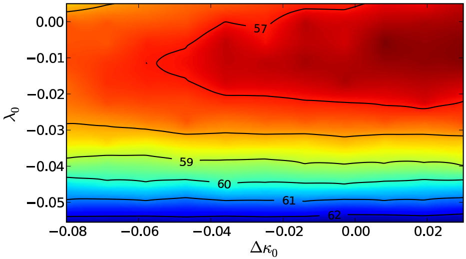
other parameters follow from gauge relations

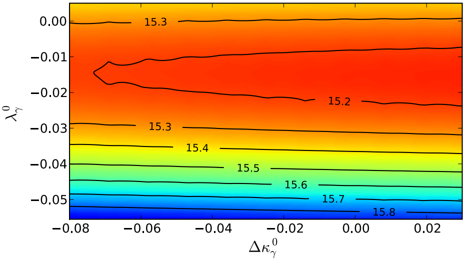
- We have performed a detailed investigation of the jet-inclusive signal processes, also including anomalous couplings [Campanario, CE, Spannowsky, Zeppenfeld '09, '10] [Campanario, CE, Kallweit ,Spannowsky, Zeppenfeld '10]
- Full inclusive analysis underway

Indirect searches

non-standard trilinear couplings

Precision phenomenology of anomalous couplings, full $\mathcal{O}(\alpha_s^2\alpha^3)$ matrix elements

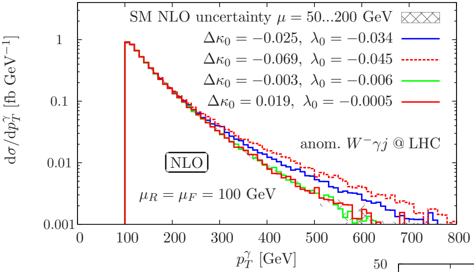


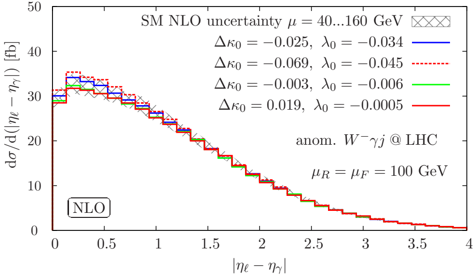


Indirect searches

non-standard trilinear couplings

Precision phenomenology of anomalous couplings





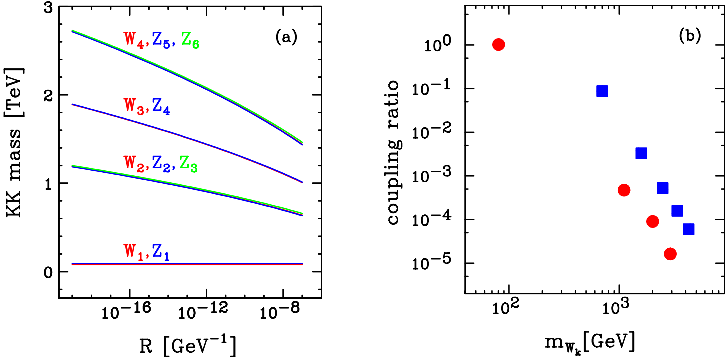
Direct searches: a Technicolor paradigm

(minimal) Higgsless Phenomenology

[Csaki, Grojean, Pilo, Terning '04]

- $\mathbb{P}_{LR} \times SU(2)_L \times SU(2)_R \times U(1)$ bulk-gauged RS2 setup, broken by BCs

$$SU(2)_R \times U(1) \to U(1)_Y \quad \text{on Planck brane } z = R$$
$$SU(2)_L \times SU(2)_R \to SU(2)_D \quad \text{on TeV brane } z = R'$$



[CE, Jager, Zeppenfeld '08]

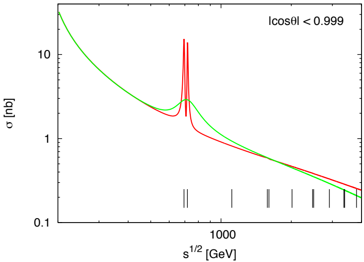
Direct searches: a Technicolor paradigm

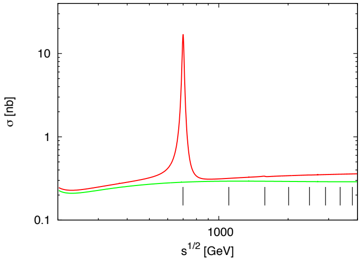
(minimal) Higgsless Phenomenology

strong sector "naturally" encodes unitarity conservation à la Sturm-Liouville

$$g_{WWZZ} = \sum_{k\geq 1} g^2_{W_k WZ} \qquad \mathcal{O}(s)$$

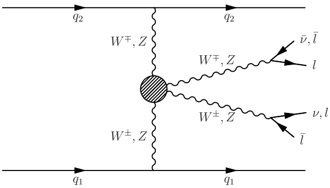
$$2(m_Z^2 + m_W^2) g_{WWZZ} = \sum_{k\geq 1} g^2_{W_k WZ} \left(3m^2_{W_k} - \frac{(m_Z^2 - m_W^2)^2}{m^2_{W_k}} \right) \qquad \mathcal{O}(\sqrt{s})$$



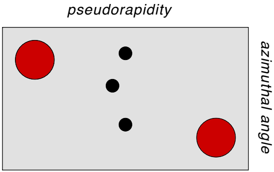


→ phenomenology dominated by first non-SM resonance (↔ unitarity)
"robust" against model-specific modifications (fermion sector)

Longitudinal gauge boson scattering @ LHC



$\Longrightarrow$



VBF signatures in general

[Bagger *et al.* '94] [Rainwater, Zeppenfeld '99]

- color singlet t-channel exchange (s-channel interference negligible)
- large Feynman-x to produce heavy resonance on-shell
- Altarelli-Parisi splitting: $p_T^{jet} \sim m_W$

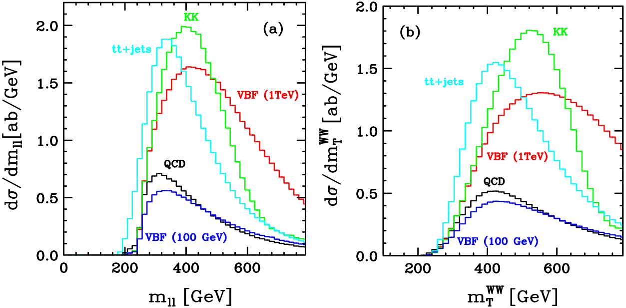
two energetic back-to-back jets to "tag" event
electroweak decay products hard and central

color correlations and kinematics are significantly different from QCD backgrounds

LHC pheno

- Full signal and background analysis for all WBF $VV'jj$ channels at the LHC all finite width and off-shell effects included beyond any approximation for signal and backgrounds [VBFNLO group '08] [CE, Jager, Worek, Zeppenfeld '08]
- Two minimal scenarios: heavy and broad techni-π-like (isoscalar) resonance $\sim$ 1 TeV, and narrow AdS/CFT – inspired techni-ρ (isovectorial)
- Take into account NLO QCD effects through efficient scale choices [Bozzi *et al.* '07] [CE, Jager, Zeppenfeld '08]

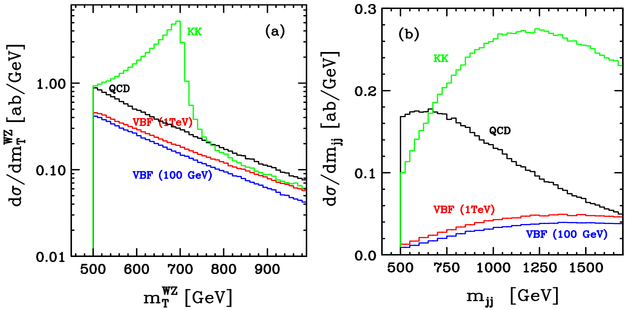
$pp \to e^- \mu^+ \not{E}_T jj$



LHC pheno

- Full signal and background analysis for all WBF $VV'jj$ channels at the LHC
  all finite width and off-shell effects included beyond any approximation for signal and backgrounds [VBFNLO group '08] [CE, Jager, Worek, Zeppenfeld '08]
- Two minimal scenarios: heavy and broad techni-π-like (isoscalar) resonance $\sim$ 1 TeV, and narrow AdS/CFT – inspired techni-ρ (isovectorial)
- Take into account NLO QCD effects through efficient scale choices
  [Bozzi *et al.* '07] [CE, Jager, Zeppenfeld '08]

$$pp \to e^{\pm}\mu^{+}\mu^{-}\not{E}_T jj$$



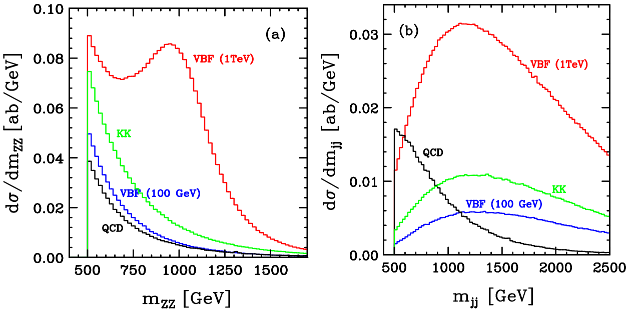
LHC pheno

- Full signal and background analysis for all WBF *VVjj* channels at the LHC
  all finite width and off-shell effects included beyond any approximation for signal and backgrounds [VBFNLO group '08] [CE, Jager, Worek, Zeppenfeld '08]

- Two minimal scenarios: heavy and broad techni-π-like (isoscalar) resonance $\sim$ 1 TeV, and narrow AdS/CFT – inspired techni-ρ (isovectorial)

- Take into account NLO QCD effects through efficient scale choices
  [Bozzi *et al.* '07] [CE, Jager, Zeppenfeld '08]

$pp \to e^- e^+ \mu^+ \mu^- jj$



High $\mathcal{L} = 300\ \text{fb}^{-1}$ discovery reach

isovectorial

Process	σ_S	σ_B	S/B	$S/\sqrt{B}$	$S/\sqrt{S+B}$	N_{signal}^{SM}	$N_{\text{bkgd.}}$
$W^\pm Zjj$	0.68	0.39	1.7	18.9	11.4	204	117
W^+W^-jj	0.40	0.78	0.5	7.9	6.4	120	234
$ZZjj \to 4\ell\, jj$	0.009	0.021	0.4	1.1	0.9	3	6
$ZZjj \to 2\ell 2\nu\, jj$	0.05	0.10	0.5	2.7	2.2	15	30

isoscalar

Process	σ_S	σ_B	S/B	$S/\sqrt{B}$	$S/\sqrt{S+B}$	N_{signal}^{SM}	$N_{\text{bkgd.}}$
$ZZjj \to 4\ell\, jj$	0.048	0.021	2.2	5.7	3.1	14	6
$ZZjj \to 2l2\nu\, jj$	0.27	0.10	2.7	14.8	7.7	81	30
W^+W^-jj	0.51	0.78	0.6	10.0	7.8	153	234
$W^\pm Zjj$	0.031	0.386	0.1	0.9	0.8	9	116

combined LHC analysis at high rates is highly sensitive to the realization of EWSB

Penalty of purity...

- WBF cross sections are small: robust against QCD corrections,

$$\text{BR}(Z \to \ell\ell) = 0.0336$$

- tiny leptonic branching ratios limits non-WBF searches, e.g. $gg \to H \to ZZ \to 4\mu$

throw away $\approx$ 99.9% of the signal!

- use subjet techniques to ameliorate BR-suppression via a hadronically-decaying Z while sufficiently reducing the backgrounds

[Butterworth, Davison, Rubin, Salam '08] [Soper, Spannowsky '10] [Hackstein, Spannowsky '10]

works to reconstruct SM-like produced Higgs resonance $m_H \gtrsim 350$ GeV

$$S/B \sim 0.5, \quad 5\sigma \text{ @ } 10 \text{ fb}^{-1}$$

- $H \to ZZ \to 4\mu$ standard candle for spin and $\mathcal{CP}$ determination for $m_H \gtrsim 300$ GeV

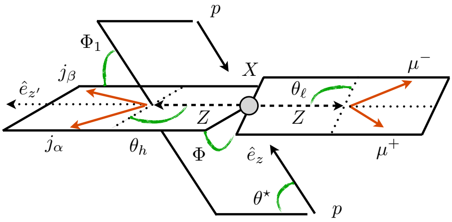
[Buszello *et al.* '02] [Gao *et al.* '10] [DeRujula *et al.* '10]

[Cabibbo, Maksymowicz '65] [Dell'Aquila, Nelson '85]

Can we supplement additional information from $X \to 2j + \ell^+\ell^-$, where X is a "Higgs-look-a-like"?

General J^{CP} production and decay

[Cabibbo, Maksymowicz '65] [Dell'Aquila, Nelson '85]
[Gao *et al.* '10] [DeRujula *et al.* '10]



$$\cos\theta_h = \frac{\mathbf{p}_\alpha \cdot \mathbf{p}_X}{\sqrt{\mathbf{p}_\alpha^2\,\mathbf{p}_X^2}}\Bigg|_{Z_h}, \quad \cos\theta_\ell = \frac{\mathbf{p}_- \cdot \mathbf{p}_X}{\sqrt{\mathbf{p}_-^2\,\mathbf{p}_X^2}}\Bigg|_{Z_\ell},$$

$$\cos\theta^\star = \frac{\mathbf{p}_{Z_\ell} \cdot \hat{e}_{z'}}{\sqrt{\mathbf{p}_{Z_\ell}^2}}\Bigg|_X, \quad \cos\tilde{\Phi} = \frac{(\hat{e}_z \times \hat{e}_{z'})\cdot(\mathbf{p}_- \times \mathbf{p}_+)}{\sqrt{(\mathbf{p}_- \times \mathbf{p}_+)^2}}\Bigg|_X,$$

$$\cos\Phi = \frac{(\mathbf{p}_\alpha \times \mathbf{p}_\beta)\cdot(\mathbf{p}_- \times \mathbf{p}_+)}{\sqrt{(\mathbf{p}_\alpha \times \mathbf{p}_\beta)^2\,(\mathbf{p}_- \times \mathbf{p}_+)^2}}\Bigg|_X$$

- Impose rapidity ordering $y_\alpha < y_\beta$
- Assume minimal effective interactions to analyze angular correlations

$$\mathcal{L}^{q\bar{q}X} = \bar{\Psi}_q \gamma^\mu \left(g_L^v \,\mathbb{P}_L + g_R^v \,\mathbb{P}_R \right) \Psi_q$$

$$\mathcal{L}^{ggX} = -\frac{1}{4}\left(g_1^s \, G^2\, X + g_2^s \, G\widetilde{G}\, X \right)$$

$$\mathcal{L}^{ZZX}_{\mu\nu} = c_1^s \, g_{\mu\nu} + \frac{c_2^s}{m_Z^2}\epsilon_{\mu\nu\rho\delta}\, p_1^\rho \, p_2^\delta \, .$$

$$\mathcal{L}^{ZZX}_{\mu\nu\rho} = c_1^v \left(g_{\mu\rho}\, p_{1,\nu} + g_{\nu\rho} p_{2,\mu} \right) - c_2^v \,\epsilon_{\mu\nu\rho\delta}\left(p_1^\delta - p_2^\delta \right)$$

[Keung, Low, Shu '08]

$$\mathcal{L}^{ZZX}_{\mu\nu\rho\delta} = c_1^t \left(p_{1,\nu}\, p_{2,\rho}\, g_{\mu\delta} + p_{1,\rho}\, p_{2,\mu}\, g_{\nu\delta} + p_{1,\rho}\, p_{2,\delta}\, g_{\mu\nu} - \frac{1}{2} m_X^2 \, g_{\mu\rho}\, g_{\mu\delta} \right)$$

$J^{\mathcal{CP}}(X)$	production	decay
0^+	$g_1^s \neq 0,\ g_2^s = 0$	$c_1^s \neq 0,\ c_2^s = 0$
0^-	$g_1^s = 0,\ g_2^s \neq 0$	$c_1^s = 0,\ c_2^s \neq 0$
1^+	$g_1^v = 0,\ g_2^v \neq 0$	$c_1^v = 0,\ c_2^v \neq 0$
1^-	$g_1^v \neq 0,\ g_2^v = 0$	$c_1^v \neq 0,\ c_2^v = 0$
2^+	$g_1^t \neq 0$	$c_1^t \neq 0$

Details on the analysis

- Include full off-shell effects in production and decay for the signal and the backgrounds (Z+jets, $t\bar{t}$, WZ, ZZ)
- Perform boosted fatjet/subjet analysis to reconstruct hadronic Z

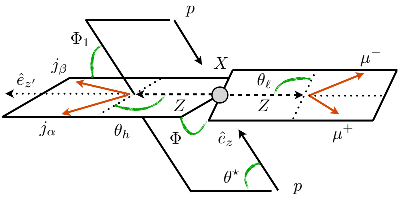
  [Butterworth, Davison, Rubin, Salam '08]

  1. Full event simulation with MadEvent + Pythia/Herwig++ [Sjostrand *et al.* '06] [Bahr *et al.* '08]
  2. Normalize to NLO results, include HCAL granularity [MCFM, HIGLU, VBFNLO, Cacciari '08]
  3. ask for a "fat" jet with large $p_T > 150$ GeV, C/A $R = 1.2$, and 2 isolated muons $p_T > 15$ GeV
  4. Undo last clustering, require "mass drop"

$$m_{j_1} < 0.67\, m_j(\text{fat jet})\,, \quad \Delta R^2_{j_1 j_2} \min(p^2_{T,j_1}, p^2_{T,j_2}) > 0.09\, m_j(\text{fat jet})^2$$

  5. "Filter" jet, i.e. recluster constituent with higher resolution (remove UEV), impose Z mass constraint
  6. Reconstruct X mass peak and center of mass system (crucial!)
  7. S/B improvement via "pruning" and "trimming" [Ellis *et al.* '09, '10] [Krohn *et al.* '10]

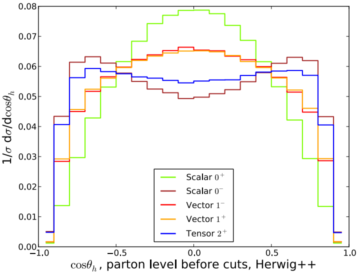
Tracing sensitivity...

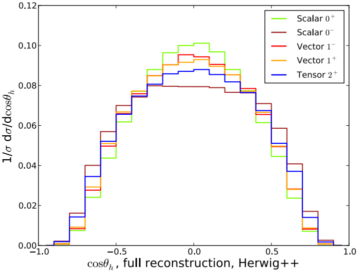


$$\cos\theta_h = \frac{\mathbf{p}_\alpha \cdot \mathbf{p}_X}{\sqrt{\mathbf{p}_\alpha^2\,\mathbf{p}_X^2}}\Big|_{Z_h}, \quad \cos\theta_\ell = \frac{\mathbf{p}_- \cdot \mathbf{p}_X}{\sqrt{\mathbf{p}_-^2\,\mathbf{p}_X^2}}\Big|_{Z_\ell},$$

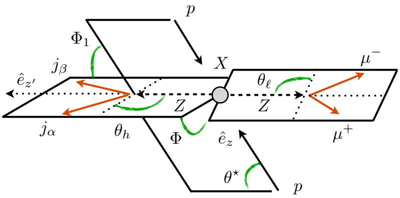
$$\cos\theta^\star = \frac{\mathbf{p}_{Z_\ell} \cdot \hat{e}_{z'}}{\sqrt{\mathbf{p}_{Z_\ell}^2}}\Big|_X, \quad \cos\tilde{\Phi} = \frac{(\hat{e}_z \times \hat{e}_{z'}) \cdot (\mathbf{p}_- \times \mathbf{p}_+)}{\sqrt{(\mathbf{p}_- \times \mathbf{p}_+)^2}}\Big|_X,$$

$$\cos\Phi = \frac{(\mathbf{p}_\alpha \times \mathbf{p}_\beta) \cdot (\mathbf{p}_- \times \mathbf{p}_+)}{\sqrt{(\mathbf{p}_\alpha \times \mathbf{p}_\beta)^2\,(\mathbf{p}_- \times \mathbf{p}_+)^2}}\Big|_X$$





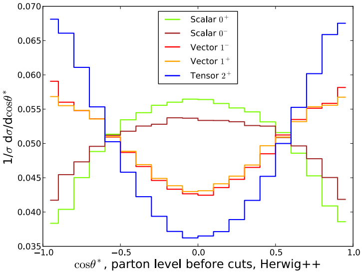
Tracing sensitivity. . .

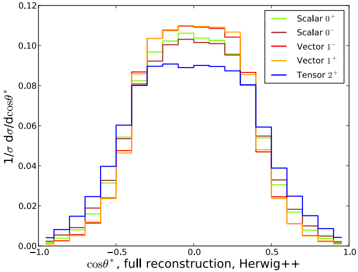


$$\cos\theta_h = \frac{\mathbf{p}_\alpha \cdot \mathbf{p}_X}{\sqrt{\mathbf{p}_\alpha^2\,\mathbf{p}_X^2}}\Bigg|_{Z_h}, \quad \cos\theta_\ell = \frac{\mathbf{p}_- \cdot \mathbf{p}_X}{\sqrt{\mathbf{p}_-^2\,\mathbf{p}_X^2}}\Bigg|_{Z_\ell},$$

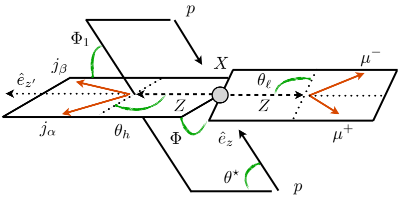
$$\cos\theta^\star = \frac{\mathbf{p}_{Z_\ell} \cdot \hat{e}_{z'}}{\sqrt{\mathbf{p}_{Z_\ell}^2}}\Bigg|_X, \quad \cos\tilde{\Phi} = \frac{(\hat{e}_z \times \hat{e}_{z'}) \cdot (\mathbf{p}_- \times \mathbf{p}_+)}{\sqrt{(\mathbf{p}_- \times \mathbf{p}_+)^2}}\Bigg|_X,$$

$$\cos\Phi = \frac{(\mathbf{p}_\alpha \times \mathbf{p}_\beta)\cdot(\mathbf{p}_- \times \mathbf{p}_+)}{\sqrt{(\mathbf{p}_\alpha \times \mathbf{p}_\beta)^2\,(\mathbf{p}_- \times \mathbf{p}_+)^2}}\Bigg|_X$$





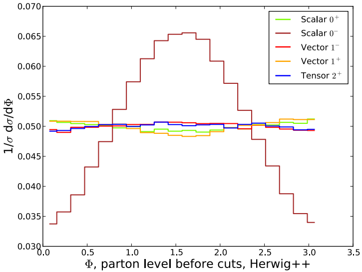
Tracing sensitivity...

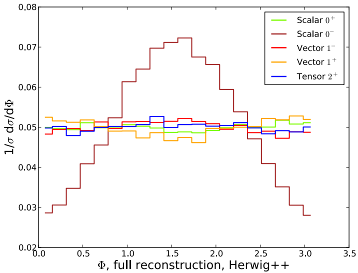


$$\cos\theta_h = \frac{\mathbf{p}_\alpha \cdot \mathbf{p}_X}{\sqrt{\mathbf{p}_\alpha^2\,\mathbf{p}_X^2}}\bigg|_{Z_h}, \quad \cos\theta_\ell = \frac{\mathbf{p}_- \cdot \mathbf{p}_X}{\sqrt{\mathbf{p}_-^2\,\mathbf{p}_X^2}}\bigg|_{Z_\ell},$$

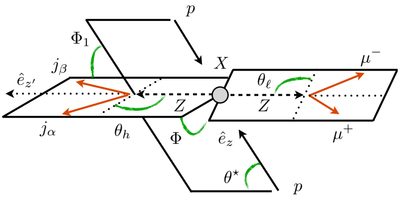
$$\cos\theta^\star = \frac{\mathbf{p}_{Z_\ell} \cdot \hat{e}_{z'}}{\sqrt{\mathbf{p}_{Z_\ell}^2}}\bigg|_X, \quad \cos\tilde{\Phi} = \frac{(\hat{e}_z \times \hat{e}_{z'}) \cdot (\mathbf{p}_- \times \mathbf{p}_+)}{\sqrt{(\mathbf{p}_- \times \mathbf{p}_+)^2}}\bigg|_X,$$

$$\cos\Phi = \frac{(\mathbf{p}_\alpha \times \mathbf{p}_\beta) \cdot (\mathbf{p}_- \times \mathbf{p}_+)}{\sqrt{(\mathbf{p}_\alpha \times \mathbf{p}_\beta)^2\,(\mathbf{p}_- \times \mathbf{p}_+)^2}}\bigg|_X$$





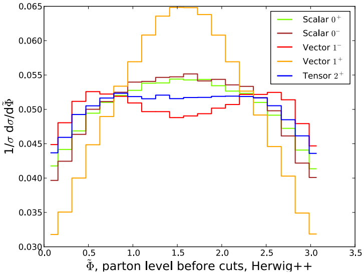
Tracing sensitivity...

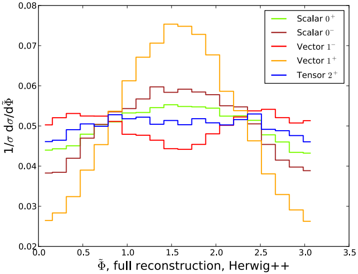


$$\cos\theta_h = \left.\frac{\mathbf{p}_\alpha\cdot\mathbf{p}_X}{\sqrt{\mathbf{p}_\alpha^2\,\mathbf{p}_X^2}}\right|_{Z_h}, \quad \cos\theta_\ell = \left.\frac{\mathbf{p}_-\cdot\mathbf{p}_X}{\sqrt{\mathbf{p}_-^2\,\mathbf{p}_X^2}}\right|_{Z_\ell},$$

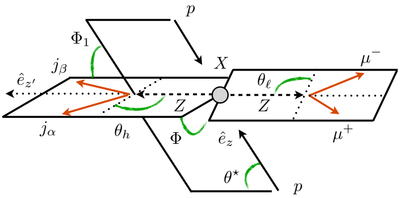
$$\cos\theta^\star = \left.\frac{\mathbf{p}_{Z_\ell}\cdot\hat{e}_{z'}}{\sqrt{\mathbf{p}_{Z_\ell}^2}}\right|_X, \quad \cos\tilde{\Phi} = \left.\frac{(\hat{e}_z\times\hat{e}_{z'})\cdot(\mathbf{p}_-\times\mathbf{p}_+)}{\sqrt{(\mathbf{p}_-\times\mathbf{p}_+)^2}}\right|_X,$$

$$\cos\Phi = \left.\frac{(\mathbf{p}_\alpha\times\mathbf{p}_\beta)\cdot(\mathbf{p}_-\times\mathbf{p}_+)}{\sqrt{(\mathbf{p}_\alpha\times\mathbf{p}_\beta)^2\,(\mathbf{p}_-\times\mathbf{p}_+)^2}}\right|_X$$





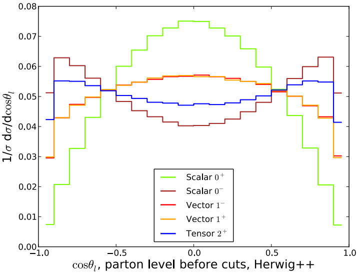
Tracing sensitivity...

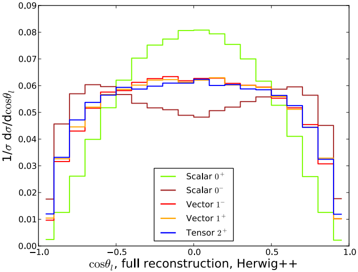


$$\cos\theta_h = \frac{\mathbf{p}_\alpha\cdot\mathbf{p}_X}{\sqrt{\mathbf{p}_\alpha^2\,\mathbf{p}_X^2}}\bigg|_{Z_h},\quad \cos\theta_\ell = \frac{\mathbf{p}_-\cdot\mathbf{p}_X}{\sqrt{\mathbf{p}_-^2\,\mathbf{p}_X^2}}\bigg|_{Z_\ell},$$

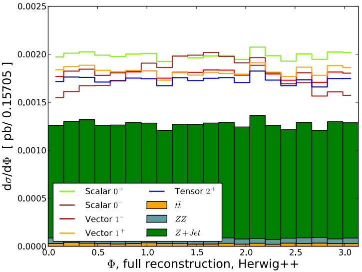
$$\cos\theta^\star = \frac{\mathbf{p}_{Z_\ell}\cdot\hat{e}_{z'}}{\sqrt{\mathbf{p}_{Z_\ell}^2}}\bigg|_X,\quad \cos\tilde{\Phi} = \frac{(\hat{e}_z\times\hat{e}_{z'})\cdot(\mathbf{p}_-\times\mathbf{p}_+)}{\sqrt{(\mathbf{p}_-\times\mathbf{p}_+)^2}}\bigg|_X,$$

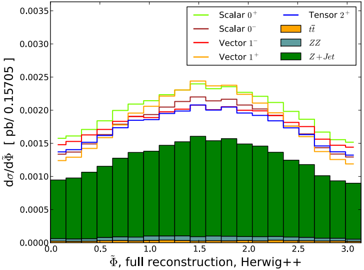
$$\cos\Phi = \frac{(\mathbf{p}_\alpha\times\mathbf{p}_\beta)\cdot(\mathbf{p}_-\times\mathbf{p}_+)}{\sqrt{(\mathbf{p}_\alpha\times\mathbf{p}_\beta)^2\,(\mathbf{p}_-\times\mathbf{p}_+)^2}}\bigg|_X$$

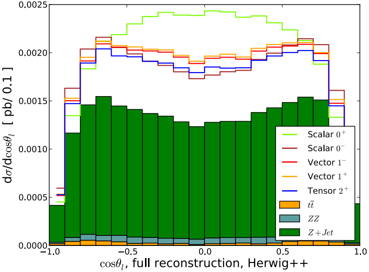




Include backgrounds

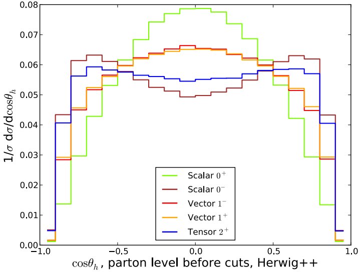




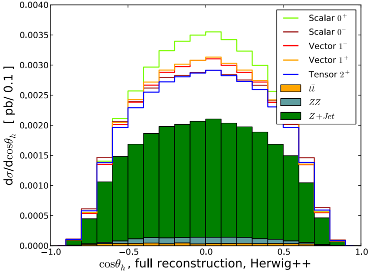


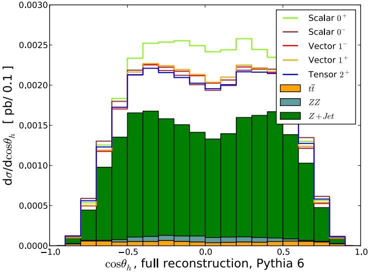
- Bulk of sensitivity is lost due to hard central requirements and degeneracies
- Z+jets fakes $\tilde{\Phi}$ (systematics $\sim$ 30%)
- residual discriminative power for $0^\pm$

Side benefit...



Sensitivity to shower strategy





Summary & Conclusions

- Measuring diboson + jet production processes at the LHC will contribute to understand the mechanism of EWSB (better)
  - WBF is perturbatively under control and exhibits experimentally clean signatures
  - theoretical (inclusive) diboson production has reached the perturbative precision to measure deviations in various phase space regions.
- New strategies in jet physics (theoretically) suggest (re)introduce new processes
  - supplement information on J^{CP} of a singly-produced resonance
  - important if LHC is not reaching its design-center of mass energy
  - we provide an observable which is sensitive to parton showering