Karlsruhe Institute of Technology

Higgsless Vector Boson Fusion at the LHC beyond leading order

GGI Conference “The Search for New States and Forces of Nature”, Florence

Christoph Englert | 29.10.2009

INSTITUTE FOR THEORETICAL PHYSICS

Outline

1. Overview over Higgsless Symmetry Breaking
2. Higgsless VBF signatures
3. Summary

based on

CE, B. Jäger and D. Zeppenfeld JHEP **0903** (2009) 060
CE, B. Jäger, M. Worek and D. Zeppenfeld, Phys. Rev. D **80** (2009) 035027

EWSB & hierarchies via.....

i) SUSY

ii) Technicolor

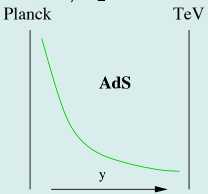
iii) Extra dimensions — unresolved spacelike dimension(s)

[Arkani-Hamed, Dimopoulos, Dvali '98], [Randall, Sundrum '99]

RS1:

5d Einstein equations exhibit 4d Lorentz-invariant solution, $S^1/\mathbb{Z}_2$ orbifold
$\longrightarrow$ slice of AdS_5

$$ds^2 = \frac{R^2}{y^2}\left(g_{\mu\nu}dx^\mu dx^\nu - dy^2\right) \to m_{\text{eff}} = \frac{R}{y} m_0$$



RS1 – bulk-gauging

[Pomarol *et al.* '99, '00], [Chang *et al.* '99],...

dictionary of duality via AdS/CFT

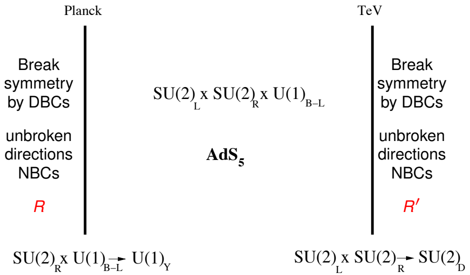
[Rattazzi, Zaffaroni *et al.* '00], [Arkani-Hamed *et al.* '00]

AdS/CFT – Bulk-gauged RS1

AdS/CFT conjecture [Maldacena '97], [Witten '98]

AdS_5 framework $\longleftrightarrow$ strongly-coupled CFT

'Realistic' Higgsless model [Csáki *et al.* '04, Agashe *et al.* '03] $T, U \approx 0$



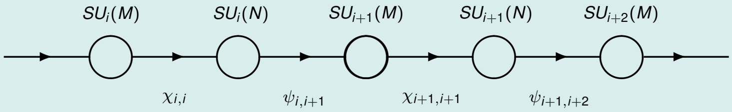
- $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ global symmetry
- $SU(2)_L \times U(1)_Y$ subgroup weakly gauged
- Strong CFT dynamics causing spontaneous breaking of CFI which also higgses the electroweak sector.

$S \approx 0 \rightarrow$ fermiophobic KKs
($\rightarrow$ bulk-fermions)

$\rightarrow$ 'Walking extended technicolor'

vectors an axial-vectors: *e.g.* Kaluza-Klein W_k (ρ-like bound states)

Notes on deconstruction [Arkani-Hamed, Cohen, Georgi '01]



- Connections with deconstruction [Randall, Shadmi, Weiner '02]
- Seminal to continuum model-building (delocalization,. . .) [Chivukula *et al.* '05]
- Popular candidates to model higgsless LHC phenomenology [He *et al.* '08]
- Phenomenologically quite identical to continuum theory [Belyaev *al.* '09]

Drawbacks, model-building issues

- 3rd generation → new discovery modes, flavor physics, . . . [Csáki *et al. 06*]
- Tension between minimal models and electroweak precision data
  [Barbieri, Pomarol, Rattazzi '03], [Barbieri *et al.* '08]

Higgsless ELW mass spectrum

- $5d$ gauge fields decompose under the unbroken $4d$ Lorentz group

$$A_M(x,y) = \left(A^k_\mu, A^k_5\right) = 4d \text{ vectors} \oplus 4d \text{ scalars}$$

- Action mixes $4d$ scalar and $4d$ vector (cf. SM)

$$S \supset \int \mathrm{d}^4x \int_R^{R'} \mathrm{d}y \frac{R}{y} \left\{ -\frac{1}{4} F^{a,\mu\nu} F^a_{\mu\nu} - \frac{1}{2} F^{a,\mu 5} F^a_{\mu 5} \right\}$$

- ∂-conditions & gauge fixing $\Rightarrow$ A_5 becomes the longitudinal component of A_μ, i.e. A_5 decouples in unitary gauge

$\Rightarrow$ no scalars in theory's spectrum,

Gauge boson mass operator $\hat{m}^2 = y^{-1}\partial_y - \partial_y^2$

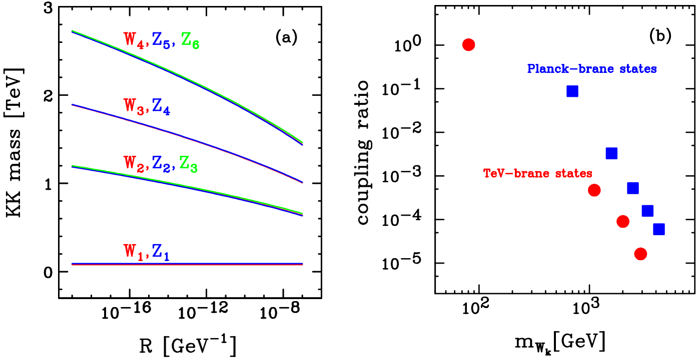
- reg. SLP along additional dimension $\Rightarrow$ KK decomposition of gauge fields,

$$\text{e.g.} \quad A^{3L}_\mu(x,y) = a Z^{(0)}_\mu(x) + \sum_{k\geq 1} \psi^B_k(y) Z^{(k)}_\mu(x)$$

massless mode massive modes

The Higgsless model - masses & couplings

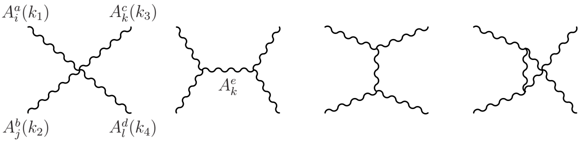
- Model is determined by a single parameter, chosen to be the localization of the *UV* brane R (T Parameter bound $\lesssim 10^{-7}\ \mathrm{GeV}^{-1}$).



[CE, B. Jäger, D. Zeppenfeld '08]

$W_k WZ$ coupling ratio wrt to WWZ coupling for $m_{W_2} = 700\ \mathrm{GeV}$

The warped Higgsless model – Unitarity



$\propto (p^0_{(A)})^0$

Necessary SM sum rules for $\sqrt{s} \gg m_k$

[Birkedal, Perelstein, Matchev '04, Chivukula *et al.* '08]

$$g_{W_1W_1W_1W_1} = \sum_{k\geq 0} g^2_{W_1W_1Z_k} \qquad \mathcal{O}(s)$$

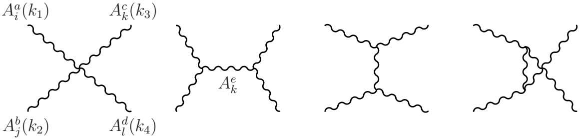
$$4m^2_{W_1} g_{W_1W_1W_1W_1} = 3\sum_{k\geq 1} m^2_{Z_k} g^2_{W_1W_1Z_k} \qquad \mathcal{O}(\sqrt{s})$$

$$g_{W_1W_1Z_1Z_1} = \sum_{k\geq 1} g^2_{W_kW_1Z_1} \qquad \mathcal{O}(s)$$

$$2(m^2_{Z_1} + m^2_{W_1}) g_{W_1W_1Z_1Z_1} = \sum_{k\geq 1} g^2_{W_kW_1Z_1}\left(3m^2_{W_k} - \frac{(m^2_{Z_1} - m^2_{W_1})^2}{m^2_{W_k}}\right) \qquad \mathcal{O}(\sqrt{s})$$

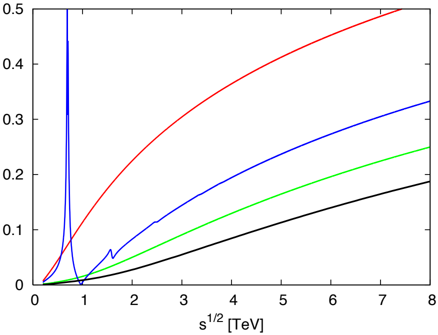
...obeyed as consequence of the regular SLP in the continuum $\surd$

The warped Higgsless model – Unitarity



$\propto (p^0_{(A)})^0$

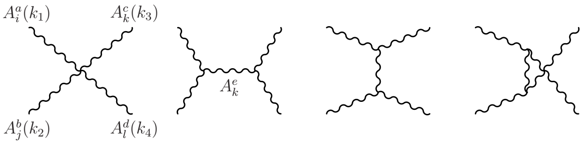
- Unitarity violation postponed to several TeV (*upper limit*).



Partial wave projection for $m_{W_2} = 700$ GeV,

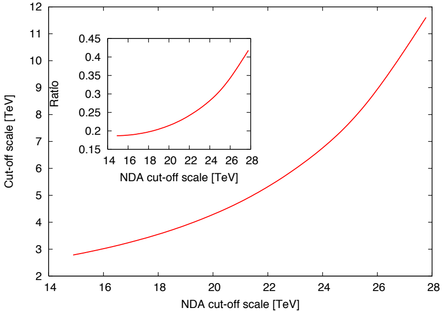
$J = 0$, $J = 1$, $J = 2$, $J = 3$

The warped Higgsless model – Unitarity



$\propto (p^0_{(A)})^0$

- Extract upper limit on NDA $\mathcal{O}(1)$ determined from AdS_5



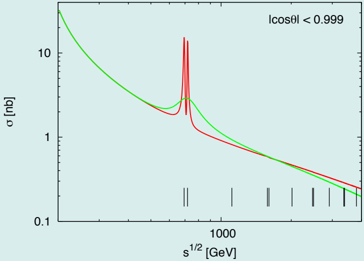
Higgsless WW, WZ cross sections

- Phenomenology with W', Z' - saturated sum rules: W' is 'smoking gun'

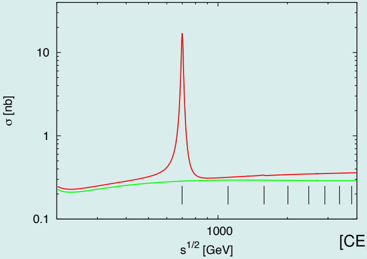
[Birkedal, Perelstein, Matchev '04]

'Saturation' in very good agreement with full calculation:

$WW \to WW$



$WZ \to WZ$



[CE, '07]

Phenomenology entirely dominated by the first non-SM mode ($\leftrightarrow$ unitarity!)

flat space $\sim$ warped space

VBF signatures in general

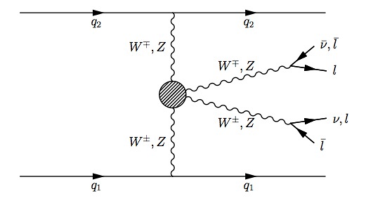
- Weak Boson fusion processes access gauge boson scattering.

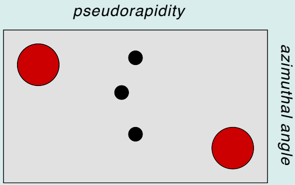
  sensitivity to the mechanism of EWSB

- Clean and distinct signatures of gold and silver plated modes at the LHC.

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

  cut on typical VBF signature highly reduces QCD backgrounds





VBF processes provide prominent discovery channels of extra vector bosons,
especially for suppressed Drell-Yan production.

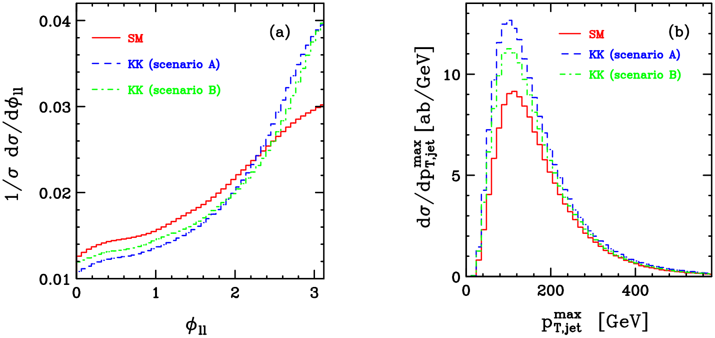
Higgsless *WWjj* signatures

VBF cuts

$$p_T^j \geq 20\ \mathrm{GeV},\ |\eta_j| \leq 4.5,\ |\Delta\eta_{jj}| \geq 4,\ \eta_{j_1} \times \eta_{j_2} < 0,\ m_{jj} \geq 600\ \mathrm{GeV},$$
$$p_T^\ell \geq 20\ \mathrm{GeV},\ |\eta_\ell| \leq 2.5,\ R_{ll} \geq 0.2,\ R_{jl} \geq 0.4,\ \text{leptons in jet rapidity gap}$$

$$\sigma^{\mathrm{tot}}(\mu_F = Q) = 1.70, 2.28, 2.03\ \mathrm{fb}$$

[CE, B. Jäger, D. Zeppenfeld '08]



smearing: CMS-Note 2006/035,036

Higgsless W^+Zjj signatures

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$$\sigma^{\text{tot}}(\mu_F = Q) = 0.18, 0.35, 0.24\ \text{fb}$$

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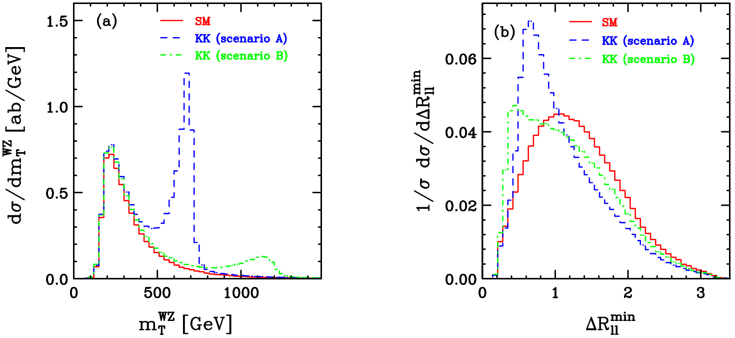

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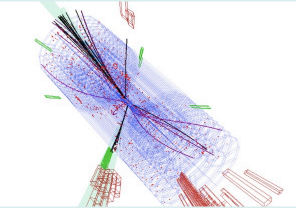
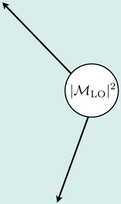
NLO-QCD?!

Why NLO corrections

- LO = "Order of magnitude approximation" ↔ scale dependence
  (lower bound on uncertainty!)
- Hadron-colliders → total QCD quantum corrections are sizable 2
- Differential QCD-corrections even more important:
  differential shapes determined @NLO, jet-definition,. . .



Experiment



hard fixed-order QCD

- RG-improved LO analysis, i.e.

$$\mu_{F,R} = \mu_{F,R}(\text{typical scales; }\underline{\text{Observable}})$$

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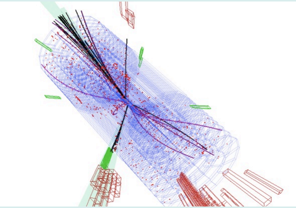

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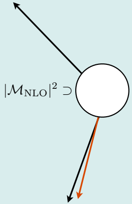

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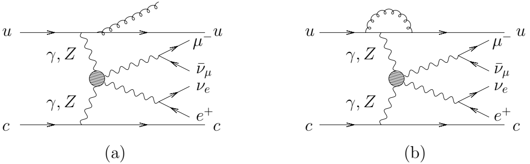
Higgsless signatures @ NLO-QCD



Anatomy of NLO-QCD corrections ('external' QCD – no gluon tower)

- Handle IR-divergencies à la Catani-Seymour [Catani, Seymour '96], [KLN '62 '64]

$$\sigma^{\mathrm{NLO}} = \sigma^{\mathrm{LO}} + \underbrace{\int_{n+1} \left(d\sigma^{\mathrm{R}} - d\sigma^{\mathrm{A}}\right)}_{\text{finite} \sim \text{(a)}} + \underbrace{\int_{n} \left(d\sigma^{\mathrm{Virt}} + \int_1 d\sigma^{\mathrm{A}}\right)}_{\text{finite} \sim \text{(b)}}$$

- Subtraction term reproduces IR-divergencies of the real emission matrix element

$$d\sigma^{\mathrm{Virt}} \sim |\mathcal{M}_B|^2 \frac{\alpha_s(\mu_R)}{\pi} \left(\frac{4\pi\mu_R^2}{Q^2}\right)^{\epsilon} \Gamma(1+\epsilon) \left[-\frac{C_F}{\epsilon^2} - \frac{\gamma_q}{\epsilon}\right] + 2\,\mathrm{Re}\,[\widetilde{\mathcal{M}}_{\mathrm{V}} \mathcal{M}_{\mathrm{B}}^*]$$

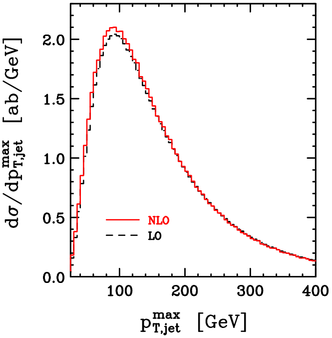
Loop corrections in terms of process-universal building blocks [Jäger, Oleari, Zeppenfeld '06]
[Campanario, CE, Spannowsky, Zeppenfeld '09]

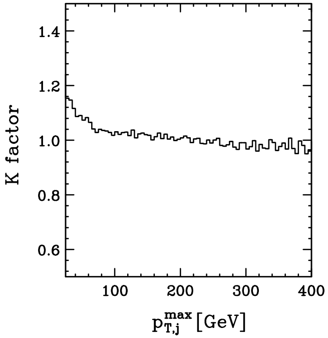
Higgsless signatures @ NLO-QCD

Total NLO correction for W^+Zjj with leptonic decay: $\sigma^{\rm NLO}/\sigma^{\rm LO}$

Scale μ	$\sigma^{\rm LO}$ [fb]	$\sigma^{\rm NLO}$ [fb]	K factor
$(m_W + m_Z)/2$	0.359	0.355	0.989
Q	0.349	0.356	1.020
m_{W_2}	0.283	0.346	1.223

← RG improvement!?





[CE, B. Jäger, D. Zeppenfeld '08], cf. SM [Bozzi *et al.* '07]

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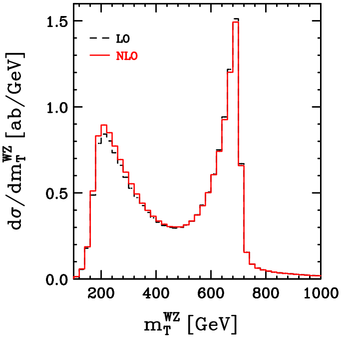
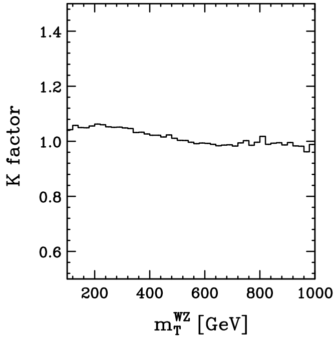




[CE, B. Jäger, D. Zeppenfeld '08]

Can we separate the signal from the background?

- VBF provides clean enough signatures to cope with very general BSM-EWSB

  [Bagger *et al.* '94 '95]

- Dedicated refinement of the analysis for all channels @ LHC

  [CE, Jäger, Worek, Zeppenfeld '08]

Signal procs	background procs
$pp \to W^\pm Zjj \to 3\ell \not{p}_T jj$ $pp \to W^+W^- jj \to 2\ell \not{p}_T jj$ $pp \to ZZjj \to 4\ell \not{p}_T jj$	$t\bar{t} + \text{jets}$ QCD $pp \to VVjj$ incl. leptonic decays

taking into account

- full matrix elements for signal and backgrounds
- double jet tagging
- full off-shell effects & leptonic final states
- central jet veto
- b-tag efficiencies,
- RG improvements

Can we separate the signal from the background?

Process	σ_S	σ_B	S/B	$S/\sqrt{B}$	$S/\sqrt{S+B}$	N^{SM}_{signal}	$N_{\text{bkgd.}}$
$W^\pm Zjj$	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

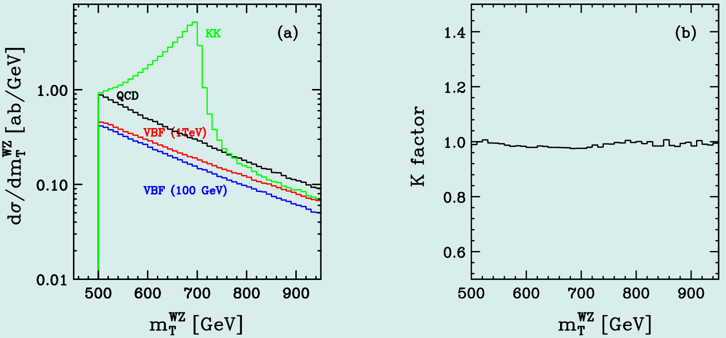
@300 fb^{-1}

LHC is highly sensitive to the scenario!

- Combined analysis of VBF @ LHC sheds light on EWSB

Can we separate the signal from the background?

QCD-impact on the signal for these selection cuts?



Summary

- Higgsless EWSB defines phenomenologically appealing BSM scenarios
- If VBF phenomenologically dominates (fermiophobic KKs), the signatures are

  (i) clearly visible and perturbatively stable,

  (ii) largely independent of the fermionic sector,

  (iii) rather model independent

- Additional KKs generically too weakly coupled $\rightarrow$ no '$d > 4$' VBF-proof
- The MC Code is publicly available at [Arnold *et al.*, '08]

  `http://www-itp.particle.uni-karlsruhe.de/~vbfnloweb/`

  and features all the stuff you need....

  (GNU-build system, libraries, LHA, manual, ...)
- 'Use your own scenario' switch — plug in your scenario and get differential NLO-QCD cross sections