Karlsruhe Institute of Technology

Higgsless Vector Boson Fusion at the LHC beyond leading order

PSI Particle Theory Seminar

Christoph Englert | 17.12.2009

Institute for Theoretical Physics

Outline

1. Review of higgsless symmetry breaking
2. Higgsless VBF signatures
3. Impact of QCD corrections
4. 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

Motivation

We still do not have a viable test of the Fermi-scale and beyond! But we may expect ...

$$\mathcal{L} = \mathcal{L}_{\text{SM w/o Higgs}} + \mathcal{L}_{[SU(2)\times U(1)/U(1)]} + \frac{1}{\Lambda_{UV}^2}\mathcal{L}^{(2)} + \dots$$

...bottom-up phenomenology

The Standard Model $\supset \mathcal{L}_{\text{Yuk}} \sim y_{ik} H \bar{f}_i f_j$

- unwanted flavor effects decouple ($\Lambda_{\text{UV}} \to \infty$) ☺ (want $[H] = 1$ $\surd$)

$$\mathcal{L}^{(2)} \sim (\bar{f}f)(\bar{f}f)$$

broken symmetry	operator	Λ_{UV}
B, L	$(fff\ell)/\Lambda_{\text{UV}}$	$10^{13}\,\text{TeV}$
1,2 family flavor	$(dsds)/\Lambda_{\text{UV}}$	$10^{3}\,\text{TeV}$

(hard to find direct evidence...)

- Higgs mass very relevant operator ☹ (want $[H^\dagger H] = 4$)

$$\mathcal{L}_{\text{SM}} \supset \Lambda_{\text{UV}}^2 H^\dagger H$$

EWSB & $M_{\text{Planck}}, M_{\text{GUT}}, \dots \to$ HIERARCHY PROBLEM

EWSB & hierarchies via.....

i) SUSY

ii) Technicolor & composite Higgs scenarios — EWSB broken by strong dynamics

$H \sim \bar{f}f$ ☺ but $m_t^2 \sim [\bar{t}t][\bar{f}f]/\Lambda^2_{\mathrm{UV}}$ ☹

. . . maybe solution in low N conformal dynamics? [Luty, Okui '09]

iii) Extra dimensions — unresolved spacelike dimension(s)

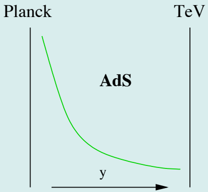
[Arkani-Hamed, Dimopoulos, Dvali '98], [Randall, Sundrum '99]

RS1:

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

$\Longrightarrow$ slice of AdS$_5$:

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



$\supset$ SM

. . . delocalized gauge fields were soon to follow e.g. [Pomarol '00]

$5d \to 4d$ mass spectrum in a nutshell

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

$$A^a_M(x,y) = (A^a_\mu, A^a_5) = 4d \text{ vectors} \oplus 4d \text{ scalars}$$

- 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 '$\Longrightarrow$' A_5 becomes the longitudinal component of A_μ, i.e. A_5 decouples in unitary gauge

[Csáki *et al.* '04]

$\Rightarrow$ no scalars in theory's spectrum,
gauge boson mass operator $\hat{m}^2 = y^{-1}\partial_y - \partial_y^2 \Rightarrow$ Bessel functions

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

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

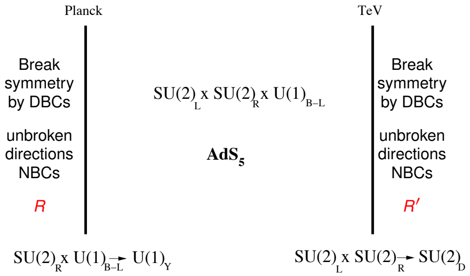
massless mode — massive modes

Strong interaction – Bulk-gauged RS1

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

AdS$_5$ framework $\longleftrightarrow$ large N 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.

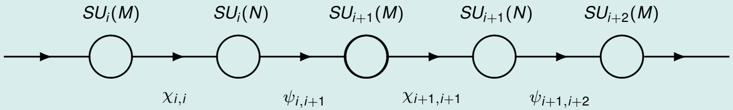
$S \approx 0 \rightarrow$ fermiophobic KKs ($\rightarrow$ bulk-fermions)

$\rightarrow$ 'Walking extended technicolor'

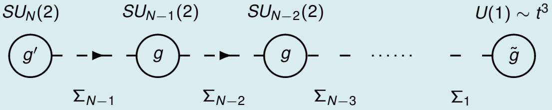
vectors an axial-vectors: *e.g.* Kaluza-Klein W_k (ρ-like bound states)

Deconstructing AdS_5

[Arkani-Hamed, Cohen, Georgi '01]



$$\chi_{i,i} = (M_i, \bar{N}_i, 1_{i+1}), \psi_{i,i+1} = (1_i, N_i, \bar{M}_{i+1}) \xrightarrow{\text{NDA}} \left\langle \chi_{i,i}\psi_{i,i+1} \right\rangle \sim \frac{\Lambda_s^{i\,3}}{(4\pi)^2} U_{i,i+1} \in (M \otimes \bar{M})$$



- Connection with deconstruction exits [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]

Disclaimer... Wo viel Licht ist, ist starker Schatten

Drawbacks, model-building issues

- Mass scale is set by the scale of EWSB (∼ compositeness scale)

  → naturally complicated to implement 3^{rd} fermion generation

  → enhanced cutsodians → new discovery signatures, exotic fermions . . .

  [Csáki *et al. 06*]

- Tension between minimal models and electroweak precision data

  [Barbieri, Pomarol, Rattazzi '03], [Barbieri *et al.* '08]

- Considerable amount of fine-tuning ← pictorial representation of effective theory

  Stable compactification, brane tension, ∂-localized operators . . .

Apart from model-building caveats...

- Model spin-one resonances in calculable way
- present in all theories of strong EWSB (→ unitarity)

→ phenomenological handle on these kind of theories @ LHC?

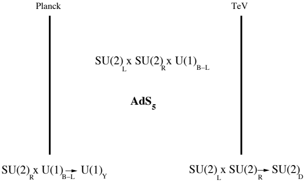
The minimal higgsless model

- Invoke additional $\mathbb{Z}_2$ symmetry: $L \leftrightarrow R$

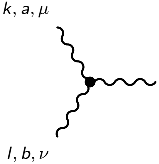
  Bulk EQM $\otimes$ ∂ conditions

  $\Downarrow$

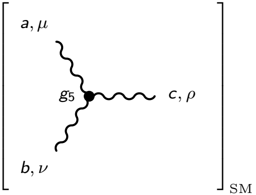
  KK decomposition of iso-vectorial resonances



- $4d$ EFT by inserting the KK decomposition



$$m, c, \rho = \left\{ \int_R^{R'} \mathrm{d}y \, \frac{R}{y} \psi_k^{(a)} \psi_l^{(b)} \psi_m^{(c)} \right\} \times$$



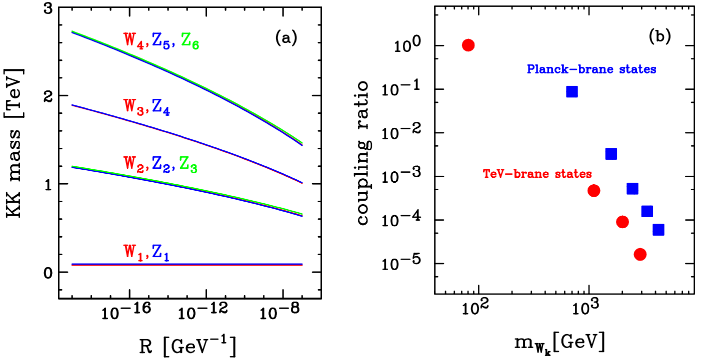
- Parameter-fixing

$$(m_W, m_Z, e) \leftrightarrow (R, R', g_5, g_{B-L})$$

leaves one free parameter, chosen to be R.

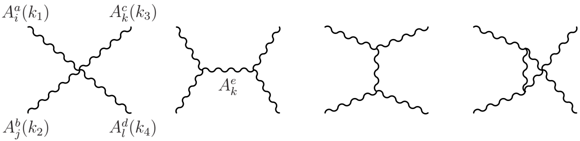
The minimal higgsless model

- T-Parameter bound translates into $R \lesssim 10^{-7}\ \text{GeV}^{-1}$



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

The minimal 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]

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

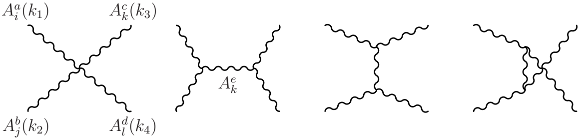
$$4m^2_{W_1} g_{W_1W_1W_1W_1} = 3\sum_{k\geq 1} m^2_{Z_k} g^2_{W_1W_1Z_k} \qquad \mathcal{O}(\sqrt{s})$$

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

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

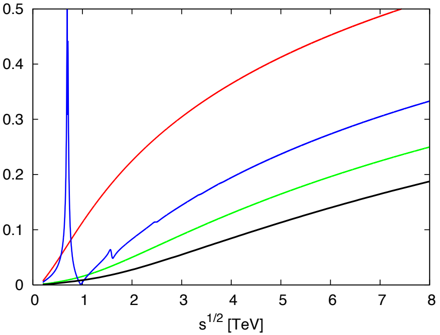
...obeyed as consequence of the regular SLP in the continuum √

The minimal higgsless model – Unitarity



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

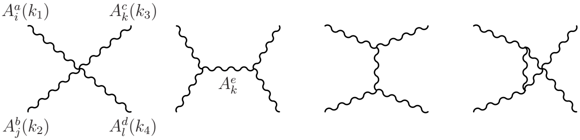
- Unitarity violation postponed to several TeV (*upper limit* ← inelastic channels)



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

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

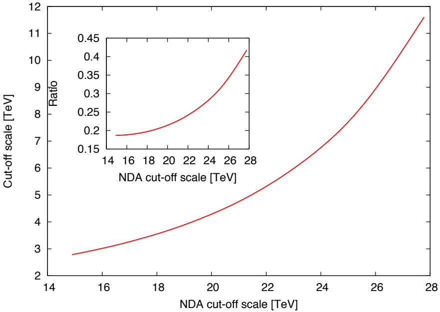
The minimal higgsless model – Unitarity



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

- Extract upper limit on NDA $\mathcal{O}(1)$ determined from AdS$_5$

[Papucci '04], [Csáki *et al.* '04]



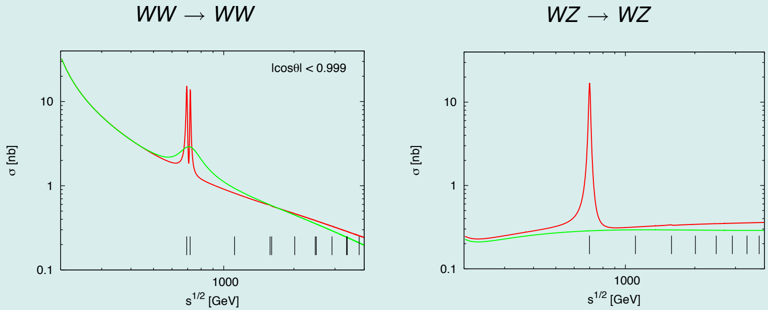
$$\Lambda_{\rm NDA} \sim \frac{24\pi^3}{g_5^2}\,\frac{R}{R'}$$

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:



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

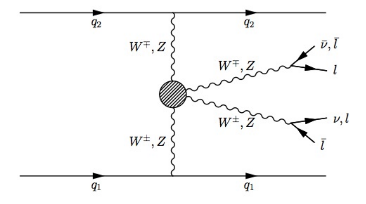
- Clean and distinct signatures of gold and silver plated modes at the LHC.

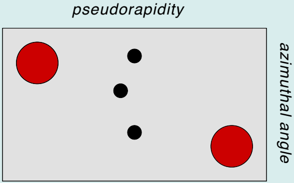
  [Bagger *et al.* '94], [Rainwater, Zeppenfeld '99]

  cut on typical VBF signature highly reduces QCD backgrounds

- QCD corrections small, electroweak corrections are sizable.

  [Ciccolini, Denner, Dittmaier '07]





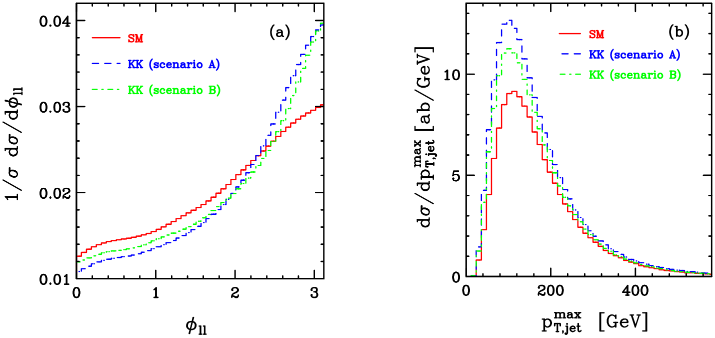
VBF processes provide prominent discovery channels of extra vector bosons, especially for suppressed Drell-Yan production.

Higgsless *WWjj* signatures

VBF cuts

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

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



smearing: CMS-Note 2006/035,036

Higgsless W^+Zjj signatures

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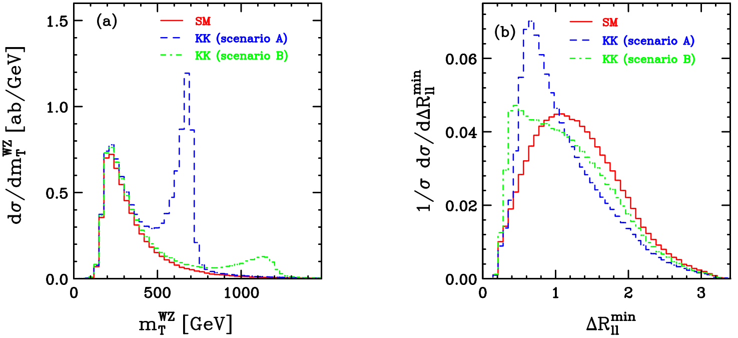

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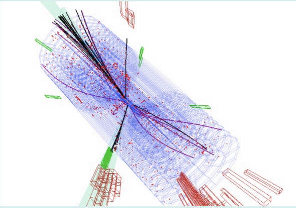
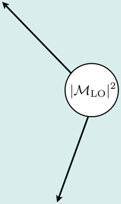
NLO-QCD — you know the business

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.

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

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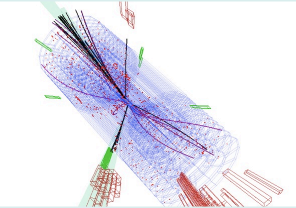

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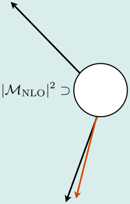

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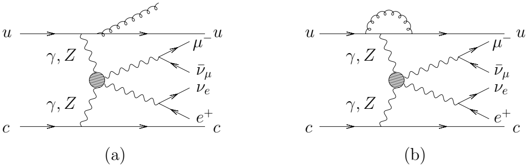
Higgsless signatures @ NLO-QCD



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

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

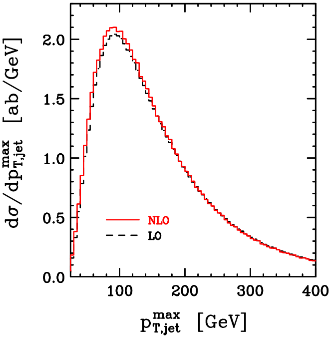
Loop corrections in terms of process-universal building blocks [Jäger, Oleari, Zeppenfeld '06]
[Campanario, CE, Spannowsky, Zeppenfeld '09]

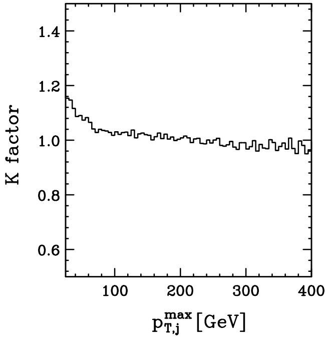
Higgsless signatures @ NLO-QCD

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

Scale μ	σ^{LO} [fb]	σ^{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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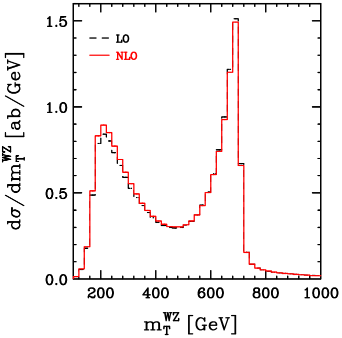
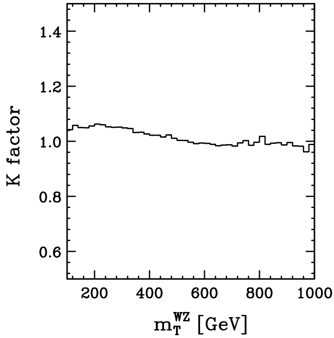




[CE, B. Jäger, D. Zeppenfeld '08]

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 taking into account [CE, Jäger, Worek, Zeppenfeld '08]
  - 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

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

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

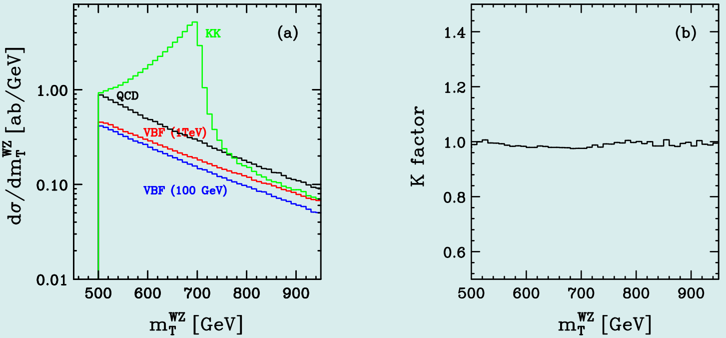
@300 fb^{-1} [30 $\text{fb}^{-1} \simeq 5\sigma$]

LHC is highly sensitive to the scenario!

- Combined analysis of VBF @ LHC sheds light on EWSB
- Subjet analysis [Butterworth *et al.* '09] not very promising, unfortunately...

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
- 'Upper limit model' on strongly interacting EWSB
- Subjet analysis not very promising
- If VBF phenomenologically dominates (fermiophobic KKs), the signatures are

  (i) clearly visible and perturbatively stable wrt QCD (!),
  (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/`

- 'Use your own scenario' switch
  — plug in your scenario and get differential NLO-QCD cross sections