Higgsless Vector Boson Fusion at the LHC

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Outline

1. Diminishing hierarchies
2. Warped Higgsless $=$ Technicolor !?
3. Higgsless VBF signatures

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

Diminishing hierarchies

Three 'big ideas' tackling EWSB/HP:

i) SUSY

Exchange of superpartners, radiative symmetry breaking

ii) Technicolor

EWSB broken by chiral condensates

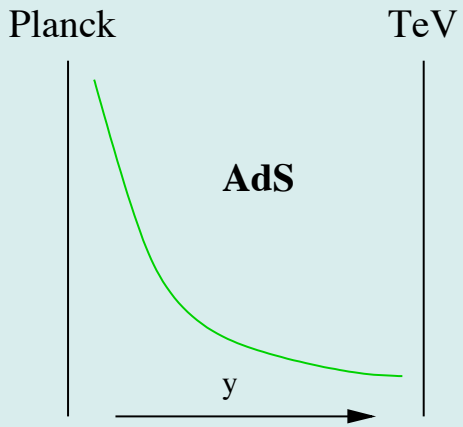
iii) Extra dimensions

unresolved spacelike dimension(s)

RS I:
$5d$ Einstein equations exhibit $4d$ Lorentz-invariant solution, compactified on $S^1/\mathbb{Z}_2 \leftrightarrow$ slice of AdS_5

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

Translation in $y \Longleftrightarrow 4d$ Weyl rescaling

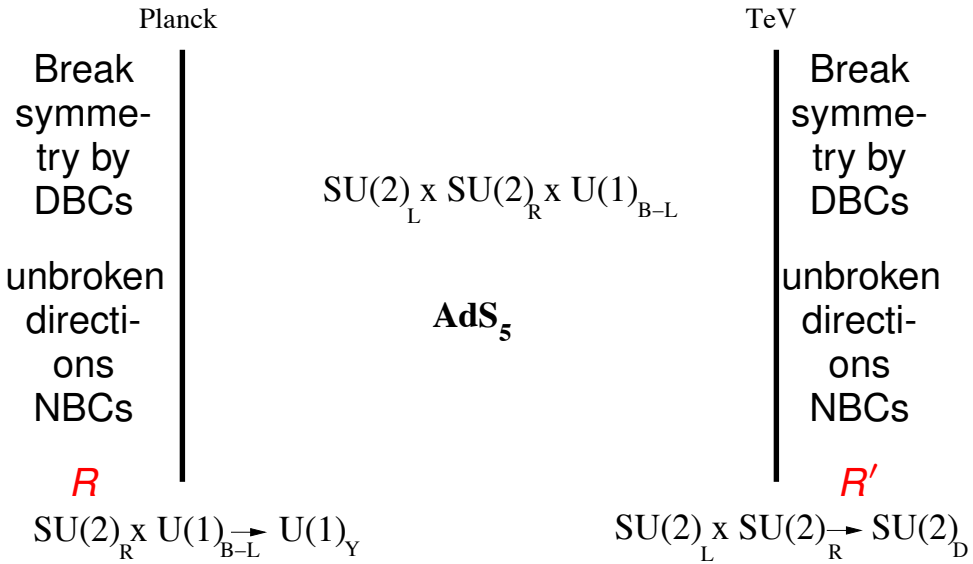


AdS/CFT Bulk-gauged RS I $\leftrightarrow$ Compositeness

AdS/CFT holography [Maldacena '97, Witten '98, Arkani-Hamed *et al.* '00,...]

AdS_5 framework $\longleftrightarrow$ strongly-coupled CFT

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



- $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ 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.

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

$\longrightarrow$ 'Walking extended technicolor'

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

ELW spectrum / hologr. matching in a nutshell

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

$$A_M(x,y) = \left(A_\mu^k, A_5^k\right) = 4d \text{ vectors} \oplus 4d \text{ scalars}$$

- Action contains mixing between $4d$ 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

  [dial contribution to recover gaugephobic or composite Higgs scenarios]

  $\Rightarrow$ no scalars in theory's spectrum

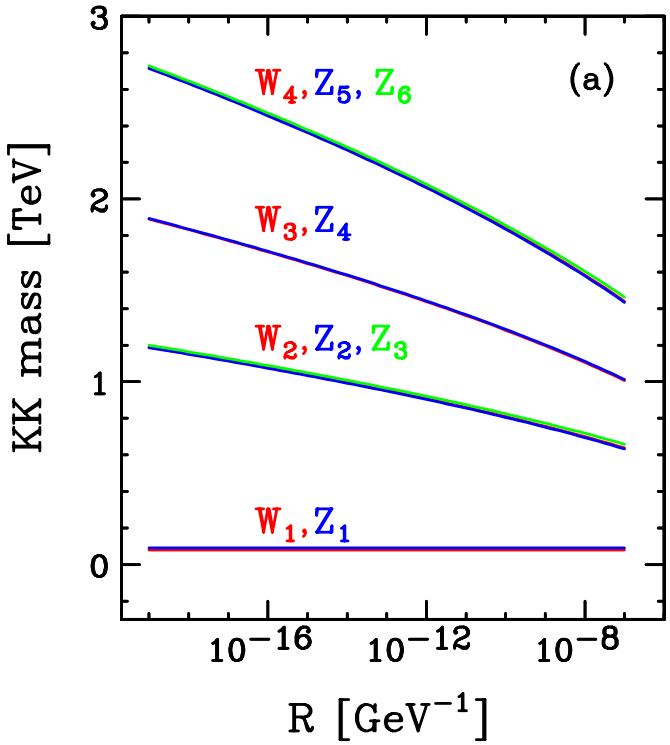
  Gauge boson mass operator $\hat{m}^2 = y^{-1}\partial_y - \partial_y^2$

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

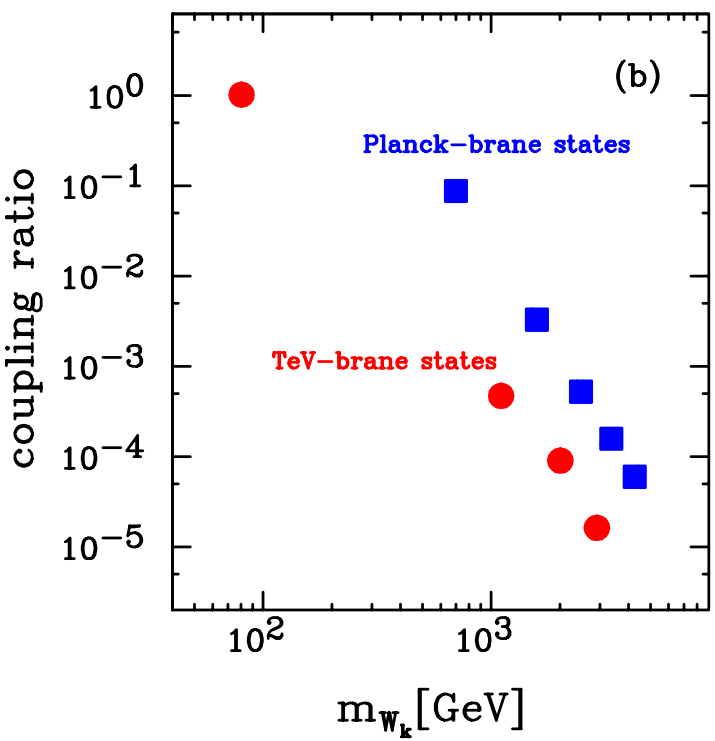
$$\text{e.g.} \quad A_\mu^{3L}(x,y) = \underbrace{a Z_\mu^{(0)}(x)}_{\text{massless mode}} + \underbrace{\sum_{k\geq 1} \psi_k^B(y) Z_\mu^{(k)}(x)}_{\text{massive modes}}$$

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 $\lesssim 10^{-7}$ GeV^{-1}).

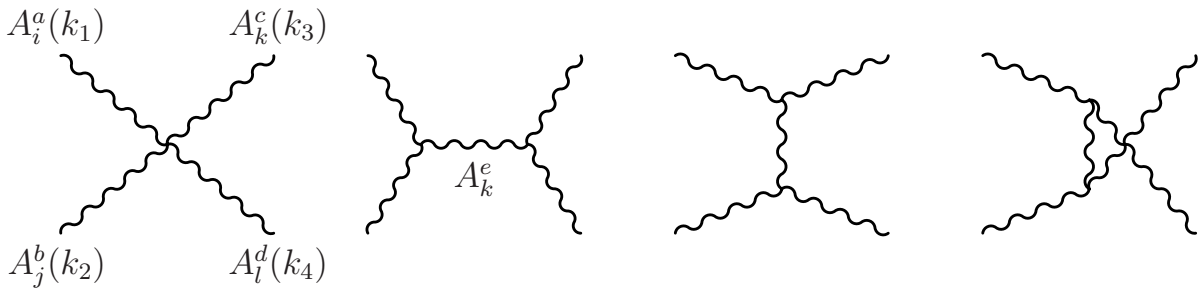


[CE, B. Jäger, D. Zeppenfeld '08]



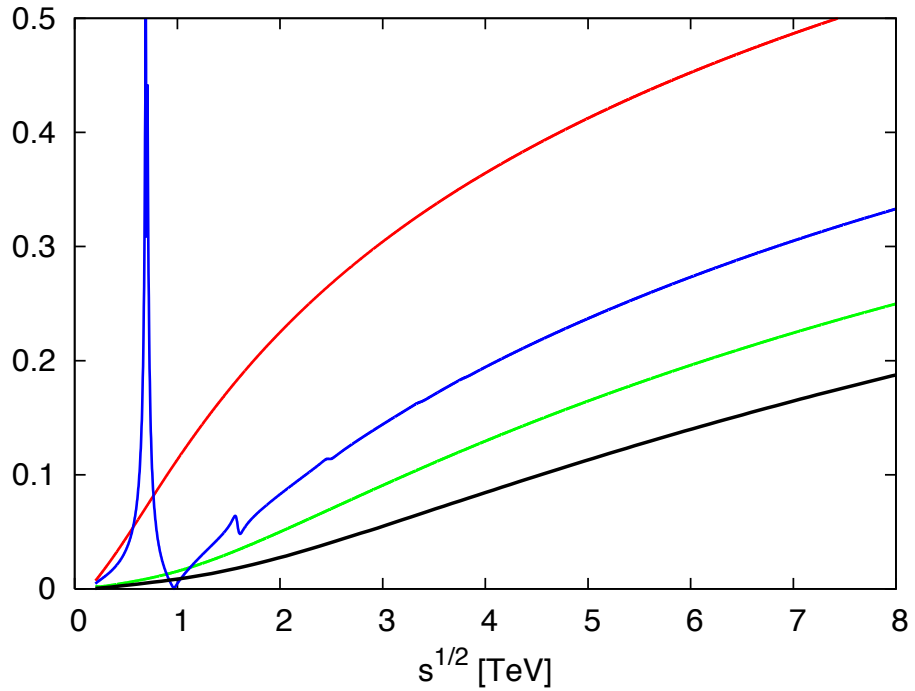
$W_k WZ$ coupling ratio wrt to WWZ coupling for $m_{W_2} = 700$ GeV

The warped Higgsless model - Unitarity



$\propto (p^0_{(A)})^4$, *naive*

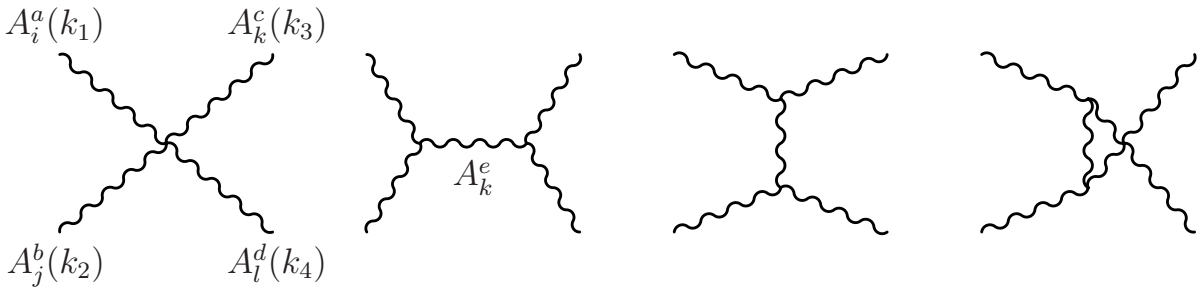
- Unitarity violation postponed to several TeV (*upper limit*).



Partial wave projection for $m_{W_2} = 700$ GeV,
$J = 0$, $J = 1$, $J = 2$, $J = 3$.

[CE, '07]

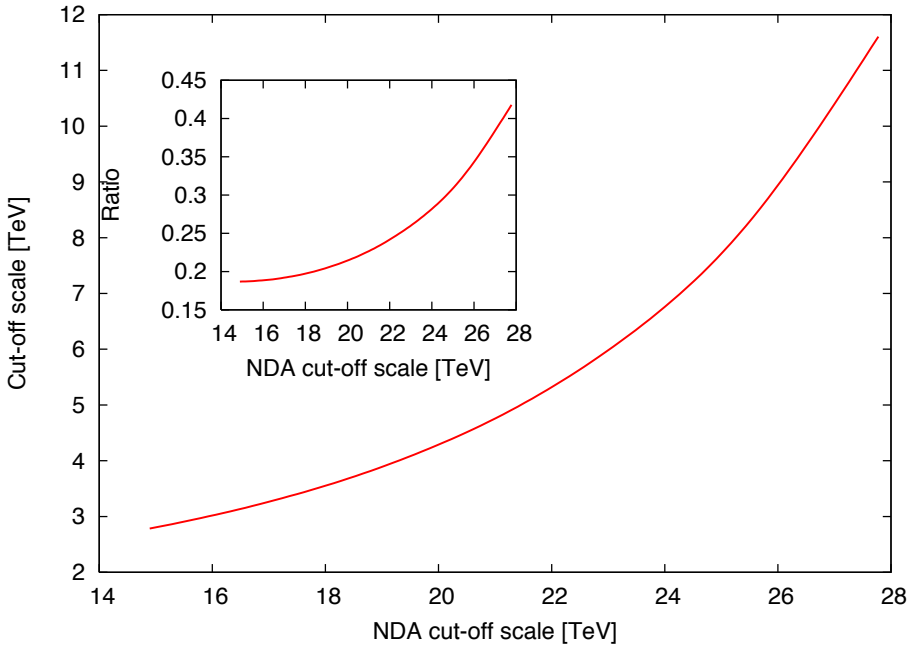
The warped Higgsless model - Unitarity



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

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

[Papucci '04, Csaki *et al.* '04]

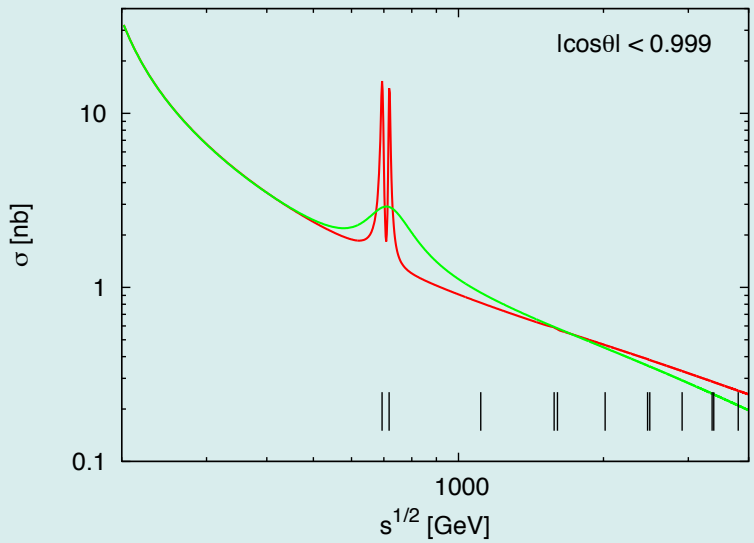


For high-energy perturbativity ~ 0.2

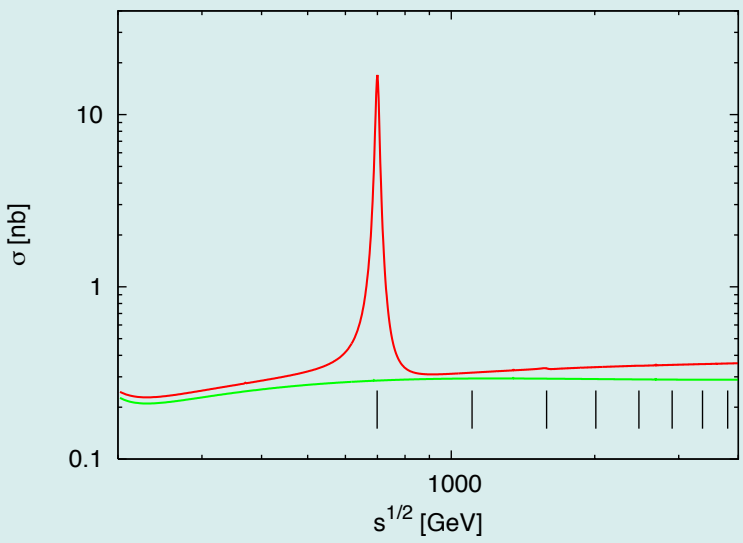
[CE, '07]

Higgsless WW, WZ cross sections

$WW \to WW$



$WZ \to WZ$



[CE, '07]

- $W^{\pm}$ resonance is a 'smoking gun' signature of these models!

[Birkedal, Perelstein, Matchev '05]

VBF signatures in general

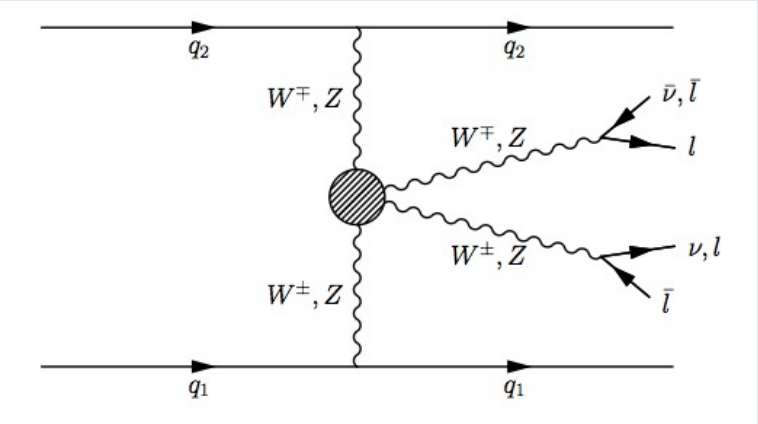
- Weak Boson fusion processes access gauge boson scattering.

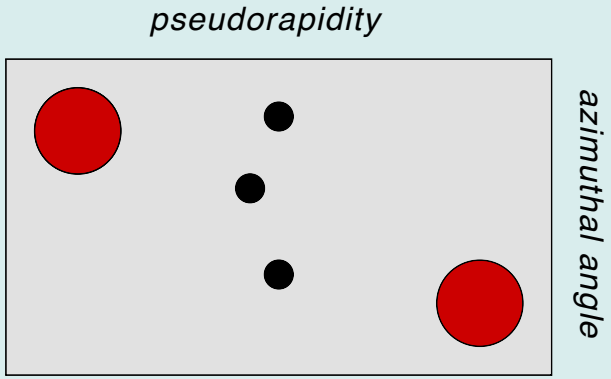
  Sensitive to mechanism of EWSB

- 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 greatly reduces QCD backgrounds





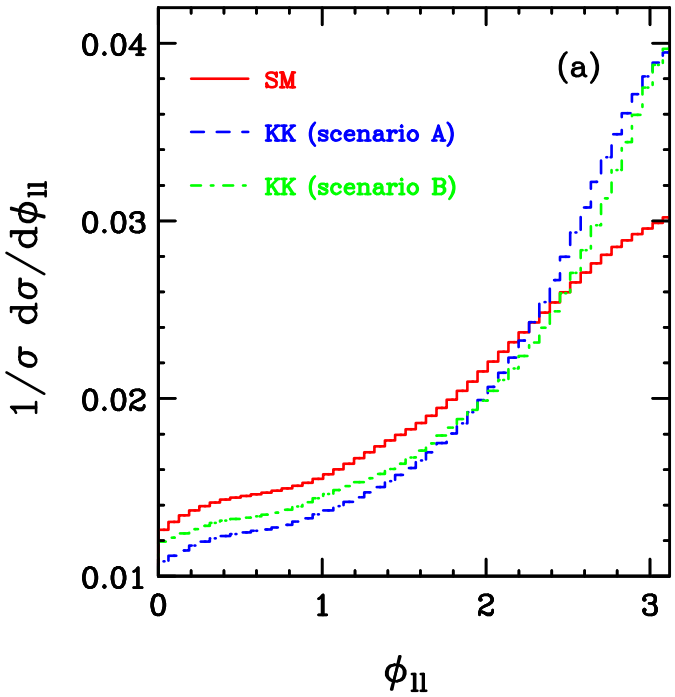
VBF processes provide prominent discovery channels of extra vector bosons, especially for suppressed Drell-Yan production.

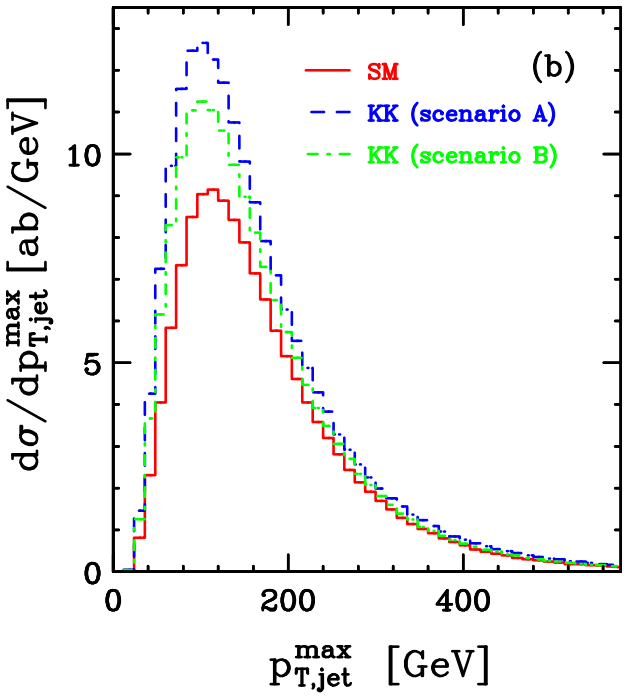
Higgsless *WW* signatures

VBF cuts

$$p_T^j \geq 20\ \text{GeV},\ |\eta_j| \leq 4.5,\ |\Delta\eta_{jj}| \geq 4,\ \eta_{j_1} \times \eta_{j_2} < 0,\ m_{jj} \geq 600\ \text{GeV},$$

$$p_T^\ell \geq 20\ \text{GeV},\ |\eta_\ell| \leq 2.5,\ R_{ll} \geq 0.2,\ R_{jl} \geq 0.4,\ \text{leptons in jet rapidity gap}$$





smearing: CMS-Note 2006/035,036

[CE, B. Jäger, D. Zeppenfeld '08]

Higgsless W^+Z signatures

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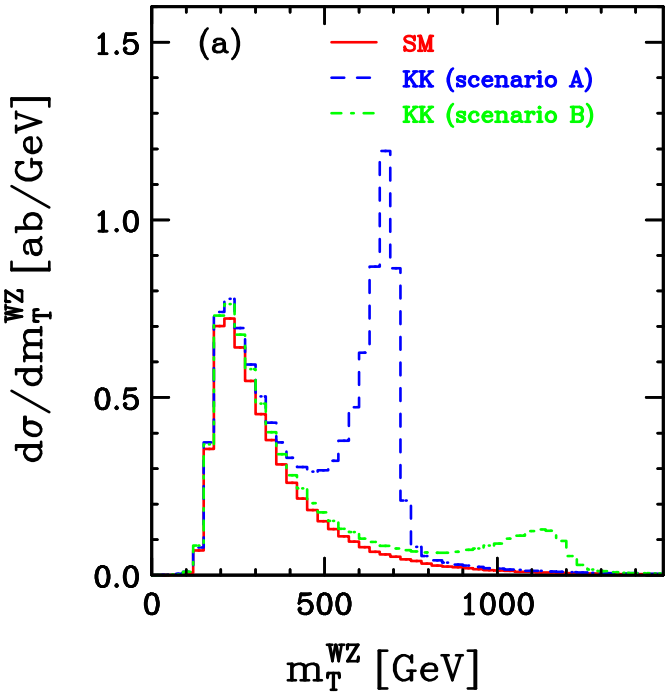

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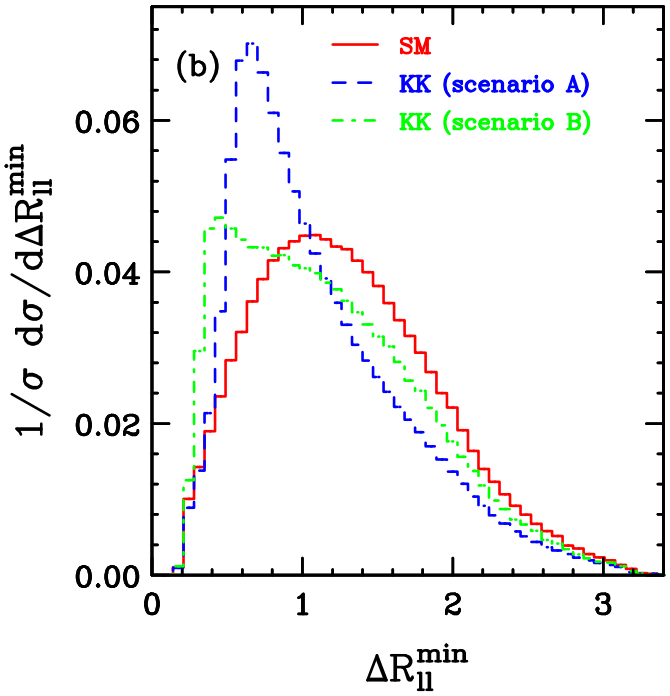

[CE, B. Jäger, D. Zeppenfeld '08]

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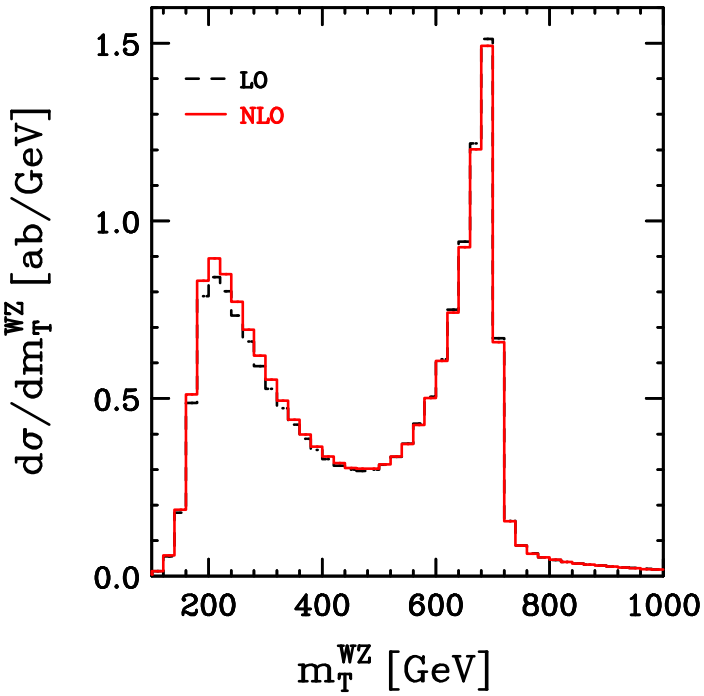

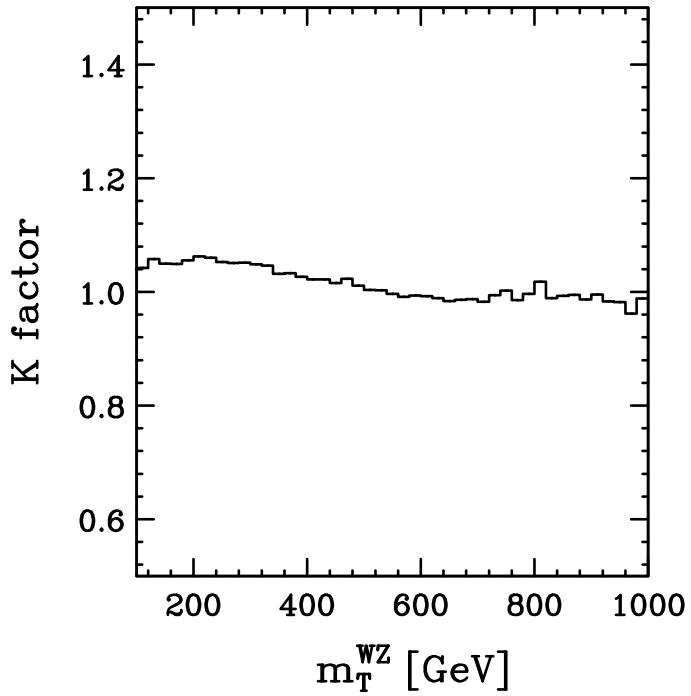

[CE, B. Jäger, D. Zeppenfeld '08]

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

$$pp \to W^{\pm} Zjj \to 3\ell \not{p}_T jj$$
$$pp \to W^{+} W^{-} jj \to 2\ell \not{p}_T jj$$
$$pp \to ZZjj \to 4\ell \not{p}_T jj$$

taking into account double jet tags, full off-shell effects, leptonic final states, CJV, b-tag efficiencies, and full matrix elements for signal and backgrounds

$$t\bar{t} + \text{jets}, \quad \text{QCD } pp \to VVjj \text{ incl. leptonic decays}$$

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}

[CE, B. Jäger, M. Worek,D. Zeppenfeld '08]

- LHC is highly sensitive to the scenario

Summary

- We have looked quite carefully into a EWSB scenario without scalar resonances:
  (i) derived EFT
  (ii) discussed bounds from the EFT
- Phenomenology is thrilling and clearly visible @ LHC.
- Perturbative stability with respect to NLO-QCD-corrections:
  cross sections and distributions are highly stable
- The MC Code is publicly available at

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

  and features all the stuff you need....
  (GNU-build system, libraries, LHA, manual, . . .)
  [Arnold *et al.*, '08]
- 'Use your own scenario' switch — plug in your scenario and get differential NLO-QCD xsections.