Weak boson scattering at the LHC

RADCOR 2009

Barbara Jäger

University of Würzburg

PHYSICS AT THE TERA SCALE
Helmholtz Alliance

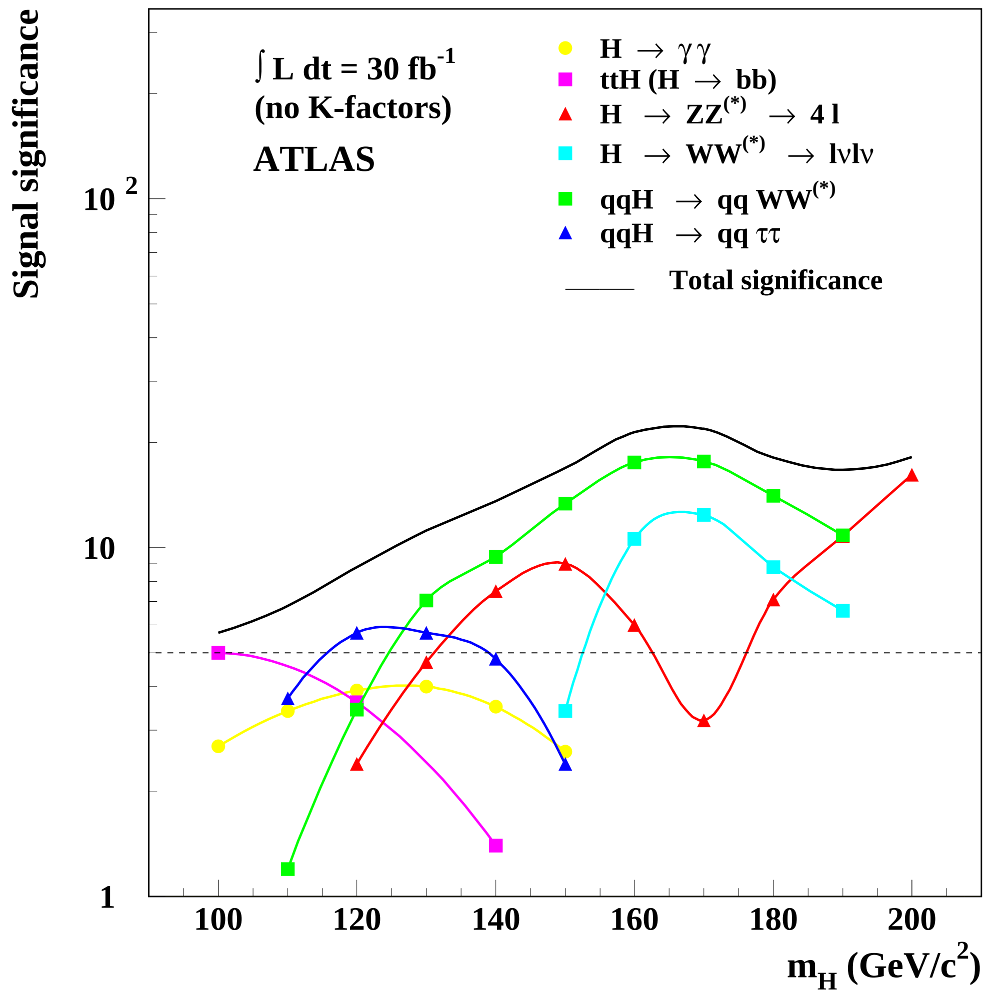
outline

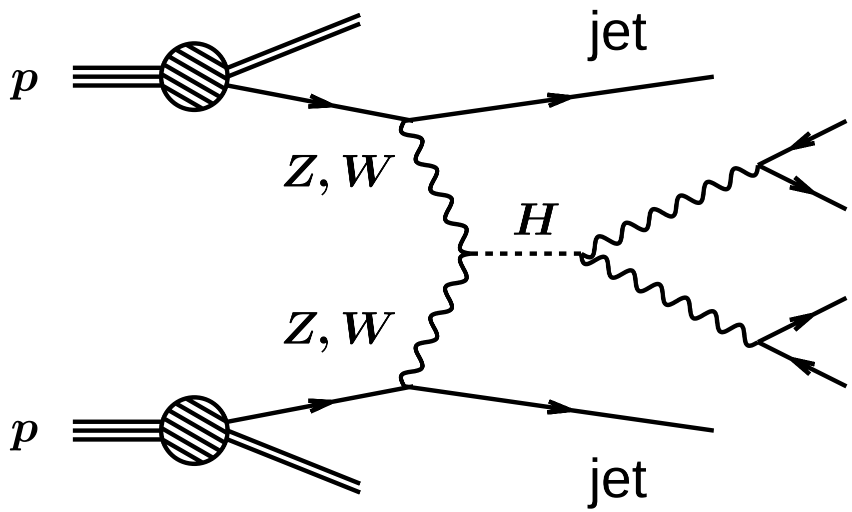
- weak boson fusion at the LHC:
  - Higgs production at high precision
  - $VVjj$ production @ NLO QCD
- strongly interacting gauge boson systems
  - heavy Higgs scenario
  - Warped Higgsless model
- summary & conclusions

LHC discovery potential

most promising production / decay modes for Higgs search at the LHC depend on M_H:

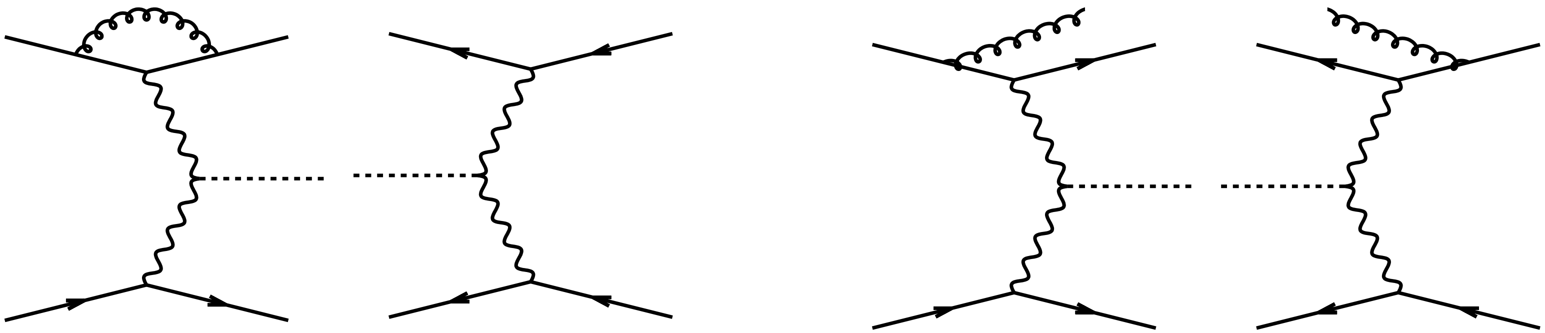
- VBF $qq \to qqH$ with $H \to W^{\pm}W^{\mp} \to e^{\pm}\mu^{\mp}\not{p}_T$ important for $M_H \gtrsim 110$ GeV





suppressed color exchange between quark lines gives rise to

- little jet activity in central rapidity region
- scattered quarks $\longrightarrow$ two forward tagging jets (energetic; large rapidity)
- Higgs decay products typically between tagging jets



NLO QCD:

inclusive cross section:

Han, Valencia, Willenbrock (1992)

distributions:

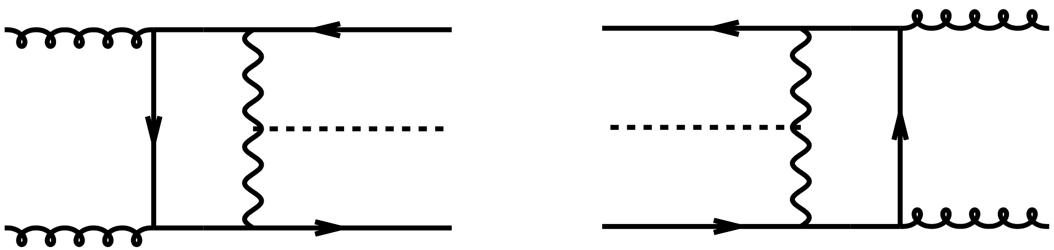
Figy, Oleari, Zeppenfeld (2003)

Berger, Campbell (2004)

→ NLO QCD corrections moderate and well under control (order 10% or less)

Harlander, Vollinga, Weber (2007):

gauge invariant, finite sub-class of virtual
two-loop QCD corrections to $pp \longrightarrow Hjj$ via VBF



important due to large gluon luminosity at LHC?

$$gg \longrightarrow q\bar{q}H,\; q\bar{q} \longrightarrow ggH,$$
$$qg \longrightarrow qgH,\; \bar{q}g \longrightarrow \bar{q}gH$$

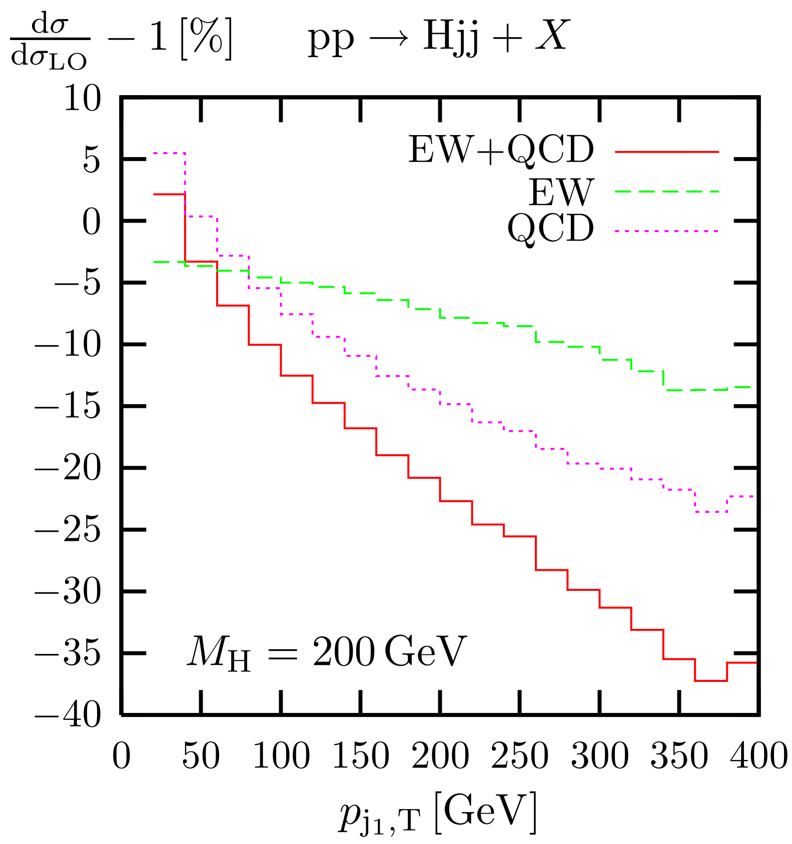
minimal set of cuts: $\sigma_{\text{gluon}}^{2-\text{loop}} \sim 2\,\%$ of $\sigma_{\text{VBF}}^{\text{LO}}$

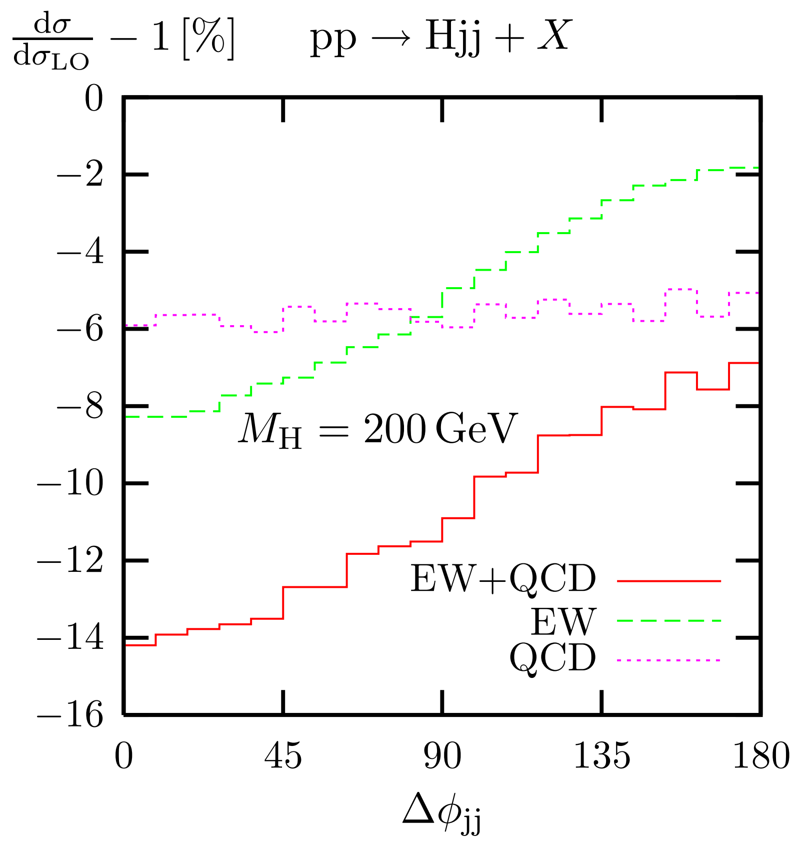
VBF cuts: relative suppression by additional order of magnitude

Ciccolini, Denner, Dittmaier (2007):

NLO EW corrections to inclusive cross sections and distributions

☞ NLO EW corrections non-negligible, modify $\boldsymbol{K}$ factors and distort distributions by up to 10%





$pp \longrightarrow Hjj$ via gluon fusion

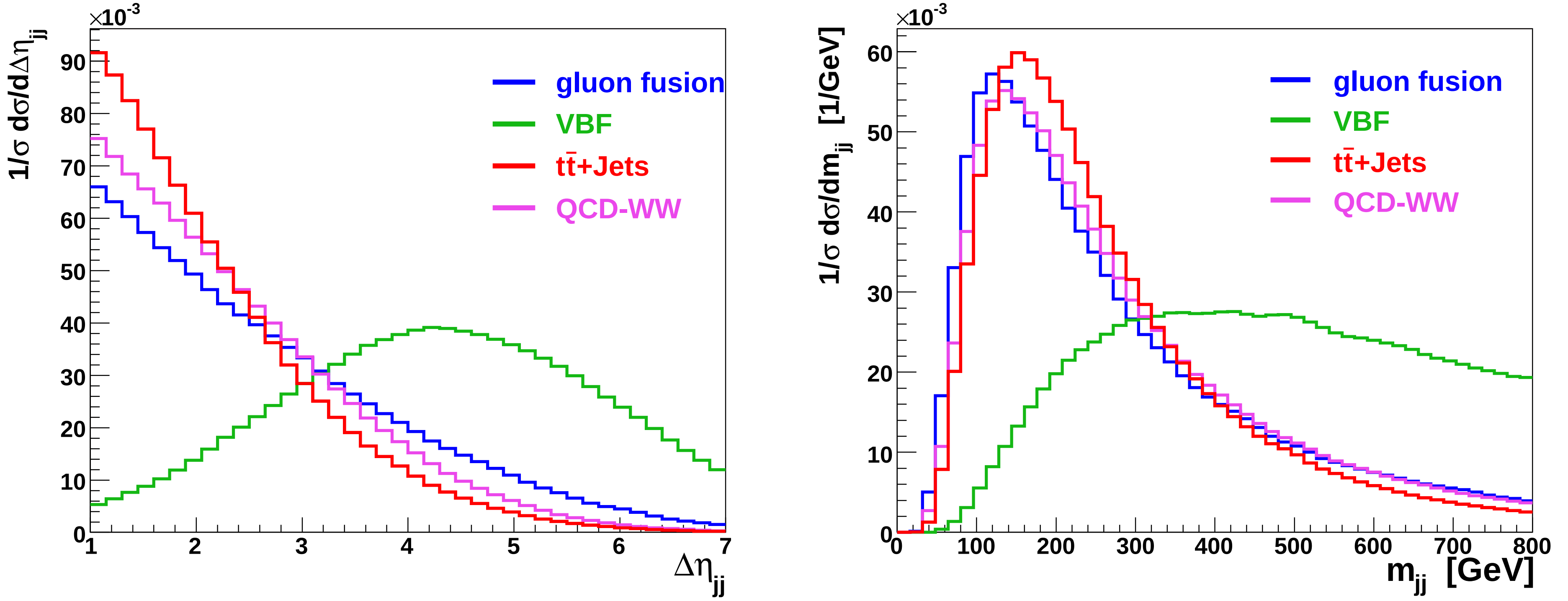
VBF Higgs signal can be faked by
double real corrections to $gg \longrightarrow H$ (“gluon fusion”)

complete LO calculation (including pentagons):
Del Duca, Kilgore, Oleari, Schmidt, Zeppenfeld (2001)

NLO QCD calculation in $m_t \longrightarrow \infty$ limit:
Campbell, Ellis, Zanderighi (2006)

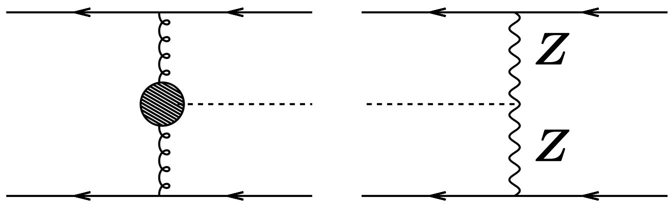
need to understand phenomenology of both processes to distinguish between them

apply cuts to separate VBF signal
from gluon fusion (GF) background



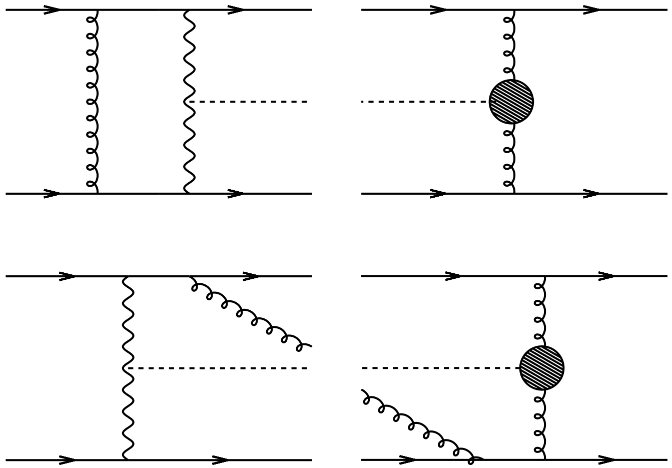
Klämke, Zeppenfeld (2007)

can VBF×GF interference pollute the clean VBF signature?



Georg (2005) & Andersen, Smillie (2006):

- neutral current graphs
  (no charged current interference)
- identical quark contributions
  with $t \leftrightarrow u$ crossing



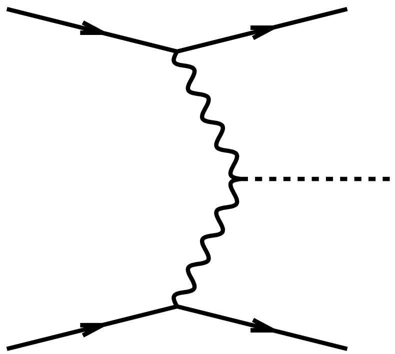
Andersen et al. (2007)

Bredenstein, Hagiwara, B. J. (2008):

- strong cancelation effects
  between contributions of
  different flavor

☞ interference effects are completely negligible

Higgs signal in VBF

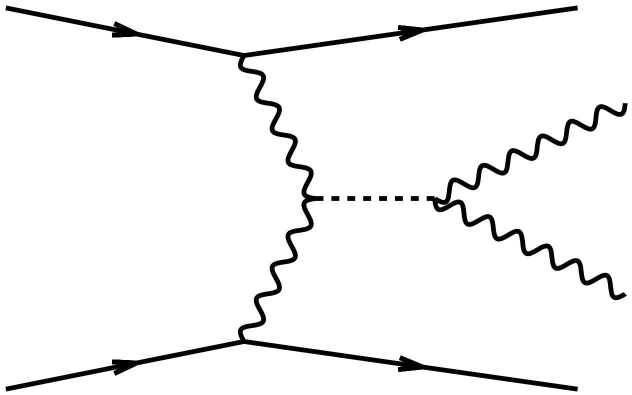


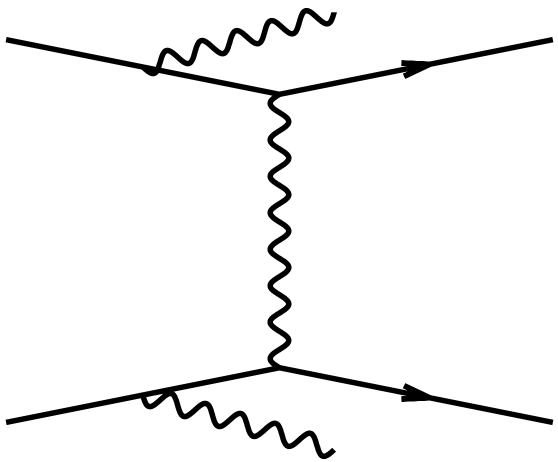
- $pp \longrightarrow Hjj$ via VBF under excellent control
- QCD & EW NLO corrections at 10% level
- dominant NNLO QCD corrections small
- SUSY QCD corrections small

  ☞ *Michael Rauch's talk*
- interference with GF Hjj production negligible
- small PDF uncertainties $\lesssim 4\%$

but: establishing a signal for the Higgs boson in VBF
requires also
calculation of background contributions

EW $VVjj$ production





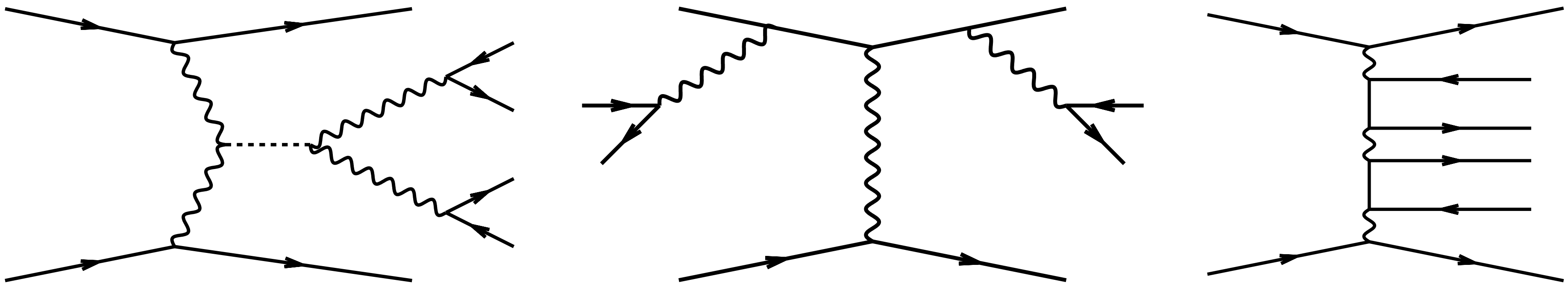
$pp \to VV + jj$ via VBF

irreducible background to Higgs signal process
in $H \to VV$ decay mode

↓

accurate predictions essential

EW $VVjj$ production



experiment: don't observe $VVjj$ final state, but
hadronic or leptonic decay products

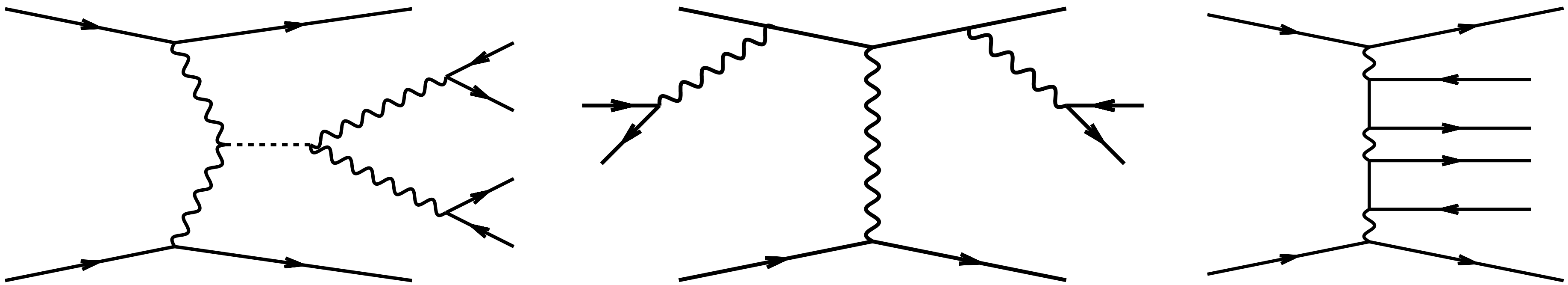
$\mathbf{4jets} + jj$

high statistics
large backgrounds

$\mathbf{4leptons} + jj$

low statistics
clean signature

EW $VVjj$ production



experiment: don't observe $VVjj$ final state, but hadronic or leptonic decay products

focus on

$$pp \longrightarrow 4\text{leptons} + jj$$

via VBF

(short: "$pp \longrightarrow VVjj$")

$4\text{leptons} + jj$

low statistics

clean signature

EW $VVjj$ production

need stable, fast & flexible Monte Carlo program allowing for

- computation of various jet observables for
  W^+W^-jj, $ZZjj$, $W^\pm Zjj$, and $W^\pm W^\pm jj$
  production via VBF at NLO-QCD accuracy
  (leptonic decay correlations are fully taken into account)

- straightforward implementation of cuts

C. Oleari, D. Zeppenfeld, B. J. (2006)

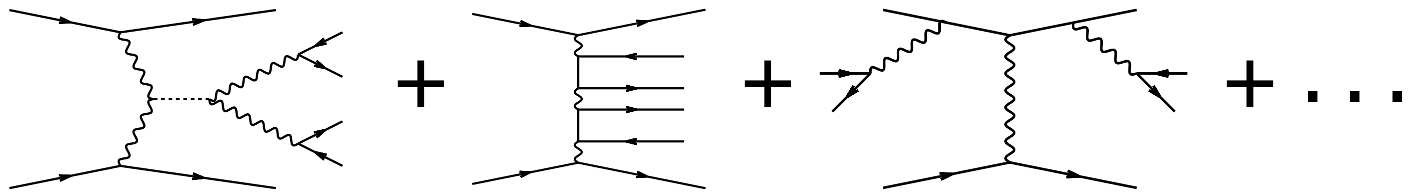
G. Bozzi, C. Oleari, D. Zeppenfeld, B. J. (2007)

C. Oleari, D. Zeppenfeld, B. J. (2009)

[c.f. also Dieter Zeppenfeld's talk]

need to compute numerical value for

$$|\mathcal{M}_B|^2 = \Bigg|$$



$$\Bigg|^2$$

at each generated phase space point in 4 dim (finite)

...depending on leptonic final state: up to 580 diagrams

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essential: organize calculation economically

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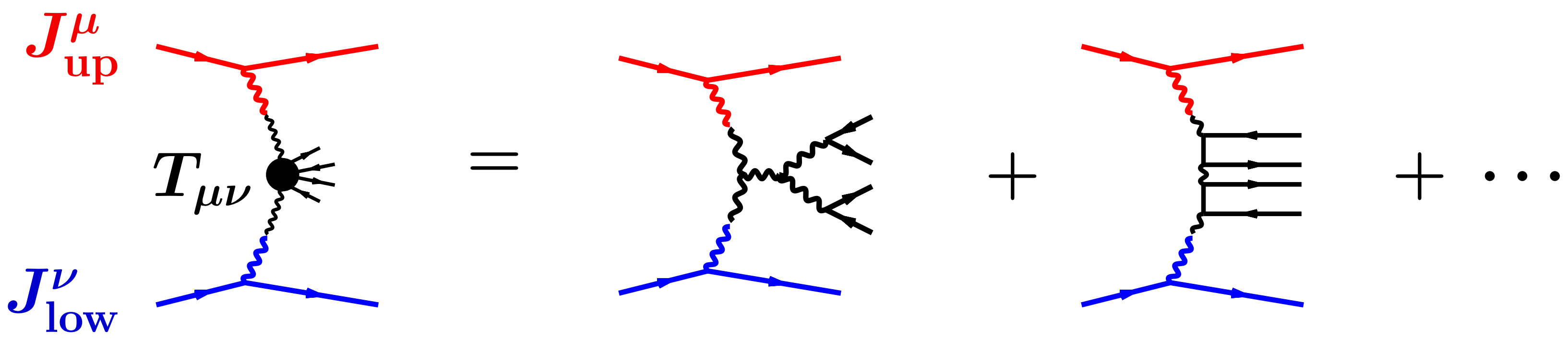
- employ amplitude techniques to evaluate $\mathcal{M}$ first (numerically) for specific helicities of external particles, then square
- avoid multiple evaluation of recurring building blocks

develop modular structure with . . .



. . . and evaluate each building block only once per phase space point (related sub-diagrams, various flavor combinations, crossed processes . . .)

such recycling is used to a very small extent by automatized programs like `MadGraph/MadEvent`

not included:

- interference effects from identical fermions
  (t- and u-channel interference)
- identical flavor annihilation processes
  (s-channel contributions)

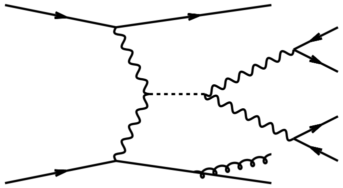
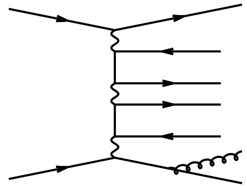
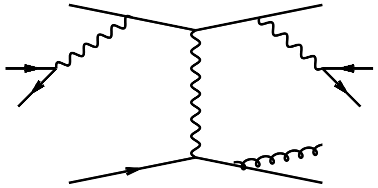
. . . strongly suppressed in phase-space region
where VBF can be observed experimentally

Oleari, Zeppenfeld (2003), Georg (2005)
Andersen, Smillie (2006)
Ciccolini, Denner, Dittmaier (2007)

the next-to-leading
order:
· real emission
· subtraction terms
· virtual corrections

real emission contributions

needed: numerical value for almost 3000 diagrams

$$|\mathcal{M}_R|^2 = \Bigg|$$  $+$  $+$  $$+ \dots \Bigg|^2$$

complication: real emission contribution diverges as unobserved parton becomes soft or collinear

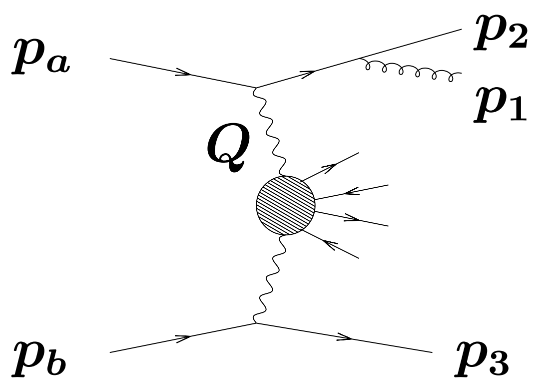
↓

- analytic calculation: divergencies canceled directly by respective singularities in virtual contributions

- numerical approach: apply subtraction formalism (phase space slicing, dipole subtraction, . . .)

☞ divergencies are absorbed by auxiliary counterterms continuous interpolation between soft and collinear gluon radiation:

$$\sim \frac{x^2 + z^2}{(1-x)(1-z)} |\mathcal{M}_B(\tilde{p})|^2$$

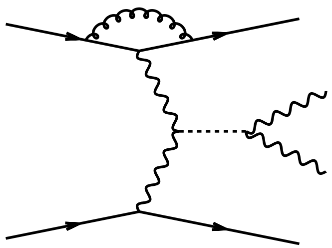
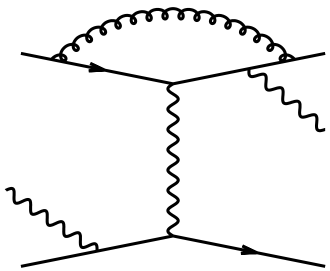
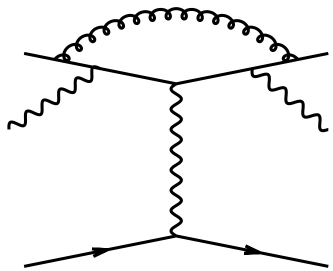


analytical integration over one-particle phase space:

$$\sim |\mathcal{M}_B(p)|^2 \left[\frac{2}{\varepsilon^2} + \frac{3}{\varepsilon} + \text{const.}\right]$$

Catani, Seymour (1996)

$$\sigma^{NLO} = \int_{m+1} \left[d\sigma^R_{\varepsilon=0} - d\sigma^A_{\varepsilon=0}\right] + \int_m \left[d\sigma^V + \int_1 d\sigma^A\right]_{\varepsilon=0}$$

$\mathcal{M}_V =$  $+$  $+$  $+ \ldots$

$$= \mathcal{M}_B \, F(Q) \left[-\frac{2}{\varepsilon^2} - \frac{3}{\varepsilon} \right] + \tilde{\mathcal{M}}_V^{finite}$$

determined numerically

[c. f. Denner, Dittmaier (2002,2005)]

combination of real emission, virtuals,
and subtraction terms:
poles canceled analytically $\longrightarrow$ finite results

phase-space integration can be performed numerically (`Vegas`)

Monte Carlo program for cross sections and distributions
which allows for the implementation of
realistic experimental selection cuts

☞ embedded in more general framework
for various VBF-type processes
`vbfnlo`

publicly available from

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

$pp \to VVjj$ @ LHC: settings

use design energy of 14 TeV, apply k_T jet algorithm,

CTEQ6 parton distributions, and typical VBF cuts:

tagging jets

$$p_{Tj} \geq 20 \text{ GeV}, \quad |y_j| \leq 4.5,$$

$$\Delta y_{jj} = |y_{j_1} - y_{j_2}| > 4,$$

$$M_{jj} > 600 \text{ GeV}$$

jets located in opposite hemispheres

charged leptons

$$p_{T\ell} \geq 20 \text{ GeV}, \quad |\eta_\ell| \leq 2.5,$$

$$\Delta R_{j\ell} \geq 0.4,$$

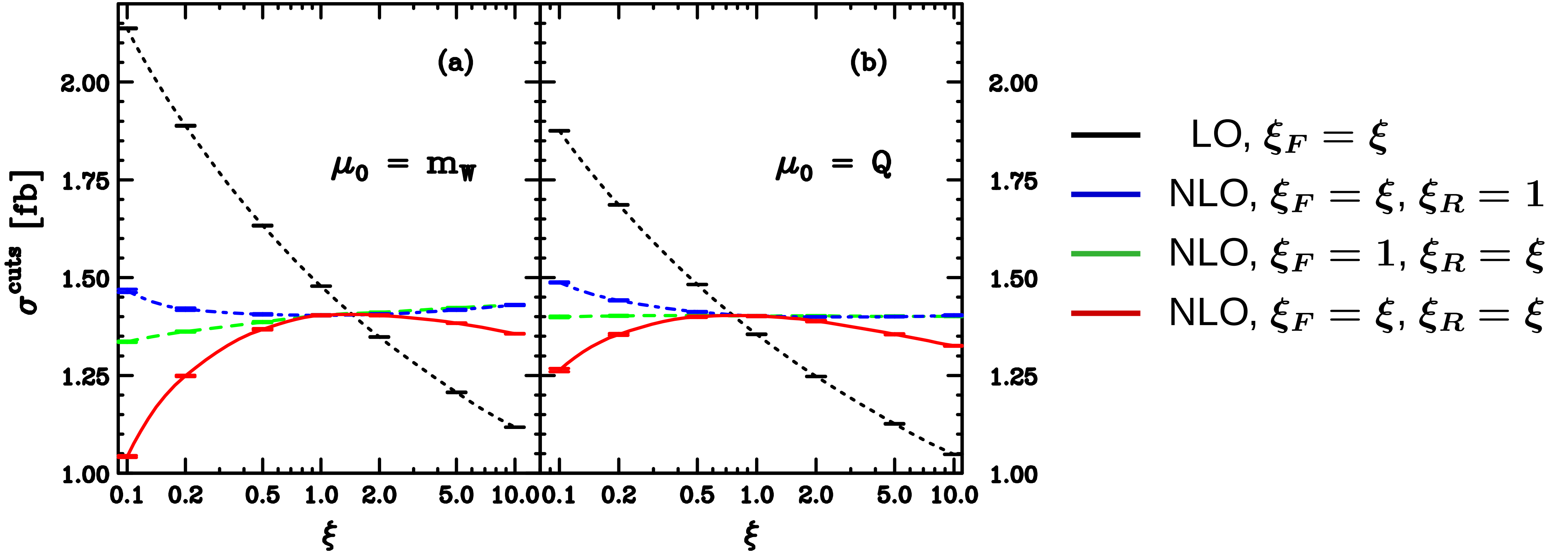
$$y_{j,min} < \eta_\ell < y_{j,max}$$

scale uncertainty: $pp \to W^+W^+jj$

choose default scale $\mu_0 = m_W$ or $\mu_0 = Q$

set $\mu_R = \xi_R \mu_0$ and $\mu_F = \xi_F \mu_0$, with variable ξ

Oleari, Zeppenfeld, B. J. (2009)

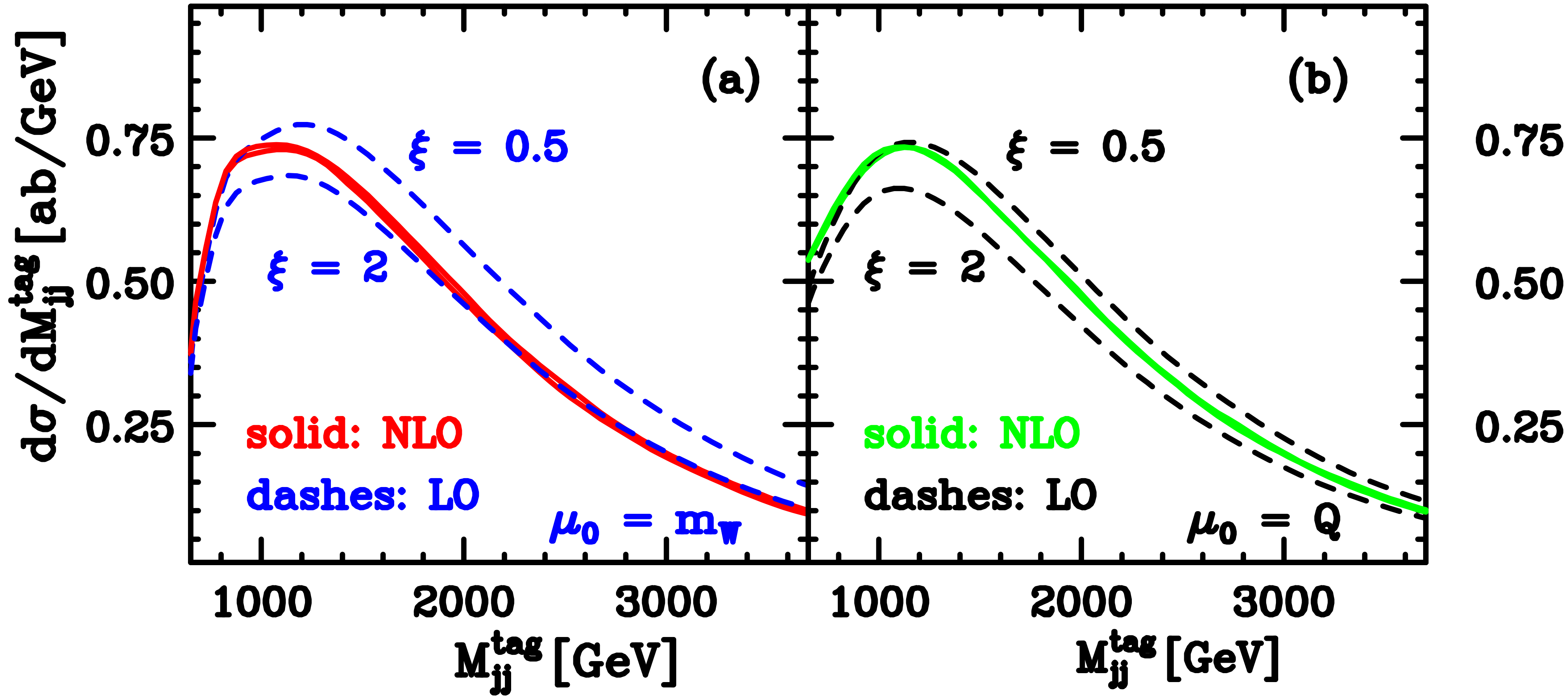


LO: no control on scale

NLO QCD: scale dependence strongly reduced

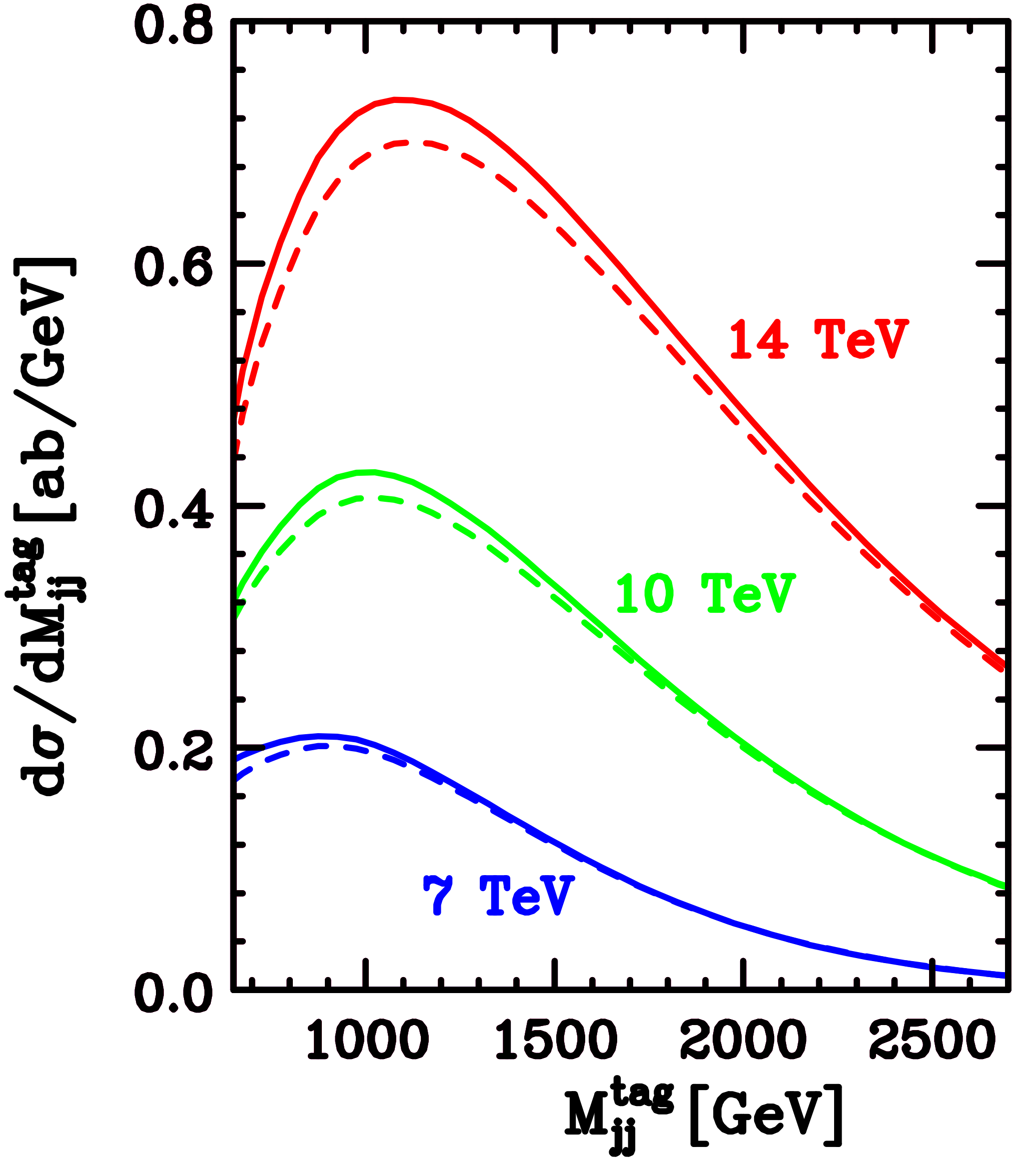
W^+W^+jj distributions: invariant mass of tagging jets

Oleari, Zeppenfeld, B. J. (2009)



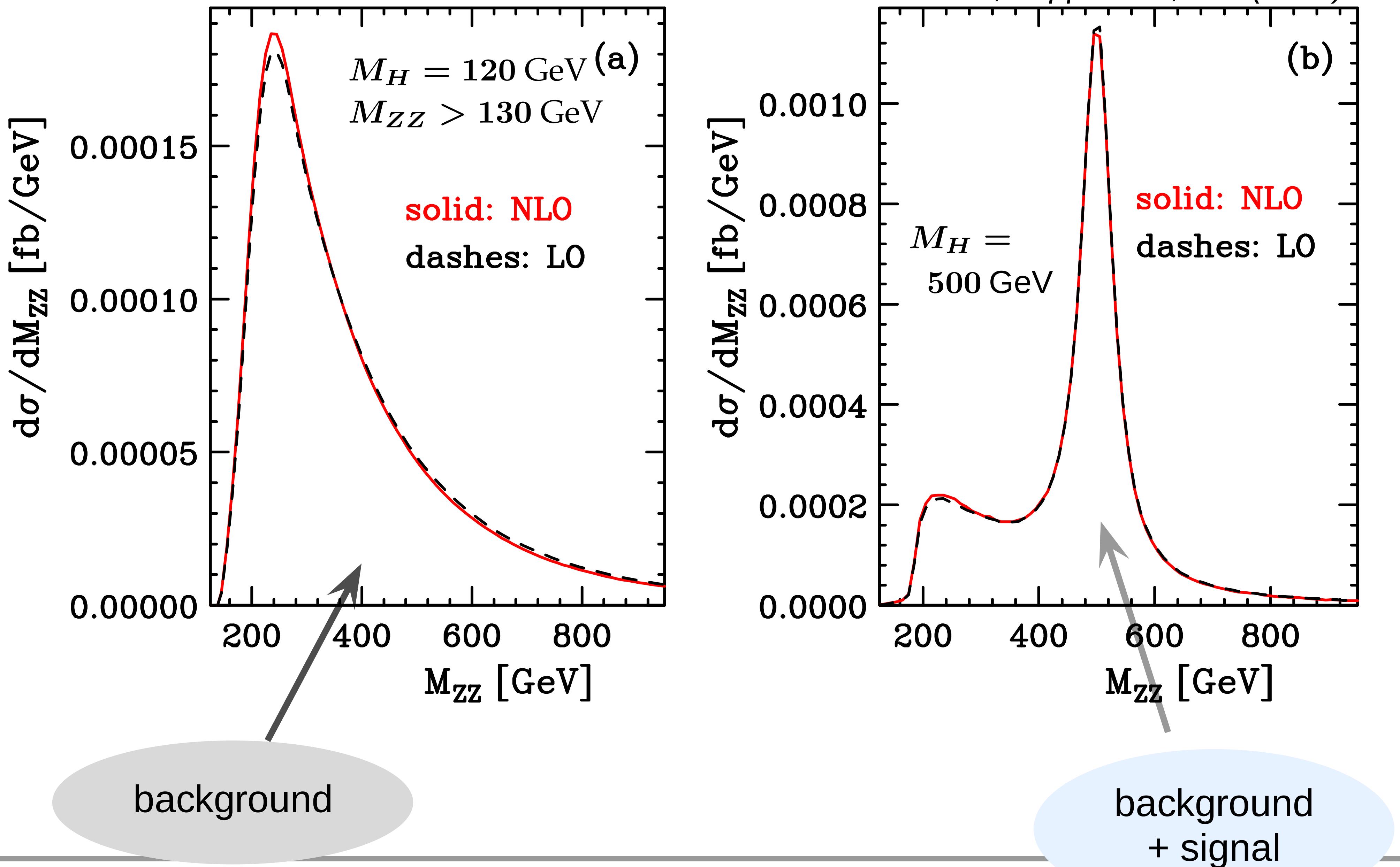
$$\mu = \xi\,\mu_0$$

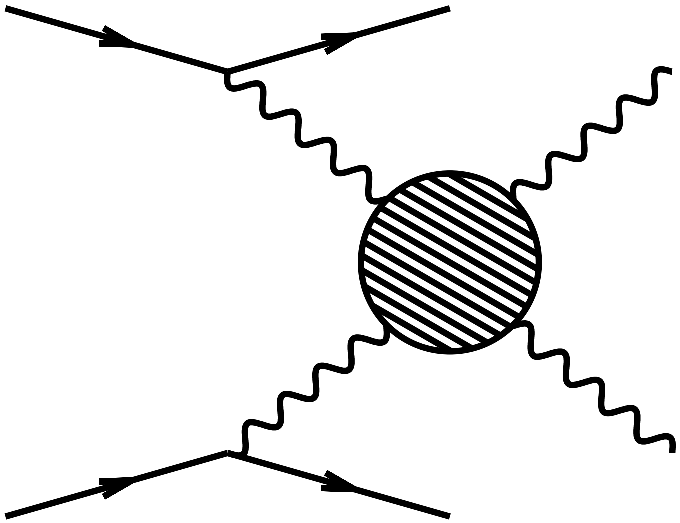
$pp \longrightarrow W^+W^+jj$: energy dependence



M_{VV} distribution: $pp \to \ell^+\ell^-\ell'^+\ell'^- jj$

Oleari, Zeppenfeld, B.J. (2006)



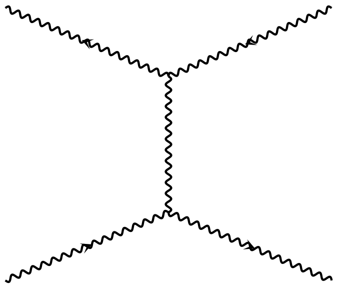
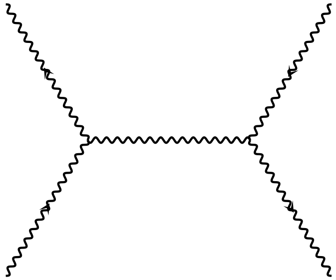
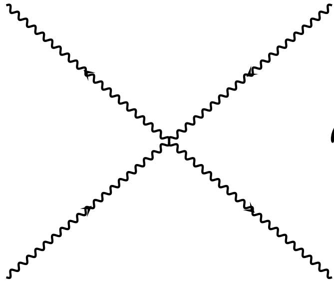


VBF processes are extremely
sensitive to new interactions in the
gauge boson sector

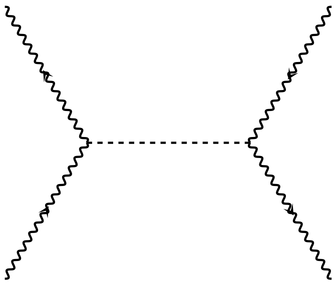
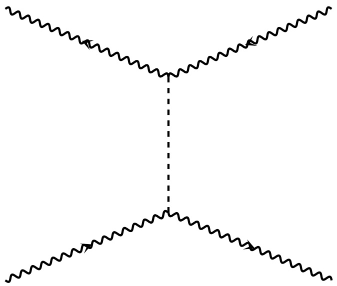
↓

can we spot signatures of
non-standard scenarios for
electroweak symmetry breaking?

$W_L^+ W_L^- \to W_L^+ W_L^-$ with $\varepsilon_L^\mu \sim \frac{\sqrt{s}}{M_W}$

$\mathcal{M} =$  $+$  $+$  $\sim \frac{s}{M_W^2}$

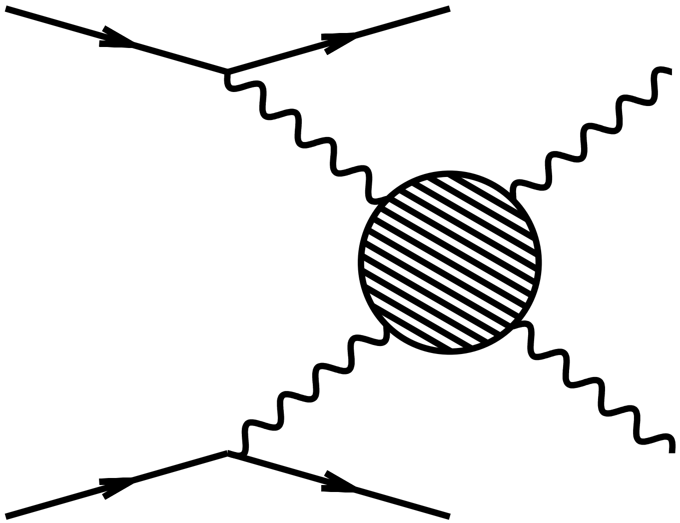
growth violates unitarity $\longrightarrow$ need:

 $+$ 

Higgs with $M_H \lesssim 1$ TeV

or new physics at TeV scale

new interactions in the gauge boson sector



can we distinguish signatures of
SM-type Higgs mechanism from other
scenarios of EW symmetry breaking?

↓

comprehensive analysis of
signal and backgrounds needed

cf. Bagger et al. (1993, 1995)

Englert, Worek, Zeppenfeld, B. J. (2008)

☞ minimize backgrounds with respect to signal

☞ maximize number of surviving signal events consider two “prototype” scenarios for the VBF signal:

- SM with heavy Higgs boson ($M_H = 1$ TeV, $\Gamma_H = 0.5$ TeV)

  naive estimate of strongly coupled sector with scalar, iso-scalar resonance at the TeV scale

- Warped Higgsless model with extra vector resonances

$$
\begin{aligned}
(\; m_{W_2} &= 700 \text{ GeV}, \; \Gamma = 13.7 \text{ GeV}, \\
m_{Z_2} &= 695 \text{ GeV}, \; \Gamma = 18.7 \text{ GeV}, \\
m_{Z_3} &= 718 \text{ GeV}, \; \Gamma = 6.4 \text{ GeV} \;)
\end{aligned}
$$

consider gauge boson sector of Randall-Sundrum scenario with one compactified extra dimension and AdS$_5$ metric

$$ds^2 = \frac{R^2}{y^2}\left\{g_{\mu\nu}dx^\mu dx^\nu - dy^2\right\}$$

$$R \leq y \leq R'$$

Planck brane

TeV brane

boundary conditions along extra dimension
[Csáki, Grojean, Murayama, Pilo, Terning]

➠ Kaluza-Klein decomposition of the gauge fields

$$W_\mu(x,y) = \sum_k \psi_k^{(W)} W_\mu^{(k)}(x)$$

$$Z_\mu(x,y) = \sum_k \psi_k^{(Z)} Z_\mu^{(k)}(x)$$

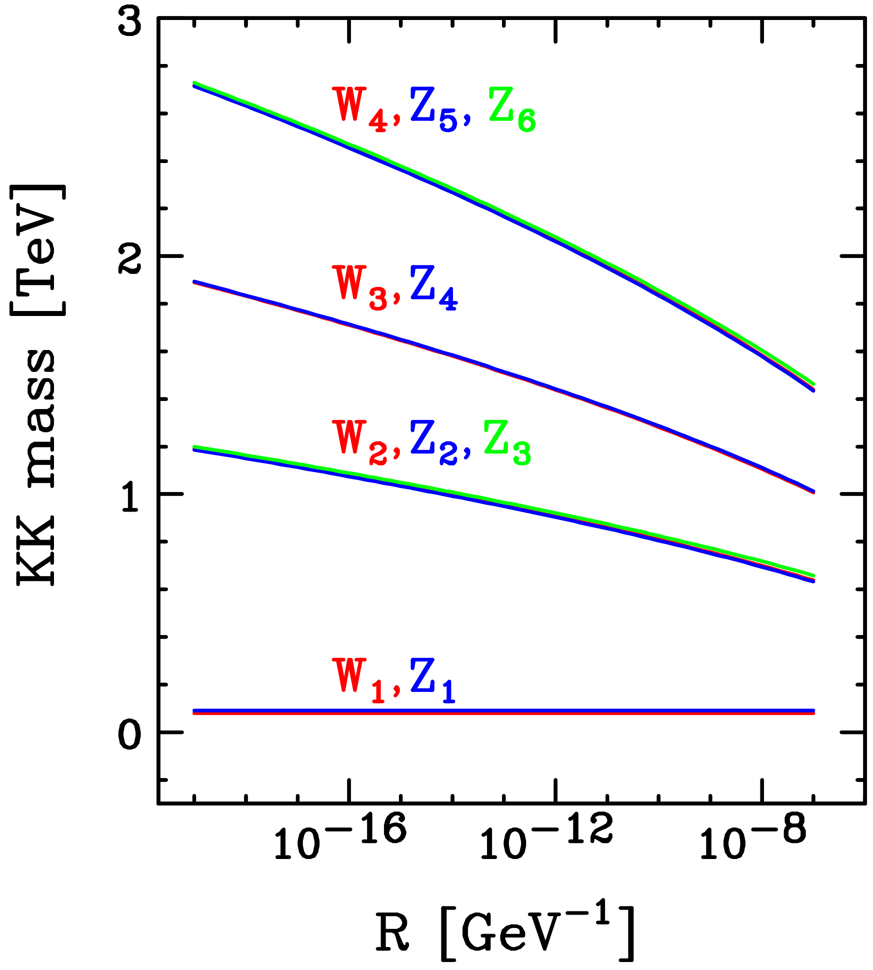
$k = 0$: photon

$k = 1$: SM Z, $W^\pm$

$k > 1$: KK Z_k, $W_k^\pm$

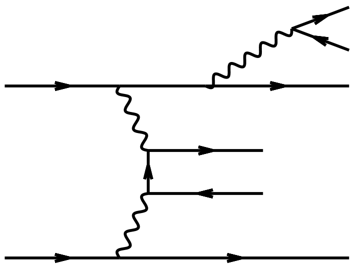
model fully determined by R

Englert, Worek, Zeppenfeld, B. J. (2008)

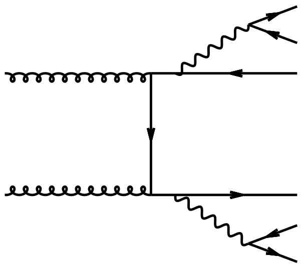


backgrounds to the strongly interacting gauge boson signal in the heavy Higgs (HH) and Kaluza-Klein (KK) scenarios:

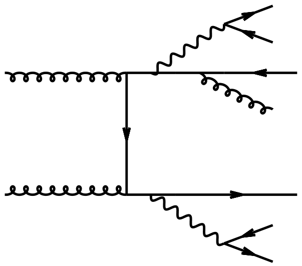
- EW $VVjj$ production



- QCD $VVjj$ production



- $t\bar{t} + \text{jets}$ production (with $t \to Wb$)



selection cuts for SEWSB analysis

inclusive cuts

$$p_{Tj}^{\text{tag}} > 30\text{ GeV}\,, |\eta_j| < 4.5\,,$$
$$\Delta R_{jj} > 0.7\,,\quad \Delta R_{\ell j} > 0.4\,,$$
$$p_{T\ell} > 20\text{ GeV},\quad |\eta_\ell| < 2.5,$$
$$m_{\ell\ell} > 15\text{ GeV}$$

VBF cuts

$$\eta_{j,min}^{tag} < \eta_\ell < \eta_{j,max}^{tag}\,,$$
$$\eta_{j_1}^{tag} \times \eta_{j_2}^{tag} < 0\,,$$
$$\Delta\eta_{jj} > 4\,, m_{jj} > m_{jj}^{min}$$

leptonic cuts
(process-specific)

central jet veto
b-tagging veto

in contrast to backgrounds, signal processes feature energetic leptons of high p_T and large invariant mass

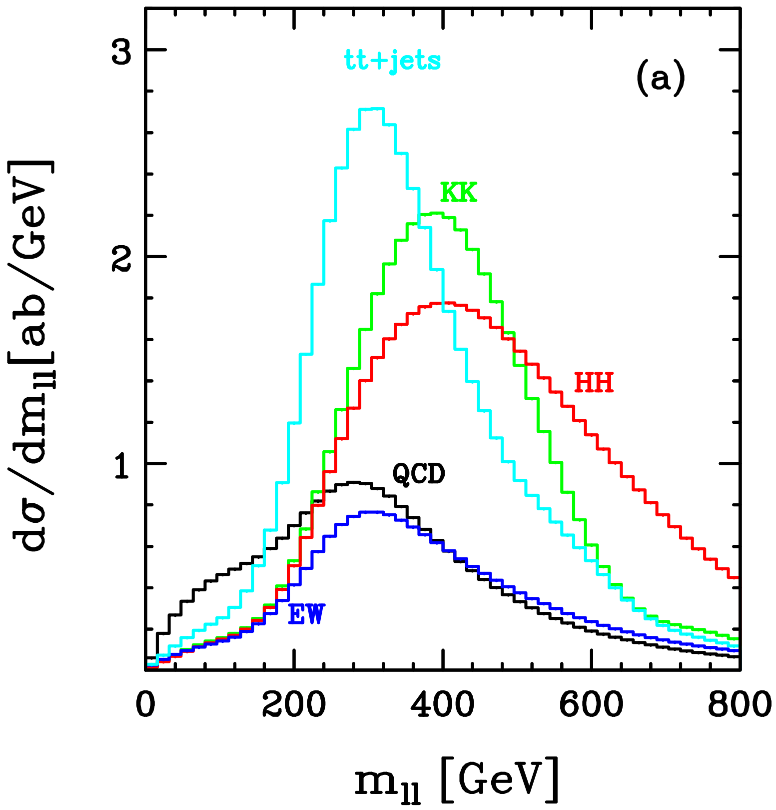
details of leptonic cuts depend on decay channel

$pp \to W^+W^-jj$:

$$p_{T\ell} > 100 \text{ GeV}$$
$$\Delta p_T(\ell\ell) > 250 \text{ GeV}$$

$$\min(m_{\ell j}) > 180 \text{ GeV}$$

Englert, Worek, Zeppenfeld, B. J. (2008)



inclusive cuts, VBF cuts, CJV & b-veto
$p_{T\ell} > 100$ GeV, $\min(m_{\ell j}) > 180$ GeV

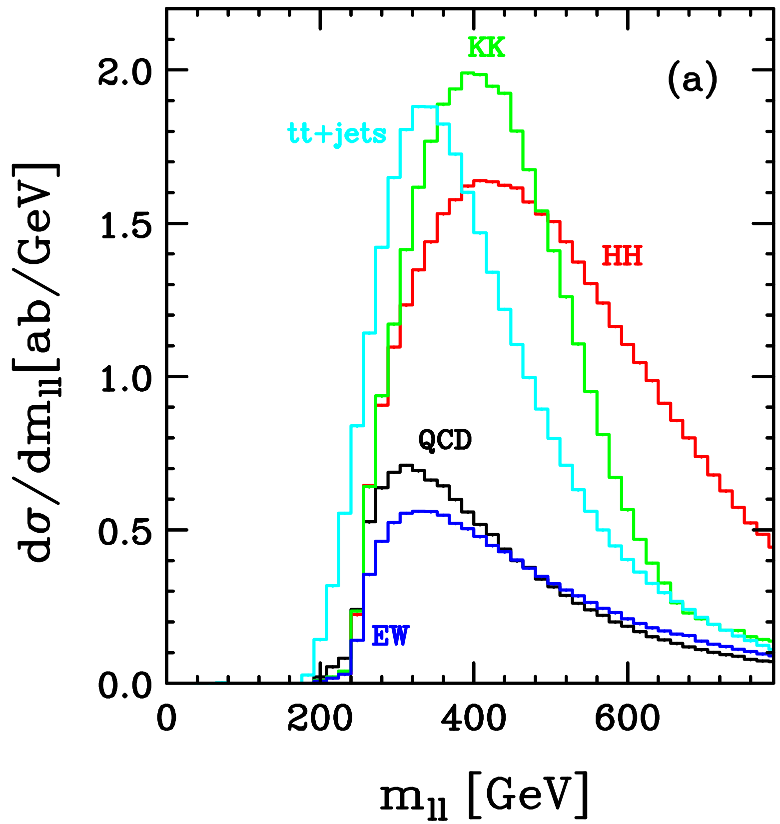
in contrast to backgrounds, signal processes feature energetic leptons of high p_T and large invariant mass

details of leptonic cuts depend on decay channel

Englert, Worek, Zeppenfeld, B. J. (2008)

$\underline{pp \to W^+W^-jj}$:

$$p_{T\ell} > 100 \text{ GeV}$$
$$\Delta p_T(\ell\ell) > 250 \text{ GeV}$$
$$m_{\ell\ell} > 200 \text{ GeV}$$
$$\min(m_{\ell j}) > 180 \text{ GeV}$$



. . . final level of cuts

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

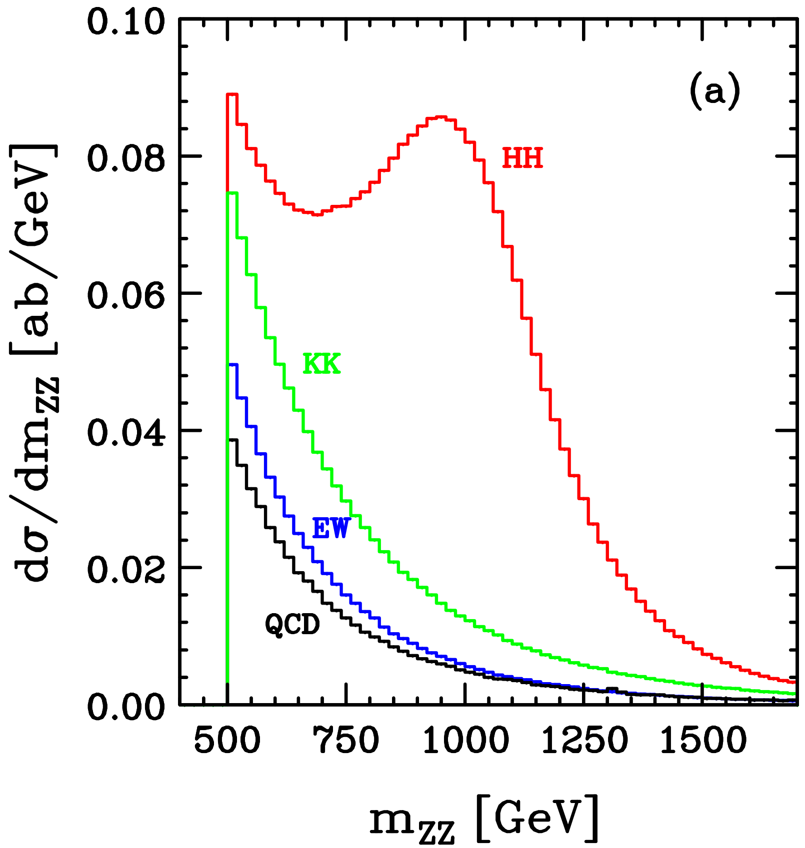
final level of cuts & integrated luminosity . . . 300 fb^{-1}

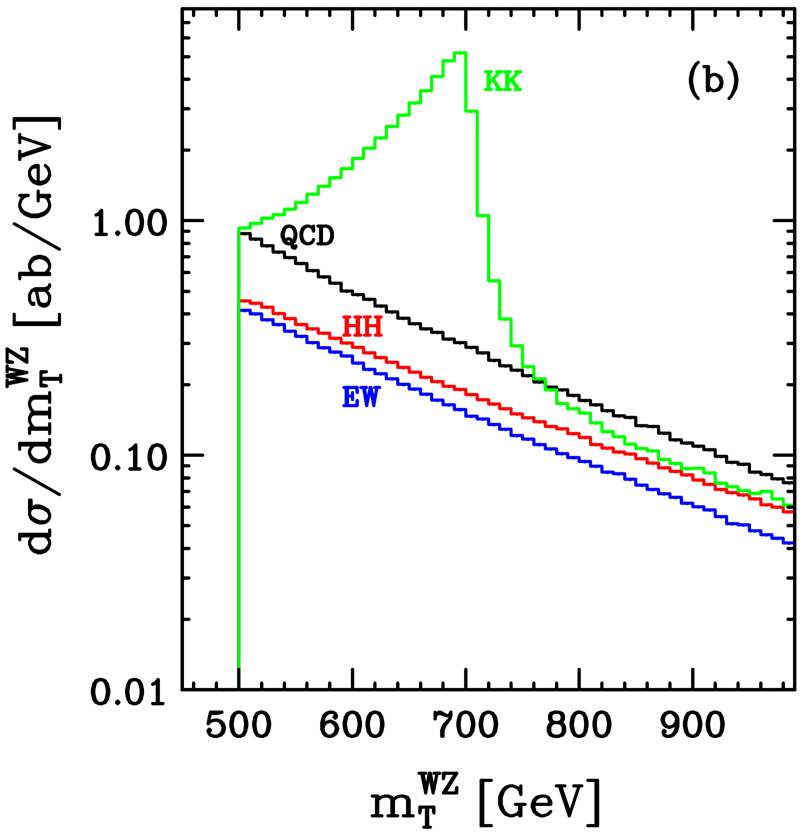
Process	σ_S	σ_B	S/B	$S/\sqrt{B}$	N_{signal}	$N_{\mathrm{bkgd.}}$
$W^{\pm}Zjj$ $W^{+}W^{-}jj$	0.68 0.40	0.39 0.78	1.7 0.5	18.9 7.9	204 120	117 234
$ZZjj \to 4\ell\, jj$ $ZZjj \to 2\ell 2\nu\, jj$	0.009 0.05	0.021 0.10	0.4 0.5	1.1 2.7	3 15	6 30

final level of cuts & integrated luminosity . . . 300 fb^{-1}

LO results: scalar / vector resonances

Englert, Worek, Zeppenfeld, B.J. (2008)

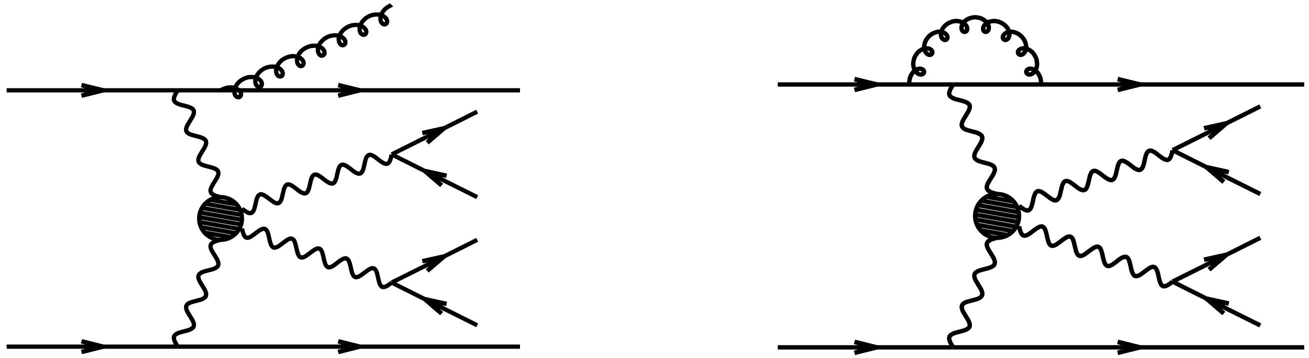




$ZZjj \to 4\ell jj$

W^+Zjj

NLO-QCD corrections

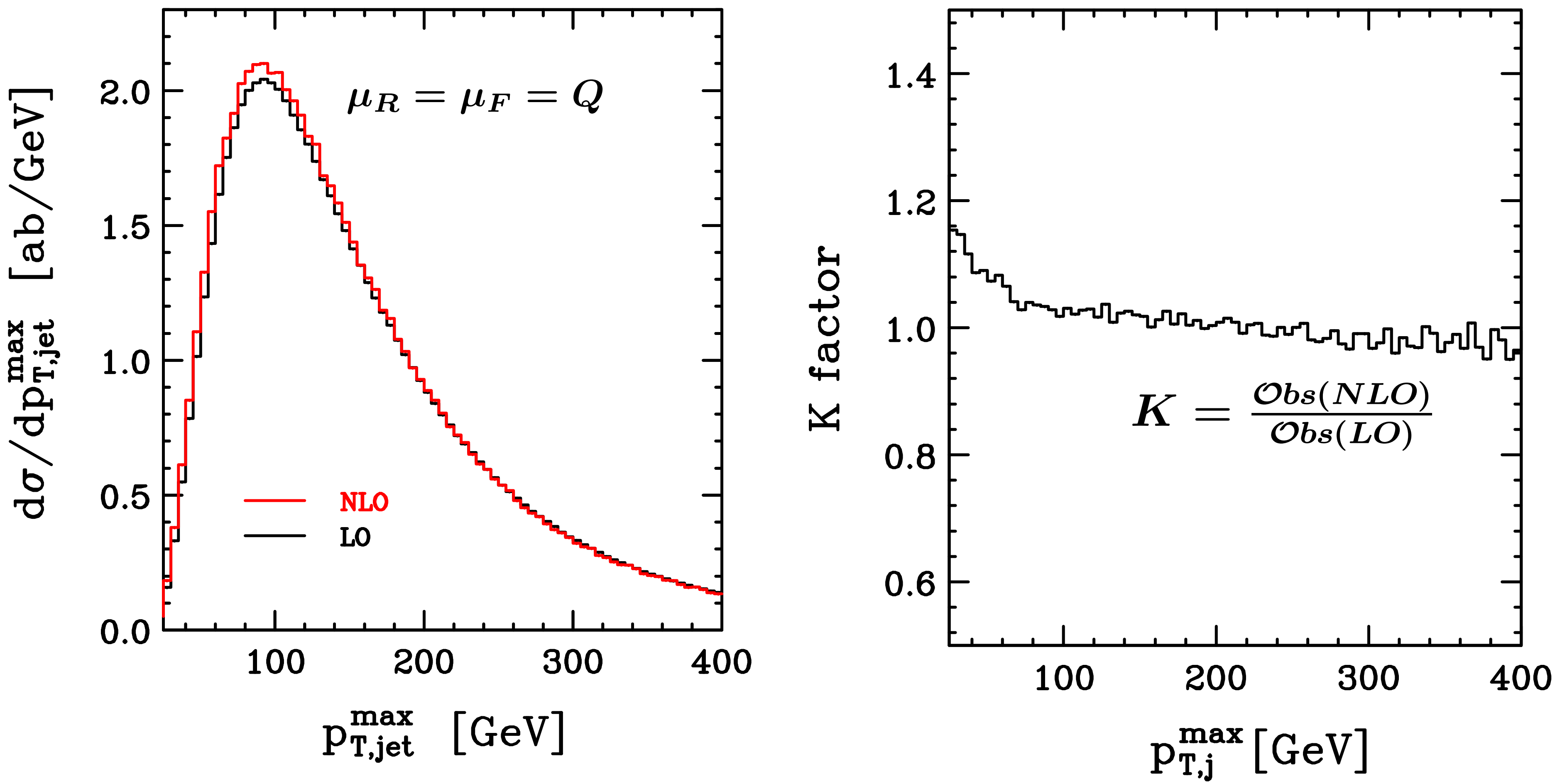


- compute real emission diagrams
- compute virtual corrections

$$2\,\mathrm{Re}[\mathcal{M}_V \mathcal{M}_B^\star] \;\propto\; \frac{\alpha_s(\mu_r)}{2\pi}|\mathcal{M}_B|^2 \times \left[-\frac{2}{\varepsilon^2} - \frac{3}{\varepsilon} + \text{const.}\right] + 2\,\mathrm{Re}[\widetilde{\mathcal{M}}_V \mathcal{M}_B^\star]$$

- handle IR divergencies by dipole subtraction approach *(Catani, Seymour)*

Englert, Zeppenfeld, B. J. (2008)



NLO-QCD corrections always in the few-percent range

✧ explicit calculations revealed that
VBF reactions are perturbatively well-behaved

(moderate NLO QCD and EW corrections,
negligible higher order and interference effects)

✧ backgrounds are well under control

signatures of new physics in the gauge boson sector
should be observable at the LHC

↓

VBF crucial for understanding mechanism of
electroweak symmetry breaking


THANK
YOU
THANK