Vector Boson Fusion – approaching the (yet) unknown

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☎ Southern Methodist University – February 2008

outline

- Higgs searches at the LHC
- Higgs production via vector boson fusion (VBF):
  - VBF beyond tree level
  - the gluon fusion background
  - interference effects
- weak boson scattering in VBF
  - theoretical concepts & techniques
  - phenomenological results
- summary & conclusions

Standard Model (SM):
couplings and parameters
strongly constrained

only free parameter: M_H
(not yet measured)

still: theory & experiment impose
variety of bounds on Higgs mass

theory: perturbative,
well-behaved SM up to high energy
☞ $130 \lesssim M_H \lesssim 180$ GeV

experiment:
direct and indirect searches
(assuming SM to be correct)

☞ $114 \lesssim M_H \lesssim 182$ GeV

the next steps

- ✘ detect Higgs boson and determine M_H
- ✘ investigate properties of the *“Higgs boson”* carefully

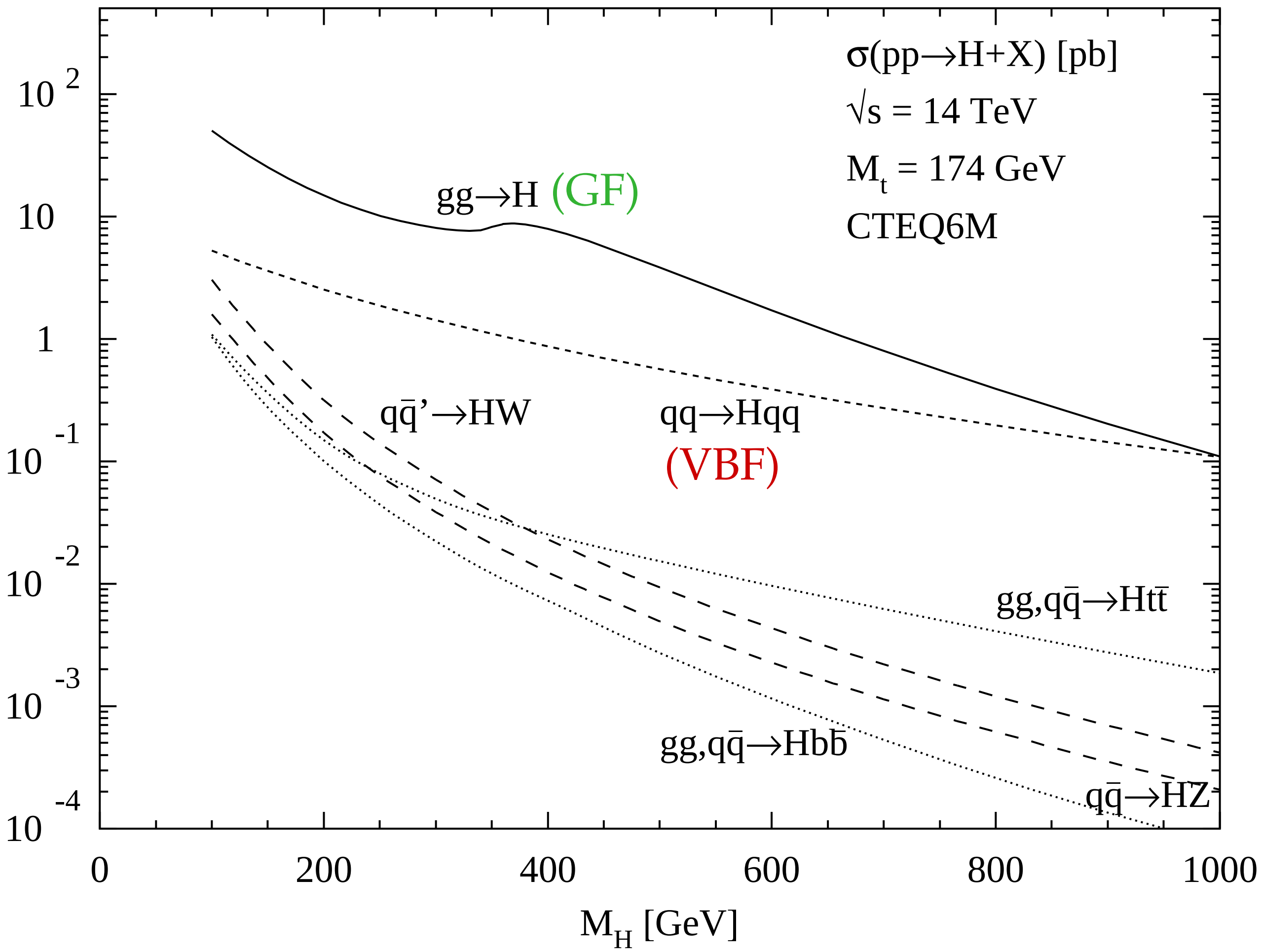
determination of
couplings, charge, spin, CP quantum numbers
necessary to reveal

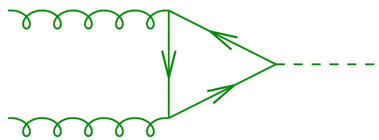
SM, SUSY, or something completely different?

⇓

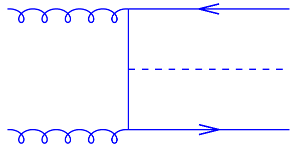
full, quantitative understanding of
most promising search channels required
from experiment and theory

M. Spira (2007)

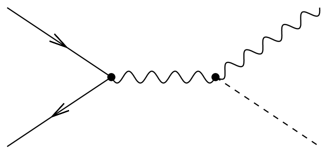




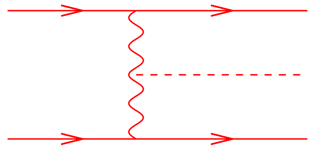
gluon fusion (GF)



$t\bar{t}$ fusion



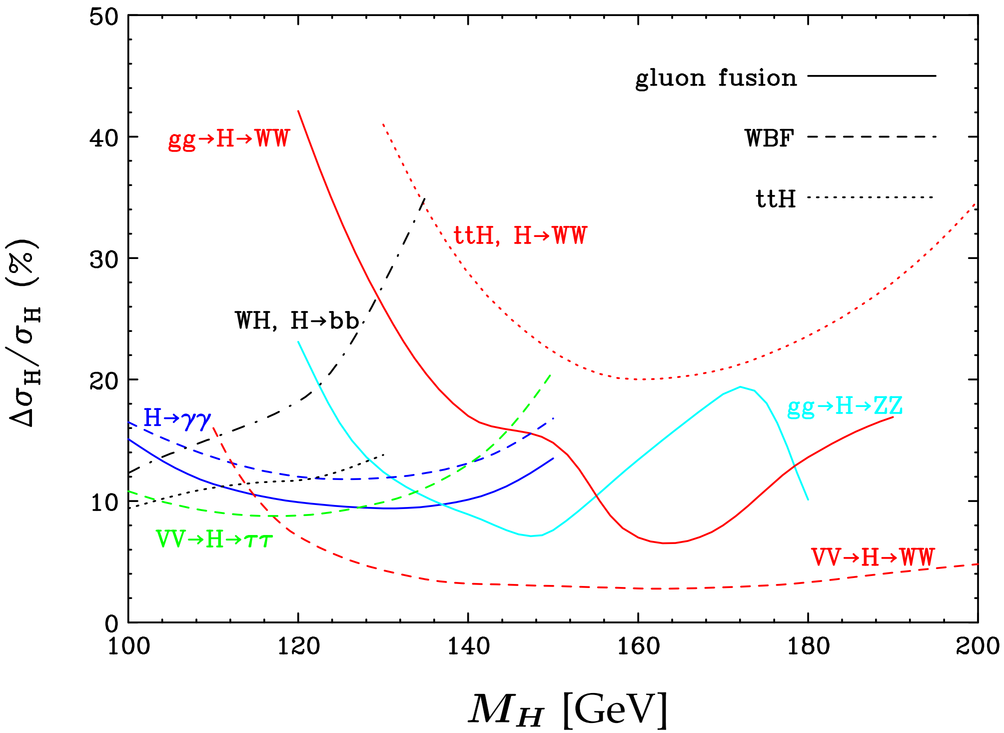
W, Z bremsstrahlung



vector boson fusion (VBF)

expected statistical & systematic errors on $\boldsymbol{\sigma \cdot B}$:

Rainwater et al. (2002)



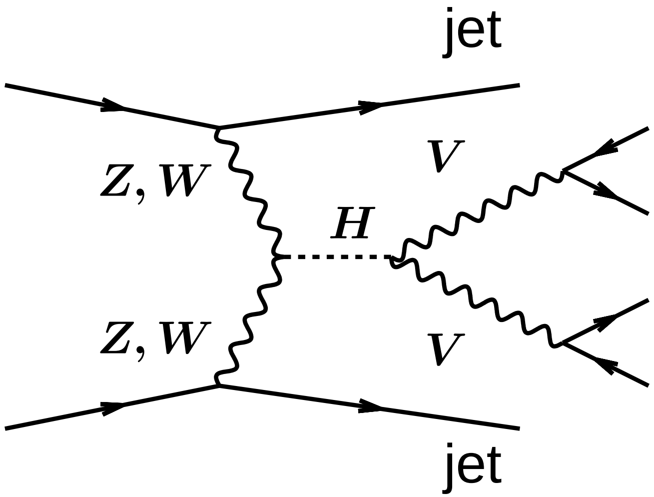
$(\mathcal{L} = 200\ \mathrm{fb}^{-1})$

- QCD/PDF uncertainties:
  - VBF: $\lesssim 5\%$ at NLO
  - GF: $\lesssim 10\%$ scale uncertainty (NNLO + resummation effects)
    $\sim 4 \div 7\%$ PDF uncertainty
- luminosity/acceptance uncertainties: $\sim 5\%$

focus

take a closer
look at
vector boson fusion

Higgs production in VBF

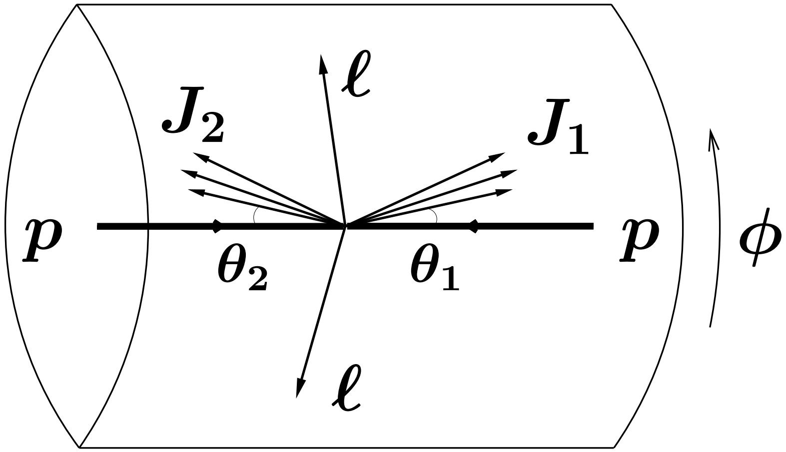


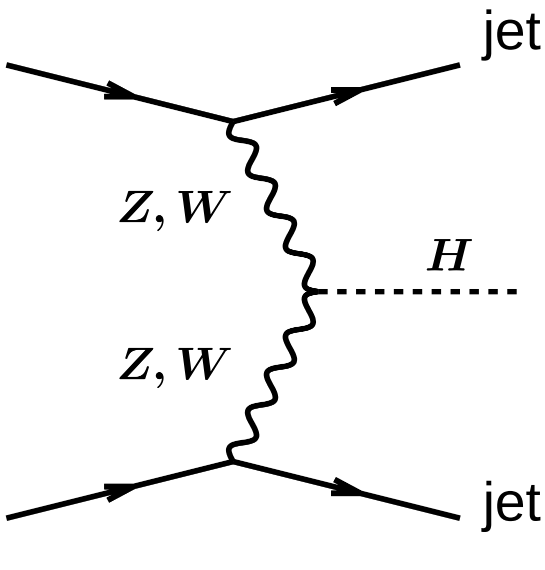
scattered quarks
$\longrightarrow$ two forward tagging jets
(energetic; $p_T > 20$ GeV)

Higgs decay products
typically between tagging jets

little jet activity in
central rapidity region

(colorless V exchange
$\longrightarrow$ gluon radiation suppressed)





inclusive cross section:

Han, Valencia, Willenbrock (1992)

distributions:

Figy, Oleari, Zeppenfeld (2003)

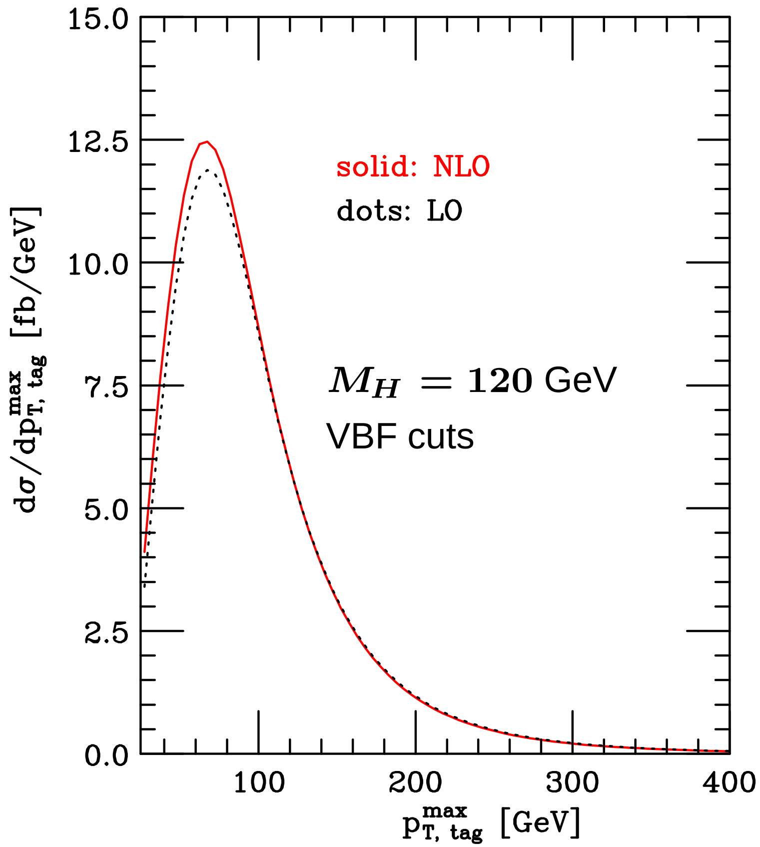
Berger, Campbell (2004)

NLO QCD corrections

moderate and

theoretically well under control

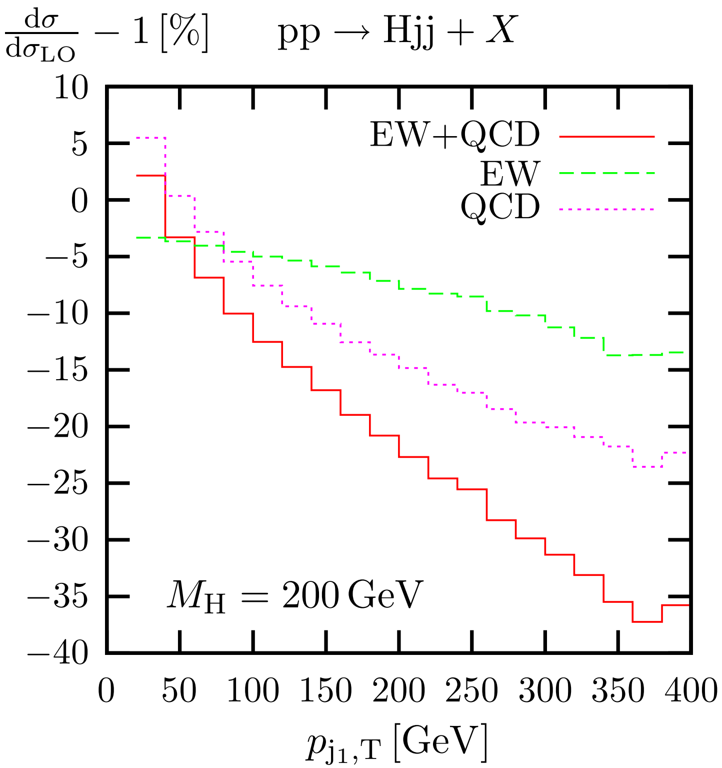
(order 10% or less)

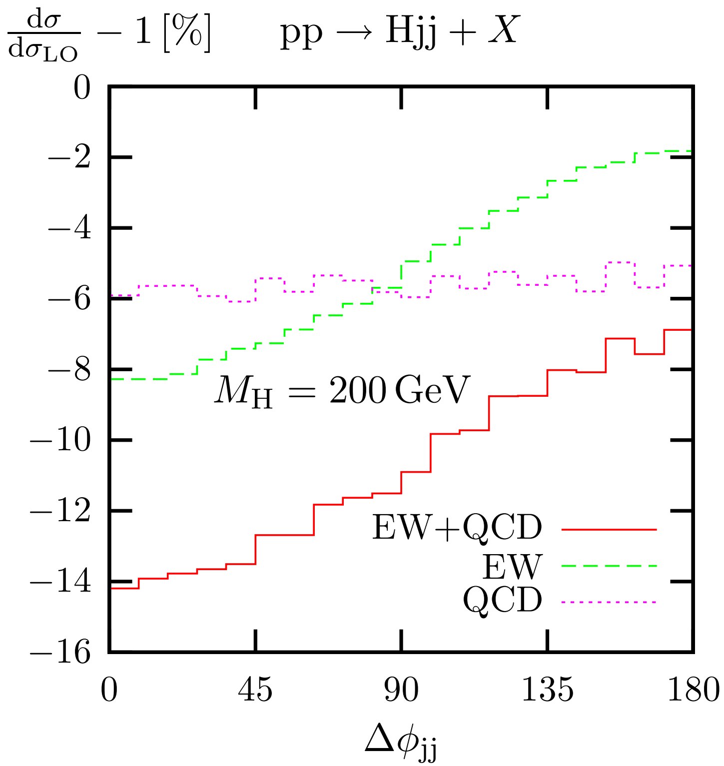


Ciccolini, Denner, Dittmaier (2007):

NLO EW corrections to inclusive cross sections and distributions

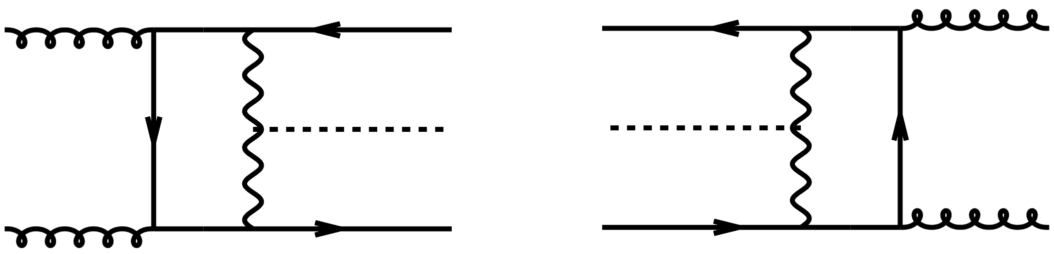
☞ NLO EW corrections non-negligible, modify $\boldsymbol{K}$ factors and distort distributions by up to 10%





Harlander, Vollinga, Weber (2007):

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



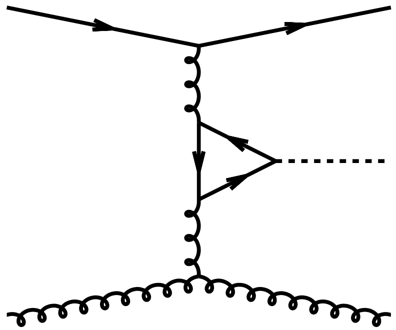
important due to large gluon luminosity at LHC?

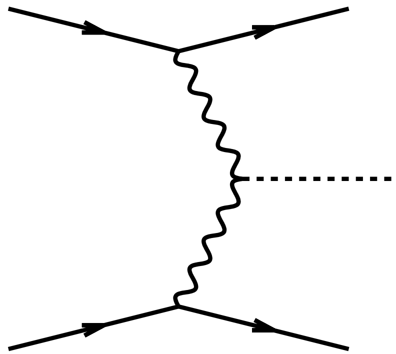
$$gg \longrightarrow q\bar{q}H,\ q\bar{q} \longrightarrow ggH,$$
$$qg \longrightarrow qgH,\ \bar{q}g \longrightarrow \bar{q}gH$$

minimal set of cuts: $\sigma^{2-\mathrm{loop}}_{\mathrm{gluon}} \sim 2\ \%$ of $\sigma^{\mathrm{LO}}_{\mathrm{VBF}}$
VBF cuts: relative suppression by additional order of magnitude

$pp \longrightarrow Hjj$ via gluon fusion

VBF can be faked by double real corrections
to $gg \longrightarrow H$ ("gluon fusion")





complete LO calculation (including pentagons):

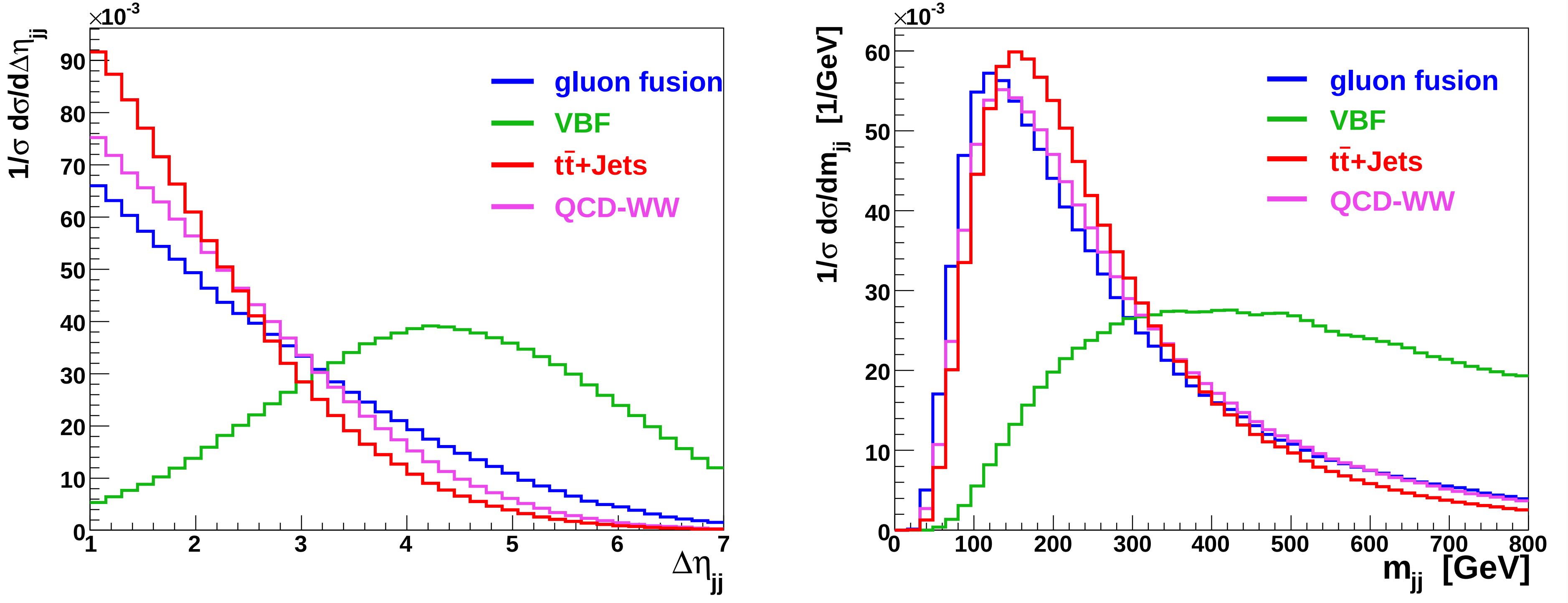
Del Duca, Kilgore, Oleari, Schmidt, Zeppenfeld (2001)

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 enhance either VBF or gluon fusion (GF)

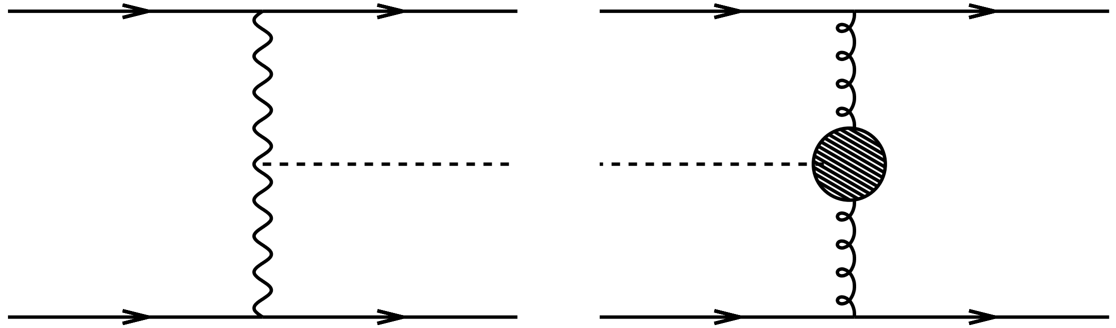
(crucial for measurement of HVV, Htt, Hgg couplings)



Klämke, Zeppenfeld (2007)

$pp \to Hjj$ via VBF×GF at tree level

can VBF×GF interference pollute the clean VBF signature?



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

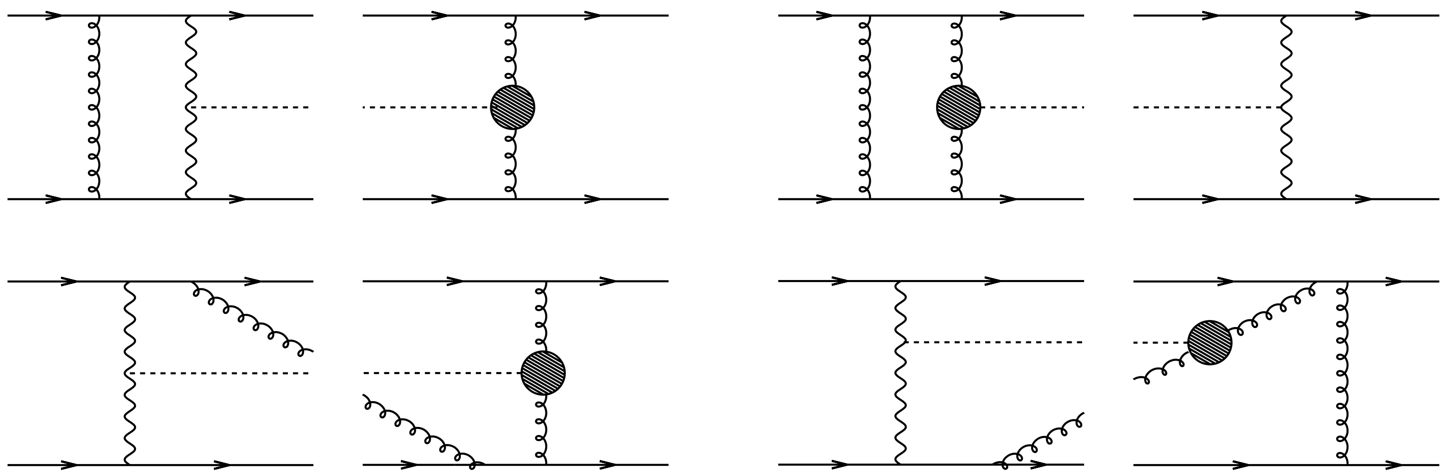
tree-level interference possible only for

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

☞ completely negligible

$pp \to Hjj$ via VBF×GF beyond tree level

additional gluon → VBF×GF interference for $qq' \to qq'H$ ✔



Andersen, Smillie (2006):

“. . . the size of the one-loop interference should be comparable to the size of the one-loop NLO corrections to the WBF and the GF processes . . . ”

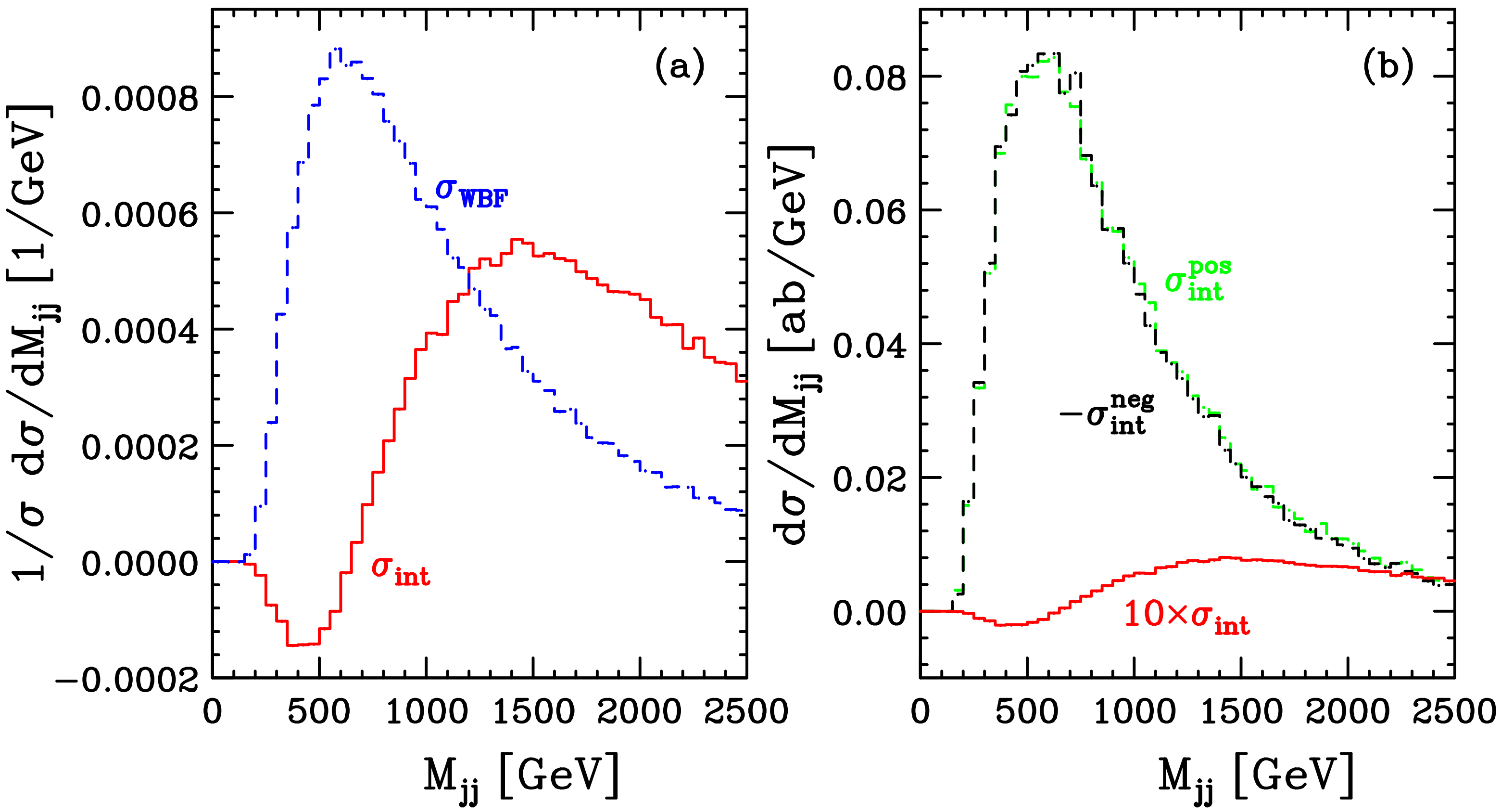
$pp \to Hjj$ via VBF×GF beyond tree level

Andersen et al. (2007) & Bredenstein, Hagiwara, B. J. (2008):

explicit loop calculation reveals strong cancelation effects

initial state	interaction	isospin	$\sigma_{\rm int}^{\rm cuts}$ [ab]	$\sigma_{\rm WBF}^{\rm cuts}$ [fb]
qq	NC	+ + or - -	51.4	72.3
	NC	+ - or - +	-49.8	70.8
	CC	+ - or - +	–	405.7
$q\bar{q}$	NC	+ - or - +	-3.1	39.3
	NC	+ + or - -	2.2	43.0
	CC	+ + or - -	–	230.7
$\bar{q}\bar{q}$	NC	- - or + +	4.0	5.1
	NC	- + or + -	-3.2	4.3
	CC	- + or + -	–	25.7
sum	NC+CC	all	1.5	896.9

$pp \longrightarrow Hjj$ via VBF×GF beyond tree level

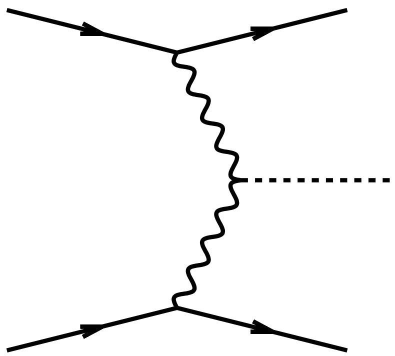


cancelations lead to unexpected shapes of distributions

but: $\sigma_{\rm int}$ tiny $\longrightarrow$ no effect on VBF signal

open issues:

- ✘ is the pattern found in VBF×GF characteristic for loop-induced QCD×EW interference contributions?
- ✘ worthwhile considering other (even simpler) processes . . .



- ✘ $pp \to Hjj$ via VBF under excellent control
- ✘ QCD & EW NLO corrections at 10% level
- ✘ dominant NNLO QCD corrections small
- ✘ interference with GF Hjj production negligible

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

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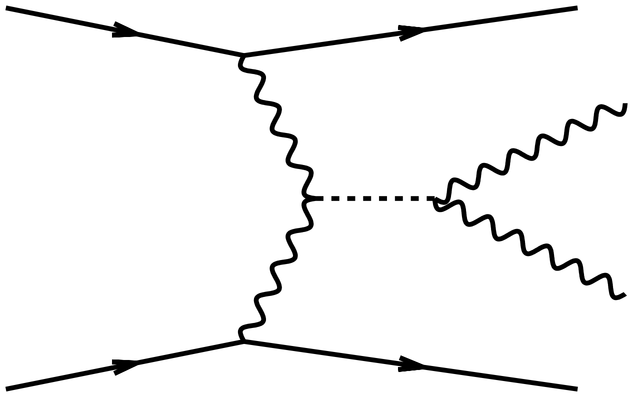
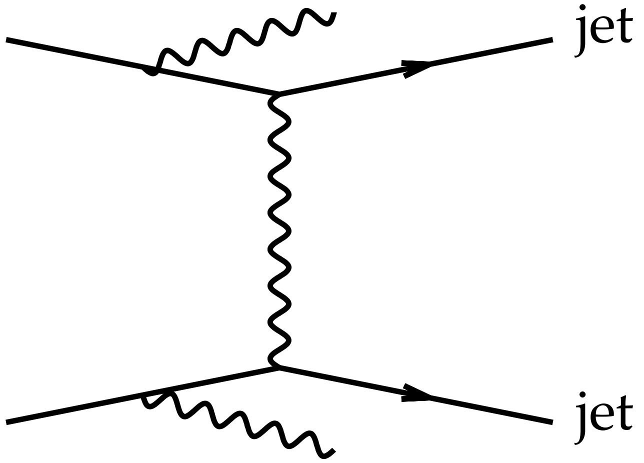
precise predictions needed to match
statistical accuracy of LHC





$pp \to VV + jj$ via VBF

similar characteristics to Higgs signal process

↓

background rejection difficult

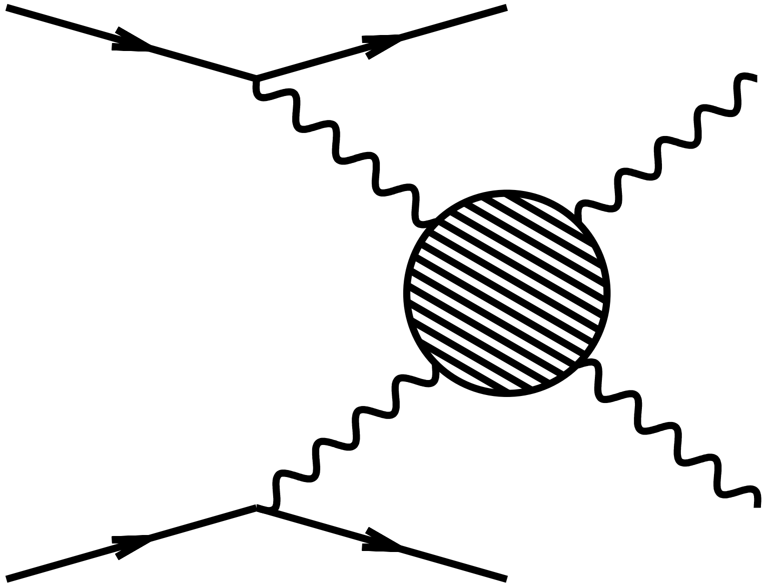
VBF induced $qq \to VVqq$

contains weak boson scattering
$V_L V_L \to V_L V_L$

↓

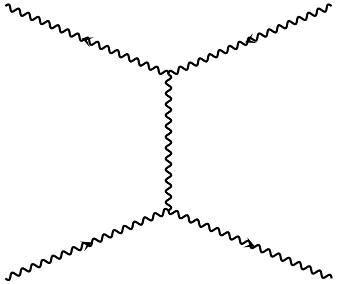
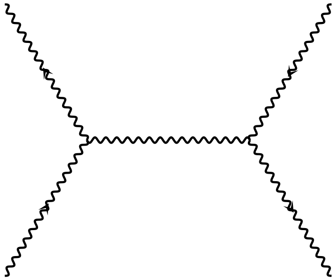
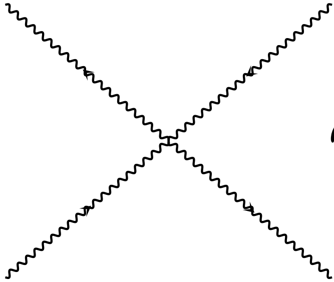
very sensitive to mechanism of
electroweak symmetry
breaking:

light Higgs boson? M_H?
strong EWSB?

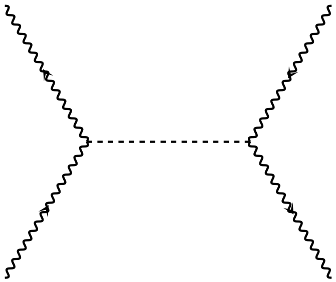
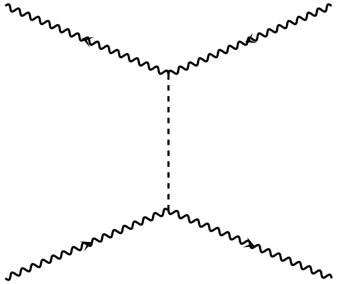


VV scattering & unitarity

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

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

growth violates unitarity $\to$ need:

 $+$ 

Higgs with $M_H \lesssim 1$ TeV

or new physics at TeV scale

weak boson scattering: a (rough) overview

1984 $qq \longrightarrow qqVV$ within the "Effective W Approximation"

1986 full $qq \longrightarrow qqVV$ without V decay

1990 $qq \longrightarrow qqVV$ with V decay in narrow width approximation

1993 application to strongly interacting gauge boson systems

SSC canceled $\longrightarrow$ focus redirected towards LHC

2005 PHASE – LO event generator for six-fermion processes

2006 `vbfnlo` – NLO QCD event generator for VBF processes, including $qqVV$ with full lepton correlations

EW $VVjj$ production

need stable, fast & flexible Monte Carlo program allowing for

- computation of various jet observables at NLO-QCD accuracy
- straightforward implementation of cuts

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

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

major challenges:

- multi-parton process: $2 \to 4$ for $qq \to qq\,VV$;
  $2 \to 6$ for $qq \to qq\,\ell^+\ell^-\nu_\ell\bar{\nu}_\ell$
  or $qq \to qq\,\ell^+\ell^-\ell^+\ell^-$
- full consideration of finite width effects
- numerically stable treatment of pentagon contributions

outline of the calculation

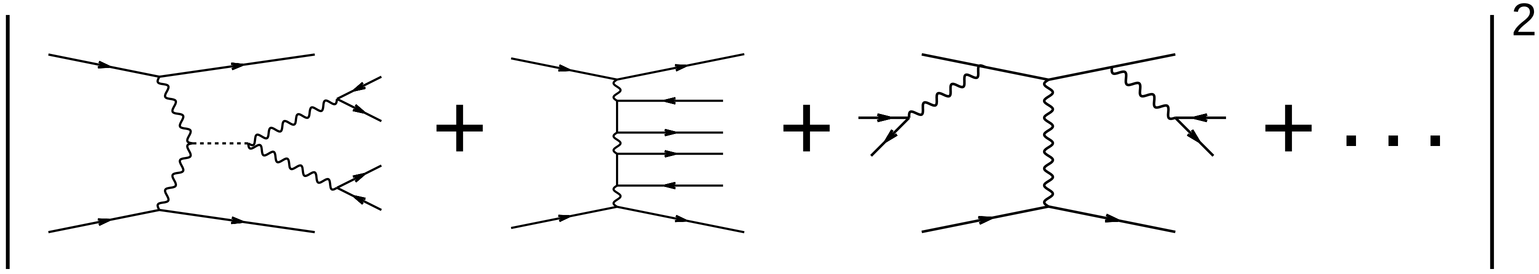
$$d\hat{\sigma}_{ab\to 4\ell+jjX} \sim \overline{\sum} |\mathcal{M}|^2_{ab\to 4\ell+cd(e)}\, \mathcal{F}_{\text{jet}}\, dPS_f$$

- ✘ calculation of $|\mathcal{M}|^2$ at $\mathcal{O}(\alpha^6)$ (LO) and $\mathcal{O}(\alpha^6\alpha_s)$ (NLO QCD)
  - dimensional reduction $(d = 4 - 2\varepsilon)$
  - $\overline{\text{MS}}$-renormalization
- ✘ handling of infrared singularities by *Catani & Seymour's* dipole subtraction approach (need real emission & virtual contributions and counterterms)
- ✘ phase space integration and convolution with PDFs with Monte Carlo techniques in 4 dimensions

$pp \to \ell\bar{\ell}\,\ell'\bar{\ell}'\,jj$: the leading order

need to compute numerical value for

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



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

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

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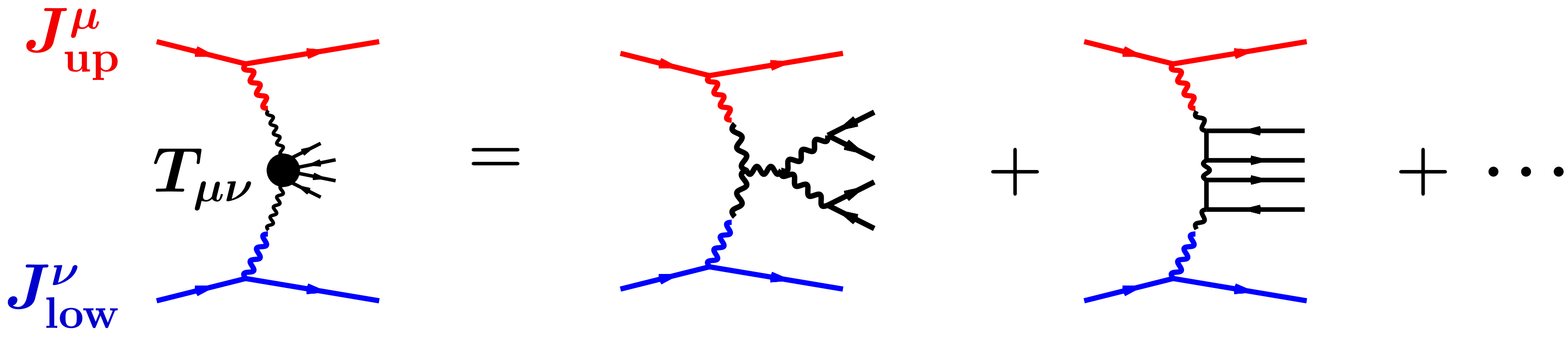
essential: organize calculation economically

↓

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

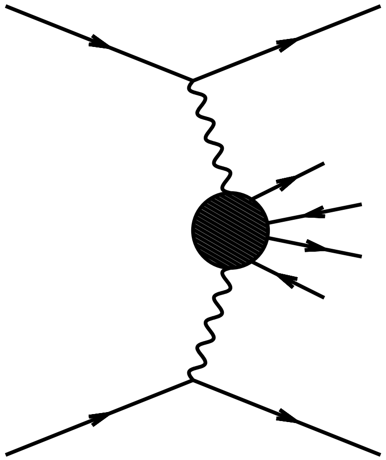
develop modular structure with leptonic tensors . . .



. . . 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`

extra feature: new physics



nice extra: implementation of new interactions in bosonic sector rather straightforward, e.g.

N. Greiner, diploma thesis:
"Anomalous couplings in W pair production via VBF",
Karlsruhe 2006

C. Englert, diploma thesis:
"Spin-1 resonances in vector boson fusion in warped Higgsless models",
Karlsruhe 2007

- employ MadGraph for computing first reference result
but: repeated calculation of similar diagrams makes code extremely slow

($1 \div 2$ months CPU time on a 3 GHz Linux PC for $\Delta\sigma/\sigma \approx 0.2\%$ for WW and even more in ZZ-case)

- high statistics needed especially for kinematic distributions
- pre-calculate leptonic tensors
  - ☞ gain speed-up of factor 70 for real emission code
- valuable check: comparison to result obtained with MadGraph

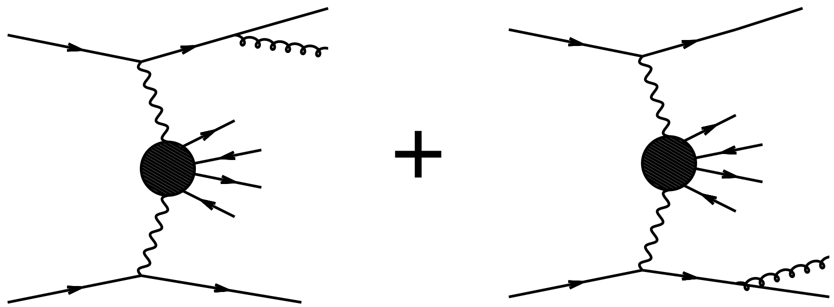
. . . more precision . . .

the next-to-leading order:

- real emission
- subtraction terms
- virtual corrections

needed: numerical value for up to 2892 diagrams ($ZZjj$ case)

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



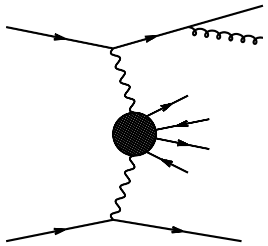
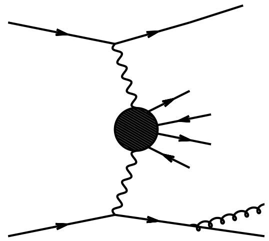
$$+ \dots \Bigg|^2$$

at each generated phase space point in 4 dimensions
$\longrightarrow$ apply same techniques as at LO

☹ the major challenge: large number of diagrams
(without optimization code extremely slow!)

☺ the solution: apply speed-up tricks developed at LO
(here even more effective)

still: `MadGraph` extensively used for debugging and cross checks

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

$$+$$

$$+ \ldots \Bigg|^2$$

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 needed: $\boldsymbol{\sigma}^{NLO} \equiv \int d\boldsymbol{\sigma}^{NLO} = \int_{m+1} d\boldsymbol{\sigma}^{R} + \int_{m} d\boldsymbol{\sigma}^{V}$

IR divergent

☞ regularize in $d = 4 - 2\varepsilon$ dim

introduce local counterterm $d\boldsymbol{\sigma}^{A}$ with same singularity structure as $d\boldsymbol{\sigma}^{R}$:

$$\boldsymbol{\sigma}^{NLO} = \int_{m+1} \underbrace{\left[d\boldsymbol{\sigma}^{R} - d\boldsymbol{\sigma}^{A}\right]}_{\text{finite}} + \int_{m+1} d\boldsymbol{\sigma}^{A} + \int_{m} d\boldsymbol{\sigma}^{V}$$

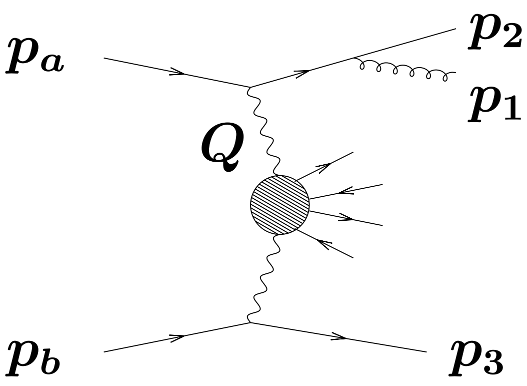
dipole subtraction

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

integrate over one-parton PS analytically

explicitly cancel poles & then set $\varepsilon \to 0$

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



$qq' \longrightarrow qq'(g)H$: upper & lower quark lines "decoupled"

☞ simple singularity structure with counterterms

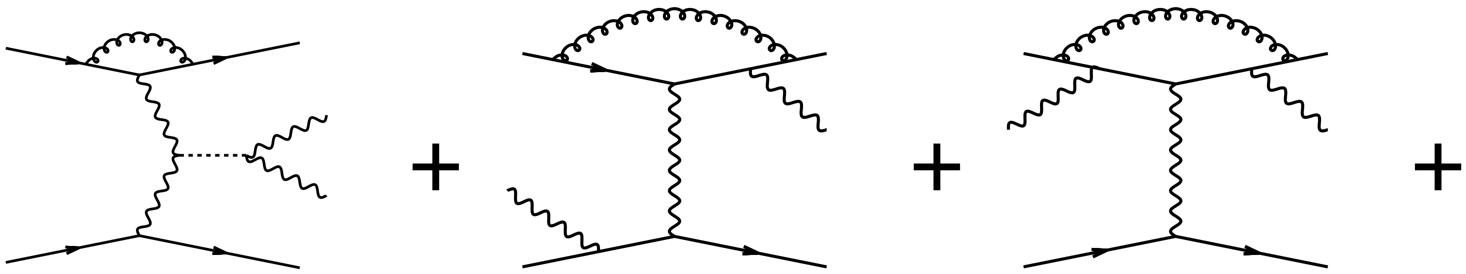
$$\frac{8\pi\alpha_s(\mu_r)}{Q^2} C_F \frac{x^2+z^2}{(1-x)(1-z)} |\mathcal{M}_B(\tilde{p})|^2$$

and $\{\tilde{p}_i\} \longrightarrow \{p_i\}$ in divergent regions

. . . continuous interpolation between soft and collinear gluon radiation (x and / or $z \longrightarrow 1$)

analytical integration over soft/collinear phase space gives

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

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

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

$\tilde{\mathcal{M}}_V^{finite}$ computed with Passarino-Veltman / Denner-Dittmaier reduction
cumbersome: (numerically small) pentagon contributions

combination of real emission, virtuals,
and subtraction terms:

poles canceled analytically $\longrightarrow$ finite results

checks

- ✔ comparison of LO and real emission amplitudes with `MadGraph`
- ✔ soft / collinear limits: $d\sigma^R \longrightarrow d\sigma^A$
- ✔ QCD gauge invariance of real emission contributions:

$$\mathcal{M} = \varepsilon^\star_\mu(p_g)\mathcal{M}^\mu = \left[\varepsilon^\star_\mu(p_g) + C\, p_{g,\mu}\right]\mathcal{M}^\mu$$

- ✔ EW gauge invariance of virtual contributions
- ✔ produce independent code for NC amplitudes
- ✔ comparison of LO result to `MadEvent` (generic cuts)

methods developed are applicable to processes with different leptonic final states:

- $pp \longrightarrow jj\, e^+\nu_e\mu^-\bar{\nu}_\mu$
  ("EW $W^+W^-\,jj$ production")
- $pp \longrightarrow jj\, e^+e^-\mu^+\mu^-$ and $pp \longrightarrow jj\, e^+e^-\nu_\mu\bar{\nu}_\mu$
  ("EW $ZZ\,jj$ production")
- $pp \longrightarrow jj\, e^+\nu_e\mu^+\mu^-$ and $pp \longrightarrow jj\, e^-\bar{\nu}_e\mu^+\mu^-$
  ("EW $W^+Z\,jj$ and $W^-Z\,jj$ production")

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

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

available from

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

[M. Bähr, G. Bozzi, C. Englert, T. Figy, J. Germer, N. Greiner, K. Hackstein, V. Hankele, G. Klämke, M. Kubocz, P. Konar, C. Oleari, M. Werner, M. Worek, D. Zeppenfeld, B. J.]

user options:

- various scale choices and PDF sets
- arbitrary selection cuts
- arbitrary differential distributions
  at LO and NLO
- anomalous gauge boson couplings
  for several channels
- differential K factors
  for all distributions
- weighted / unweighted events
  and LHA format files

implemented processes:
$pp \to Hjj$, $H \to \gamma\gamma$ $H \to \mu^+\mu^-$ $H \to \tau^+\tau^-$ $H \to b\bar{b}$
$pp \to W^+W^-jj \to \ell^+\nu\ell'^-\bar{\nu}'jj$ $pp \to ZZjj \to \ell^+\ell^-\ell'^+\ell'^-jj$ $pp \to ZZjj \to \ell^+\ell^-\nu\bar{\nu}jj$
$pp \to Wjj \to \ell^+\nu jj$ $pp \to Zjj \to \ell^+\ell^-jj$ $pp \to Zjj \to \nu\bar{\nu}jj$

with k_T algorithm, CTEQ6 parton distributions,
and typical VBF cuts:

tagging jets	$p_{Tj} \geq 20$ GeV, $\|y_j\| \leq 4.5$, $\Delta y_{jj} = \|y_{j_1} - y_{j_2}\| > 4$, ($M_{jj} > 600$ GeV) jets located in opposite hemispheres
charged leptons	$p_{T\ell} \geq 20$ GeV, $\|\eta_\ell\| \leq 2.5$, $\Delta R_{j\ell} \geq 0.4$, $y_{j,min} < \eta_\ell < y_{j,max}$
	$M_H = 120$ GeV, $M_{WW,ZZ} > 130$ GeV (for WW and ZZ case: VV continuum only)

for judging the reliability of our prediction:
estimate theoretical uncertainties associated with it

✘ PDF uncertainties:

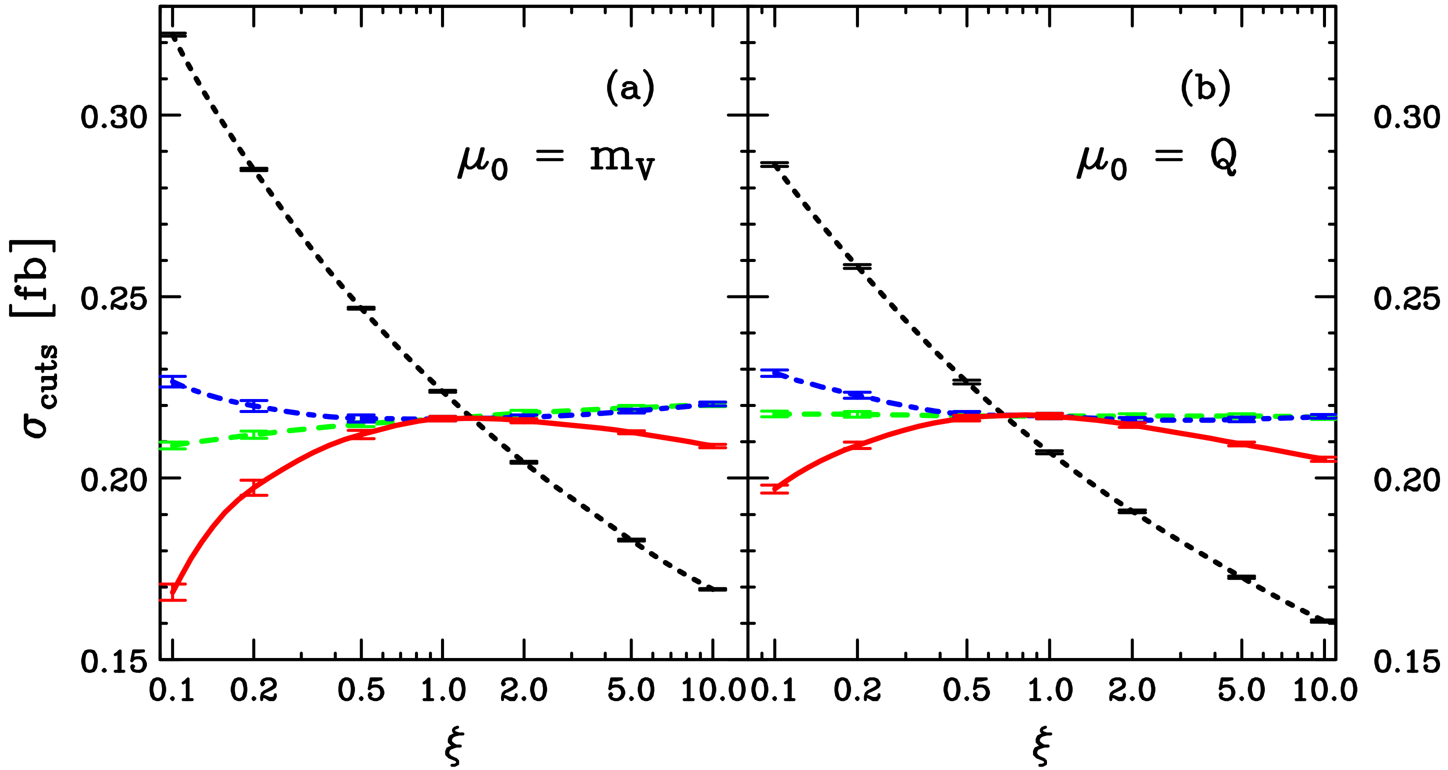
Figy, Oleari, Zeppenfeld (2003):

- applied 40 error eigenvector sets of CTEQ6M
- estimated 3.5% uncertainty for VBF type reactions

✘ dependence on unphysical renormalization and factorization scales

$$\mu \frac{d}{d\mu} \sum_{n=0}^{N} \alpha_s^n \sigma^{(n)} = -\mu \frac{d}{d\mu} \sum_{n=N+1}^{\infty} \alpha_s^n \sigma^{(n)}$$

$\longrightarrow$ scale dependence $\sim$ measure for reliability of perturbative calculation



choose $\mu_R = \xi\mu_0$ and $\mu_F = \xi\mu_0$ with variable ξ
and set $\mu_0 = m_V$ or $\mu_0 = Q$

LO: no control on scale
NLO QCD: scale dependence strongly reduced

compare: $pp \to WWZ$ @ NLO

crossed process: $pp \to WWZ$

Hankele, Zeppenfeld (2007)

LO: very mild scale dependence

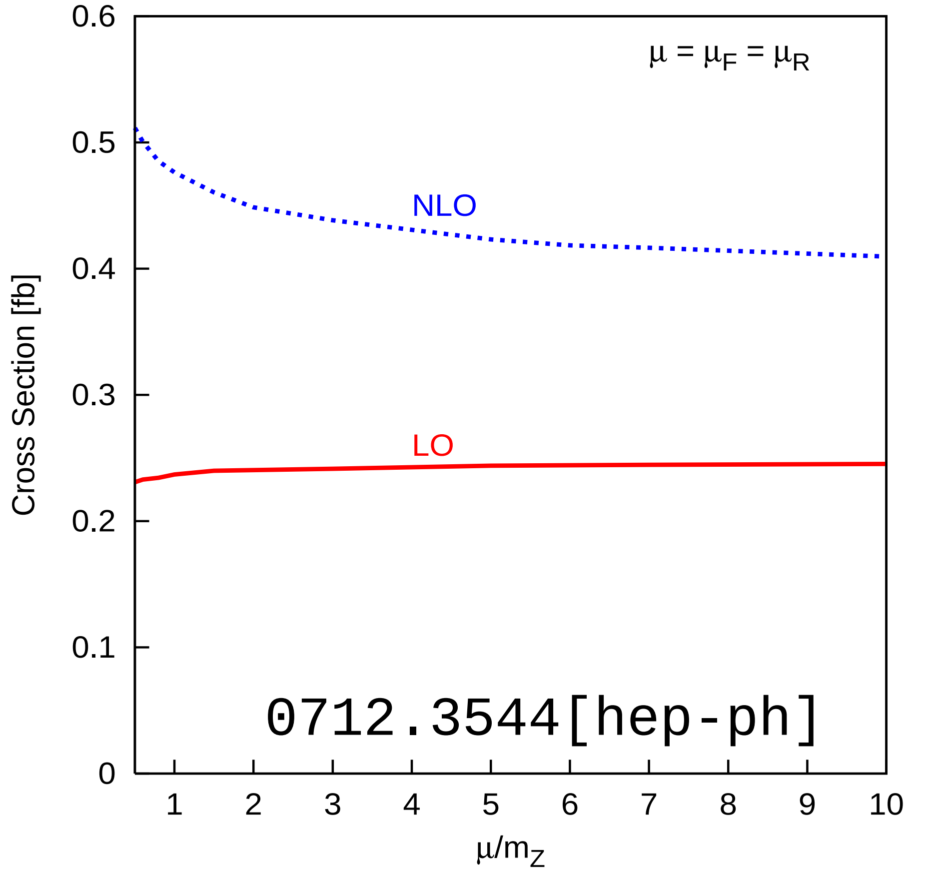
LO is $\mathcal{O}(\alpha_s^0)$,

PDFs probed in regions

with small μ_f dependence

but large QCD corrections with

$$\frac{\sigma^{NLO}}{\sigma^{LO}} \sim 1.7 \div 2.2$$



parton-level Monte Carlo program:
can calculate cross sections and kinematic distributions

→

often more interesting than integrated cross sections

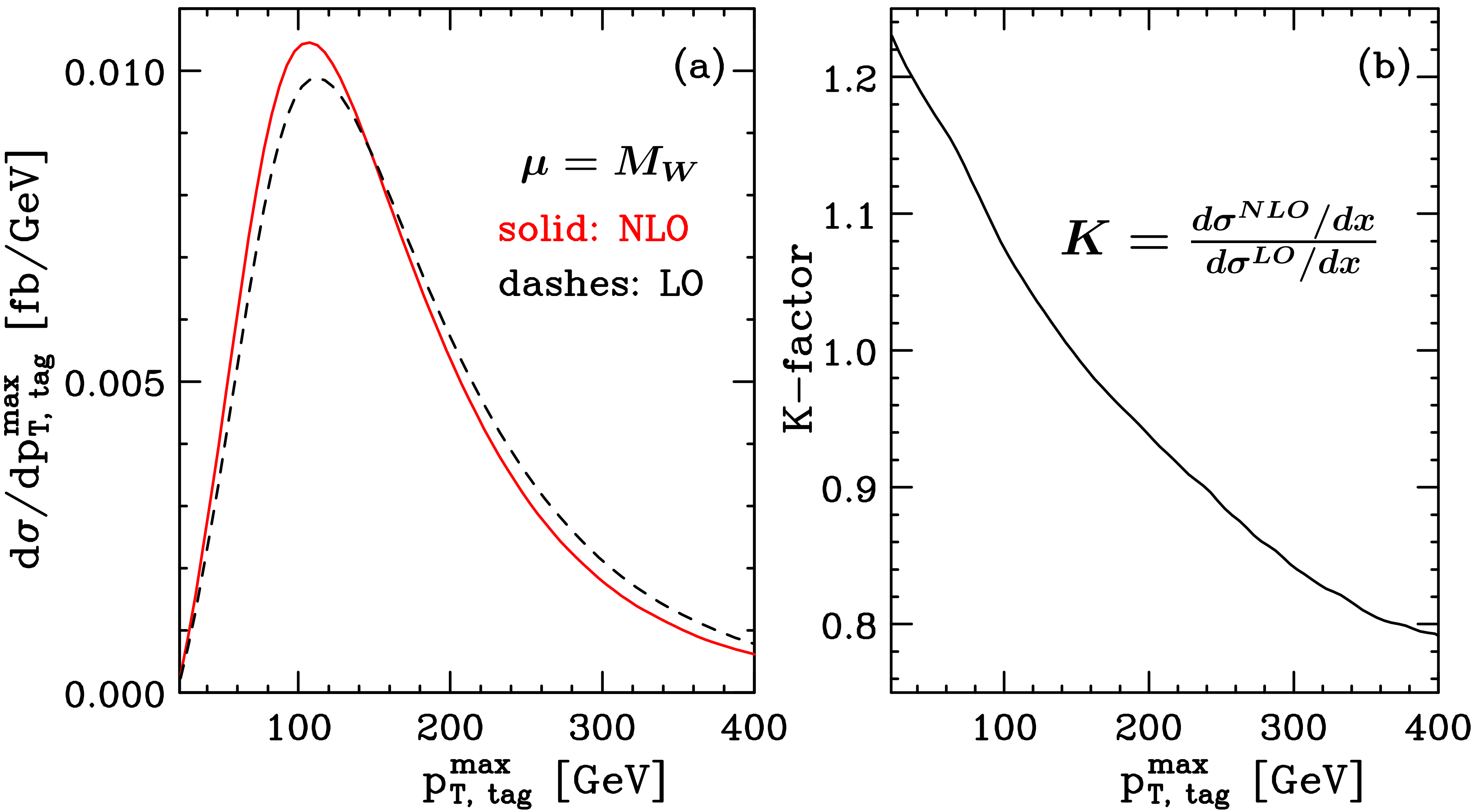
↕

simplify separation of signal from backgrounds

estimate for importance of NLO contributions:
dynamical K-factor

$$K(x) = \frac{d\sigma_{NLO}/dx}{d\sigma_{LO}/dx}$$

W^+W^-jj distributions: p_T of tagging jet

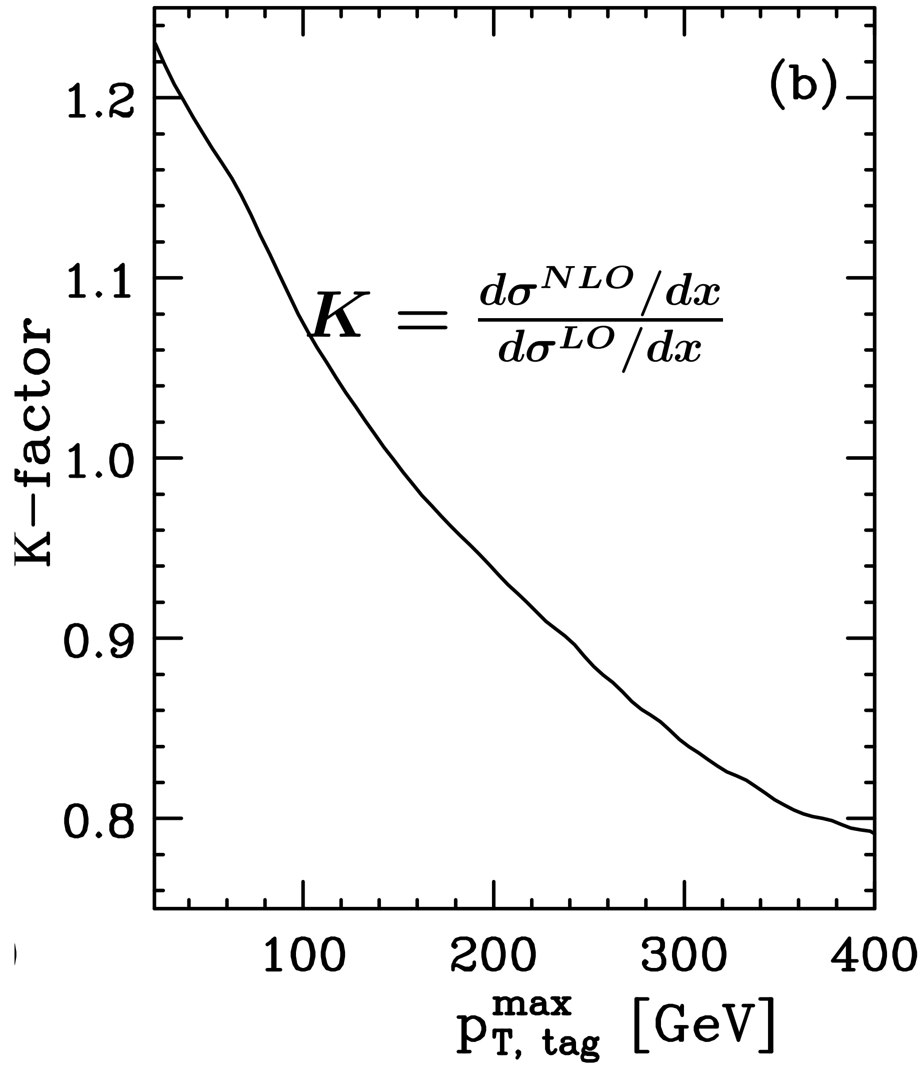


note: significant change in shape at NLO

extra gluon in real emission contributions

↓

quarks which produce tag-jets carry lower transverse momenta



in $H \to W^+W^-$: spins anti-correlated

↓

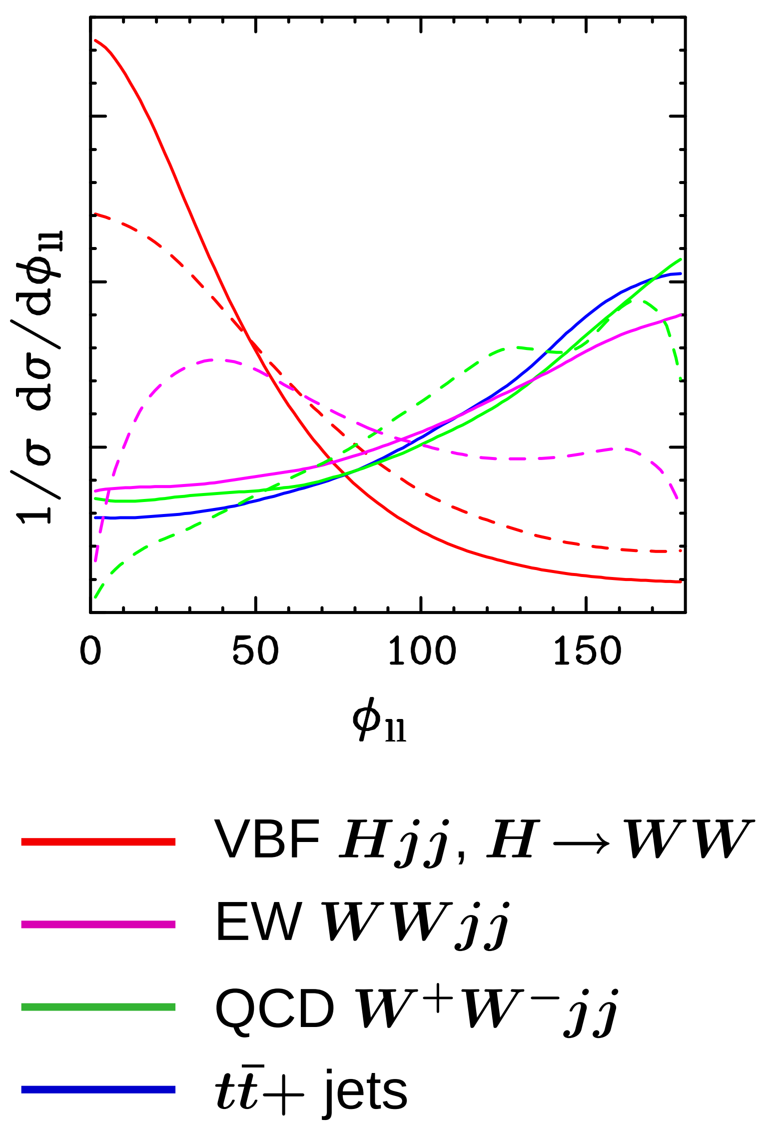
leptons emitted preferentially in same direction

no such correlation, if W bosons do not stem from the Higgs

Dittmar, Dreiner (1996)

distribution for EW W^+W^- production significantly different from Higgs signal

Rainwater, Zeppenfeld (1999)



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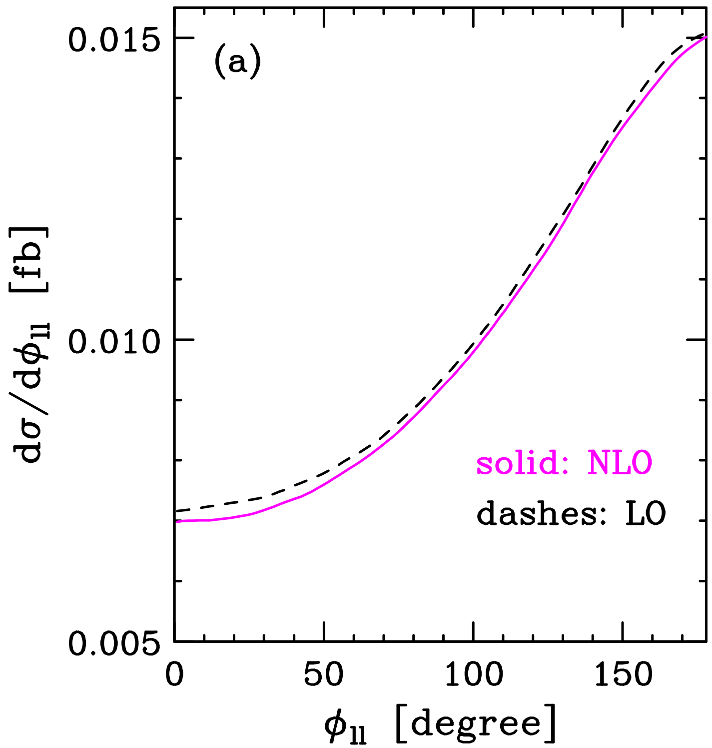


VBF $\boldsymbol{Hjj}$, $\boldsymbol{H \to WW}$

EW $\boldsymbol{WWjj}$

QCD $\boldsymbol{W^+W^-jj}$

$\boldsymbol{t\bar{t}}+$ jets

$pp \to ZZ\,jj$

- clean final state for $pp \to \ell^+\ell^-\ell'^+\ell'^-\,jj$
  (all leptons can be detected)

- small branching ratios $Z \to$ leptons:

$$BR\,(W \to \ell\nu) \sim 10.8\%$$
$$BR\,(Z \to \ell^+\ell^-) \sim 3.3\%$$
$$BR\,(Z \to \nu\bar{\nu}) \sim 6.6\%$$

$\to$ cross sections small: $\sigma_{ZZ} \ll \sigma_{WW}$

work-around: consider $pp \to \ell^+\ell^-\nu\bar{\nu}\,jj$

[more difficult to reconstruct from experiment,
but larger BR and x-sec]

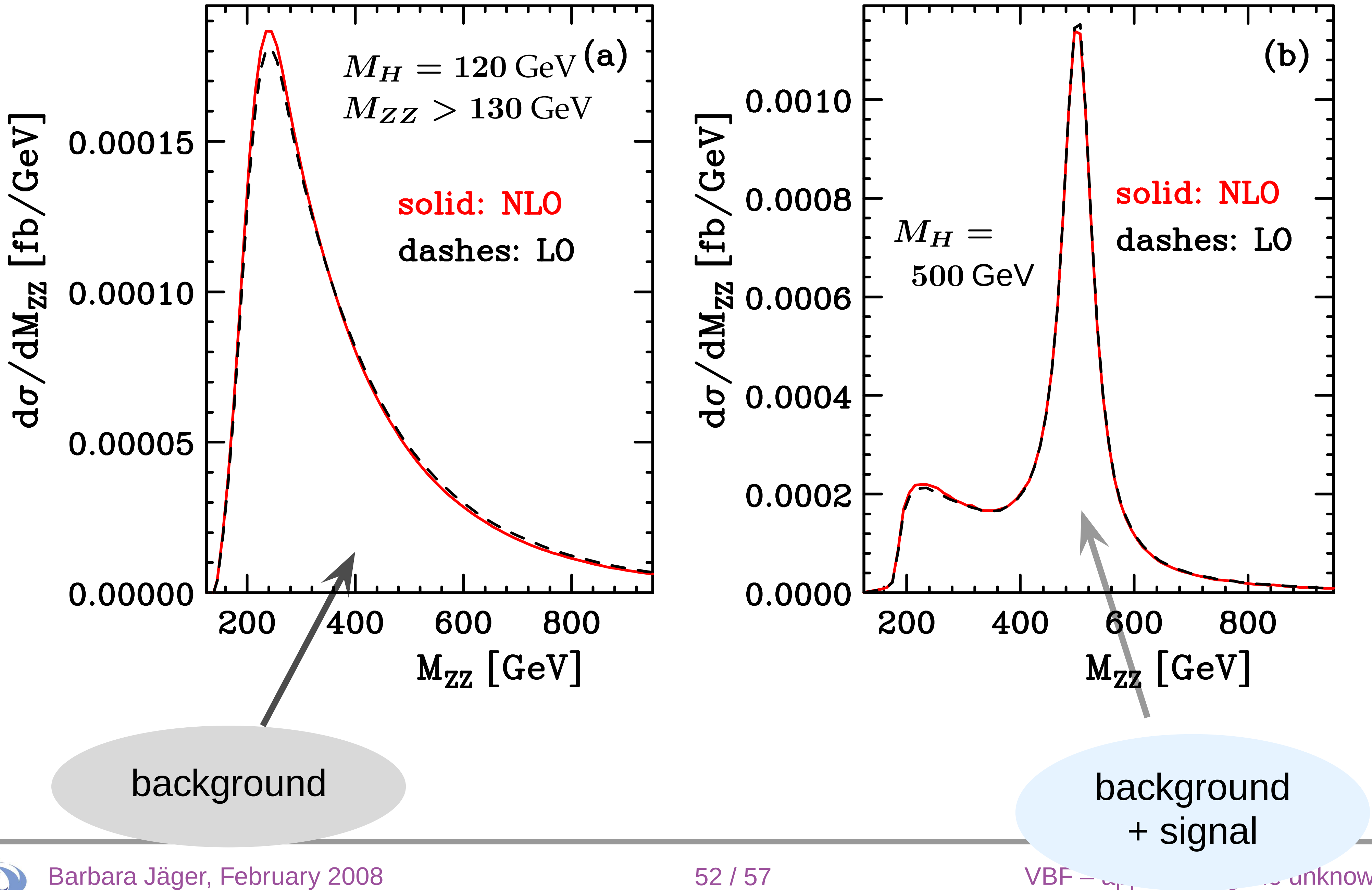
reminder:

$$M_{ZZ} = \sqrt{(p_{\ell^+} + p_{\ell^-} + p_{\ell'^+} + p_{\ell'^-})^2}$$

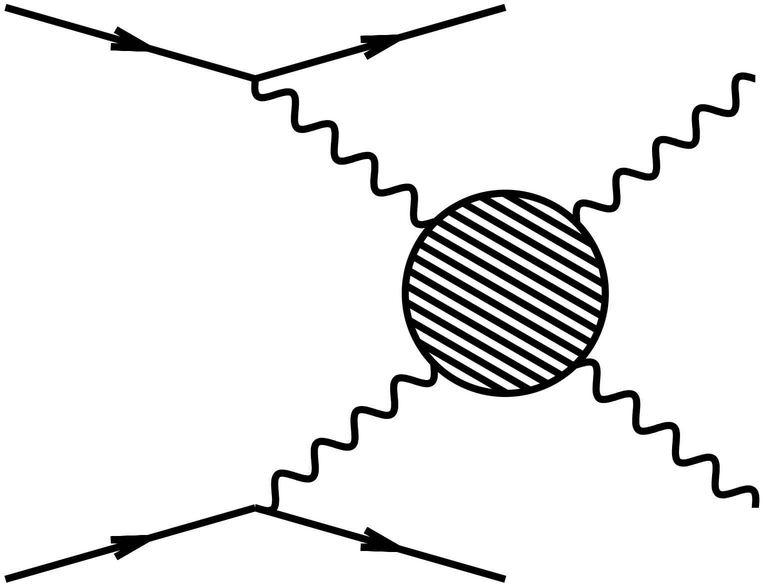
- observable very sensitive to light Higgs boson:
  pronounced resonance behavior for $m_H \lesssim 800$ GeV

- for $m_H \sim 1$ TeV: peak diluted ($\Gamma_H \sim 500$ GeV)
  $\longrightarrow$ signal distributed over wide range in M_{ZZ}

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



strongly interacting gauge bosons



…back to $V_L V_L \to V_L V_L$ …

can we distinguish signatures of SM type Higgs boson from strong EWSB?

cf. Bagger et al. (1993, 1995)

need detailed, up-to-date phenomenological analysis of signal and backgrounds

work in progress

M. Worek, D. Zeppenfeld, B. J.

✘ VBF crucial for understanding mechanism of electroweak symmetry breaking

↓

need to know signal and backgrounds precisely

✘ developed fully flexible parton-level Monte Carlo program with NLO QCD cross sections and distributions for

$pp \longrightarrow W^+W^- jj$ and $pp \longrightarrow ZZ jj$

$pp \longrightarrow W^+Z jj$ and $pp \longrightarrow W^-Z jj$

(including leptonic decays)

[`vbfnlo` now available from the web]

- ✘ VBF reactions under excellent control perturbatively
  (moderate K-factors and mild scale dependences at NLO)
- ✘ shape of some distributions changes noticeably at NLO
  (e.g. p_T distributions)

…and this implies …

for understanding and interpreting physics
at the LHC (and beyond . . .) it is vital to prepare:

✘ precise predictions for signals and backgrounds, including

- NLO QCD corrections
- NLO EW corrections
- and more: interference effects, resummations, well-constrained PDFs, . . .

✘ cross sections and distributions within realistic acceptance cuts

☟

need to develop flexible precision tools which can be used by experimentalists and intensify communication between theory and experiment

. . . get prepared for the journey towards the unknown