Vector Boson Fusion at the LHC

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outline

- vector boson fusion:
  - Higgs searches in VBF
  - features and uncertainties
- focus on VV scattering
  - theoretical concepts & techniques
  - results
  - `vbfnlo`
- summary & conclusions

Standard Model:
couplings and parameters
strongly constrained

only free parameter: M_H
(not yet measured)

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

theory: triviality, vacuum stability
☞ $130 \lesssim M_H \lesssim 180$ GeV

experiment:
direct and indirect searches
(assuming SM to be correct)
☞ $M_H \simeq 76^{+33}_{-24}$ 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?

↓

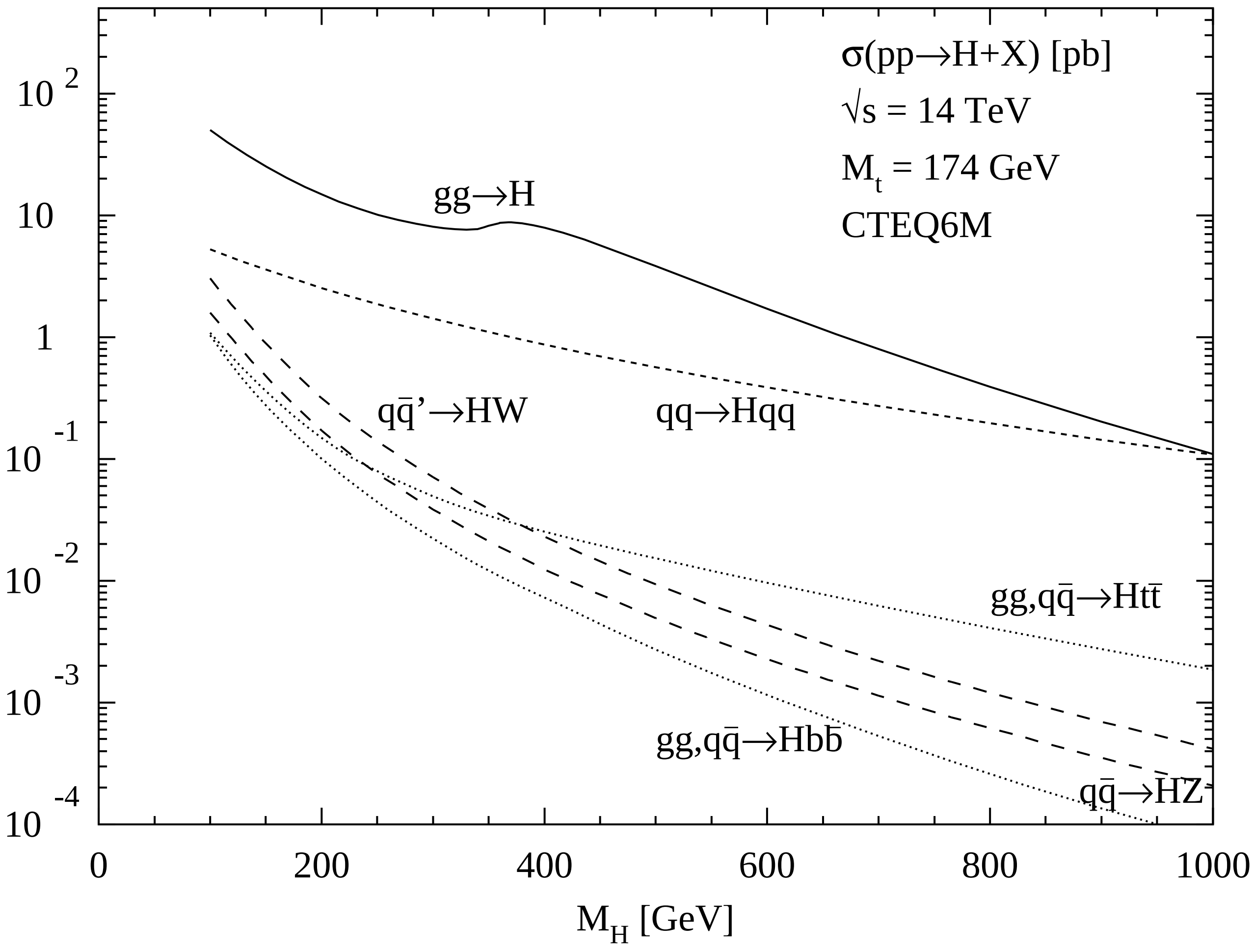
full, quantitative understanding of

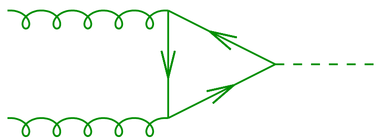
most promising search channels required

from experiment and theory

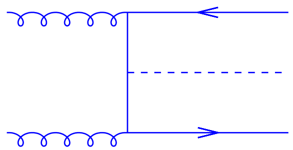
Higgs production @ hadron colliders

M. Spira, 2007

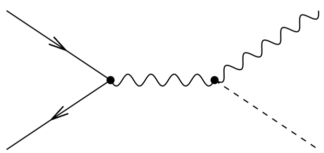




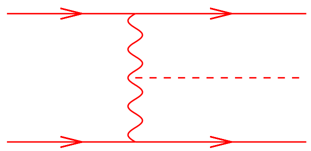
gg fusion



$t\bar{t}$ fusion



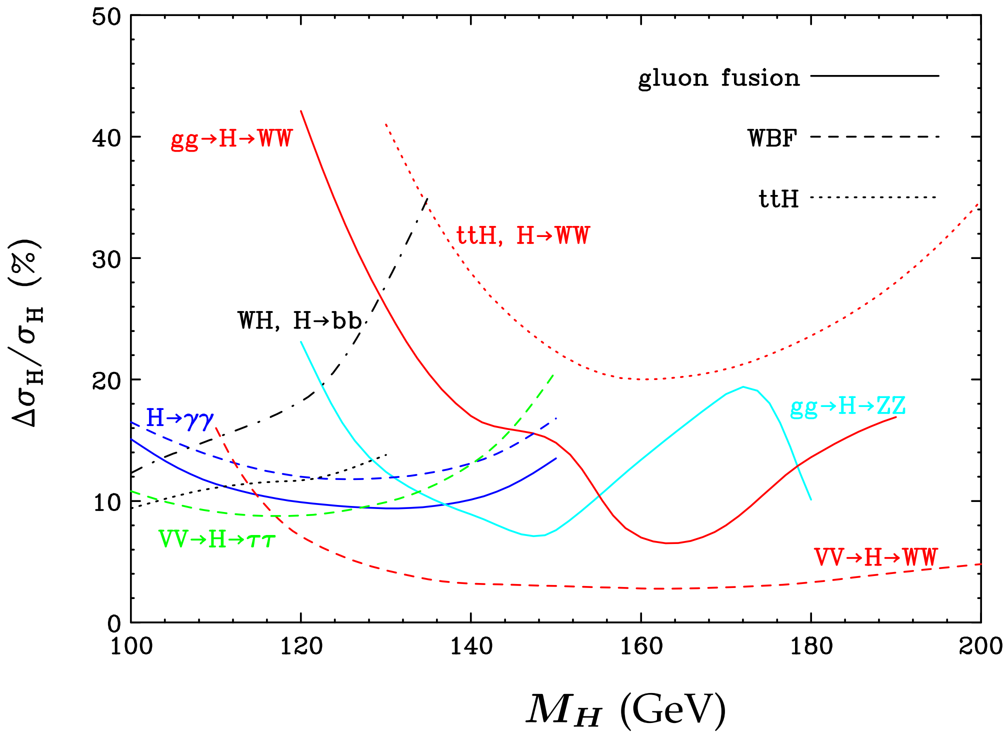
W, Z bremsstrahlung



vector boson fusion

uncertainties at the LHC

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



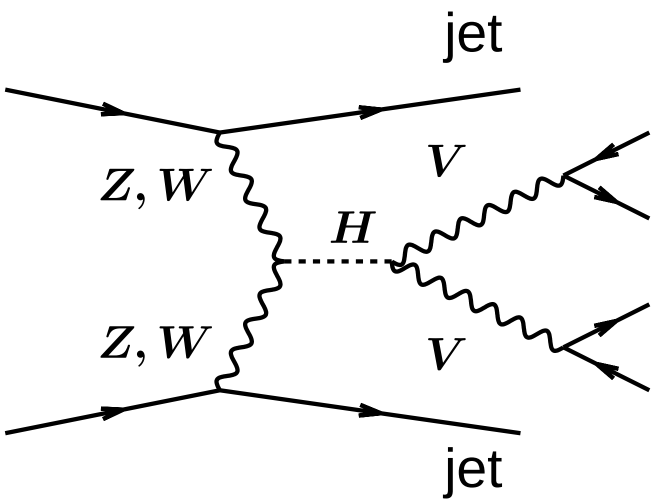
$(\mathcal{L} = 200\ \text{fb}^{-1})$

- QCD/PDF uncertainties:

  $\pm 5\%$ for VBF
  $\pm 15\%$ for gluon fusion
  (including resummation effects)

- luminosity/acceptance uncertainties: $\pm 5\%$

Higgs production in VBF

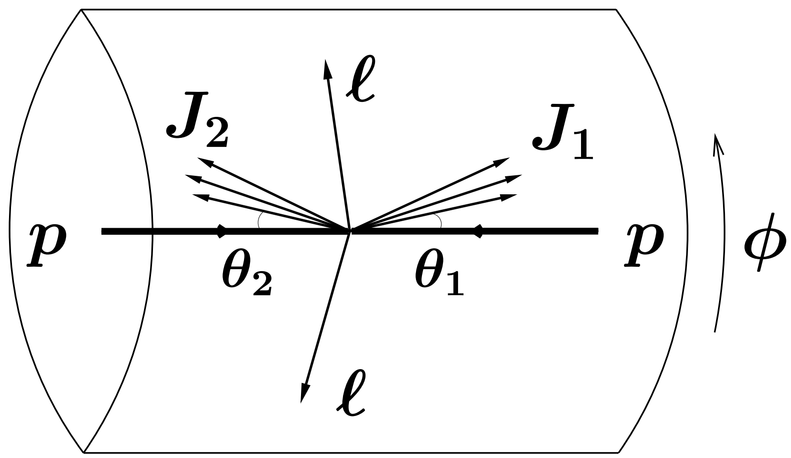


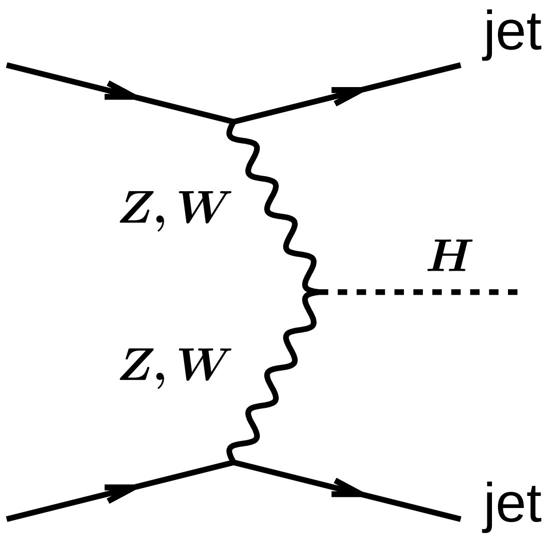
scattered quarks
$\longrightarrow$ two forward tagging jets
(energetic; $p_T > 20$ GeV)

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)

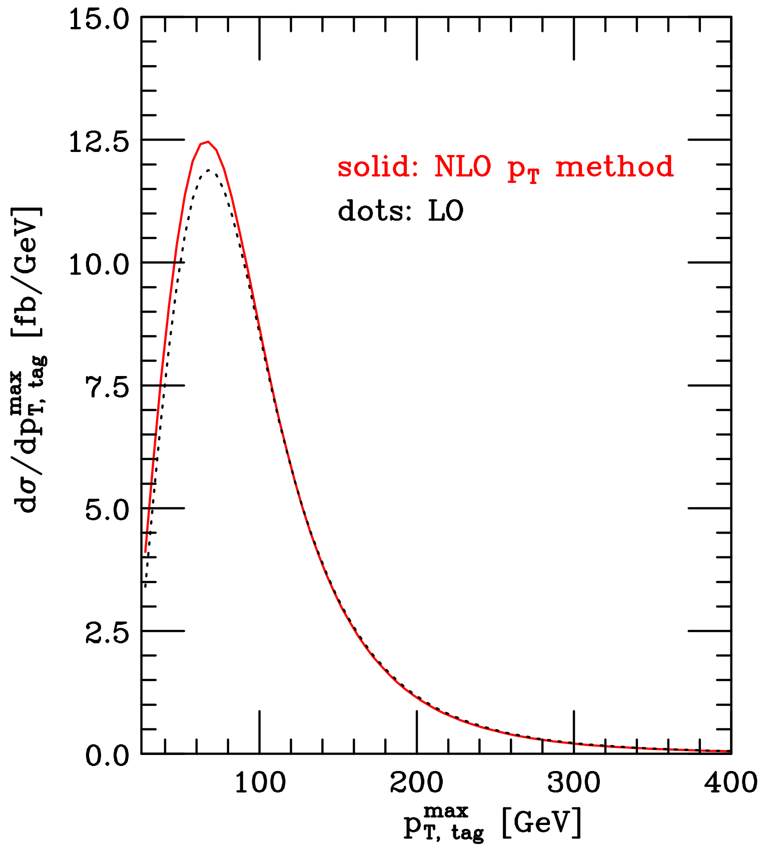
Berger, Campbell (2004)

NLO QCD corrections

moderate and

theoretically well under control

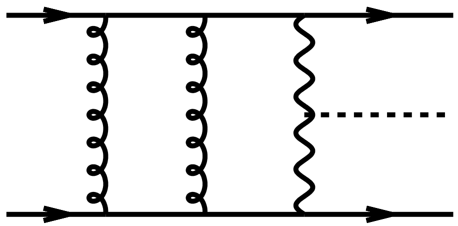
(order 10% or less)



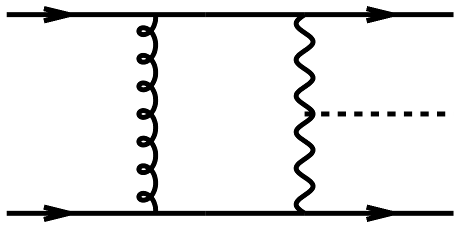
higher orders in VBF

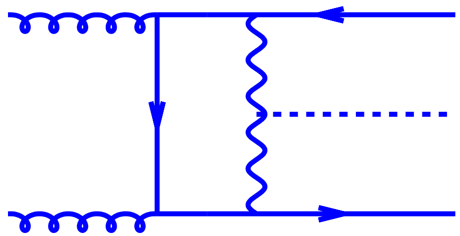
M. Weber considered a gauge invariant, finite sub-class of virtual two-loop QCD corrections to $pp \longrightarrow Hjj$ via VBF

two-loop $\star$ Born:



one-loop squared:





$gg \longrightarrow q\bar{q}H$ important due to large gluon luminosity at LHC?

higher orders in VBF?

- minimal set of cuts:

  $$\sigma^{(2-loop)}(gg \to q\bar{q}H) \sim 0.3\% \text{ of } \sigma^{VBF}(q\bar{q} \to q\bar{q}H)$$

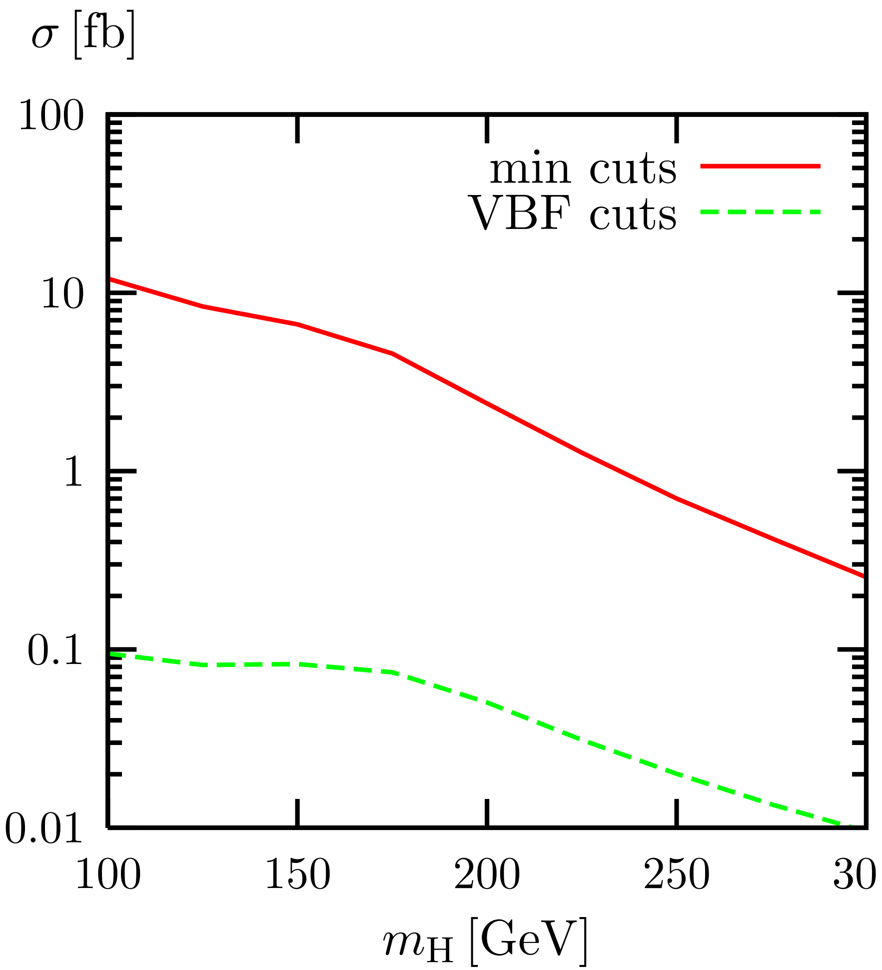
- VBF cuts: strong suppression

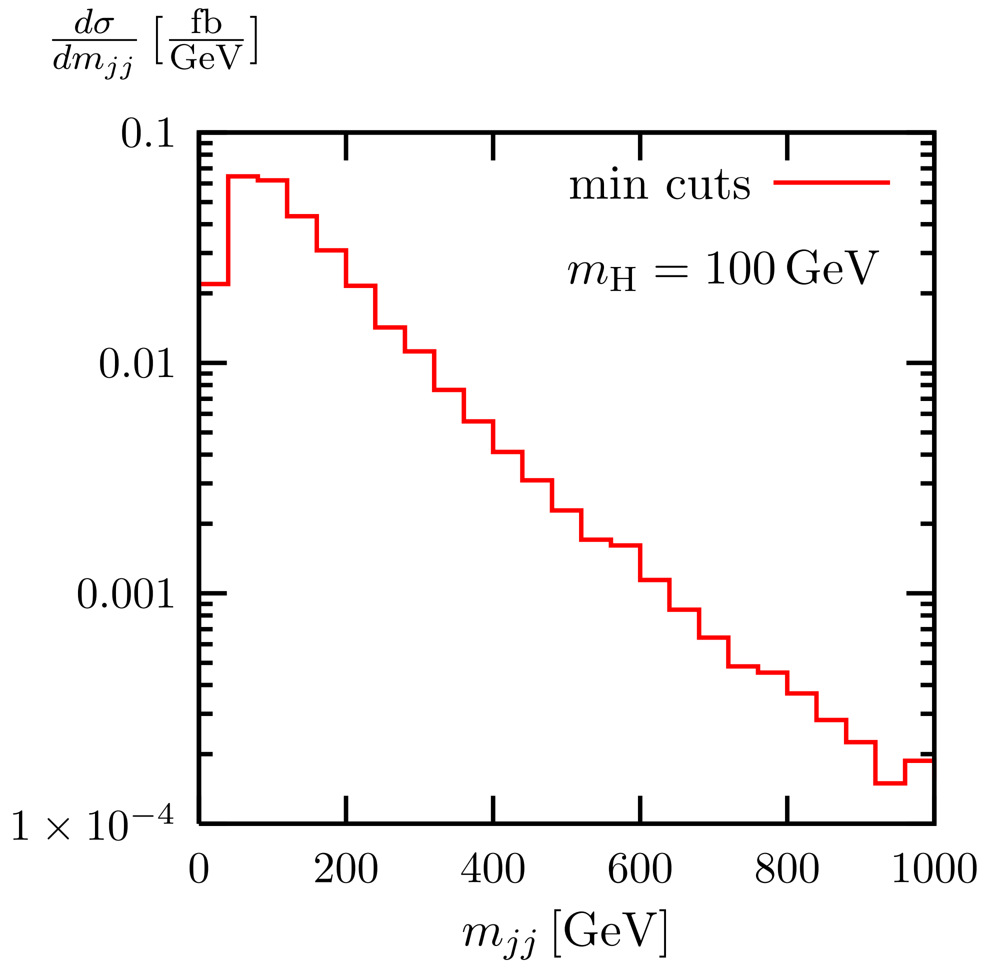
  (∼ 2 orders of magnitude)

  - rapidity gap $\Delta\eta_{jj}$ smaller than in VBF
  - M_{jj} ... rapid fall-down

see: *M. Weber, "Loops and Legs 2006", proceedings;*
M. Weber, arXiv:0709.2668 (hep-ph)

higher orders in VBF?



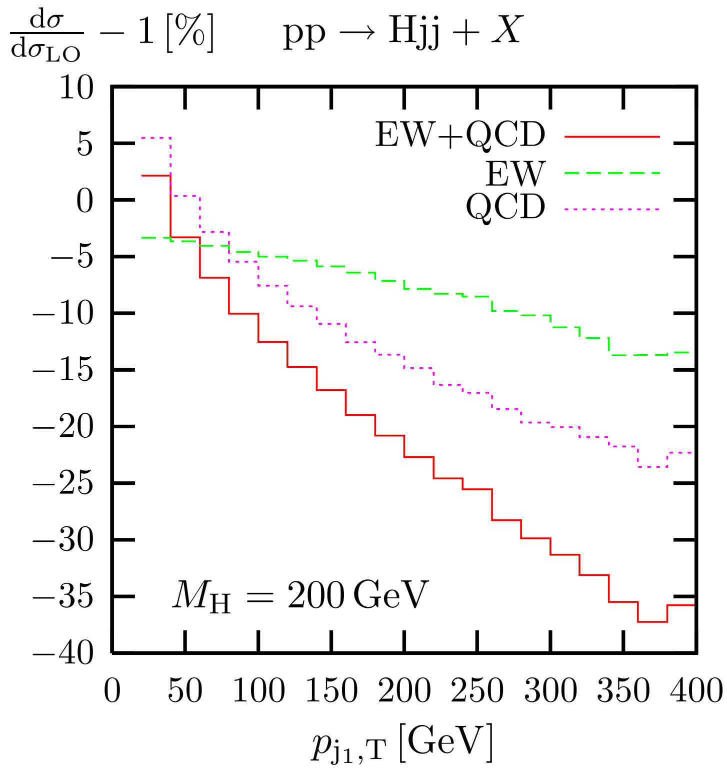


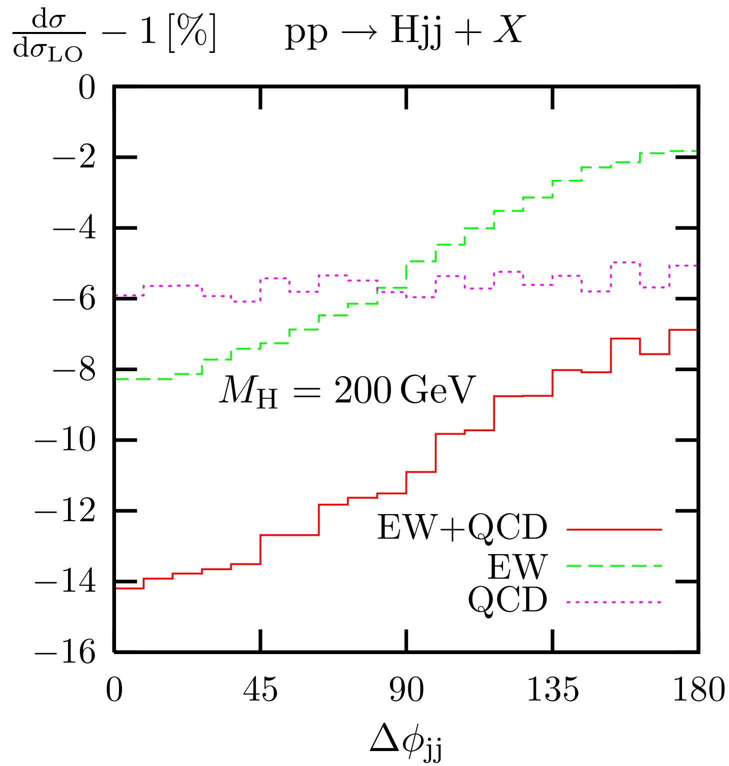
taken from *M. Weber, proceedings contributions to "Loops and Legs 2006"*

Ciccolini, Denner, Dittmaier (2007):

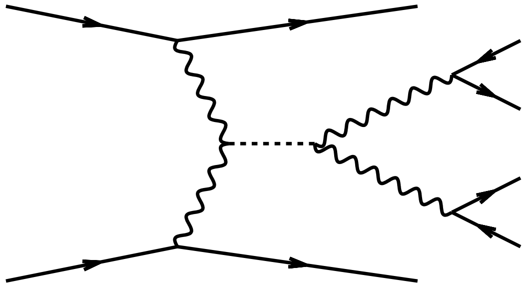
NLO EW corrections to inclusive cross sections and distributions

☞ NLO EW corrections non-negligible, modify K-factors and distort distributions by up to 10%





Higgs signal in VBF



establishing a signal for

$$H \to W^+W^- \to e^\pm \mu^\mp \not{p}_T$$
$$H \to ZZ \to e^+e^-\mu^+\mu^-$$
$$H \to ZZ \to e^+e^- \not{p}_T$$

in VBF requires:

– calculation of signal and background distributions

ideally (at least) NLO QCD predictions
to match statistical accuracy of LHC

– identification of suitable cuts to isolate the signal

Rainwater, Zeppenfeld (1999)

Kauer, Plehn, Rainwater, Zeppenfeld (2000)

$pp \longrightarrow Hjj$ via VBF: signal & backgrounds

signal rates at the LHC:

cuts	VBF Hjj	$t\bar{t} + jets$	QCD $WWjj$	EW $WWjj$	S/B
forward tagging	17.1	1080	4.4	3.0	1/65
all cuts	7.5	1.09	0.11	0.25	4.6/1

taken from *Rainwater, Zeppenfeld hep-ph/9906218*

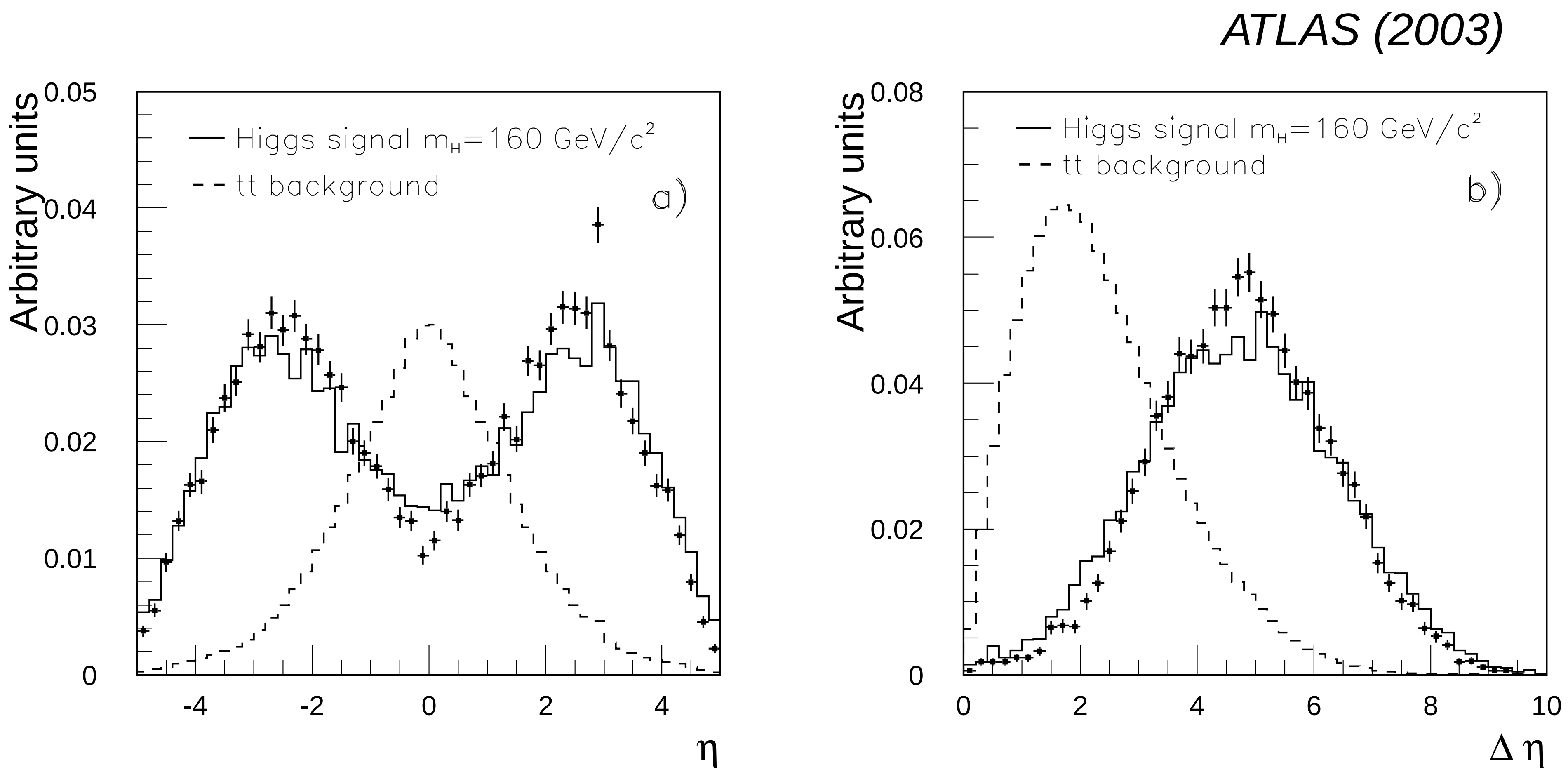
backgrounds: QCD $t\bar{t} + jets$

…constitute major backgrounds to
$\boldsymbol{H \longrightarrow WW}$ decay channel in VBF at LHC

- precision calculations challenging
  see, e.g., *Kauer; Dittmaier, Weinzierl, Uwer*
- large top production cross section
- $\boldsymbol{t \longrightarrow Wb}$ branching ratio $\sim$ 100%
- leptonic decays of $\boldsymbol{W}$: signature similar
  to $\boldsymbol{H \longrightarrow WW}$ signal in VBF
- $\boldsymbol{b}$ quarks may be identified as tagging jets

☞ need to impose suitable cuts to suppress this background!

backgrounds: QCD $t\bar{t} + jets$



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 (hep/0108030)

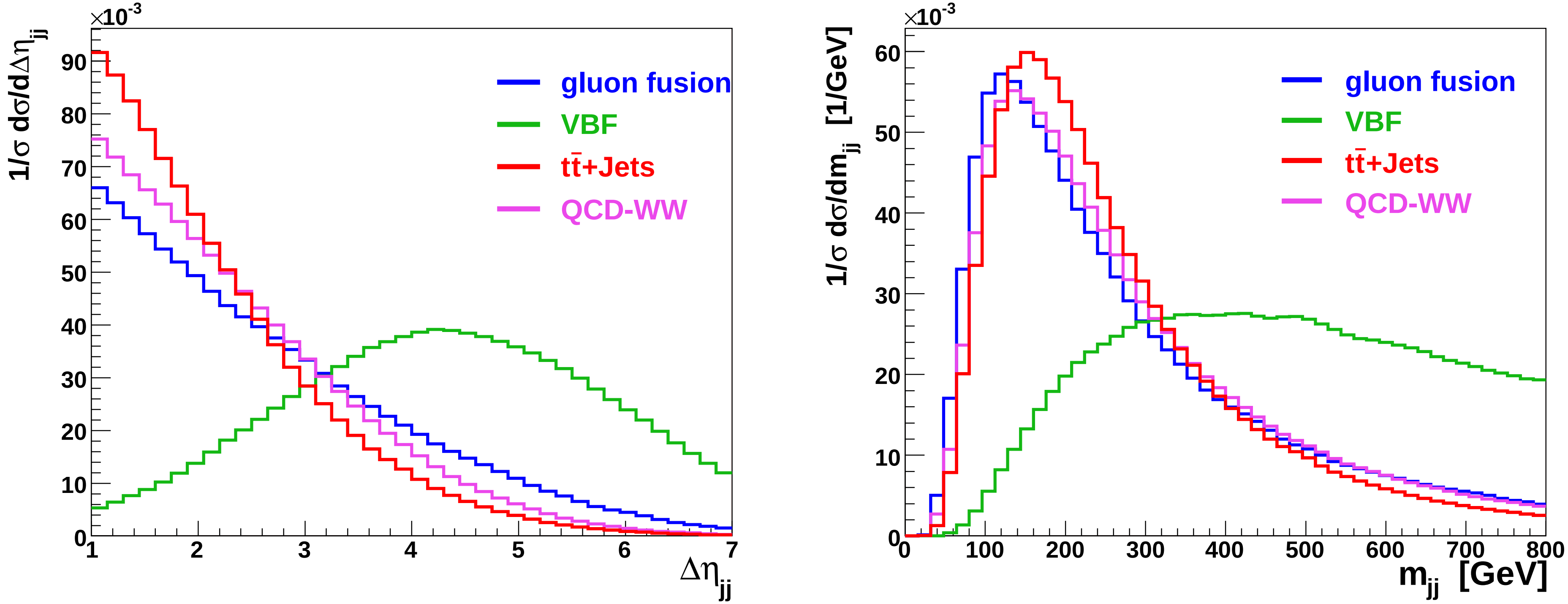
NLO QCD calculation in $m_t \longrightarrow \infty$ limit:
Campbell, Ellis, Zanderighi (hep-ph/0608194)

need to understand phenomenology of both processes to distinguish between them

$pp \to Hjj$ via gluon fusion

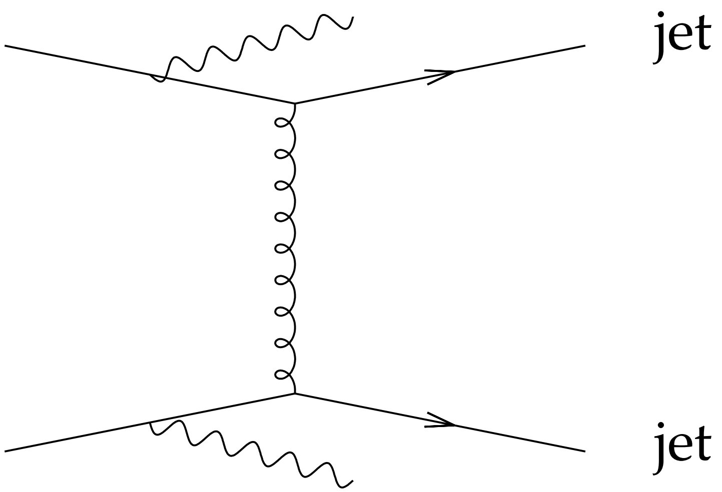
apply cuts to enhance either VBF or gluon fusion

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



figures by courtesy of *Gunnar Klämke*

QCD $W^+W^- jj$ production



color flow between jets

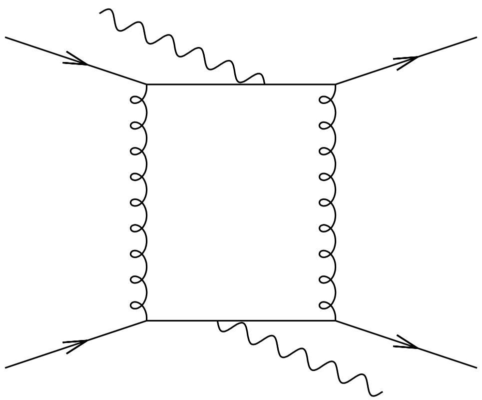
↓

- enhanced central jet activity
- jets close in rapidity
- small invariant dijet mass

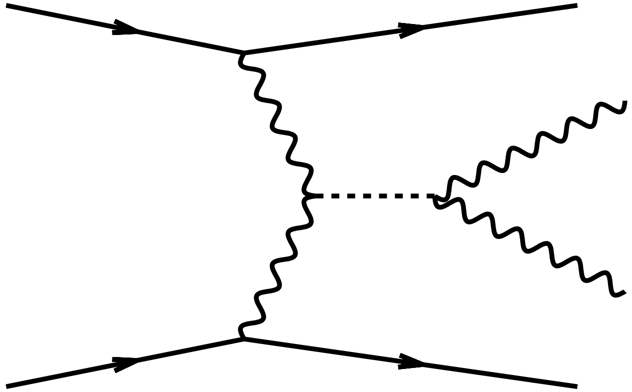
really difficult . . .

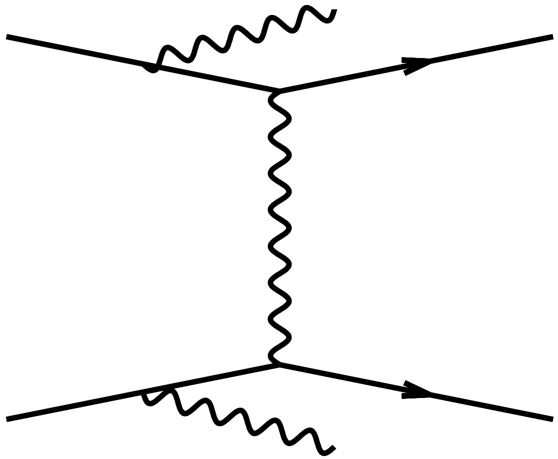
NLO QCD corrections to QCD $WW\,jj$ production:
due to color exchange between upper & lower fermion line
structure of the NLO contributions
much more complicated than in VBF

most cumbersome:
hexagon integrals



→ no work in that direction





$pp \longrightarrow VV + jj$ via VBF

similar characteristics to H signal process

background rejection difficult

↓

precise predictions crucial!

VV scattering

hadron collider:

VV scattering accessible via

VBF-induced $qq \to qqVV$

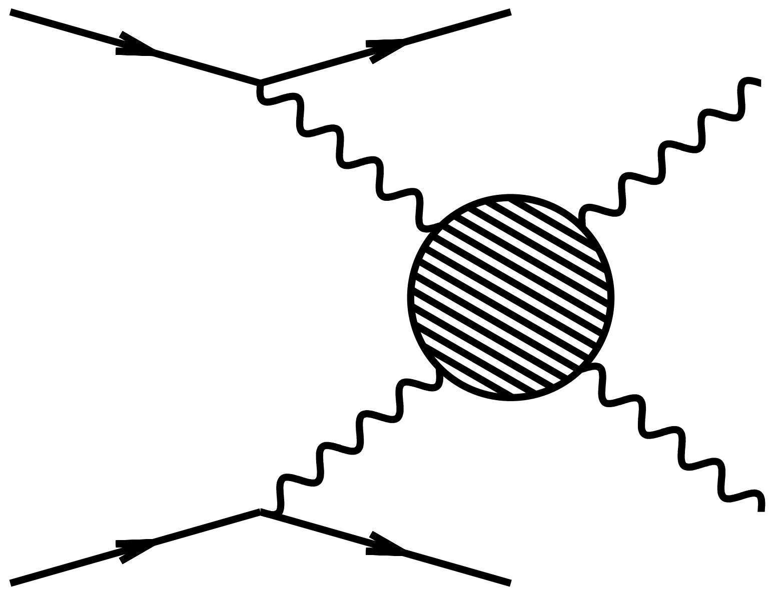
contains $V_L V_L \to V_L V_L$

↓

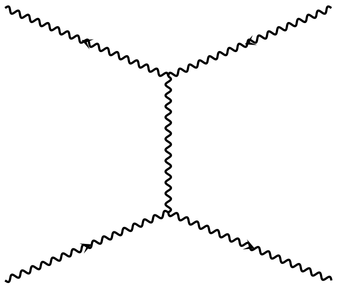
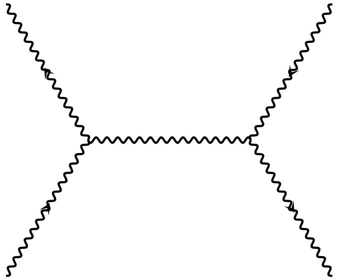
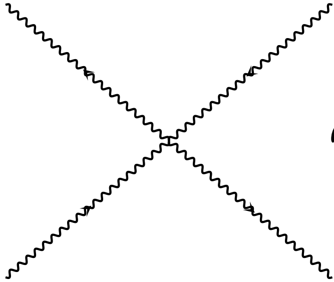
electroweak symmetry breaking:

light Higgs boson? M_H?

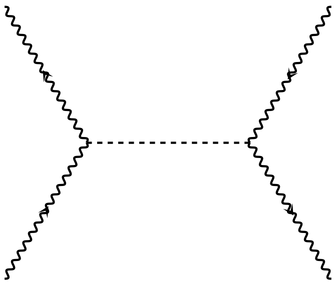
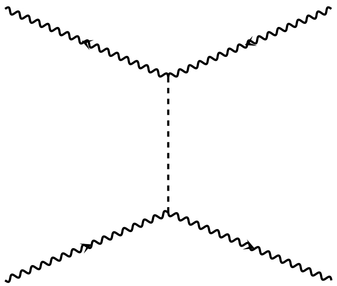
strong EWSB? specific mechanism?



$W_L^+ W_L^- \to W_L^+ W_L^-$ 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

weak boson scattering in the literature

- $qq \rightarrow qqVV$ within the "Effective W Approximation":

  Cahn, Dawson (1984); Dawson (1985);

  Duncan et al. (1986); Dobado et al. (1991)

- full $qq \rightarrow qqVV$ (without W decay / W decay in NWA):

  Gunion et al. (1986); Dicus, Vega (1986);

  Baur, Glover (1990); Barger et al. (1991f);

- application to strongly interacting gauge boson systems:

  e.g. Bagger et al. (1994f)

- LO event generator for six-fermion processes at the LHC

  Accomando et al. (2005f)

- Study of the quartic electroweak gauge boson couplings

  Eboli et al. (2006)

- ...

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:

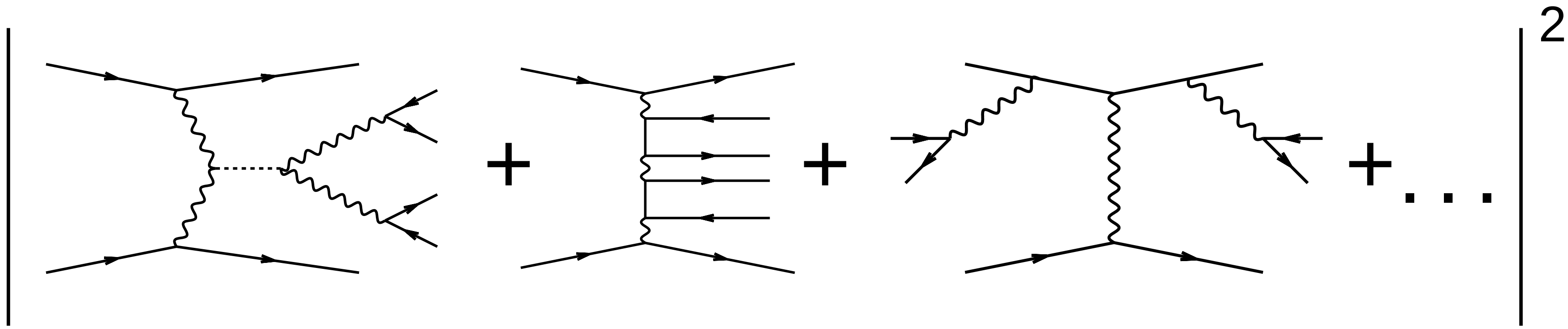
- multi-parton process: $2 \longrightarrow 4$ for $qq \longrightarrow qq\,VV$;
  $2 \longrightarrow 6$ for $qq \longrightarrow qq\,\ell^+\ell^-\nu_\ell\bar{\nu}_\ell$
  or $qq \longrightarrow qq\,\ell^+\ell^-\ell^+\ell^-$
- full consideration of finite width effects
- numerically stable treatment of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

outline of the LO calculation

- calculation of $d\hat{\sigma}$ at $\mathcal{O}(\alpha^6)$ (LO QCD) using the helicity amplitude formalism of *Hagiwara, Zeppenfeld (1986)*
- approximations
- implementation in the code
- efficiency

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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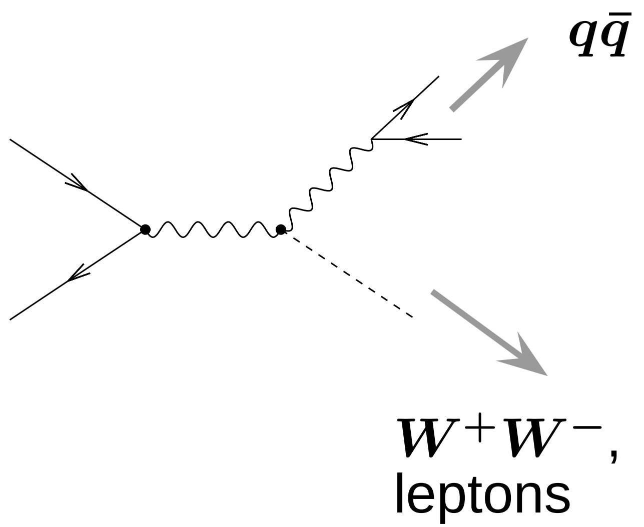
essential: organize calculation economically

↓

- develop modular structure
- compute each building block only once per phase space point

- interference effects from diagrams obtained by interchanging identical initial- or final-state (anti)quarks

- identical flavor annihilation processes with subsequent decay into quarks and similar contributions like



not included

neglected terms strongly suppressed in PS region where VBF can be observed experimentally

(require two widely separated quark jets of large invariant mass)

. . . both contributions on sub-percent level for related VBF processes (checked)

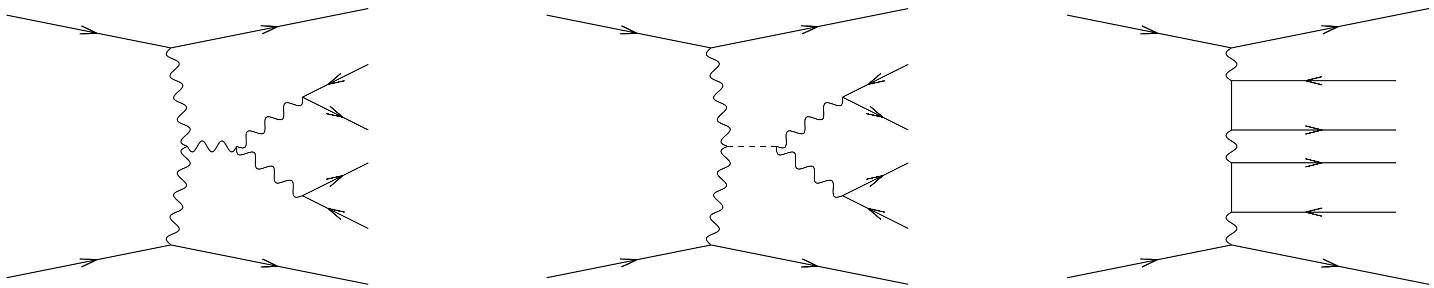
see: *Oleari, Zeppenfeld, hep-ph/0310156*

Georg, diploma thesis, Karlsruhe (2005)

confirmed by

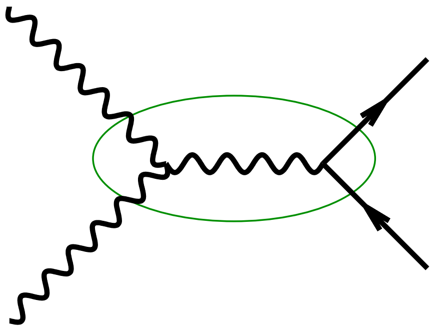
Ciccolini, Denner, Dittmaier (2007)

. . . all t-channel diagrams that contribute
to specified final state



leptons not necessarily produced
via $(V \to \ell\bar{\ell})(V \to \ell'\bar{\ell}')$
i.e., non-resonant diagrams considered

finite width effects

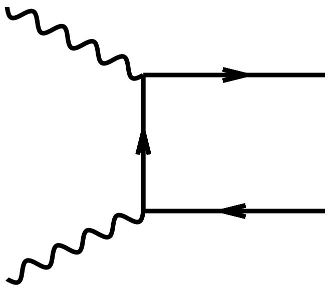


resonant diagrams: need

$$\frac{1}{q^2 - M_V^2} \longrightarrow \frac{1}{q^2 - M_V^2 + iM_V\Gamma_V}$$

in s-channel vector-boson propagators

but: how should non-resonant graphs be treated?



naive implementation: violation of EW gauge invariance $\longrightarrow$ handle with care!

- overall factor scheme *(Baur, Vermaseren, Zeppenfeld)*:

$$\mathcal{M}_{tot} \longrightarrow \frac{q^2 - M_V^2}{q^2 - M_V^2 + iM_V\Gamma_V}\mathcal{M}_{tot}$$

- complex mass scheme *(Denner et al.)*:

$M_V^2 \longrightarrow M_V^2 - iM_V\Gamma_V$ in propagators and couplings

finite width effects

our approach: modified complex mass scheme

replace $$M_V^2 \longrightarrow M_V^2 - i M_V \Gamma_V$$

in all weak boson propagators, but not in couplings,

i.e. keep real value for $\sin\theta_W^2 = 1 - \frac{M_W^2}{M_Z^2}$

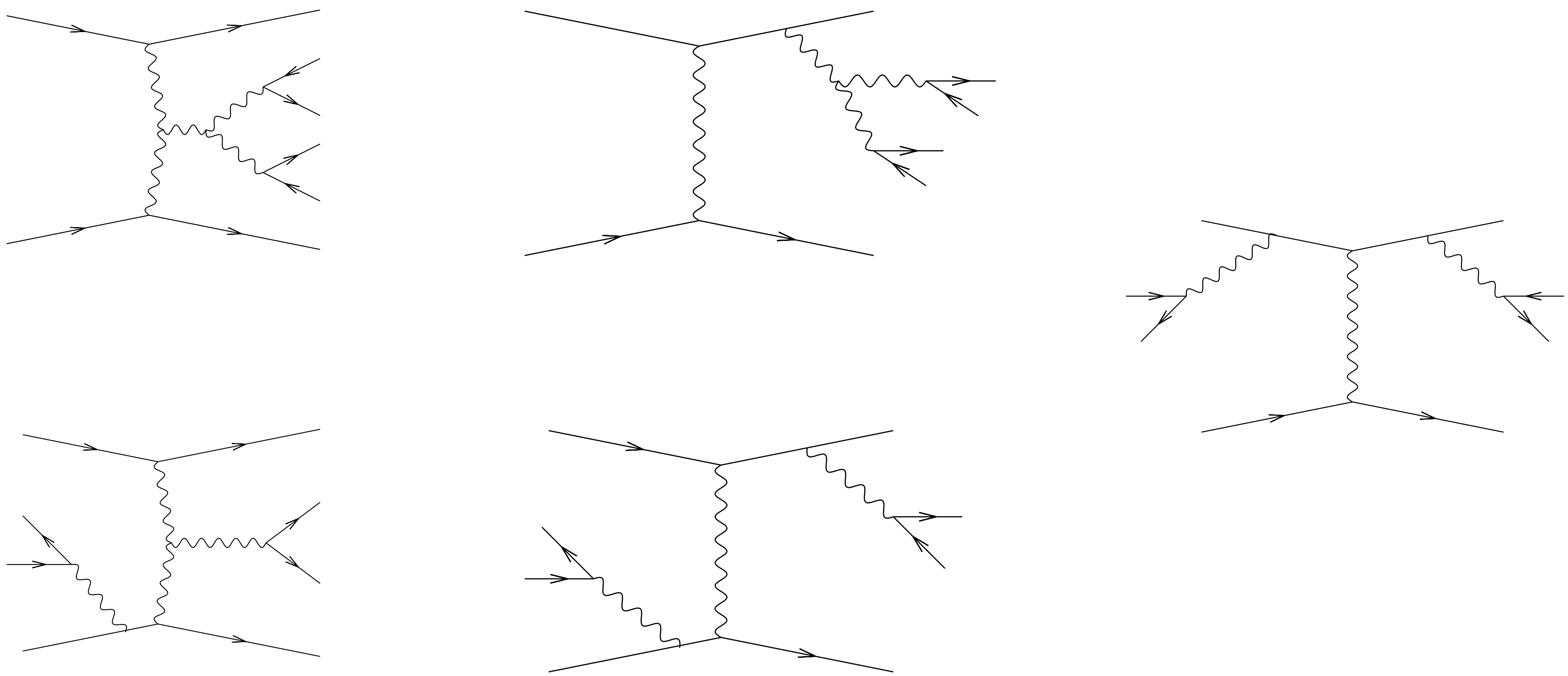
$\Downarrow$

- easy to implement (cf. `MadGraph`)
- preserves em. gauge invariance
- check for $pp \longrightarrow Vjj$: ambiguity $\lesssim 0.5\ \%$

structure of the LO amplitudes

$pp \longrightarrow VVjj$: need helicity amplitudes

for five different topologies:

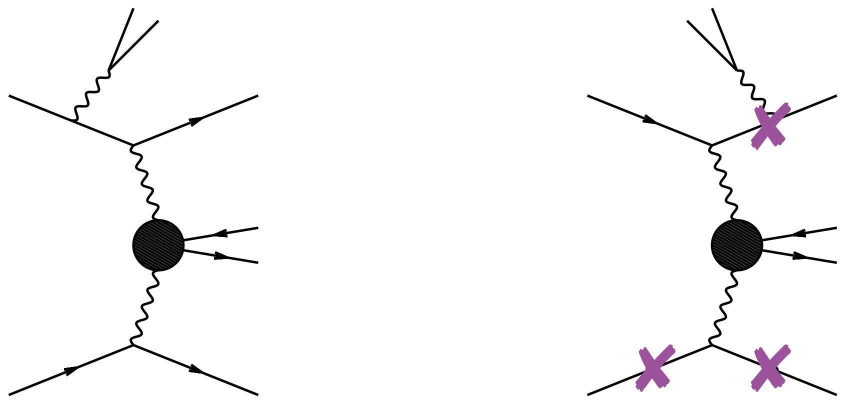


practical implementation

- compute polarization vectors, quark currents etc. by hand in helicity amplitude formalism of *Hagiwara, Zeppenfeld (1986)*

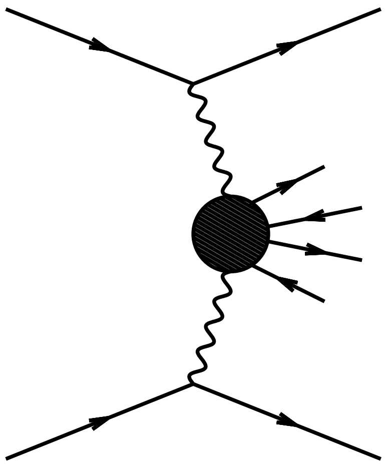
- combine them with leptonic tensors adapted from `MadGraph` generated code

- recycle all building blocks emerging repeatedly (related sub-diagrams, various flavor combinations, crossed processes . . .)



such recycling is used to a very small extent by `MadGraph/MadEvent` (within each sub-process and esp. for different sub-processes)

extra feature: new physics



nice extra: implementation of new interactions in leptonic tensors straightforward, e.g.

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

extend SM to effective theory by adding additional terms:

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum_i \frac{f_i^5}{\Lambda}\mathcal{O}_i^5 + \sum_i \frac{f_i^6}{\Lambda^2}\mathcal{O}_i^6 + \dots$$

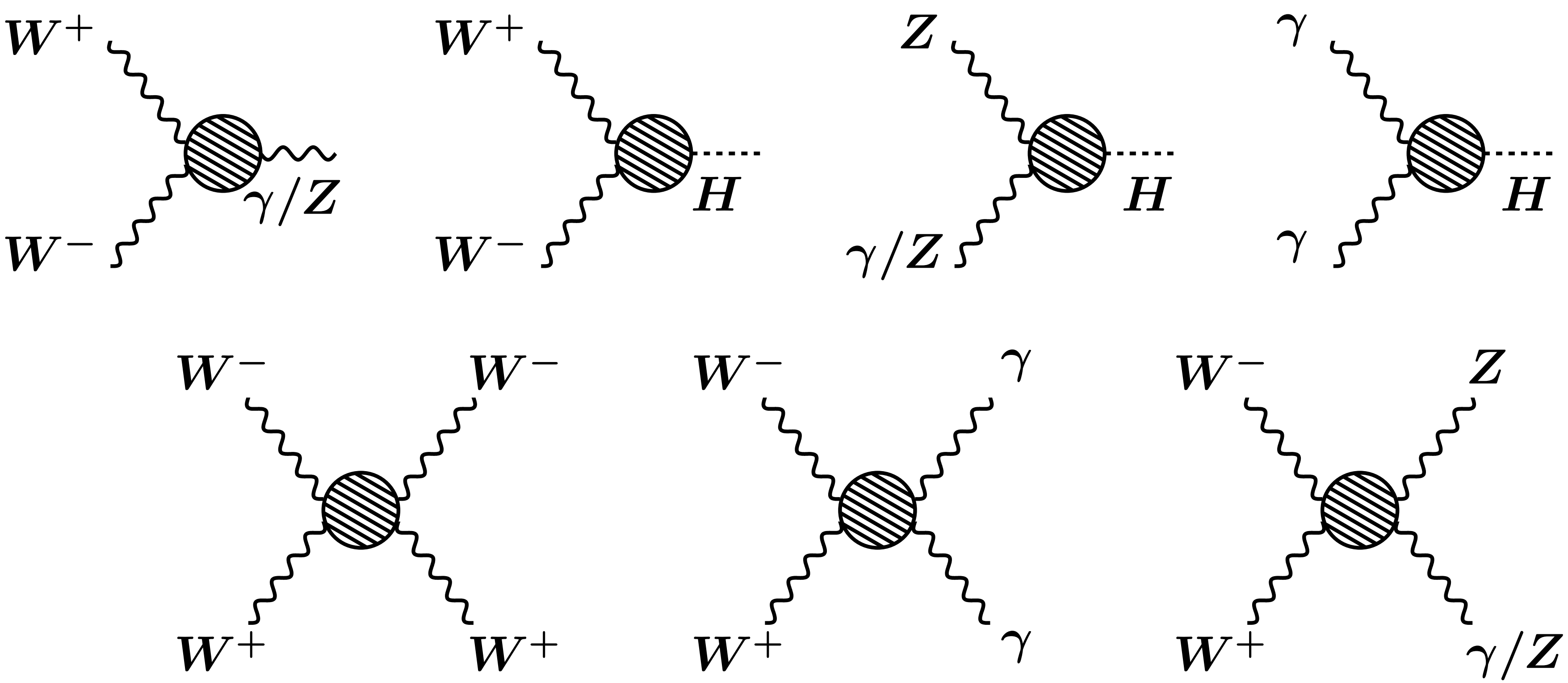
f_i^5, f_i^6 ... dimensionless coupling constants
Λ ... "new physics" scale
$\mathcal{O}_i^5$ ... not SU(2) and Lorentz invariant

☞ consider only dimension 6 operators $\mathcal{O}_i^6$

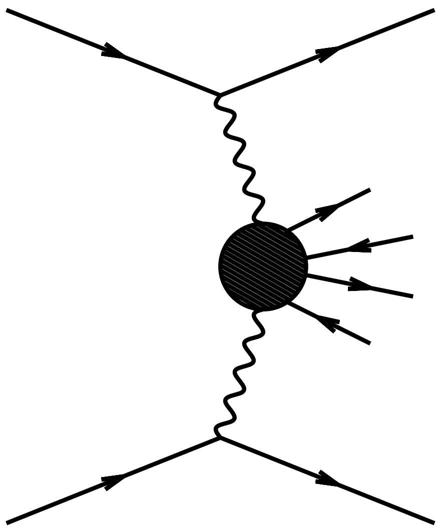
extra feature: new physics

- consider only dim 6 operators which can be built from scalar and vector fields
- derive new Feynman rules from Lagrangian

☞ additional contributions to 3- and 4-boson vertices:



extra feature: new physics



implementation in `vbfnlo`:

- use new Feynman rules to construct leptonic tensors
- fermionic pieces don't change

efficiency

- ✘ 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 of `vbfnlo` to result obtained with `MadGraph`

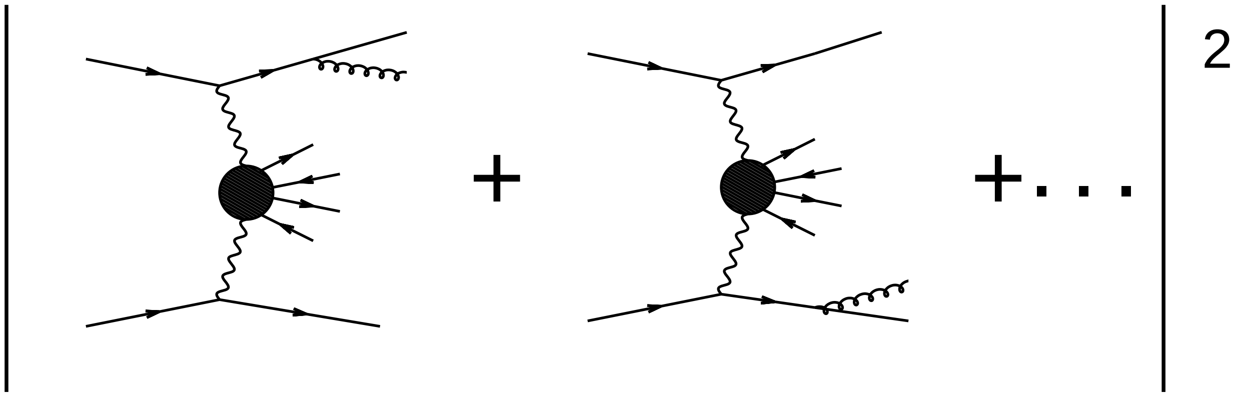
outline of the NLO calculation

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

real emission contributions

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

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



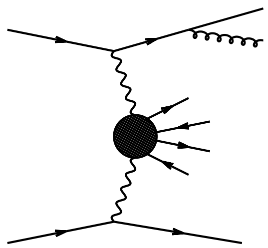
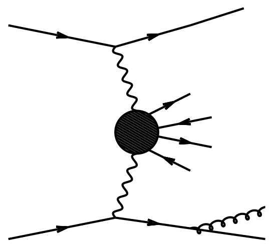
at each generated phase space point in 4 dimensions
$\longrightarrow$ apply same techniques as at LO

☹ 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

real emission contributions

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

three final-state partons observed as hard jets ☞ $|\mathcal{M}_R|^2$ finite

but: want to compute two-jet cross section!

real emission contribution diverges as unobserved parton becomes soft or collinear

the solution:

analytic calculation: divergencies canceled by respective singularities in virtual contributions

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

dipole subtraction

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 $d\boldsymbol{\sigma}^{R}$:

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

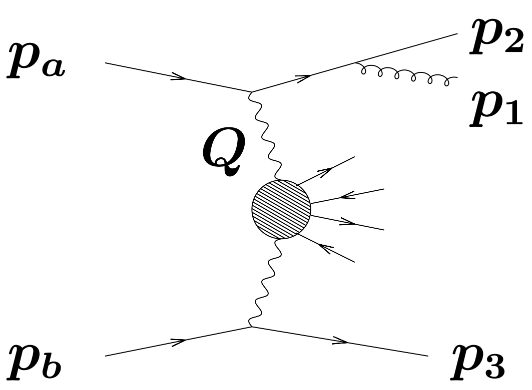
dipole subtraction

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

integrate over one-parton PS analytically

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

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



upper & lower quark lines "decoupled"

$\longrightarrow$ simple singularity structure with counterterms

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

$\mathcal{M}_B(\tilde{p})$ ... Born amplitude for $qq' \longrightarrow qq'VV$ for shifted set of momenta $\tilde{p}$

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

subtraction for three-parton contributions:

$$\sigma_3^{NLO} \sim \int dx_a dx_b \, dPS_3 \; f_a(x_a, \mu_f) \, f_b(x_b, \mu_f) \times \left[|\mathcal{M}_R|^2 \mathcal{F}_J^{(3)}(p_1, p_2, p_3) - |\mathcal{M}_A|^2 \mathcal{F}_J^{(2)}(\tilde{p}_2, p_3) \right]$$

with

$$|\mathcal{M}_A|^2 \to |\mathcal{M}_R|^2 \, , \quad \mathcal{F}_J^{(3)} \to \mathcal{F}_J^{(2)}$$

in the soft and collinear limits

↓

$$\int_{m+1} \left[d\sigma^R - d\sigma^A \right] \quad \ldots \text{finite}$$

subtraction

contribution of $d\sigma^A$ to two-parton final state:

analytical integration over gluon phase space gives

$$\langle \mathbf{I}(\varepsilon) \rangle = |\mathcal{M}_B(p)|^2 \underbrace{\frac{\alpha_s(\mu_r)}{2\pi} C_F \left(\frac{4\pi\mu_r^2}{Q^2}\right)^{\varepsilon} \Gamma(1+\varepsilon)}_{F(Q)}$$

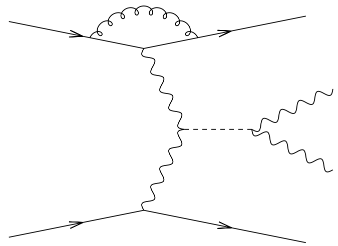
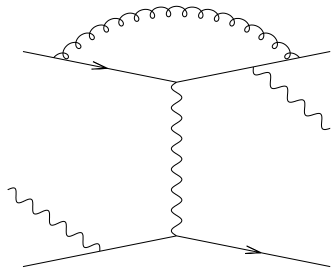
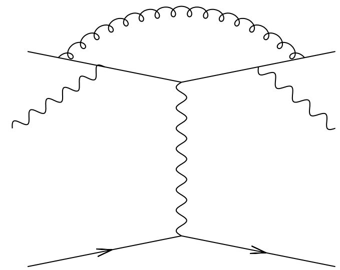
2-parton kinematics

$$\times \left[\frac{2}{\varepsilon^2} + \frac{3}{\varepsilon} + \underbrace{9 - \frac{4}{3}\pi^2}\right]$$

depends on reg. scheme

will see that poles are cancelled exactly in the following

. . . interference of LO diagrams with

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

no color exchange between upper / lower quark line at $\mathcal{O}(\alpha_s)$
$\longrightarrow$ consider radiative corrections to single quark line only

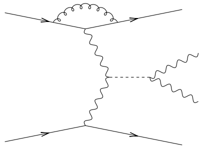
strategy:

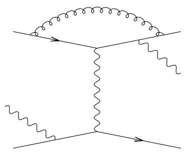
✘ split virtual corrections into classes depending on the number of gauge bosons attached to a quark line:

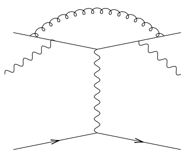
✘ encounter tensor integrals with up to three / four / five internal propagators

virtual contributions

after some algebra find

 $+\ldots \quad \sim \mathcal{M}_B F(Q)\left[-\frac{2}{\varepsilon^2}-\frac{3}{\varepsilon}+c_{\text{virt}}\right]$

 $+\ldots \quad \sim \mathcal{M}_B F(Q)\left[-\frac{2}{\varepsilon^2}-\frac{3}{\varepsilon}+c_{\text{virt}}\right]+\tilde{\mathcal{M}}_V^B$

 $+\ldots \quad \sim \mathcal{M}_B F(Q)\left[-\frac{2}{\varepsilon^2}-\frac{3}{\varepsilon}+c_{\text{virt}}\right]+\tilde{\mathcal{M}}_V^P$

poles cancel respective divergencies in integrated counterterms

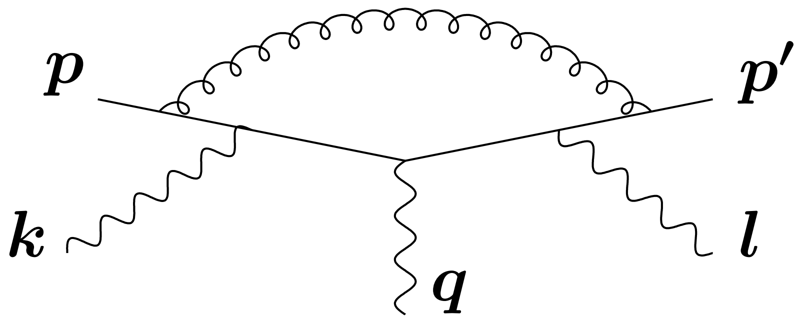
finite pieces are calculated numerically by means of Passarino-Veltman type tensor reduction, complemented by

- interpolation procedure for critical pentagon configurations
- Denner-Dittmaier type tensor reduction

pentagon contributions: PV approach

$$\mathcal{M}_5 = \varepsilon_\mu(k)\varepsilon_\nu(l)j_\rho(q)P^{\mu\nu\rho}(p,k,q,l)$$

$P^{\mu\nu\rho}$ can be expressed in terms of tensor coefficients E_{ij}



planar configurations with linearly dependent momenta
$\longrightarrow$ trouble with Passarino-Veltman reduction

but: singularity unphysical!
$\longrightarrow$ perform interpolation to “safe” regions of phase space

further improvement by gauge invariant decomposition:

$$\boldsymbol{\varepsilon_\mu(k) \longrightarrow \varepsilon'_\mu(k) = \varepsilon_\mu(k) - \beta\, k_\mu}$$

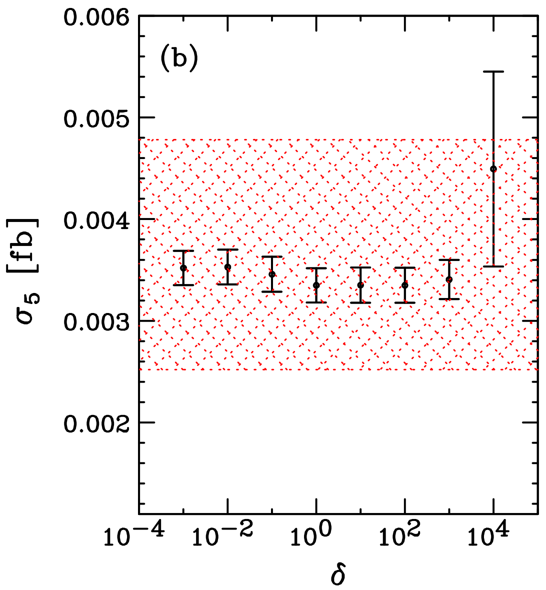
use $\boldsymbol{k_\mu \mathcal{E}^{\mu\nu\rho}(p,k,q,l) = \mathcal{D}^{\nu\rho}(p,k+q,l)}$

$$\boldsymbol{\begin{aligned} \mathcal{M}_5 &= \left[\varepsilon'_\mu(k) + \beta\, k_\mu\right] \varepsilon_\nu(l)\, j_\rho(q)\, \mathcal{E}^{\mu\nu\rho}(p,k,q,l) \\ &= \varepsilon'_\mu(k)\; \varepsilon_\nu(l)\, j_\rho(q)\, \mathcal{E}^{\mu\nu\rho}(p,k,q,l) \\ &\quad +\beta\; \varepsilon_\nu(l)\, j_\rho(q) \mathcal{D}^{\nu\rho}(p,k+q,l) \end{aligned}}$$

proper choice of $\boldsymbol{\beta}$ $\longrightarrow$ remaining “true” pentagon small

box-type contributions numerically stable numerical stability of genuine pentagon contributions:

check Ward identities for each phase space point and keep only satisfactory events (violation $\delta \lesssim 10\%$)



even better: apply new reduction method that avoids inverse Gram determinants *[Denner, Dittmaier (2002, 2005)]*

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:

- ✘ $pp \to jj\, e^+\nu_e\mu^-\bar{\nu}_\mu$
  ("EW $W^+W^-\,jj$ production")

- ✘ $pp \to jj\, e^+e^-\mu^+\mu^-$ and $pp \to jj\, e^+e^-\nu_\mu\bar{\nu}_\mu$
  ("EW $ZZ\,jj$ production")

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

$pp \to VV\,jj$ @ LHC

using k_T algorithm, CTEQ6 parton distributions,
and applying following cuts:

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

total $pp \to jj\, W^+W^-$ cross section

resonant $H \to WW$ contribution
(around m_H)

WW continuum
(above W-pair treshold)

separate by invariant mass cut

$$M_{WW} = \sqrt{(p_e + p_{\nu_e} + p_\mu + p_{\nu_\mu})^2} > m_H + 10\text{ GeV}$$

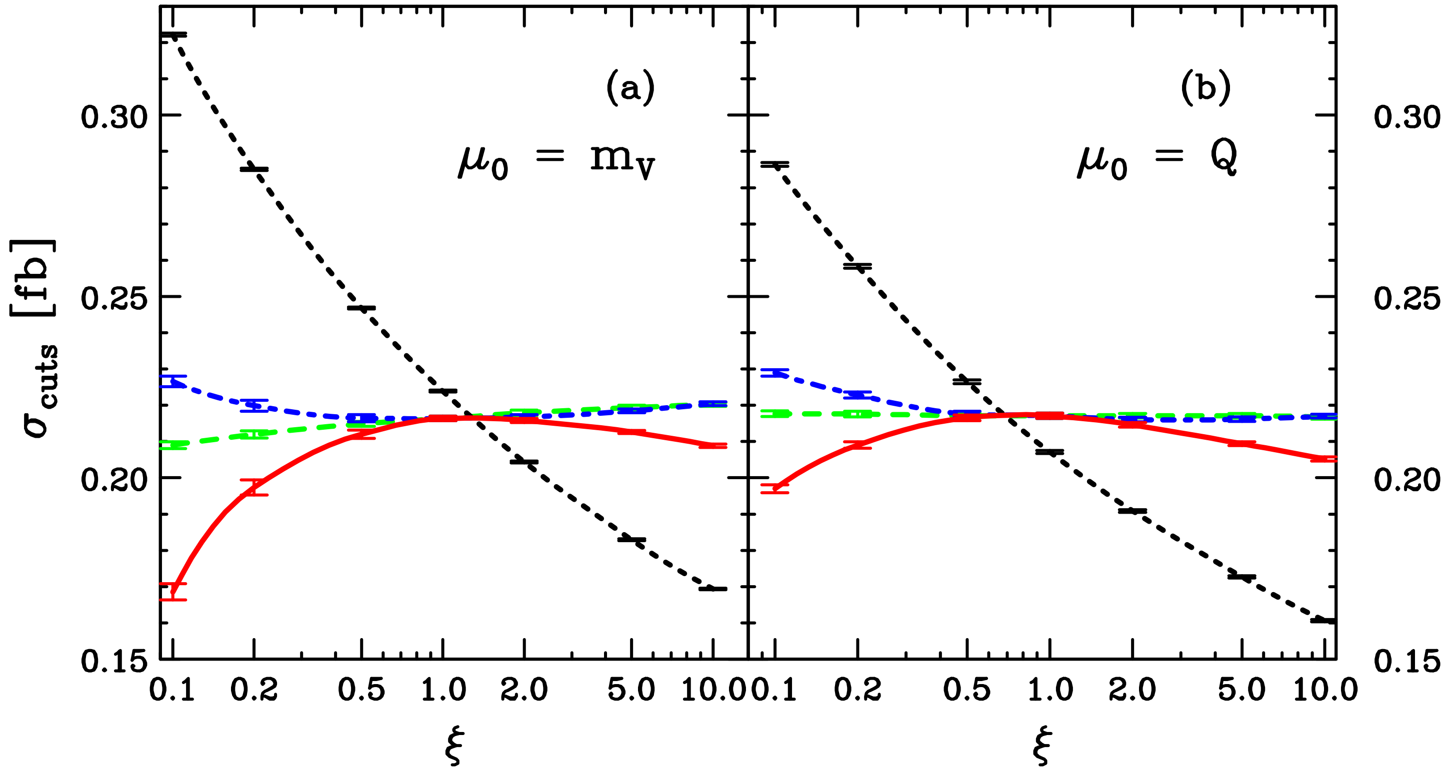
(m_H below W-pair treshold)

theoretical uncertainty

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

- ✘ errors in our code: performed lots of checks ...
- ✘ numerical instabilities (e.g., pentagons)
- ✘ PDF uncertainties:
  c.f. $\mathbf{3.5\%}$ uncertainty for related reactions ($\boldsymbol{pp \to jjH}$)
- ✘ effect of neglected contributions:
  - interference effects
  - $\boldsymbol{s}$-channel vector boson production
  - neglected higher order contributions
  - ...
- ✘ dependence on unphysical renormalization and factorization scales

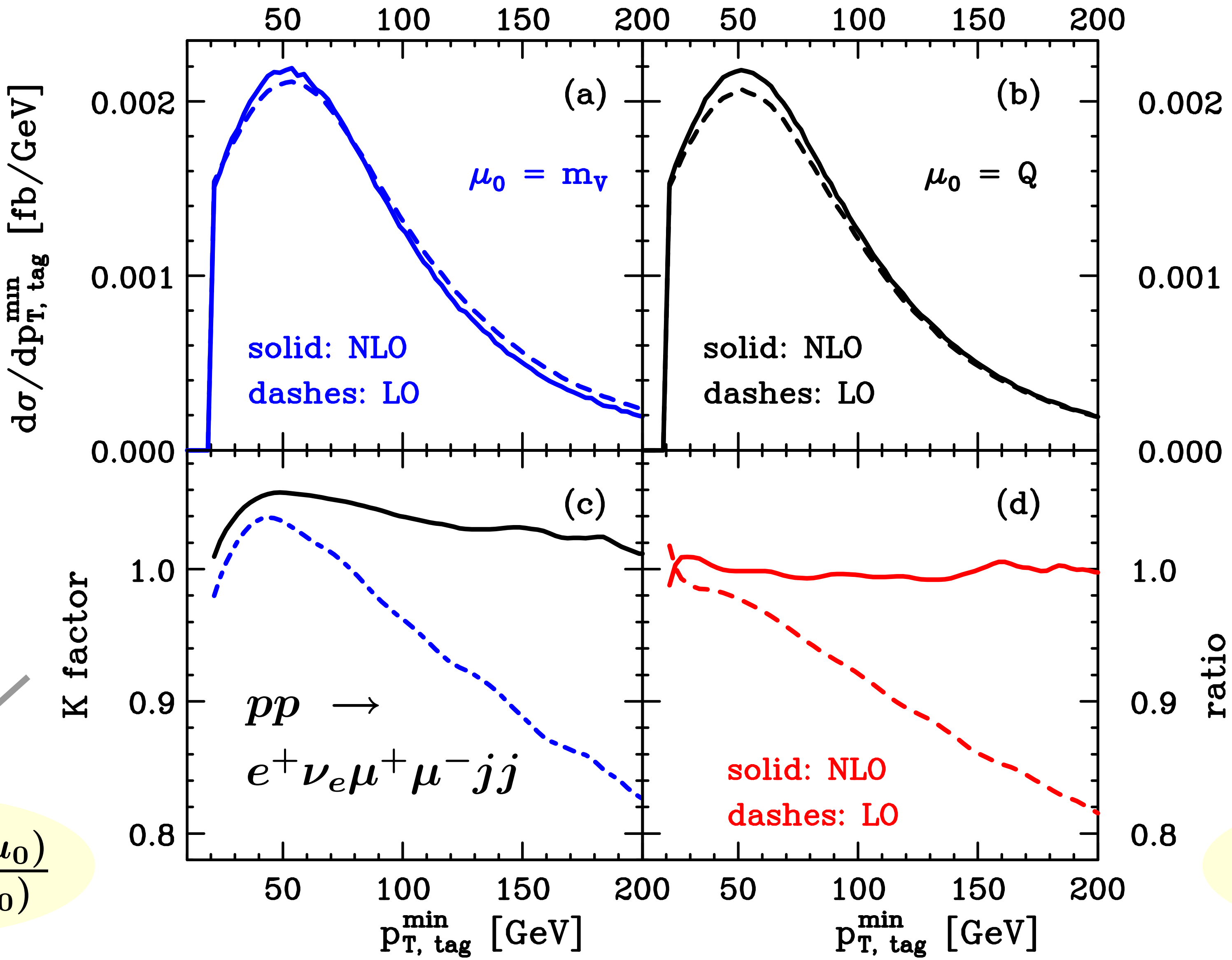
scale uncertainty: $pp \to W^+Zjj$



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: scale dependence strongly reduced

scales matter (at LO) . . .



$$\frac{\mathcal{O}bs^{NLO}(\mu_0)}{\mathcal{O}bs^{LO}(\mu_0)}$$

$$\frac{\mathcal{O}bs(\mu_0{=}m_V)}{\mathcal{O}bs(\mu_0{=}Q)}$$

compare: gluon fusion beyond NLO

NLO: large corrections with

$$\frac{\sigma^{NLO}}{\sigma^{LO}} \sim 1.7 \div 2.0$$

convergence properties

and uncertainties

much improved at NNLO

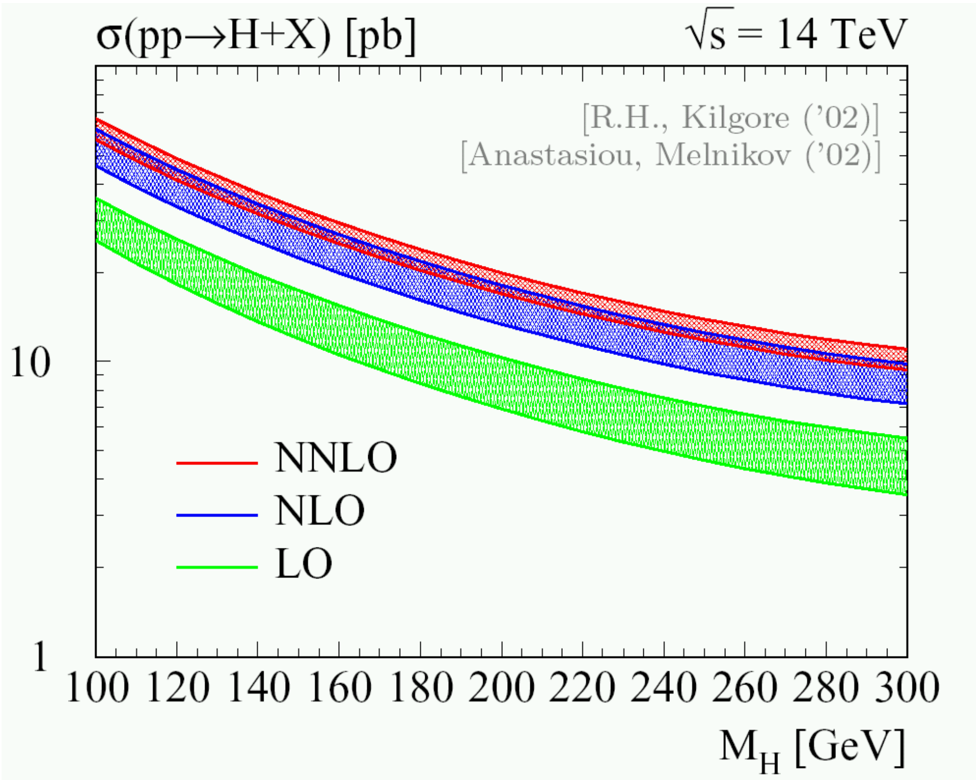
Harlander, Kilgore (2002)

Anastasiou, Melnikov (2002)

N^3LO_{app} results by

Moch, Vogt (2005)

stabilize NNLO result



compare: $pp \to WWZ$ @ NLO

crossed process: $pp \to WWZ$

Hankele, Zeppenfeld (2007)

LO: very mild scale dependence

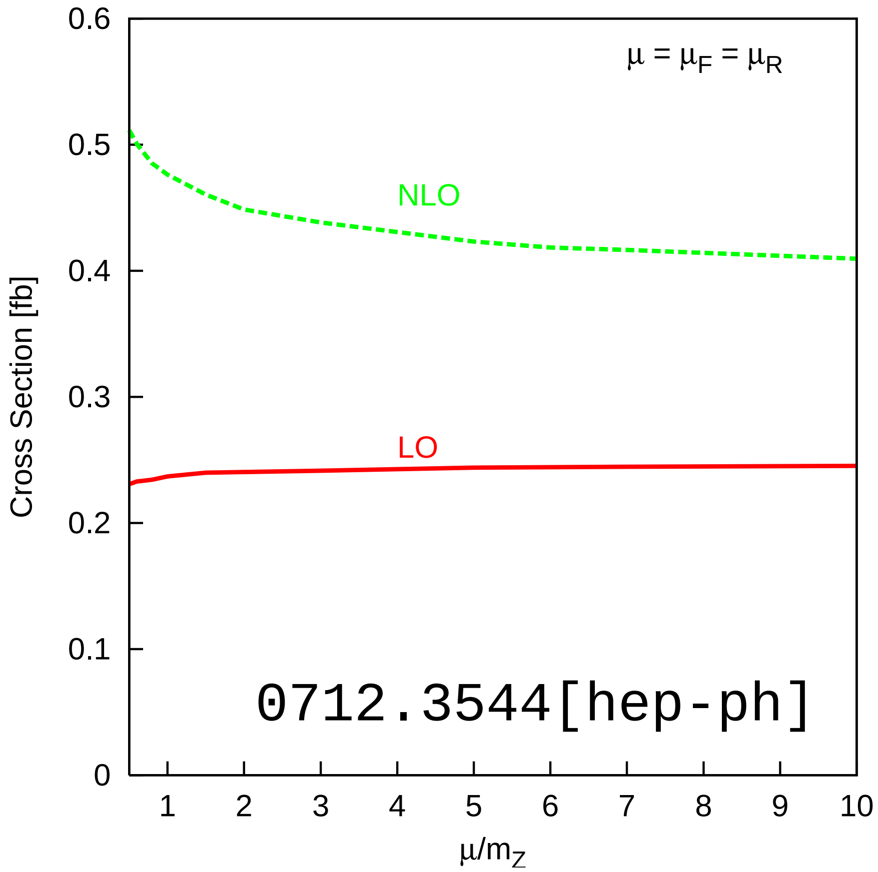
LO is $\mathcal{O}(\alpha_s^0)$,

PDFs probed in regions

with small μ_f dependence

but large NLO 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 inclusive cross sections

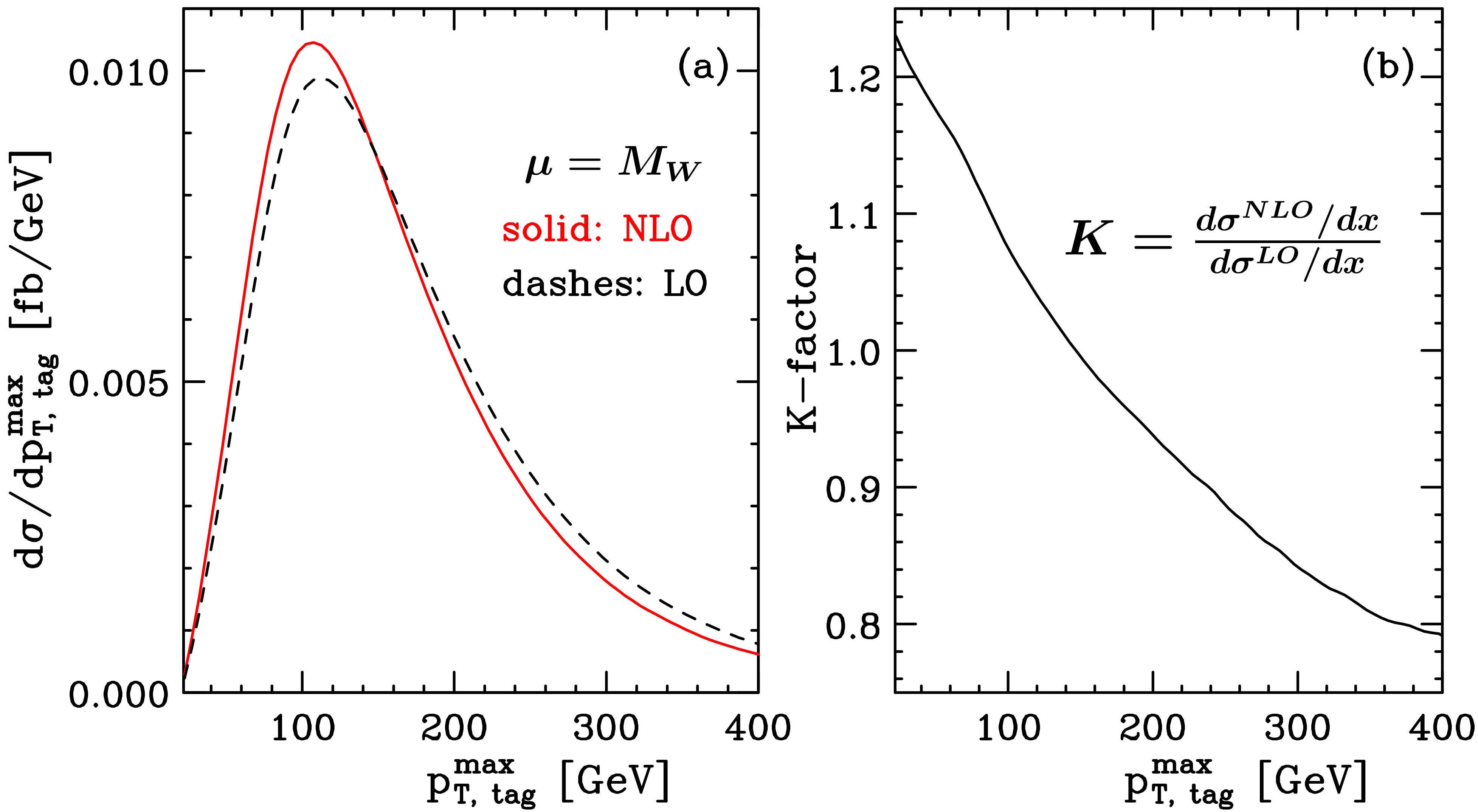
$\updownarrow$

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



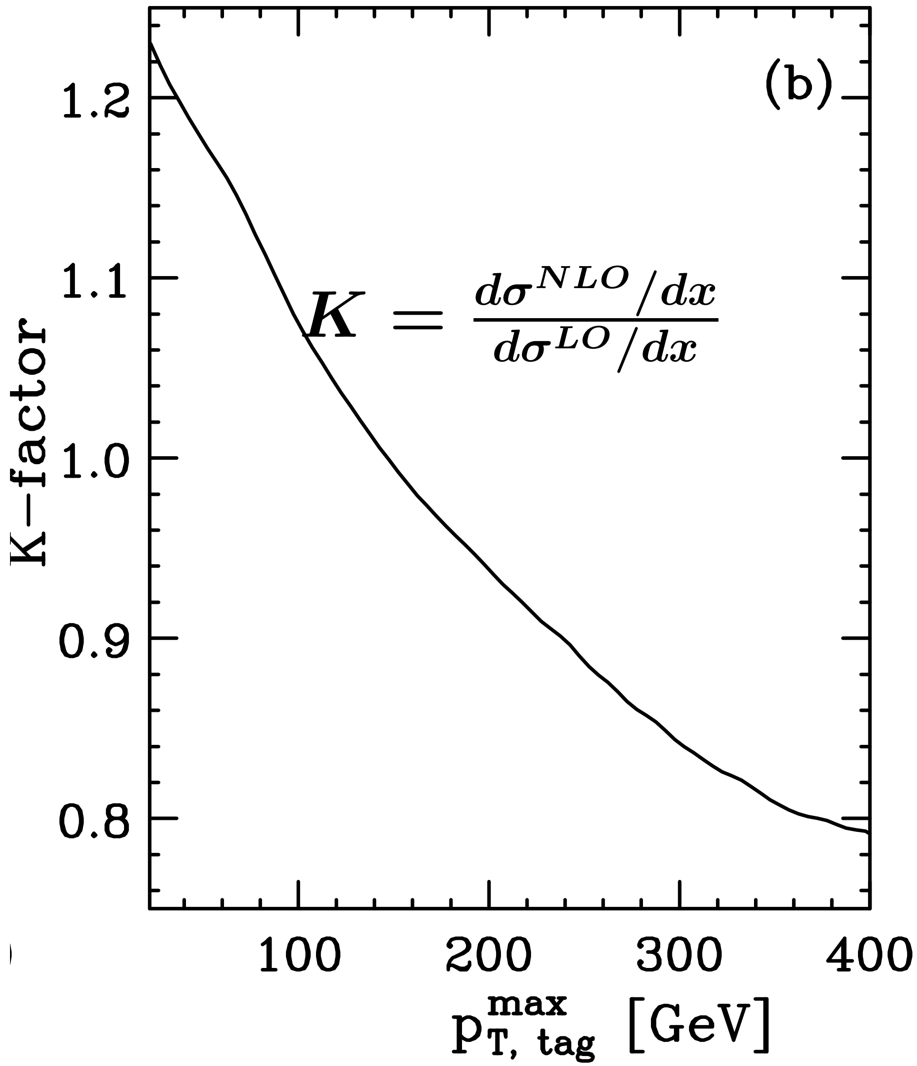
W^+W^-jj distribution: p_T of tagging jets

note: significant change in shape at NLO

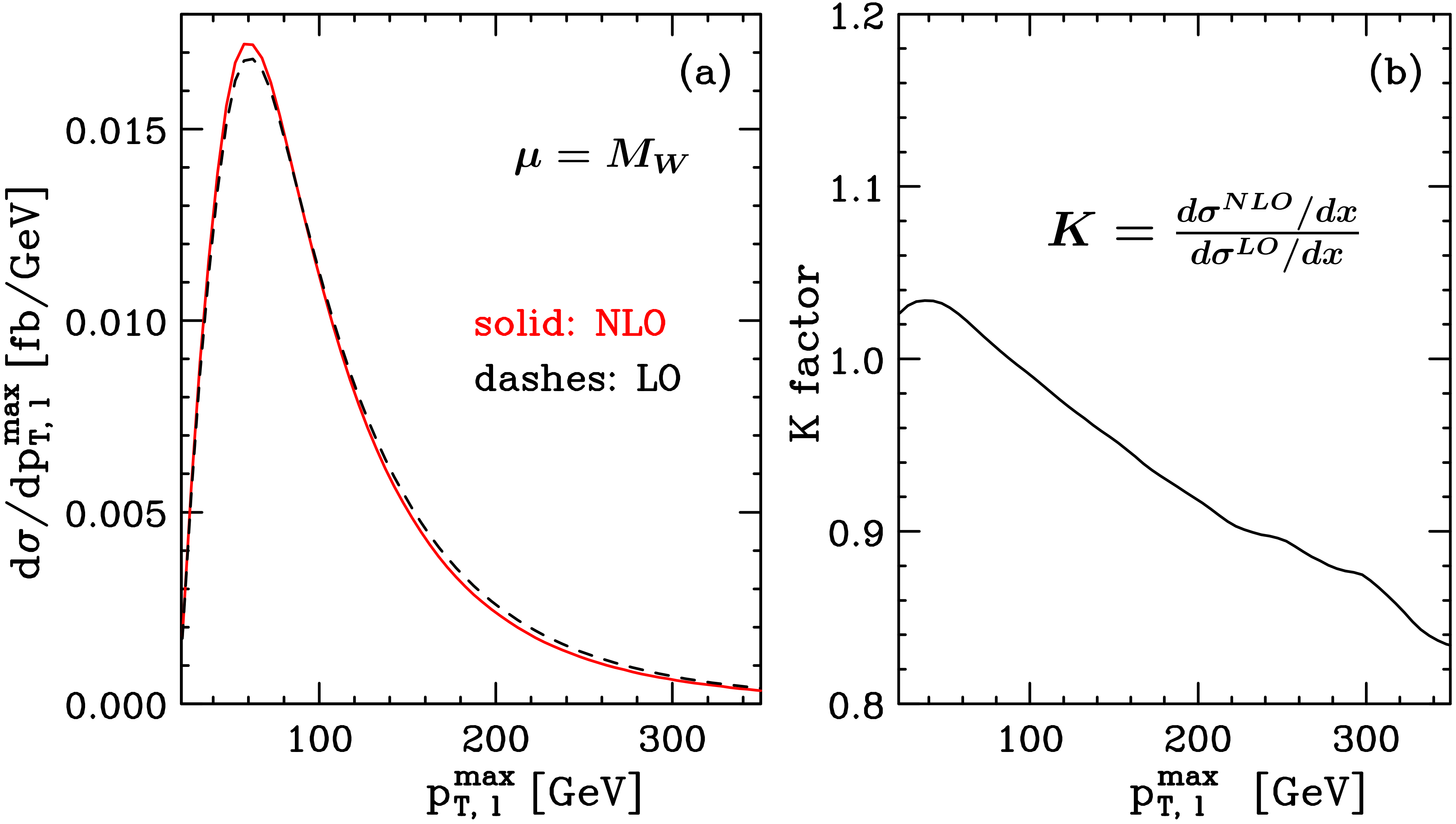
extra gluon in real emission contributions

↓

quarks which build tag-jets carry lower transverse momenta



W^+W^-jj distributions: p_T of charged lepton



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

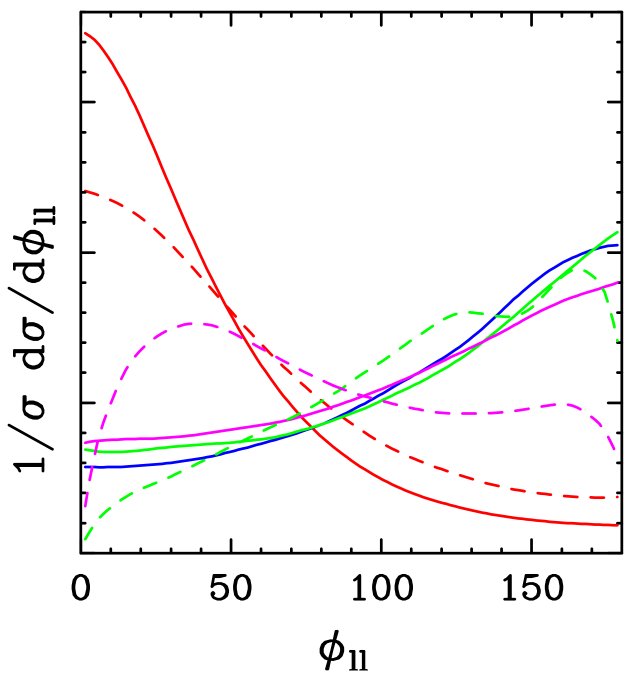
leptons emitted preferentially in same direction

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)



angular distribution of charged leptons

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

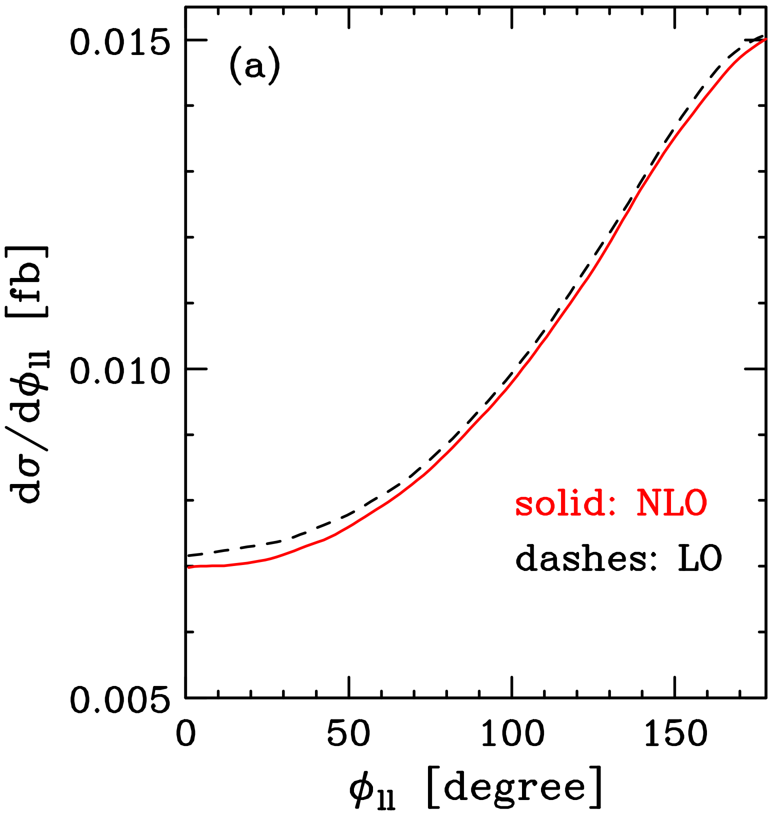
↓

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



$pp \longrightarrow ZZjj$

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

- ✘ small branching ratios $Z \longrightarrow$ leptons:

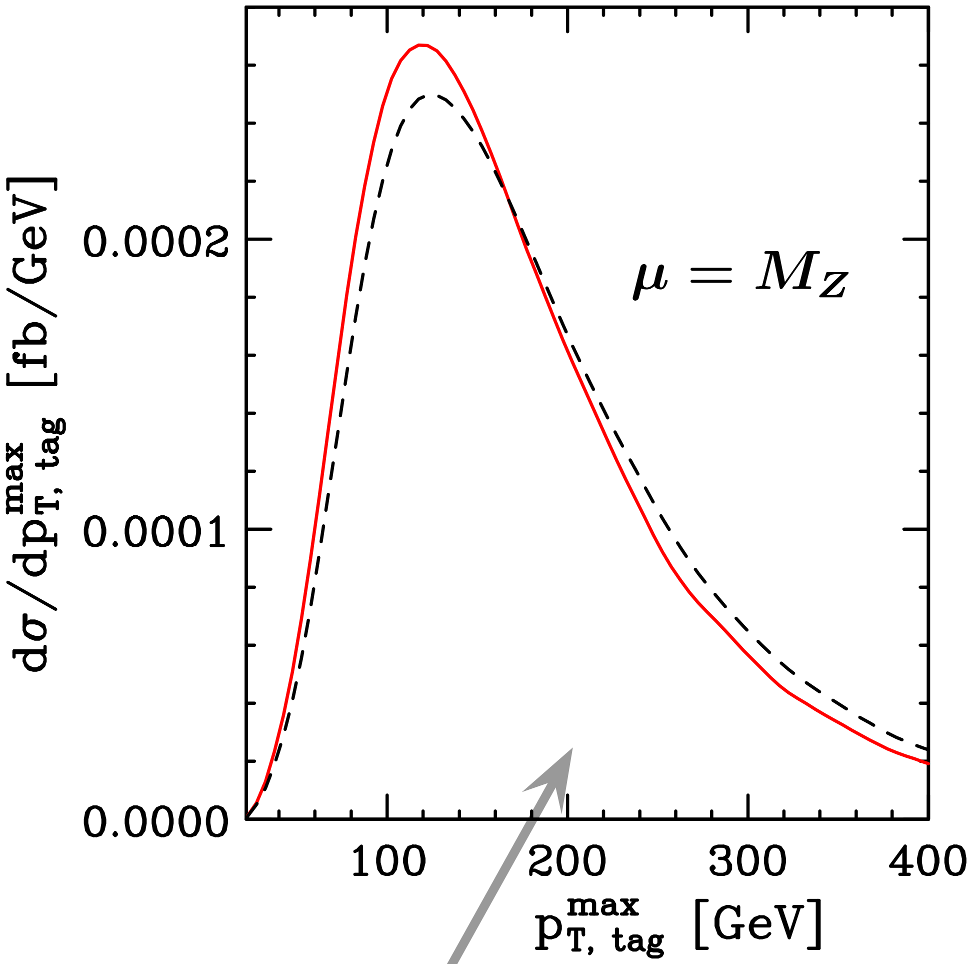
$$BR(W \rightarrow \ell\nu) \sim 10.8\%$$
$$BR(Z \rightarrow \ell^+\ell^-) \sim 3.3\%$$
$$BR(Z \rightarrow \nu\bar{\nu}) \sim 6.6\%$$

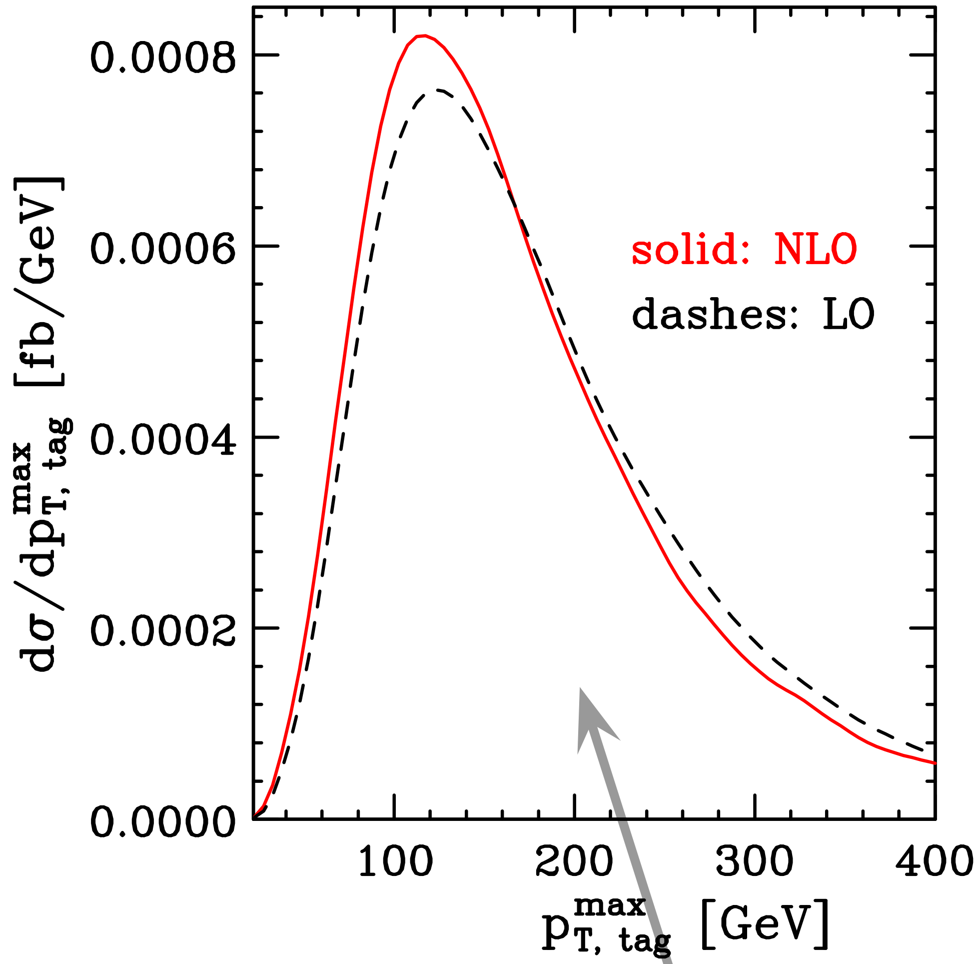
$\longrightarrow$ cross sections small: $\sigma_{ZZ} \ll \sigma_{WW}$

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

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

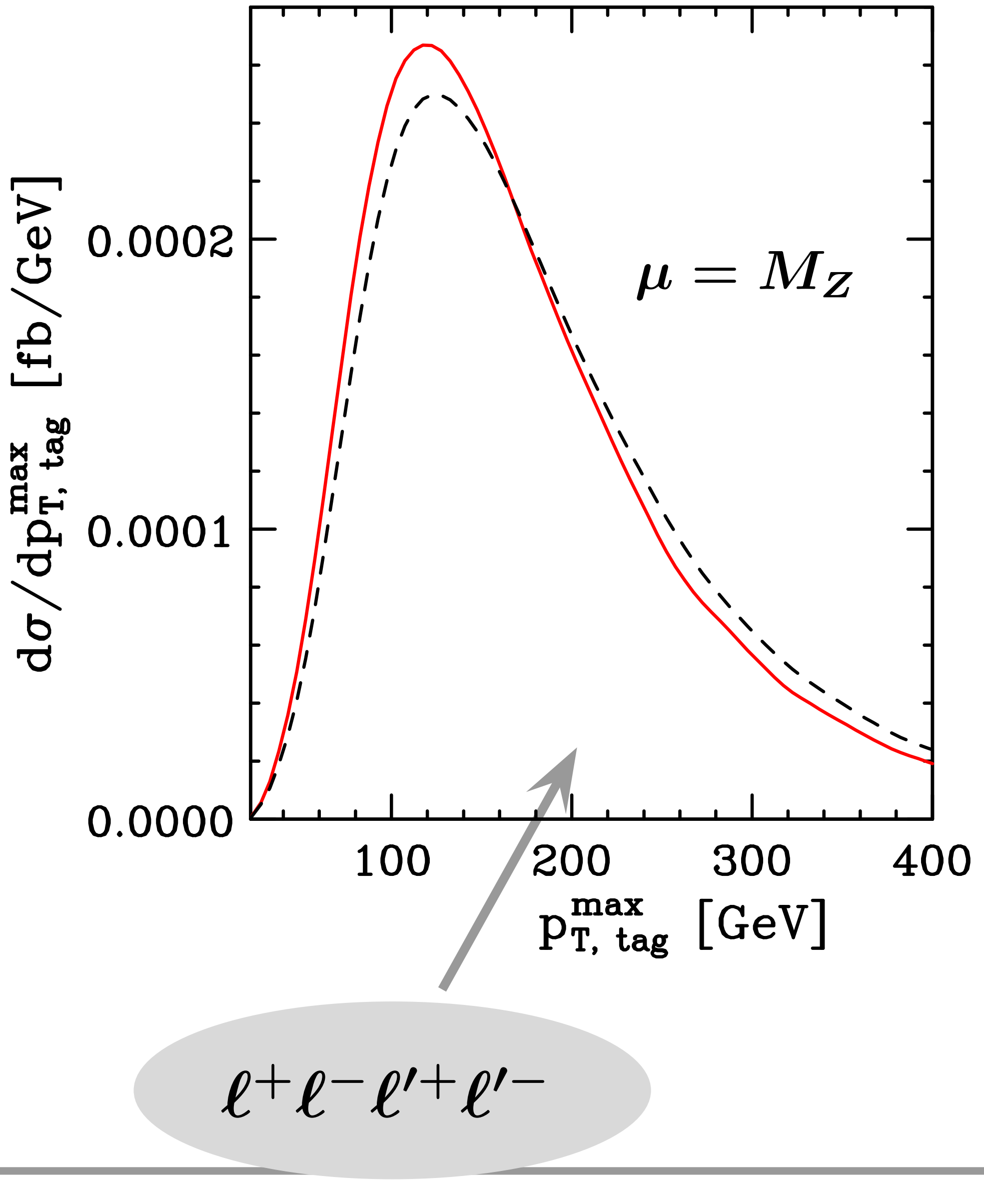
distributions: p_T of tag jet





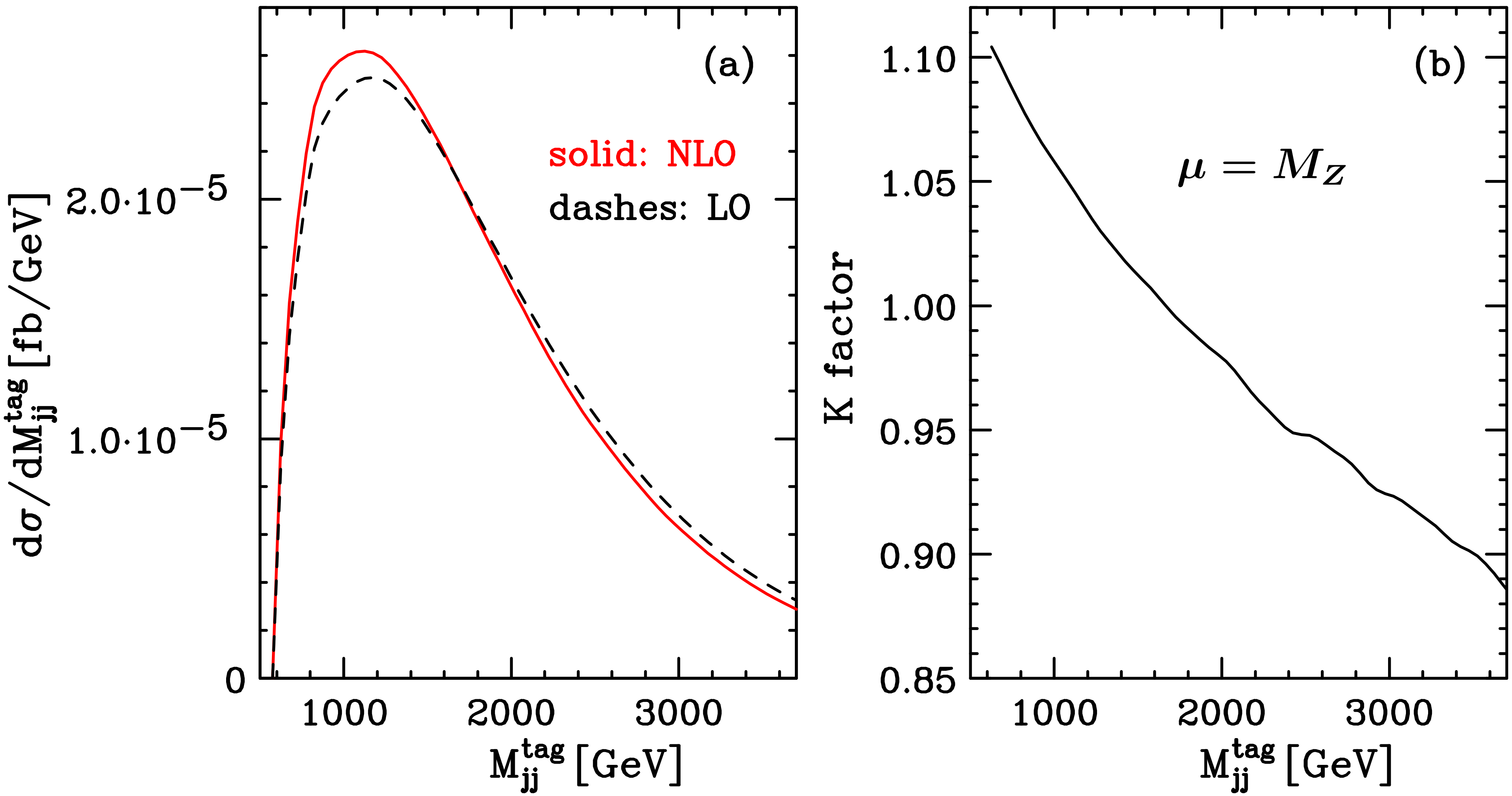
$\ell^+\ell^-\ell'^+\ell'^-$

$\ell^+\ell^-\nu\bar{\nu}$



$\boldsymbol{K}$-factor for
p_T-distributions behaves
completely analogous to
$pp \to W^+W^- jj$ case

M_{jj} distribution for $pp \longrightarrow jj\, e^+e^-\mu^+\mu^-$



signature typical for VBF $\longrightarrow$ helps to suppress backgrounds,
e.g., from gluon fusion of QCD $VVjj$ production

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

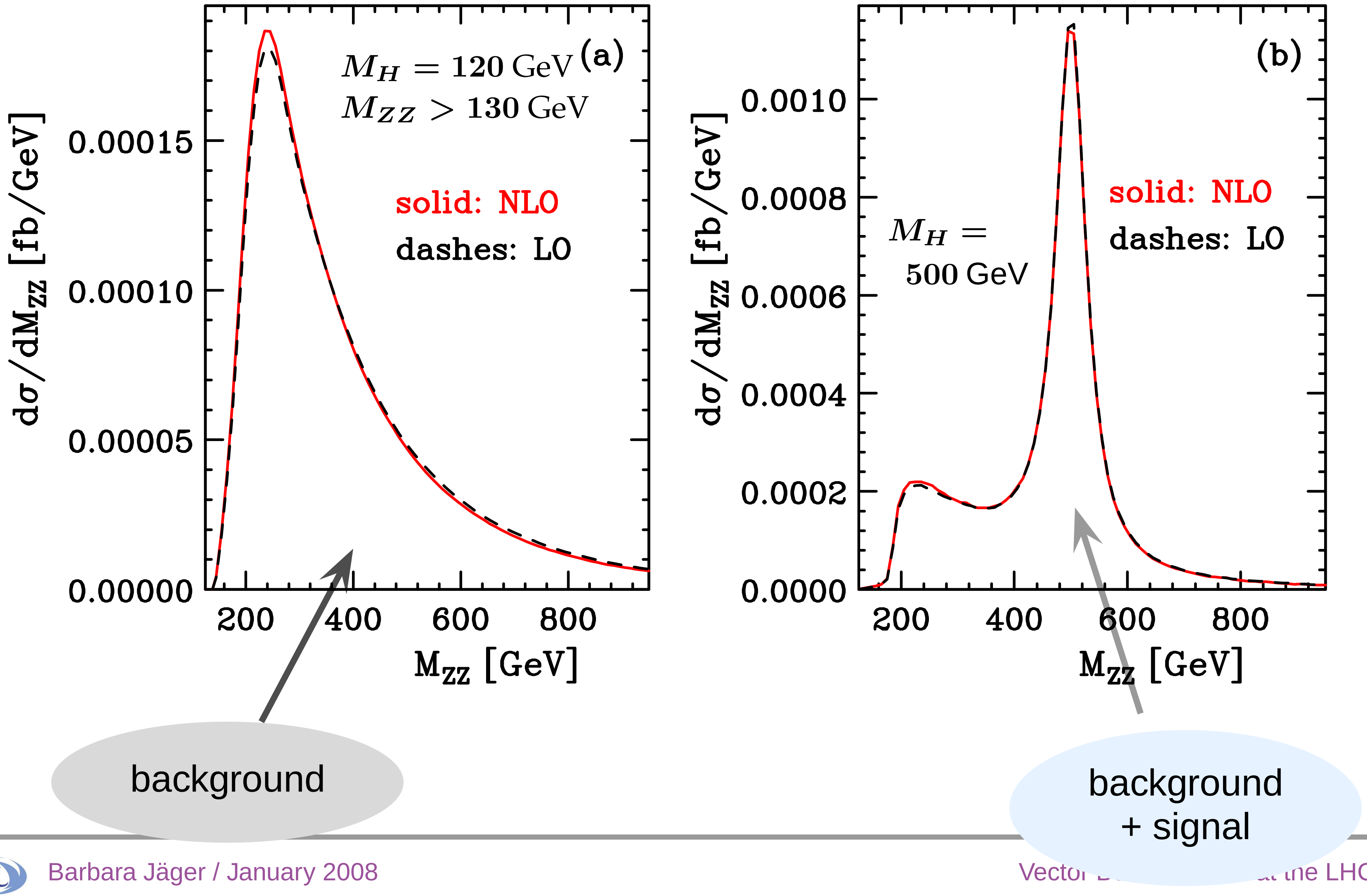
reminder:

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

· 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: $pp \longrightarrow \ell^+\ell^-\ell'^+\ell'^- jj$



results: summary

- obtained numerical results for

$$\cdot\ pp \to jj\ e^+\nu_e\mu^-\bar{\nu}_\mu\ (pp \to W^+W^-\ jj)$$

$$\cdot\ pp \to jj\ e^+e^-\mu^+\mu^- \text{ and } pp \to jj\ e^+e^-\nu_\mu\bar{\nu}_\mu\ (pp \to ZZ\ jj)$$

$$\cdot\ pp \to jj\ e^+\nu_e\mu^+\mu^- \text{ and } pp \to jj\ e^-\bar{\nu}_e\mu^+\mu^-$$

$$(pp \to W^+Z\ jj \text{ and } pp \to W^-Z\ jj)$$

- all 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)

- identified observables which are rather sensitive to Higgs mass

precision tools

need precision tools for cross sections and distributions which allow for the implementation of realistic experimental selection cuts

☞ for VBF-type processes developed NLO parton level Monte Carlo program **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, B. J., G. Klämke, M. Kubocz, P. Konar, C. Oleari, M. Werner, M. Worek, D. Zeppenfeld]

user options:

- arbitrary selection cuts
- various scale choices and PDF sets
- 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:

$$pp \to Hjj,$$
$$H \to \gamma\gamma$$
$$H \to \mu^+\mu^-$$
$$H \to \tau^+\tau^-$$
$$H \to b\bar{b}$$

$$pp \to W^+W^-jj \to \ell^+\nu\ell'^-\bar{\nu}'jj$$
$$pp \to ZZjj \to \ell^+\ell^-\ell'^+\ell'^-jj$$
$$pp \to ZZjj \to \ell^+\ell^-\nu\bar{\nu}jj$$

$$pp \to Wjj \to \ell^+\nu jj$$
$$pp \to Zjj \to \ell^+\ell^-jj$$
$$pp \to Zjj \to \nu\bar{\nu}jj$$

conclusions

✘ VBF crucial for understanding mechanism of electroweak symmetry breaking

↓

need to know signal and background 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