NLO QCD corrections to Vector Boson Pair Production via Vector Boson Fusion

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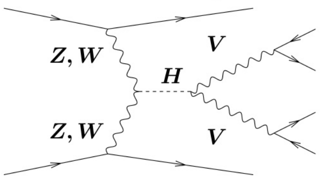
Outline

1. Motivation
   - Why Vector Boson Fusion?
2. Elements of the calculation
   - Tree-level features
   - NLO: real contributions
   - NLO: virtual contributions
3. Selected results
   - Differential distributions at the LHC

Outline

Higgs production via VBF



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- Clean experimental signature
  - → *two highly energetic outgoing jets*
  - → *large rapidity interval between jets*
  - → *no hadronic activity in the rapidity interval between jets*
- NLO QCD corrections moderate (5-10%)

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[Figy,Oleari,Zeppenfeld(2003)]

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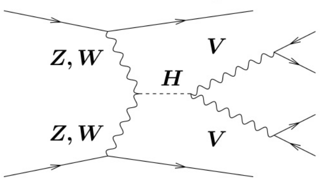

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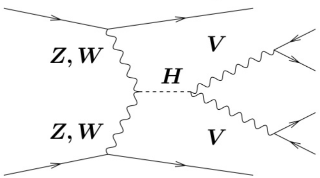

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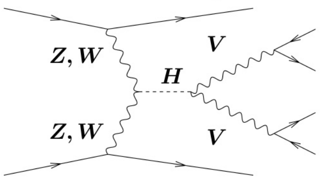

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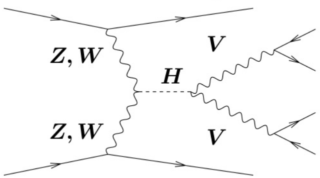

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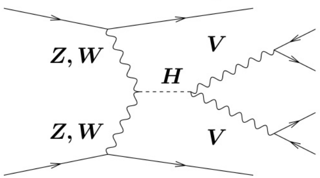

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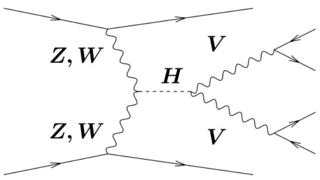

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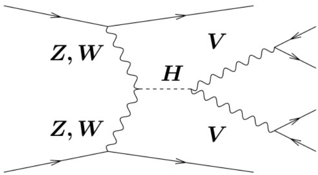

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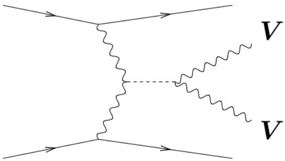

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  - $\sigma(qq \to qqW^+W^-)$ between 3.5% and 15% of the Higgs signal for 115 GeV $\leq M_H \leq$ 160 GeV

    [Kauer,Plehn,Rainwater,Zeppenfeld(2001)]
  - similar features as H production $\to$ *irreducible* background
- New Physics
  - possible signal: enhancement of $qq \to qqVV$ over SM predictions at high $\sqrt{s}$
  - subprocess $V_L V_L \to V_L V_L$ intimately related to EWSB

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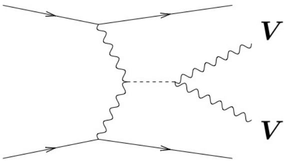

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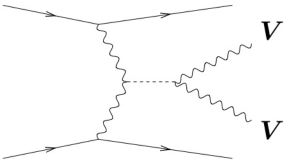

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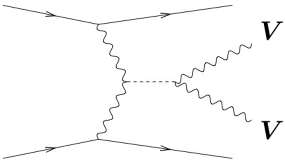

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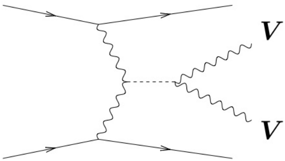

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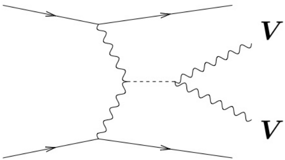

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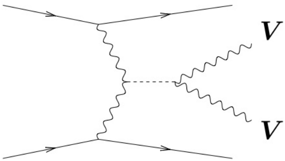

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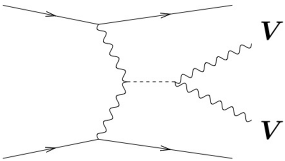

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- Multi-parton process: huge number of Feynman diagrams
  - **2**→**4** for $qq \to qqVV$
  - **2**→**6** for $qq \to qql^+l^-\nu_l\bar{\nu}_l, qql^+l^-l^+l^-, qql^+l^-l^+\nu_l$

  → how to speed up the evaluation?
- Suitable treatment of pentagon contributions

  → how to solve numerical instabilities?

→ Build a fully-flexible partonic Monte Carlo program allowing for
  - computation of jet observables at NLO-QCD accuracy
  - straightforward implementation of cuts

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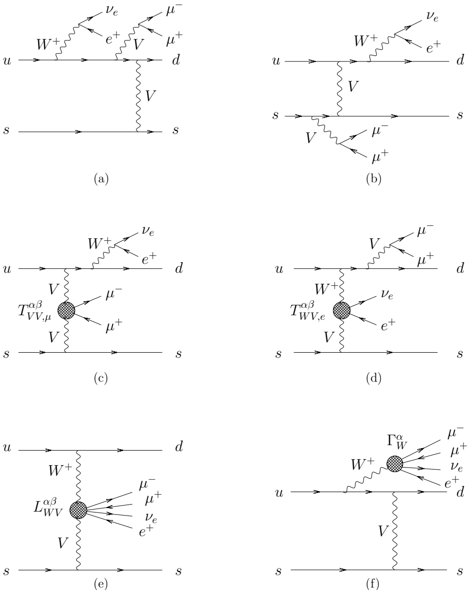

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- only $us \to ds$ shown

$\to$ add $u\bar{s} \to d\bar{s}, \ldots$

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(b) different quark lines

(c) quark line + *leptonic tensor* $T_{VV,\mu}$

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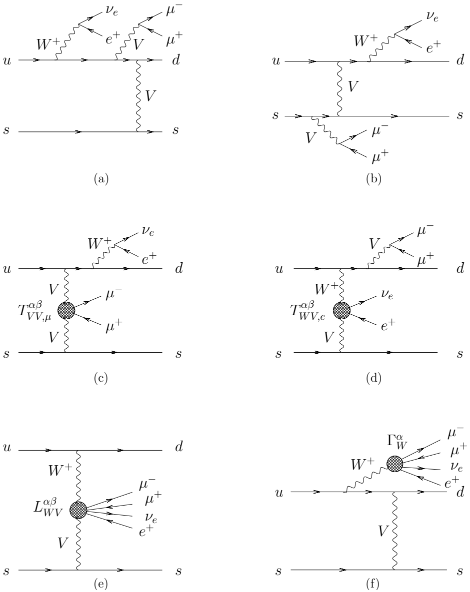

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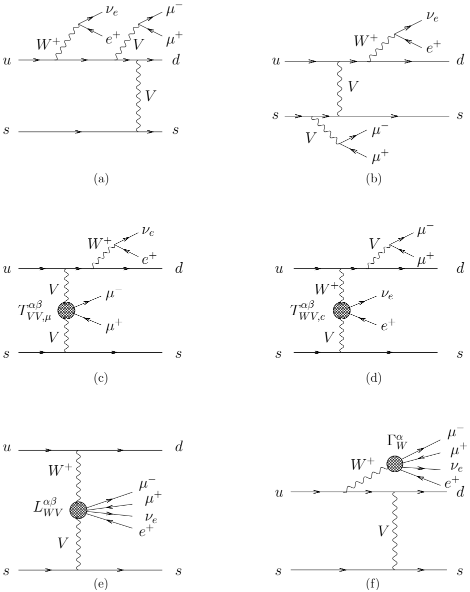

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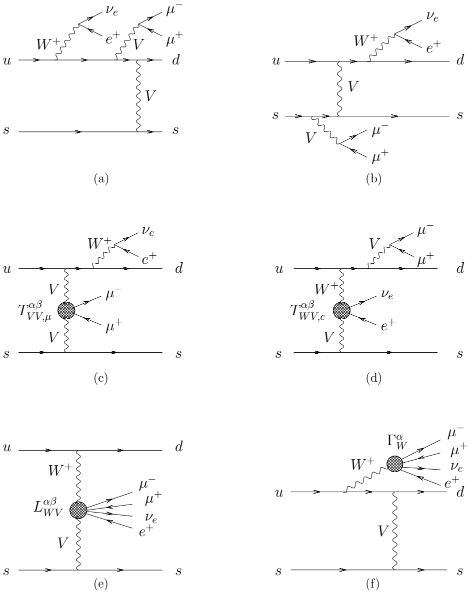

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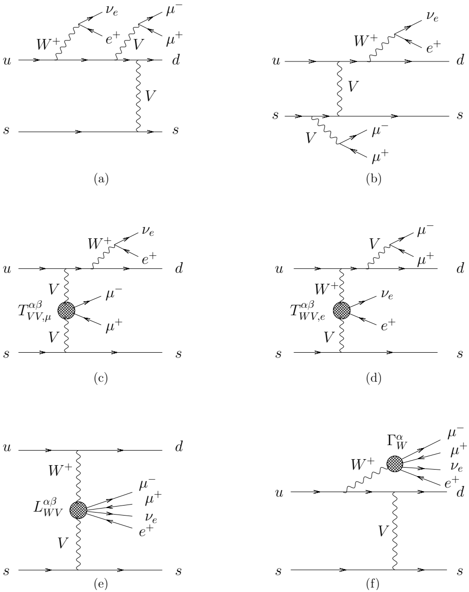

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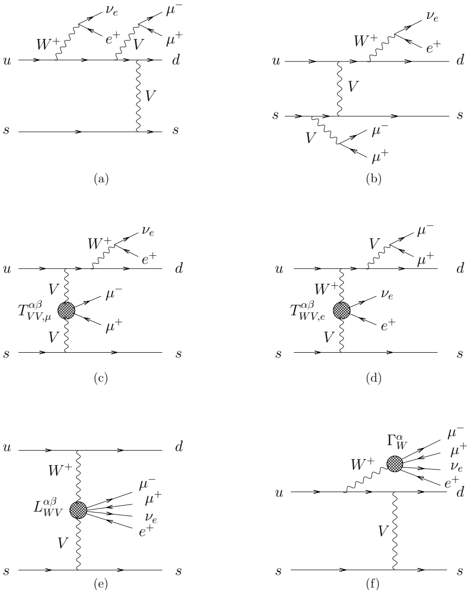

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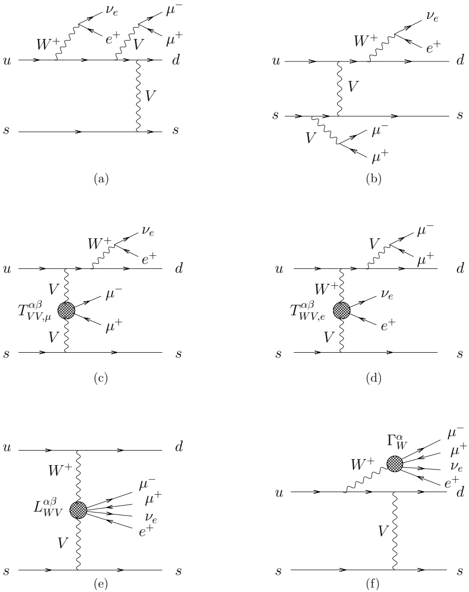

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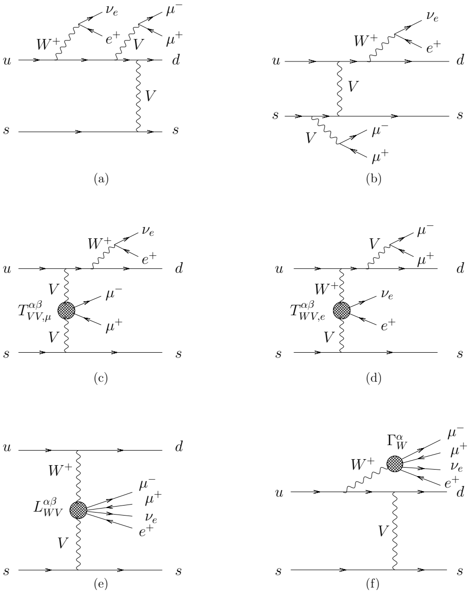

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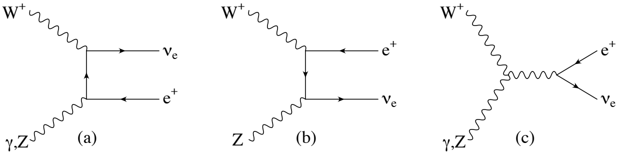
Leptonic tensors

Example: T_{WV} built up from



- Sum of sub-amplitudes involving EW bosons and leptons only
- Use them for diagrams with *same* topology but *differences* in quark propagators
- Develop modular structure to speed up the calculation:
  - → compute common building blocks of several diagrams only once per phase-space point
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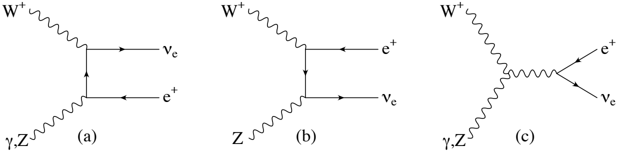

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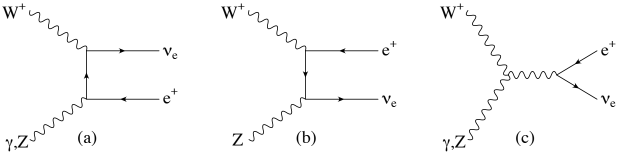

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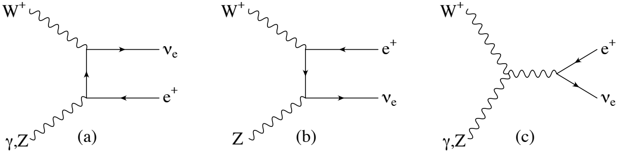

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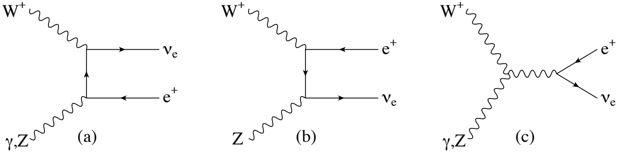

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Outline

Real corrections

- Attach a gluon to the quark lines in all possible ways
- Crossing diagrams: initial gluon splitting in a $q\bar{q}$ pair
- Soft and collinear singularities
  - → standard *Catani-Seymour* dipole subtraction

[Catani,Seymour(1997)]

- Divergences only depend on the colour structure of the external partons
  - → subtraction terms *identical* to Higgs production via VBF

$$< I(\epsilon) >= |M_B|^2 \frac{\alpha_s(\mu_R)}{2\pi} C_F \left(\frac{4\pi\mu_R^2}{Q^2}\right)^{\epsilon} \Gamma(1+\epsilon)\left[\frac{2}{\epsilon^2}+\frac{3}{\epsilon}+9-\frac{4}{3}\pi^2\right]$$

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Outline

1. Motivation
   - Why Vector Boson Fusion?
2. Elements of the calculation
   - Tree-level features
   - NLO: real contributions
   - NLO: virtual contributions
3. Selected results
   - Differential distributions at the LHC

Virtual corrections

- Add interference between Born and virtual amplitudes
- EW bosons exchanged in the $t-$channel are colour-singlet
  - $\rightarrow$ no contributions from gluons attached both to upper and lower quark lines!
  - $\rightarrow$ consider radiative corrections to single quark line only
- Regularization performed in the Dimensional Reduction scheme
  - $\rightarrow$ PV reduction performed in $d = 4 - 2\epsilon$ dimensions
  - $\rightarrow$ algebra of γ, p, ϵ performed in $d = 4$ dimensions

[Siegel(1979)]

- Three classes of contributions: virtual corrections along a quark line with 1,2,3 vector boson(s) attached $\rightarrow$ up to pentagons!

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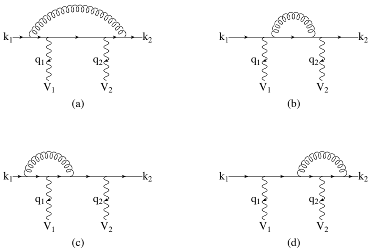

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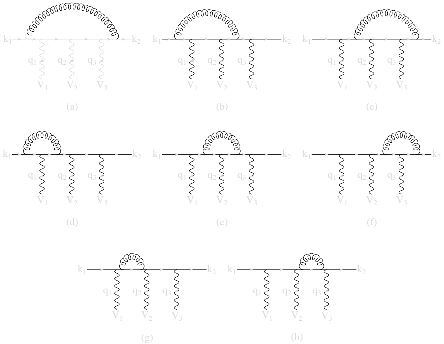
quark line with 3 bosons attached



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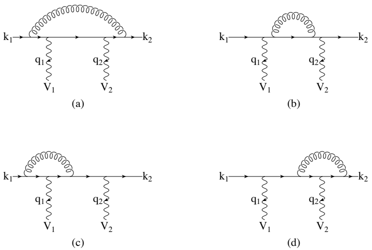

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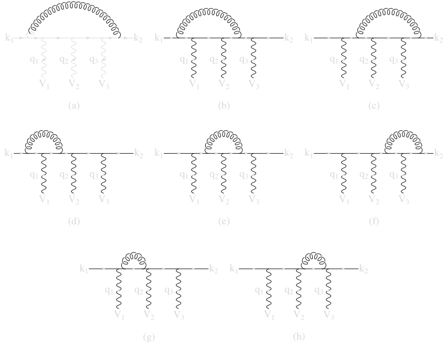

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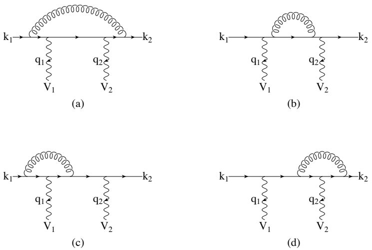

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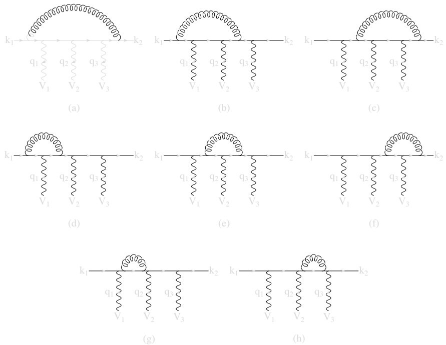

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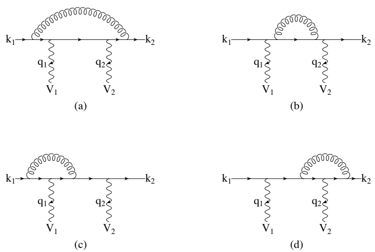

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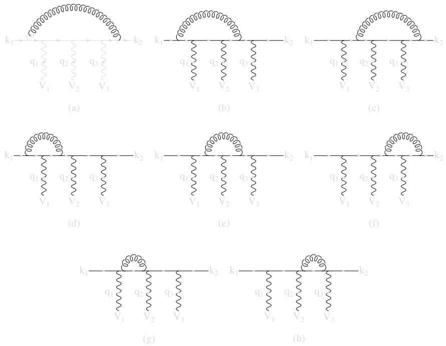

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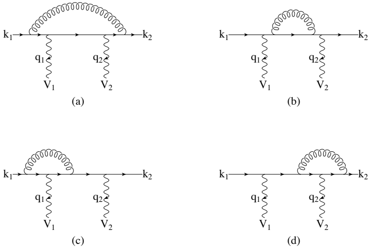

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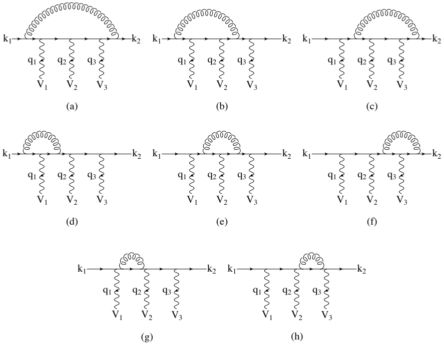

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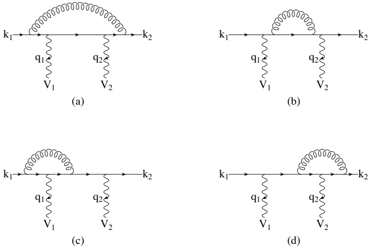

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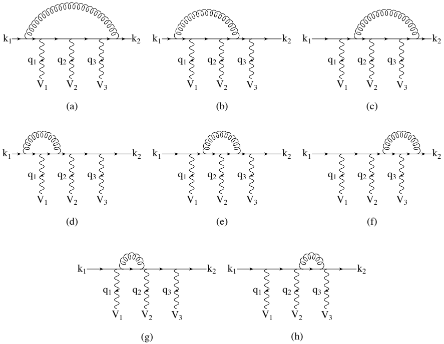

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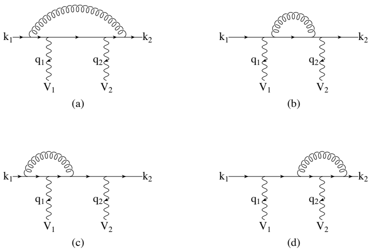

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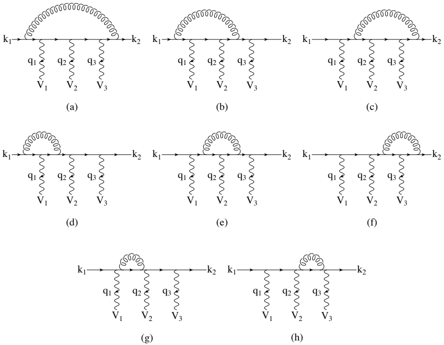

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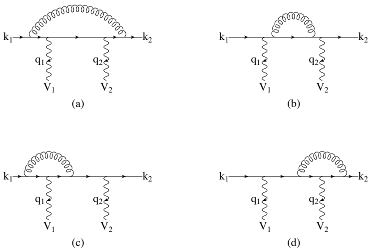

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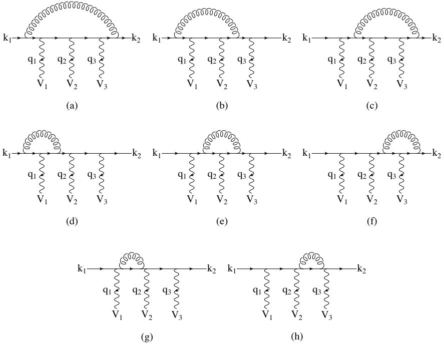

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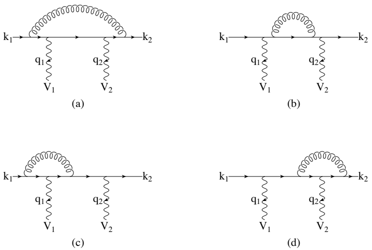

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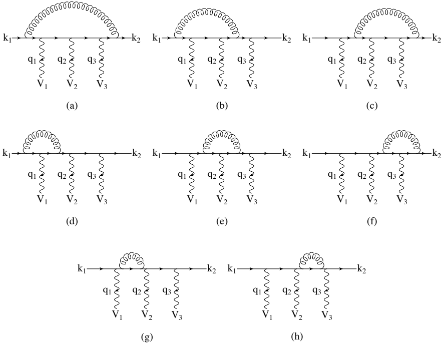

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Finite contributions

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- divergent part proportional to Born amplitude
  - → exactly cancels the phase-space integral of the dipole terms
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Evaluation of $\widetilde{\mathcal{M}}_V$

- Divergent contributions in the expression of scalar integrals can generate finite terms by multiplying tensor coefficients with a $(d-4)$ in the numerator
  - → keep track of how the divergent contributions feed into the expression of tensor coefficients

[Oleari,Zeppenfeld(2003)]

- Two-, Three-, Four-point tensor integrals
  - → computed through Passarino-Veltman reduction procedure
  - → numerically stable in phase-space regions relevant for VBF

[Passarino,Veltman(1979)]

- Five-point tensor integrals
  - → numerical instabilities if kinematical invariants (Gram determinant) become small
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  - $\rightarrow$ numerical instabilities if kinematical invariants (Gram determinant) become small
  - $\rightarrow$ use Dennar-Dittmaier reduction formalism

[Dennar,Dittmaier(2005)]

Evaluation of $\widetilde{\mathcal{M}}_V$

- Divergent contributions in the expression of scalar integrals can generate finite terms by multiplying tensor coefficients with a $(d-4)$ in the numerator
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- Two-, Three-, Four-point tensor integrals
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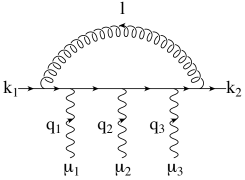
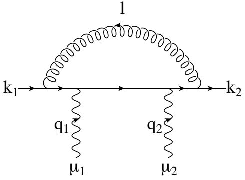
Electromagnetic Ward Identities

Gauge invariance: a pentagon can be reduced to box integrals



(a)



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$$\mathcal{E}_{\mu_1\mu_2\mu_3}(k_1, q_1, q_2, q_3) \equiv \int \frac{d^d l}{(2\pi)^d} \gamma^\alpha \frac{1}{\not l + \not k_1 + \not q_{123}} \gamma_{\mu_3} \frac{1}{\not l + \not k_1 + \not q_{12}} \gamma_{\mu_2} \frac{1}{\not l + \not k_1 + \not q_1} \gamma_{\mu_1} \frac{1}{\not l + \not k_1} \gamma_\alpha \frac{1}{l^2}$$

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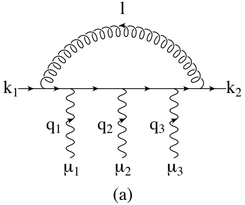

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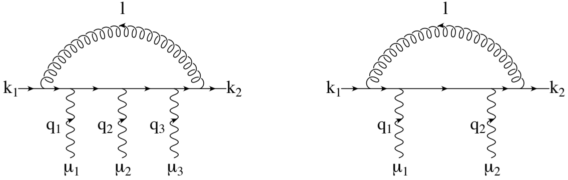

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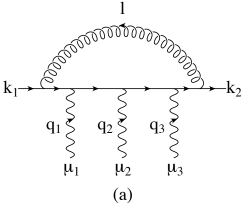

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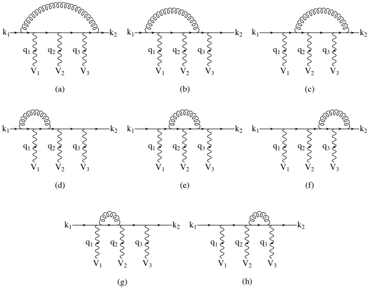

- Loop amplitudes eventually contracted with leptonic currents
- Example: $W^+(q_+)$, $W^-(q_-)$, $\gamma/Z(q_0)$ with leptonic decays J_+, J_-
- $M_5 = J_+^{\mu_1} J_-^{\mu_2} \tilde{\mathcal{P}}_{\mu_1\mu_2\mu_3}(k_1, q_+, q_-, q_0)$
- Project $J_\pm$ on the respective momenta ($J_\pm^\mu = x_\pm\, q_\pm^\mu + r_\pm^\mu$), so that the vectors $r_\pm$, in the center-of-mass system of the W pair, have zero time component ($r_\pm \cdot (q_+ + q_-) = 0$)

→ $M_5 = r_+^{\mu_1}\, r_-^{\mu_2} \tilde{\mathcal{P}}_{\mu_1\mu_2\mu_3} + \text{boxes}$

→ Ward Identities reduce magnitude of coefficients multiplying pentagon loops and thus, the overall pentagon contribution to cross section

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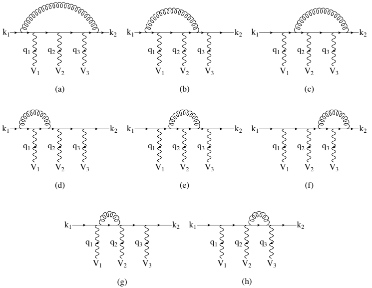

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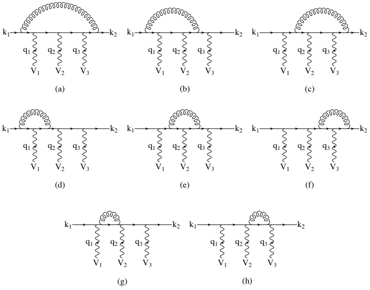

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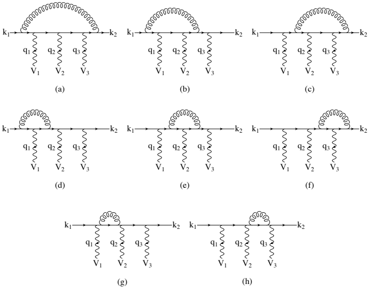

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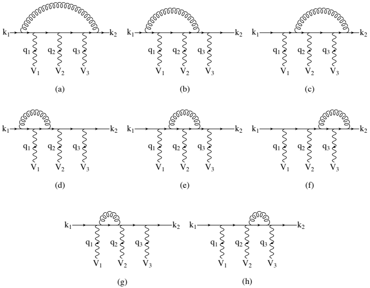

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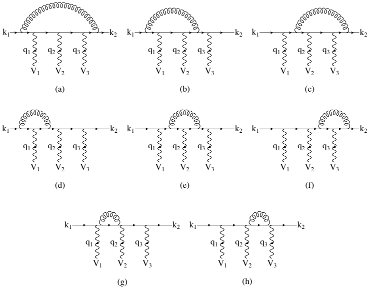

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Numerical stability of pentagon contributions

- Gauge-check procedure
  - Identify the fraction f of events for which numerical pentagon reduction violates Ward identity by more than 10%
  - Discard these points for the calculation of the finite parts
  - Correct the remaining pentagon contributions by a factor $1/(1-f)$
  - Error induced by this approximation: far below numerical accuracy of Monte Carlo program
- PV formalism: $f \sim 15\%$
- DD formalism: $f \sim 0.1\%$

$\longrightarrow$ Pentagons under control using DD formalism!

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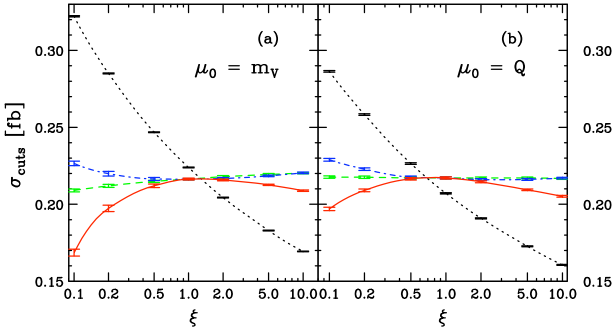
Outline

VBF cuts

Tagging Jets	$p_{Tj} \geq 20$ GeV, $\quad |y_j| \leq 4.5$ $\Delta y_{jj} = |y_{j_1} - y_{j_2}| > 4$, $y_{j_1} \cdot y_{j_2} < 0$
Charged Leptons	$p_{Tl} > 20$ GeV, $\quad |\eta_l| \leq 2.5$ $y_{j,min} < \eta_l < y_{j,max}$ $\Delta R_{jl} \geq 0.4$
Higgs on/off	$M_{VV} > M_H + 10$ GeV (WW,ZZ continuum only)

Scale dependence - total σ (WZ case)



- Two possible scales
  - $m_V = (m_Z + m_W)/2$
  - Q=momentum-transfer of exchanged vector boson in VBF graphs
- K-factor ∼1 (± few percent) in both cases
- LO depends on μ_F only → ∼10% dependence (0.5<ξ<2)
- NLO improvement → ∼2% dependence (0.5<ξ<2)

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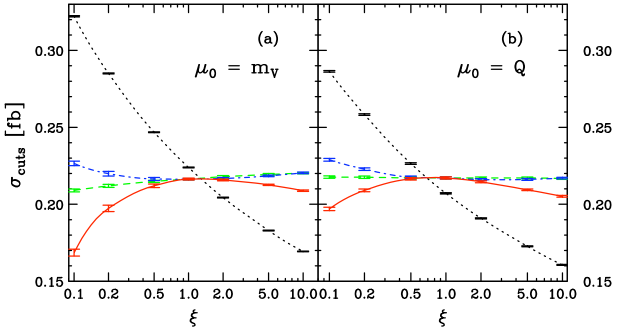

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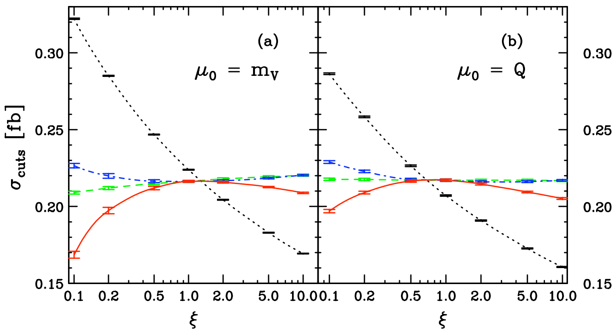

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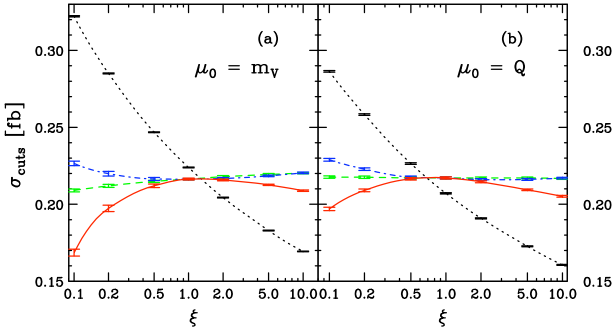

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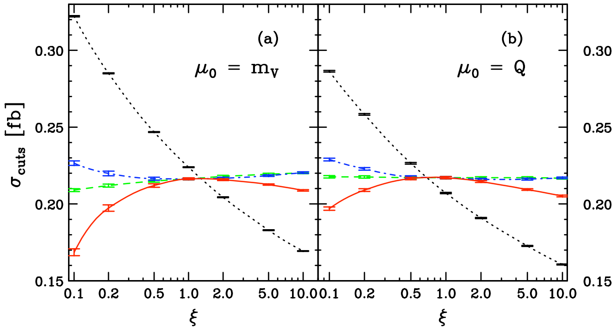

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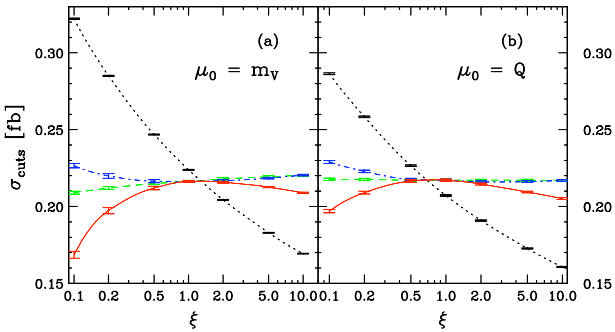

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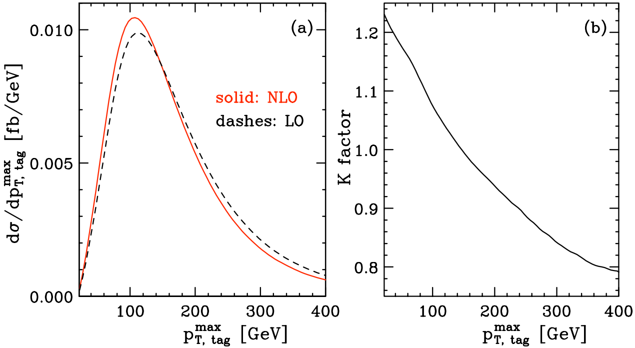
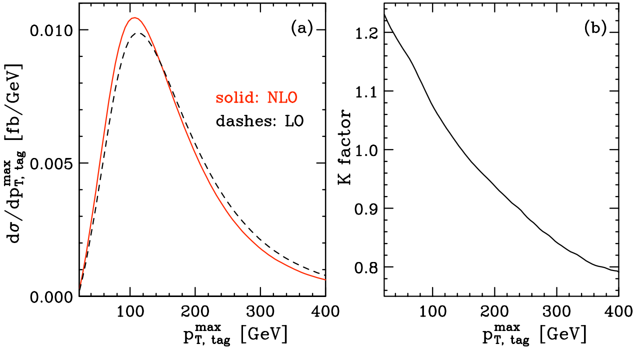
K-factor - $p_{T,jet}^{max}$ (WW case)



- Strong change in shape → shift to smaller p_T at NLO
- Mainly due to extra parton from real emission
- K-factor varying between 1.2 and 0.8 (20 GeV < p_T < 400 GeV)

K-factor - $p_{T,jet}^{max}$ (WW case)



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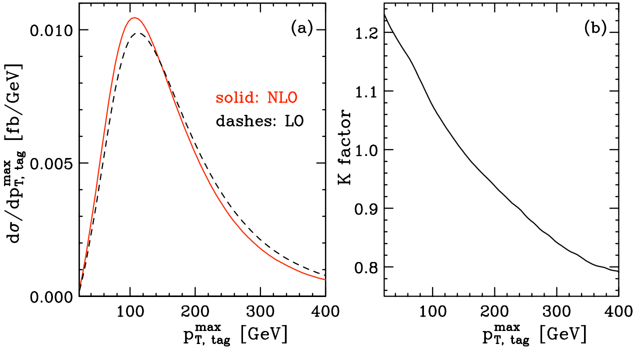

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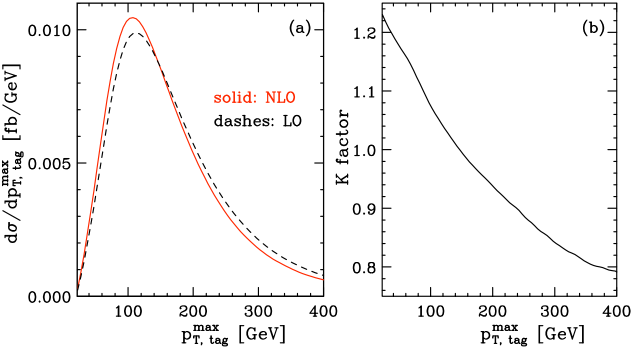

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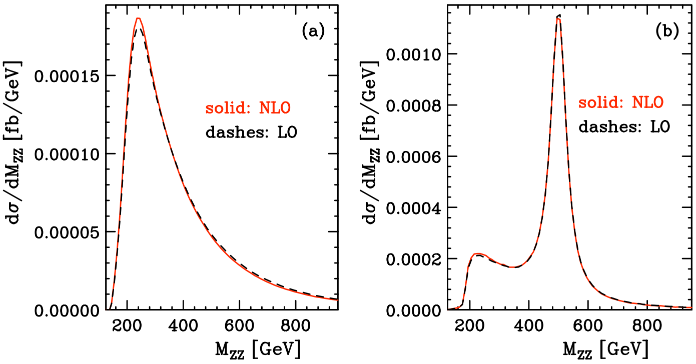
Invariant mass - lepton pairs (ZZ case)



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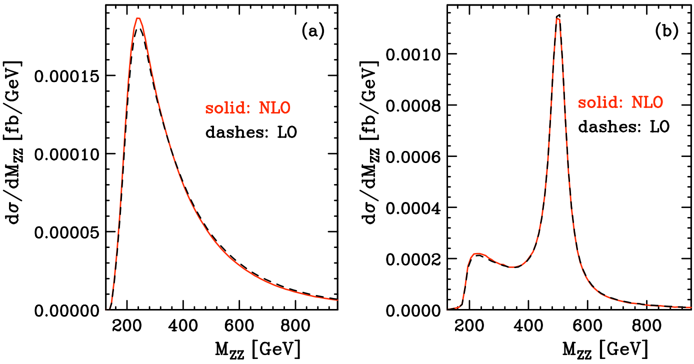

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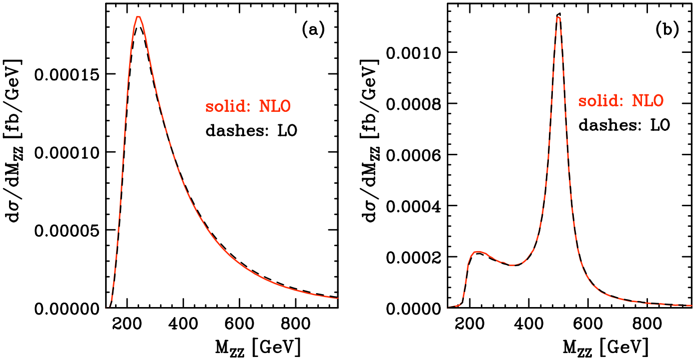

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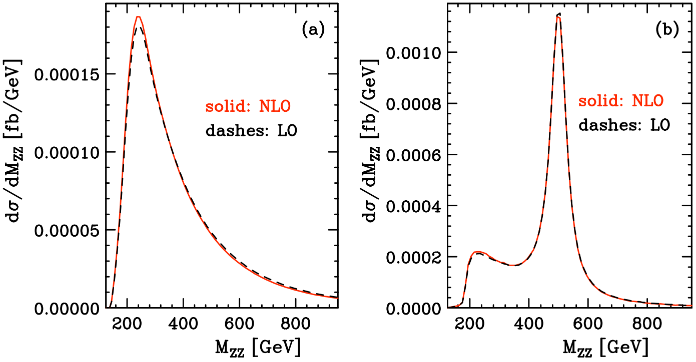

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  $pp \to W^+W^-jj \qquad pp \to ZZjj \qquad pp \to W^\pm Zjj$

  including leptonic decays
- Modular structure: separate (one-time) computation of leptonic tensors and decay width
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- *Outlook: VBFNLO*
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