

QCD Corrections to Vector Boson Pair Production via Weak Boson Fusion



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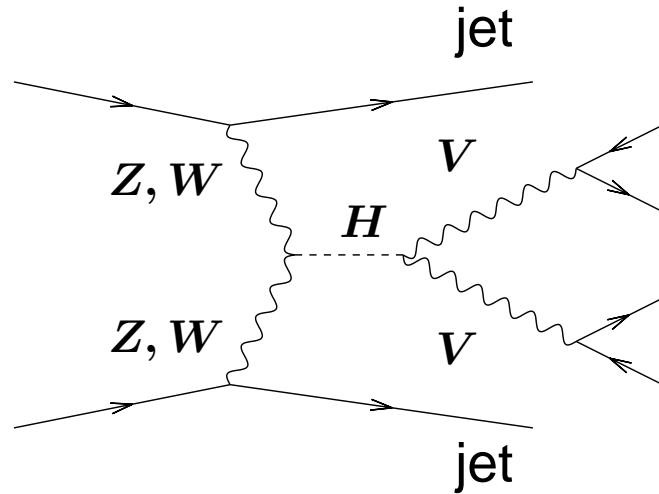
Outline

- ✗ motivation: why vector boson fusion?
- ✗ focus on VV production in VBF
 - ☞ theoretical concepts & techniques
 - ☞ results
- ✗ summary & conclusions

VBF: features

- ✘ total $qq \rightarrow qqH$ cross section $\sigma_{VBF} \sim 0.2 \cdot \sigma_{gg}$ in intermediate mass range and comparable to σ_{gg} for $M_H \gtrsim 600$ GeV
- ✘ **tagging jets** \rightarrow additional cuts to suppress background to the Higgs signal in VBF
- ✘ NLO corrections moderate and under theoretical control
- ✘ allows for a **determination of couplings** and CP-properties of the Higgs boson
- ✘ $V_L V_L \rightarrow V_L V_L$ in $qq \rightarrow qqVV$ via VBF: distinguish **strong EWSB** / light Higgs boson

Higgs production in VBF



scattered quarks

→ two forward tagging jets:

Higgs decay products
typically between tagging jets

NLO: *Han, Valencia, Willenbrock (1992)*

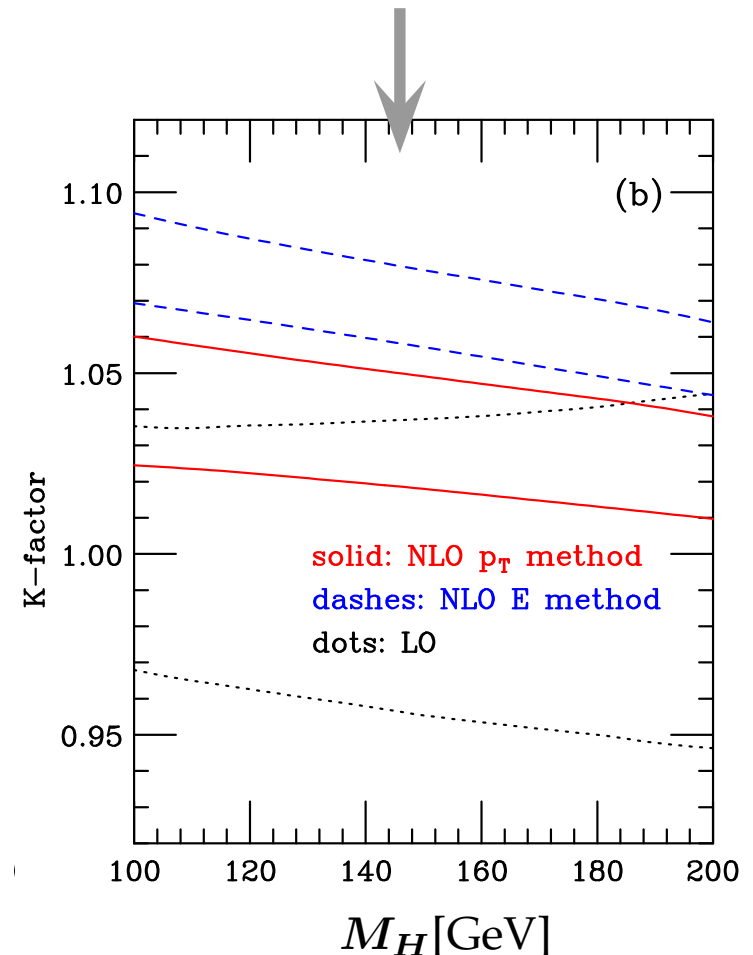
Campbell, Ellis (2003)

Figy, Oleari, Zeppenfeld (2003)

“ K -factor” = $\sigma(\mu)/\sigma^{LO}(Q)$

and scale uncertainties

moderate



VV scattering & VBF

$qq \rightarrow qqVV$ via VBF

- info on **gauge boson interactions**:
(quartic) EW gauge boson vertex
anomalous gauge boson couplings

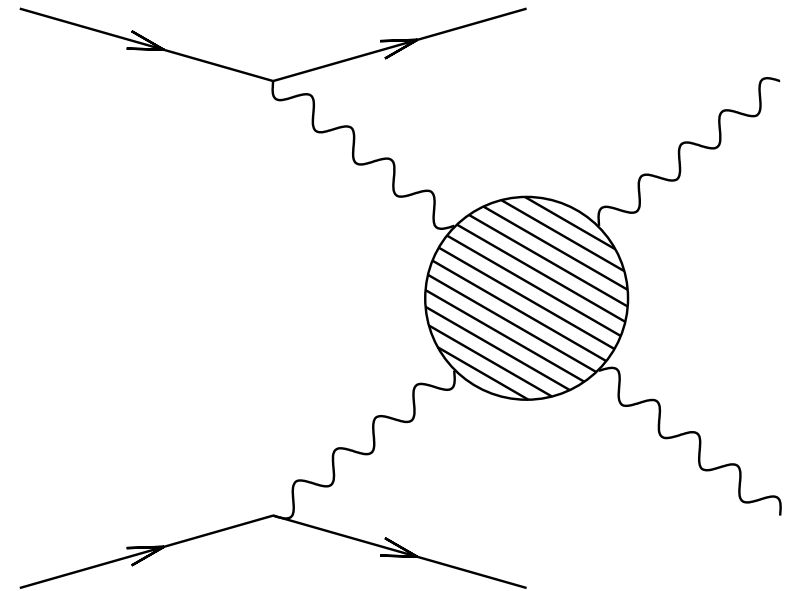
- gives access to $V_L V_L \rightarrow V_L V_L$



electroweak symmetry breaking:

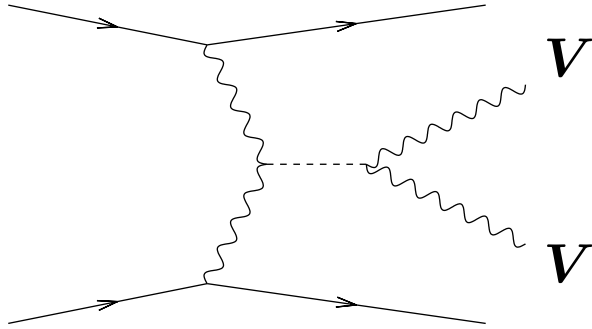
light Higgs boson? M_H ?

strong EWSB? specific mechanism?



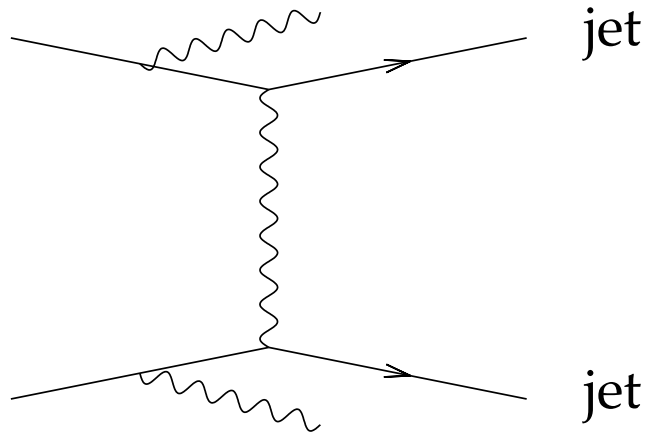
go to sessions on BSM:
Thursday

VBF: background



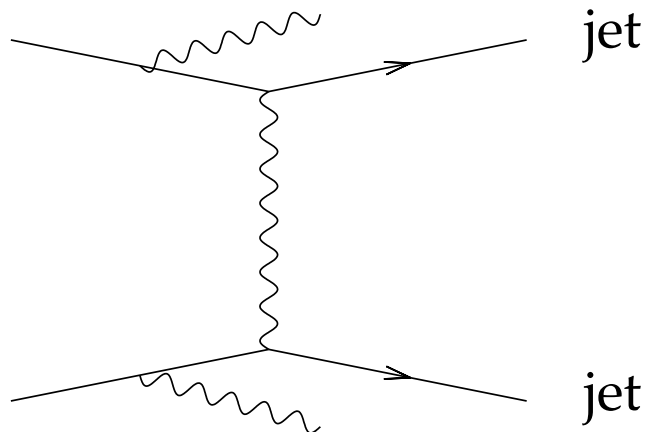
EW $VV + jj$ production:

VBF: background



EW $VV + jj$ production:

VBF: background



EW $VV + jj$ production:

similar characteristics to H signal process
→ background rejection difficult

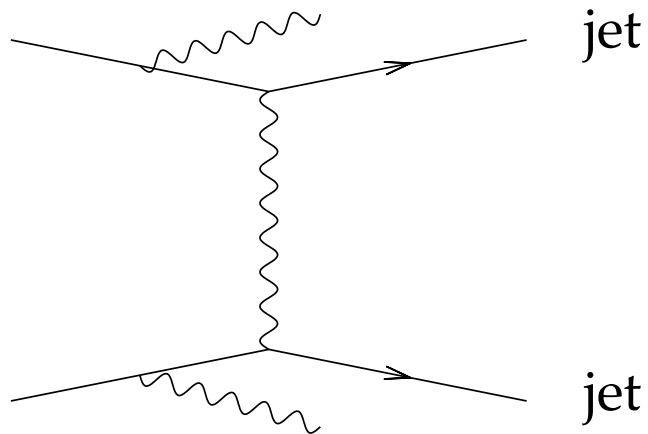
need **flexible Monte Carlo program** which allows for

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

[C. Oleari, D. Zeppenfeld, B. J. ,

hep-ph/0603177, hep-ph/0604200]

VBF: background



EW $VV + jj$ production:

similar characteristics to H signal process
→ background rejection difficult

major challenges:

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

$pp \rightarrow W^+W^-jj$: the leading order

need to compute numerical value for amplitude

$$\mathcal{M}_B = \text{[diagram 1]} + \text{[diagram 2]} + \text{[diagram 3]} + \dots$$

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

... altogether 92 diagrams for CC, 181 diagrams for NC processes

essential: organize calculation economically



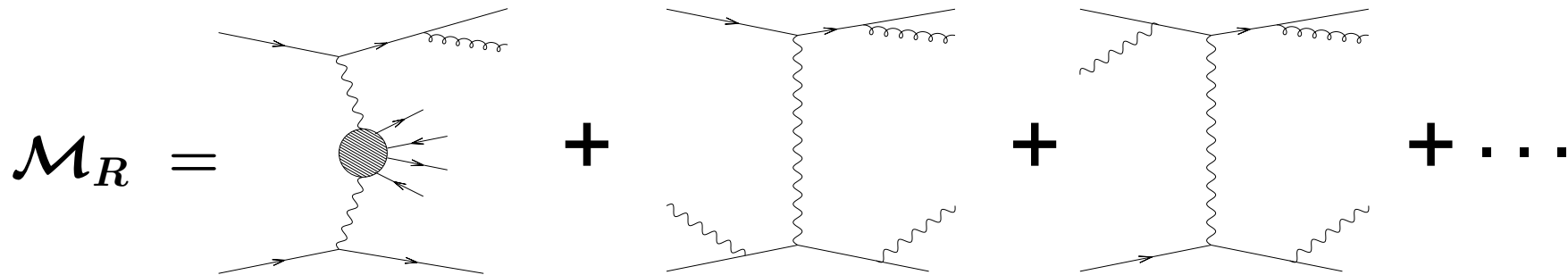
- develop **modular structure**
- compute each building block only once per phase space point

Real emission contributions

large number of diagrams:

real emission
graphs

		$uc \rightarrow uc \dots$	
	NC	CC	$us \rightarrow dc \dots$
LO	181	92	
NLO	836	444	



... speed crucial!

Virtual Corrections

... interference of LO diagrams with

$$\mathcal{M}_V = \text{[diagram 1]} + \text{[diagram 2]} + \text{[diagram 3]} + \dots$$
$$= \mathcal{M}_B F(Q) \left[-\frac{2}{\epsilon^2} - \frac{3}{\epsilon} \right] + \tilde{\mathcal{M}}_V^{finite}$$



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

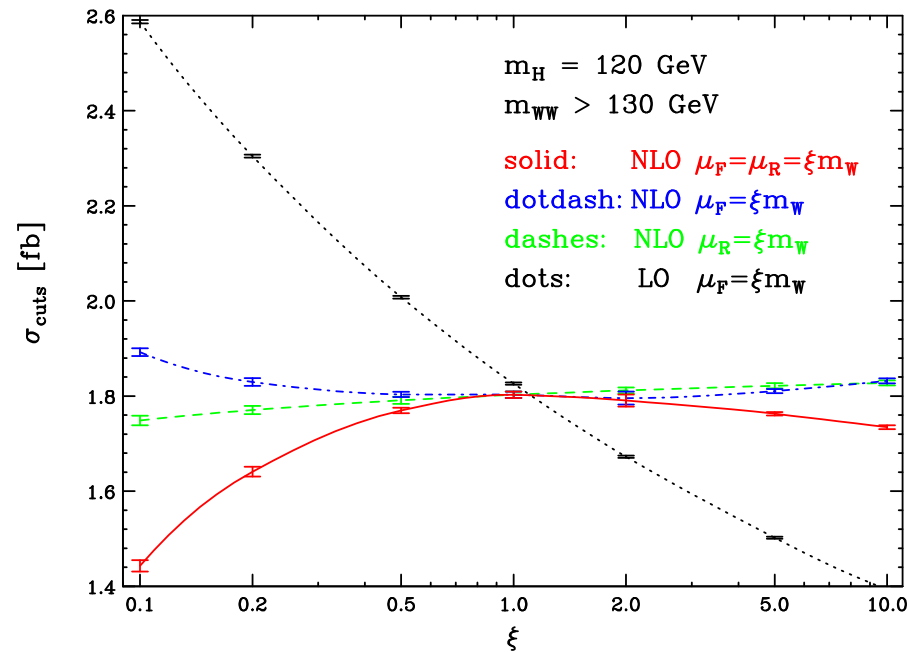
combination of real emission and virtual contributions with
subtraction terms according to dipole approach of
Catani & Seymour → **finite** results

Results: $pp \rightarrow W^+W^- jj$ @ LHC

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

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

Scale Uncertainty



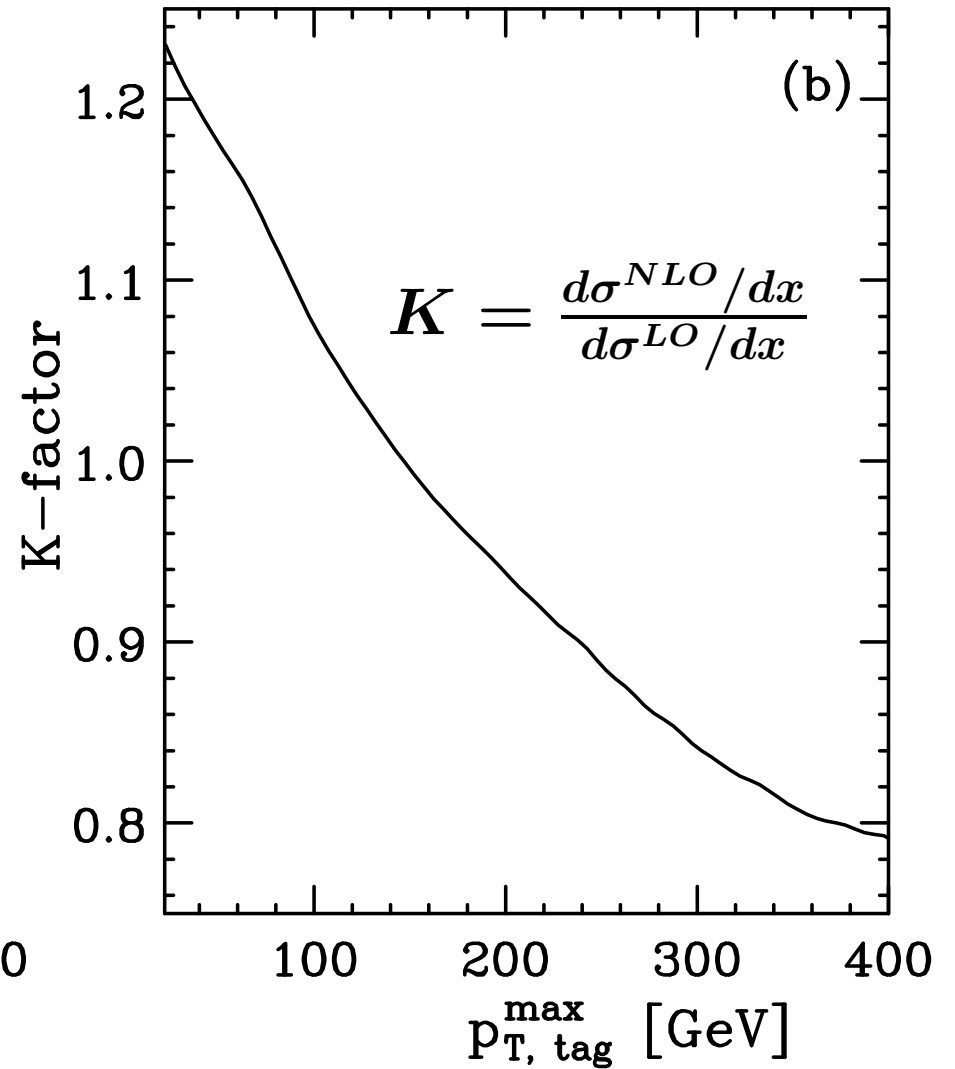
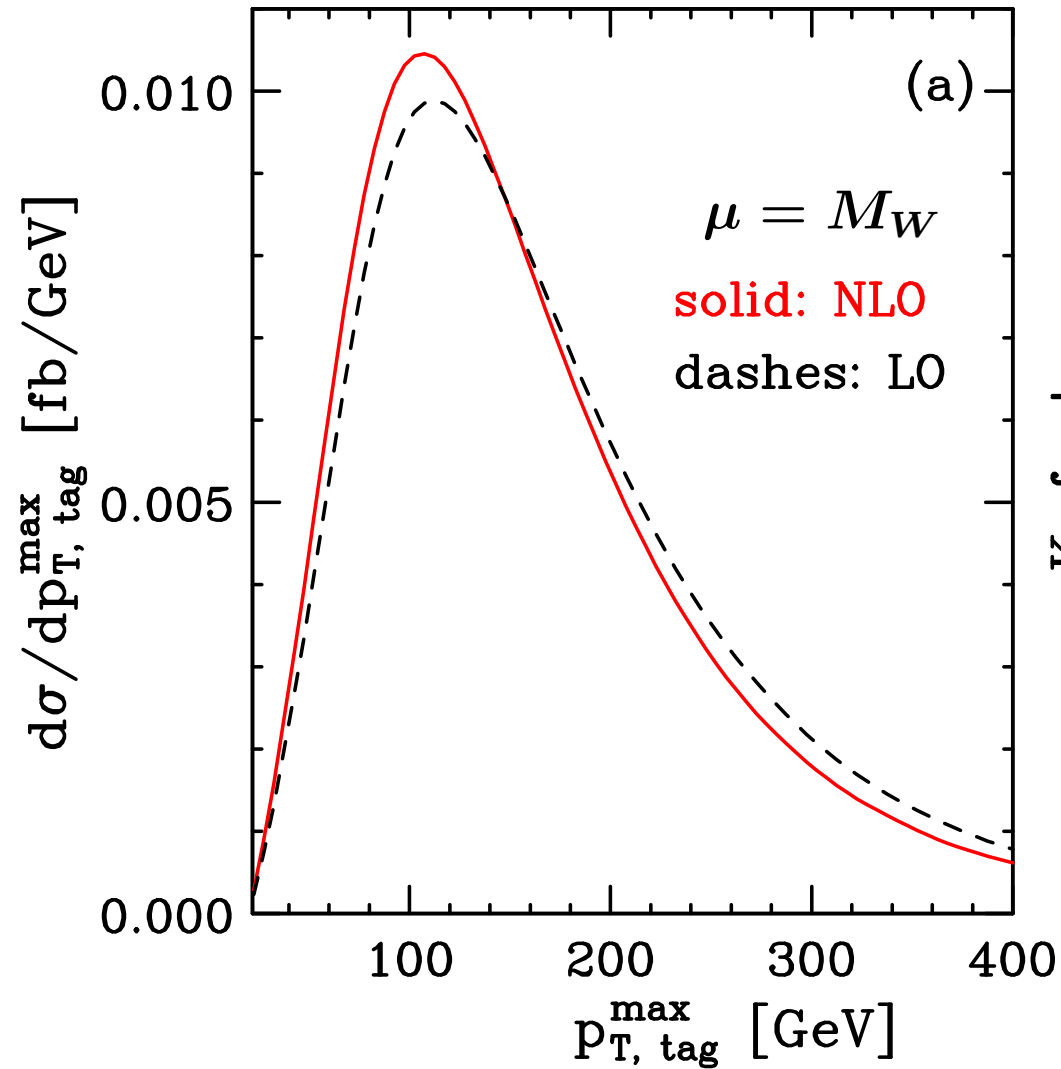
choose $\mu_R = \xi M_W$ and $\mu_F = \xi M_W$ with variable ξ



LO: no control on scale

NLO: scale dependence strongly reduced

Distributions



Angular Distribution of Charged Leptons

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



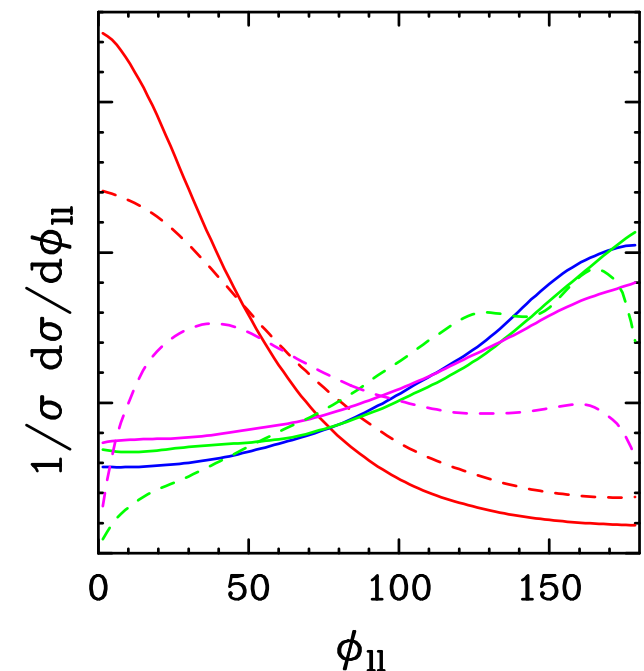
leptons emitted preferentially in same direction

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

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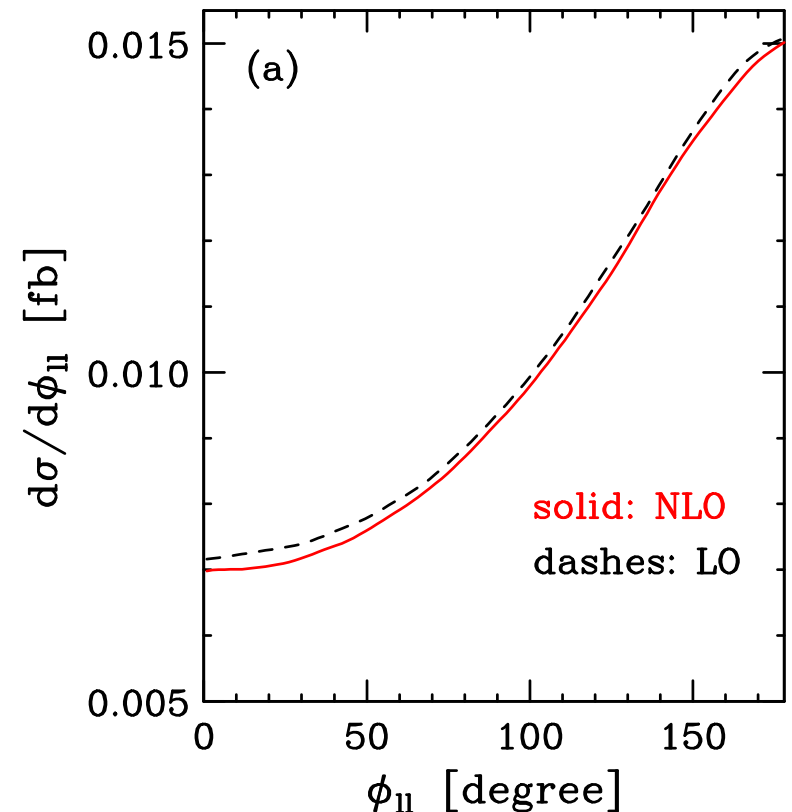


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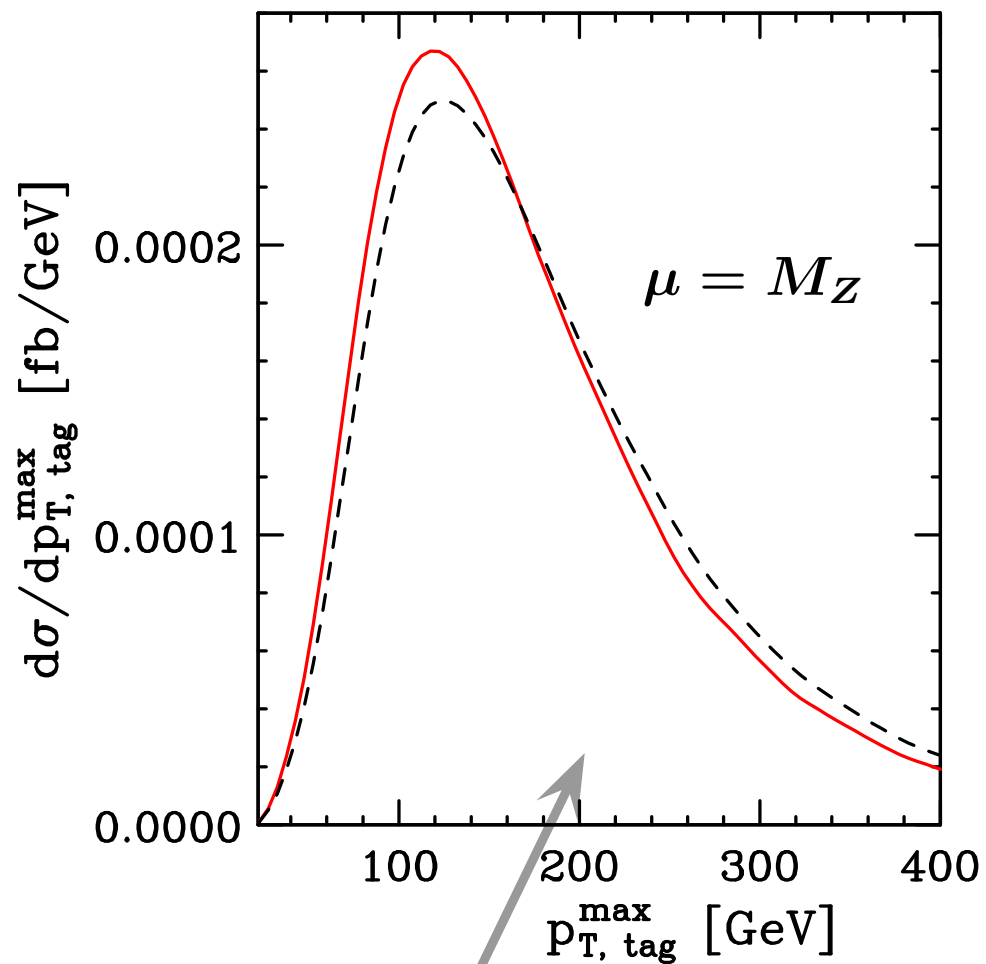
$pp \rightarrow ZZjj$

- clean final state for $pp \rightarrow \ell^+ \ell^- \ell'^+ \ell'^- jj$
- small branching ratios $\rightarrow \sigma_{ZZ} \ll \sigma_{WW}$

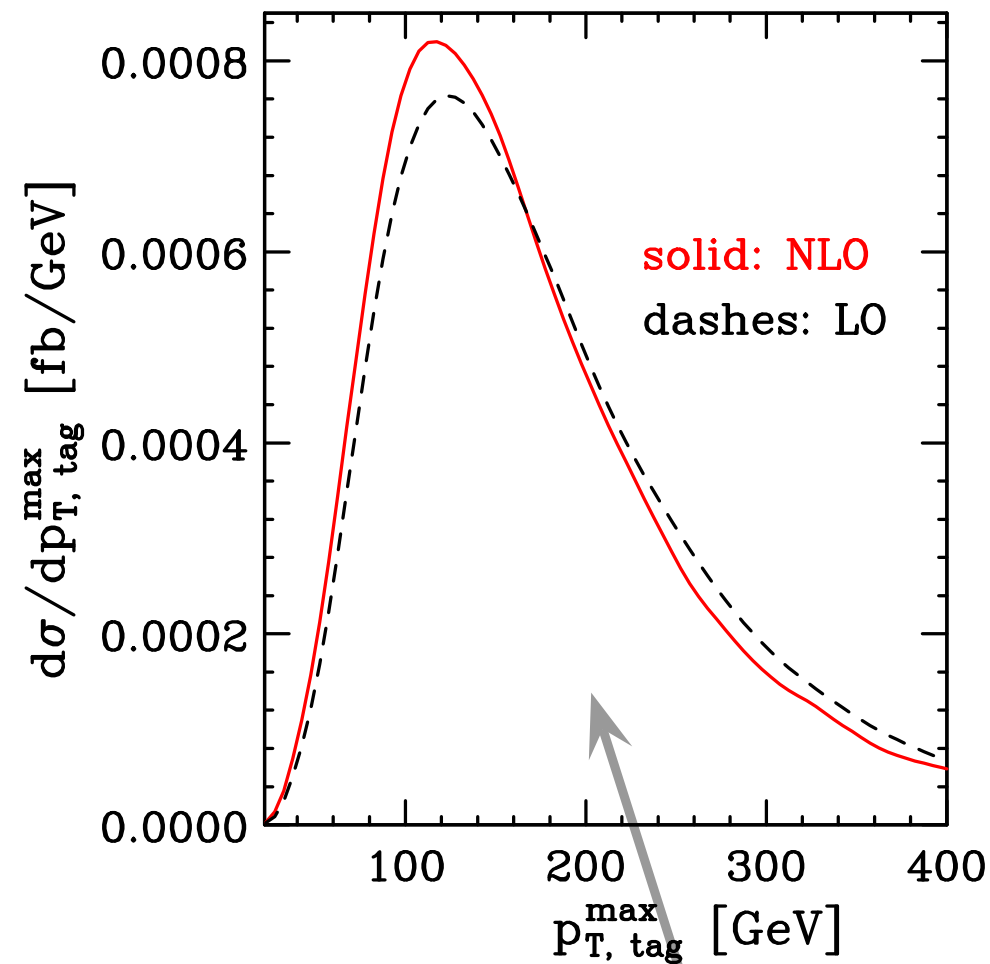
work-around: consider $pp \rightarrow \ell^+ \ell^- \nu \bar{\nu} jj$
[more difficult to reconstruct,
but larger BR and x-sec]

- charged leptons produced by Z bosons or photons
 \rightarrow large number of diagrams
- helicity of final state leptons not fixed
- other features very similar to $pp \rightarrow W^+ W^- jj$ case

Distributions: $pp \rightarrow ZZ jj$

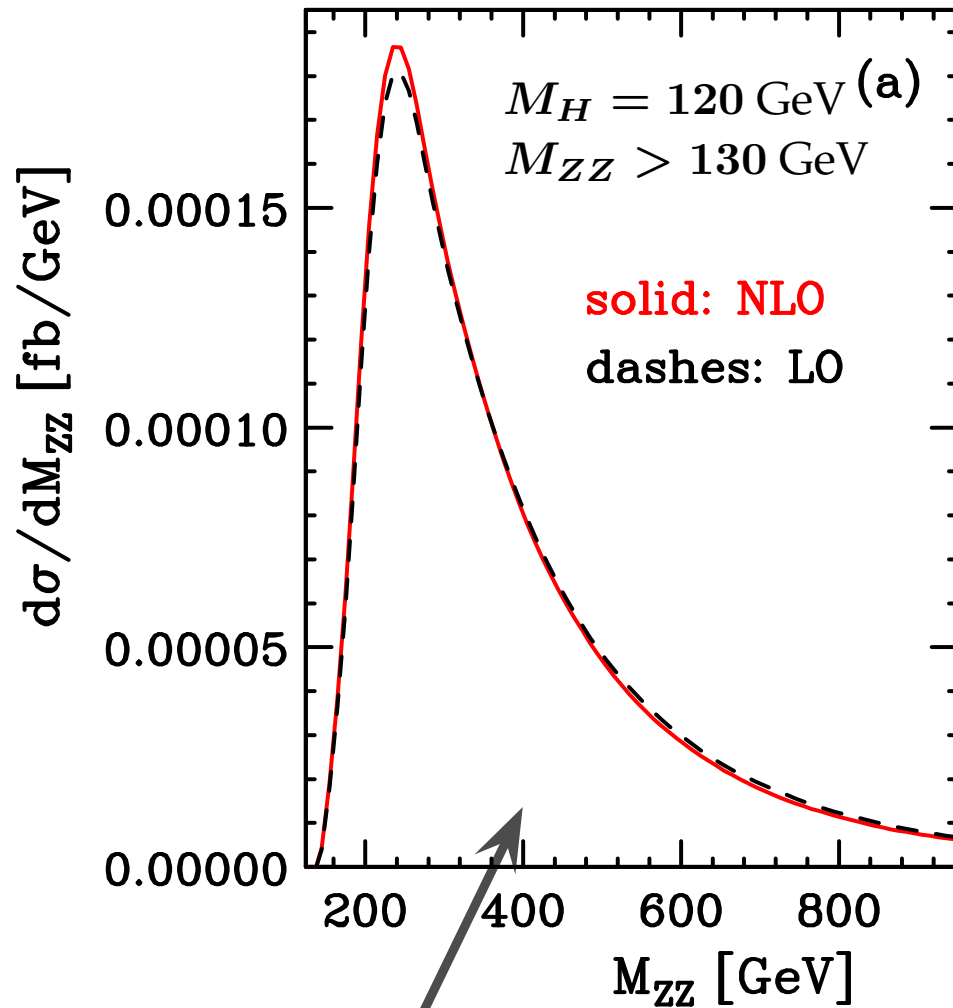


$l^+ l^- l'^+ l'^-$

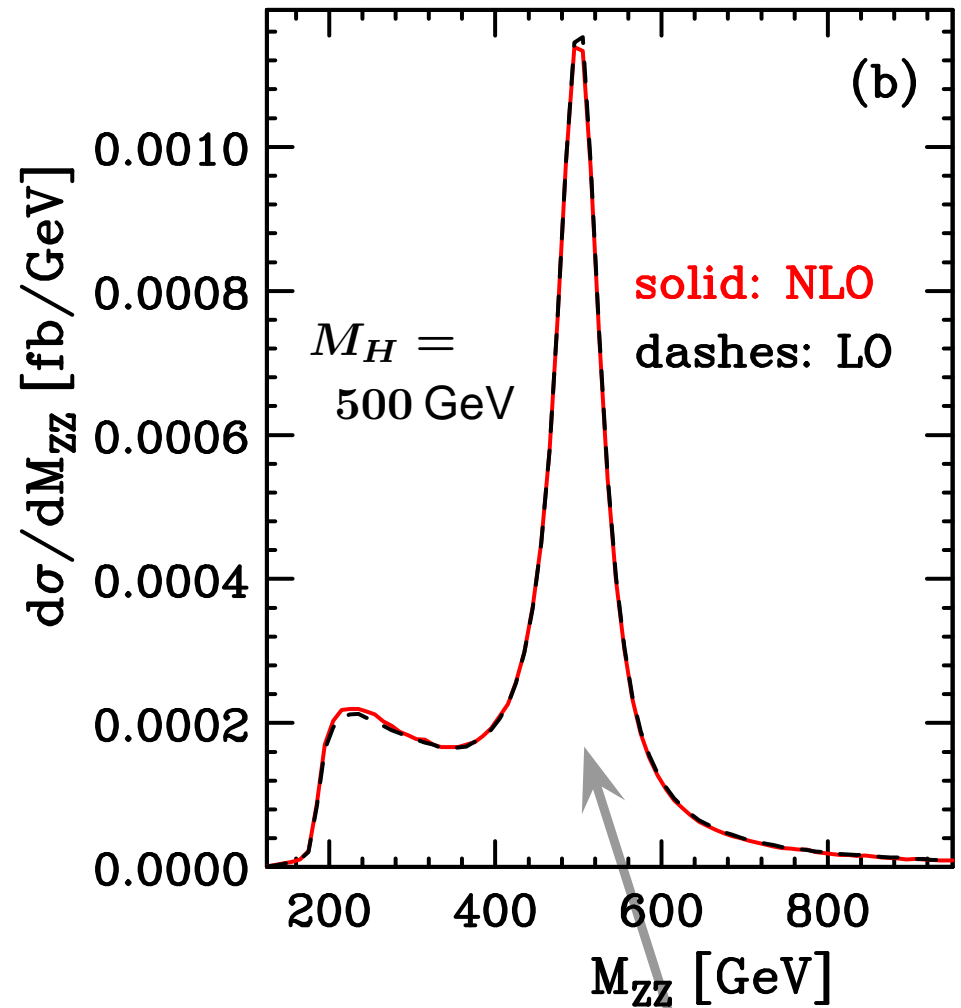


$l^+ l^- \nu \bar{\nu}$

Distributions: $pp \rightarrow \ell^+ \ell^- \ell'^+ \ell'^- jj$



background



background + signal

Conclusions

- ✘ VBF offers promising prospects for discovery of Higgs boson and investigation of its properties



need to know signal and background precisely

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

$$pp \rightarrow W^+W^- jj \text{ and } pp \rightarrow ZZ jj$$

(including leptonic decays)

- ✘ perturbative corrections under excellent control (modest scale uncertainties & K -factors)

- ✘ in progress: extensions to related processes

$$pp \rightarrow W^\pm W^\pm jj \text{ and } pp \rightarrow ZW^\pm jj$$

Backup Slide



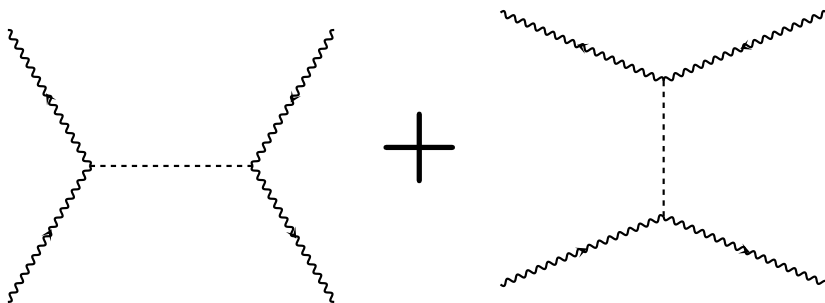
VBF & new physics

$$W_L^+ W_L^- \rightarrow W_L^+ W_L^-$$

$$\text{with } \epsilon_L^\mu \sim \frac{\sqrt{s}}{M_W}$$

$$\mathcal{M} = \text{[diagram 1]} + \text{[diagram 2]} + \text{[diagram 3]} \sim \frac{s}{M_W^2}$$

growth violates unitarity \rightarrow need:



Higgs with $M_H \lesssim 1$ TeV
or new physics at TeV scale