

Effective Field Theory Approaches to Vector Boson Fusion Processes



EFT Workshop
Mainz – November 2014
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vector boson fusion (VBF) &
vector boson scattering (VBS)

Standard Model:

- ❖ important production mode for the Higgs boson
- ❖ sensitive to Higgs couplings and CP properties

the big advantage:

- ✓ experimentally clean signature
- ✓ perturbatively well under control

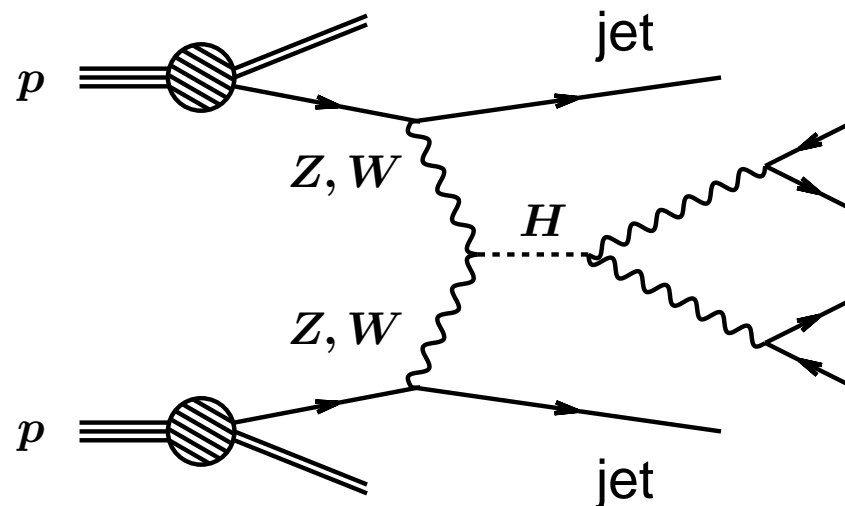
beyond the Standard Model:

sensitive to the mechanism of electroweak symmetry breaking



strongly interacting weak sector,
new resonances, ... ?

VBF / VBS event topology



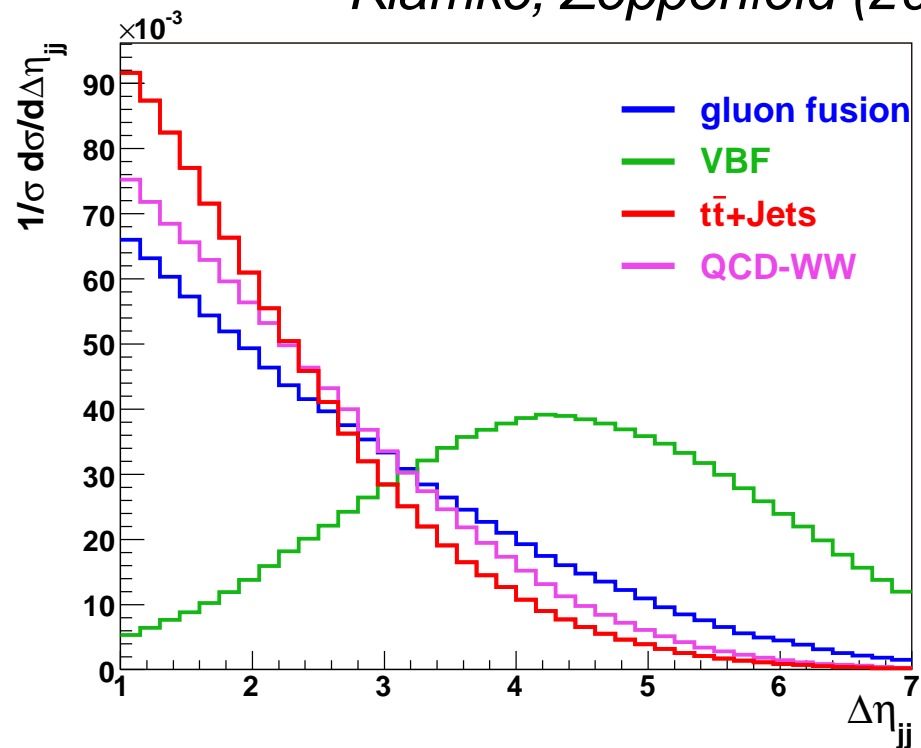
suppressed color exchange between quark lines gives rise to

- ❖ little jet activity in central rapidity region
- ❖ scattered quarks \rightarrow two forward tagging jets (energetic; large rapidity)
- ❖ decay products of the weak-boson system typically between tagging jets

tagging jets: properties

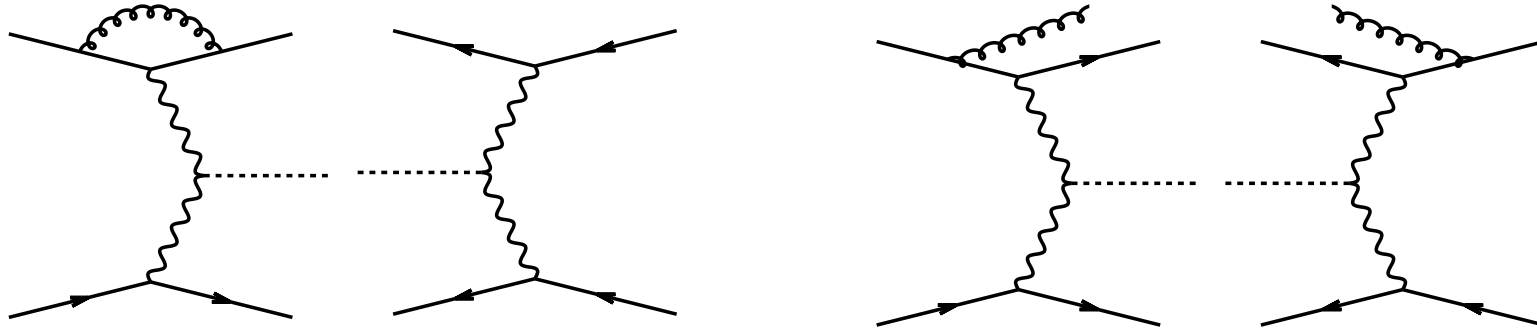
rapidity separation of the tagging jets

Klämke, Zeppenfeld (2007)



jets more central in QCD- than in EW-induced production processes

Higgs production in VBF @ NLO QCD



NLO QCD:

inclusive cross section:

Han, Valencia, Willenbrock (1992)

distributions:

Figy, Oleari, Zeppenfeld (2003)

Berger, Campbell (2004)



**NLO QCD corrections
moderate**

and well under control
(order 10% or less)

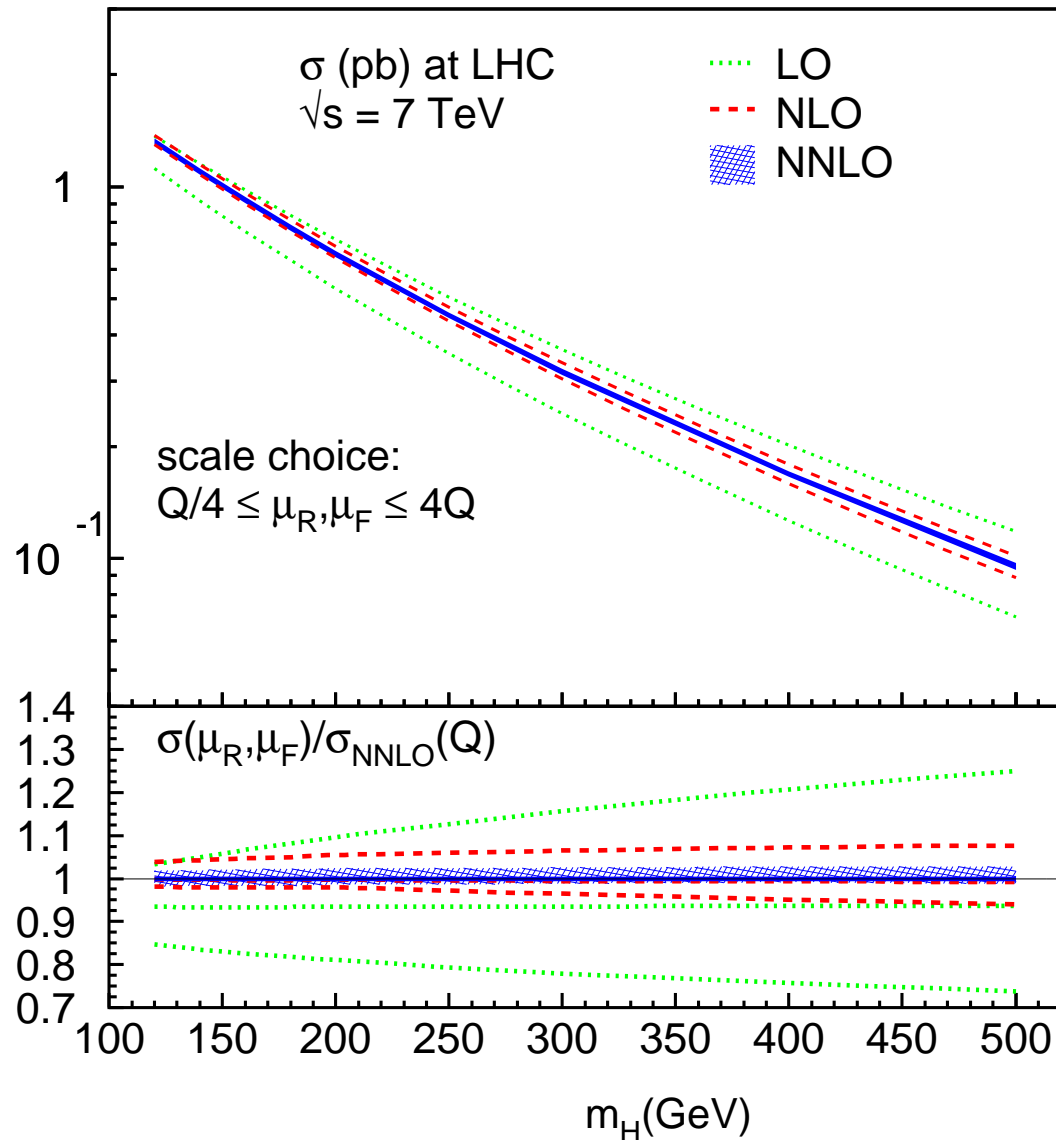
publicly available
parton-level Monte Carlos:

VBFNLO

MCFM

higher orders of QCD in VBF

Bolzoni et al. (2011)



partial NNLO-QCD results:

$gg \rightarrow q\bar{q}H$:

Harlander, Vollinga, Weber (2007)

$qq \rightarrow qqH$:

Bolzoni, Maltoni, Moch, Zaro (2019)

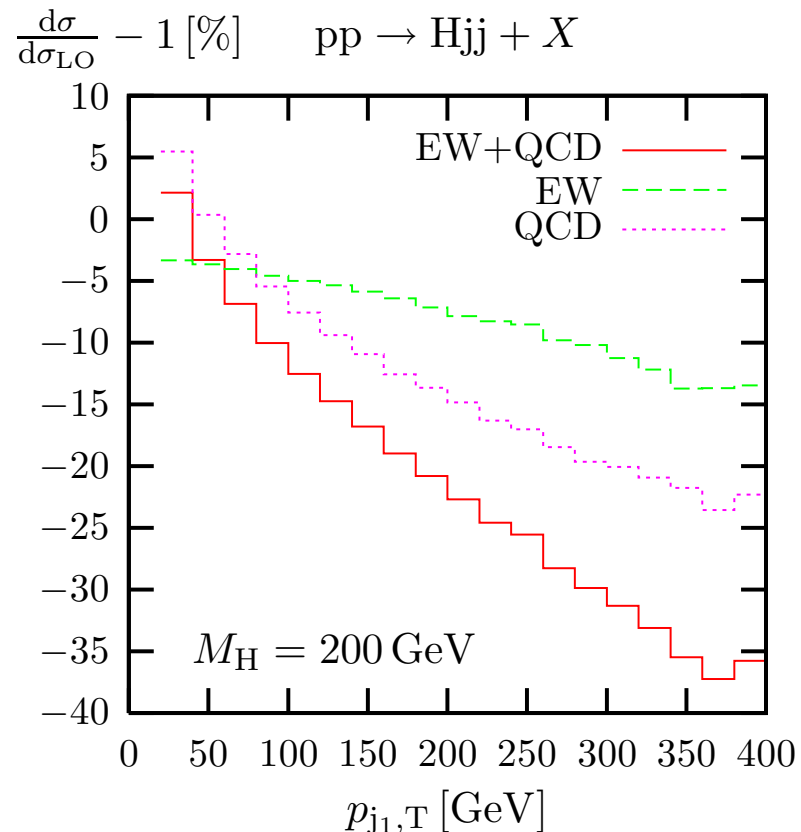
- ◆ NNLO predictions are in full agreement with NLO results
- ◆ residual scale uncertainties are reduced from $\sim 4\%$ to 2%
- ◆ NNLO PDF uncertainties are at the 2% level

Higgs production in VBF @ NLO EW

Ciccolini, Denner, Dittmaier (2007):

NLO EW corrections to inclusive cross sections and distributions

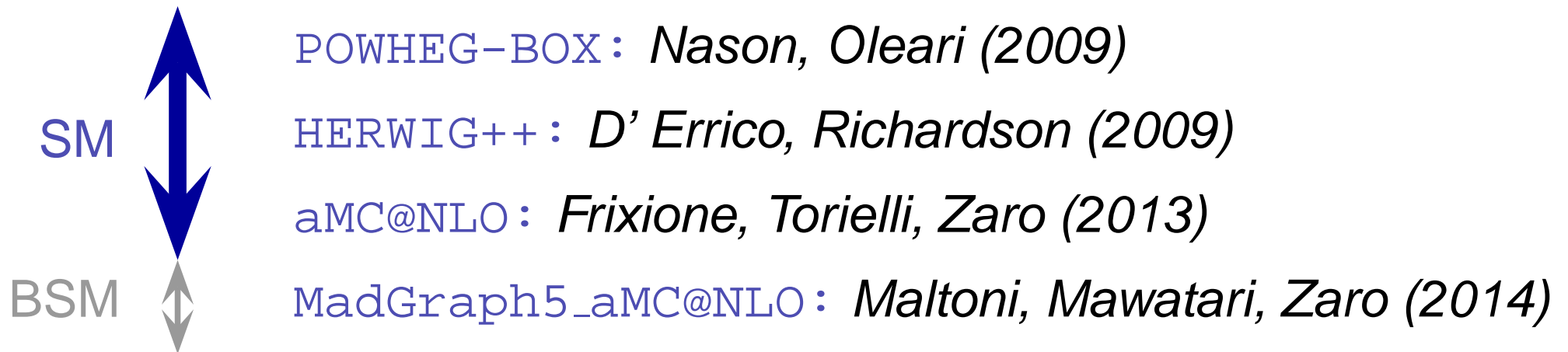
- 👉 **NLO EW corrections non-negligible**, modify K factors and distort distributions by up to 10%



publicly available
parton-level Monte Carlo:
HAWK
[Denner, Dittmaier, Mück]

$pp \rightarrow Hjj$ via VBF @ NLO QCD with parton shower

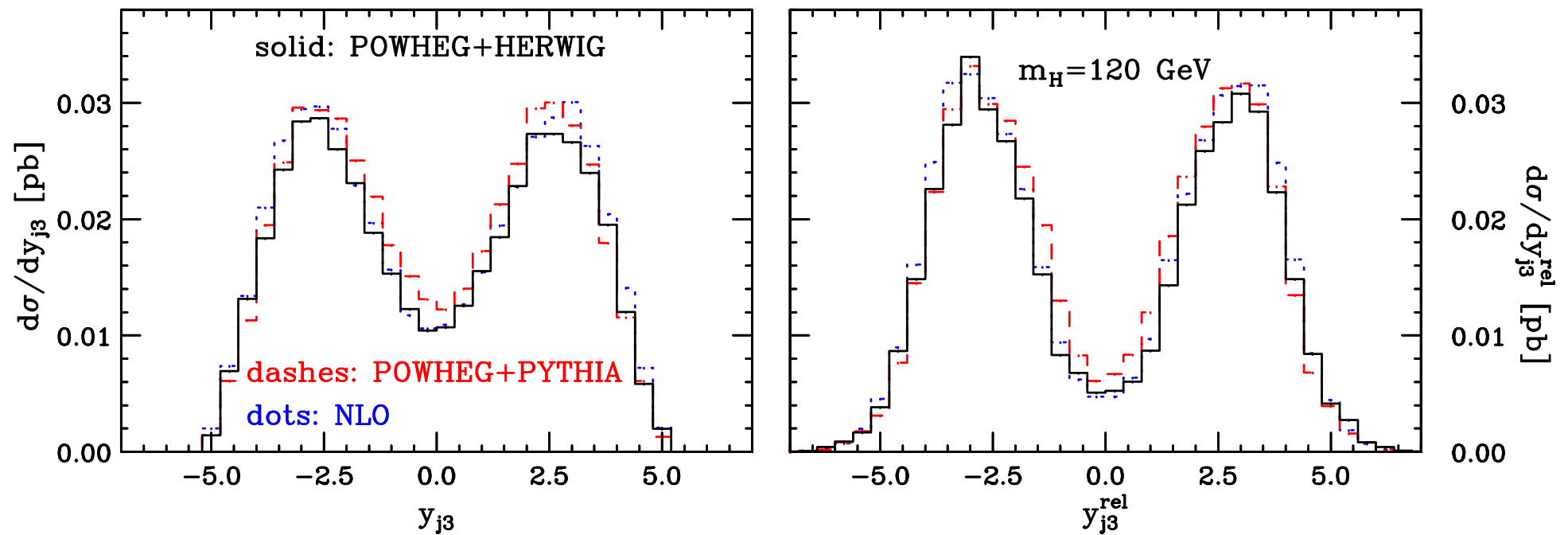
various implementations in different frameworks available:



generally **parton shower does not significantly modify**
distributions related to **tagging jets**

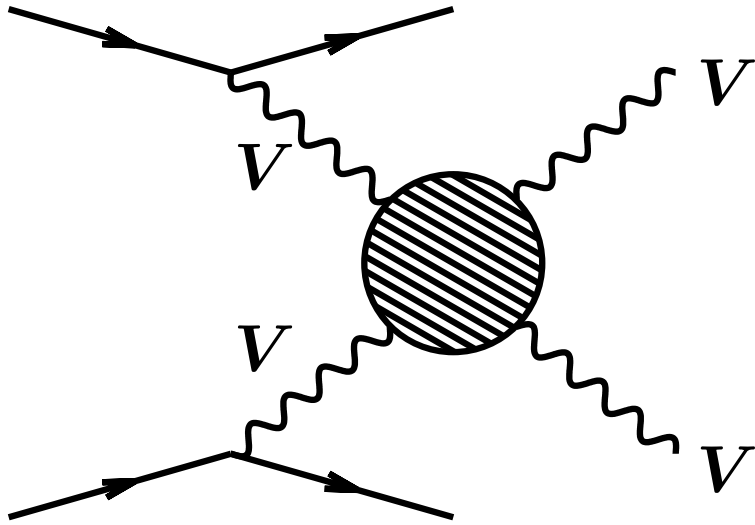
$pp \rightarrow Hjj$ via VBF @ NLO QCD with parton shower

Nason, Oleari (2009)



distributions related to the **third jet** are more **sensitive to parton shower effects** and details of the **implementation**

vector boson scattering: $VV \rightarrow VV$



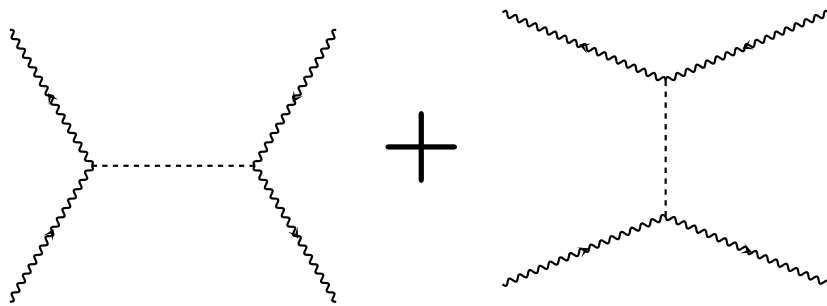
vector-boson scattering processes
are extremely **sensitive to**
new interactions in the
gauge boson sector

vector boson scattering & unitarity

$$W_L^+ W_L^- \rightarrow W_L^+ W_L^- \quad \text{with } \epsilon_L^\mu \sim \frac{\sqrt{s}}{M_W}$$

$$\mathcal{M} = \text{[s-channel diagram]} + \text{[t-channel diagram]} + \text{[u-channel diagram]} \sim \frac{s}{M_W^2}$$

growth violates unitarity \rightarrow need:



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

implications of unitarity in VBS

historic speculations:

❖ heavy Higgs boson?

challenging: in TeV range $\Gamma_H \sim M_H$

❖ no Higgs boson?

- strong interactions of V_L modes?
- resonances in TeV range?
- spectacular signals ?

implications of unitarity in VBS

historic speculations:

- ❖ heavy Higgs bosons
couplings in TeV range $\Gamma_H \sim M_H$
- ❖ no Higgs boson
 - strong interactions of V_L modes?
 - resonances in TeV range?
 - spectacular signals ?

... OUTDATED!!

approaches to VBS today

experimental fact: $M_H = 125 \text{ GeV} \ll 1 \text{ TeV}$

➡ BSM effects expected to be small

- ❖ specific models with one or more Higgs boson(s)
- ❖ model-independent effective analysis

based on particle content of the SM:

$$\mathcal{L}_{\text{eff}} = \sum \frac{c_i^{(d)}}{\Lambda^{d-4}} \mathcal{O}_i^{(d)} = \mathcal{L}_{\text{SM}} + \sum \frac{c_i^{(6)}}{\Lambda^2} \mathcal{O}_i^{(6)} + \dots$$

effective operator approach

$$\mathcal{L}_{\text{eff}} = \sum \frac{c_i^{(d)}}{\Lambda^{d-4}} \mathcal{O}_i^{(d)} = \mathcal{L}_{\text{SM}} + \sum \frac{c_i^{(6)}}{\Lambda^2} \mathcal{O}_i^{(6)} + \dots$$

- operators constructed to **obey all symmetries** of the theory
- choice of operator parameterization is **not unique**
(most useful basis depends on process)
- equations of motion relate different operators
- generically EFT operators yield contributions of order $\mathcal{O}(s/\Lambda^2)$
- approach **valid at scales far below new physics** ($E \ll \Lambda$)
at large scales, expect violations of unitarity
(can be cured by form factors, but introduce arbitrariness)

effective operator approach

model-independent effective analysis

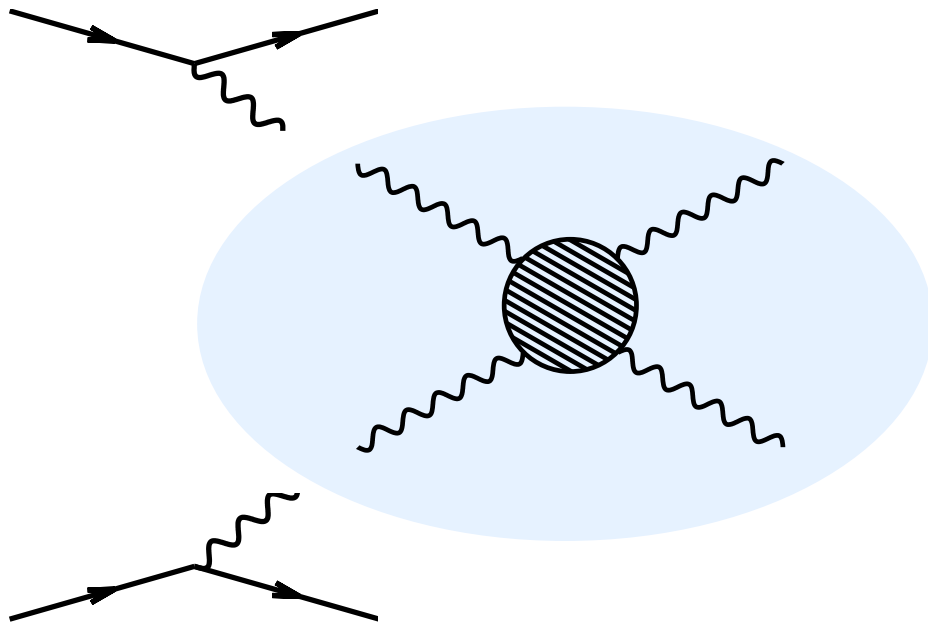
based on particle content of the SM:

$$\mathcal{L}_{\text{eff}} = \sum \frac{c_i^{(d)}}{\Lambda^{d-4}} \mathcal{O}_i^{(d)} = \mathcal{L}_{\text{SM}} + \sum \frac{c_i^{(6)}}{\Lambda^2} \mathcal{O}_i^{(6)} + \dots$$

higher-dim operators may give rise to
anomalous triple and quartic gauge couplings

👉 **precision** in theory and experiment needed
to identify **small deviations** from SM

vector boson scattering in hadronic collisions



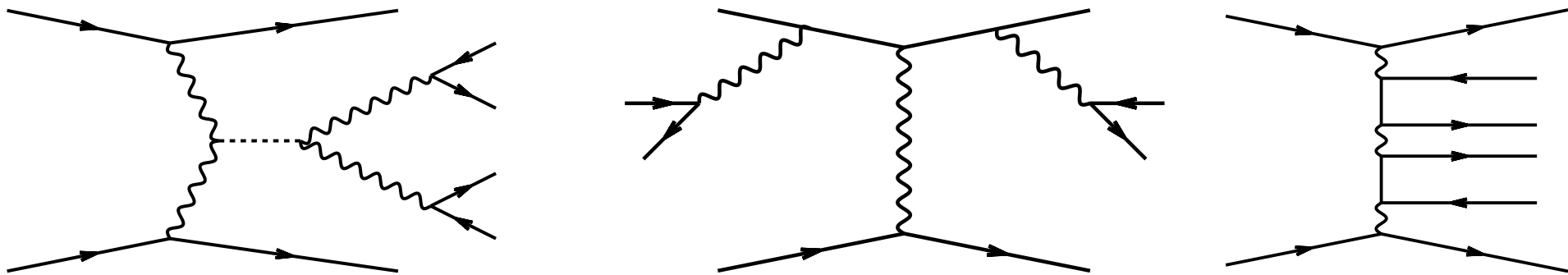
$$\sigma_{pp} \sim f_{V_1/p_1} \otimes f_{V_2/p_2} \otimes \hat{\sigma}_{V_1 V_2 \rightarrow V_3 V_4}$$

poor man's approach:

consider heavy gauge bosons as
effective constituents of the proton

“effective V boson approximation”

$pp \rightarrow VVjj$: the full picture



note: effective V boson approximation expected to work only in high-energy domain, but

still **uncertainties of several 10%** at 3 TeV !

[*Accomando, Denner, Pozzorini (2006)*]

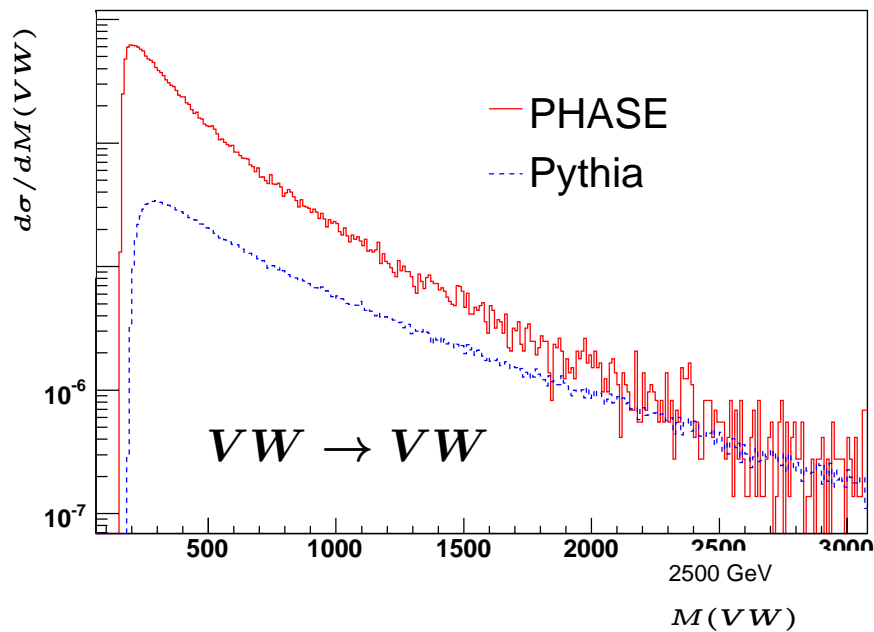
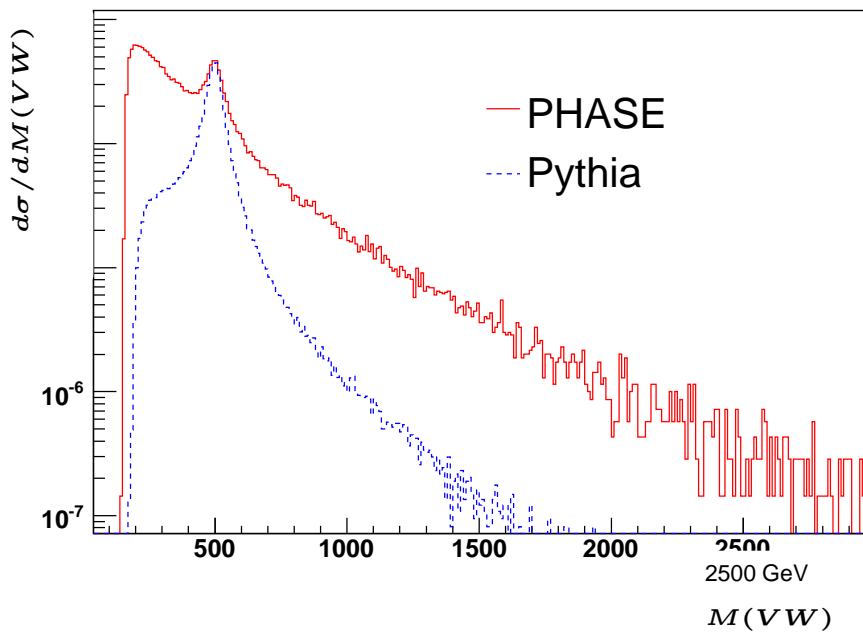
in **realistic calculation** need to consider:

- ❖ non-resonant contributions
- ❖ off-shell effects

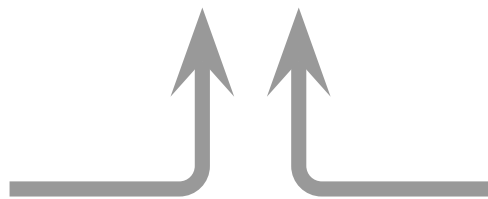
first step: full $2 \rightarrow 6$ amplitudes

PHASE: LO event generator for six fermion physics at the LHC

Accomando, Ballestrero, Maina (2004)



PHASE:
off-shell effects fully
considered



PYTHIA:
EWA with longitudinal
vector bosons

Accomando et al. (2005)

EW $VVjj$ production at NLO-QCD

NLO-QCD calculation for VBF production of

$$pp \rightarrow W^+W^-jj, ZZjj, W^\pm Zjj, \text{ and } W^\pm W^\pm jj$$

(including off-shell effects and leptonic decay correlations)

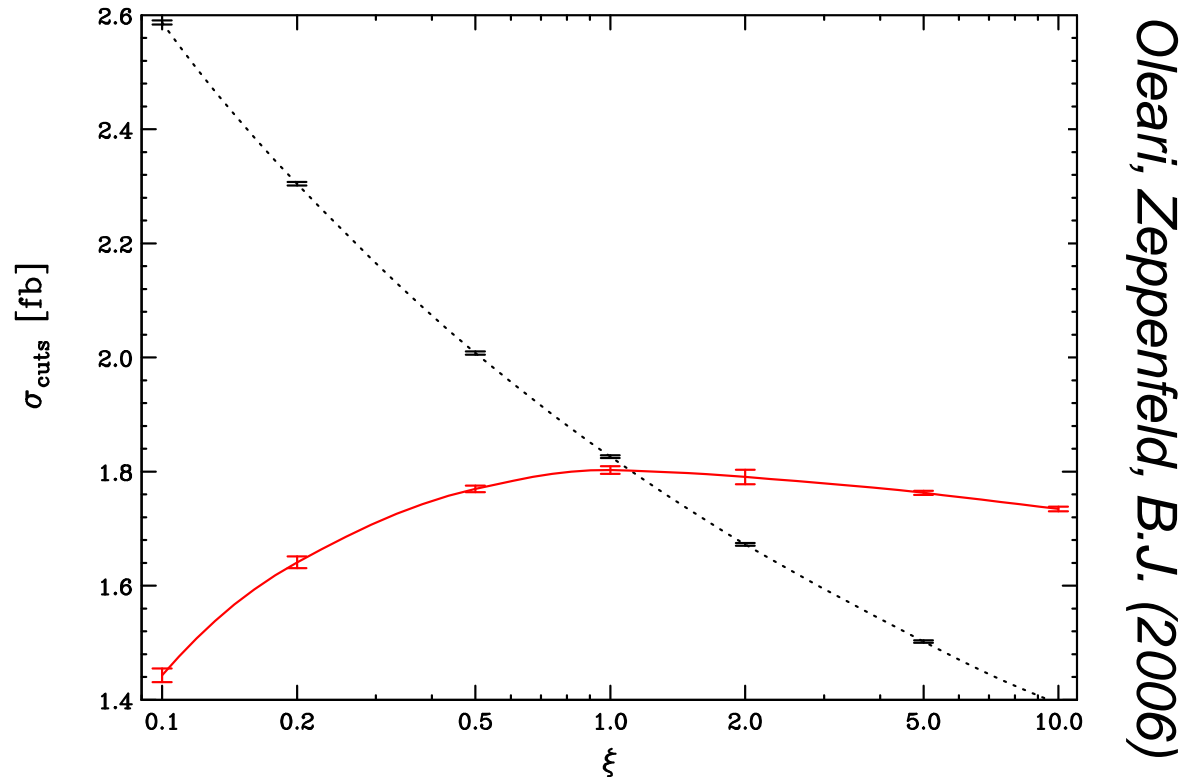
available in [VBFNLO](#) Monte Carlo program

G. Bozzi, C. Oleari, D. Zeppenfeld, B. J. (2006-2009)

A. Denner, L. Hosekova, S. Kallweit (2012)

EW W^+W^-jj production: theoretical uncertainty

estimate theoretical uncertainty by studying dependence of cross section on unphysical scale parameter $\mu = \xi M_W$



LO: no control on scale

NLO QCD: scale dependence strongly reduced

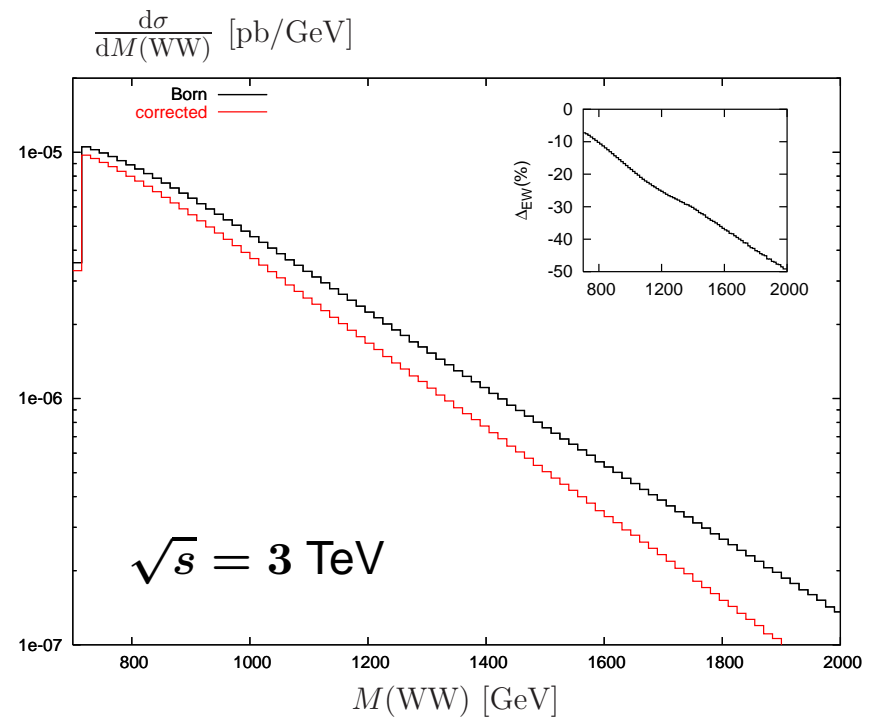
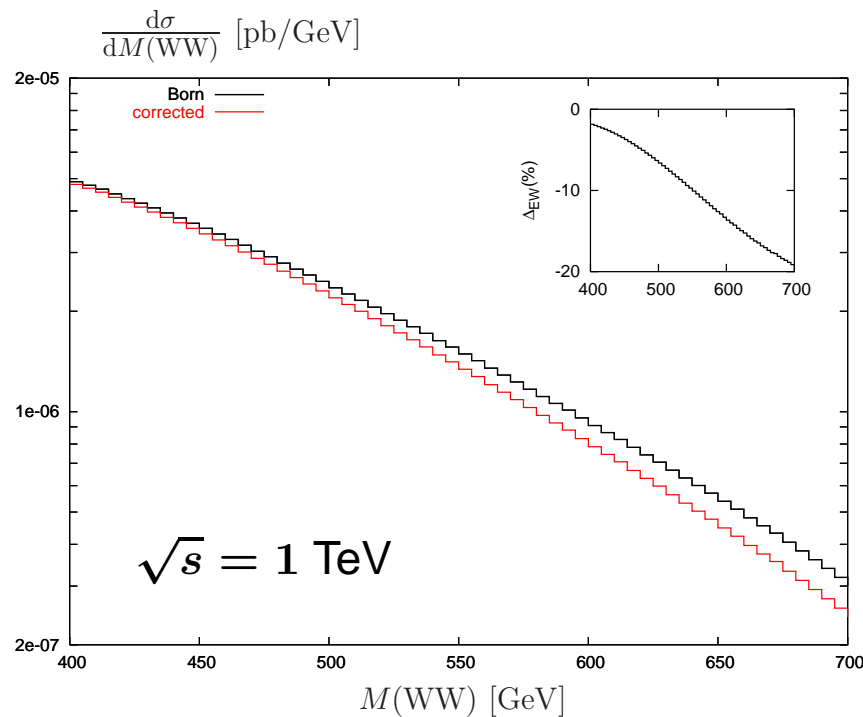
$pp \rightarrow VVjj$ via VBF: electroweak corrections

very tough – no calculations available to date

related case of $e^+e^- \rightarrow \nu_e\bar{\nu}_e W^+W^-$:

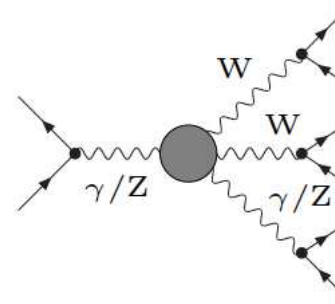
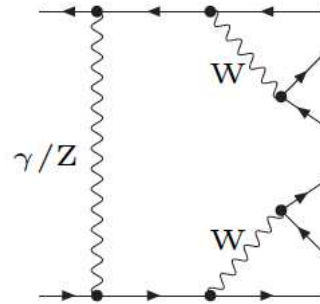
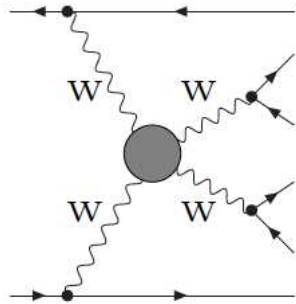
dominant EW corrections can be as **large** as 50% in TeV range

[Accomando, Denner, Pozzorini (2006)]



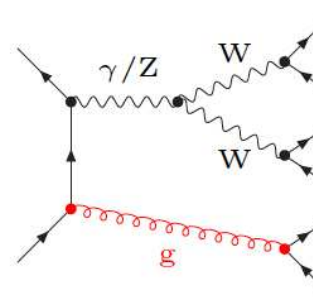
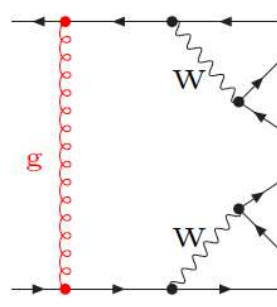
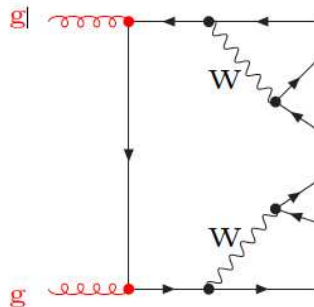
the various contributions to the VVjj final state

EW channels:



$$|\mathcal{M}_{EW}|^2 \propto \alpha^6$$

QCD channels:

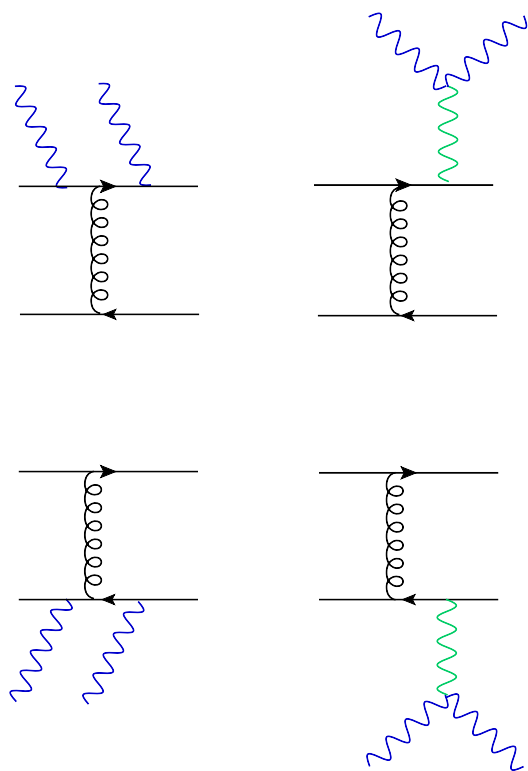


$$|\mathcal{M}_{QCD}|^2 \propto \alpha_s^2 \alpha^4$$

interference between QCD and EW channels:

possible, but suppressed

QCD-induced $VVjj$ production



QCD-induced $VVjj$ production
constitutes irreducible background to
EW $VVjj$ production

NLO-QCD predictions available for

W^+W^+jj (★), W^+W^-jj (*),
 $WZjj$ (◆), $ZZjj$ (◆):

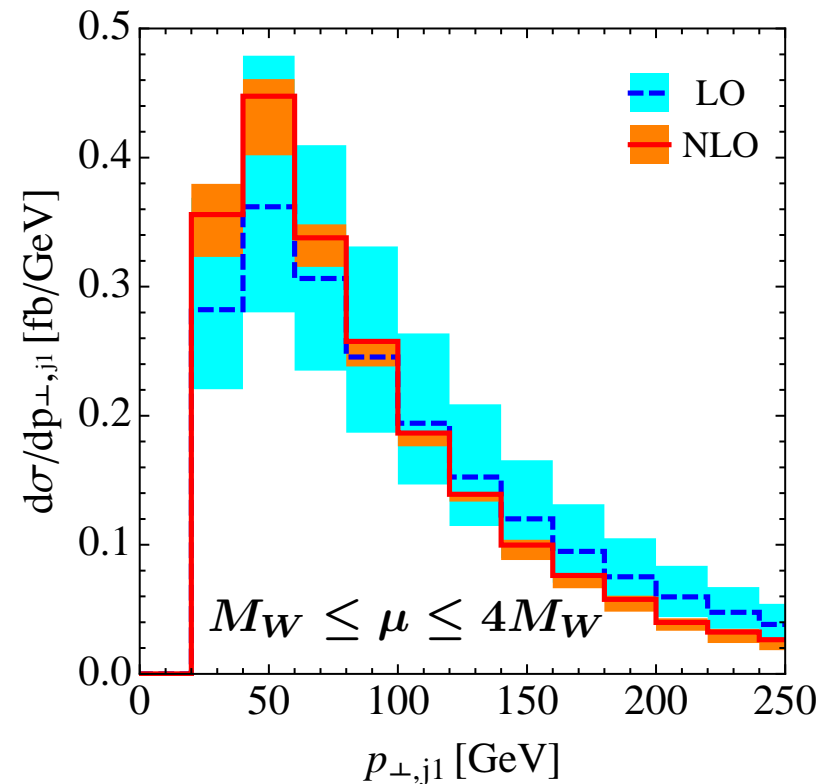
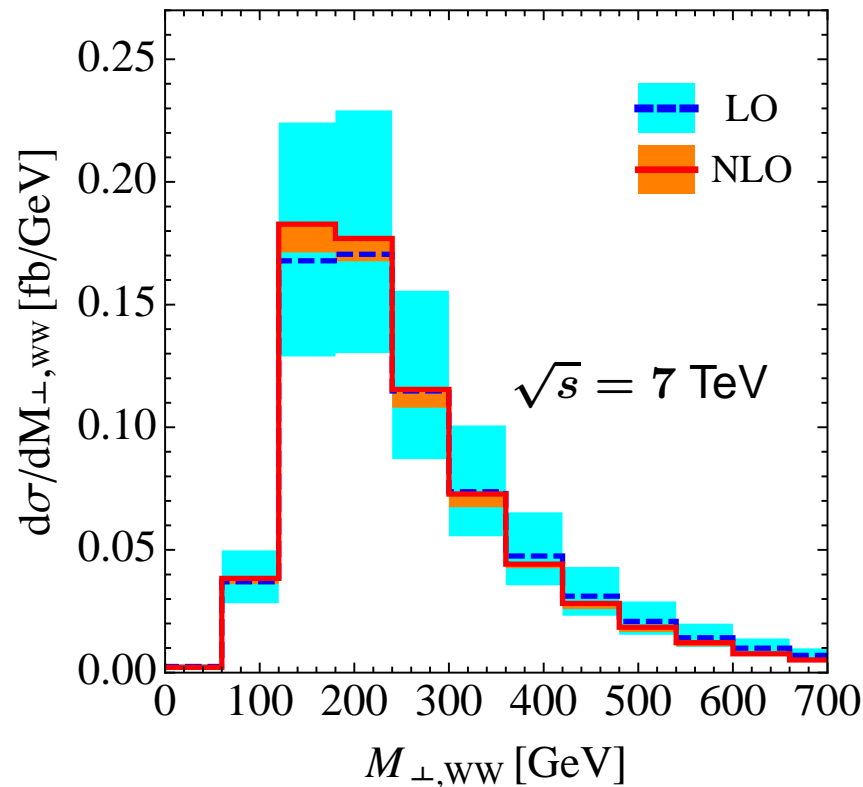
★, * *Melia et al. (2010, 2011)*

* *Greiner et al. (2012)*

◆ *Campanario et al. (2013,2014)*

QCD-induced W^+W^-jj production at NLO

Melia, Melnikov, Rontsch, Zanderighi (2011)



NLO-QCD corrections significantly reduce
scale uncertainty

$VVjj$ matched with parton showers & NLO-QCD

so far only implementation of EW- and QCD-induced $VVjj$ production processes available in the POWHEG-BOX:

<http://powhegbox.mib.infn.it/>

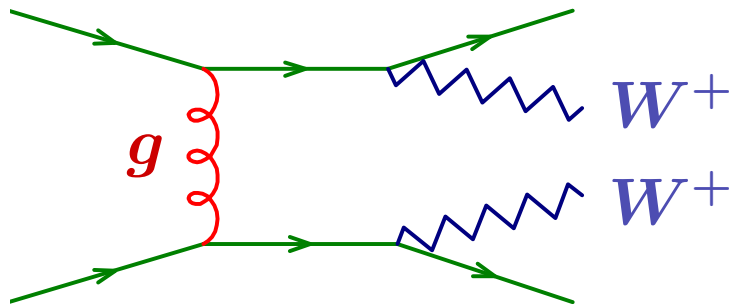


- ❖ QCD W^+W^+jj production [*Melia, Nason, Rontsch, Zanderighi (2011)*]
- ❖ EW W^+W^+jj production [*Zanderighi, B.J. (2011)*]
- ❖ EW W^+W^-jj production [*Zanderighi, B.J. (2013)*]
- ❖ EW $ZZjj$ production [*Karlberg, Zanderighi, B.J. (2013)*]

$pp \rightarrow W^+W^+jj$ in the POWHEG-BOX

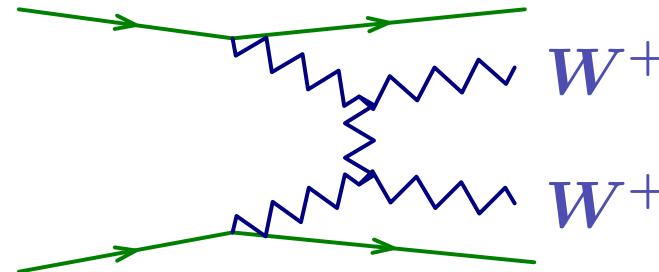
QCD-induced production

*Melia, Melnikov, Rontsch, Zanderighi (2010);
Melia, Nason, Rontsch, Zanderighi (2011)*



EW production

*Oleari, Zeppenfeld, B.J. (2009);
Zanderighi, B.J. (2011)*



NLO results for $\sqrt{s} = 7$ TeV with basic jet cuts only ($p_T^{\text{tag}} > 20$ GeV):

$$\sigma_{\text{QCD}}^{\text{inc}} = 2.12 \text{ fb}$$

$$\sigma_{\text{EW}}^{\text{inc}} = 1.097 \text{ fb}$$

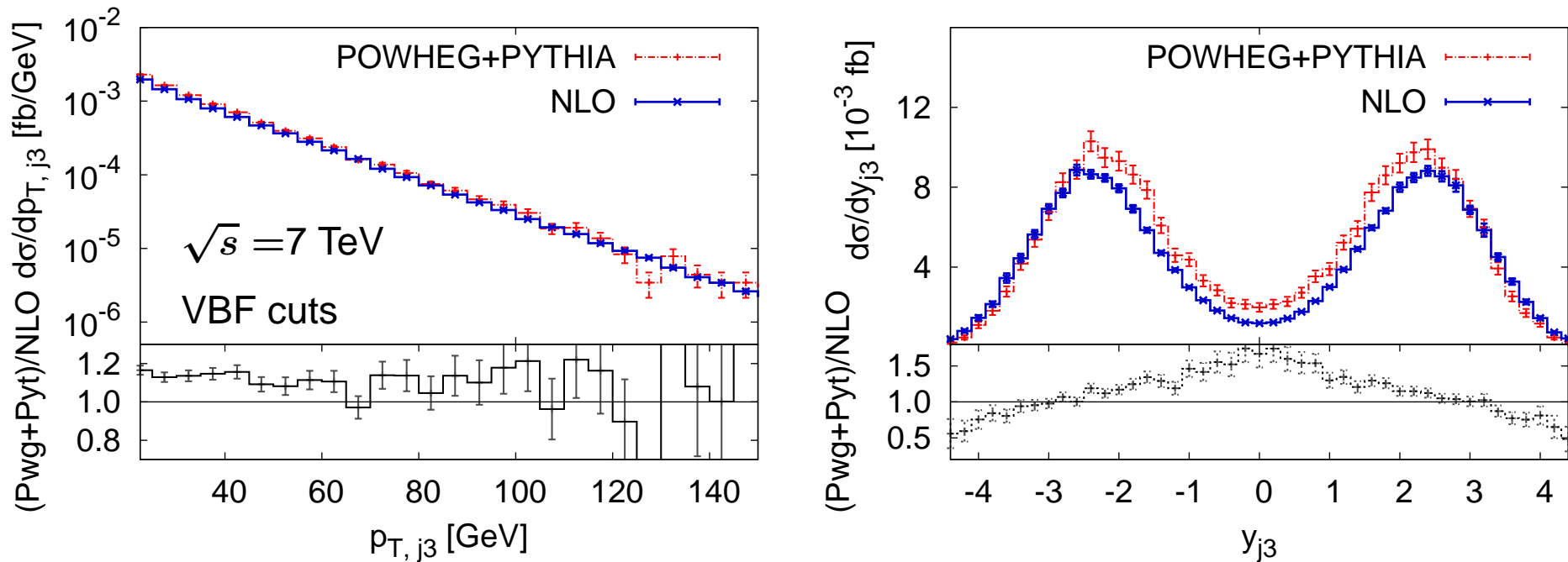
NLO results with VBF cuts:

$$\sigma_{\text{QCD}}^{\text{cuts}} = 0.0074 \text{ fb}$$

$$\sigma_{\text{EW}}^{\text{cuts}} = 0.201 \text{ fb}$$

$pp \rightarrow W^+W^+jj$ via VBF in the POWHEG-BOX

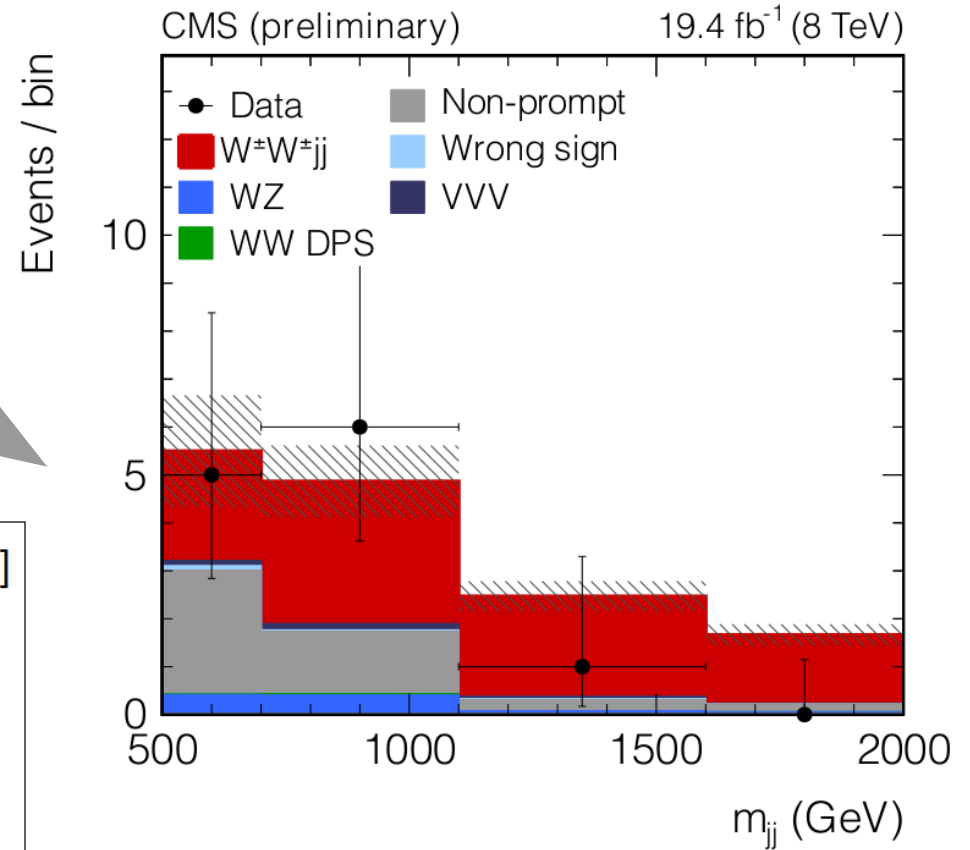
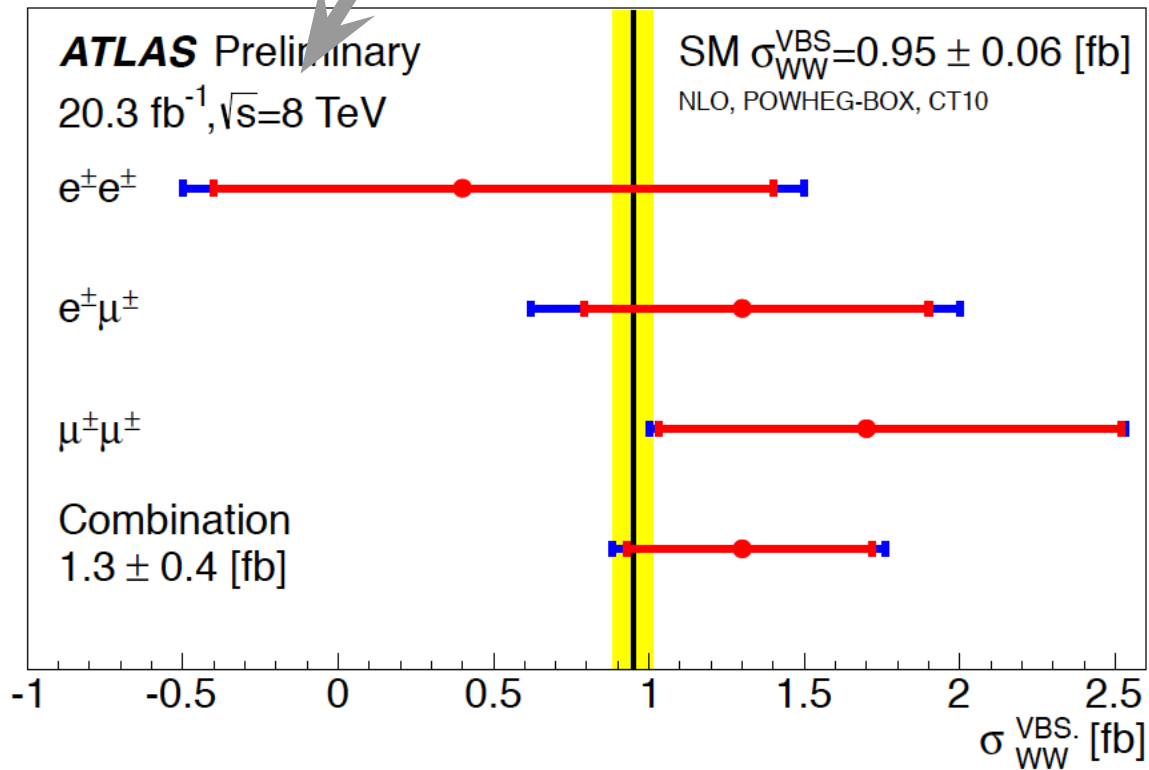
Zanderighi, B.J. (2011)



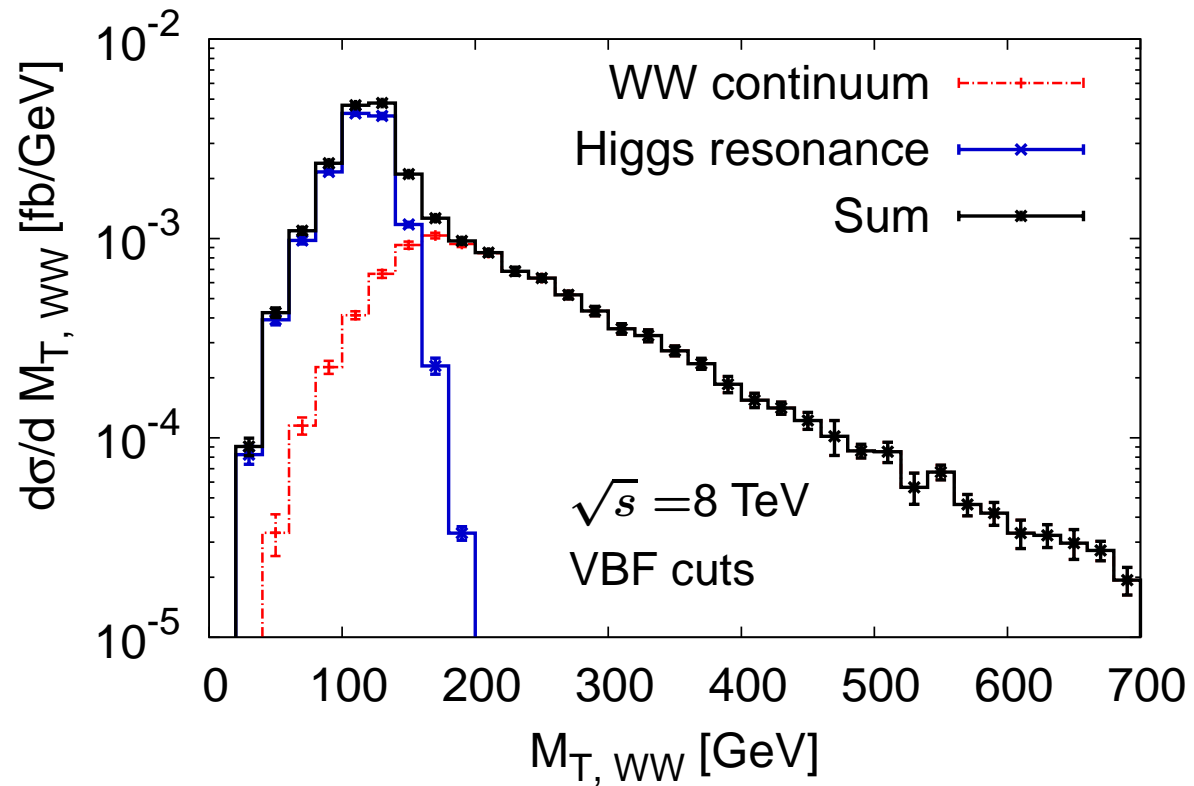
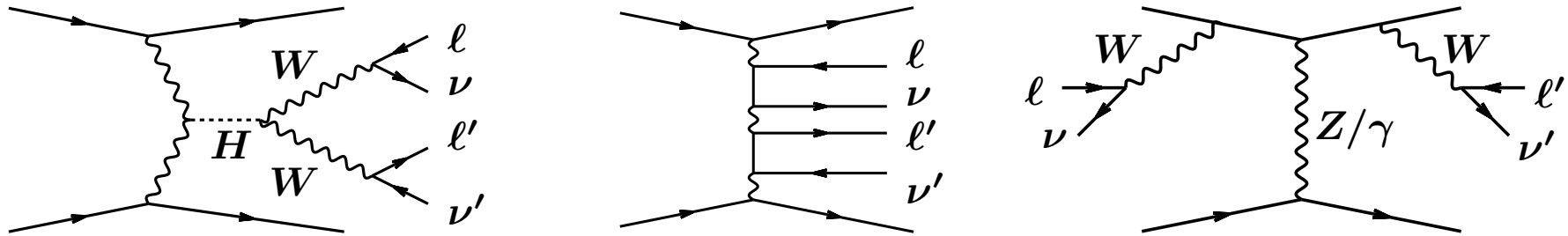
typical for VBF processes: little jet activity at central rapidities
→ exploited by central-jet veto techniques

note: parton-shower effects slightly enhance central jet activity

evidence for $W^\pm W^\pm jj$ from ATLAS and CMS



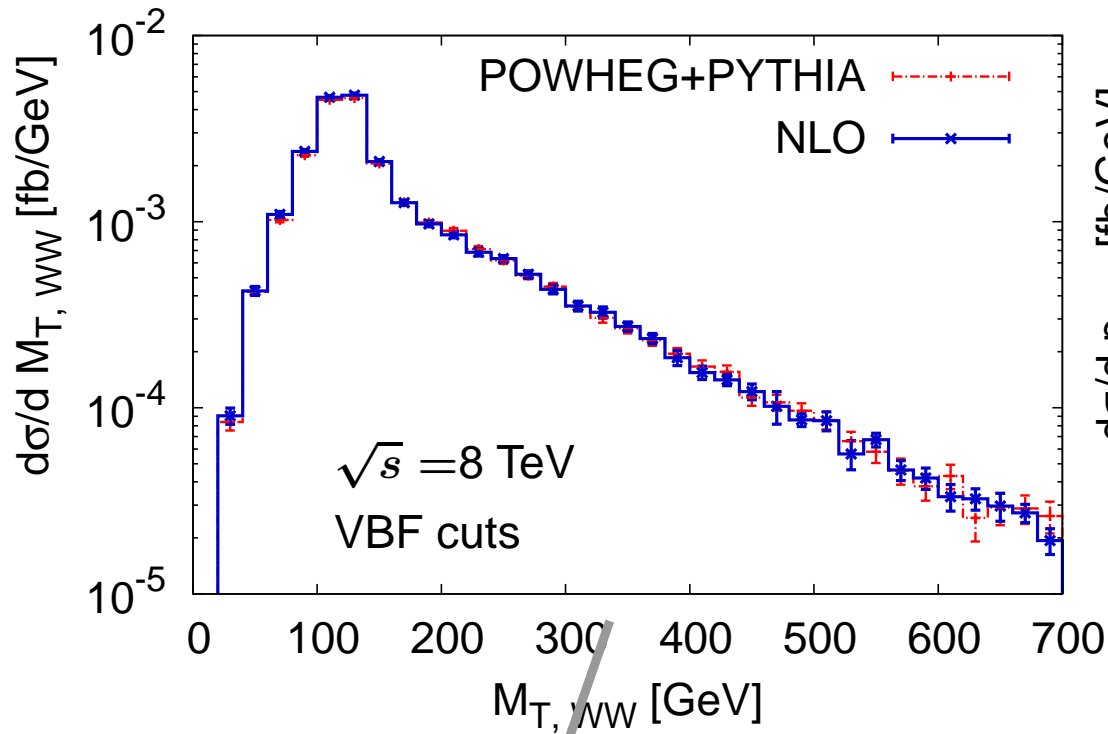
W^+W^-jj via VBF: resonance and continuum



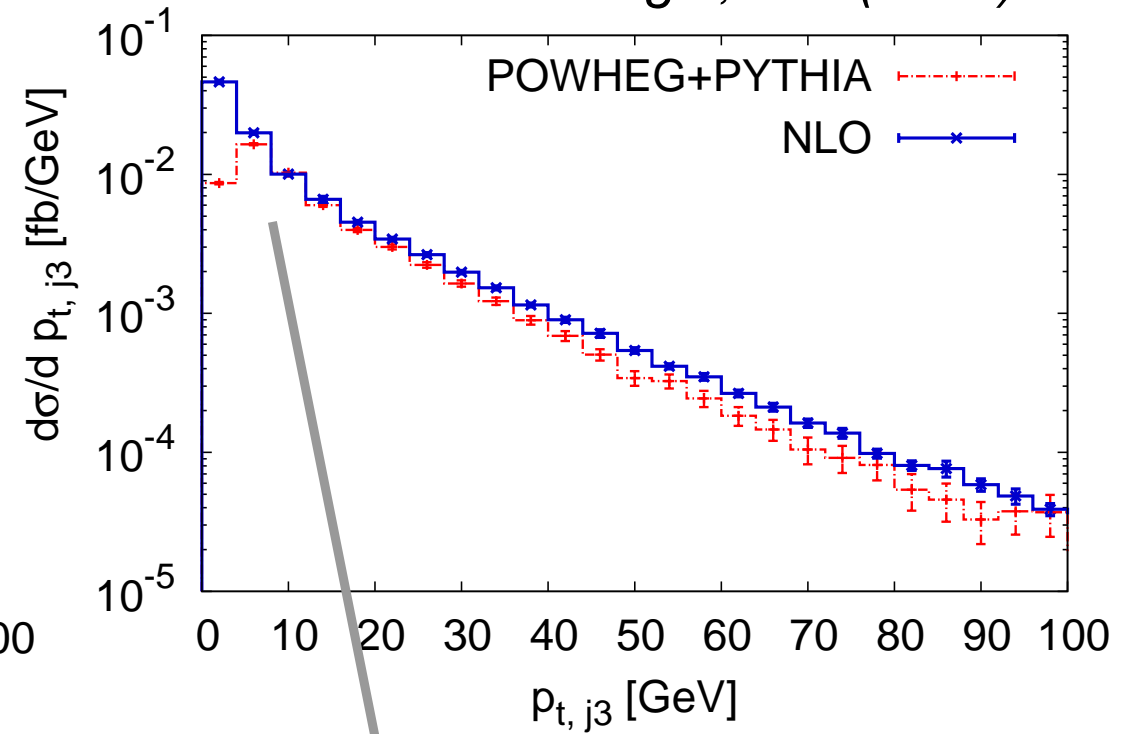
G. Zanderighi, B.J. (2013)

$pp \rightarrow W^+W^-jj$ via VBF with leptonic decays

G. Zanderighi, B.J. (2013)

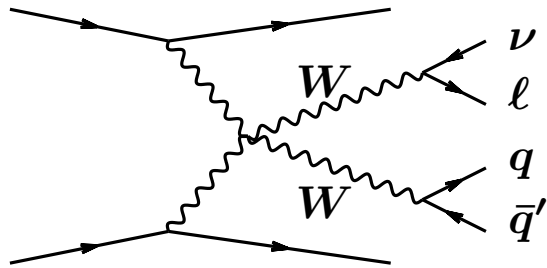


leptonic observables
not very sensitive to
parton shower



growth of jet distribution
tamed by Sudakov factor

$pp \rightarrow W^+W^-jj$ via VBF with semi-leptonic decays



“semi-leptonic” final state:

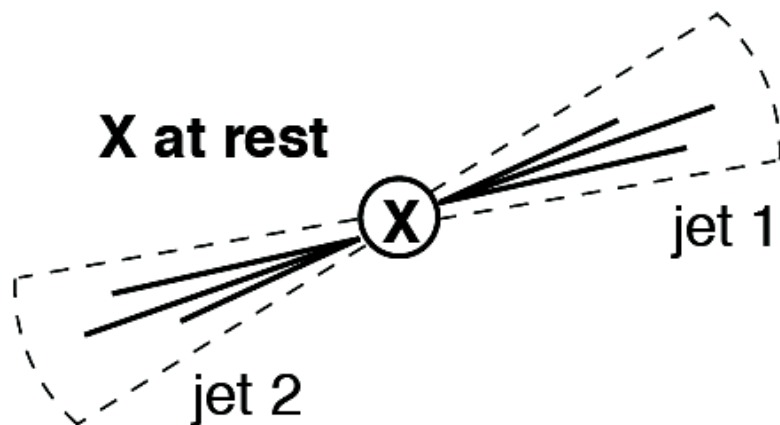
$$W^+W^- \rightarrow \ell\nu + q\bar{q}'$$

different from fully leptonic modes:

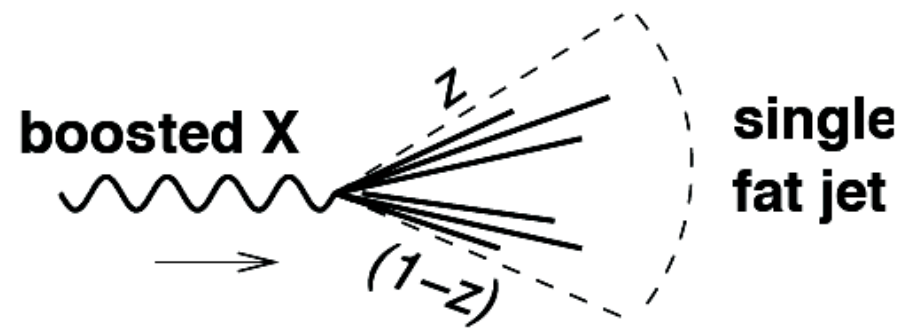
- ✓ branching ratio $\text{BR}_{W \rightarrow q\bar{q}'} \approx 3 \times \text{BR}_{W \rightarrow \ell\nu} \rightarrow$ larger x-sec
- ✓ only one neutrino \rightarrow on-shell: M_{WW} reconstruction possible
- ✗ sophisticated analysis techniques needed to isolate signal

boosted jet techniques

Normal analyses: two quarks from $X \rightarrow q\bar{q}$ reconstructed as two jets



High- p_t regime: EW object X is boosted, decay is collimated, $q\bar{q}$ both in same jet



- ❖ pioneering work on WW scattering at the LHC

Butterworth, Cox, Forshaw (2002)

- ❖ break-through in $pp \rightarrow VH$

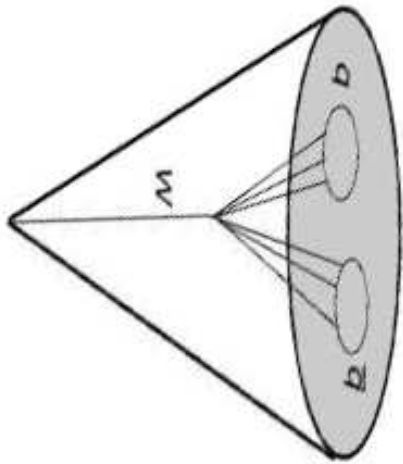
Butterworth, Davison, Rubin, Salam (2008)

- ❖ today: established field in its own

$pp \rightarrow W^+W^-jj$ via VBF with semi-leptonic decays

$$pp \rightarrow W^+(q\bar{q}')W^-(\ell\nu)jj:$$

require a **highly boosted fat jet**
with invariant mass close to M_W



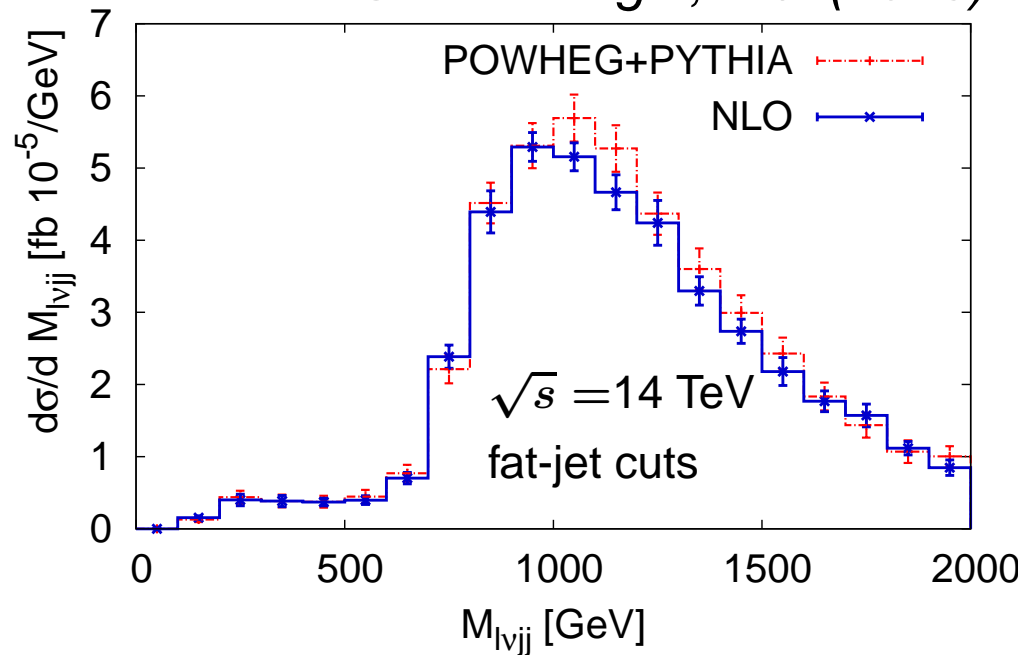
make use of jet properties / composition:

→ distinguish hadronically decaying
heavy bosons
from ordinary QCD jets

(stable against parton-shower effects)

$pp \rightarrow W^+W^-jj$ via VBF with semi-leptonic decays

G. Zanderighi, B.J. (2013)



selection cuts
specific for fat-jet analysis:

$$p_{T,J}^{\text{boosted}} > 300 \text{ GeV},$$
$$M_J \in (M_W \pm 10 \text{ GeV}),$$
$$p_{T,\ell} > 300 \text{ GeV}$$

results stable against
parton-shower effects

cuts enforce highly energetic
 WW system
(above light Higgs resonance)

BSM effects: effective operator approach

parameterize deviations from Standard Model via
effective field theory expansion
(valid up to scale Λ):

$$\mathcal{L}_{\text{eff}} = \sum \frac{c_i^{(d)}}{\Lambda^{d-4}} \mathcal{O}_i^{(d)} = \mathcal{L}_{\text{SM}} + \sum \frac{c_i^{(6)}}{\Lambda^2} \mathcal{O}_i^{(6)} + \dots$$

[cf. Degrande et al. (2012)]



modifications of triple and
quartic gauge couplings

note: higher dim. operator coefficients severely constrained by data from LEP, Tevatron, LHC

dimension six operators

CP conserving:

$$\mathcal{O}_{WWW} = \text{Tr}[W_{\mu\nu} W^{\nu\rho} W_{\rho}^{\mu}]$$

$$\mathcal{O}_W = (D_{\mu}\Phi)^{\dagger} W^{\mu\nu} (D_{\nu}\Phi)$$

$$\mathcal{O}_B = (D_{\mu}\Phi)^{\dagger} B^{\mu\nu} (D_{\nu}\Phi)$$

CP violating:

$$\mathcal{O}_{\tilde{W}WW} = \text{Tr}[\tilde{W}_{\mu\nu} W^{\nu\rho} W_{\rho}^{\mu}]$$

$$\mathcal{O}_{\tilde{W}} = (D_{\mu}\Phi)^{\dagger} \tilde{W}^{\mu\nu} (D_{\nu}\Phi)$$

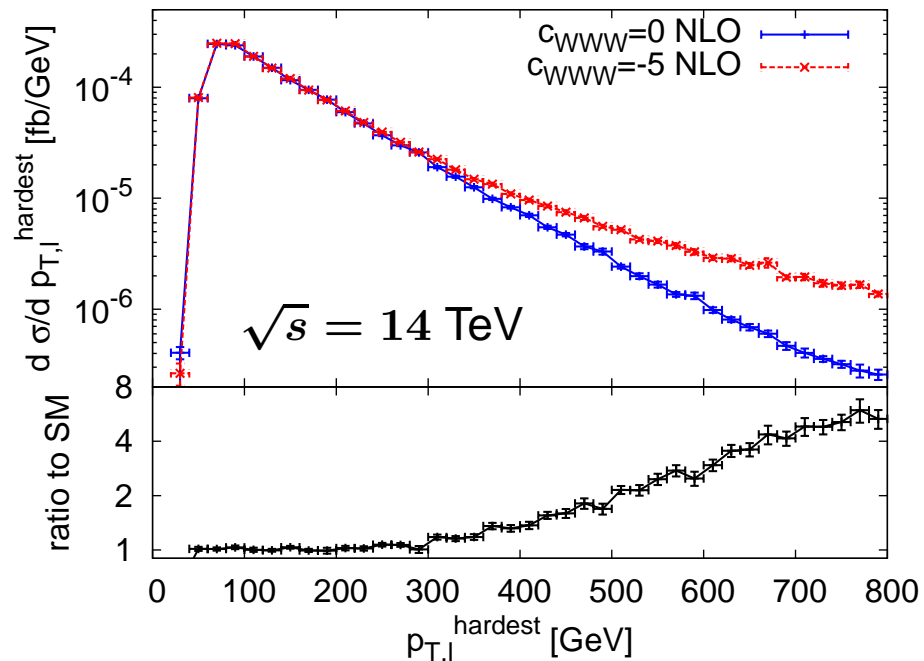
| | WWZ | $WW\gamma$ | WWH | ZZH | γZH | $WWWW$ | $WWZZ$ | $WWZ\gamma$ | $WW\gamma\gamma$ |
|-----------------------------|-------|------------|-------|-------|-------------|--------|--------|-------------|------------------|
| \mathcal{O}_{WWW} | x | x | - | - | - | x | x | x | x |
| \mathcal{O}_W | x | x | x | x | x | x | x | x | - |
| \mathcal{O}_B | x | x | - | x | x | - | - | - | - |
| $\mathcal{O}_{\tilde{W}WW}$ | x | x | - | - | - | x | x | x | x |
| $\mathcal{O}_{\tilde{W}}$ | x | x | x | x | x | - | - | - | - |



impact of dim-6 operators on triple and quartic gauge couplings

new interactions in electroweak $ZZjj$ production

Karlberg, Zanderighi, B.J. (2013)



allow for non-zero dimension-six operator coefficients

(compatible with exp. limits)

→ tails of transverse momentum distributions enhanced

but:

very demanding at LHC14 because of small signal rates

(much better limits possible with 33 or 100 TeV)

limitations of EFT

effective field theory **valid up to scale Λ** by construction

higher-dim operators suppressed by extra powers of $1/\Lambda$

→ no problems with unitarity

contributions from regime beyond validity:

→ violations of unitarity (unphysical)

need to **avoid regions where EFT breaks down** by:

- kinematic cuts
- form factors (damp contributions $> \Lambda$)
- unitarization prescriptions,
e.g. K-matrix unitarization (WHIZARD)

summary

VBF crucial for understanding mechanism of electroweak symmetry breaking:

- * Hjj : very clean Higgs production channel
- * $VVjj$: sensitive to signatures of new physics in the gauge boson sector

important pre-requisites:

- ✓ explicit calculations revealed that VBF reactions are **perturbatively well-behaved** (NLO-QCD corrections and parton-shower effects moderate)

open issues

- * all **QCD-induced $VVjj$** production processes matched to parton shower at NLO-QCD
- * flexible Monte Carlo tools for all $VVjj$ production modes in **BSM scenarios** including NLO-QCD corrections and parton-shower effects
- * **electroweak corrections** to all $VVjj$ production modes
- * **mixing** between QCD- and EW-induced production modes



...for your attention