Vector Boson Scattering:
A Theory Perspective

Higgs Couplings Workshop

Torino – October 2014

Barbara Jäger
University of Tübingen

vector boson fusion (VBF) &
vector boson scattering (VBS)

Standard Model:

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

beyond the Standard Model:

sensitive to the mechanism of electroweak symmetry breaking

↕

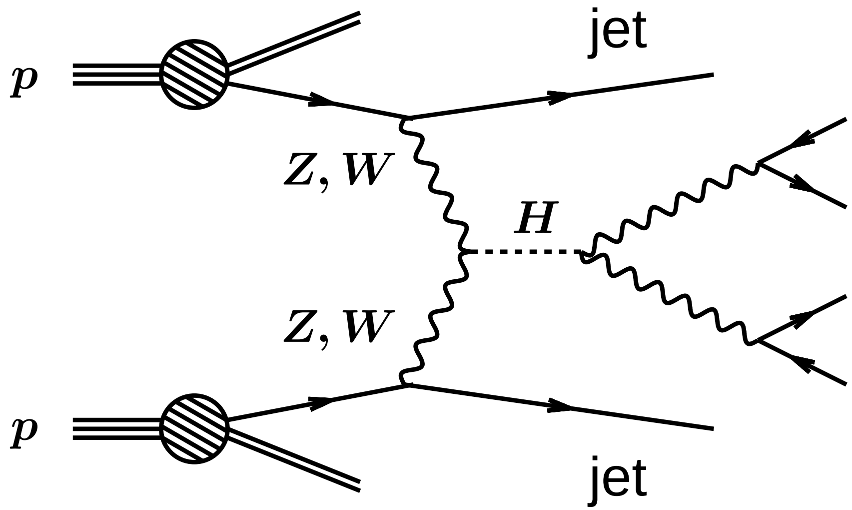
strongly interacting weak sector, new resonances, . . . ?

the big advantage:

✔ experimentally clean signature

✔ perturbatively well under control

VBF / VBS event topology



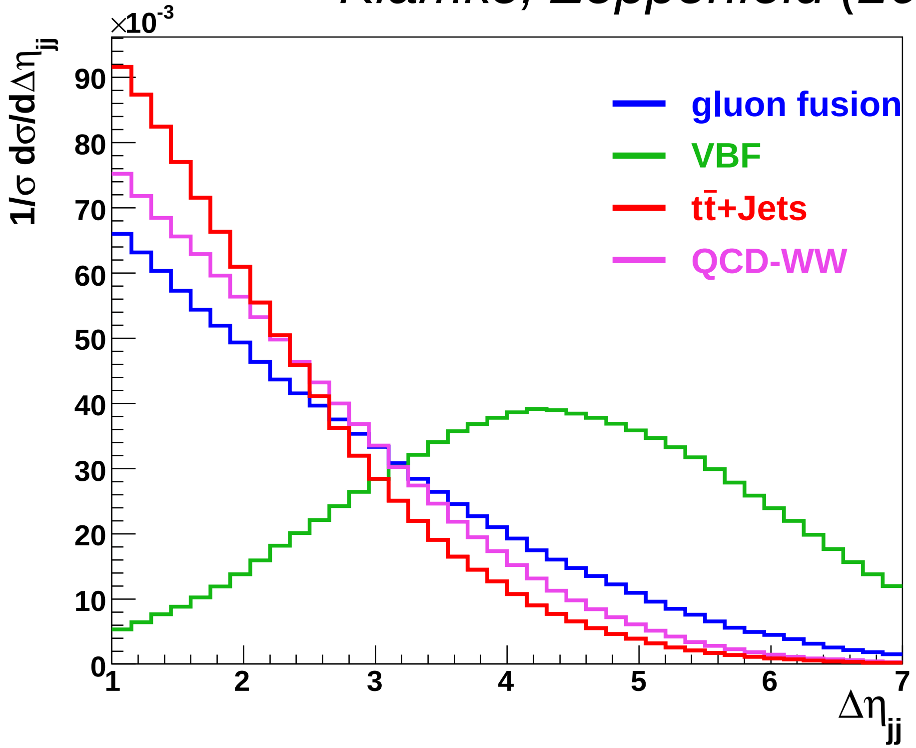
suppressed color exchange between quark lines gives rise to

- 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

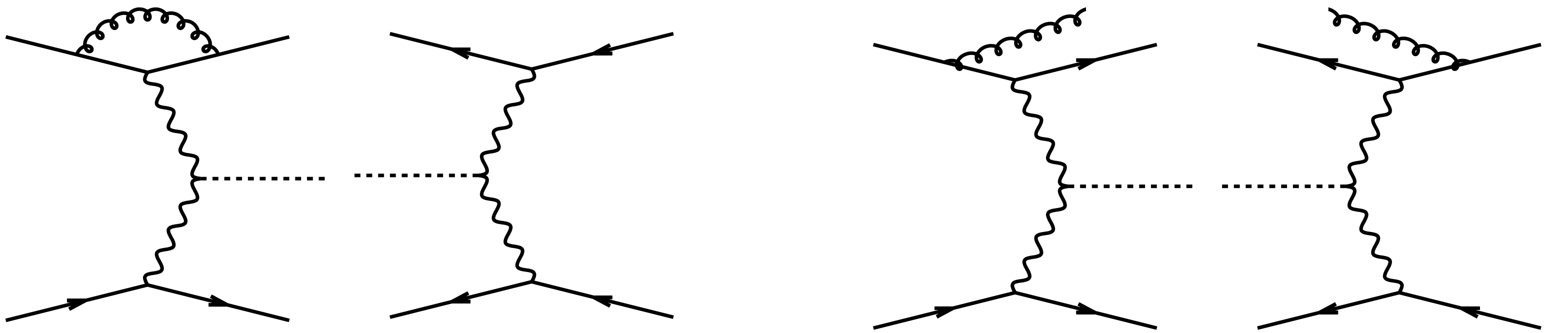
rapidity separation of the tagging jets

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)

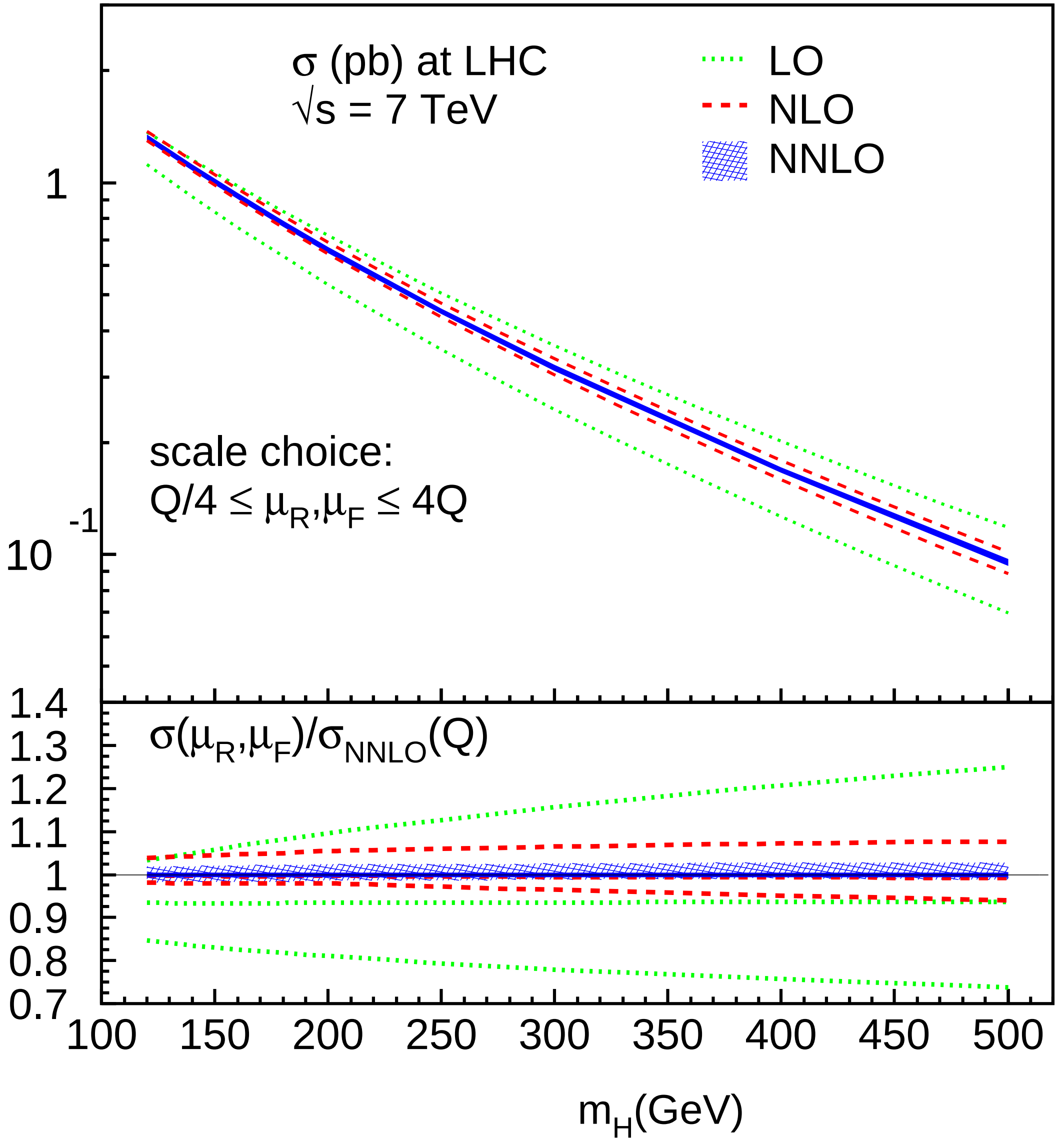
→

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:

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

Harlander, Vollinga, Weber (2007)

$qq \to qqH$:

Bolzoni, Maltoni, Moch, Zaro (2019)

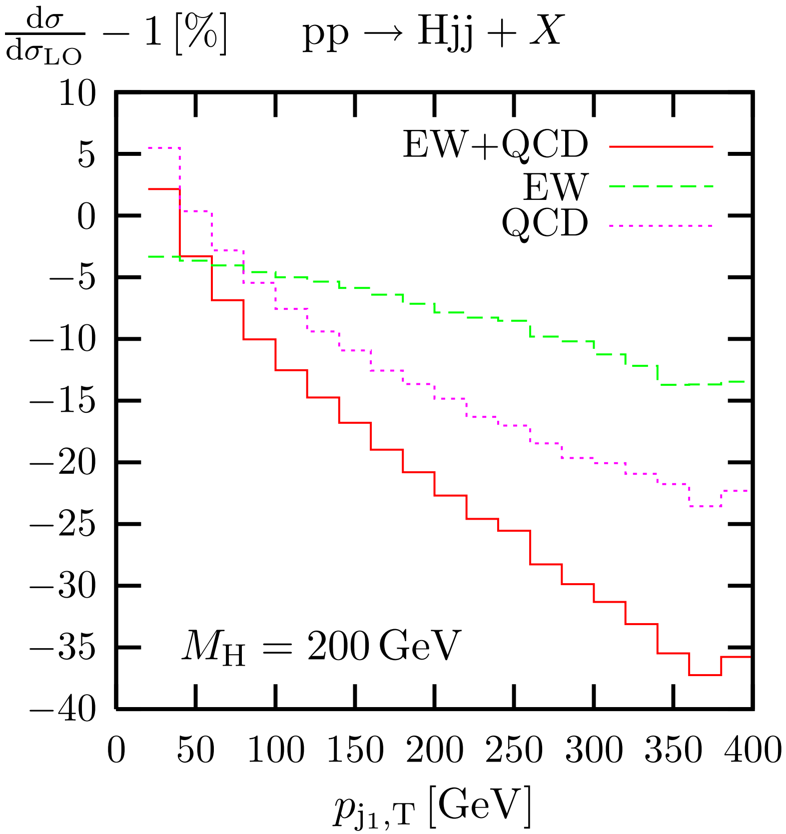
- NNLO predictions are in full agreement with NLO results
- residual scale uncertainties are reduced from ∼4% to 2%
- NNLO PDF uncertainties are at the 2% level

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]

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

various implementations in different frameworks available:

SM ↕

`POWHEG-BOX:` *Nason, Oleari (2009)*

`HERWIG++:` *D' Errico, Richardson (2009)*

`aMC@NLO:` *Frixione, Torielli, Zaro (2013)*

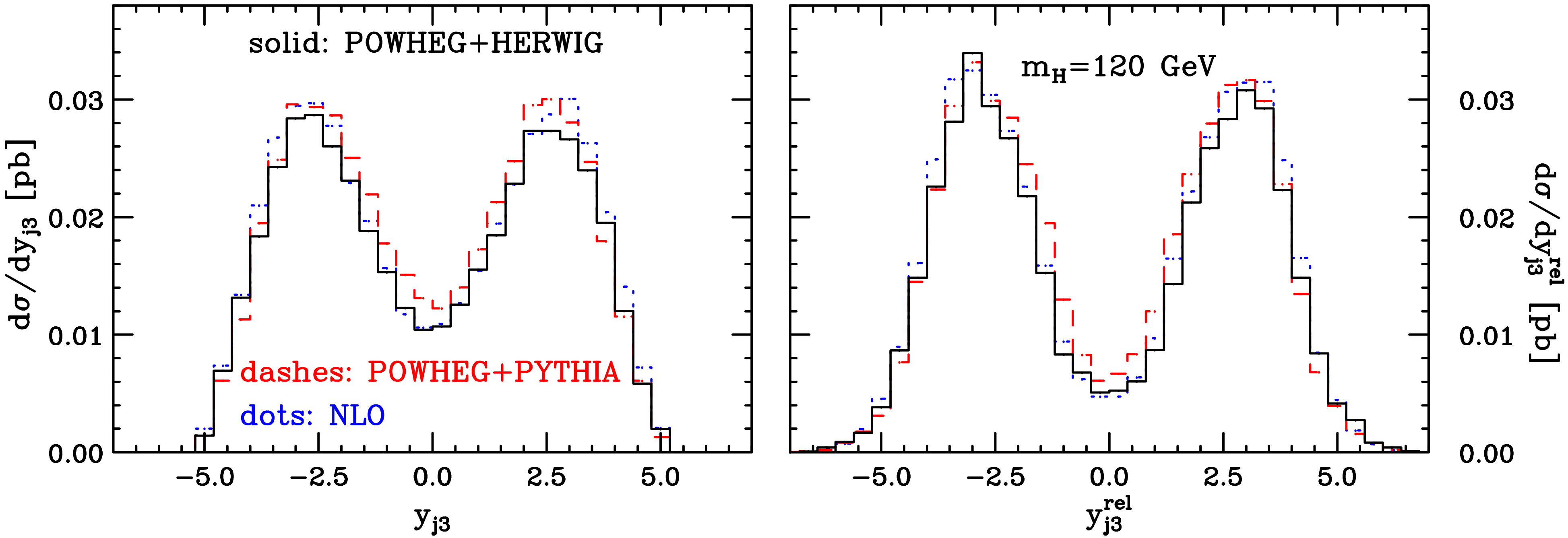
BSM ↕

`MadGraph5_aMC@NLO:` *Maltoni, Mawatari, Zaro (2014)*

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

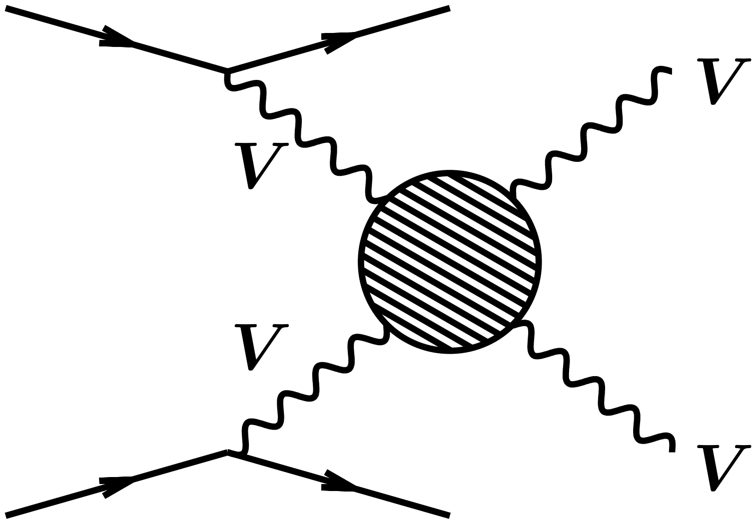
$pp \to Hjj$ via VBF @ NLO QCD with parton shower

Nason, Oleari (2009)



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

vector boson scattering: $VV \to VV$

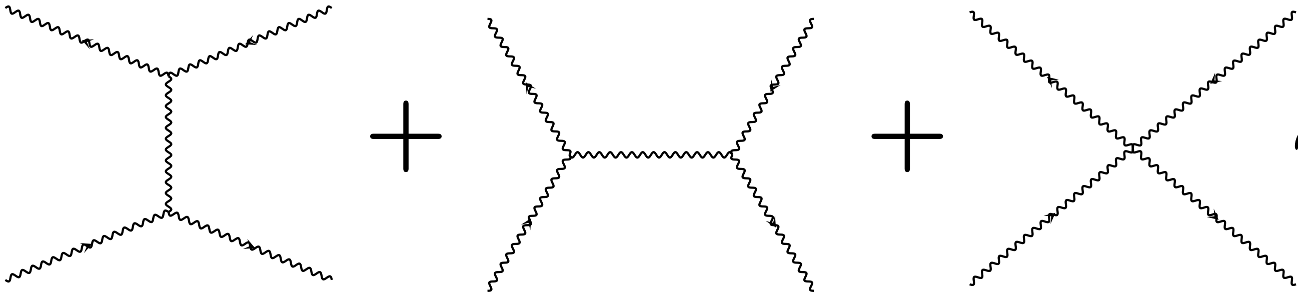


vector-boson scattering processes
are extremely sensitive to
new interactions in the
gauge boson sector

vector boson scattering & unitarity

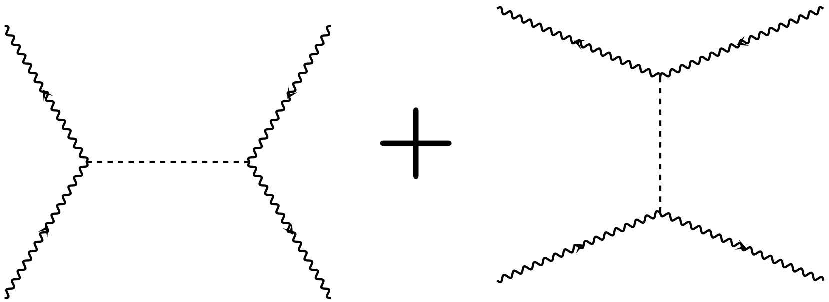
$W_L^+ W_L^- \to W_L^+ W_L^-$ with $\varepsilon_L^\mu \sim \frac{\sqrt{s}}{M_W}$

$\mathcal{M} =$



$\sim \frac{s}{M_W^2}$

growth violates unitarity $\to$ 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 boso[illegible]
  - c[illegible]en[illegible] in TeV range $\Gamma_H \sim M_H$

- no Higg[illegible]
  - st[illegible]g inter[illegible]tions of V_L modes?
  - resonances in TeV range?
  - spectacular signals ?

. . . OUTDATED!!

approaches to VBS today

experimental fact: $M_H = 125$ GeV $\ll 1$ 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:

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

higher-dim operators may give rise to

anomalous triple and quartic gauge couplings

approaches to VBS today

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

☞ BSM effects expected to be small

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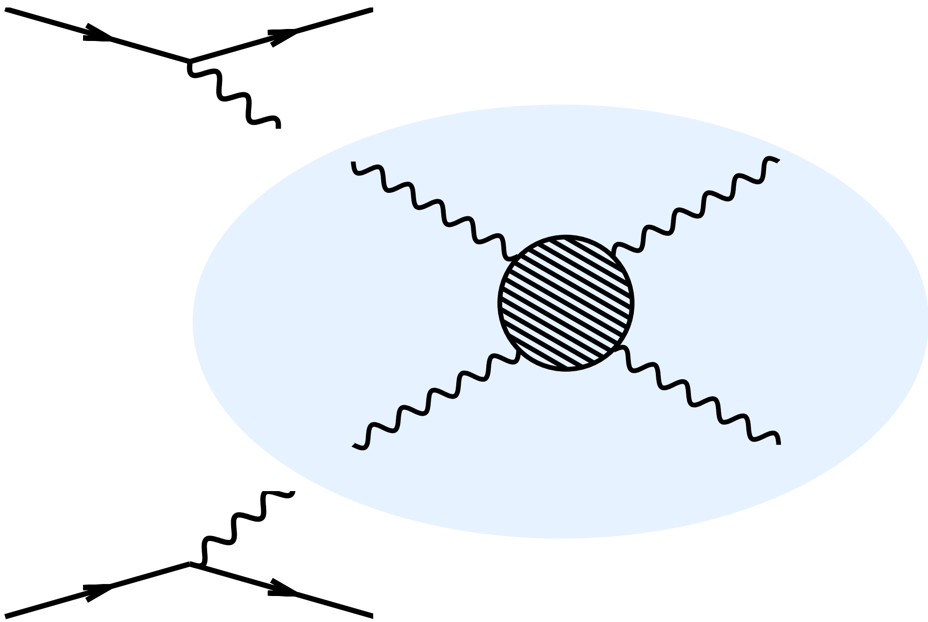
precision in theory and experiment needed
to identify small deviations from SM

vector boson scattering in hadronic collisions



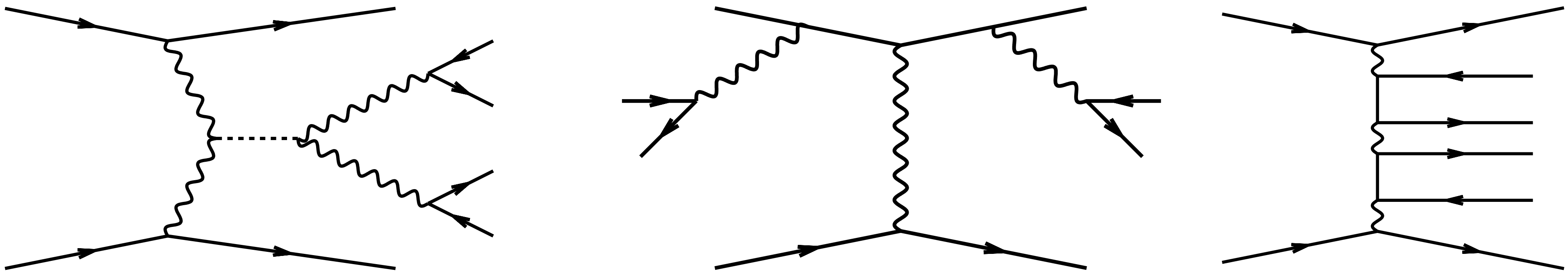
$$\boldsymbol{\sigma}_{\mathrm{pp}} \sim \boldsymbol{f}_{V_1/p_1} \otimes \boldsymbol{f}_{V_2/p_2} \otimes \hat{\boldsymbol{\sigma}}_{V_1 V_2 \to V_3 V_4}$$

poor man's approach:

consider heavy gauge bosons as
effective constituents of the proton

"effective $\boldsymbol{V}$ boson approximation"

$pp \to VVjj$: 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)]

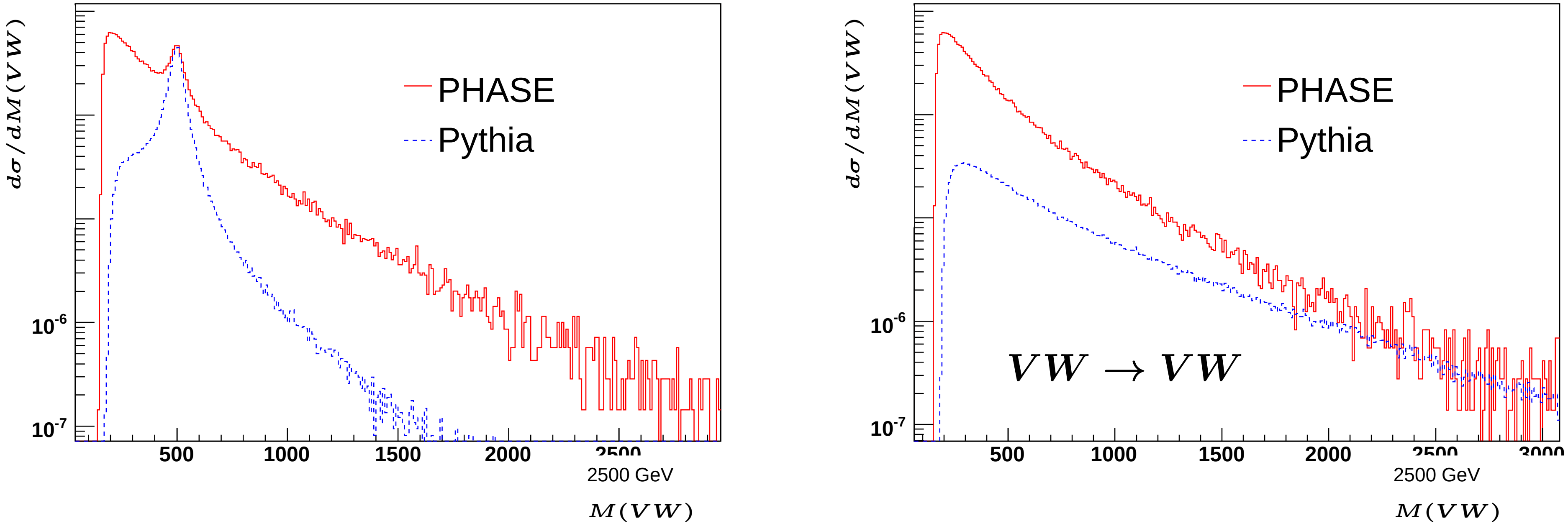
in realistic calculation need to consider:

- 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)



Accomando et al. (2005)

PHASE:
off-shell effects fully considered

PYTHIA:
EWA with longitudinal vector bosons

EW $VVjj$ production at NLO-QCD

NLO-QCD calculation for VBF production of

$pp \to \boldsymbol{W^+W^-jj}$, $\boldsymbol{ZZjj}$, $\boldsymbol{W^\pm Zjj}$, and $\boldsymbol{W^\pm W^\pm jj}$

(including off-shell effects and leptonic decay correlations)

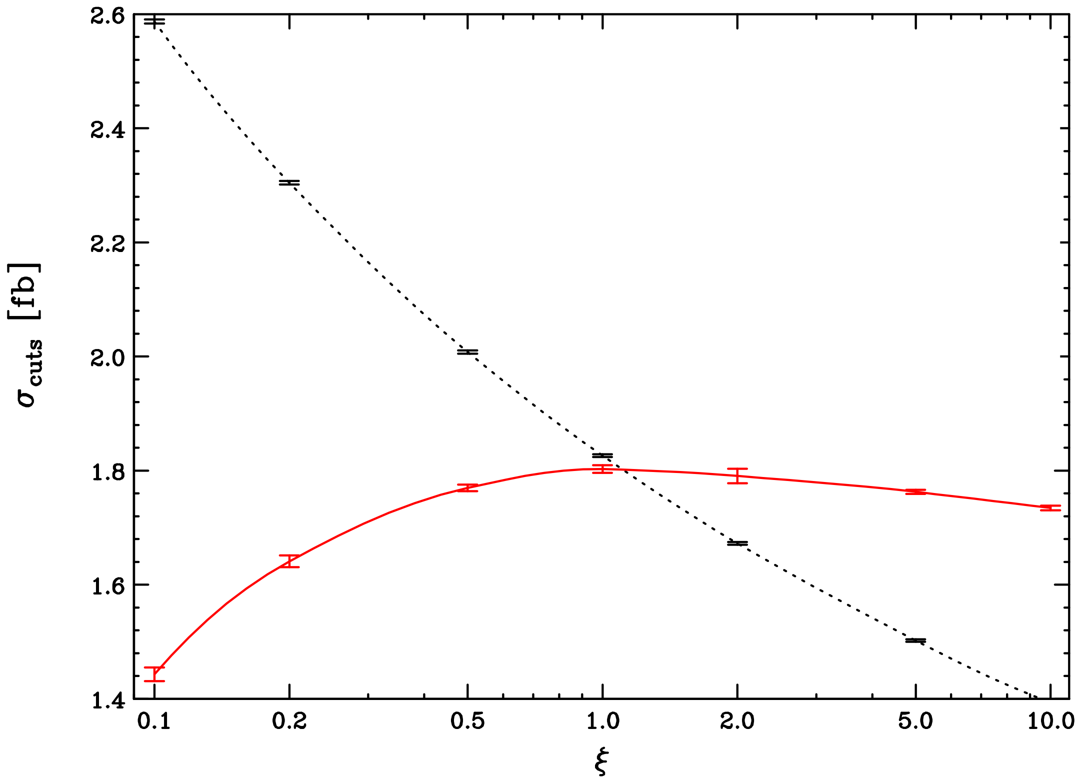
available in VBFNLO Monte Carlo program

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 $\mu = \xi M_W$



Oleari, Zeppenfeld, B.J. (2006)

LO: no control on scale

NLO QCD: scale dependence strongly reduced

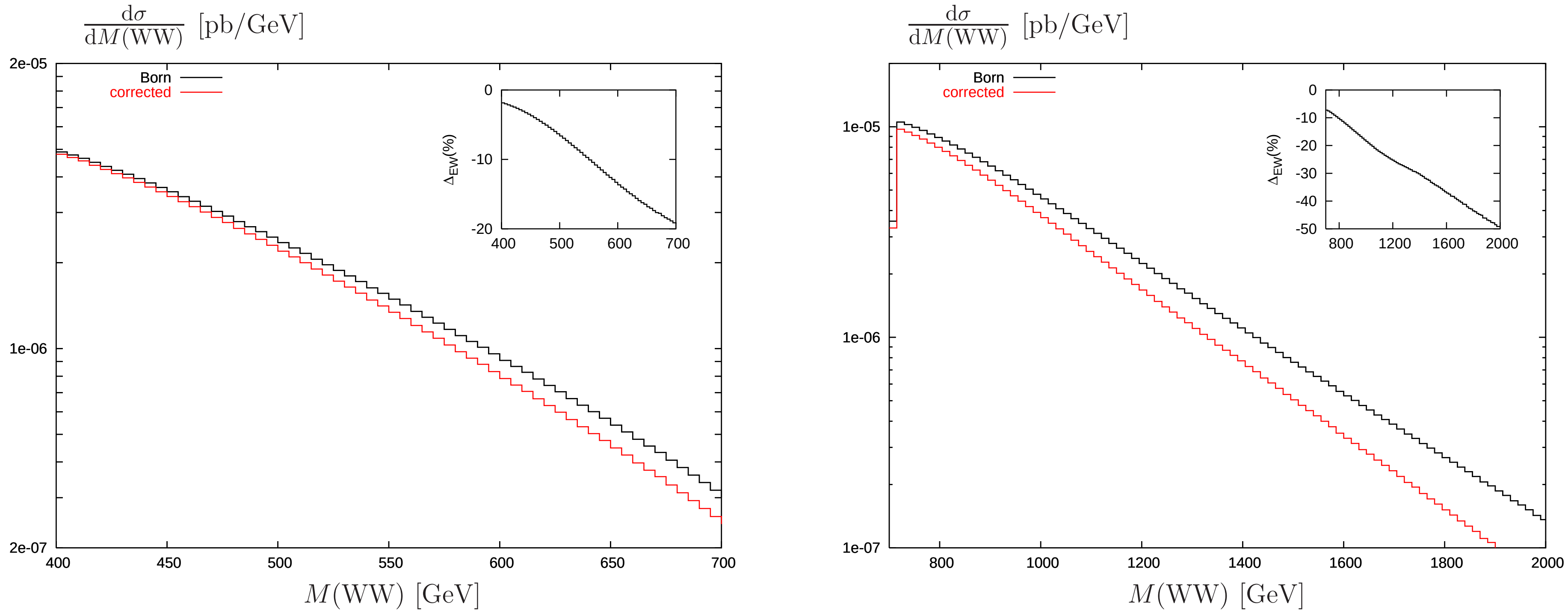
$pp \to VVjj$ via VBF: electroweak corrections

very tough – no calculations available to date

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

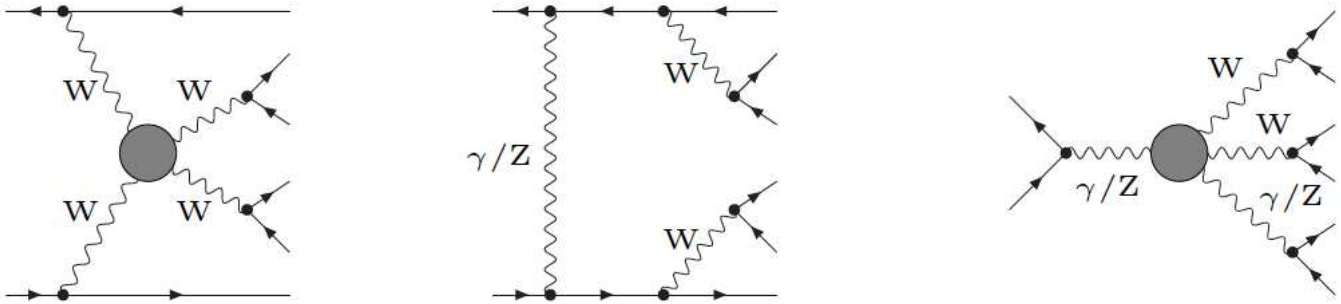
dominant EW corrections can be as large as 50% in TeV range

[Accomando, Denner, Pozzorini (2006)]



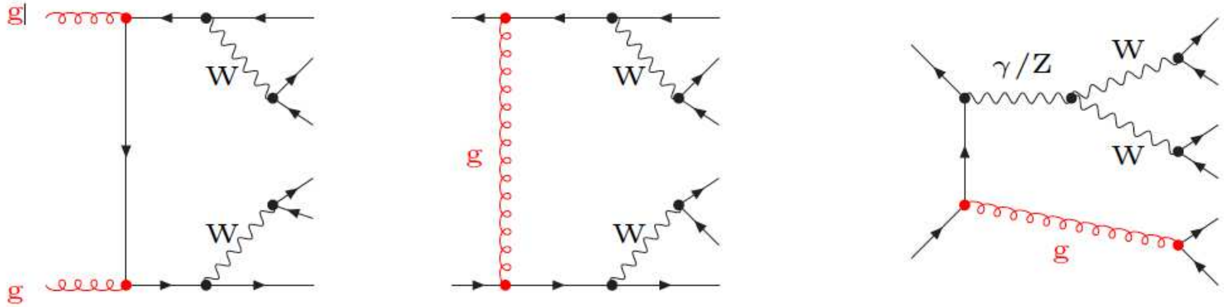
the various contributions to the VVjj final state

EW channels:



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

QCD channels:

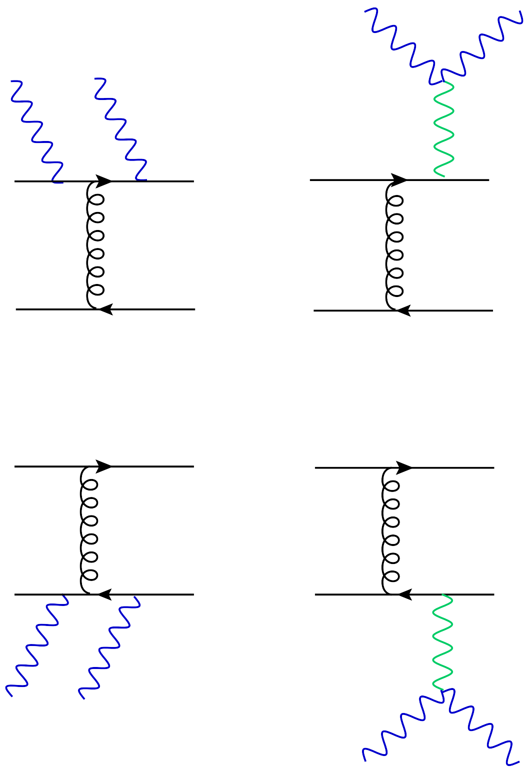


$$|\mathcal{M}_{\mathrm{QCD}}|^2 \propto \alpha_s^2 \alpha^4$$

interference between QCD and EW channels:

possible, but suppressed

QCD-induced $VVjj$ production



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

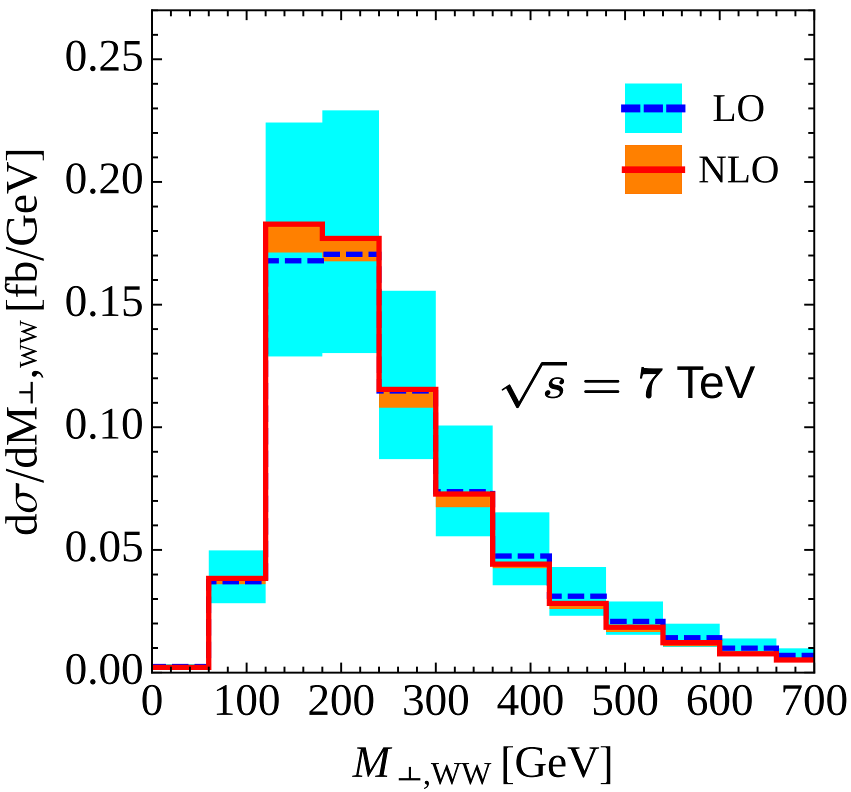
NLO-QCD predictions available for

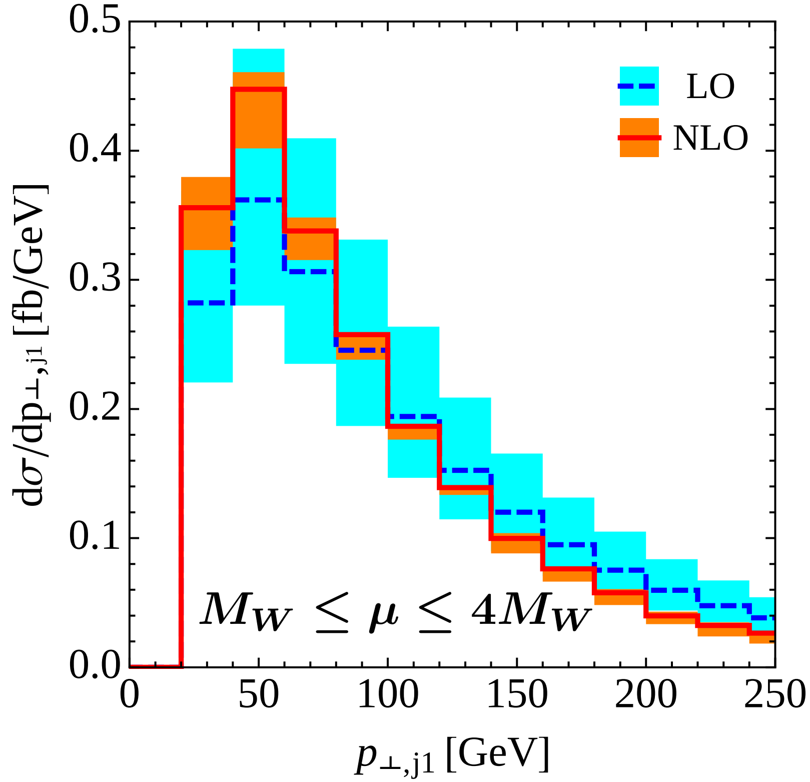
W^+W^+jj (★), W^+W^-jj (❋), $WZjj$ (❖),$ZZjj$ (❖):

- ★, ❋ *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)

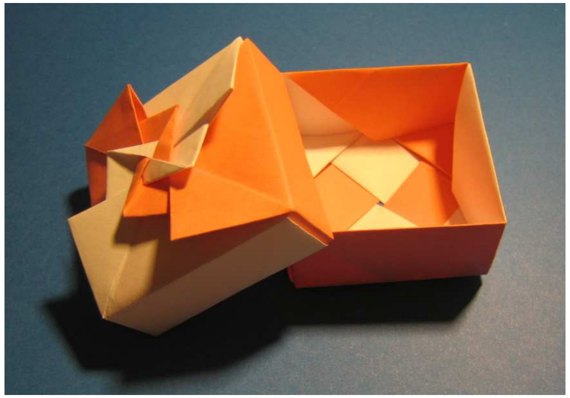




NLO-QCD corrections significantly reduce
scale uncertainty

$VVjj$ matched with parton showers & NLO-QCD

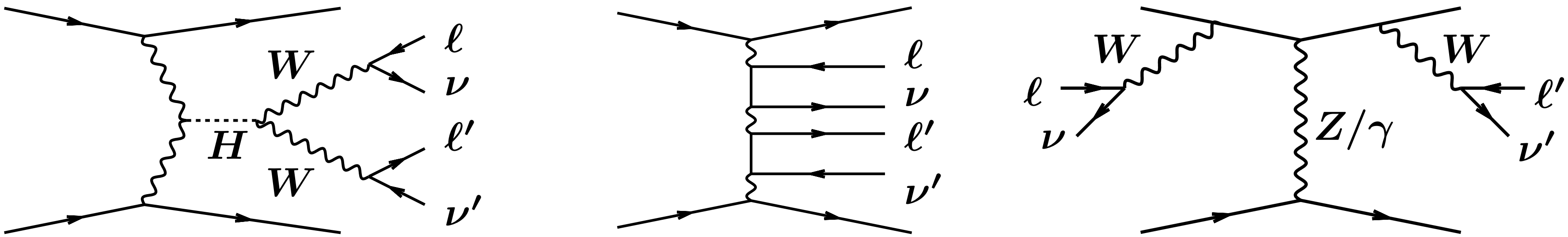
so far only implementation of EW- and QCD-induced $VVjj$ production processes available in the `POWHEG-BOX`:

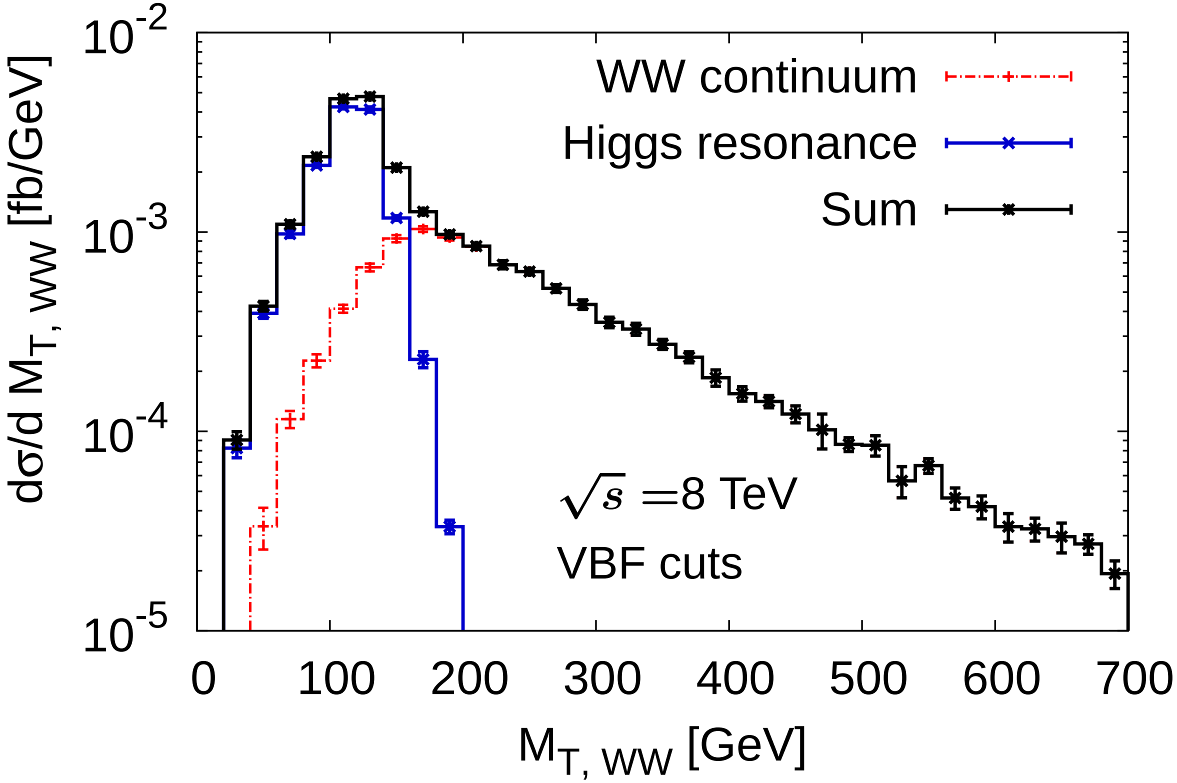


`http://powhegbox.mib.infn.it/`

- 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)]*

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

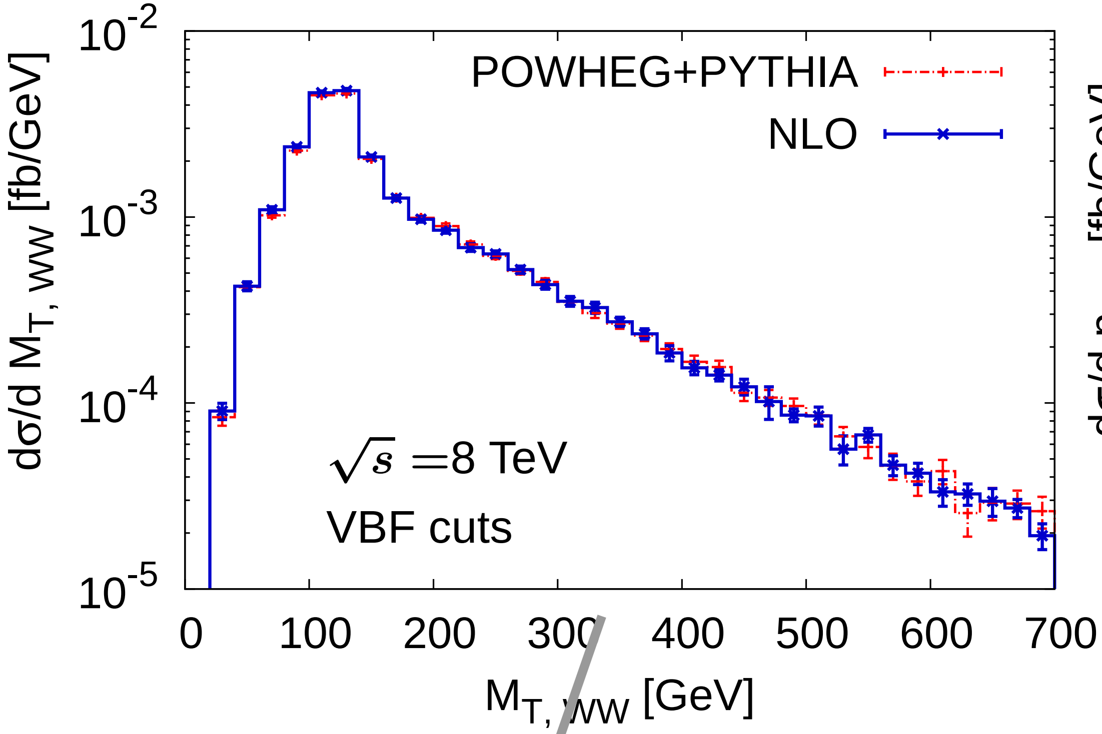


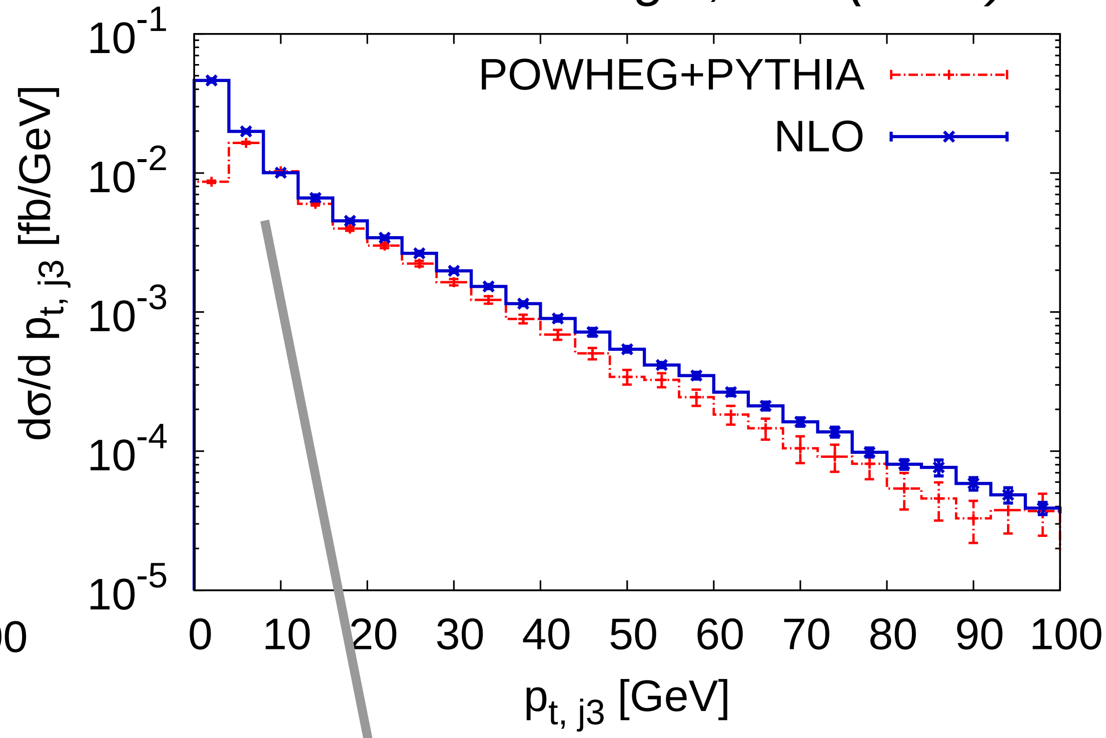


G. Zanderighi, B.J. (2013)

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

G. Zanderighi, B.J. (2013)

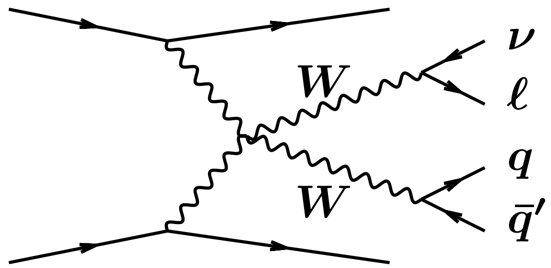




leptonic observables not very sensitive to parton shower

growth of jet distribution tamed by Sudakov factor

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



"semi-leptonic" final state:

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

different from fully leptonic modes:

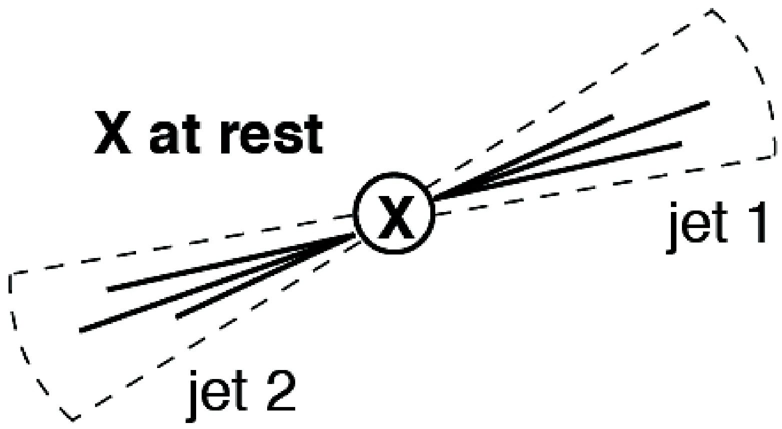
✔ branching ratio $\mathrm{BR}_{W\to q\bar{q}'} \approx 3 \times \mathrm{BR}_{W\to \ell\nu} \to$ larger x-sec

✔ only one neutrino $\to$ on-shell: M_{WW} reconstruction possible

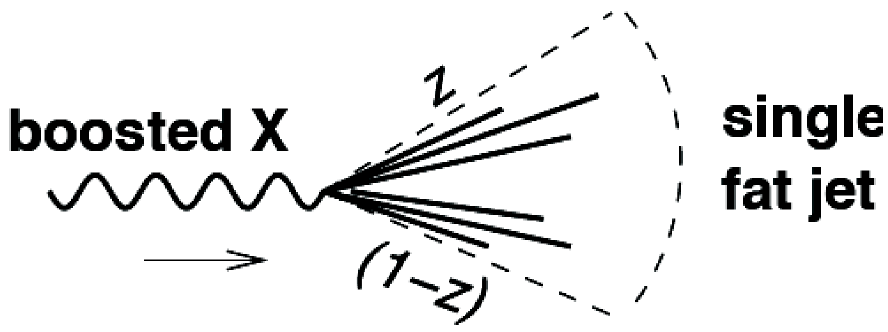
✘ sophisticated analysis techniques needed to isolate signal

boosted jet techniques

Normal analyses: two quarks from $X \to q\bar{q}$ 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

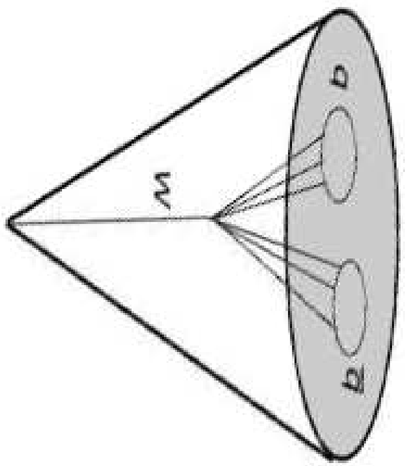
  Butterworth, Cox, Forshaw (2002)

- break-through in $pp \to VH$

  Butterworth, Davison, Rubin, Salam (2008)

- today: established field in its own

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



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

require a highly boosted fat jet

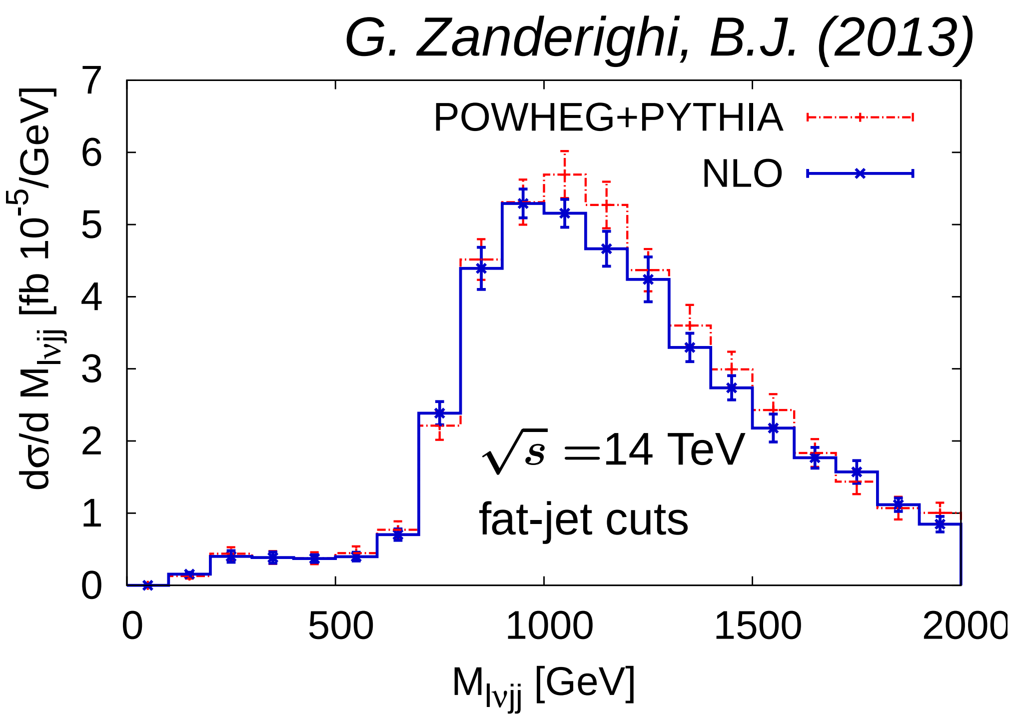
with invariant mass close to M_W

make use of jet properties / composition:

$\to$ distinguish hadronically decaying
heavy bosons
from ordinary QCD jets

(stable against parton-shower effects)

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



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 $\boldsymbol{\Lambda}$):

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

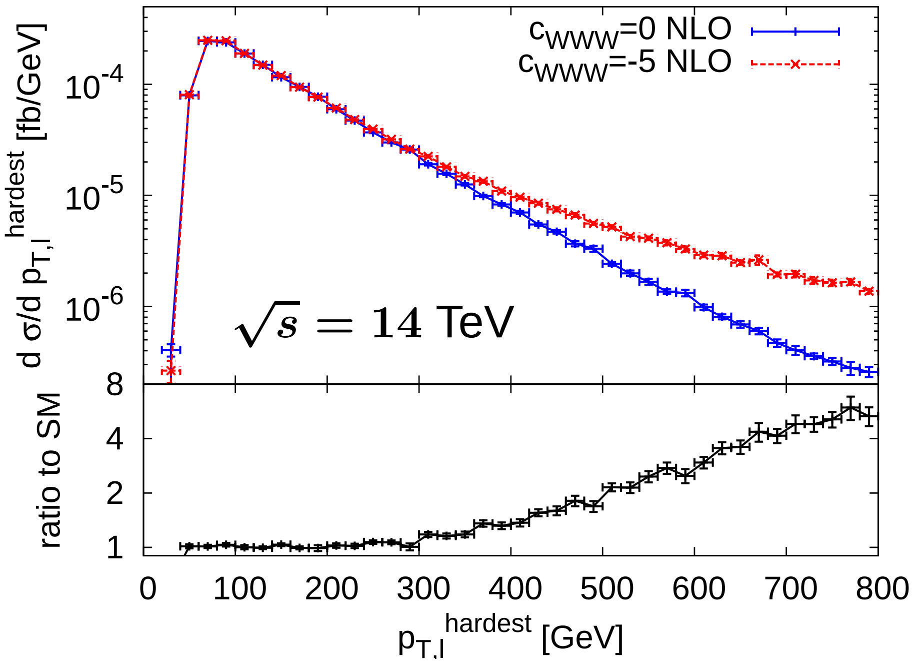
[cf. Degrande et al. (2012)]

modifications of triple and
quartic gauge couplings

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

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 $1/\Lambda$
$\rightarrow$ no problems with unitarity

contributions from regime beyond validity:
$\rightarrow$ 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`)

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

QCD-induced production

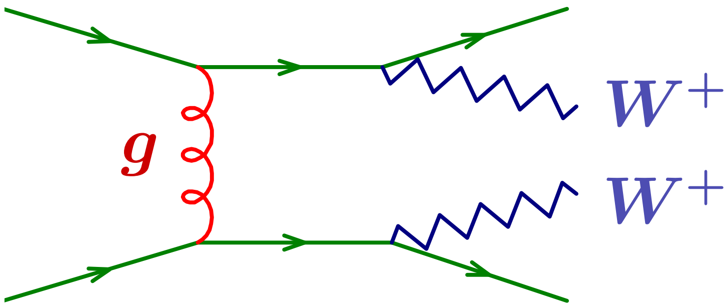
Melia, Melnikov, Rontsch, Zanderighi (2010);

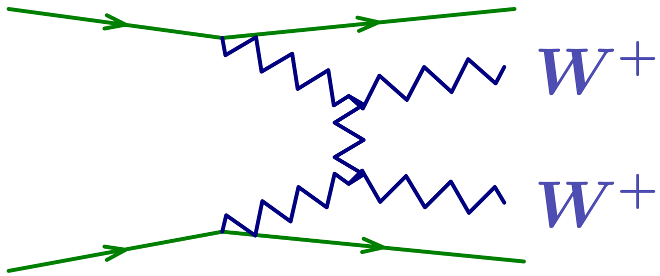
Melia, Nason, Rontsch, Zanderighi (2011)

EW production

Oleari, Zeppenfeld, B.J. (2009);

Zanderighi, B.J. (2011)





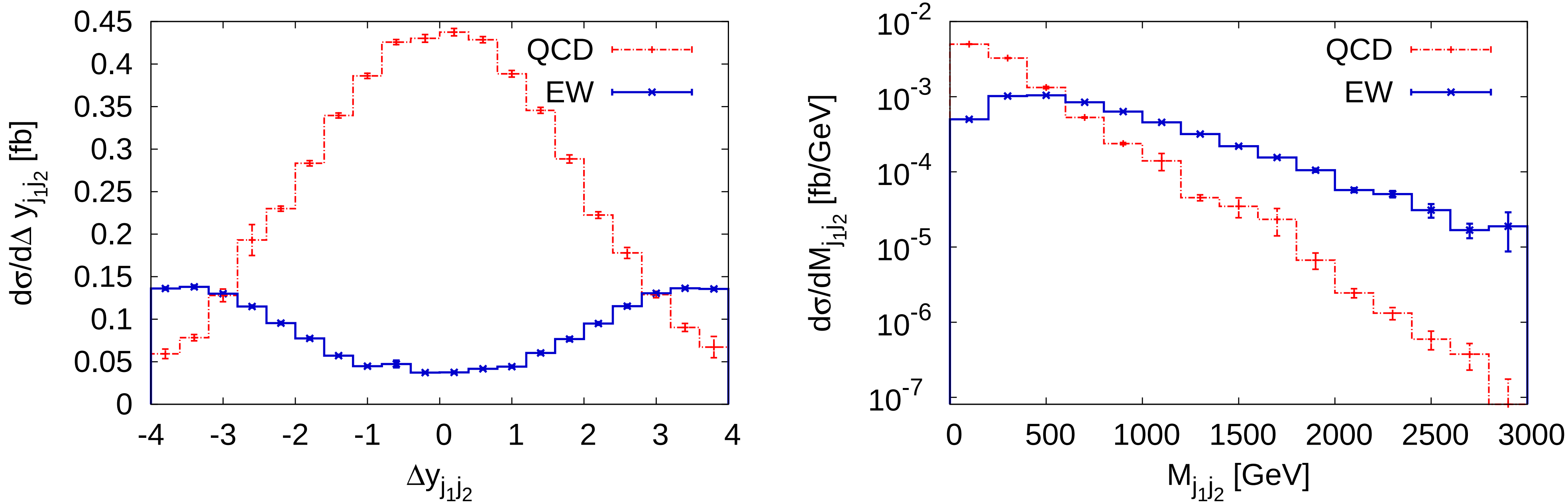
NLO-QCD results for $\sqrt{s}$ =7 TeV with basic jet cuts only ($p_T^{\text{tag}} > 20$ GeV):

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

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

$pp \to W^+W^+jj$: QCD versus EW production

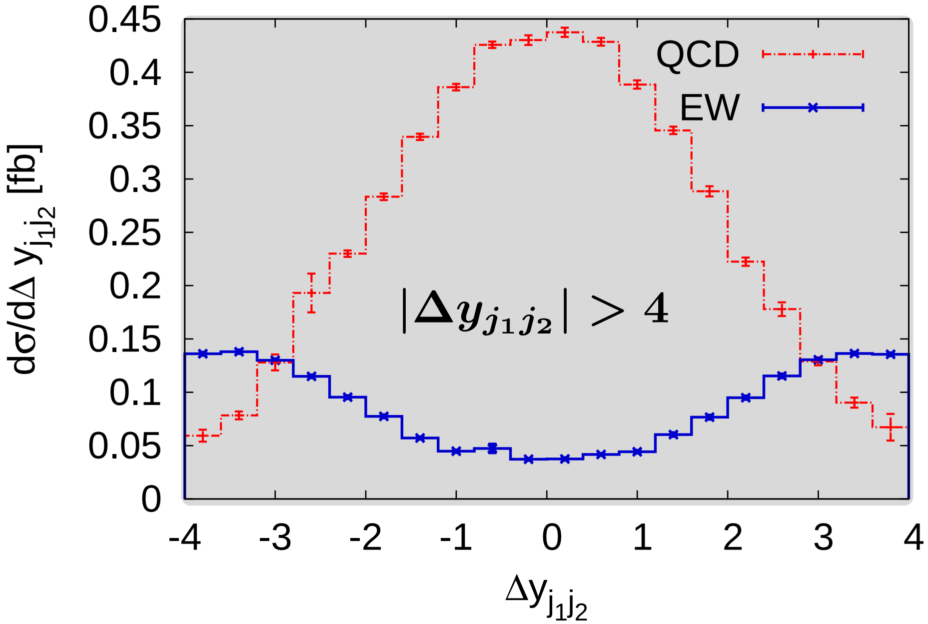
Zanderighi, B.J. (2011)

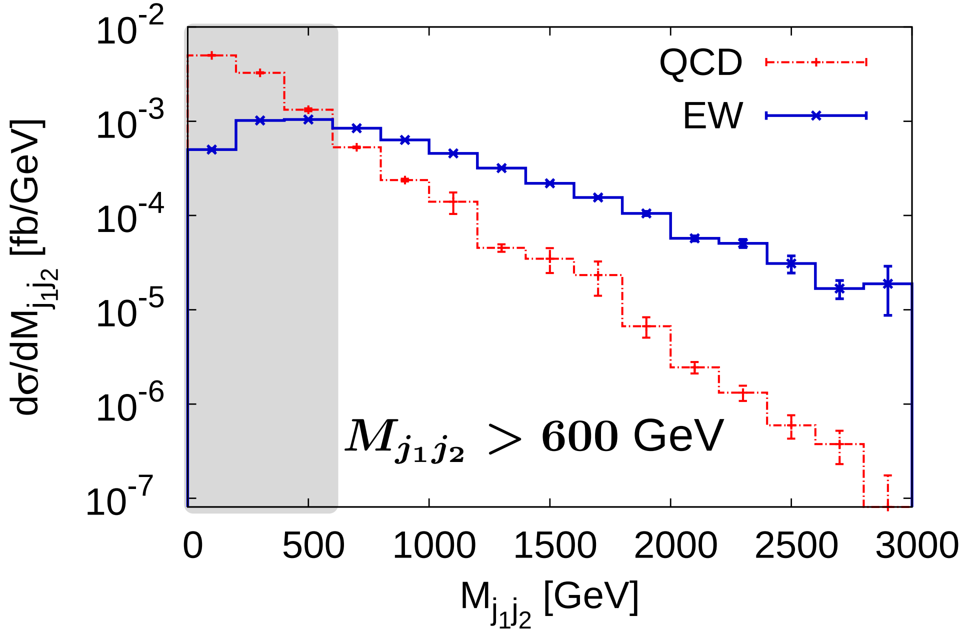


- $\sqrt{s} = 7$ TeV
- basic jet cuts only
- NLO-QCD accuracy

$pp \to W^+W^+jj$: QCD versus EW production

Zanderighi, B.J. (2011)





- $\sqrt{s} = 7$ TeV
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$pp \to W^+W^+jj$ in the POWHEG-BOX

QCD-induced production

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

EW production

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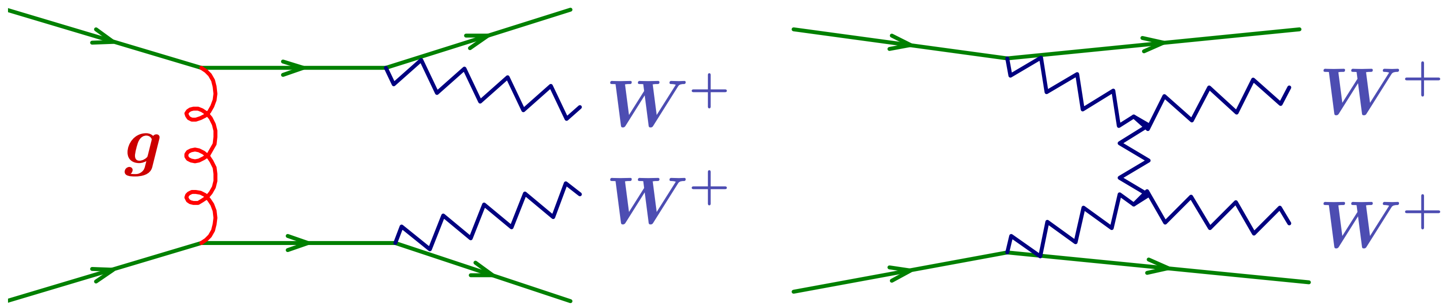


NLO results for $\sqrt{s}$ =7 TeV with basic jet cuts only ($p_T^{\rm tag} > 20$ GeV):

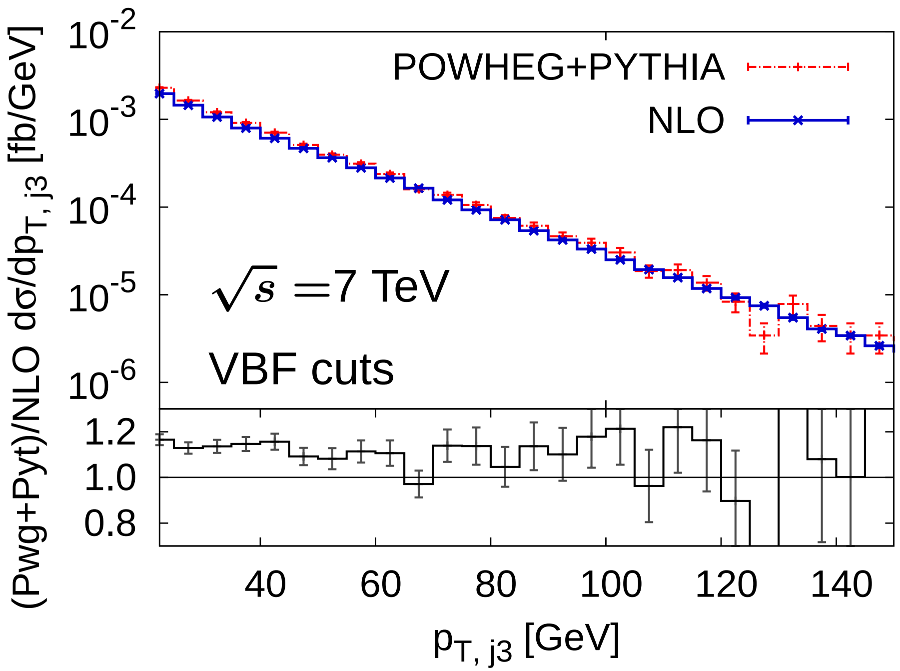
$$\sigma^{\rm inc}_{\rm QCD} = 2.12 \text{ fb} \qquad \sigma^{\rm inc}_{\rm EW} = 1.097 \text{ fb}$$

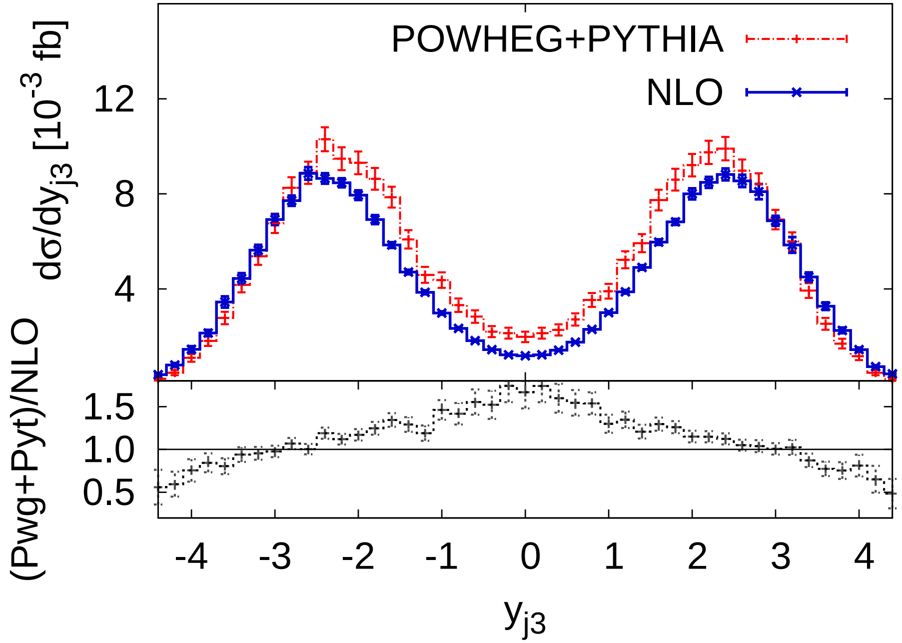
NLO results with VBF cuts:

$$\sigma^{\rm cuts}_{\rm QCD} = 0.0074 \text{ fb} \qquad \sigma^{\rm cuts}_{\rm EW} = 0.201 \text{ fb}$$

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

Zanderighi, B.J. (2011)





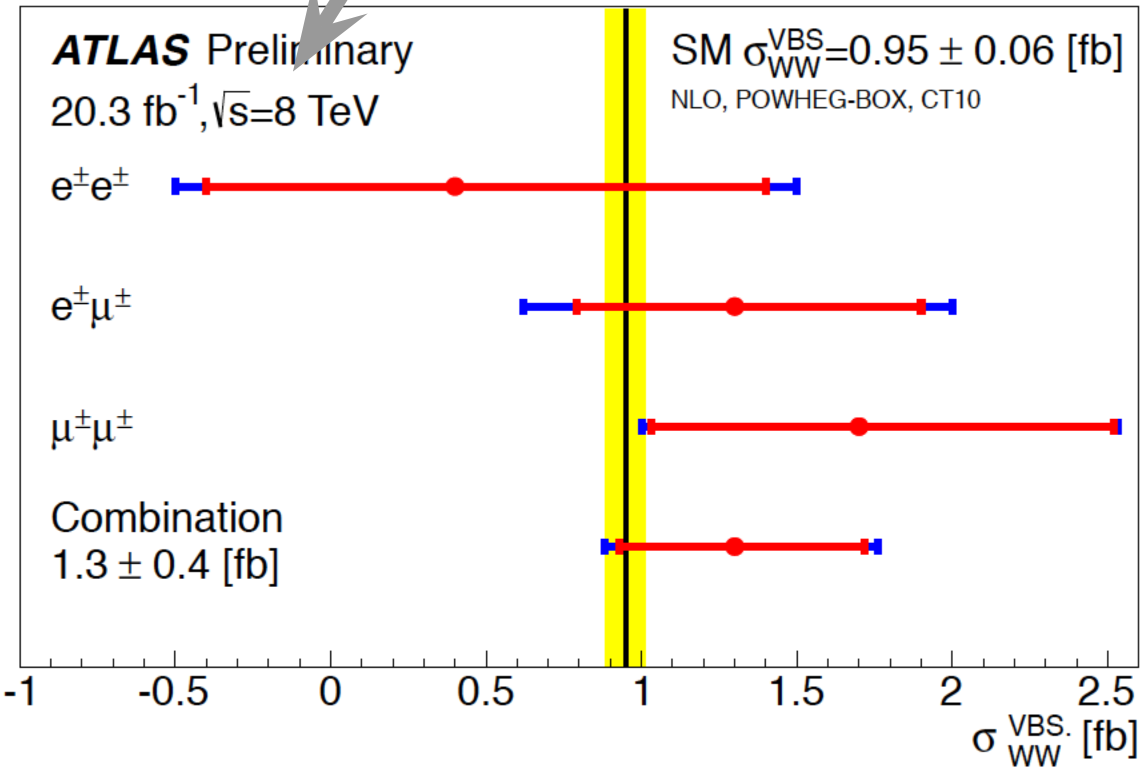
typical for VBF processes: little jet activity at central rapidities

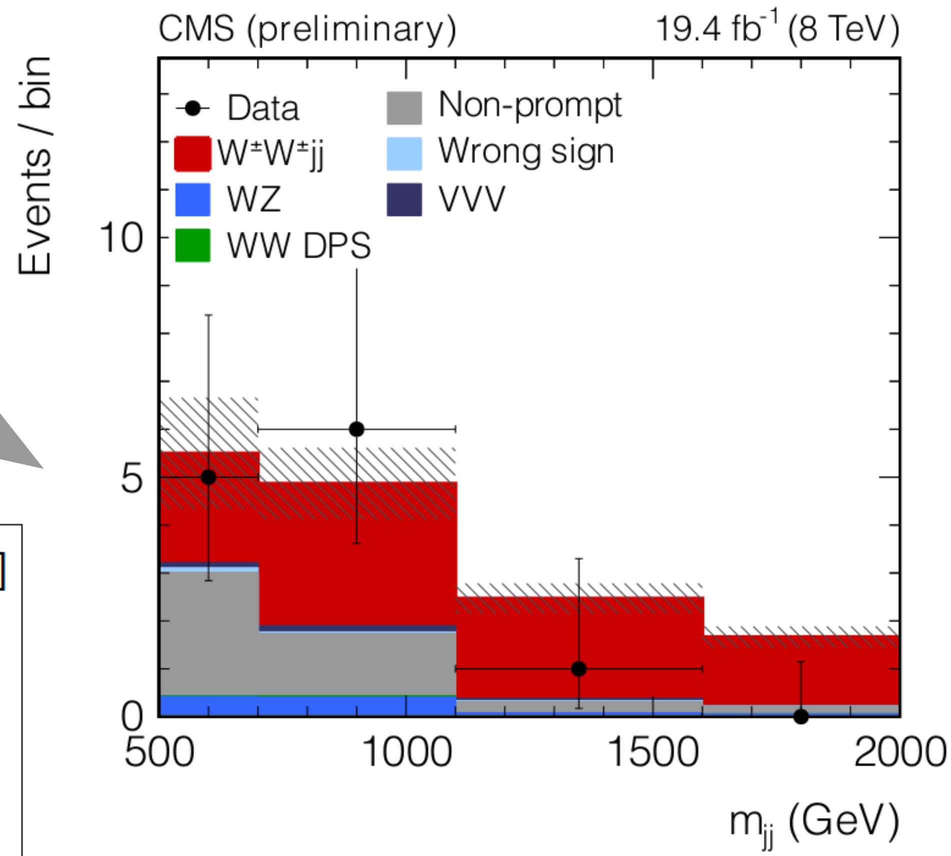
$\to$ exploited by central-jet veto techniques

note: parton-shower effects slightly enchance central jet activity

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

details in
Nicolas Pierre
Chanon's talk





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

summary

recent years have seen much progress on the theory side:

✔ precision calculations for $VVjj$ processes

✔ tool development: public codes including

- NLO-QCD corrections
- parton-shower effects

. . . can develop their full potential only

if used by experimentalists . . .

...for your attention