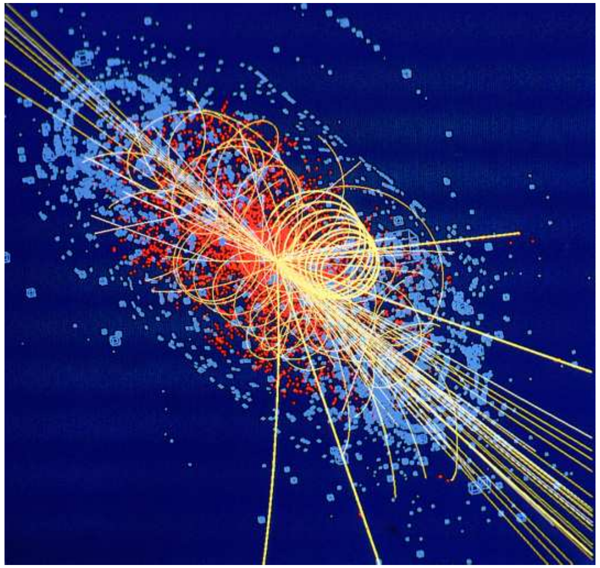
Weak boson fusion processes and parton showers

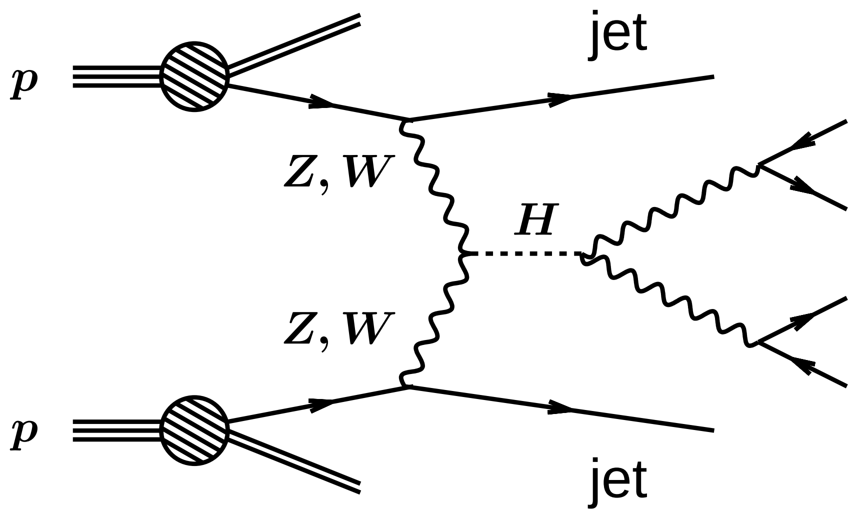


Annual Workshop of the Helmholtz Alliance "Physics at the Terascale"

December 2012

Barbara Jäger
Johannes-Gutenberg University Mainz

weak vector boson fusion (VBF): event topology



suppressed color exchange between quark lines gives rise to

- little jet activity in central rapidity region
- scattered quarks $\longrightarrow$ two forward tagging jets
  (energetic; large rapidity)
- Higgs decay products typically between tagging jets

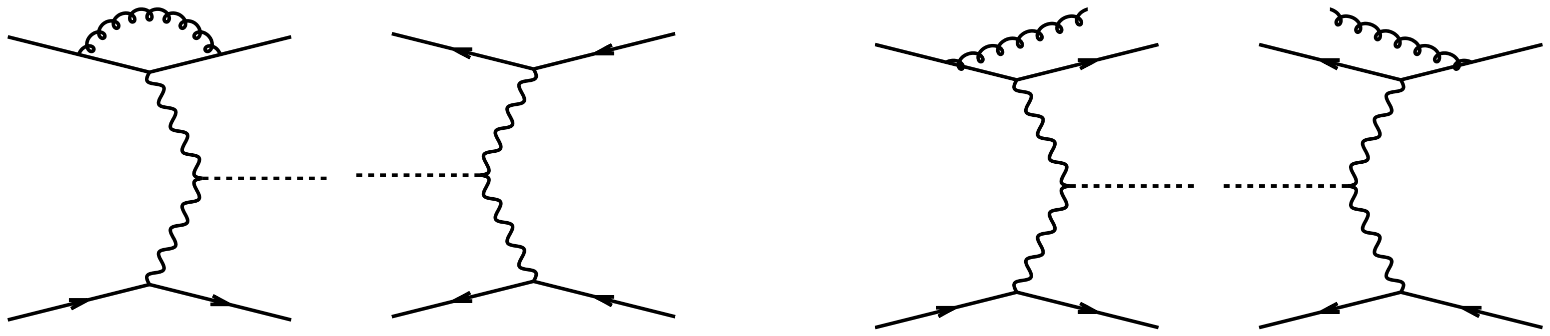
weak vector boson fusion (VBF)

CMS & ATLAS:
VBF selection included in
$H \to \gamma\gamma$, $H \to WW$,
$H \to \tau\tau$

- important Higgs search channel over entire mass range
- sensitive to Higgs couplings and CP properties

☞ accurate predictions and flexible tools essential for signal and backgrounds!

Higgs production in VBF @ NLO QCD and EW



NLO QCD:
inclusive cross section:
Han, Valencia, Willenbrock (1992)

distributions:
Figy, Oleari, Zeppenfeld (2003)
Berger, Campbell (2004)

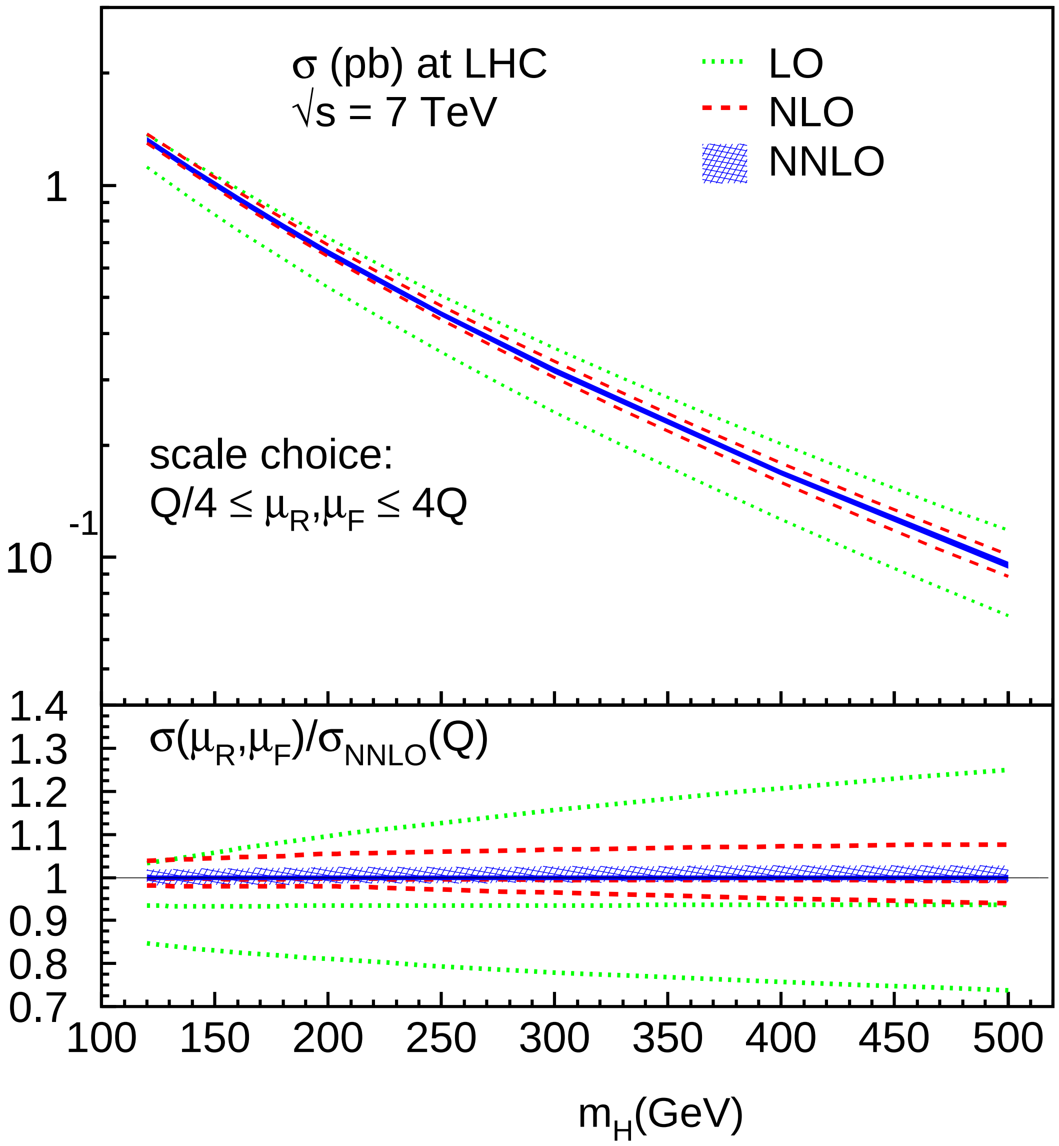
inclusion of NLO EW corrections:
Ciccolini, Denner, Dittmaier, Mück (2007)

→

NLO QCD corrections moderate and well under control (order 10% or less)

publicly available parton-level Monte Carlos:
`vbfnlo`, MCFM, HAWK

higher orders of QCD in VBF



- 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

VBF signal / background analysis

☞ selection of signal and background rates

for $M_H = 160$ GeV (in [fb])

in the $H \to e^+\mu^- \not{p}_T$ decay mode at the LHC :

cuts	Hjj	$t\bar{t}$+jets	QCD $WWjj$	EW $WWjj$	...	S / B
forward tagging	17.1	1080	4.4	3.0	...	1/65
+b veto		64			...	1/5.1
+angular cuts	11.4	5.1	0.50	0.45	...	1.7/1
+central jet veto	10.1	1.48	0.15	0.34	...	4.6/1
all cuts	7.5	1.09	0.11	0.25	...	4.6/1

Rainwater, Zeppenfeld (1999)

central jet veto

central jet veto (CJV):

remove events with extra jet(s) in central-rapidity region

$p_T^{\text{veto}} > 20$ GeV, $\eta_{\text{jet}}^{\text{min}} < \eta_{\text{jet}}^{\text{veto}} < \eta_{\text{jet}}^{\text{max}}$

cuts	Hjj	$t\bar{t}$+jets	QCD $WWjj$	EW $WWjj$	...	S / B
forward tagging	17.1	1080	4.4	3.0	...	1/65
+b veto		64			...	1/5.1
+angular cuts	11.4	5.1	0.50	0.45	...	1.7/1
+central jet veto	10.1	1.48	0.15	0.34	...	4.6/1
all cuts	7.5	1.09	0.11	0.25	...	4.6/1

Rainwater, Zeppenfeld (1999)

central jet veto (CJV):

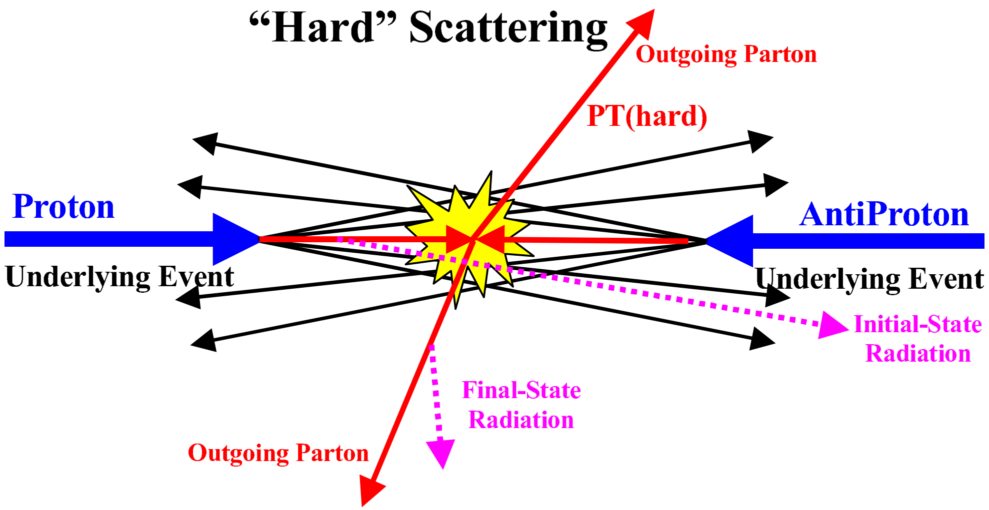
remove events with extra jet(s) in central-rapidity region

$$p_T^{\text{veto}} > 20 \text{ GeV}, \ \eta_{\text{jet}}^{\min} < \eta_{\text{jet}}^{\text{veto}} < \eta_{\text{jet}}^{\max}$$

☞ precise knowledge of extra jet activity essential, requiring

- $pp \to Hjj$ interfaced to parton shower programs
- $pp \to Hjjj$ at NLO-QCD accuracy

$pp \to Hjj$ via VBF and parton showers



for realistic description of scattering processes at hadron colliders:

- combine matrix elements for hard scattering with programs for simulation of

underlying event, parton shower, and hadronization

`(Pythia, Herwig, Sherpa,...)`

NLO-QCD vs. shower Monte Carlo

NLO QCD:

- ✔ accurate shapes at high p_T
- ✔ normalization accurate at NLO
- ✔ reduced scale dependence
- ✘ wrong shapes at low p_T
- ✘ description only at parton level

LO SMC:

- ✘ bad description at high p_T
- ✘ normalization accurate only at LO
- ✔ Sudakow suppression at low p_T
- ✔ events at hadron level

☞ merge the two approaches, keeping the advantages of both:

- `MC@NLO` *[Frixione, Webber]*
- `POWHEG` *[Nason et al.]*

parton showers & NLO-QCD: the POWHEG method

general prescription for matching parton-level NLO-QCD calculations with parton shower programs

[Frixione, Nason, Oleari]

- applicable to any p_T-ordered parton shower program
- no double counting of real-emission contributions
- produces events with positive weights
- tools for "do-it-yourself" implementation publicly available (the `POWHEG-BOX`)

[Alioli, Nason, Oleari, Re]

parton showers & NLO-QCD: the POWHEG-BOX

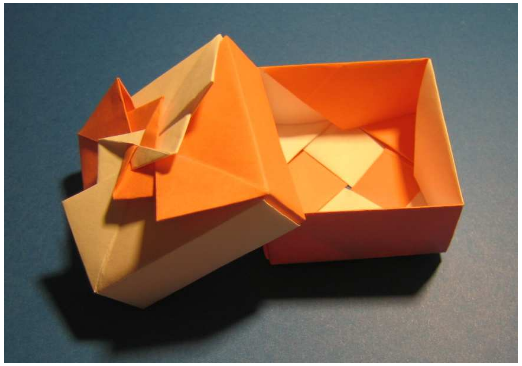
✘ user has to supply process-specific quantities:

- lists of flavor structures for Born and real emission processes
- Born phase space
- Born amplitudes squared, color-and spin-correlated amplitudes
- real-emission amplitudes squared
- finite part of the virtual corrections
- Born color structure in the limit of a large number of colors

✔ all general, process-independent aspects of the matching are provided by the POWHEG-BOX

up-to-date info on the POWHEG-BOX
and code download:

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

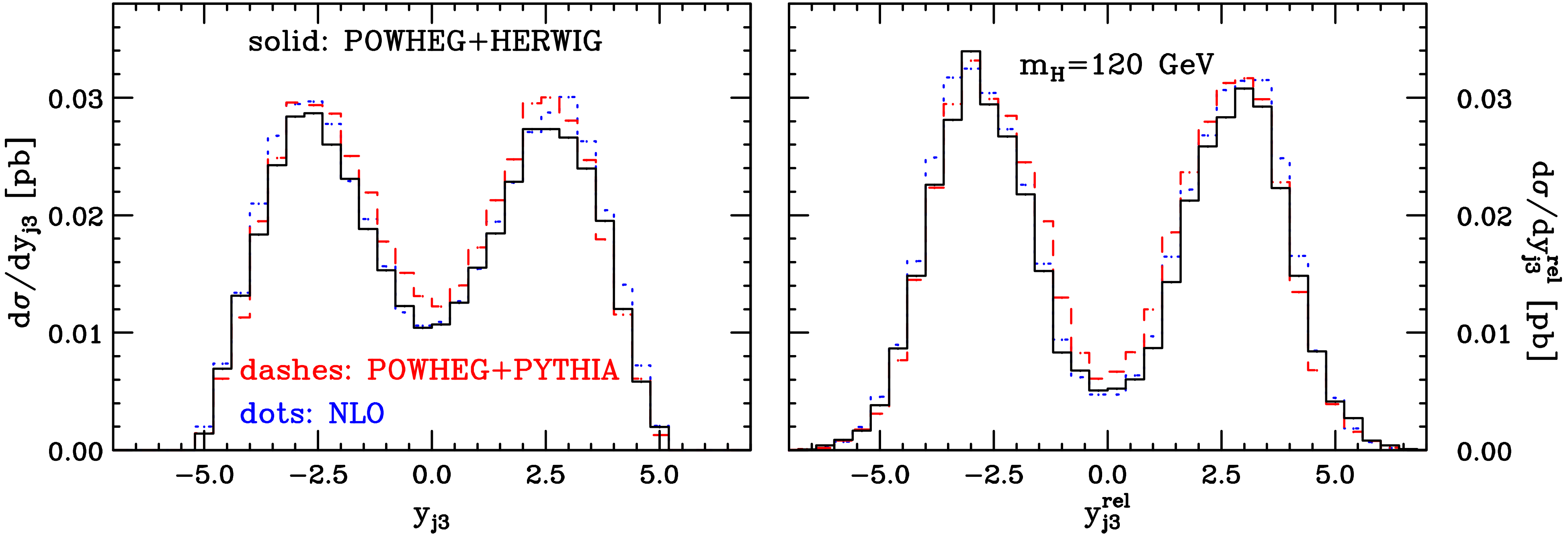


VBF processes in the POWHEG-BOX:

- Higgs production via VBF *[Oleari, Nason (2009)]*
- Z-boson production via VBF *[Schneider, Zanderighi, B.J. (2012)]*
- W^+W^+ production via VBF *[Zanderighi, B.J. (2011)]*

. . . and various background processes

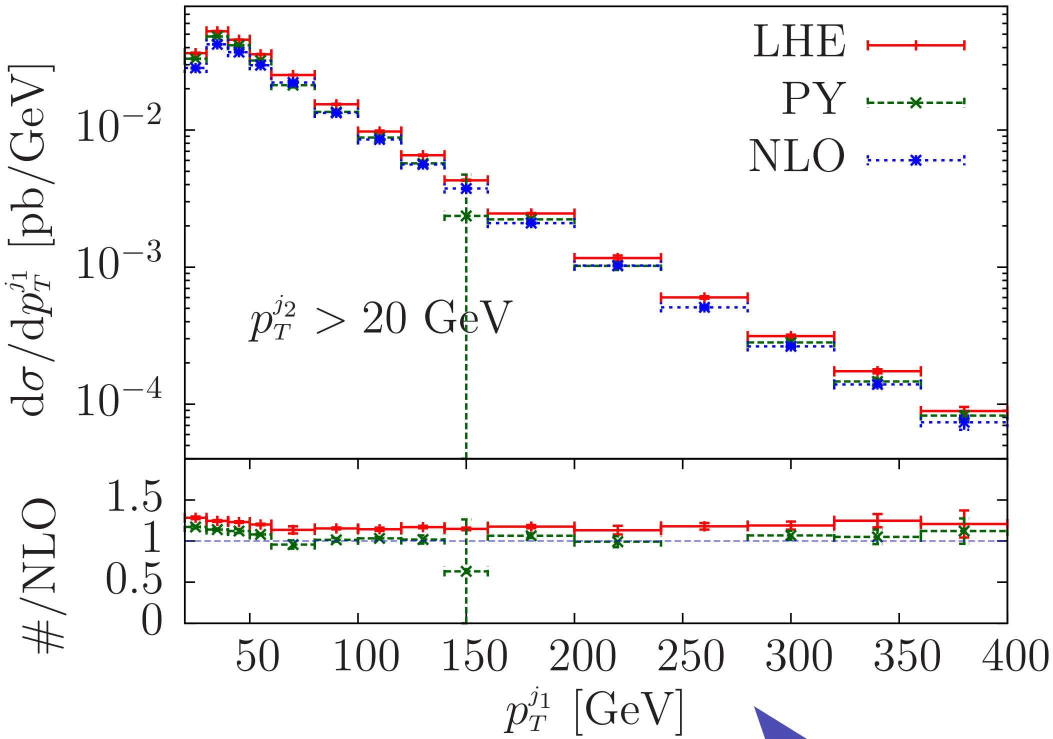
Nason, Oleari (2009)

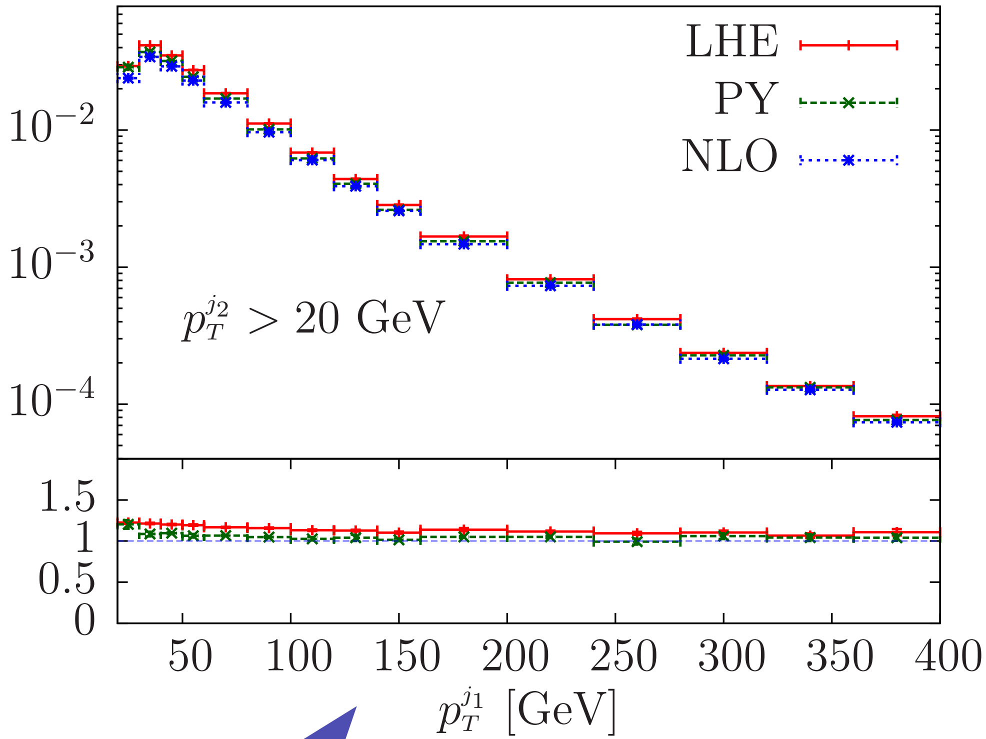


- good agreement between parton-level NLO calculation and POWHEG matched with HERWIG or PYTHIA for many observables
- for high multiplicities, HERWIG produces harder jets than PYTHIA

$pp \to Hjj$ via GF in the POWHEG-BOX

Campbell et al. (2012)





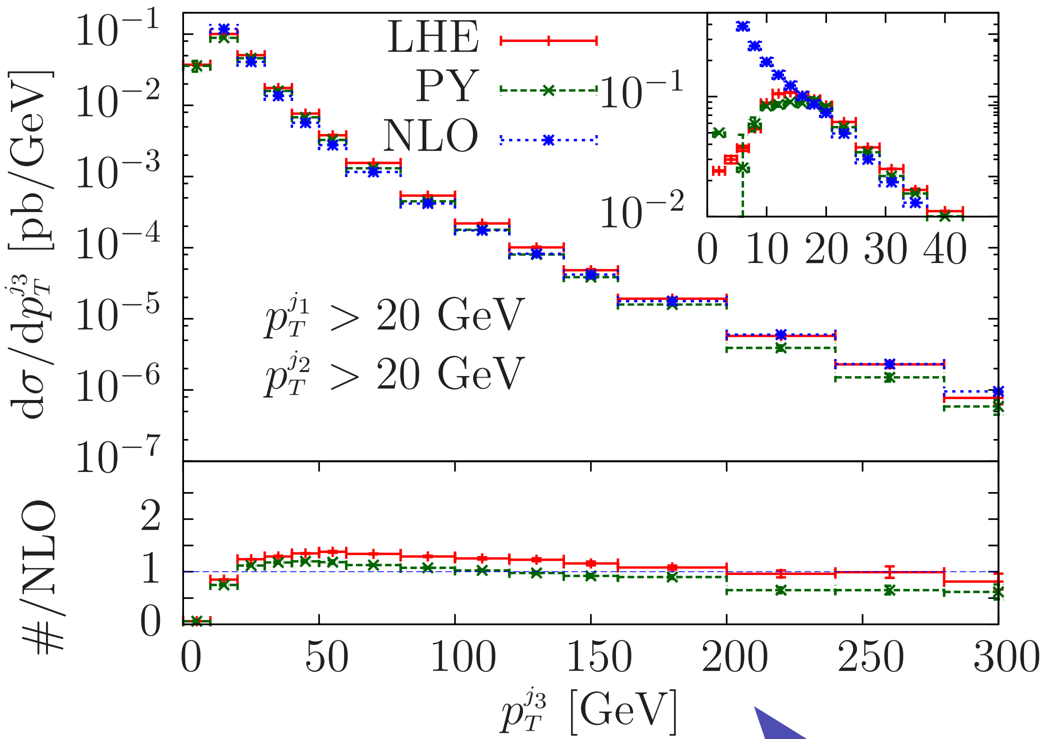
fixed scale $\mu = M_H$

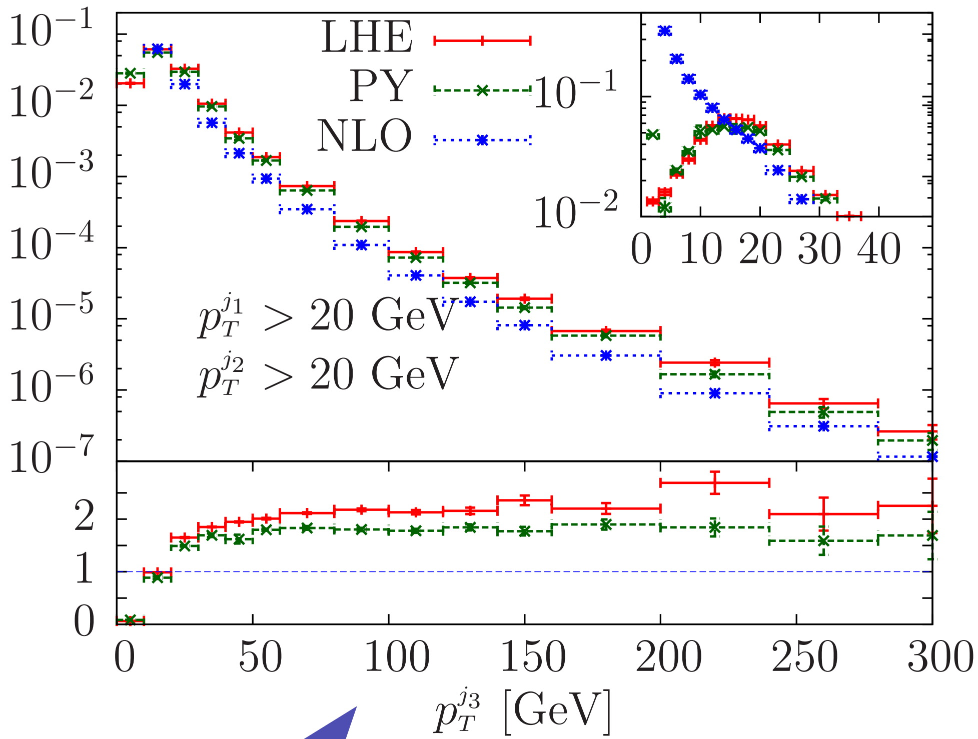
running scale: $\mu = \hat{H}_{\mathrm{tot}}$

good agreement between parton-level NLO calculation and POWHEG matched with PYTHIA for many observables

$pp \to Hjj$ via GF in the POWHEG-BOX

Campbell et al. (2012)



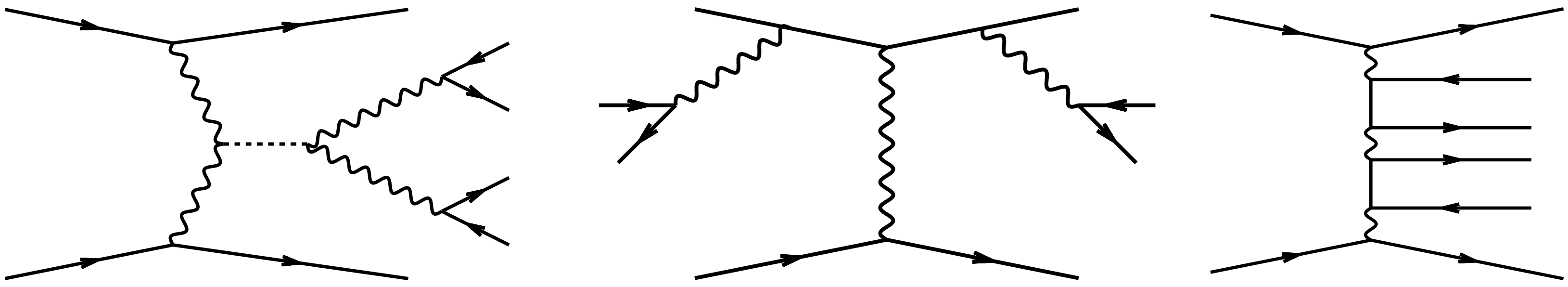


fixed scale $\mu = M_H$

running scale: $\mu = \hat{H}_{\mathrm{tot}}$

impact of matching to parton shower depends on observable and scale settings

$VVjj$ production via VBF



W^+W^-jj, $ZZjj$, $W^\pm Zjj$, and $W^\pm W^\pm jj$

production via VBF at NLO-QCD accuracy

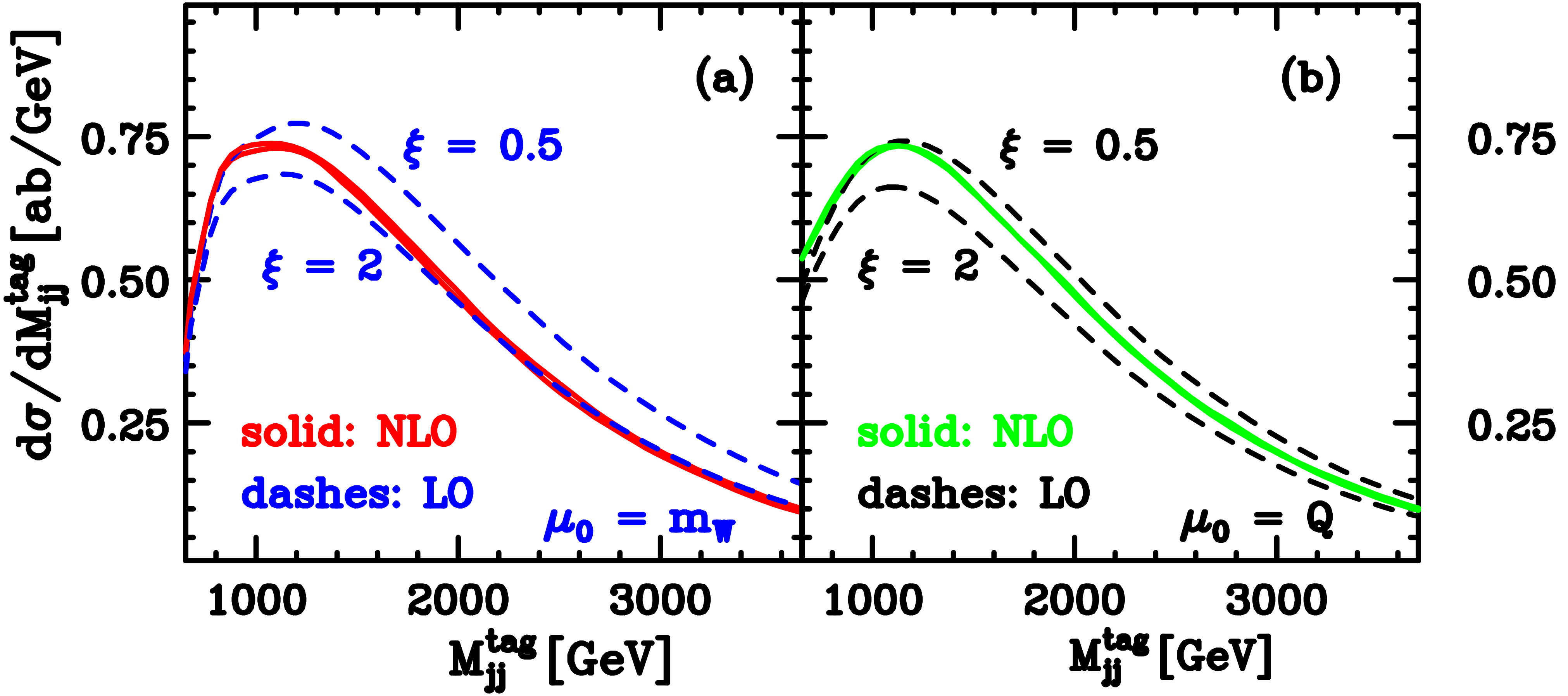
G. Bozzi, C. Oleari, D. Zeppenfeld, B. J. (2006- 2009)

- leptonic decay correlations fully taken into account
- straightforward implementation of cuts

publicly available in VBFNLO

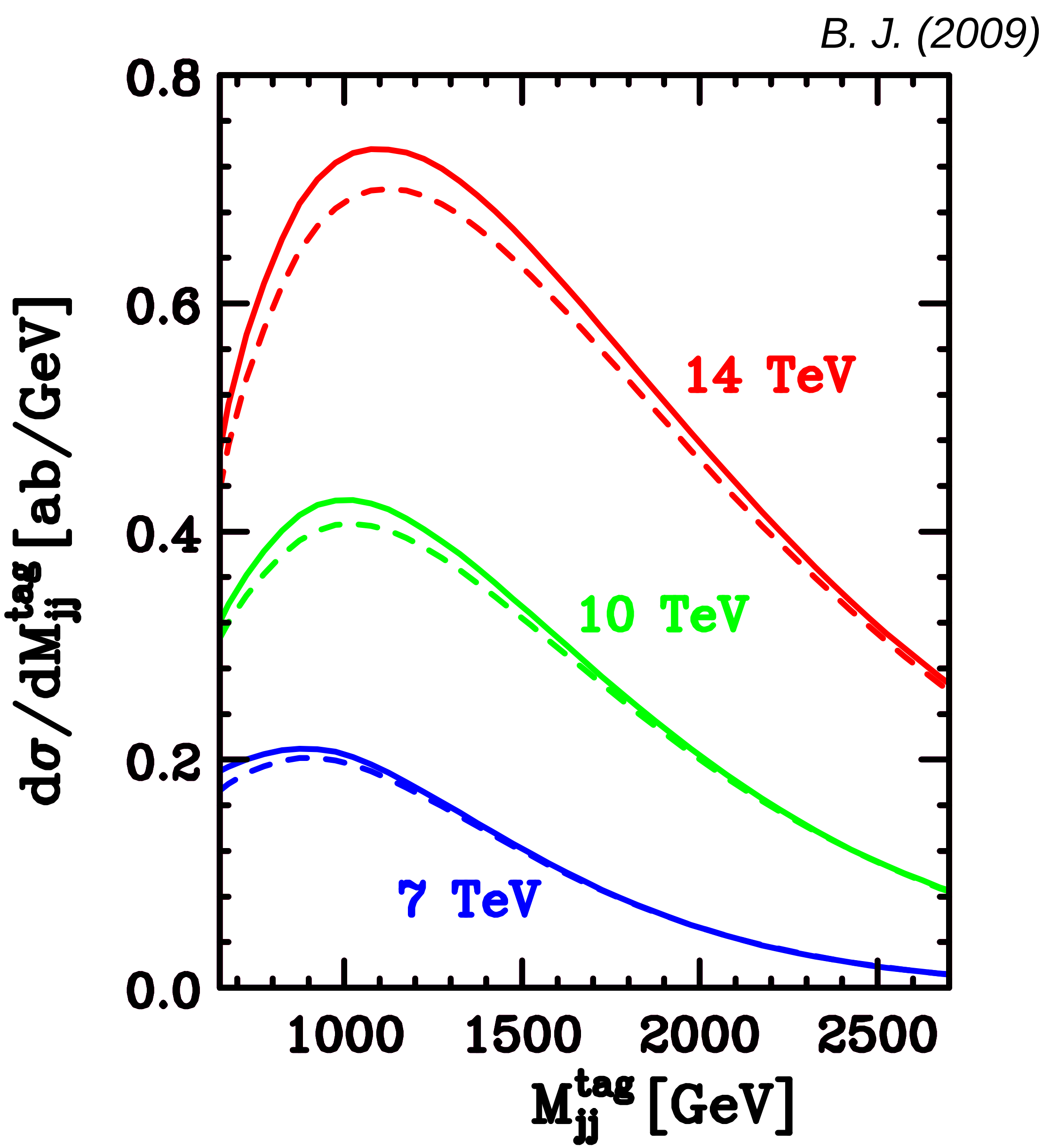
W^+W^+jj distributions: invariant mass of tagging jets

Oleari, Zeppenfeld, B. J. (2009)



$$\mu = \xi\,\mu_0$$

$pp \to W^+W^+jj$: energy dependence



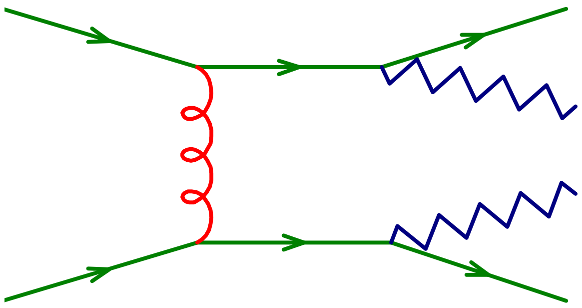
$pp \to W^+W^+jj$ in the POWHEG-BOX

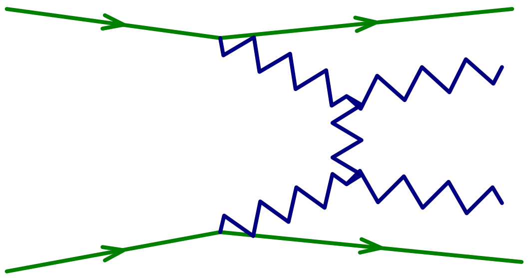
QCD-induced production

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

EW production

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





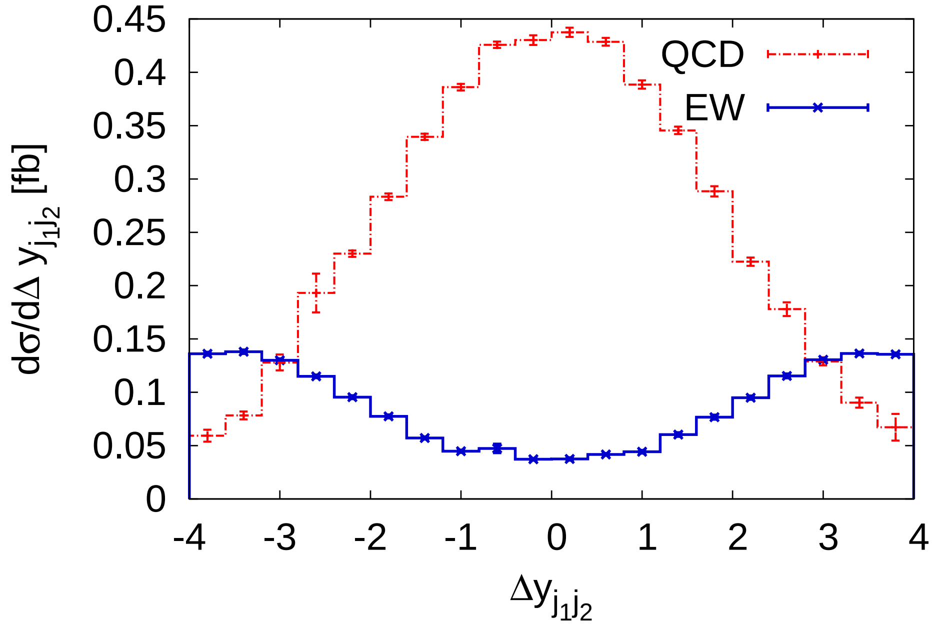
NLO-QCD results with basic jet cuts only ($p_T^{\text{tag}} > 20$ GeV):

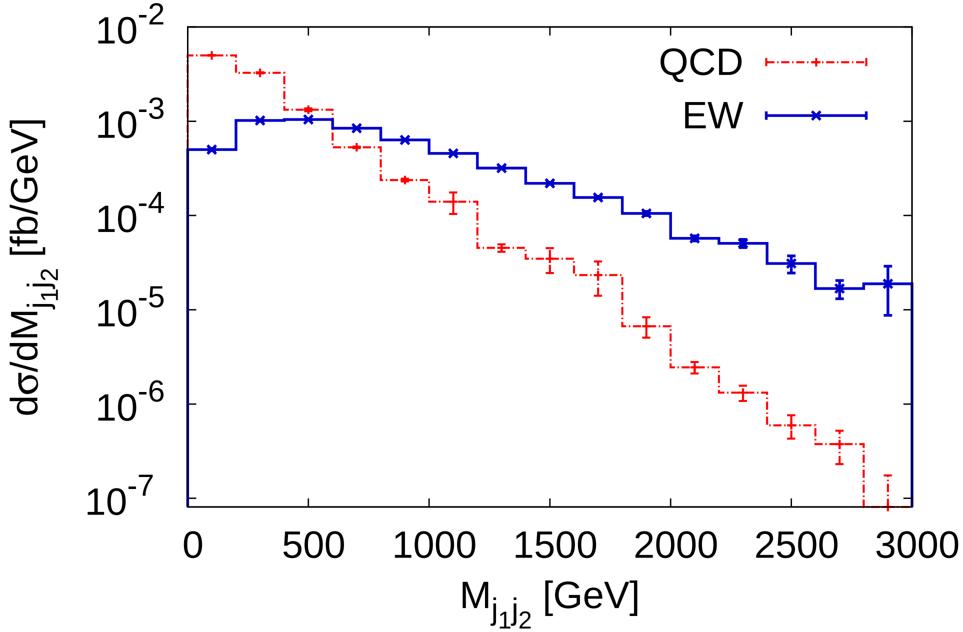
$\sigma_{\text{QCD}}^{\text{inc}} = 2.12$ fb

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

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

Zanderighi, B.J. (2011)





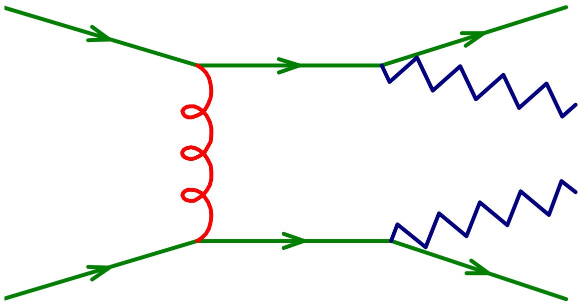
- $\sqrt{s} = 7$ TeV
- basic jet cuts only
- NLO-QCD accuracy

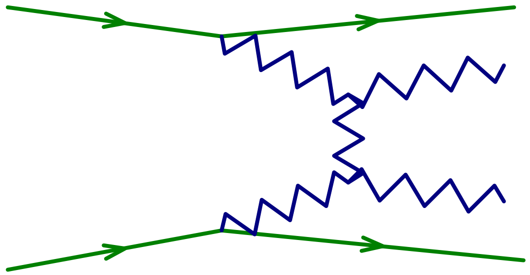
QCD-induced production

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

EW production

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





NLO results with basic jet cuts only ($p_T^{tag} > 20$ GeV):

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

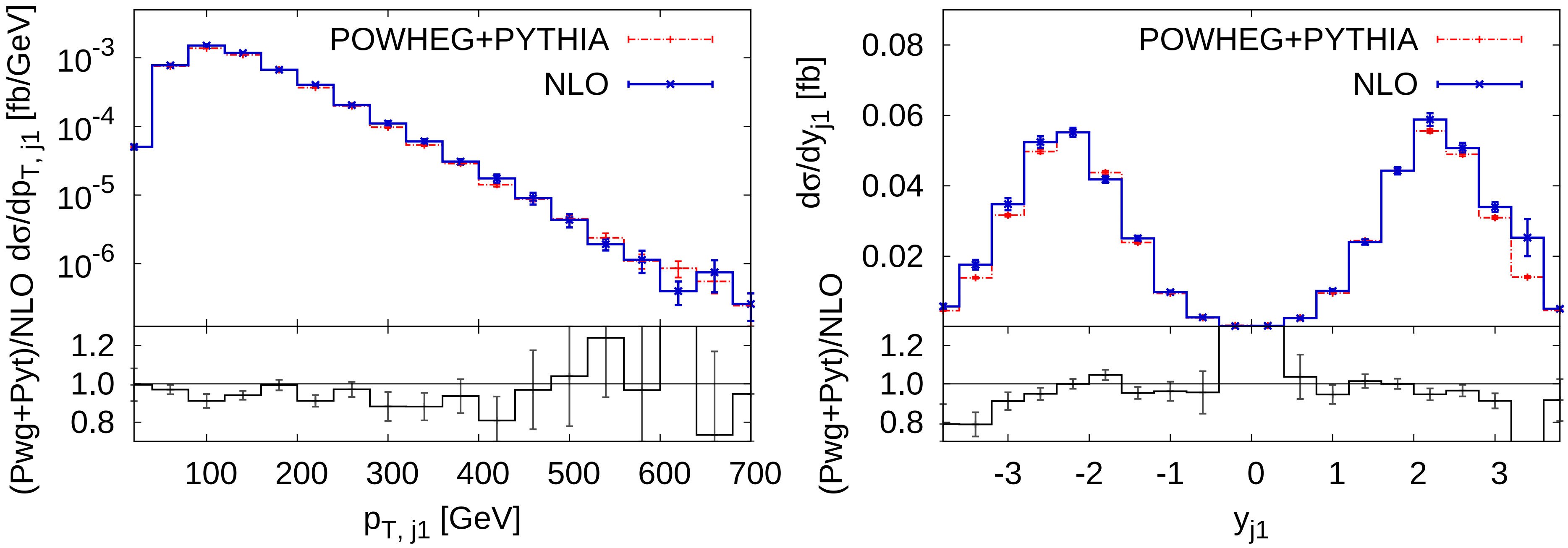
$\sigma_{EW}^{inc} = 1.097$ fb

NLO results with VBF cuts:

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

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

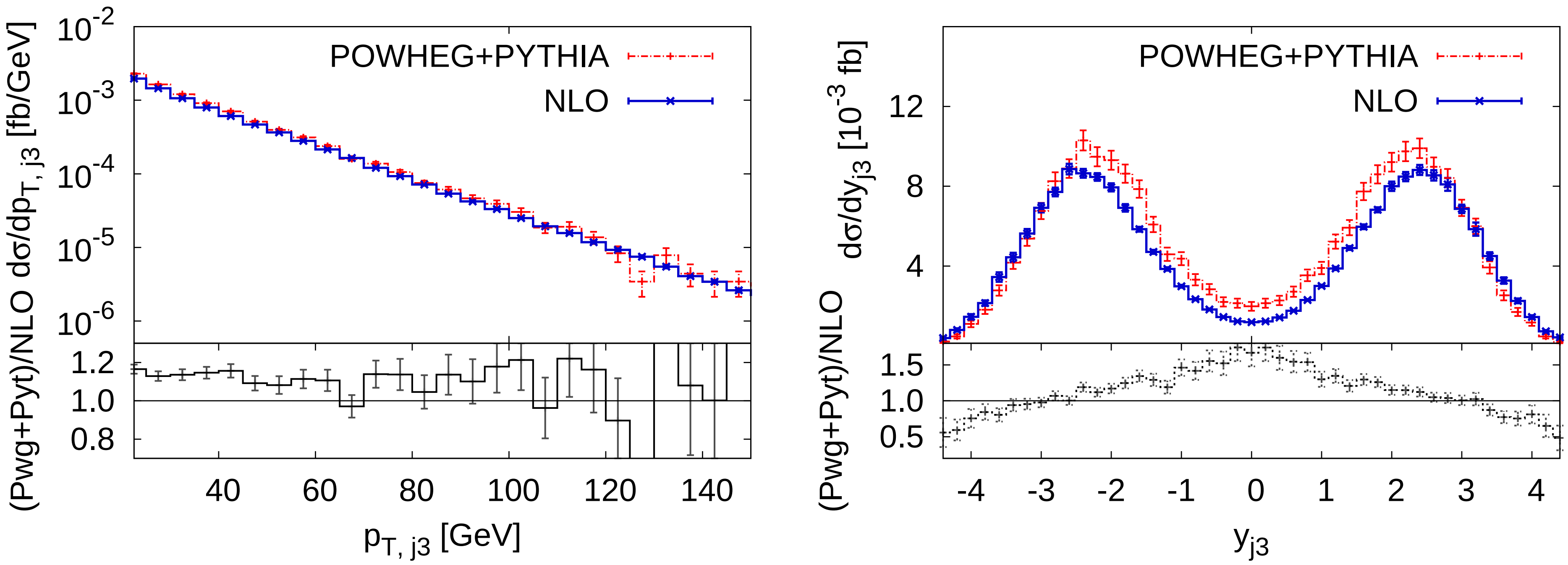
Zanderighi, B.J. (2011)



good agreement between parton-level NLO calculation and POWHEG matched with PYTHIA for many observables

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

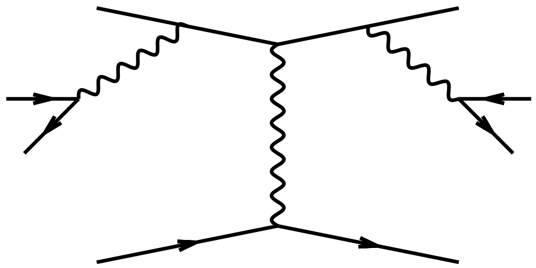
Zanderighi, B.J. (2011)



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

note: parton-shower effects slightly enchance central jet activity

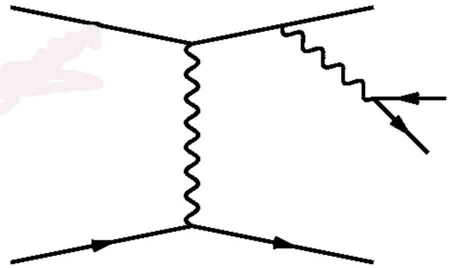
$pp \longrightarrow Zjj$ via VBF



$pp \longrightarrow Zjj$

versus

$pp \longrightarrow W^+W^+jj$

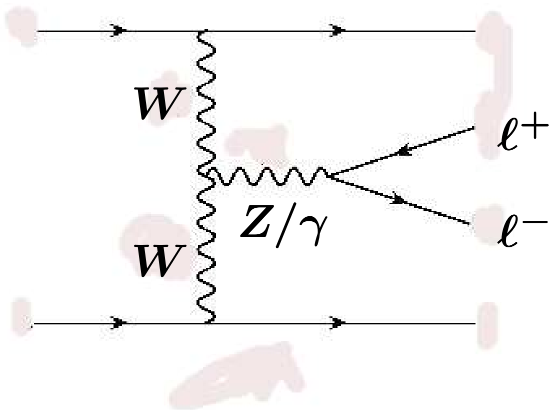


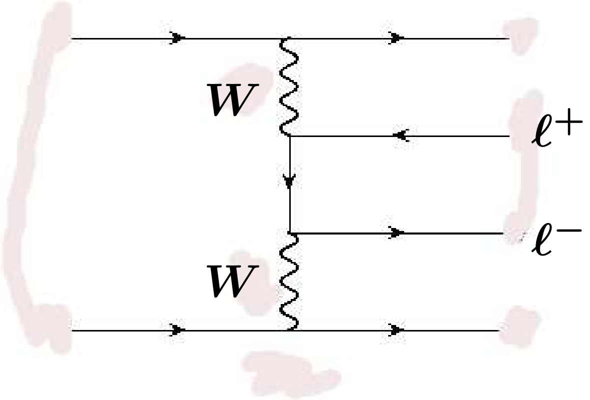
less particles in final state
$\longrightarrow$ simpler matrix elements

more massless particles
$\longrightarrow$ more involved singularity structure

$pp \longrightarrow Zjj$ via VBF in the POWHEG-BOX

charged current modes:





singularity structure similar to $pp \longrightarrow W^+W^+jj$ via VBF, but

$\gamma^\star \longrightarrow \ell^+\ell^-$ singular as $Q^2_{\ell\ell} \longrightarrow 0$

$\longrightarrow$ introduce generation cut

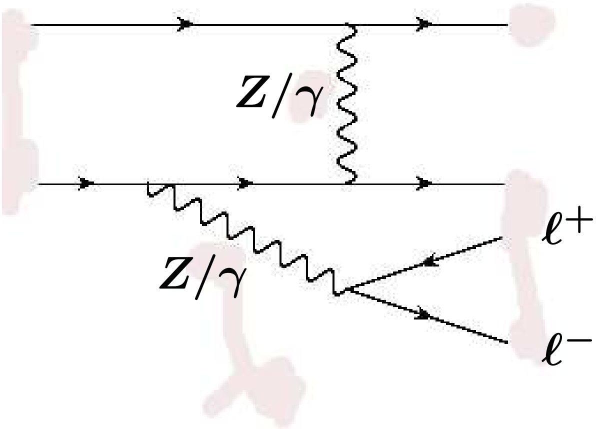
$$m_{\ell\ell}^{\rm gen} = 30\ {\rm GeV}\,,$$

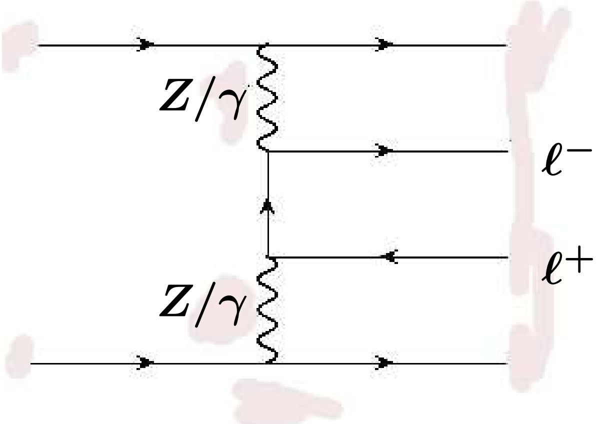
supplemented by analysis cut

$$m_Z - 10\ \text{GeV} < m_{\ell\ell} < m_Z + 10\ \text{GeV}$$

$pp \to Zjj$ via VBF in the POWHEG-BOX

neutral current modes:





extra singularity for photons in t-channel

with $Q^2_\gamma \to 0$

($\leftrightarrow$ related to low-p_T jets)

☞ damping factor in matrix elements

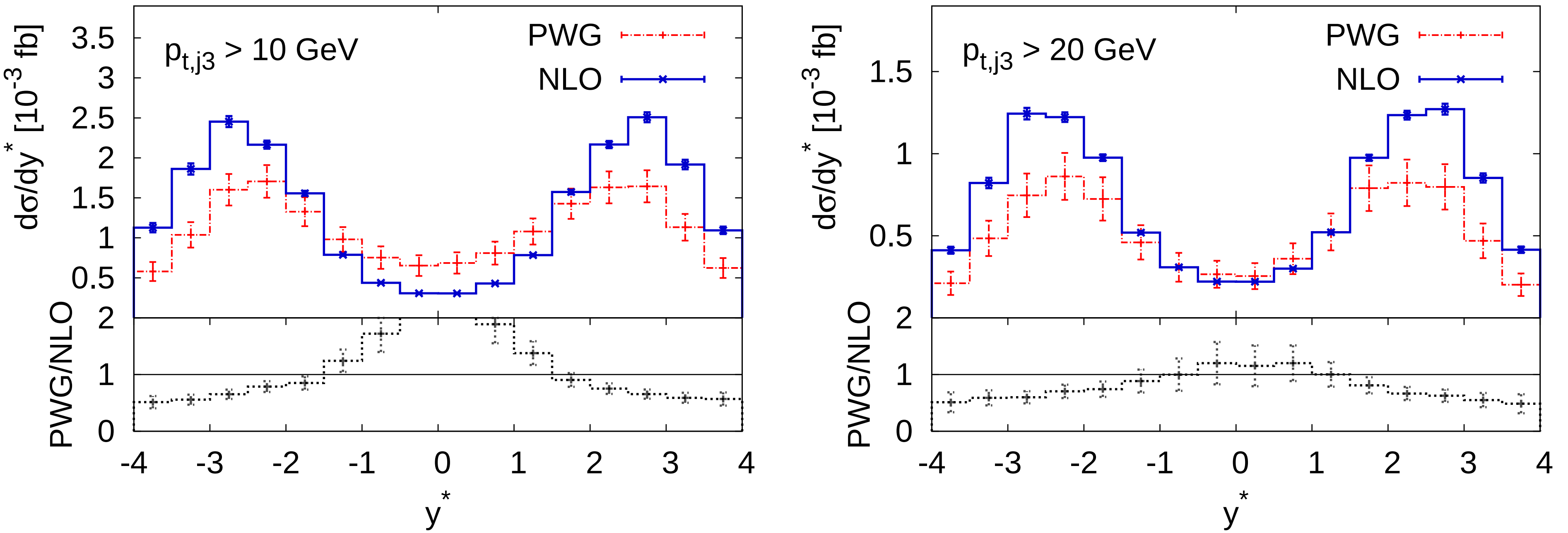
☞ Born-suppression factor

$$F \sim \left(\frac{p^2_{T,1}}{p^2_{T,1}+\Lambda^2}\right)^2 \left(\frac{p^2_{T,2}}{p^2_{T,2}+\Lambda^2}\right)^2$$

(alternative: generation cuts)

$pp \longrightarrow Zjj$ via VBF in the POWHEG-BOX

Schneider, Zanderighi, B.J. (2012)



location of third jet relative to tagging jets

$$y^\star = y_{j3} - \frac{y_{j1} - y_{j2}}{2}$$

note: transverse momentum cut on extra jets matters

parton showers and NLO-QCD

- for precise and realistic predictions NLO-QCD calculations matched to parton shower programs are important

- codes for several VBF processes are publicly available in the `POWHEG-BOX` from

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

☞ please use and cite