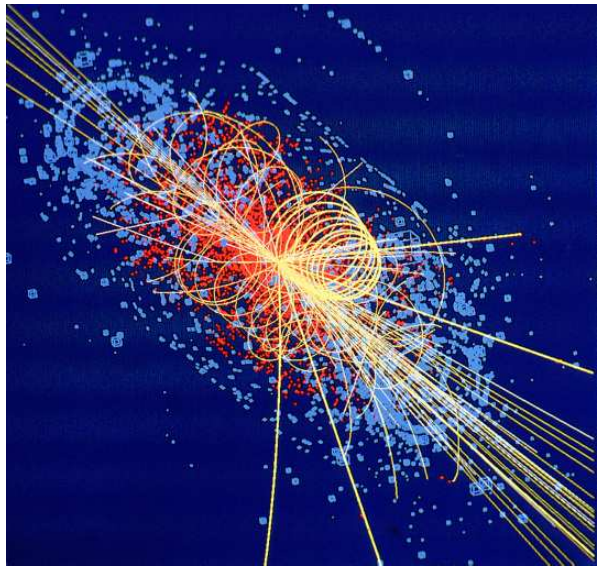
Matching $WWjj$ processes with parton shower programs



Snowmass Energy Frontier Workshop

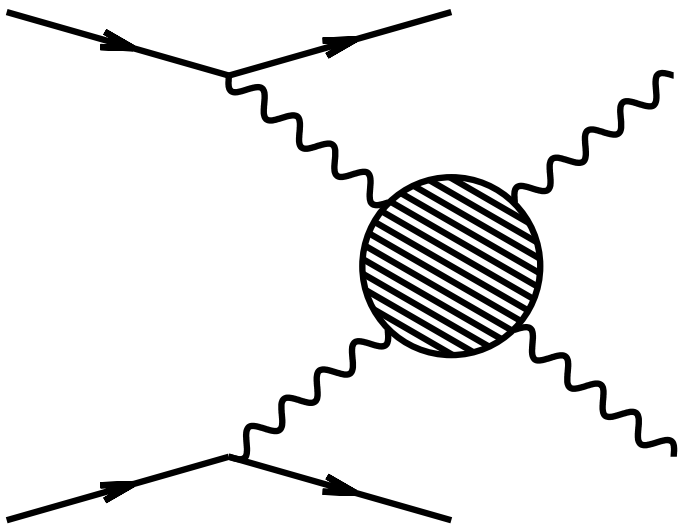
Brookhaven National Laboratory

April 2013

Barbara Jäger

Johannes-Gutenberg University Mainz

new interactions in the gauge boson sector



VBF processes are extremely sensitive to new interactions in the gauge boson sector

↓

can we spot signatures of non-standard scenarios for electroweak symmetry breaking?

EW $VVjj$ production

VBFNLO: fast & flexible Monte Carlo program allowing for

- computation of various observables for

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

production via VBF at NLO-QCD accuracy

(leptonic decay correlations are fully taken into account)

- straightforward implementation of cuts

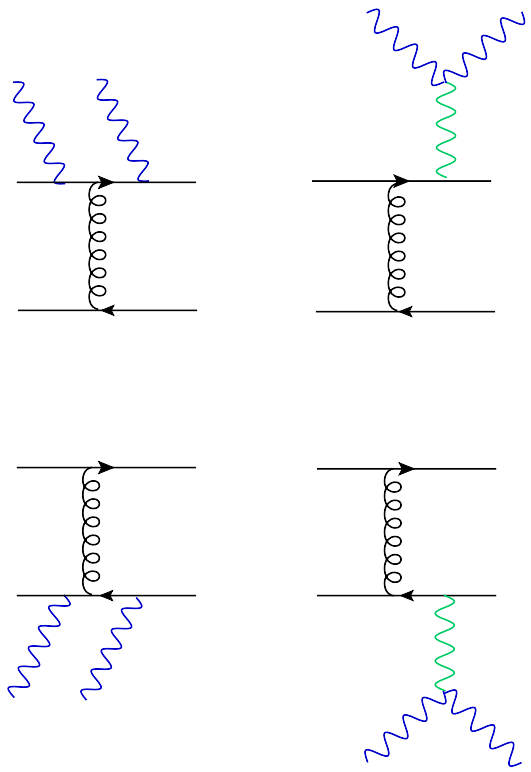
C. Oleari, D. Zeppenfeld, B. J. (2006)

G. Bozzi, C. Oleari, D. Zeppenfeld, B. J. (2007)

C. Oleari, D. Zeppenfeld, B. J. (2009)

[c. f. also: A. Denner, L. Hosekova, S. Kallweit (2012)]

QCD-induced $VVjj$ production



NLO-QCD predictions available:

$\underline{W^+W^+jj}$:

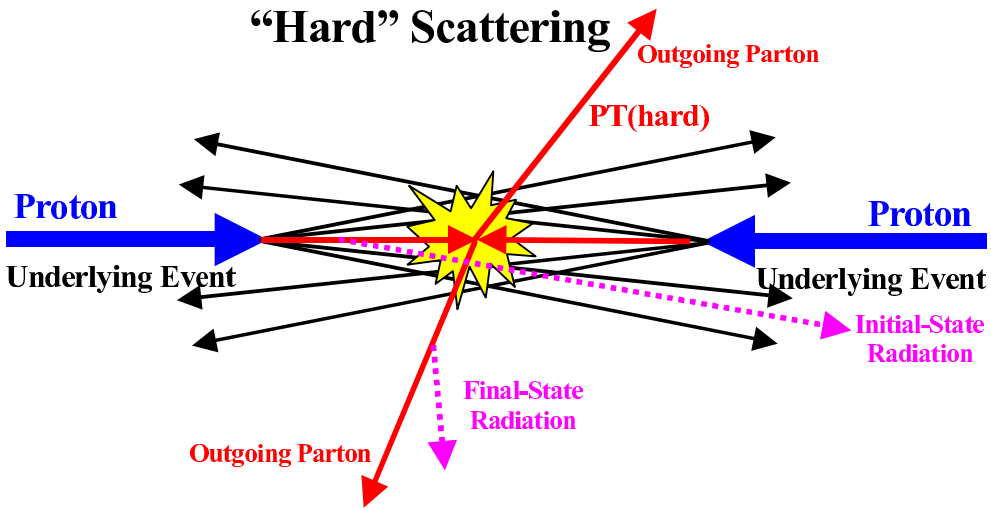
Melia, Melnikov, Rontsch, Zanderighi (2010);

$\underline{W^+W^-jj}$:

Melia, Melnikov, Rontsch, Zanderighi (2011);

Greiner et al. (2012)

more realistic simulation



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 Shower Monte Carlo:

- ✘ 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:

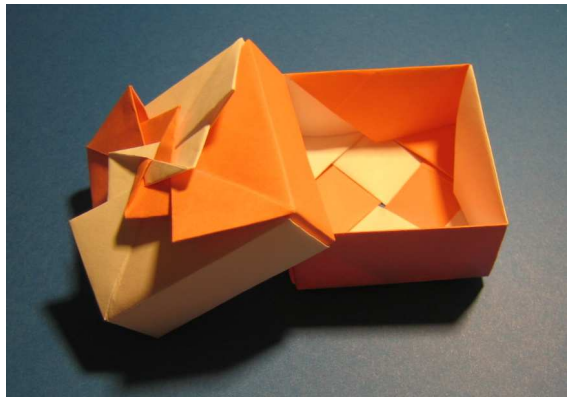
- lists of flavor structures for Born and real emission processes
- Born phase space
- Born amplitudes squared, color-and spin-correlated amplitudes
- real-emission amplitudes squared
- finite part of the virtual corrections
- Born color structure in the limit of a large number of colors

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

parton showers & NLO-QCD: 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- and Z-boson production via VBF *[Schissler, Zeppenfeld (2013)]*
- W^+W^+ production via VBF *[Zanderighi, B.J. (2011)]*
- W^+W^- production via VBF *[Zanderighi, B.J. (2013)]*

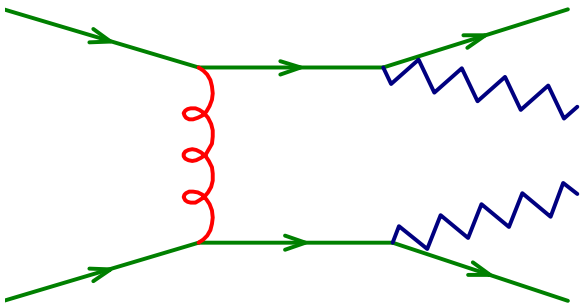
$pp \to W^+W^+jj$ in the POWHEG-BOX

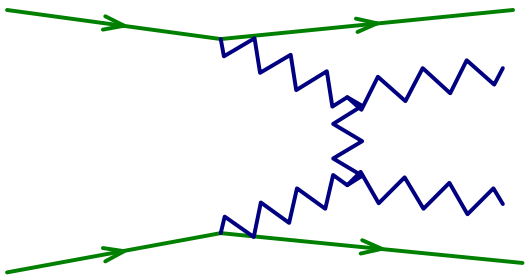
QCD-induced production

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

EW production

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



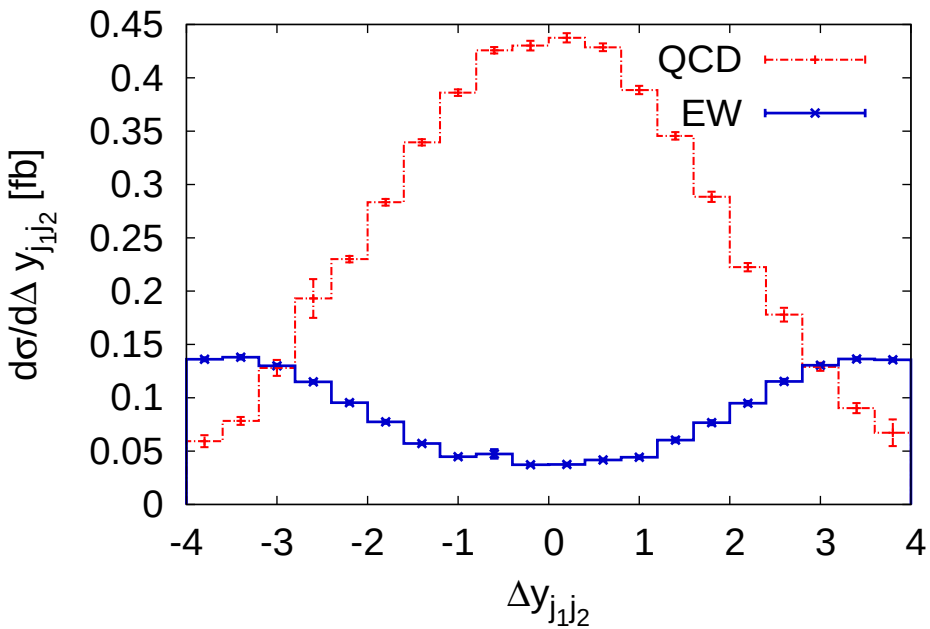


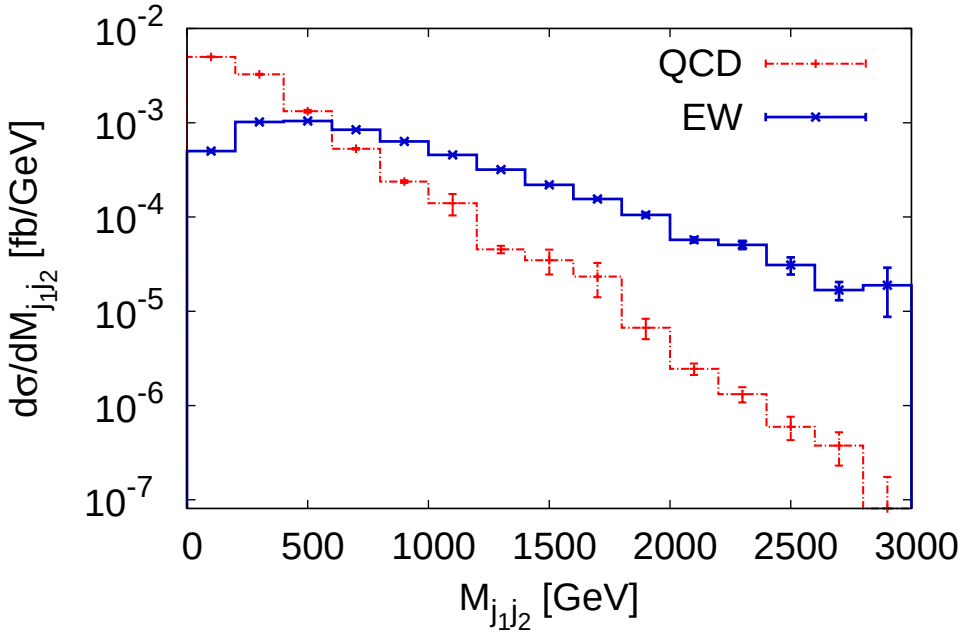
NLO-QCD results for $\sqrt{s}$ =7 TeV with basic jet cuts only ($p_T^{\rm tag} > 20$ GeV):

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

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

Zanderighi, B.J. (2011)

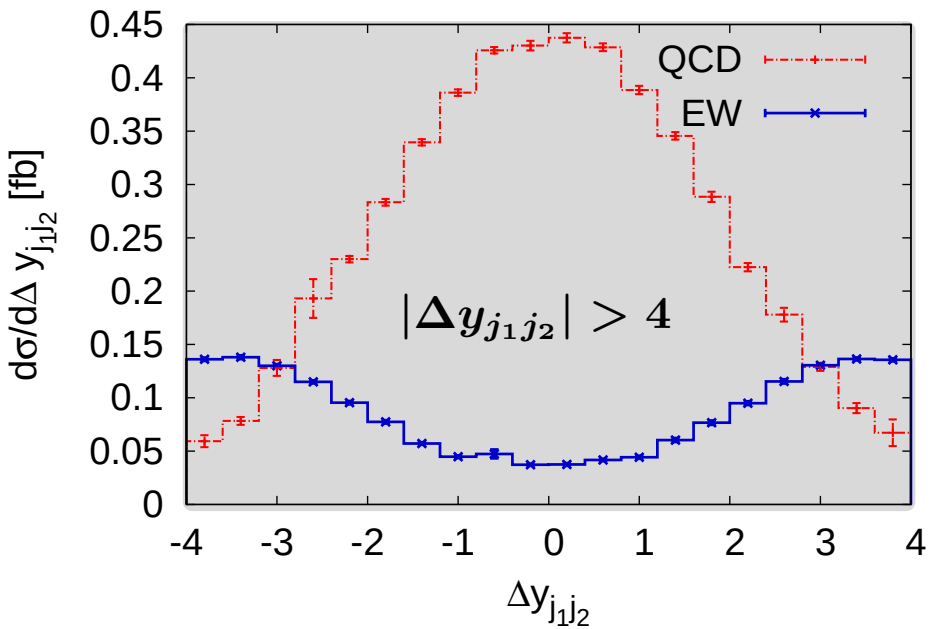


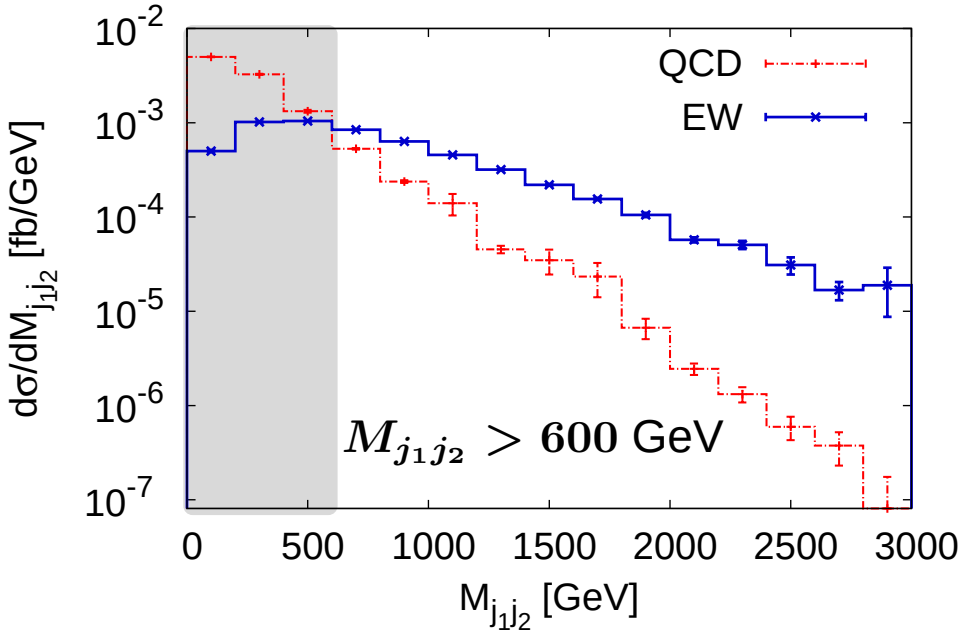


- $\sqrt{s} = 7$ TeV
- basic jet cuts only
- NLO-QCD accuracy

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

Zanderighi, B.J. (2011)

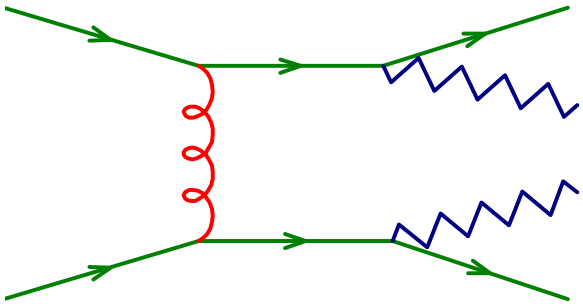


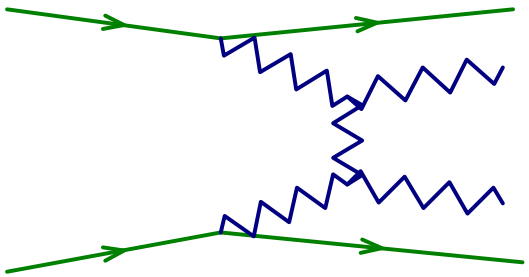


- $\sqrt{s} = 7$ TeV
- basic jet cuts only
- NLO-QCD accuracy

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

QCD-induced production	EW production
Melia, Melnikov, Rontsch, Zanderighi (2010); Melia, Nason, Rontsch, Zanderighi (2011)	*Oleari, Zeppenfeld, B.J. (2009); Zanderighi, B.J. (2011)*





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

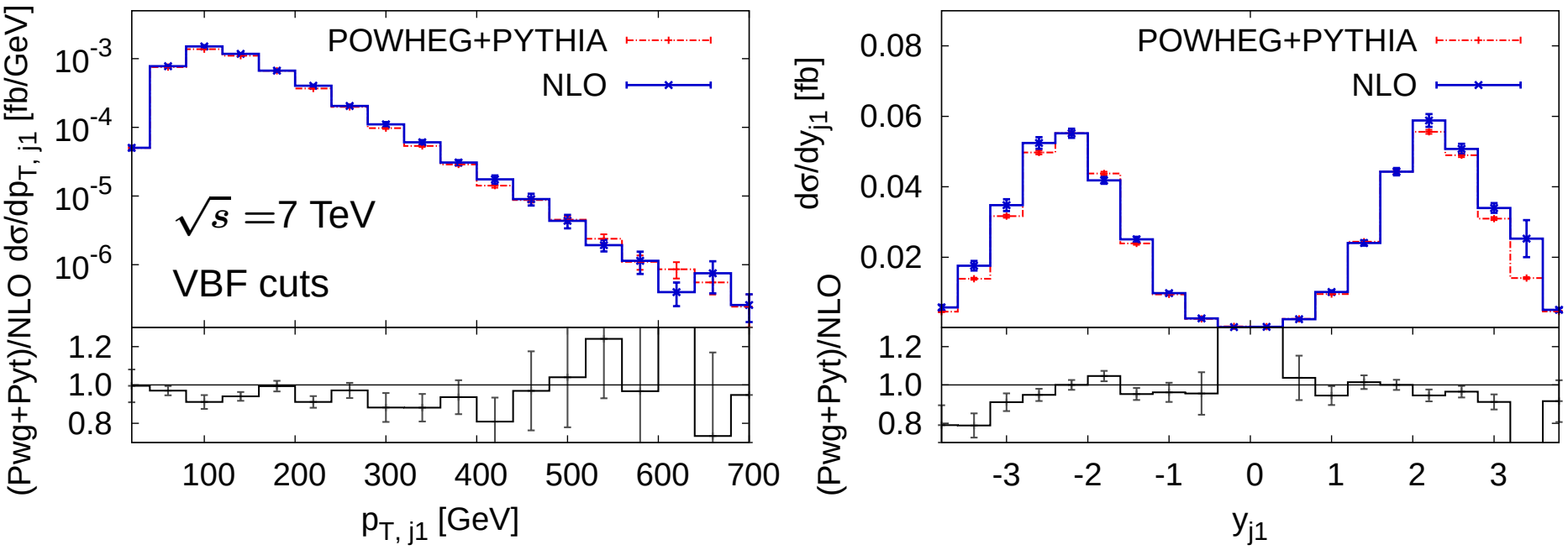
$$\sigma_{\rm QCD}^{\rm inc} = 2.12 \text{ fb} \qquad \sigma_{\rm EW}^{\rm inc} = 1.097 \text{ fb}$$

NLO results with VBF cuts:

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

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

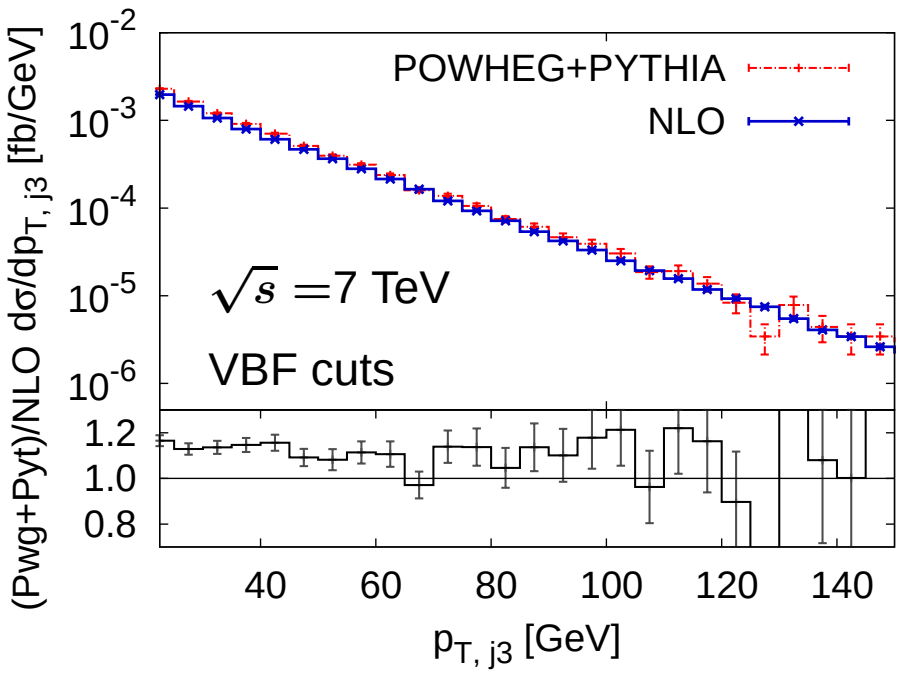
Zanderighi, B.J. (2011)

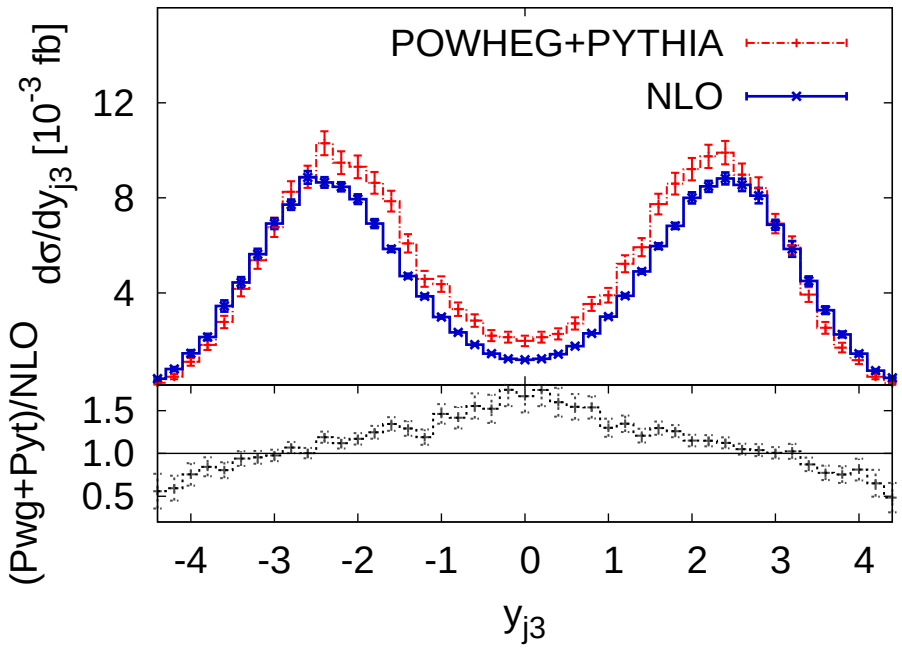


good agreement between parton-level NLO calculation and POWHEG matched with PYTHIA for many observables

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

Zanderighi, B.J. (2011)

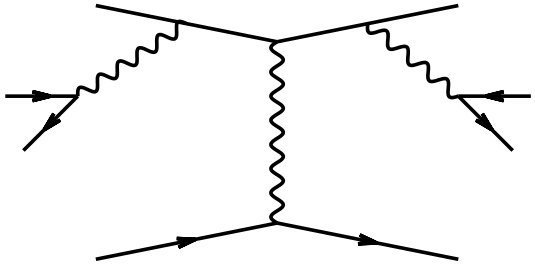




typical for VBF processes: little jet activity at central rapidities
$\to$ exploited by central-jet veto techniques

note: parton-shower effects slightly enchance central jet activity

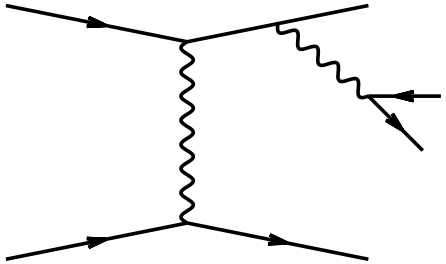
$pp \to Zjj$ via VBF



$pp \to Zjj$

versus

$pp \to W^+W^+jj$

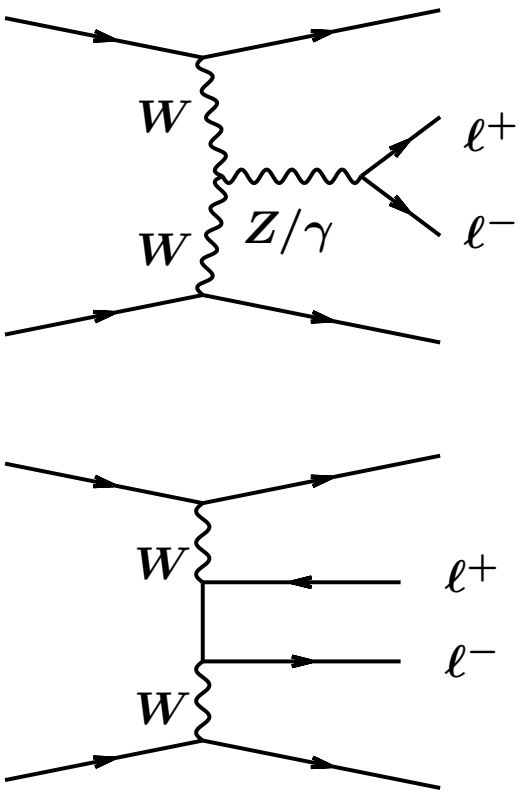


less particles in final state
$\to$ simpler matrix elements

more massless particles
$\to$ more involved singularity structure

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

charged current modes:



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

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

$\to$ introduce generation cut

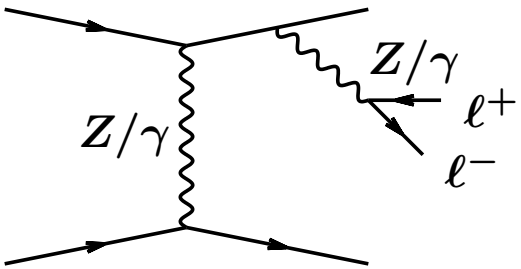
$$m_{\ell\ell}^{\rm gen} = 30 \text{ GeV} ,$$

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

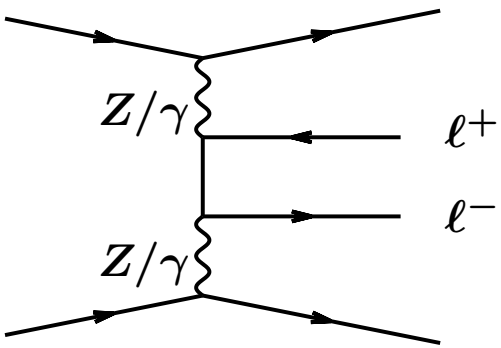
neutral current modes:



extra singularity for photons in t-channel

with $Q_\gamma^2 \to 0$

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



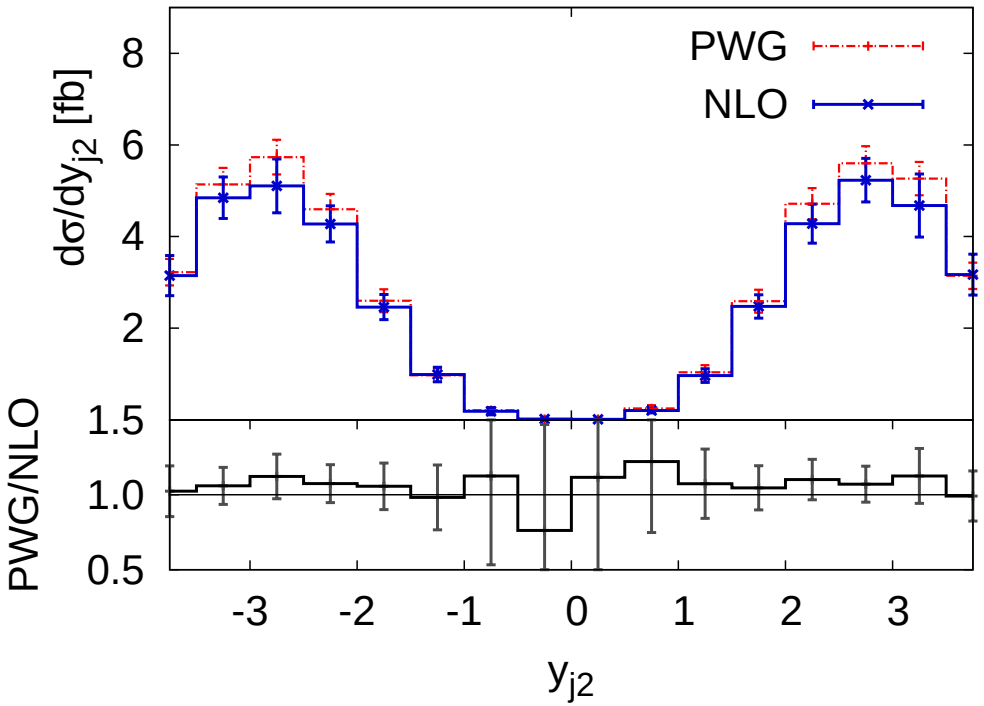
- ☞ damping factor in matrix elements
- ☞ Born-suppression factor

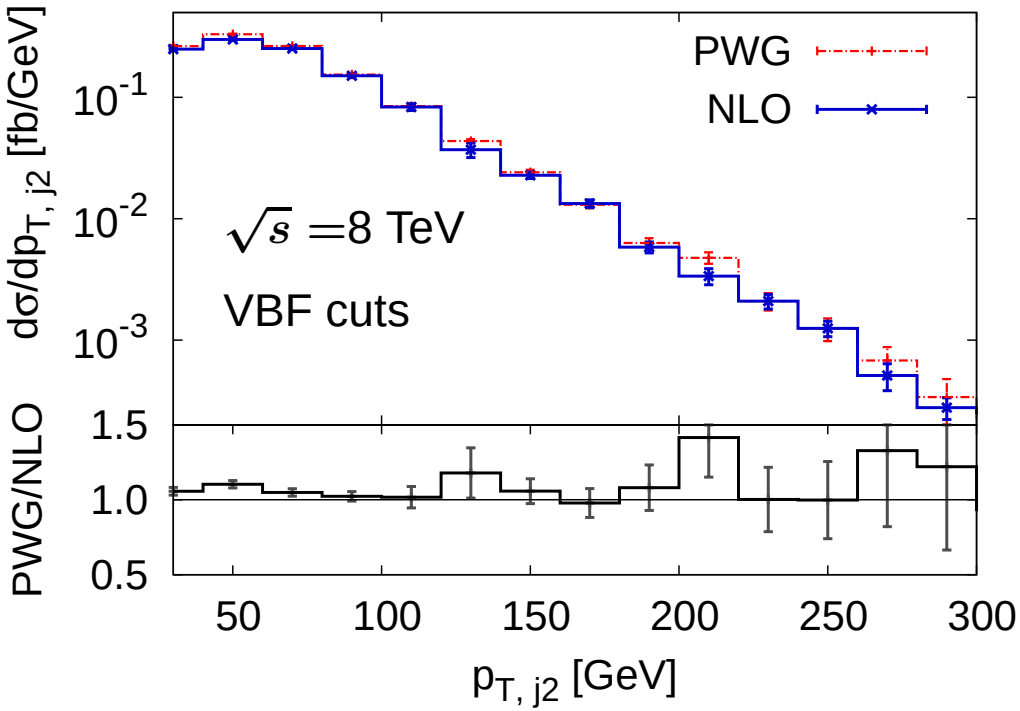
$$F \sim \left(\frac{p_{T,1}^2}{p_{T,1}^2+\Lambda^2}\right)^2 \left(\frac{p_{T,2}^2}{p_{T,2}^2+\Lambda^2}\right)^2$$

(alternative: generation cuts)

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

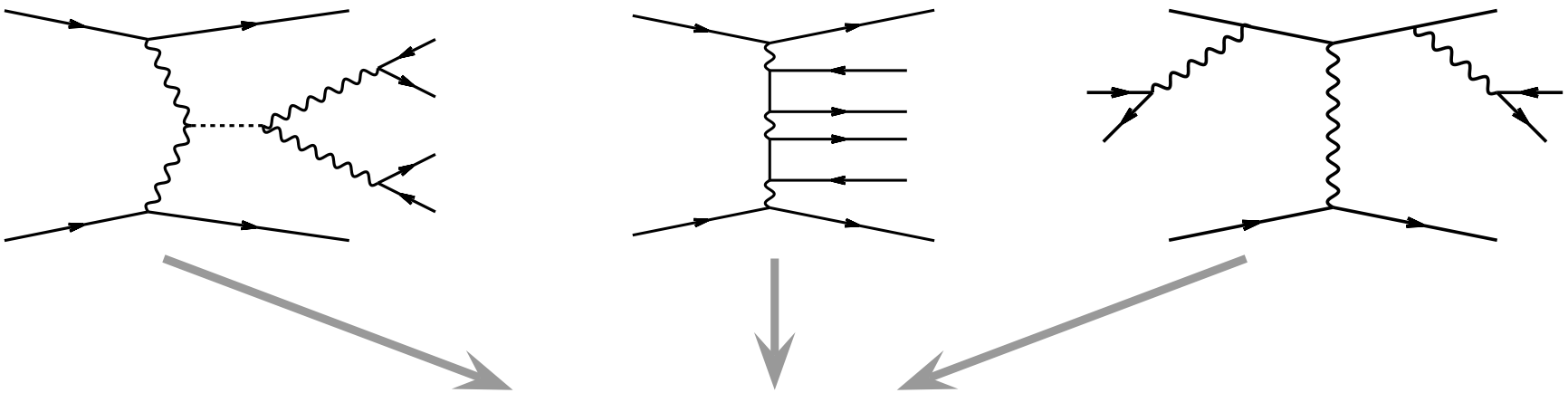
Schneider, Zanderighi, B.J. (2012)



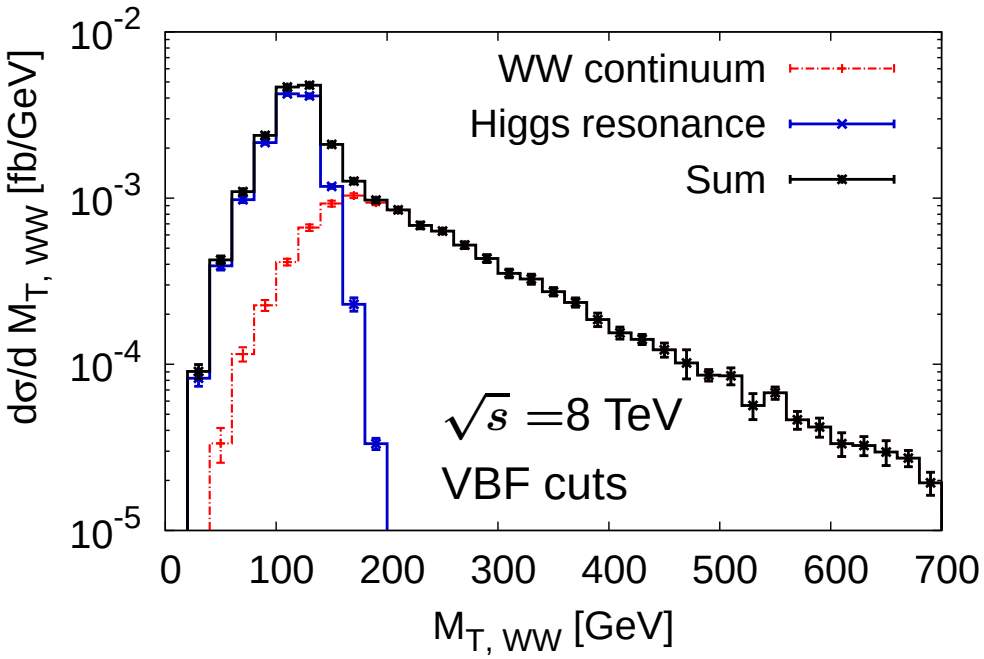


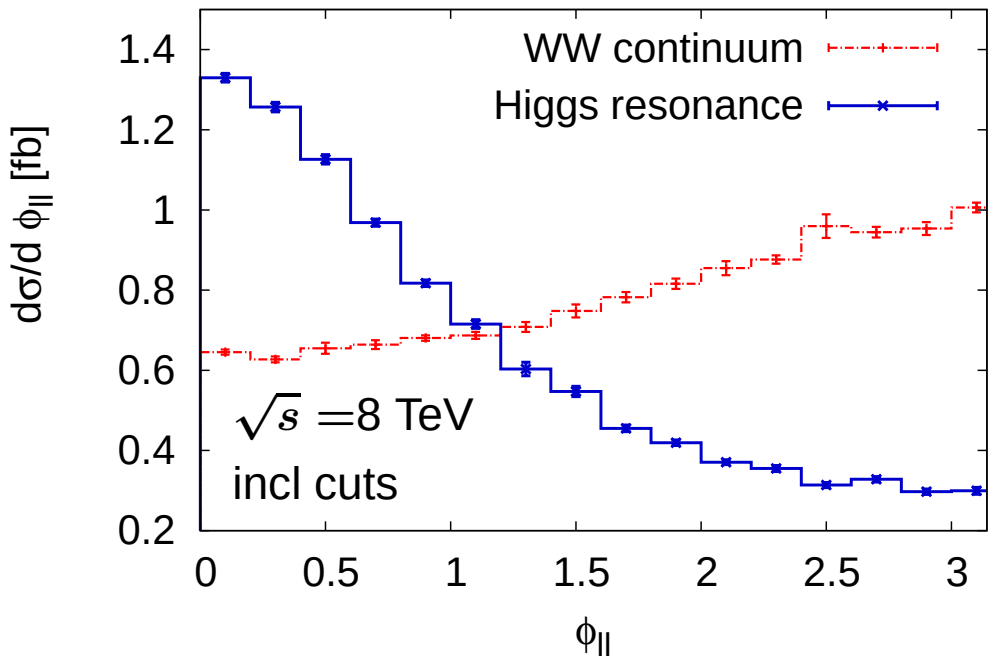
parton shower effects are moderate
for distributions related to hard jets

$pp \to W^+W^-jj$: technicalities

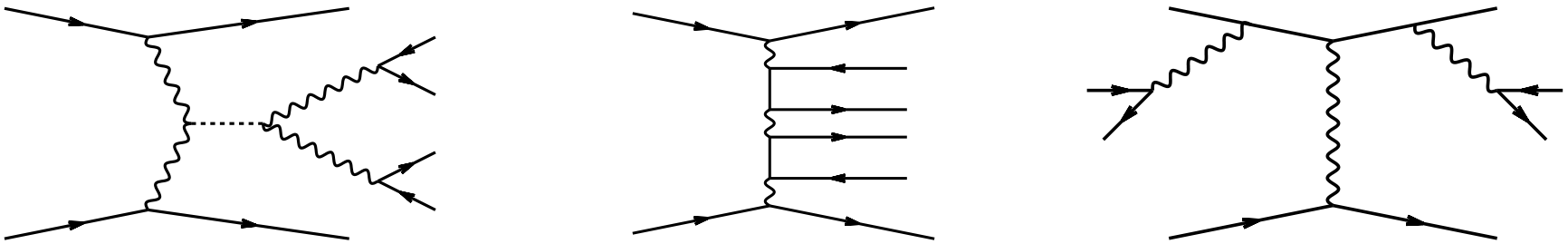


different topologies populate different regions in phase space:

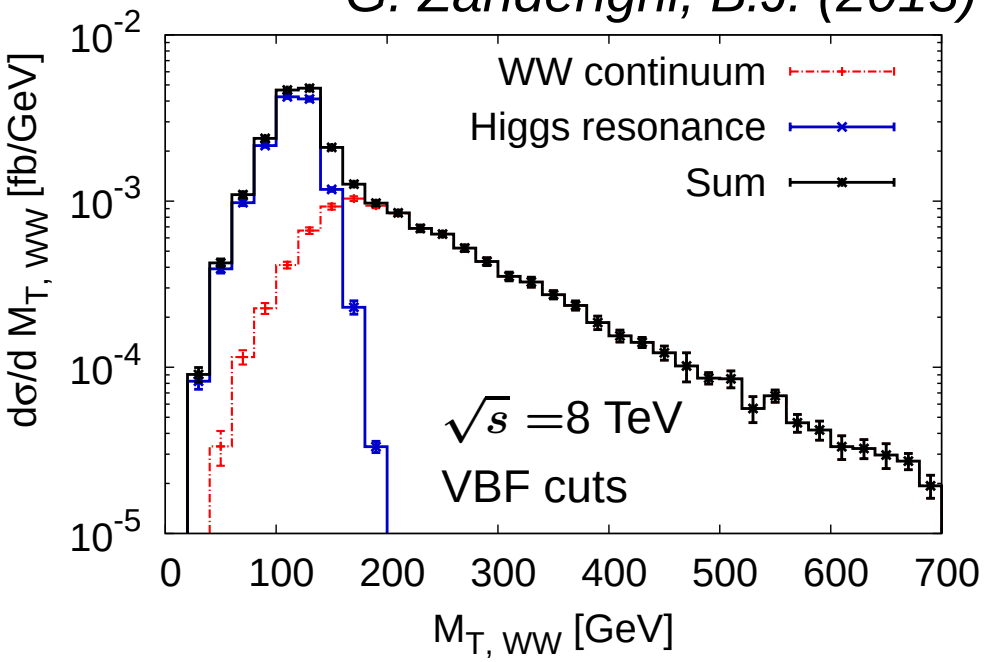




$pp \to W^+W^-jj$: technicalities



G. Zanderighi, B.J. (2013)

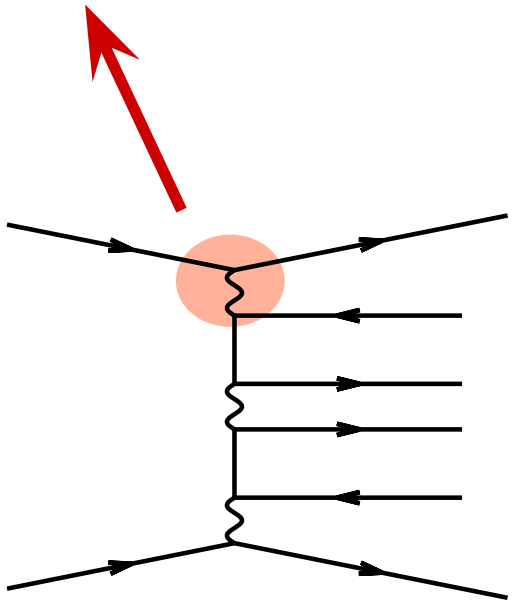


different topologies in phase space:

☞ sample different regions separately

$pp \to W^+W^-jj$: technicalities

photon propagator $\sim 1/Q_\gamma^2$



need to handle
singularities for photons in t-channel
with $Q_\gamma^2 \to 0$
(numerically irrelevant for meaningful observables)

(1) damping factor to effectively suppress matrix elements

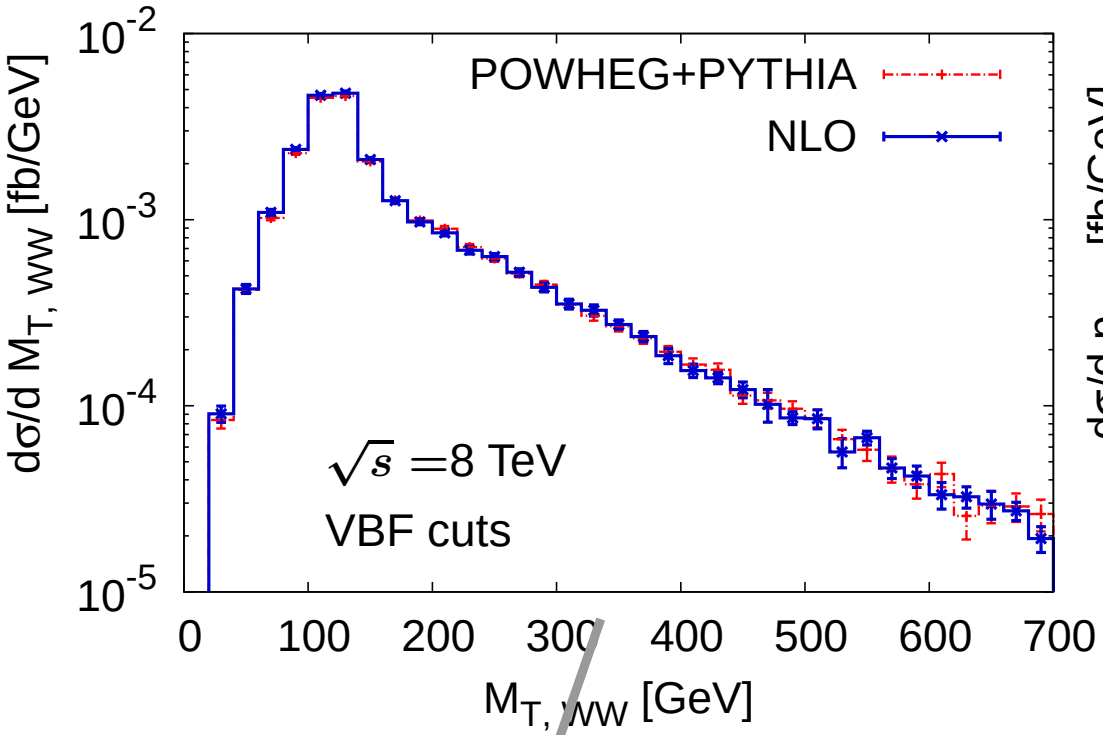
(2) Born-suppression factor to achieve efficient phase space integration

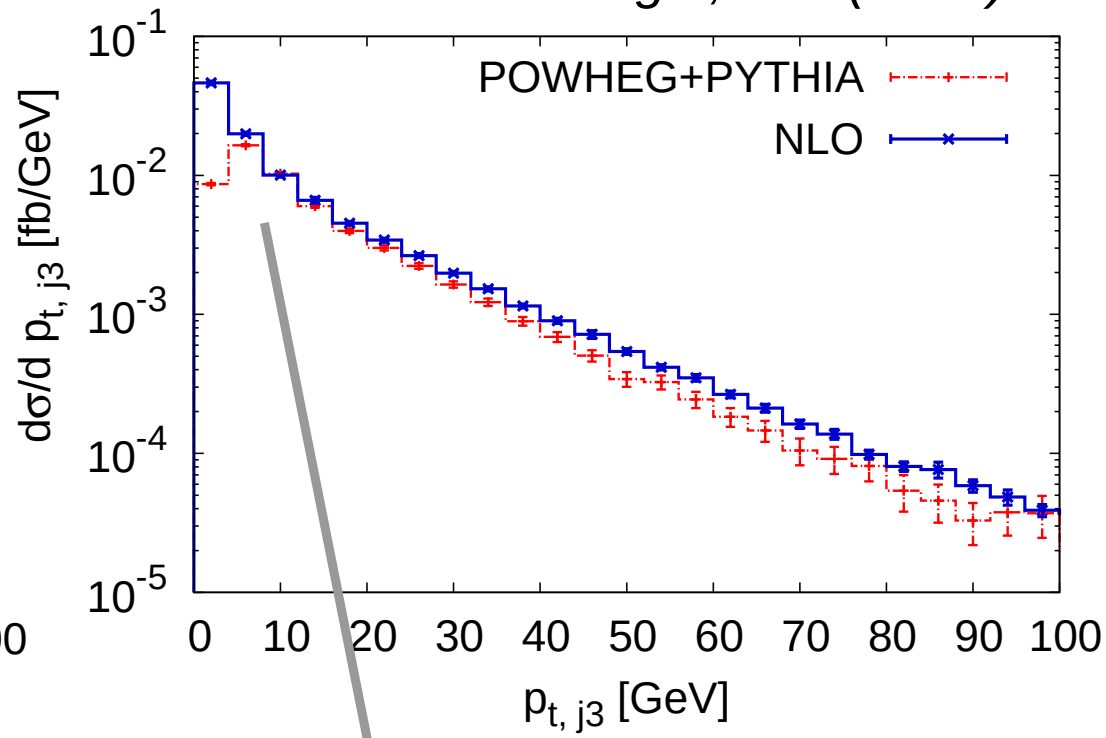
$$F \sim \left(\frac{p_{T,1}^2}{p_{T,1}^2+\Lambda^2}\right)^2 \left(\frac{p_{T,2}^2}{p_{T,2}^2+\Lambda^2}\right)^2$$

(alternative: explicit generation cuts)

$pp \to W^+W^-jj$ with leptonic decays: results

G. Zanderighi, B.J. (2013)

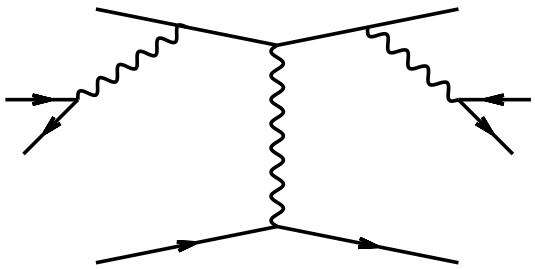




leptonic observables not very sensitive to parton shower

growth of jet distribution tamed by Sudakov factor

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



"semi-leptonic" final state:

$$W^+W^- \to \ell\nu + 2 \text{ jets}$$

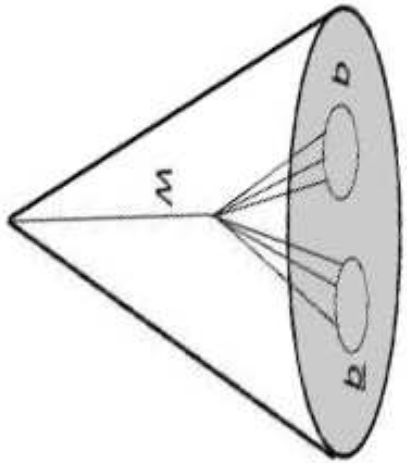
different from fully leptonic modes:

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

✔ only one neutrino $\to M_{WW}$ reconstruction possible

✘ sophisticated analysis techniques needed to isolate signal

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



make use of jet properties / composition:

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

(stable against parton-shower effects)

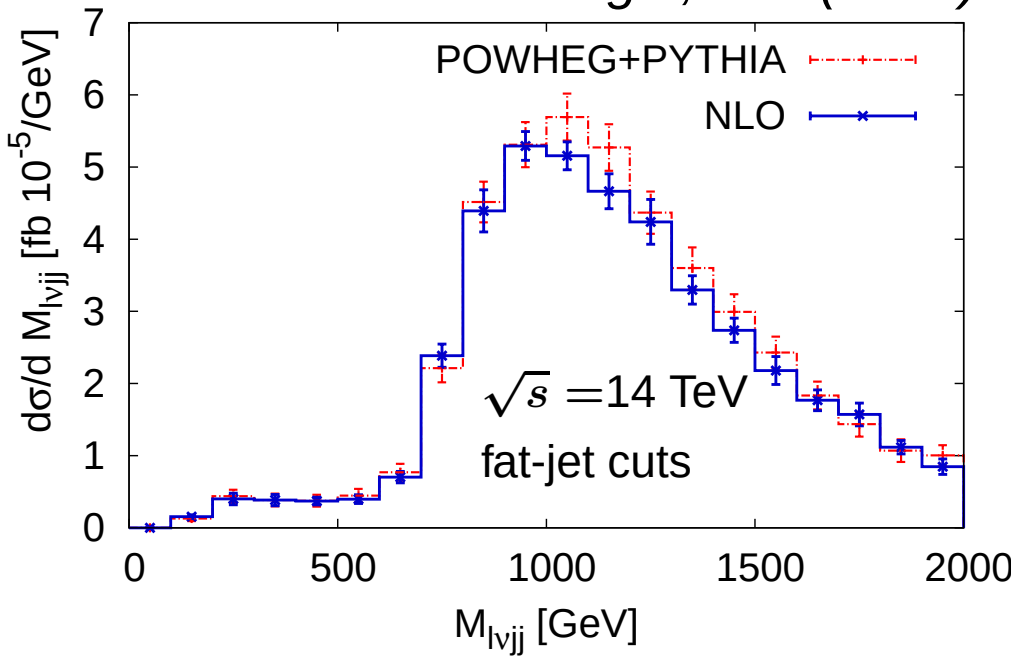
$$pp \to W^+(q\bar{q}')W^-(\ell\nu)jj:$$

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

[c.f. J. Butterworth et al., G. Salam et al. (2002-2013)]

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

G. Zanderighi, B.J. (2013)



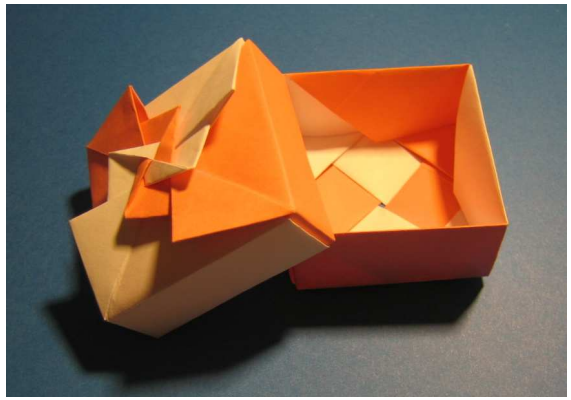
selection cuts
specific for fat-jet analysis:

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

results stable against
parton-shower effects

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

$VVjj$ in the POWHEG-BOX: getting started



- get access to a computing farm
- download the POWHEG-BOX from:

  http://powhegbox.mib.infn.it/
- go to the directory of the process you are interested in, e.g.,
  $ cd POWHEG-BOX/VBF_Wp_Wm
- for instructions on running the code refer to
  the documentation in POWHEG-BOX/VBF_Wp_Wm/Docs
- use sample files for input and analysis,
  or replace them with your own files

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/`

Thank you for your attention!