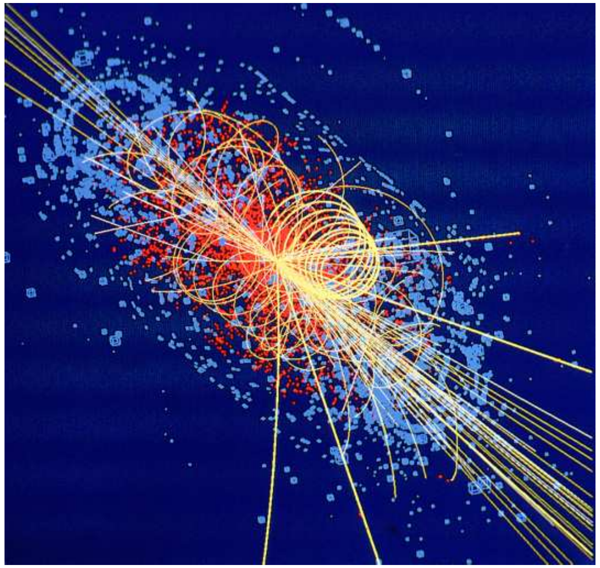
Matching weak boson scattering processes at NLO in QCD with parton shower programs



Barbara Jäger

Johannes Gutenberg University Mainz

LHC – the first part of the journey
KITP, July 2013

work done in collaboration with Giulia Zanderighi
[arXiv: 1108.0864, 1301.1695]

outline

- setting the stage: weak boson scattering
- developing precision tools:
  - next-to-leading order QCD corrections
  - matching with parton shower
  - phenomenological analyses
- conclusions & outlook

vector boson fusion (VBF)

Standard Model:

- $qq \to qqH$: prominent production mode for the Higgs boson over a wide mass range
- sensitive to Higgs couplings and CP properties

beyond the Standard Model:

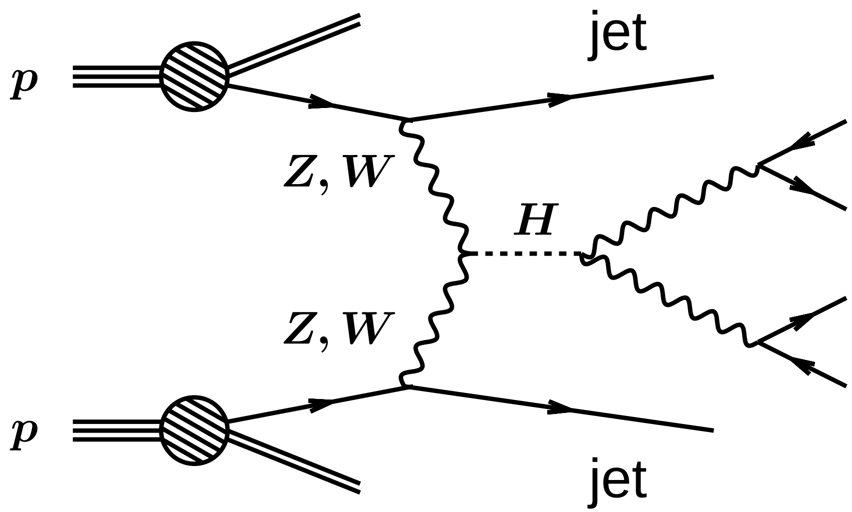
$qq \to qqVV$: sensitive to the mechanism of electroweak symmetry breaking

↕

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

✔ the big advantage: backgrounds can be controlled!

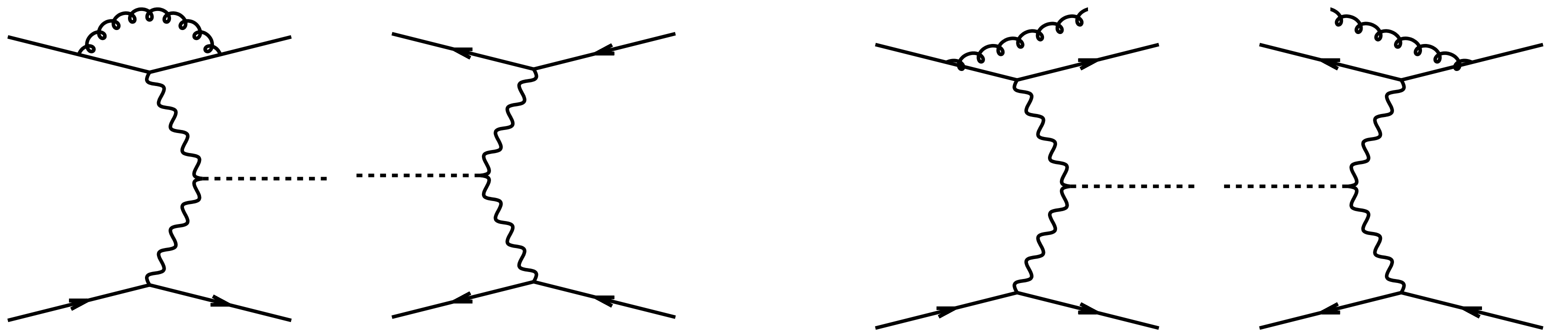
VBF event topology



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)
- Higgs decay products typically between tagging jets

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`

Higgs production in VBF: more corrections

- NLO EW corrections to cross sections and distributions: modify K factors and distort distributions by up to 10%
  [Ciccolini, Denner, Dittmaier, Mück (2007-10)]

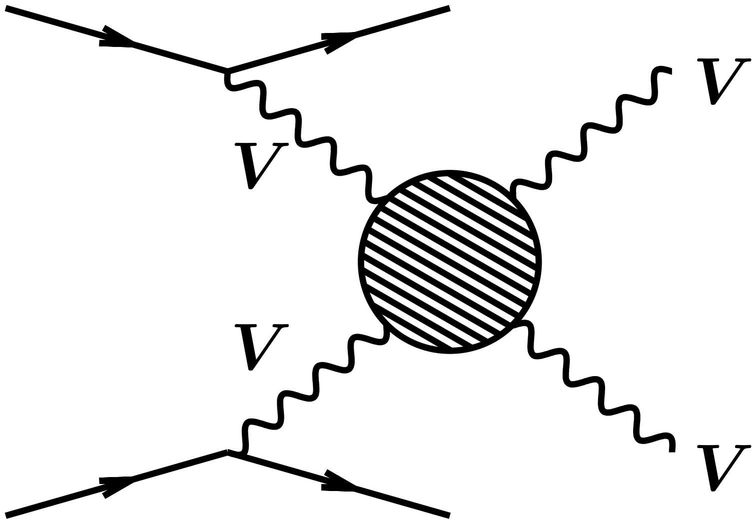
- SUSY QCD & EW corrections: typically $\lesssim$ 1%
  [Hollik, Plehn, Rauch, Rzehak (2008) & Figy, Palmer, Weiglein (2010)]

- sub-set of virtual NNLO-QCD corrections (one-loop squared): numerically irrelevant in all considered regions
  [Harlander, Vollinga, Weber (2007)]

- sub-set of NNLO-QCD corrections (structure function approach): further reduce scale uncertainties of total cross sections
  [Bolzoni, Maltoni, Moch, Zaro (2010-11)]

- interference with Hjj production via gluon fusion: negligible
  [Andersen et al.; Bredenstein, Hagiwara, B.J. (2006-08)]

vector boson scattering: $VV \to VV$

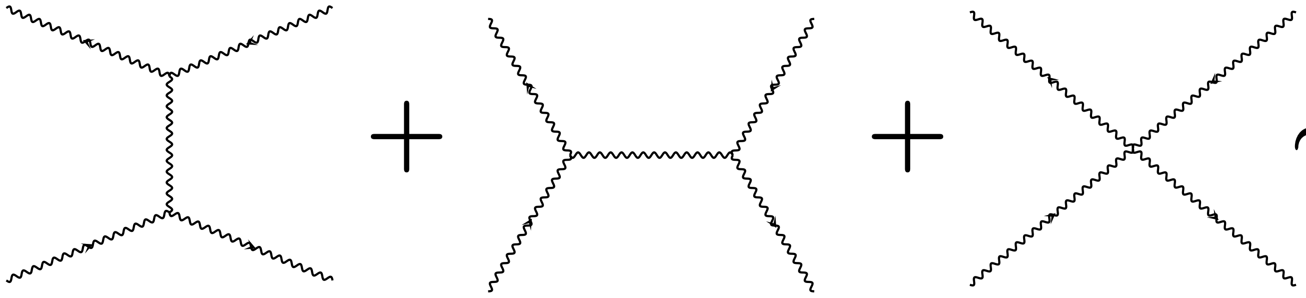


vector-boson scattering processes
are extremely sensitive to
new interactions in the
gauge boson sector

vector boson scattering & unitarity

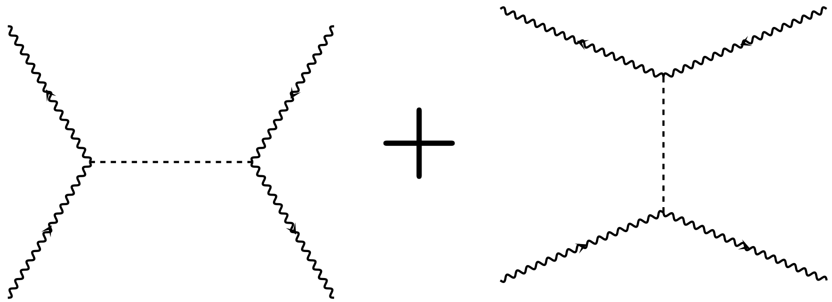
$$W_L^+ W_L^- \to W_L^+ W_L^- \qquad \text{with } \varepsilon_L^\mu \sim \frac{\sqrt{s}}{M_W}$$

$\mathcal{M} =$



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

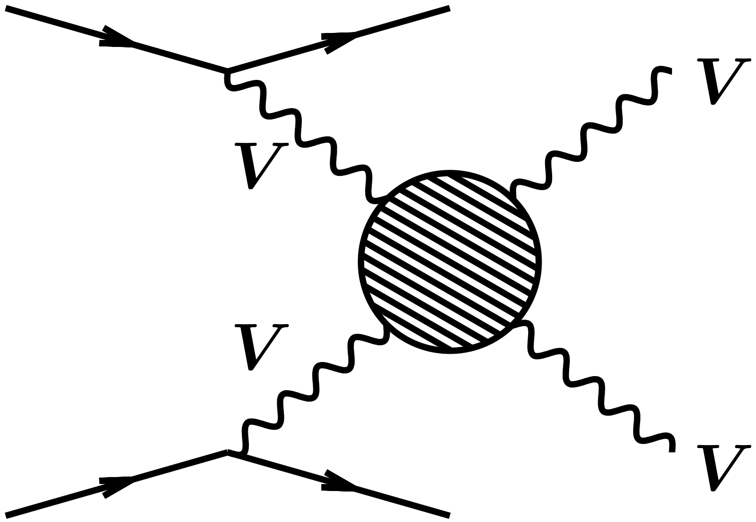
growth violates unitarity $\to$ need:



Higgs with $M_H \lesssim 1$ TeV

or new physics at TeV scale

vector boson scattering: $VV \to VV$

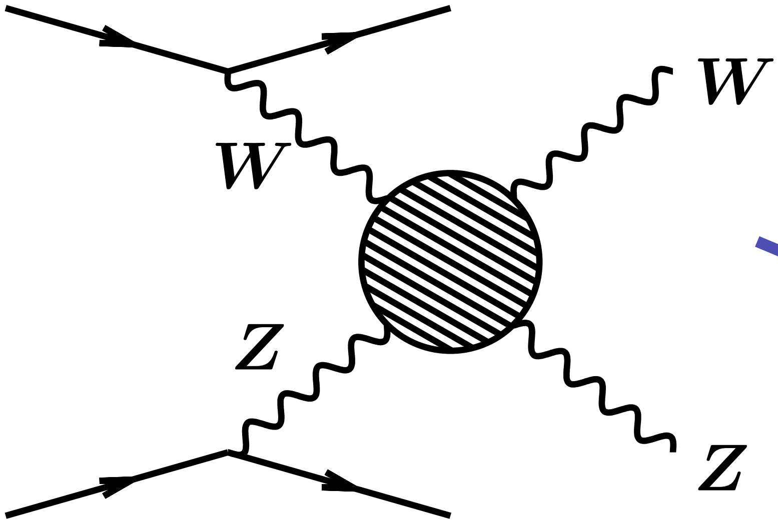


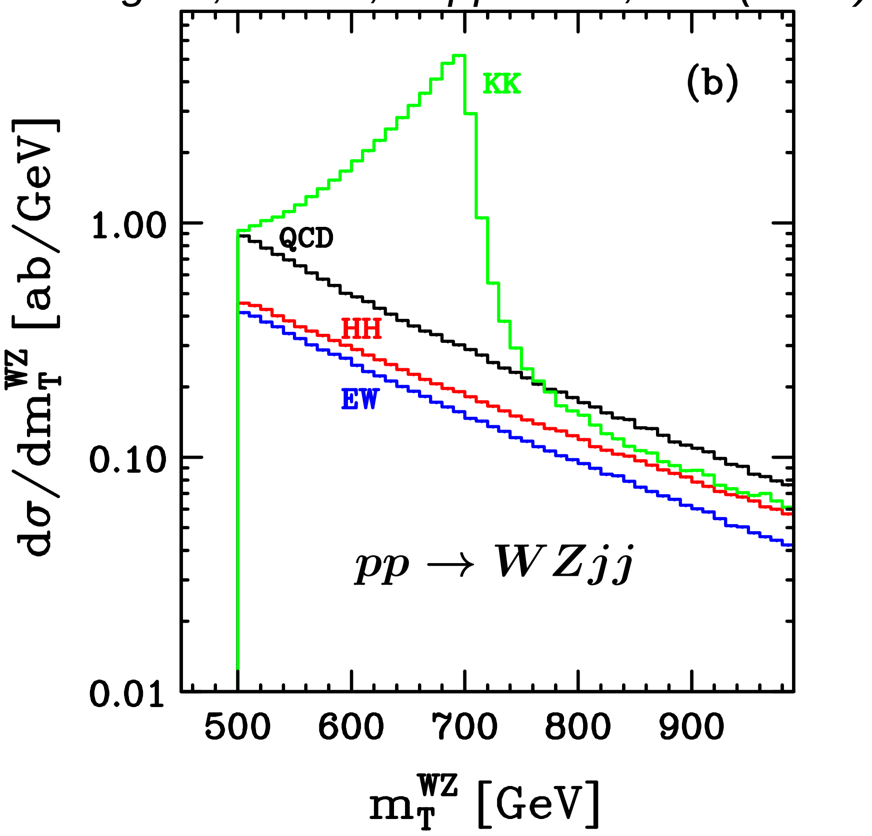
vector-boson scattering processes
are extremely sensitive to
new interactions in the
gauge boson sector

↓

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

vector boson scattering: $VV \to VV$



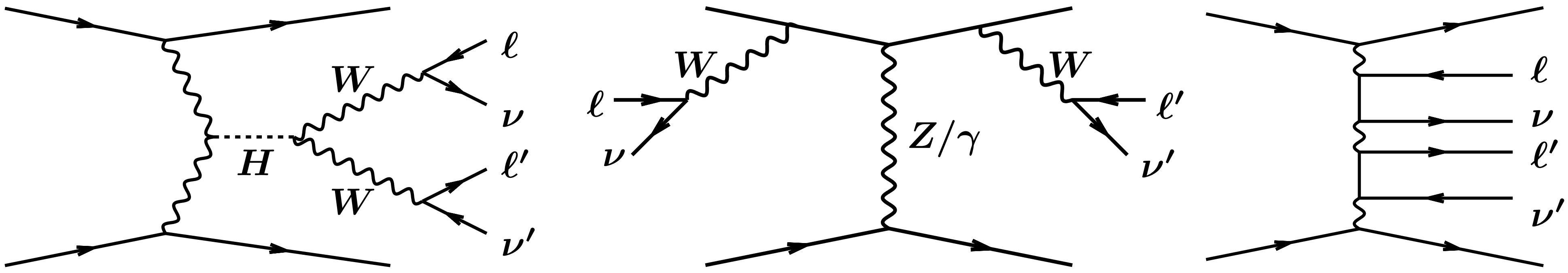


example:

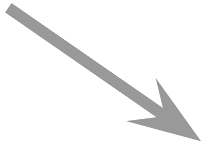
new resonant states are visible as enhancement in characteristic distributions

[here: Kaluza-Klein resonances]

$pp \to VVjj$: vector boson scattering in the Standard Model



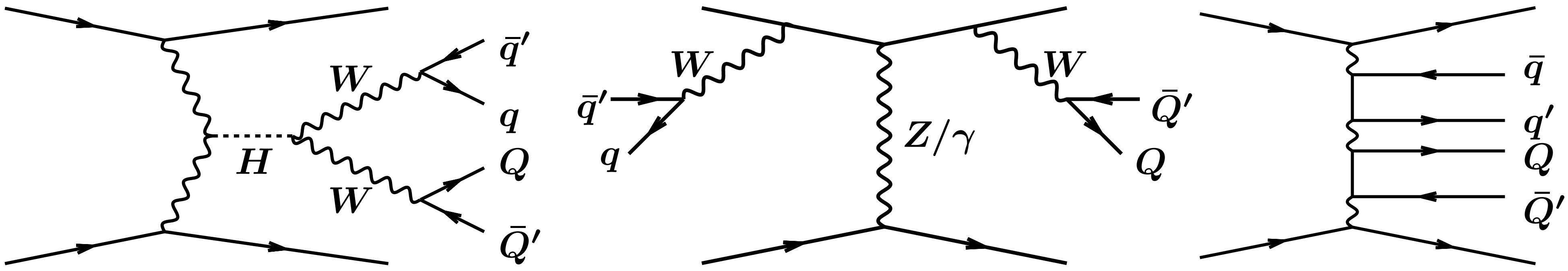
experiment: don't observe $VVjj$ final state, but
hadronic or leptonic decay products



$4\text{leptons} + jj$

low statistics
clean signature

$pp \to VVjj$: vector boson scattering in the Standard Model



experiment: don't observe $VVjj$ final state, but hadronic or leptonic decay products

$4\text{jets} + jj$

high statistics

large backgrounds

$4\text{leptons} + jj$

low statistics

clean signature

$pp \to VVjj$ in the Standard Model

need stable, fast & flexible Monte Carlo program allowing for

- computation of various jet and lepton observables for

  VBF production of

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

  at NLO-QCD accuracy

  (leptonic decay correlations fully taken into account)

- straightforward implementation of experimental selection cuts

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

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

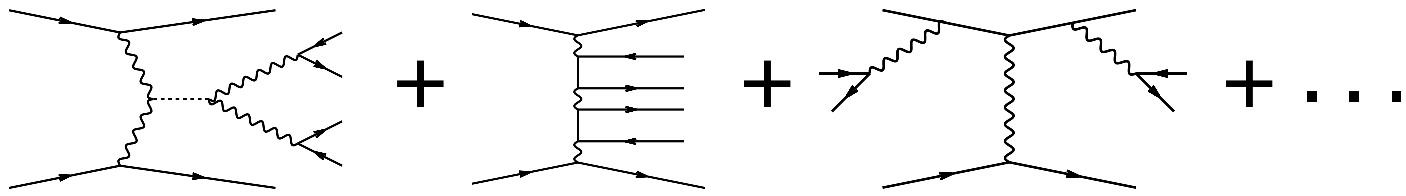
C. Oleari, D. Zeppenfeld, B. J. (2009)

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

ingredients of the calculation

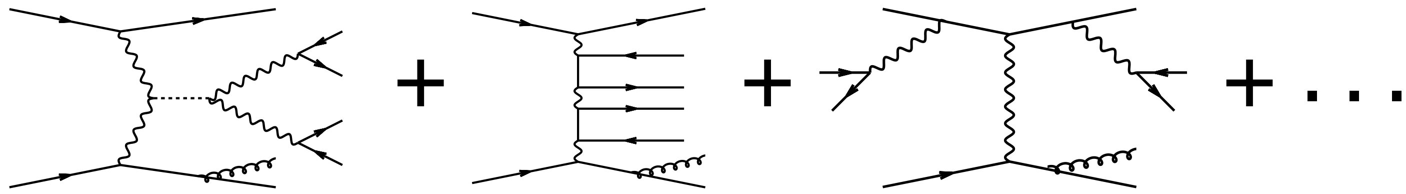
need to compute numerical value for . . .

$$|\mathcal{M}_B|^2 = \Big| \quad \Big|^2$$



. . . Born amplitude squared in 4 dim

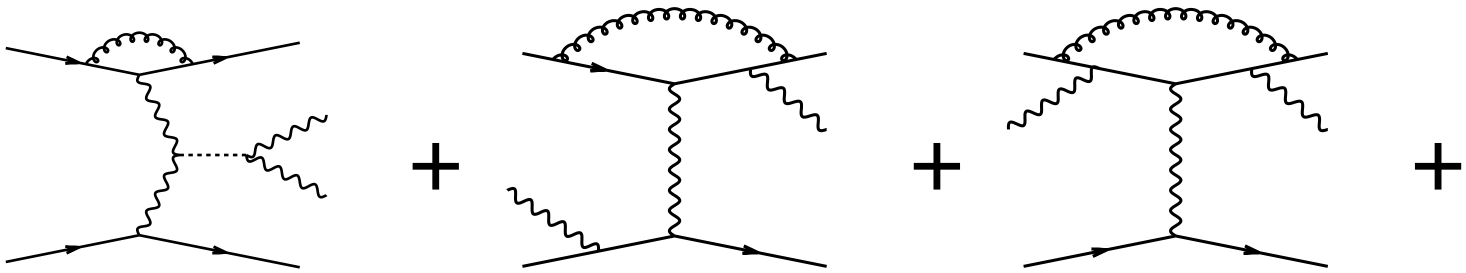
$$|\mathcal{M}_R|^2 = \Big| \quad \Big|^2$$



. . . real-emission amplitude squared in 4 dim and counter-terms for infrared-divergent configurations

almost 3000 diagrams $\to$ essential: organize calculation economically!

virtual contributions

$\mathcal{M}_V =$  $+ \ldots$

$$= \mathcal{M}_B\, F(Q) \left[-\frac{2}{\varepsilon^2} - \frac{3}{\varepsilon} \right] + \tilde{\mathcal{M}}_V^{finite}$$

determined numerically

[c. f. Denner, Dittmaier (2002,2005)]

combination of real emission, virtuals,
and subtraction terms:
poles canceled analytically $\rightarrow$ finite results

phase-space integration can be performed numerically (Vegas)

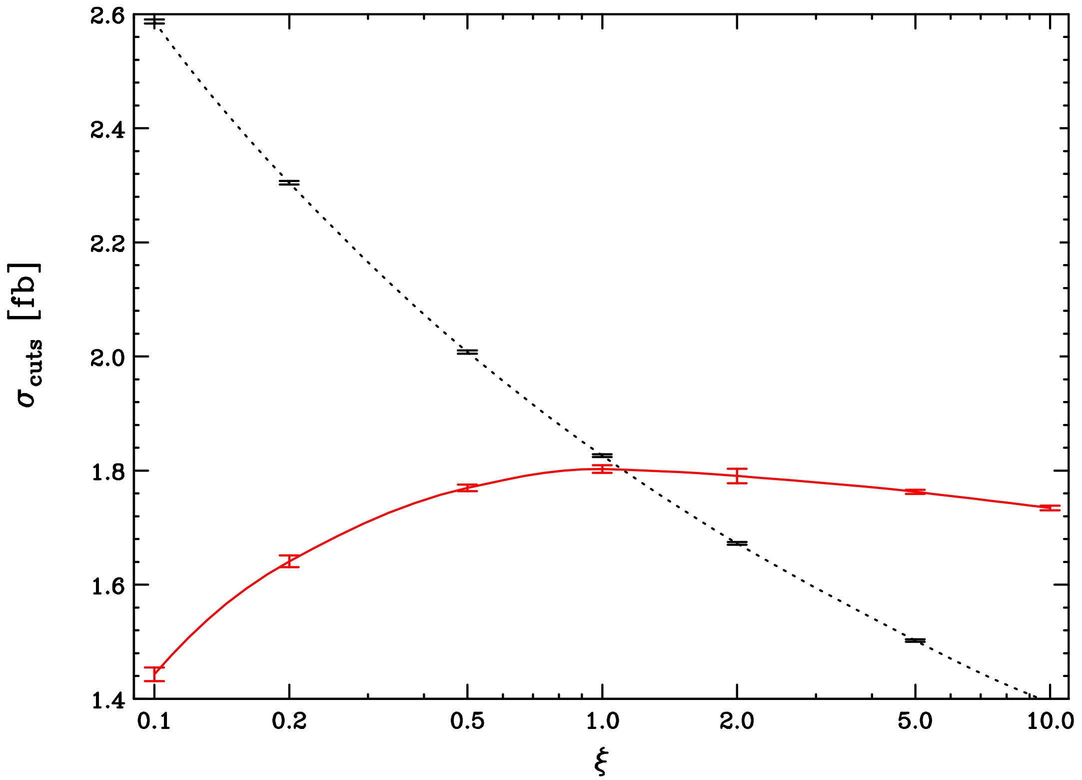
implementation

. . . put everything into dedicated

Monte-Carlo program VBFNLO . . .

$pp \to W^+W^-jj$: theoretical uncertainty

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

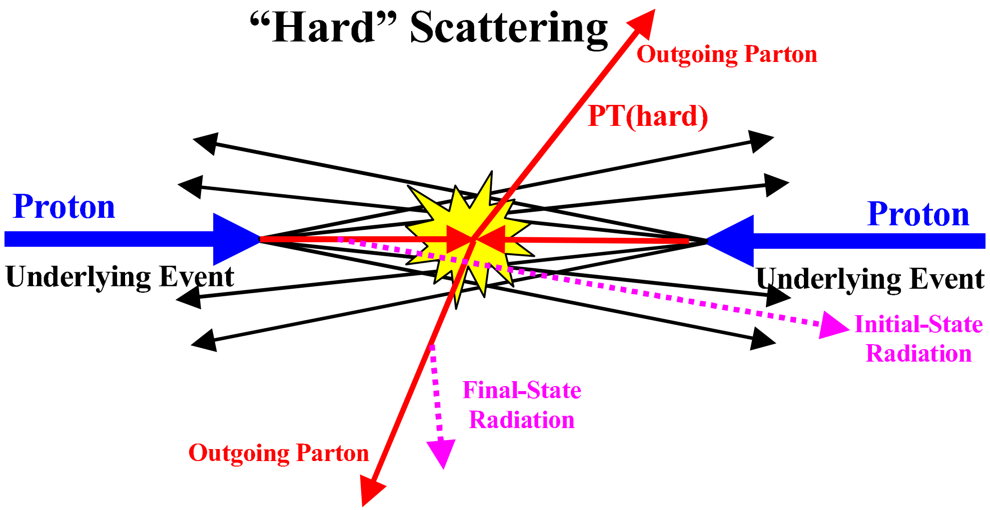


Oleari, Zeppenfeld, B.J. (2006)

LO: no control on scale

NLO QCD: scale dependence strongly reduced

more realistic simulation



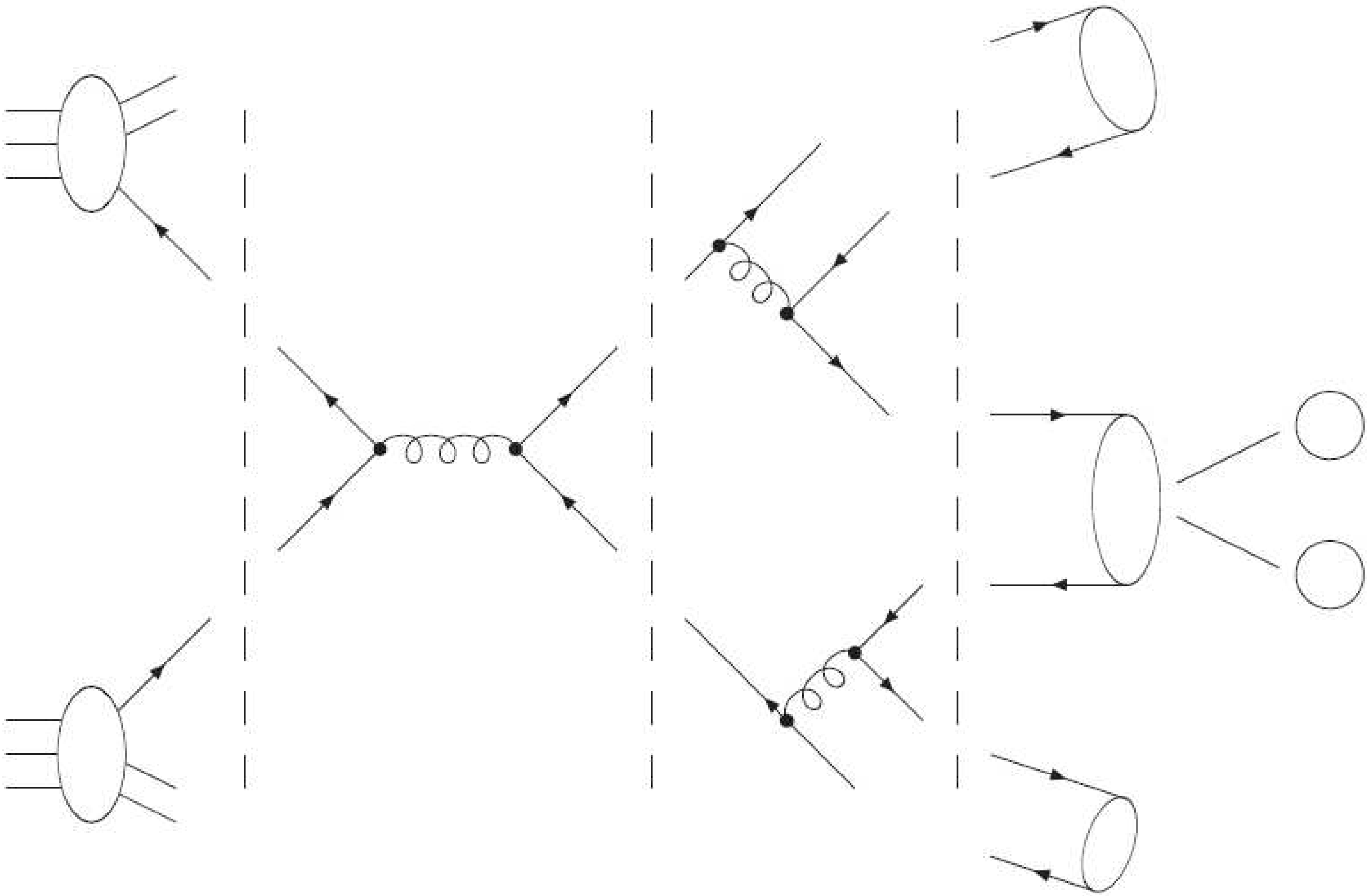
for realistic description of scattering processes at hadron colliders:

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

underlying event, parton shower, and hadronization

(PYTHIA, HERWIG, SHERPA,...)

stages of a hadronic collision



hard partonic scattering

$\mu \sim Q \gg \Lambda_{\mathrm{QCD}}$

parton shower

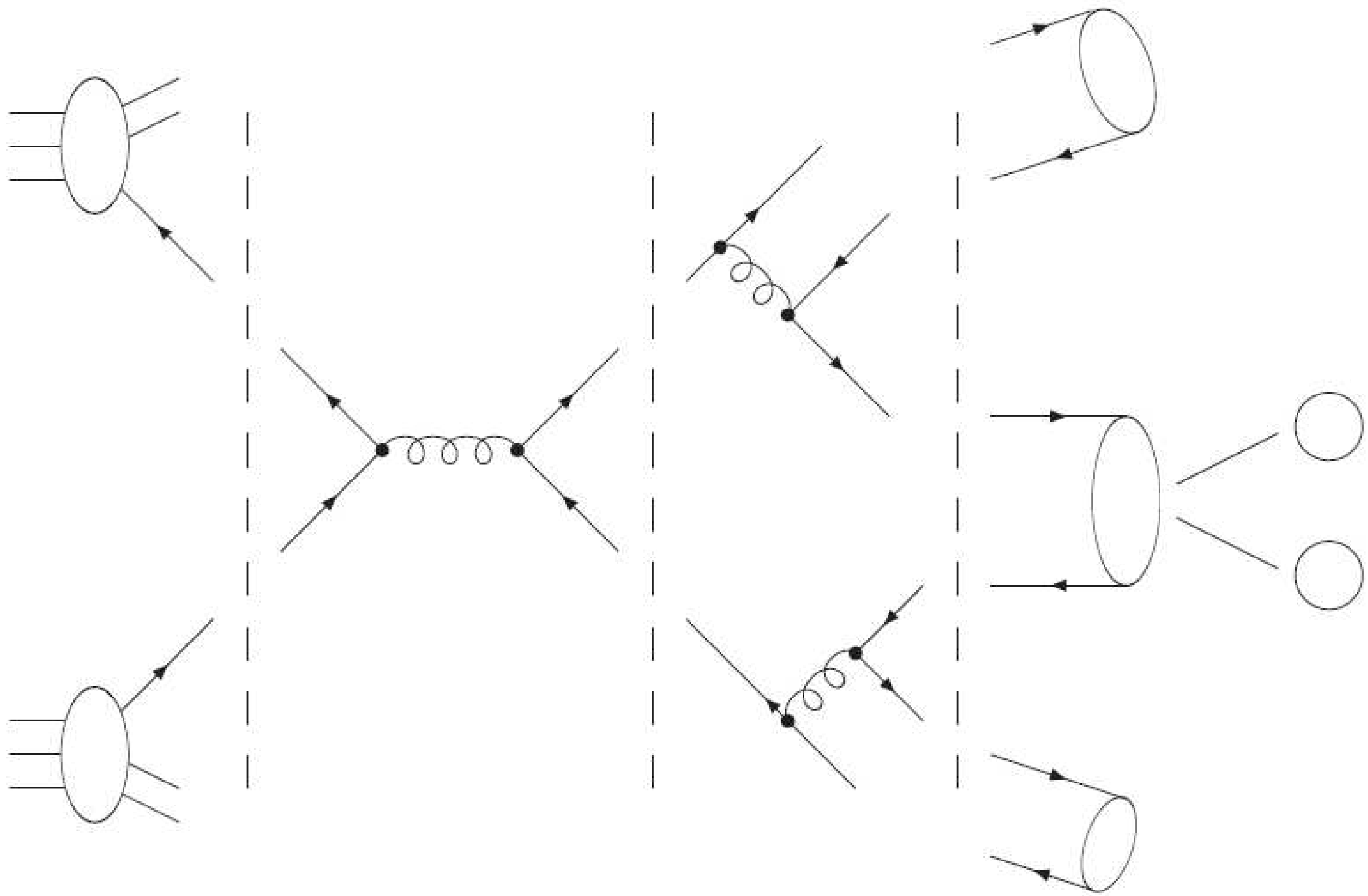
$Q > \mu > \Lambda_{\mathrm{QCD}}$

hadronization and decay

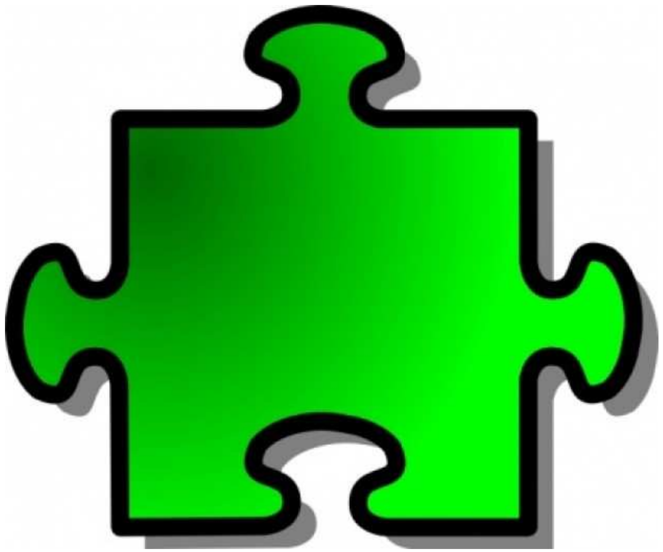
$\mu \sim \Lambda_{\mathrm{QCD}}$

stages of a hadronic collision

perturbation theory | multiple soft & collinear emissions | non-perturbative; pheno models tuned on data

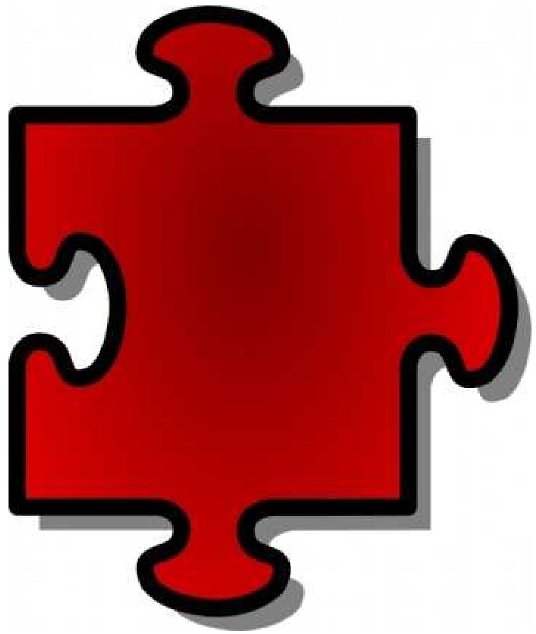


hard partonic scattering | parton shower | hadronization and decay



exploit merits of flexible
Monte Carlo tools

retain NLO accuracy
for hard scattering



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

POsitive Weight Hardest Emission Generator

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

[Frixione, Nason, Oleari]

- generate partonic event with single emission at NLO-QCD
- all subsequent radiation must be softer than the first one
- event is written on a file in standard Les Houches format

  $\longrightarrow$ can be processed by default parton shower program (HERWIG, PYTHIA, . . .)

POsitive Weight Hardest Emission Generator

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]

reminder: differential NLO cross section

Born

real emission and counter-terms

$$d\sigma_{\mathrm{NLO}} = d\Phi_n \left\{ B(\Phi_n) + V(\Phi_n) + \left[R(\Phi_n, \Phi_r) - C(\Phi_n, \Phi_r) \right] d\Phi_r \right\}$$

finite virtuals:

$$V_b(\Phi_n) + \int d\phi_r \, C(\Phi_n, \Phi_r)$$

radiation phase space:

$$d\Phi_r = dt dz d\phi$$

leading order shower Monte Carlo cross section

Born

first emission
(governed by
splitting function P)

$$d\sigma_{\mathrm{LO-SMC}} = d\Phi_n B(\Phi_n)\left\{\Delta_{t_0} + \Delta_t \frac{\alpha_s}{2\pi} P(z) \frac{1}{t} d\Phi_r\right\}$$

Sudakov factor:

$$\Delta_t = \exp\left[-\int d\Phi'_r \frac{\alpha_s}{2\pi} P(z') \frac{1}{t'} \theta(t'-t)\right]$$

…probability for no emission at scale $t' > t$

POWHEG cross sections

$$\overline{B} = \left\{ B(\Phi_n) + V(\Phi_n) + \int d\Phi_r \left[R(\Phi_n, \Phi_r) - C(\Phi_n, \Phi_r) \right] \right\}$$

$$d\sigma_{\rm POWHEG} = d\Phi_n \overline{B}(\Phi_n) \left\{ \Delta(\Phi_n, p_T^{\rm min}) + \Delta(\Phi_n, p_T) \frac{R(\Phi_n, \Phi_r)}{B(\Phi_n, \Phi_r)} d\Phi_r \right\}$$

POWHEG "Sudakov" factor:

$$\Delta(\Phi_n, p_T) = \exp \left[- \int d\Phi_r' \frac{R(\Phi_n, \Phi_r')}{B(\Phi_n)} \theta \left(k_T(\Phi_n, \Phi_r') - p_T \right) \right]$$

the POWHEG cross section

$$d\sigma_{\rm NLO} = d\Phi_n \left\{ B(\Phi_n) + V(\Phi_n) + \left[R(\Phi_n, \Phi_r) - C(\Phi_n, \Phi_r) \right] d\Phi_r \right\}$$

$$d\sigma_{\rm LO-SMC} = d\Phi_n B(\Phi_n) \left\{ \Delta_{t_0} + \Delta_t \frac{\alpha_s}{2\pi} P(z) \frac{1}{t}\, d\Phi_r \right\}$$

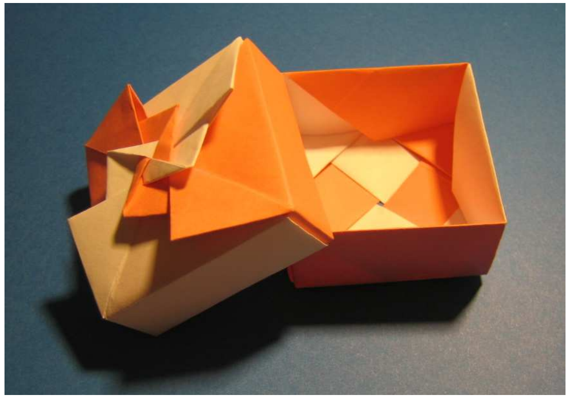
$$d\sigma_{\rm POWHEG} = d\Phi_n \overline{B}(\Phi_n) \left\{ \Delta(\Phi_n, p_T^{\rm min}) + \Delta(\Phi_n, p_T) \frac{R(\Phi_n, \Phi_r)}{B(\Phi_n, \Phi_r)}\, d\Phi_r \right\}$$

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- 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)]*

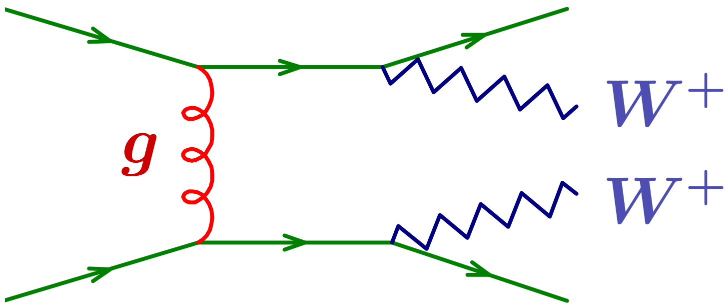
impact of different production modes

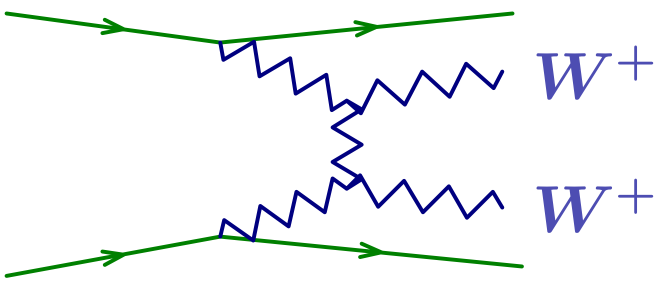
QCD-induced production

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

EW production

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





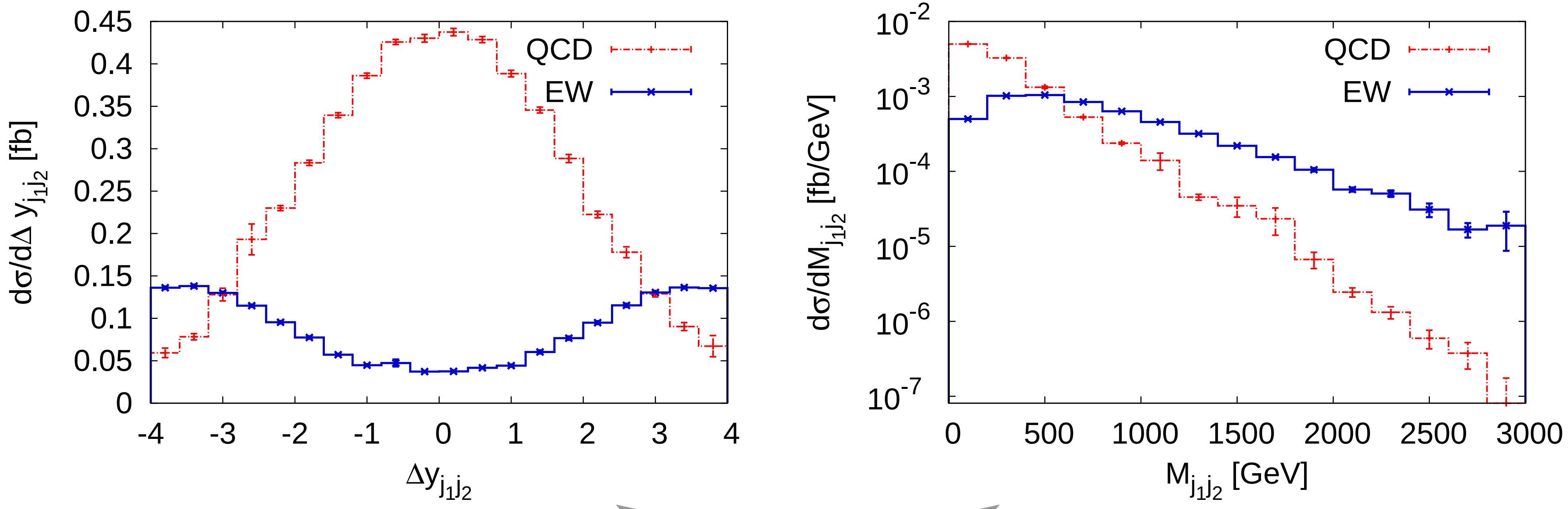
NLO-QCD results for $\sqrt{s}$ =7 TeV with basic jet cuts only ($p_T^{\text{tag}} > 20$ GeV):

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

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

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

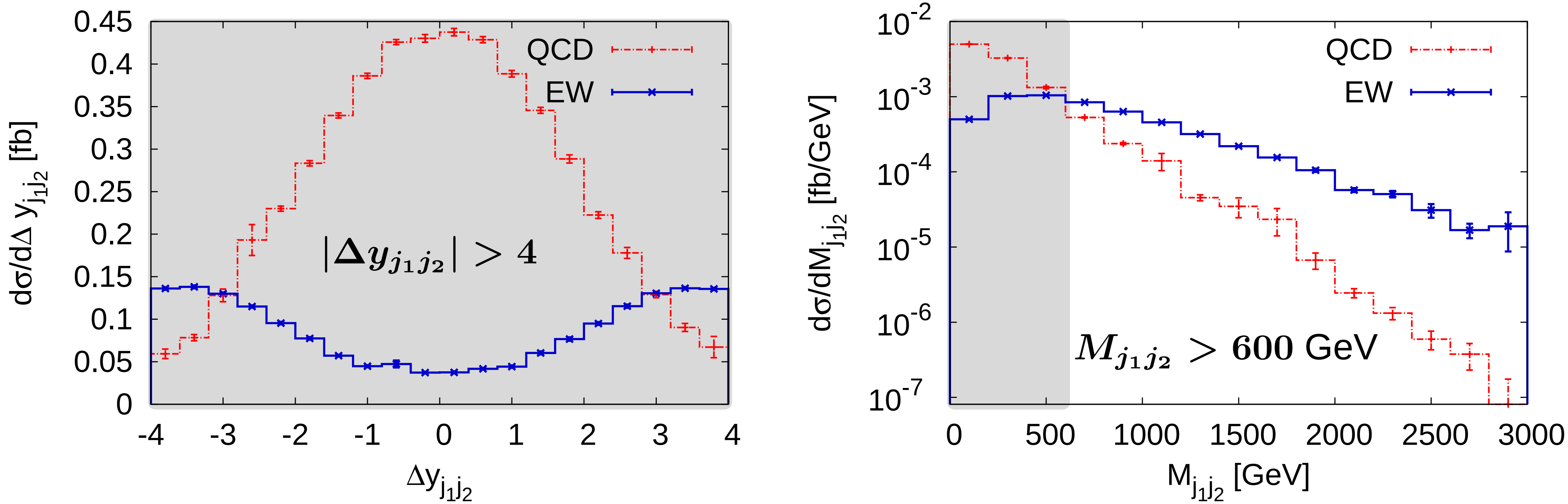
Zanderighi, B.J. (2011)



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

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

QCD-induced production

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

EW production

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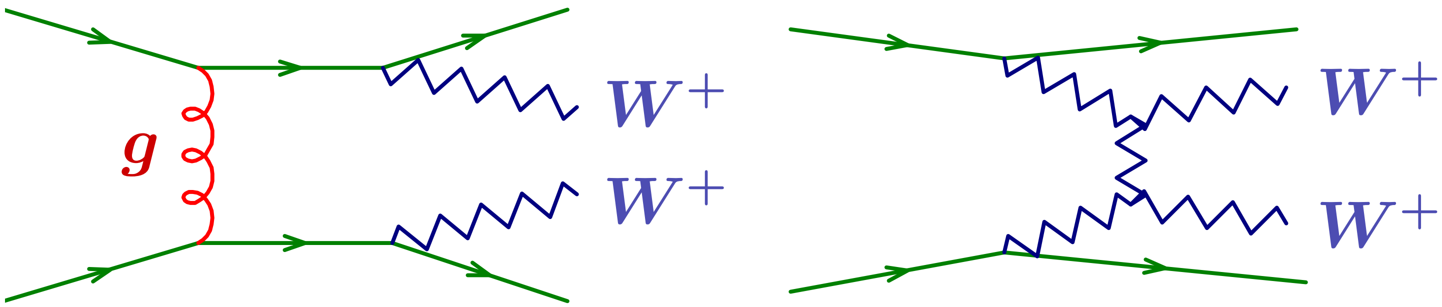


NLO results for $\sqrt{s}$ =7 TeV with basic jet cuts only ($p_T^{tag} > 20$ GeV):

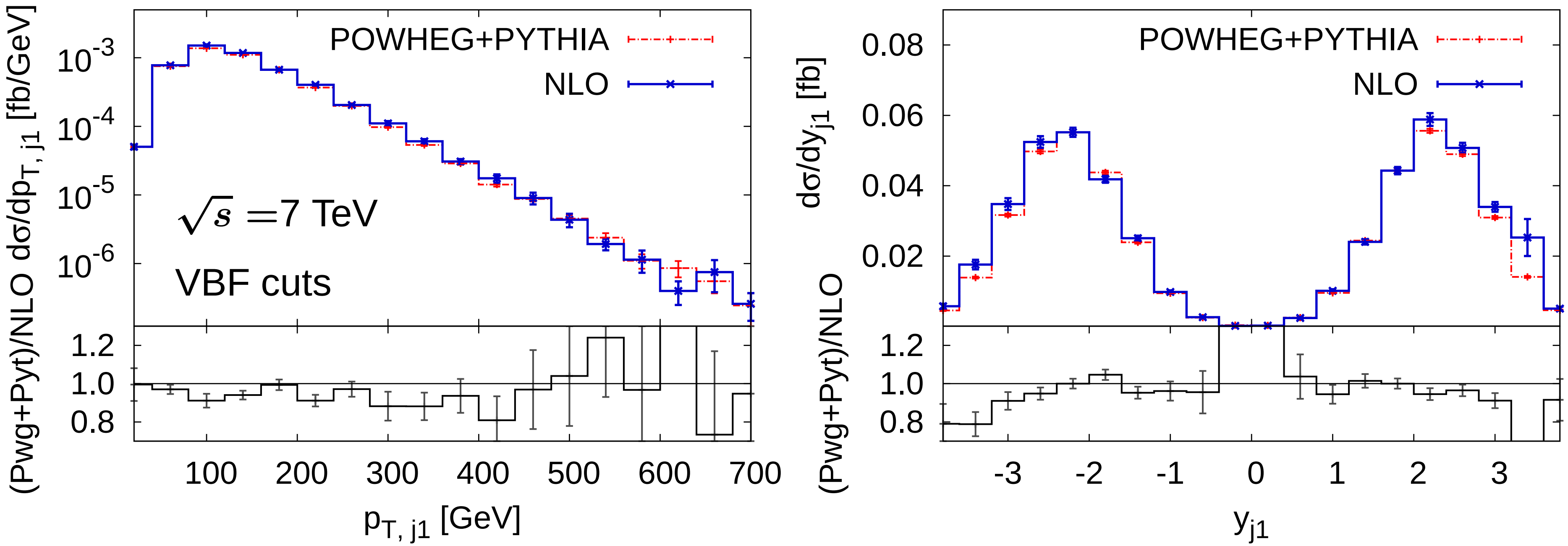
$$\sigma_{QCD}^{inc} = 2.12 \text{ fb} \qquad \sigma_{EW}^{inc} = 1.097 \text{ fb}$$

NLO results with VBF cuts:

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

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

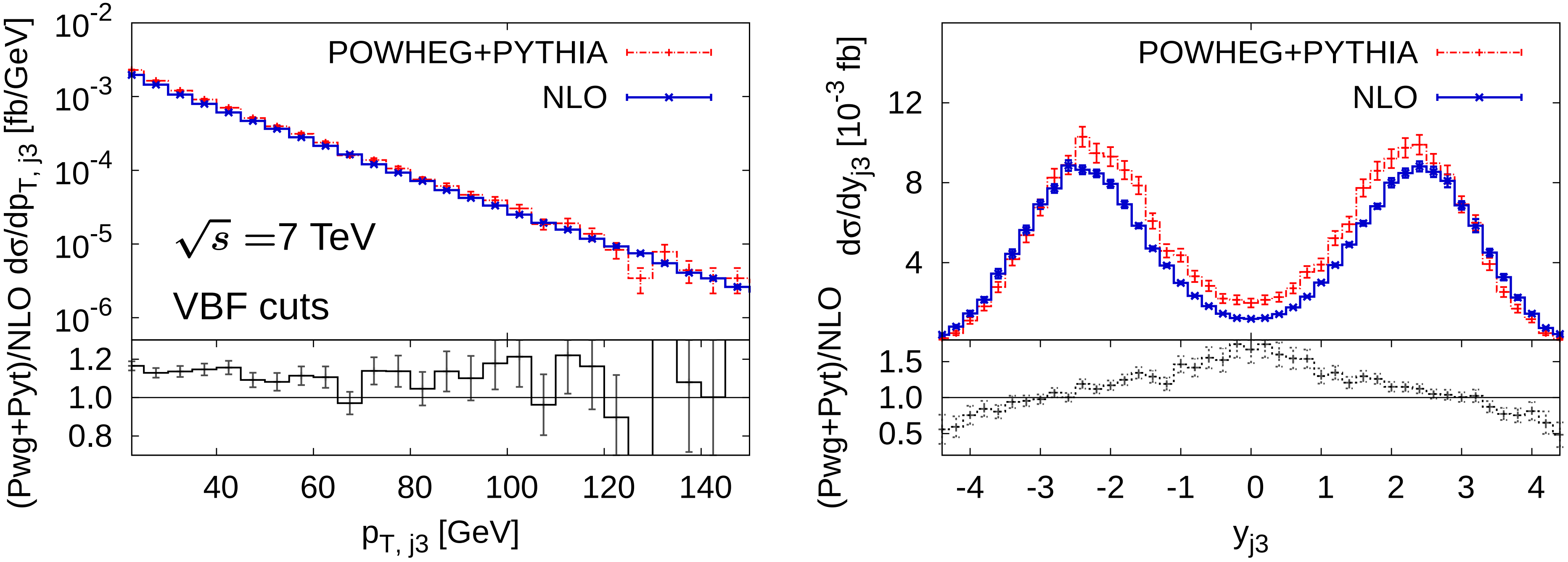
Zanderighi, B.J. (2011)



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
$\longrightarrow$ exploited by central-jet veto techniques

note: parton-shower effects slightly enchance central jet activity

full description of EW process $pp \to W^+W^-jj$,
including fully leptonic and semi-leptonic decays:

matching of hard matrix elements
with parton shower at NLO QCD

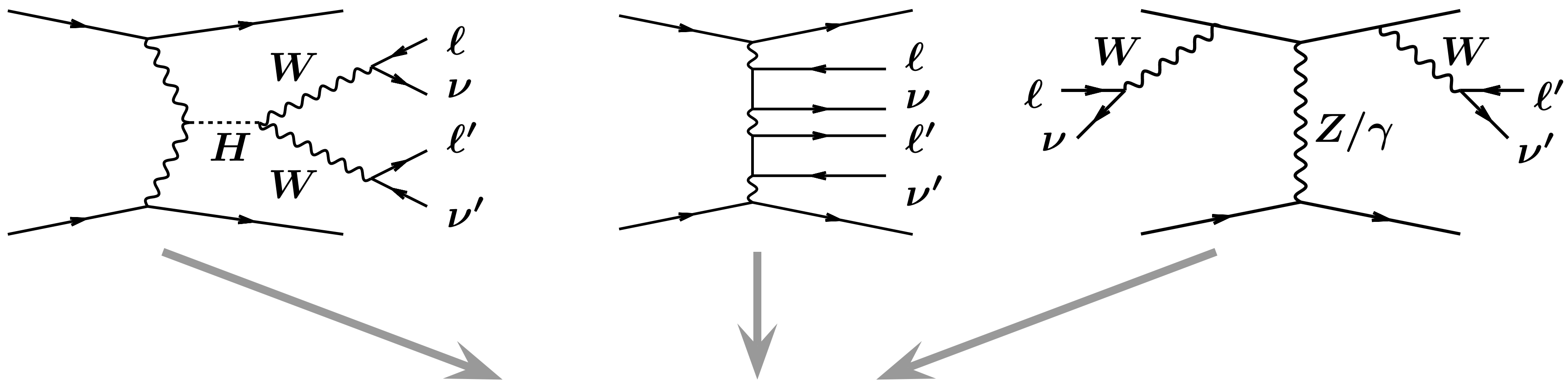
✔ provide implementation in versatile
public program package POWHEG-BOX

✘ challenge: complex multi-leg process with
involved resonance structure

$\to$ conceptually and computationally demanding*

$\star$ requires about 12 hours$\times$100 nodes on a HPC cluster

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

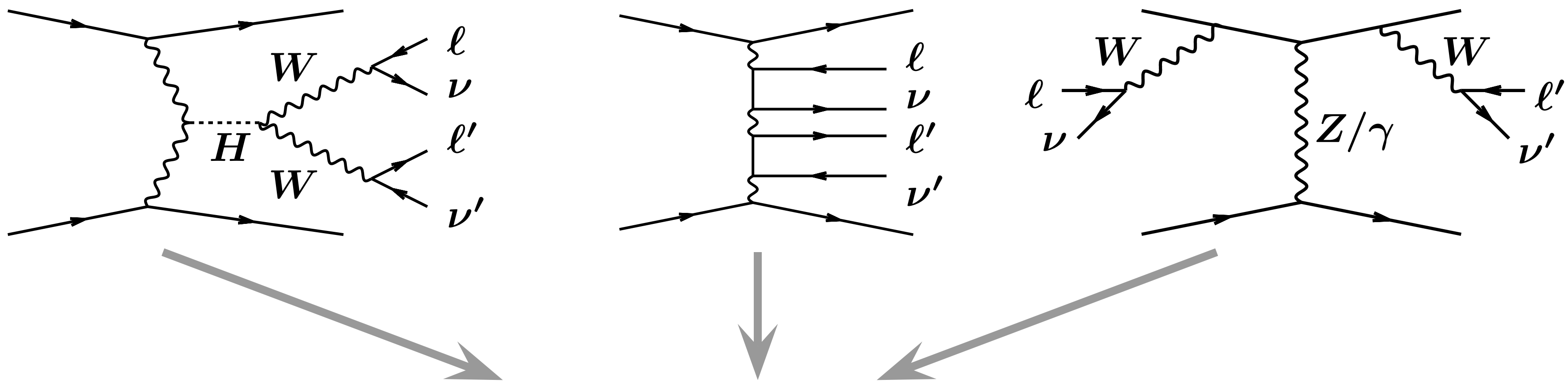


different topologies populate different regions in phase space

☞ split phase space into two regions for :

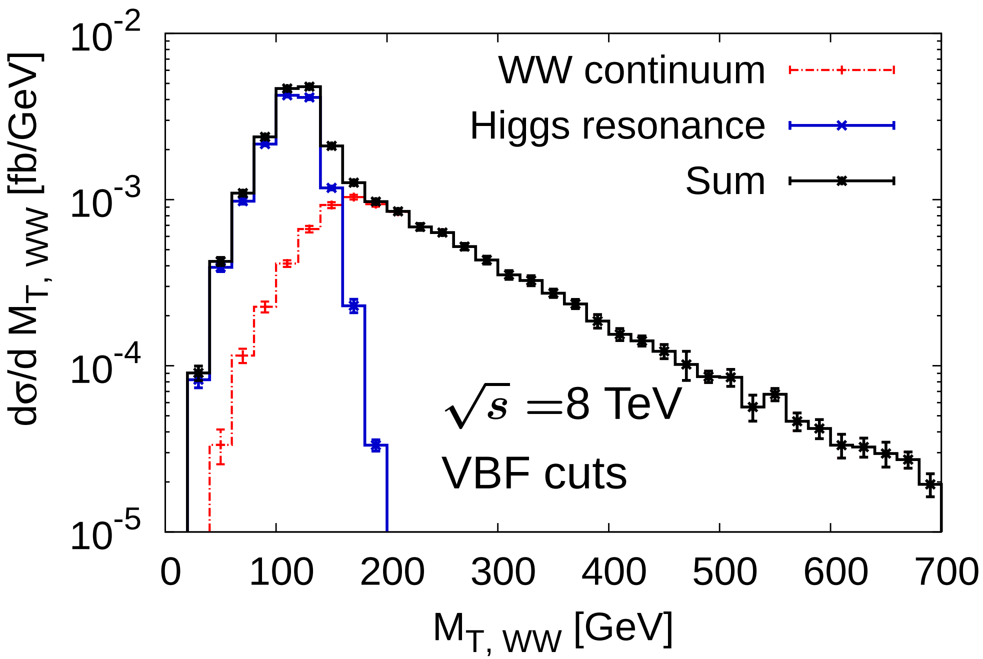
- $M_H - \Delta M \le M_{2\ell 2\nu} \le M_H + \Delta M$
- all other values of $M_{2\ell 2\nu}$

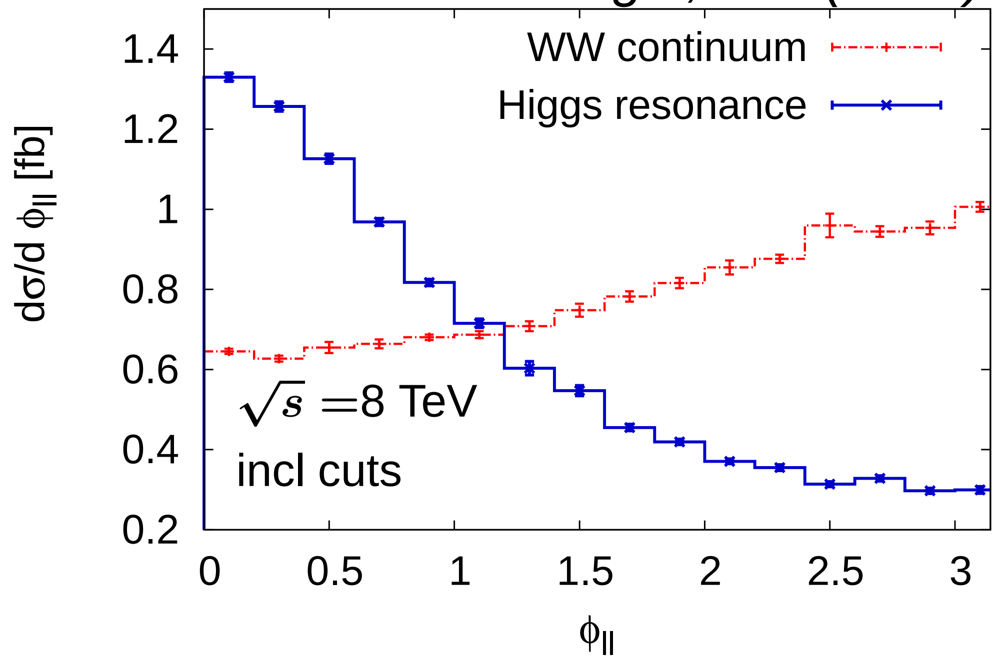
$pp \to W^+W^-jj$: technicalities



different topologies populate different regions in phase space:

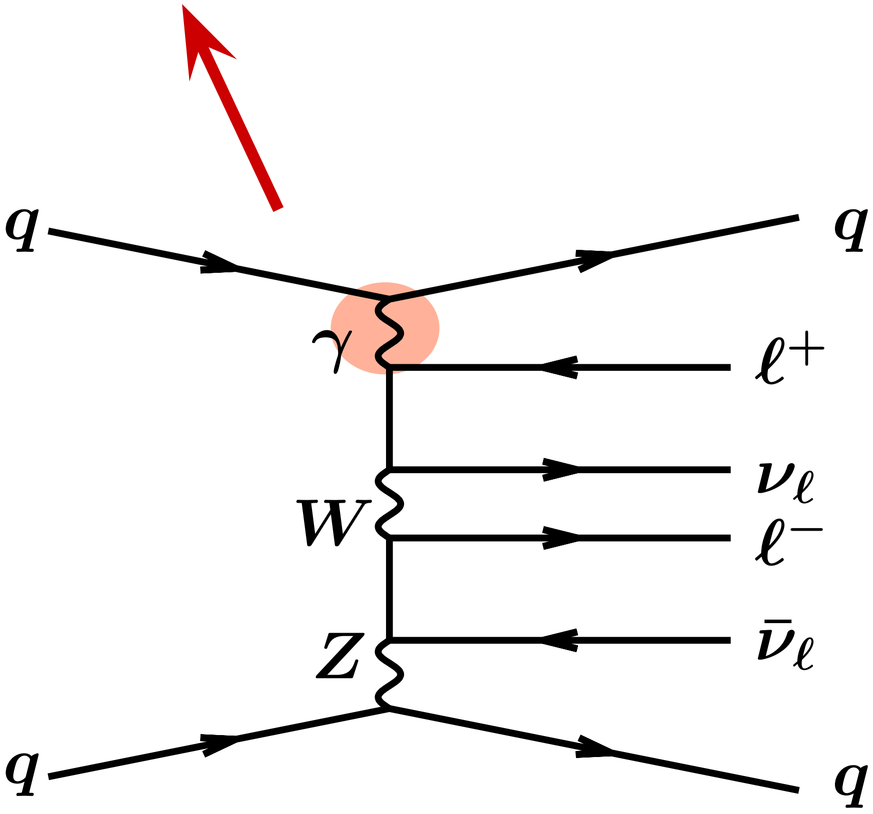
G. Zanderighi, B.J. (2013)





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

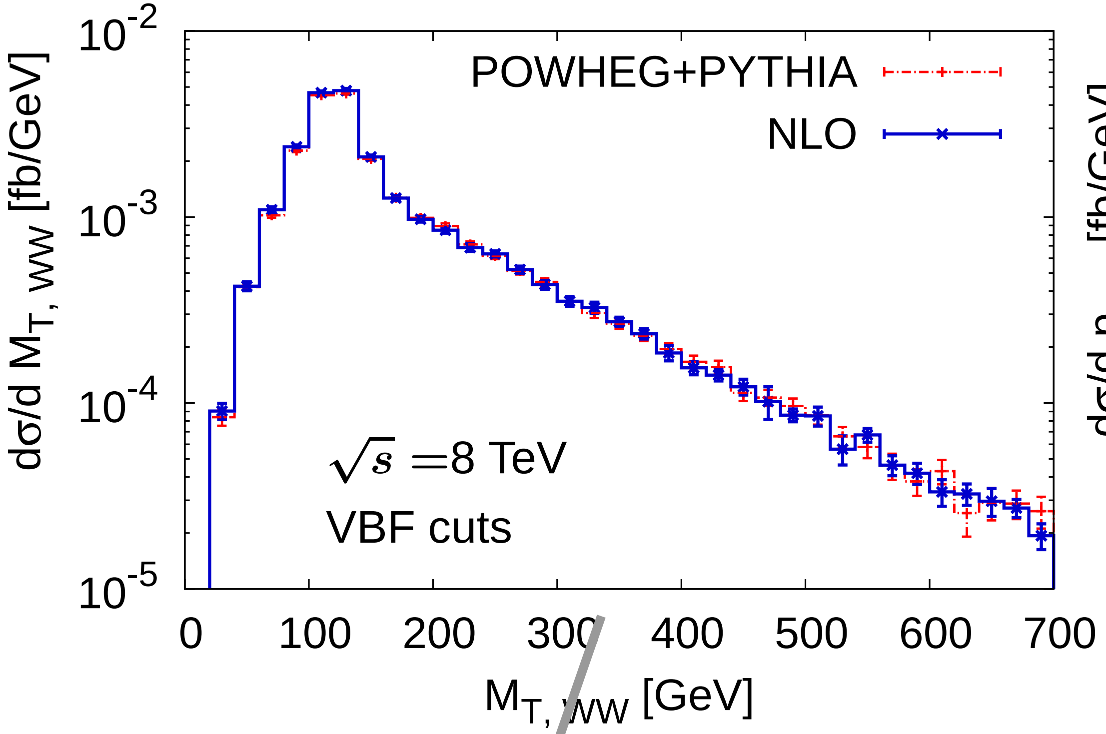
(2) Born-suppression factor to achieve efficient phase space integration

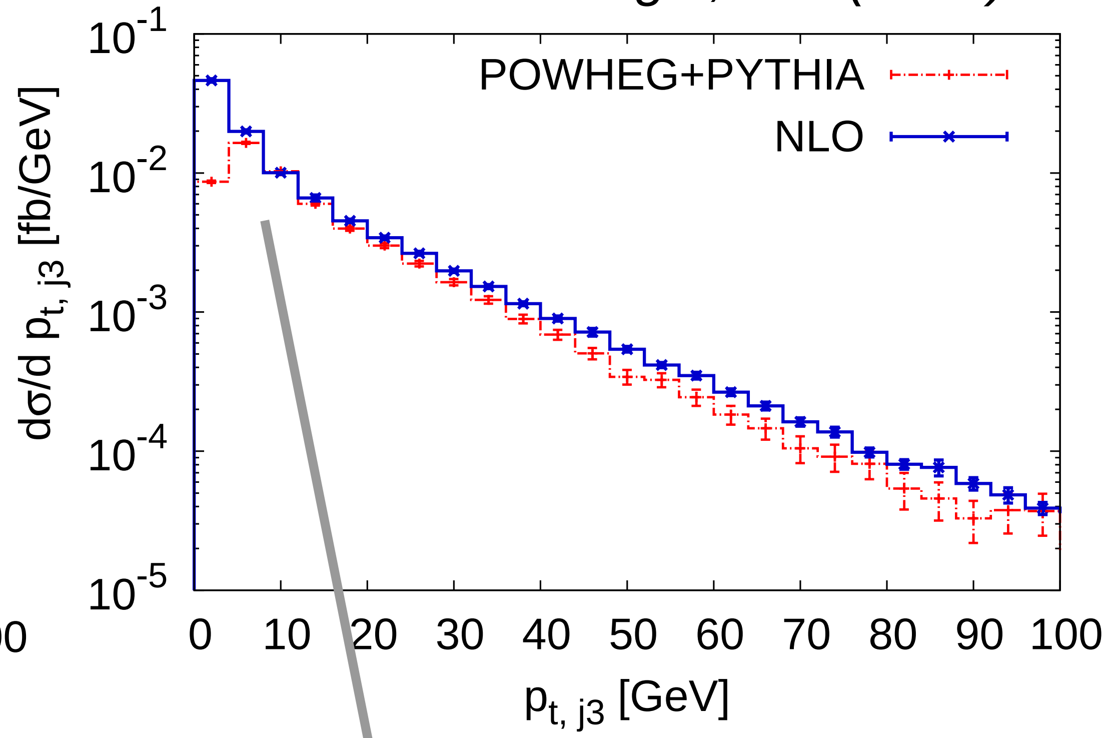
$$F \sim \left(\frac{p_{T,1}^2}{p_{T,1}^2+\Lambda^2}\right)^2 \left(\frac{p_{T,2}^2}{p_{T,2}^2+\Lambda^2}\right)^2$$

(alternative: explicit generation cuts)

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

G. Zanderighi, B.J. (2013)

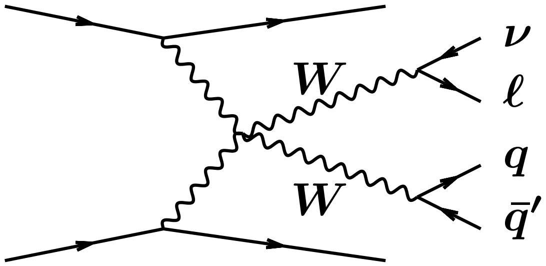




leptonic observables not very sensitive to parton shower

growth of jet distribution tamed by Sudakov factor

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



"semi-leptonic" final state:

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

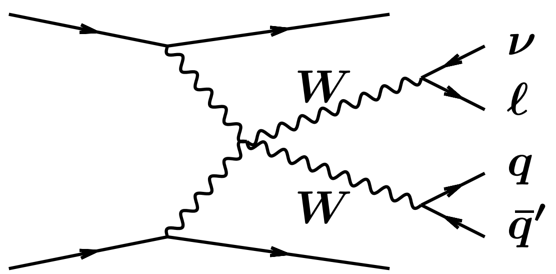
different from fully leptonic modes:

✔ 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

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



consider fictitious scenario with heavy Higgs

$$m_H = 400 \text{ GeV} > 2M_W$$

$\to W$ bosons are typically on-shell

- require VBF topology for tagging jets:

$$p_{T,j}^{\text{tag}} > 25 \text{ GeV}\,, \qquad |y_j^{\text{tag}}| < 4.5$$
$$\Delta y_{jj}^{\text{tag}} > 3\,, \qquad m_{jj}^{\text{tag}} > 600 \text{ GeV}$$

- two decay jets have to be compatible with W decay

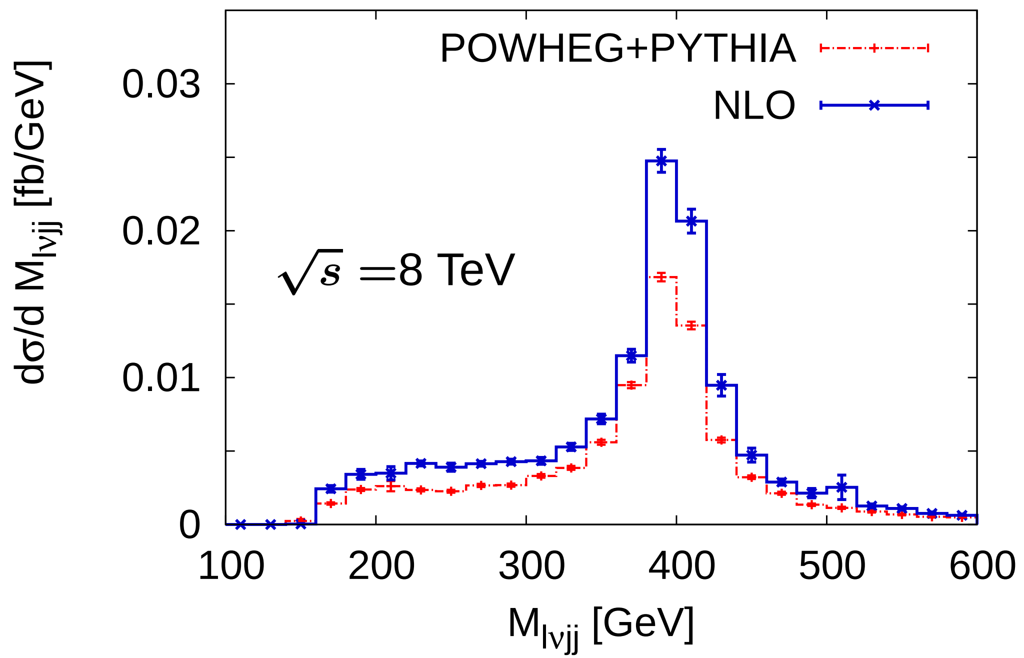
$$M_W - 10 \text{ GeV} \le m_{jj}^{\text{dec}} \le M_W + 10 \text{ GeV}$$

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

- reconstruct $M_{\ell\nu jj}$ using the assumption that

$$M_{\ell\nu} = M_W$$

($\to$ neutrino momentum)

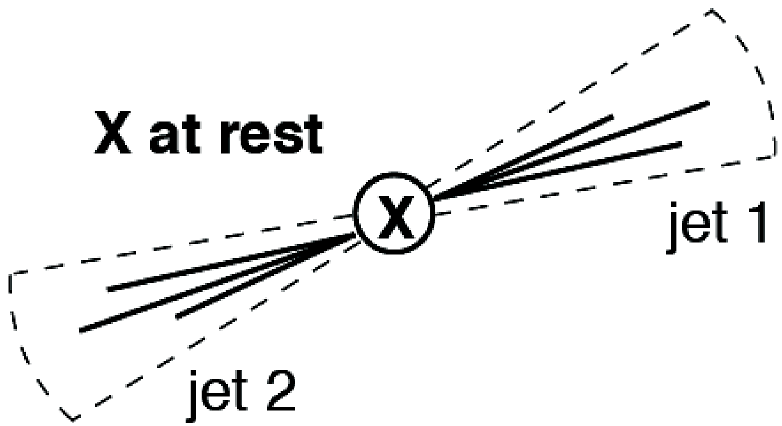


✘ $M_{\ell\nu jj}$ distribution very sensitive to parton-shower effects!

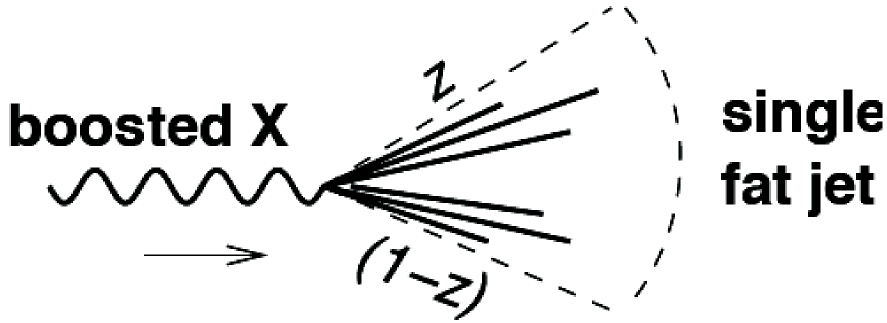
soft radiation smears distribution of W decay jets
$\to m_{jj}^{\rm dec} \sim M_W$ requirement no longer fulfilled

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

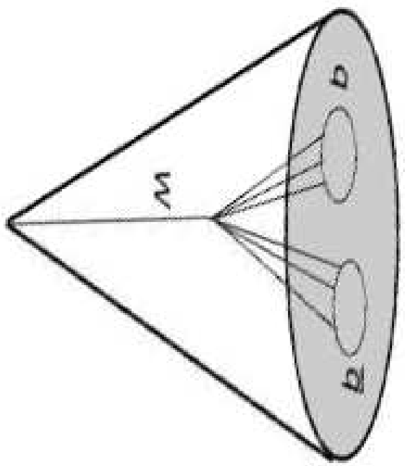
  Butterworth, Cox, Forshaw (2002)

- break-through in $pp \to VH$

  Butterworth, Davison, Rubin, Salam (2008)

- today: established field in its own

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

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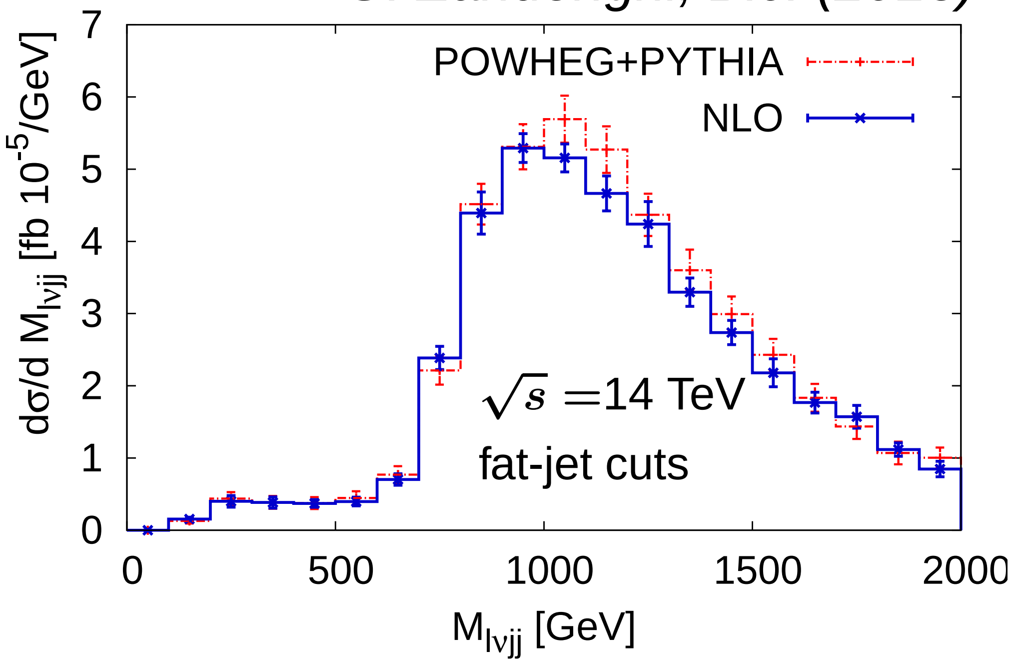


results stable against parton-shower effects

selection cuts

specific for fat-jet analysis:

$$p_{T,J}^{\text{boosted}} > 300 \text{ GeV},$$

$$M_J \in (M_W \pm 10 \text{ GeV}),$$

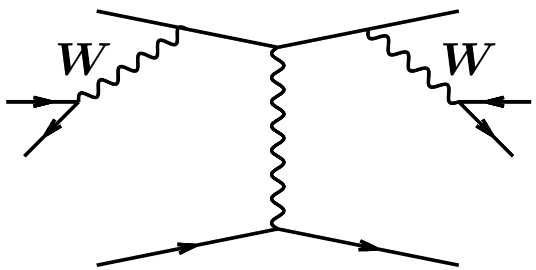
$$p_{T,\ell} > 300 \text{ GeV}$$

cuts enforce highly energetic WW system

(above light Higgs resonance)

less massive final state

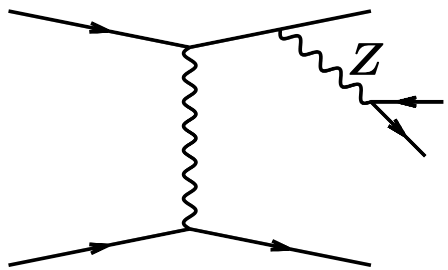
$pp \to Zjj$ via VBF



$pp \to Zjj$

versus

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

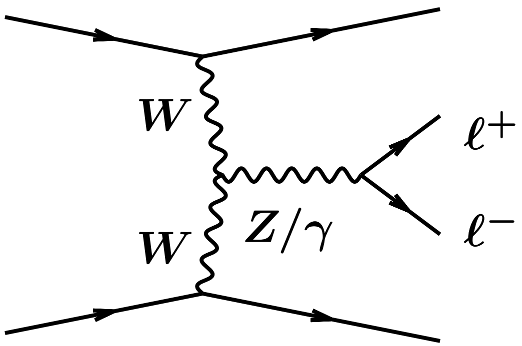


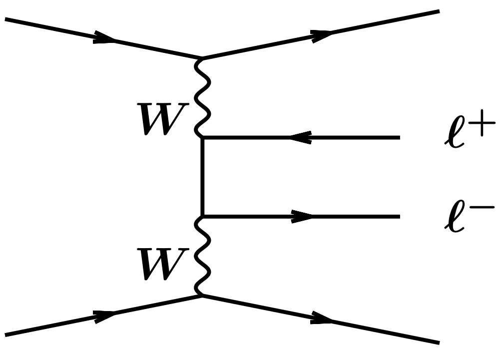
less particles in final state $\to$ simpler matrix elements

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 $Q^2_{\ell\ell} \to 0$

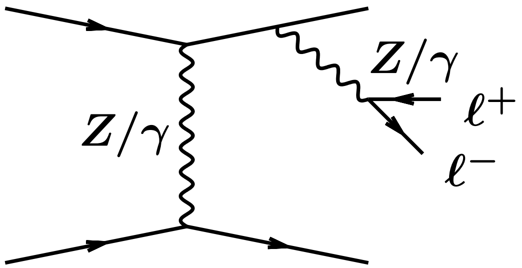
$\to$ introduce generation cut

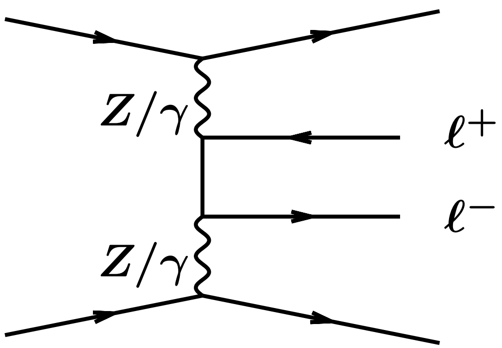
$$m_{\ell\ell}^{\rm gen} = 30\ {\rm GeV}\,,$$

supplemented by analysis cut

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

neutral current modes:





extra singularity for photons in t-channel

with $Q_\gamma^2 \to 0$

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

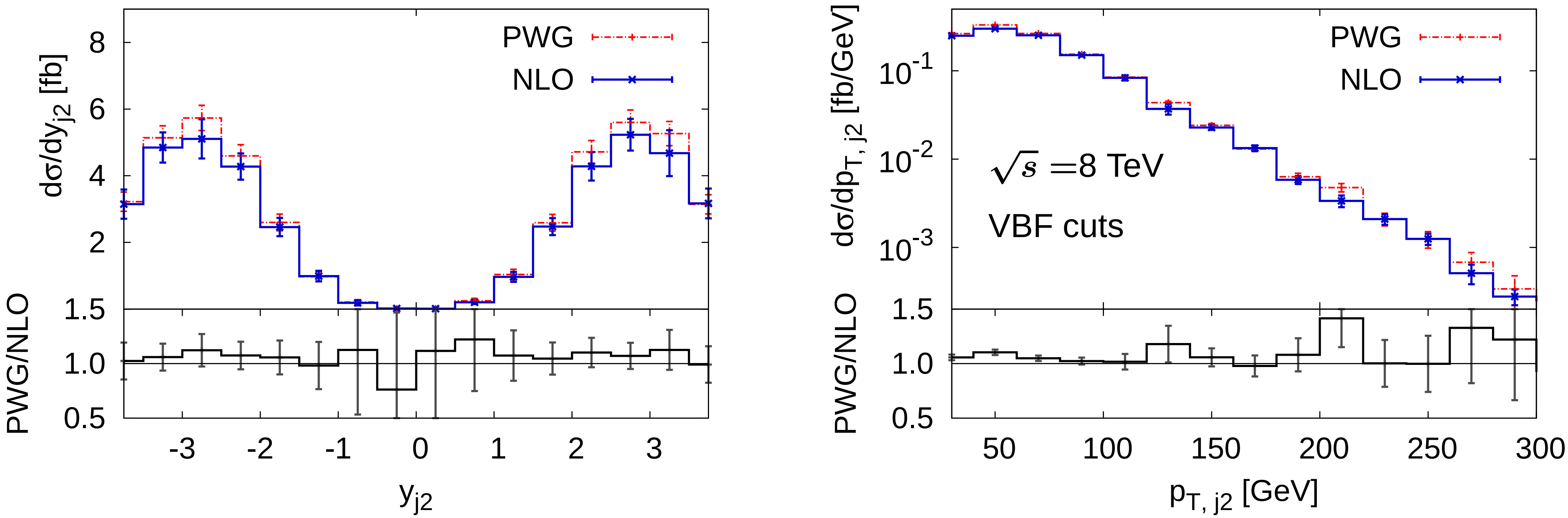
- ☞ damping factor in matrix elements
- ☞ Born-suppression factor

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

(alternative: generation cuts)

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

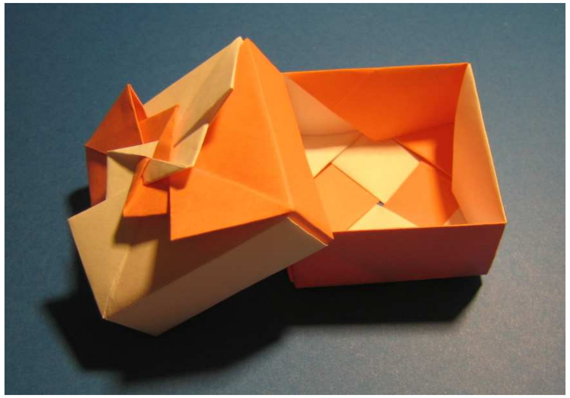
Schneider, Zanderighi, B.J. (2012)



parton shower effects are moderate

for distributions related to hard jets

VBF 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

summary

VBF crucial for understanding mechanism of electroweak symmetry breaking:

- ❋ very clean Higgs production channel
- ❋ 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)

✔ backgrounds are well under control

conclusions

for a quantitative understanding of VBF processes it is vital to provide:

❋ precise predictions, including

- NLO QCD corrections
- NLO EW corrections, interference effects, realistic PDFs, . . .

❋ realistic predictions, allowing for

- calculation of distributions within experimental selection cuts
- matching to parton-shower Monte Carlos at NLO-QCD accuracy

❋ sophisticated analysis techniques, requiring cross links between experimentalists and theorists / phenomenologists

...for your attention