$VVjj$ production at the LHC – a Standard Model perspective

Anomalous Quartic Gauge Couplings

Dresden – September 2013

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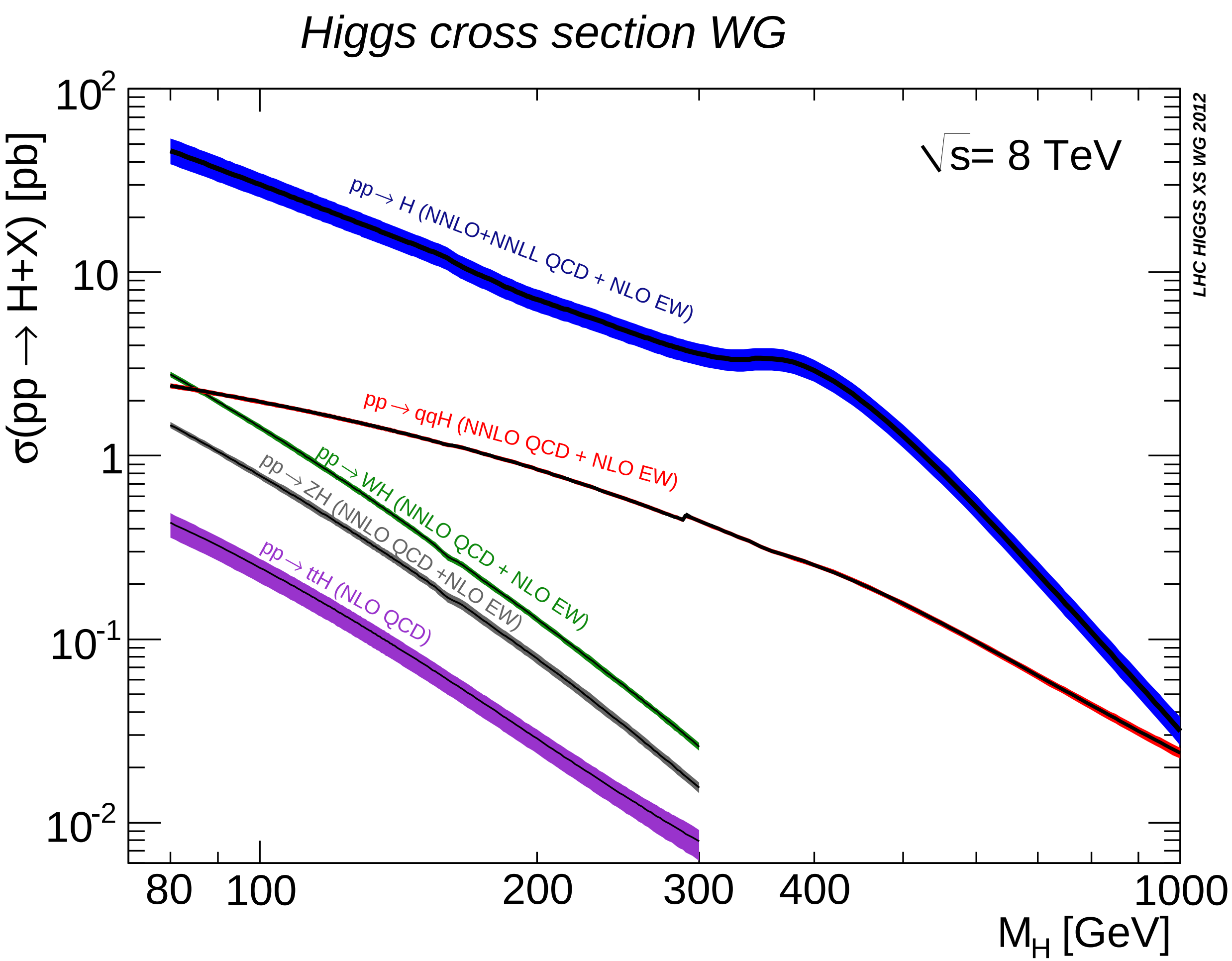
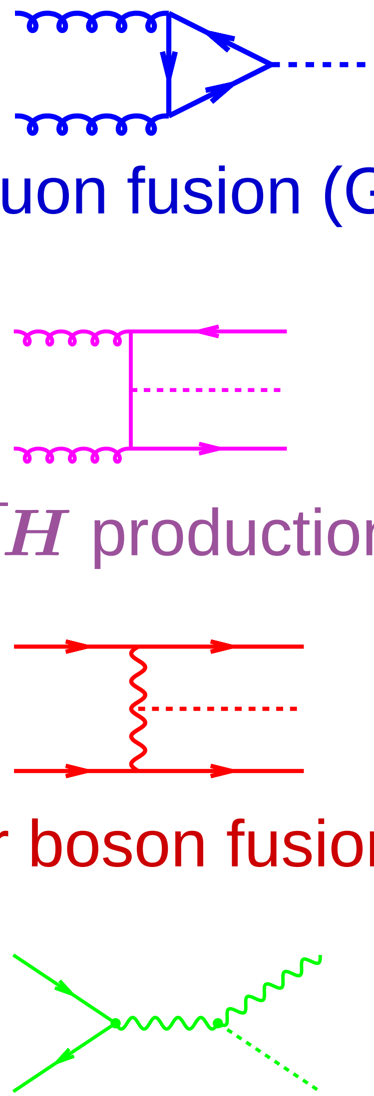
Higgs production @ LHC





gluon fusion (GF)

$t\bar{t}H$ production

vector boson fusion (VBF)

W, Z bremsstrahlung

vector boson fusion (VBF)

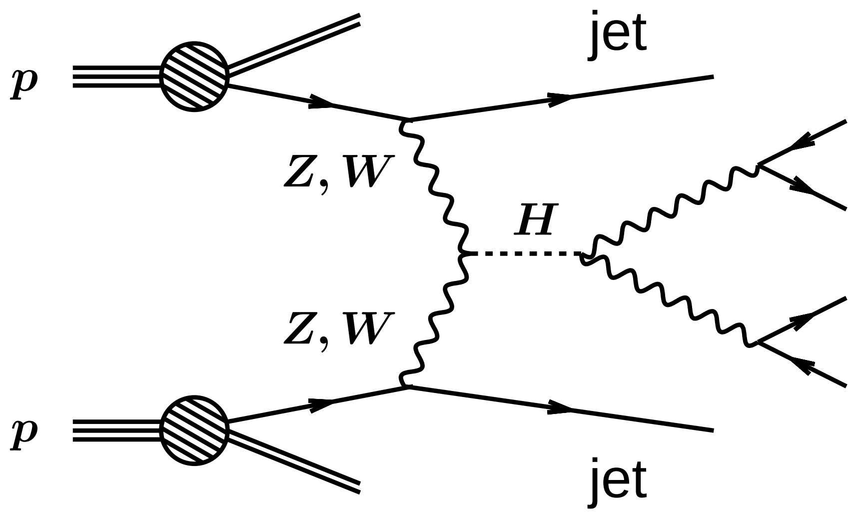
- important production mode for:
  - Higgs boson at $M_H = 126$,
  - heavy Higgs boson(s),
  - scalar bosons in new physics scenarios

- perturbatively well under control
- experimentally clean signature

- sensitive to Higgs couplings and CP properties

☞ accurate predictions essential!

$pp \to Hjj$ via 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

VBF: signal & backgrounds

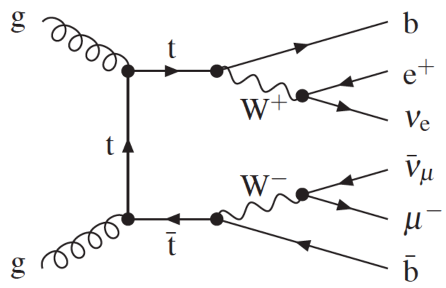
distinct event topology of the Higgs signal in

$pp \to Hjj$ via VBF with

$$H \to W^+W^- \to e^\pm \mu^\mp \not{p}_T$$

☞ important for suppression of backgrounds

- $t\bar{t} + 0, 1, 2\,\mathrm{jets}$ production
  (note: $t\bar{t} \to W^+W^-b\bar{b}$)



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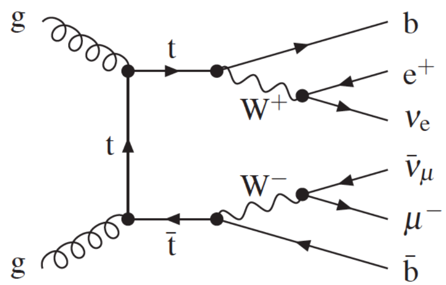

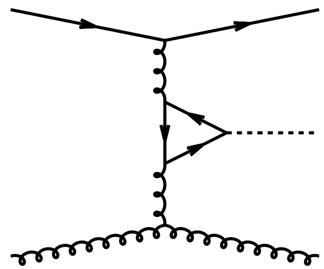

- $pp \to Hjj$ via gluon fusion
  (followed by $H \to W^+W^-$)

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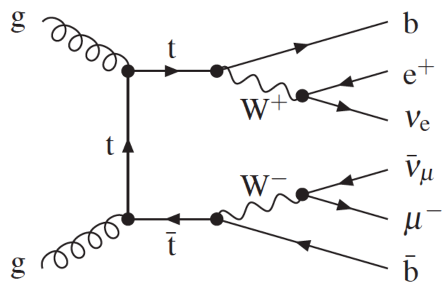

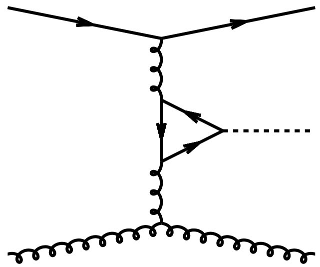

- $pp \to Hjj$ via gluon fusion
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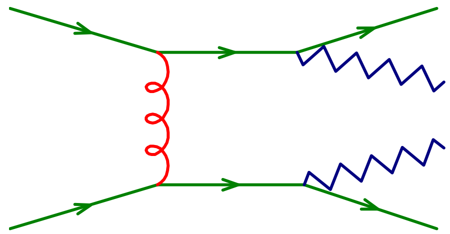
- QCD W^+W^-jj production



VBF: signal & backgrounds

distinct event topology of the Higgs signal in

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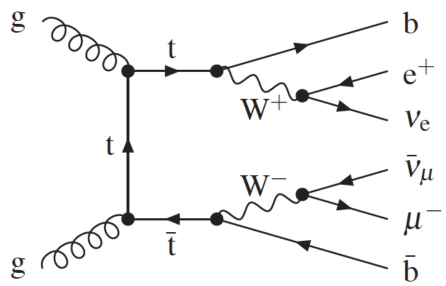

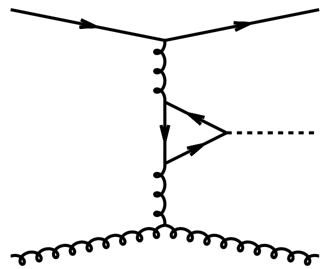

- $pp \to Hjj$ via gluon fusion
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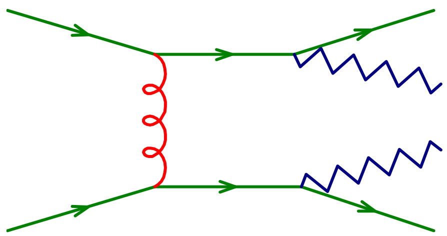
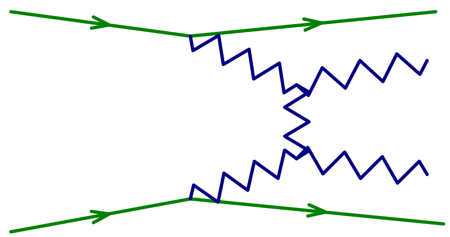
- QCD W^+W^-jj production
- EW W^+W^-jj production

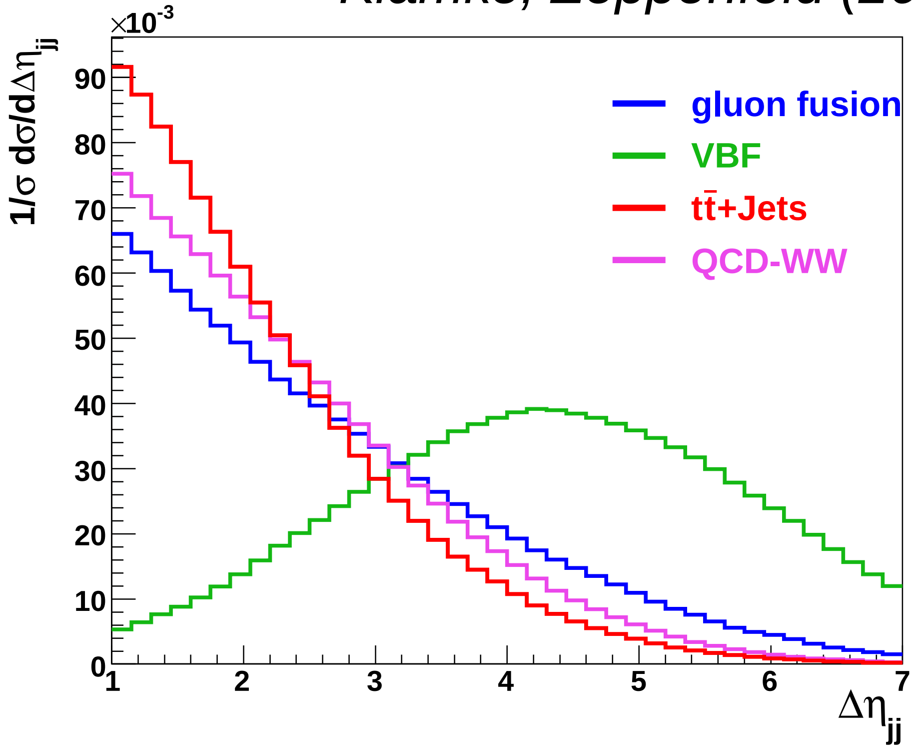




tagging jets: properties

rapidity separation of the tagging jets

Klämke, Zeppenfeld (2007)



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

angular distribution of charged leptons

in $H \to W^+W^-$: spins anti-correlated

↓

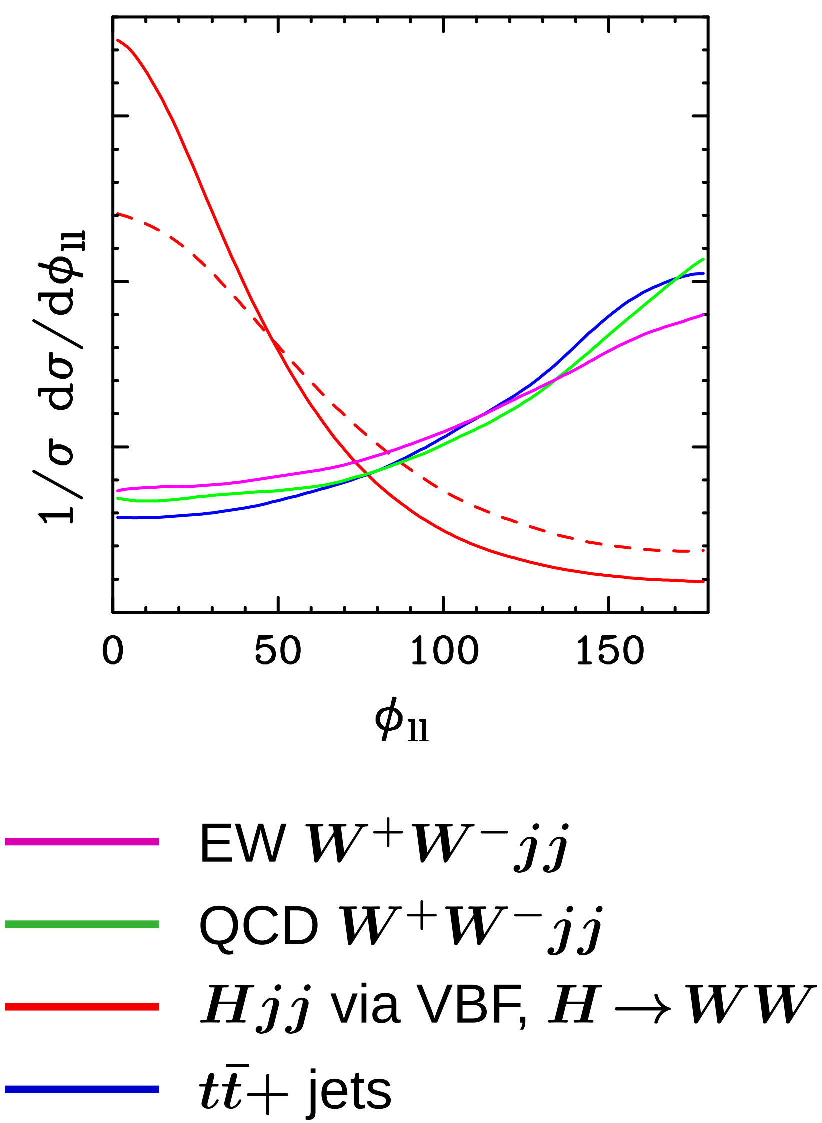
leptons emitted preferentially in same direction

no such correlation, if W bosons do not stem from the Higgs

Dittmar, Dreiner (1996)

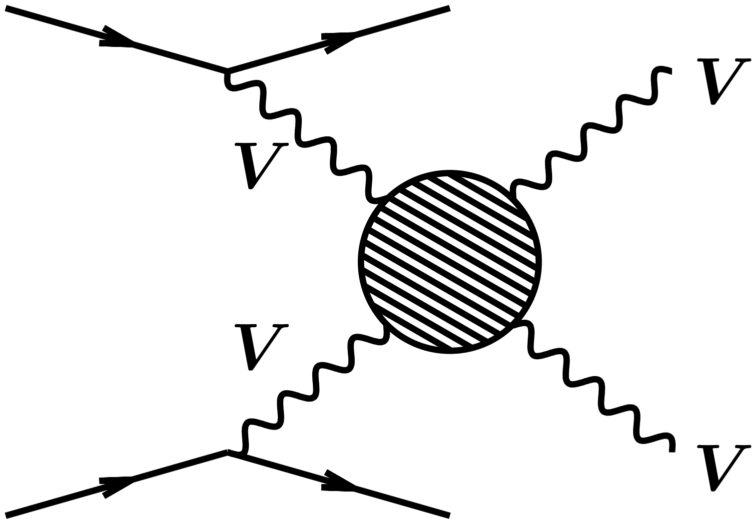
distribution for EW W^+W^- production significantly different from Higgs signal

Rainwater, Zeppenfeld (1999)



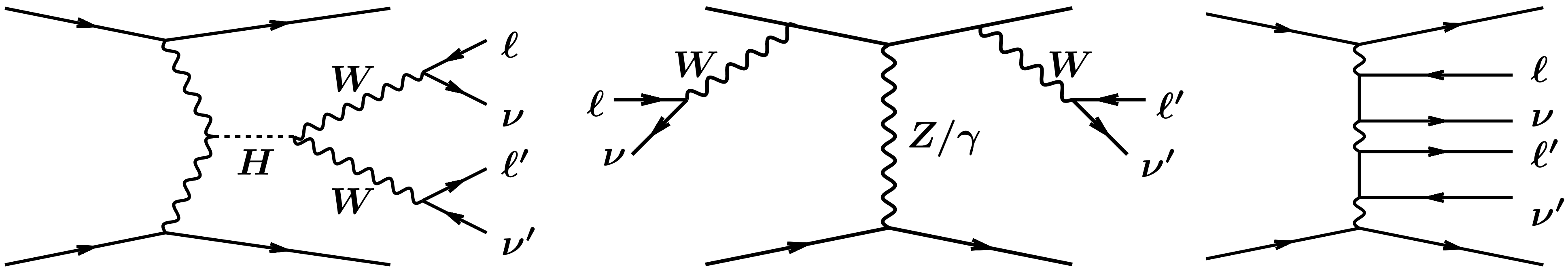
. . . today’s background – tomorrow’s signal . . . ?

vector boson scattering: $VV \to VV$



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

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

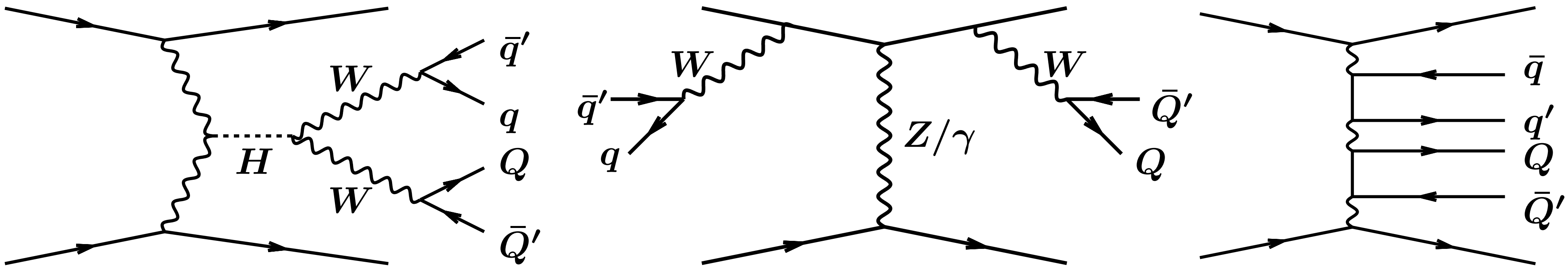


experiment: don't observe $VVjj$ final state, but
hadronic or leptonic decay products

$\mathbf{4leptons} + jj$

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

EW $VVjj$ production 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)

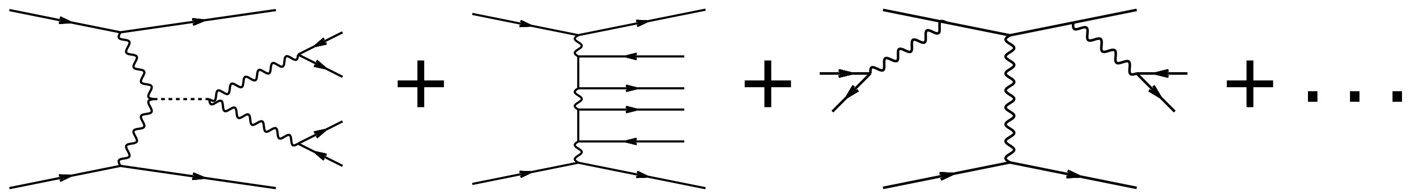
- straightforward implementation of experimental selection cuts

  - *G. Bozzi, C. Oleari, D. Zeppenfeld, B. J. (2006–2009)*
  - *A. Denner, L. Hosekova, S. Kallweit (2012)*

ingredients of the calculation

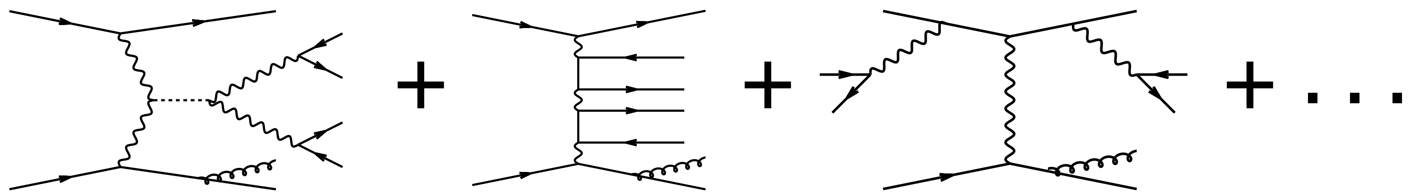
need to compute numerical value for . . .

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



. . . Born amplitude squared in 4 dim

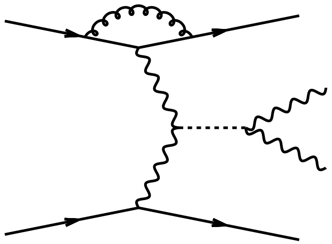
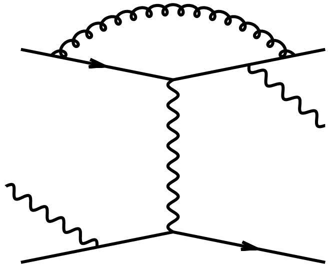
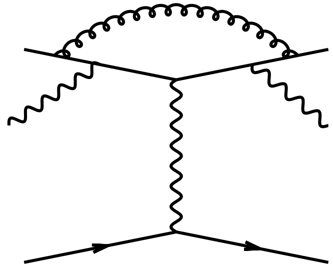
$$|\mathcal{M}_R|^2 = \Big| \quad \Big|^2$$



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

almost 3000 diagrams $\rightarrow$ 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`)

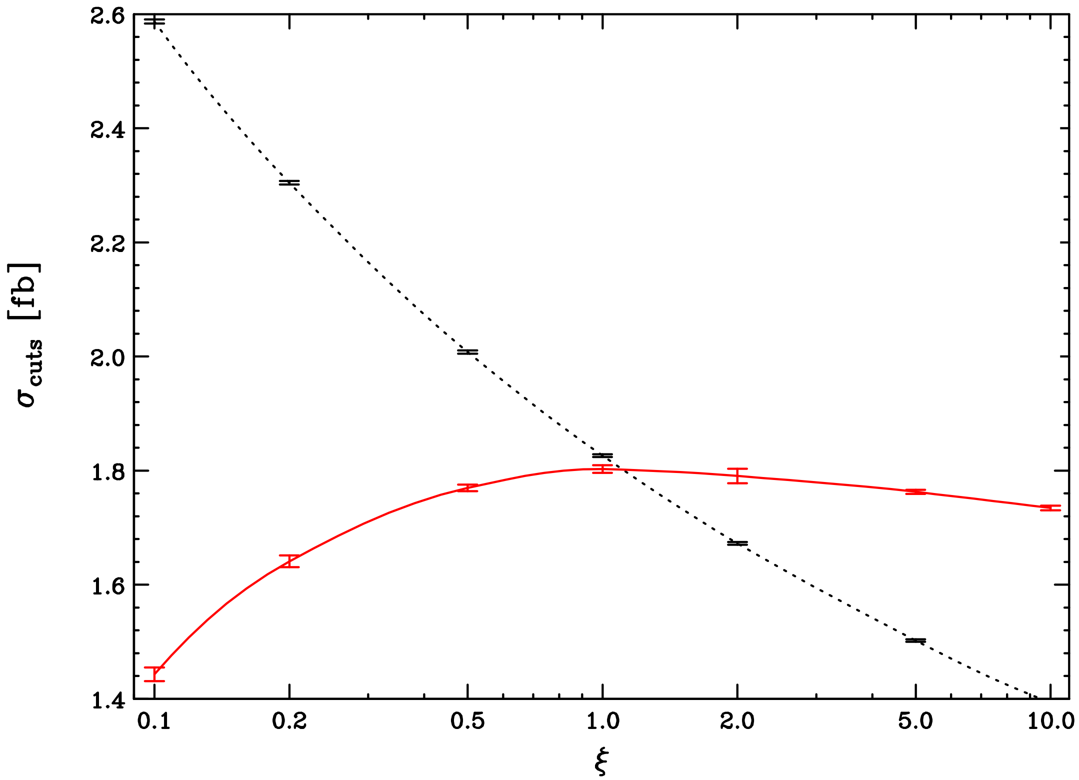
implementation

. . . put everything into dedicated

Monte-Carlo program VBFNLO . . .

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

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

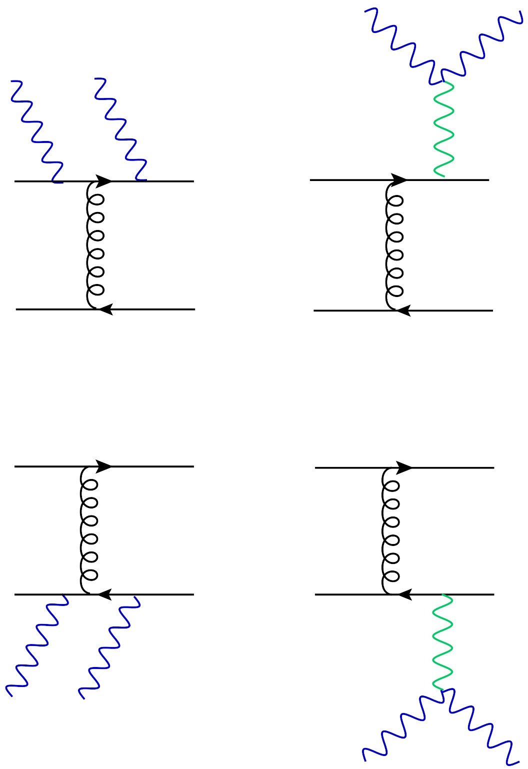


Oleari, Zeppenfeld, B.J. (2006)

LO: no control on scale

NLO QCD: scale dependence strongly reduced

QCD-induced $VVjj$ production



QCD-induced W^+W^-jj production constitutes irreducible background to

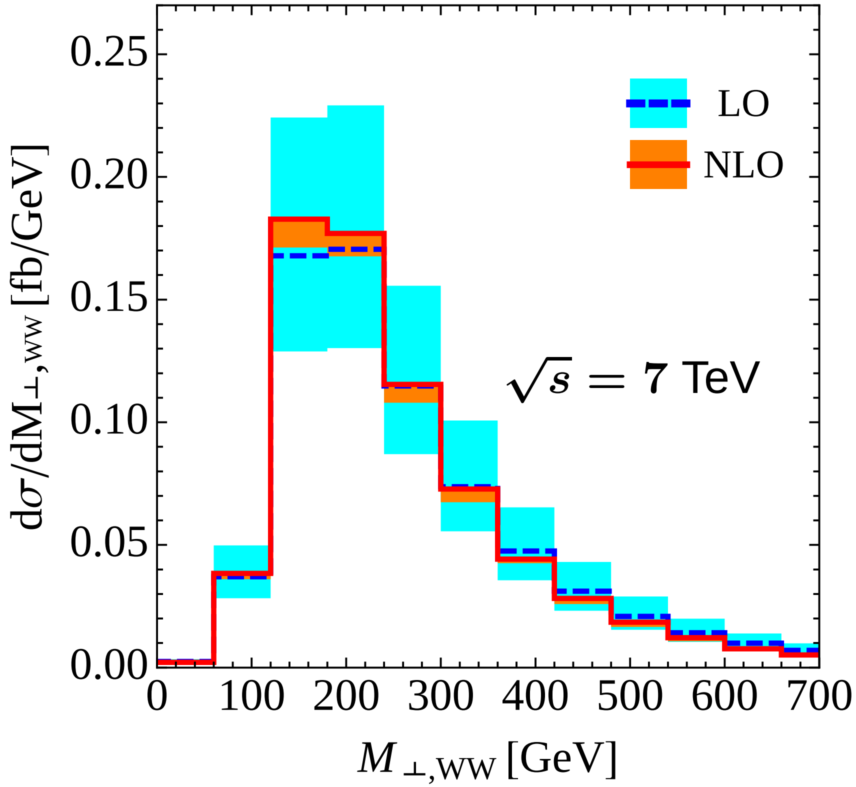
$$pp \to Hjj \to W^+W^-jj$$

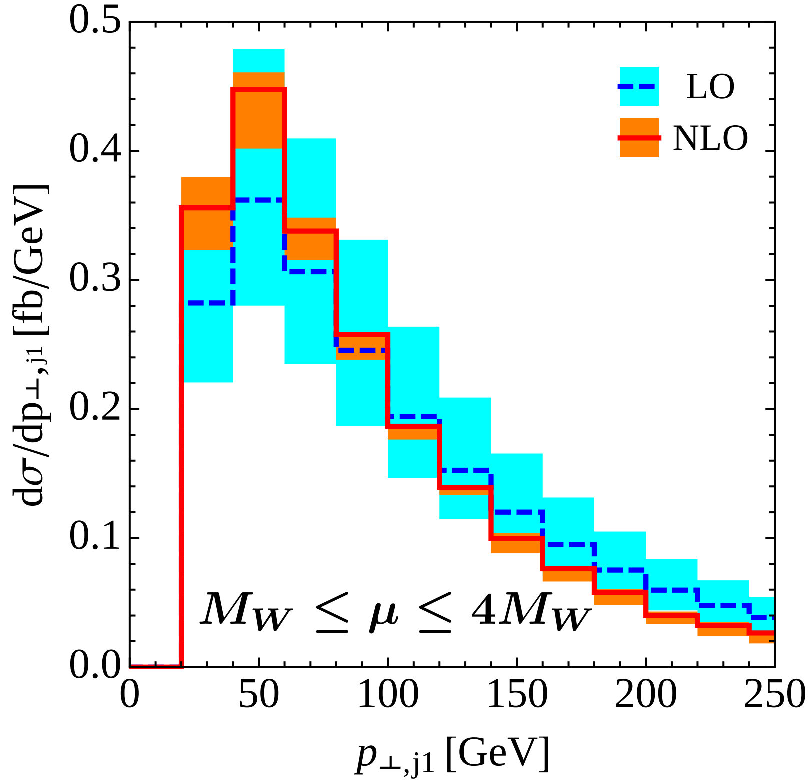
NLO-QCD predictions available

Melia, Melnikov, Rontsch, Zanderighi (2011); Greiner et al. (2012)

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

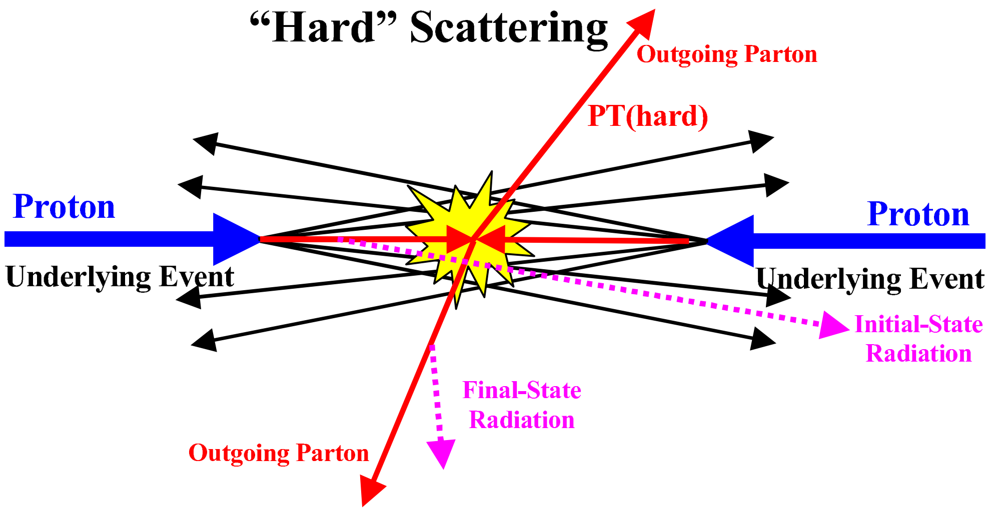
Melia, Melnikov, Rontsch, Zanderighi (2011)





NLO-QCD corrections significantly reduce scale uncertainty

more realistic simulation



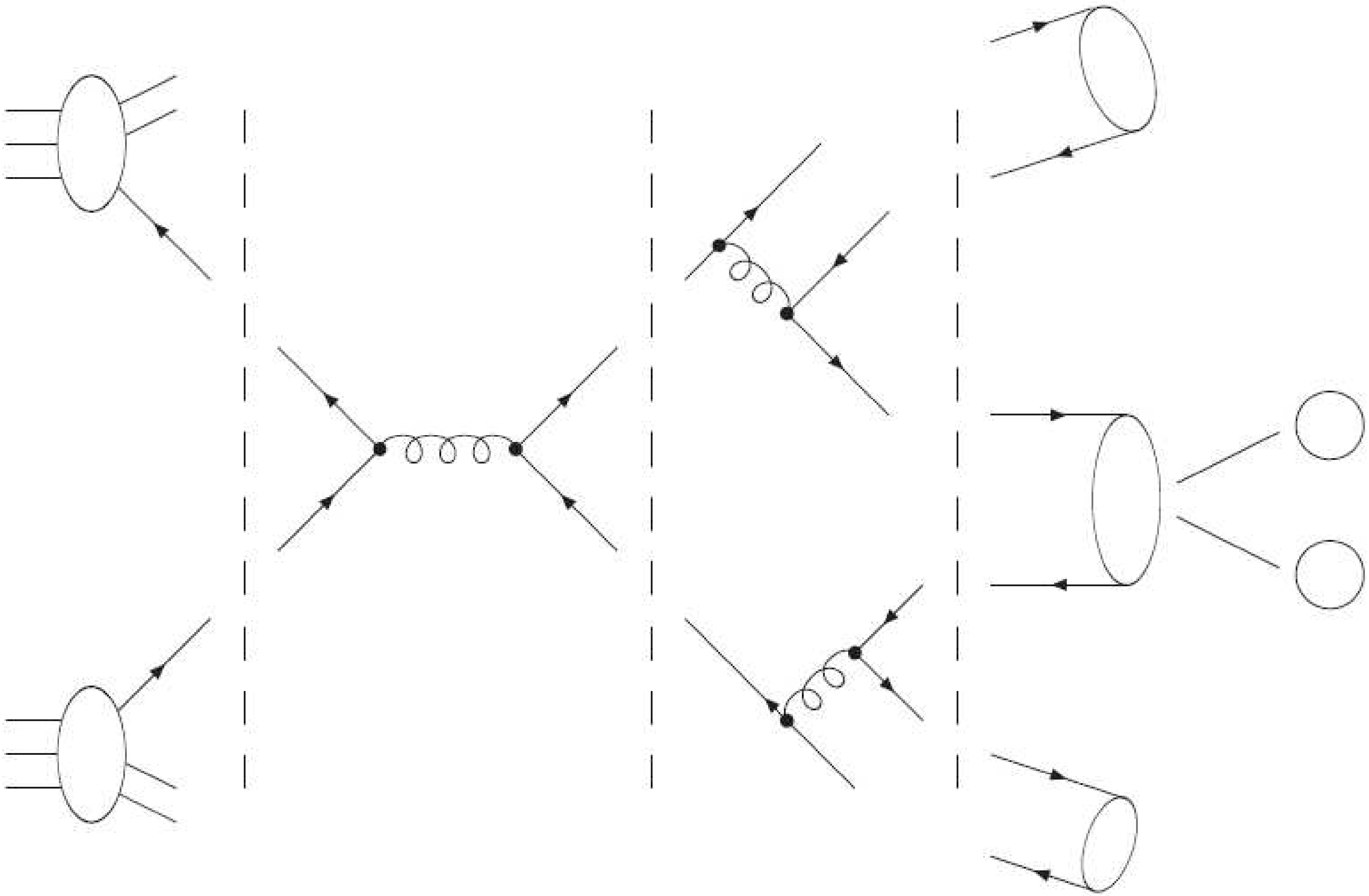
for realistic description of scattering processes at hadron colliders:

- 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

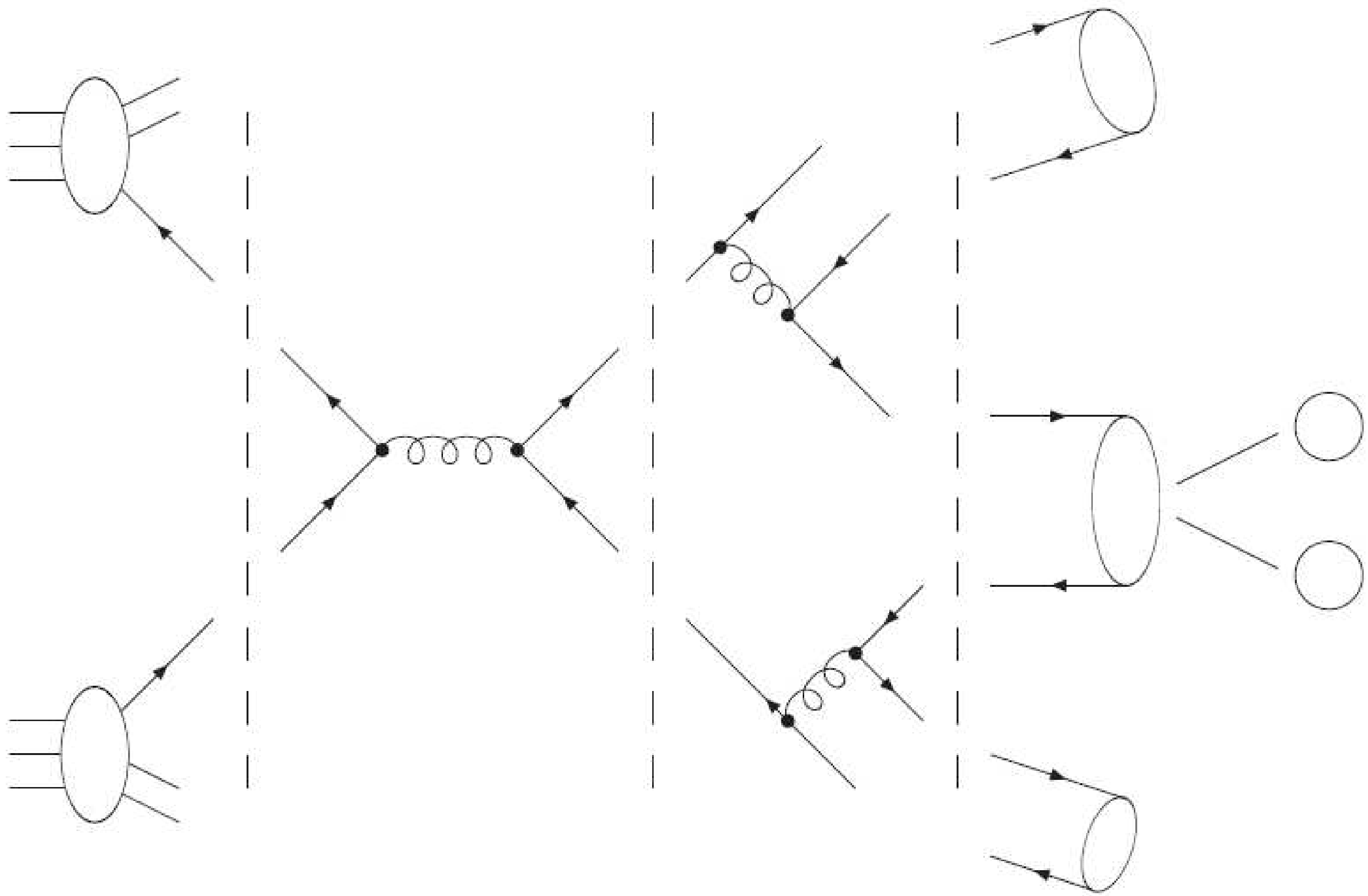
$\mu \sim \Lambda_{\mathrm{QCD}}$

stages of a hadronic collision

perturbation theory

multiple soft & collinear emissions

non-perturbative; pheno models tuned on data

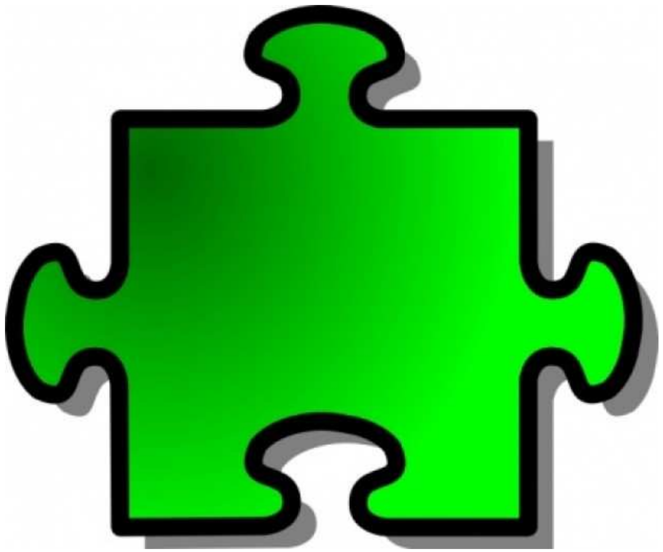


hard partonic scattering

parton shower

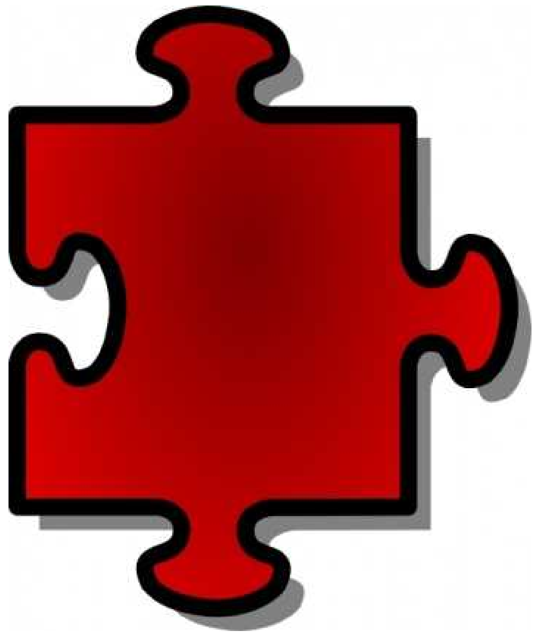
hadronization and decay

realistic & precise predictions



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 **W**eight **H**ardest **E**mission **G**enerator

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, ...`)

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]

- 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]

NLO cross sections

reminder: differential NLO cross section

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

Born

real emission and counter-terms

finite virtuals:

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

radiation phase space:

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

shower Monte Carlo cross sections

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

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

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

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

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

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

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

parton showers & NLO-QCD: the POWHEG-BOX

✘ user has to supply process-specific quantities:

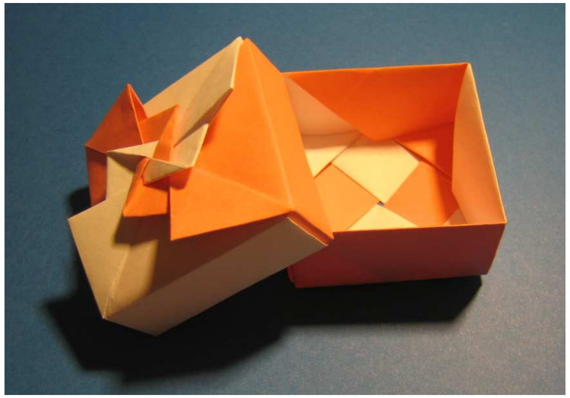
- lists of flavor structures for Born and real emission processes
- Born phase space
- Born amplitudes squared, color-and spin-correlated amplitudes
- real-emission amplitudes squared
- finite part of the virtual corrections
- Born color structure in the limit of a large number of colors

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

parton showers & NLO-QCD: the POWHEG-BOX

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

http://powheghbox.mib.infn.it/



selected processes in the POWHEG-BOX:

- Hjj production via VBF *[Oleari, Nason (2009)]*
- Hjj production via gluon fusion *[Campbell et al. (2012)]*
- 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)]*

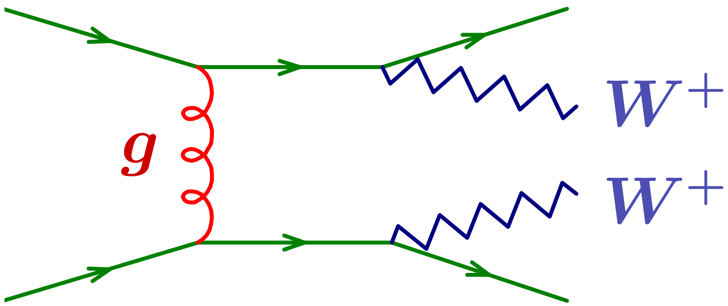
$pp \to W^+W^+jj$ in the POWHEG-BOX

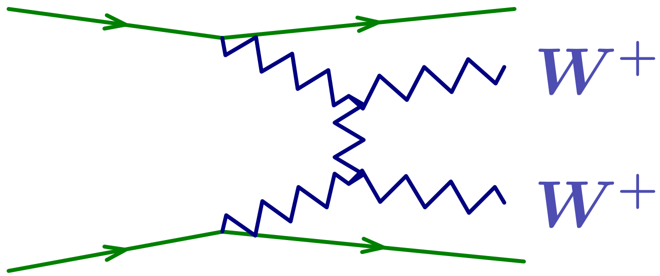
QCD-induced production

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

EW production

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





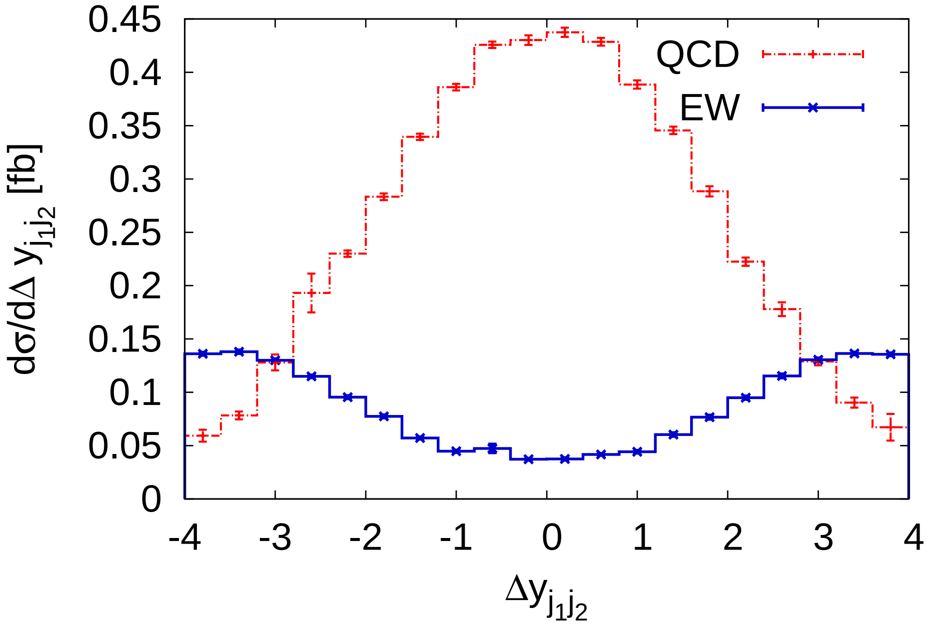
NLO-QCD results for $\sqrt{s}$ =7 TeV with basic jet cuts only ($p_T^{\mathrm{tag}} > 20$ GeV):

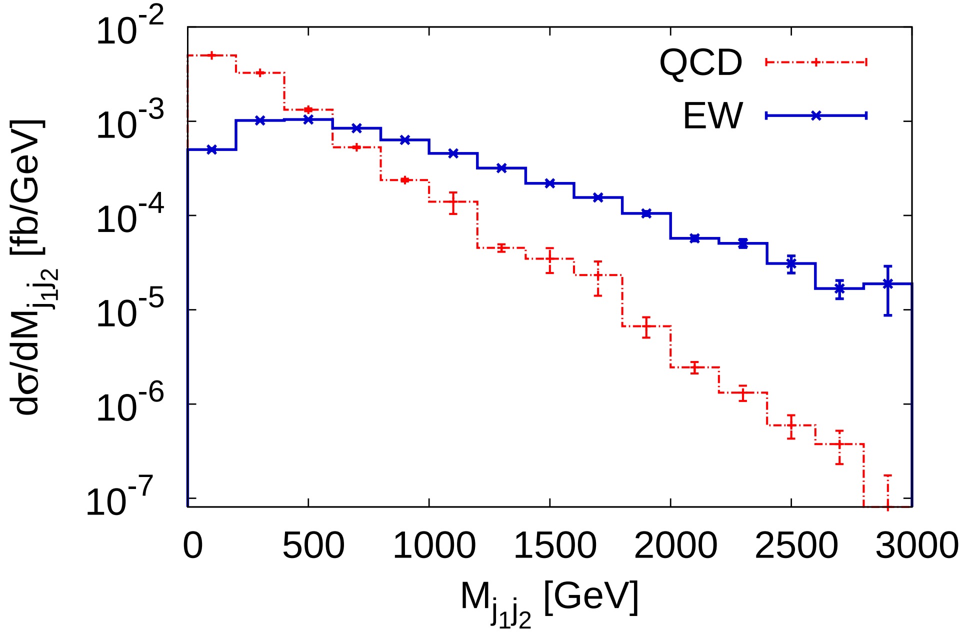
$\sigma_{\mathrm{QCD}}^{\mathrm{inc}} = 2.12$ fb

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

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

Zanderighi, B.J. (2011)

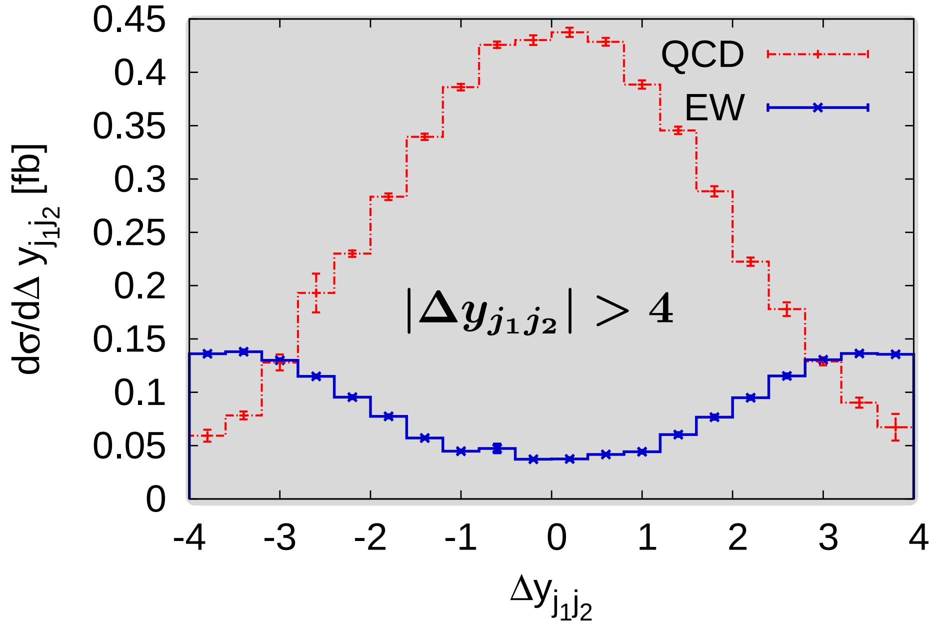


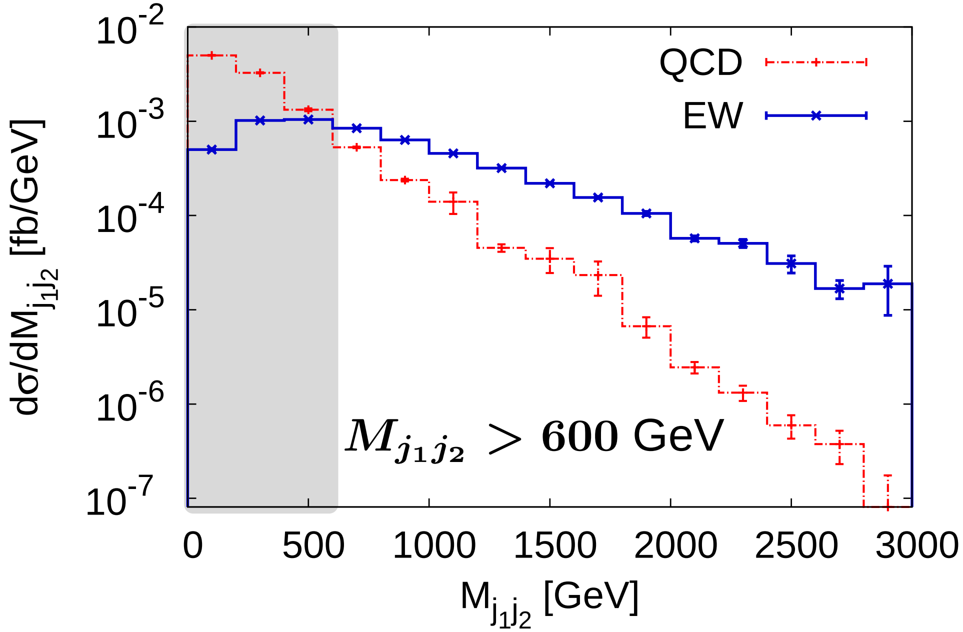


- $\sqrt{s} = 7$ TeV
- basic jet cuts only
- NLO-QCD accuracy

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

Zanderighi, B.J. (2011)





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

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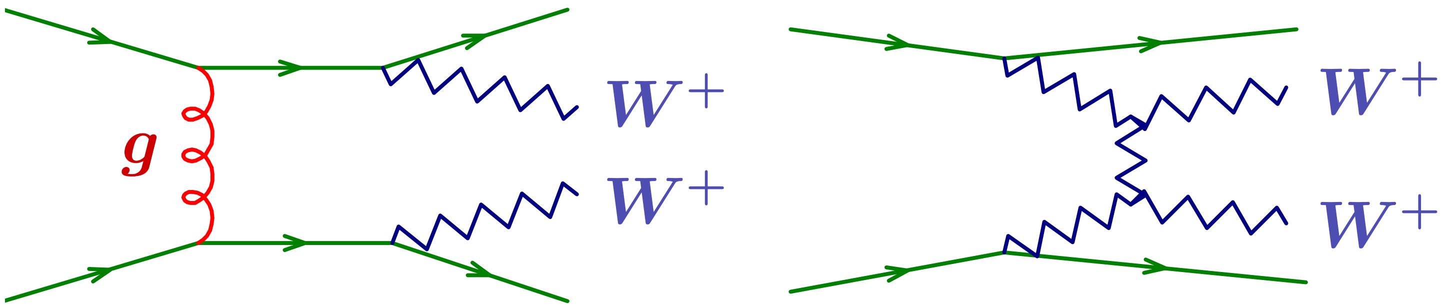
Zanderighi, B.J. (2011)



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

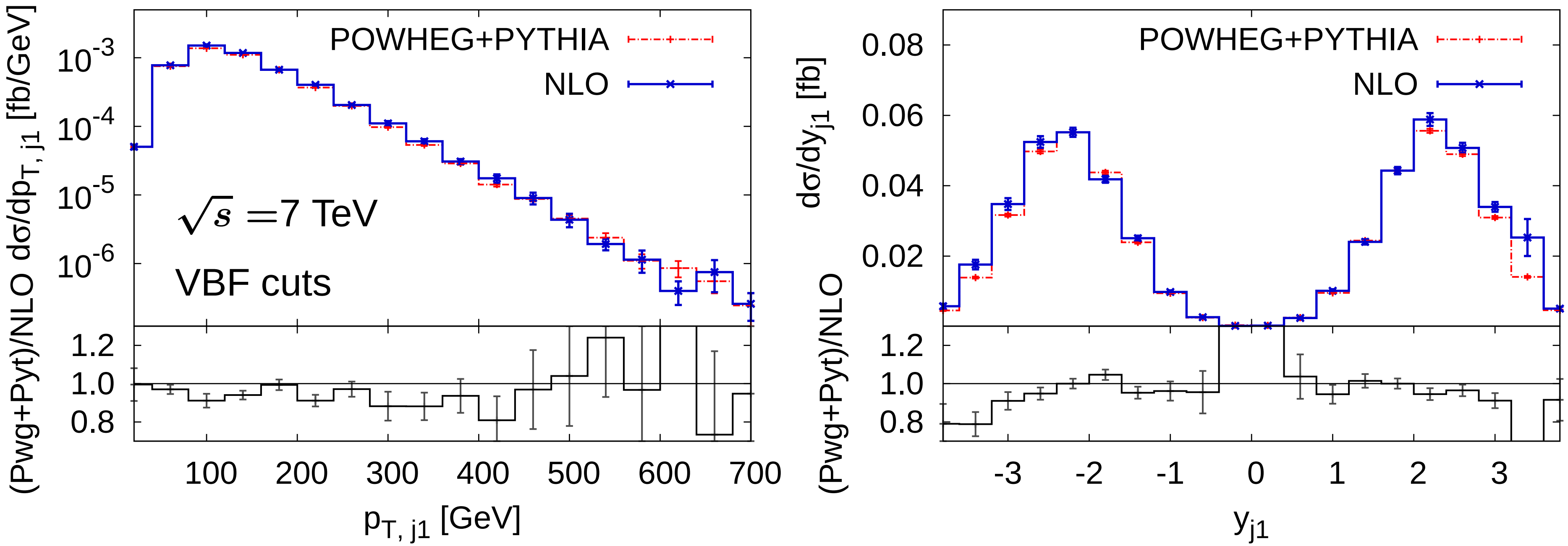
$\sigma_{\text{QCD}}^{\text{inc}} = 2.12$ fb $\quad\quad \sigma_{\text{EW}}^{\text{inc}} = 1.097$ fb

NLO results with VBF cuts:

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

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

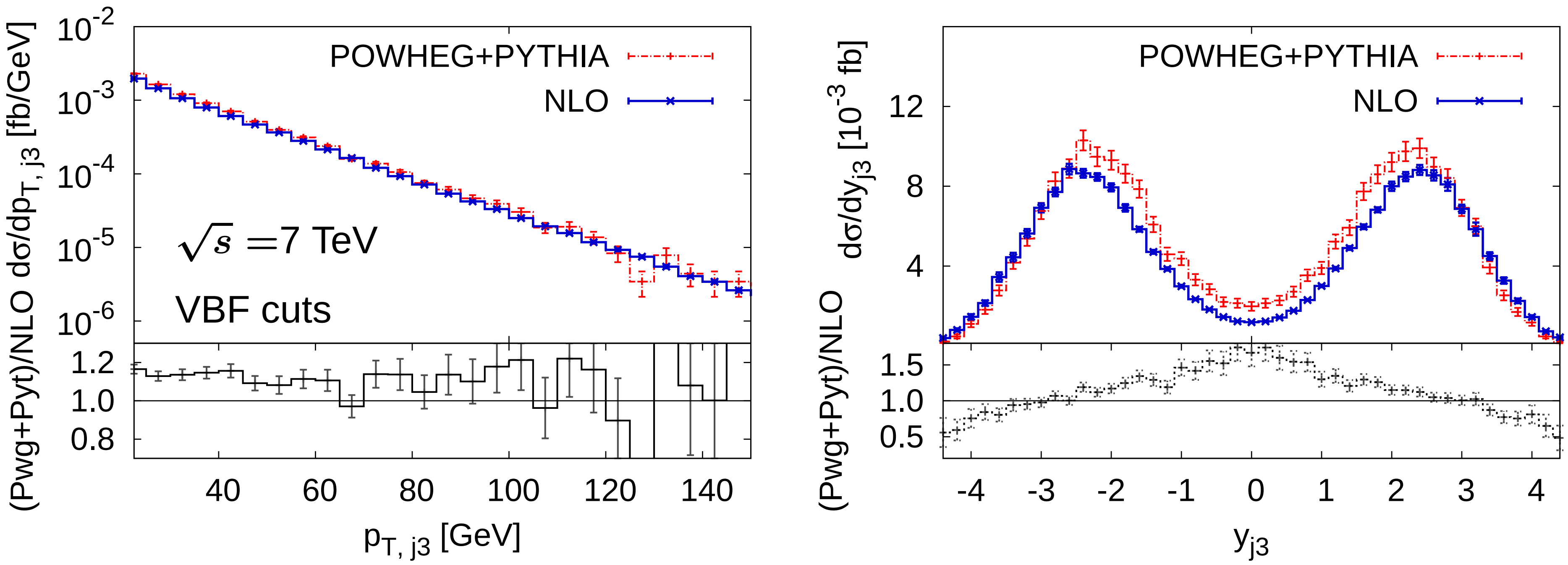
Zanderighi, B.J. (2011)



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

the next step: $pp \to W^+W^-jj$

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

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

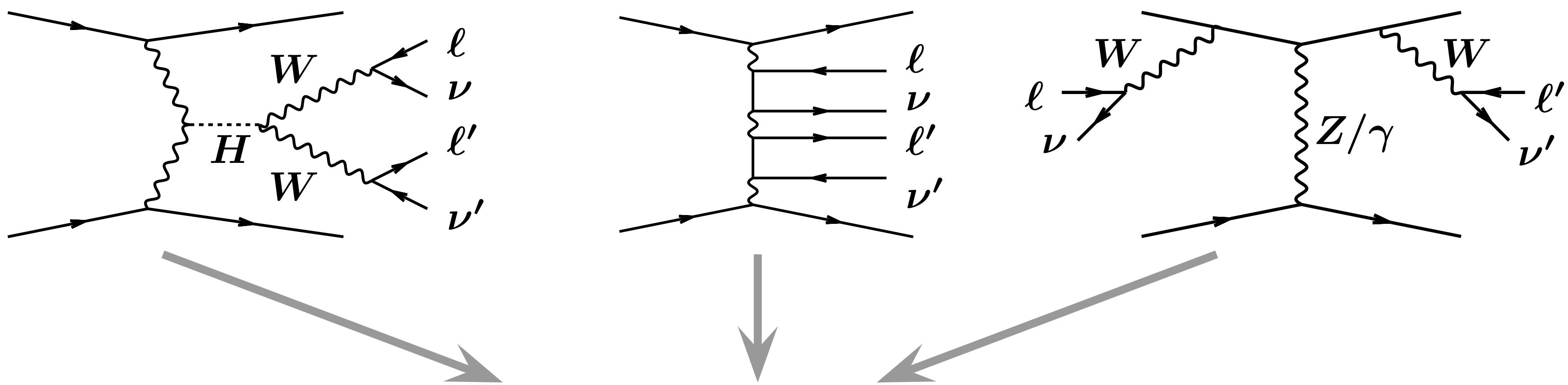
✔ provide implementation in versatile
public program package POWHEG-BOX

✘ 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

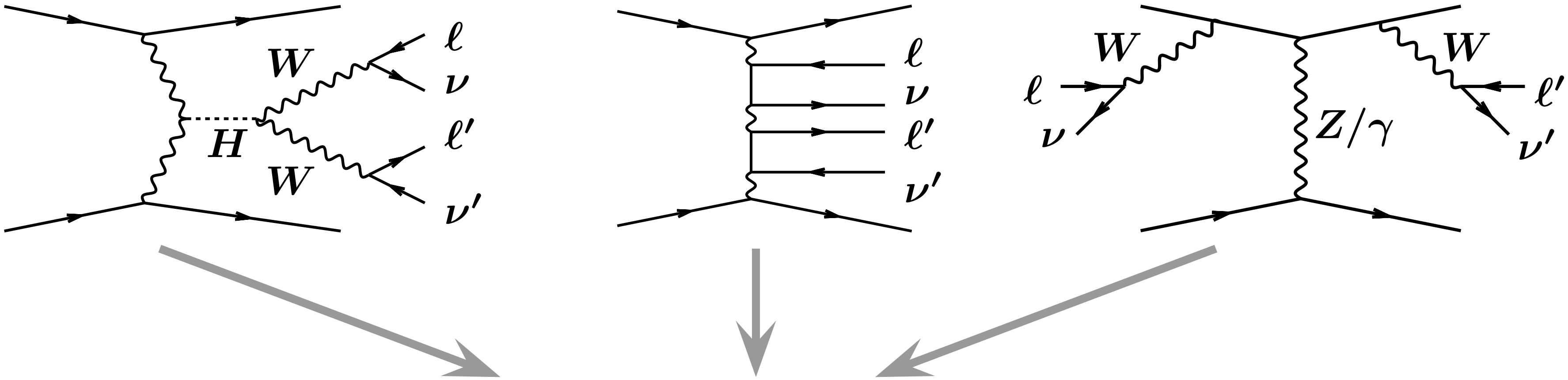


different topologies populate different regions in phase space

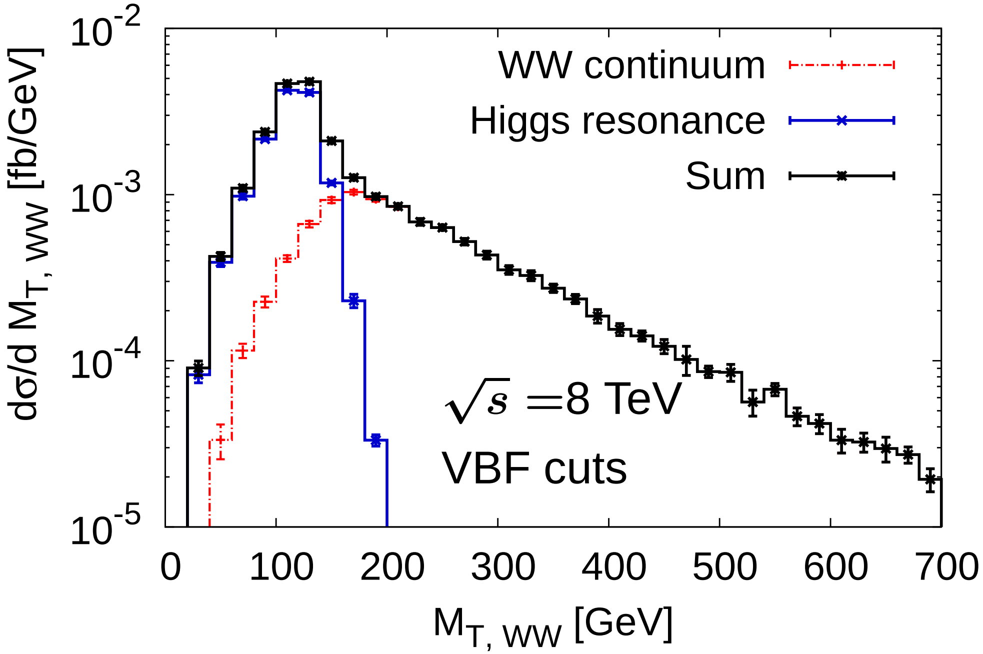
☞ split phase space into two regions for :

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

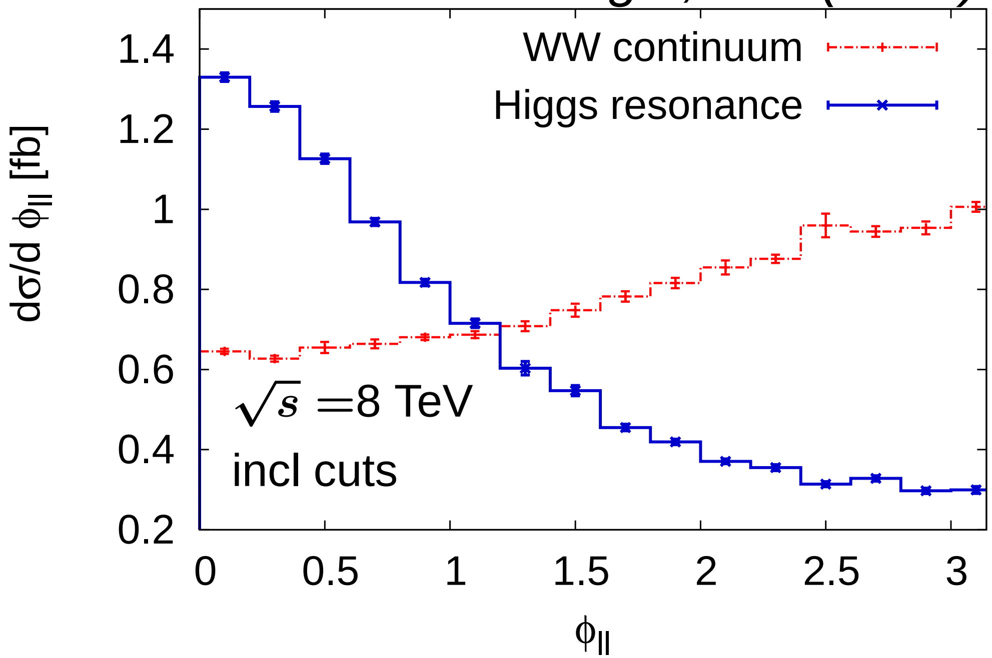
$pp \to W^+W^-jj$: technicalities



different topologies populate different regions in phase space:

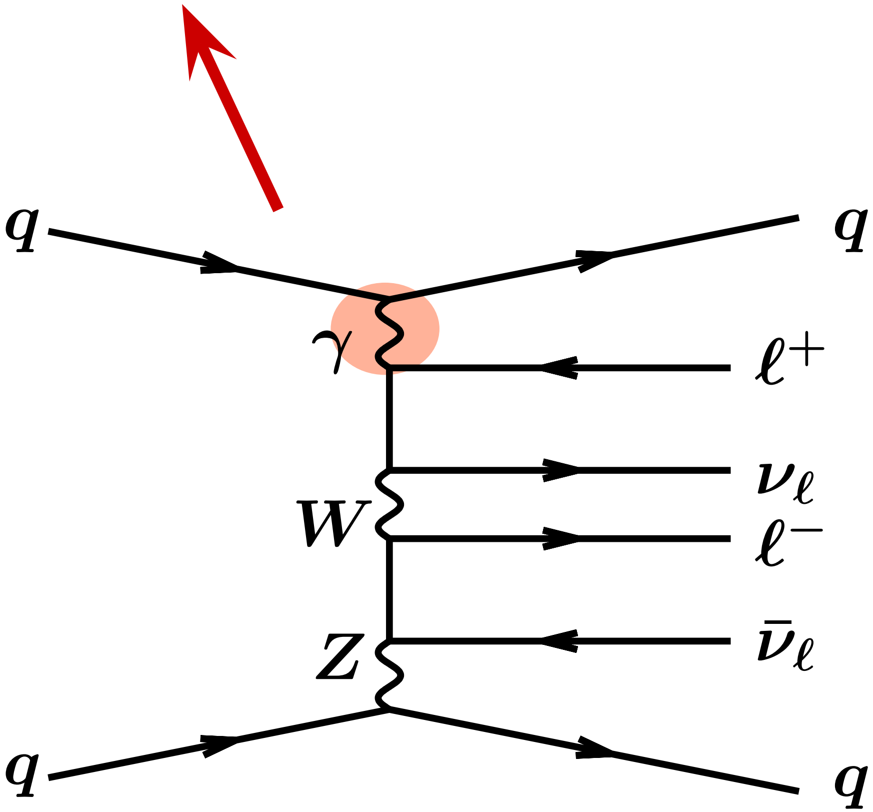


G. Zanderighi, B.J. (2013)



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

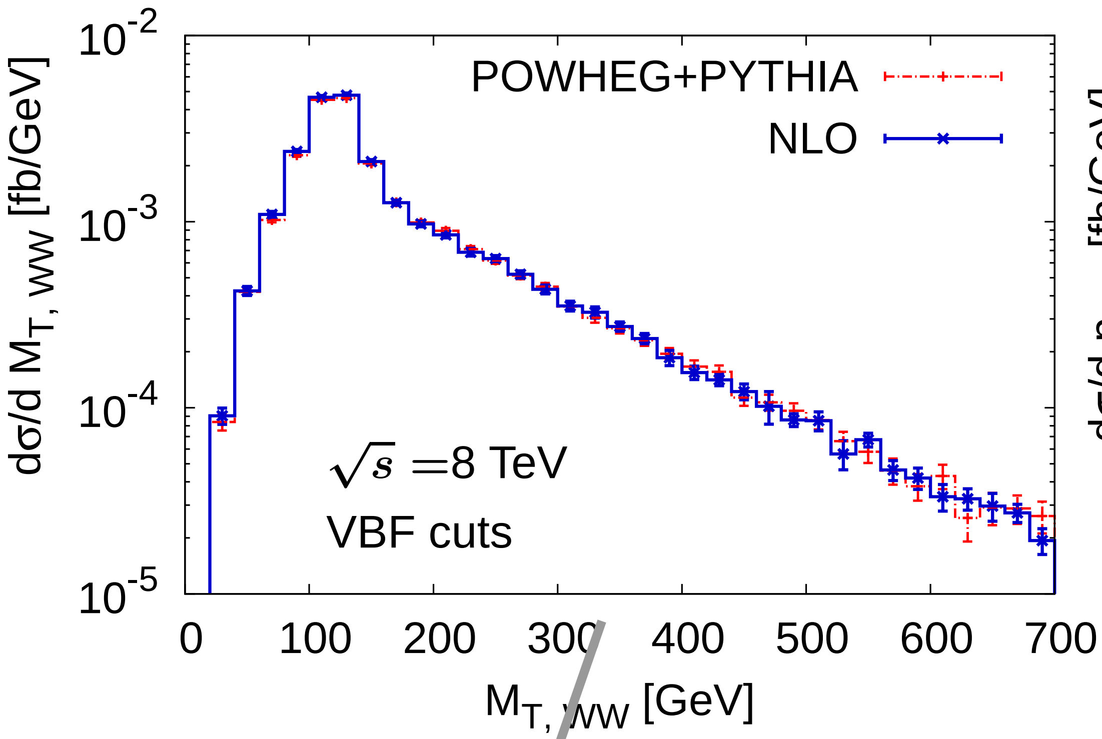
(1) damping factor to effectively suppress matrix elements

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

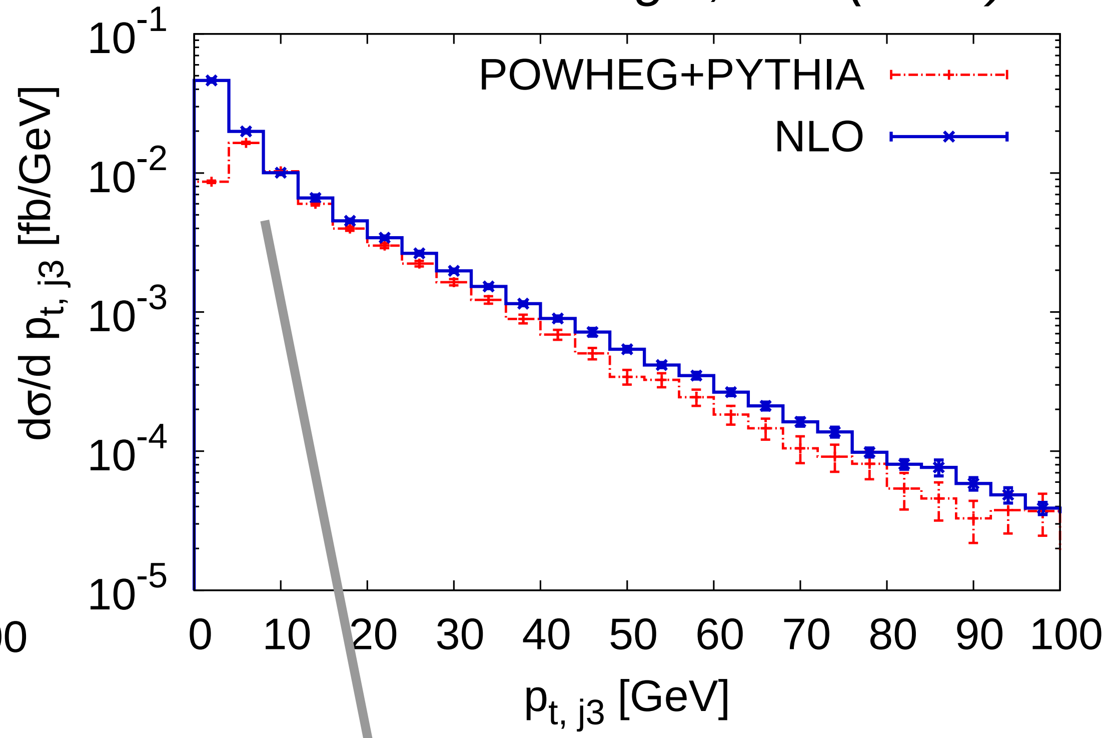
$$F \sim \left(\frac{p_{T,1}^2}{p_{T,1}^2+\Lambda^2}\right)^2 \left(\frac{p_{T,2}^2}{p_{T,2}^2+\Lambda^2}\right)^2$$

(alternative: explicit generation cuts)

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



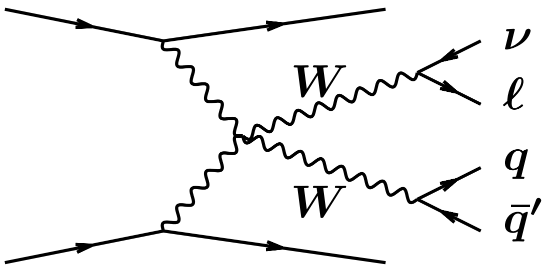
G. Zanderighi, B.J. (2013)



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:

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

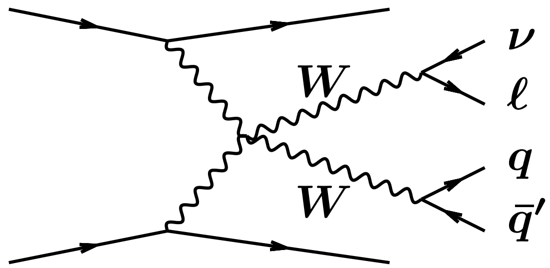
different from fully leptonic modes:

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

✔ only one neutrino → 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

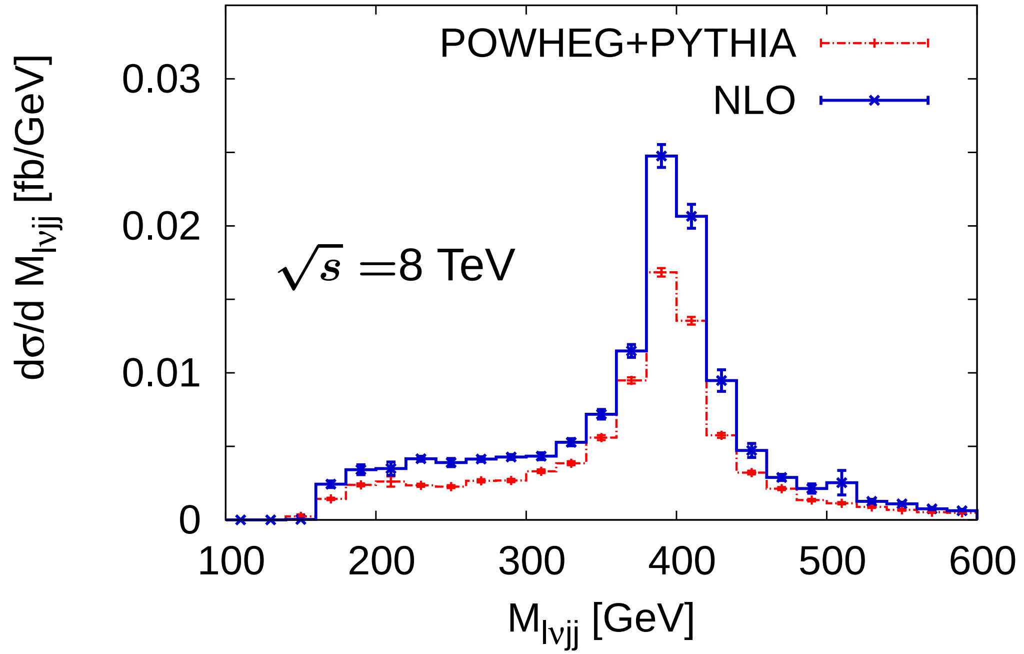
$$M_W - 10 \text{ GeV} \le m_{jj}^{\text{dec}} \le M_W + 10 \text{ GeV}$$

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

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

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

($\to$ neutrino momentum)



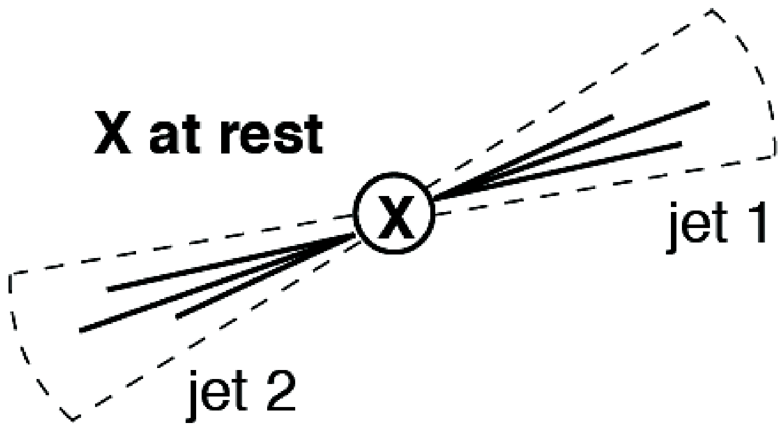
✘ $M_{\ell\nu jj}$ distribution very sensitive to parton-shower effects!

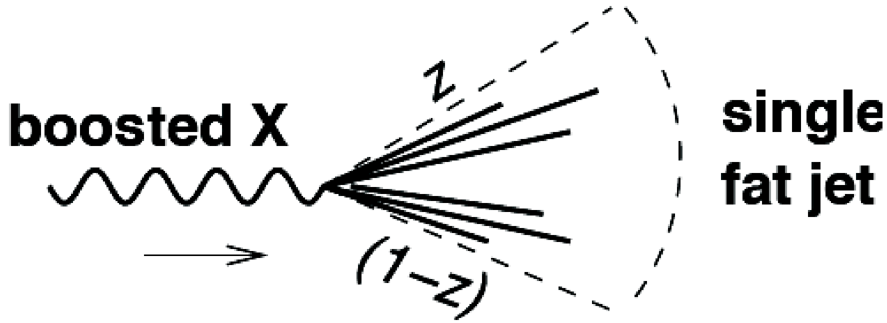
soft radiation smears distribution of W decay jets
$\to m_{jj}^{\rm dec} \sim M_W$ requirement no longer fulfilled

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

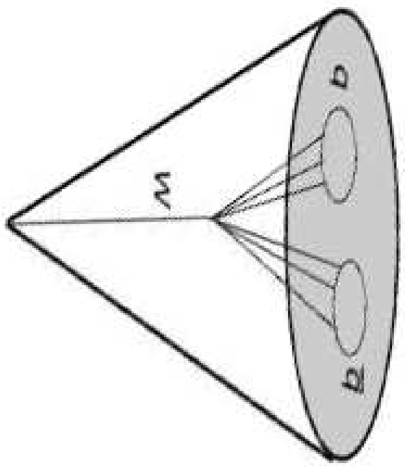
  Butterworth, Cox, Forshaw (2002)

- 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



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

require a highly boosted fat jet

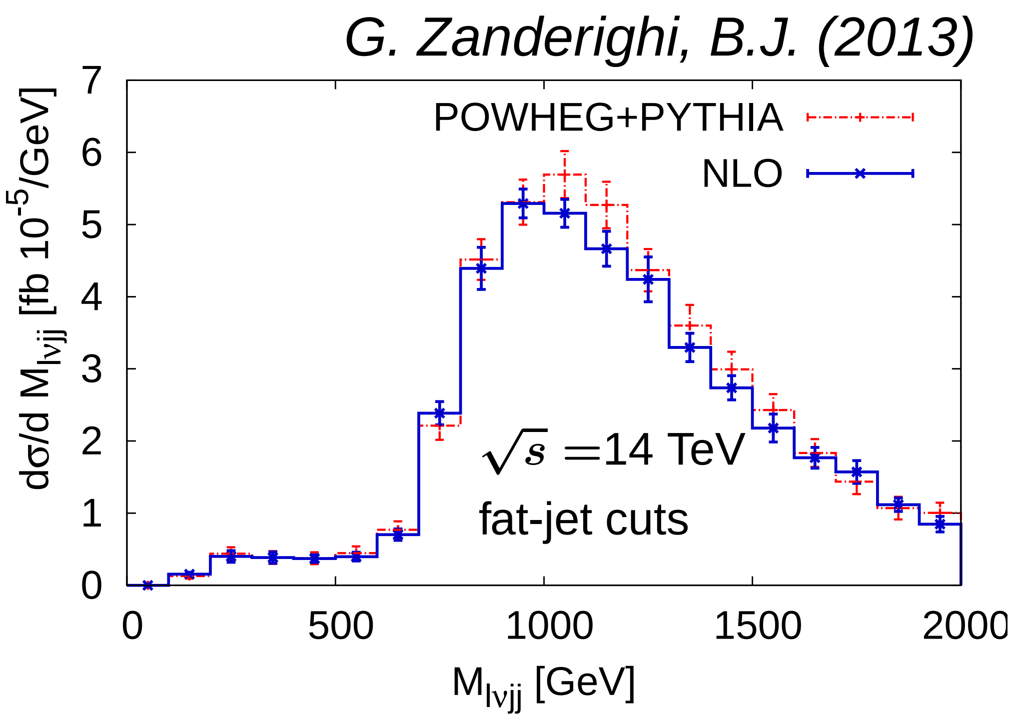
with invariant mass close to M_W

make use of jet properties / composition:

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

(stable against parton-shower effects)

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



selection cuts

specific for fat-jet analysis:

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

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

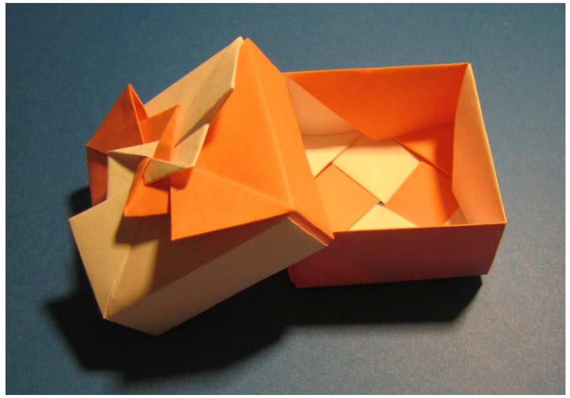
$$p_{T,\ell} > 300\ \text{GeV}$$

results stable against parton-shower effects

cuts enforce highly energetic WW system

(above light Higgs resonance)

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:

- 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)

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