The status of Higgs production in vector boson fusion

Particle Physics Symposium

Amsterdam – December 2011

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The (theory) status of Higgs production in vector boson fusion

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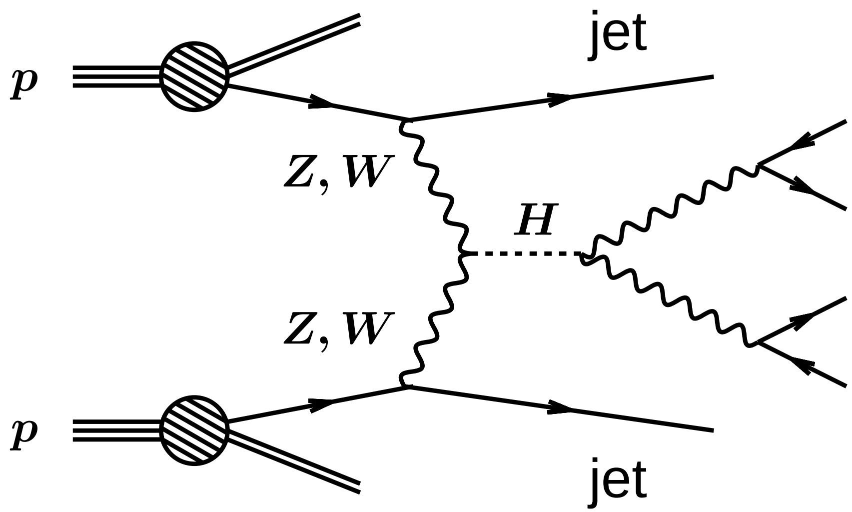
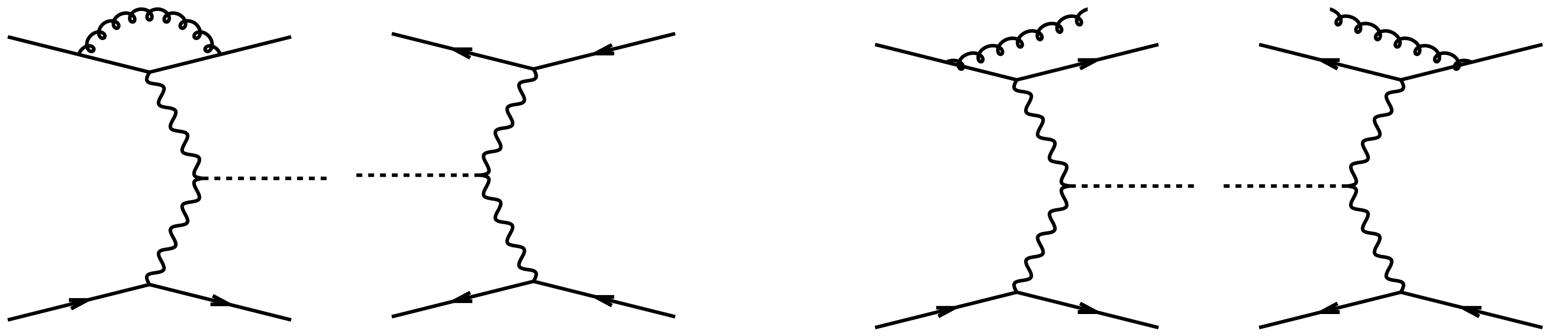
VBF event topology



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)

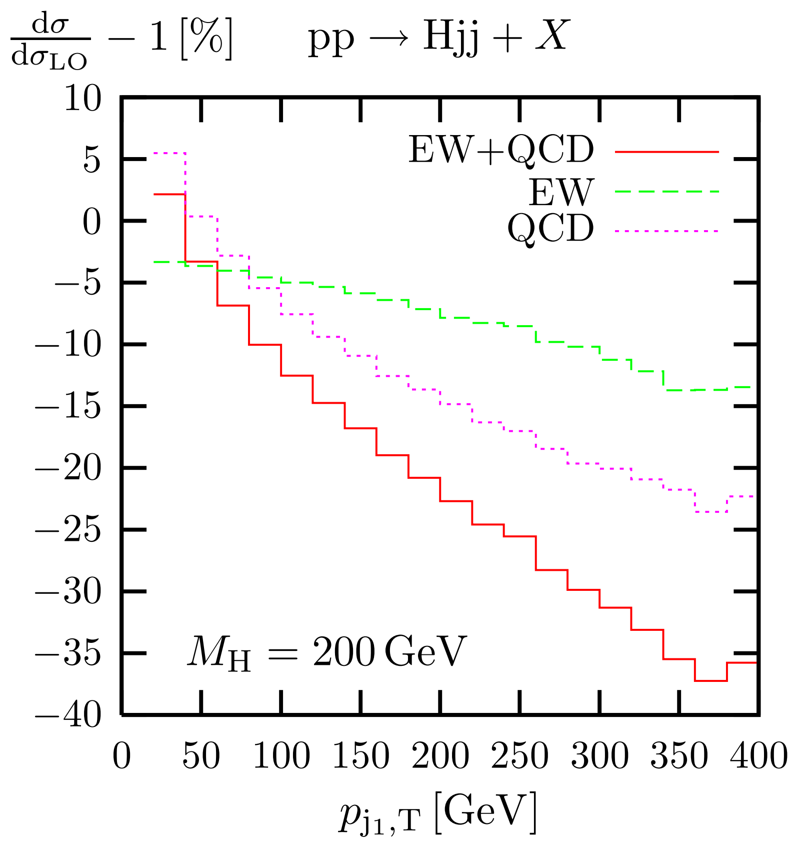
publicly available parton-level Monte Carlos:
`vbfnlo`
`MCFM`

Higgs production in VBF @ NLO EW

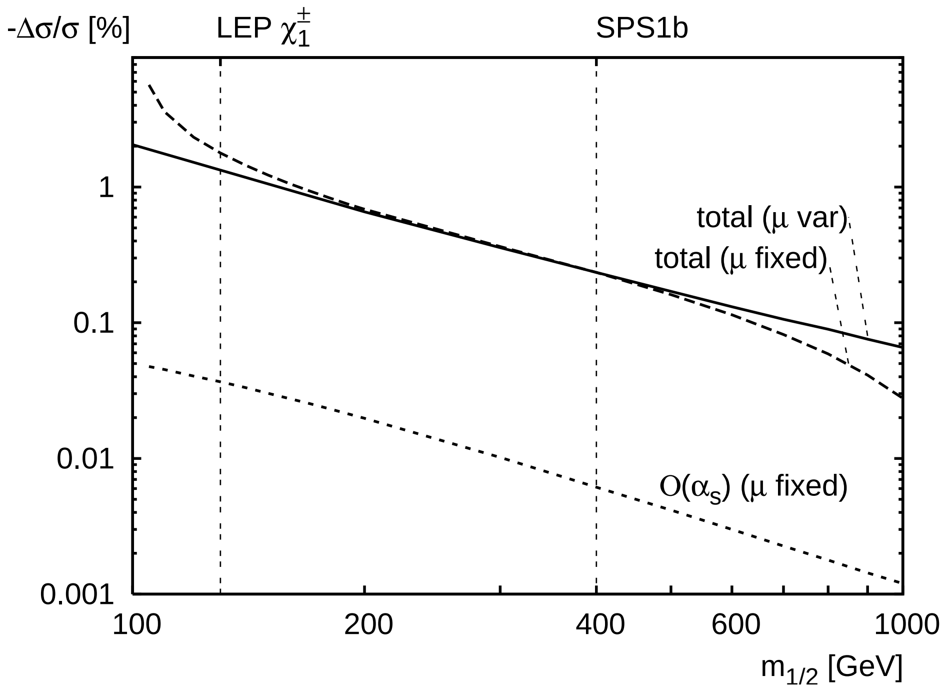
Ciccolini, Denner, Dittmaier, Mück:

NLO EW corrections to inclusive cross sections and distributions

☞ NLO EW corrections non-negligible, modify K factors and distort distributions by up to 10%



SUSY QCD+EW corrections to VBF



Hollik, Plehn, Rauch, Rzehak (2008) &

Figy, Palmer, Weiglein (2010):

SUSY QCD & EW corrections $\lesssim 1\%$

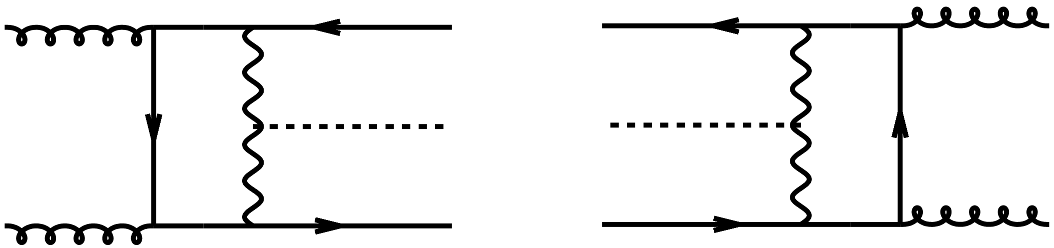
for inclusive cross sections

in typical regions of the MSSM parameter space

higher orders of QCD in VBF

Harlander, Vollinga, Weber (2007):

gauge invariant, finite sub-class of virtual
two-loop QCD corrections to $pp \to Hjj$ via VBF



important due to large gluon luminosity at LHC?

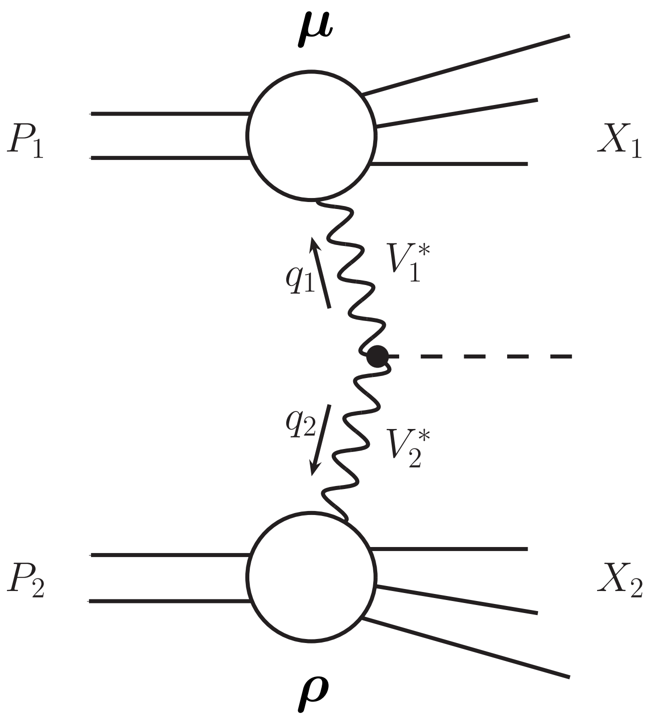
$$gg \to q\bar{q}H,\; q\bar{q} \to ggH,$$
$$qg \to qgH,\; \bar{q}g \to \bar{q}gH$$

minimal set of cuts: $\sigma_{\text{gluon}}^{2-\text{loop}} \sim 2\,\%$ of $\sigma_{\text{VBF}}^{\text{LO}}$

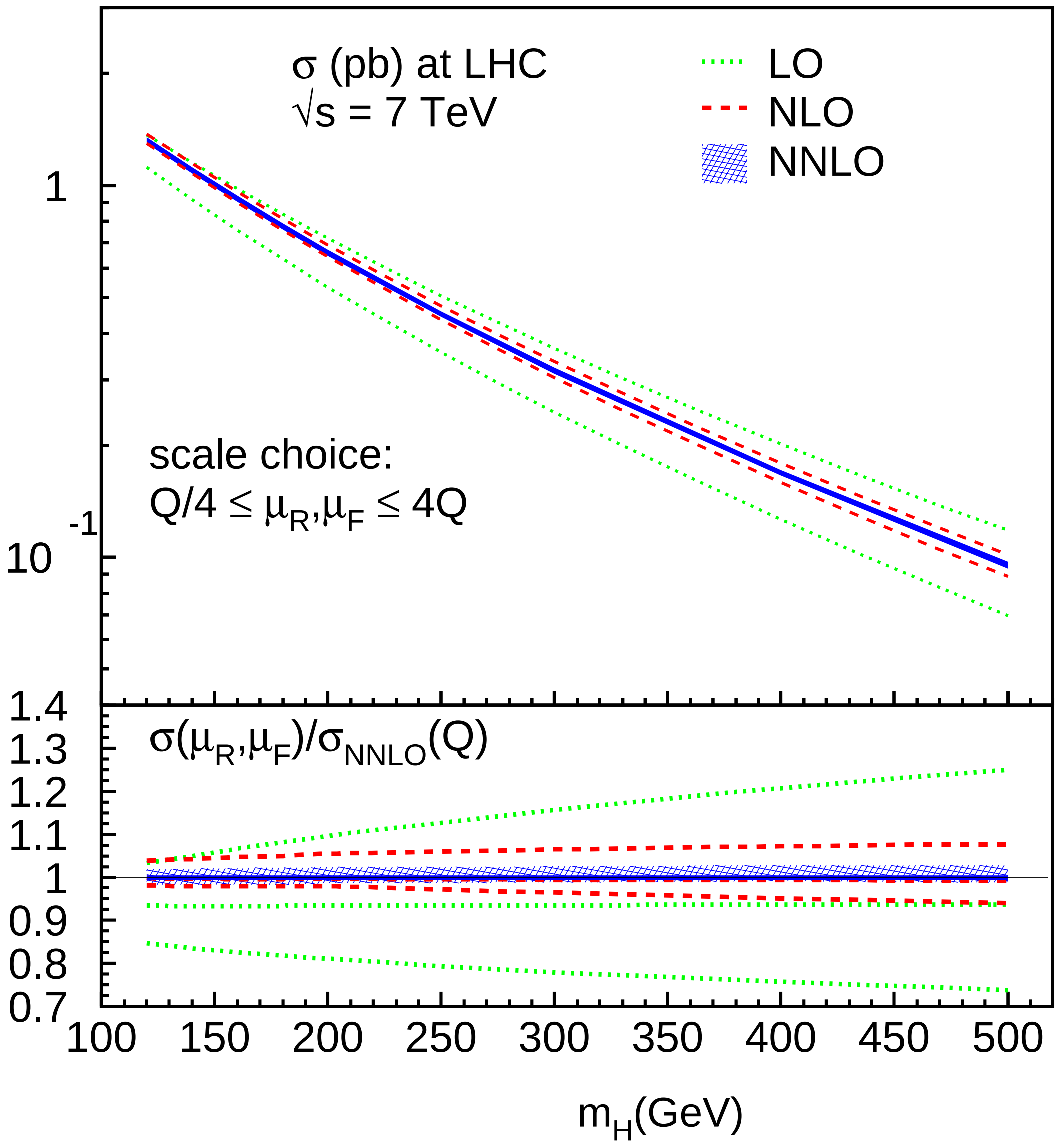
VBF cuts: relative suppression by additional order of magnitude

Bolzoni, Maltoni, Moch, Zaro (2010,2011):

subset of the NNLO QCD contributions
to the total cross section for $pp \to Hjj$ via VBF
in the structure function approach

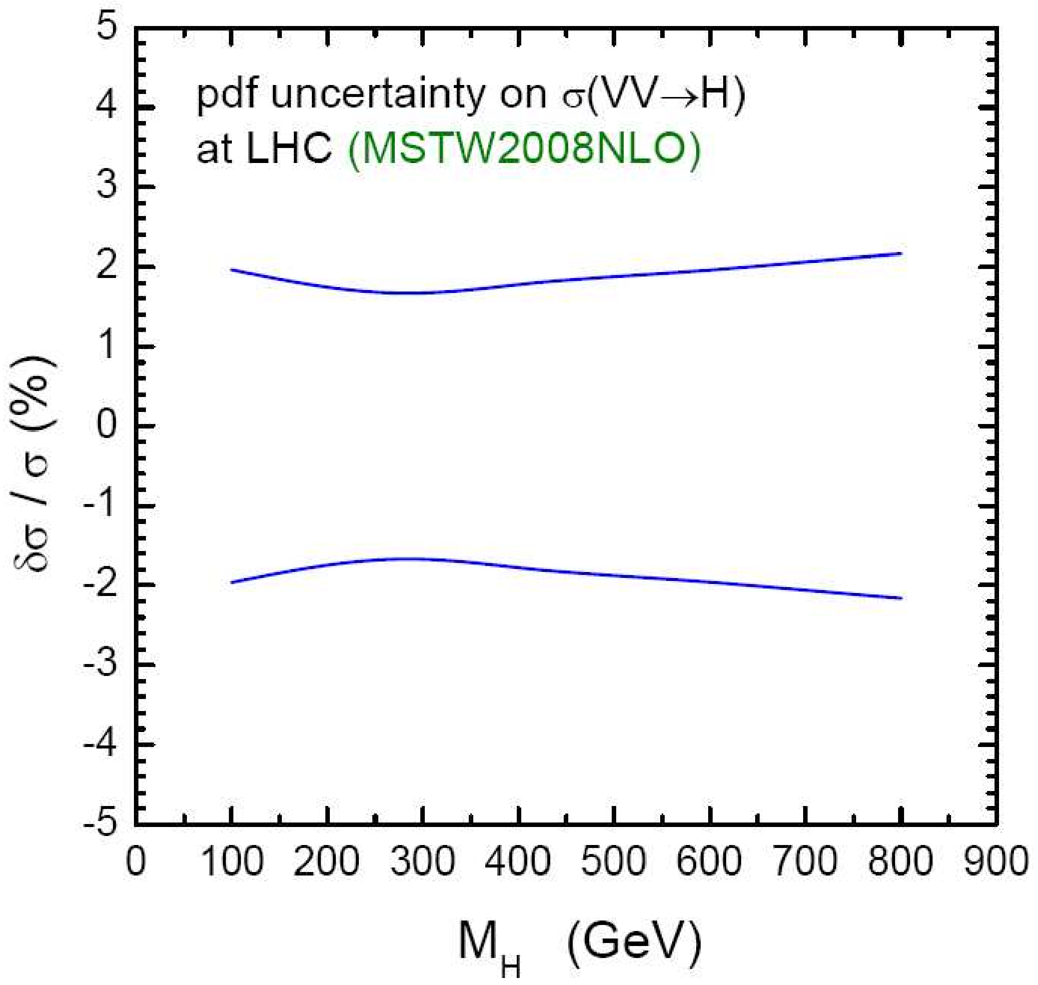


$$\sigma \sim \int dPS \frac{1}{2s} \frac{1}{\left(Q_1^2 + M_{V_1}^2\right)^2} \frac{1}{\left(Q_2^2 + M_{V_2}^2\right)^2} \times W_{\mu\nu}\left(x_1, Q_1^2\right) \mathcal{A}^{\mu\rho} \mathcal{A}^{*\nu\sigma} W_{\rho\sigma}\left(x_2, Q_2^2\right)$$



- 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

PDF uncertainties in VBF



CTEQ:

difference between sets
$\boldsymbol{\sigma_{6.1}/\sigma_{6.6} \lesssim 4\%}$

PDF uncertainty
$\boldsymbol{\Delta_{\mathrm{PDF}} \lesssim 3.5\ \%}$

for 100 GeV $\leq M_H \leq$ 800 GeV

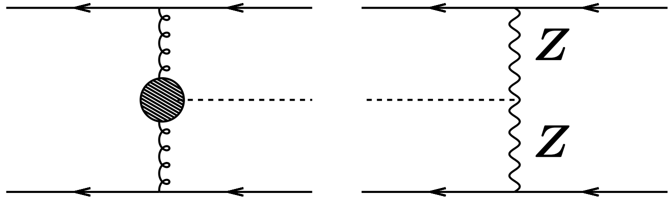
$pp \to Hjj$ via gluon fusion

VBF can be faked by double real corrections
to $gg \to H$ ("gluon fusion")

- complete LO calculation (including pentagons) in the SM
  Del Duca, Kilgore, Oleari, Schmidt, Zeppenfeld (2001)
- and in a generic two-Higgs doublet model:
  Campanario, Kubocz, Zeppenfeld (2011)
- complementary: NLO QCD calculation in $m_t \to \infty$ limit:
  Campbell, Ellis, Zanderighi (2006)

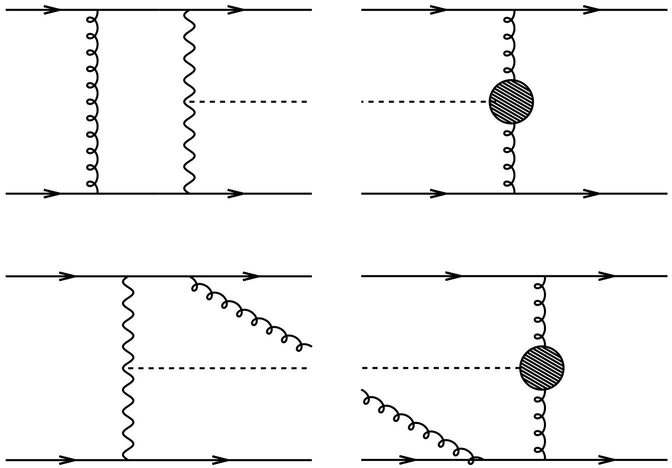
$pp \to Hjj$ via VBF×GF

can VBF×GF interference pollute the clean VBF signature?



Georg (2005) & Andersen, Smillie (2006):

- neutral current graphs
  (no charged current interference)
- identical quark contributions
  with $t \leftrightarrow u$ crossing



Andersen et al. (2007)

Bredenstein, Hagiwara, B. J. (2008):

- strong cancelation effects
  between contributions of
  different flavor

☞ interference effects are completely negligible distinct event topology

of the Higgs signal in

$pp \to Hjj$ via VBF with

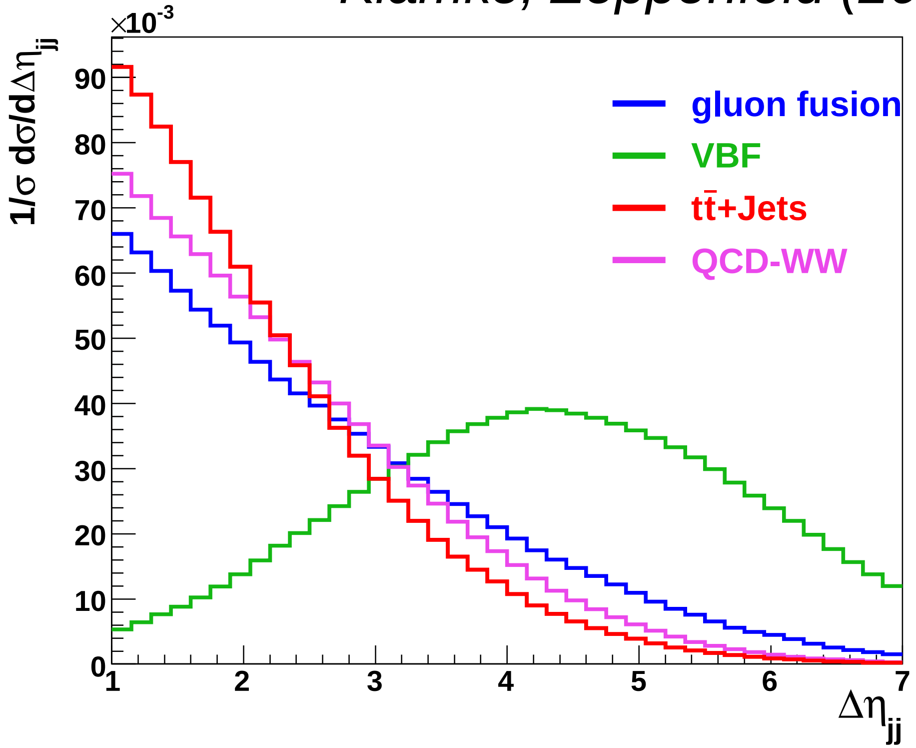
$H \to W^+W^- \to e^\pm \mu^\mp \not{p}_T$

☞ important for suppression of backgrounds

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

rapidity separation of the tagging jets

Klämke, Zeppenfeld (2007)



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

☞ 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 (CJV):

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

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

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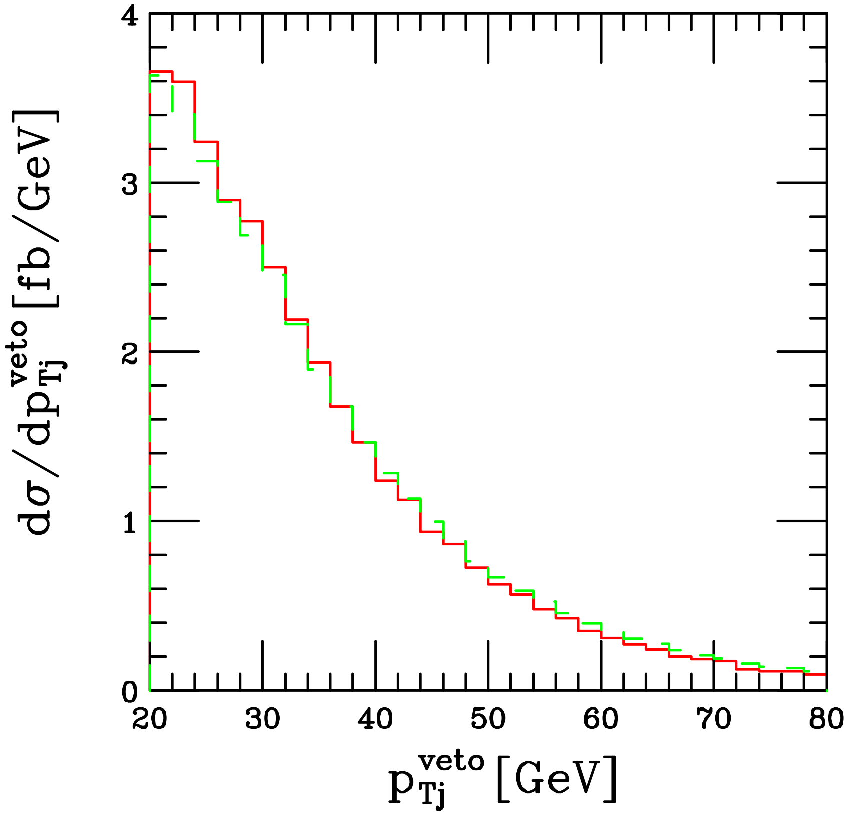
$$p_T^{\text{veto}} > 20\ \text{GeV},\ \eta_{\text{jet}}^{\min} < \eta_{\text{jet}}^{\text{veto}} < \eta_{\text{jet}}^{\max}$$

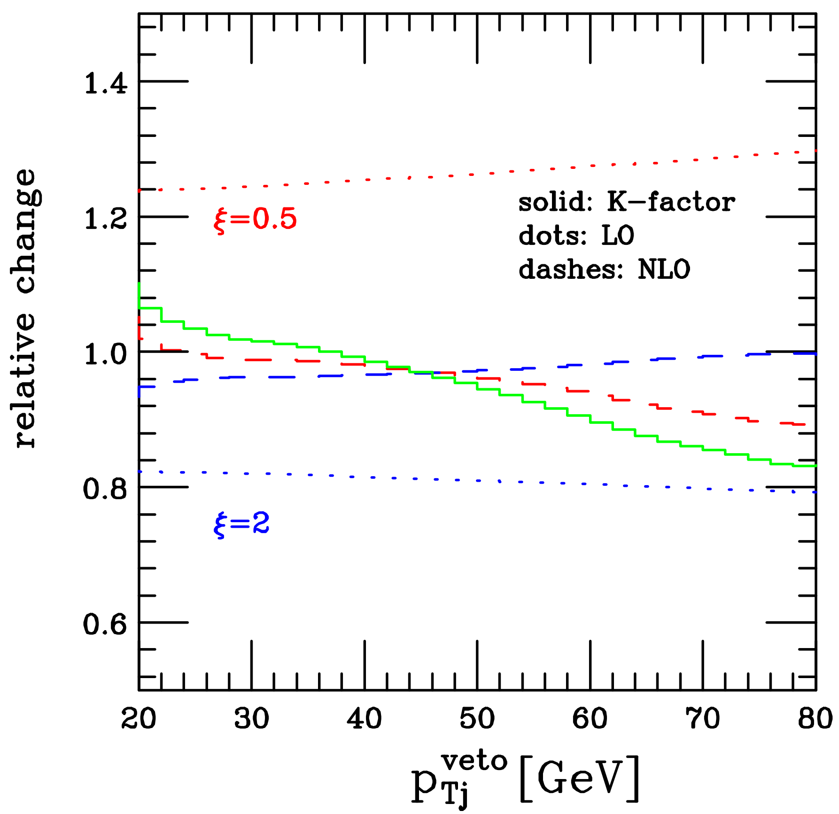
☞ precise knowledge of extra jet activity essential, requiring

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

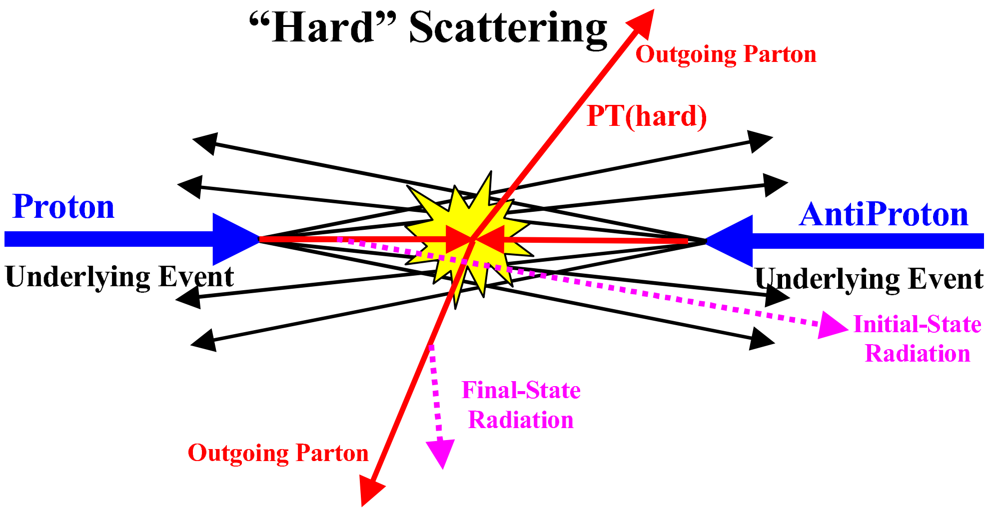
$pp \to Hjjj$ via VBF

Figy, Hankele, Zeppenfeld (2007)





- dominant NLO-QCD corrections modest
- scale uncertainties of CJV observables significantly reduced



for realistic description of scattering processes at hadron colliders:

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

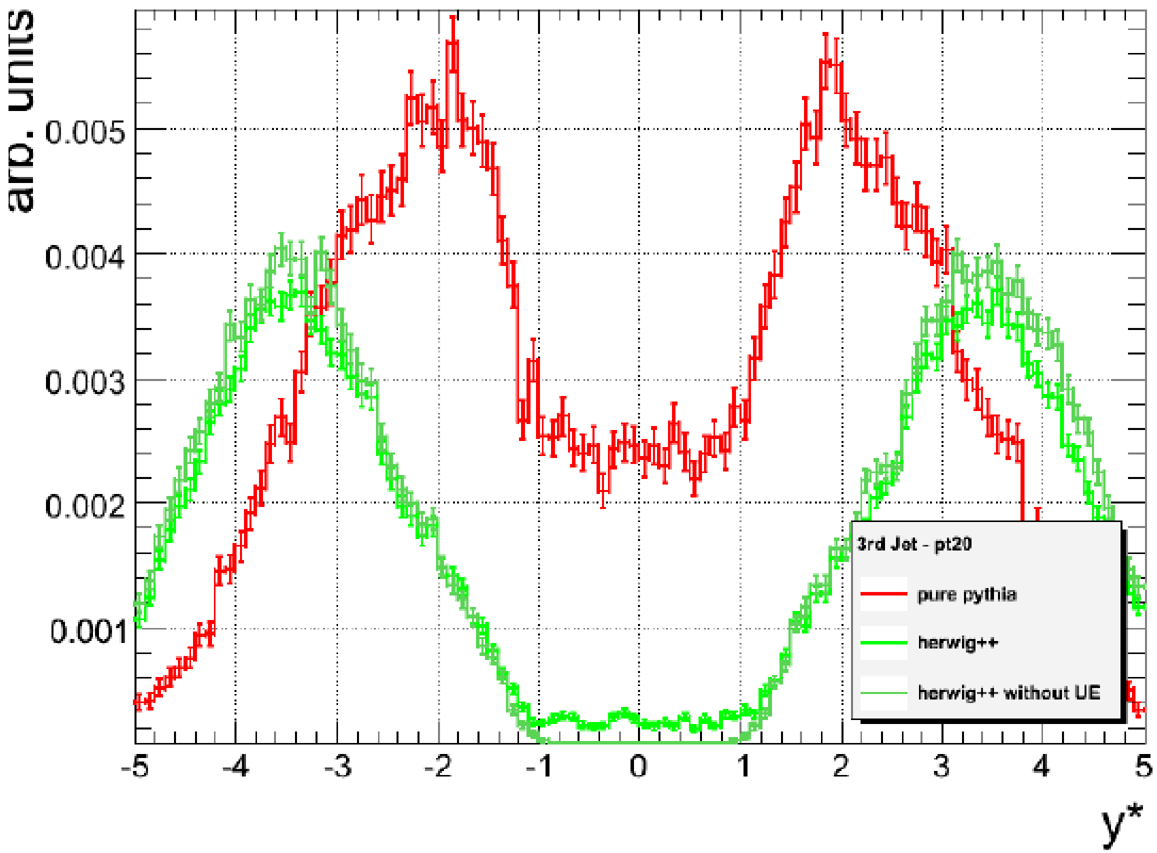
  underlying event, parton shower, and hadronization

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

$pp \to Hjj$ via VBF and parton showers

rapidity separation of the third jet: $y^\star = y_3 - \frac{1}{2}(y_1 + y_2)$

Hackstein et al. (2008)



Pythia: rapidity gap filled by parton shower

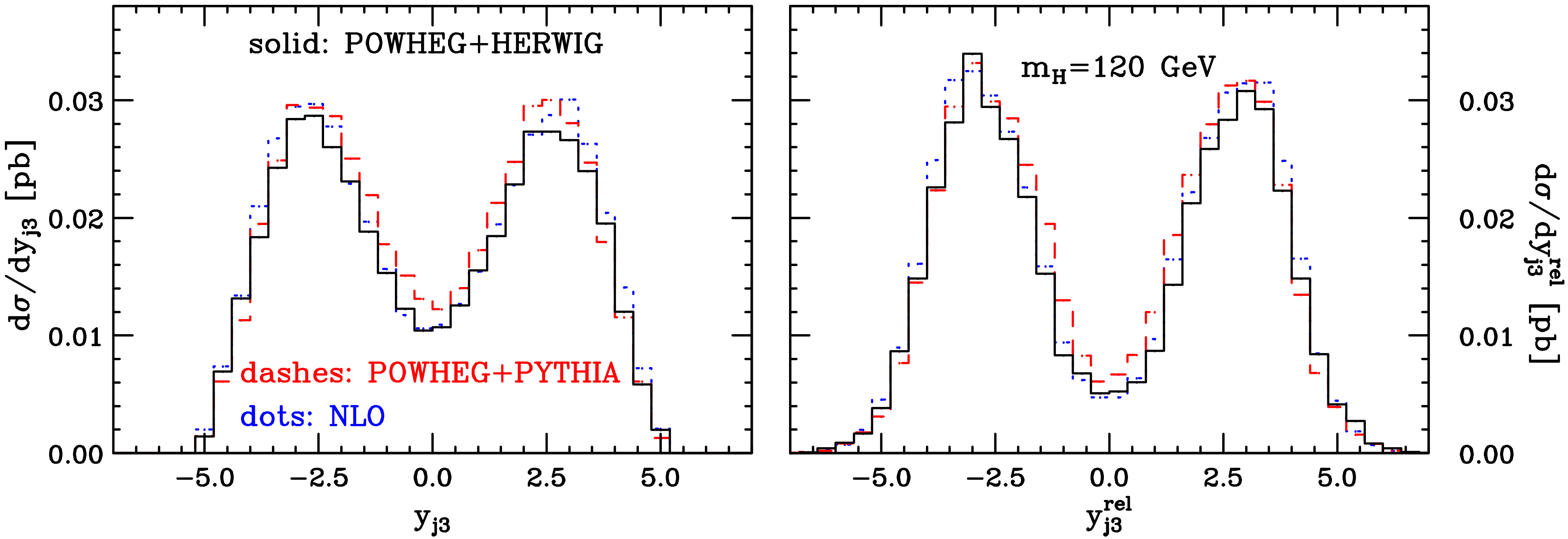
☞ better understanding and modeling needed recent progress: the POWHEG method *(Nason et al.)*

prescription for matching parton-level NLO-QCD calculation with parton shower program:

- no double counting of real-emission contributions
- produces events with positive weights
- method in principle applicable to any process
- tools for “do it yourself” implementation publicly available (the POWHEG box)

$pp \to Hjj$ via VBF and parton showers @ NLO

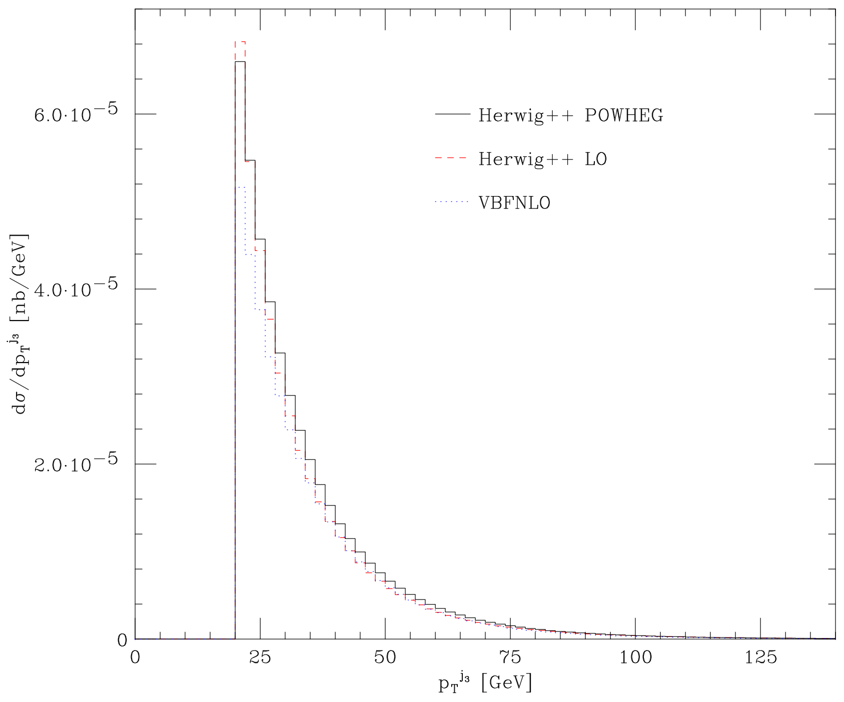
Nason, Oleari (2009)

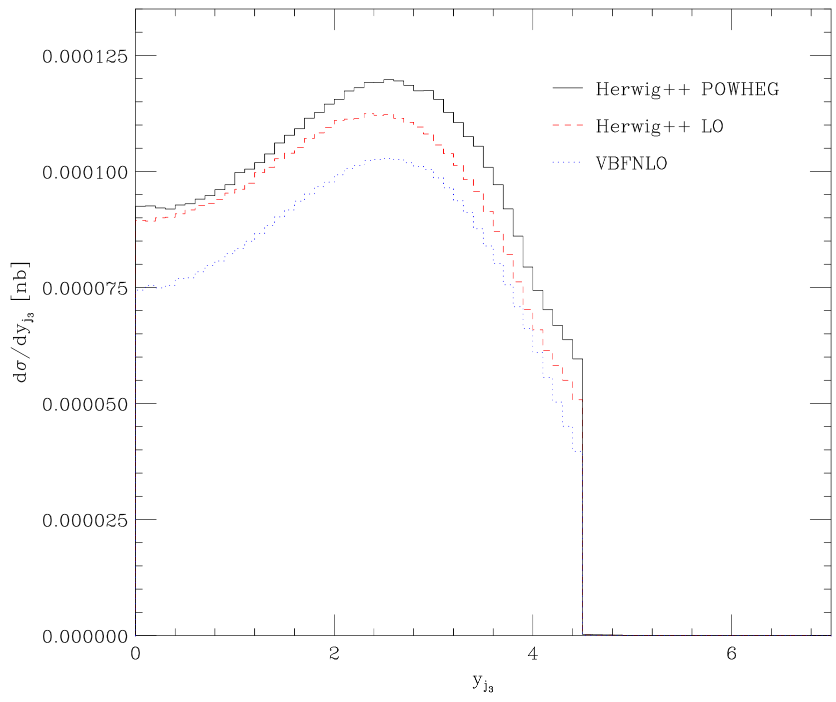


- **good agreement** between parton-level NLO calculation and POWHEG matched with HERWIG or PYTHIA for many observables
- for high multiplicites, HERWIG produces harder jets than PYTHIA

$pp \to Hjj$ via VBF and parton showers @ NLO

Richardson, De Luca (2011)





- parton-level NLO calculation matched with HERWIG
- HERWIG results differ from pure parton level at LO and NLO
- due to different shower algorithm ☞ "worthy of future study"

necessary improvements

- full understanding of parton-shower programs for signal and backgrounds

- thorough study of:
  - underlying event
  - multiple parton interactions
  - double parton scattering

- parton-shower cannot be used to simulate hard jets; multi-purpose programs are often not fast and flexible enough to account for complex multi-particle processes

↓

flexible (dedicated) Monte Carlo codes that can be matched to parton-shower programs are needed for all multi-leg processes at the LHC

determination of partial widths

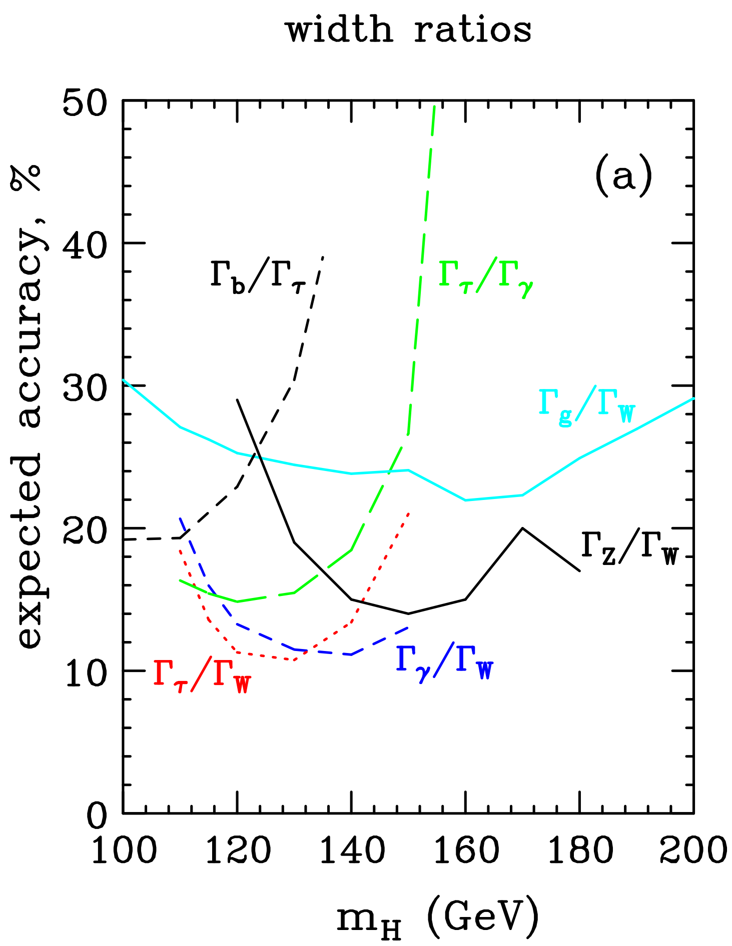
LHC rates for partonic process $aa \to H \to dd$ given by

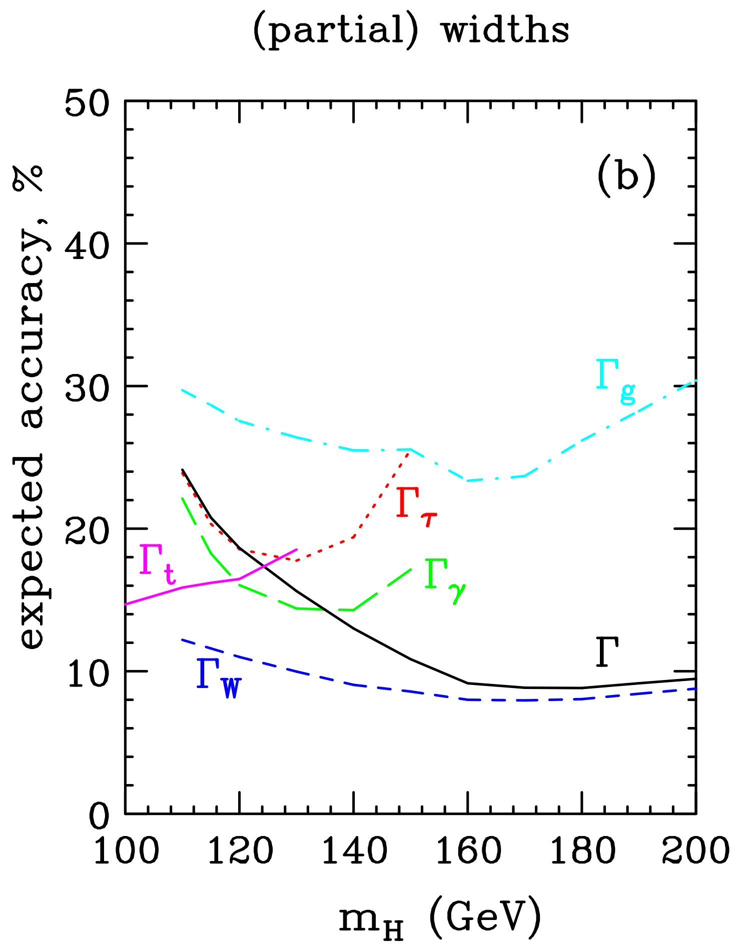
$$\sigma(aa \to H) \cdot BR(H \to dd) \;☞\; \frac{\Gamma_a \cdot \Gamma_d}{\Gamma}$$

combining information from various production and decay modes
with only mild assumptions

↓

yields information on partial widths and couplings

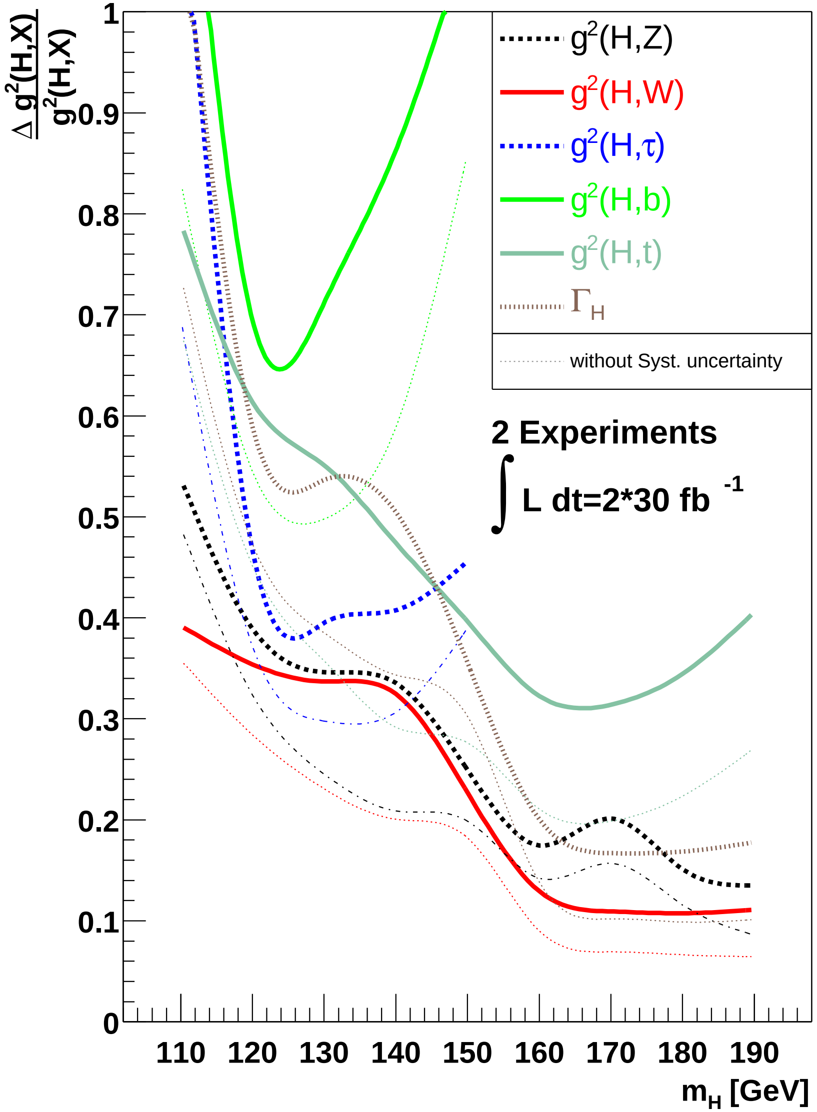




Zeppenfeld et al. (2002)

with 200 fb^{-1} measure partial widths with 10-30% errors, couplings with 5-15% errors

Dührssen et al. (2004)



difficult: the $Hb\bar{b}$ coupling

needed: alternative strategies for getting backgrounds under control

- require additional W boson or central photon in WBF Higgs production at the LHC

  ☞ signal / background ratio dramatically improved

  Rainwater (2000), *Gabrielli et al. (2007)*

- consider Higgs production at a future lepton-hadron collider, such as the Large Hadron electron Collider (LHeC)

  LHC proton beam combined with electron beam

  → separate linac

  → extra ring in LHC tunnel

extra photon radiation in VBF: $pp \to H\gamma jj$

effects of hard central photon requirement:

✘ "naive expectation": signal and background suppressed by same factor $\sim \mathcal{O}(\alpha)$

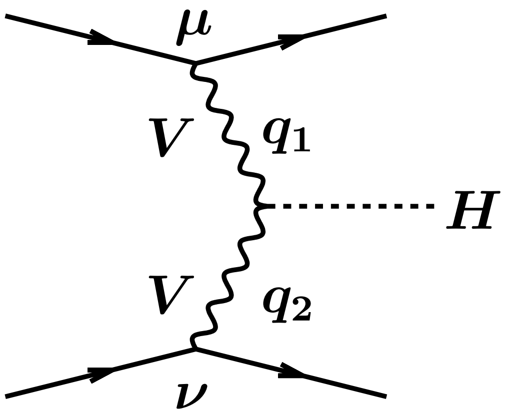
✔ de facto: reduction factors different for S and B

backgrounds: $\sigma_\gamma/\sigma \sim 1/3000$

signal: $\sigma_\gamma/\sigma \sim 1/100$

✔ $\left(S/\sqrt{B}\right)_{H\gamma jj} \lesssim 3$ for $m_H = 120$ GeV, $\mathcal{L} = 100$ fb^{-1} and optimized selection cuts

✦ NLO-QCD corrections available *[Arnold, Figy, BJ, Zeppenfeld (2010)]*



most general HVV vertex:

$$T^{\mu\nu} = a_1\, g^{\mu\nu} + a_2\, (q_1 \cdot q_2\, g^{\mu\nu} - q_1^\nu\, q_2^\mu) + a_3\, \epsilon^{\mu\nu\rho\sigma} q_{1\rho} q_{2\sigma}$$

physical interpretation:

SM Higgs scenario: $\mathcal{L} \sim H V_\mu V^\mu \quad \rightarrow a_1$

CP even scenario: $\mathcal{L}_{eff} \sim H V_{\mu\nu} V^{\mu\nu} \quad \rightarrow a_2$

CP odd scenario: $\mathcal{L}_{eff} \sim H V_{\mu\nu} \tilde{V}^{\mu\nu} \quad \rightarrow a_3$

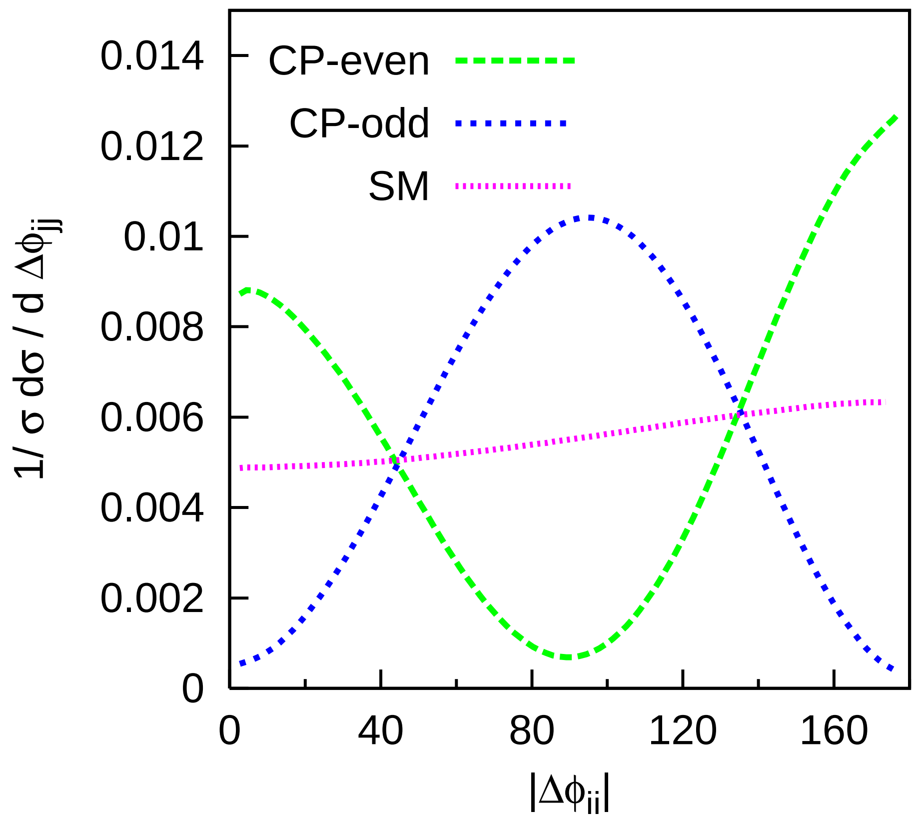
azimuthal angle between
tagging jets

↓

dip structure at 90° (CP even)
or $0/180°$ (CP odd)
only depends on tensor structure of HVV vertex

(little dependence on actual size of form factor, QCD corrections, Higgs mass etc.)

Figy et al. (2006)



summary: Higgs signal in VBF

✔ $pp \rightarrow Hjj$ via VBF under excellent control:

- background suppression possible
- QCD & EW NLO corrections at 10% level
- dominant NNLO QCD/SUSY corrections small
- small PDF uncertainties

✱ reliable prediction of CJV observables requires

- matching NLO-QCD calculations to parton shower programs
- NLO-QCD predictions for $pp \rightarrow Hjjj$

✘ determination of Higgs properties requires more data

conclusions

VBF crucial for understanding mechanism of electroweak symmetry breaking

important pre-requisites:

- explicit calculations revealed that VBF reactions are perturbatively well-behaved
- backgrounds are well under control

essential: provide and use flexible precision tools for signal and background processes which allow for calculation of accurate cross sections and distributions within realistic acceptance cuts

backup slides . . .

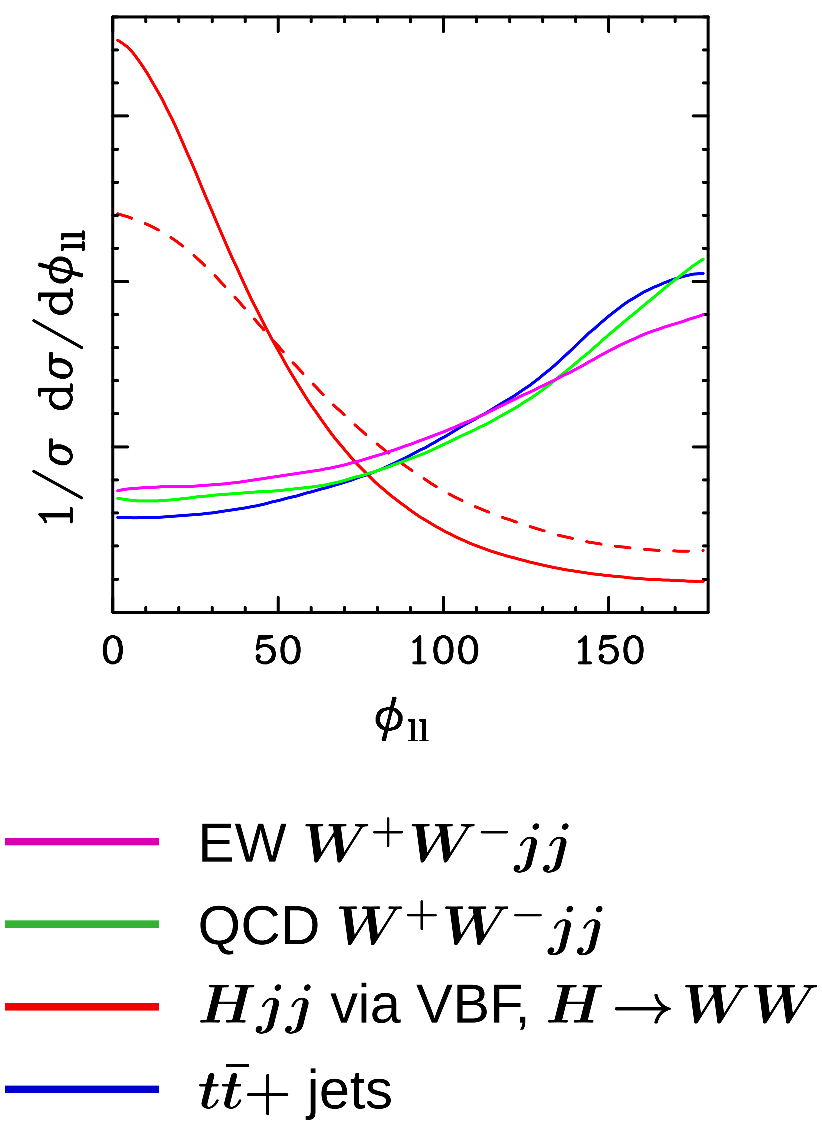
. . . for details and supplementary material

Rainwater, Zeppenfeld (1999)

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

↓

leptons emitted preferentially in same direction

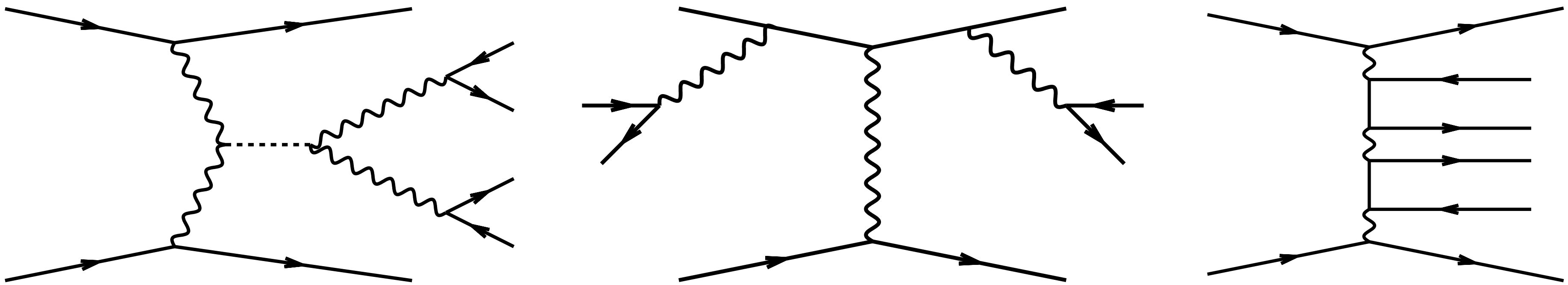


no such correlation, if W bosons do not stem from the Higgs

Dittmar, Dreiner (1996)

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

EW $VVjj$ production



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

$\mathbf{4jets} + jj$

high statistics
large backgrounds

$\mathbf{4leptons} + jj$

low statistics
clean signature

vbfnlo

K. Arnold, G. Bozzi, M. Brieg, F. Campanario, C. Englert, B. Feigl, T. Figy, J. Frank, F. Geyer, K. Hackstein, V. Hankele, B. J., M. Kerner, M. Kubocz, C. Oleari, S. Palmer, S. Plätzer, M. Rauch, H. Rzehak, F. Schissler, M. Spannowsky, M. Worek, D. Zeppenfeld

http://www-itp.particle.uni-karlsruhe.de/∼vbfnloweb `vbfnlo` is a fully flexible parton level Monte Carlo for processes with electroweak bosons at NLO-QCD

it can simulate:

- various weak vector boson fusion processes
- double and triple weak boson production processes
- double weak boson production processes in association with a hard jet
- Higgs production via gluon fusion in association with two jets

features

- cross sections and distributions at NLO-QCD accuracy
- arbitrary selection cuts
- various choices for factorization and renormalization scales
- LO predictions for all processes with one extra jet
- interface to LHAPDF $\longrightarrow$ any currently available PDF set;
  hardwired: CTEQ6L1, CT10, MRST2004qed
- LO: event files in Les Houches Accord (LHA) format
- MSSM: SUSY parameters input via standard SLHA file

$pp \to Hjj$ via VBF in vbfnlo

- QCD & EW NLO corrections in the SM and MSSM
  (without interference and annihilation contributions)

- decay of the Higgs boson in narrow width approximation for:

$$pp \to Hjj \to \gamma\gamma jj$$
$$pp \to Hjj \to \mu^+\mu^- jj$$
$$pp \to Hjj \to \tau^+\tau^- jj$$
$$pp \to Hjj \to b\bar{b}jj$$
$$pp \to Hjj \to W^+W^- jj \to \ell_1^+\nu_1\ell_2^-\bar{\nu}_2 jj$$
$$pp \to Hjj \to ZZjj \to \ell_1^+\ell_1^-\ell_2^+\ell_2^- jj$$
$$pp \to Hjj \to ZZjj \to \ell_1^+\ell_1^-\nu_2\bar{\nu}_2 jj$$

- dominant NLO-QCD corrections to $pp \to Hjjj$
  ($\to$ extra jet activity in VBF)

- anomalous Higgs-gauge boson couplings

vbfnlo is a fully flexible parton-level Monte-Carlo program for the simulation of weak boson processes at NLO QCD

2011 release contains:

new processes:

- Higgs production via WBF in association with a photon
- photon production via WBF
- diboson+ jet production: $W\gamma j$ and WZj
- triboson production: $WW\gamma$, $ZZ\gamma$, $WZ\gamma$, $W\gamma\gamma$, $Z\gamma\gamma$, $\gamma\gamma\gamma$

new features:

- EW corrections to WBF Hjj in the SM and the MSSM
- new BSM effects for several processes:
  - – anomalous couplings of the Higgs and gauge bosons
  - – Kaluza-Klein models