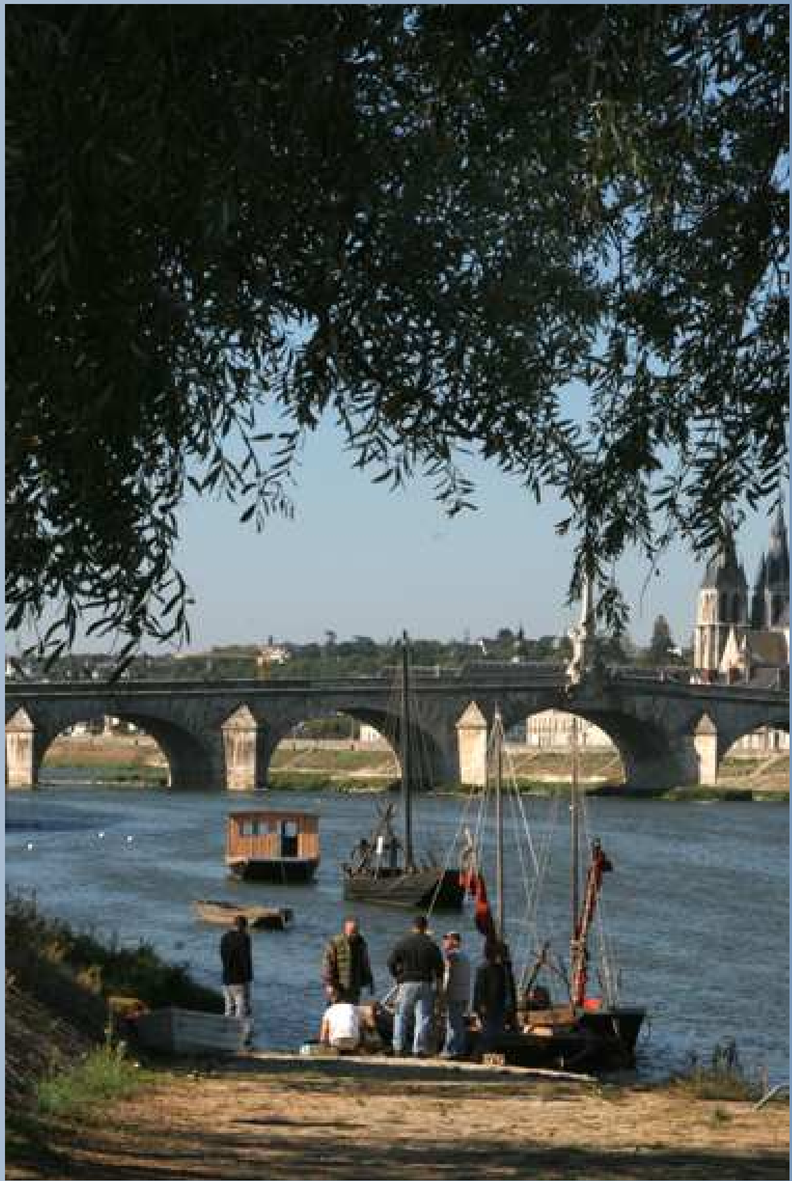

Rencontres de Blois

May 2012

Higgs boson searches in vector boson fusion

Barbara Jäger
Johannes Gutenberg University
Mainz

Rencontres de Blois

May 2012

Higgs boson searches in vector boson fusion – a theorist's point of view

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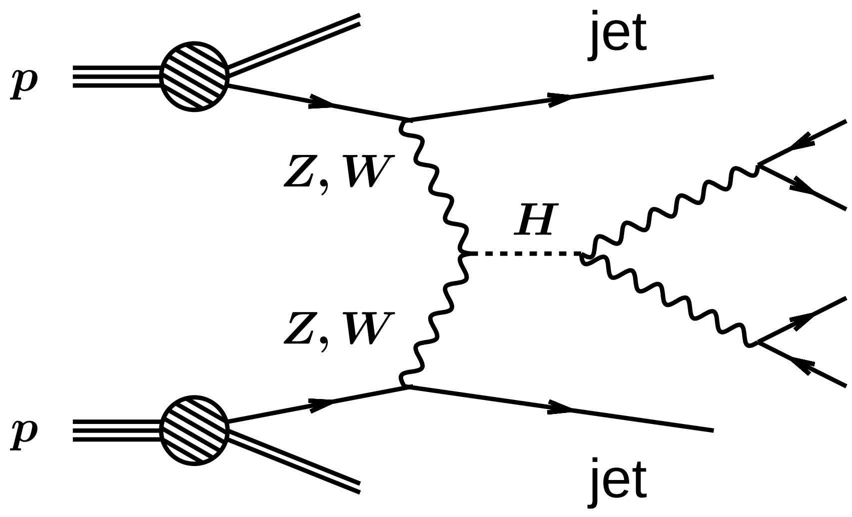
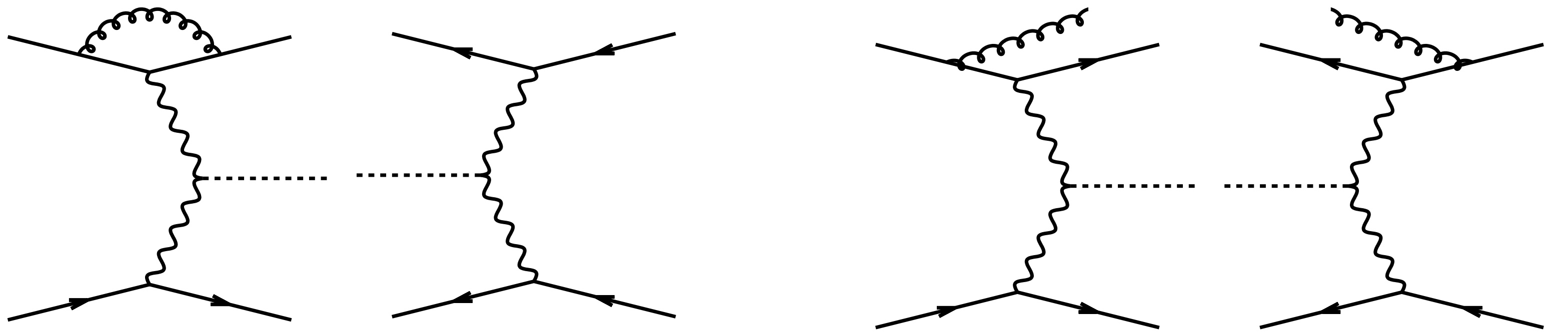
VBF event topology



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`

vbfnlo is a fully flexible parton level Monte Carlo for processes with electroweak bosons at NLO-QCD in the SM and beyond

http://www-itp.particle.uni-karlsruhe.de/∼vbfnloweb

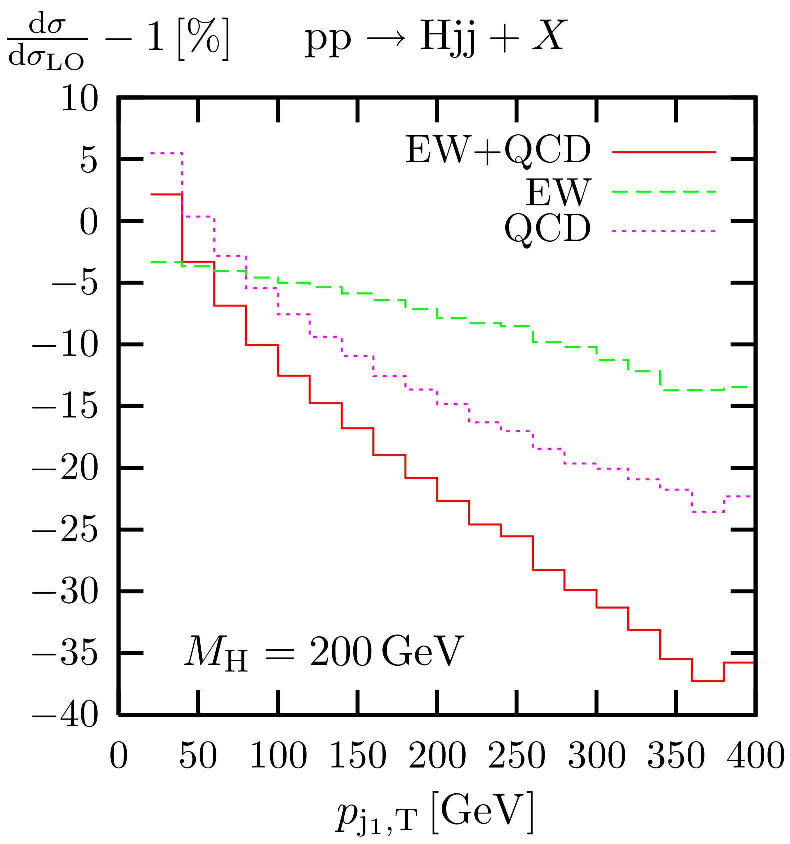
- cross sections and distributions at NLO-QCD (NLO-EW) accuracy for VBF Hjj production and various other processes
- user-defined cuts, factorization / renormalization scales, PDF sets
- LO: event files in Les Houches Accord (LHA) format
- various BSM features:
  MSSM, anomalous couplings, Kaluza-Klein models, . . .

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%



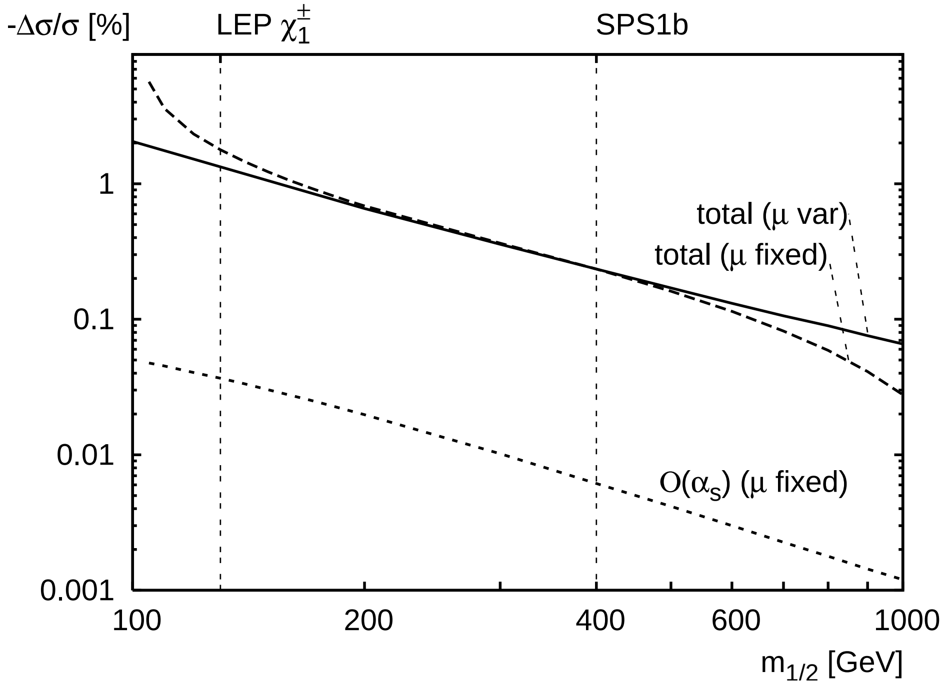
publicly available parton-level Monte Carlo program: HAWK

VBF @ NLO EW and QCD

HAWK:
"A Monte Carlo generator for the production of Higgs bosons Attached to WeaK bosons at hadron colliders"
(Ciccolini, Denner, Dittmaier, Mück)

- NLO QCD and EW corrections
- all weak-boson fusion and quark-antiquark annihilation graphs
- interference effects at LO and NLO
- contributions from incoming photons
- leading heavy-Higgs-boson effects at two-loop order
- contributions of b-quark pdfs at LO
- an interface to LHAPDF

SUSY QCD+EW corrections to VBF



Hollik, Plehn, Rauch, Rzehak (2008) &

Figy, Palmer, Weiglein (2010):

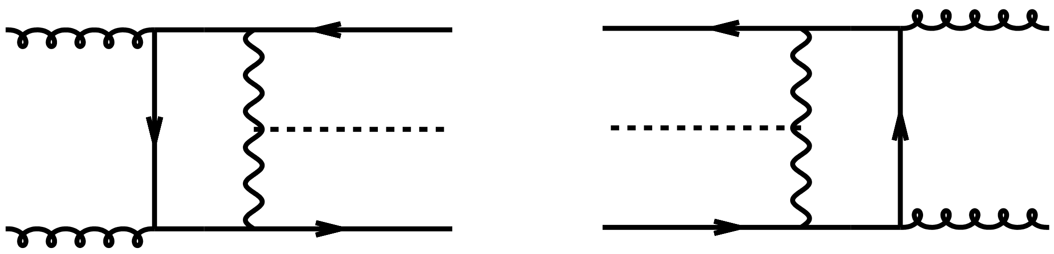
SUSY QCD & EW corrections $\lesssim 1\%$

for inclusive cross sections

in typical regions of the MSSM parameter space

Harlander, Vollinga, Weber (2007):

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



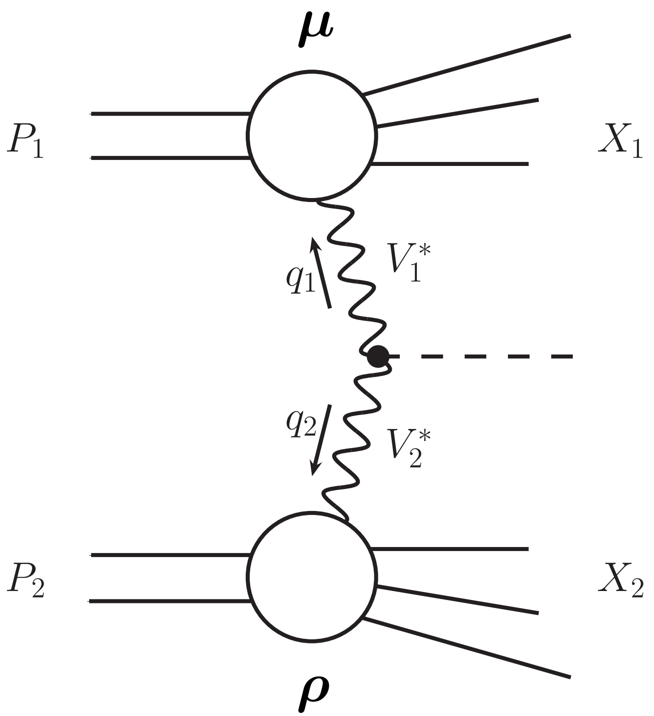
$gg \to q\bar{q}H$, $q\bar{q} \to ggH$,
$qg \to qgH$, $\bar{q}g \to \bar{q}gH$

important due to large gluon luminosity at LHC?

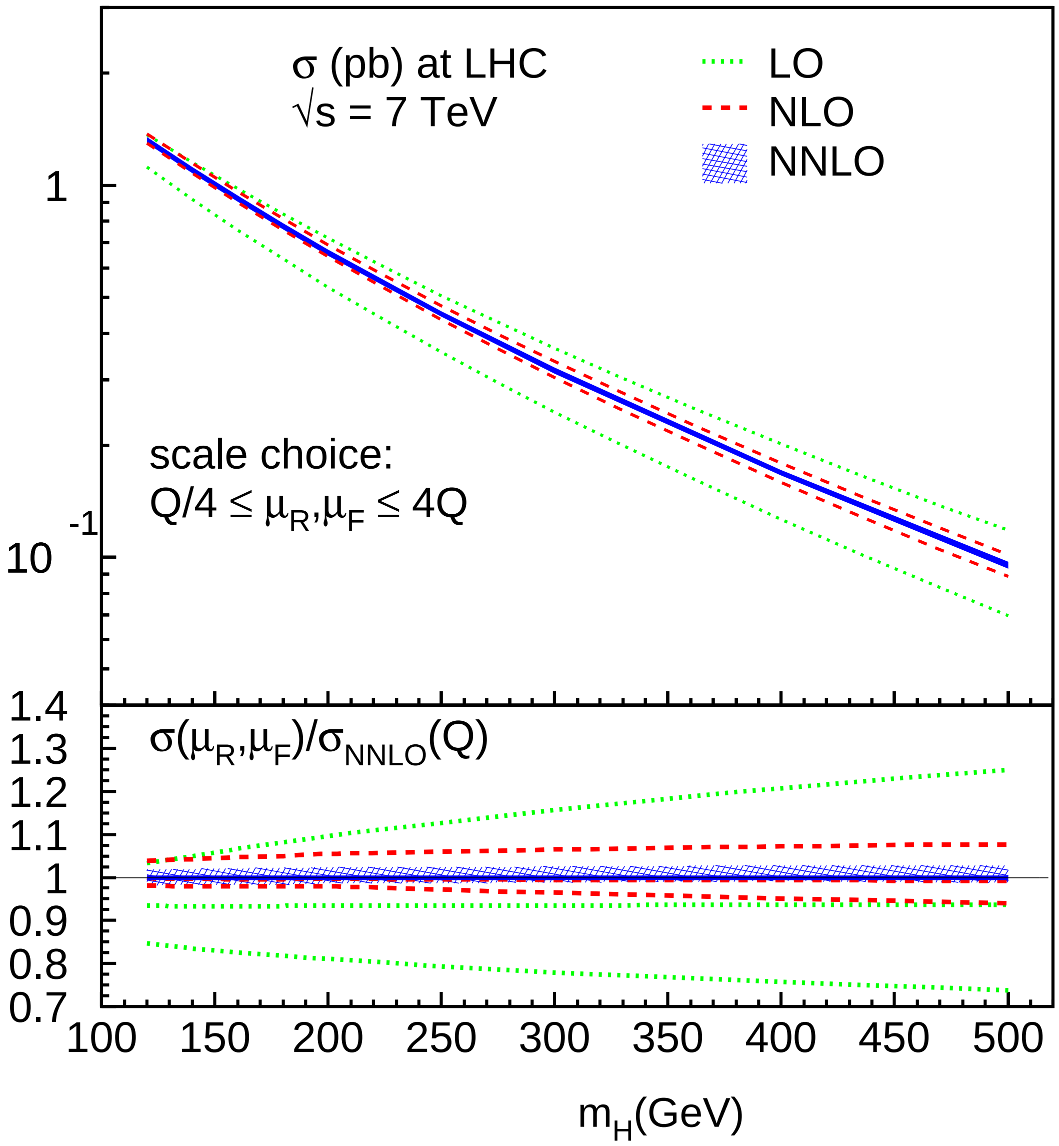
minimal set of cuts: $\sigma^{2-\mathrm{loop}}_{\mathrm{gluon}} \sim 2\,\%$ of $\sigma^{\mathrm{LO}}_{\mathrm{VBF}}$
VBF cuts: relative suppression by additional order of magnitude

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

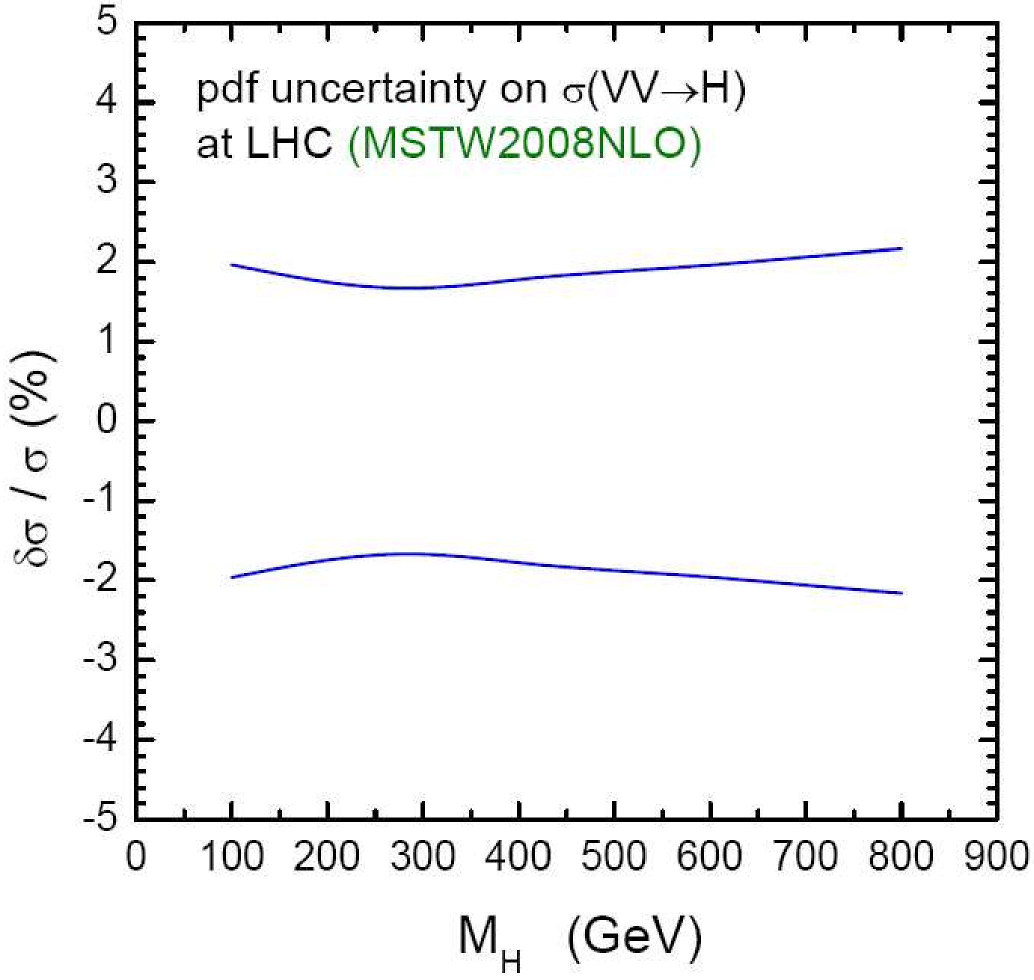


$$\sigma \sim \int dPS \frac{1}{2s} \frac{1}{\left(Q_1^2 + M_{V_1}^2\right)^2} \frac{1}{\left(Q_2^2 + M_{V_2}^2\right)^2}$$
$$\times \; W_{\mu\nu}\left(x_1, Q_1^2\right) \mathcal{A}^{\mu\rho} \mathcal{A}^{*\nu\sigma} W_{\rho\sigma}\left(x_2, Q_2^2\right)$$



- 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

$\sigma_{6.1}/\sigma_{6.6} \lesssim 4\%$

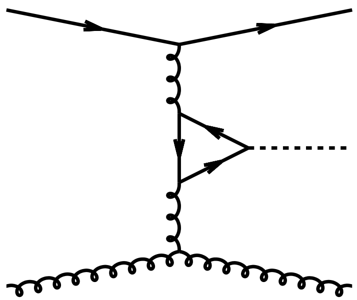
PDF uncertainty

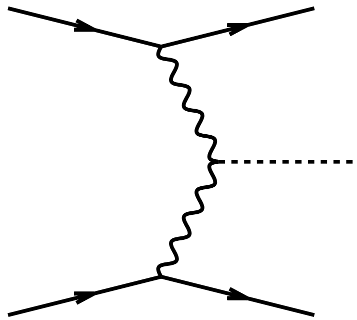
$\Delta_{\mathrm{PDF}} \lesssim 3.5\ \%$

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

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)

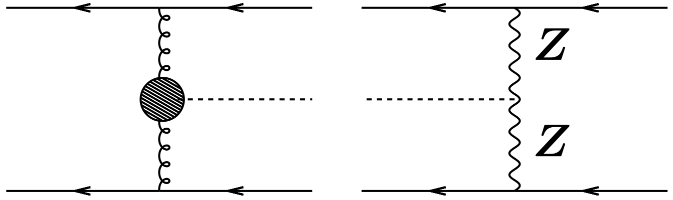
- and in a generic two-Higgs doublet model:

  Campanario, Kubocz, Zeppenfeld (2011)

- complementary: NLO QCD calculation in $m_t \to \infty$ limit:

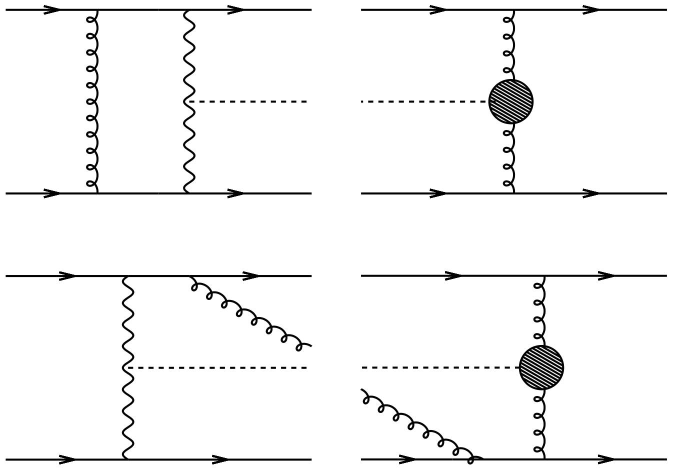
  Campbell, Ellis, Zanderighi (2006)

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

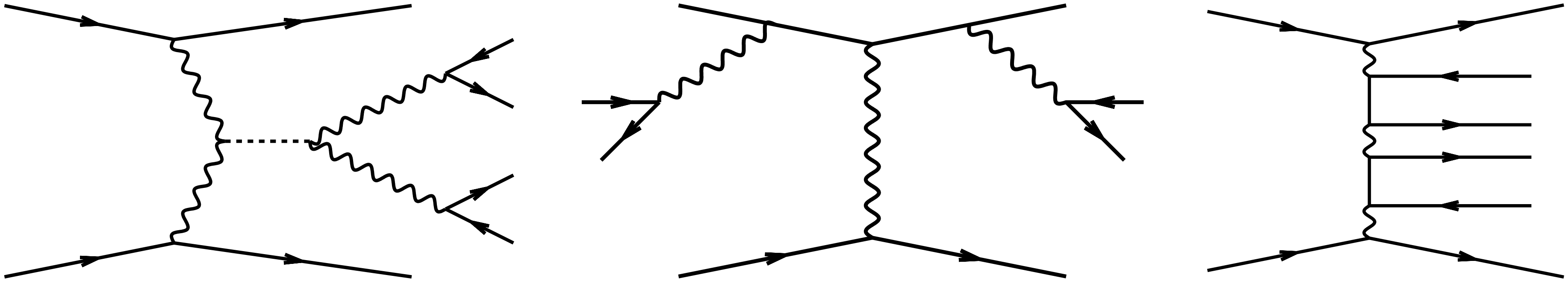
$pp \to Hjj$ via VBF with

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

☞ 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

EW $VVjj$ production



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

irreducible background to
VBF-induced Higgs production, followed by
decay into W bosons

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

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

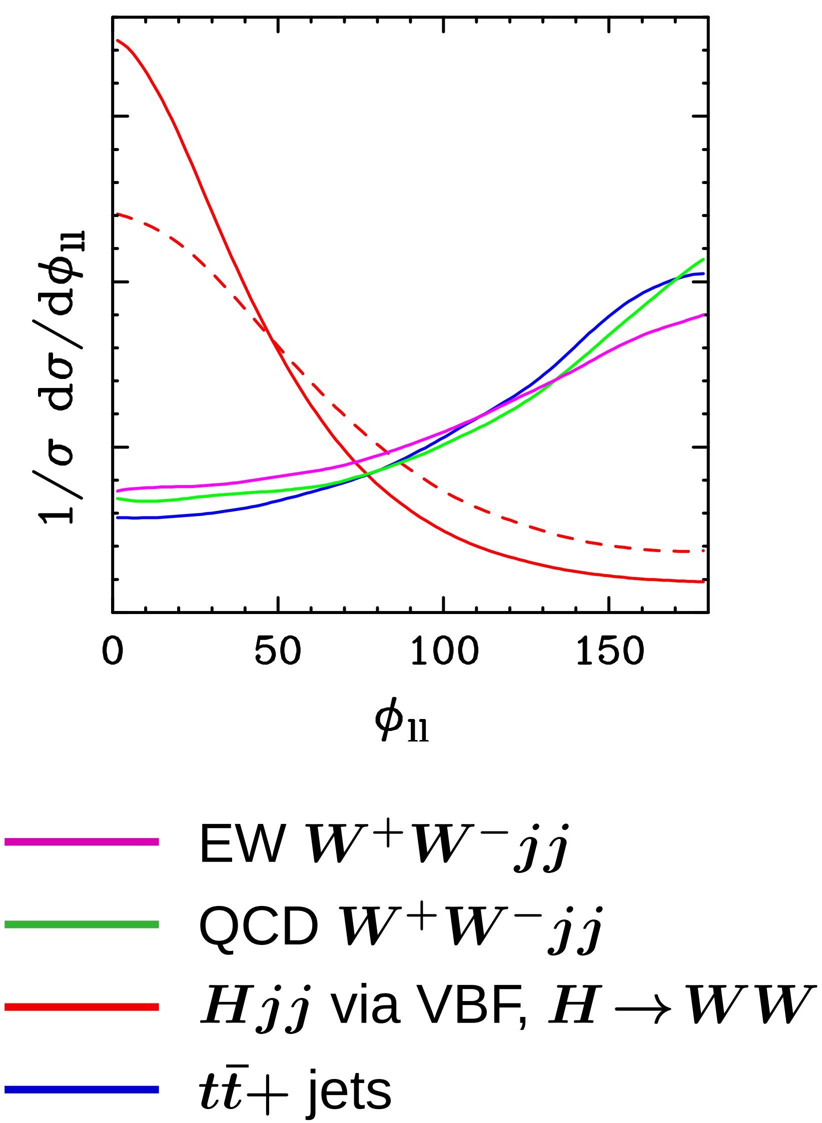
leptons emitted preferentially in same direction

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

Dittmar, Dreiner (1996)

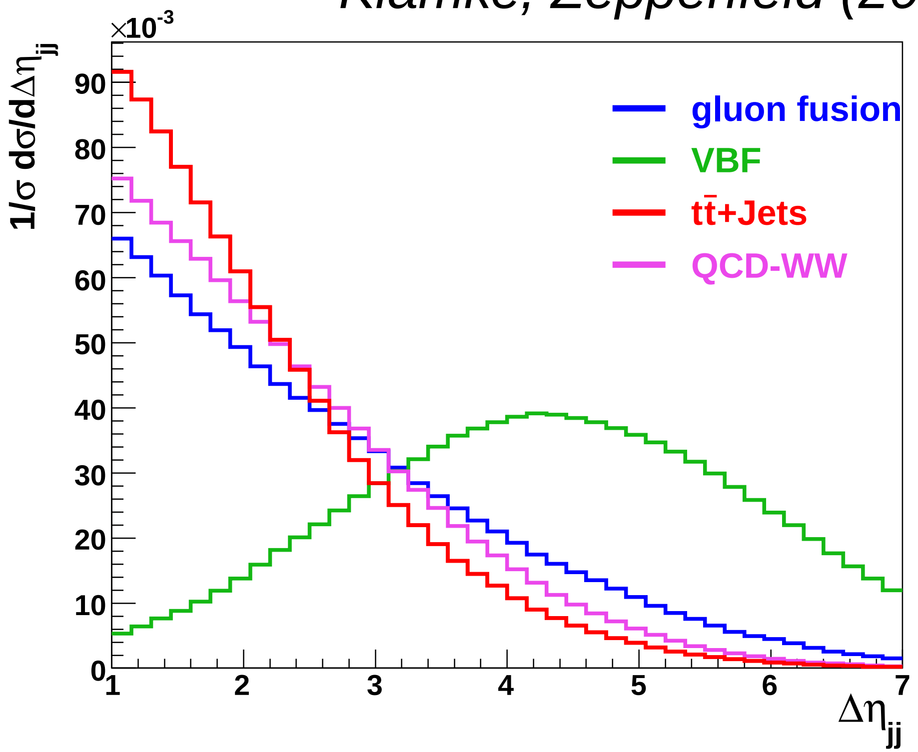
distribution for EW W^+W^- production significantly different from Higgs signal

Rainwater, Zeppenfeld (1999)



rapidity separation of the tagging jets

Klämke, Zeppenfeld (2007)



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

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

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

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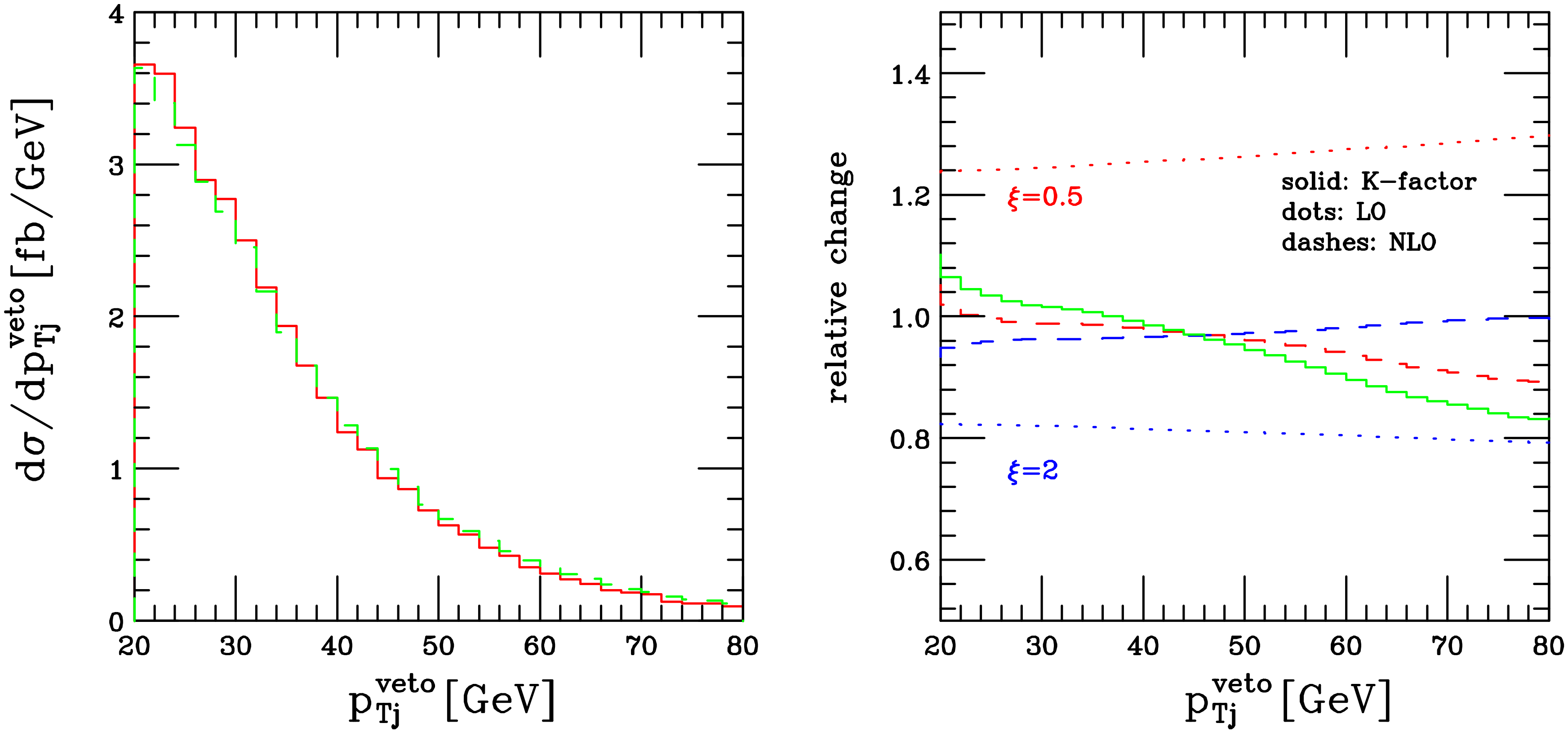
$$p_T^{\mathrm{veto}} > 20 \text{ GeV}, \ \eta_{\mathrm{jet}}^{\mathrm{min}} < \eta_{\mathrm{jet}}^{\mathrm{veto}} < \eta_{\mathrm{jet}}^{\mathrm{max}}$$

☞ precise knowledge of extra jet activity essential, requiring

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

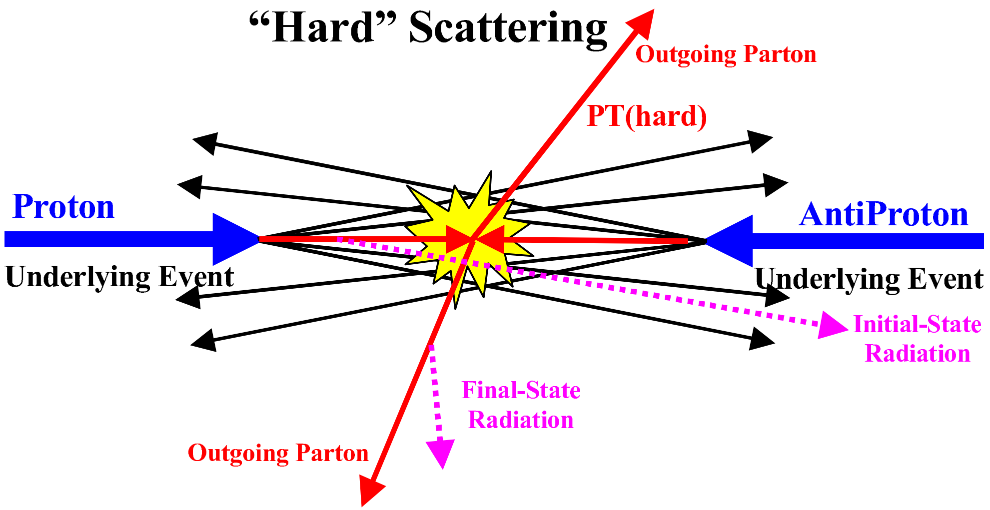
$pp \to Hjjj$ via VBF

Figy, Hankele, Zeppenfeld (2007)



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

$pp \to Hjj$ 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

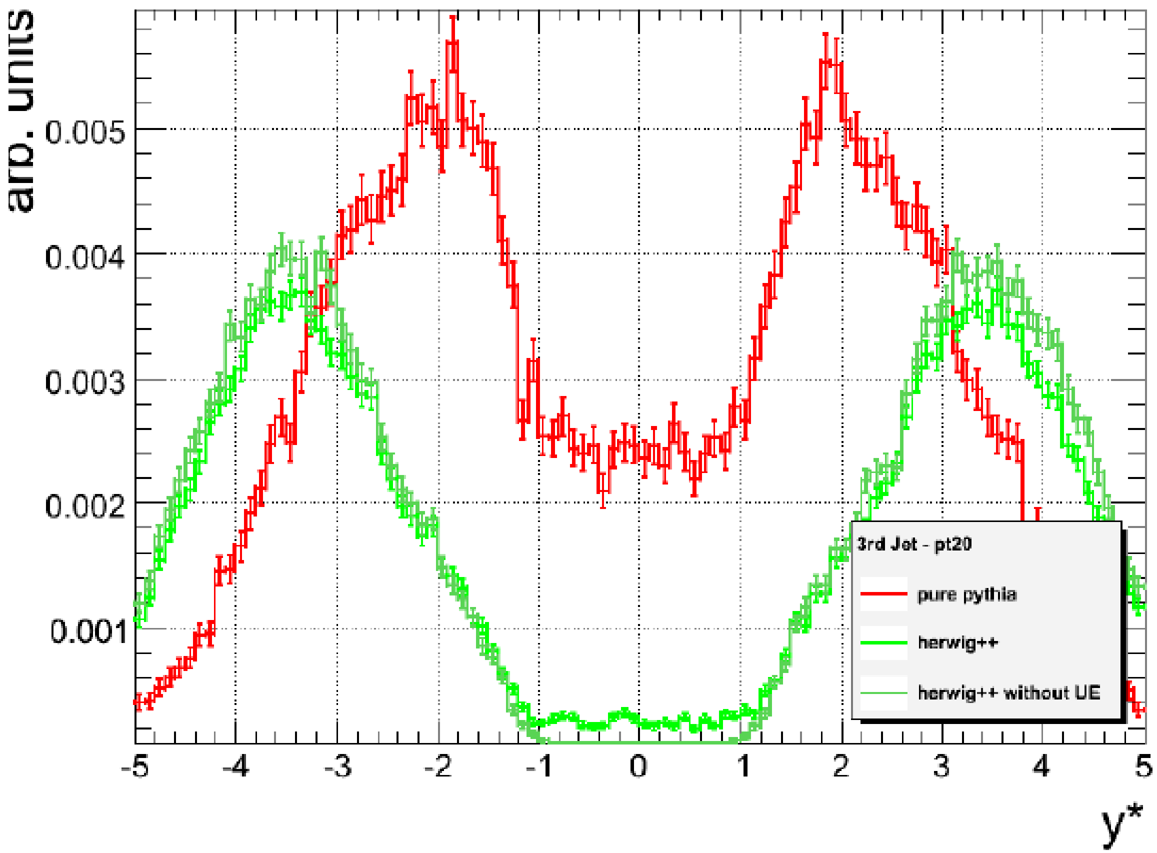
underlying event, parton shower, and hadronization

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

$pp \to Hjj$ 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

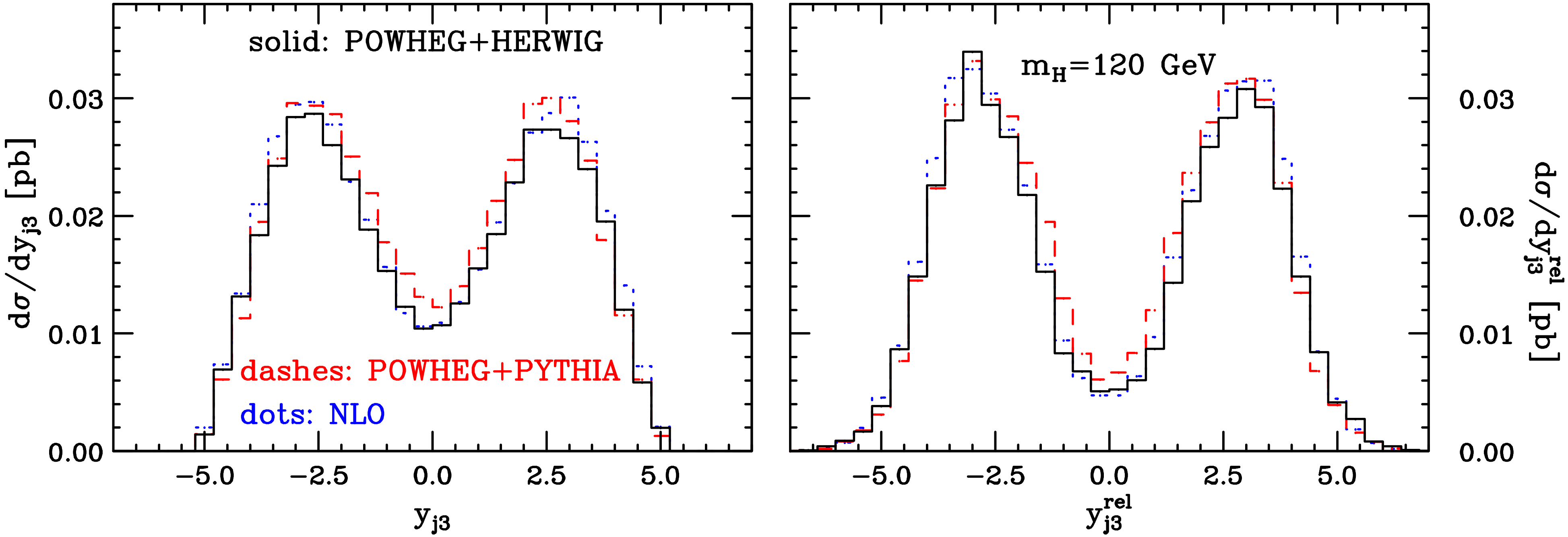
☞ better understanding and modeling needed recent progress: the POWHEG method *(Nason et al.)*

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)

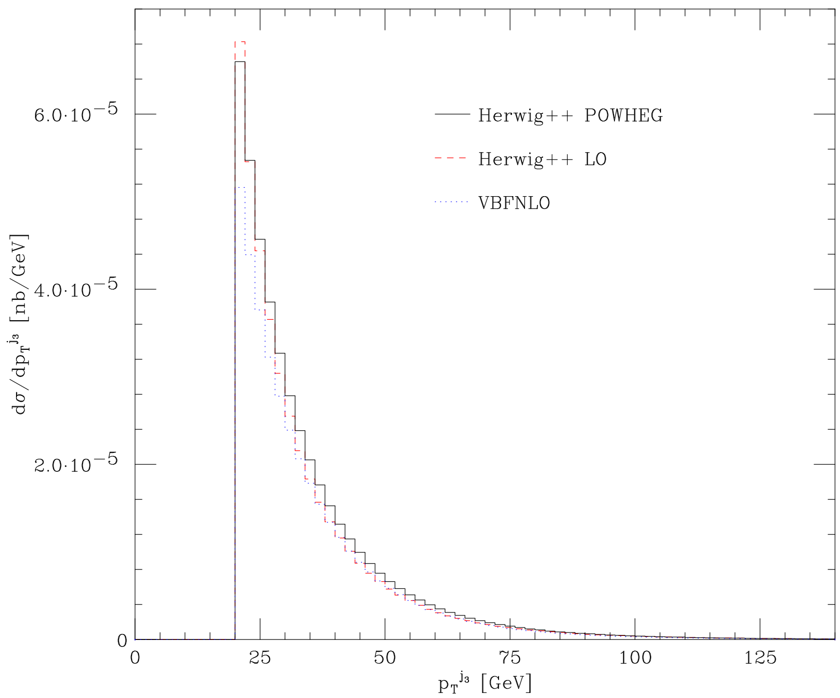
$pp \to Hjj$ via VBF and parton showers @ NLO

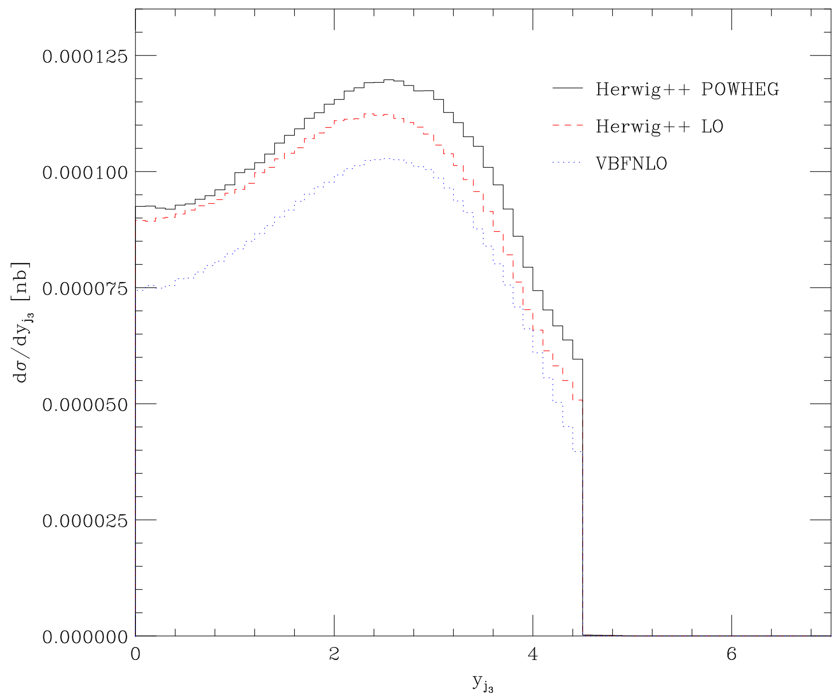
Nason, Oleari (2009)



- 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`

Richardson, De Luca (2011)

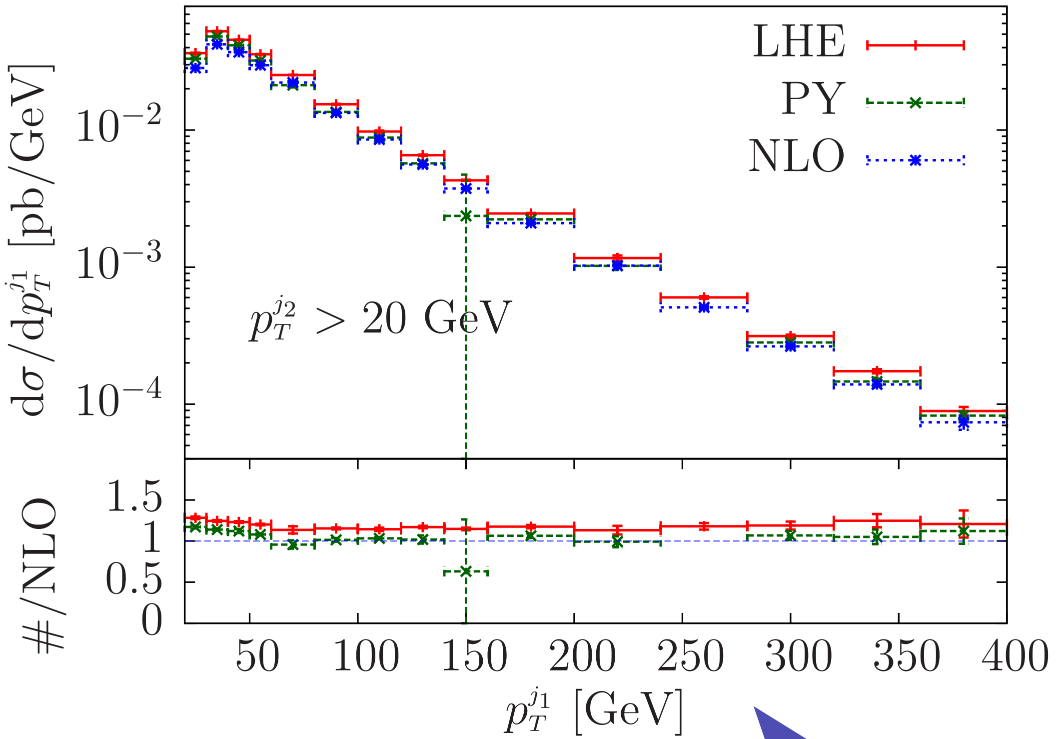


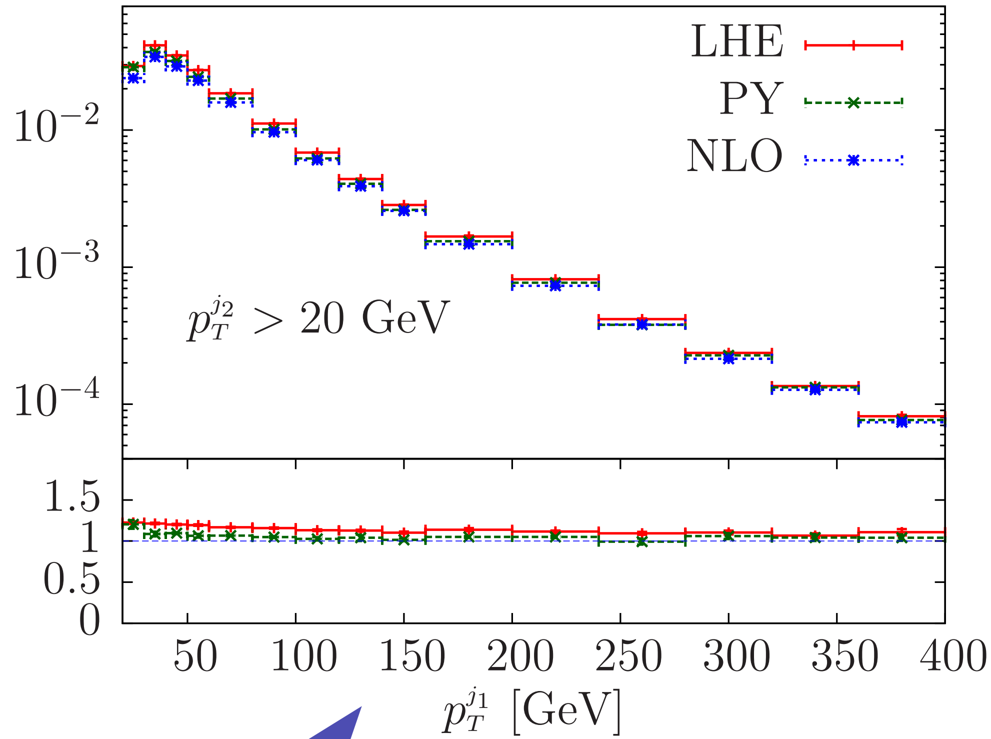


- parton-level NLO calculation matched via POWHEG with HERWIG++ including vetoed truncated shower ($\leftrightarrow$ angular-ordered PS)
- HERWIG++ results differ from pure parton level at LO and NLO

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

Campbell et al. (2012)





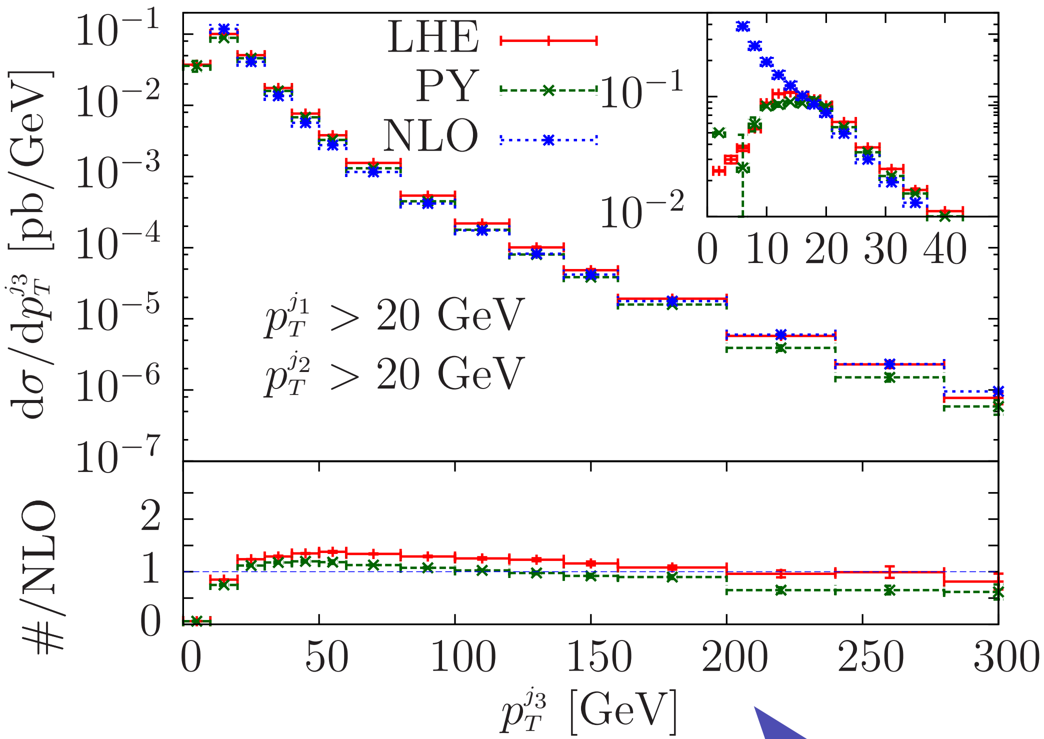
fixed scale $\mu = M_H$

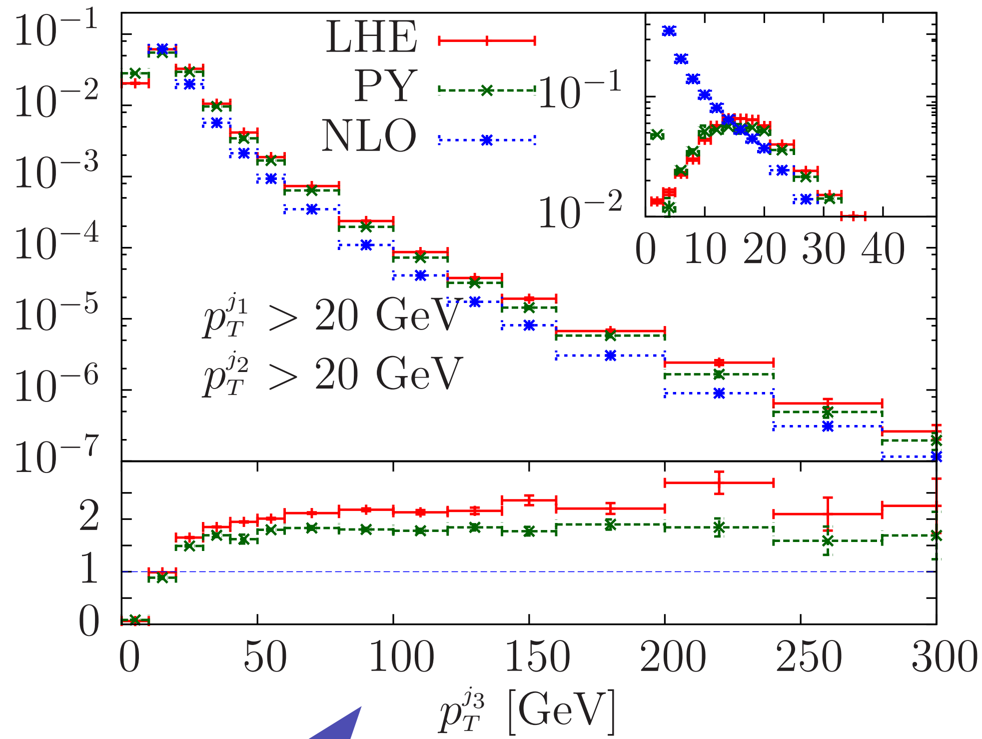
running scale: $\mu = \hat{H}_{\mathrm{tot}}$

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

necessary improvements

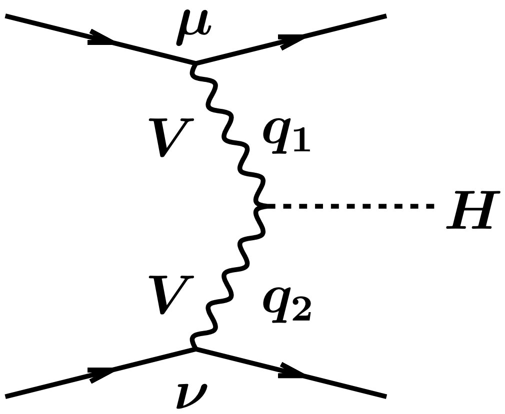
✧ full understanding of parton-shower programs for signal and backgrounds

✧ 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



most general HVV vertex:

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

physical interpretation:

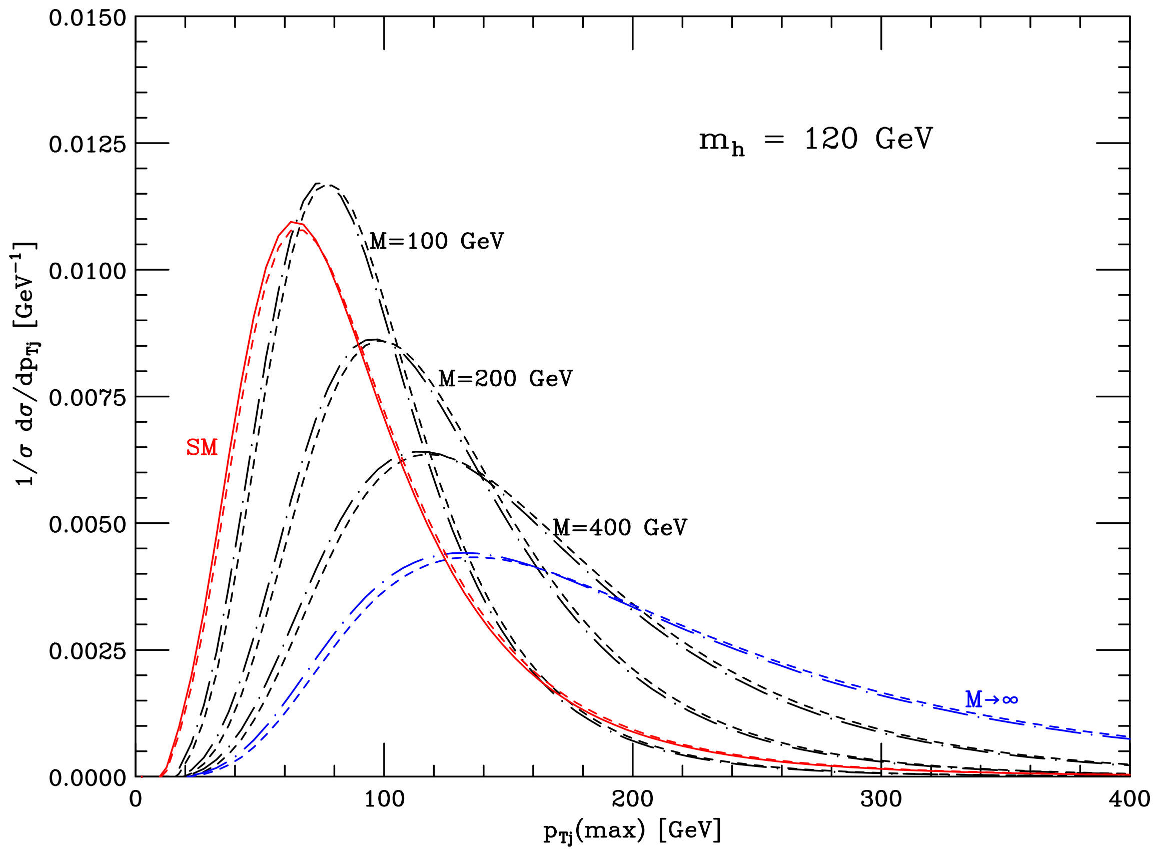
SM Higgs scenario: $\mathcal{L} \sim H V_\mu V^\mu \quad \rightarrow a_1$

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

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

tensor structure of the HVV coupling

ansatz: $$a_2(q_1, q_2) \sim \frac{M^2}{q_1^2 - M^2}\frac{M^2}{q_2^2 - M^2}\,,$$ $M\ldots$ scale of new physics



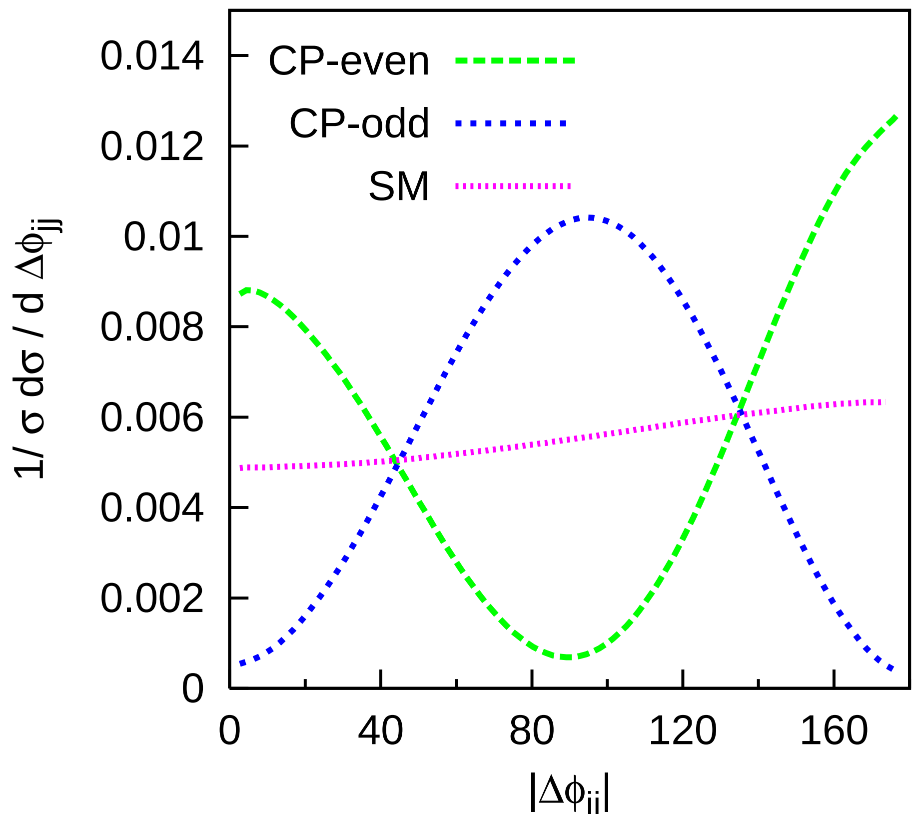
☞ tagging jet p_T distributions sensitive to anomalous couplings azimuthal angle between tagging jets

↓

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)



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

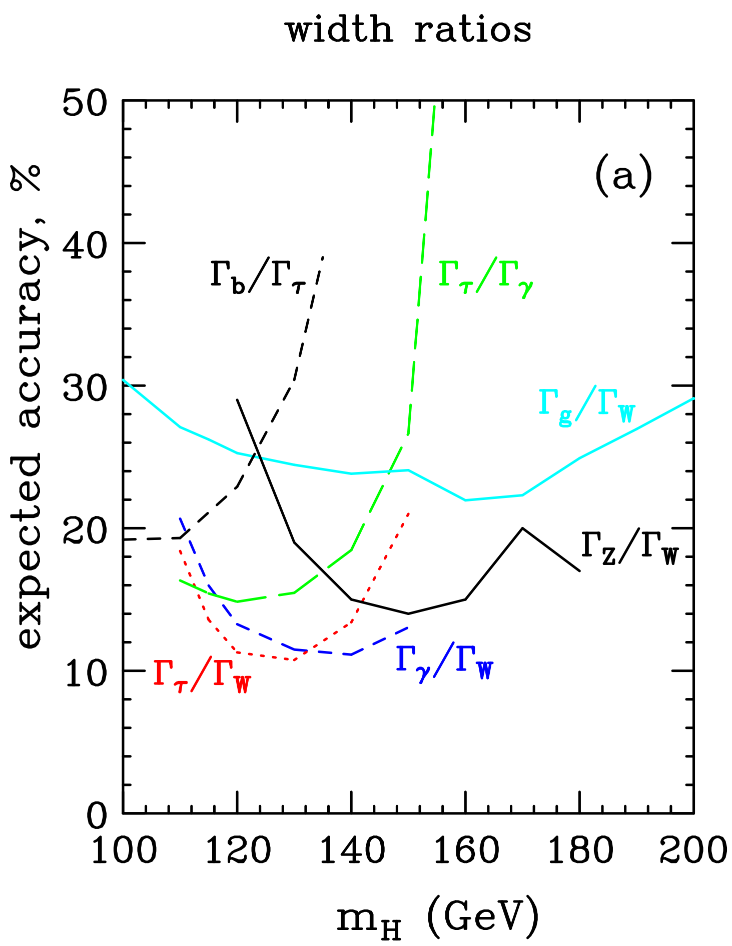
$$\sigma(aa \to H) \cdot BR(H \to dd) ☞ \frac{\Gamma_a \cdot \Gamma_d}{\Gamma}$$

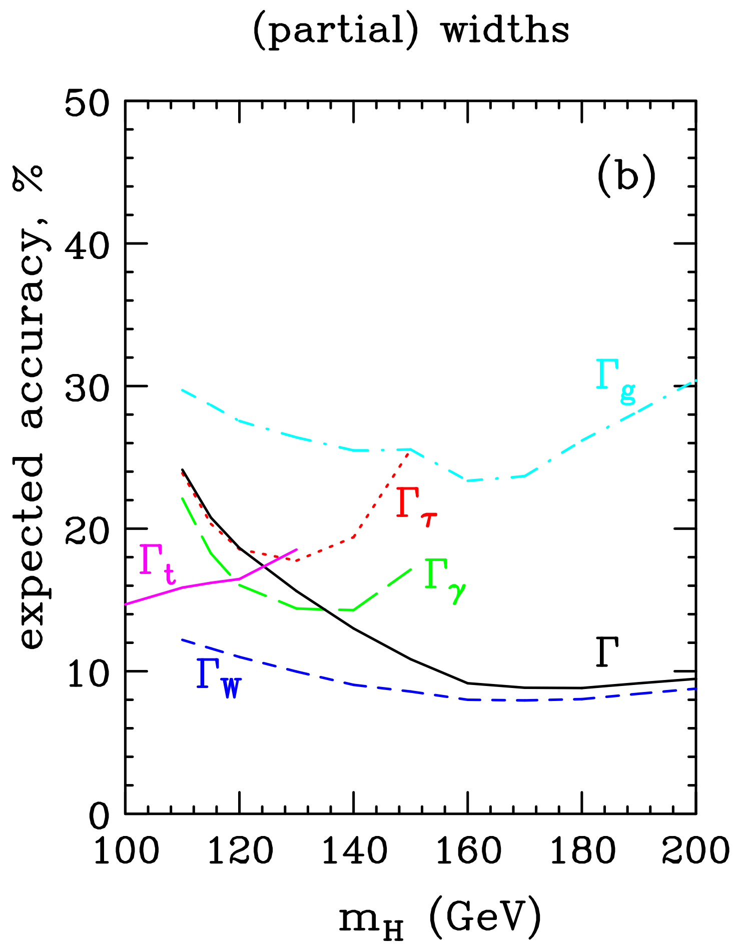
combining information from various production and decay modes
(including VBF)
with only mild model assumptions

↓

yields information on partial widths and couplings

determination of partial widths

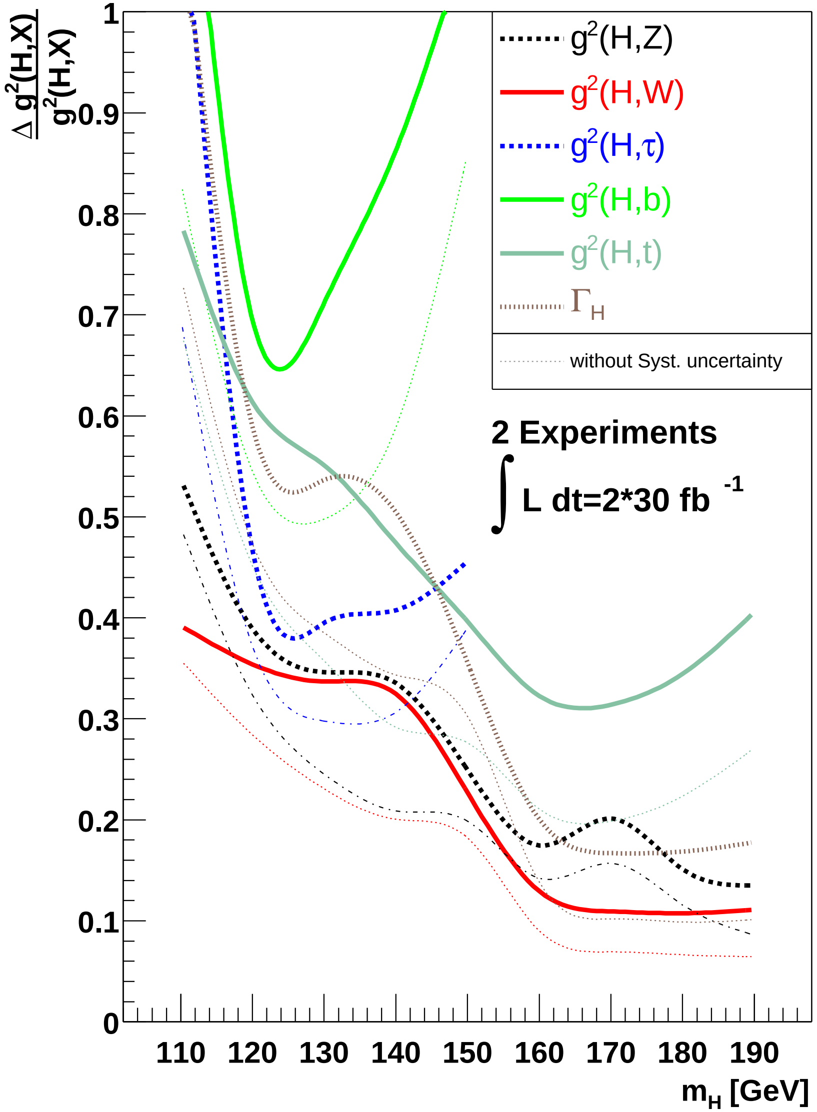




Zeppenfeld et al. (2002)

with 200 fb^{-1}@14 TeV 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

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)]*

summary: Higgs signal in VBF

✔ $pp \to Hjj$ 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 $pp \to Hjjj$

✘ 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