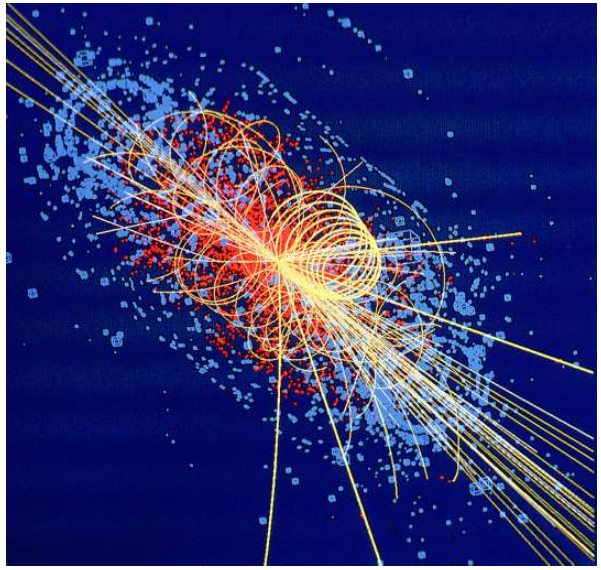
Weak boson fusion at the Large Hadron Collider



Particle Physics Seminar

Brookhaven National Laboratory

October 2012

Barbara Jäger

Johannes-Gutenberg University Mainz

what's on the menu today?

weak vector boson fusion (VBF)

the appetizer: Higgs production

- signal topology
- backgrounds
- quantum corrections

main course: weak boson scattering

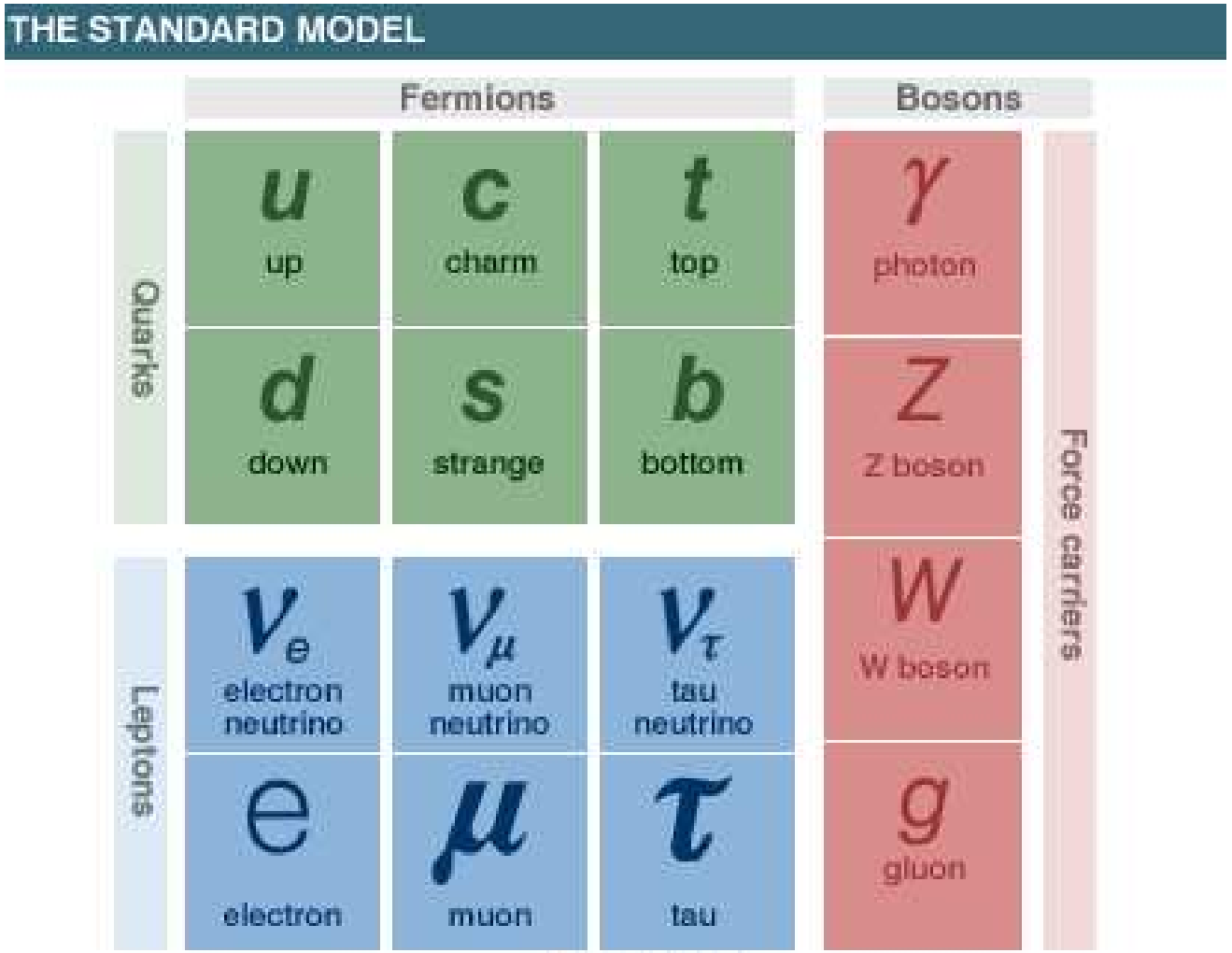
- precision calculations
- phenomenological results
- signatures of new physics

dessert:

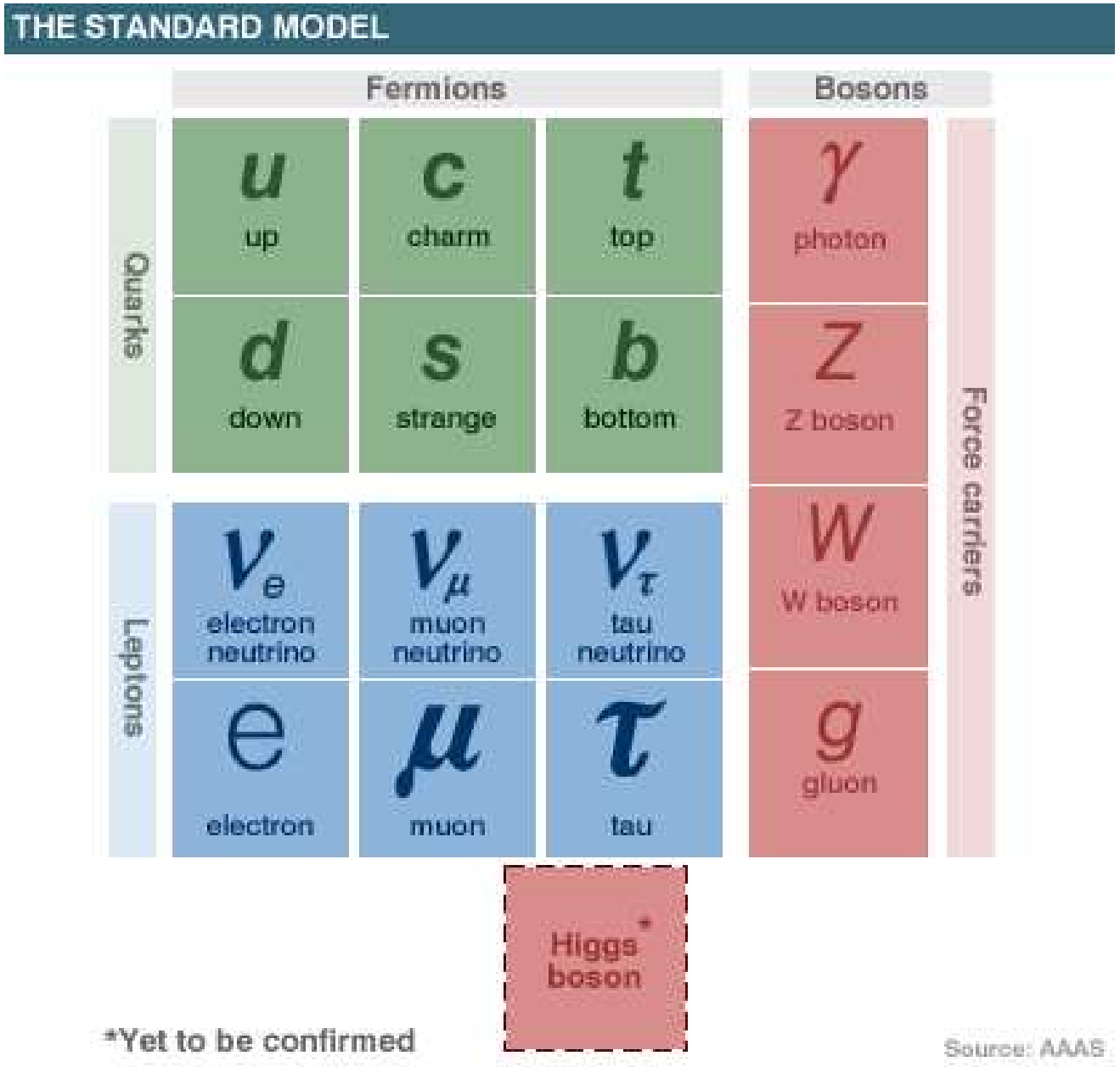
- VBF and parton showers



the standard model of elementary particles



the standard model of elementary particles



experimental bounds on the Higgs mass



information on the Higgs boson is obtained via

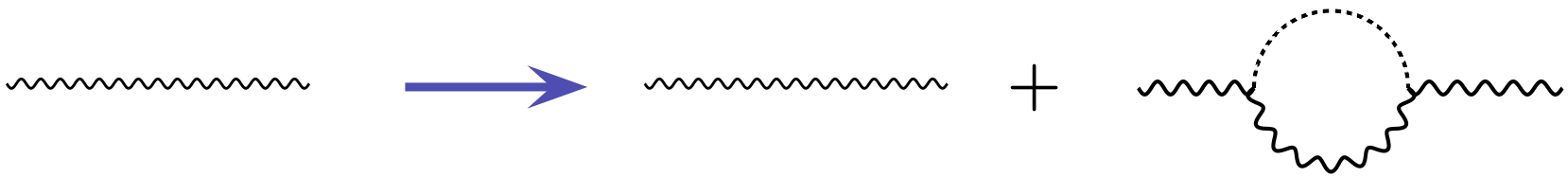
- indirect searches:

Higgs boson affects various observables indirectly via quantum corrections

- direct searches for explicit Higgs production in
  - e^+e^- collisions
  - hadronic collisions

indirect searches

Higgs boson affects electroweak precision data
(e.g. gauge boson mass determination)
via quantum corrections



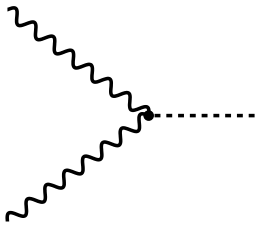
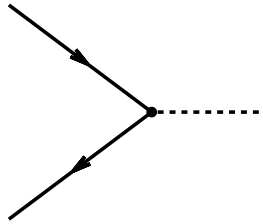
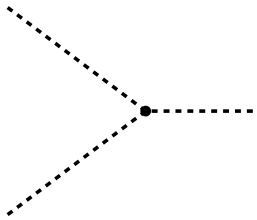
corrections proportional to $\ln \frac{M_H^2}{M_Z^2}$

☞ constrain M_H by precision data from various experiments (LEP, SLC, CDF, D0):

$$M_H \lesssim 161 \text{ GeV} \text{ @ } 95\% \text{ CL}$$

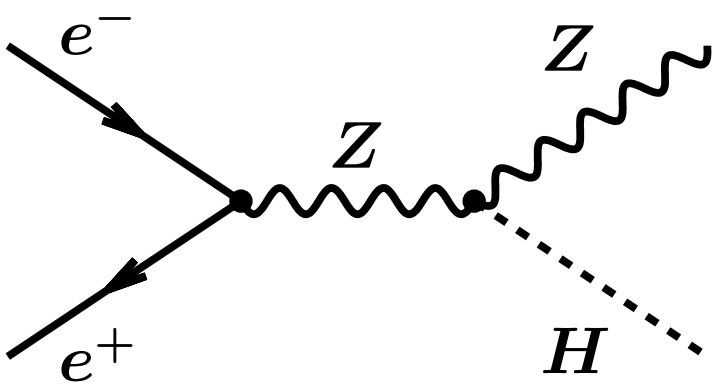
[LEP EWWG, July 2011]

Higgs couplings

gauge boson V	fermion f	self interaction
		
$\propto M_V$	$\propto m_f$	$\propto M_H^2$

coupling of the Higgs boson to any particle
proportional to its mass

direct search in electron-positron collisions



direct Higgs production

at the CERN-LEP e^+e^- collider

(c.m.s. energy $\sqrt{S} \lesssim 209$ GeV):

mainly via Higgs-strahlung

$$M_H \gtrsim 114 \text{ GeV}$$

the first hadron collider at the terascale



the Tevatron at Fermilab:

high energy synchrotron

with proton–anti-proton collisions

at c.m.s. energy

$\sqrt{S} \simeq 2$ TeV

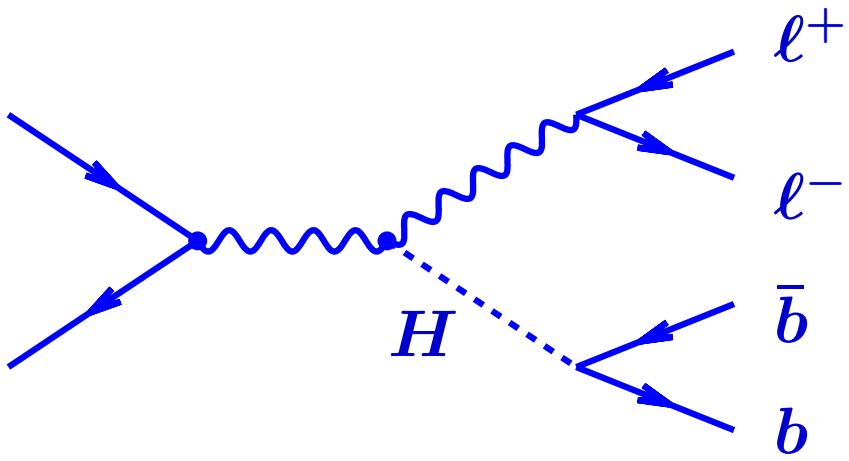
two major experiments:





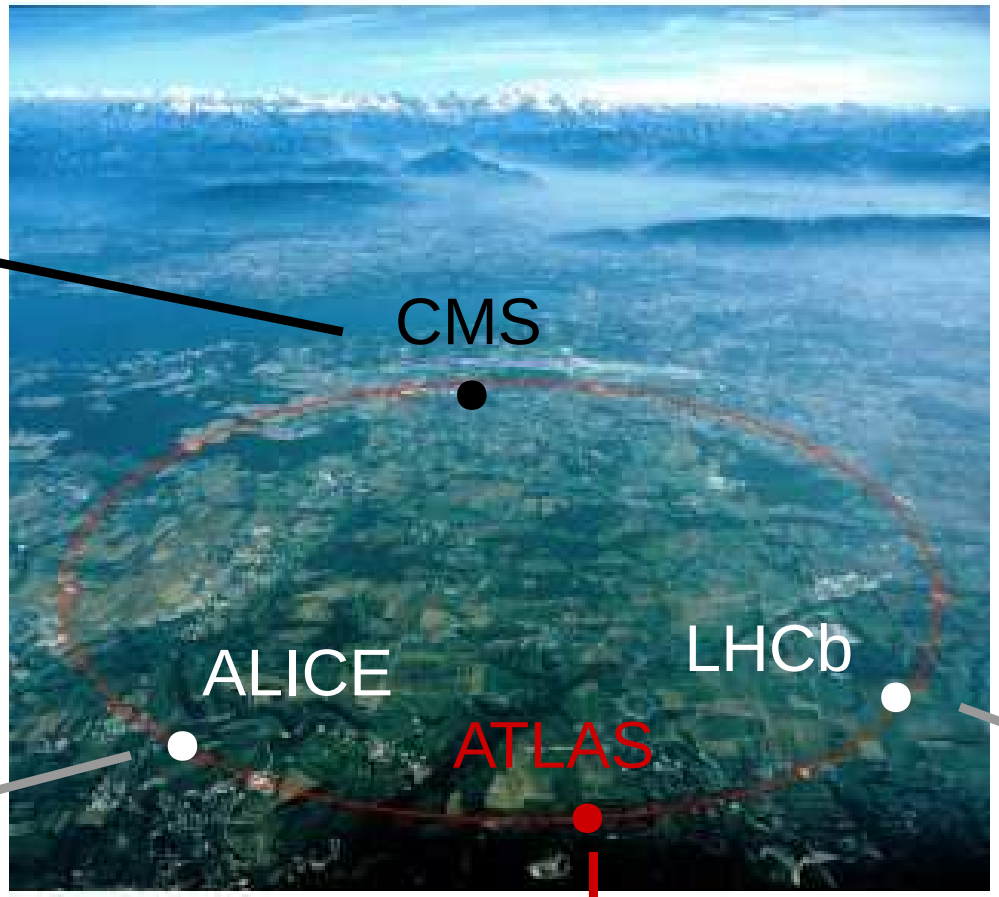
combination of CDF & D0 searches
with up to 10 fb^{-1} of data
(July 2, 2012):

excess with 2.9 σ in
$H \to b\bar{b}$ channels



the world's largest hadron collider . . .

. . . and its four major experiments . . .



Compact Muon Solenoid

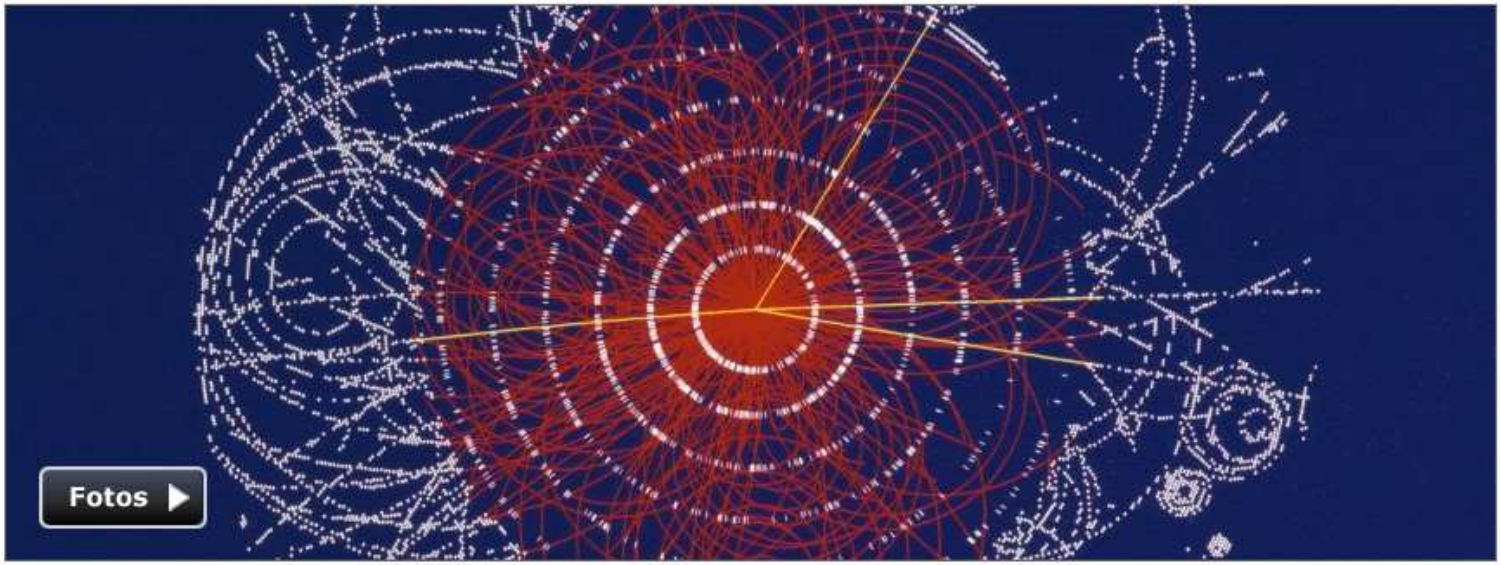
A Large Ion Collider Experiment

LHC-beauty

A Toroidal LHC Apparatus

Higgs-Boson

Physiker feiern Durchbruch bei der Gottesteilchen-Suche



Physiker am Kernforschungszentrum Cern sind euphorisch, feiern eine wissenschaftliche Sensation: Sie haben ein neues Elementarteilchen aufgespürt, bei dem es sich vermutlich um das lange gesuchte Higgs-Boson handelt. Sein Feld verleiht anderen Teilchen ihre Masse. mehr... [Forum]

- Beschleuniger LHC: Heiße Spur zum Gottesteilchen
- Fotostrecke: Die Jagd nach dem Higgs-Teilchen

VIDEO



Spiegel Online, July 4, 2012

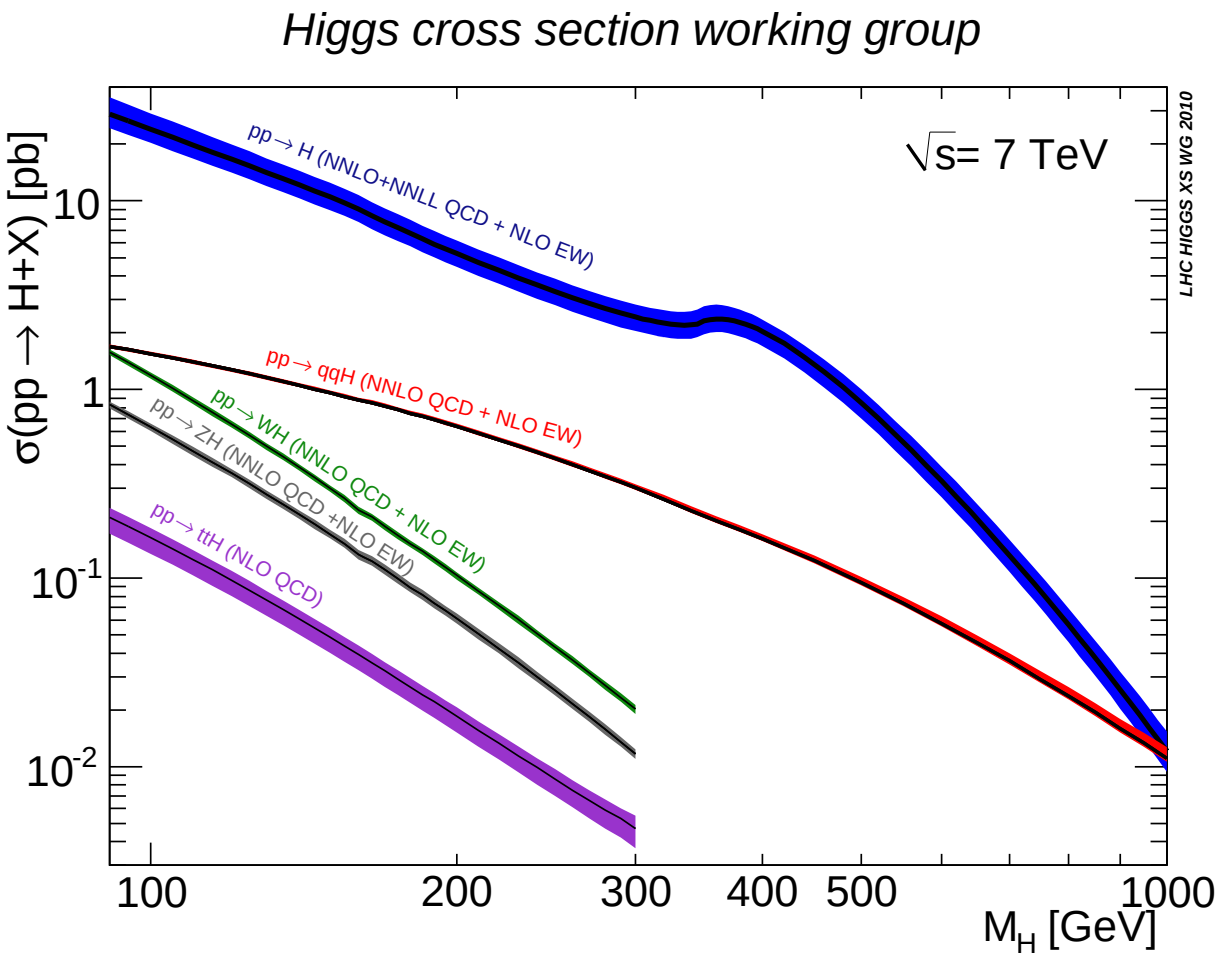


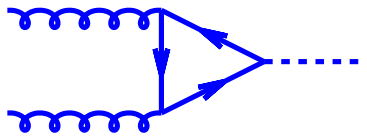
the CMS experiment reports the
observation of a new boson
with a mass of
125.3 ± 0.6 GeV
at $4.9\ \sigma$ significance

status as of July 4, 2012

the ATLAS experiment reports the
observation of an excess of events
at a mass of 126.5 GeV
with local significance of $5.0\ \sigma$

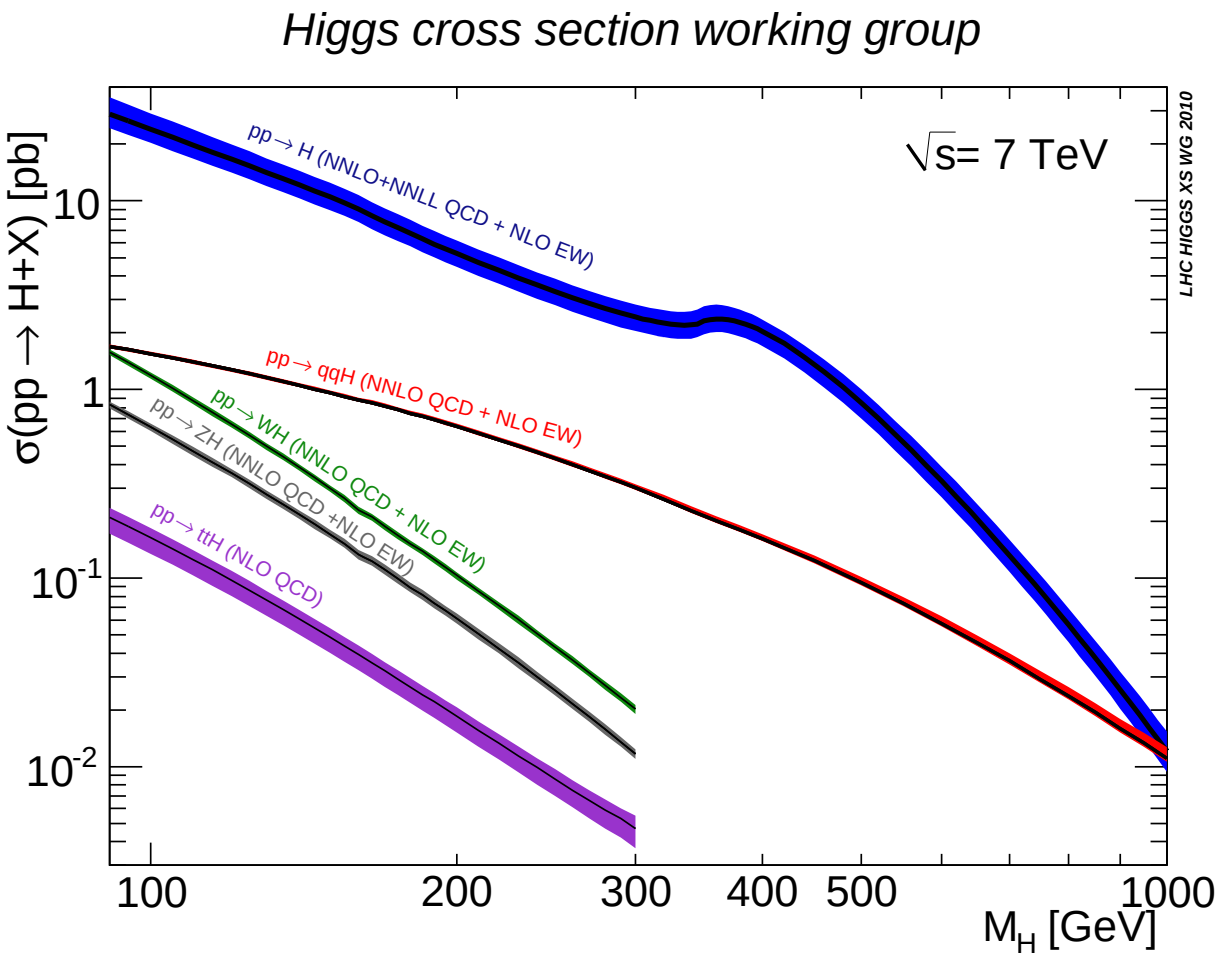
Higgs production @ LHC

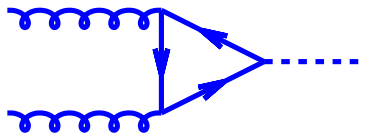




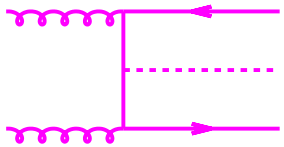
gluon fusion (GF)

Higgs production @ LHC



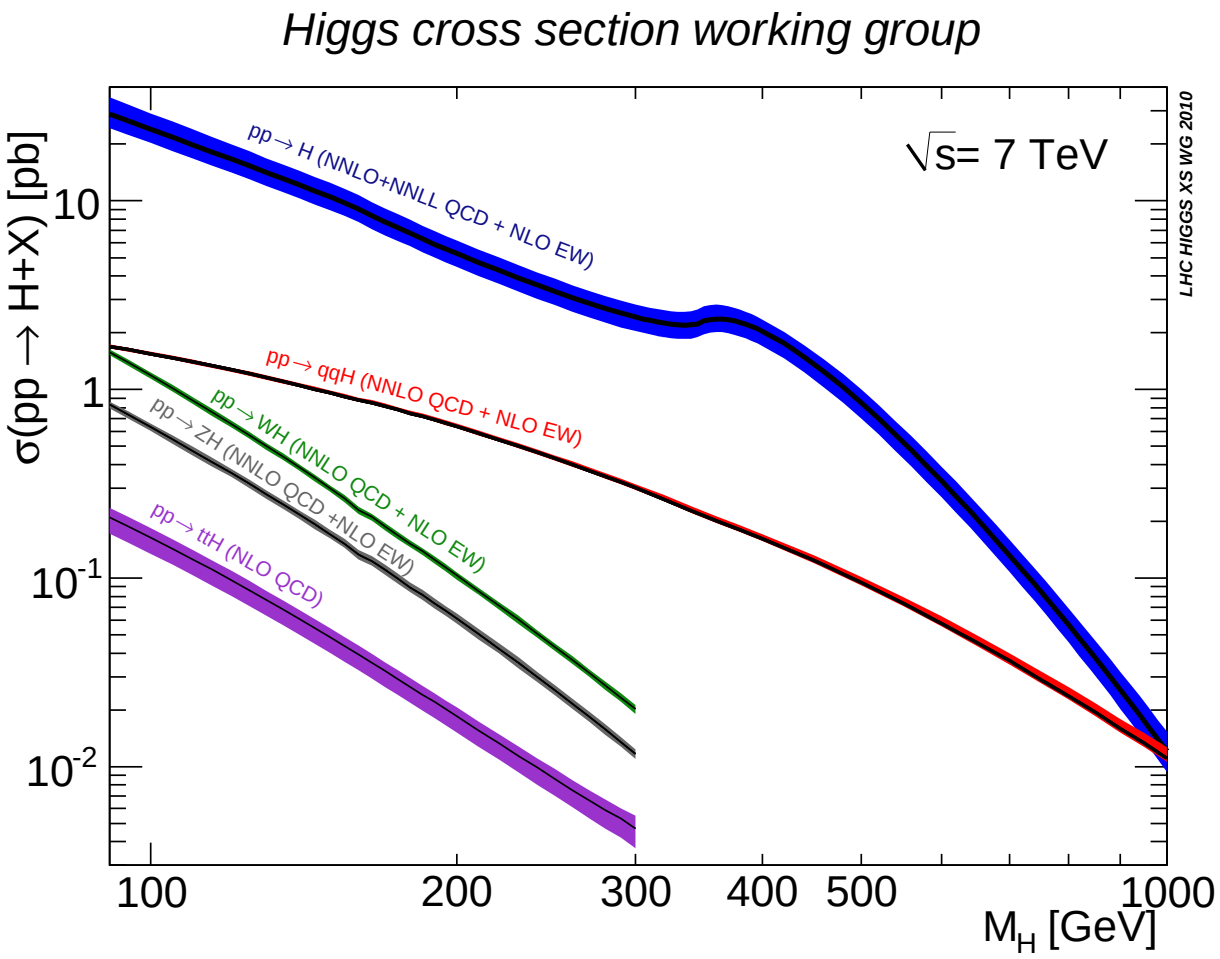


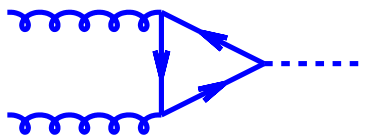
gluon fusion (GF)



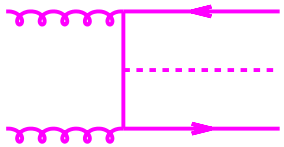
$t\bar{t}H$ production

Higgs production @ LHC

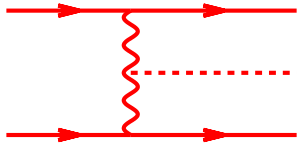




gluon fusion (GF)

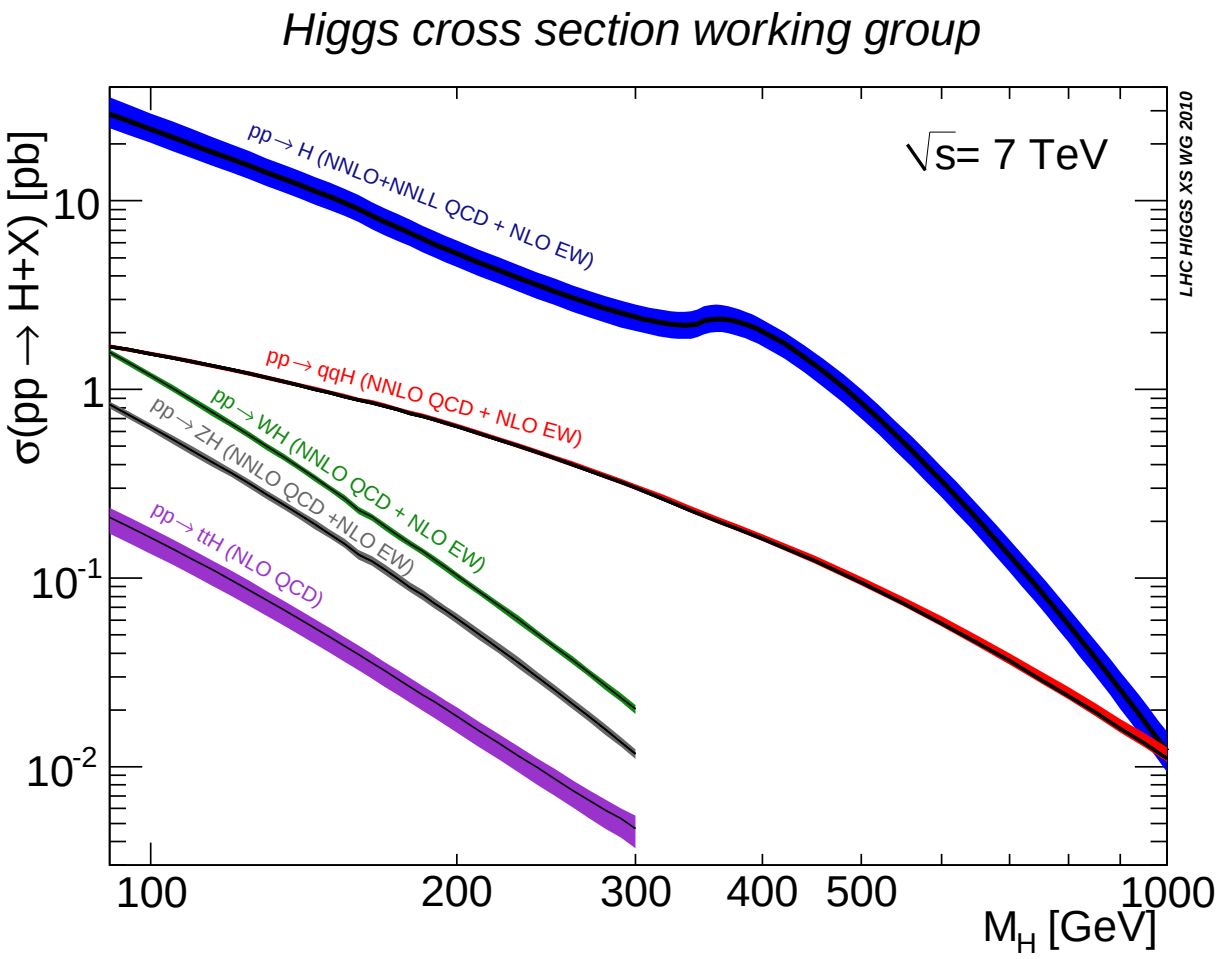


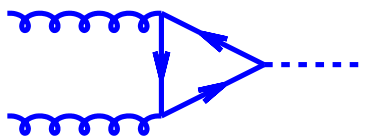
$t\bar{t}H$ production



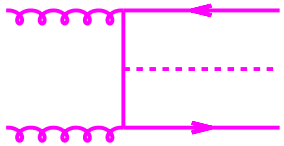
vector boson fusion (VBF)

Higgs production @ LHC

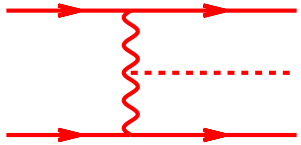




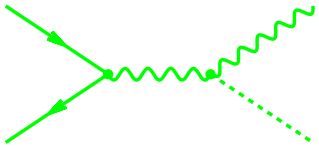
gluon fusion (GF)



$t\bar{t}H$ production

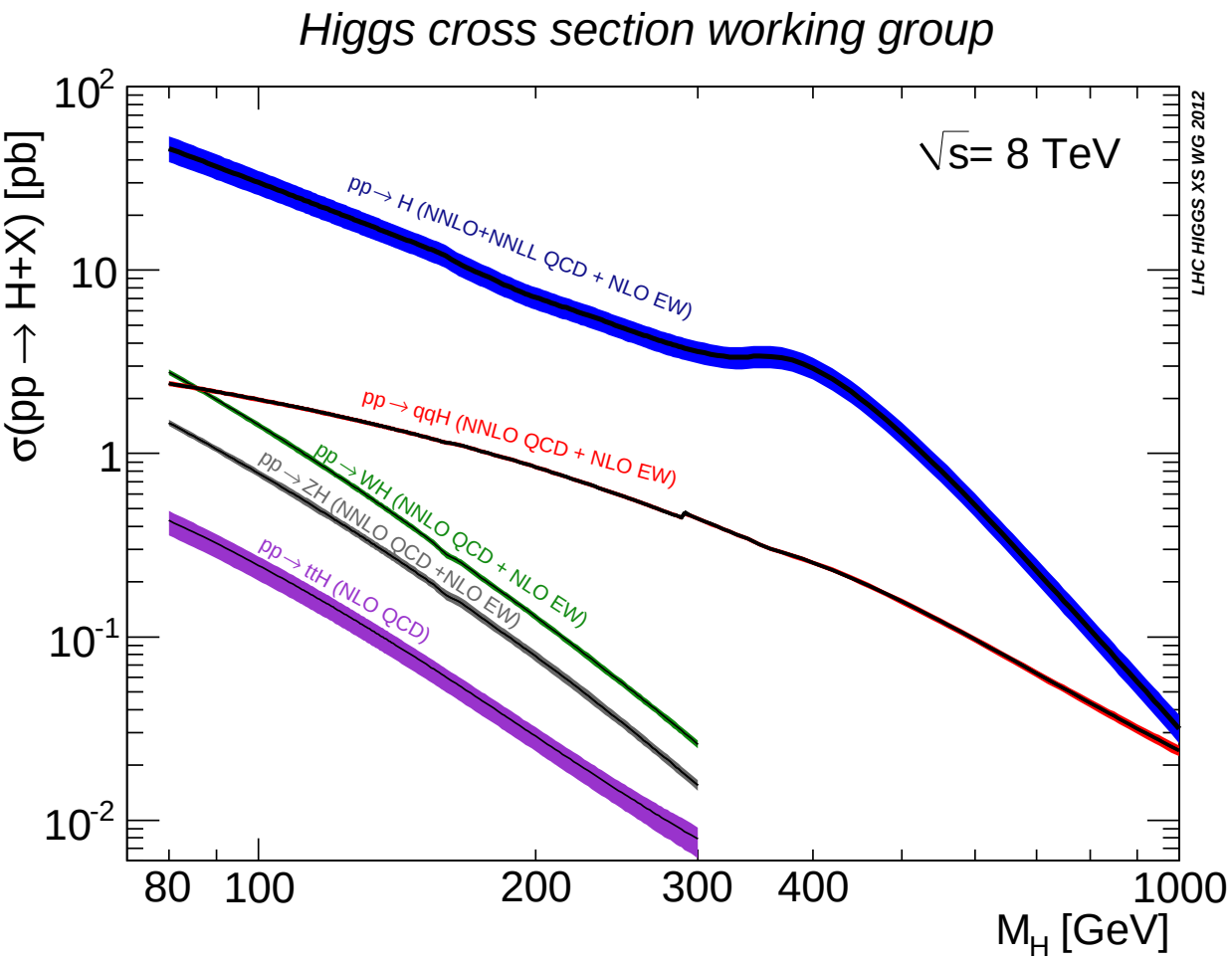


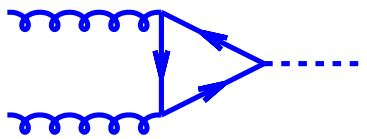
vector boson fusion (VBF)



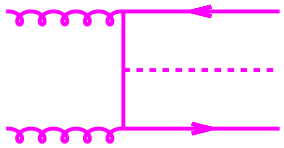
W, Z bremsstrahlung

Higgs production @ LHC

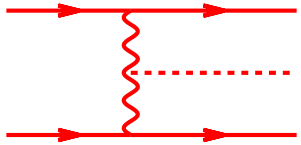




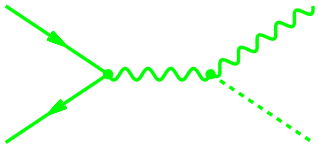
gluon fusion (GF)



$t\bar{t}H$ production

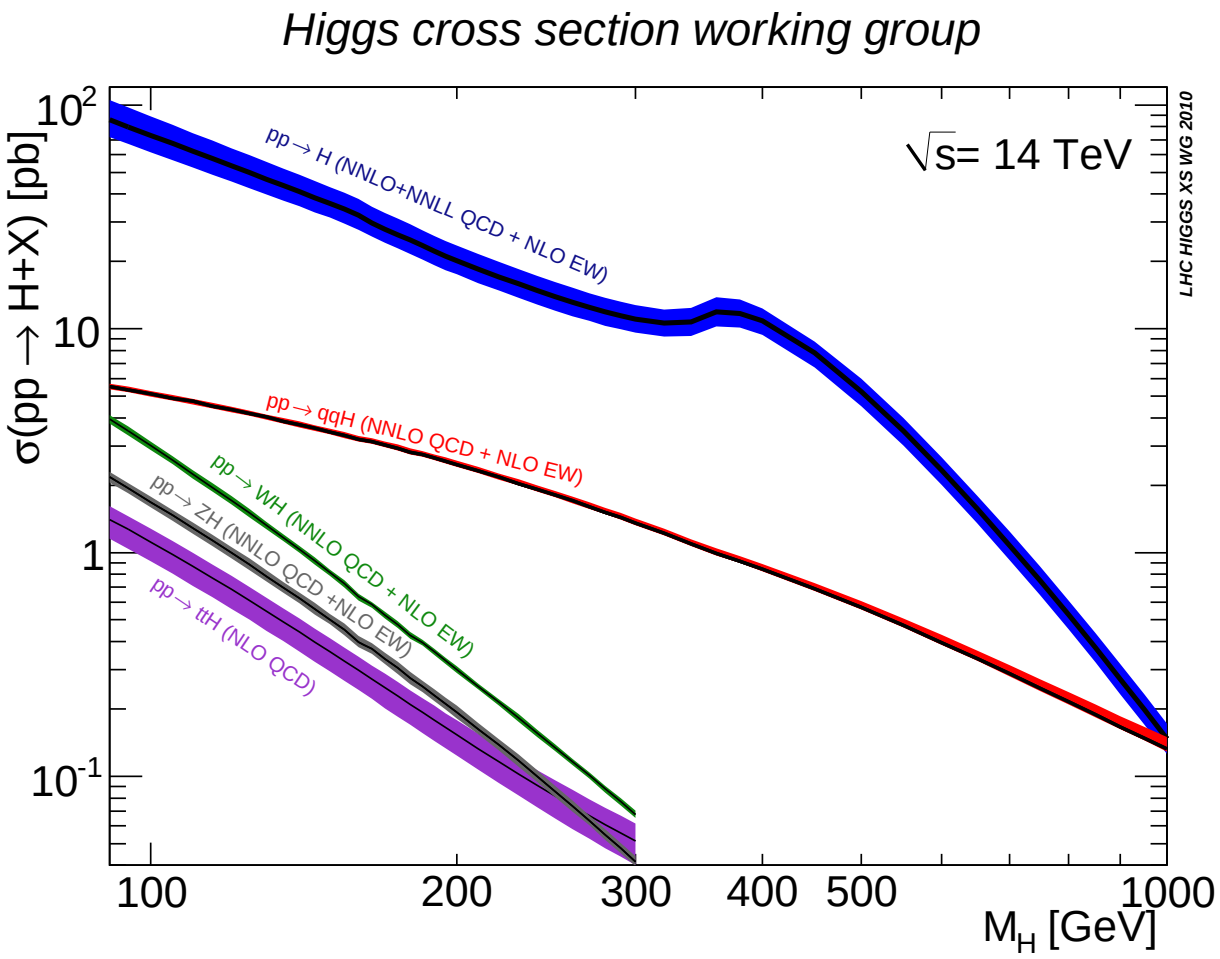


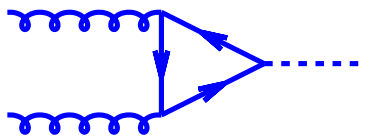
vector boson fusion (VBF)



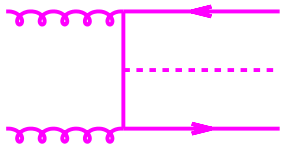
W, Z bremsstrahlung

Higgs production @ LHC

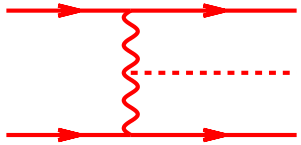




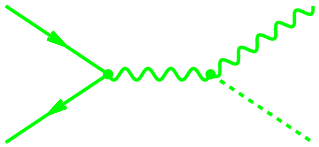
gluon fusion (GF)



$t\bar{t}H$ production



vector boson fusion (VBF)



W, Z bremsstrahlung

weak vector boson fusion (VBF)

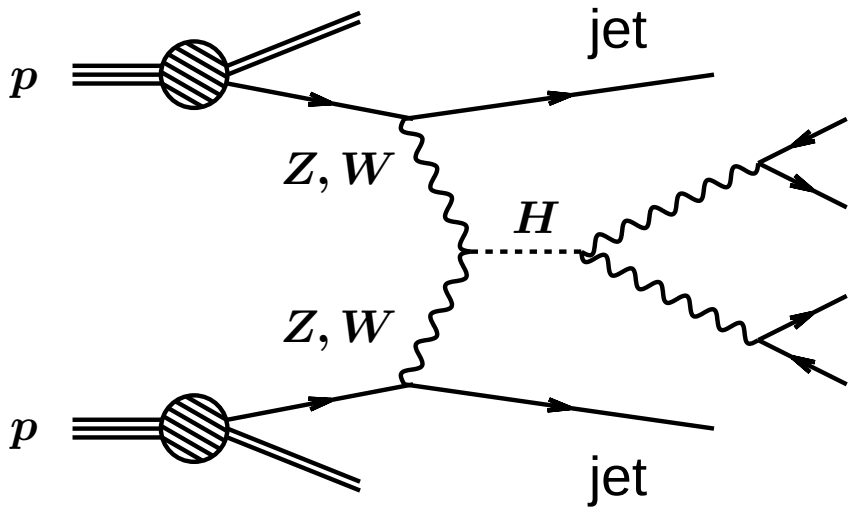
CMS & ATLAS:
VBF selection included in
$H \to \gamma\gamma$, $H \to WW$,
$H \to \tau\tau$

- important Higgs search channel
  over entire mass range

- sensitive to Higgs couplings
  and CP properties

☞ accurate predictions and
flexible tools essential
for signal and backgrounds!

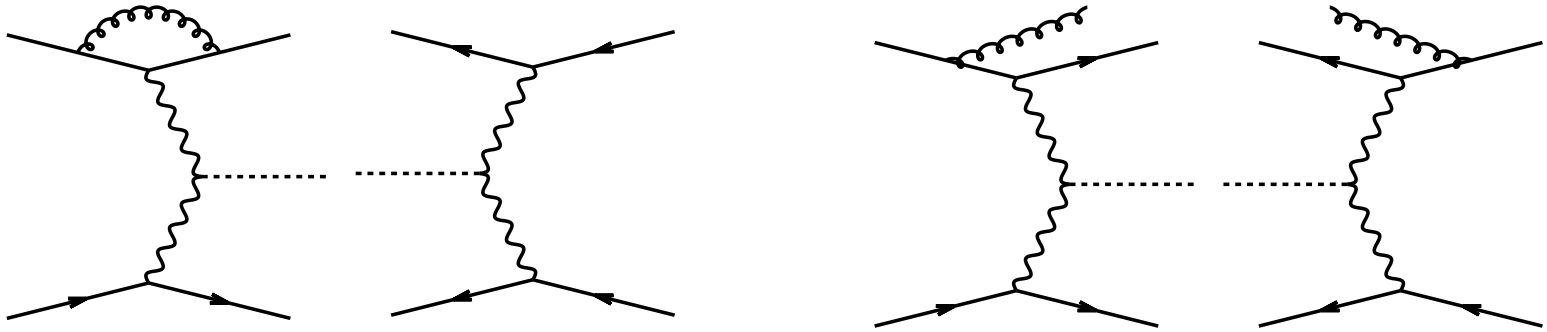
VBF event topology



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)

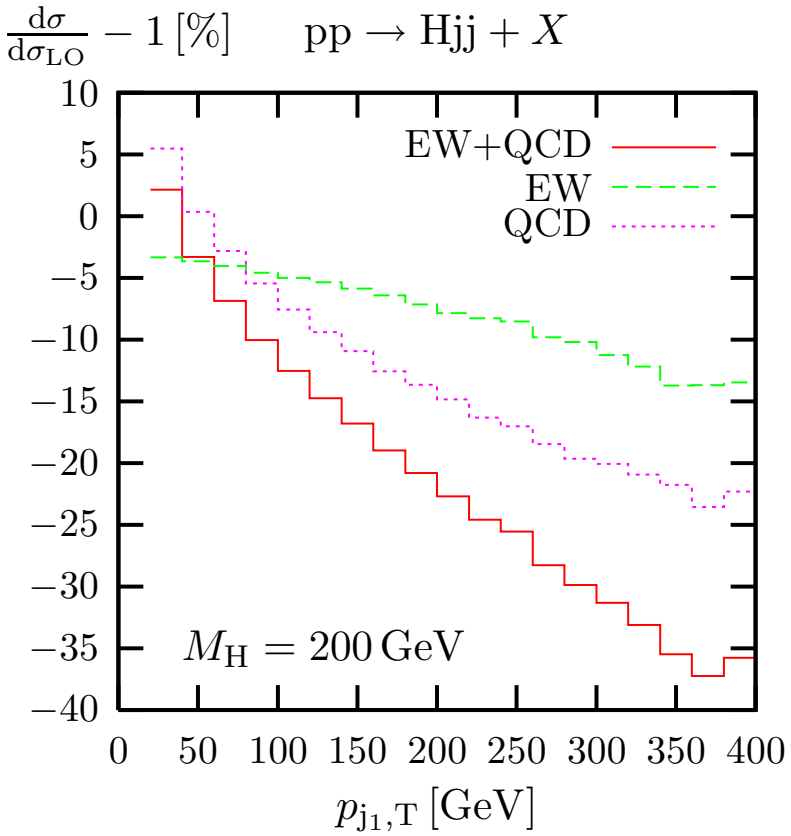
publicly available
parton-level Monte Carlos:
`vbfnlo`
`MCFM`

Higgs production in VBF @ NLO EW

Ciccolini, Denner, Dittmaier, Mück:

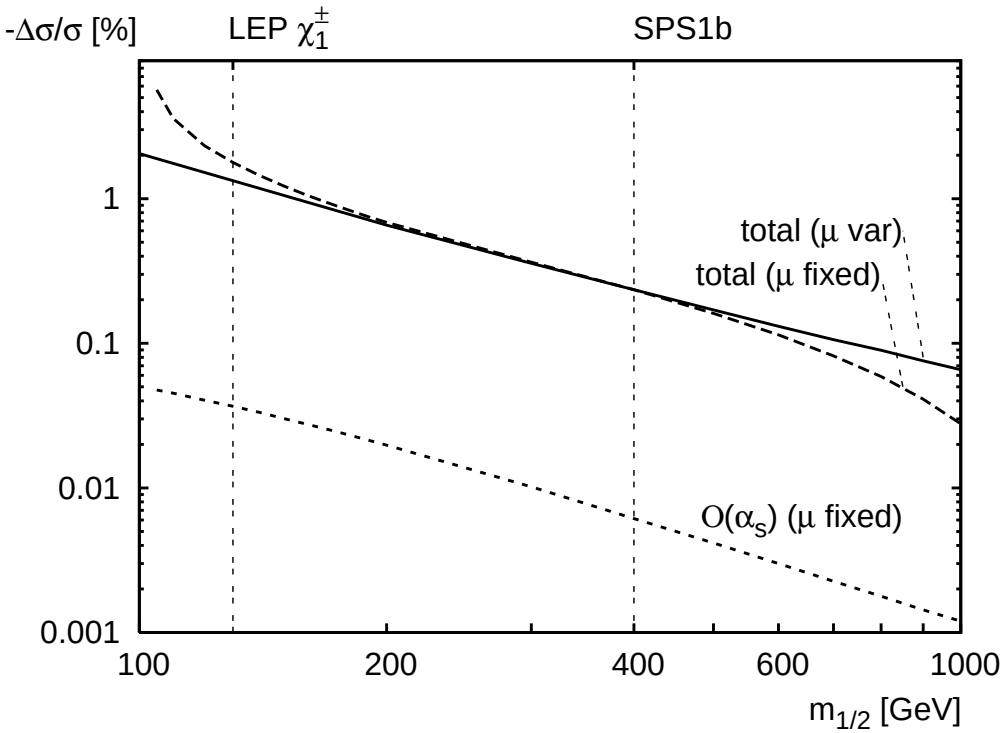
NLO EW corrections to inclusive cross sections and distributions

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



publicly available parton-level Monte Carlo program: HAWK

SUSY QCD+EW corrections to VBF



Hollik, Plehn, Rauch, Rzehak & Figy, Palmer, Weiglein (2008-2010):

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

for inclusive cross sections

in typical regions of the MSSM parameter space

vbfnlo

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

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



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

vbfnlo: features

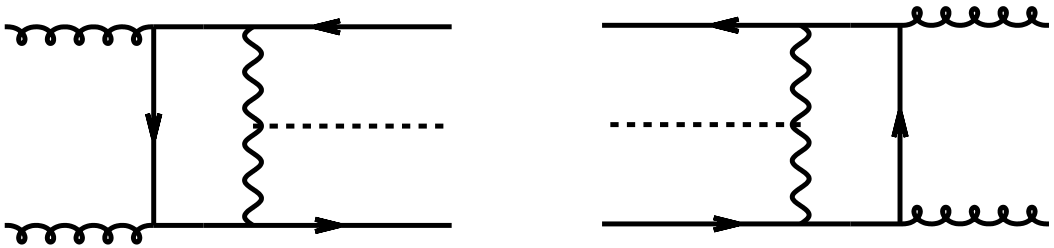
- cross sections and distributions at NLO-QCD accuracy
- NLO-EW corrections to VBF Hjj production
- arbitrary selection cuts
- various choices for factorization and renormalization scales
- LO predictions for all processes with one extra jet
- interface to LHAPDF $\rightarrow$ any currently available PDF set
- LO: event files in Les Houches Accord (LHA) format
- MSSM: SUSY parameters input via standard SLHA file
- various BSM features:
  anomalous couplings, Kaluza-Klein models, ...

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?

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

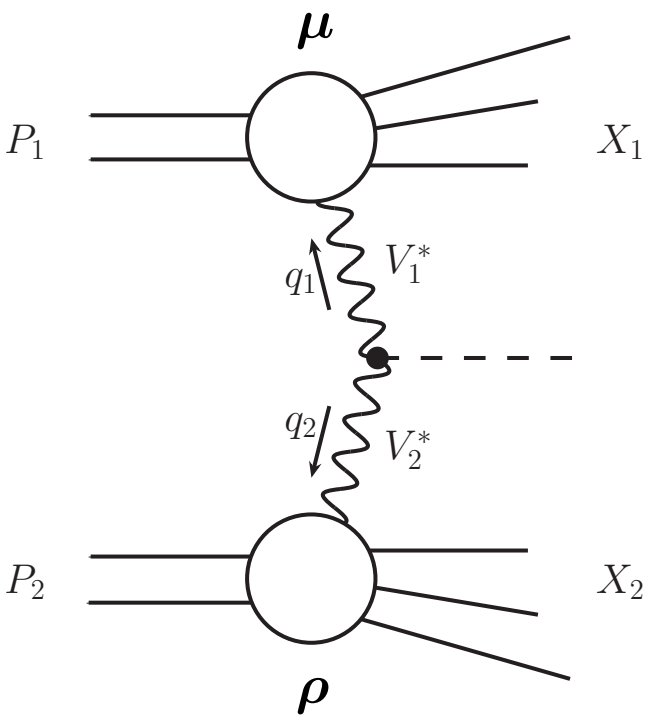
minimal set of cuts: $\sigma^{2-\text{loop}}_{\text{gluon}} \sim 2\,\%$ of $\sigma^{\text{LO}}_{\text{VBF}}$

VBF cuts: relative suppression by additional order of magnitude

higher orders of QCD in VBF

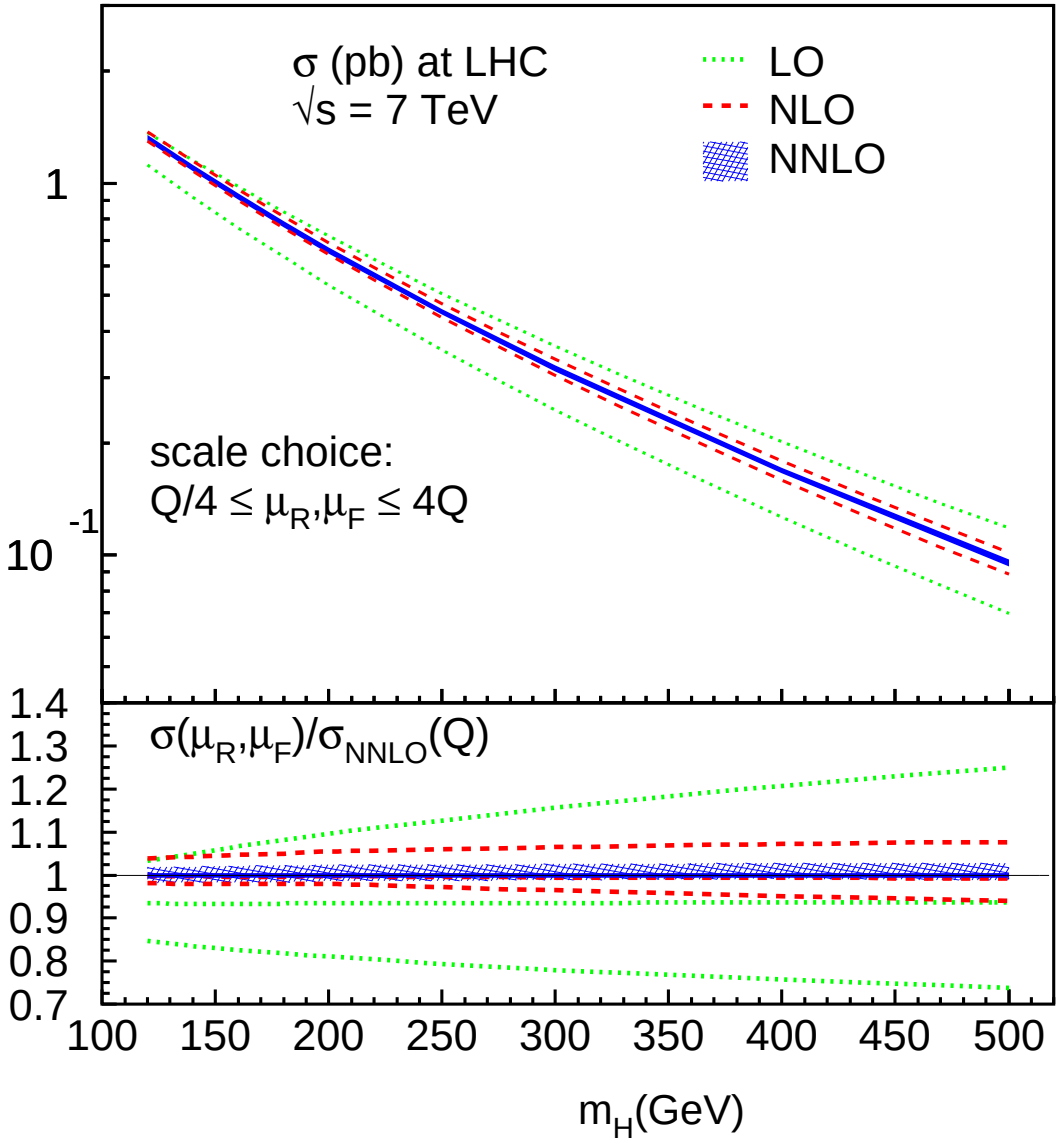
Bolzoni, Maltoni, Moch, Zaro (2010,2011):

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



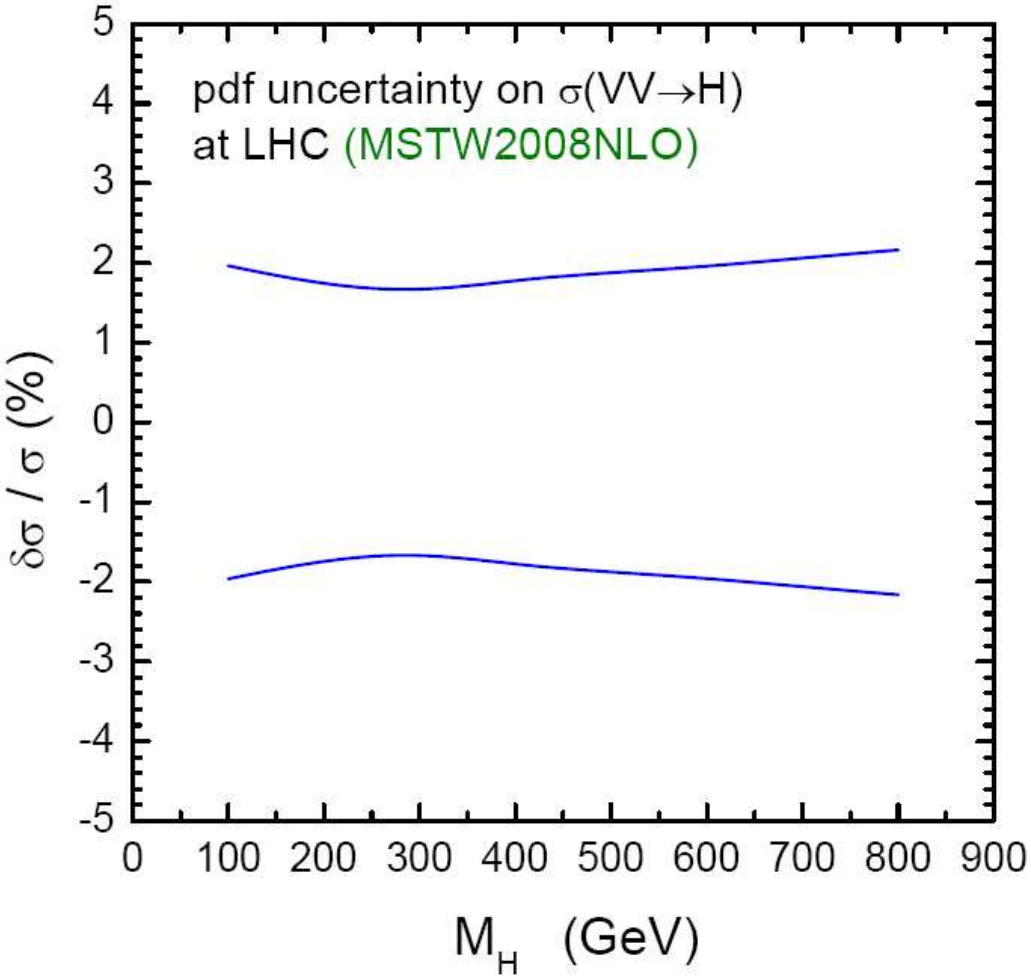
$$\sigma \sim \int dPS \, \frac{1}{2s} \frac{1}{\left(Q_1^2 + M_{V_1}^2\right)^2} \frac{1}{\left(Q_2^2 + M_{V_2}^2\right)^2}$$
$$\times \; W_{\mu\nu}\left(x_1, Q_1^2\right) \mathcal{A}^{\mu\rho} \mathcal{A}^{*\nu\sigma} W_{\rho\sigma}\left(x_2, Q_2^2\right)$$

higher orders of QCD in VBF



- 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

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

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:

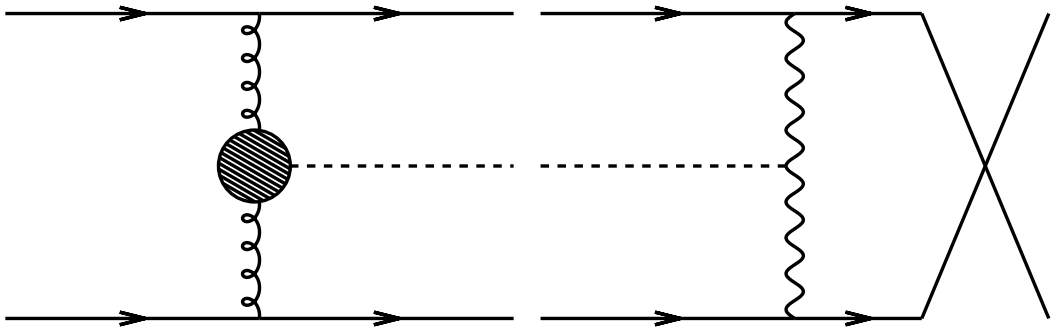
    Campanario, Kubocz, Zeppenfeld (2011)

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

  Campbell, Ellis, Zanderighi (2006)

$pp \to Hjj$ via VBF×GF at tree level

can VBF×GF interference pollute the clean VBF signature?



Georg (2005) & Andersen, Smillie (2006):
tree-level interference possible only for

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

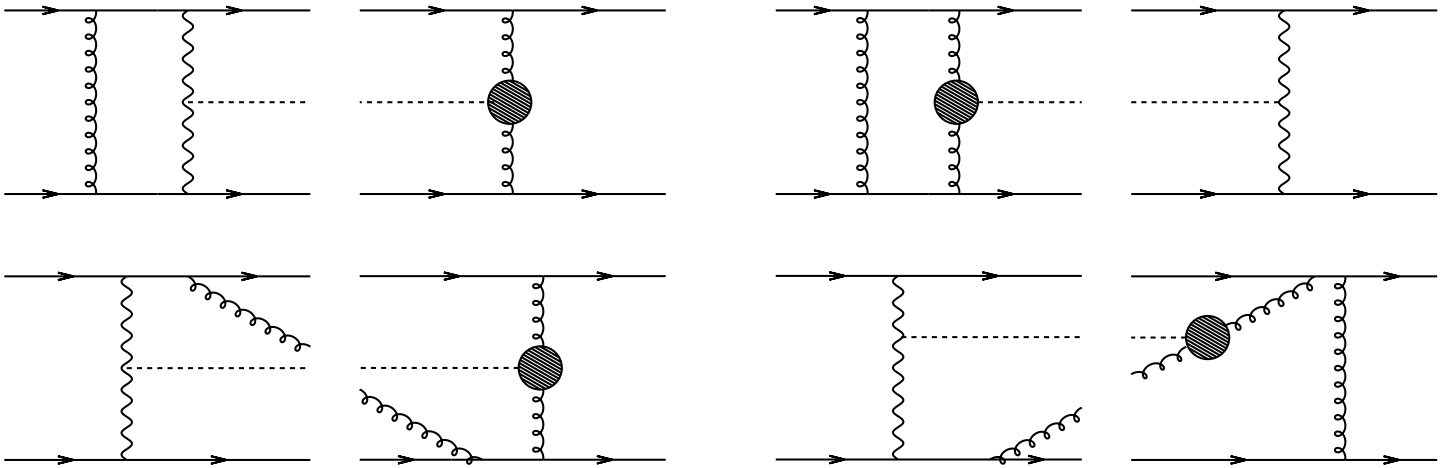
☞ completely negligible

$pp \to Hjj$ via VBF×GF beyond tree level

additional gluon → VBF×GF interference for $qq' \to qq'H$ ✔

Andersen et al. (2007)

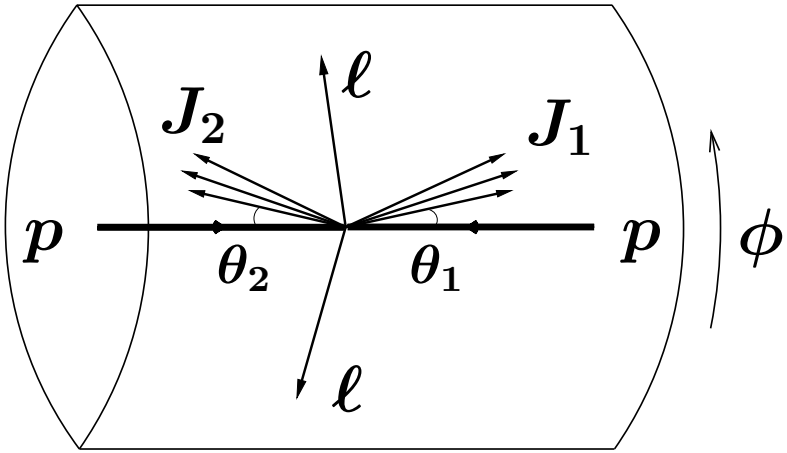
Bredenstein, Hagiwara, B. J. (2008)



strong cancelation effects between
contributions of different flavor

interaction cross section tiny → no effect on VBF signal

VBF event topology



distinct event topology

of the Higgs signal in

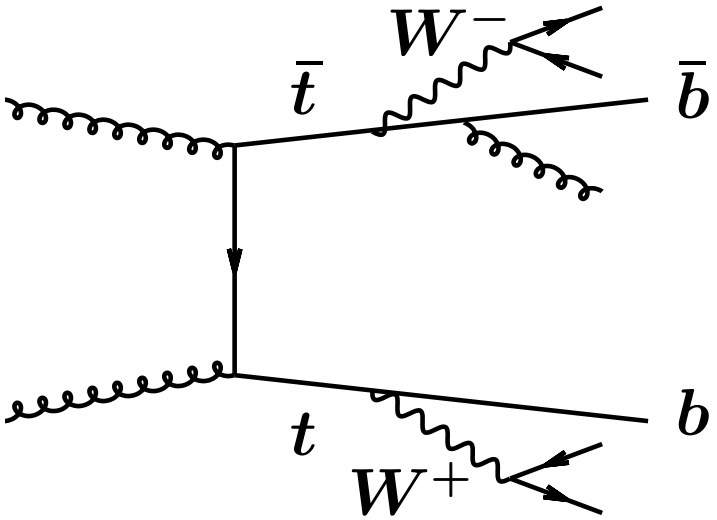
$pp \to Hjj$ via VBF with

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

☞ important for suppression of backgrounds

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

$t\bar{t}$ + jets backgrounds

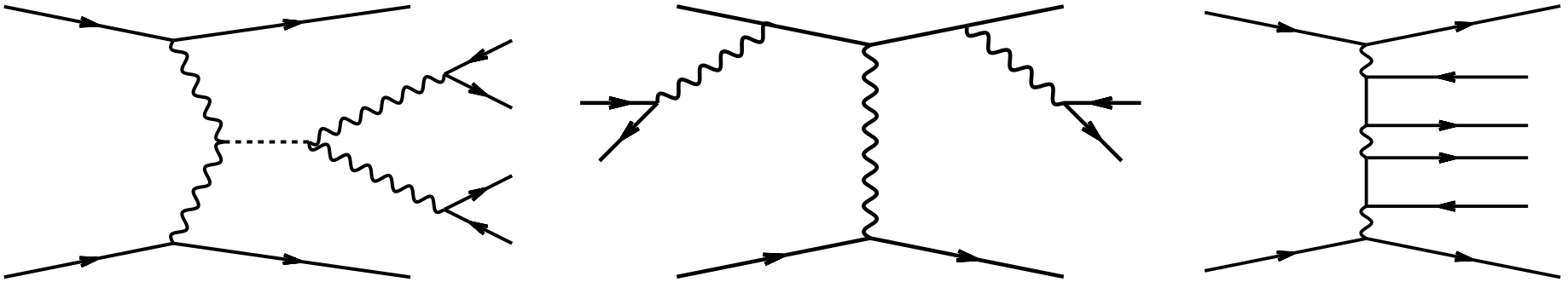


- large top production cross section at the LHC
- $t \to Wb$ branching ratio $\sim 100\%$
- b quarks may be identified as tagging jets
- exploit kinematic features for background suppression

NLO-QCD predictions available:

Denner et al.; Bevilaqua et al. (2011-2012)

EW $VVjj$ production



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

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

NLO-QCD predictions available

Oleari, Zeppenfeld, B.J. (2006)

angular distribution of charged leptons

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

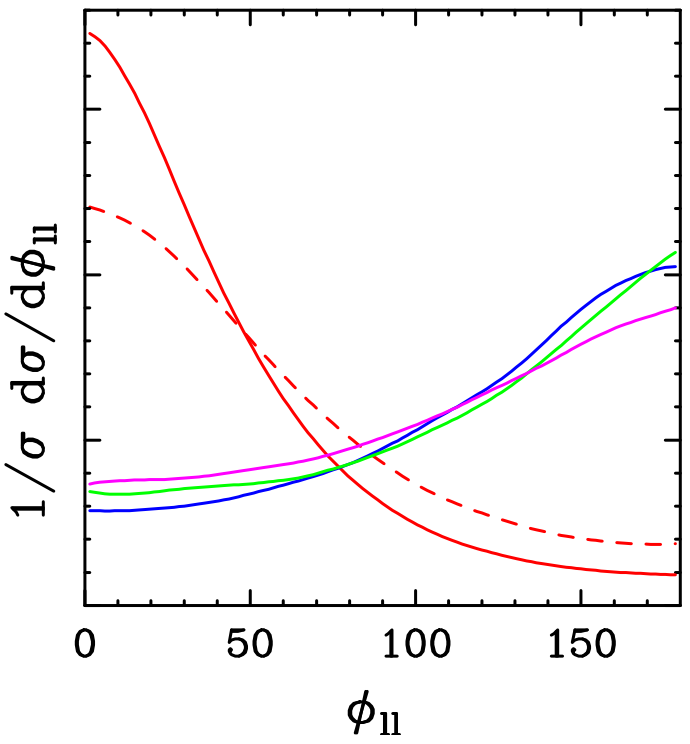
leptons emitted preferentially in same direction

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

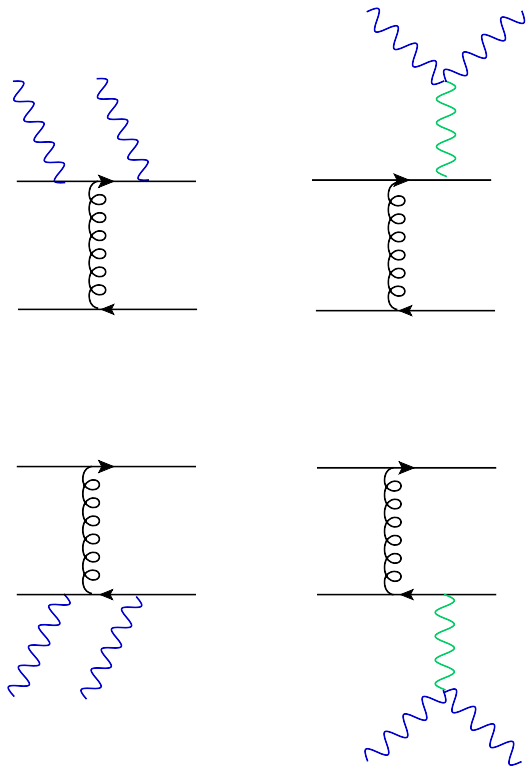
Dittmar, Dreiner (1996)

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

Rainwater, Zeppenfeld (1999)



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

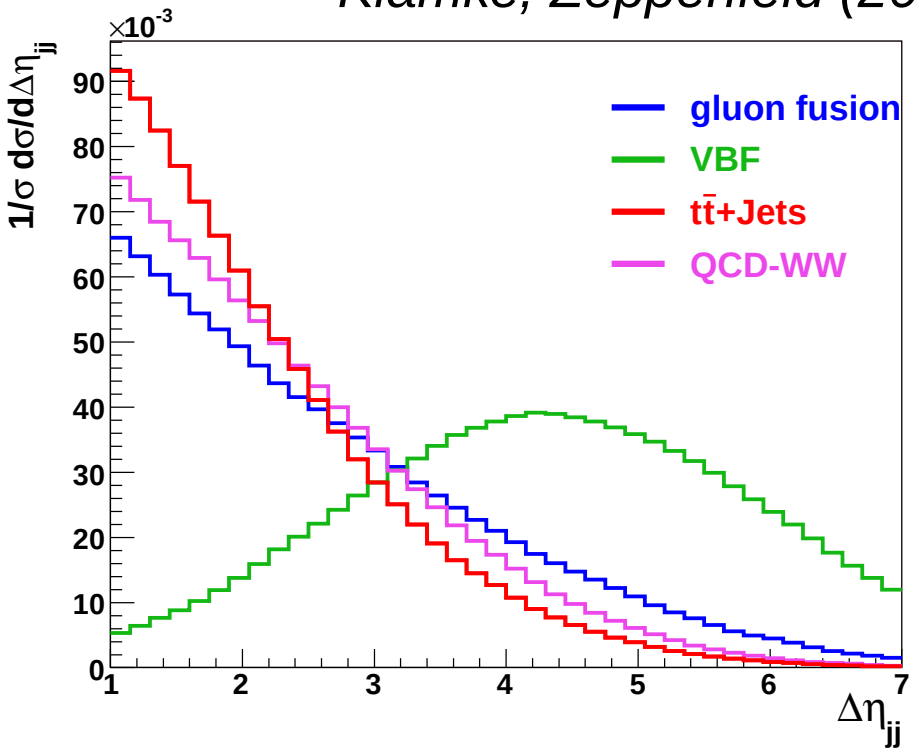
Melia, Melnikov, Rontsch, Zanderighi (2011);

Greiner et al. (2012)

tagging jets: properties

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

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

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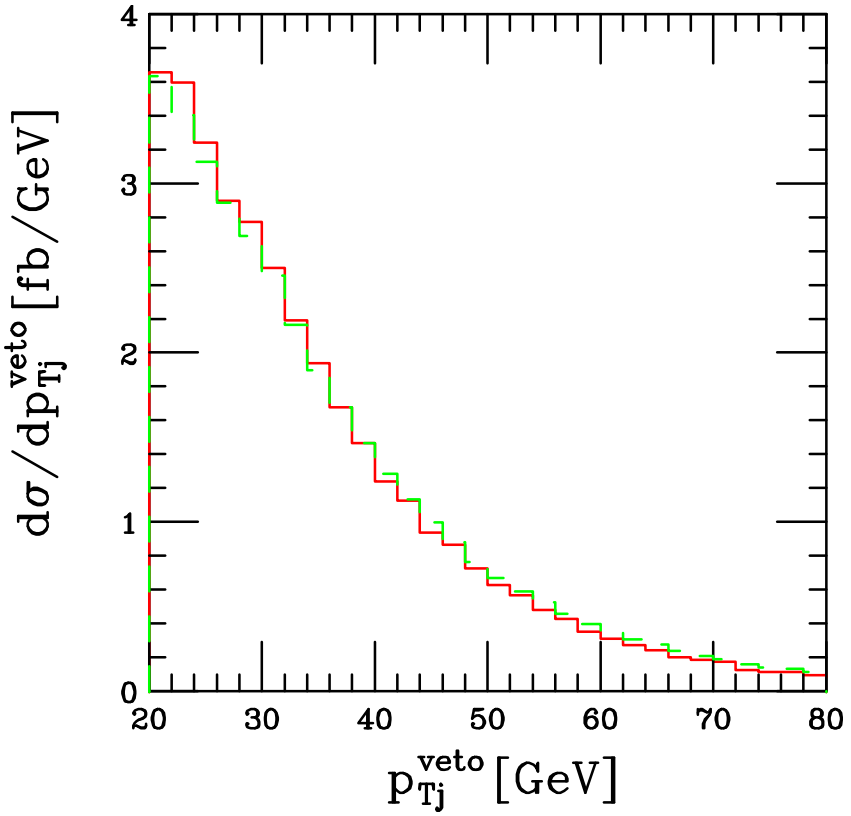
$$p_T^{\text{veto}} > 20 \text{ GeV}, \eta_{\text{jet}}^{\text{min}} < \eta_{\text{jet}}^{\text{veto}} < \eta_{\text{jet}}^{\text{max}}$$

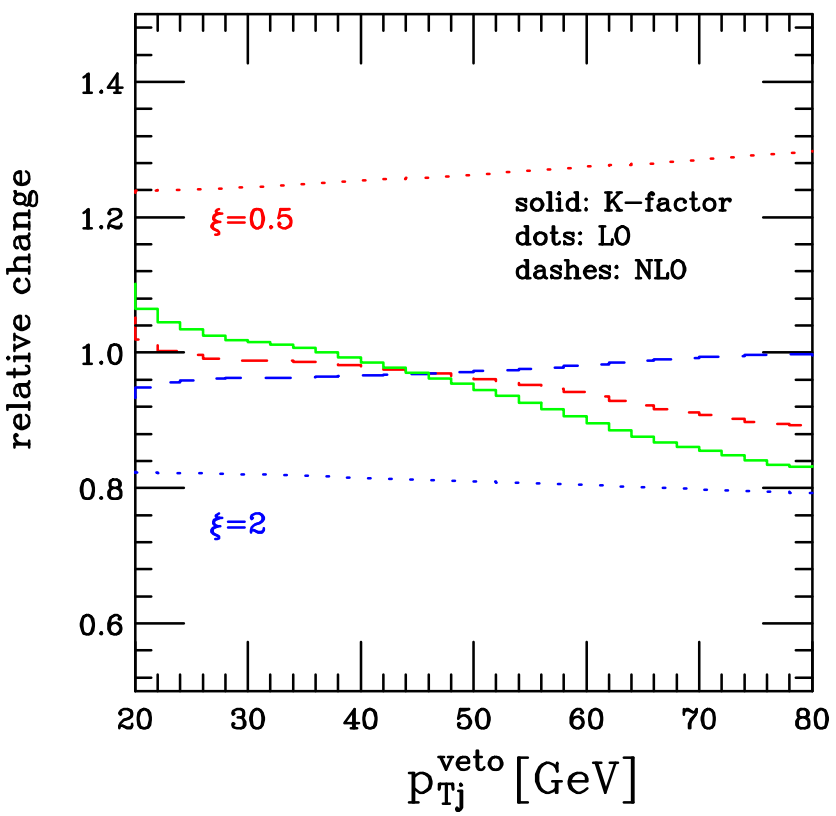
☞ precise knowledge of extra jet activity essential, requiring

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

$pp \to Hjjj$ via VBF

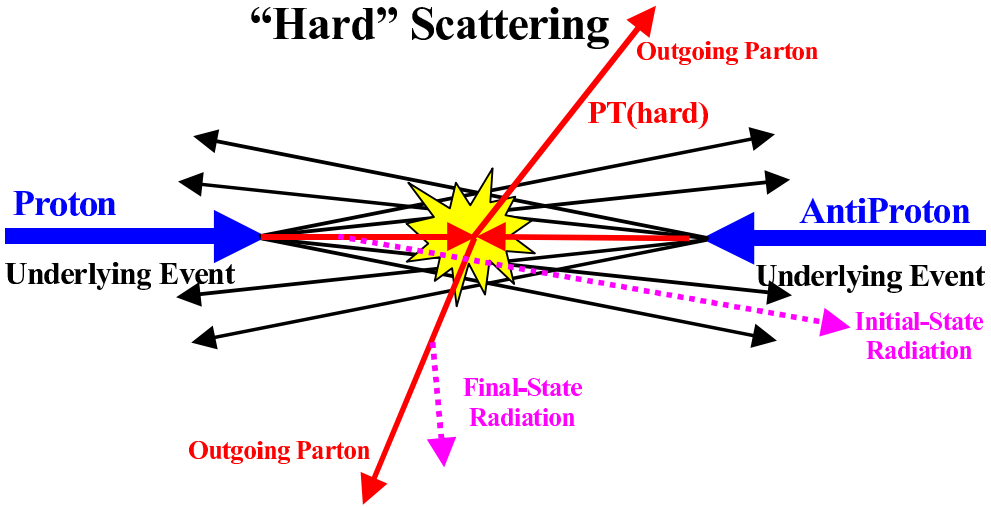
Figy, Hankele, Zeppenfeld (2007)





- 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

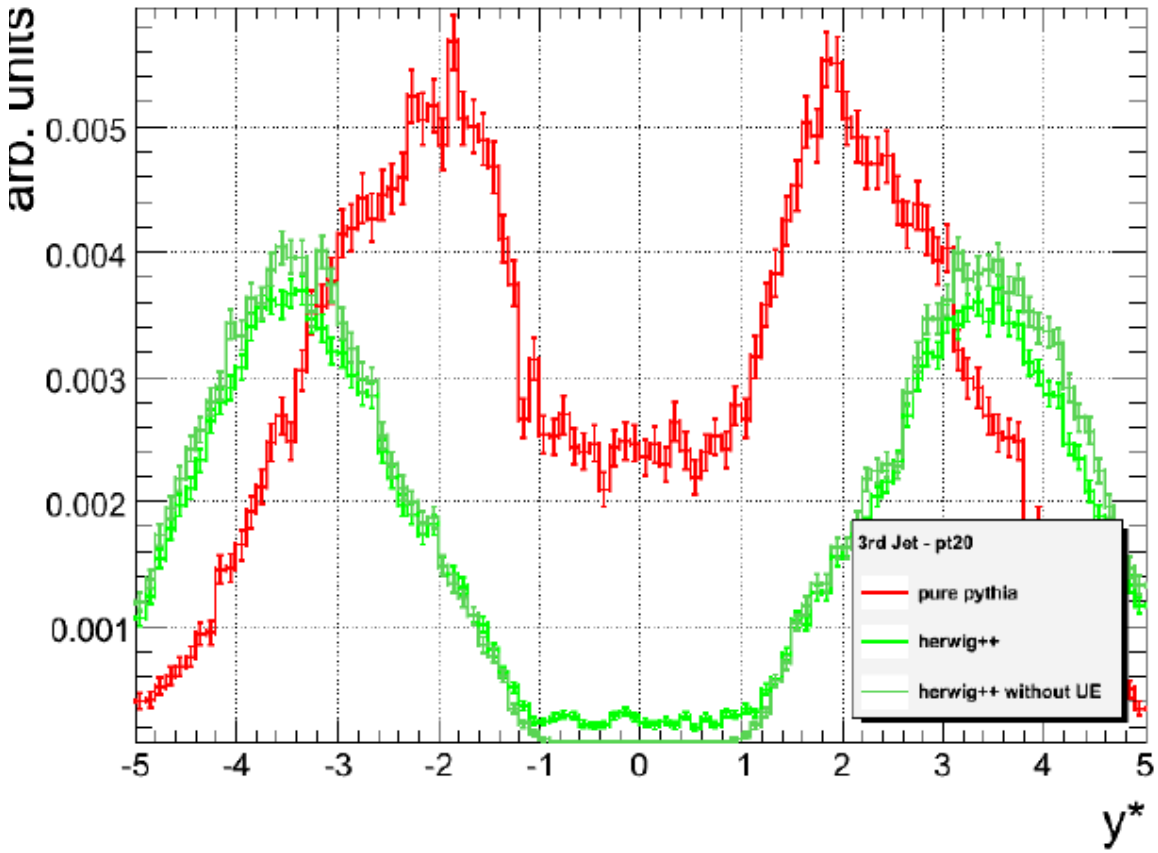
underlying event, parton shower, and hadronization

(Pythia, Herwig, Sherpa,...)

$pp \to Hjj$ via VBF & parton showers @ LO

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

Hackstein et al. (2008)



leading order:

no third jet from matrix element for hard partonic scattering

`Pythia`/ `Herwig`:

very different patterns in filling of rapidity gap by parton shower

☞ better understanding and modeling needed

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 SMC:

- ✘ bad description at high p_T
- ✘ normalization accurate only at LO
- ✔ Sudakow suppression at low p_T
- ✔ events at hadron level

☞ merge the two approaches, keeping the advantages of both:

- MC@NLO *[Frixione, Webber]*
- POWHEG *[Nason et al.]*

parton showers & NLO-QCD: the POWHEG method

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

[Frixione, Nason, Oleari]

- applicable to any p_T-ordered parton shower program
- no double counting of real-emission contributions
- produces events with positive weights
- tools for “do-it-yourself” implementation publicly available (the POWHEG-BOX)

[Alioli, Nason, Oleari, Re]

parton showers & NLO-QCD: the POWHEG-BOX

✘ user has to supply process-specific quantities:

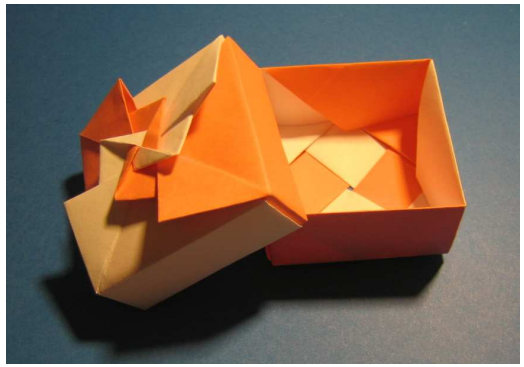
- lists of flavor structures for Born and real emission processes
- Born phase space
- Born amplitudes squared, color-and spin-correlated amplitudes
- real-emission amplitudes squared
- finite part of the virtual corrections
- Born color structure in the limit of a large number of colors

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

parton showers & NLO-QCD: the POWHEG-BOX

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

`http://powhegbox.mib.infn.it/`



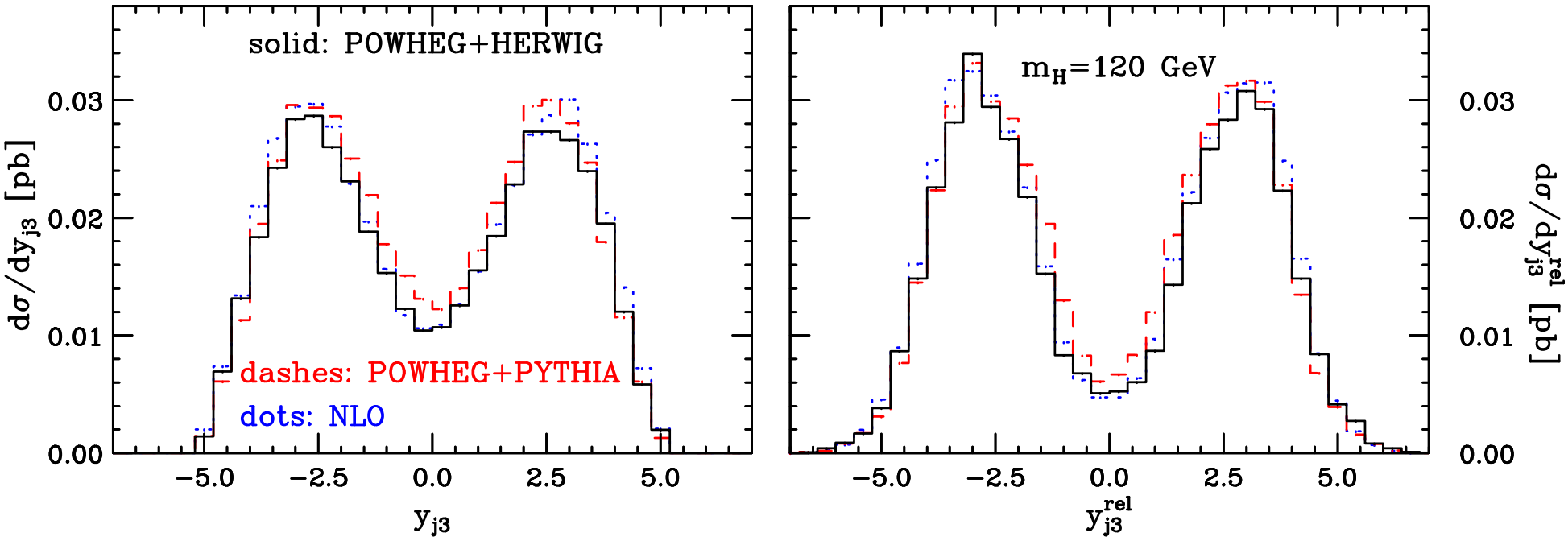
VBF processes in the POWHEG-BOX:

- Higgs production via VBF *[Oleari, Nason (2009)]*
- Z-boson production via VBF *[Schneider, Zanderighi, B.J. (2012)]*
- W^+W^+ production via VBF *[Zanderighi, B.J. (2011)]*

. . . and various background processes

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

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

Higgs signal in VBF

$pp \to Hjj$ via VBF under excellent control:

- QCD & EW NLO corrections at 10% level
- dominant NNLO QCD corrections small
- interference with GF Hjj production negligible
- SUSY corrections small within the MSSM
- small PDF uncertainties $\lesssim 4\%$
- NLO-QCD matched with parton shower available



what else is VBF good for?



the versatility of VBF processes

vector boson fusion (VBF)

Standard Model:

important production mode for the Higgs boson

sensitive to Higgs couplings and CP properties

beyond the Standard Model:

sensitive to the mechanism of electroweak symmetry breaking

↕

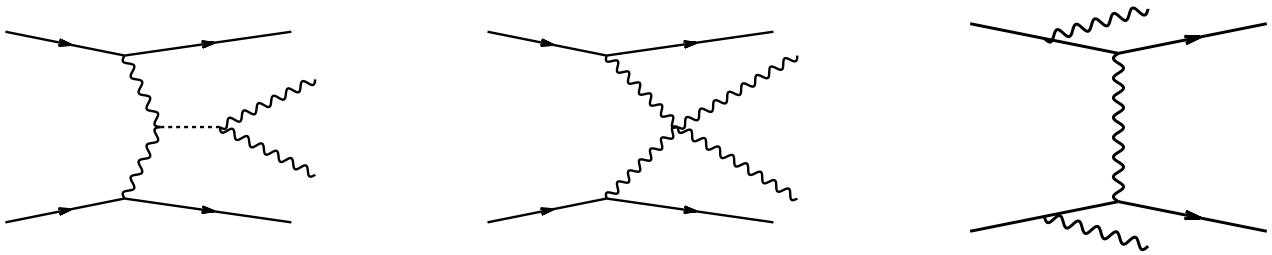
strongly interacting weak sector, new resonances, . . . ?

gauge boson scattering

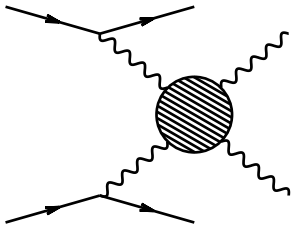
reminder: $pp \to Hjj$ via VBF with $H \to VV$
important production mode for SM-type Higgs boson

(used in official ATLAS and CMS analyses)

important irreducible background: EW $VVjj$ production



interesting *per se*: contains $V_L V_L \to V_L V_L$ scattering
sensitive to origin of electroweak symmetry breaking



EW $VVjj$ production

need stable, fast & flexible Monte Carlo program allowing for

- computation of various jet observables for

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

production via VBF at NLO-QCD accuracy

(leptonic decay correlations being fully taken into account)

- straightforward implementation of cuts

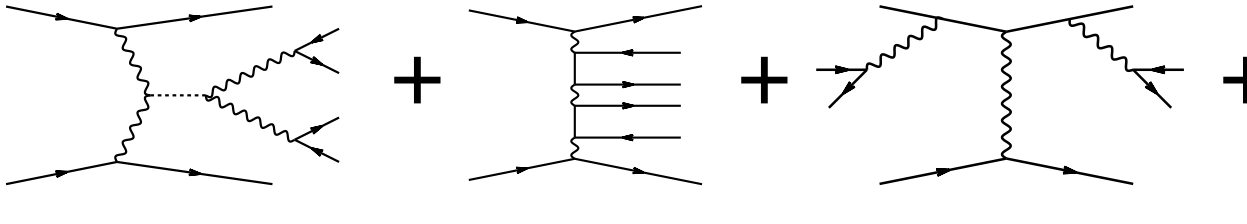
C. Oleari, D. Zeppenfeld, B. J. (2006, 2009)

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

ingredients of the calculation

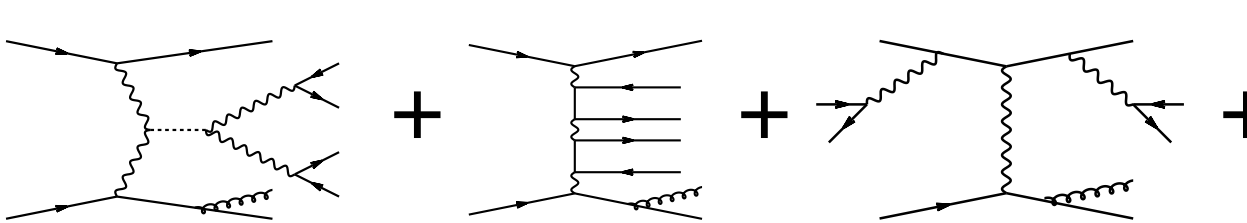
need to compute numerical value for . . .

$$|\mathcal{M}_B|^2 = \left| \quad + \quad + \quad + \ldots \right|^2$$



. . . Born amplitude squared in 4 dim

$$|\mathcal{M}_R|^2 = \left| \quad + \quad + \quad + \ldots \right|^2$$

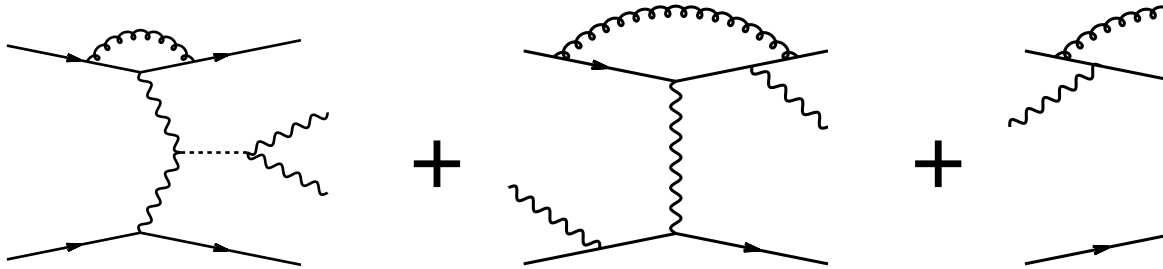


. . . real-emission amplitude squared in 4 dim and
counter-terms for infrared-divergent configurations

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

virtual contributions

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



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

determined numerically

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

combination of real emission, virtuals,
and subtraction terms:
poles canceled analytically → finite results

phase-space integration can be performed numerically (Vegas)

precision tools

Monte Carlo program for cross sections and distributions
which allows for the implementation of
realistic experimental selection cuts

☞ embedded in more general framework
for various VBF-type processes
vbfnlo

publicly available from

`http://www-itp.physik.uni-karlsruhe.de/~vbfnloweb/`

$pp \to VVjj$ @ LHC: settings

use design energy of 14 TeV, apply k_T jet algorithm,

CTEQ6 parton distributions, and typical VBF cuts:

tagging jets

$$p_{Tj} \geq 20 \text{ GeV}, \quad |y_j| \leq 4.5,$$

$$\Delta y_{jj} = |y_{j_1} - y_{j_2}| > 4,$$

$$M_{jj} > 600 \text{ GeV}$$

jets located in opposite hemispheres

$$p_{T\ell} \geq 20 \text{ GeV}, \quad |\eta_\ell| \leq 2.5,$$

$$\Delta R_{j\ell} \geq 0.4,$$

$$y_{j,min} < \eta_\ell < y_{j,max}$$

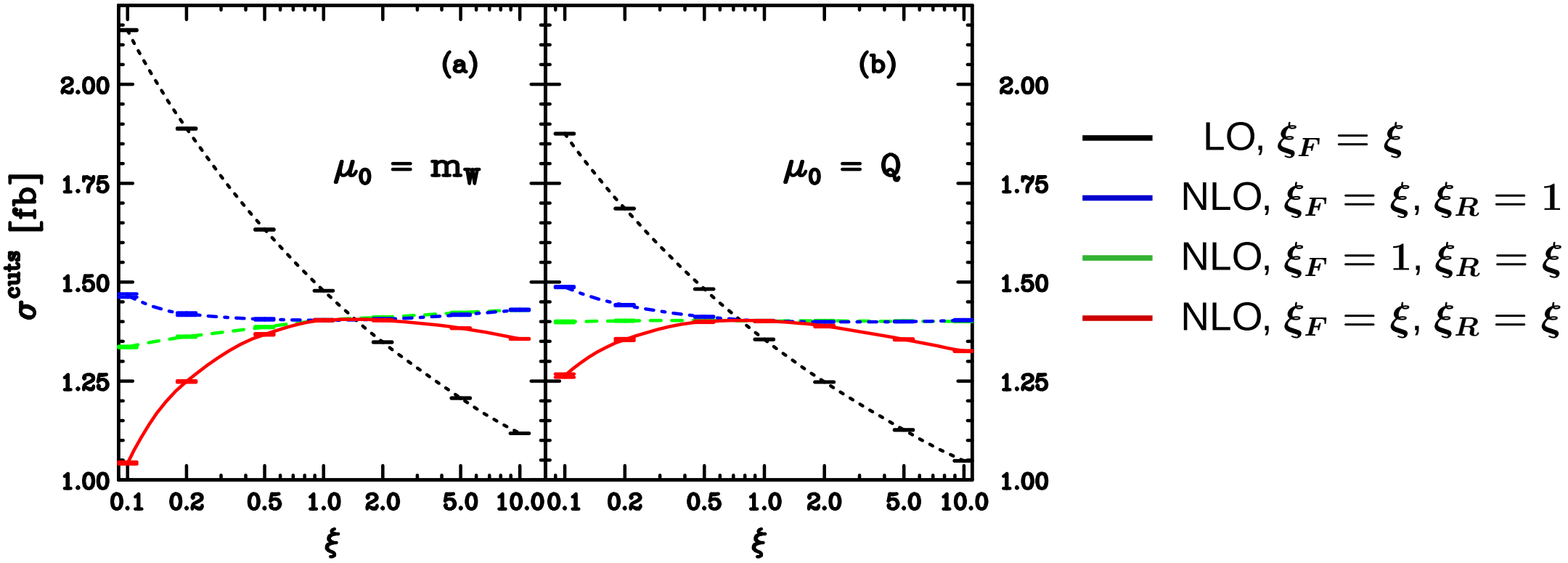
charged leptons

scale uncertainty: $pp \to W^+W^+jj$

choose default scale $\mu_0 = m_W$ or $\mu_0 = Q$

set $\mu_R = \xi_R \mu_0$ and $\mu_F = \xi_F \mu_0$, with variable ξ

Oleari, Zeppenfeld, B. J. (2009)

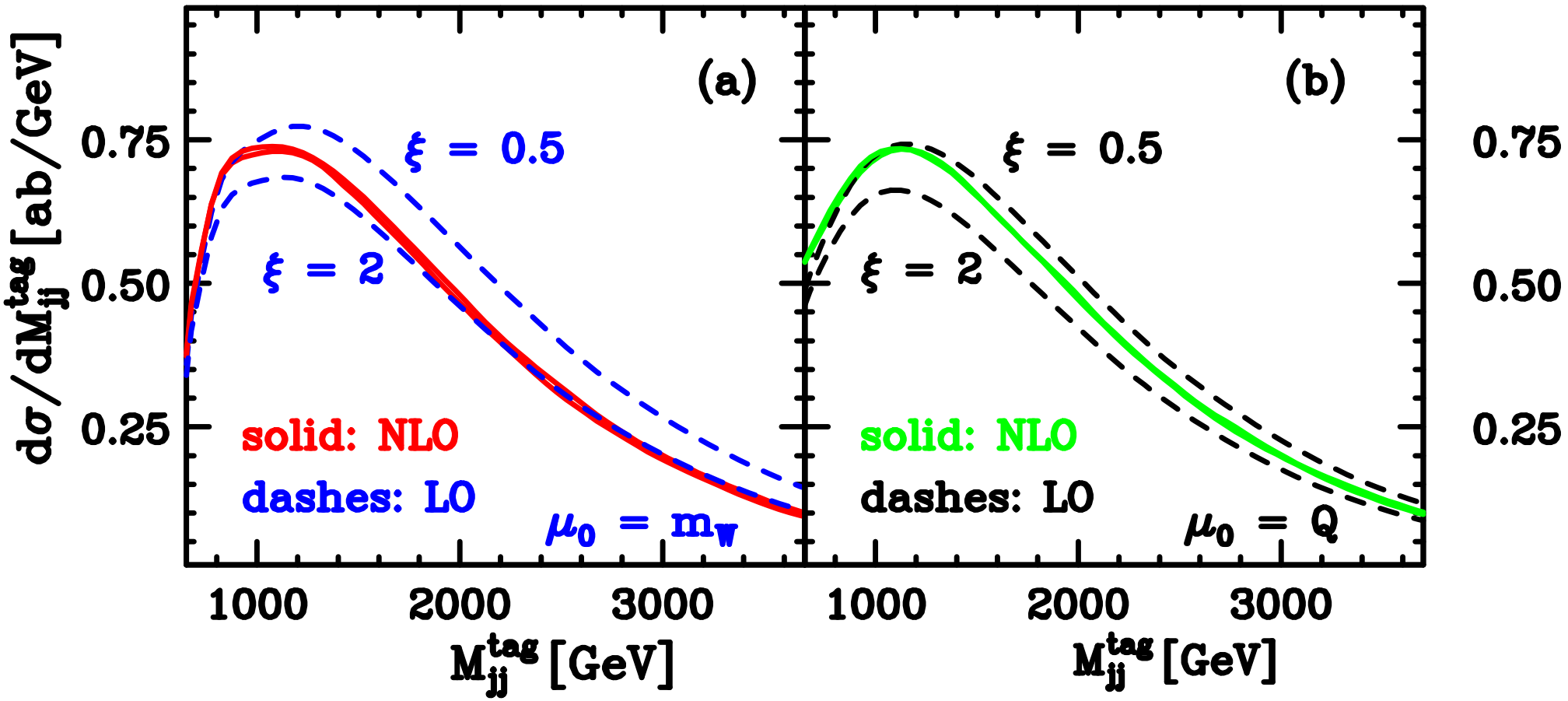


LO: no control on scale

NLO QCD: scale dependence strongly reduced

W^+W^+jj distributions: invariant mass of tagging jets

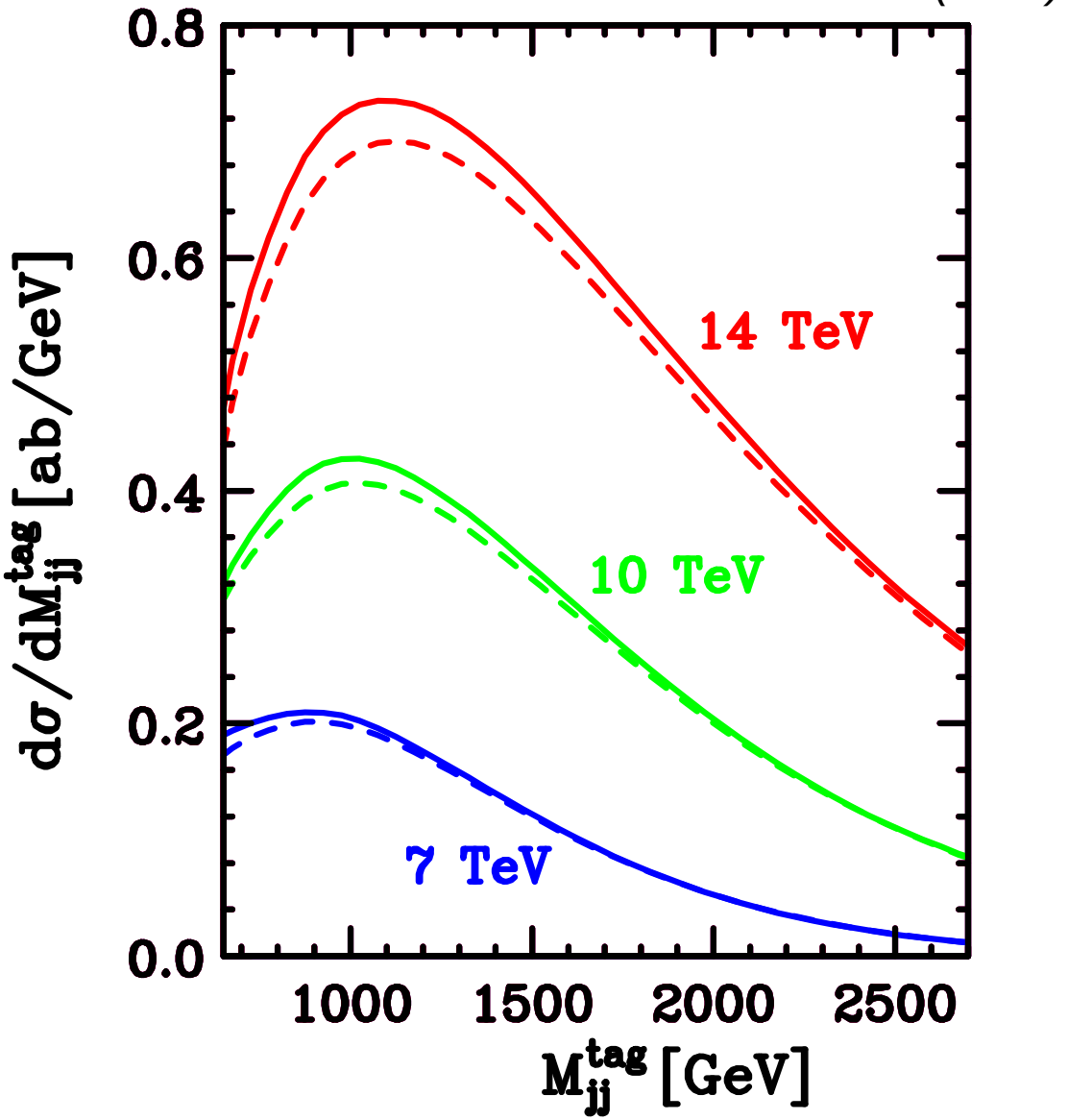
Oleari, Zeppenfeld, B. J. (2009)



$$\mu = \xi\,\mu_0$$

$pp \to W^+W^+jj$: energy dependence

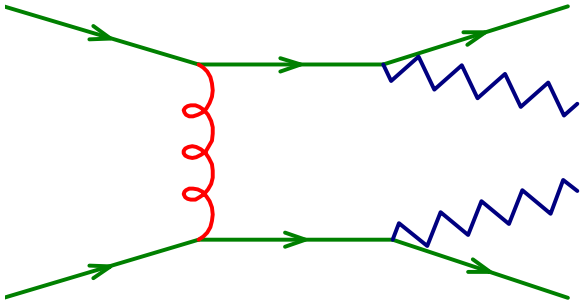
B. J. (2009)



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

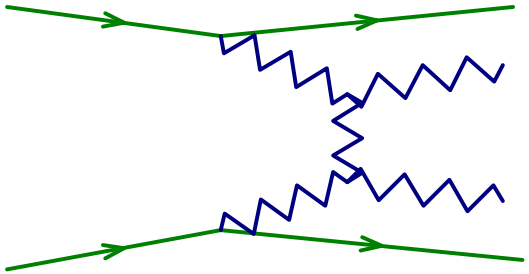
QCD-induced production

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



EW production

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

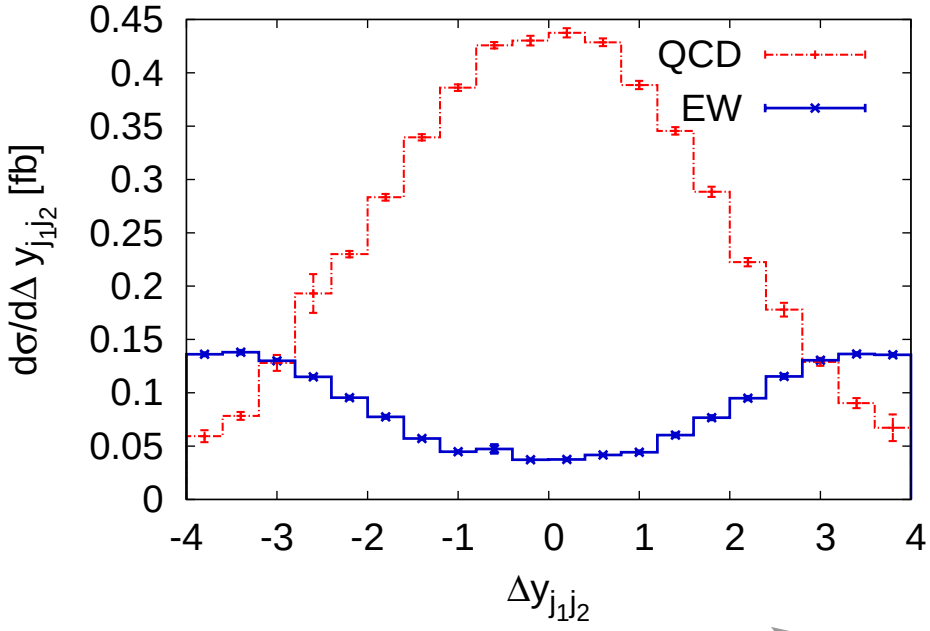


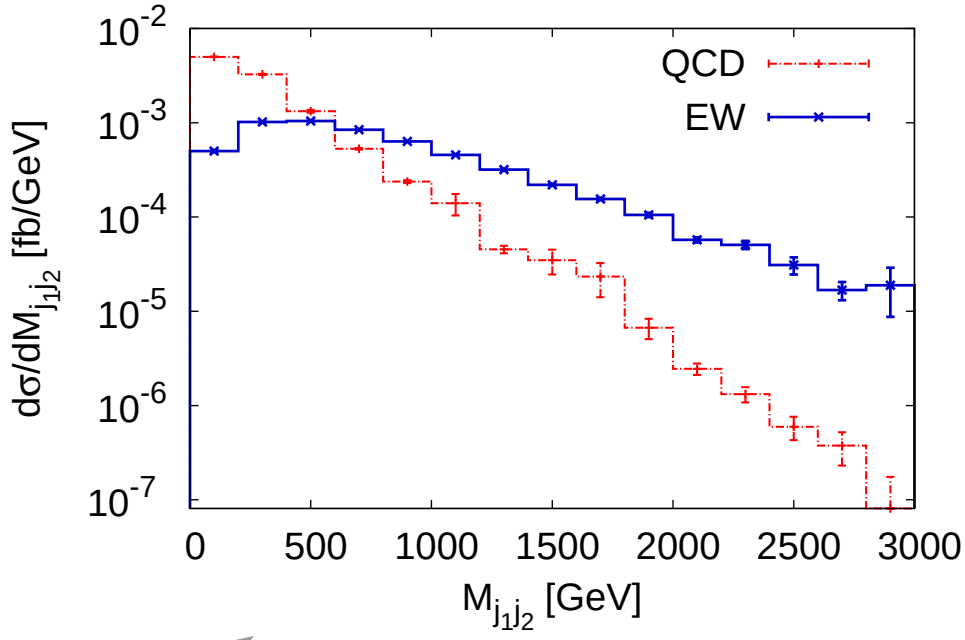
NLO-QCD results with basic jet cuts only ($p_T^{\text{tag}} > 20$ GeV):

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

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

Zanderighi, B.J. (2011)



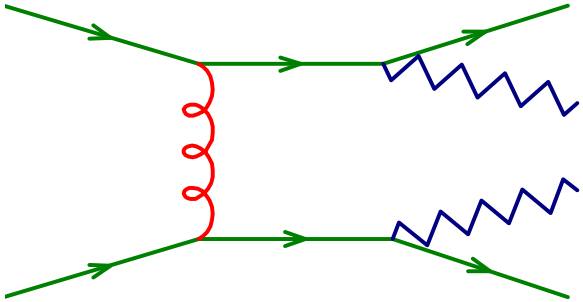


- $\sqrt{s} = 7$ TeV
- basic jet cuts only
- NLO-QCD accuracy

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

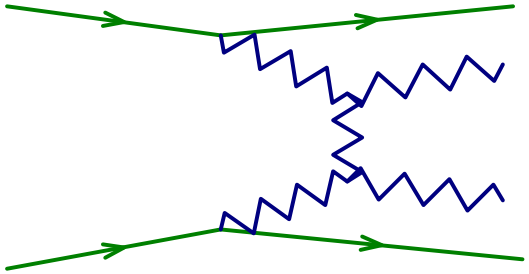
QCD-induced production

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



EW production

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



NLO results with basic jet cuts only ($p_T^{\rm tag} > 20$ GeV):

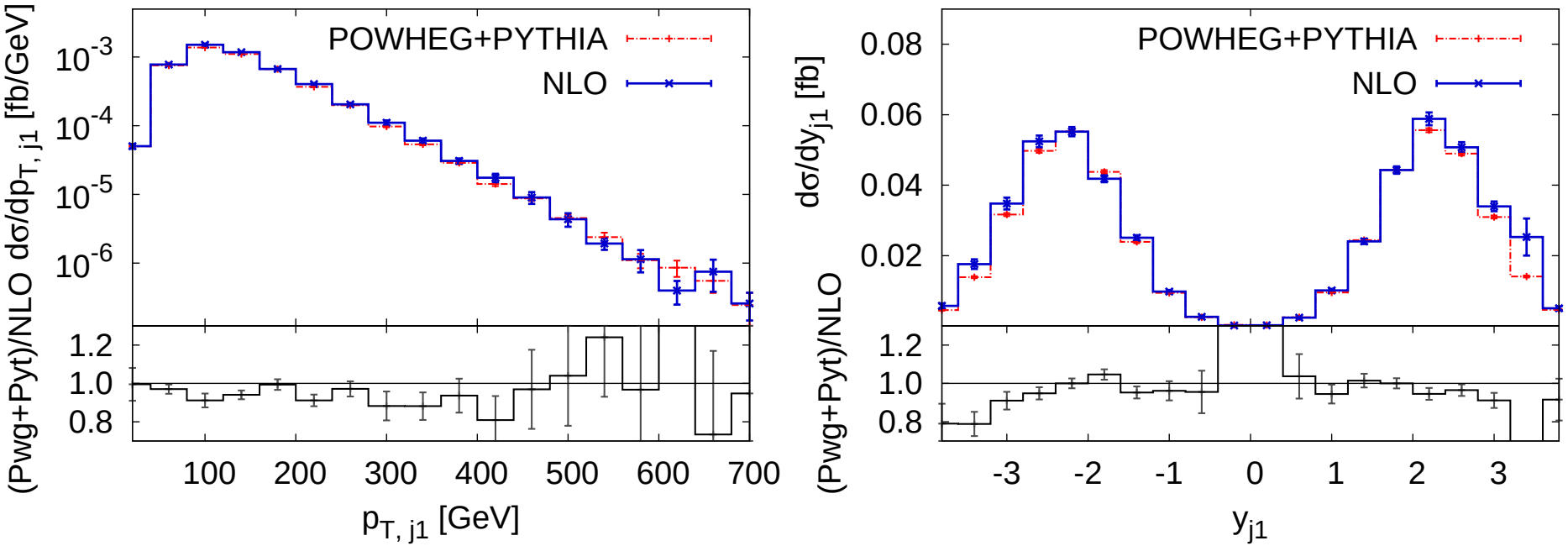
$$\sigma^{\rm inc}_{\rm QCD} = 2.12 \text{ fb} \qquad \sigma^{\rm inc}_{\rm EW} = 1.097 \text{ fb}$$

NLO results with VBF cuts:

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

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

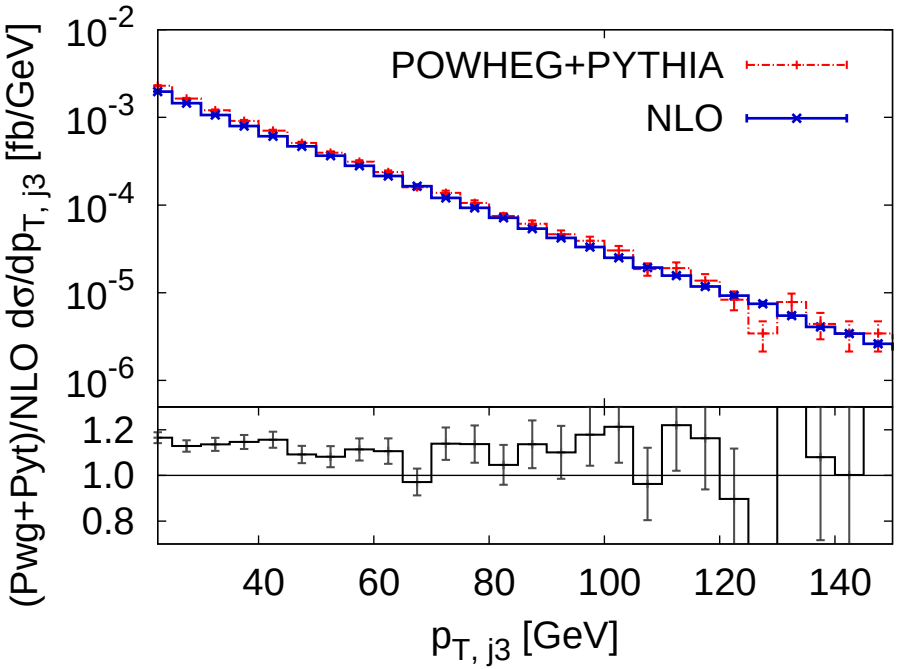
Zanderighi, B.J. (2011)

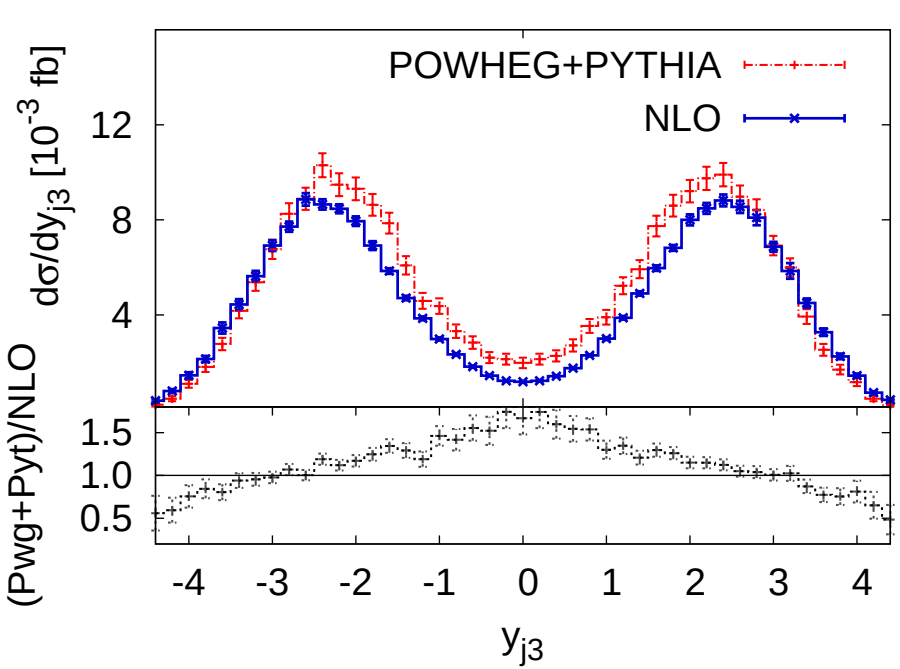


good agreement between parton-level NLO calculation and POWHEG matched with PYTHIA for many observables

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

Zanderighi, B.J. (2011)





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

note: parton-shower effects slightly enchance central jet activity

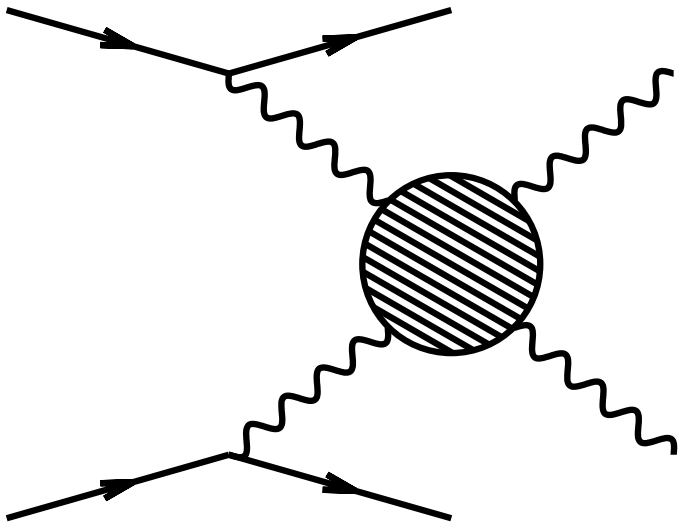
parton showers and NLO-QCD

- for precise and realistic predictions NLO-QCD calculations matched to parton shower programs are important

- codes for several VBF processes are publicly available in the POWHEG-BOX from

`http://powhegbox.mib.infn.it/`

new interactions in the gauge boson sector



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



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

framework: signal

consider two “prototype” scenarios for the VBF signal:

- SM with heavy Higgs boson ($M_H = 1$ TeV, $\Gamma_H = 0.5$ TeV)

  naive estimate of strongly coupled sector with scalar, iso-scalar resonance at the TeV scale

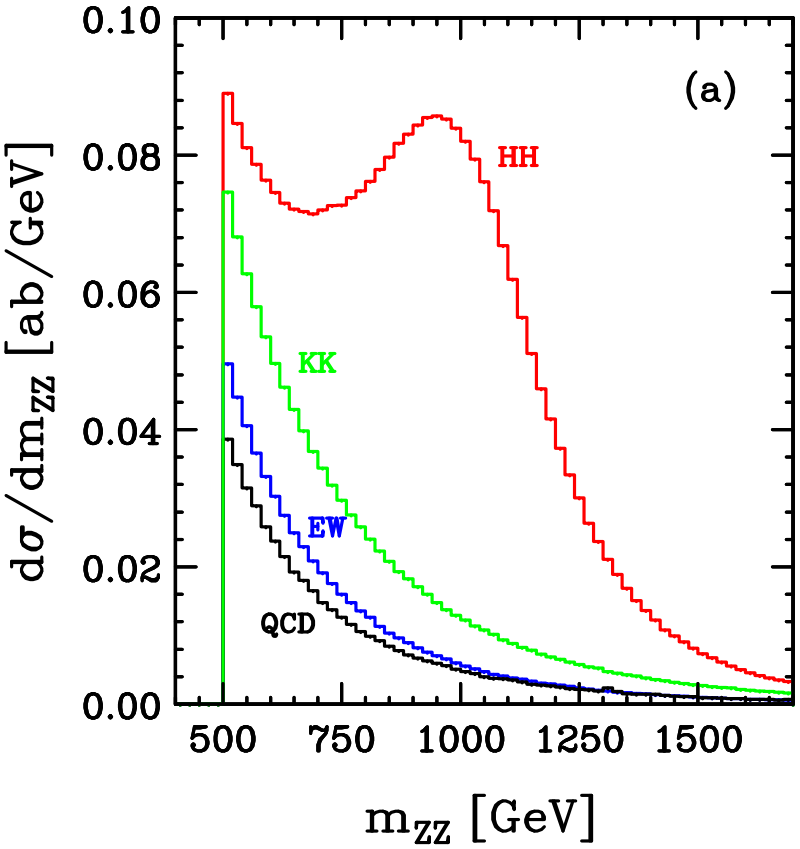
- Warped Higgsless model with

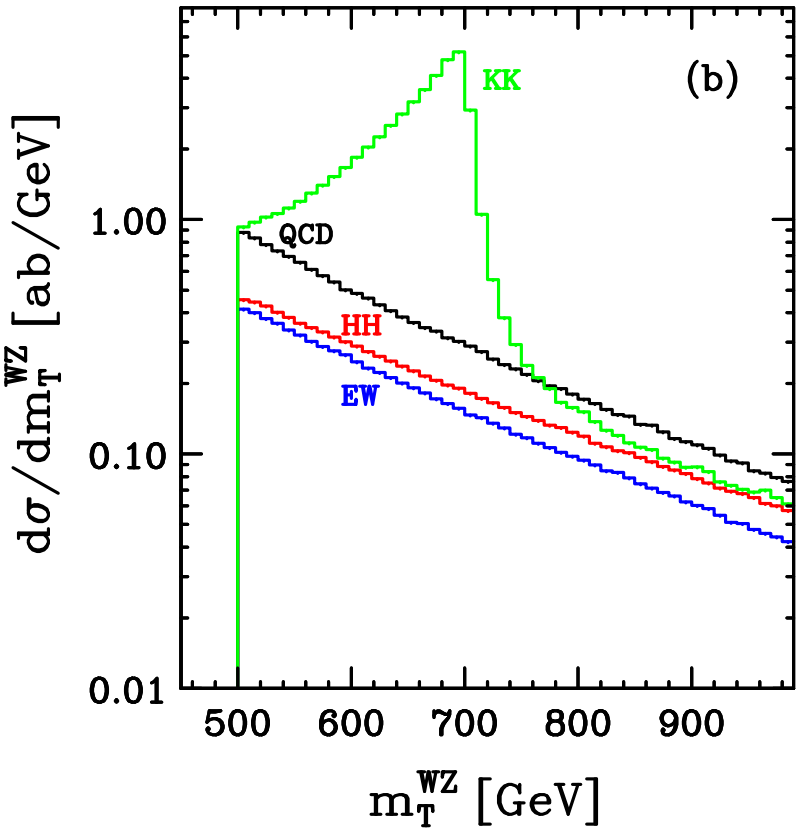
  extra vector resonances (“Kaluza-Klein excitations”)

$$
\begin{aligned}
(\, m_{W_2} &= 700 \text{ GeV}, \ \Gamma = 13.7 \text{ GeV}, \\
m_{Z_2} &= 695 \text{ GeV}, \ \Gamma = 18.7 \text{ GeV}, \\
m_{Z_3} &= 718 \text{ GeV}, \ \Gamma = 6.4 \text{ GeV} \,)
\end{aligned}
$$

LO results: scalar / vector resonances

Englert, Worek, Zeppenfeld, B.J. (2008)

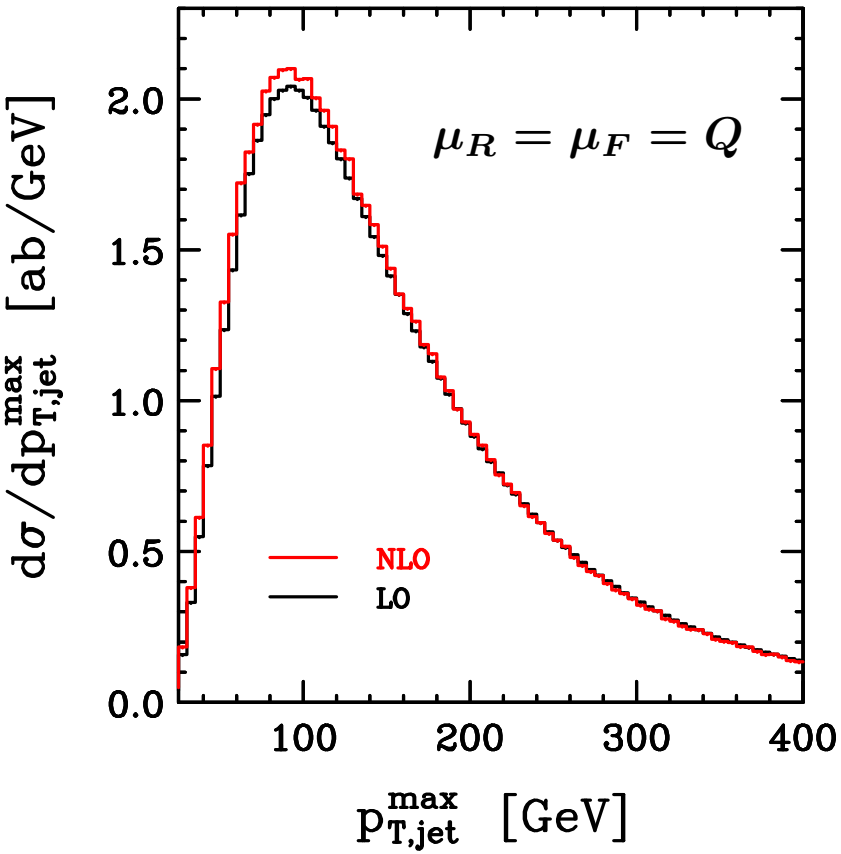




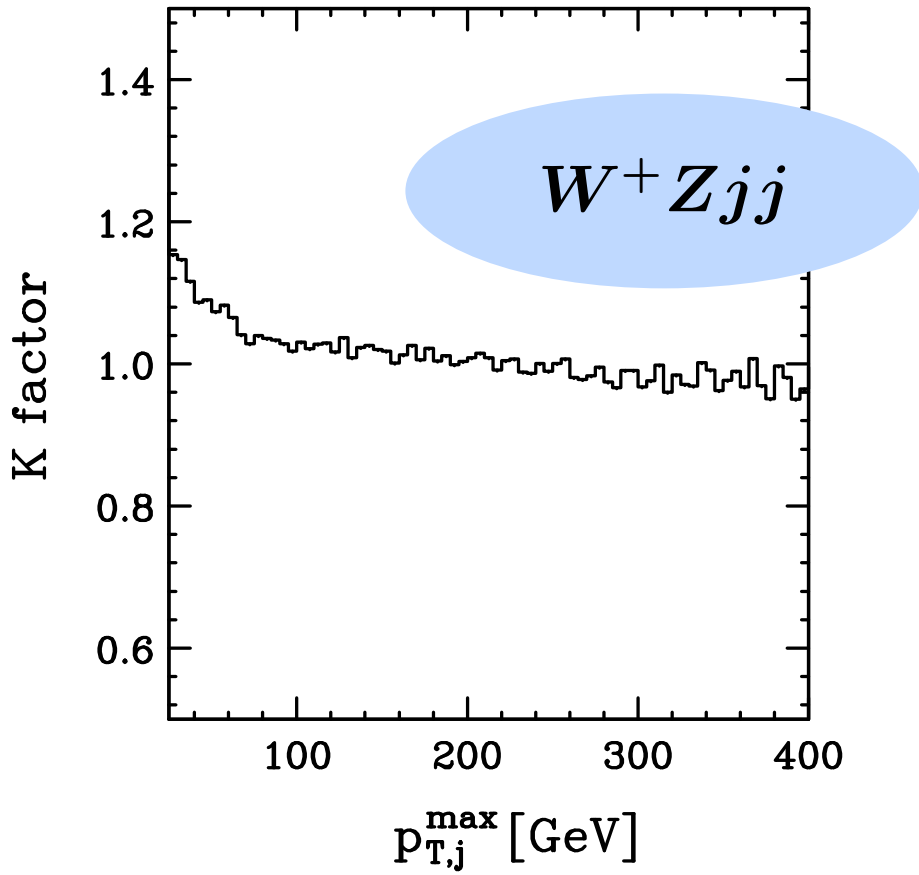
$ZZjj \to 4\ell jj$

W^+Zjj

impact of NLO-QCD corrections



Englert, Zeppenfeld, B.J. (2008)



NLO-QCD corrections always in the few-percent range
for $VVjj$ production in Warped Higgsless model

summary

VBF crucial for understanding
mechanism of
electroweak symmetry breaking

important pre-requisites:

- explicit calculations revealed that VBF reactions are perturbatively well-behaved

  (moderate NLO QCD and EW corrections,
  negligible higher order and interference effects)

- backgrounds are well under control

conclusions

for understanding and interpreting physics
at the LHC (and beyond . . .) it is vital to provide:

- precise predictions for signals and backgrounds, including
  - NLO QCD corrections
  - NLO EW corrections
  - and more: interference effects, resummations, well-constrained PDFs, . . .

- realistic predictions, allowing for
  - calculation of distributions within experimental selection cuts
  - matching to parton-shower Monte Carlos

