Vector Boson Scattering:

A Phenomenological Perspective

HiggsTools Summer School

Valle d'Aosta – July 2015

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outline

vector boson scattering:

- theoretical concepts & techniques
- phenomenological results
- the quest for more realistic predictions

Higgs production via vector boson fusion:

- motivation: a super-clean environment
- precise predictions and unexpected features
- omipresent: backgrounds

VBS: outline of the NLO-QCD Calculation

- calculation of $d\hat{\sigma}$ at $\mathcal{O}(\alpha^6\alpha_s)$ (NLO QCD)
  - dimensional reduction $(d = 4 - 2\varepsilon)$
  - $\overline{\mathrm{MS}}$-renormalization
- handling of infrared singularities by dipole subtraction approach of *Catani & Seymour*
- need to compute
  - real emission contributions
  - counterterms
  - virtual corrections
- phase space integration and convolution with PDFs with Monte Carlo techniques in 4 dimensions

VBS results: summary

- ✔ obtained numerical results at NLO-QCD for various weak boson scattering processes

  (focusing on fully leptonic final states)

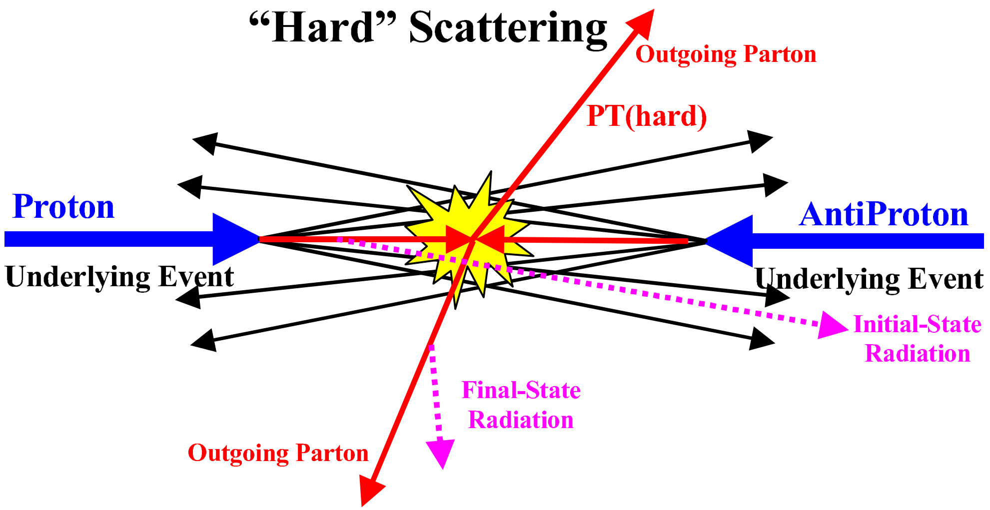
- ✔ all reactions under excellent control perturbatively

  (moderate K-factors and small scale dependencies at NLO)

- ✔ shape of some distributions changes noticeably at NLO

  (advantageous: dynamical scale choice)

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

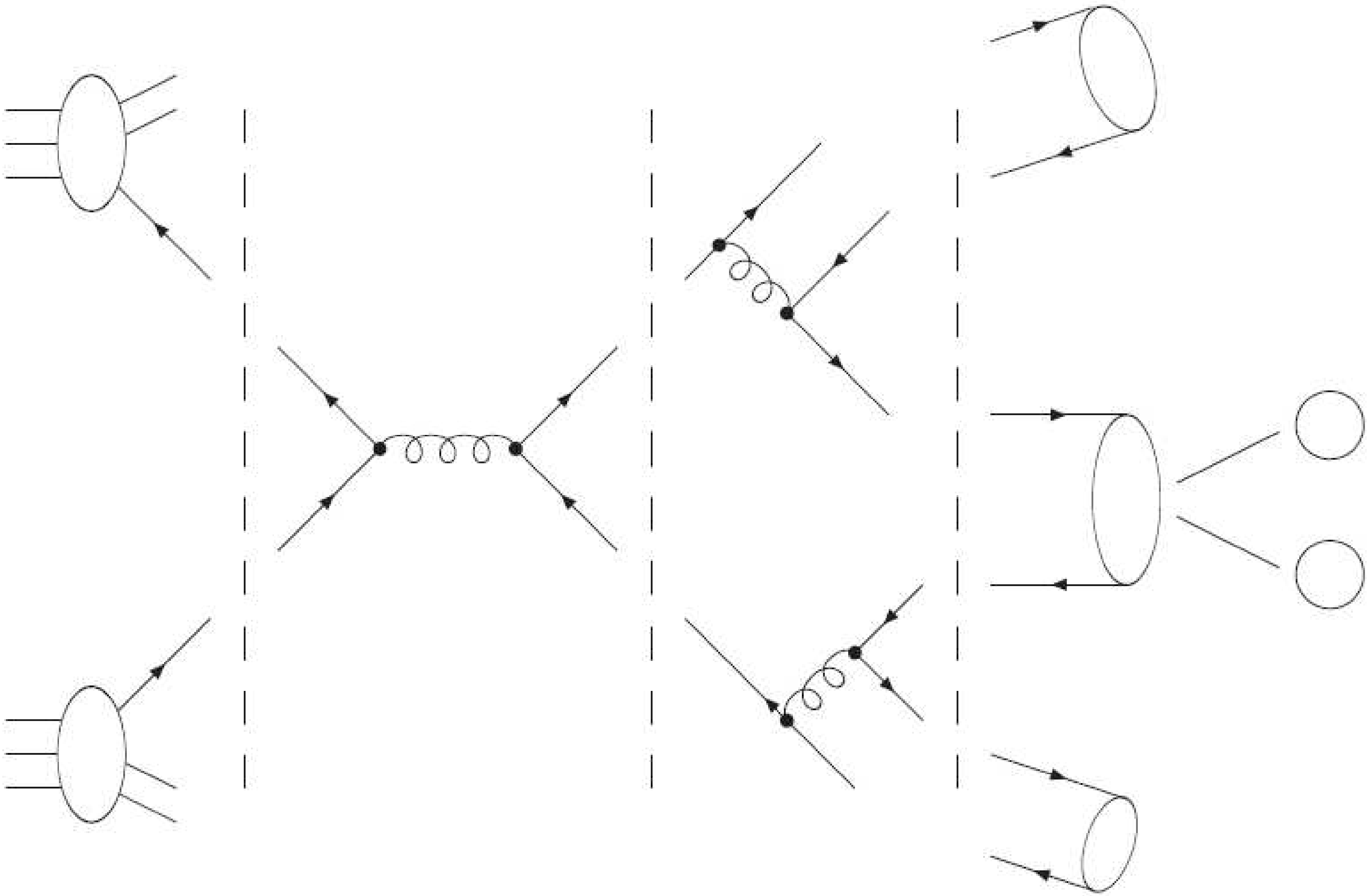
(PYTHIA, HERWIG, SHERPA,...)

details on event simulation

for details:

Frank Krauss' lecture

hadron-hadron collision

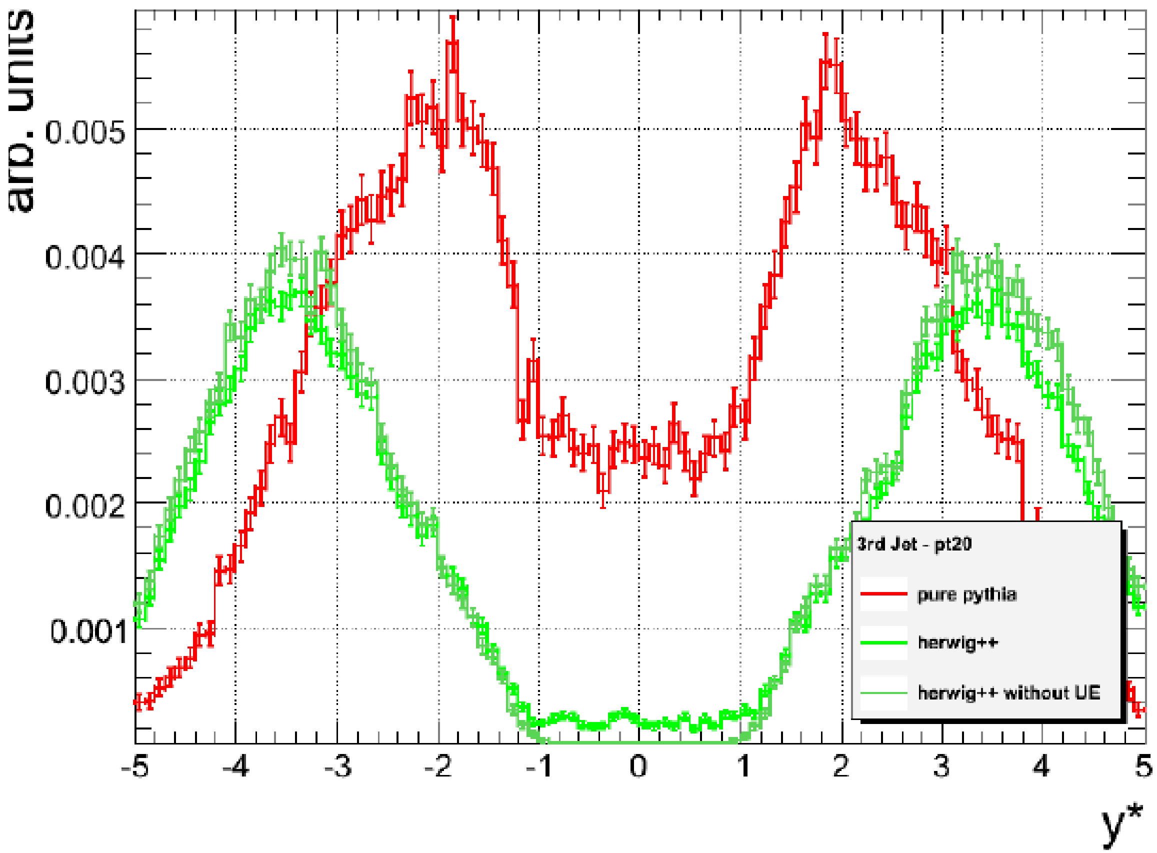


PDFs | hard partonic scattering | parton shower | hadronization and decay

$pp \to Hjj$ via VBF and parton showers

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

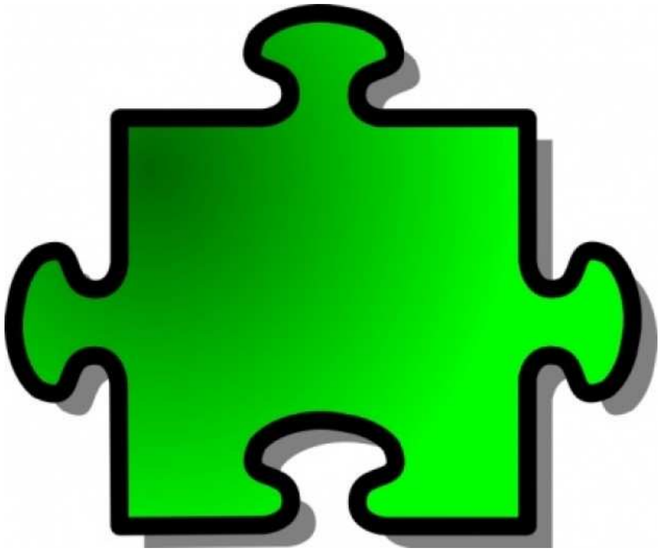
Hackstein et al. (2008)



Pythia: rapidity gap filled by parton shower

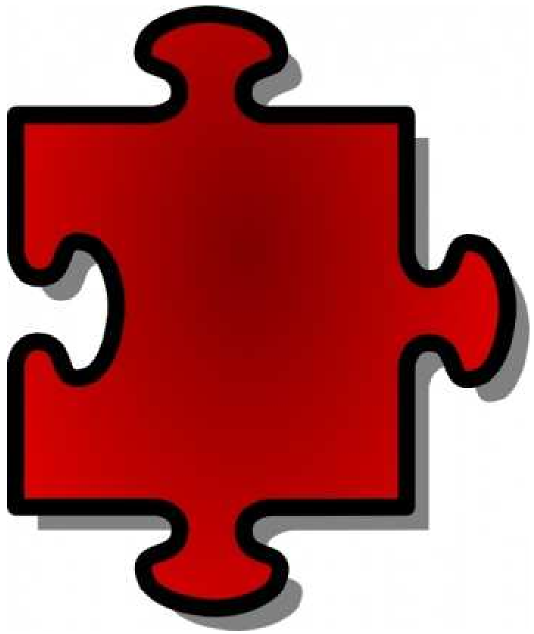
☞ better understanding and modeling needed

realistic & precise predictions

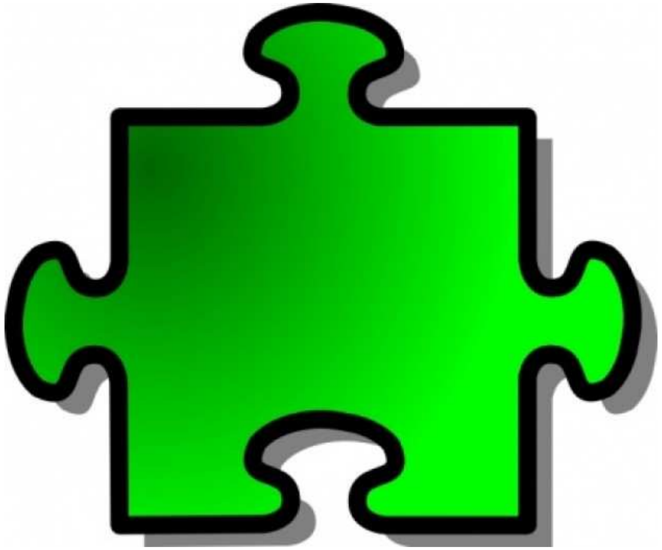


exploit merits of flexible
Monte Carlo tools

retain NLO accuracy
for hard scattering



realistic & precise predictions

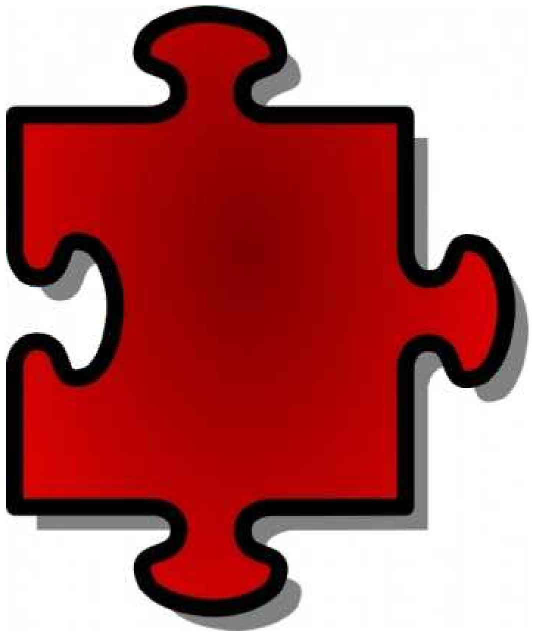


shower Monte Carlo:

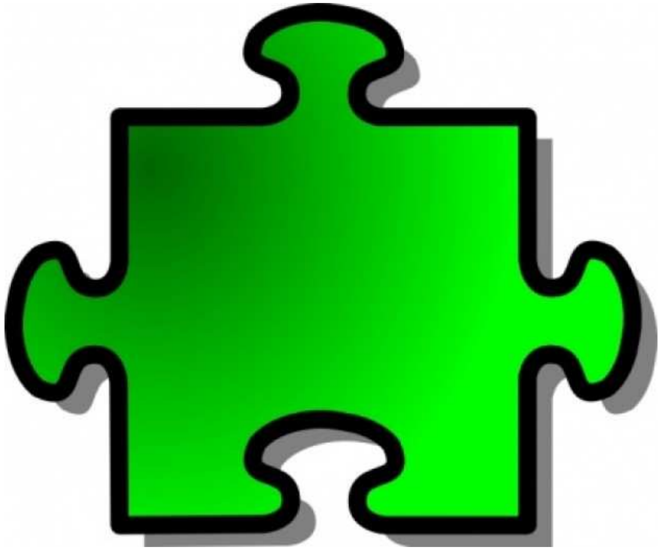
- good description at low transverse momenta (p_T)
- events at hadron level

NLO-QCD calculation:

- accurate shapes at high p_T
- normalization accurate at NLO
- reduced scale dependence

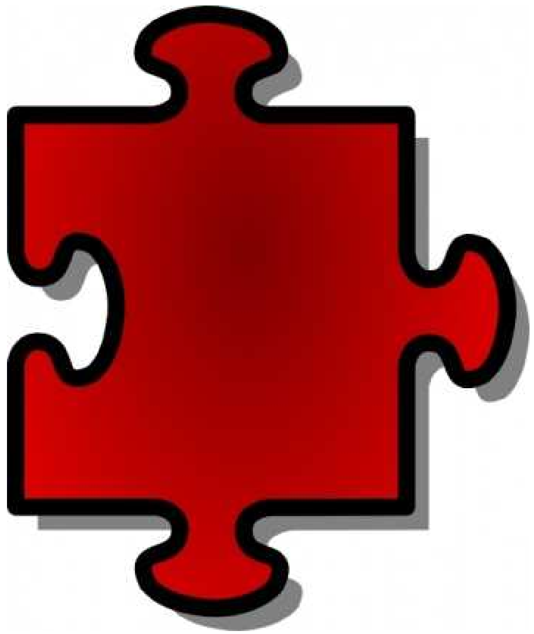


realistic & precise predictions



POWHEG

MC@NLO

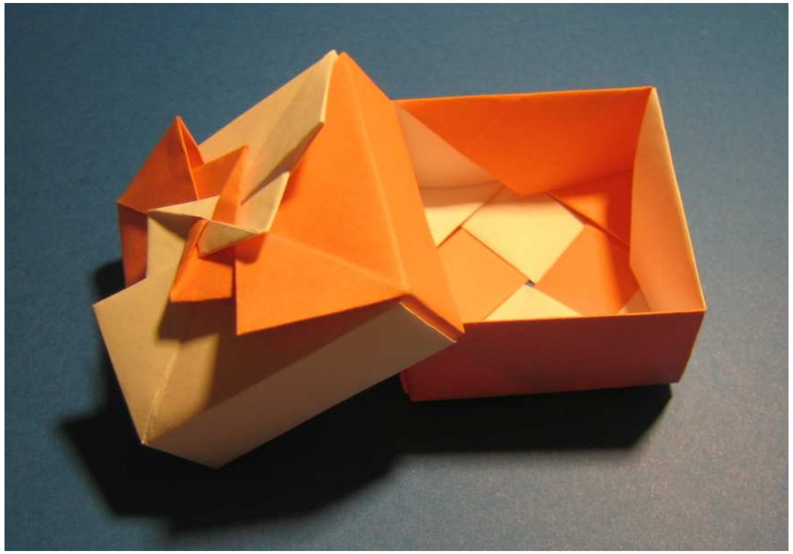


realistic & precise predictions

general presciption for matching
parton-level NLO-QCD calculation
with parton-shower programs

[Frixione, Nason, Oleari]

POWHEG



a public multi-purpose tool
for “do-it-yourself” implementations:

the `POWHEG-BOX`

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

[Alioli, Nason, Oleari, Re]

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

  $\rightarrow$ 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

Born

real emission and counter-terms

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

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

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

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

POWHEG "Sudakov" factor:

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

the POWHEG cross section

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

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

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

parton showers & NLO-QCD: the POWHEG-BOX

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

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

✘ user has to supply process-specific quantities:

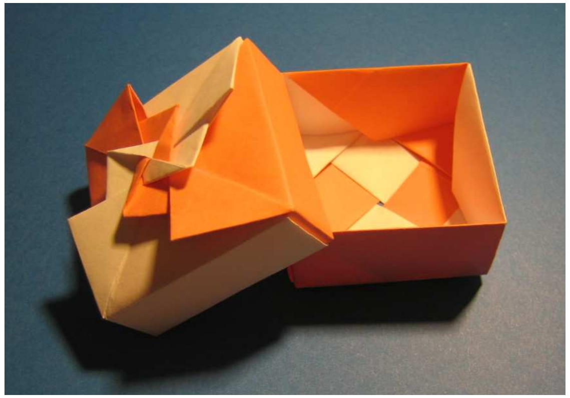
- lists of flavor structures for Born and real emission processes
- Born phase space
- Born amplitudes squared, color-and spin-correlated amplitudes
- real-emission amplitudes squared
- finite part of the virtual corrections
- Born color structure in the limit of a large number of colors

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

$VVjj$ matched with parton showers & NLO-QCD

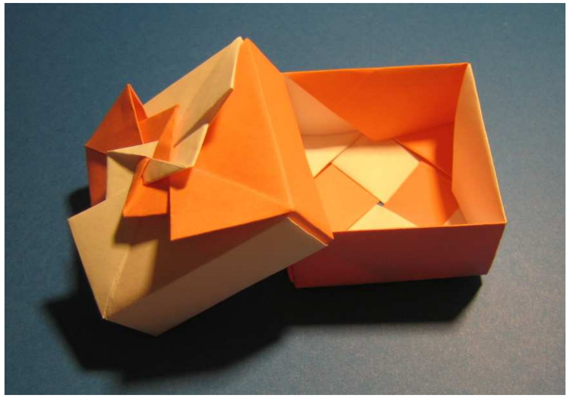
so far only implementation of EW- and QCD-induced $VVjj$ production processes available in the `POWHEG-BOX`:

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



- 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)]*
- EW $ZZjj$ production *[Karlberg, Zanderighi, B.J. (2013)]*

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

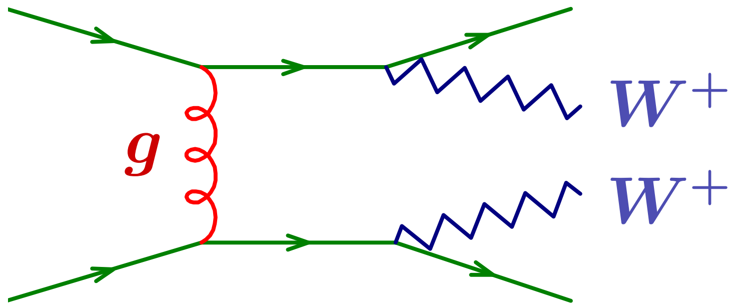
$pp \to W^+W^+jj$ in the POWHEG-BOX

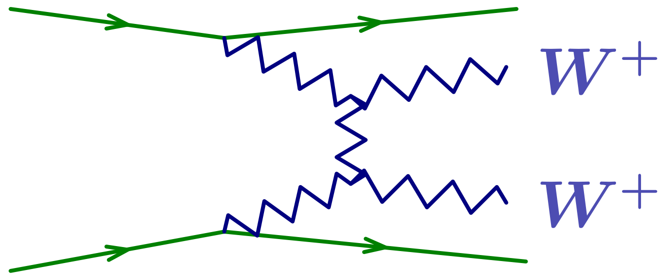
QCD-induced production

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

EW production

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





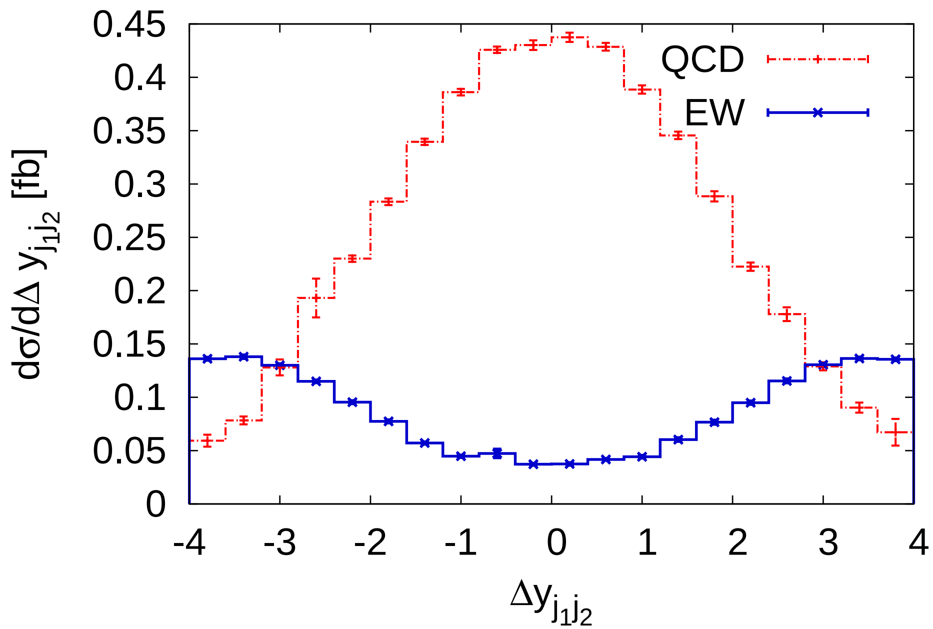
NLO-QCD results for $\sqrt{s}$ =7 TeV with basic jet cuts only ($p_T^{\rm tag} > 20$ GeV):

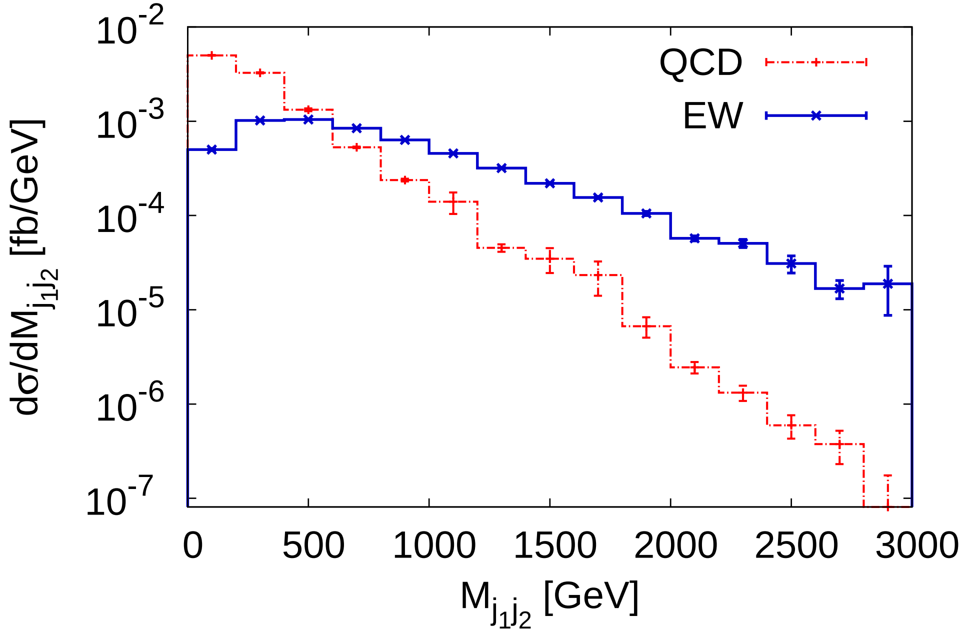
$\sigma_{\rm QCD}^{\rm inc} = 2.12$ fb

$\sigma_{\rm EW}^{\rm inc} = 1.097$ 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

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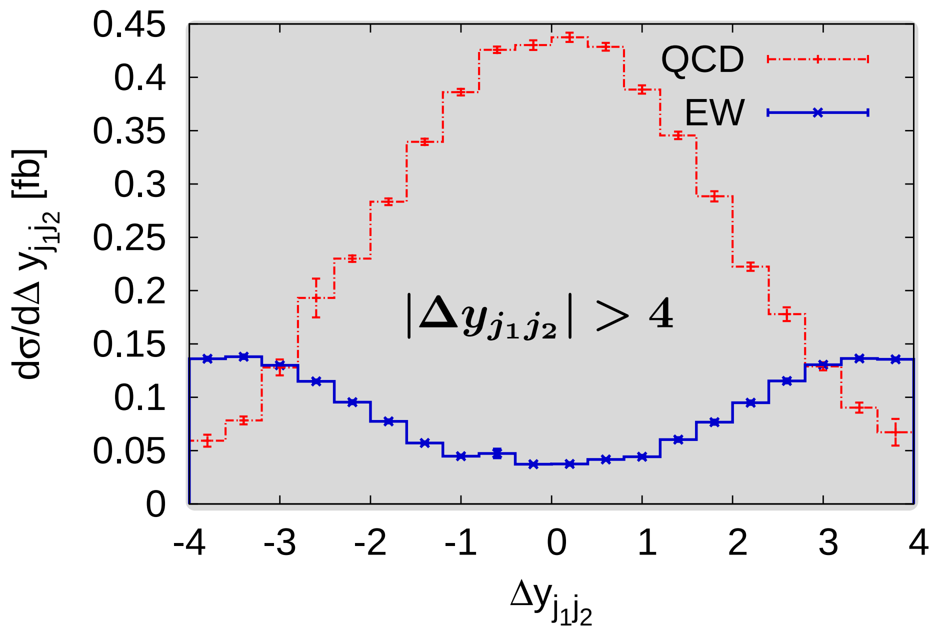

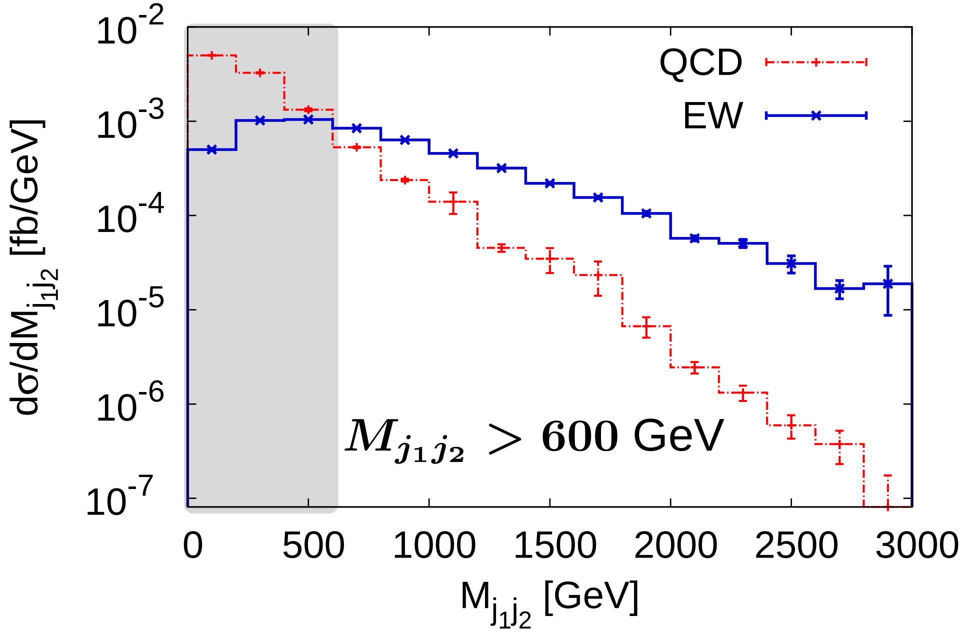

- $\sqrt{s} = 7$ TeV
- basic jet cuts only
- NLO-QCD accuracy

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

QCD-induced production

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

EW production

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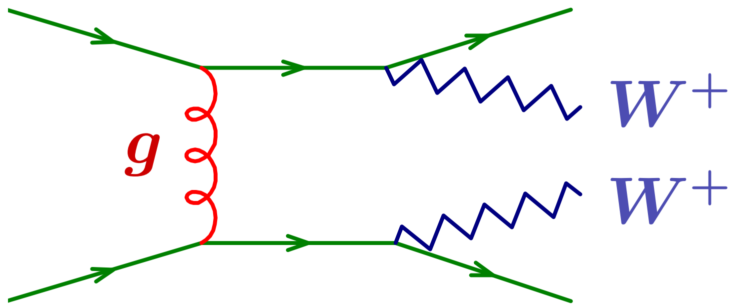
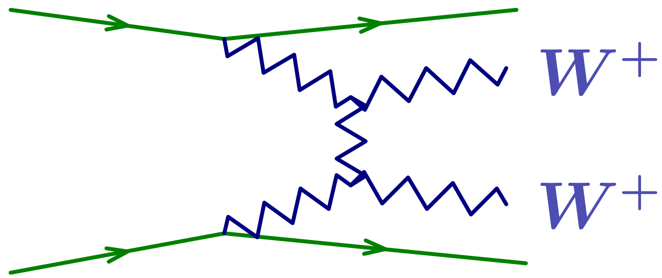




NLO results for $\sqrt{s}$ =7 TeV with basic jet cuts only ($p_T^{\text{tag}} > 20$ GeV):

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

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

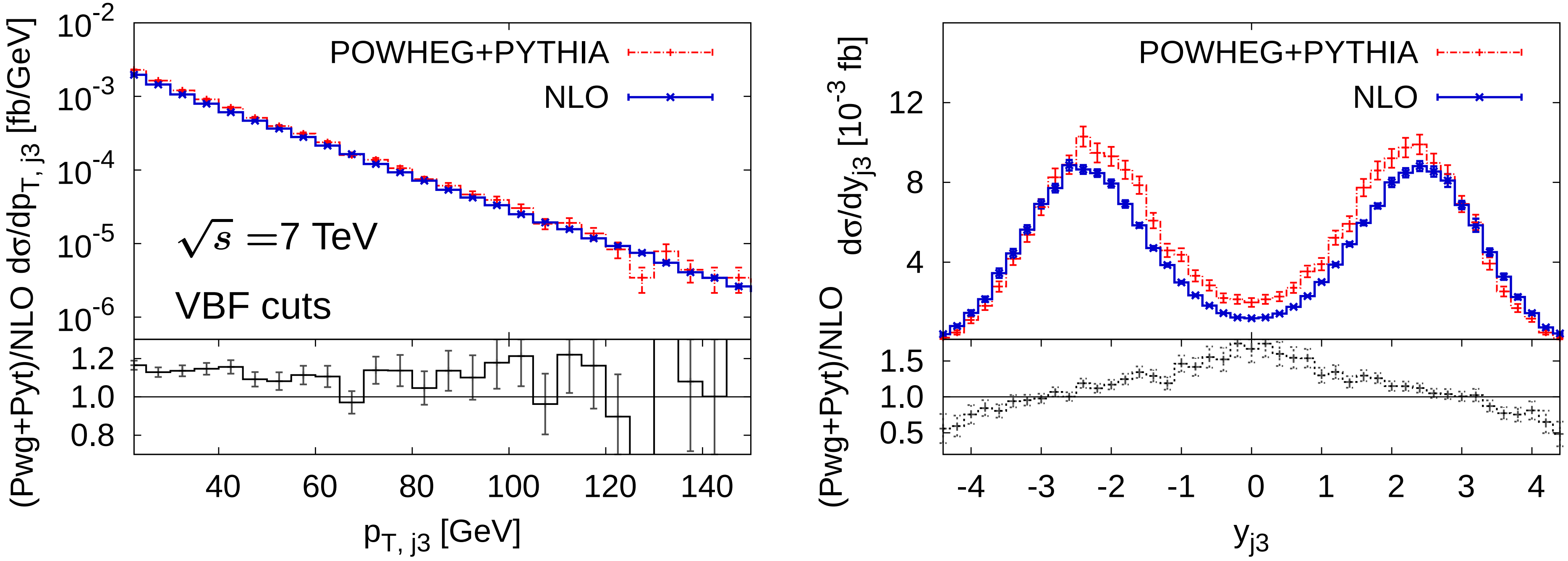
NLO results with VBF cuts:

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

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

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

Zanderighi, B.J. (2011)

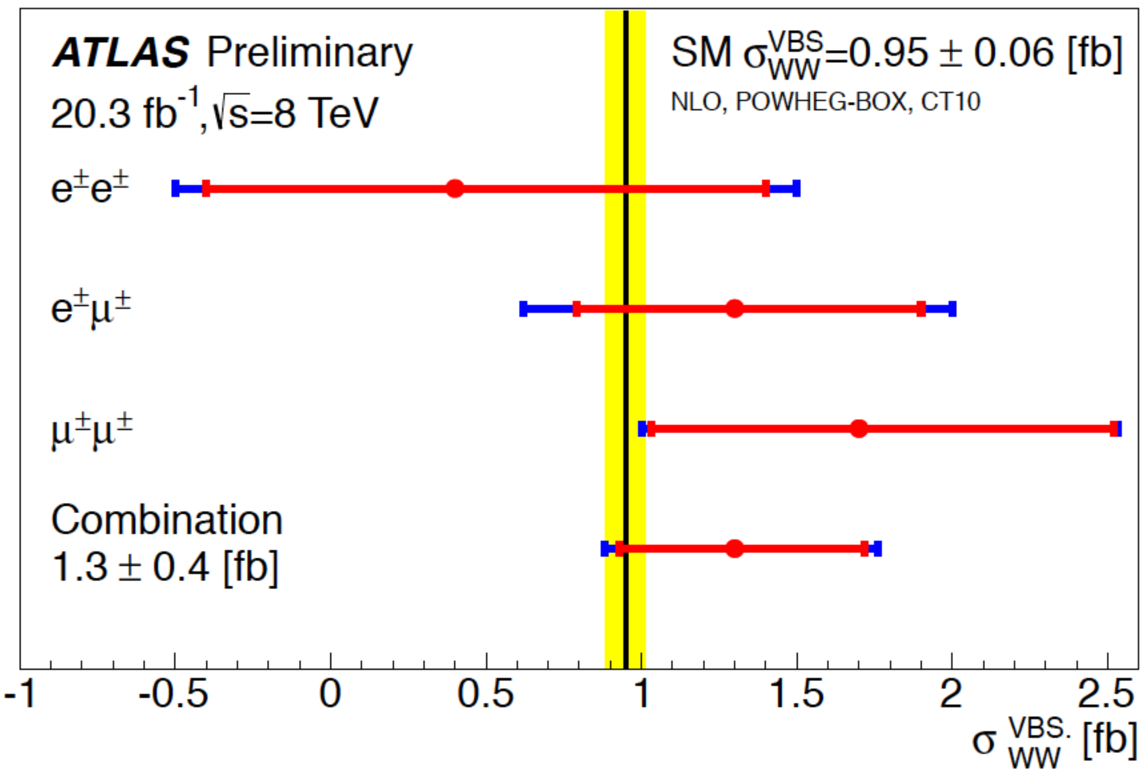


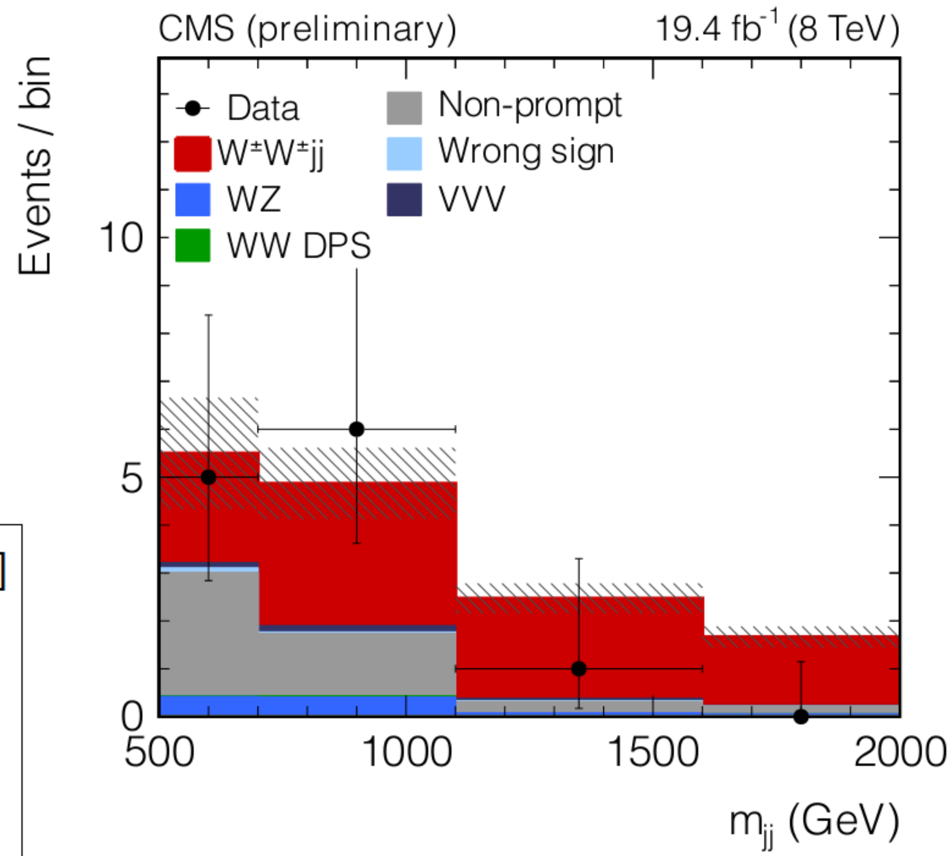
typical for VBF processes: little jet activity at central rapidities

$\to$ exploited by central-jet veto techniques

note: parton-shower effects slightly enchance central jet activity

evidence for $W^{\pm}W^{\pm}jj$ from ATLAS and CMS





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

$pp \to W^+W^-jj$ via VBF 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

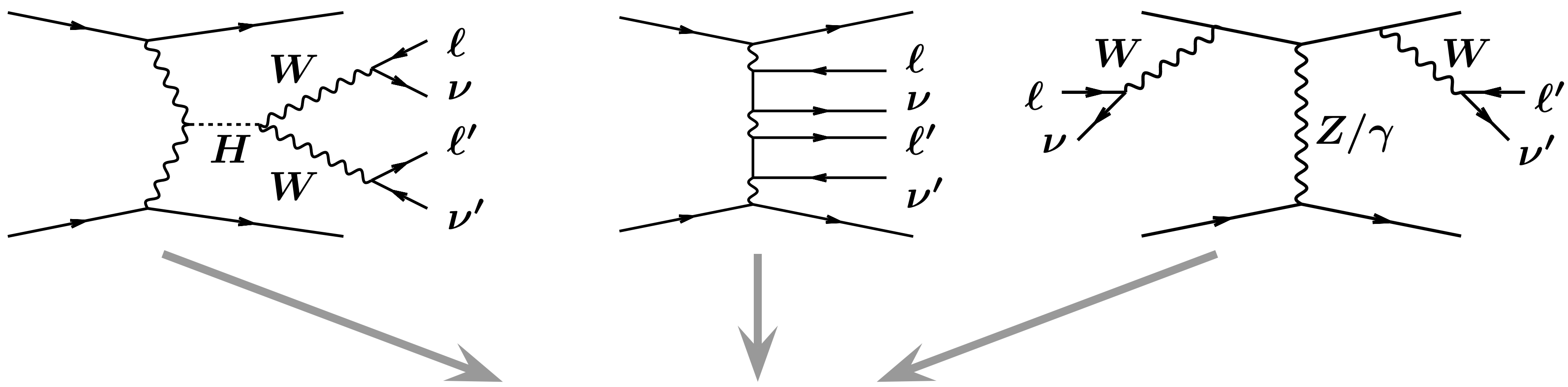
✔ provide implementation in versatile
public program package POWHEG-BOX

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

$\to$ conceptually and computationally demanding*

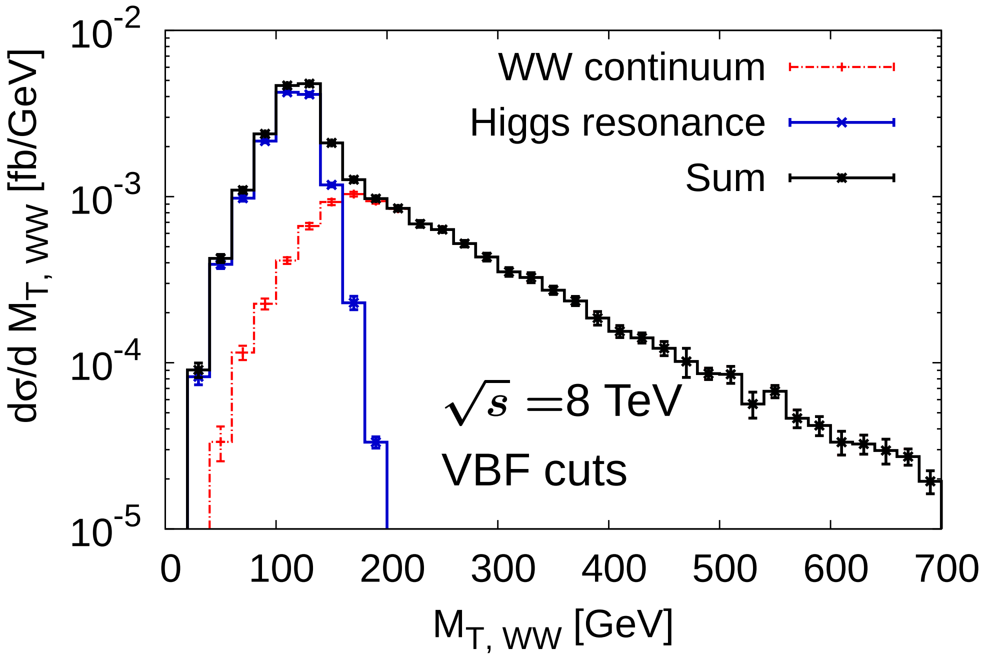
$\star$ requires about 12 hours $\times$ 100 nodes on a HPC cluster

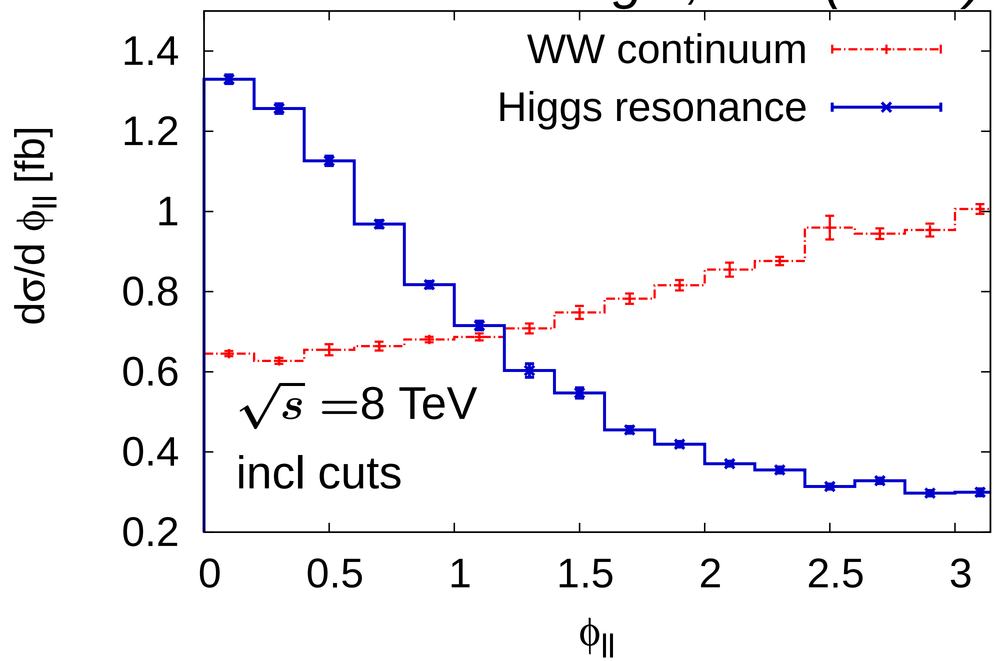
$pp \to W^+W^-jj$ via VBF: technicalities



different topologies populate different regions in phase space:

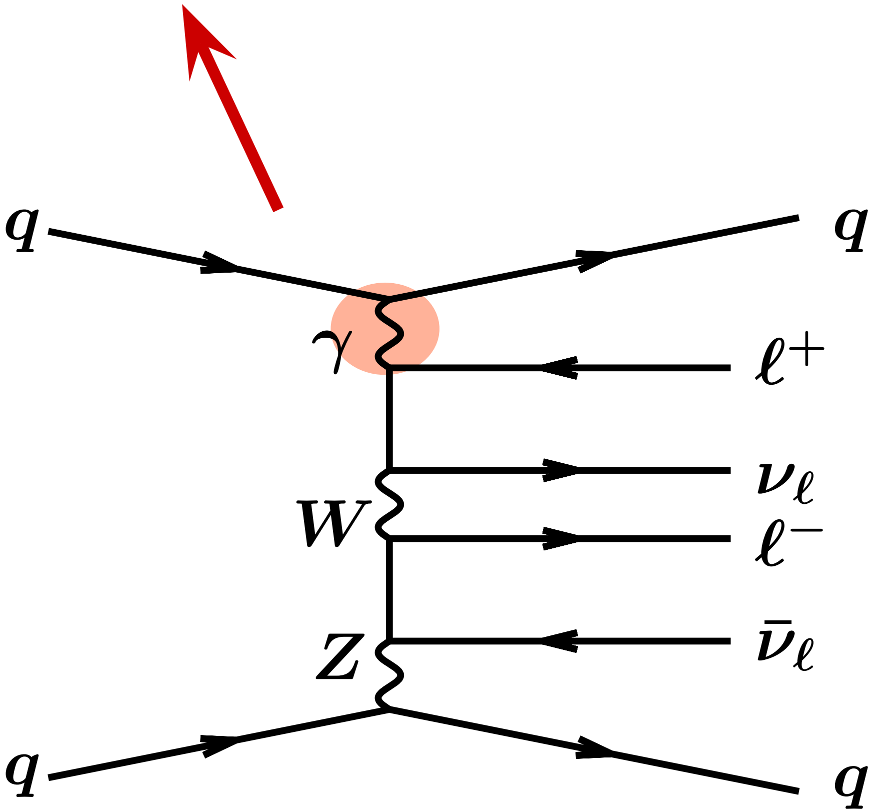
G. Zanderighi, B.J. (2013)





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

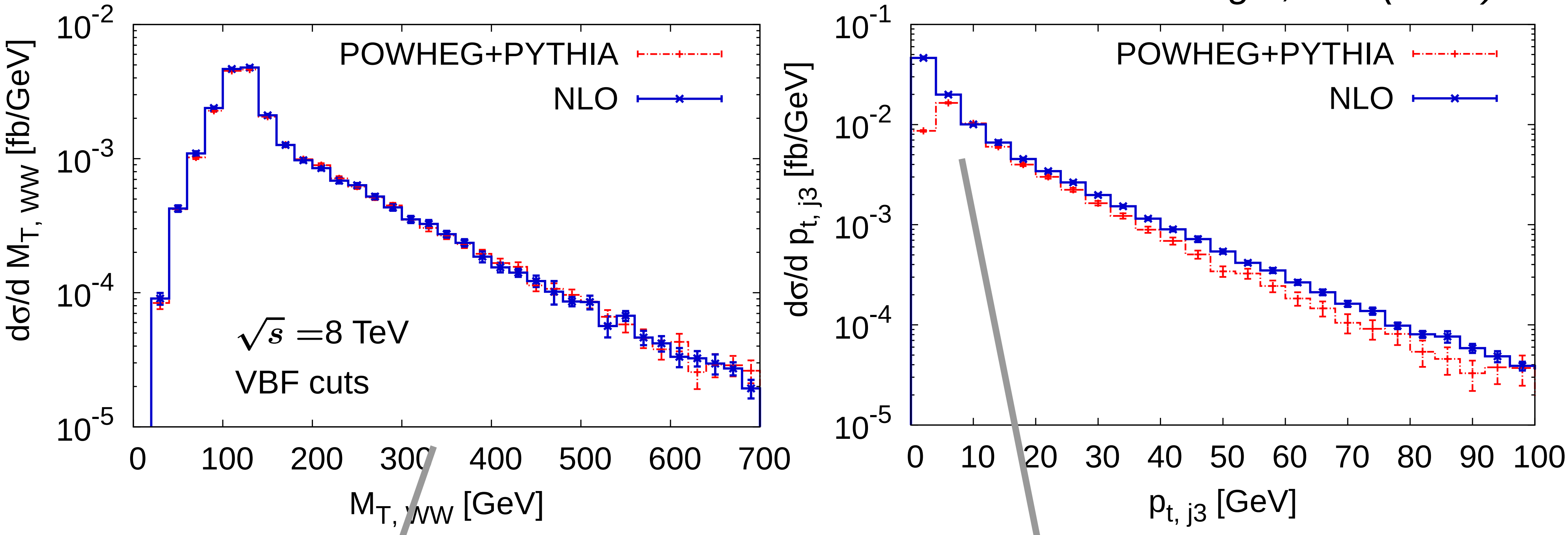
(2) Born-suppression factor to achieve efficient phase space integration

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

(alternative: explicit generation cuts)

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

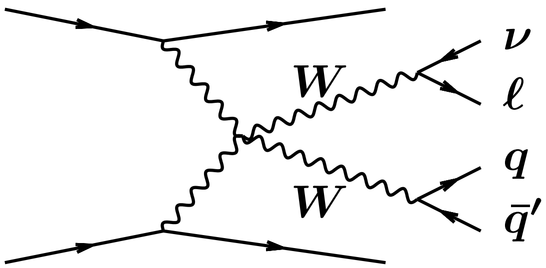
G. Zanderighi, B.J. (2013)



leptonic observables not very sensitive to parton shower

growth of jet distribution tamed by Sudakov factor

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



"semi-leptonic" final state:

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

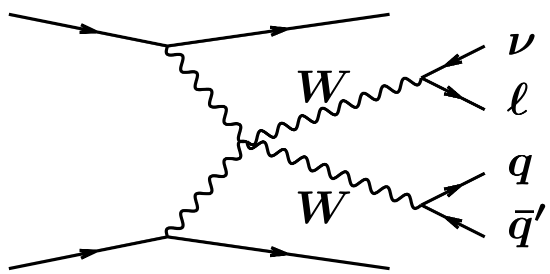
different from fully leptonic modes:

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

✔ only one neutrino $\to$ on-shell: M_{WW} reconstruction possible

✘ sophisticated analysis techniques needed to isolate signal

$pp \to W^+W^-jj$ via VBF 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

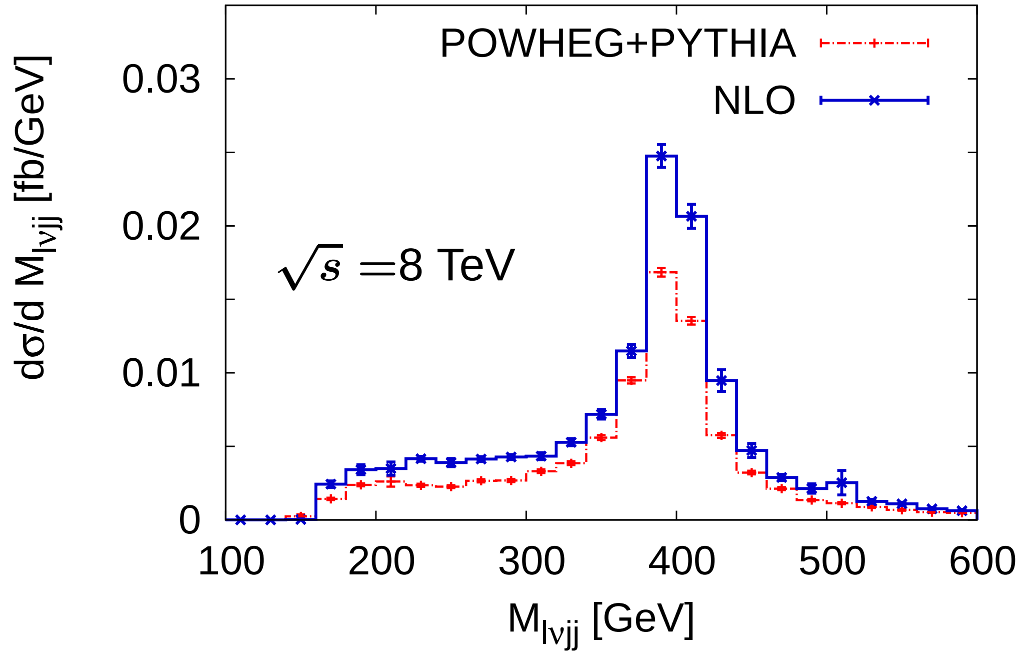
$$M_W - 10\ \text{GeV} \leq m_{jj}^{\text{dec}} \leq M_W + 10\ \text{GeV}$$

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

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

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

($\to$ neutrino momentum)

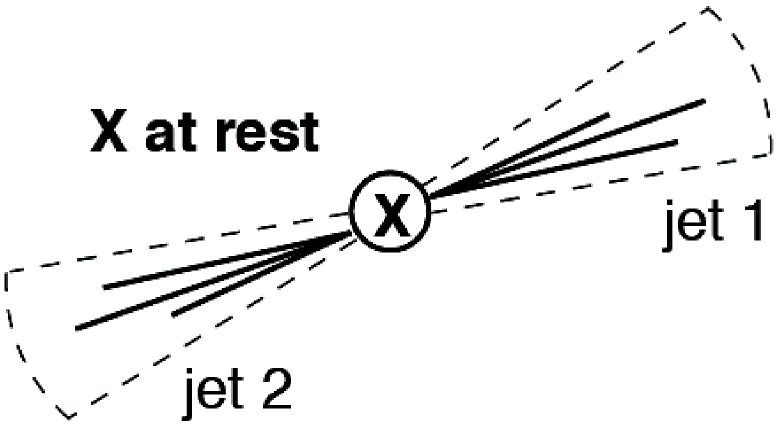


✘ $M_{\ell\nu jj}$ distribution very sensitive to parton-shower effects!

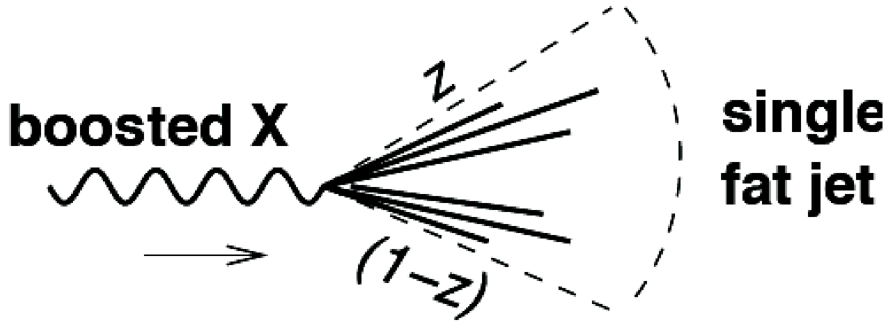
soft radiation smears distribution of W decay jets
$\to m_{jj}^{\mathrm{dec}} \sim M_W$ requirement no longer fulfilled

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

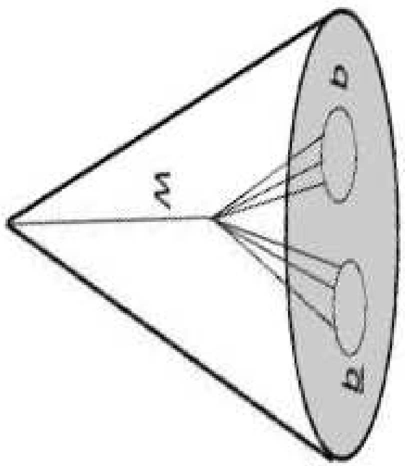
  Butterworth, Cox, Forshaw (2002)

- break-through in $pp \to VH$

  Butterworth, Davison, Rubin, Salam (2008)

- today: established field in its own

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



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

require a highly boosted fat jet

with invariant mass close to M_W

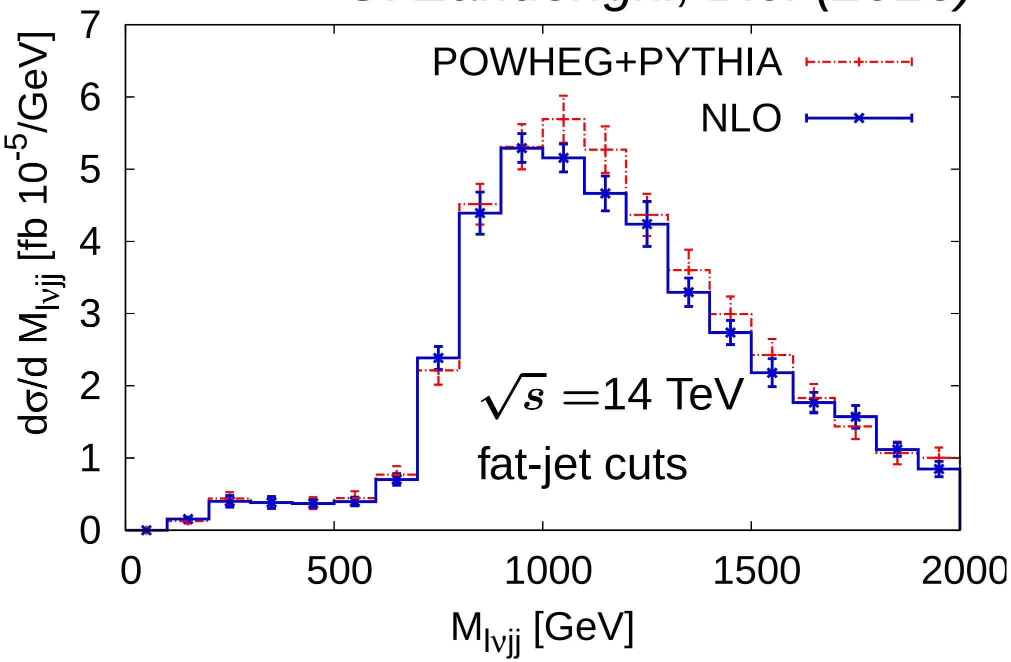
make use of jet properties / composition:

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

(stable against parton-shower effects)

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

G. Zanderighi, B.J. (2013)



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)

BSM effects: effective operator approach

parameterize deviations from Standard Model via
effective field theory expansion
(valid up to scale $\mathbf{\Lambda}$):

$$\mathcal{L}_{\text{eff}} = \sum \frac{c_i^{(d)}}{\Lambda^{d-4}} \mathcal{O}_i^{(d)} = \mathcal{L}_{\text{SM}} + \sum \frac{c_i^{(6)}}{\Lambda^2} \mathcal{O}_i^{(6)} + \ \ldots$$

[cf. Degrande et al. (2012)]

modifications of triple and
quartic gauge couplings

note: higher dim. operator coefficients severly constrained by data from LEP, Tevatron, LHC

dimension six operators

CP conserving:

$$\mathcal{O}_{WWW} = \mathrm{Tr}[W_{\mu\nu}W^{\nu\rho}W_\rho^\mu]$$

$$\mathcal{O}_W = (D_\mu\Phi)^\dagger W^{\mu\nu}(D_\nu\Phi)$$

$$\mathcal{O}_B = (D_\mu\Phi)^\dagger B^{\mu\nu}(D_\nu\Phi)$$

CP violating:

$$\mathcal{O}_{\tilde{W}WW} = \mathrm{Tr}[\tilde{W}_{\mu\nu}W^{\nu\rho}W_\rho^\mu]$$

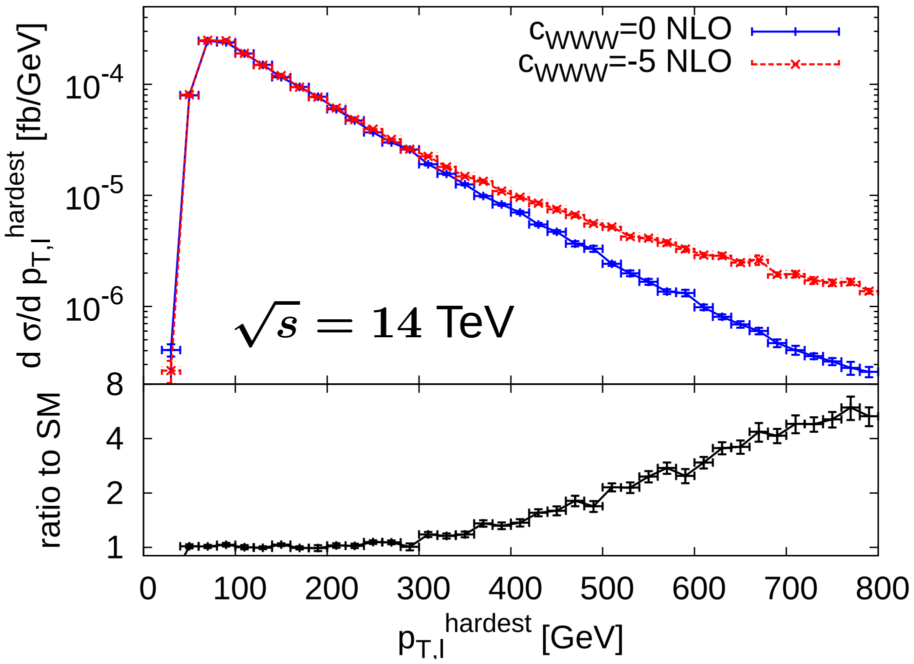
$$\mathcal{O}_{\tilde{W}} = (D_\mu\Phi)^\dagger \tilde{W}^{\mu\nu}(D_\nu\Phi)$$

	WWZ	$WW\gamma$	WWH	ZZH	γZH	$WWWW$	$WWZZ$	$WWZ\gamma$	$WW\gamma\gamma$
$\mathcal{O}_{WWW}$	x	x	-	-	-	x	x	x	x
$\mathcal{O}_W$	x	x	x	x	x	x	x	x	-
$\mathcal{O}_B$	x	x	-	x	x	-	-	-	-
$\mathcal{O}_{\tilde{W}WW}$	x	x	-	-	-	x	x	x	x
$\mathcal{O}_{\tilde{W}}$	x	x	x	x	x	-	-	-	-

impact of dim-6 operators on triple and quartic gauge couplings

new interactions in electroweak $ZZjj$ production

Karlberg, Zanderighi, B.J. (2013)



allow for non-zero dimension-six operator coefficients (compatible with exp. limits)

☞ tails of transverse momentum distributions enhanced

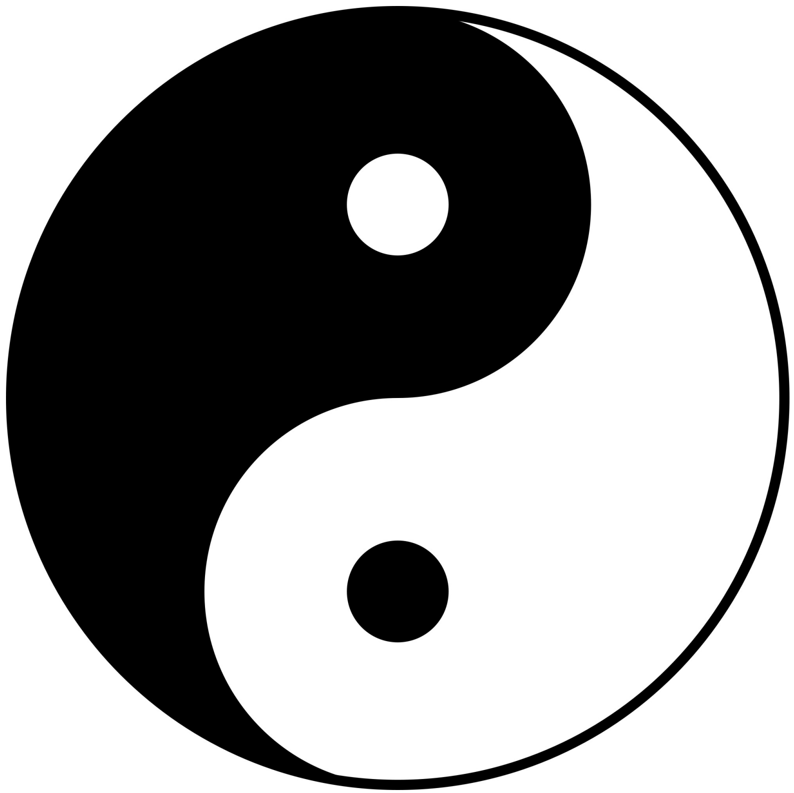
but:
very demanding at LHC14 because of small signal rates

(much better limits possible with 33 or 100 TeV)

two sides of the same picture

Higgs sector

vector boson scattering



vector boson fusion

electroweak symmetry breaking

Higgs as a tool

Higgs sector

Higgs boson is becoming precision tool
for exploring the electro-weak sector

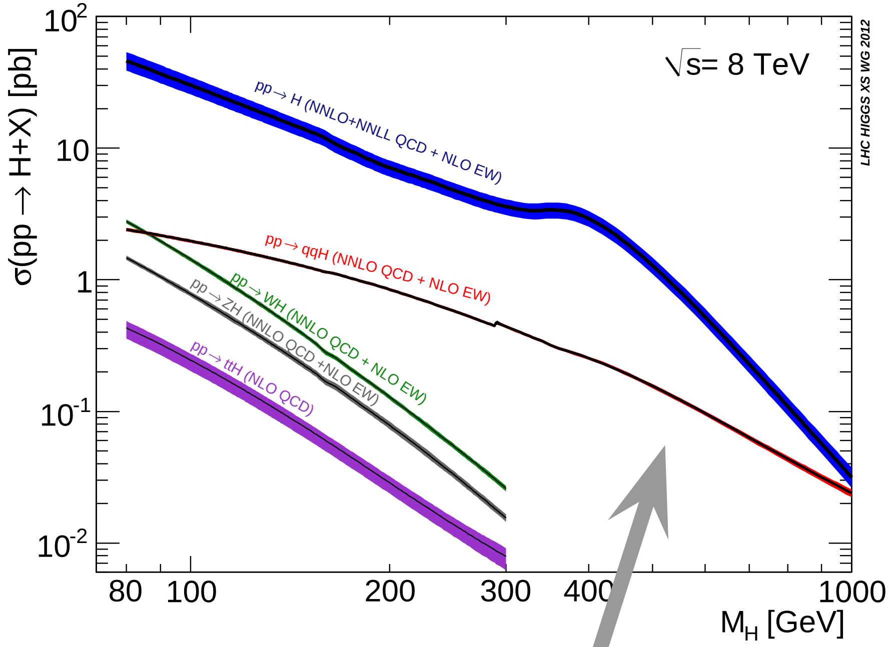
higgstools

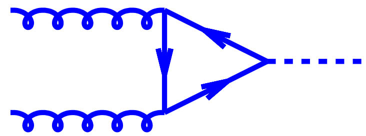
vector boson fusion

electroweak symmetry breaking

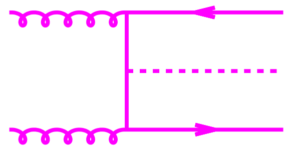
why VBF Higgs production?

Higgs cross section WG

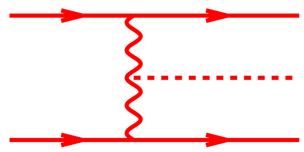




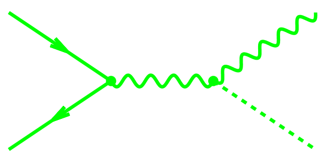
gluon fusion (GF)



$t\bar{t}H$ production



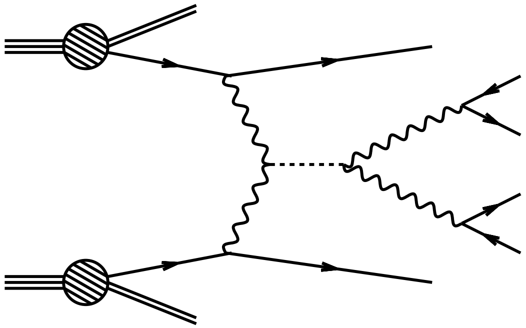
vector boson fusion (VBF)



W, Z bremsstrahlung

- second-largest Higgs production cross section at the LHC
- largest cross section that involves only tree-level production

why VBF Higgs production?



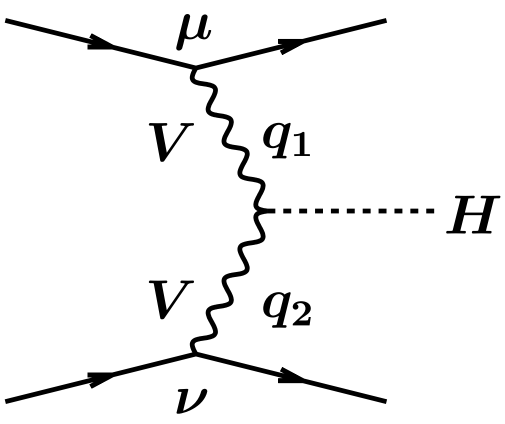
distinctive signature $\longrightarrow$ very useful for signal extraction and background suppression

suppressed color exchange between quark lines gives rise to

- little jet activity in central rapidity region
- scattered quarks $\longrightarrow$ two forward tagging jets
- Higgs decay products typically between tagging jets

☞ allows a determination of couplings and CP-properties of the Higgs boson

tensor structure of the HVV coupling



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: $\mathcal{L} \sim H V_\mu V^\mu \quad \to a_1$

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

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

CP properties of the Higgs boson

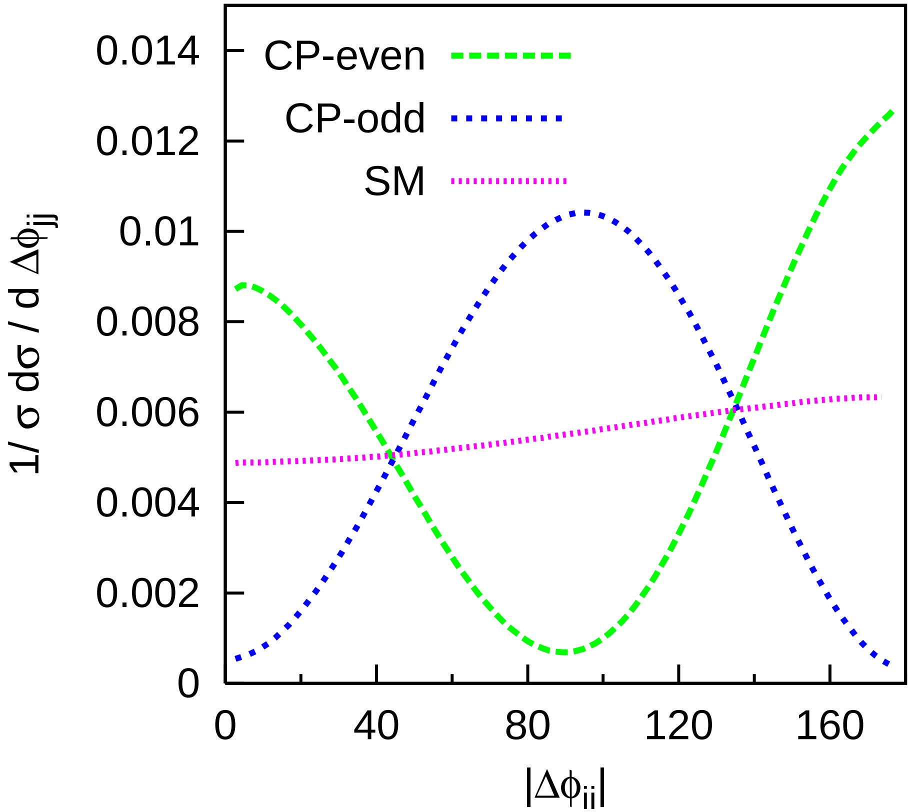
azimuthal angle between tagging jets

↓

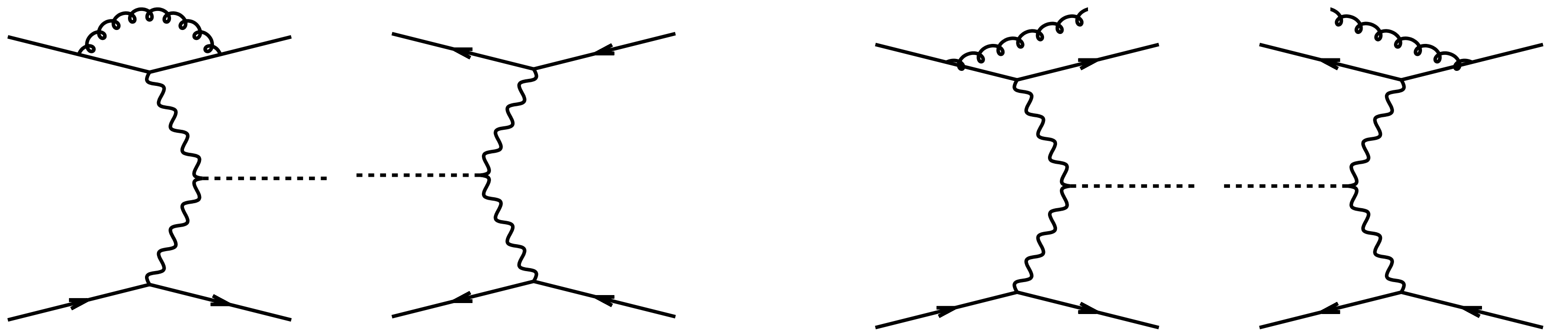
dip structure at 90° (CP even) or $0/180°$ (CP odd) only depends on tensor structure of HVV vertex

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

Figy et al. (2006)



Higgs production in VBF @ NLO QCD



NLO QCD:
inclusive cross section:
Han, Valencia, Willenbrock (1992)

distributions:
Figy, Oleari, Zeppenfeld (2003)
Berger, Campbell (2004)

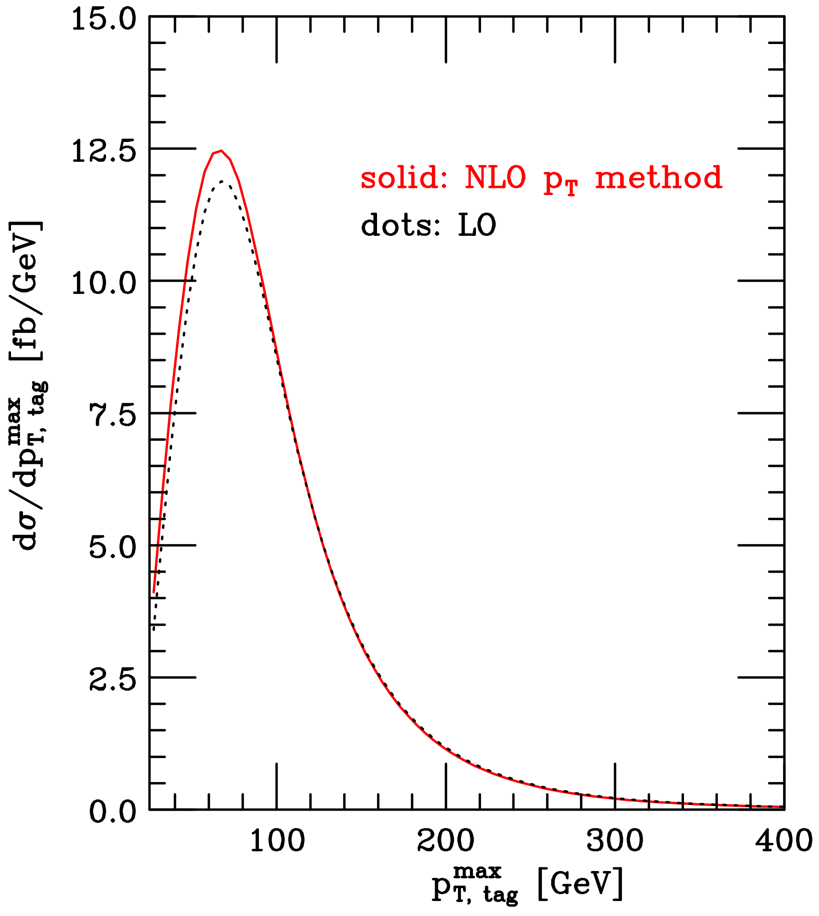
→

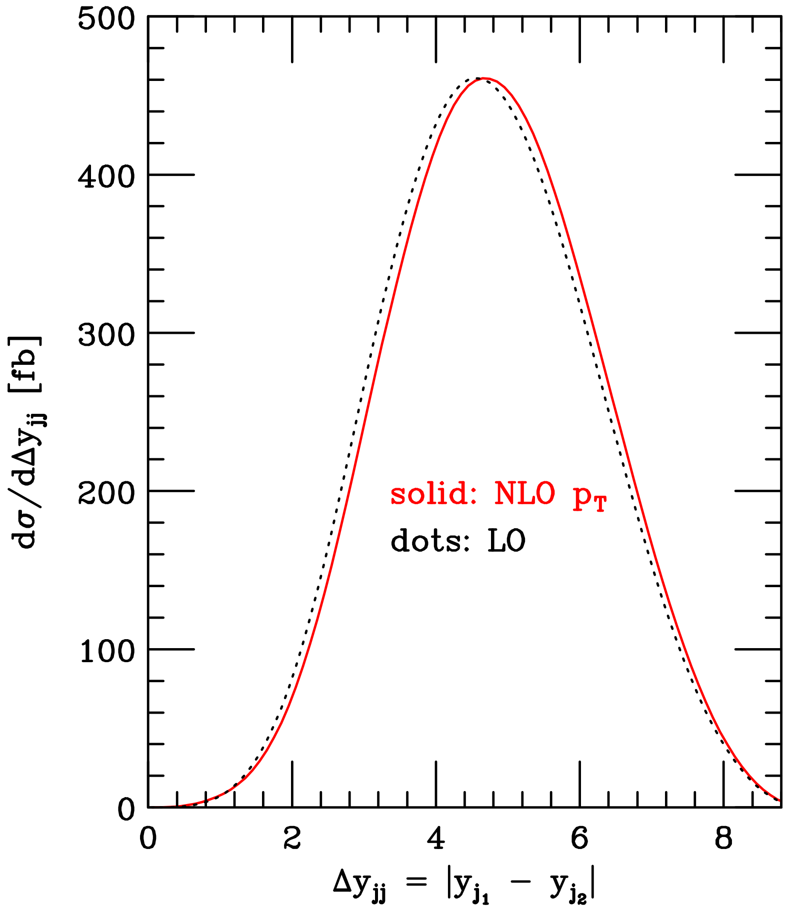
NLO QCD corrections moderate
and well under control
(order 10% or less)

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

Higgs production in VBF @ NLO QCD

Figy, Oleari, Zeppenfeld (2003)





$pp \to Hjj$ via VBF @ NLO QCD with parton shower

various implementations in different frameworks available:

SM

- `POWHEG-BOX:` *Nason, Oleari (2009)*
- `HERWIG++:` *D' Errico, Richardson (2009)*
- `aMC@NLO:` *Frixione, Torielli, Zaro (2013)*

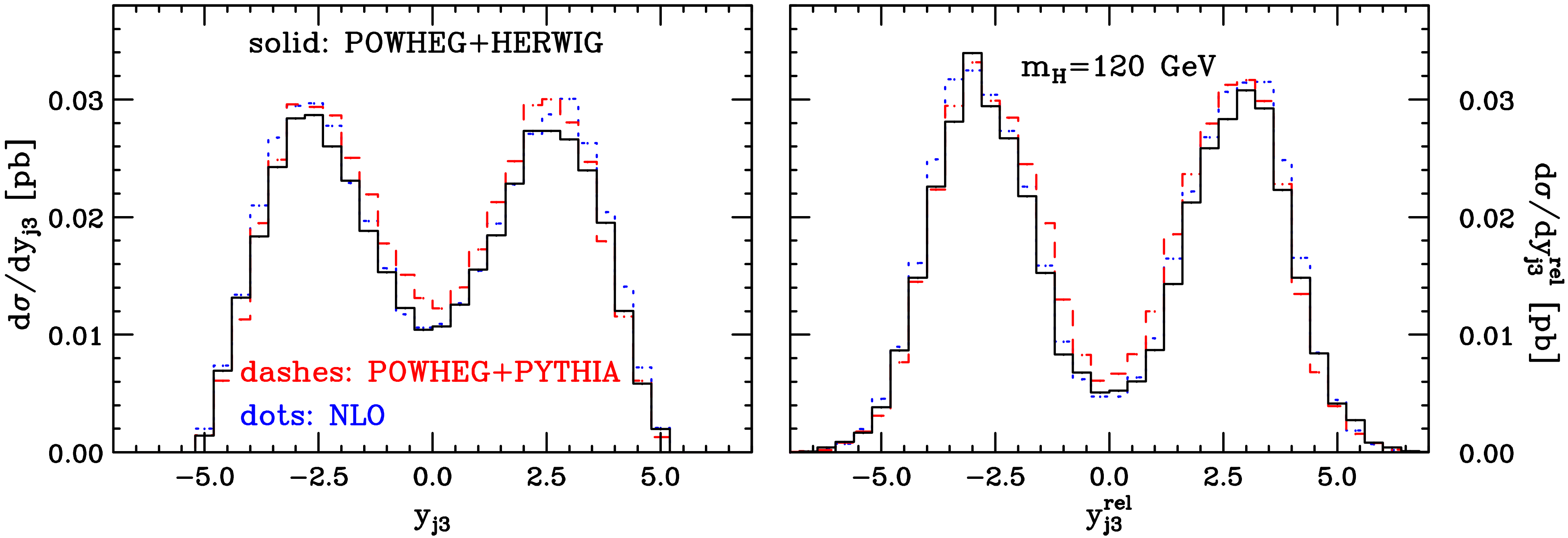
BSM

- `MadGraph5_aMC@NLO:` *Maltoni, Mawatari, Zaro (2014)*

generally parton shower does not significantly modify distributions related to tagging jets

$pp \to Hjj$ via VBF @ NLO QCD with parton shower

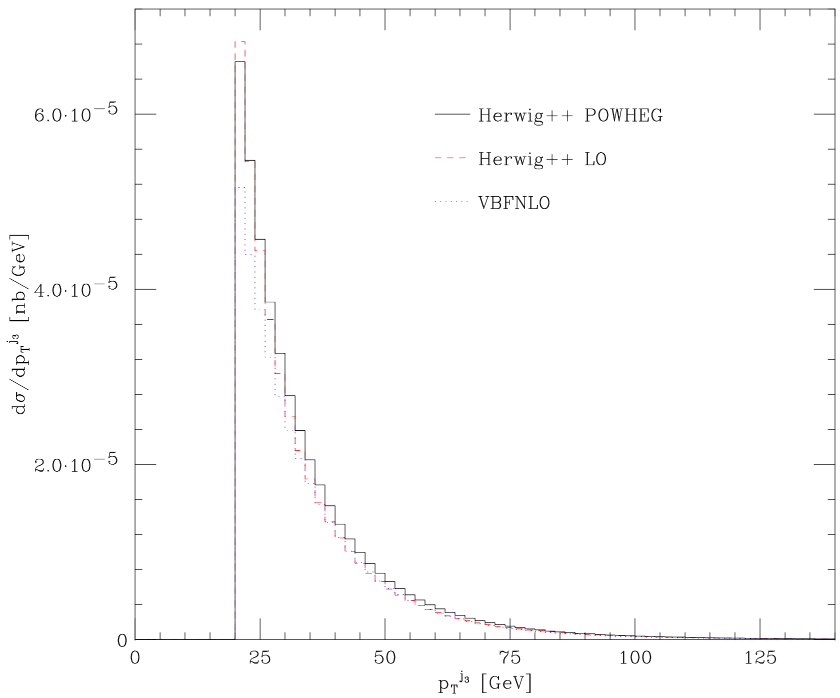
Nason, Oleari (2009)

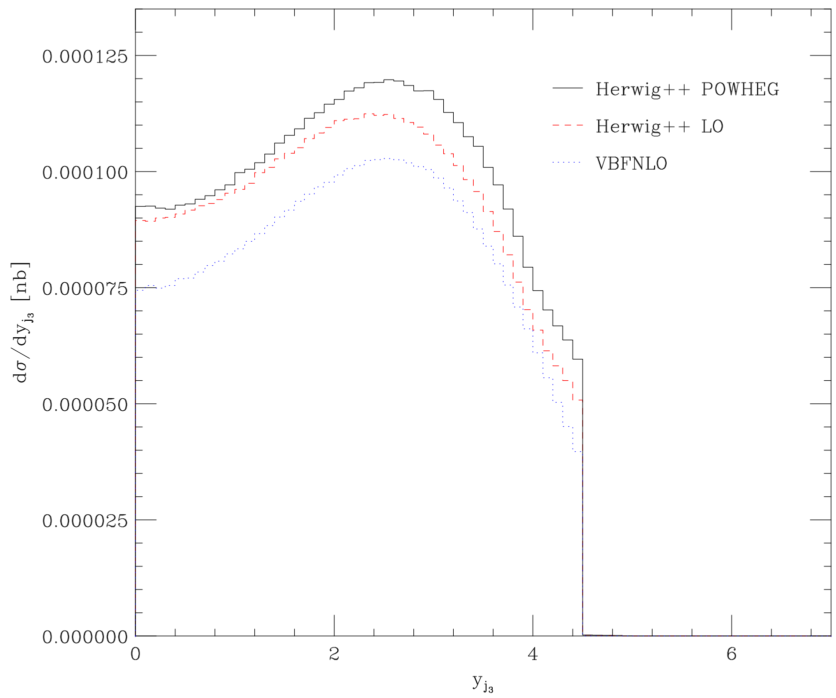


distributions related to the third jet are more sensitive to parton shower effects and details of the implementation

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

Richardson, De Luca (2011)

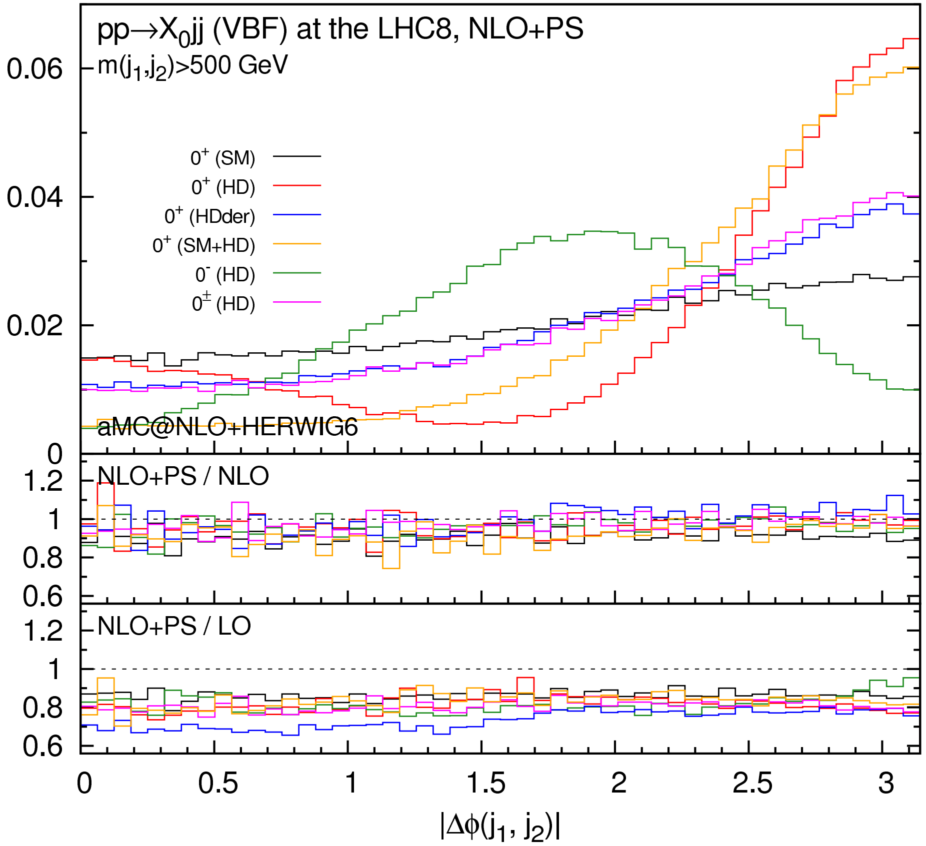




- parton-level NLO calculation matched via `POWHEG` with `HERWIG++` including vetoed truncated shower ($\leftrightarrow$ angular-ordered PS)
- `HERWIG++` results differ from pure parton level at LO and NLO

$pp \to Hjj$ via VBF: NLO+PS and BSM effects

Maltoni, Mawatari, Zaro (2013)

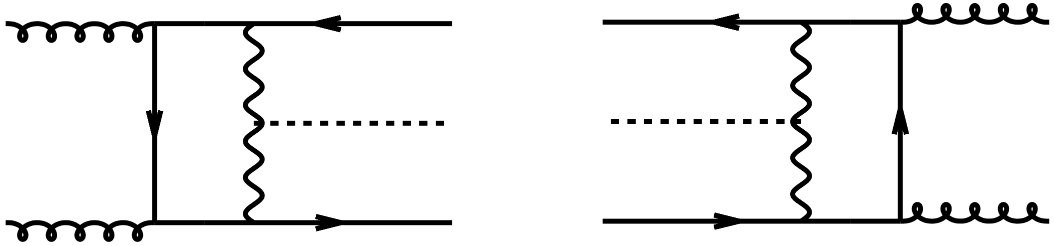


impact of higher-dimensional operators on azimuthal angle correlation of tag jets not depleted by parton shower

higher orders of QCD in VBF

Harlander, Vollinga, Weber (2007):

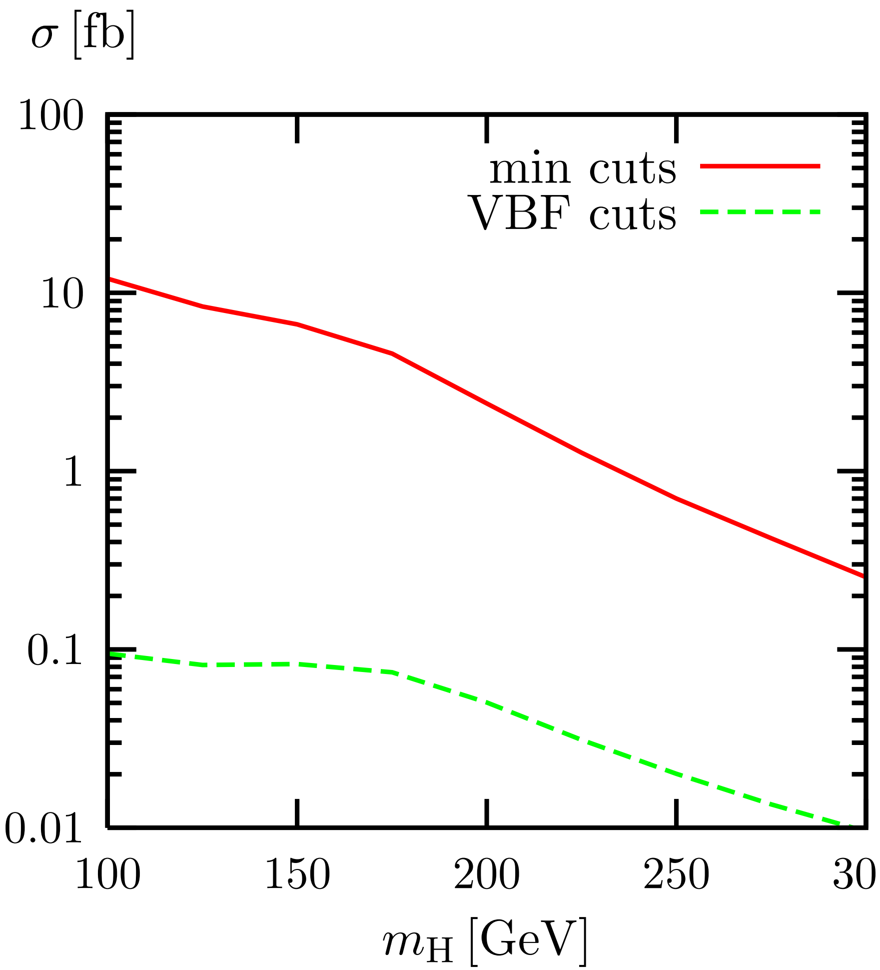
gauge invariant, finite sub-class of virtual
two-loop QCD corrections to $pp \to Hjj$ via VBF

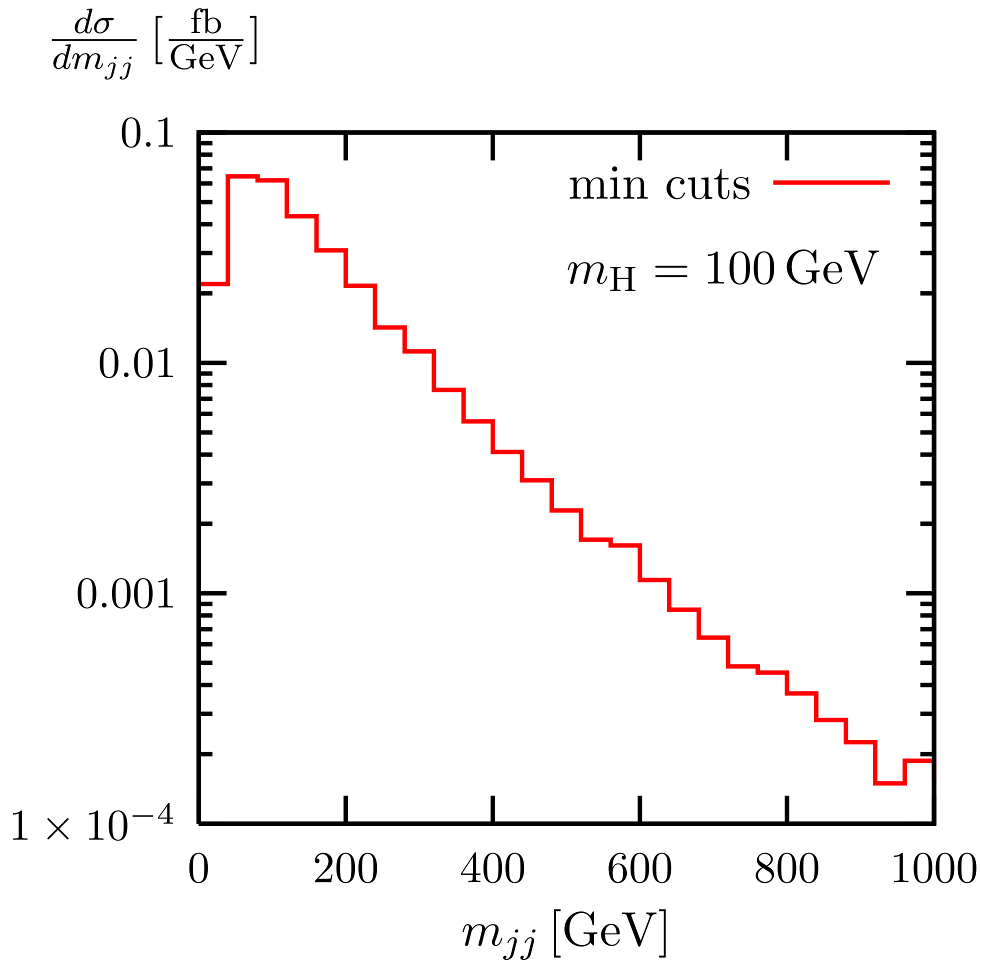


important due to large gluon luminosity at LHC?

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

higher orders in VBF?





taken from *M. M. Weber, proceedings contributions to "Loops and Legs 2006"*

higher orders in VBF?

- minimal set of cuts:

  $\sigma^{(2-loop)}(gg \to q\bar{q}H) \sim 0.3\%$ of $\sigma^{NLO}(q\bar{q} \to q\bar{q}H)$

- VBF cuts: strong suppression

  (∼ 2 orders of magnitude)

  - rapidity gap $\Delta\eta_{jj}$ smaller than in VBF
  - M_{jj} . . . rapid decrease

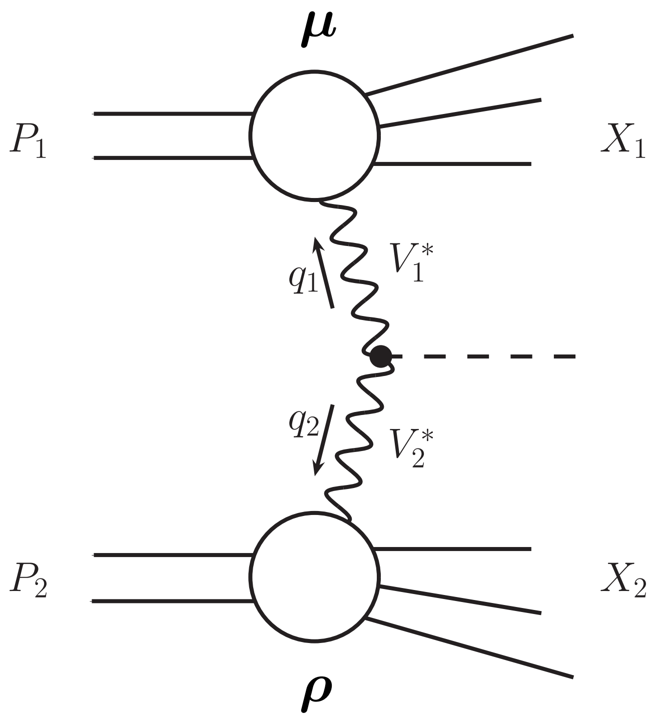
Harlander, Weber, Vollinga (2006)

higher orders of QCD in VBF

Bolzoni, Maltoni, Moch, Zaro (2010):

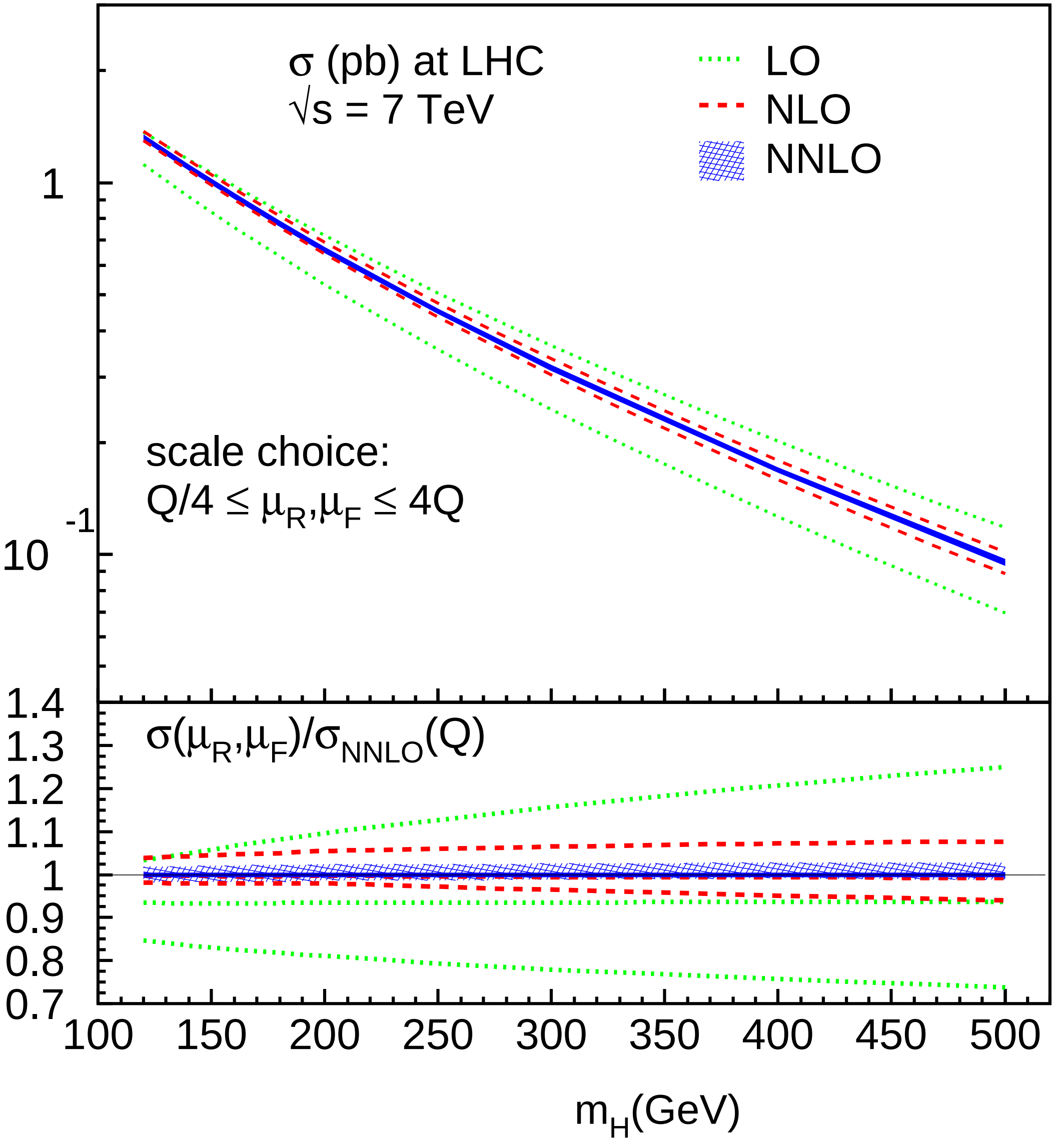
subset of the NNLO QCD contributions
to the total cross section for $pp \to Hjj$ via VBF
in the structure function approach

1



higher orders of QCD in VBF

Bolzoni et al. (2011)



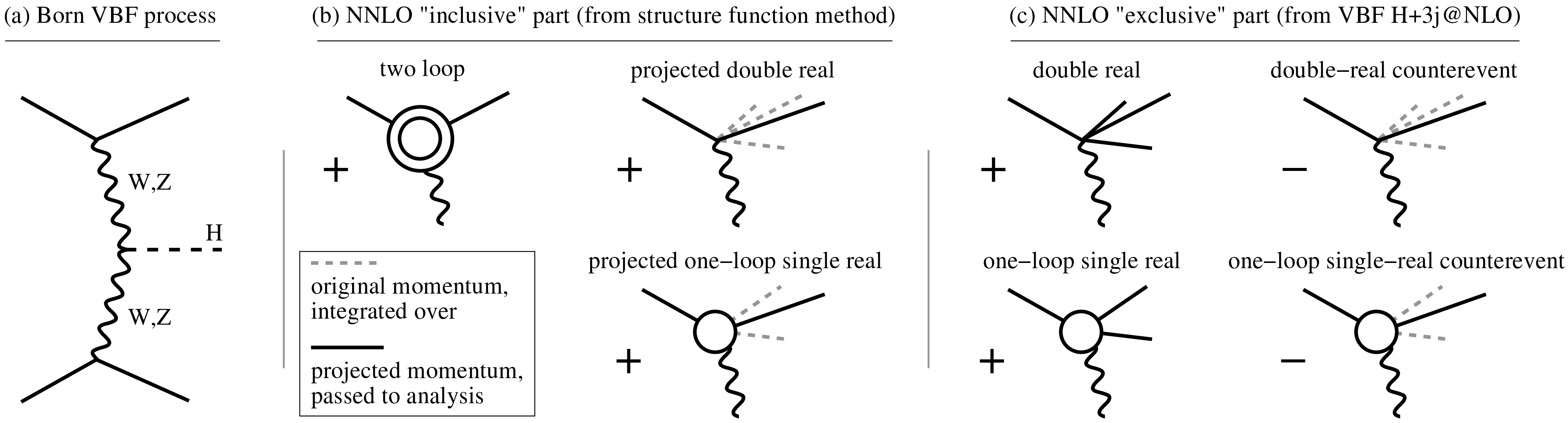
- NNLO predictions are in full agreement with NLO results
- residual scale uncertainties are reduced from ∼4% to 2%
- NNLO PDF uncertainties are at the 2% level

VBF @ NNLO: exclusive results

brandnew (June 2015):

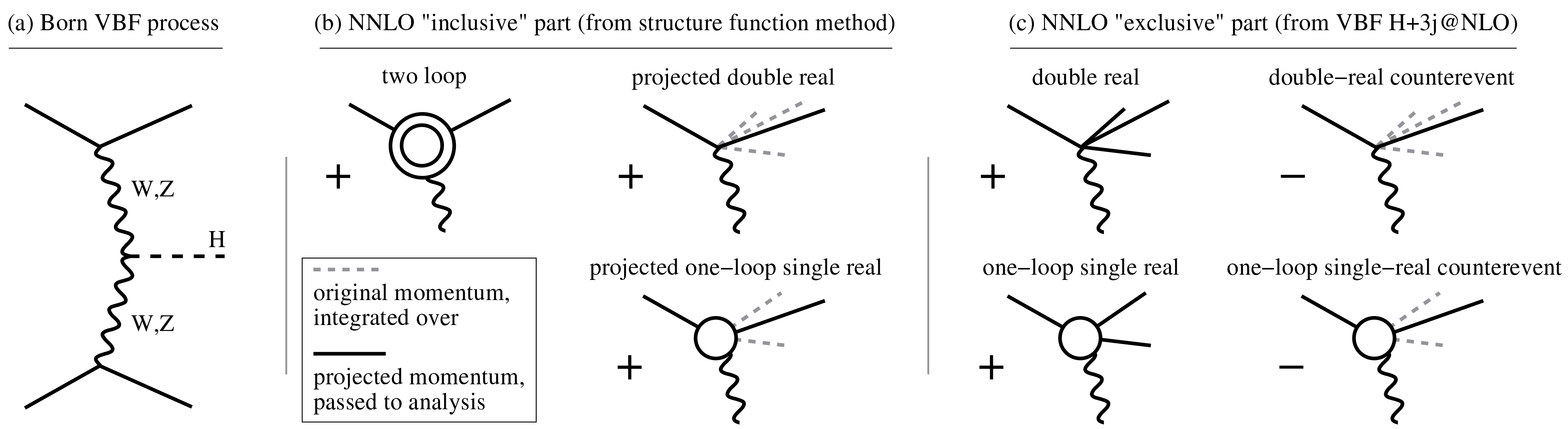
fully differential VBF Higgs production at NNLO QCD

Cacciari, Dreyer, Karlberg, Salam, Zanderighi



VBF @ NNLO: exclusive results

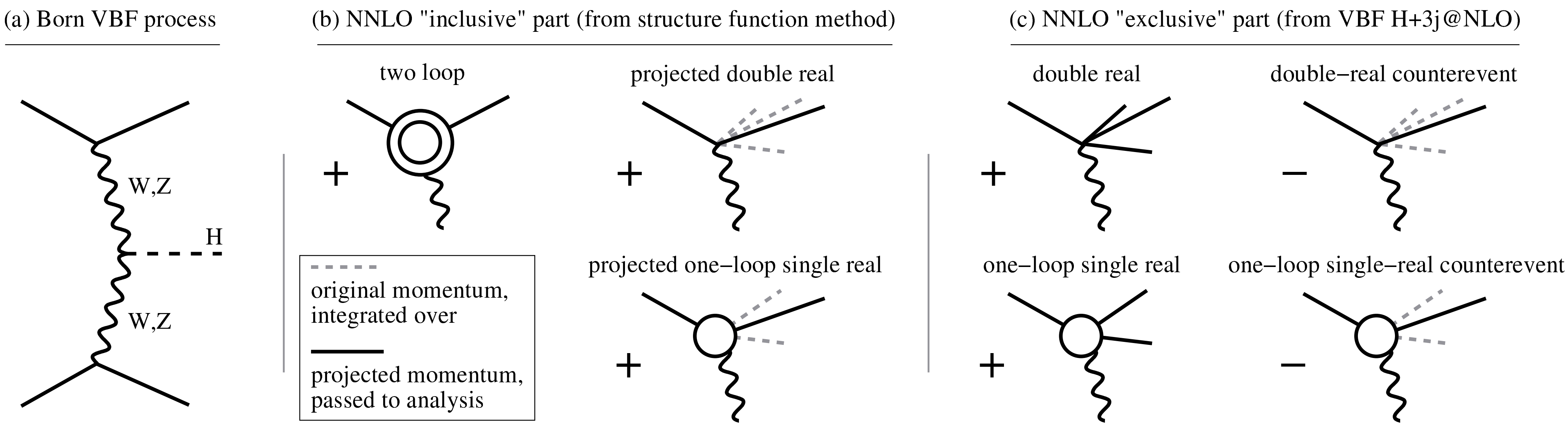
- retain NNLO accuracy of structure function approach
- provide fully differential information on final-state kinematics



VBF @ NNLO: exclusive results

$$\sigma = \int d\Phi_B(B+V) + \int d\Phi_R R$$

$$= \underbrace{\int d\Phi_B(B+V) + \int d\Phi_R R_{\text{proj}}}_{\text{from inclusive contribution}} + \underbrace{\int d\Phi_R R - \int d\Phi_R R_{\text{proj}}}_{\text{finite, from exclusive contribution}}$$



VBF @ NNLO: exclusive results

Cacciari, Dreyer, Karlberg, Salam, Zanderighi (2015)

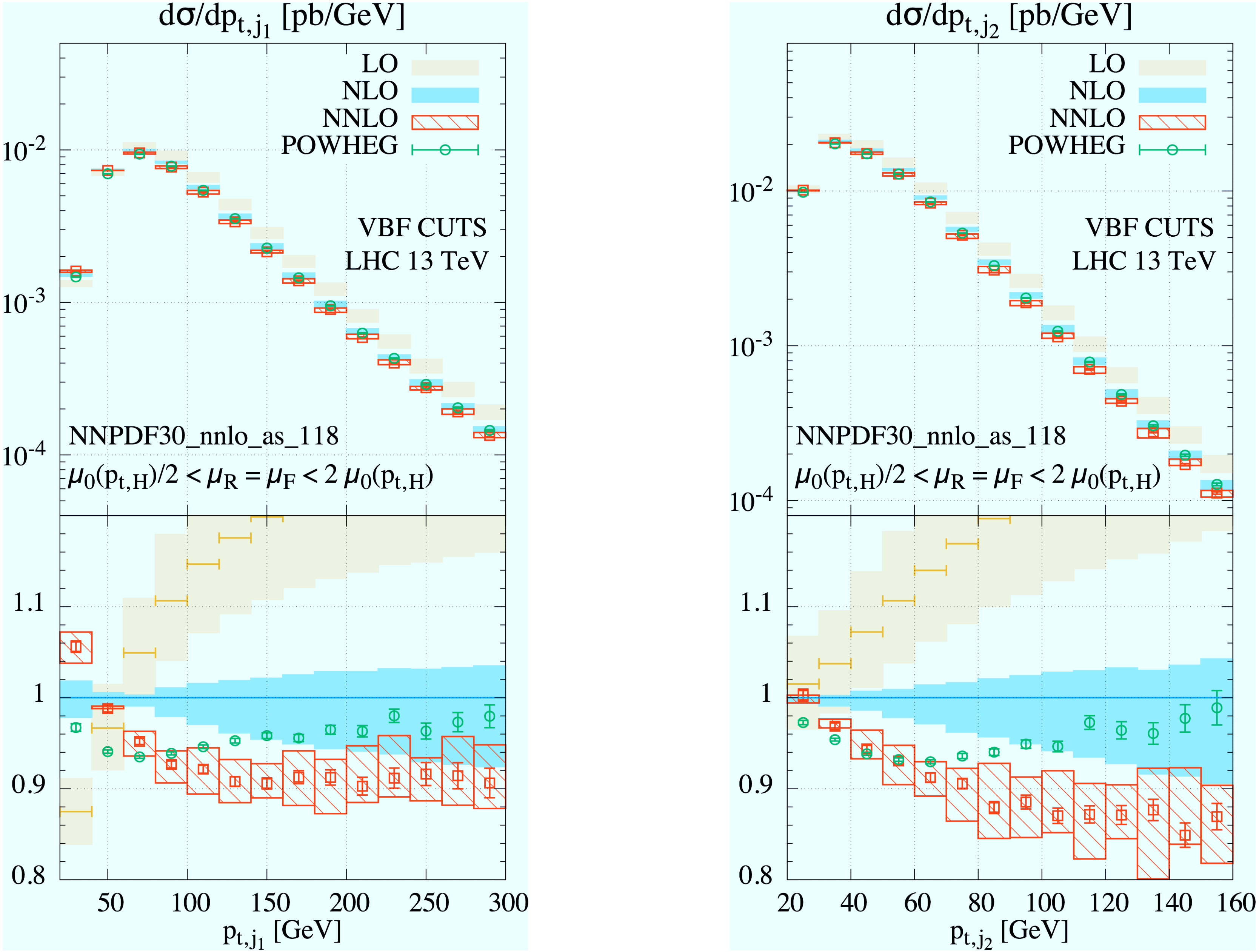
	$\sigma^{\text{(no cuts)}}$ [pb]	$\sigma^{\text{(VBF cuts)}}$ [pb]
LO	$4.032^{+0.057}_{-0.069}$	$0.957^{+0.066}_{-0.059}$
NLO	$3.929^{+0.024}_{-0.023}$	$0.876^{+0.008}_{-0.018}$
NNLO	$3.888^{+0.016}_{-0.012}$	$0.826^{+0.013}_{-0.014}$

relative NNLO corrections $\sim 1\%$

relative NNLO corrections $\sim 6\%$

NNLO QCD corrections are much larger in VBF setup than for inclusive cuts

VBF @ NNLO: exclusive results

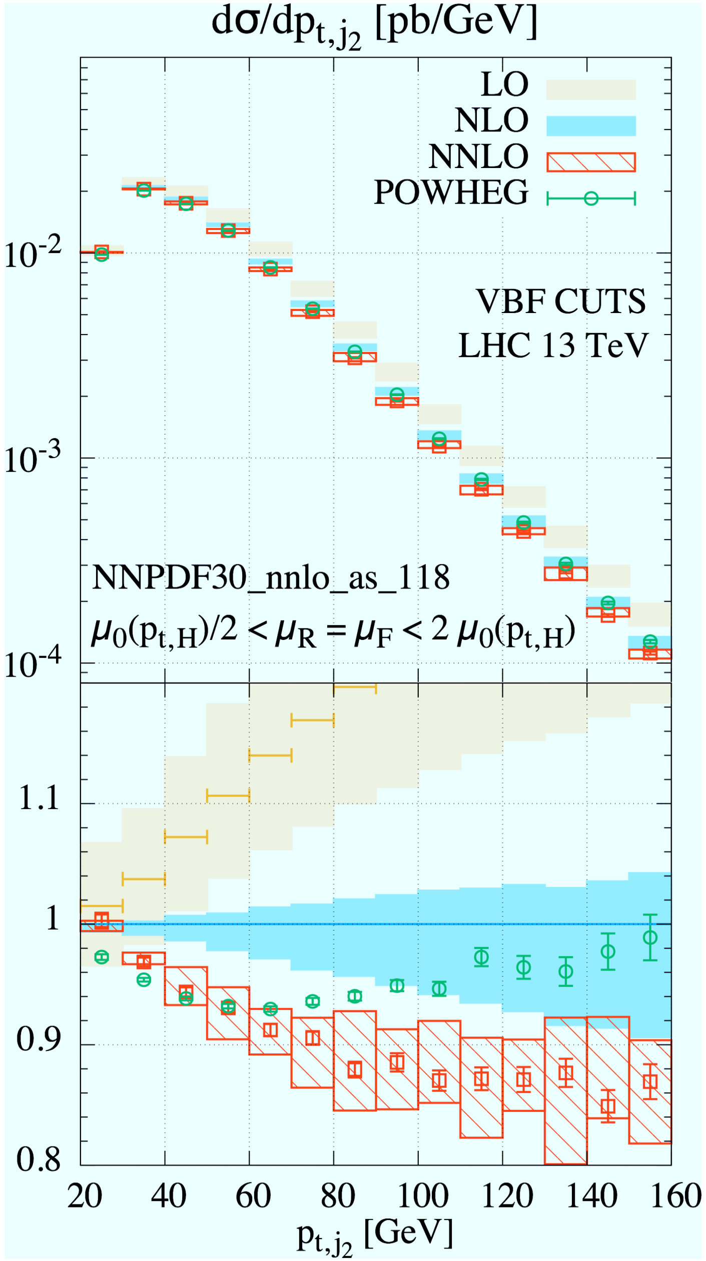


Cacciari et al. (2015)

VBF @ NNLO: exclusive results

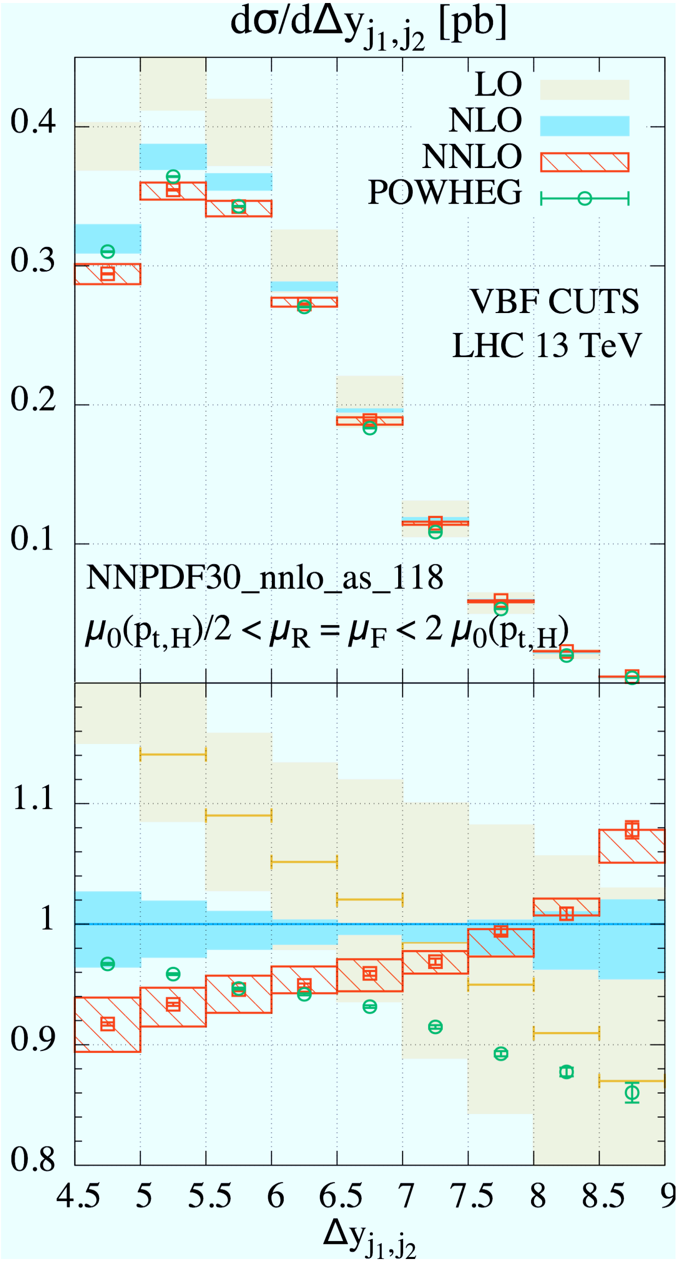
NNLO corrections
make jets softer

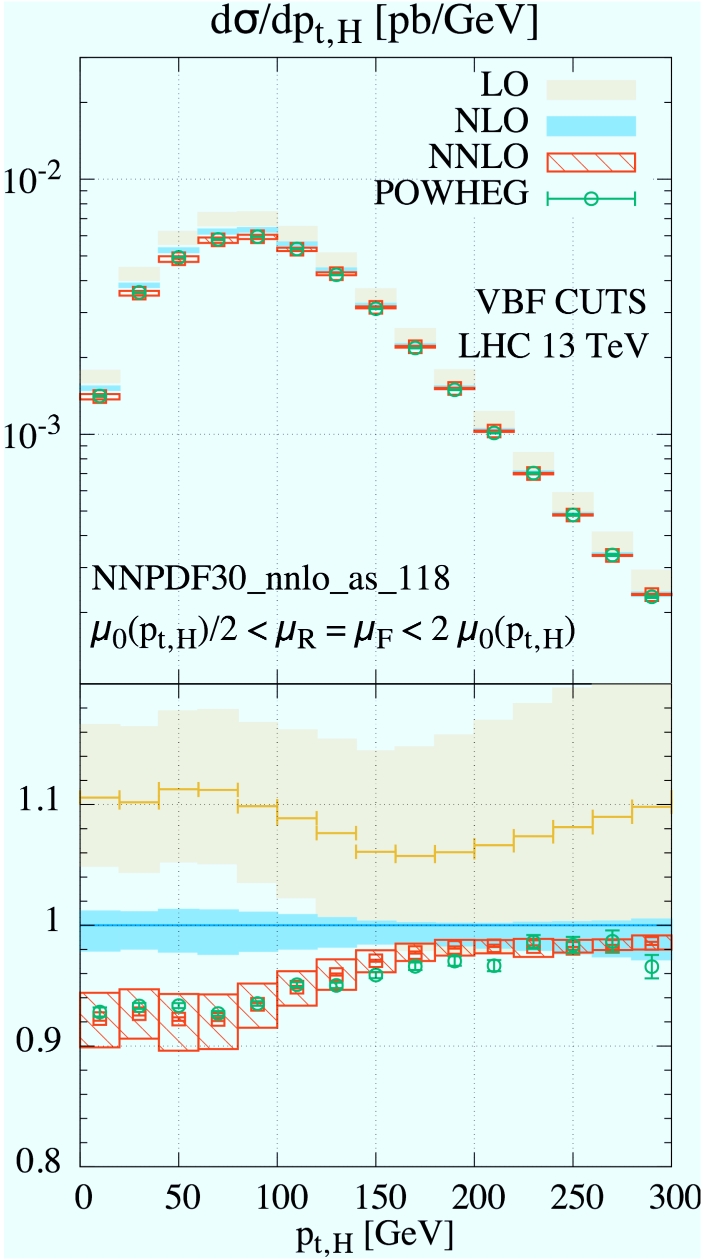
$\rightarrow$ fewer events pass VBF cuts



Cacciari et al. (2015)

VBF @ NNLO: exclusive results

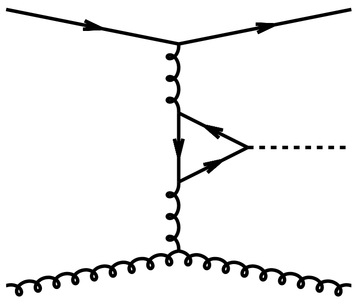


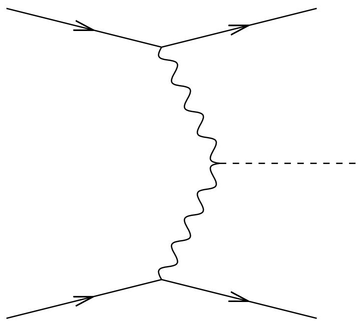


Cacciari et al. (2015)

$pp \to Hjj$ via gluon fusion

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





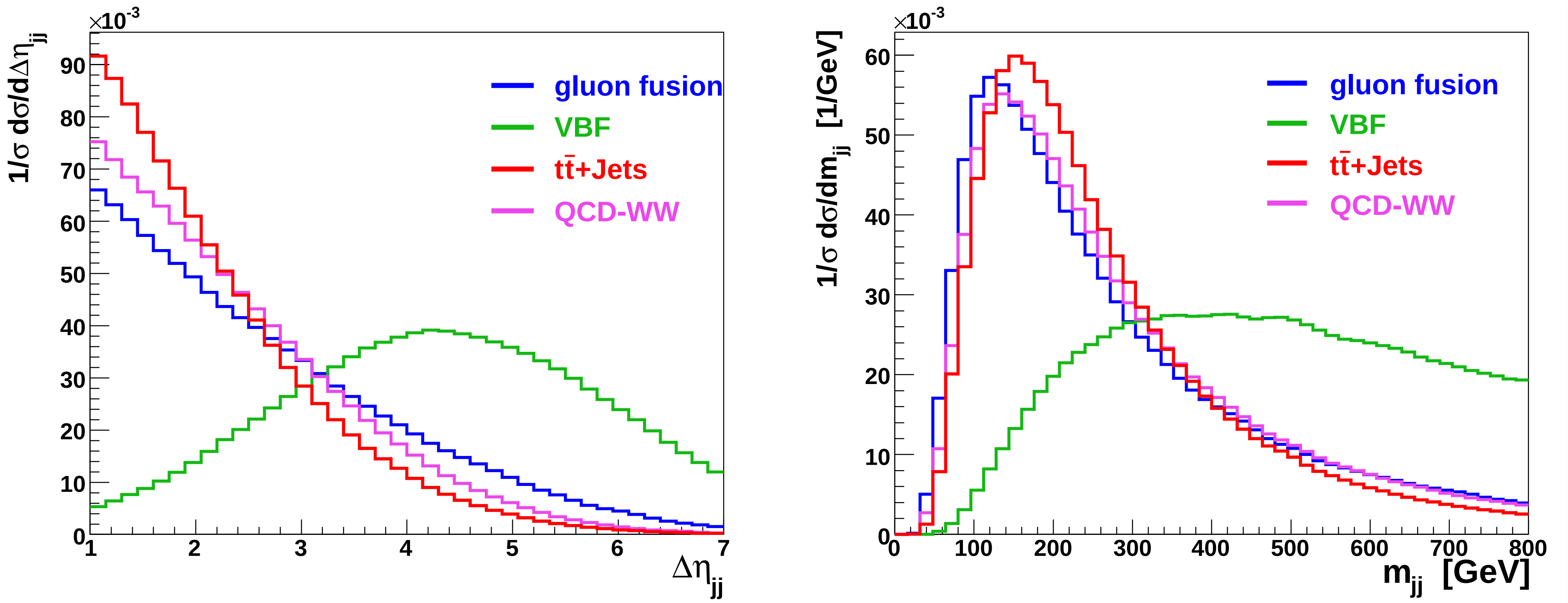
complete LO calculation (including pentagons):
Del Duca, Kilgore, Oleari, Schmidt, Zeppenfeld (2001)

NLO QCD calculation in $m_t \to \infty$ limit:
Campbell, Ellis, Zanderighi (2006); Greiner et al. (2013)

need to understand phenomenology of both processes to distinguish between them

$pp \to Hjj$ via gluon fusion

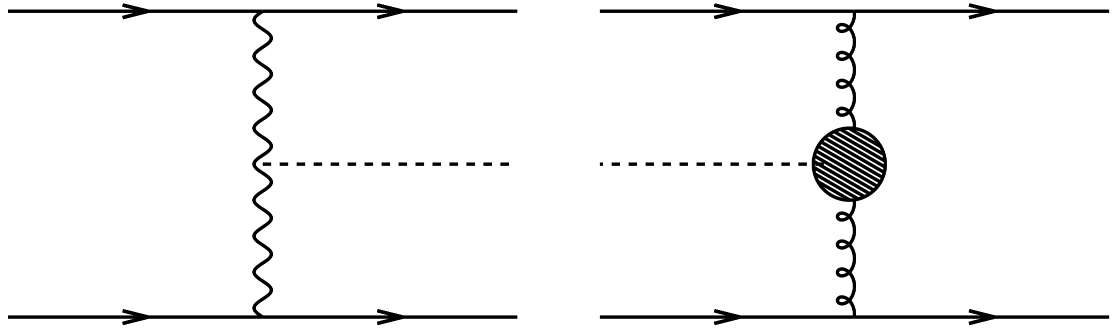
apply cuts to separate VBF from gluon fusion (GF)



Klämke, Zeppenfeld (2007)

$pp \to Hjj$ 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

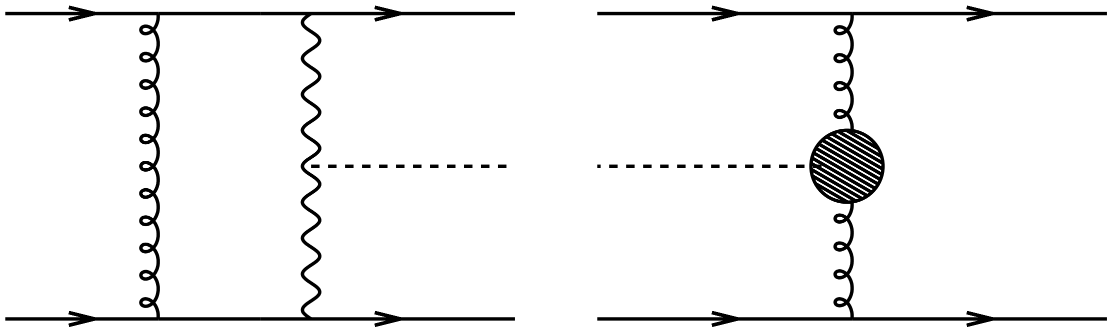
- neutral current graphs (no charged current interference)
- identical quark contributions with $t \leftrightarrow u$ crossing (kinematically suppressed)

☞ completely negligible

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

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

(no $t \leftrightarrow u$ crossing necessary)

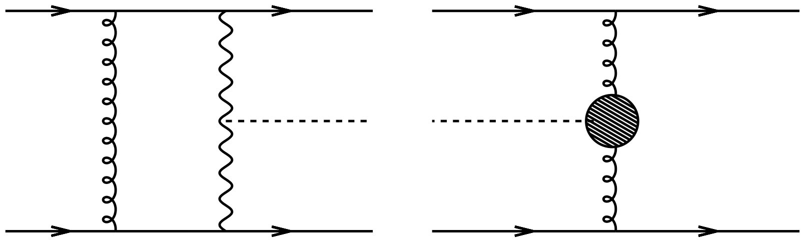


☞ speculations that the size of the one-loop interference could be comparable to the size of the one-loop NLO-QCD corrections to the VBF and the GF processes

virtual contributions

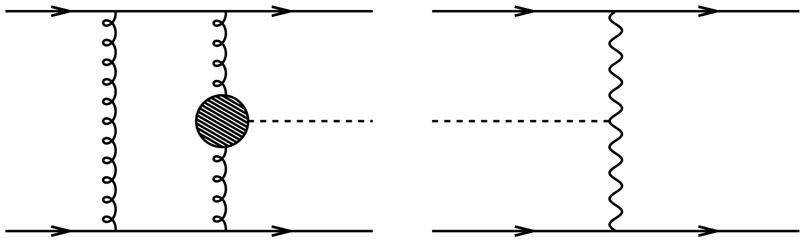
within VBF approximation need two types of loop contributions:

- interference of VBF@1-loop with GF at LO



$$\mathcal{M}_{\mathbf{VBF}}^{(\mathbf{1-loop})} \cdot \mathcal{M}_{\mathbf{GF}}^{(\mathbf{0})\star}$$

- interference of GF@1-loop with VBF at LO

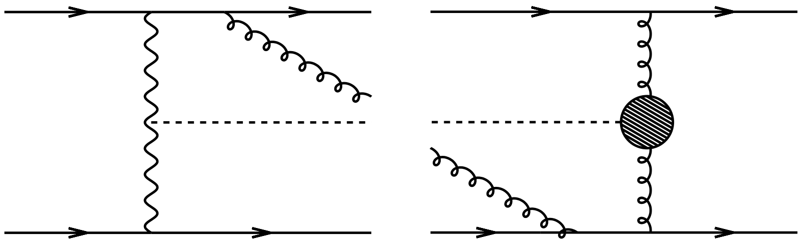


$$\mathcal{M}_{\mathbf{GF}}^{(\mathbf{1-loop})} \cdot \mathcal{M}_{\mathbf{VBF}}^{(\mathbf{0})\star}$$

all bubble, triangle, and box corrections vanish
due to color conservation ➠ pentagon diagrams only!

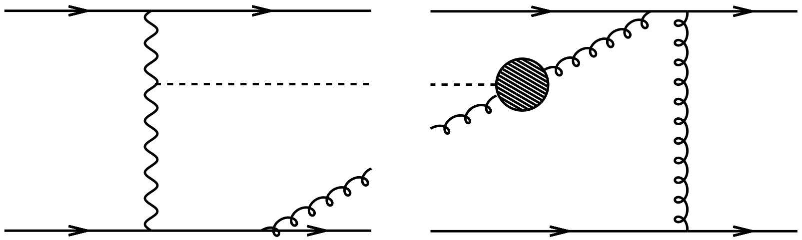
real emission contributions

- gluons emitted from different fermion lines, Higgs in t-channel



$$\mathcal{M}_{\mathbf{VBF}}^{(\mathbf{real})} \cdot \mathcal{M}_{\mathbf{GF}}^{(\mathbf{real,t})\star}$$

- gluon (VBF) / gluon-plus-Higgs (GF) from different fermion lines



$$\mathcal{M}_{\mathbf{VBF}}^{(\mathbf{real})} \cdot \mathcal{M}_{\mathbf{GF}}^{(\mathbf{real,f})\star}$$

- no contributions from: · gq-scattering diagrams
  · interference of graphs with gluon emission from the same fermion line in VBF and GF

. . . numbers . . .

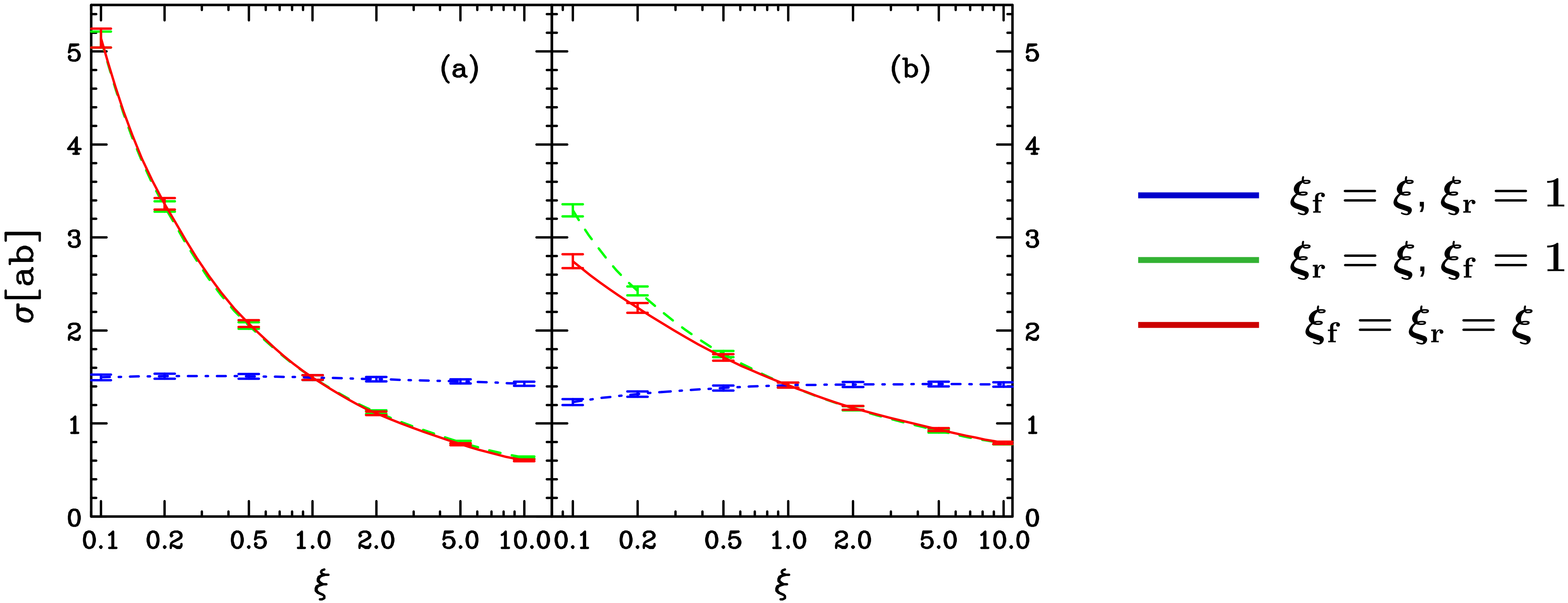
is clean VBF signature
contaminated by
interference
contribution?

cuts and settings

apply k_T algorithm, CTEQ6 parton distributions, and typical VBF cuts:

tagging jets	$p_{Tj} \geq 20$ GeV, $\lvert y_j\rvert \leq 4.5$, $\Delta y_{jj} = \lvert y_{j_1} - y_{j_2}\rvert > 4$, $M_{jj} > 600$ GeV jets located in opposite hemispheres
for $H \to \ell\ell'$ $(\ell = \gamma, b \ldots)$	$p_{T\ell} \geq 20$ GeV, $\lvert\eta_\ell\rvert \leq 2.5$, $\Delta R_{j\ell} \geq 0.6$, $y_{j,min} < \eta_\ell < y_{j,max}$ $m_H = 120$ GeV

scale uncertainty



study dependence of interference x-sec on choice and value of scale $\to$ two settings:

(a) $\mu_f = \xi_f m_H\,, \alpha_s^3(\mu_r) = \alpha_s^3(\xi_r m_H)$

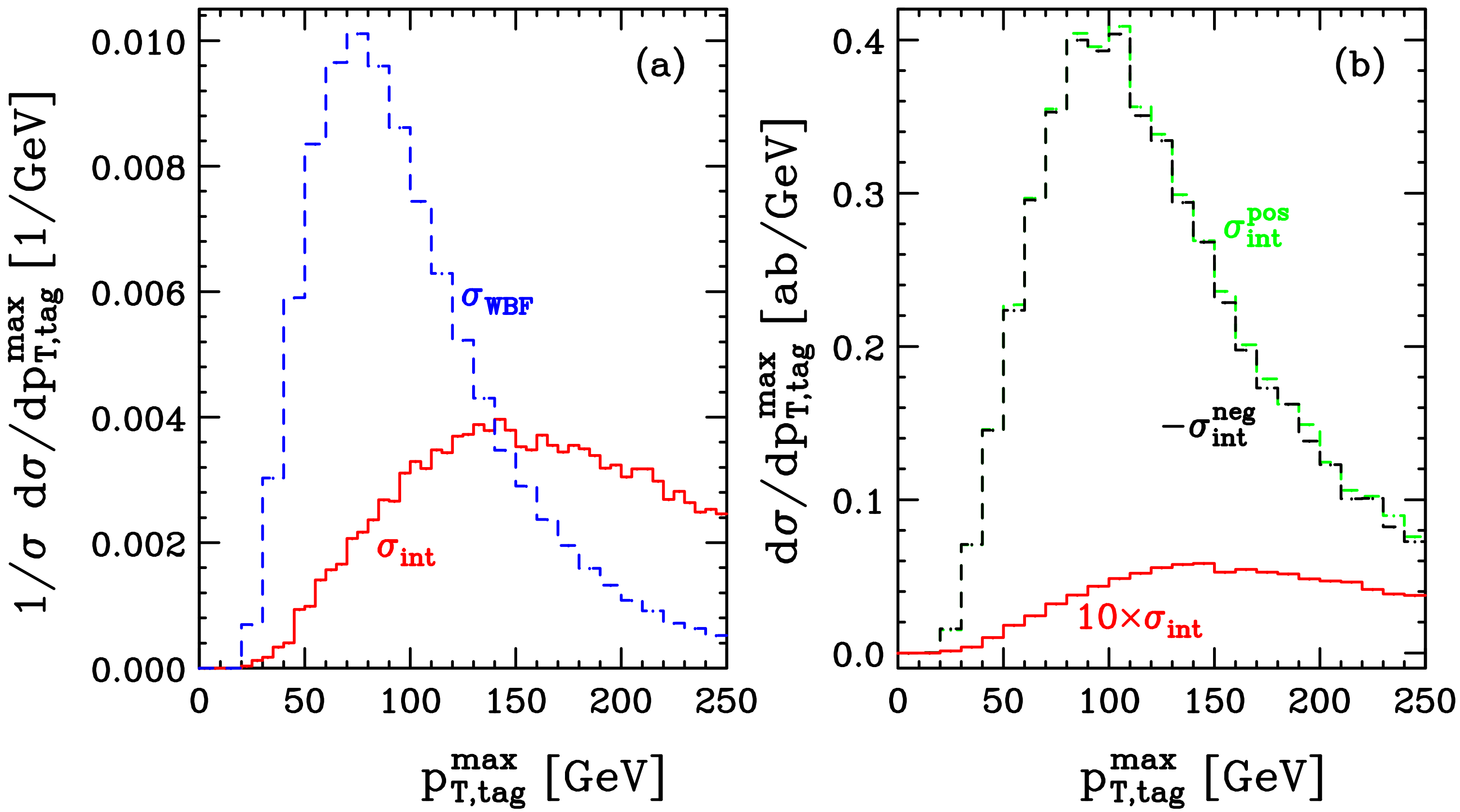
(b) $\mu_f = \xi_f\, p_{Tj}\,, \alpha_s^3(\mu_r) = \alpha_s(\xi_r p_{T1}) \cdot \alpha_s(\xi_r p_{T2}) \cdot \alpha_s(\xi_r m_H)$

. . . numbers . . .

explicit calculation reveals strong cancelation effects
in the total interference cross section

initial state	interaction	isospin	$\sigma_{\text{int}}^{\text{cuts}}$ [ab]	$\sigma_{\text{VBF}}^{\text{cuts}}$ [fb]
qq	NC	+ + or - -	51.4	72.3
	NC	+ - or - +	-49.8	70.8
	CC	+ - or - +	–	405.7
$q\bar{q}$	NC	+ - or - +	-3.1	39.3
	NC	+ + or - -	2.2	43.0
	CC	+ + or - -	–	230.7
$\bar{q}\bar{q}$	NC	- - or + +	4.0	5.1
	NC	- + or + -	-3.2	4.3
	CC	- + or + -	–	25.7
sum	NC+CC	all	1.5	896.9

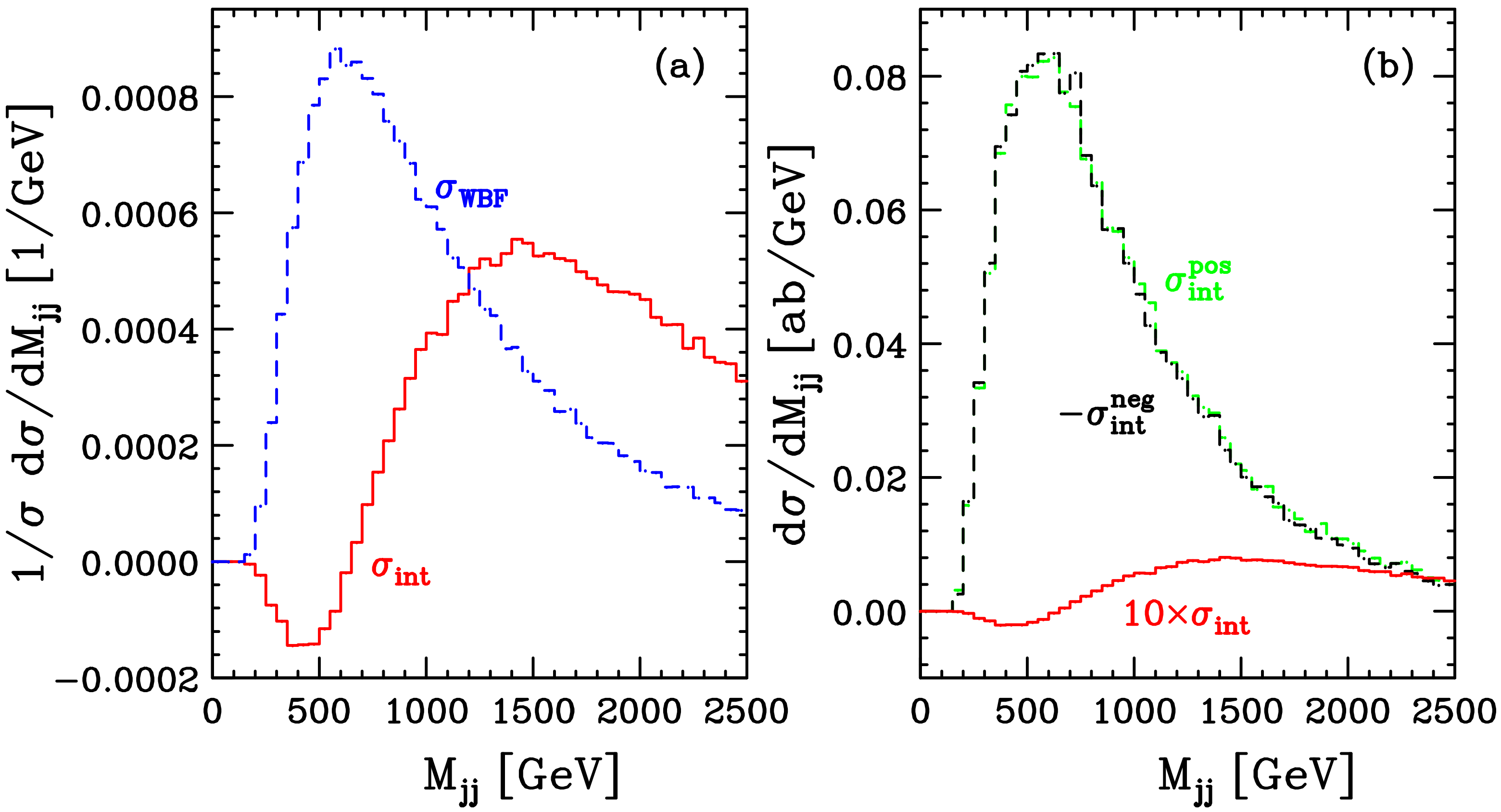
distributions: p_T of tagging jet



cancelations lead to unexpected shapes of distributions

but: σ_{int} tiny $\rightarrow$ no effect on VBF signal

distributions: dijet invariant mass



reminder: pure GF . . . softer M_{jj} distribution than pure VBF!

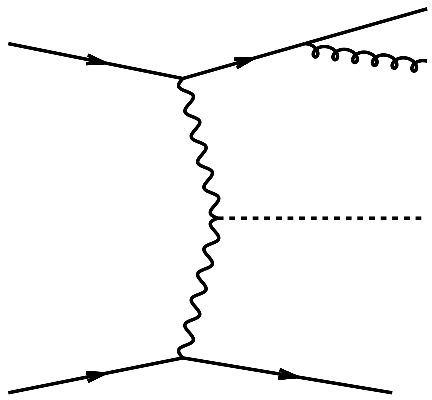
distributions: rapidity separation

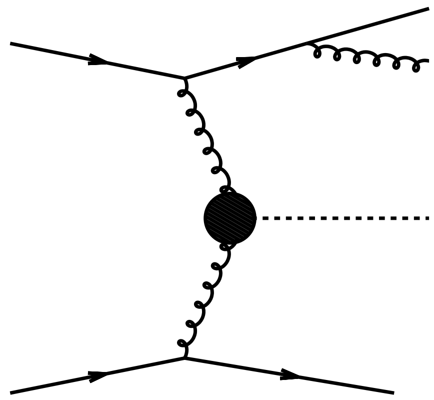
what about rapidity distribution of

third, non-tagged jet in $Hjjj$ events?

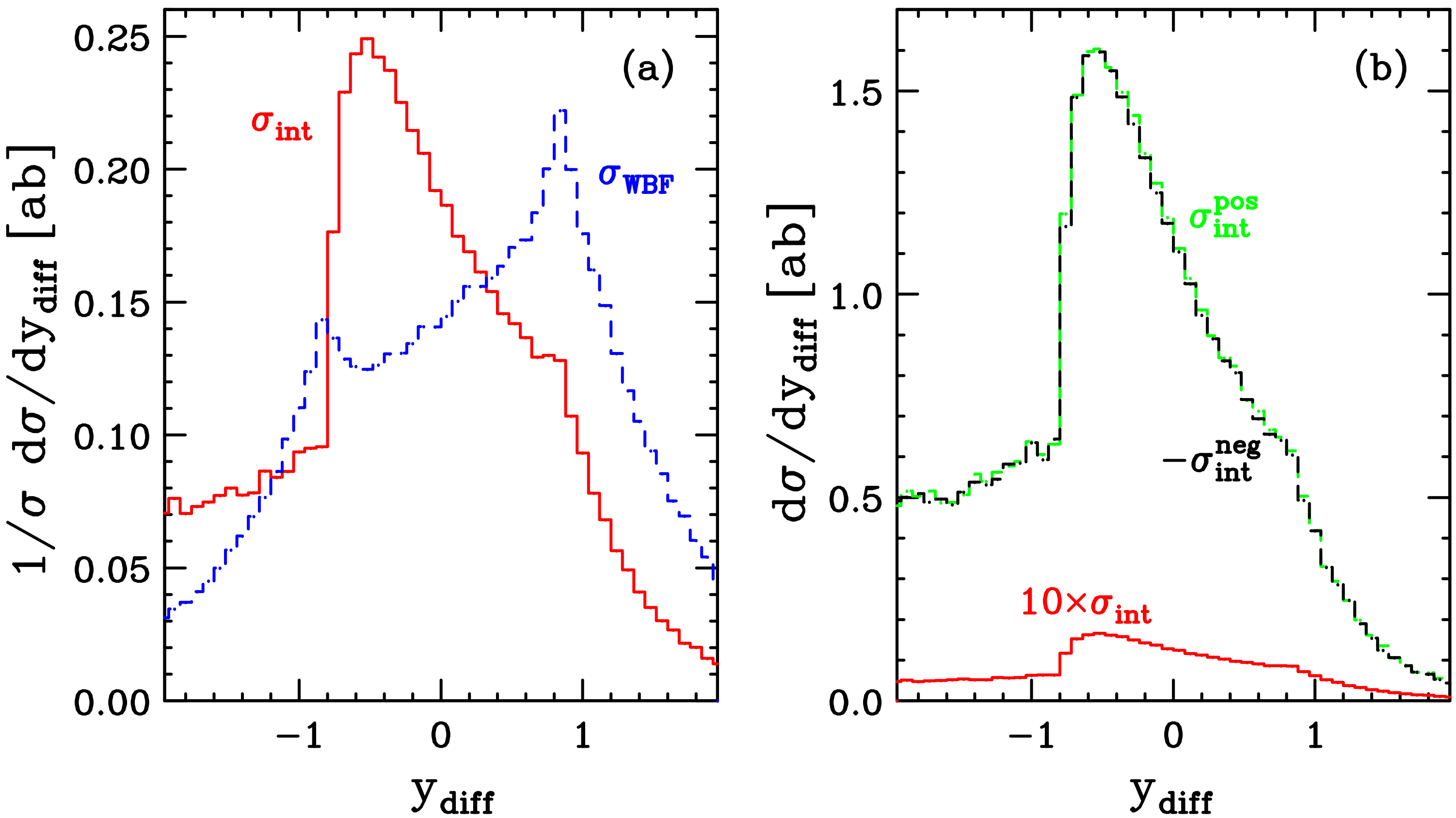
consider separation of third jet from positive-rapidity jet:

$$y_{\text{diff}} = y_3 - \max(y_1, y_2)$$



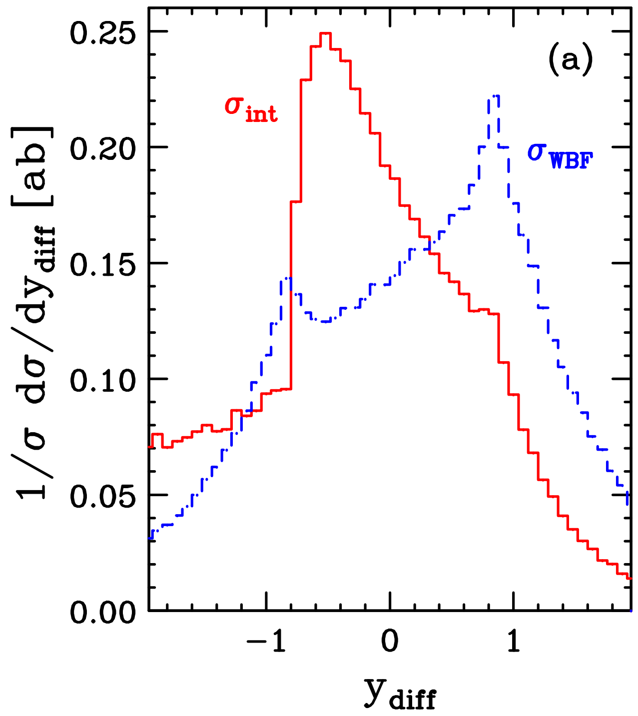


distributions: rapidity separation



cancelations do not affect shape of $y_{\text{diff}} = y_3 - \max(y_1, y_2)$
as strongly as M_{jj} and p_{Tj} distributions

distributions: rapidity separation



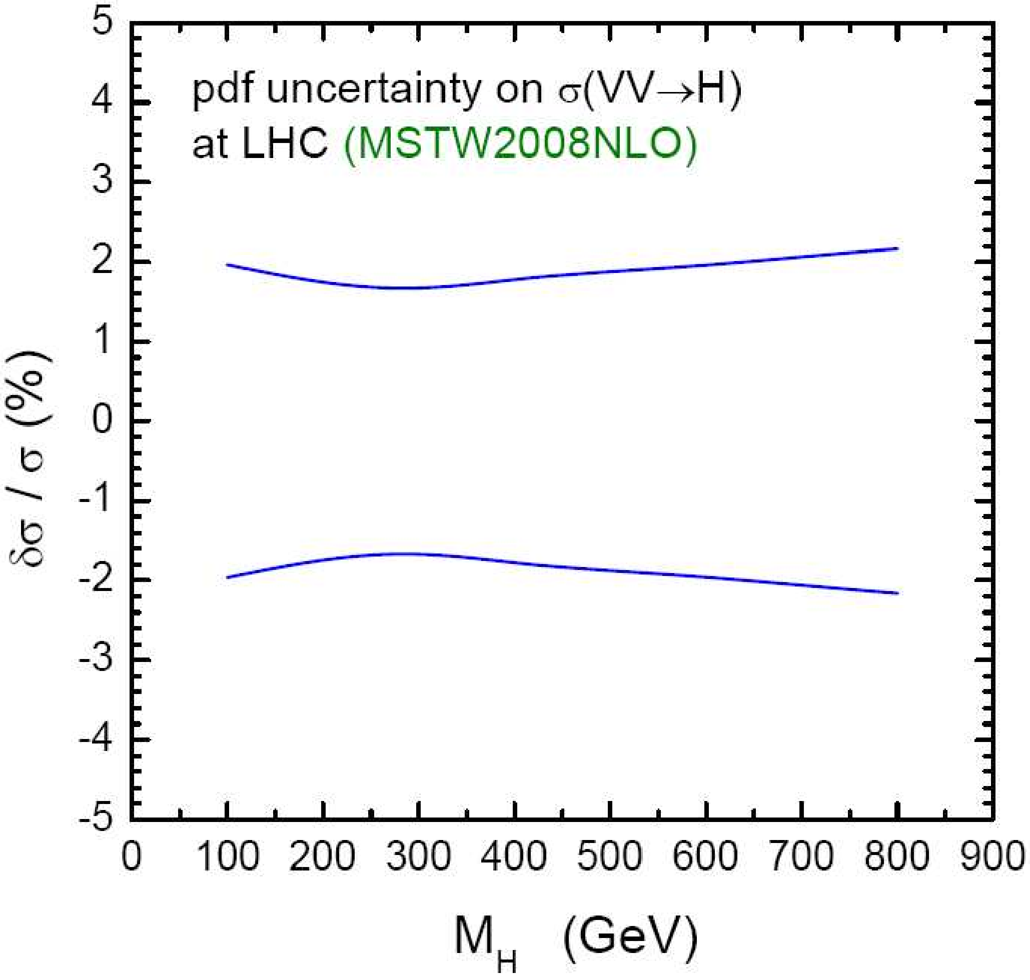
- $|\mathbf{VBF}|^2$ and VBF× GF peak at small values of $|y_{\rm diff}| \lesssim 1$
  - ➠ soft jet close to considered hard jet
- $|\mathbf{VBF}|^2$: $y_{\rm soft} > y_{\rm hard}$
  - ➠ soft jet located “outside” tag jets
- VBF× GF: $y_{\rm soft} < y_{\rm hard}$
  - ➠ soft jet located between tag jets

☞ rapidity gap for color singlet weak boson exchange can be filled by QCD-EW interference contribution

wrap up: interference contributions

- GF$\times$ VBF loop-interference contributions for Hjj production at the LHC exibit interesting features different from VBF (unexpected shapes of distributions due to cancellation effects)
- but: numerical effects on the signal are tiny
- predicting size and shape of higher order corrections by plausibility considerations can be dangerous
- confirming the small impact of higher order contributions and interference effects by explicit calculations strengthens VBF as a promising Higgs boson search channel at the LHC

PDF uncertainties in VBF



CTEQ:

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

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

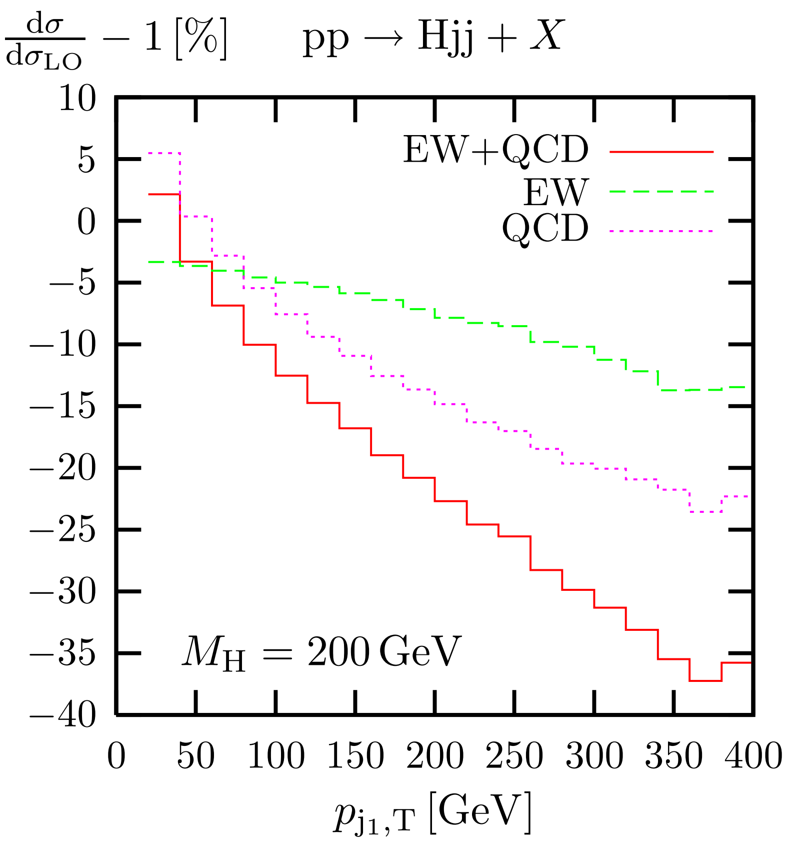
for 100 GeV $\leq \boldsymbol{M_H} \leq$ 800 GeV

Higgs production in VBF @ NLO EW

Ciccolini, Denner, Dittmaier (2007):

NLO EW corrections to inclusive cross sections and distributions

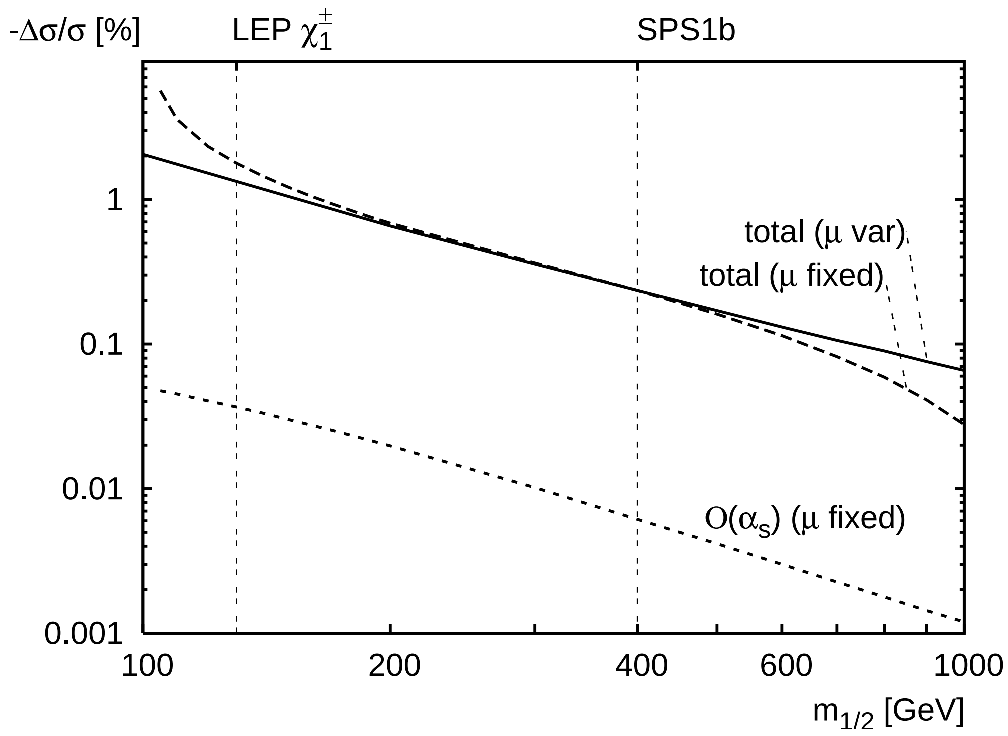
☞ NLO EW corrections non-negligible, modify K factors and distort distributions by up to 10%



publicly available parton-level Monte Carlo: HAWK

[Denner, Dittmaier, Mück]

SUSY QCD+EW corrections to VBF



Hollik, Plehn, Rauch, Rzehak (2008):

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

for inclusive cross sections

in typical regions of the MSSM parameter space

review perturbative corrections

- NLO QCD and EW corrections:
  modify K factors and distort distributions by up to 10%
- interference with Hjj production via gluon fusion: negligible
- SUSY corrections: $\lesssim$ 1% for representative parameter points
- gluon-induced virtual NNLO-QCD corrections (one-loop squared):
  numerically irrelevant in all considered regions
- DIS-type NNLO-QCD corrections (structure function approach):
  - further reduce scale uncertainties of total cross sections;
  - effects on differential distributions non-negligible

Higgs production in VBF: more corrections

- NLO QCD and EW corrections:
  modify K factors and distort distributions by up to 10%
- interference with Hjj production via gluon fusion: negligible
- SUSY corrections: $\lesssim$ 1% for representative parameter points
- gluon-induced virtual NNLO-QCD corrections (one-loop squared):
  numerically irrelevant in all considered regions
- DIS-type NNLO-QCD corrections (structure function approach):
  - further reduce scale uncertainties of total cross sections;
  - effects on differential distributions non-negligible

PERTURBATIVE CORRECTIONS ARE SMALL

but:

establishing a signal requires also sufficient knowledge of ...

...background contributions

VBF: signal & backgrounds

distinct event topology of the Higgs signal in

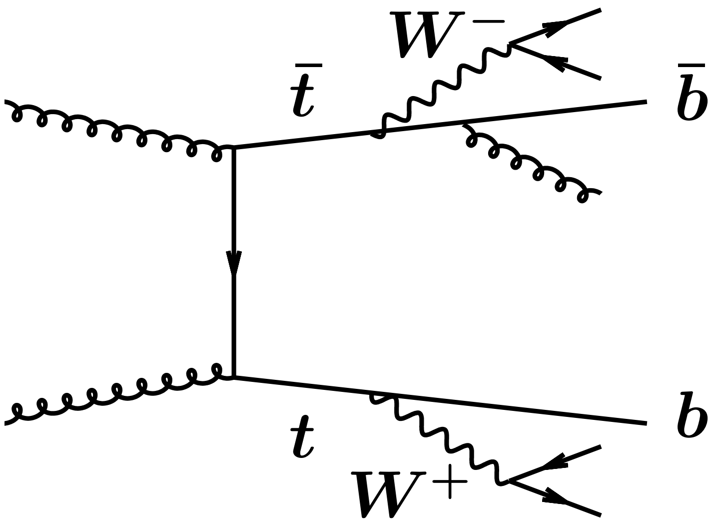
$pp \to Hjj$ via VBF with

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

☞ important for suppression of backgrounds

- $t\bar{t} + 0, 1, 2\,\mathrm{jets}$ production
  (note: $t\bar{t} \to W^+W^- b\bar{b}$)
- $pp \to Hjj$ via gluon fusion
  (followed by $H \to W^+W^-$)
- 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

↓

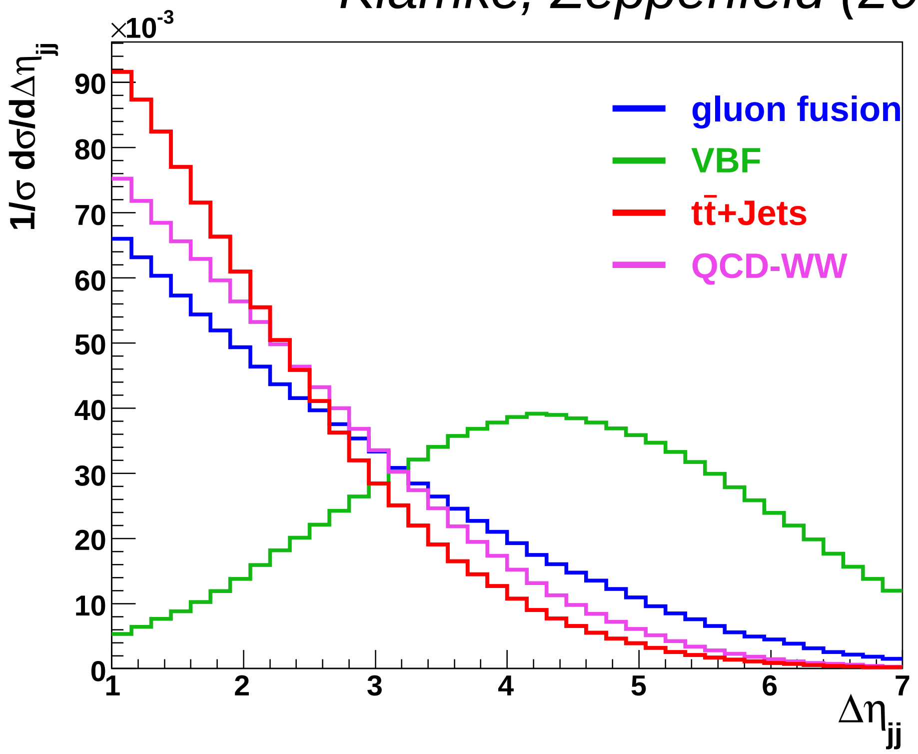
final-state configuration similar to Higgs signal in VBF

but distributions can be employed to suppress top backgrounds

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

↓

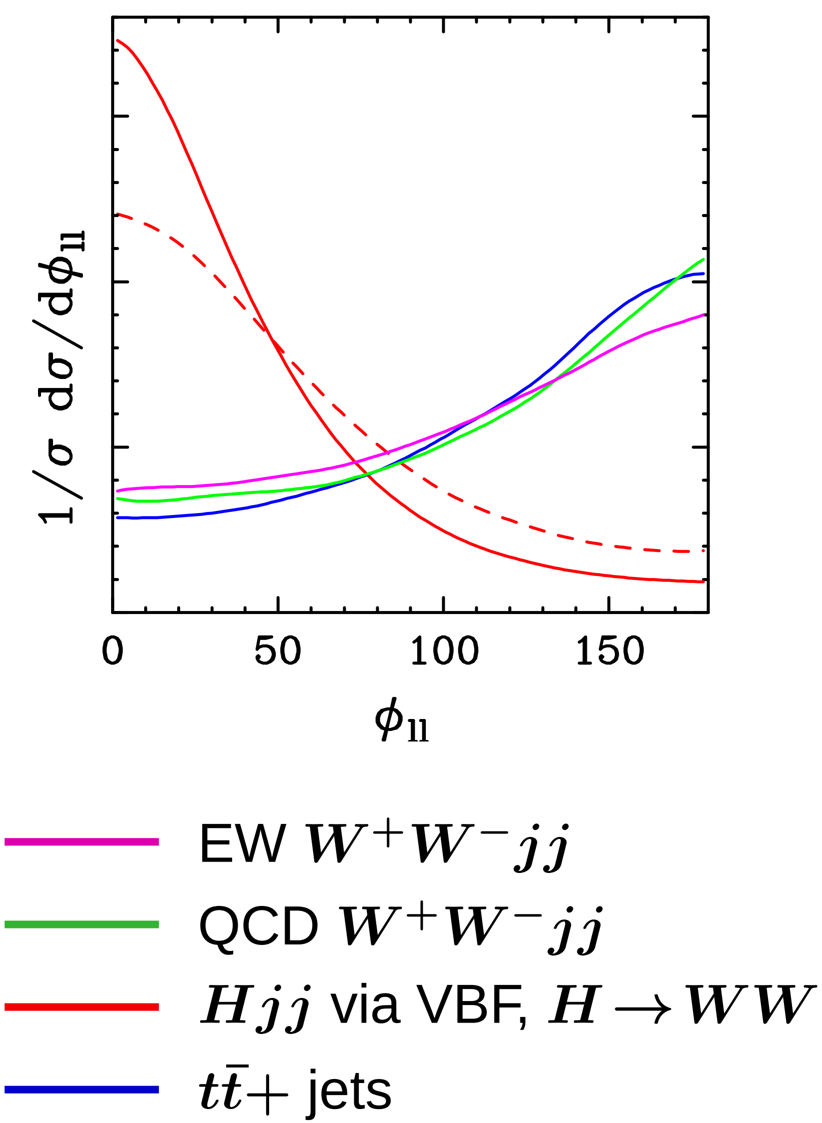
leptons emitted preferentially in same direction

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)



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

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

cuts	Hjj	$t\bar{t}$+jets	QCD $WWjj$	EW $WWjj$	...	S / B
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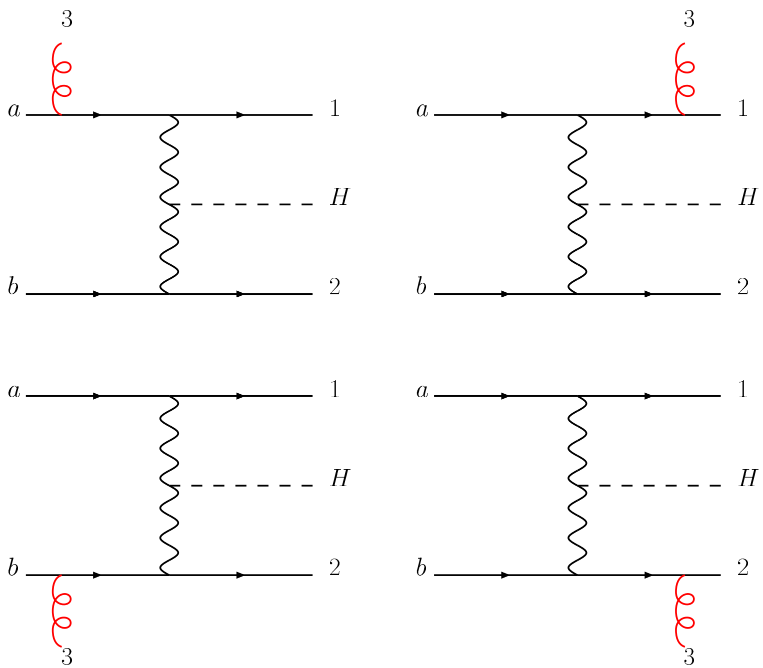
$$p_T^{\mathrm{veto}} > 20 \text{ GeV}, \ \eta_{\mathrm{jet}}^{\mathrm{min}} < \eta_{\mathrm{jet}}^{\mathrm{veto}} < \eta_{\mathrm{jet}}^{\mathrm{max}}$$

☞ 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

$$\mathcal{M}_B(Hjjj) \leftrightarrow \mathcal{M}_R(Hjj)$$



Figy, Hankele, Zeppenfeld (2007):

NLO-QCD in VBF approximation

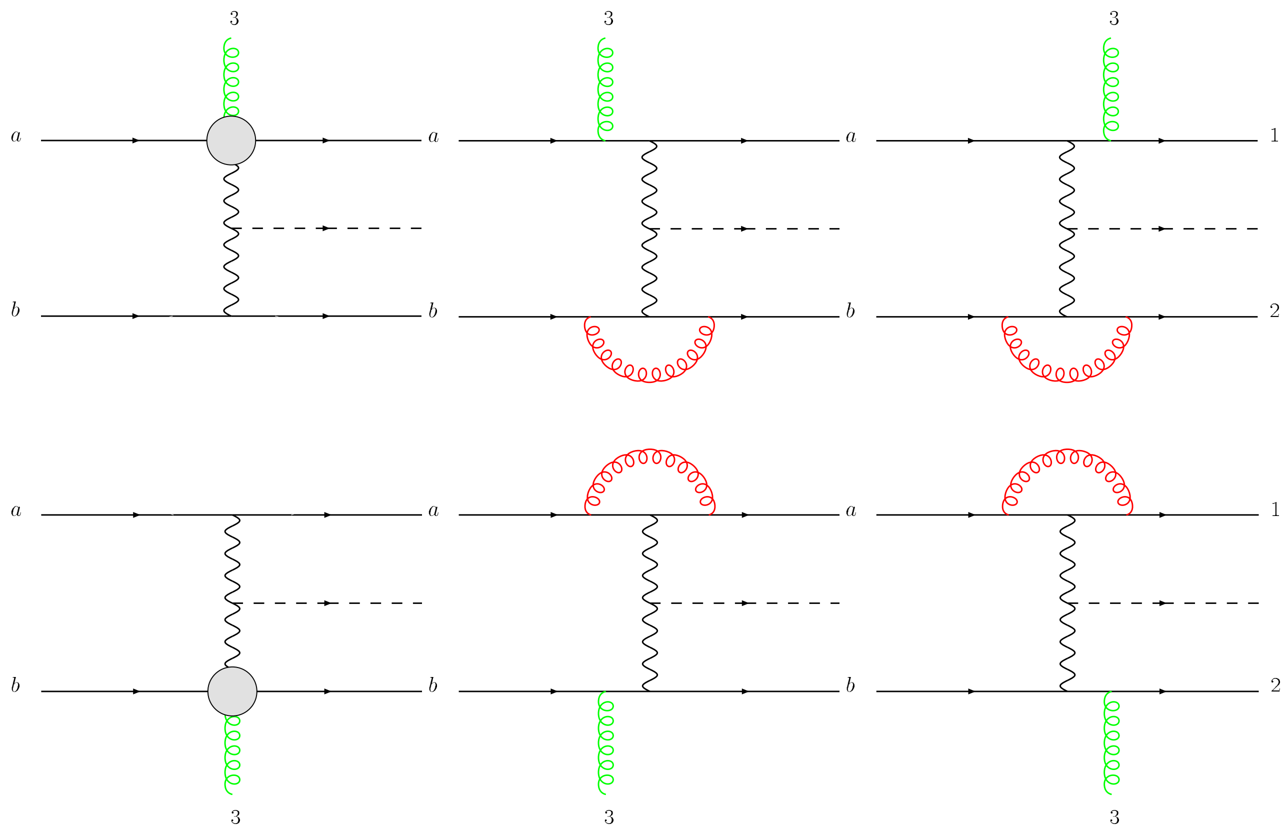
(no color exchange between upper/lower quark lines, no VH-type contributions)

Campanario, Figy, Plätzer, Sjödahl (2013):

full NLO-QCD calculation

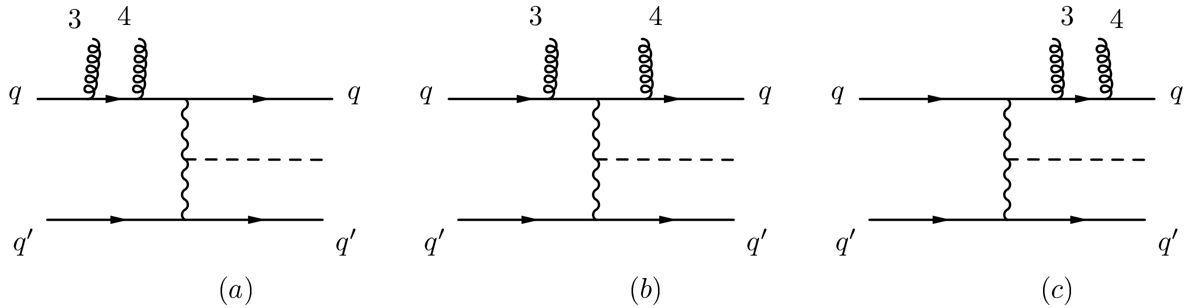
(good agreement with approximative calculation)

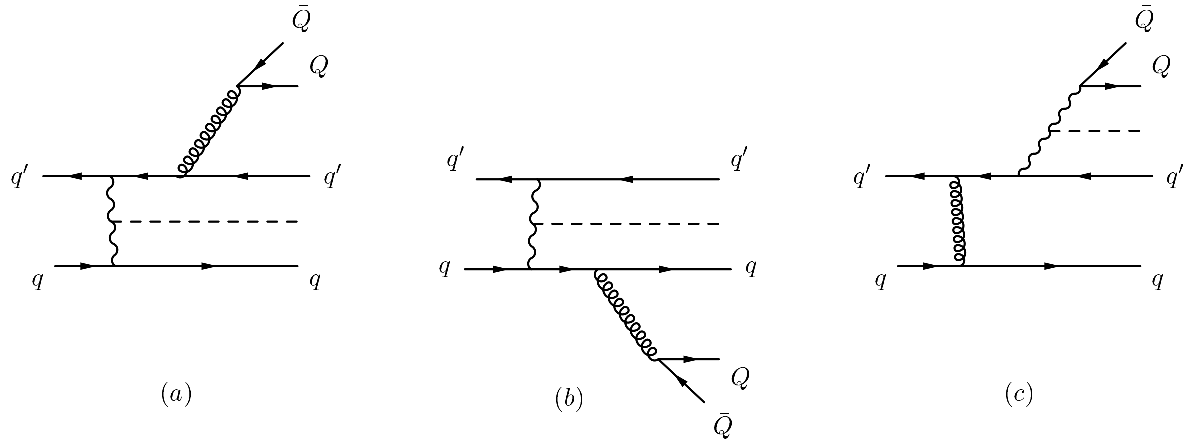
$pp \to Hjjj$ via VBF @ NLO QCD



dominant virtual corrections require computation of triangle, box, and pentagon diagrams

$pp \to Hjjj$ via VBF @ NLO QCD

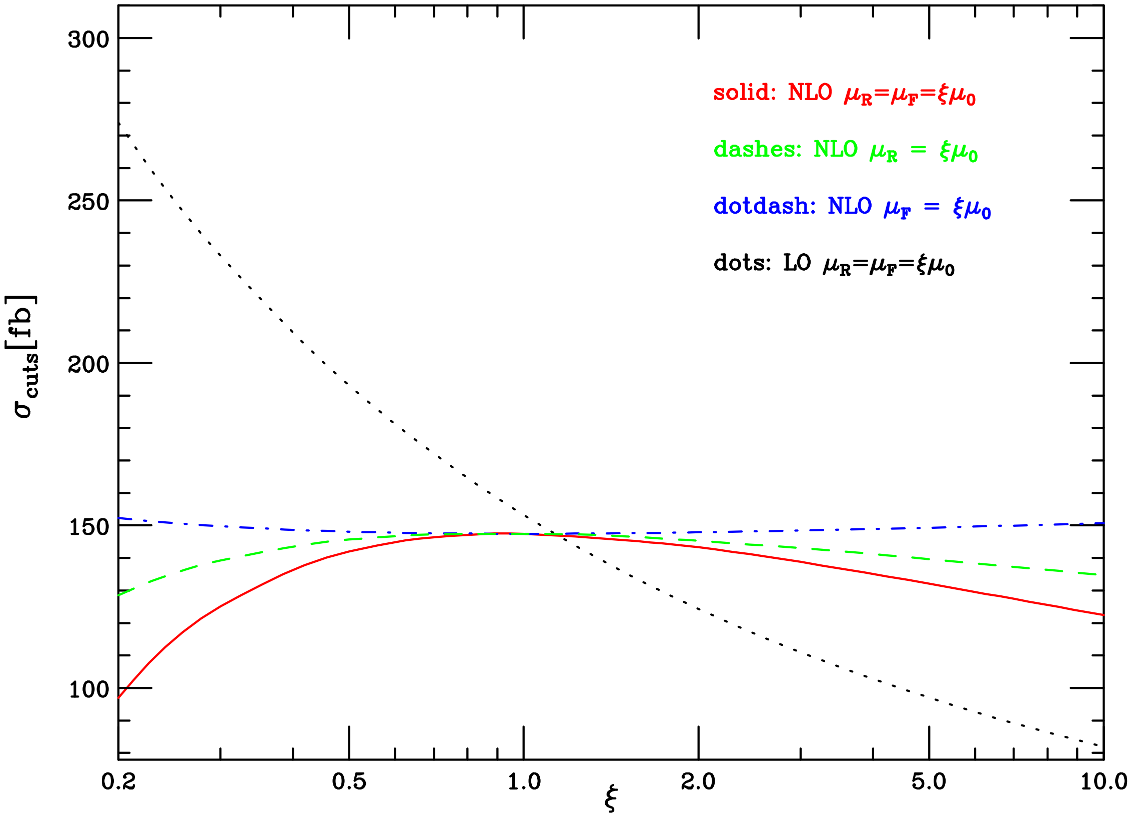




real emission contributions comprise processes with
4 quarks+2 gluons and processes with 6 quarks

$pp \to Hjjj$ via VBF @ NLO QCD

Figy, Hankele, Zeppenfeld (2007)



scale dependence moderate
(comparable to other VBF processes)

$pp \to Hjjj$ via VBF @ NLO QCD

central jet veto (CJV):

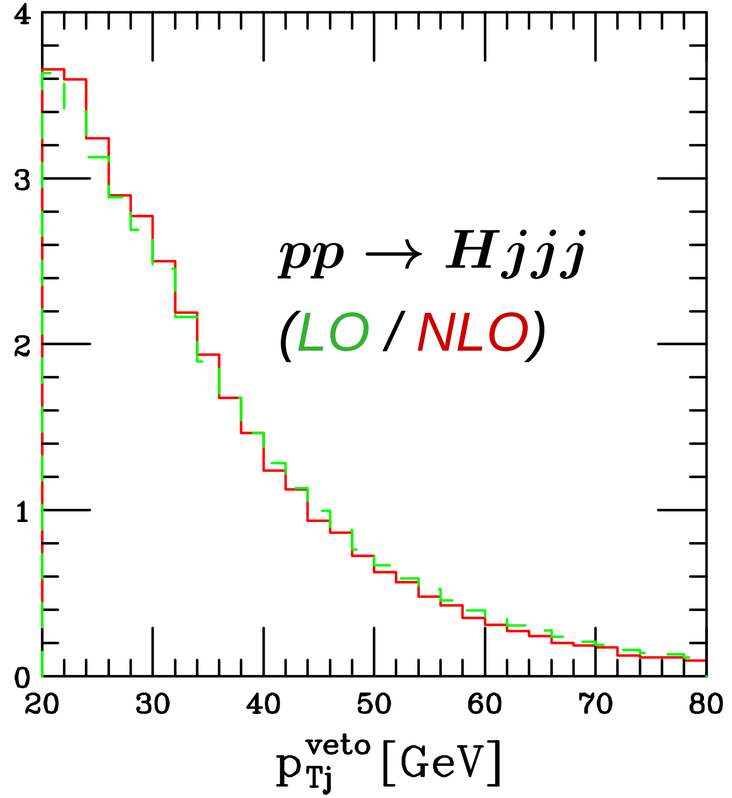
important tool for suppression of QCD backgrounds

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

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

☞ need precise predictions for distributions of $3^{\rm rd}$ jet

Figy, Hankele, Zeppenfeld (2007)



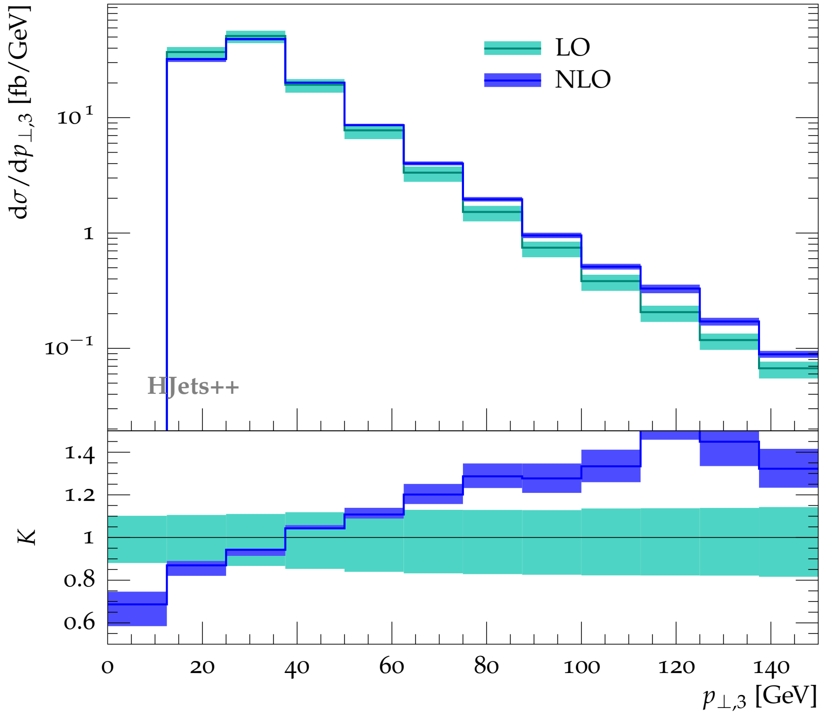
✦ (dominant) NLO-QCD corrections modest

✦ scale uncertainties of CJV observables significantly reduced

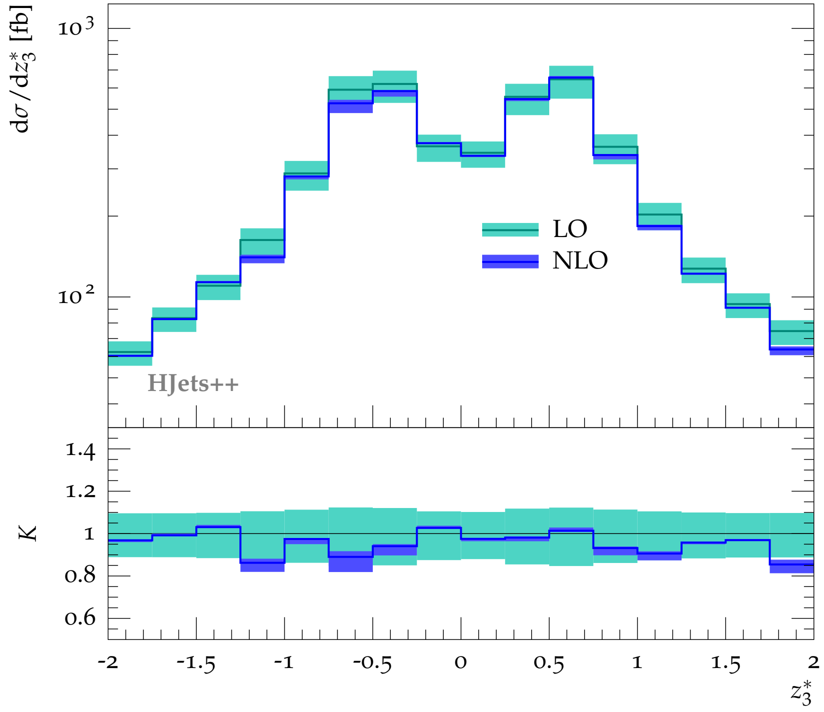
$pp \to Hjjj$ via VBF @ NLO QCD

Campanario et al. (2013)

transverse momentum of 3^{rd} jet

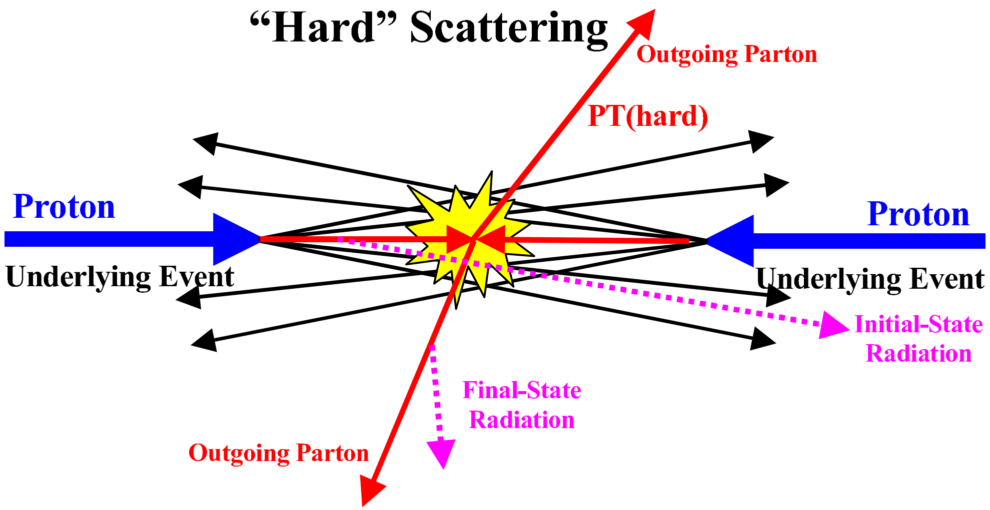


relative rapidity of 3^{rd} jet



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

more realistic simulation



for realistic description of scattering processes at hadron colliders:

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

underlying event, parton shower, and hadronization

(PYTHIA, HERWIG, SHERPA,...)

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

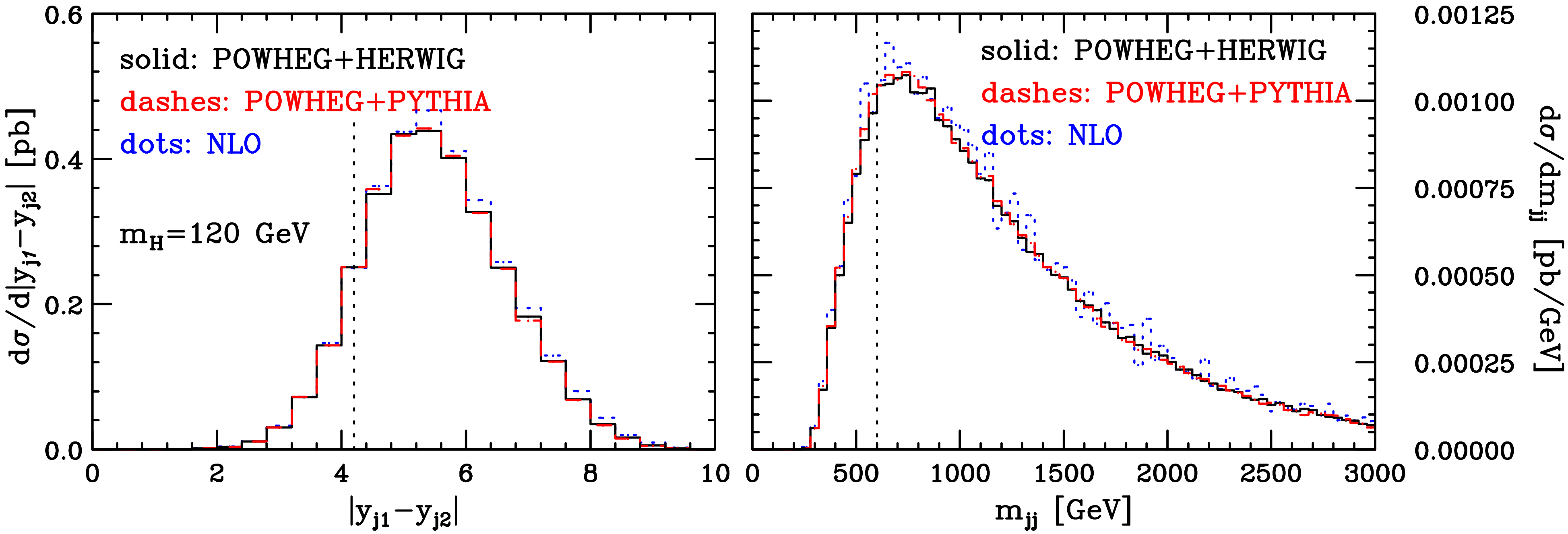
[Frixione, Nason, Oleari]

- 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

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

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

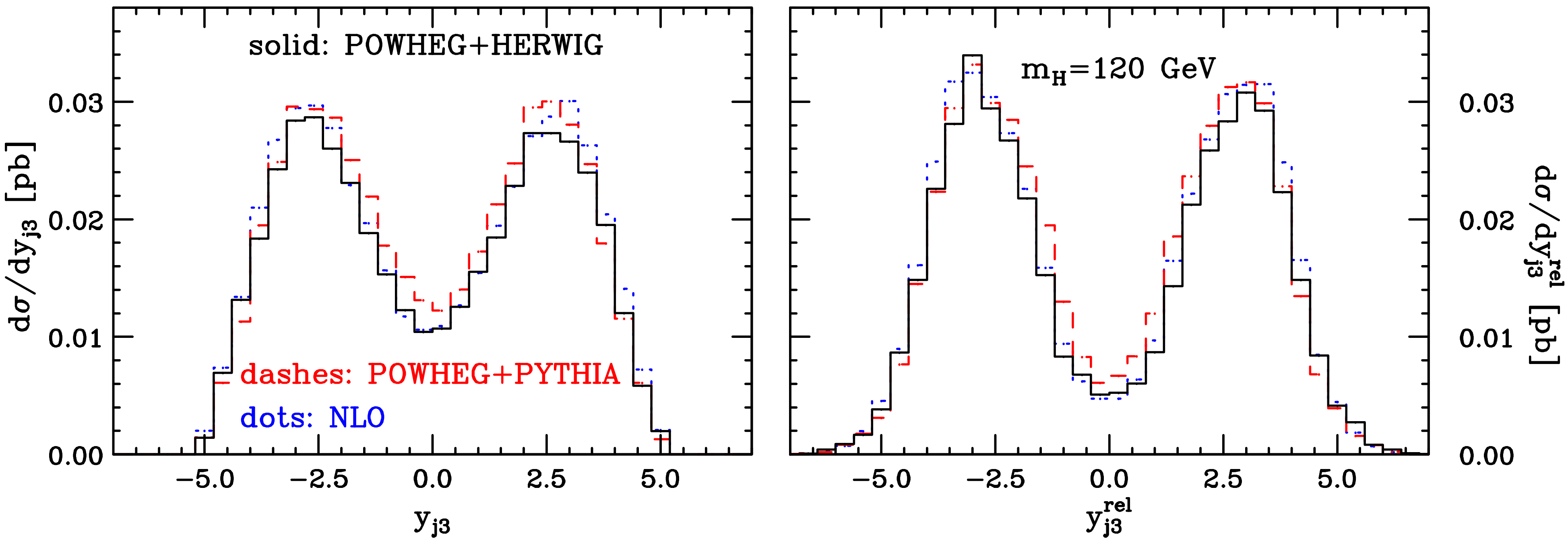
Nason, Oleari (2009)



good agreement between parton-level NLO calculation and POWHEG matched with HERWIG or PYTHIA for many observables related to hard tagging jets

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

Nason, Oleari (2009)

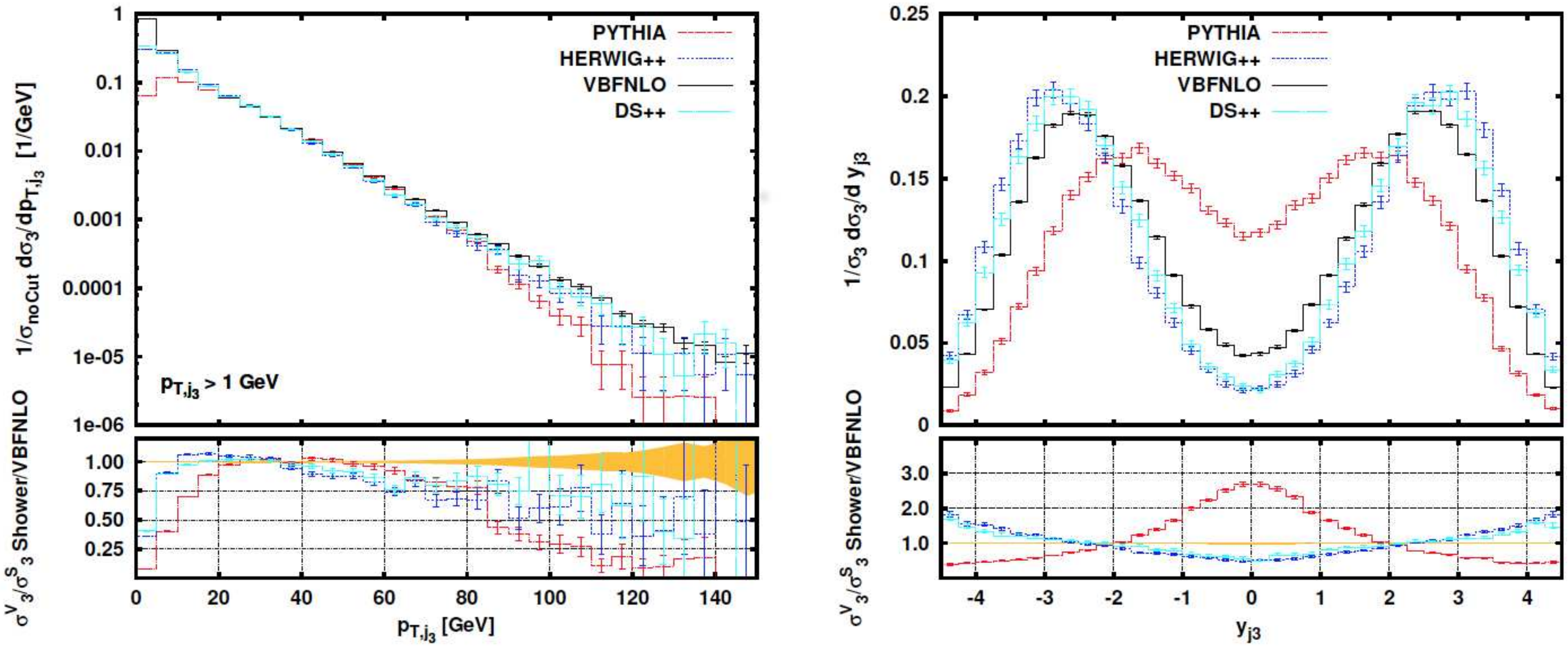


VBF Hjj matrix elements at NLO combined with parton shower

$\to$ improvement w.r.t. LO simulation

$pp \to Hjj(j)$ via VBF and parton shower @ LO

Schissler (2014)

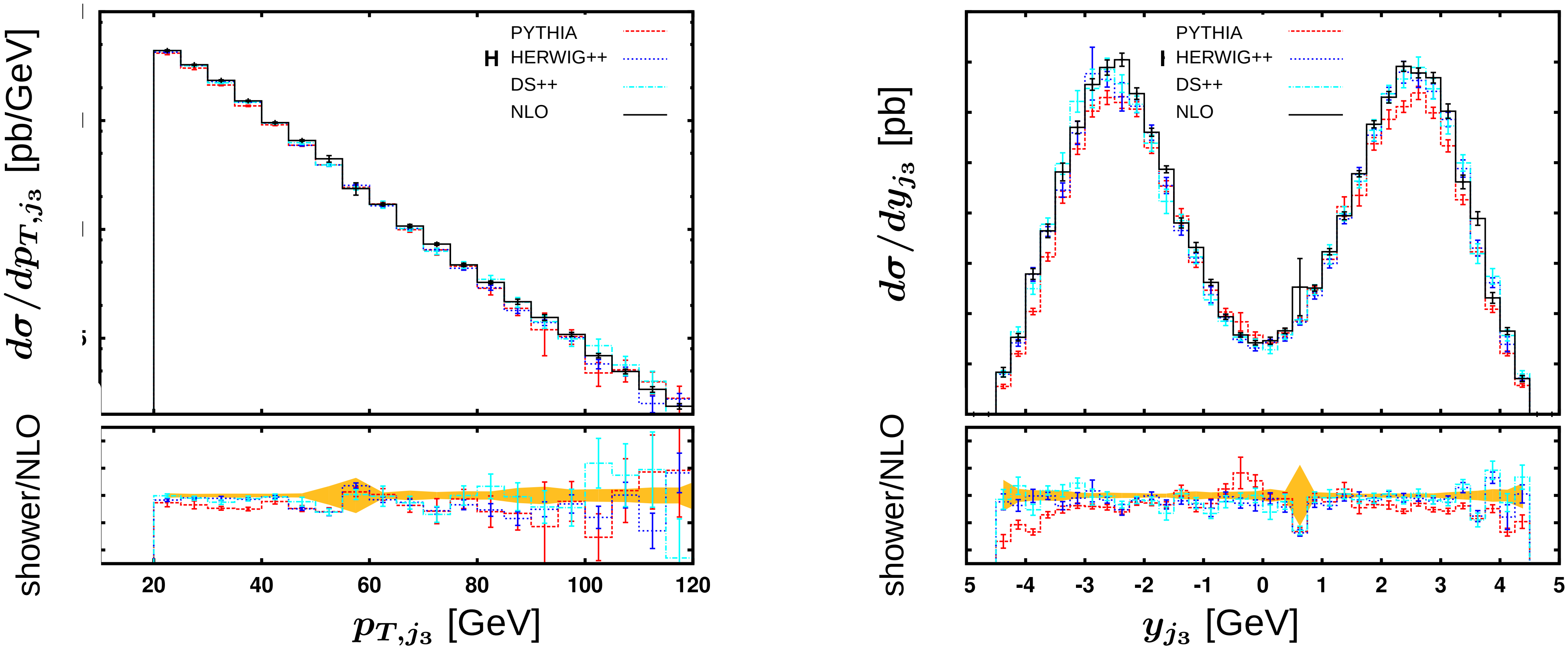


VBF Hjj matrix elements at LO combined with parton shower

$\to$ large uncertainty on 3rd jet (problematic for CJV observables)

$pp \to Hjjj$ via VBF and parton shower @ NLO QCD

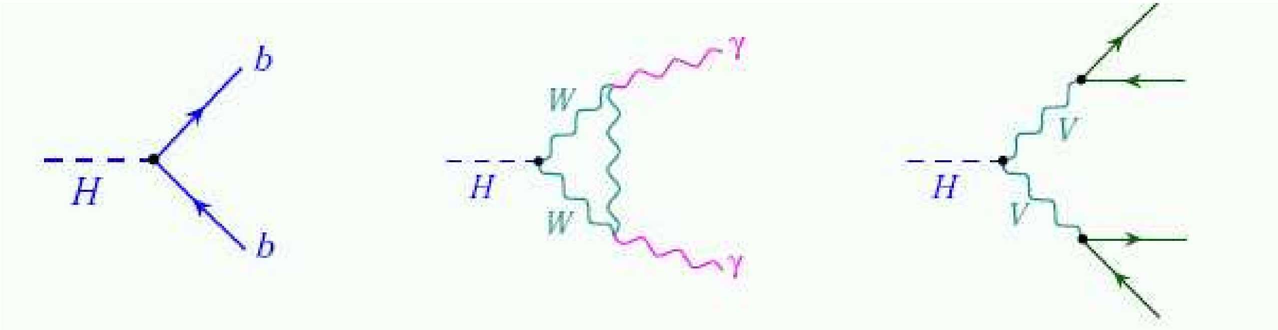
Schissler, Zeppenfeld, B.J. (2014)

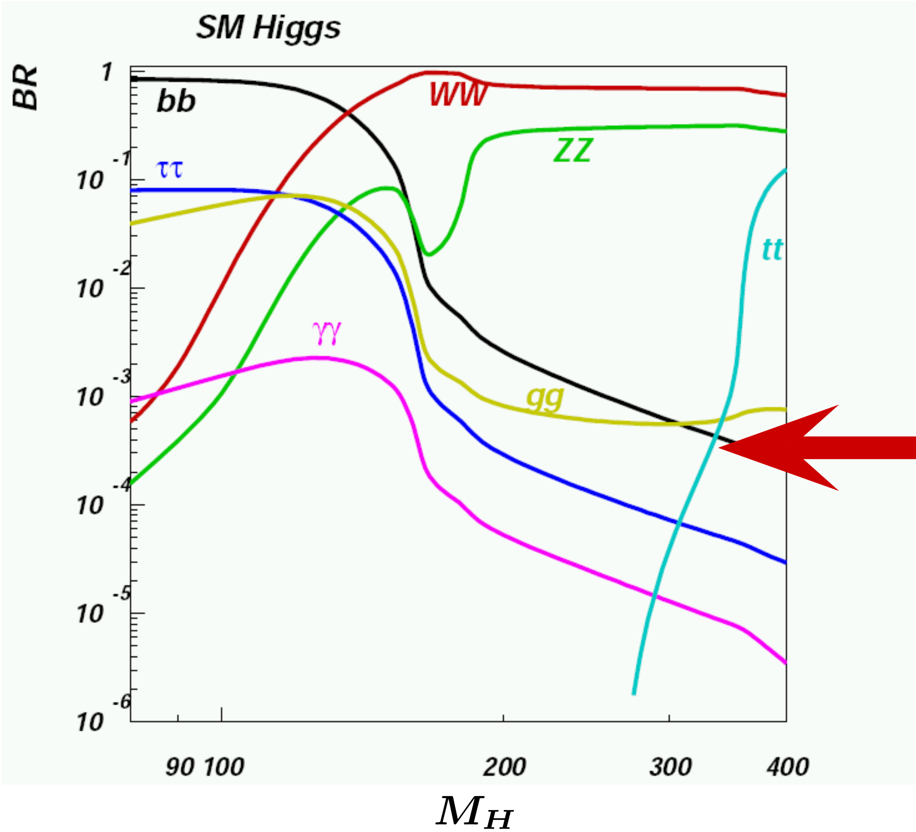


VBF $Hjjj$ matrix elements at NLO combined with parton shower

$\to$ description of 3rd jet well under control

Higgs decay





branching fractions

determination of the $Hb\bar{b}$ coupling

$H \to b\bar{b}$ is dominant decay mode for $m_H \lesssim 140$ GeV, but

accessing the bottom-quark Yukawa coupling remains difficult

$\to$ consider Higgs production at a future lepton-hadron collider

idea goes back to the 1980ies: *Hioki et al. (1983)*

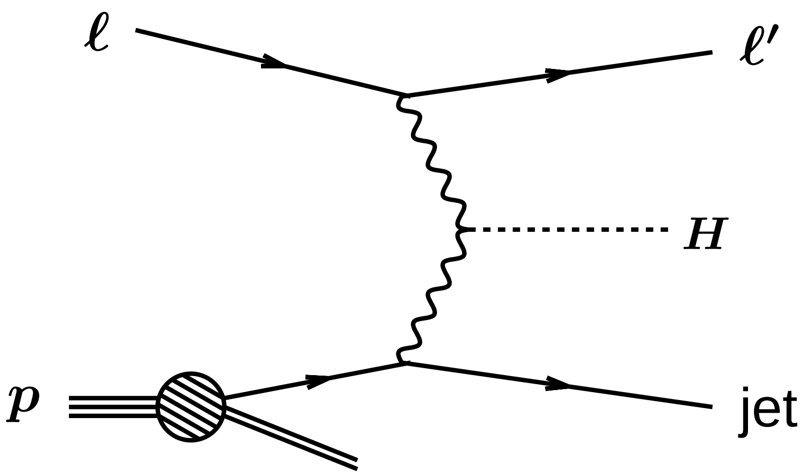
Han et al. (1985), . . .

revived in the context of ep collider project at CERN:

Large Hadron electron Collider (LHeC)

LHC proton beam combined with electron beam

Higgs production at the LHeC



sample scenario:

$$E_p = 7\ \mathrm{TeV}$$
$$E_e = 140\ \mathrm{GeV}$$
$$M_H = 120\ \mathrm{GeV}$$

- production modes: $ep \to e\,j\,H$ (NC) and $ep \to \nu_e\,j\,H$ (CC)
- clean environment facilitates separation of signal from backgrounds
- extraction of bottom Yukawa coupling in $H \to b\bar{b}$ decay mode feasible

[for details see, e.g., Han, Mellado (2009)]

determination of the $Hb\bar{b}$ coupling

$H \to b\bar{b}$ is dominant decay mode for $m_H \lesssim 140$ GeV, but

accessing the bottom-quark Yukawa coupling remains difficult

$\to$ consider WBF $H\gamma\, jj$ production with $H \to b\bar{b}$ decay:

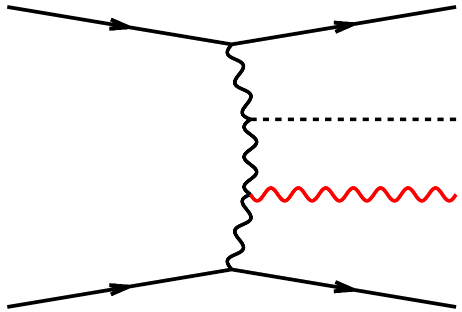
- detailed signal-background analysis:

  Gabrielli, Maltoni, Mele, Moretti, Piccinini, Pittau (2007)

- NLO-QCD calculation of signal process:

  Arnold, Figy, B. J., Zeppenfeld (2010)

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



Gabrielli et al. (2007):

extra hard, central photon in $pp \to Hjj$

powerful tool for suppression of (gluon-dominated) QCD backgrounds

☞ can the WBF $H \to b\bar{b}$ mode be tackled that way?

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

effects of hard central photon requirement:

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

- S/B not much affected:

$$\left(\frac{S}{B}\right)_{Hjj} \sim \left(\frac{S}{B}\right)_{H\gamma jj}$$

- signal significance decreases:

$$\left(\frac{S}{\sqrt{B}}\right)_{H\gamma jj} \sim \sqrt{\alpha}\left(\frac{S}{\sqrt{B}}\right)_{Hjj} \lesssim 1/10\left(\frac{S}{\sqrt{B}}\right)_{Hjj}$$

☞ no advantage?

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

effects of hard central photon requirement:

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

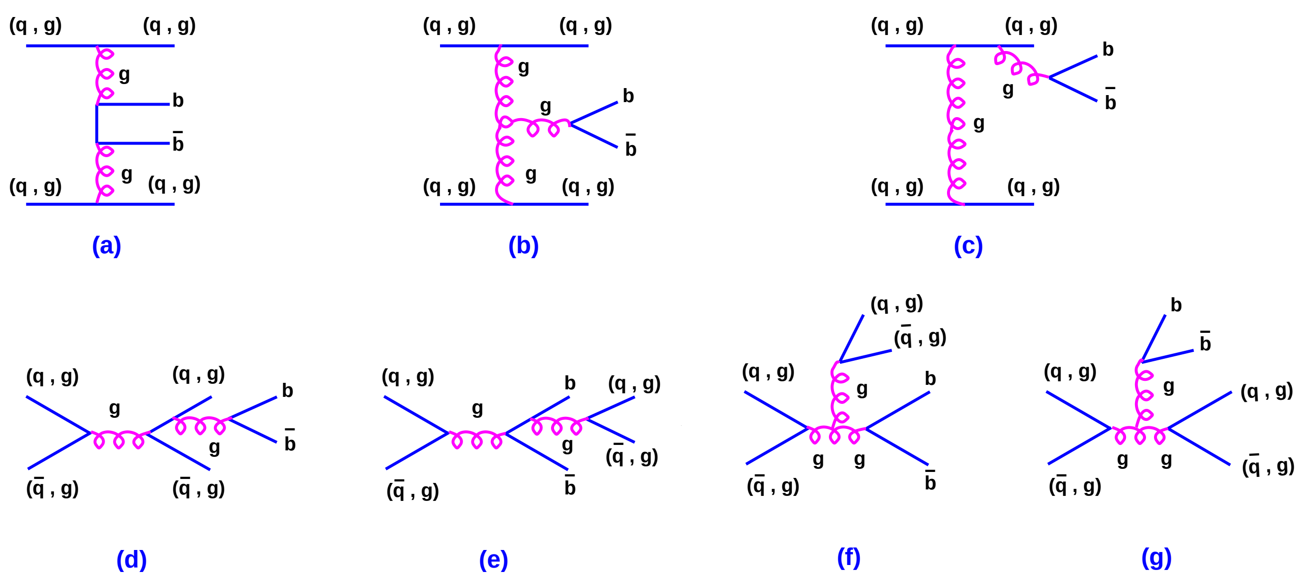
- S/B not much affected
- signal significance decreases

☞ no advantage?

✔ decrease in rate for QCD multi-jet final states

☞ improvement on trigger efficiencies for $b\bar{b}jj$ events

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



✔ large gluonic component in $b\bar{b}jj$ background ($\sim 80\%$ of σ_{bbjj})

$\to$ QCD backgrounds less active in radiating photon than quark-dominated WBF signal

✔ WBF-specific selection cuts favor large values of x

$\to$ valence-quarks more relevant than gluons in initial state

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

effects of hard central photon requirement:

✔ destructive interference between photon emission
off initial-state and off final-state quarks
that are linked by neutral t-channel-exchange boson

☞ central photon emission in backgrounds further suppressed

✔ similar interference effects in WBF signal
suppress ZZ fusion, but enhance WW fusion contributions

☞ relative contribution of ZZ fusion depleted w.r.t. WW fusion

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

[Gabrielli et al. (2007)]

photon isolation

problem: collinear photon-fermion configurations are singular

cure:

a) compute parton-to-photon fragmentation contributions;
absorb singularities in non-perturbative functions

- ✔ theoretically well-defined
- ✘ introduces poorly known photon fragmentation functions

b) naive photon-jet separation criterion $R_{j\gamma} \geq R_{min}$

- ✔ easy to implement
- ✘ theoretically ill-defined:
  soft-gluon contributions in cone are also removed and
  can't fully cancel IR singularities of virtual contributions

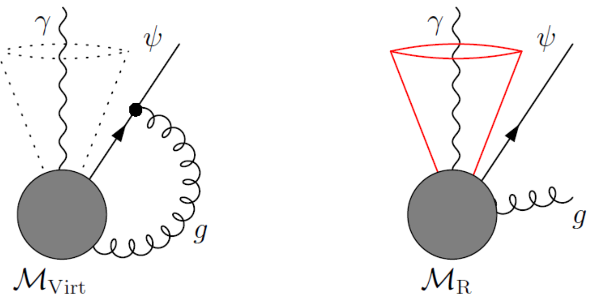
photon isolation

our implementation: cone-isolation criterion of *Frixione (1998)*

idea: veto collinear photon-jet configurations, but allow soft QCD emission

in practice: limit hadronic energy deposited in a cone around the direction of the photon by

$$\sum_{i:R_{i\gamma}<R} p_{Ti} \leq \frac{1-\cos R}{1-\cos \delta_0} p_{T\gamma} \qquad (\forall R \leq \delta_0 = 0.7)$$



$pp \to H\gamma jj$ @ LHC: settings

apply k_T jet algorithm and use CTEQ6 parton distributions

inclusive cuts

$$p_{Ti} \geq 20 \text{ GeV},$$
$$|y_j| \leq 5, \;\; |y_{\gamma,b}| \leq 2.5,$$
$$\Delta R_{ik} \geq 0.4,$$
$$M_{jj}^{\text{tag}} > 100 \text{ GeV}$$

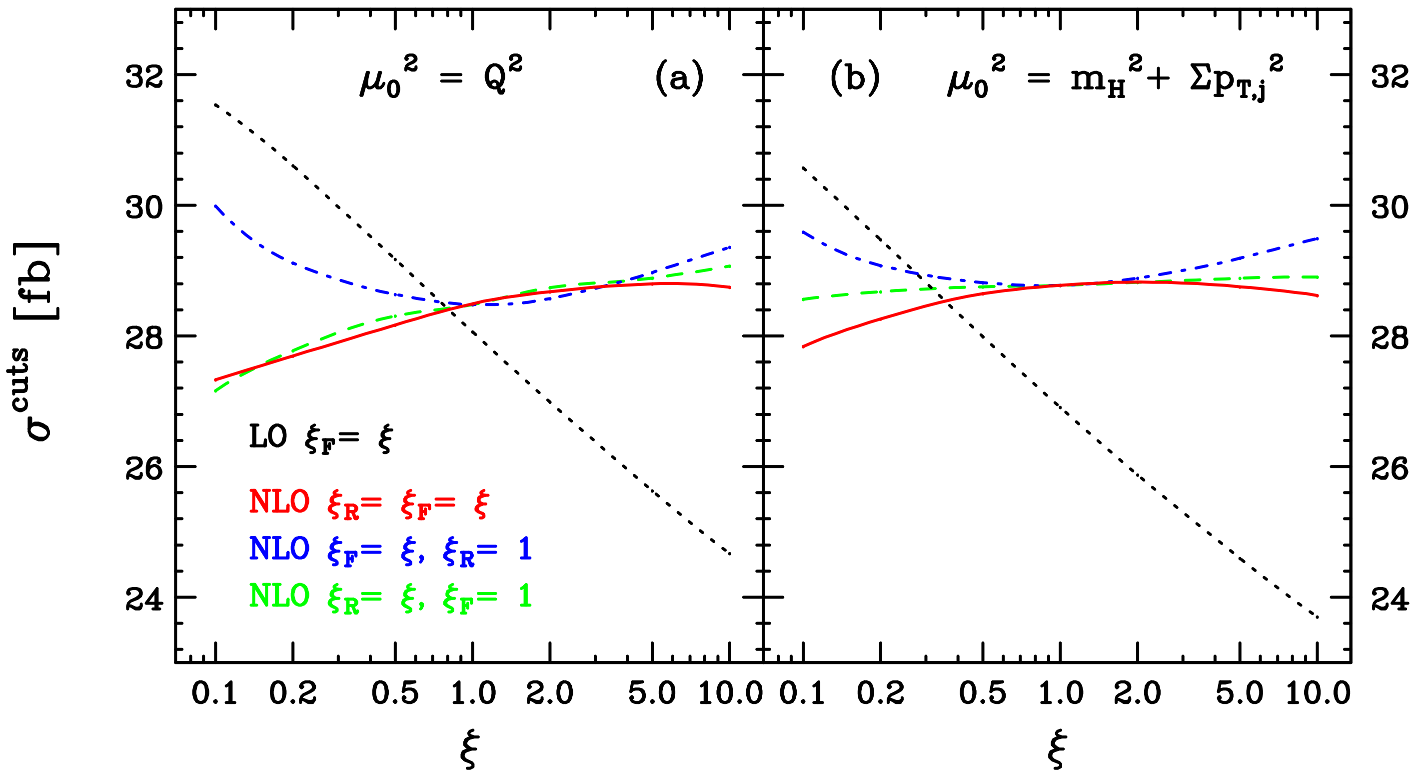
WBF cuts

$$y_j^{\text{min}} < y_\gamma, y_b < y_j^{\text{max}}$$
$$\Delta y_{jj} = |y_{j_1} - y_{j_2}| > 4,$$
$$\Delta R_{ik} \geq 0.7,$$
$$M_{jj}^{\text{tag}} > 600 \text{ GeV}$$

jets located in opposite hemispheres

scale uncertainty

choose default scale $\mu_0^2 = Q_i^2$ or $\mu_0^2 = m_H^2 + \sum p_{Tj}^2$
set $\mu_R = \xi_R \mu_0$ and $\mu_F = \xi_F \mu_0$, with variable ξ



LO: no control on scale
NLO QCD: scale dependence strongly reduced

impact of PDFs and scales

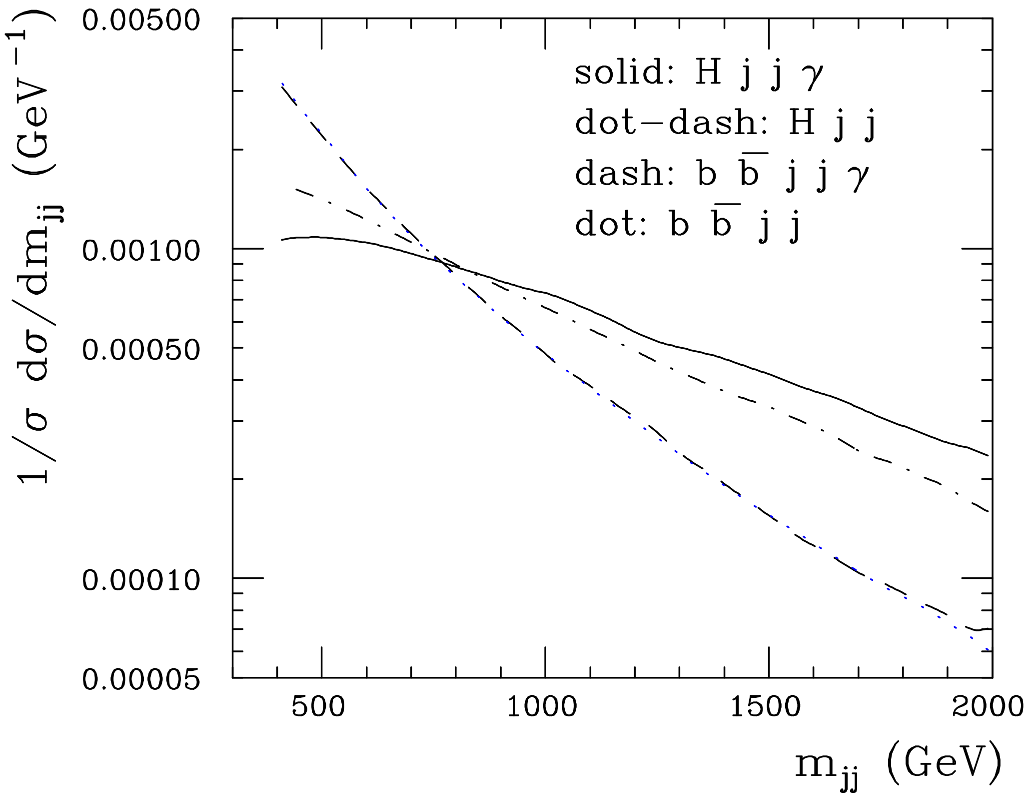
variation of cross section σ^{WBF} for $Q^2/2 \leq \mu^2 \leq 2Q^2$:

CTEQ6	LO:	$14.65^{+1.07}_{-0.95}$ fb
	NLO:	$14.79^{+0.14}_{-0.19}$ fb
MSTW	LO:	$14.40^{+1.13}_{-1.0}$ fb
	NLO:	$14.91^{+0.03}_{-0.21}$ fb

☞ $\Delta\sigma^{\mathrm{WBF}}_{\mathrm{LO}} \sim 14\%$ and $\Delta\sigma^{\mathrm{WBF}}_{\mathrm{NLO}} \sim 2\%$

invariant mass of the tagging jets

Gabrielli et al. (2007)

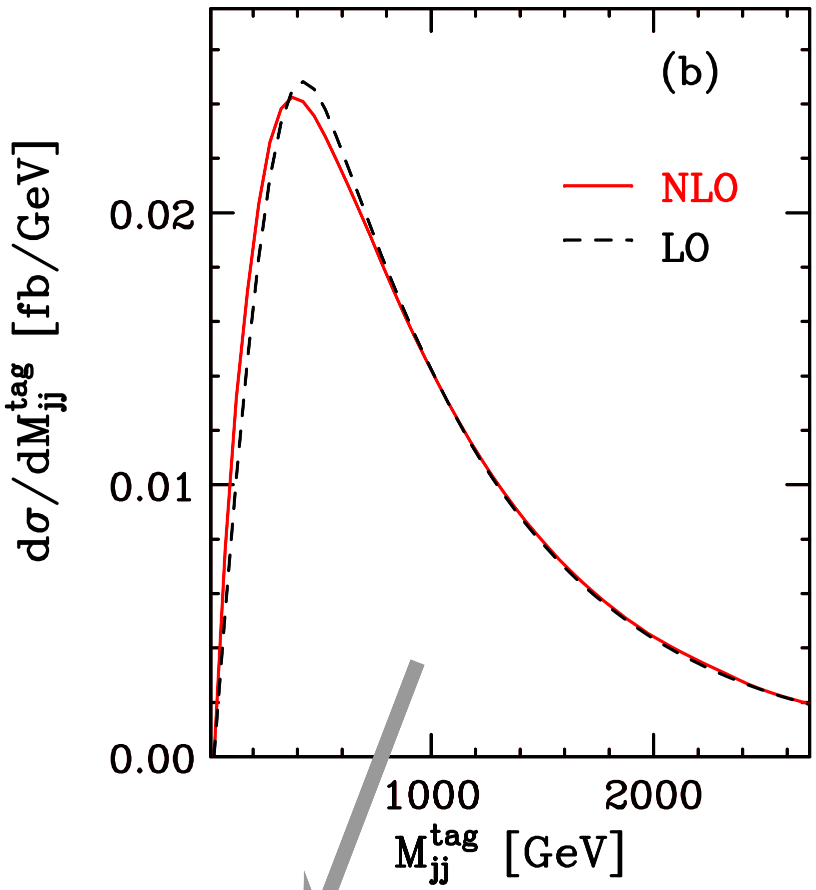


- $d\sigma/dm_{jj}$ slightly flatter for $H\gamma jj$ signal than for Hjj
- $b\bar{b}jj$ and $b\bar{b}\gamma jj$ backgrounds have very similar shapes
- background distributions exhibit much steeper slope than signal

☞ stringent cut on m_{jj} is powerful tool for background suppression

invariant mass of the tagging jets

Arnold, Figy, B. J., Zeppenfeld (2010)



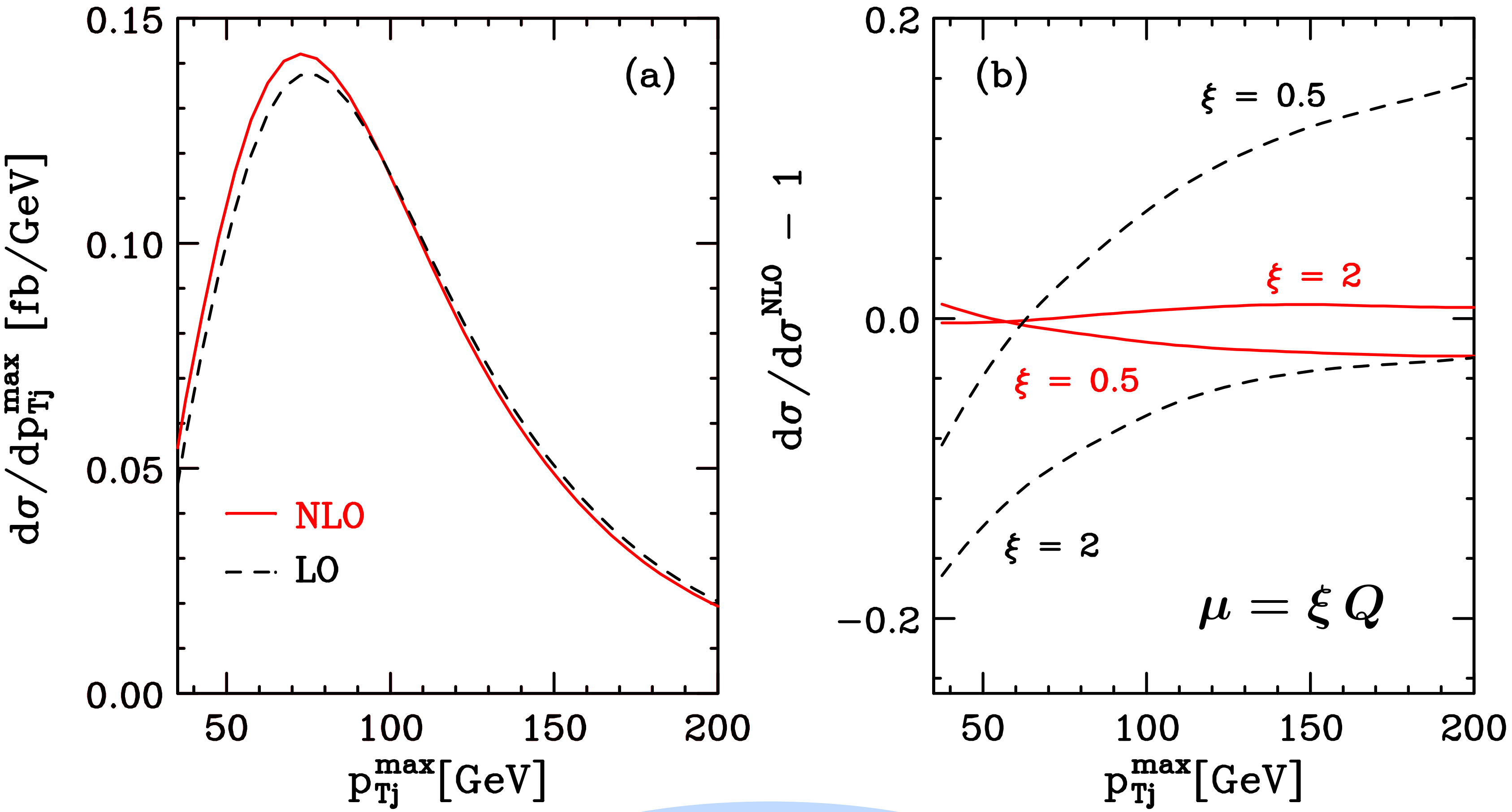
effect of NLO-QCD corrections small

- $d\sigma/dm_{jj}$ slightly flatter for $H\gamma jj$ signal than for Hjj
- $b\bar{b}jj$ and $b\bar{b}\gamma jj$ backgrounds have very similar shapes
- background distributions exhibit much steeper slope than signal

☞ stringent cut on m_{jj} is powerful tool for background suppression

transverse momentum of the hardest jet

Arnold, Figy, B. J., Zeppenfeld (2010)



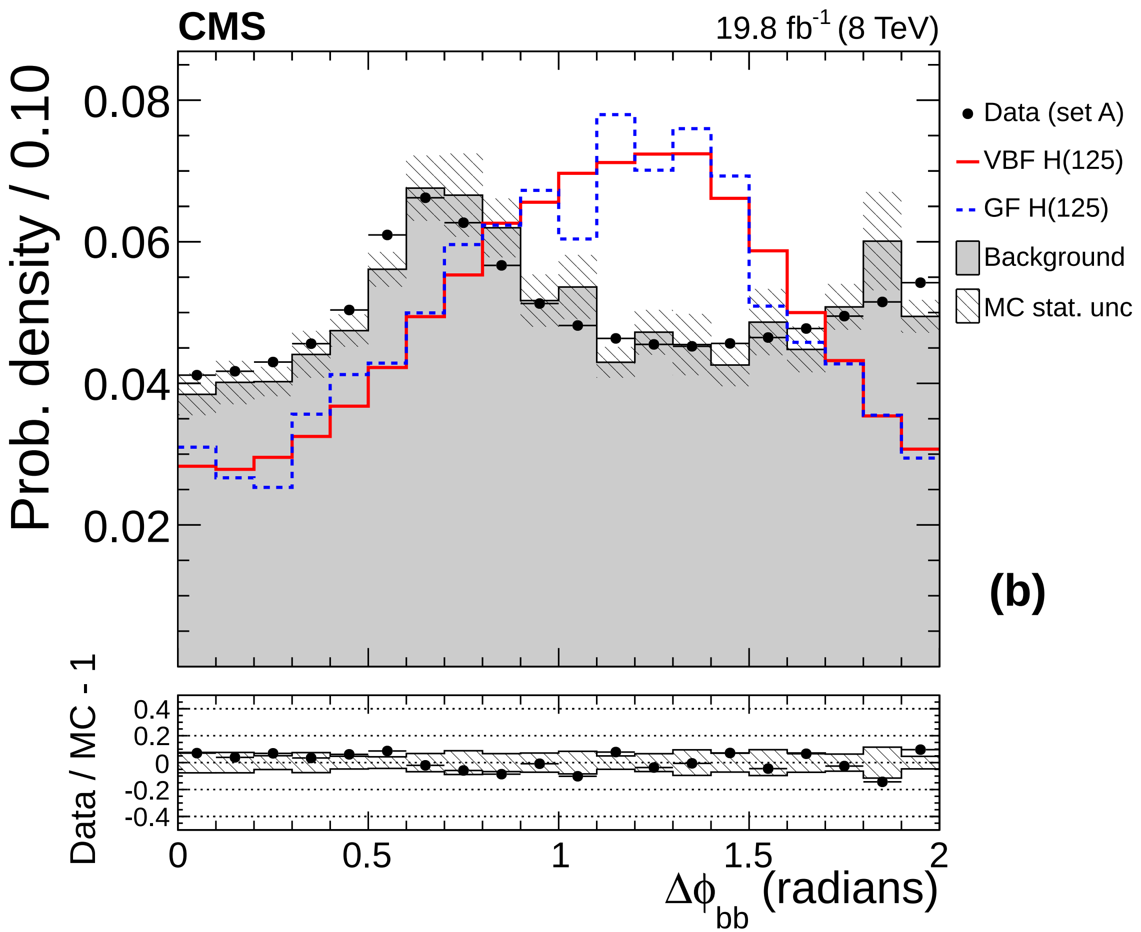
$\sqrt{S} = 14$ TeV

$H\gamma jj$: conclusions

- WBF offers promising prospects for Higgs boson search
- $H \to b\bar{b}$ mode profits from requirement of hard, central photon:
  - trigger efficiencies improved
  - QCD backgrounds suppressed significantly
  - signal significance $S/\sqrt{B} \sim 3$ for 100 fb^{-1}
- perturbative QCD corrections well under control
  (modest scale uncertainties & K-factors)
- shape of some distributions sensitive to radiative corrections

news from CMS: $H \to b\bar{b}$ in VBF

arXiv: 1506.01010

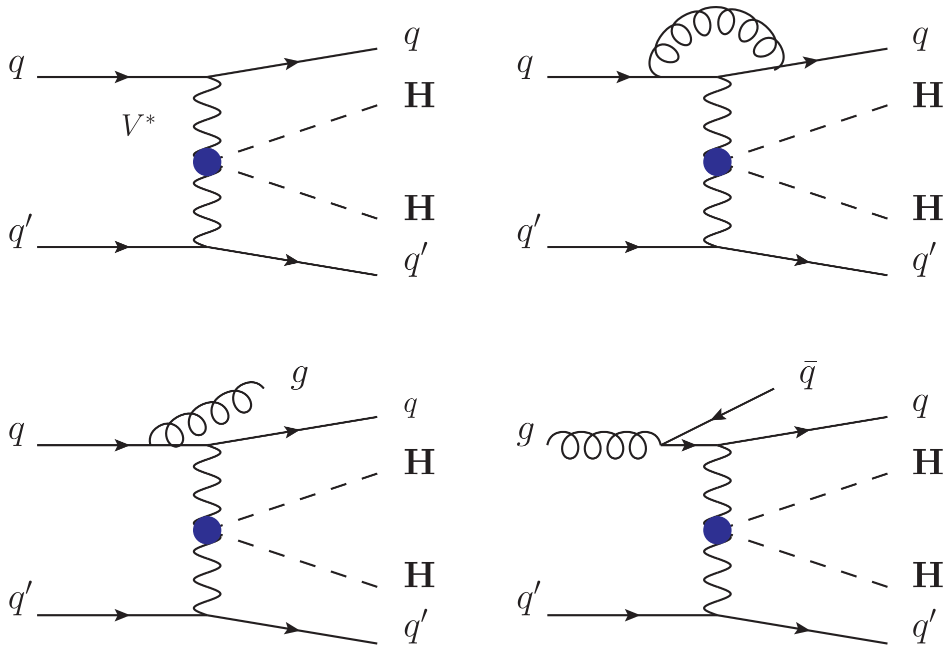


search for Higgs production via VBF with decay $H \to b\bar{b}$ at $\sqrt{s} = 8$ TeV

signal strength
$$\mu = \sigma/\sigma_{\mathrm{SM}} = 2.8^{+1.6}_{-1.4}$$

compare to
$$\mu = 1.03^{+0.44}_{-0.42}\ (VH + ttH)$$

Higgs pair production via VBF



sensitive to

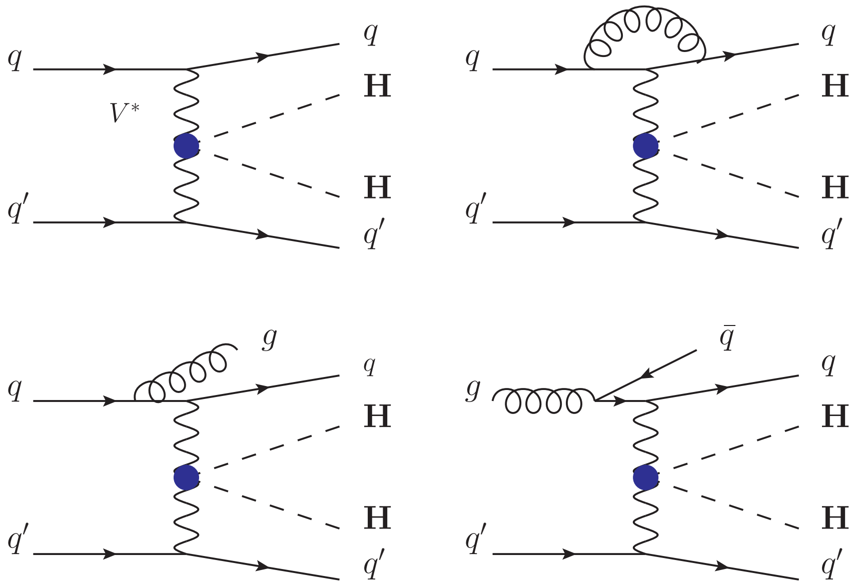
- $VVHH$ coupling
- Higgs self coupling

$\rightarrow$ access Higgs potential

recall: Higgs potential

$$V(H^\dagger H) = -\mu^2 H^\dagger H + \frac{\lambda}{4}(H^\dagger H)^2$$

Higgs pair production via VBF



✔ same (simple) QCD structure as single Higgs production via VBF

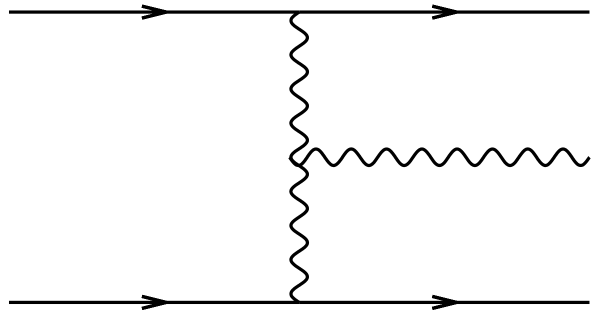
✘ cross sections very small

$\sqrt{s}$ [TeV]	$\sigma^{\rm NLO}_{gg\to HH}$ [fb]	$\sigma^{\rm NLO}_{qq'\to HHqq'}$ [fb]	$\sigma^{\rm NNLO}_{q\bar{q}'\to WHH}$ [fb]	$\sigma^{\rm NNLO}_{q\bar{q}\to ZHH}$ [fb]	$\sigma^{\rm LO}_{q\bar{q}/gg\to t\bar{t}HH}$ [fb]
8	8.16	0.49	0.21	0.14	0.21
14	33.89	2.01	0.57	0.42	1.02
33	207.29	12.05	1.99	1.68	7.91
100	1417.83	79.55	8.00	8.27	77.82

taken from *Baglio et al. (2012)*

the Higgs: only one part of the full picture

$pp \to Vjj$ via VBF



- sensitive to triple gauge boson couplings

  complementary to di-boson production

  (2 bosons spacelike, not timelike)

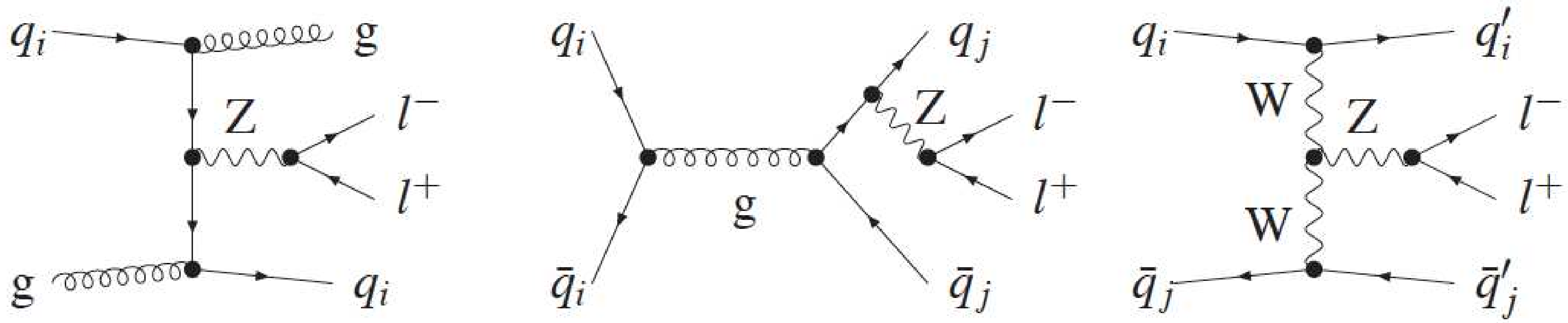
- similar signature as Higgs production via VBF

  $\to$ explore systematics of Hjj final state

Z boson production in association with two jets

$pp \to \ell^+\ell^- jj$ procedes via different production modes;

tree-level: $\mathcal{O}(\alpha^2\alpha_s^2)$, $\mathcal{O}(\alpha^3\alpha_s)$, $\mathcal{O}(\alpha^4)$



NLO-QCD to QCD contributions *[Campbell, Ellis, Rainwater (2002-03)]*

NLO-QCD to VBF contributions *[Oleari, Zeppenfeld (2003)]*

NLO-EW at order $\mathcal{O}(\alpha^2\alpha_s^3)$ *[Denner, Hofer, Scharf, Uccirati (2013-14)]*

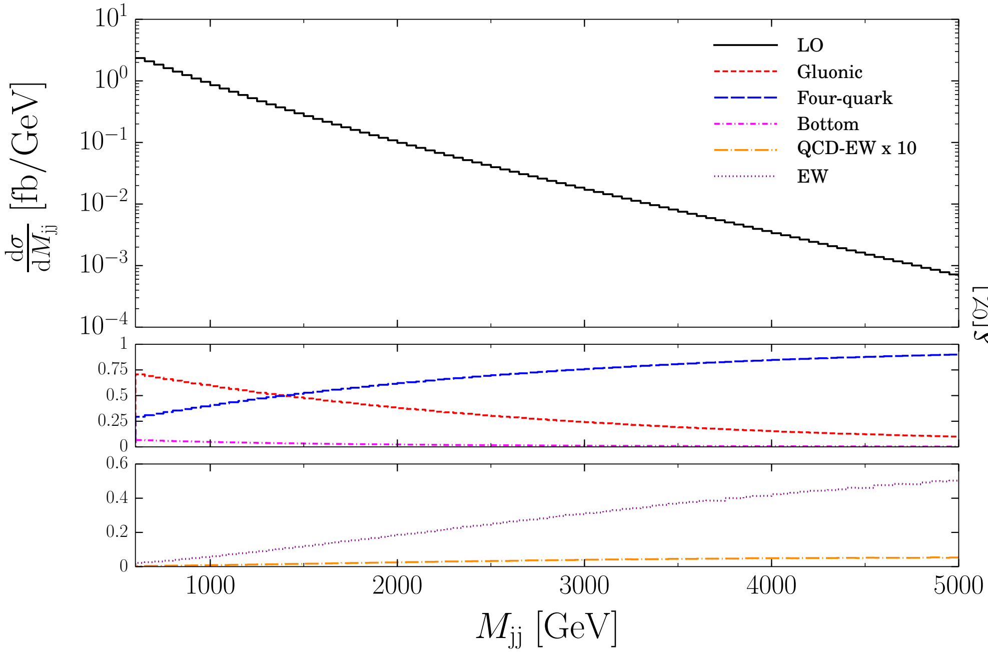
[similar calculation for $W + \leq 3$ jets by *Kallweit et al. (2014)*]

$pp \to Zjj$@ LO: basic and VBF cuts

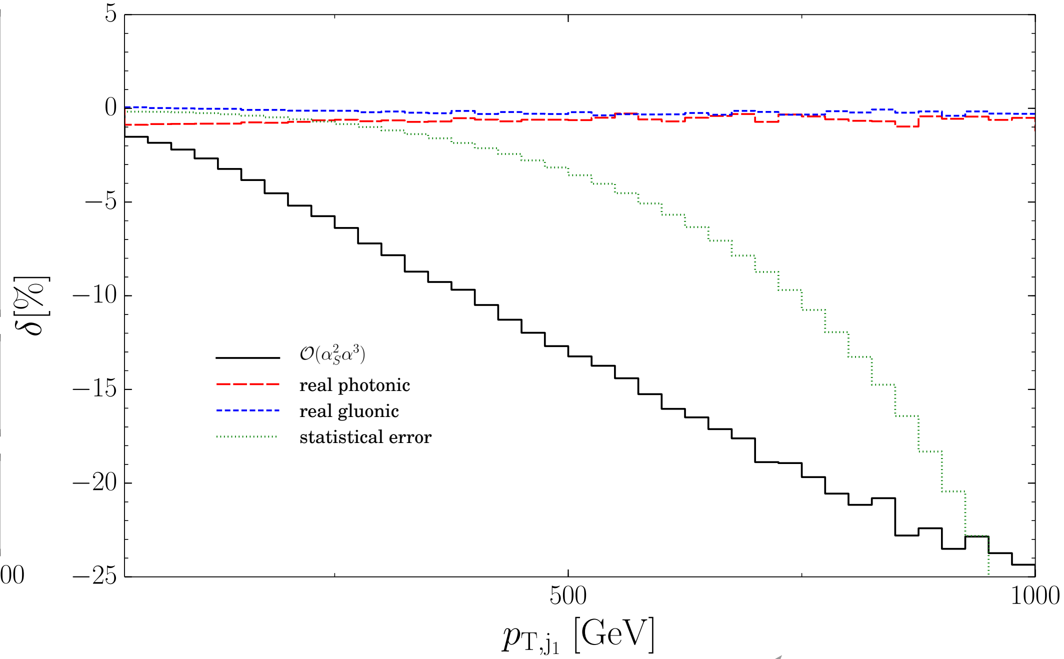
process class	σ [fb]	$\sigma/\sigma_{\mathrm{tot}}$ [%]	$\sigma_{\alpha_s^2\alpha^2}/\sigma$ [%]	$\sigma_{\alpha_s\alpha^3}/\sigma$ [%]	σ_{α^4}/σ [%]
gluonic	40910(8)	79.9	100	—	—
four-quark	10299(1)	20.1	94.7	+0.4	4.8
bottom quarks	4376(3)	8.54	—	—	—
sum (basic)	51209(8)	100	98.9	< 0.1	1.0
gluonic	617.8(4)	59.4	100	—	—
four-quark	421.7(1)	40.6	82.9	0.2	16.9
bottom quarks	51.82(2)	4.98	—	—	—
sum (VBF)	1039.6(4)	100	93.1	0.01	6.9

numbers taken from *Denner, Hofer, Scharf, Uccirati (2014)*

$pp \to \ell^+\ell^- jj$ with VBF cuts



[Denner, Hofer, Scharf, Uccirati (2014)]



gluonic channels dominant in bulk of x-sec

large EW Sudakov logs

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

Schneider, Zanderighi, B.J. (2012)

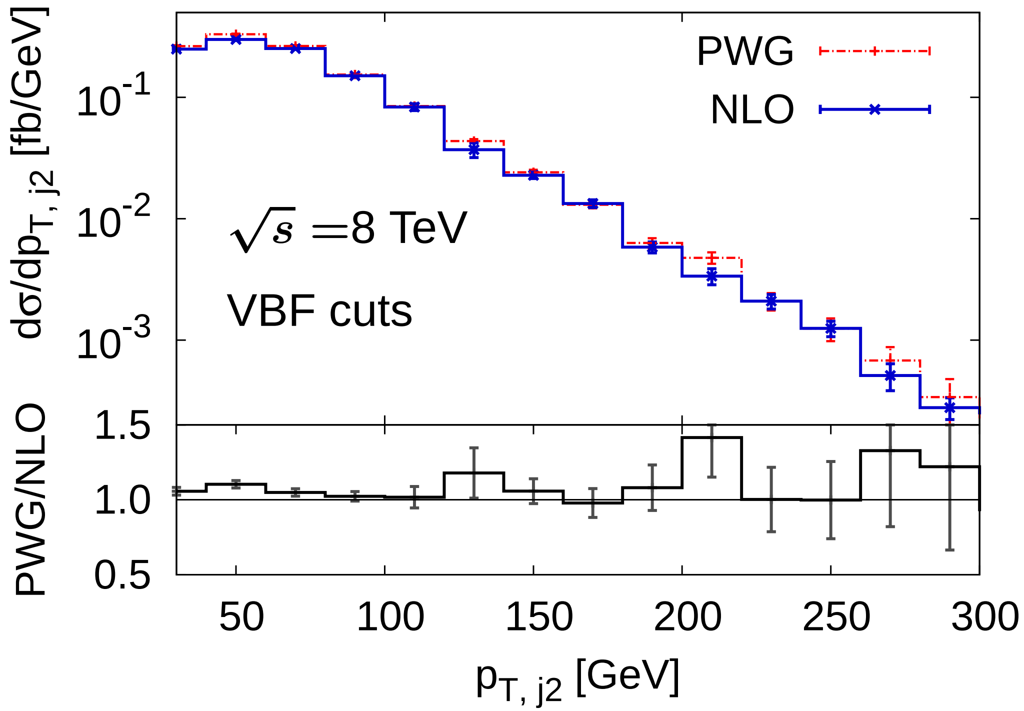
matching with parton shower programs in the POWHEG-BOX:

QCD production:

Campbell, Ellis, Nason, Zanderighi; Re (2012-13)

VBF production:

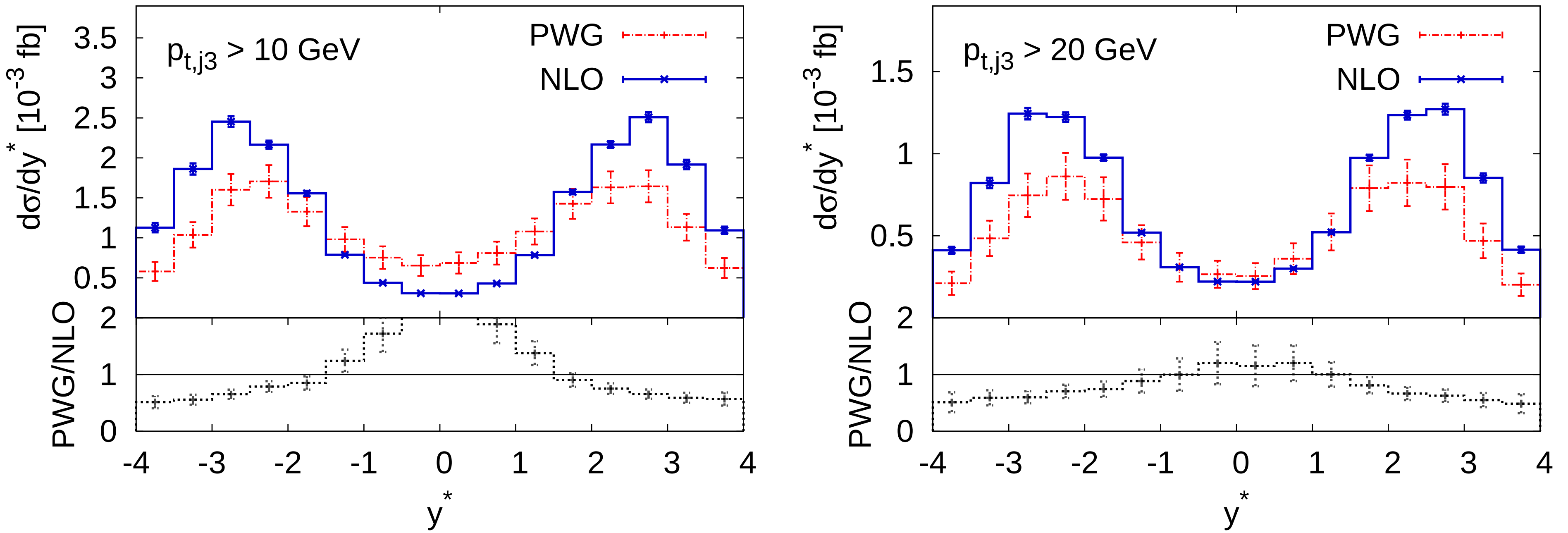
Schneider, Zanderighi, BJ (2012); Schissler, Zeppenfeld (2013)



parton shower effects are moderate for hard jets

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

Schneider, Zanderighi, B.J. (2012)



location of third jet relative to tagging jets

$$y^\star = y_{j3} - \frac{y_{j1} - y_{j2}}{2}$$

note: transverse momentum cut on extra jets matters

further developments in $pp \to V + n$ jets

- NLO QCD for QCD production mode:

  $Z+ \leq 4$ jets in `BlackHat` *[Ita et al. (2011)]*
  $W+ \leq 5$ jets in `BlackHat` *[Bern et al. (2013)]*

- NLO QCD+EW for QCD production mode:

  $W+ \leq 3$ jets in `OpenLoops+Sherpa/Munich`
  [Kallweit, Lindert, Maierhöfer, Pozzorini, Schönherr (2014)]

- room for improvements:
  - matching and merging for QCD-induced $V + n$ jets beyond LO QCD (including more than two jets)
  - NLO(+PS) for higher jet multiplicities in EW production mode

summary

VBF crucial for understanding mechanism of electroweak symmetry breaking:

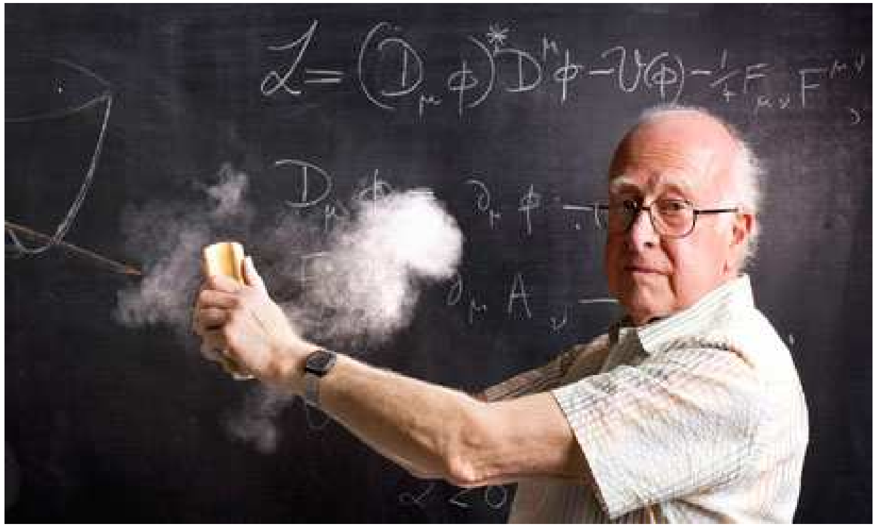
- ❋ Hjj: very clean Higgs production channel
- ❋ $VVjj$: sensitive to signatures of new physics in the gauge boson sector

important pre-requisites:

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

(NLO-QCD corrections and parton-shower effects moderate)

summary



✔ exciting times as the Higgs boson is being discovered and explored

* crucial pre-requisite: modern methods in collider physics

we have seen how methods become more advanced and sophisticated as time goes by:

LO → NLO-QCD

↓

NLO-QCD matched with parton shower → ...

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
  - interference effects, resummations, well-constrained PDFs, . . .
- realistic predictions, allowing for
  - calculation of distributions within experimental selection cuts
  - matching to parton-shower Monte Carlos at NLO-QCD accuracy
- sophisticated analysis techniques, requiring cross links
  between experimentalists and theorists / phenomenologists

outlook

- the future will ask for more precise predictions, including
  - NLO electroweak corrections
  - NNLO-QCD predictions for standard-candle processes
  - precision calculations beyond the Standard Model

- we'll need more realistic predictions, requiring
  - tools that are fast and easy-to-use
  - better parton-shower Monte Carlos

    (new tunes, better modeling of non-perturbative effects,. . .)
  - matching beyond NLO in QCD
  - matching & merging

    (combination of processes with different jet multiplicities)
  - matching NLO electroweak calculations to parton showers