VBF Higgs production: status and recent developments

Higher orders and jets for LHC

MITP – July 2015

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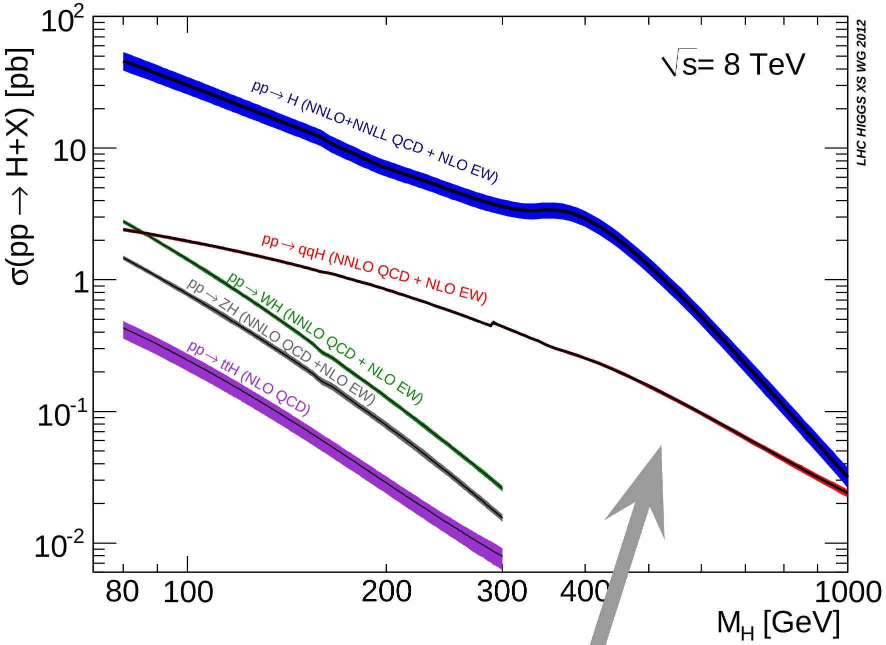
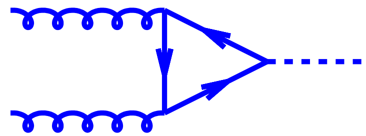
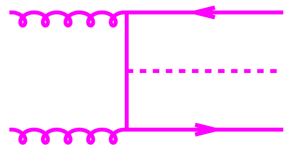
why VBF Higgs production?

Higgs cross section WG

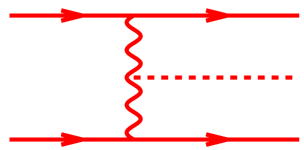




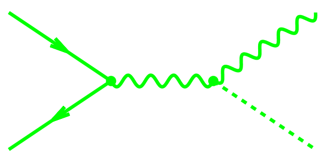
gluon fusion (GF)



$t\bar{t}H$ production



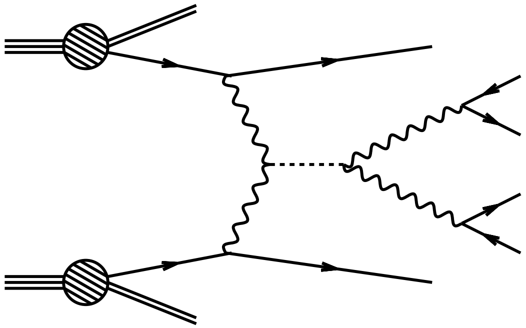
vector boson fusion (VBF)



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?



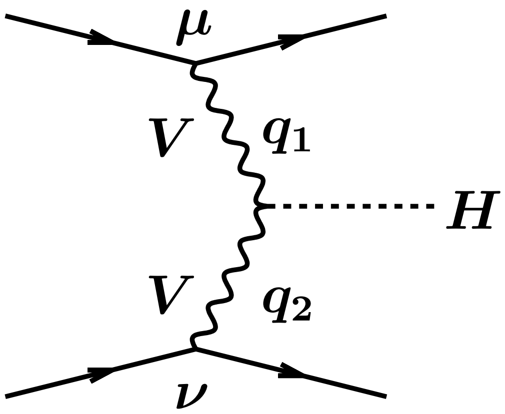
distinctive signature $\longrightarrow$ very useful for signal extraction and background suppression

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

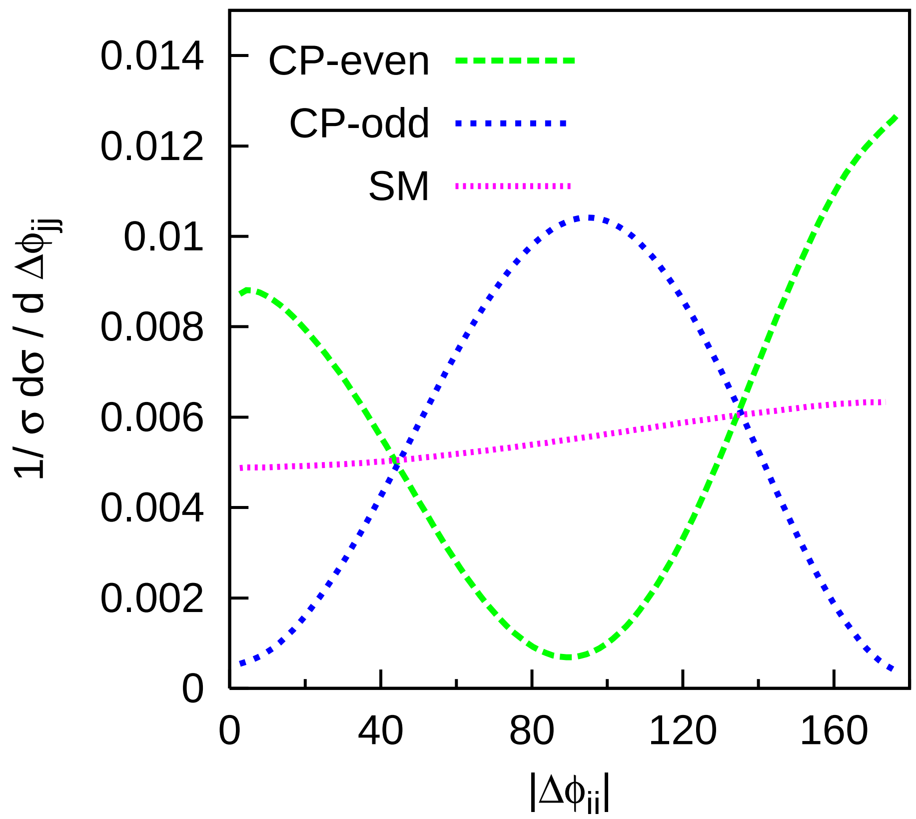
azimuthal angle between tagging jets

↓

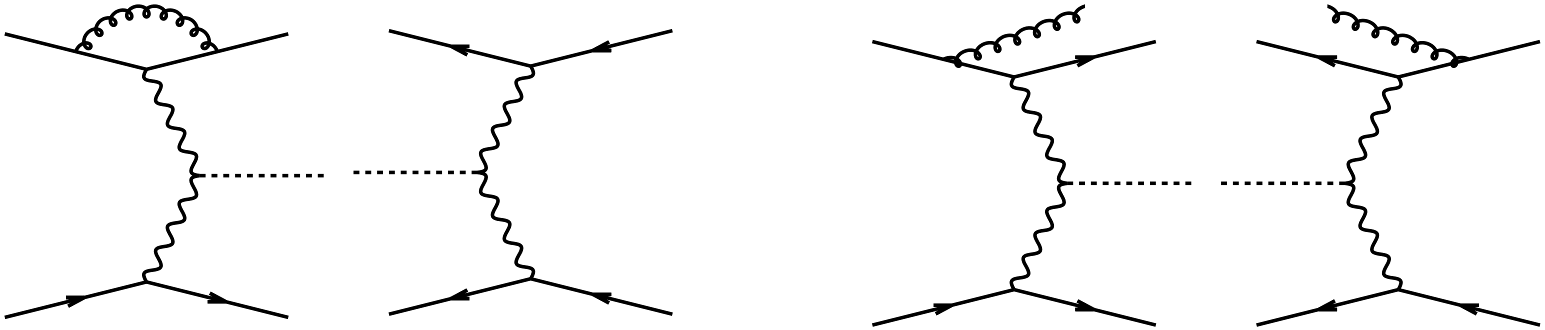
dip structure at 90° (CP even) or $0/180°$ (CP odd) only depends on tensor structure of HVV vertex

(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`

the "t-channel approximation"

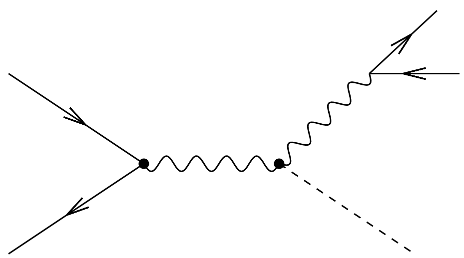
disregard all but genuine VBF contributions ($\leftrightarrow$ t-channel):

❋ interference effects from diagrams obtained by interchanging identical initial- or final-state (anti-)quarks

❋ identical flavor annihilation processes with subsequent decay into quarks and similar contributions like

neglected terms strongly suppressed in PS region where VBF can be observed experimentally

(require two widely separated quark jets of large invariant mass)



typically at sub-percent level

impact of neglected contributions

detailed analysis for EW Hjj production *[Ciccolini et al. (2007)]*

σ [fb]	120 GeV	150 GeV	120 GeV	150 GeV
LO	5943(1)	4331(1)	1876.3(5)	1589.8(4)
NLO	5872(2)	4202(2)	1665(1)	1407.5(8)
LO, s	1294.4(2)	639.4(1)	0.0025	0.0015
NLO, s	1582.1(4)	769.4(2)	9.45(1)	5.21(1)
LO, t/u-int	−9.2	−5.6	−0.12	−0.091
NLO, t/u-int	−27.6	−9.4	−0.75	0.17

no cuts

VBF cuts

$pp \to Hjj$ 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)*

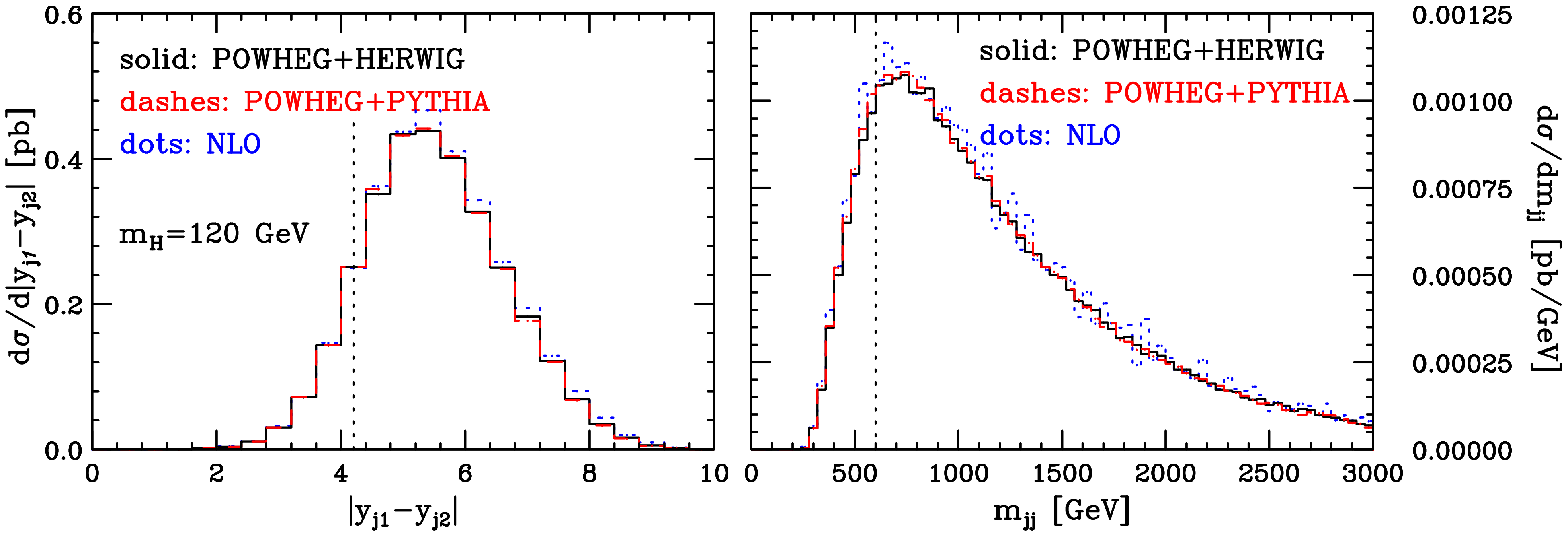
BSM

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

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

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

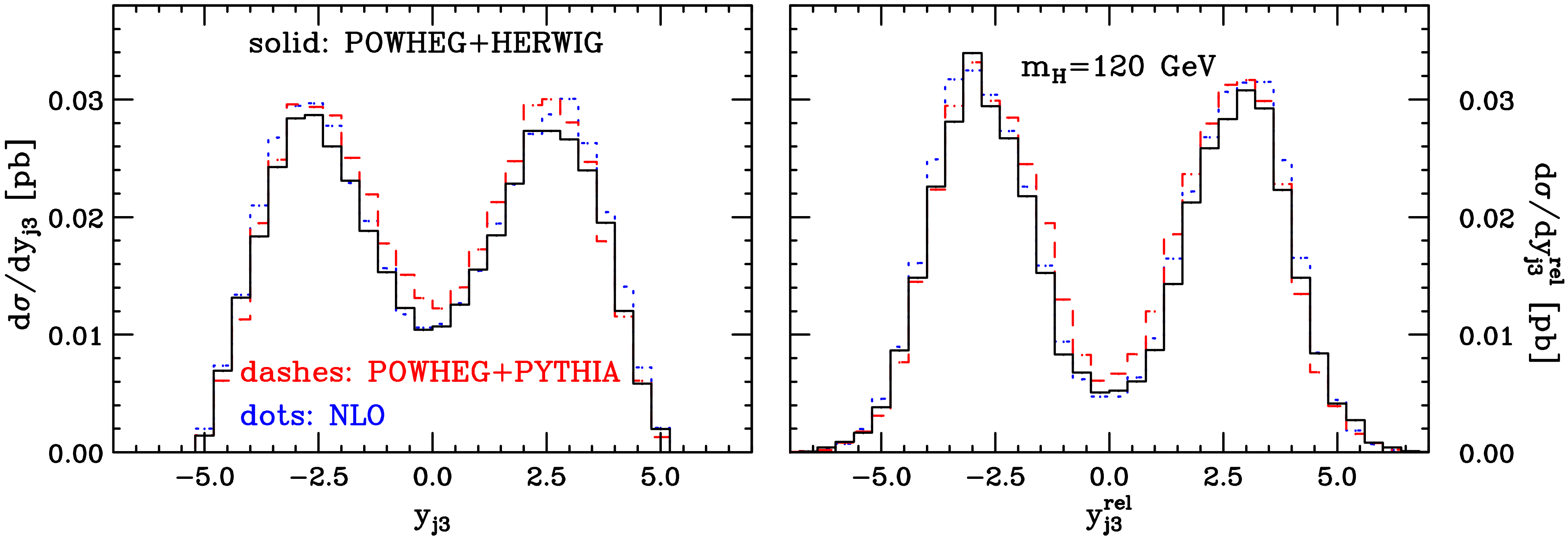
Nason, Oleari (2009)



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

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

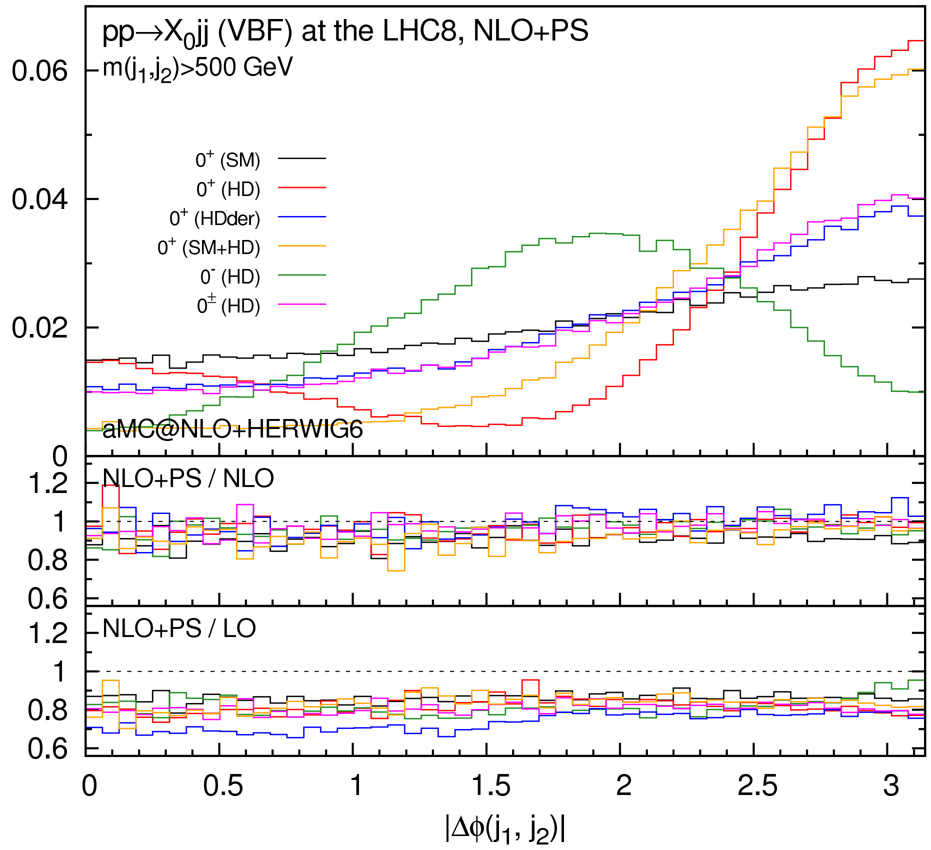
Nason, Oleari (2009)



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

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

Maltoni, Mawatari, Zaro (2013)

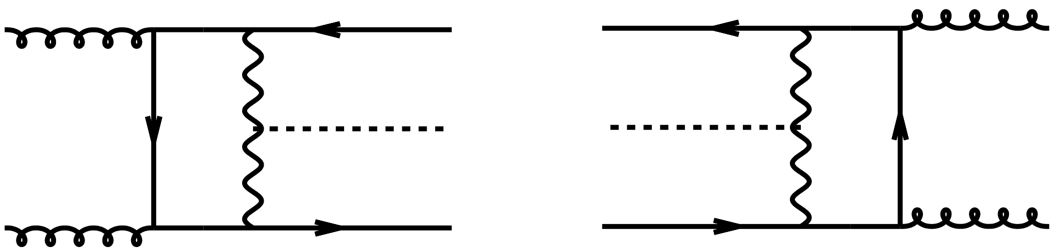


impact of higher-dimensional operators on azimuthal angle correlation of tag jets not depleted by parton shower

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?

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

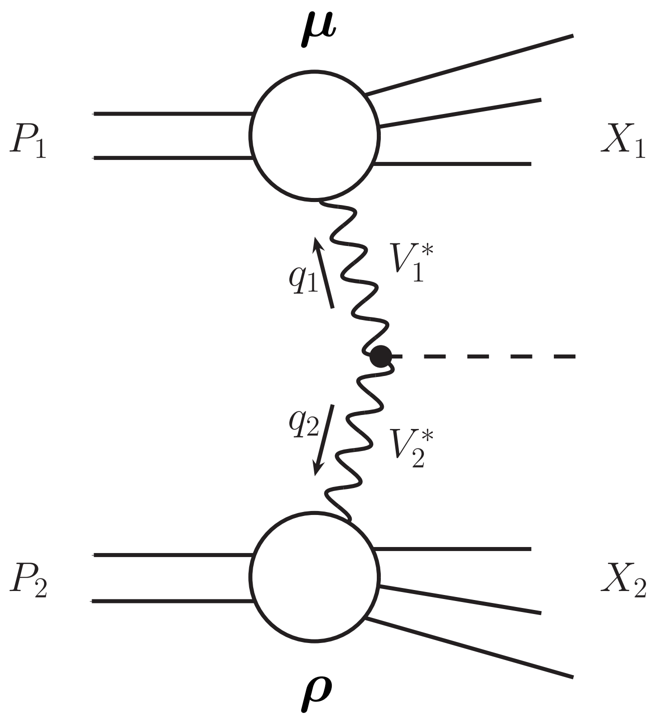
minimal set of cuts: $\sigma^{2-\mathrm{loop}}_{\mathrm{gluon}} \sim 2\,\%$ of $\sigma^{\mathrm{LO}}_{\mathrm{VBF}}$
VBF cuts: relative suppression by additional order of magnitude

higher orders of QCD in VBF

Bolzoni, Maltoni, Moch, Zaro (2010):

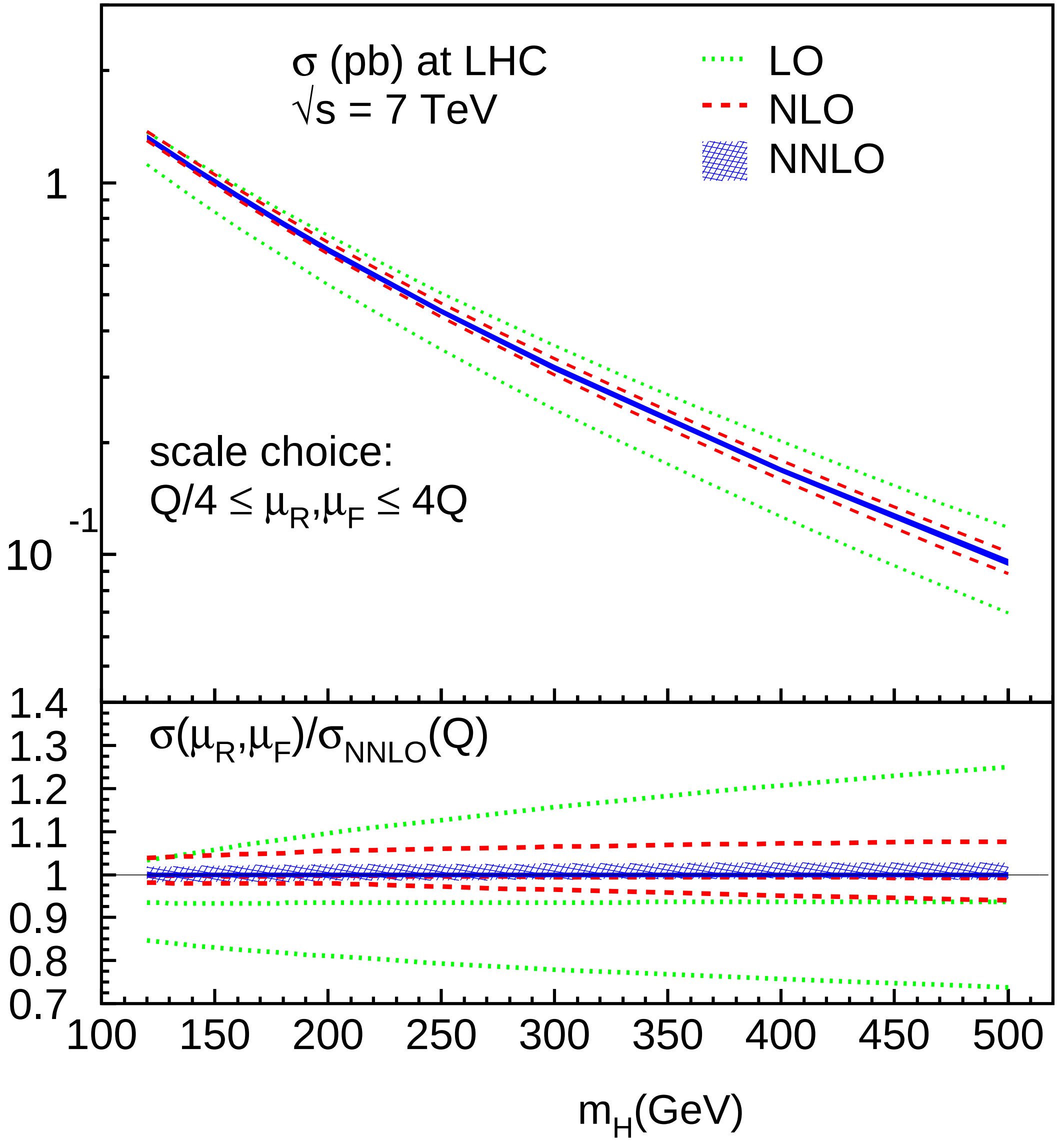
subset of the NNLO QCD contributions
to the total cross section for $pp \to Hjj$ via VBF
in the structure function approach

1



higher orders of QCD in VBF

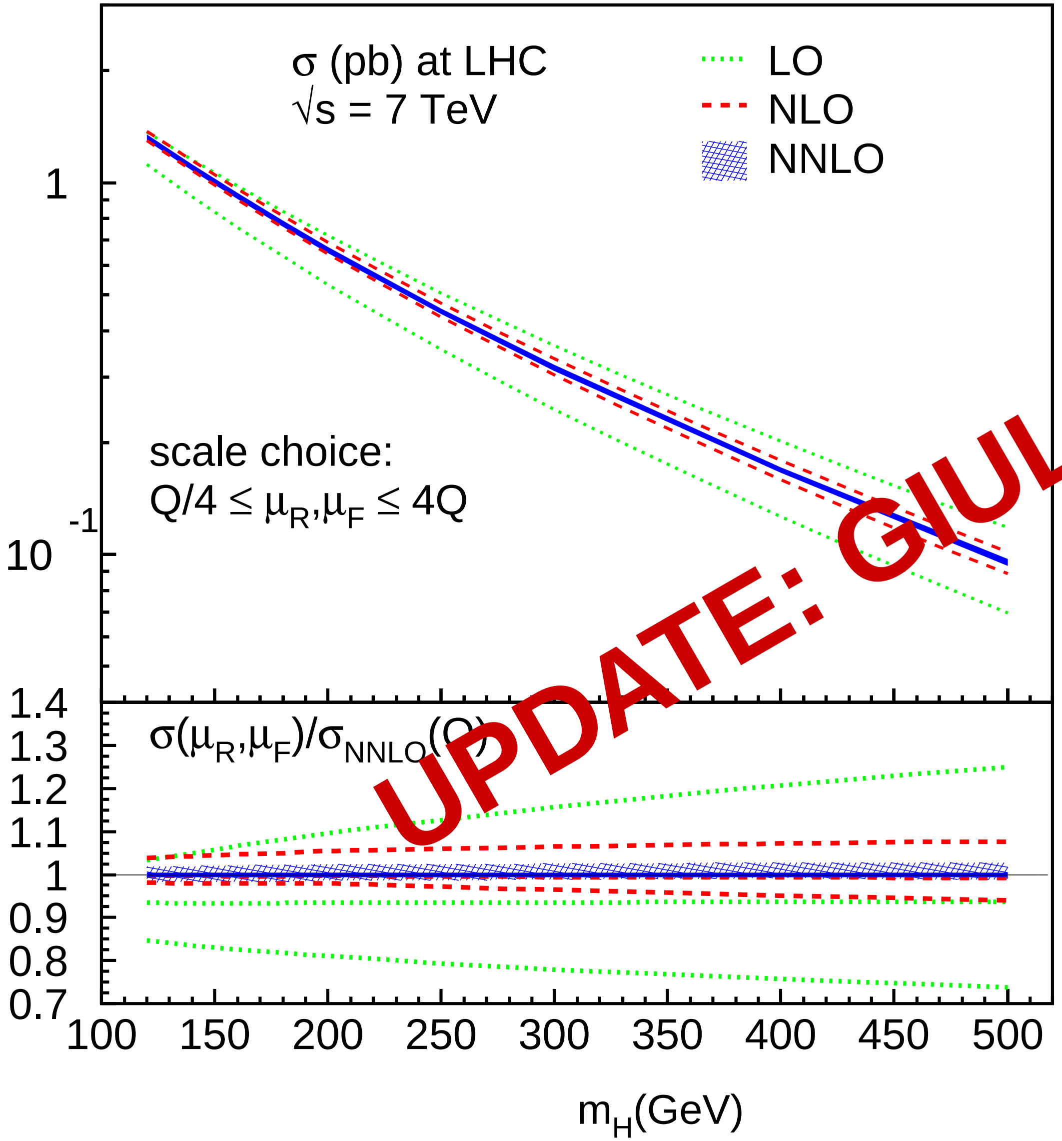
Bolzoni et al. (2011)



- 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

higher orders of QCD in VBF

Bolzoni et al. (2011)

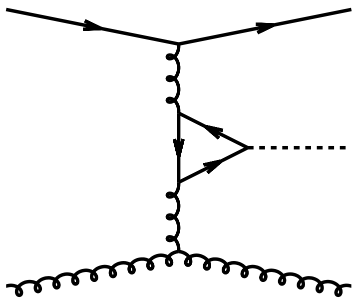
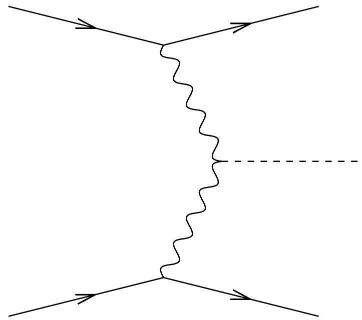


UPDATE: GIULIA'S TALK

- 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

$pp \to Hjj$ via gluon fusion

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

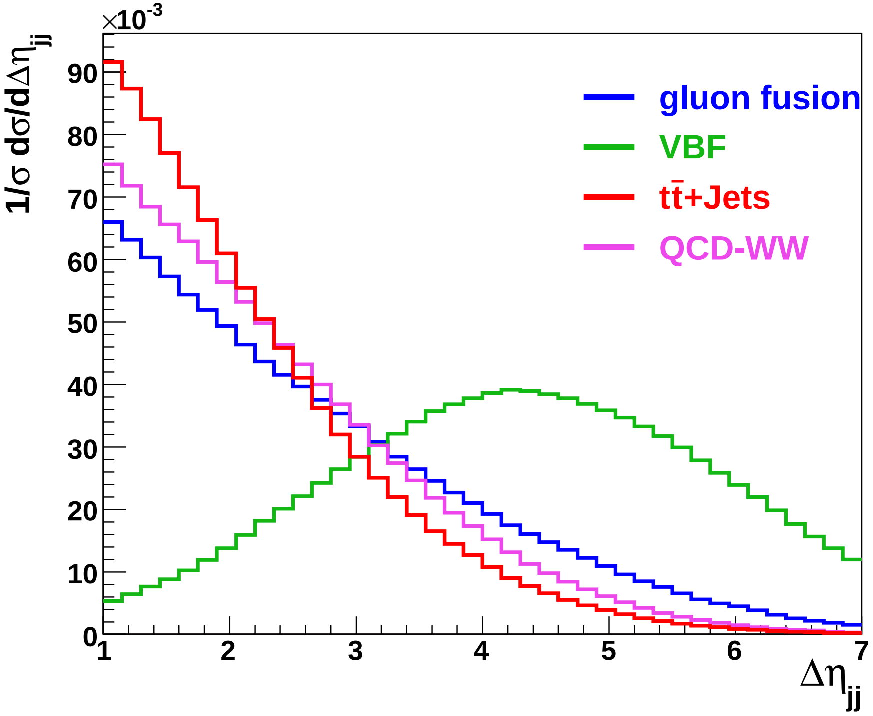
complete LO calculation (including pentagons):
Del Duca, Kilgore, Oleari, Schmidt, Zeppenfeld (2001)

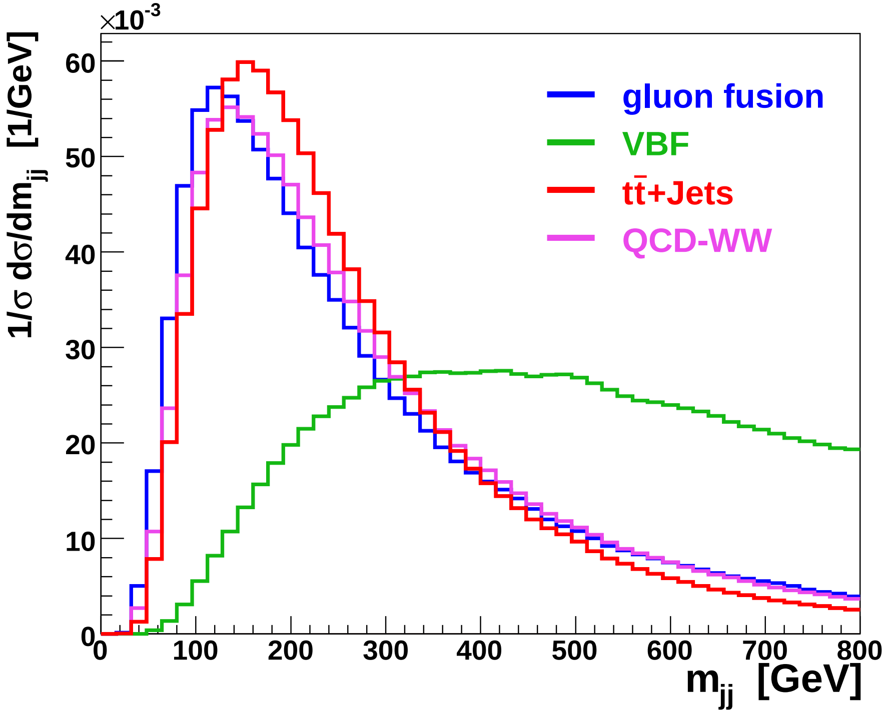
NLO QCD calculation in $m_t \to \infty$ limit:
Campbell, Ellis, Zanderighi (2006); Greiner et al. (2013)

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)

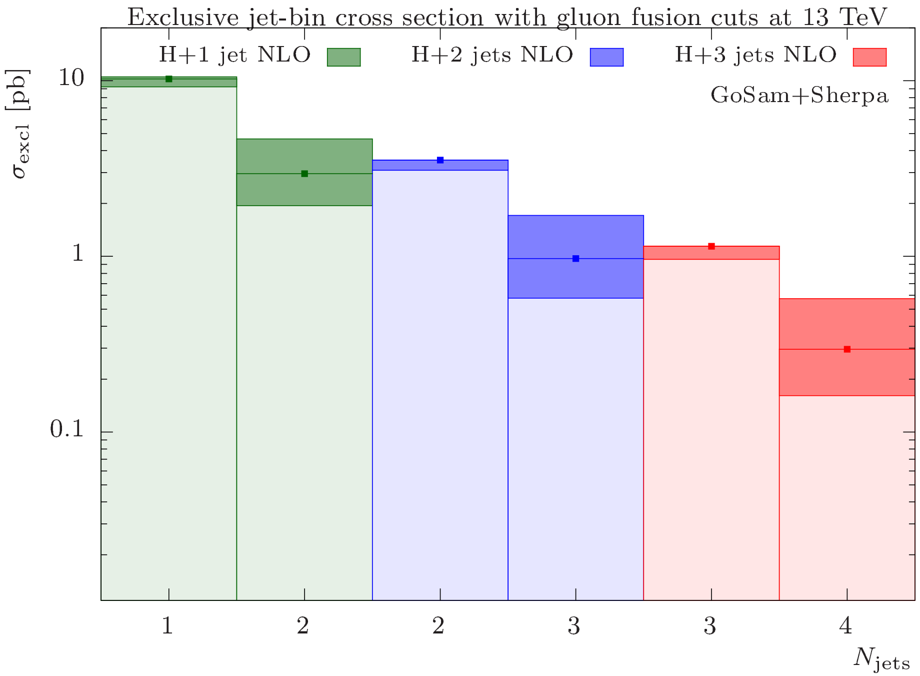


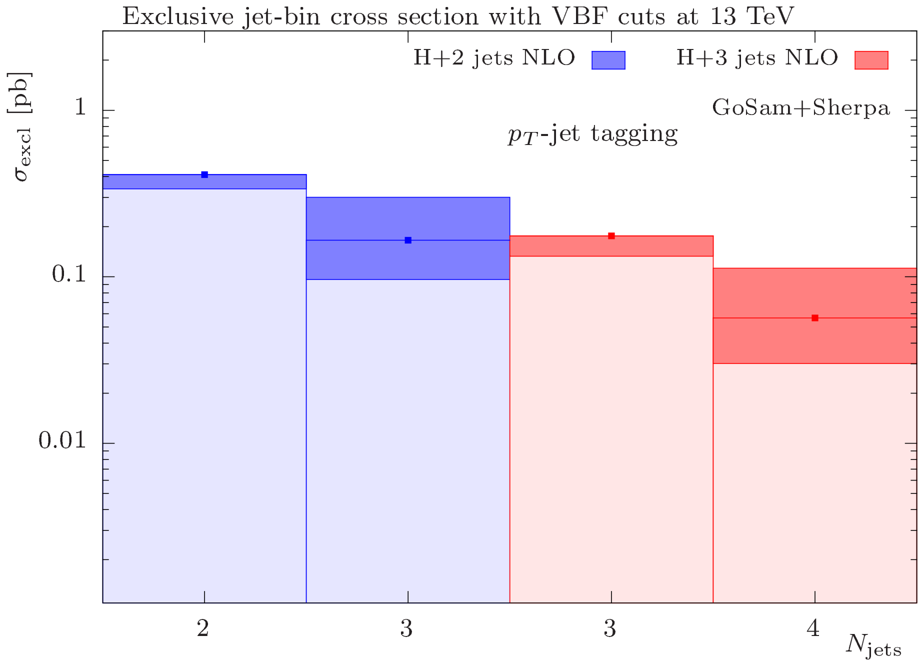


Klämke, Zeppenfeld (2007)

$pp \to Hjjj$ via GF @ NLO QCD

Greiner et al. (2015)



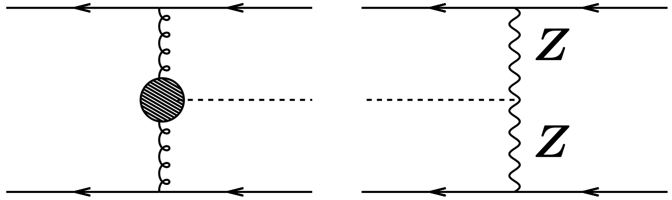


pheno study for $H + 2$ jets and $H + 3$ jets
via gluon fusion at NLO-QCD in VBF setup

☞ improved description of background

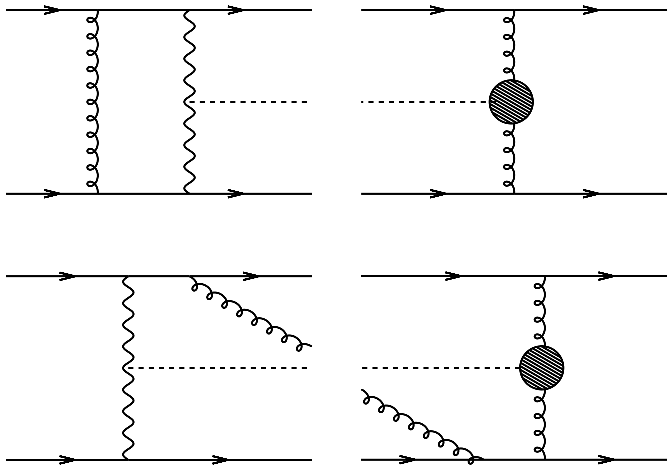
$pp \to Hjj$ via VBF×GF

can VBF×GF interference pollute the clean VBF signature?



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

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



Andersen et al. (2007)

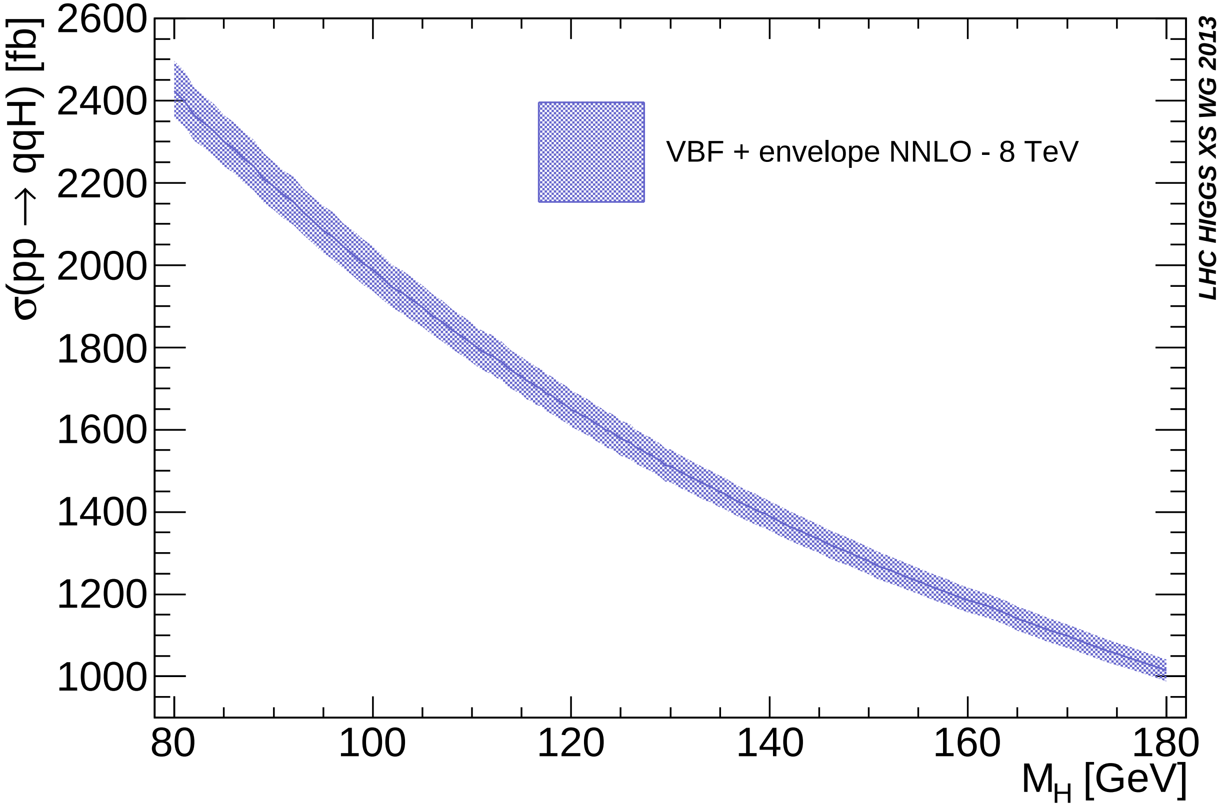
Bredenstein, Hagiwara, B. J. (2008):

- strong cancelation effects
  between contributions of
  different flavor

☞ interference effects are completely negligible

PDF uncertainties in VBF

HXSWG YR3 (2013)



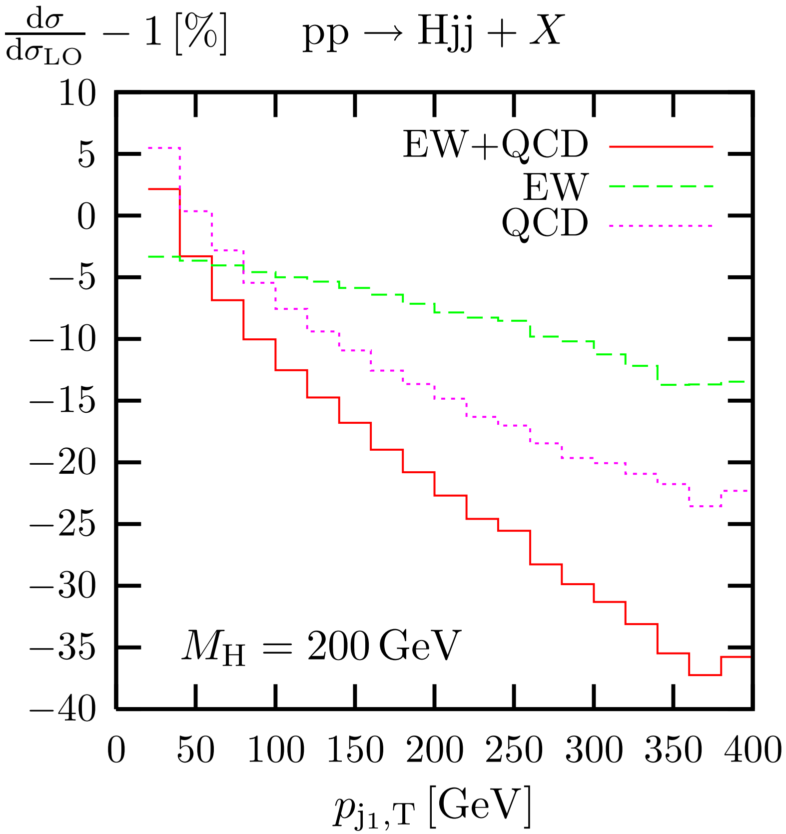
PDF and α_s uncertainties at NNLO-QCD + NLO-EW according to PDF4LHC prescription (CT10, MSTW2008, and NNPDF2.1)

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, Kallweit, Mück]

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

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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

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

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

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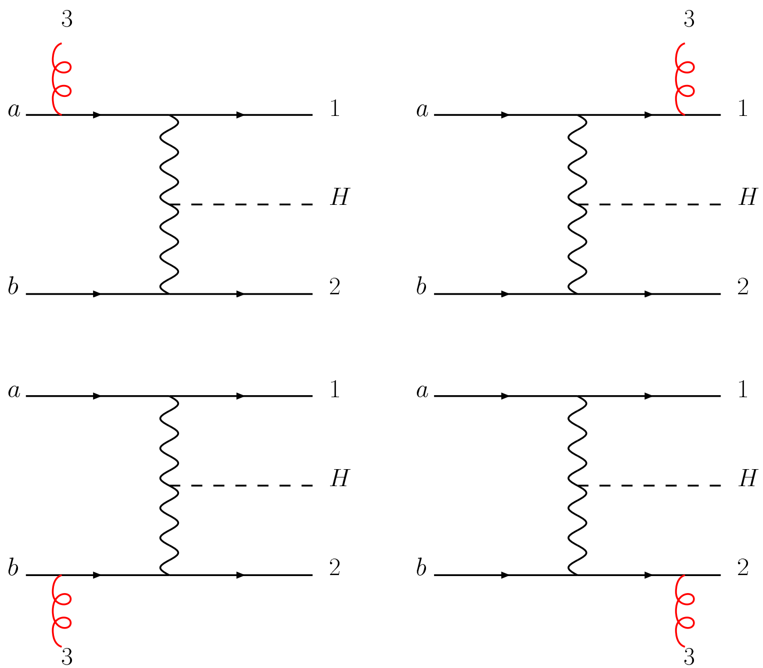
☞ precise knowledge of extra jet activity essential, requiring

- $pp \to Hjj$ 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

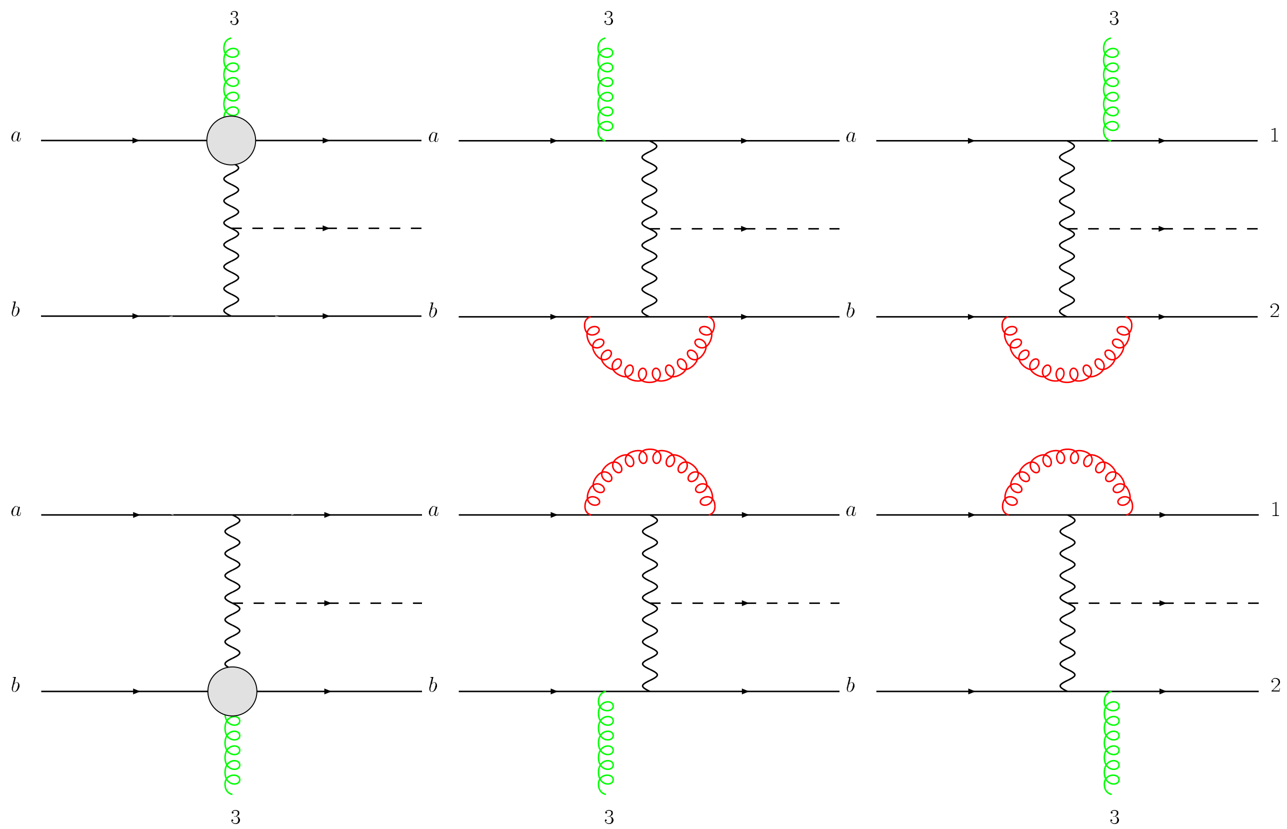
(no color exchange between upper/lower quark lines, no VH-type contributions)

Campanario, Figy, Plätzer, Sjödahl (2013):

full NLO-QCD calculation

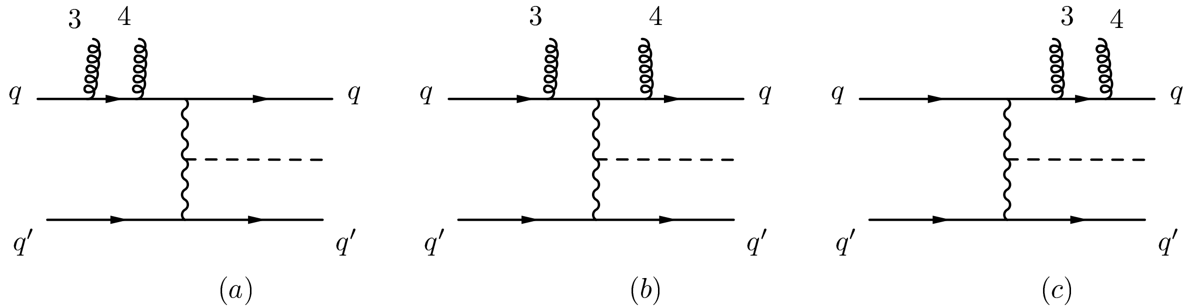
(good agreement with approximative calculation)

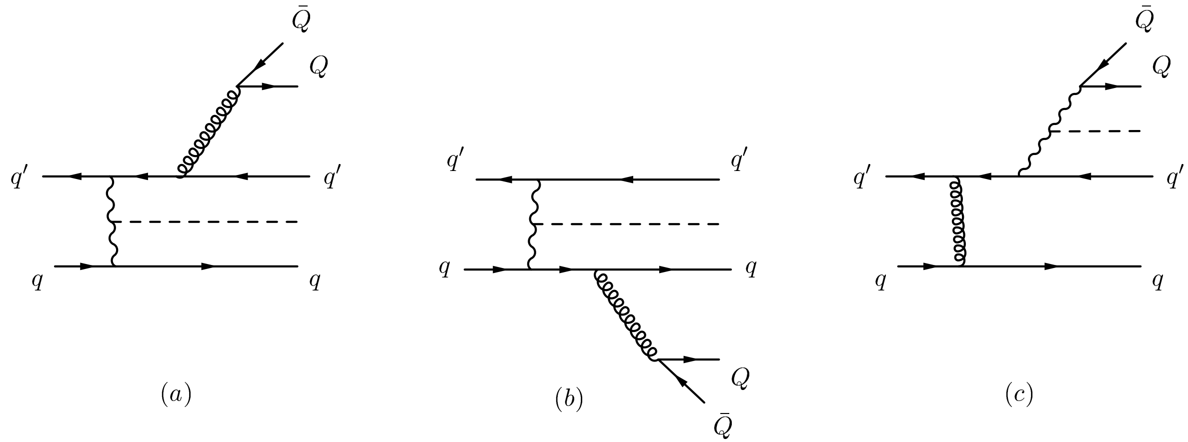
$pp \to Hjjj$ via VBF @ NLO QCD



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

$pp \to Hjjj$ via VBF @ NLO QCD

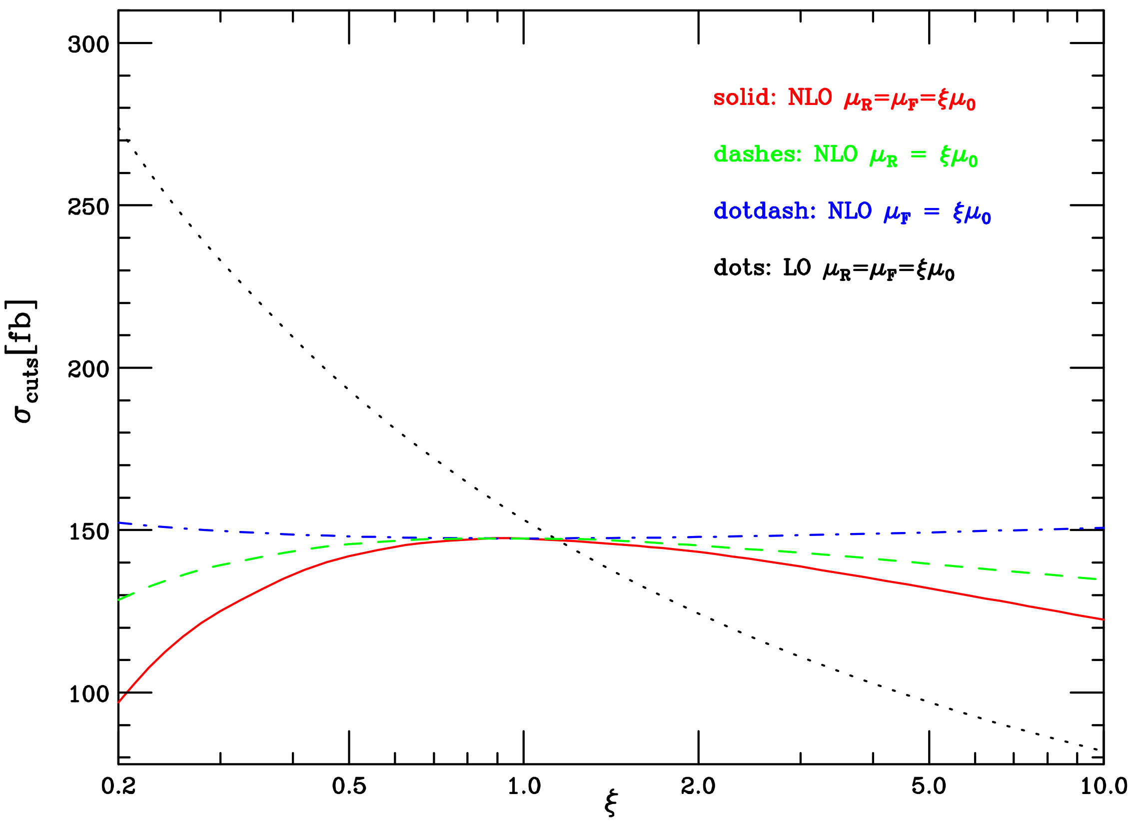




real emission contributions comprise processes with 4 quarks+2 gluons and processes with 6 quarks

$pp \to Hjjj$ via VBF @ NLO QCD

Figy, Hankele, Zeppenfeld (2007)

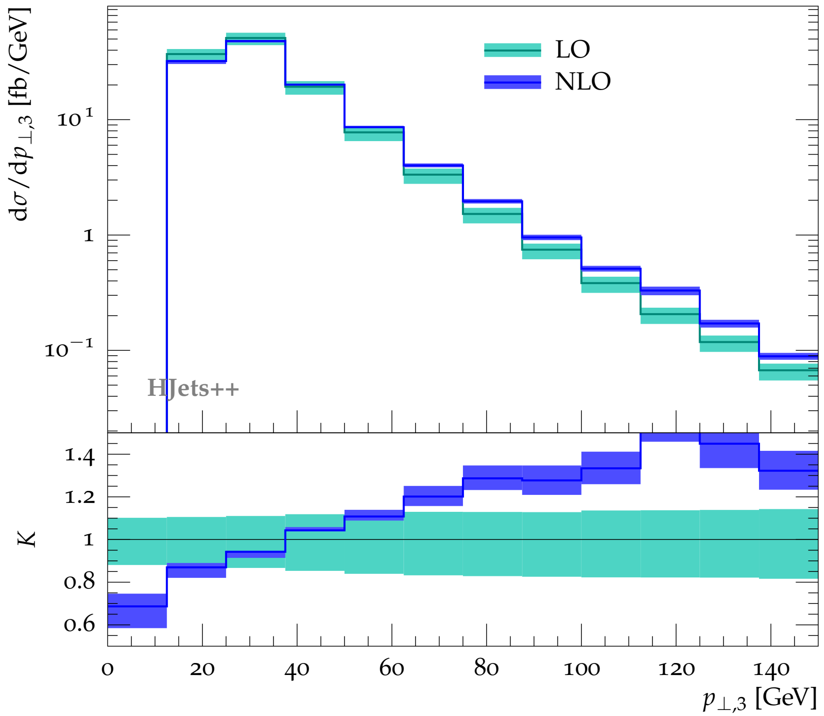


scale dependence moderate
(comparable to other VBF processes)

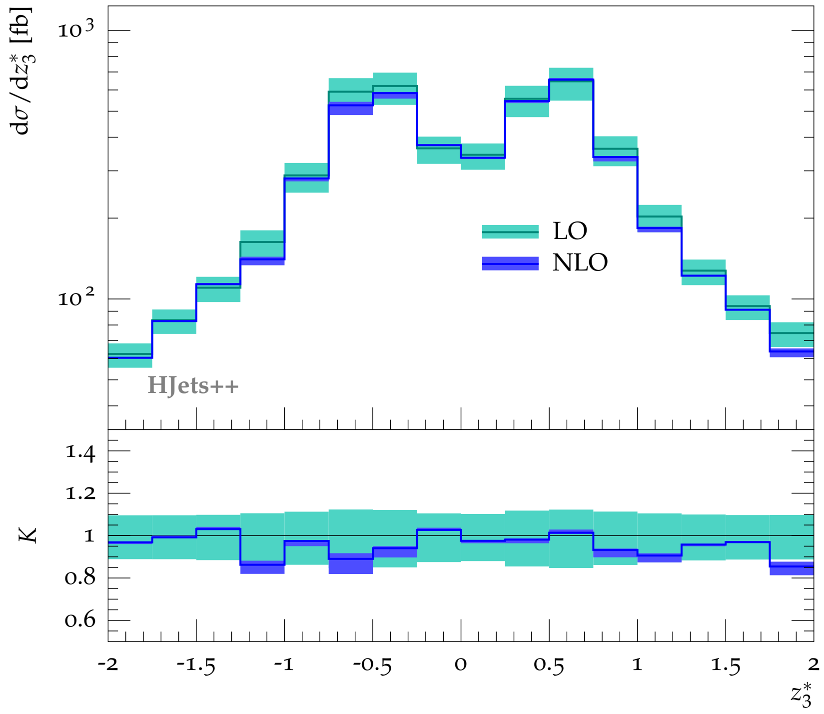
$pp \to Hjjj$ via VBF @ NLO QCD

Campanario et al. (2013)

transverse momentum of 3^{rd} jet

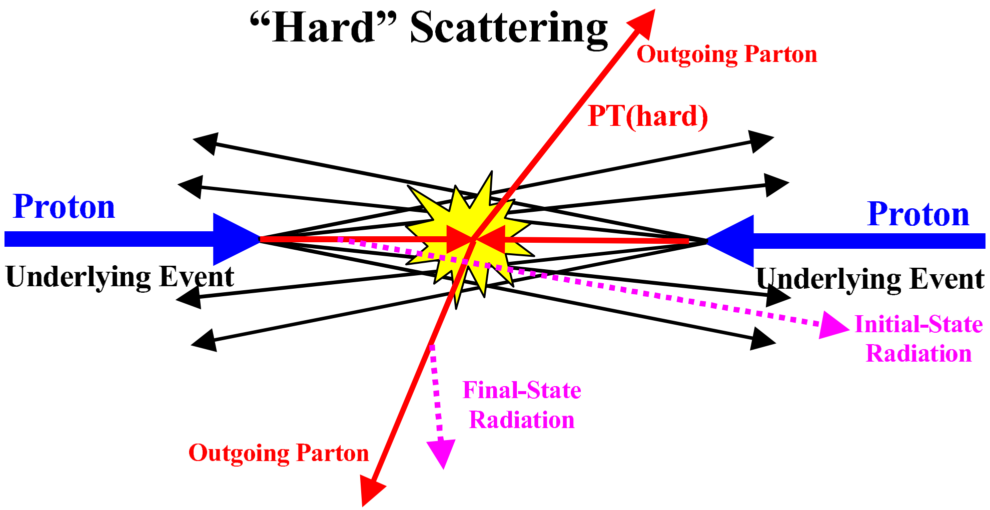


relative rapidity of 3^{rd} jet



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

more realistic simulation



for realistic description of scattering processes at hadron colliders:

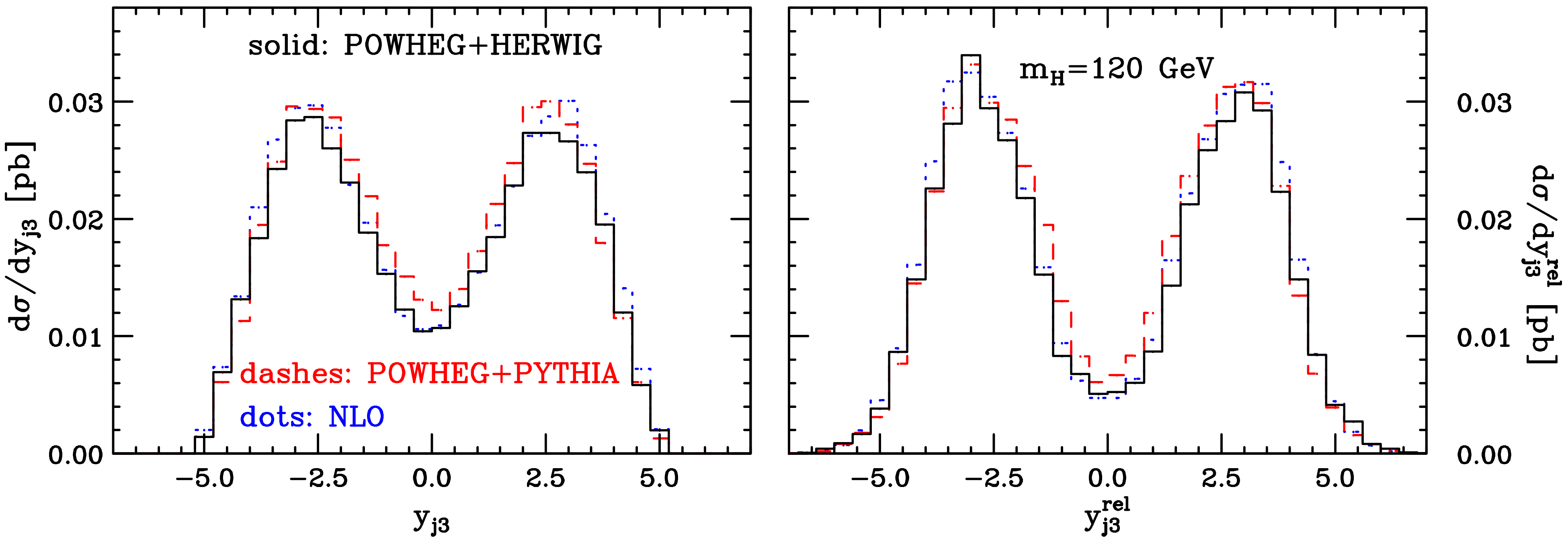
- combine matrix elements for hard scattering with programs for simulation of

underlying event, parton shower, and hadronization

(PYTHIA, HERWIG, SHERPA,...)

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

Nason, Oleari (2009)

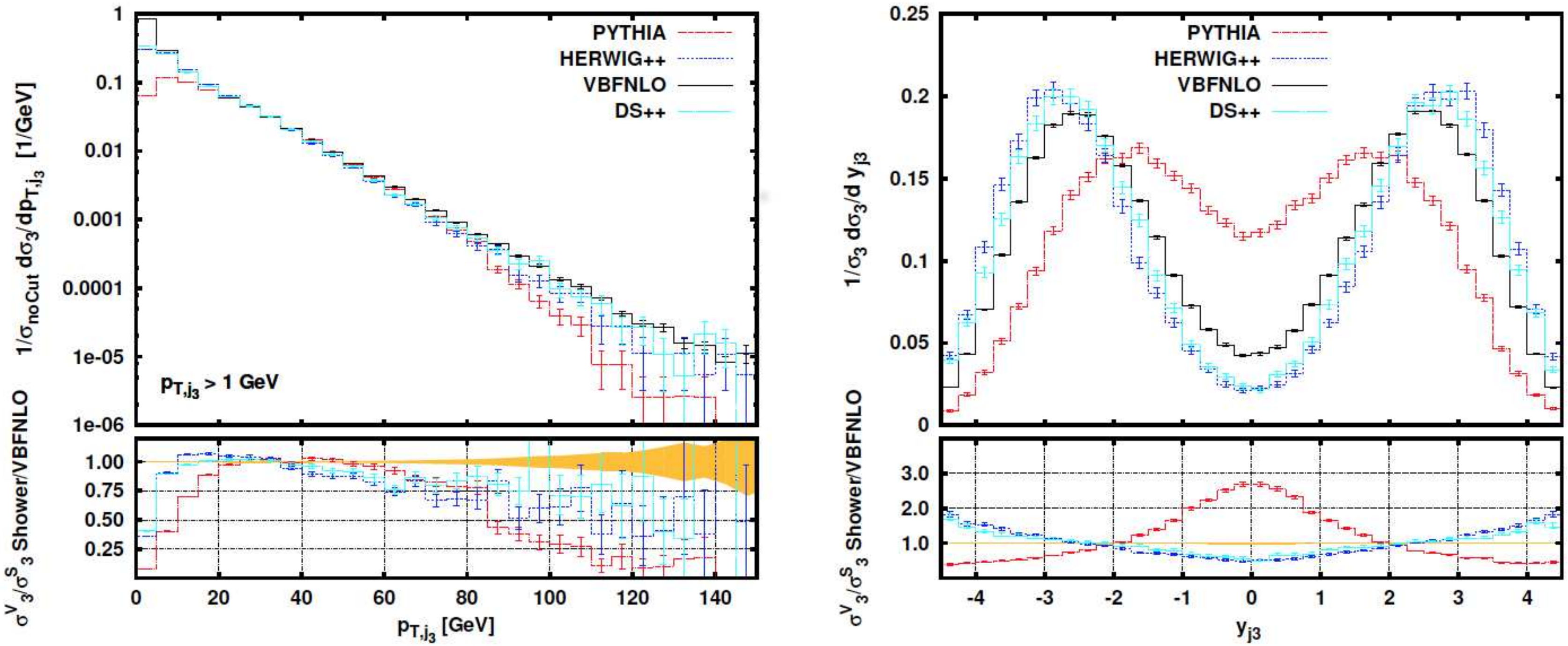


VBF Hjj matrix elements at NLO combined with parton shower

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

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

Schissler (2014)

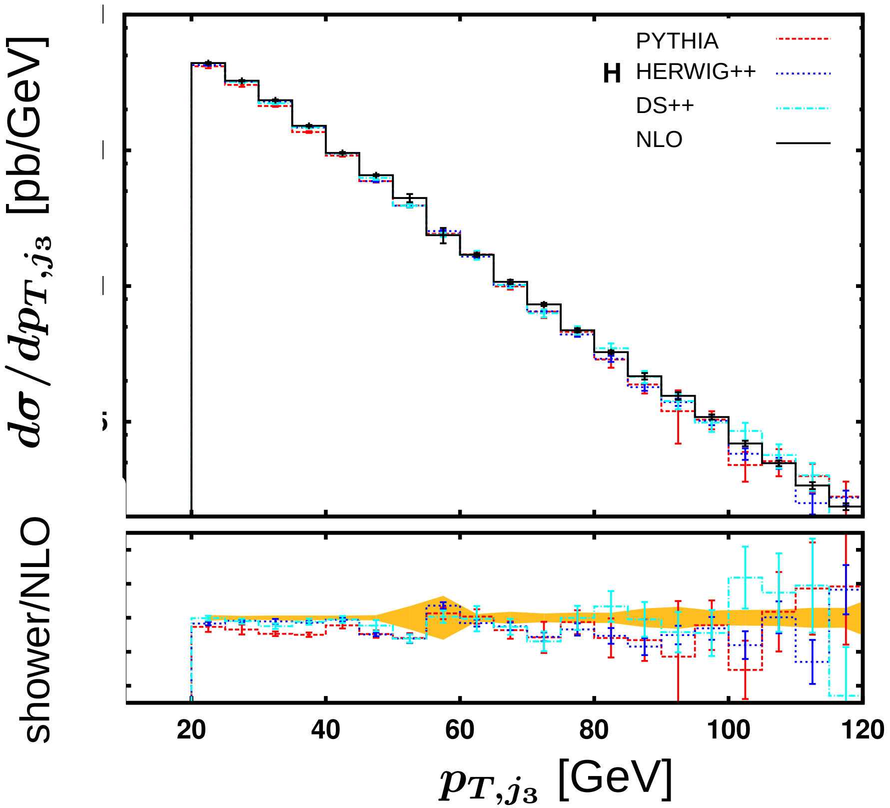


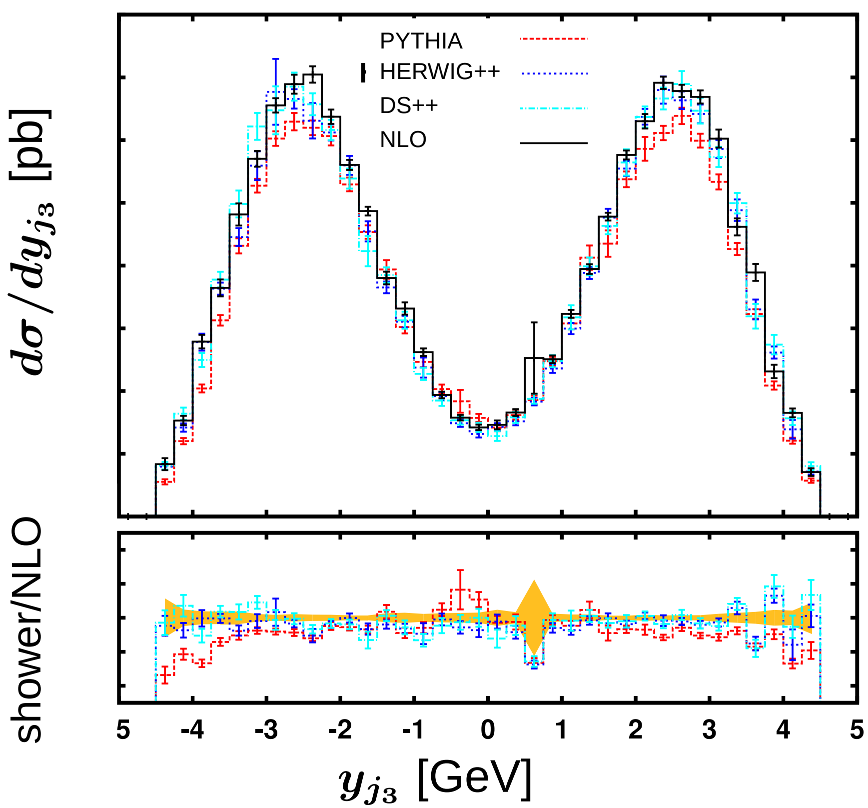
VBF Hjj matrix elements at LO combined with parton shower

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

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

Schissler, Zeppenfeld, B.J. (2014)



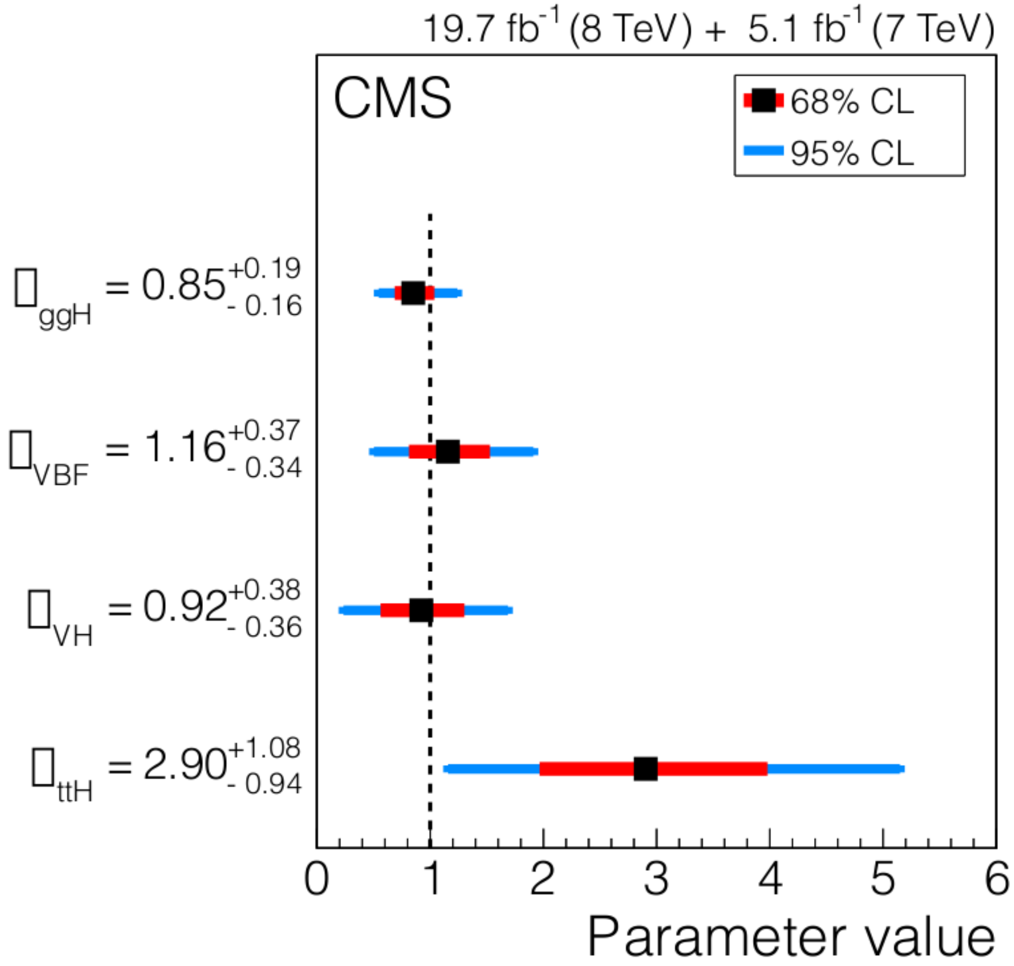


VBF $Hjjj$ matrix elements at NLO combined with parton shower

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

experimental status

arXiv: 1412.8662



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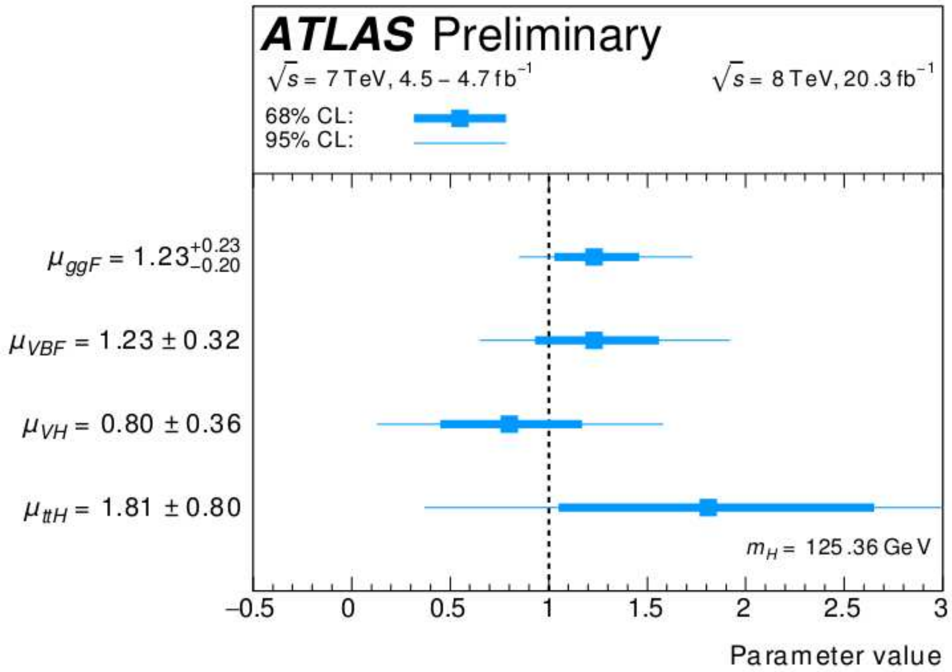
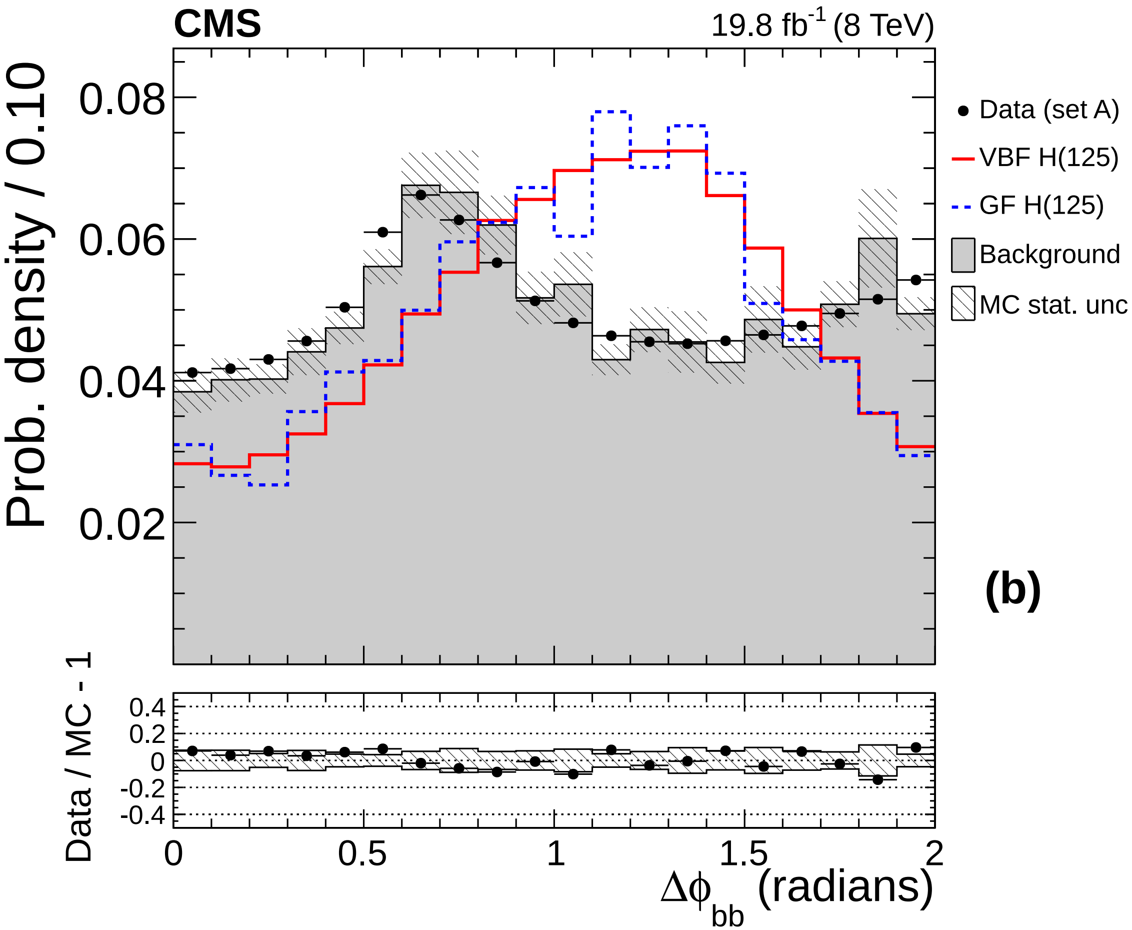


news from CMS: $H \to b\bar{b}$ in VBF

arXiv: 1506.01010



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

signal strength

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

compare to

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

VBF analyses in ATLAS

- VBF signal modelling at NLO-QCD
  with PS via POWHEG+PYTHIA8

- NLO-EW corrections from HAWK:

$$d\sigma = d\sigma_{\mathrm{QCD}}^{\mathrm{best}} \times (1 + \delta_{\mathrm{EW}})$$

central jet veto requires control over the 3rd jet:

- simulations for VBF $Hjjj$ available
  in POWHEG and aMC@NLO

- no jet merging available as of yet

VBF theory systematics and corrections

VBF Higgs production has small theory uncertainty in itself (see Run1 **H→ττ** example)

Run1 experience from the H→ττ analysis:

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- **UE / PS / hadronization / MPI effects**: encoded in Powheg+Pythia8 vs Powheg+Herwig comparison, leading to 5-10% on signal yield
- **ME+PS matching**: Powheg+Herwig vs aMC@NLO +Herwig leading to 5% effect on signal yield
- **Missing higher orders** (scale variations): range of 1.4-2%
- **EW corrections**: differential modelling of the truth pTH spectrum from HAWK + associated uncertainty
- **PDFs**: following PDF4LHC prescription give a 2-3% yield variation + shape effect up to 5% in the tail of the dijet distribution

Source of Uncertainty	Uncertainty on μ
Signal region statistics (data)	$^{+0.27}_{-0.26}$
Jet energy scale	± 0.16
Tau energy scale	± 0.07
Tau identification	± 0.06
Background normalisation	± 0.12
Background estimate stat.	± 0.10
BR ($H \to \tau\tau$)	± 0.08
Parton shower/Underlying event	± 0.04
PDF	± 0.03

(BR uncertainty not negligible for **H→ττ**)

Main message: Dominant systematic uncertainties are [UE / PS / hadronization and MPI effects] and [ME+PS matching]

Both estimated through “2-point” comparison of different generators.

ggF contamination in VBF-regions

Gluon-fusion induced H+jets production is an important background for VBF signal resgions

Some examples from ATLAS analyses: **ggF contamination (%)**

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- $H\rightarrow\gamma\gamma$: VBF-tight(loose) = **20**%(**40**%)
- $H\rightarrow WW$: **30**%
- $H\rightarrow\tau\tau$(lep-had) : **35**-**43**% [10-15% from the last BDT bin]

MC tools for H+2jets modelling are under study (in parallel with ggF WG1 subgroup):

- HJ, HJJ from Powheg+MiNLO
- MEPS@NLO
- aMC@NLO merged with FxFx procedure
- New GoSAM ggH HJJJ included in Sherpa for ME+PS (in developement)

During Run1 we relied on **Powheg (H inclusive) NLO+PS prediction**, reweighting the Powheg pTH spectrum of the 2-jet bin to match the HJJ Powheg+MiNLO prediction.
This means that the >= 2-jet region relies on the **parton shower modelling** of extra radiation.

New tools are under study to get a more accurate modelling of this (important) background for VBF-like final states.

VBF reweighting tools

VBF production mode could be an interesting tool to probe BSM physics signature, e.g. CP-violation for the Higgs sector.

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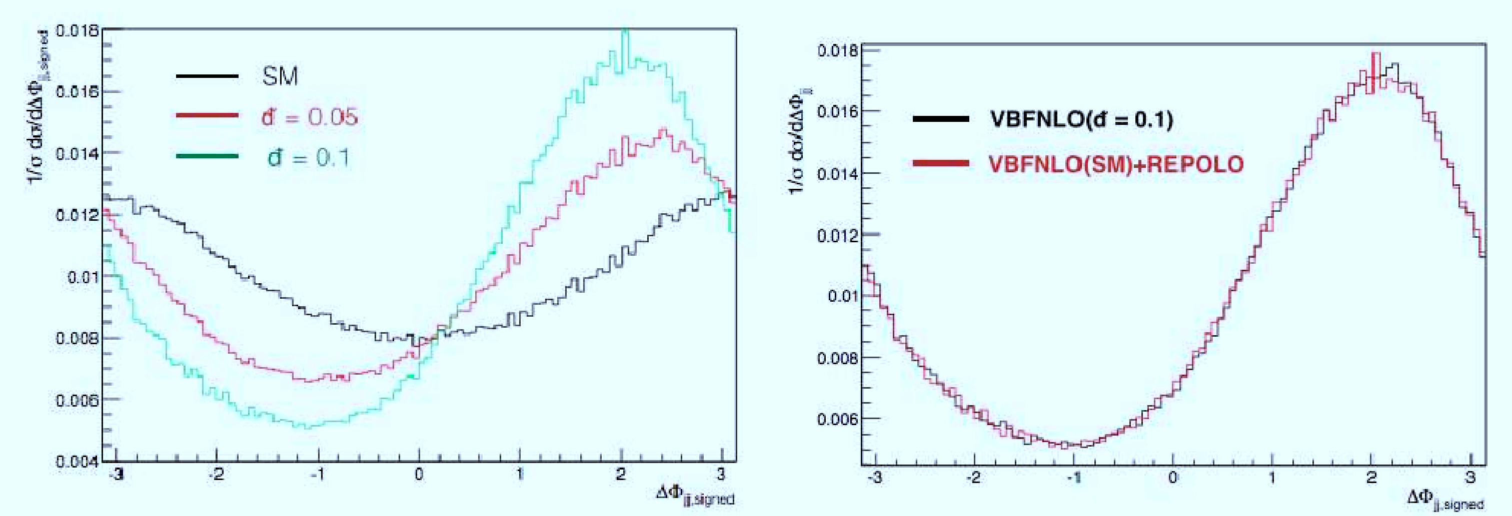
Generating full detector simulation samples for different scenarios is very expensive:

- Powheg provides the “nominal” SM VBF prediction
- aMC@NLO provides benchmark scenarios for CP-even/CP-odd mixing
- **REPOLO** tool used to reweight Powheg prediction / validated vs aMC@NLO
  REPOLO is a **LO ME reweighting tool** - still under validation
- First studies reweighting Powheg prediction to **HAWK matrix-element**
  HAWK can provide ME at LO for (2->2+H) and (2->3+H) processes, giving a good approximation of the full NLO reweighting

$$\frac{|\mathcal{M}_{\rm BSM}|^2}{|\mathcal{M}_{\rm SM}|^2}$$



SM vs 2 mixture scenarios in VBFNLO

REPOLO validation

summary

VBF crucial for understanding mechanism of electroweak symmetry breaking:

* $\boldsymbol{Hjj}$: very clean Higgs production channel

important pre-requisites:

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

NLO-QCD corrections and parton-shower effects moderate;

nota bene: NLO-EW effects non-negligible

✔ backgrounds are well under control