Simulation of processes with electroweak bosons at hadron colliders

Loopfest X

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Barbara Jäger

for the vbfnlo collaboration

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- to take advantage of data from LHC
  - ☞ need accurate predictions for signal and background processes

- Monte Carlo methods allow us to:
  - simulate final states with several jets and/or identified particles
  - impose realistic selection cuts
  - calculate a variety of observables

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

implemented processes

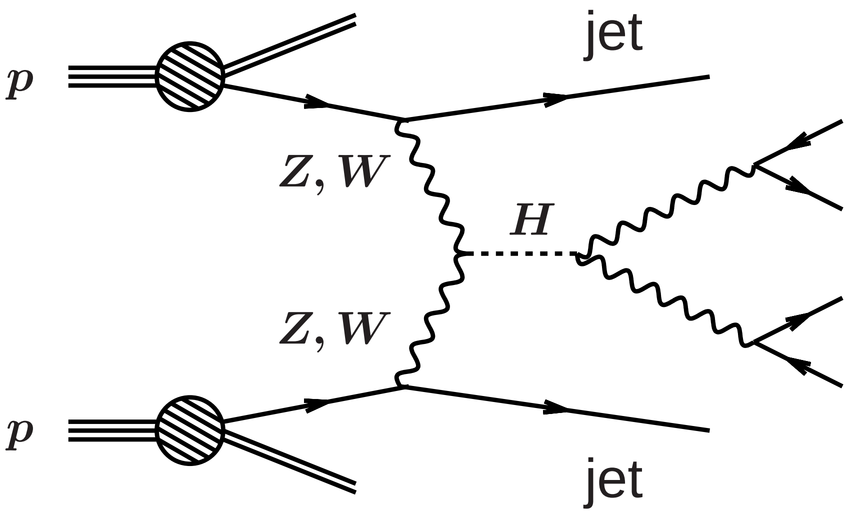
`vbfnlo` is a fully flexible parton level Monte Carlo for processes with electroweak bosons at NLO-QCD

it can simulate:

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

features

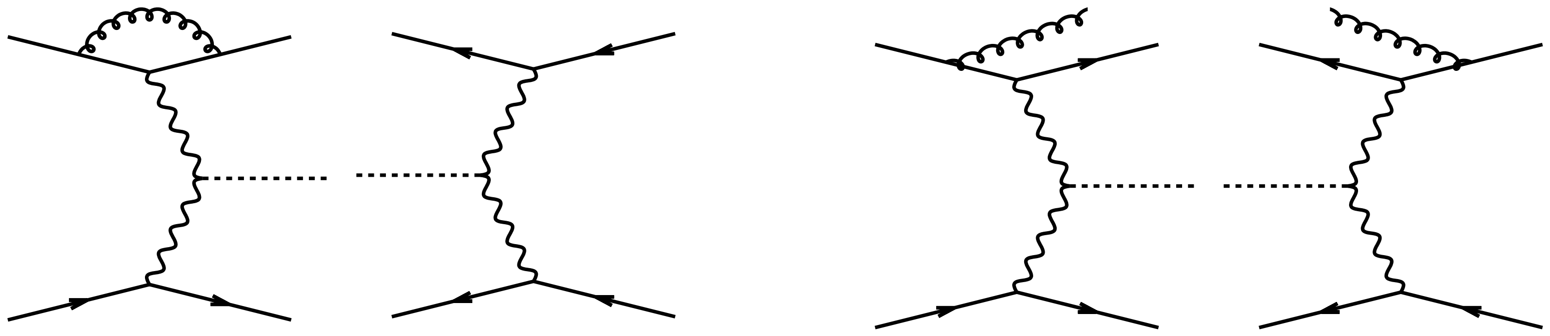
- cross sections and distributions at NLO-QCD accuracy
- arbitrary selection cuts
- various choices for factorization and renormalization scales
- LO predictions for all processes with one extra jet
- interface to LHAPDF $\longrightarrow$ any currently available PDF set;
  hardwired: CTEQ6L1, CT10, MRST2004qed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



suppressed color exchange between quark lines gives rise to

- little jet activity in central rapidity region
- scattered quarks $\longrightarrow$ 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)

higher orders of QCD in VBF

- *Harlander, Vollinga, Weber (2007):*

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

  minimal set of cuts: $\sigma_{\rm gluon}^{\rm 2-loop} \sim 2\ \%$ of $\sigma_{\rm VBF}^{\rm LO}$
  VBF cuts: extra order-of-magnitude suppression

- *Bolzoni, Maltoni, Moch, Zaro (2010):*

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

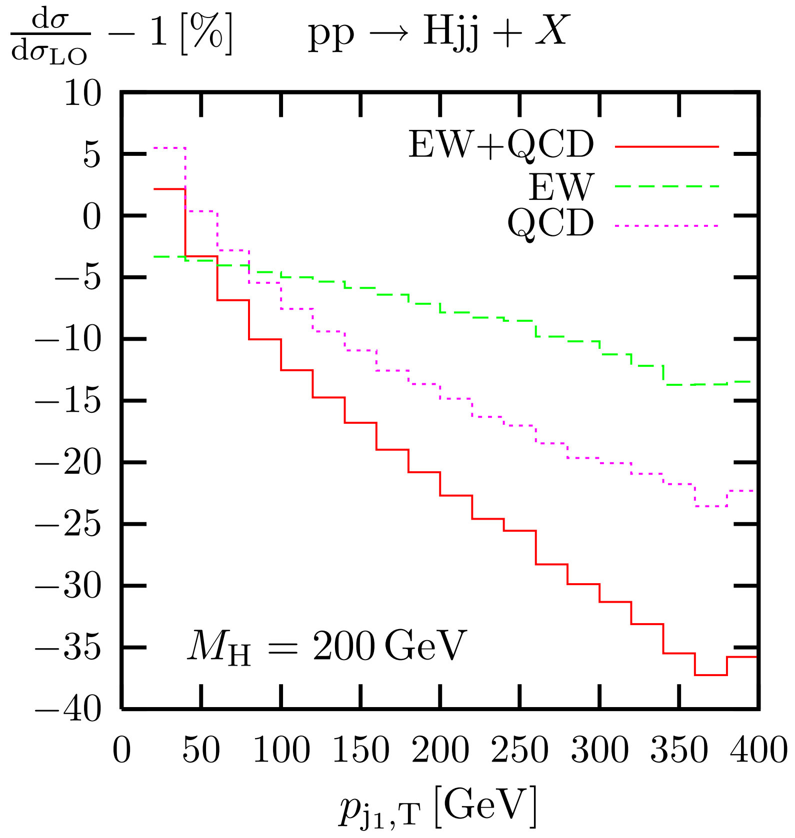
  residual scale uncertainties:
  reduced from $\sim 4\%$ to $\sim 2\%$

Higgs production in VBF @ NLO EW

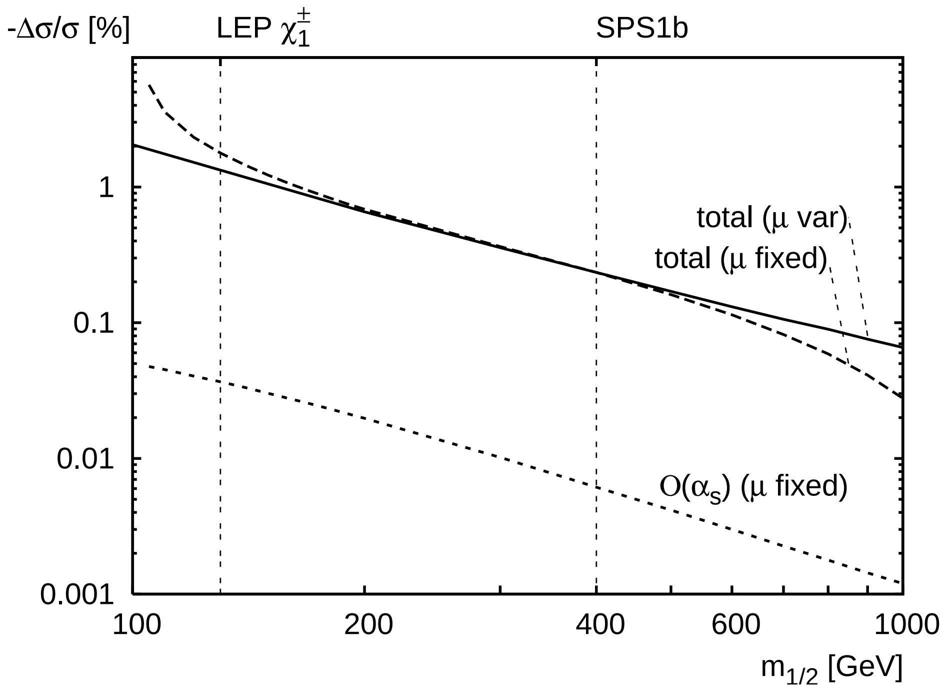
Ciccolini, Denner, Dittmaier, Mück:

NLO EW corrections to inclusive cross sections and distributions

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



SUSY QCD+EW corrections to VBF



Hollik, Plehn, Rauch, Rzehak (2008) &

Figy, Palmer, Weiglein (2010):

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

for inclusive cross sections

in typical regions of the MSSM parameter space

$pp \longrightarrow Hjj$ via VBF in vbfnlo

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

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

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

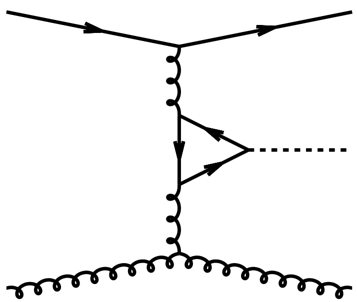
- dominant NLO-QCD corrections to $pp \longrightarrow Hjjj$
  ($\longrightarrow$ extra jet activity in VBF)

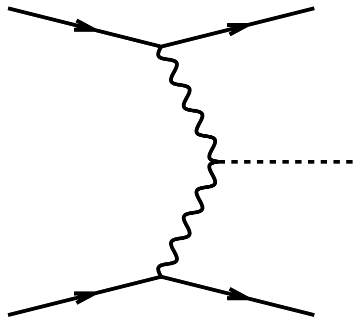
- anomalous Higgs-gauge boson couplings

$pp \longrightarrow Hjj$ via gluon fusion

VBF can be faked by double real corrections

to $gg \longrightarrow H$ (“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:

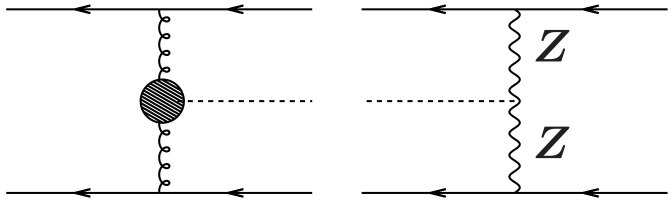
  Campanario, Kubocz, Zeppenfeld (2011)

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

  Campbell, Ellis, Zanderighi (2006)

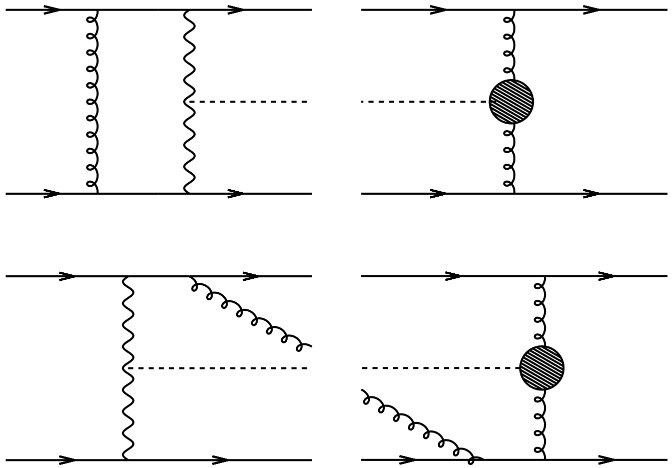
$pp \longrightarrow Hjj$ via VBF×GF

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

$pp \to Hjj$ via gluon fusion in vbfnlo

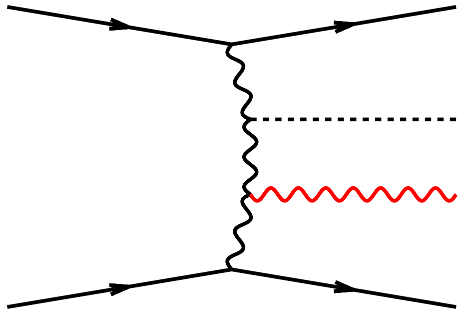
- one-loop contributions in the SM, the (complex) MSSM,
  and a generic two-Higgs doublet model
  (without GF$\times$WBF interference)

- mass dependence of top and bottom quarks is fully retained

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

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

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



Gabrielli et al. (2007):

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

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

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

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

effects of hard central photon requirement:

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

- ✔ de facto: reduction factors different for S and B

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

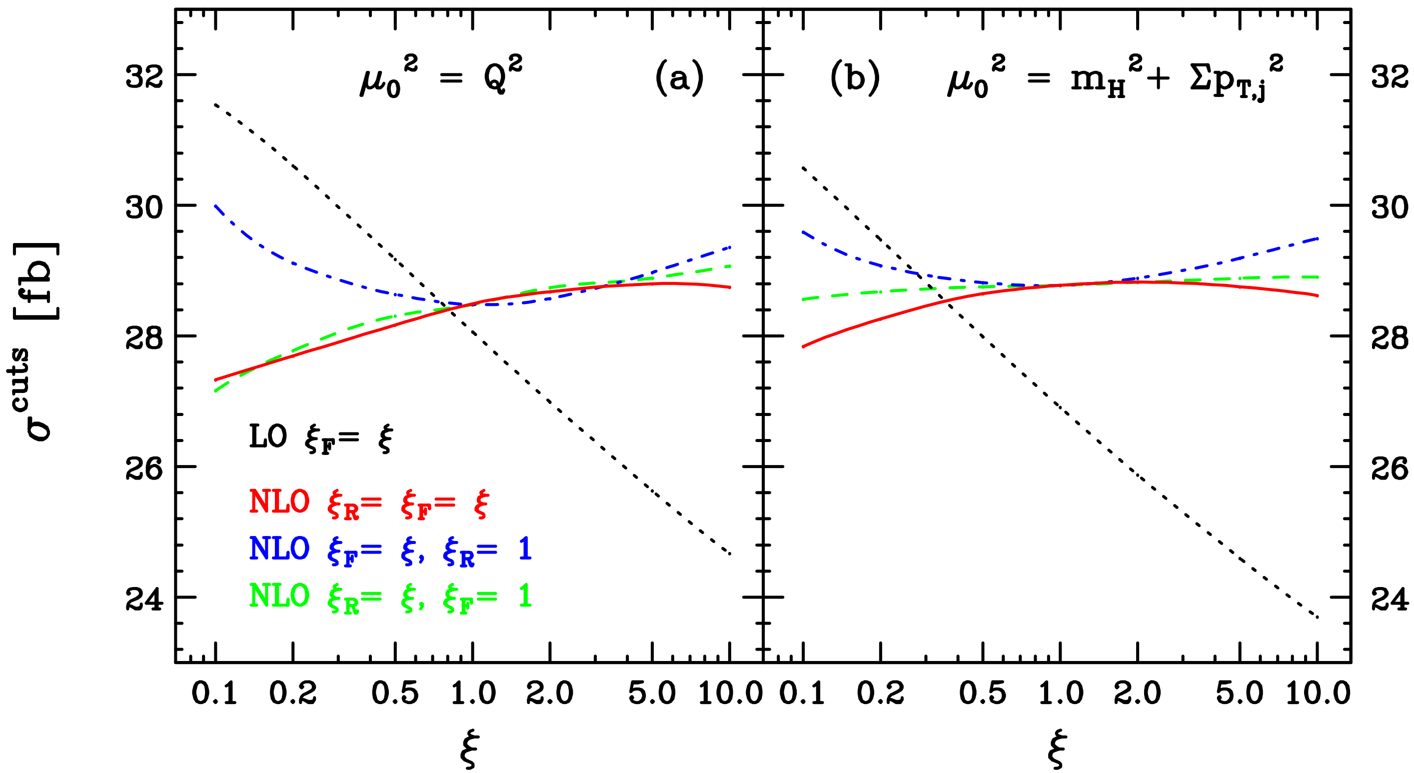
  signal: $\sigma_\gamma/\sigma \sim 1/100$

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

[Gabrielli et al. (2007)]

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

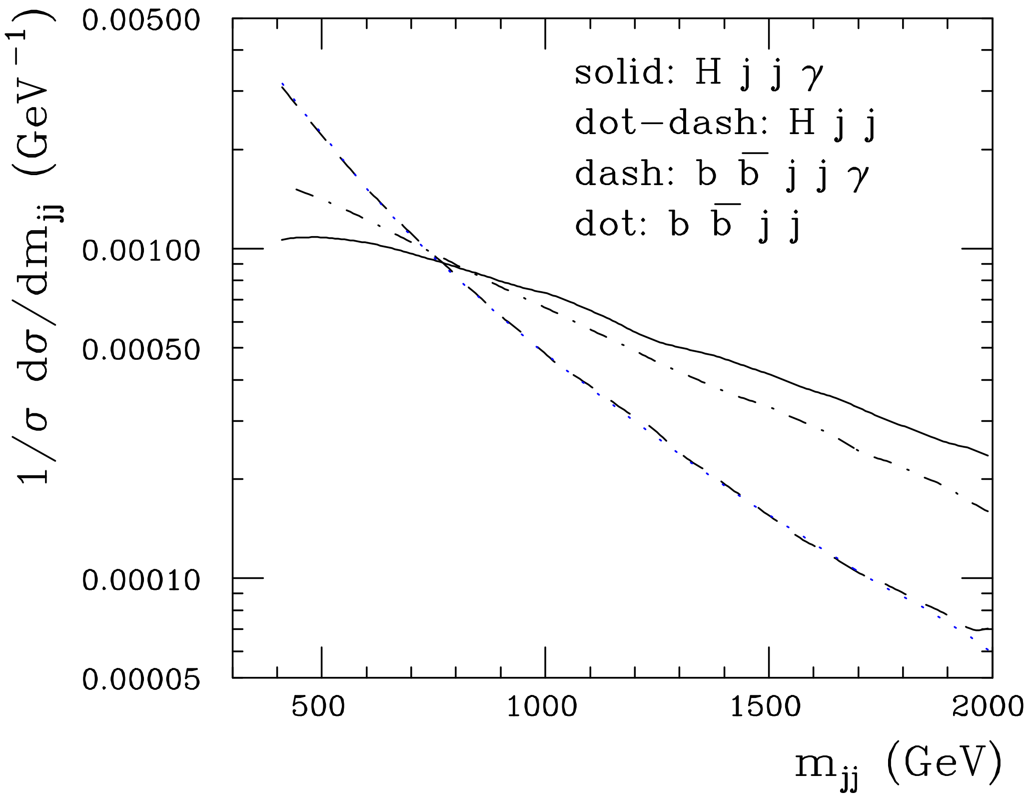


Arnold, Figy, BJ, Zeppenfeld (2010)

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

invariant mass of the tagging jets

Gabrielli et al. (2007)

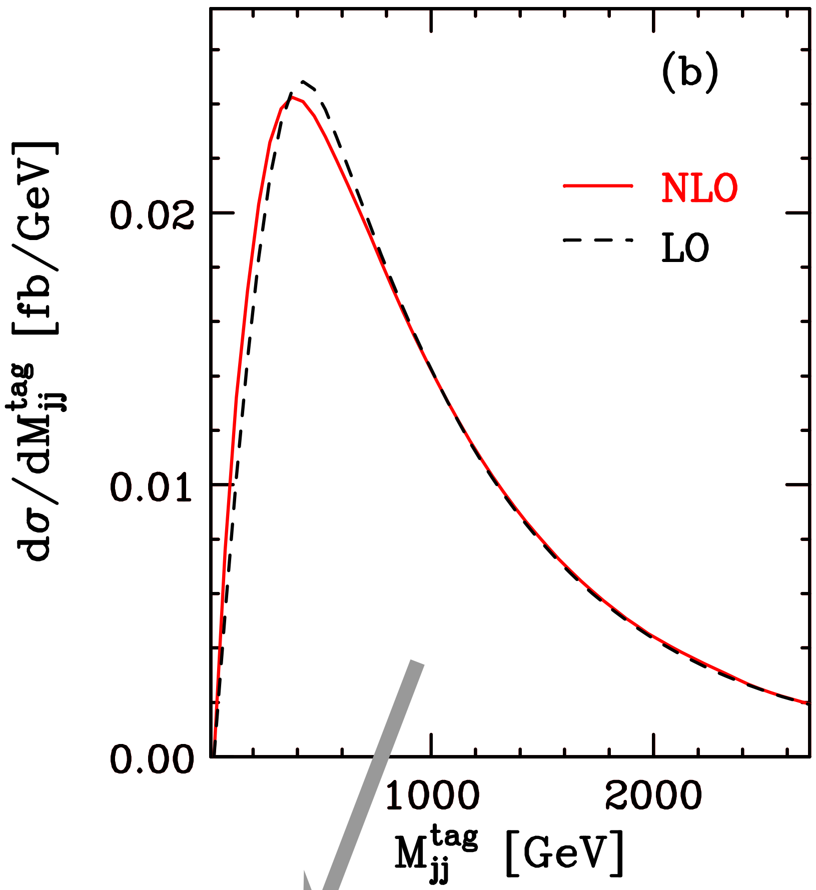


- $d\sigma/dm_{jj}$ slightly flatter for $H\gamma jj$ signal than for Hjj
- $b\bar{b}jj$ and $b\bar{b}\gamma jj$ backgrounds have very similar shapes
- background distributions exhibit much steeper slope than signal

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

invariant mass of the tagging jets

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



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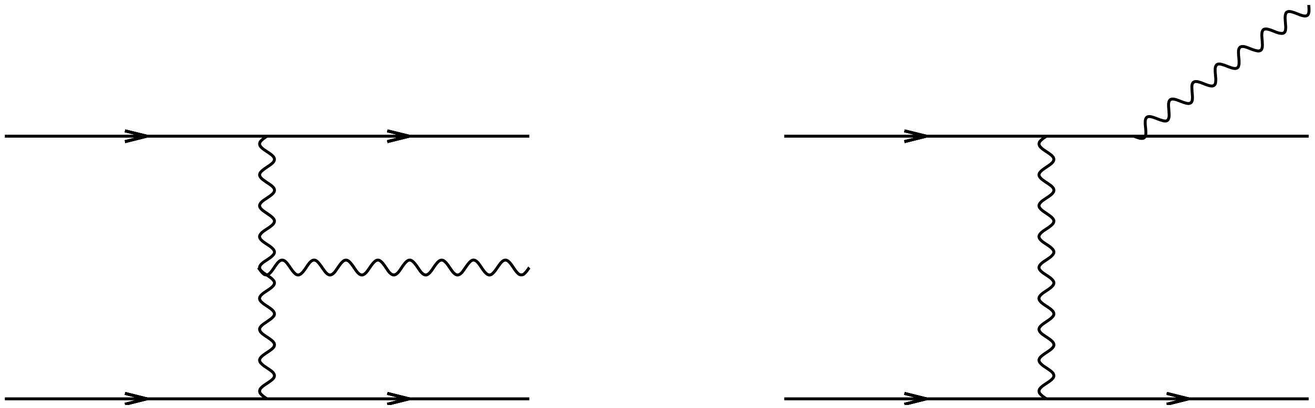
effect of NLO-QCD corrections small

$pp \longrightarrow Vjj$ via VBF



- $pp \longrightarrow W^{\pm}jj$ & $pp \longrightarrow Zjj$
  [Oleari, Zeppenfeld (2003)]
- $pp \longrightarrow \gamma jj$ *[BJ (2010)]*

- sensitive to triple gauge boson couplings
  - $Z \longrightarrow \tau\tau \ldots$ background to $H \longrightarrow \tau\tau$
  - measure central jet veto acceptance

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

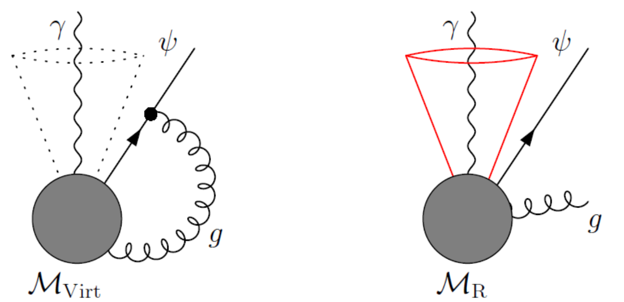
photon isolation

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

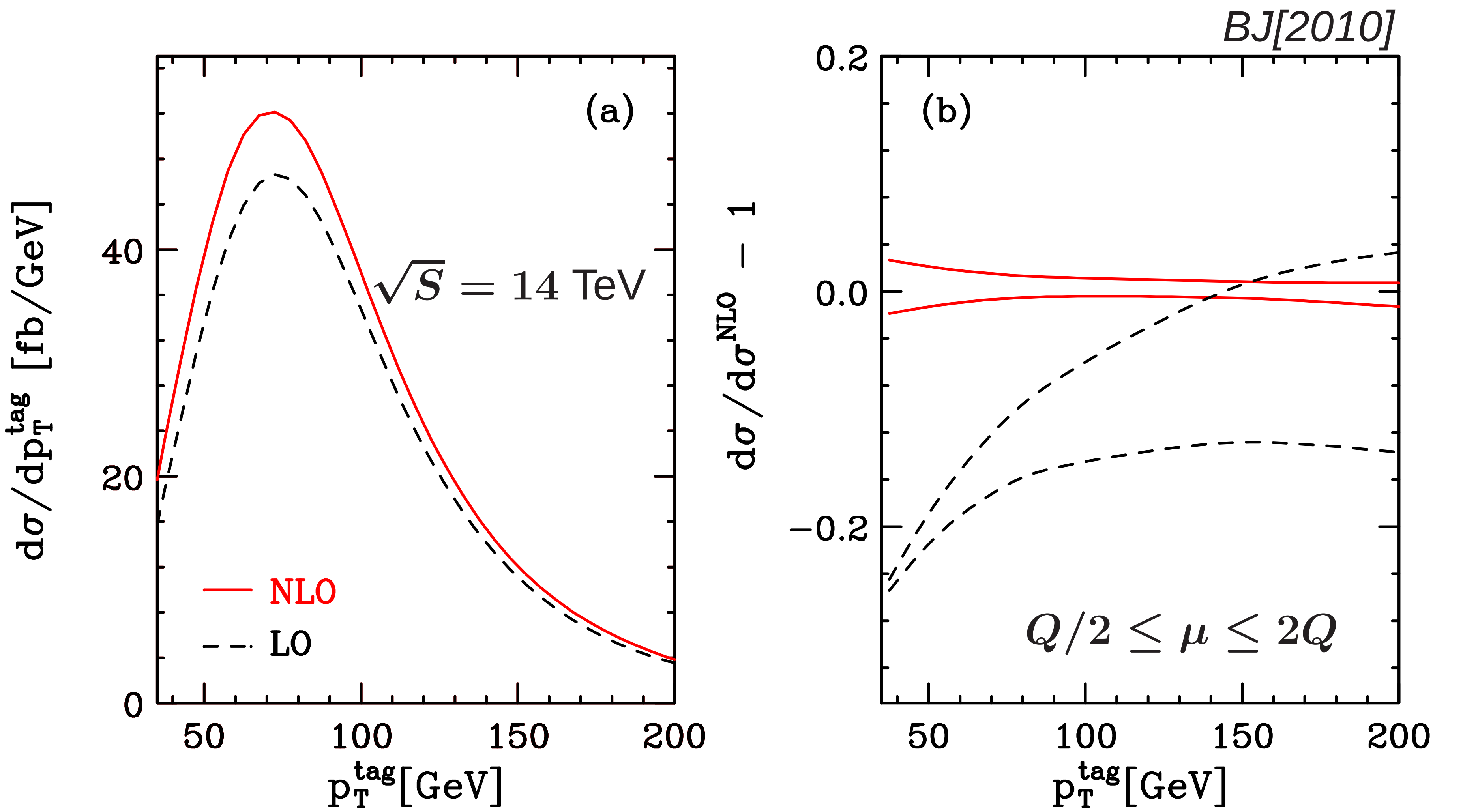
idea: veto collinear photon-jet configurations, but allow soft QCD emission

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

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

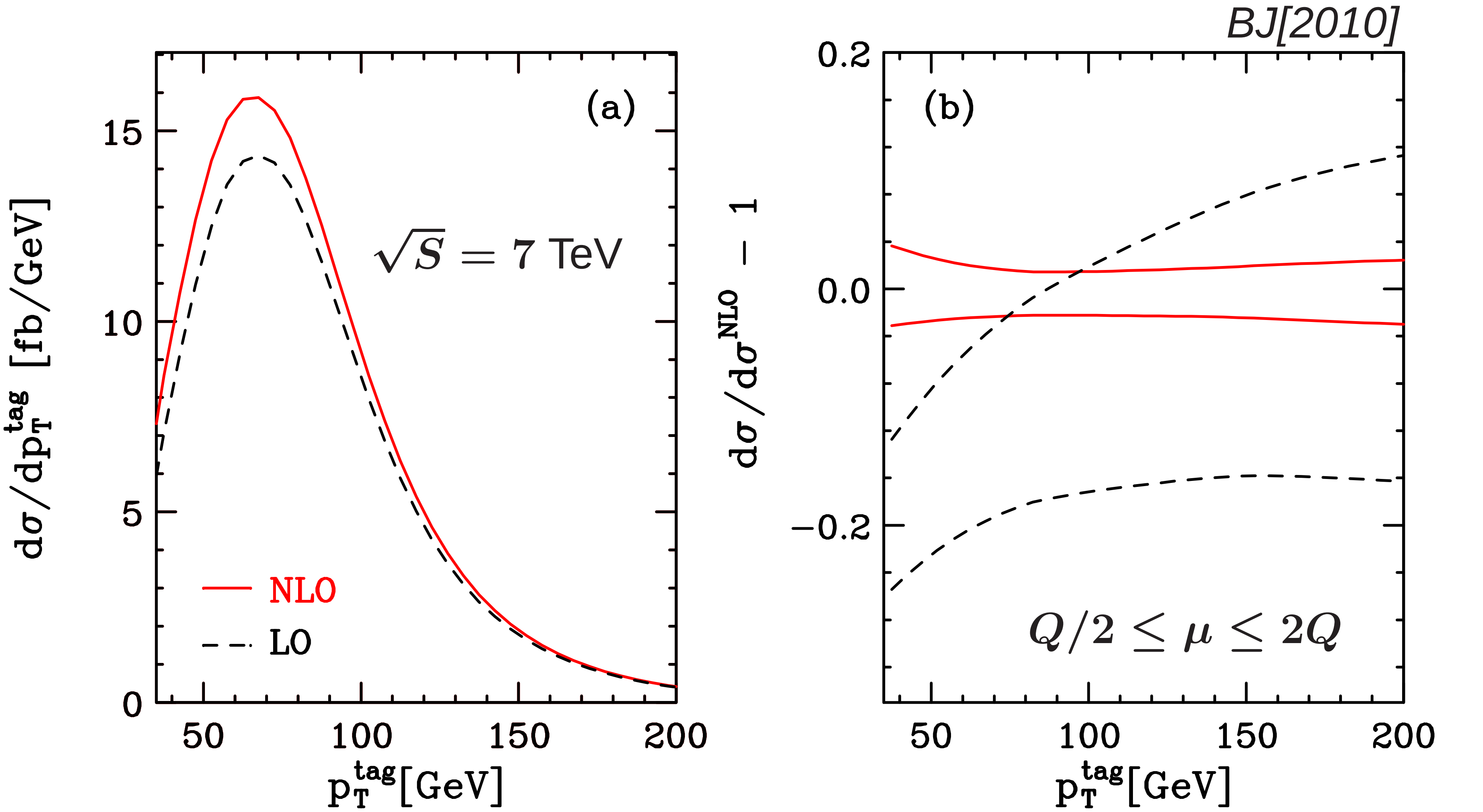


$pp \longrightarrow \gamma jj$ via VBF @ NLO-QCD



NLO-QCD corrections affect the shape of some distributions

$pp \longrightarrow \gamma jj$ via VBF @ NLO-QCD



NLO-QCD corrections affect the shape of some distributions

anomalous couplings

anomalous photon-weak boson couplings $\longrightarrow$ generalized vertex:

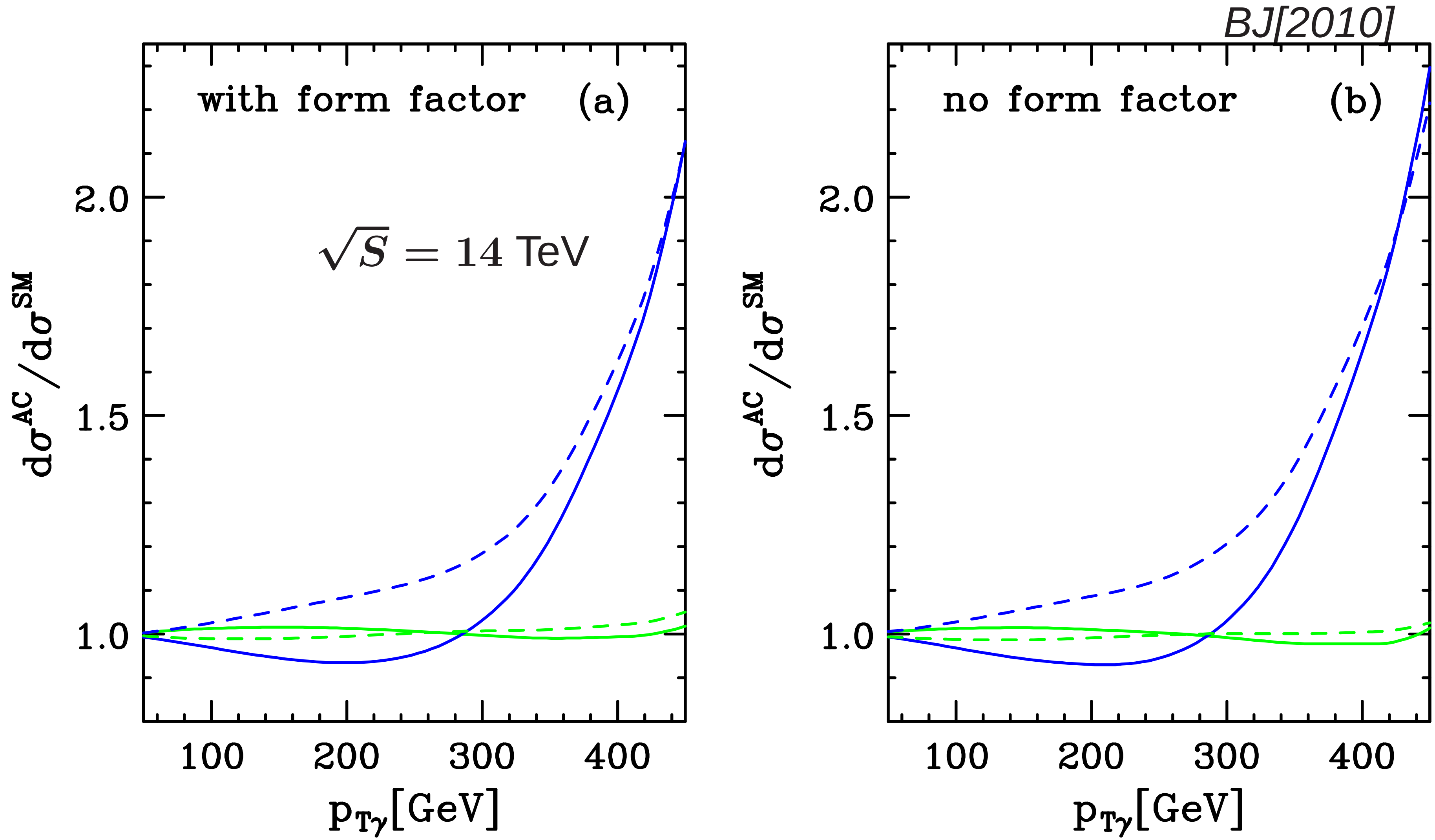
$$\Gamma^{\alpha\beta\mu}_{WW\gamma}(q,q',p) = q'^{\alpha}g^{\beta\mu}\left(2+\Delta\kappa^\gamma+\lambda^\gamma\frac{q^2}{m_W^2}\right) - q^{\beta}g^{\alpha\mu}\left(2+\Delta\kappa^\gamma+\lambda^\gamma\frac{q'^2}{m_W^2}\right)$$
$$+(q'^{\mu}-q^{\mu})\left[-g^{\alpha\beta}\left(1+\frac{1}{2}p^2\frac{\lambda^\gamma}{m_W^2}\right)+\frac{\lambda^\gamma}{m_W^2}p^\alpha p^\beta\right],$$

unitarity violations of effective Lagrangian at high energies

tamed via form factors:

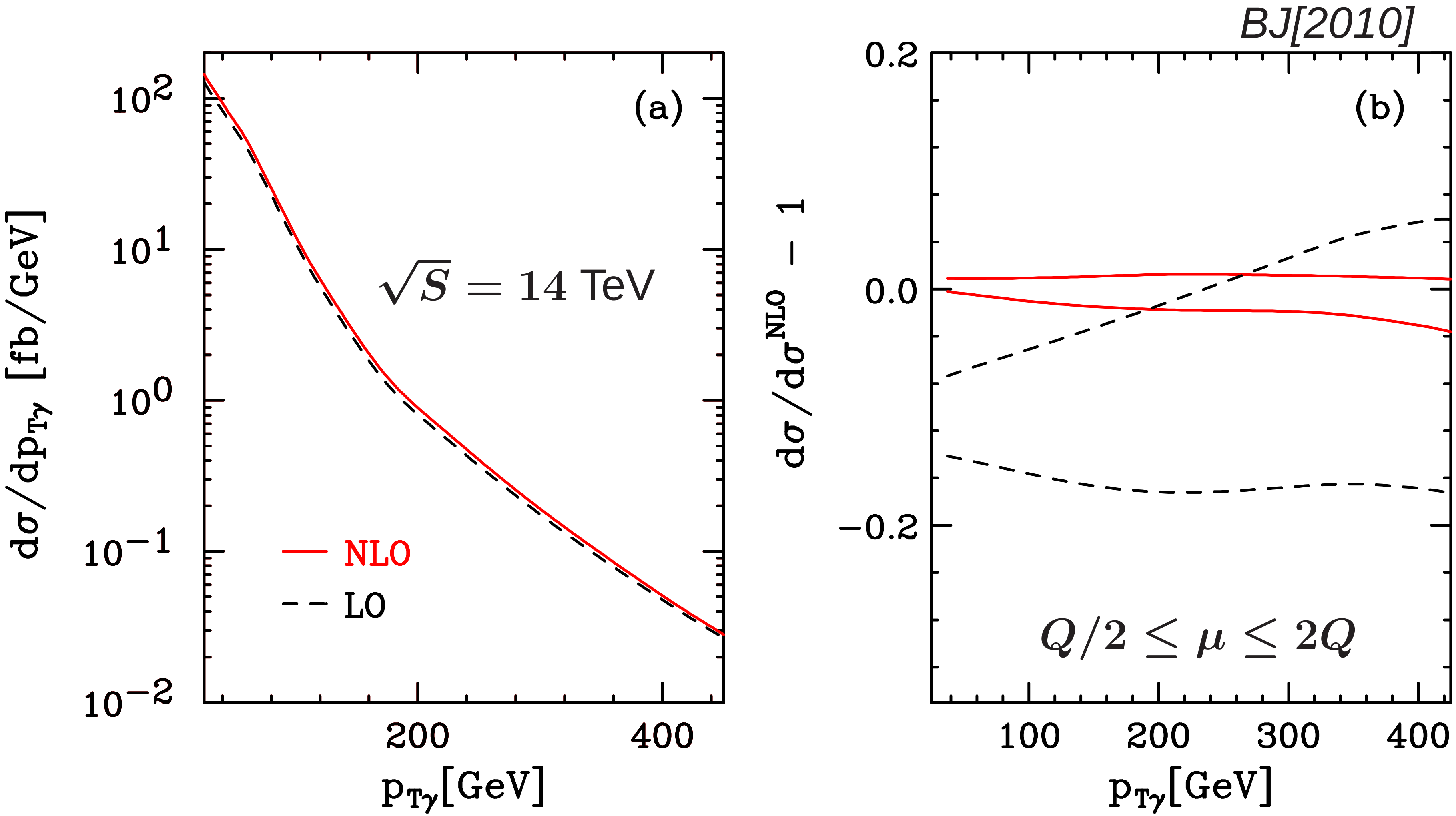
$$\Delta\kappa^\gamma \longrightarrow \frac{\Delta\kappa^\gamma}{\left[\left(1+\frac{|q^2|}{\Lambda^2}\right)\left(1+\frac{|q'^2|}{\Lambda^2}\right)\right]^n}, \qquad \lambda^\gamma \longrightarrow \frac{\lambda^\gamma}{\left[\left((1+\frac{|q^2|}{\Lambda^2}\right)\left((1+\frac{|q'^2|}{\Lambda^2}\right)\right]^n}$$

$pp \to \gamma jj$ via VBF @ NLO-QCD



$\Delta\kappa^\gamma = \pm 0.02,\ \lambda^\gamma = 0$ & $\Delta\kappa^\gamma = 0,\ \lambda^\gamma = \pm 0.02$

$pp \longrightarrow \gamma jj$ via VBF @ NLO-QCD



$$\Delta\kappa^\gamma = 0 \;\&\; \lambda^\gamma = 0$$

$pp \longrightarrow Vjj$ via VBF in vbfnlo

- NLO-QCD corrections to cross sections and distributions (without interference and annihilation contributions)

- full off-shell effects and decay correlations for leptonic decays of the weak bosons:

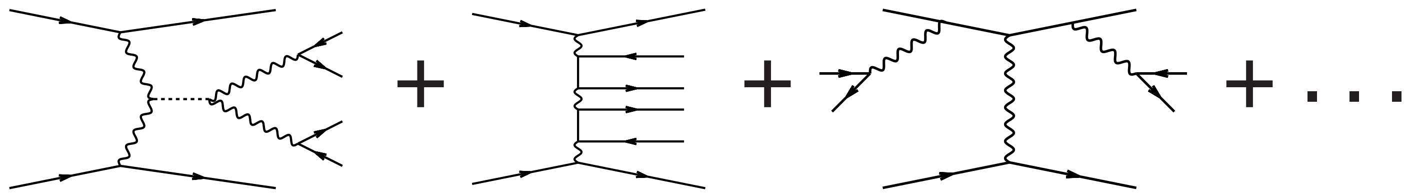
$$pp \longrightarrow Zjj \longrightarrow \ell^+\ell^- jj$$
$$pp \longrightarrow Zjj \longrightarrow \nu\bar{\nu} jj$$
$$pp \longrightarrow W^+ jj \longrightarrow \ell^+\nu jj$$
$$pp \longrightarrow W^- jj \longrightarrow \ell^-\bar{\nu} jj$$

- photon isolation with Frixione criterion in $pp \longrightarrow \gamma jj$

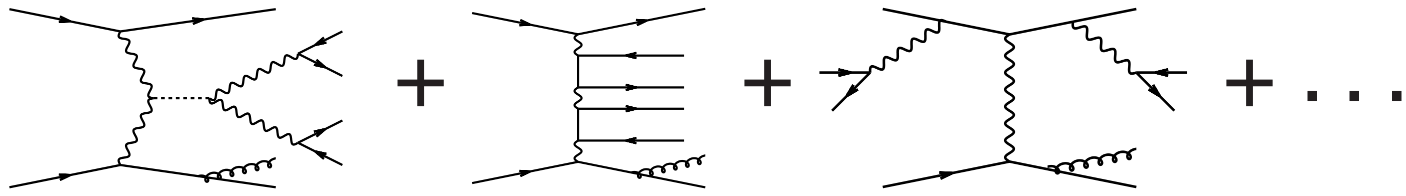
- anomalous photon-gauge boson couplings

EW $VVjj$ production

need to compute numerical value for . . .

$$|\mathcal{M}_B|^2 = \Bigg|$$  $$\Bigg|^2$$

. . . Born amplitude squared in 4 dim

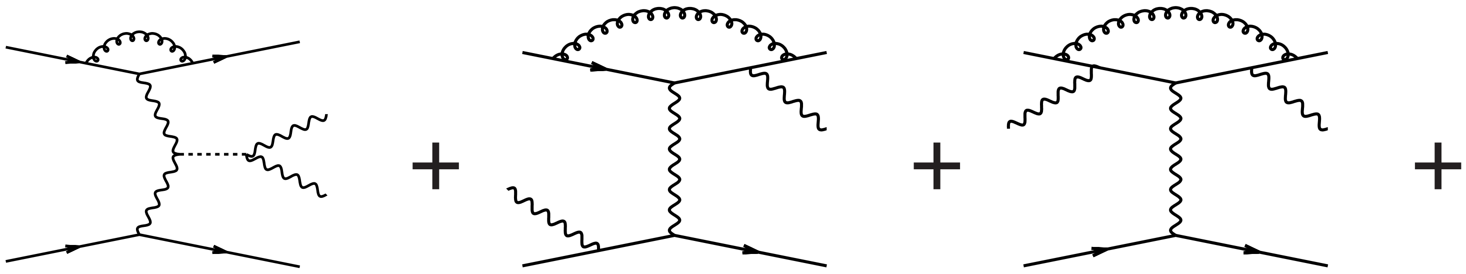
$$|\mathcal{M}_R|^2 = \Bigg|$$  $$\Bigg|^2$$

. . . real-emission amplitude squared in 4 dim and
counter terms for infrared-divergent configurations
(dipole subtraction a la *Catani & Seymour*)

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

EW $VVjj$ production

interference of Born amplitude with virtual contributions

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

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

$\tilde{\mathcal{M}}_V^{\text{finite}}$ computed with Passarino-Veltman / Denner-Dittmaier reduction;
stability monitored via Ward identities at every PS point

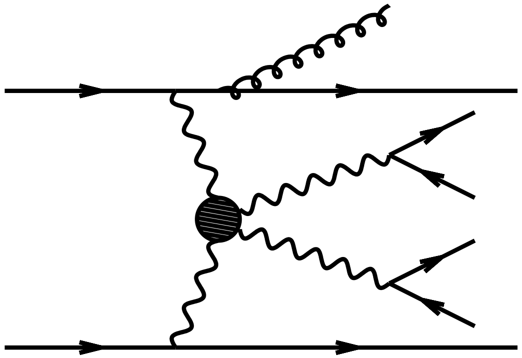
finite sum of real emission, virtuals, and subtraction terms:
phase-space integration and convolution with PDFs can be performed numerically in 4 dimensions (`Vegas`)

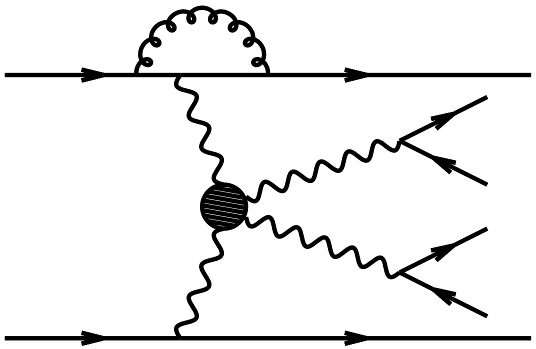
a representative model of new physics

Warped Higgsless model with extra vector resonances;

lowest Kaluza-Klein modes:

$$m_{W_2} = 700 \text{ GeV}, \;\; \Gamma = 13.7 \text{ GeV}$$
$$m_{Z_2} = 695 \text{ GeV}, \;\; \Gamma = 18.7 \text{ GeV}$$
$$m_{Z_3} = 718 \text{ GeV}, \;\; \Gamma = 6.4 \text{ GeV}$$

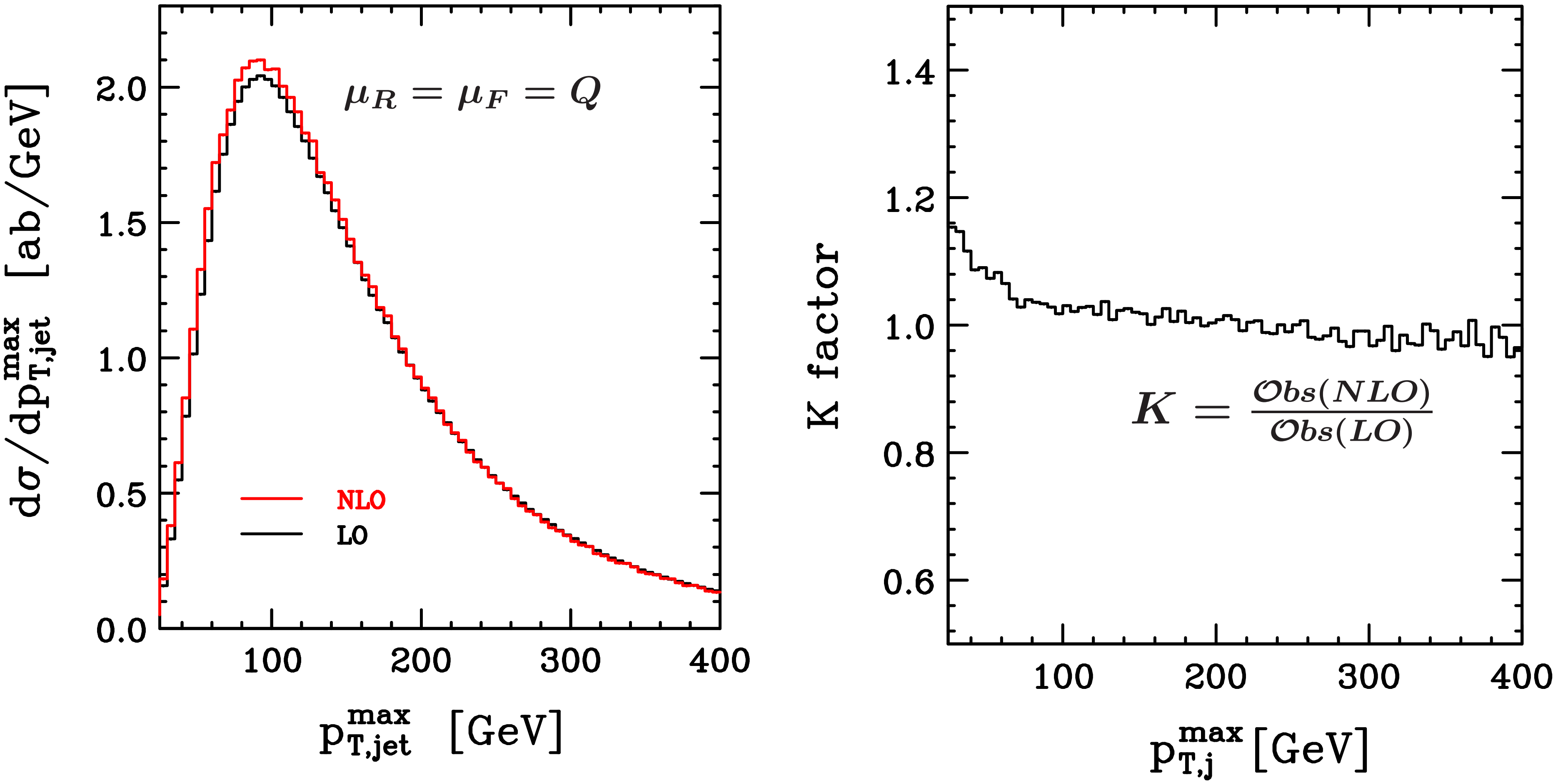




structure of NLO-QCD corrections identical to SM

impact of NLO-QCD corrections in KK scenario

Englert, BJ, Zeppenfeld (2008)



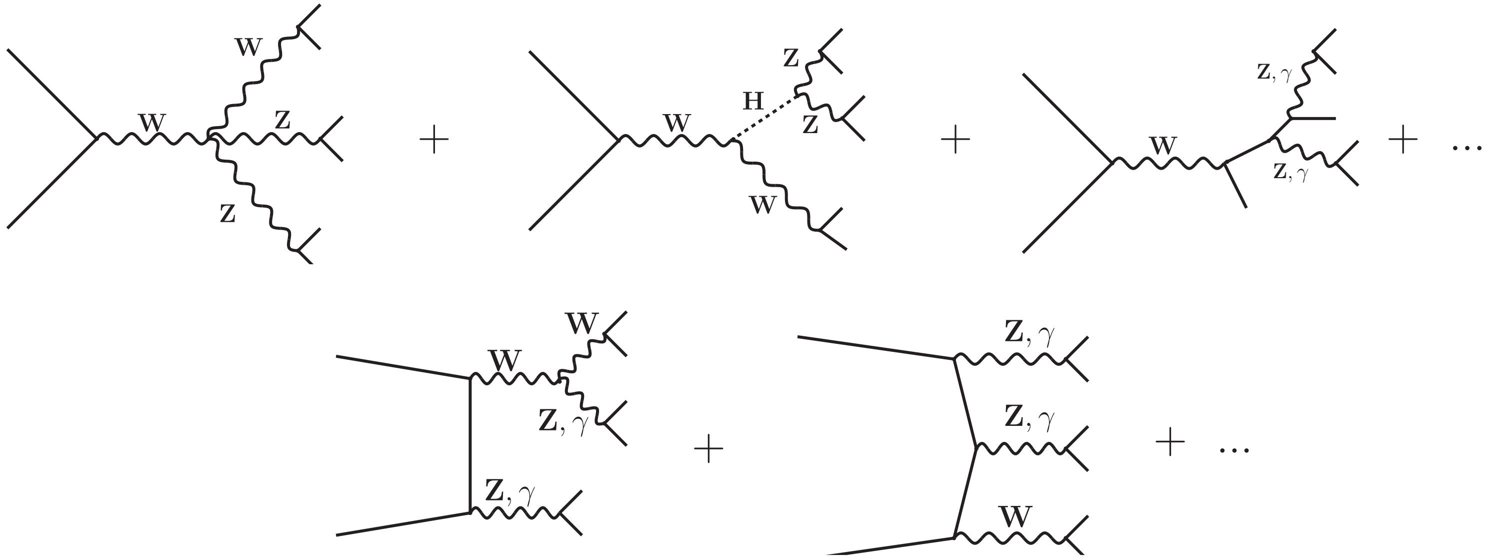
NLO-QCD corrections always in the few-percent range

$pp \to VVjj$ via VBF in vbfnlo

- NLO-QCD corrections to cross sections and distributions (without interference and annihilation contributions)
- full off-shell effects and decay correlations for leptonic decays of the weak bosons:

$$pp \to W^+W^-jj \to \ell_1^+\nu_1\ell_2^-\bar{\nu}_2 jj$$
$$pp \to ZZjj \to \ell_1^+\ell_1^-\ell_2^+\ell_2^- jj$$
$$pp \to ZZjj \to \ell_1^+\ell_1^-\nu_2\bar{\nu}_2 jj$$
$$pp \to W^+Zjj \to \ell_1^+\nu_1\ell_2^+\ell_2^- jj$$
$$pp \to W^-Zjj \to \ell_1^-\bar{\nu}_1\ell_2^+\ell_2^- jj$$
$$pp \to W^+W^+jj \to \ell_1^+\nu_1\ell_2^+\nu_2 jj$$

- anomalous gauge boson couplings
- Kaluza-Klein modes in a Warped-Higgsless model
- Three-Site Higgsless model



- SM background for new physics signatures with multi-leptons$+\not{p}_T$
- sensitive to (anomalous) triple and quartic gauge boson couplings
- NLO QCD corrections are large and strongly depend on observable and phase space region (drastically underestimated by LO scale variations)

$$pp \to WWZ$$

Hankele, Zeppenfeld (2007)

LO: very mild scale dependence

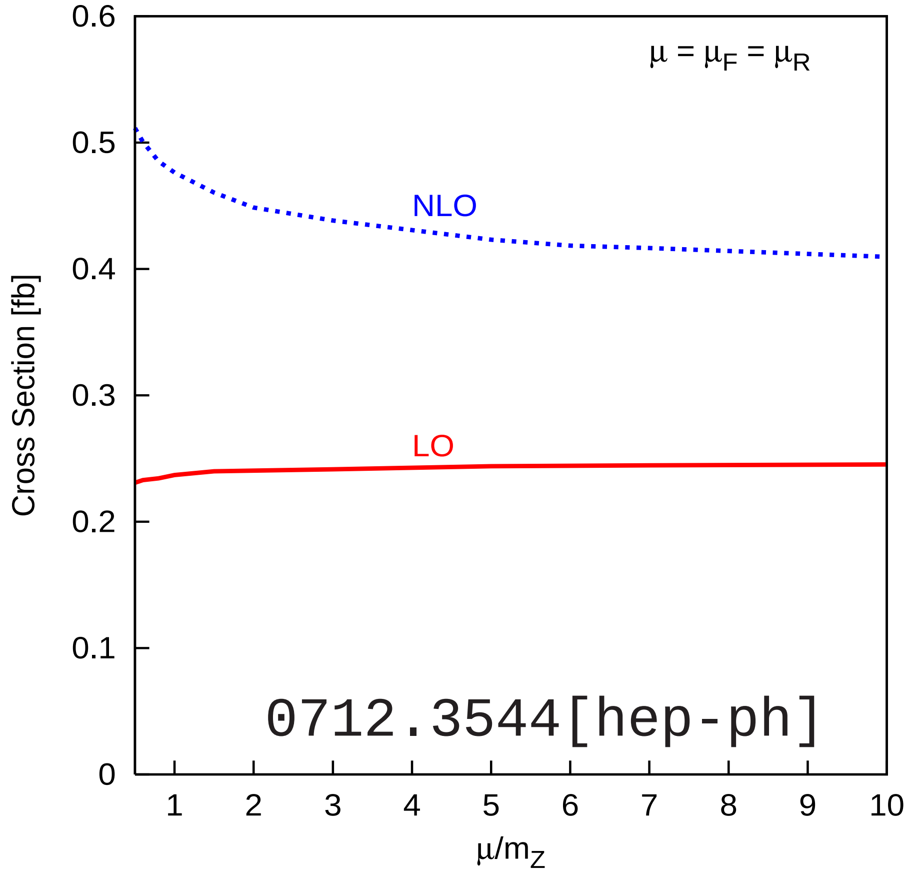
LO is $\mathcal{O}(\alpha_s^0)$,

PDFs probed in regions

with small μ_f dependence

but large QCD corrections with

$$\frac{\sigma^{NLO}}{\sigma^{LO}} \sim 1.7 \div 2.2$$



$pp \longrightarrow VVV$ in vbfnlo

- NLO-QCD corrections to cross sections and distributions
- full off-shell effects and decay correlations for leptonic decays of the weak bosons:

$$pp \longrightarrow W^+W^- \longrightarrow \ell_1^+ \nu_{\ell_1} \ell_2^- \bar{\nu}_{\ell_2}$$

$$pp \longrightarrow W^+W^-Z \longrightarrow \ell_1{}^+ \nu_{\ell_1} \ell_2{}^- \bar{\nu}_{\ell_2} \ell_3{}^+ \ell_3{}^-$$

$$pp \longrightarrow ZZW^+ \longrightarrow \ell_1{}^+ \ell_1{}^- \ell_2{}^+ \ell_2{}^- \ell_3{}^+ \nu_{\ell_3}$$

$$pp \longrightarrow ZZW^- \longrightarrow \ell_1{}^+ \ell_1{}^- \ell_2{}^+ \ell_2{}^- \ell_3{}^- \bar{\nu}_{\ell_3}$$

$$pp \longrightarrow W^+W^-W^+ \longrightarrow \ell_1{}^+ \nu_{\ell_1} \ell_2{}^- \bar{\nu}_{\ell_2} \ell_3{}^+ \nu_{\ell_3}$$

$$pp \longrightarrow W^-W^+W^- \longrightarrow \ell_1{}^- \bar{\nu}_{\ell_1} \ell_2{}^+ \nu_{\ell_2} \ell_3{}^- \bar{\nu}_{\ell_3}$$

$$pp \longrightarrow ZZZ \longrightarrow \ell_1{}^+ \ell_1{}^- \ell_2{}^+ \ell_2{}^- \ell_3{}^+ \ell_3{}^-$$

- anomalous gauge boson couplings
- Warped-Higgsless and Three-Site Higgsless model

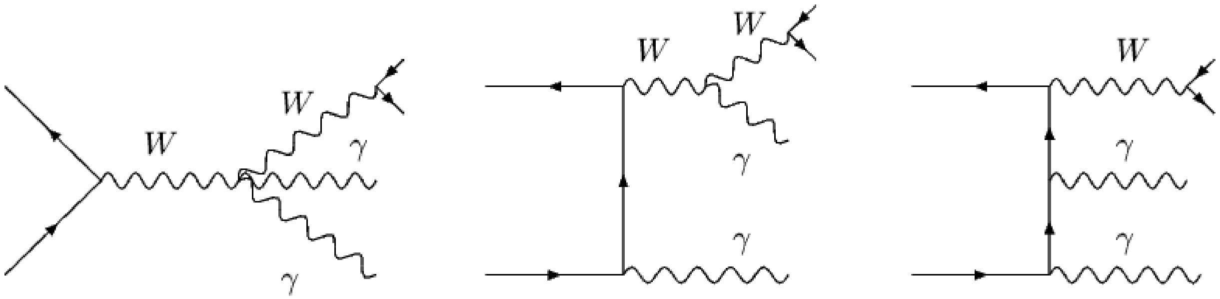
$pp \longrightarrow VVV$ in vbfnlo

- NLO-QCD corrections to cross sections and distributions
- full off-shell effects and decay correlations for leptonic decays of the weak bosons:

$$pp \longrightarrow W^+W^-\gamma \longrightarrow \ell_1{}^+\nu_{\ell_1}\ell_2{}^-\bar{\nu}_{\ell_2}\gamma$$
$$pp \longrightarrow ZZ\gamma \longrightarrow \ell_1{}^+\ell_1{}^-\ell_2{}^+\ell_2{}^-\gamma$$
$$pp \longrightarrow W^+Z\gamma \longrightarrow \ell_1{}^+\nu_{\ell_1}\ell_2{}^+\ell_2{}^-\gamma$$
$$pp \longrightarrow W^-Z\gamma \longrightarrow \ell_1{}^-\bar{\nu}_{\ell_1}\ell_2{}^+\ell_2{}^-\gamma$$
$$pp \longrightarrow W^+\gamma\gamma \longrightarrow \ell_1{}^+\nu_{\ell_1}\gamma\gamma$$
$$pp \longrightarrow W^-\gamma \longrightarrow \ell_1{}^-\bar{\nu}_{\ell_1}\gamma\gamma$$
$$pp \longrightarrow Z\gamma\gamma \longrightarrow \ell_1{}^+\ell_1{}^-\gamma\gamma$$
$$pp \longrightarrow Z\gamma\gamma \longrightarrow \nu_{\ell_1}\bar{\nu}_{\ell_1}\gamma\gamma$$
$$pp \longrightarrow \gamma\gamma\gamma \longrightarrow \gamma\gamma\gamma$$

- photon isolation via Frixione criterion

$pp \to W\gamma\gamma$ in vbfnlo



$$pp \to \ell^+ \nu_\ell \gamma\gamma$$
$$pp \to \ell^- \bar{\nu}_\ell \gamma\gamma$$

Bozzi, Campanario, Rauch, Zeppenfeld (2011)

- off-shell effects of the W boson are fully taken into account (e.g. γ radiation off final-state lepton)
- photon isolation via Frixione criterion

c.f. complementary approach of

Baur, Wackeroth, Weber (2009)

- $q \to q\gamma$ fragmentation contributions included
- $W^{\pm}$ treated as stable particle

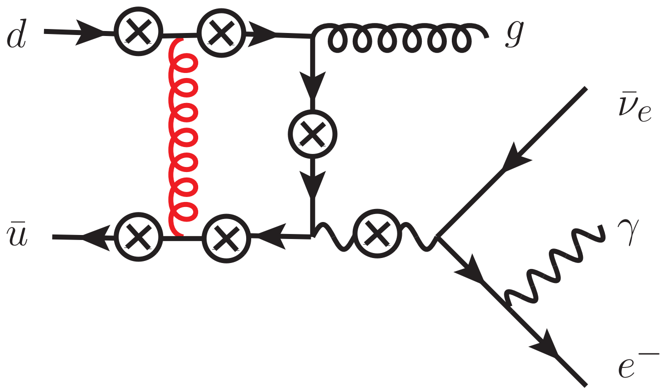
$pp \longrightarrow V_1 V_2 + \text{jet}$ in vbfnlo

- NLO-QCD corrections to cross sections and distributions
- full off-shell effects and decay correlations for leptonic decays of the weak bosons:

$$pp \rightarrow W^+\gamma j \rightarrow {\ell_1}^+\nu_{\ell_1}\gamma j$$
$$pp \rightarrow W^-\gamma j \rightarrow {\ell_1}^-\bar{\nu}_{\ell_1}\gamma j$$
$$pp \rightarrow W^+ Z j \rightarrow {\ell_1}^+\nu_{\ell_1}{\ell_2}^+{\ell_2}^- j$$
$$pp \rightarrow W^- Z j \rightarrow {\ell_1}^-\bar{\nu}_{\ell_1}{\ell_2}^+{\ell_2}^- j$$

- anomalous gauge boson couplings
- photon isolation via Frixione criterion

example: $pp \longrightarrow W\gamma j$ @ NLO



Campanario, Englert, Spannowksy, Zeppenfeld (2010):

$$pp \longrightarrow e^+\nu_e\gamma j$$
$$pp \longrightarrow e^-\bar{\nu}_e\gamma j$$

- cross section sizeable at LHC (1.2 pb) and Tevatron (15 fb) for $p_T^{\text{jet}}, p_T^{\gamma} > 50$ GeV and generic separation cuts
- measurement of anomalous $WW\gamma$ couplings: veto on jets in $W\gamma$ events requires good knowledge of cross sections and distributions including NLO corrections
- virtual corrections up to pentagons
- number of subtraction terms larger than in pure gauge boson production or VBF processes

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

new release will be available very soon! it will contain:

new processes:

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

new features:

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

if you have questions, comments, suggestions . . .

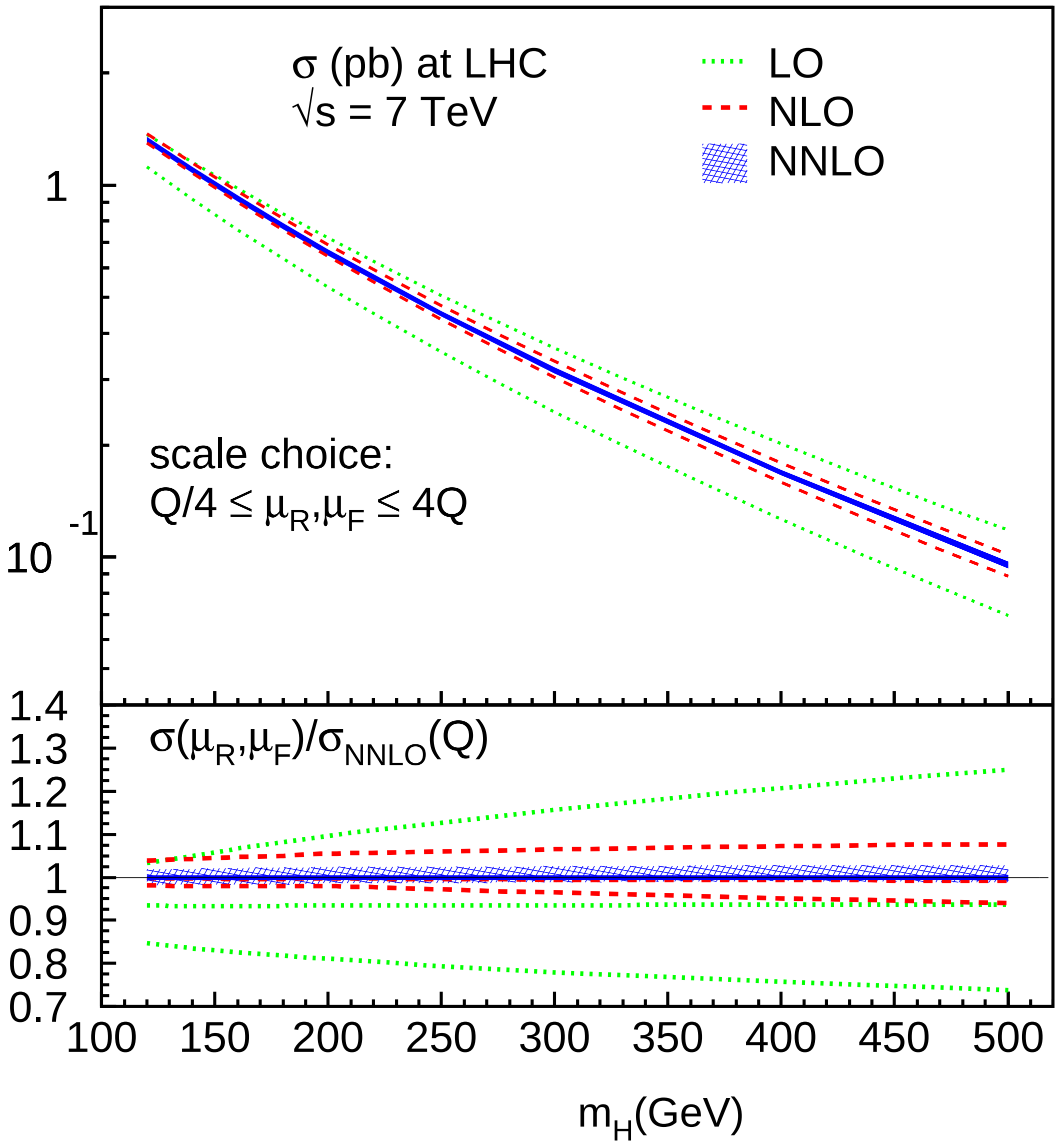
please e-mail us at

`vbfnlo@particle.uni-karlsruhe.de`

. . . for details and supplementary material

higher orders of QCD in VBF

Bolzoni et al. (2010)



- 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

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: $pp \longrightarrow H\gamma jj$

effects of hard central photon requirement:

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

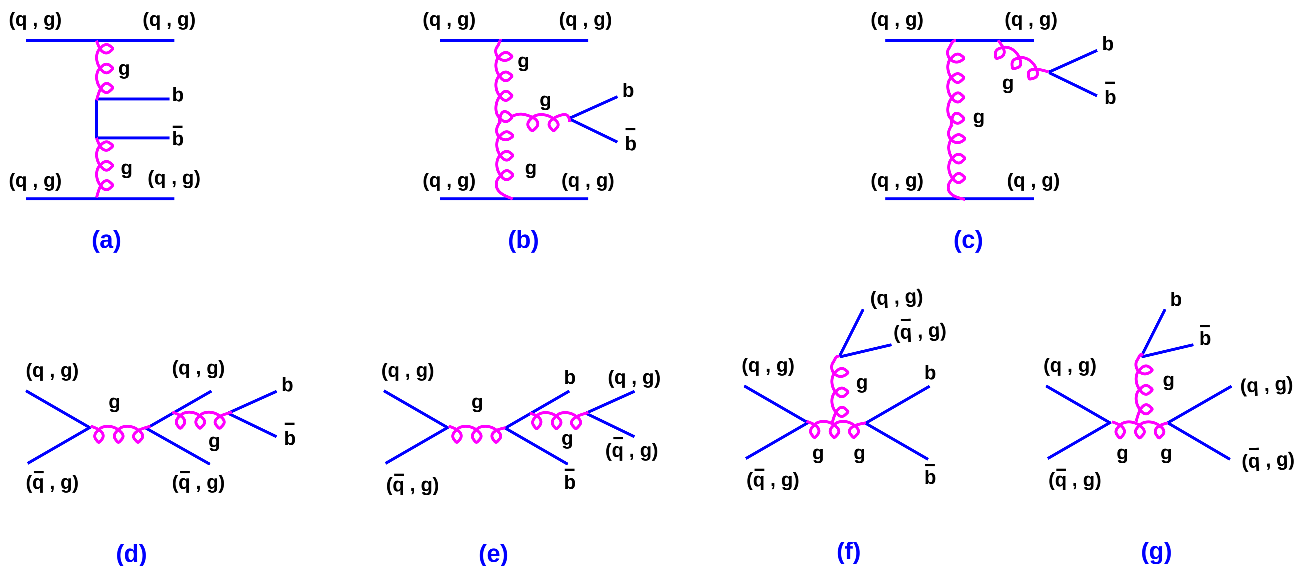
- S/B not much affected
- signal significance decreases

☞ 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: $pp \longrightarrow H\gamma jj$



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

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

✔ WBF-specific selection cuts favor large values of x

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

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

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