Simulation of processes with electroweak bosons at hadron colliders

Loopfest X

Evanston – May 2011

Barbara Jäger

for the `vbfnlo` collaboration

K. Arnold, G. Bozzi, M. Brieg, F. Campanario, C. Englert, B. Feigl, T. Figy,
J. Frank, F. Geyer, K. Hackstein, V. Hankele, B. J., M. Kerner, M. Kubocz,
C. Oleari, S. Palmer, S. Plätzer, M. Rauch, H. Rzehak, F. Schissler,
M. Spannowsky, M. Worek, D. Zeppenfeld

motivation

- 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

vbfnlo

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

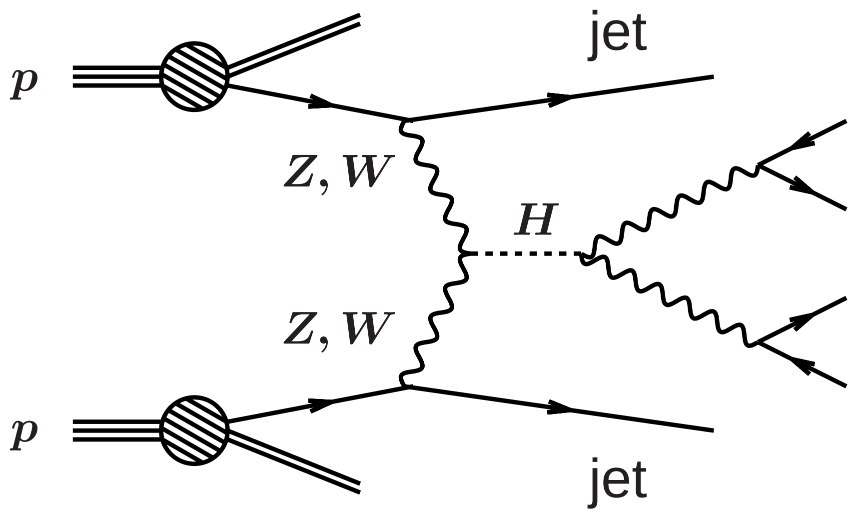
it can simulate:

- 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 Houches Accord (LHA) format
- MSSM: SUSY parameters input via standard SLHA file

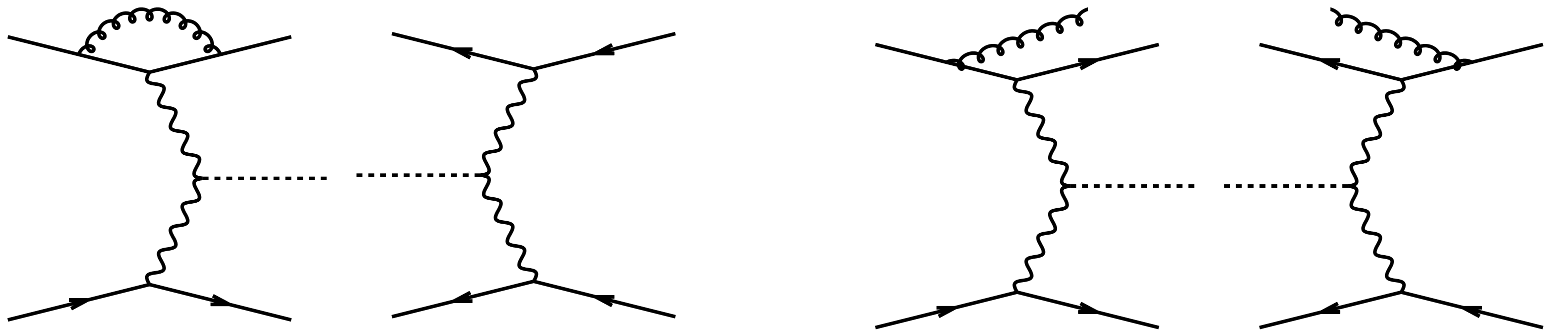
VBF event topology



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 $pp \to Hjj$

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

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

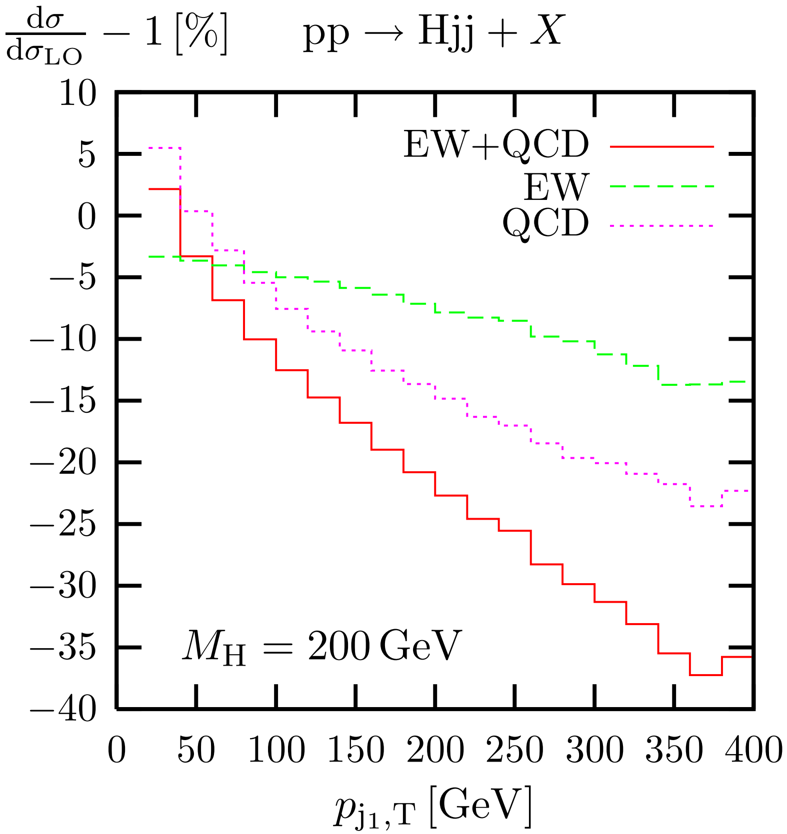
  subset of the NNLO QCD contributions
  to the total cross section for VBF $pp \to Hjj$
  in the structure function approach

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

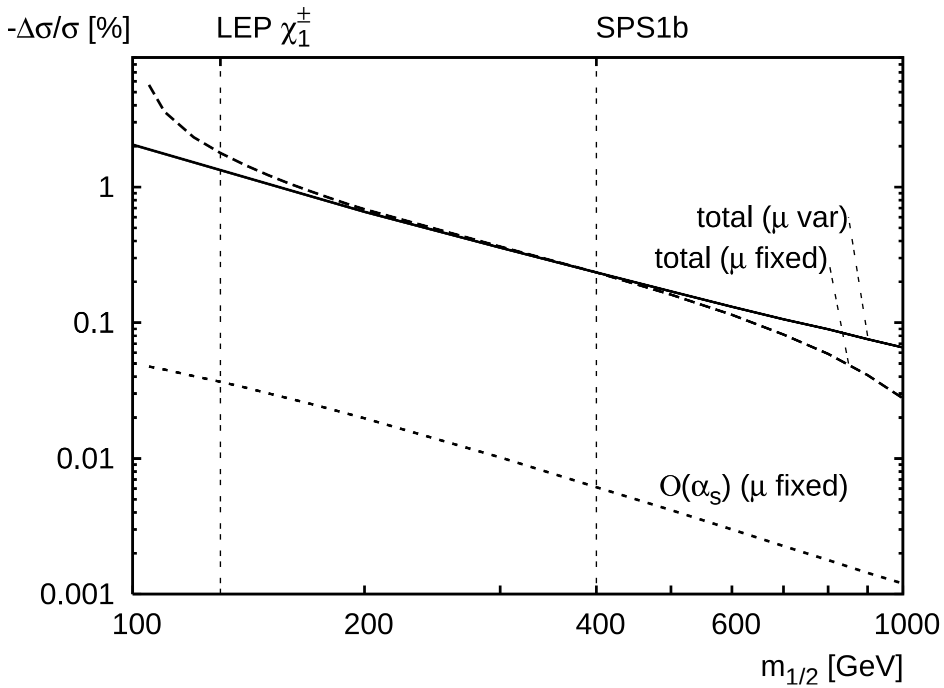
Ciccolini, Denner, Dittmaier, Mück:

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

$pp \to Hjj$ 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:

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

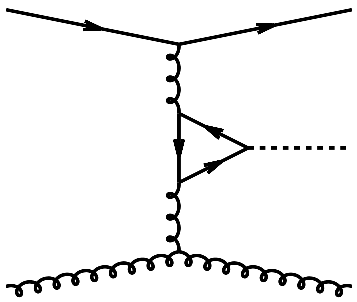
- dominant NLO-QCD corrections to $pp \to Hjjj$
  ($\to$ extra jet activity in VBF)

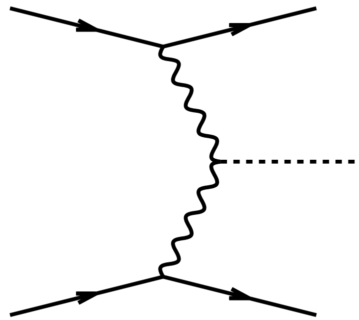
- anomalous Higgs-gauge boson couplings

$pp \to Hjj$ via gluon fusion

VBF can be faked by double real corrections

to $gg \to H$ (“gluon fusion”)





- complete LO calculation (including pentagons) in the SM

  Del Duca, Kilgore, Oleari, Schmidt, Zeppenfeld (2001)

- and in a generic two-Higgs doublet model:

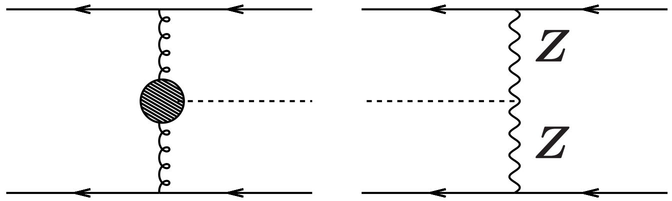
  Campanario, Kubocz, Zeppenfeld (2011)

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

  Campbell, Ellis, Zanderighi (2006)

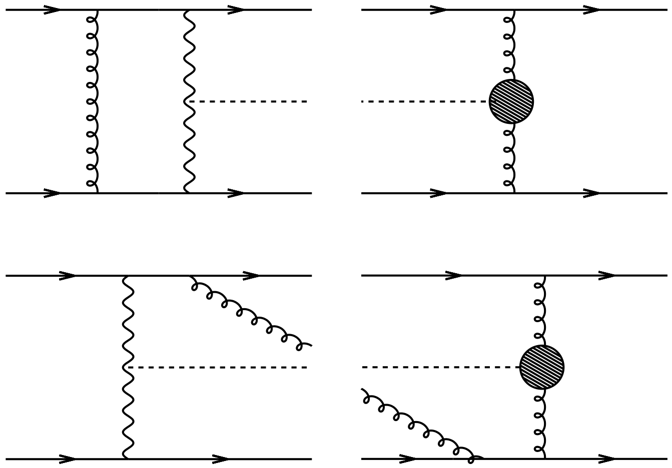
$pp \to Hjj$ via VBF×GF

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):

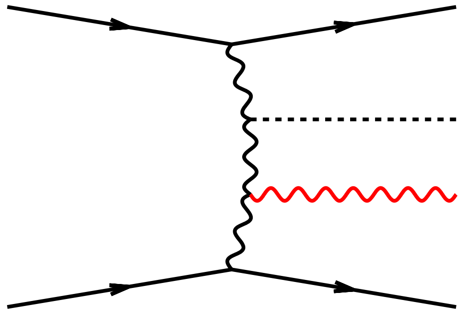
- strong cancelation effects
  between contributions of
  different flavor

☞ 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:

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



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?

effects of hard central photon requirement:

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

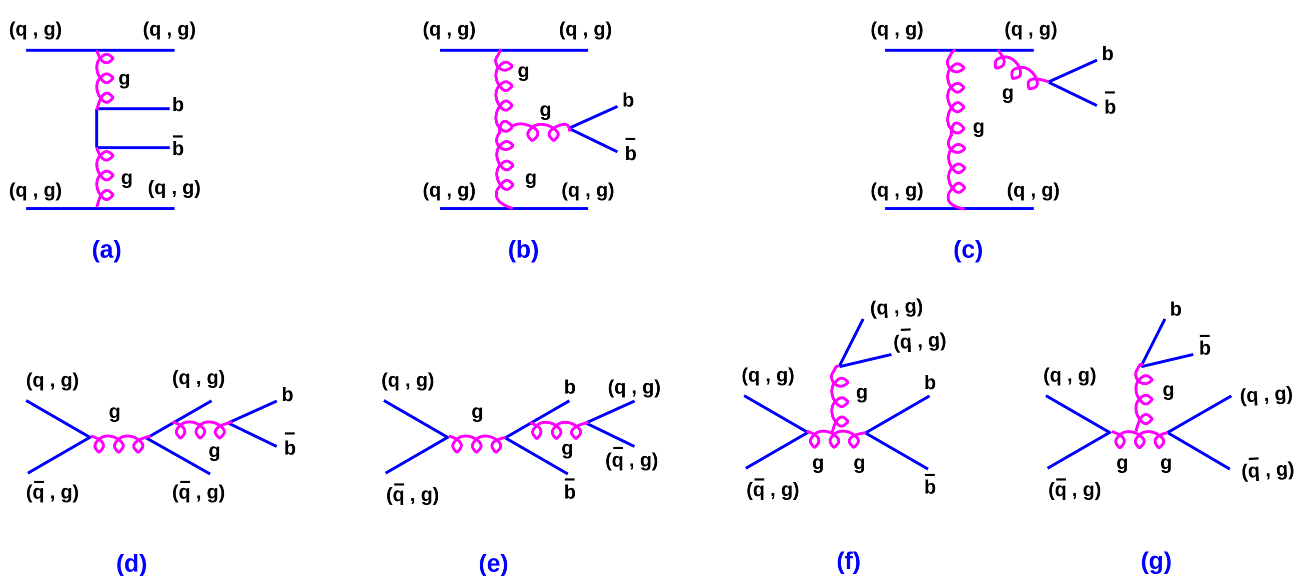
- S/B not much affected
- signal significance decreases

☞ 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})

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

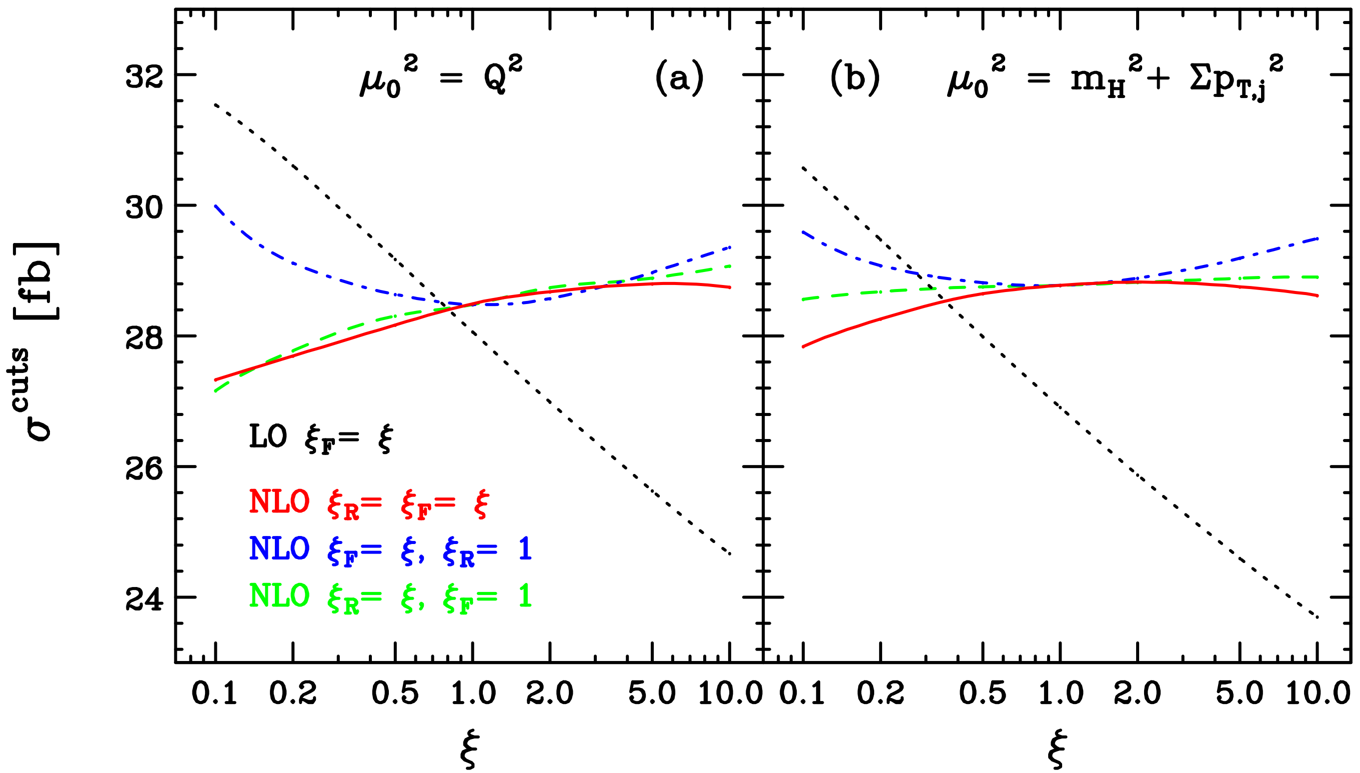
signal: $\sigma_\gamma/\sigma \sim 1/100$

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

[Gabrielli et al. (2007)]

scale uncertainty

choose default scale $\mu_0^2 = Q_i^2$ or $\mu_0^2 = m_H^2 + \sum p_{Tj}^2$
set $\mu_\mathrm{R} = \xi_\mathrm{R}\mu_0$ and $\mu_\mathrm{F} = \xi_\mathrm{F}\mu_0$, with variable ξ



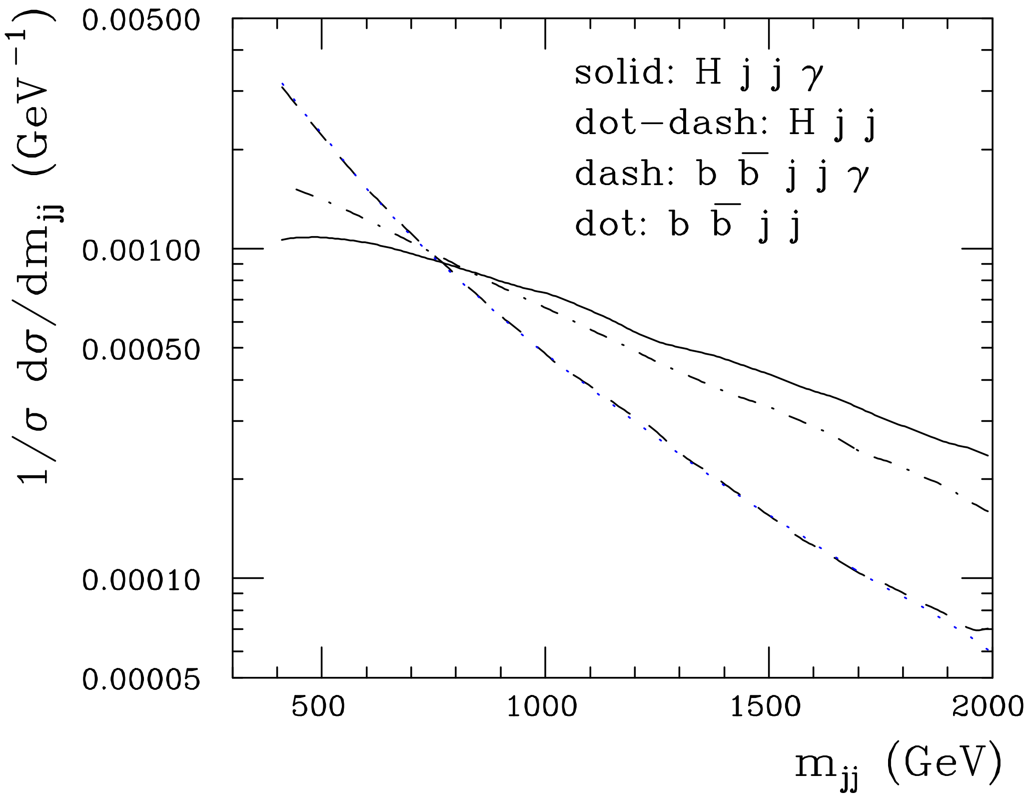
Arnold, Figy, BJ, Zeppenfeld (2010)

LO: no control on scale

NLO QCD: scale dependence strongly reduced

invariant mass of the tagging jets

Gabrielli et al. (2007)

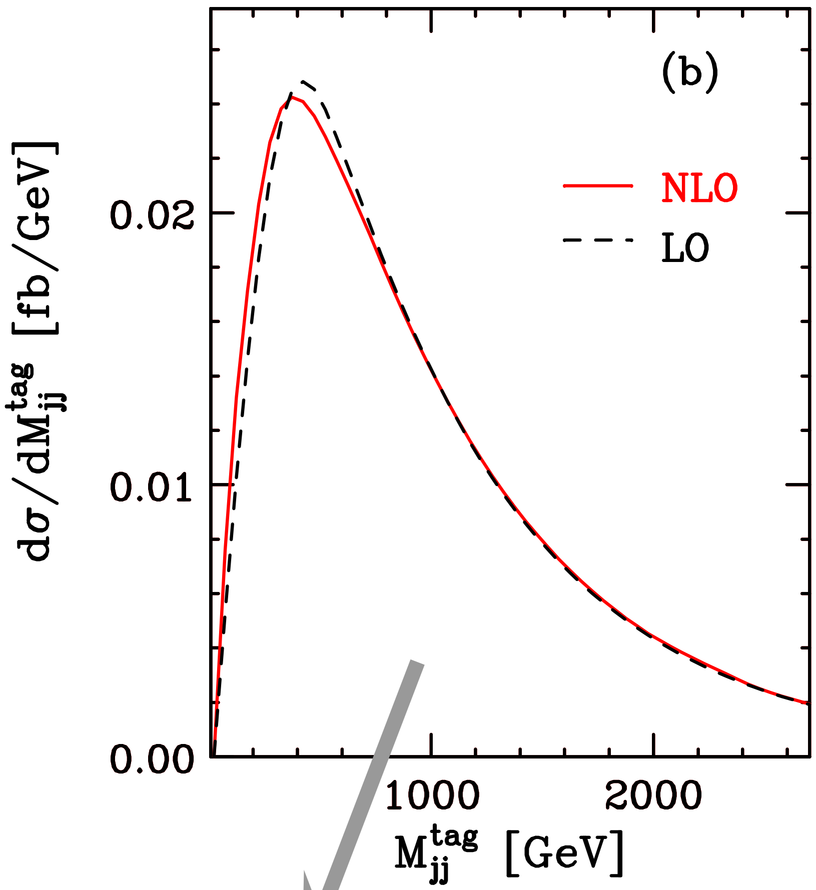


- $d\sigma/dm_{jj}$ slightly flatter for $H\gamma jj$ signal than for Hjj
- $b\bar{b}jj$ and $b\bar{b}\gamma jj$ backgrounds have very similar shapes
- background distributions exhibit much steeper slope than signal

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

invariant mass of the tagging jets

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

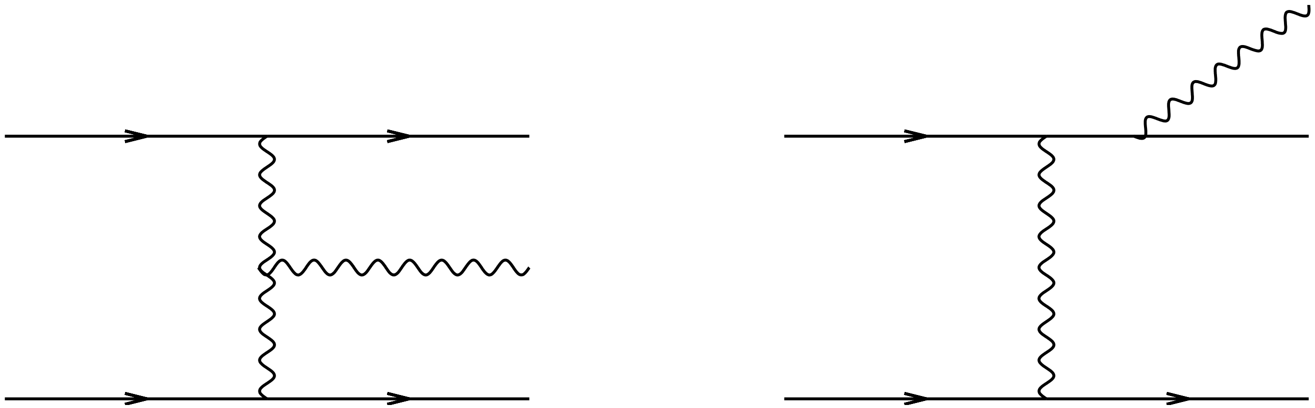


effect of NLO-QCD corrections small

- $d\sigma/dm_{jj}$ 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

$pp \to Vjj$ via VBF



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

- sensitive to triple gauge boson couplings
  - $Z \to \tau\tau$ . . . background to $H \to \tau\tau$
  - 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

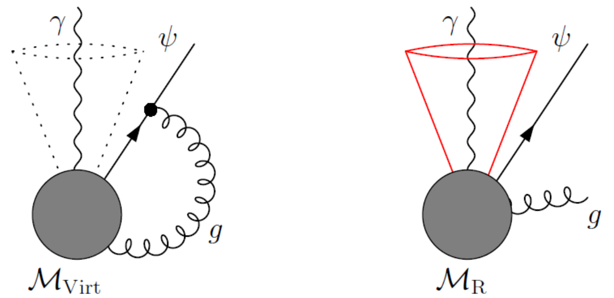
photon isolation

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

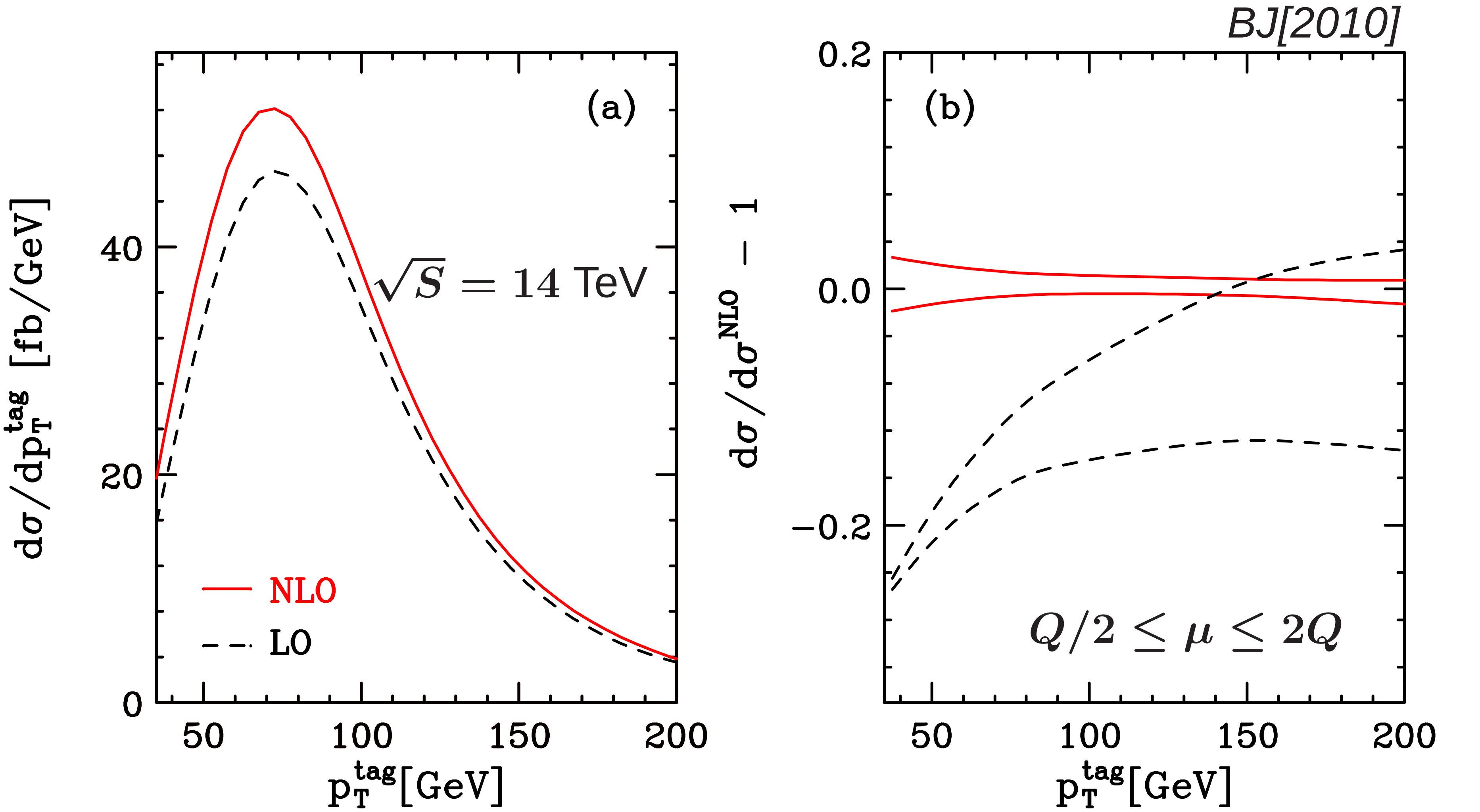
idea: veto collinear photon-jet configurations, but allow soft QCD emission

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

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

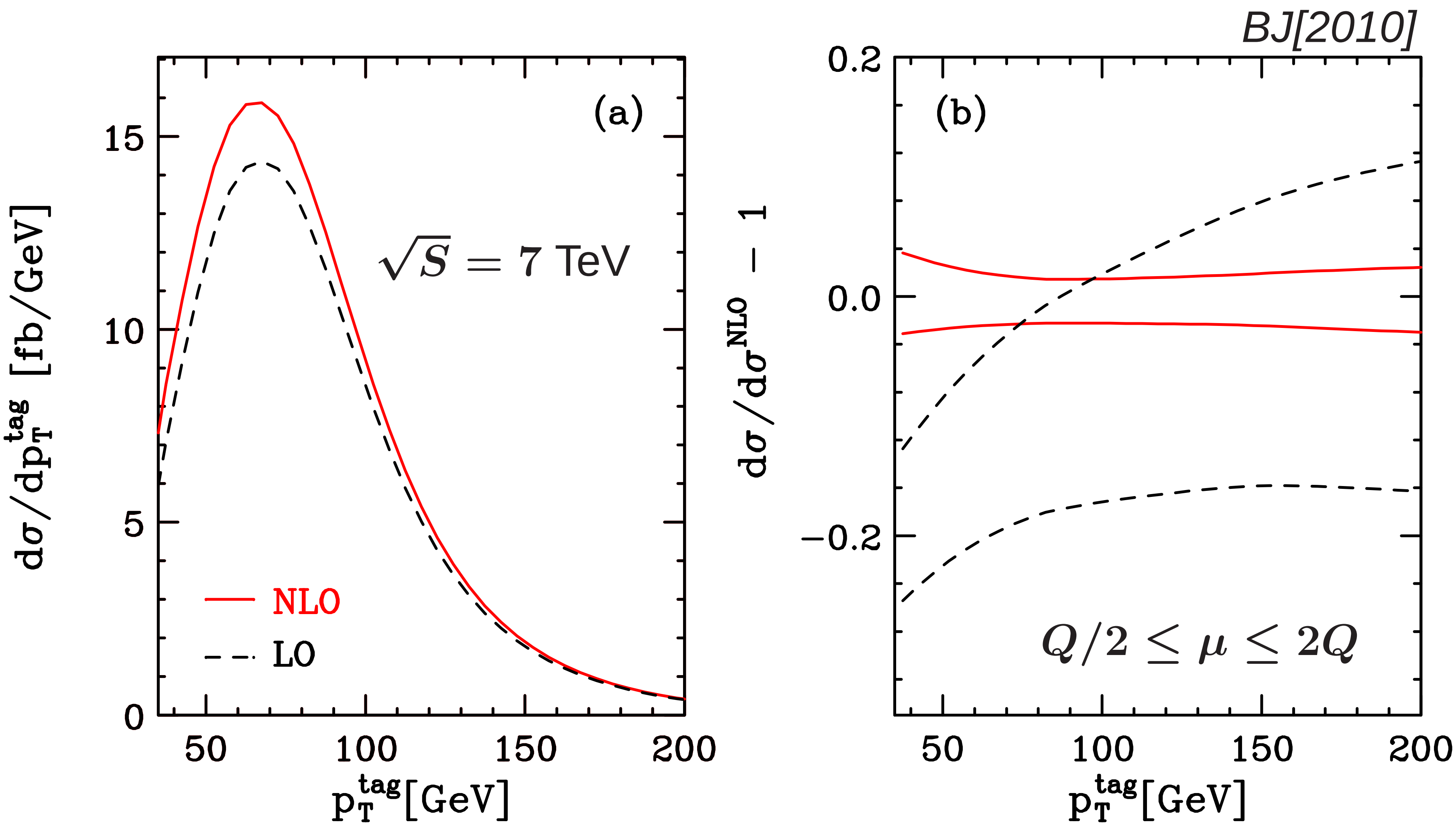


$pp \to \gamma jj$ via VBF @ NLO-QCD



NLO-QCD corrections affect the shape of some distributions

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



NLO-QCD corrections affect the shape of some distributions

anomalous couplings

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

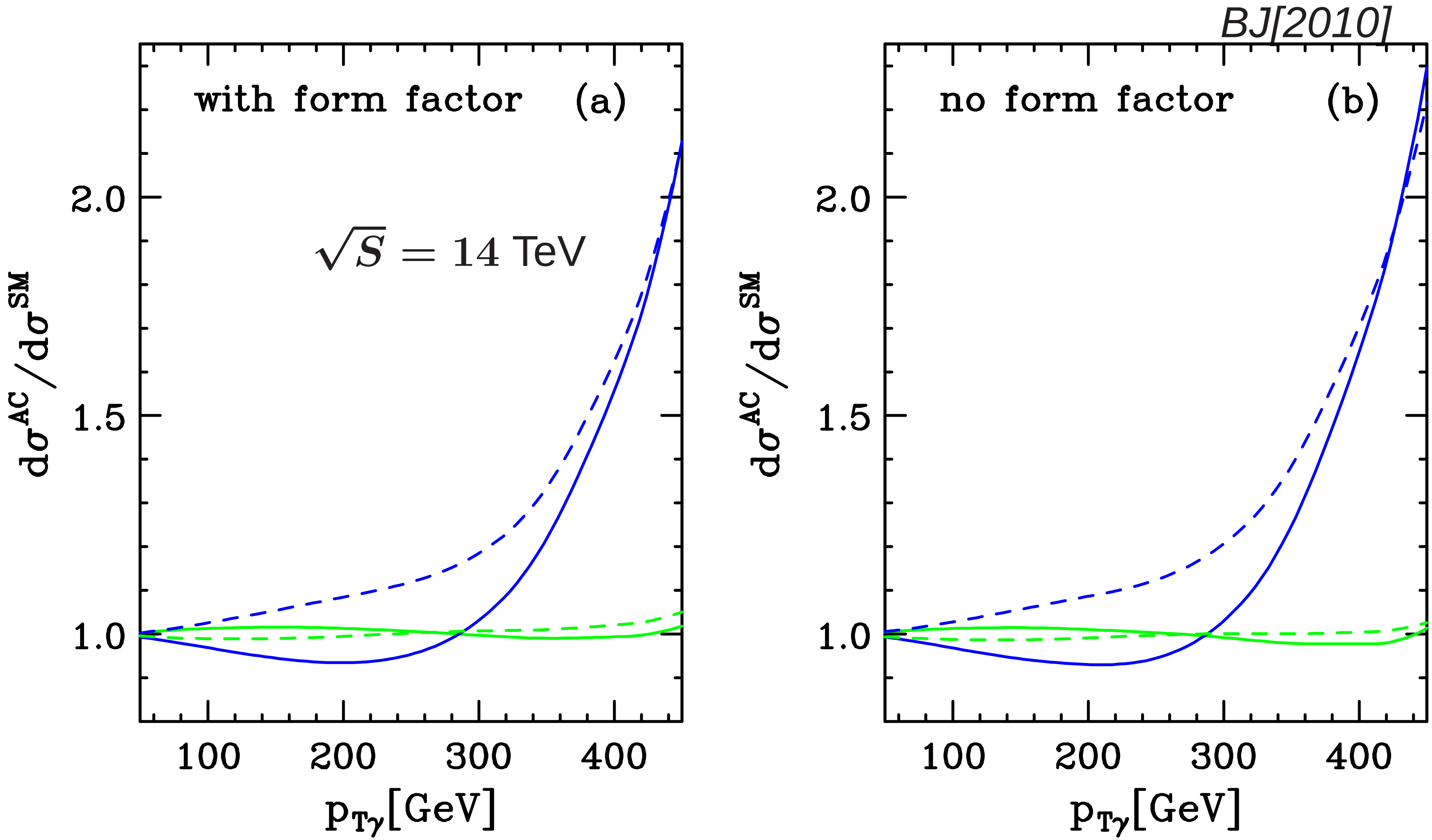
$$
\begin{aligned}
\Gamma^{\alpha\beta\mu}_{WW\gamma}(q,q',p) \;=\; & q'^{\alpha} g^{\beta\mu}\left(2+\Delta\kappa^{\gamma}+\lambda^{\gamma}\frac{q^2}{m_W^2}\right) - q^{\beta} g^{\alpha\mu}\left(2+\Delta\kappa^{\gamma}+\lambda^{\gamma}\frac{q'^2}{m_W^2}\right) \\
& + (q'^{\mu}-q^{\mu})\left[-g^{\alpha\beta}\left(1+\frac{1}{2}p^2\frac{\lambda^{\gamma}}{m_W^2}\ri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

unitarity violations of effective Lagrangian at high energies

tamed via form factors:

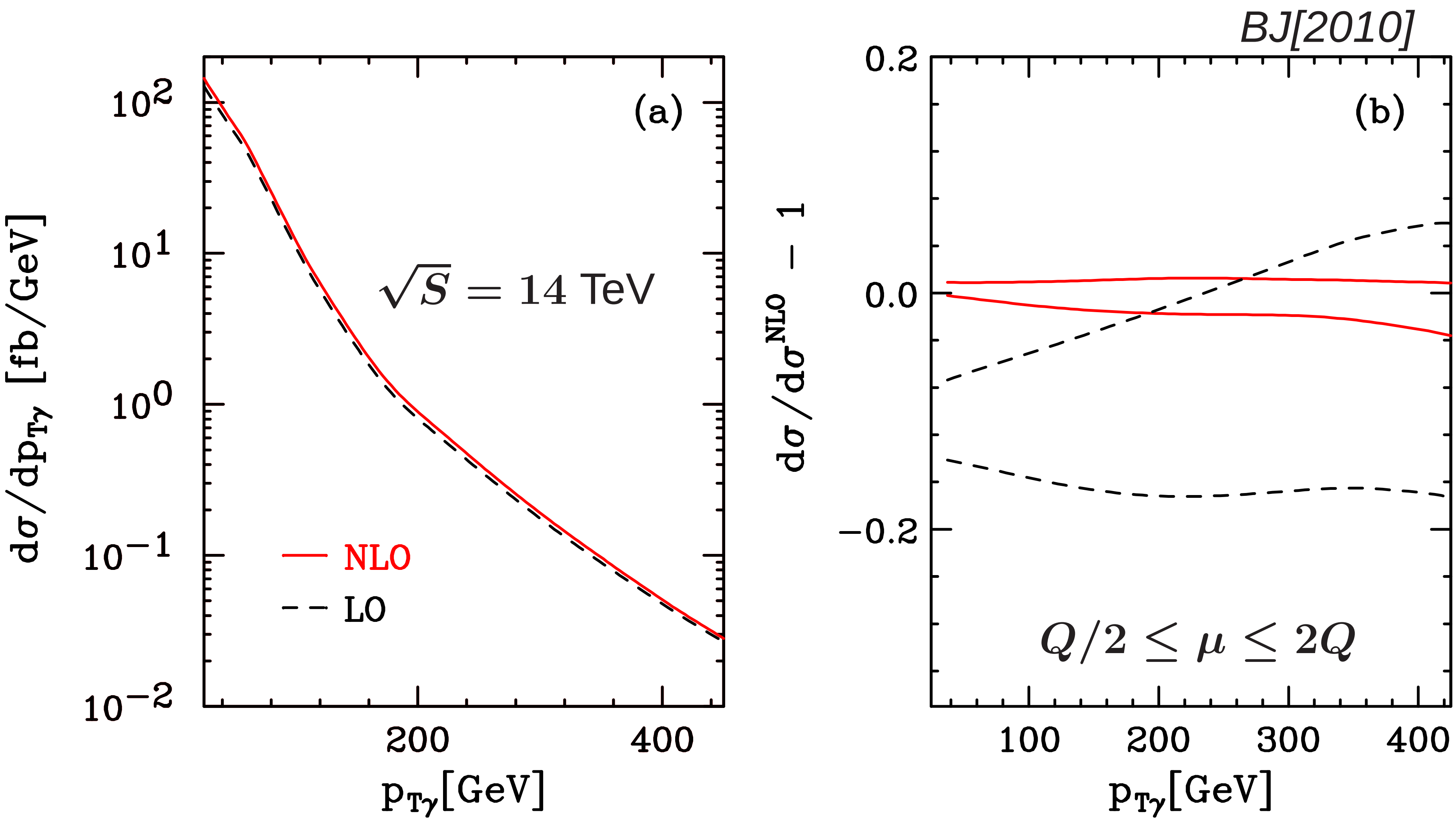
$$
\Delta\kappa^{\gamma} \rightarrow \frac{\Delta\kappa^{\gamma}}{\left[\left(1+\frac{|q^2|}{\Lambda^2}\right)\left(1+\frac{|q'^2|}{\Lambda^2}\right)\right]^n}, \qquad \lambda^{\gamma} \rightarrow \frac{\lambda^{\gamma}}{\left[\left((1+\frac{|q^2|}{\Lambda^2}\right)\left((1+\frac{|q'^2|}{\Lambda^2}\right)\right]^n}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

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



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

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



$$\Delta\kappa^{\gamma} = 0 \ \& \ \lambda^{\gamma} = 0$$

$pp \to Vjj$ via VBF in `vbfnlo`

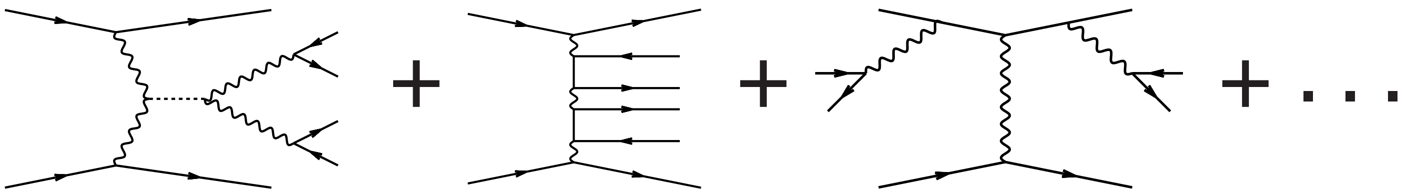
- NLO-QCD corrections to cross sections and distributions (without interference and annihilation contributions)
- full off-shell effects and decay correlations for leptonic decays of the weak bosons:

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

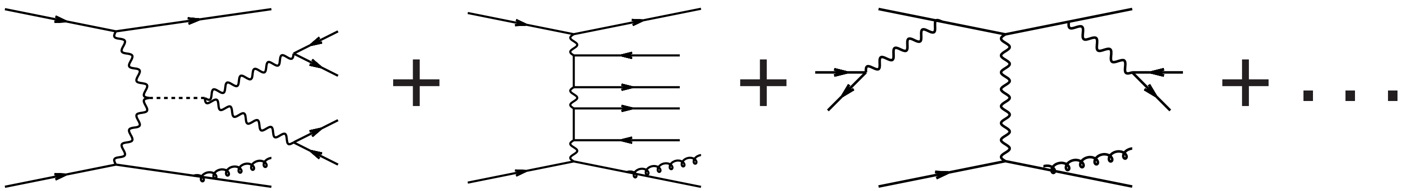
- photon isolation with Frixione criterion in $pp \to \gamma jj$
- anomalous photon-gauge boson couplings

EW $VVjj$ production

need to compute numerical value for . . .

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

. . . Born amplitude squared in 4 dim

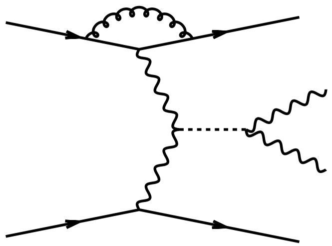
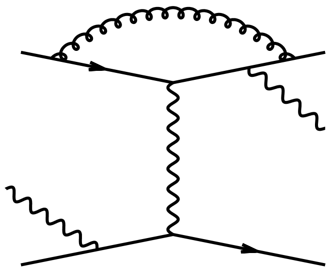
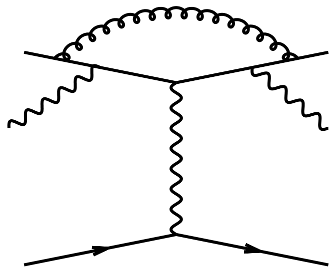
$|\mathcal{M}_R|^2 = \Big|$  $\Big|^2$

. . . 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

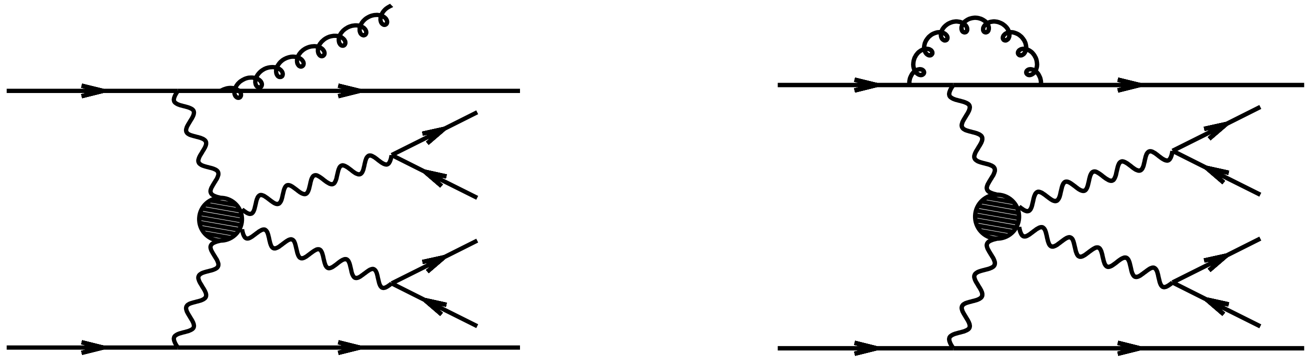
finite sum of real emission, virtuals, and subtraction terms:
phase-space integration and convolution with PDFs can be performed numerically in 4 dimensions (`Vegas`)

a representative model of new physics

Warped Higgsless model with extra vector resonances;

lowest Kaluza-Klein modes:

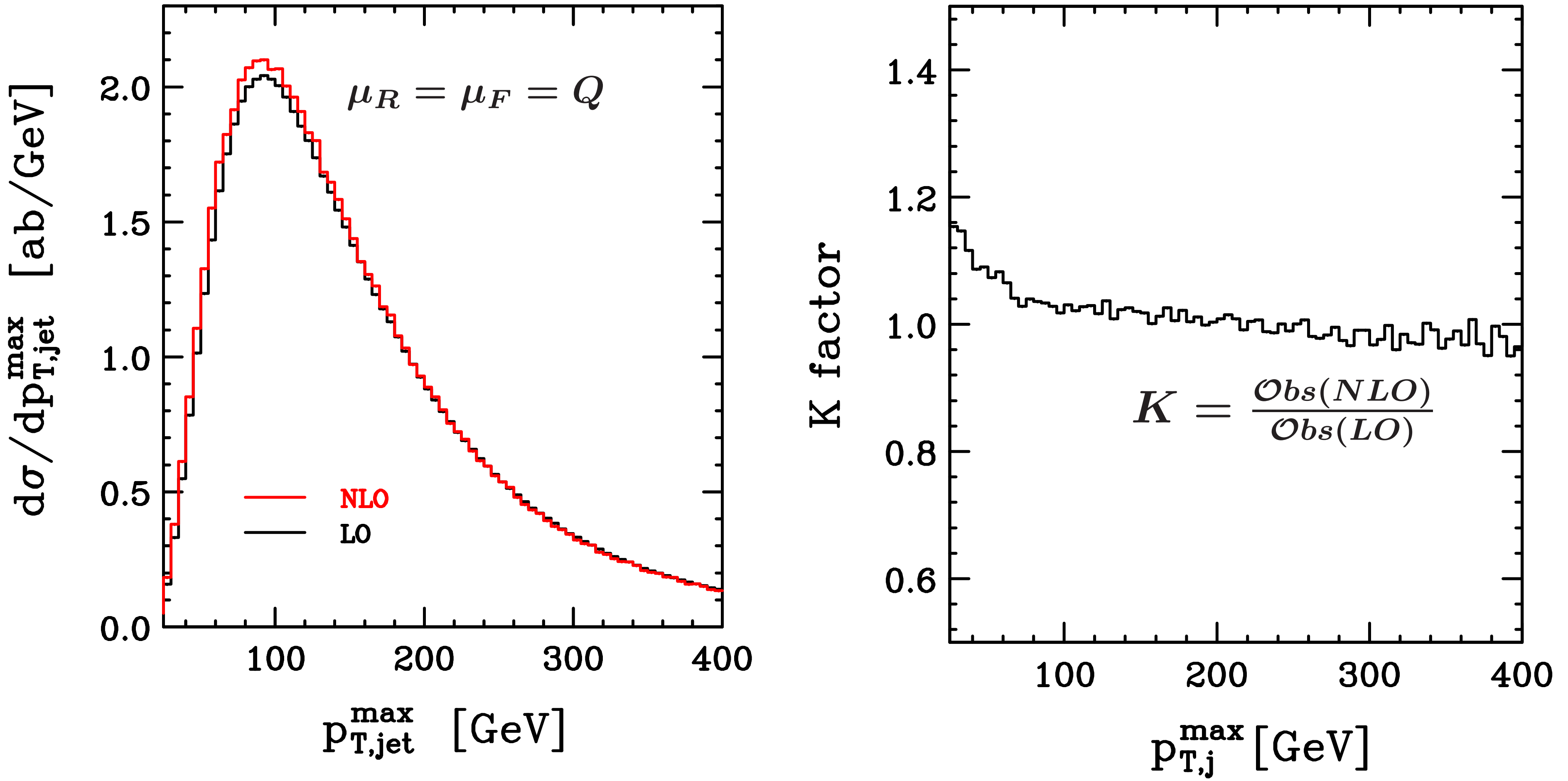
$$m_{W_2} = 700 \text{ GeV}\,,\ \Gamma = 13.7 \text{ GeV}$$
$$m_{Z_2} = 695 \text{ GeV}\,,\ \Gamma = 18.7 \text{ GeV}$$
$$m_{Z_3} = 718 \text{ GeV}\,,\ \Gamma = 6.4 \text{ GeV}$$



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

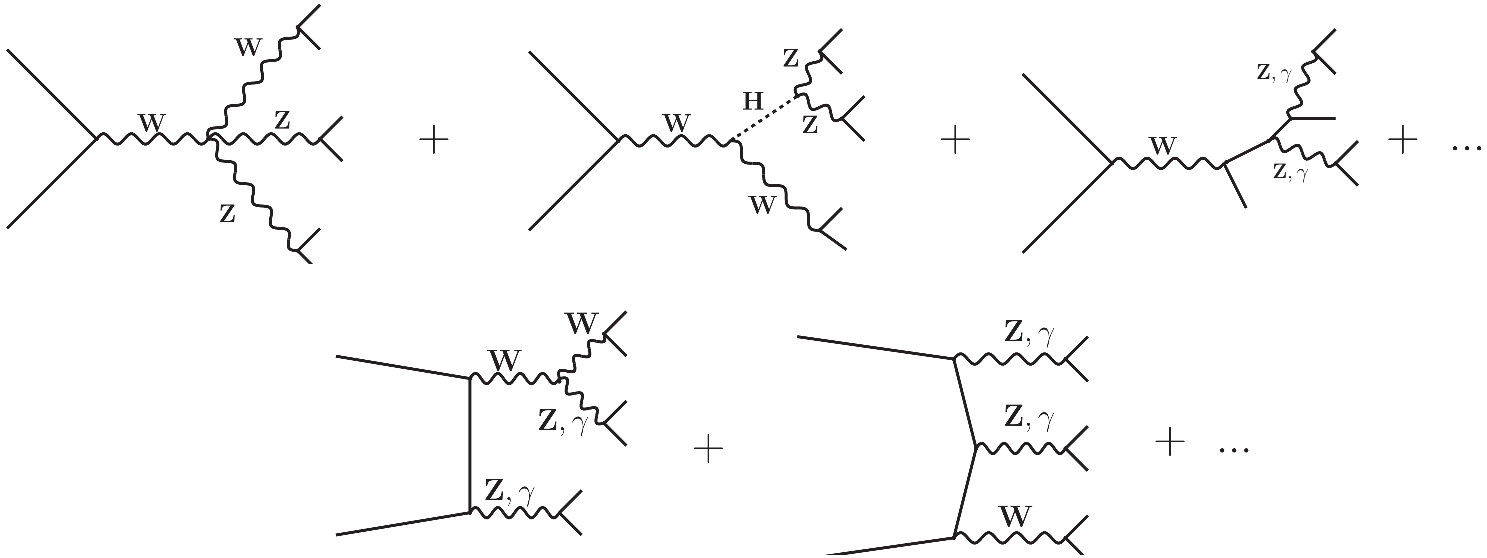
$pp \to VVjj$ via VBF in vbfnlo

- 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

triboson production



- 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

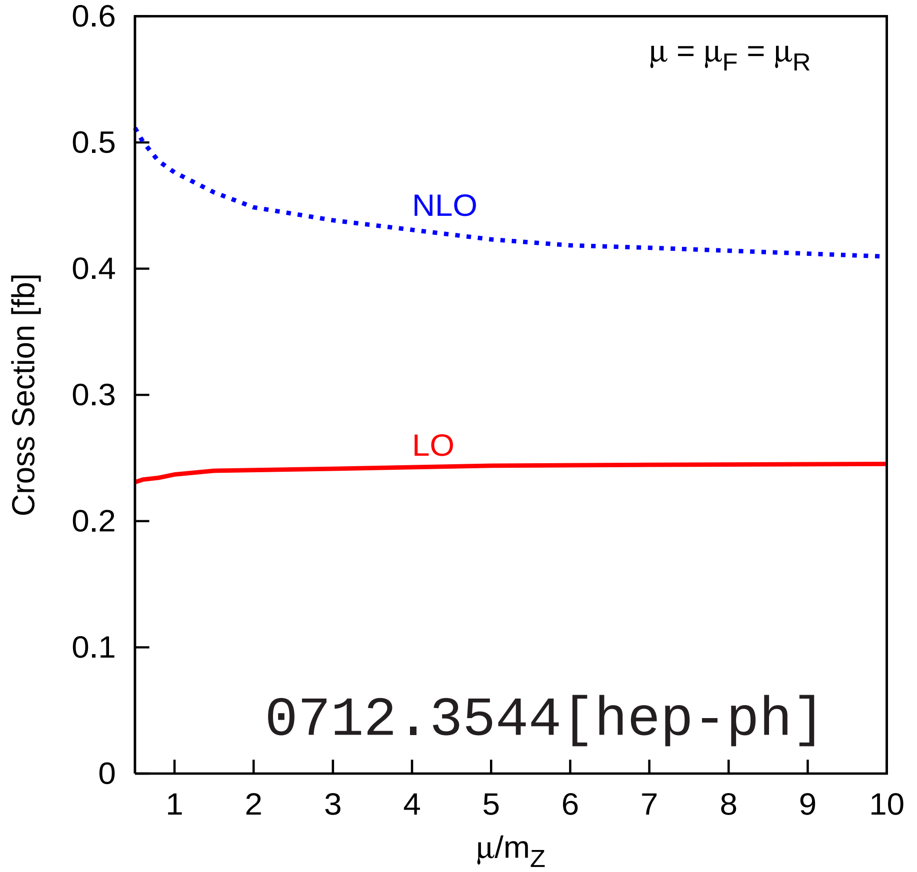
LO is $\mathcal{O}(\alpha_s^0)$,

PDFs probed in regions

with small μ_f dependence

but large QCD corrections with

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



$pp \to VV$ & $pp \to VVV$ in vbfnlo

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

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

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

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

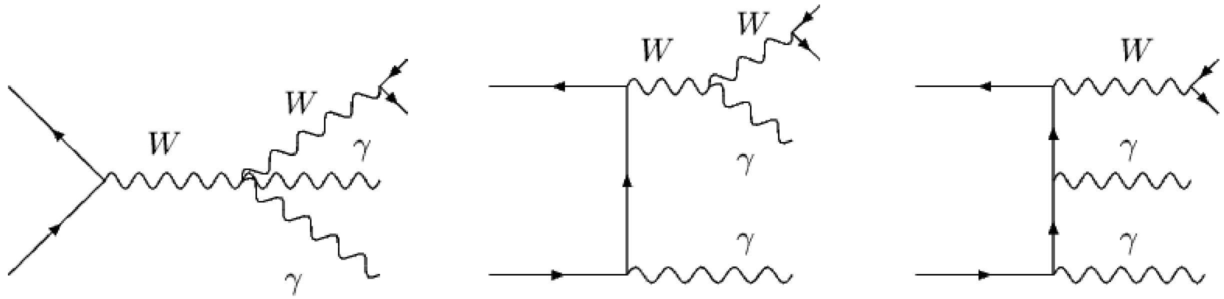
$pp \to VVV$ in vbfnlo

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

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

- 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

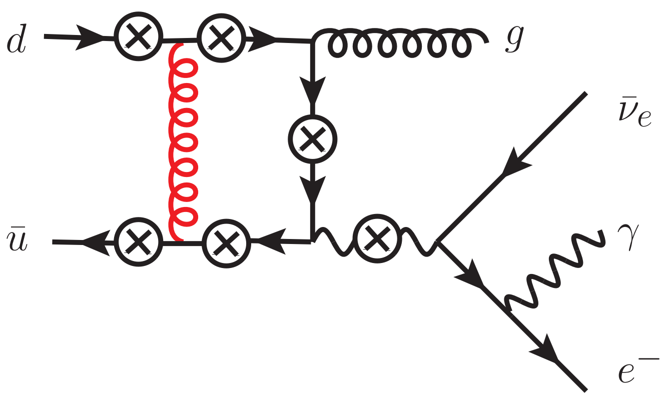
$pp \to V_1V_2 + \text{jet}$ in vbfnlo

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

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

- anomalous gauge boson couplings
- photon isolation via Frixione criterion

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



Campanario, Englert, Spannowksy, Zeppenfeld (2010):

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

- 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

contact

if you have questions, comments, suggestions . . .

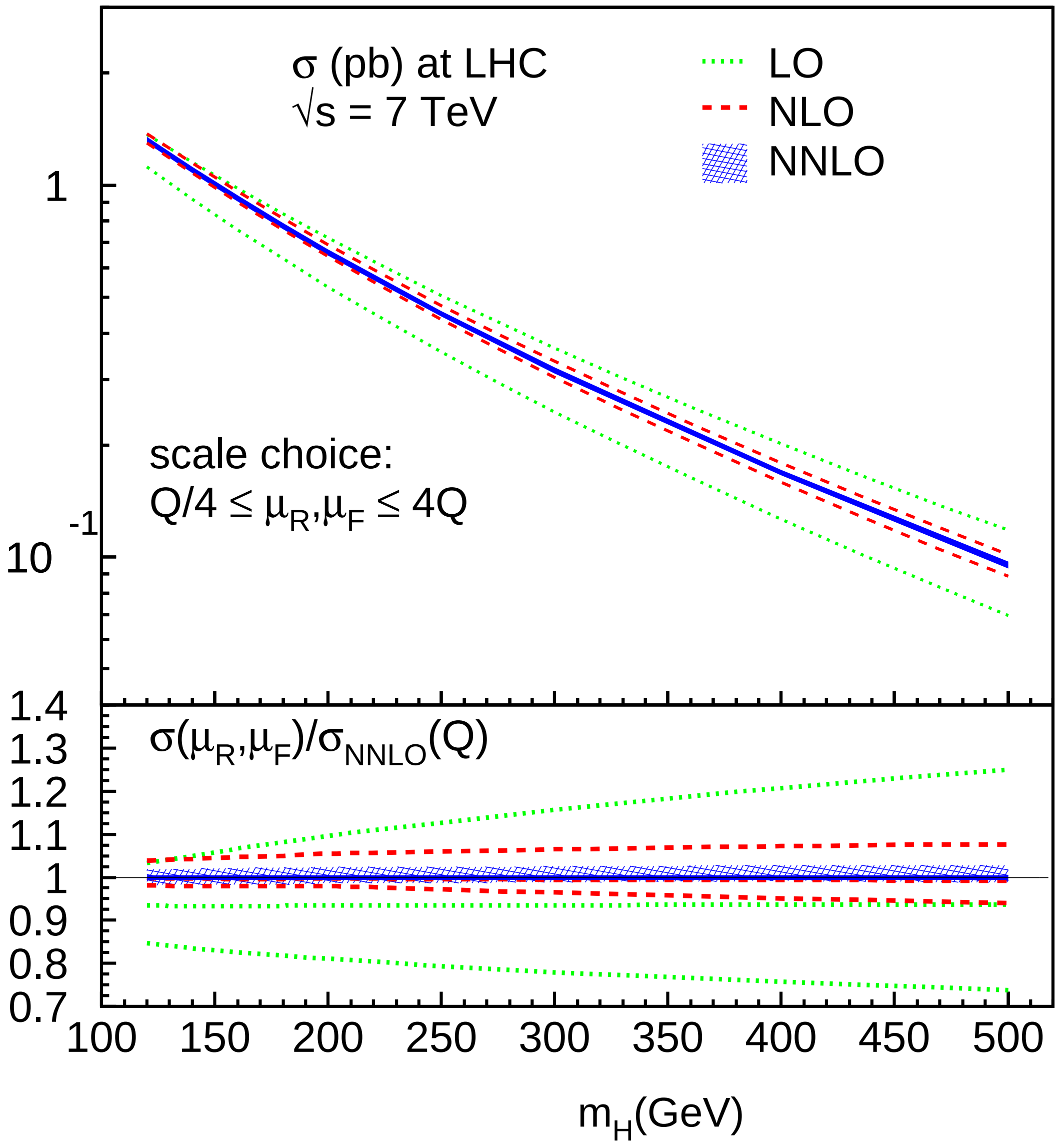
please e-mail us at

`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