Karlsruhe Institute of Technology

Multi-boson Production in Weak Boson Fusion

Michael Rauch | DIS 2014, Apr 2014

INSTITUTE FOR THEORETICAL PHYSICS

VBF event topology

VBF (vector-boson fusion) topology shows distinct signature

- two tagging jets in forward region
- reduced jet activity in central region
- leptonic decay products typically between tagging jets

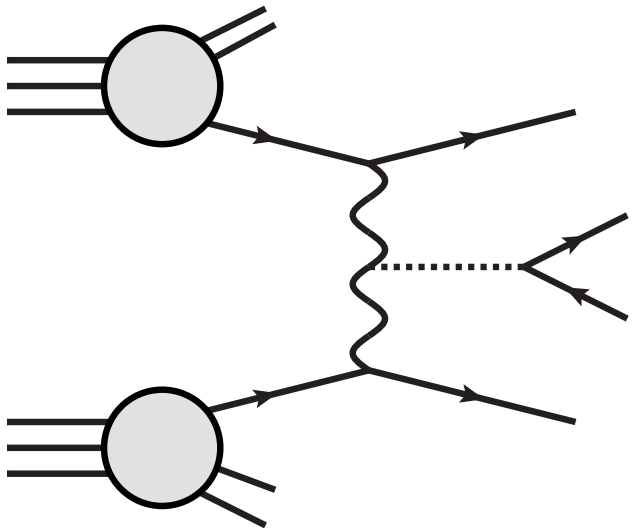
$\rightarrow$ two-sided DIS

First studied in context of Higgs searches [Han, Valencia, Willenbrock; Figy, Oleari, Zeppenfeld; . . .]

- $\sim$ 10% compared to main production mode gluon fusion
- NLO QCD corrections moderate ($\mathcal{O}(\lesssim 10\%)$)
- NLO EW same size, opposite sign as QCD for $M_H \sim 126$ GeV

  [Ciccolini *et al.* , Figy *et al.*]
- NNLO QCD known for subsets: no significant contributions

  [Harlander *et al.* , Bolzoni *et al.*]
- advantageous scale choice: momentum transfer q^2 of intermediate vector bosons



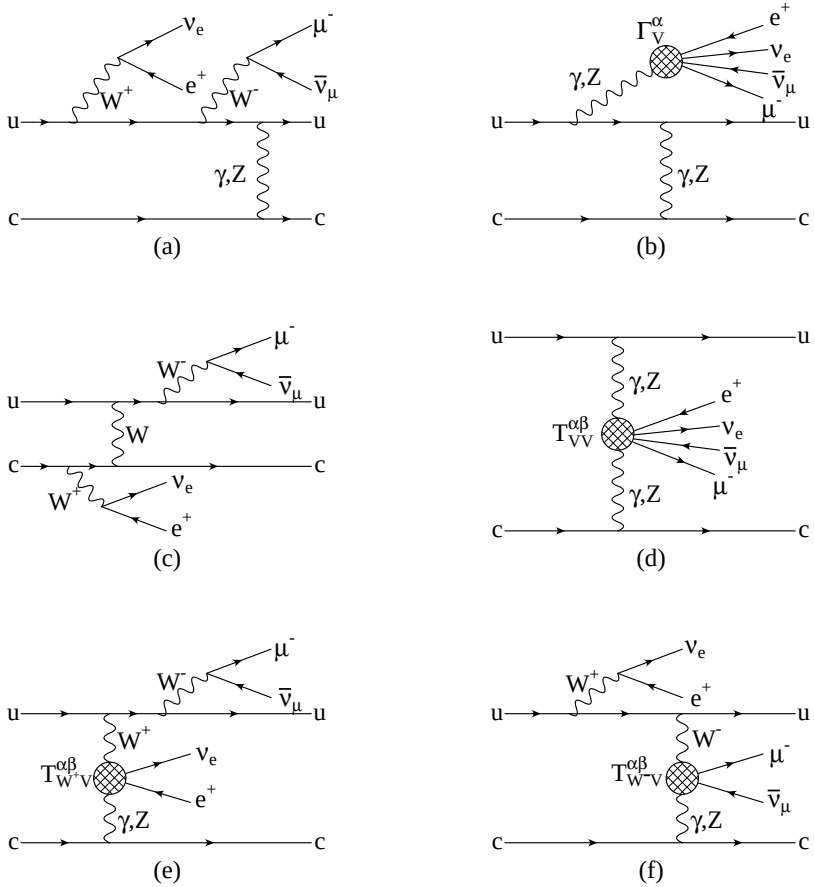
Diboson-VBF production

[Bozzi, Jäger, Oleari, Zeppenfeld (VV); Campanario, Kaiser, Zeppenfeld ($W^{\pm}\gamma$)]

[Denner, Hosekova, Kallweit (W^+W^+)]

- Part of the NLO wish list

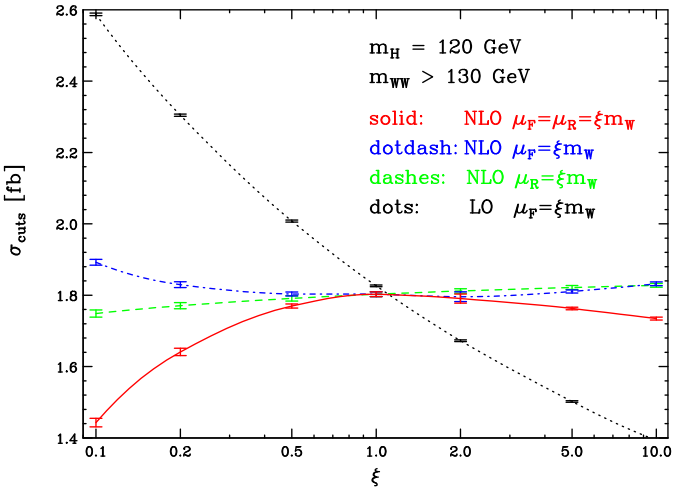
  [Les Houches 2005]
- background to Higgs searches
- access to anomalous triple and quartic gauge couplings



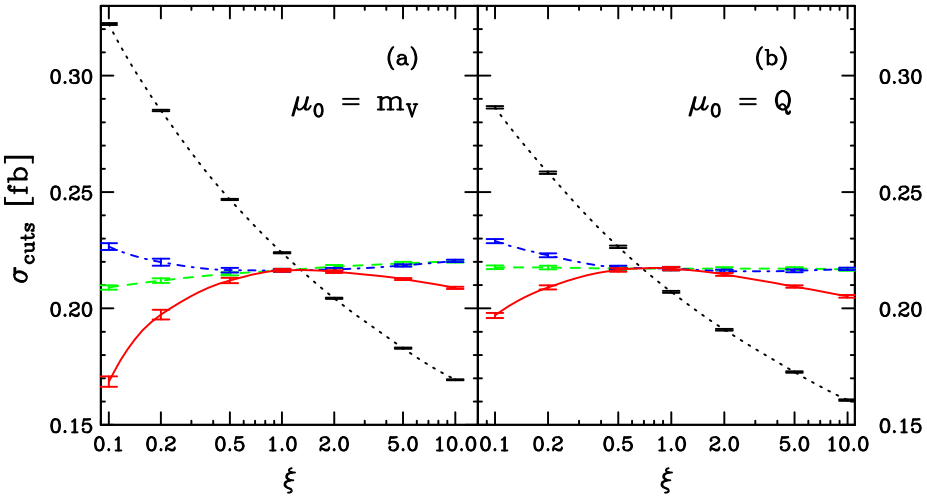
Scale dependence

Dependence on factorization and renormalization scale [Bozzi, Jäger, Oleari, Zeppenfeld]

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



$pp \to W^+Zjj$



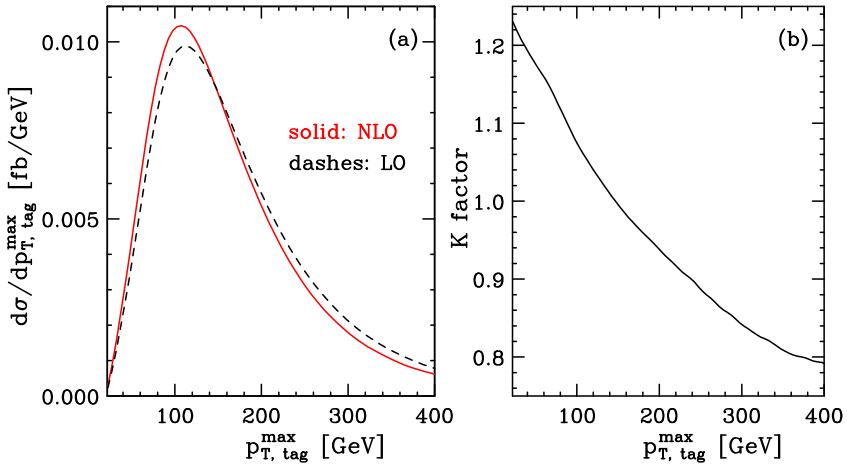
- sizable scale dependence at LO: $\sim \pm$ 10%
- strongly reduced at NLO: $\sim \pm$ 2% (up to 6% in distributions)
- K-factor around 0.98 for $\mu = m_V$, 1.04 for $\mu = Q$ (momentum transfer)

Distributions

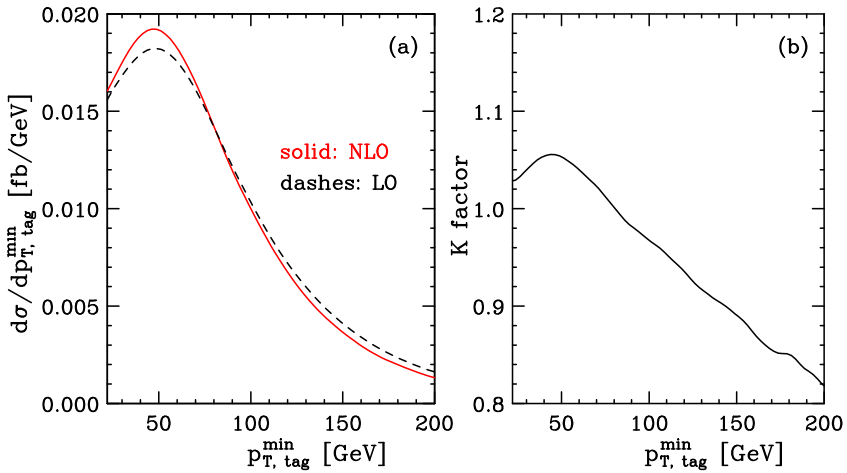
Differential distributions: $p_T(j)$ ($W^+ W^-$)

[Jäger, Oleari, Zeppenfeld]

p_T of the leading tagging jet



p_T of the second tagging jet

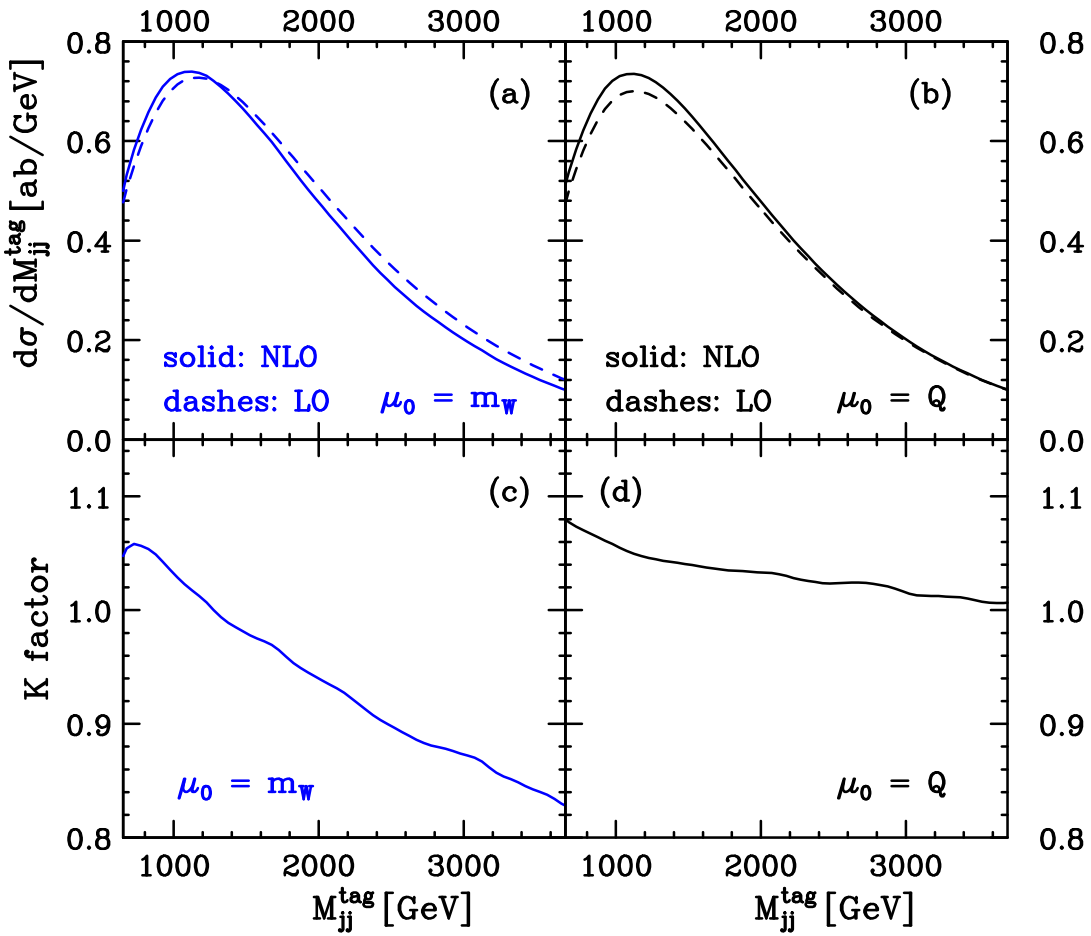


- K factor not constant over range of distribution
- $\rightarrow$ shape of distributions changes
- $\rightarrow$ simple rescaling with K factor not sufficient

Distributions

Differential distributions: m_{jj} ($W^+ W^+$)

[Jäger, Oleari, Zeppenfeld]



$\rightarrow$ scale choice $\mu_0 = Q$ leads to flatter differential K factor

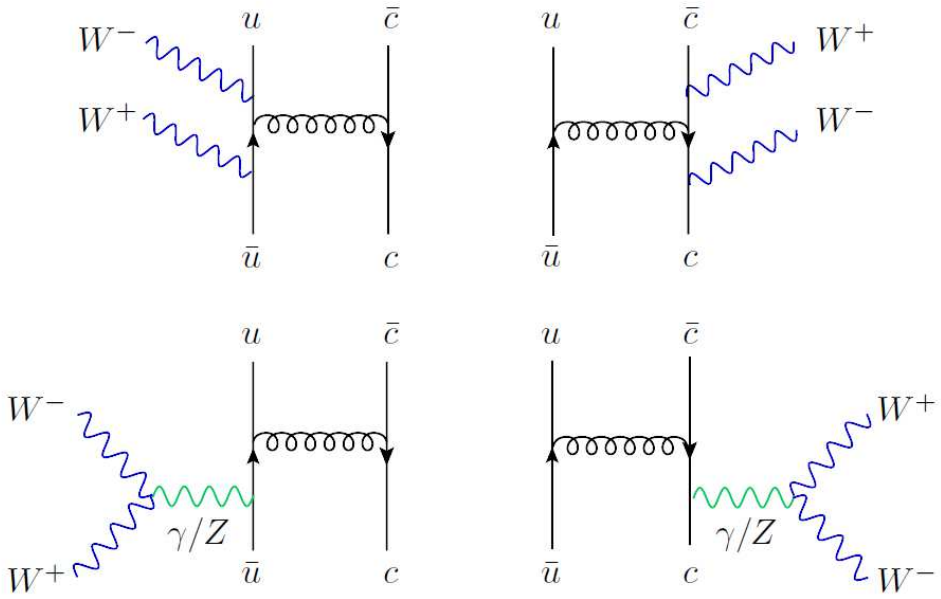
QCD-Diboson production

Calculations at NLO QCD:
$W^{\pm} W^{\pm}$ jj, $W^{+} W^{-}$ jj, $W^{\pm} Z$ jj, $W^{\pm} \gamma$ jj, $\gamma \gamma$ jj

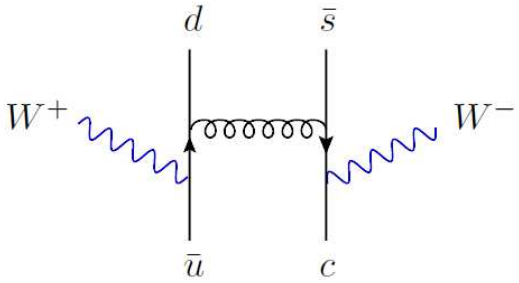
[Melia, Melnikov, Röntsch, Zanderighi; Greiner, Heinrich, Mastrolia, Ossola, Reiter, Tramontano]

[Campanario, Kerner, Ninh, Zeppenfeld; Gehrmann, Greiner, Heinrich]

W^+W^-jj



W^+W^-jj & W^+W^+jj
(latter after changing quark flavors appropriately)



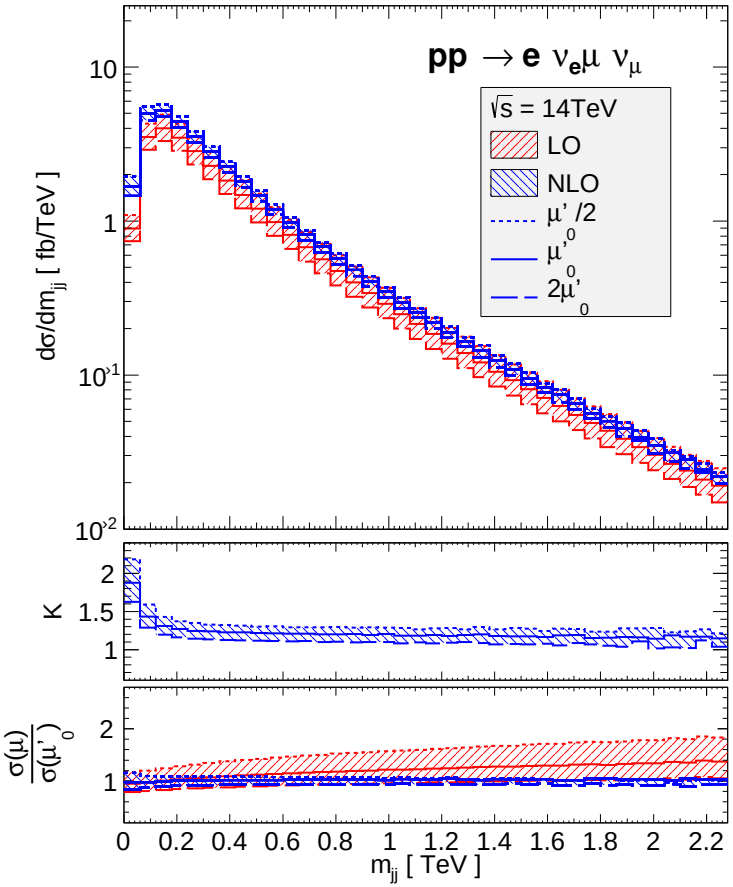
+ diagrams where quark line without attached vector bosons is replaced by gluons

QCD-Diboson production

$pp \to e^+\nu_e\mu^+\nu_\mu$

[Campanario, Kerner, Ninh, Zeppenfeld]

Impact of NLO QCD corrections



- K factors typically between 1 and 1.5
- corrections $< 20\%$ for invariant mass of two leading jets > 200 GeV
- huge correction for small m_{jj} due to new phase-space region (almost collinear quark-gluon splitting)
- good scale choice (interpolates between different regions):

$$\mu_0' = \frac{1}{2}\Big(\sum_{\text{jets}} p_{T,i}\exp|y_i - y_{12}| + \sum_{W}\sqrt{p_{T,i}^2 + m_{W,i}^2}\Big)$$

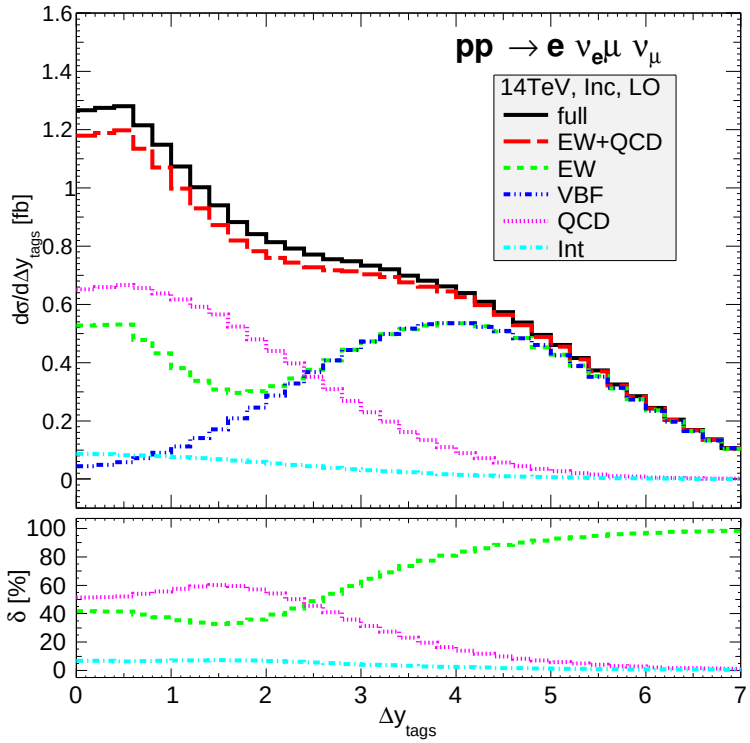
$$(y_{12} = (y_1 + y_2)/2)$$

QCD-EW interference

$pp \to e^+\nu_e\mu^+\nu_\mu$

[Campanario, Kerner, Ninh, Zeppenfeld]

Comparing contributions at LO



EW: full $\mathcal{O}(\alpha^6)$ calculation
VBF: VBF approximation
(only t-/u-channel diagrams)

- QCD and EW contributions of similar size
  (destructive interference for QCD, no gluon-initiated contributions)
- QCD-EW interference largest for large $p_{T,j}$, small Δy_{tags}
  up to 20% reducing to 10% (3%) for loose (tight) VBF cuts
- VBF contribution by far dominant in VBF region (96%)
  $\to$ good approximation

Matching with parton shower

NLO calculation

- normalization correct to NLO
- additional jet at high-p_T accurately described
- theoretical uncertainty reduced
- low-p_T jet emission badly modeled
- parton level description

LO + parton shower

- LO normalization only
- further high-p_T jets badly described
- Sudakov suppression at small p_T
- events at hadron level possible

POWHEG-BOX
implementation of W^+W^-, $W^\pm W^\pm$ and ZZ via VBF available [Alioli, Hamilton, Nason, Oleari, Re] [Jäger, Zanderighi]

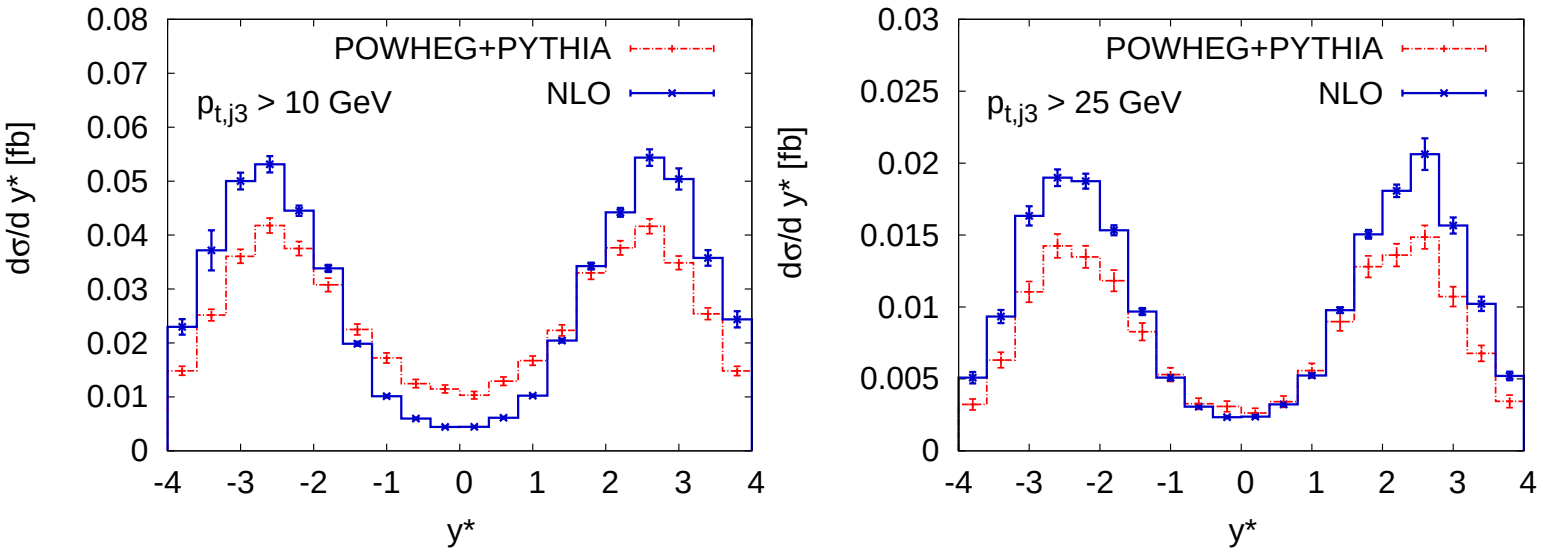
Matching with parton shower

W^+W^- via VBF

[Jäger, Zanderighi]

Relative position of third jet with respect to the two tagging jets:

$$y^\star = y_{j_3} - \frac{y_{j_1} + y_{j_2}}{2}$$



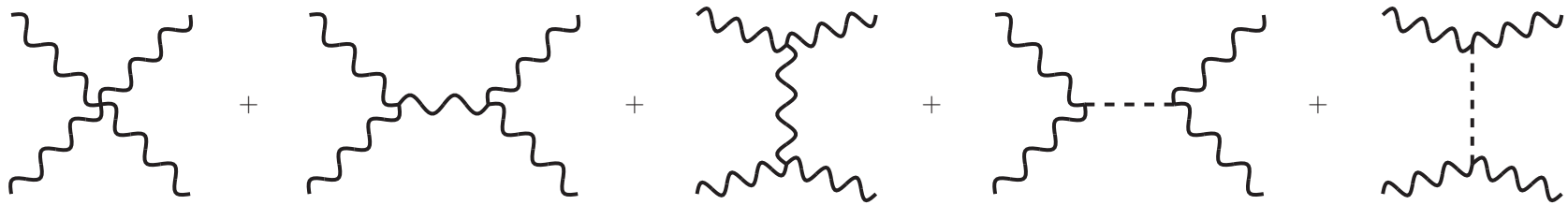
Extra jet activity in central region predicted by parton-shower calculation

Relevant differences to pure NLO calculation

Unitarization of WW-scattering

Test of electro-weak symmetry breaking

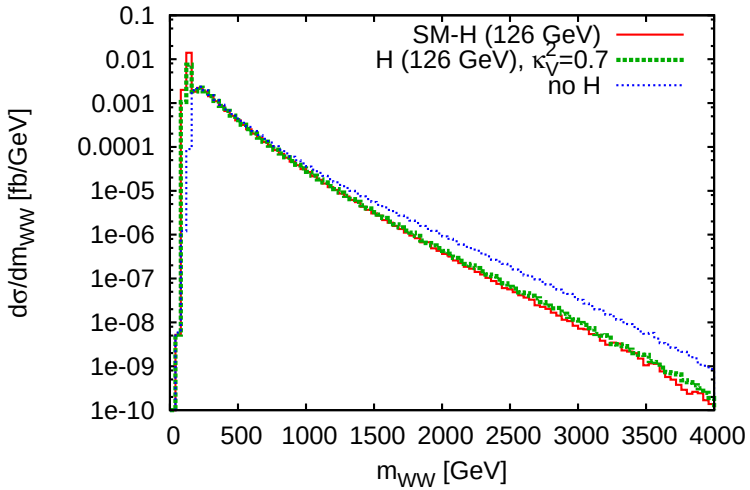
Longitudinal *WW* scattering contains Higgs graphs:



necessary for correct high-energy behaviour (otherwise unitarity violation at ~ 1 TeV)

$\mathcal{M}_H \sim \frac{s}{v^2}$ Signal amplitude for s-, t- and u-channel exchange of *H*

$\mathcal{M}_B \sim \frac{-s}{v^2}$ continuum electroweak background amplitude



exact cancellation only for SM couplings
(Higgs part may be split
over different bosons with
$\sum_i g^2_{h_i VV} = g^2_{HVV,\mathrm{SM}}$, e.g. 2HDM)

Anomalous quartic gauge couplings

New physics at high scale Λ could influence gauge couplings
$\Rightarrow$ anomalous gauge couplings

[Eboli *et al.* ; recent review: Wackeroth (ed.), Degrande, MR *et al.*]

Different approaches to parametrize effects $\rightarrow$ Effective field theory

$$\mathcal{L}_{\text{EFT}} = \sum_d \sum_i \frac{f_i^{(d)}}{\Lambda^{d-4}} \mathcal{O}_i^{(d)}$$

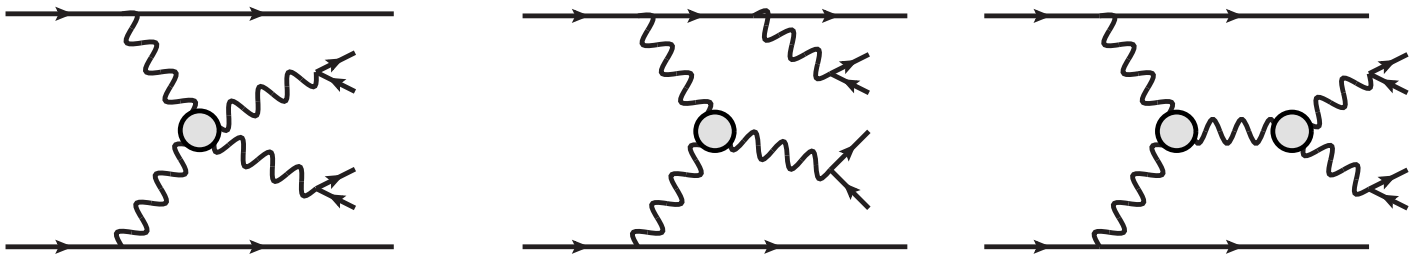
Operators $\mathcal{O}$ with low energy degrees of freedom respect gauge symmetries

Dimension-8 operators in Lagrangian
(Φ Higgs doublet, $W^{\mu\nu}/B^{\mu\nu}$: SU(2)/U(1) field strength tensors):

e.g. $\mathcal{L}_{M,2} \propto \left[B^{\mu\nu} B_{\mu\nu}\right] \times \left[\left(D^{\beta}\Phi\right)^{\dagger} D_{\beta}\Phi\right]$, $\mathcal{L}_{T,1} \propto \left[W^{\alpha\nu} W_{\mu\beta}\right] \times \left[W^{\mu\beta} W_{\alpha\nu}\right]$, ...

(at least) four gauge fields in each term $\rightarrow$ modify quartic gauge couplings

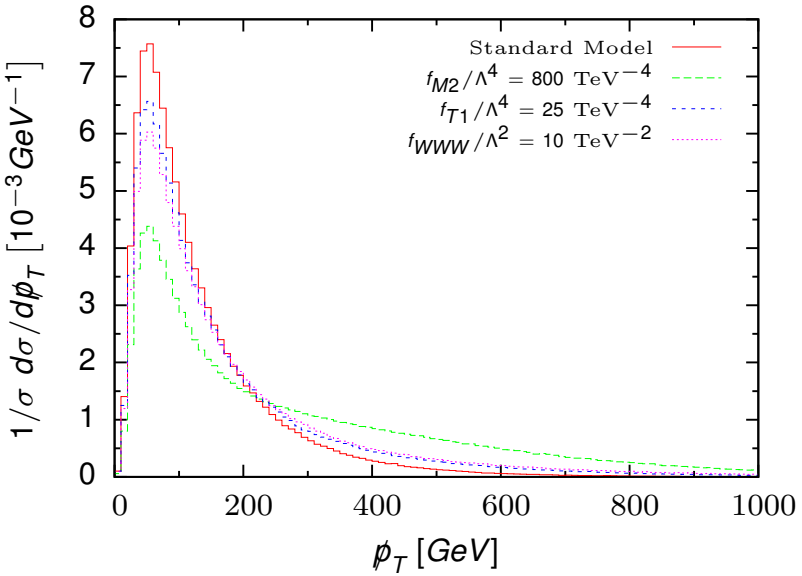
triple gauge couplings contribute as well



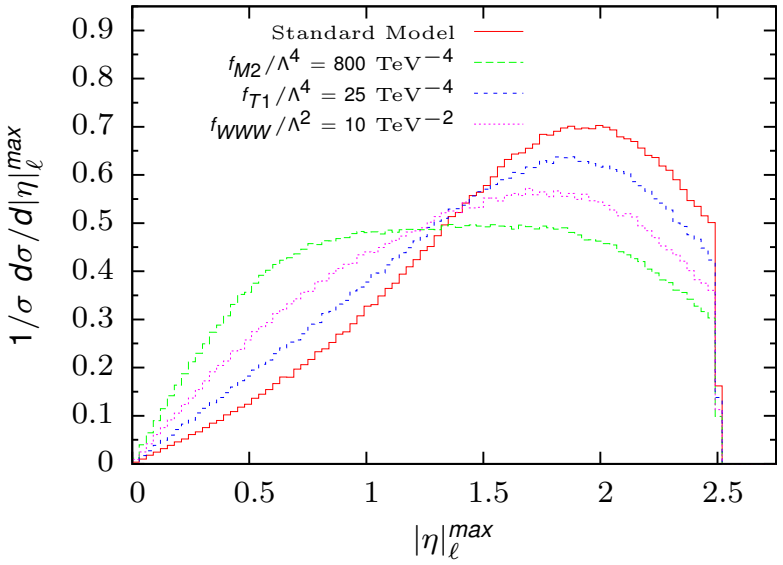
Anomalous quartic gauge couplings

[Schlimpert, Zeppenfeld]

Normalized $\not{p}_t$ distribution



Normalized $|\eta|_\ell^{\max}$ distribution



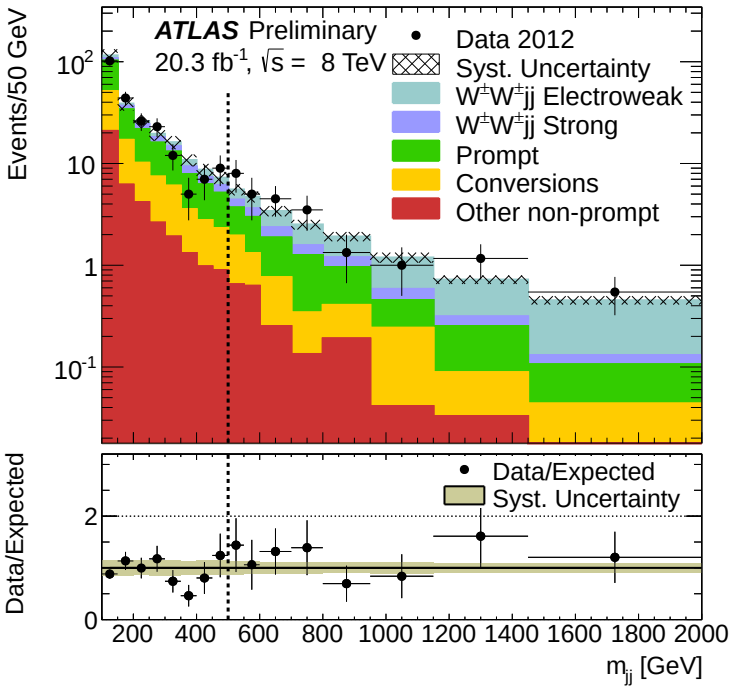
- Anomalous couplings enhance predominantly high-energy region
- $\Delta\sigma \sim \mathcal{O}(1-4\%)$ for total cross section,
  $\Delta\sigma \sim \mathcal{O}(20-100\%)$ in high-energy region, $m_{WW}^T > 800$ GeV
- Visible changes in distributions, different for individual couplings
- $\rightarrow$ distinguish between different couplings

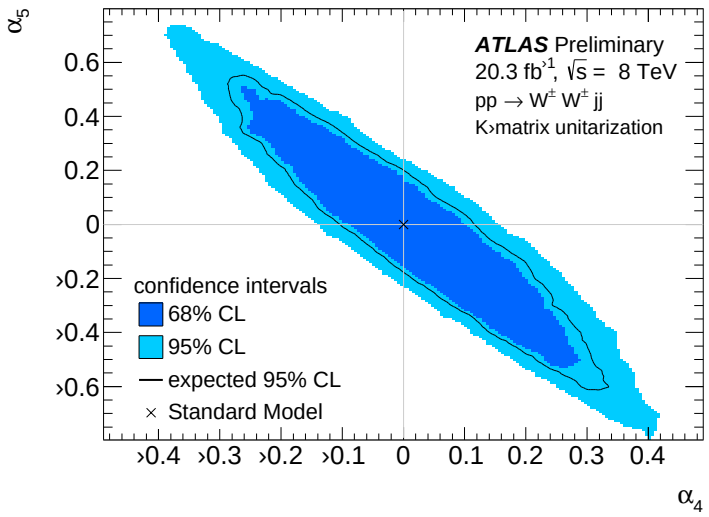
Experimental Results

[ATLAS-CONF-2014-013]

Recently first evidence (3.6σ) for $W^{\pm}W^{\pm}$ via VBF by ATLAS ($W \to e\nu_e$, $\mu\nu_\mu$)

($4.5\ \sigma$ for $W^{\pm}W^{\pm}jj$ production total (QCD+EW))





Good agreement with SM prediction $\Rightarrow$ Limits on anomalous couplings

$\sigma^{\text{fid}}_{\text{exp}} = 1.3 \pm 0.4\ (\text{stat}) \pm 0.2\ (\text{syst})$ fb

$\sigma^{\text{fid}}_{\text{th}} = 0.95 \pm 0.06$ fb

Conclusions

Di-boson production via Weak Boson Fusion

- important process for the LHC
  - Higgs searches – unitarity in WW scattering
  - testing anomalous (triple and) quartic gauge couplings
- NLO QCD corrections modest
- for some processes NLO QCD + parton shower available
- VBF approximation in VBF region justified
  in general also QCD and QCD-EW interference contributions
- first experimental evidence in $W^{\pm}$ $W^{\pm}$ jj production by ATLAS