Karlsruher Institut für Technologie

B1c: Central Jet Veto in Vector-Boson Scattering

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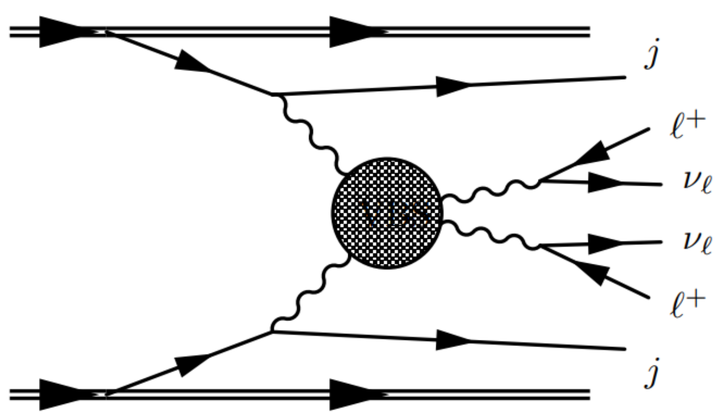
KIT Center Elementary Particle and Astroparticle Physics - KCETA

Outline of talk:

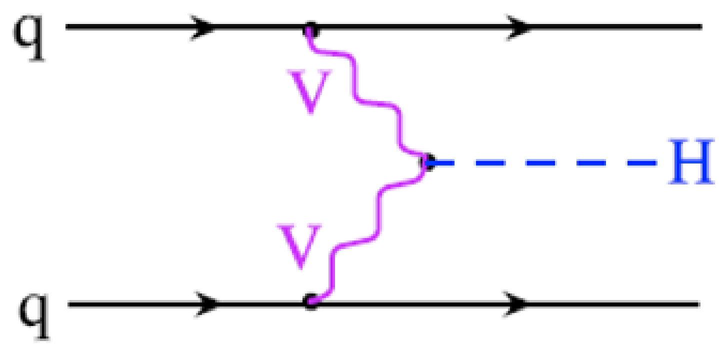
- Introduction: properties of VBF and VBS
- Central jet activity in VBF
- Experience with parton shower
- NLO QCD corrections to VBF and VBS
- hjjj and Zjjj production via VBF at NLO
- Conclusions

Introduction

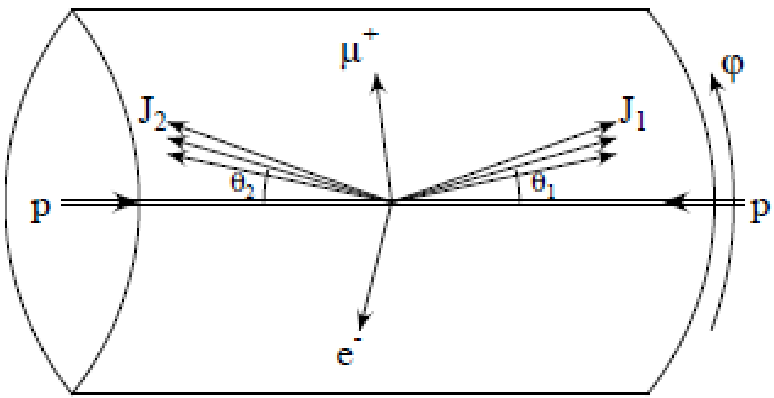
- Vector boson scattering (VBS)
  - Basic process: VV→VV
  - accompanied by 2 quark jets = tagging jets
  - Observe decay leptons of weak bosons or hadronic V decay

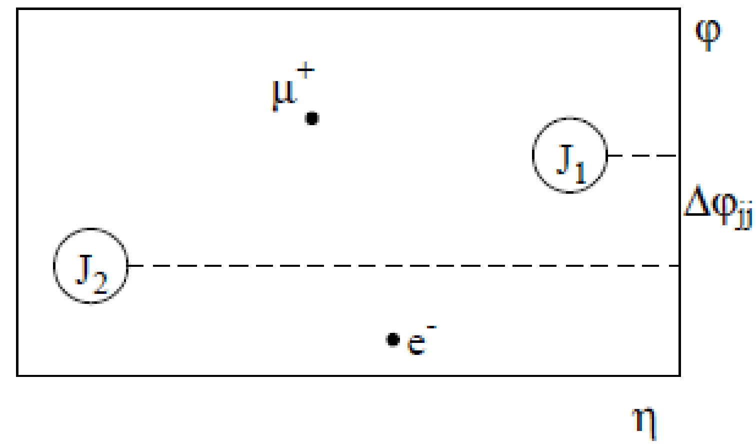


- Vector boson fusion (VBF)
  - Important Higgs production mode, e.g. H→tau+tau-
  - Determine HVV coupling from production cross section
  - Relatively low background
  - Similar: VBF Zjj and Wjj production



VBF and VBS signature





Characteristics:

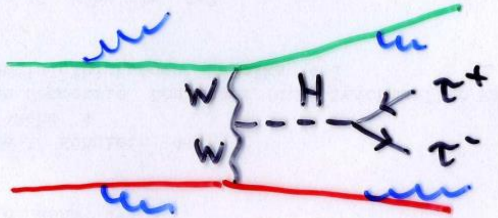
- energetic jets in the forward and backward directions ($p_T > 20$ GeV)
- large rapidity separation and large invariant mass of the two tagging jets
  $\Longrightarrow$ Enhance signal contributions by "VBF cuts", e.g.

$$m_{jj} > 600\,\text{GeV} \qquad\qquad |y_{j_1} - y_{j_2}| > 4$$

- Higgs/V/VV decay products between tagging jets

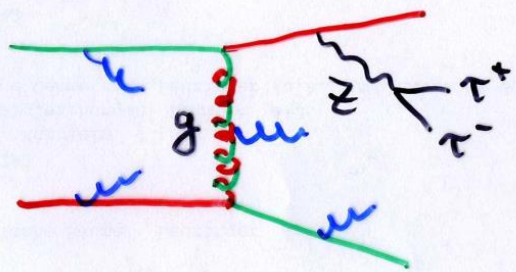
Extra jet activity: VBF/VBS signal vs QCD background

- t-channel color singlet exchange



"synchrotron" radiation between initial and final quark direction
⇒ central jets suppressed

- Major QCD backgrounds: t-channel color octet exch.



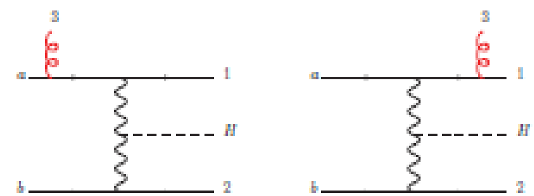
deflection of color charge by ~180° ⇒ strong color acceleration
⇒ enhanced central gluon emis.

- General feature of signal with t-channel color singlet exchange: all VBF and VBS processes
- Develop quantitative tools for using CJV in VBF/VBS precision measurements

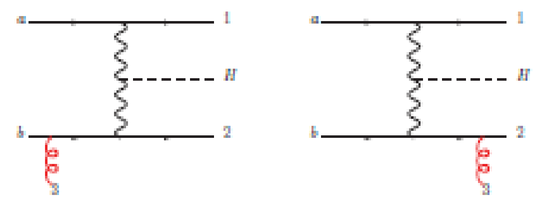
VBF $hjjj$ production

- Born: 3 final state partons + Higgs via VBF

$$\mathcal{M}_B = t^{a_3}_{i_1 i_a}\delta_{i_2 i_b}\left[\mathcal{M}_{B,1a} : \right]$$

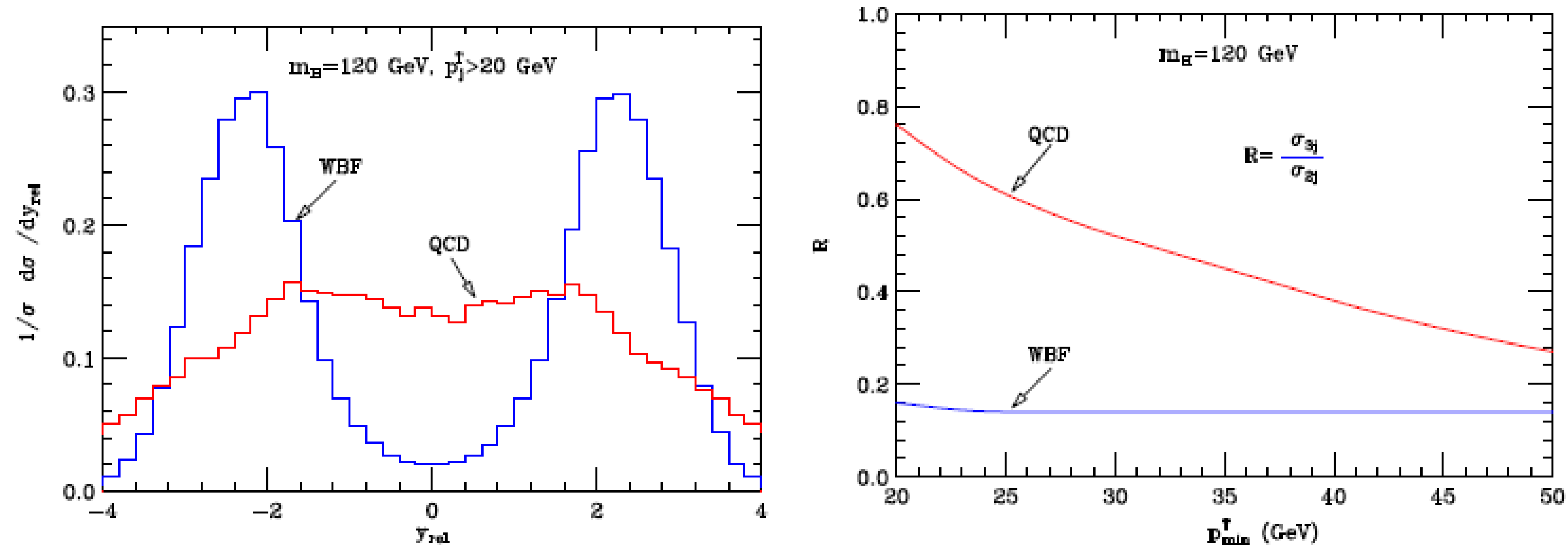


$$+ \ \delta_{i_1 i_a} t^{a_3}_{i_2 i_b}\left[\mathcal{M}_{B,2b} : \right]$$



- No interference between upper and lower set of Feynman graphs due to color structure
- Two emission graphs off upper quark line interfere destructively for gluon emission at larger angles than scattered quark
- Anlogous for gluon emission off lower quark line
- $\Longrightarrow$ Little gluon radiation in rapidity region between the two quark jets

Central Jet Veto: $Hjjj$ from VBF vs. gluon fusion



[Del Duca, Frizzo, Maltoni, JHEP 05 (2004) 064]

- Angular distribution of third (softest) jet follows classically expected radiation pattern
- QCD events have higher effective scale and thus produce harder radiation than VBF (larger three jet to two jet ratio for QCD events)
- Central jet veto can be used to distinguish Higgs production via GF from VBF

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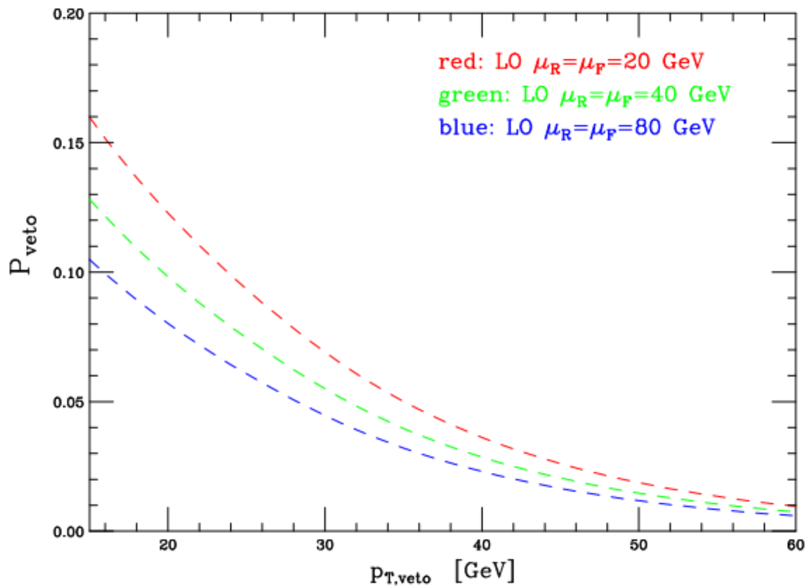
VBF Higgs signal and CJV



$$p_{Tj}^{veto} > p_{T,veto}, \quad \eta_j^{veto} \in (\eta_j^{\text{tag 1}}, \eta_j^{\text{tag 2}})$$

$$P_{\text{veto}} = \frac{1}{\sigma_2^{NLO}} \int_{p_{T,veto}}^{\infty} dp_{Tj}^{veto} \frac{d\sigma_3^{LO}}{dp_{Tj}^{veto}}$$

- Scale variation at LO for σ_{3j}: $+33\%$ to -17% for $p_{T,veto} = 15$ GeV
- The uncertainty in P_{veto} feeds into the uncertainty of coupling measurements at the LHC
- In order to constrain couplings more precisely, the NLO QCD corrections to $Hjjj$ are needed: T. Figy, V. Hankele, and DZ, arXiv:0710.5621 (JHEP)

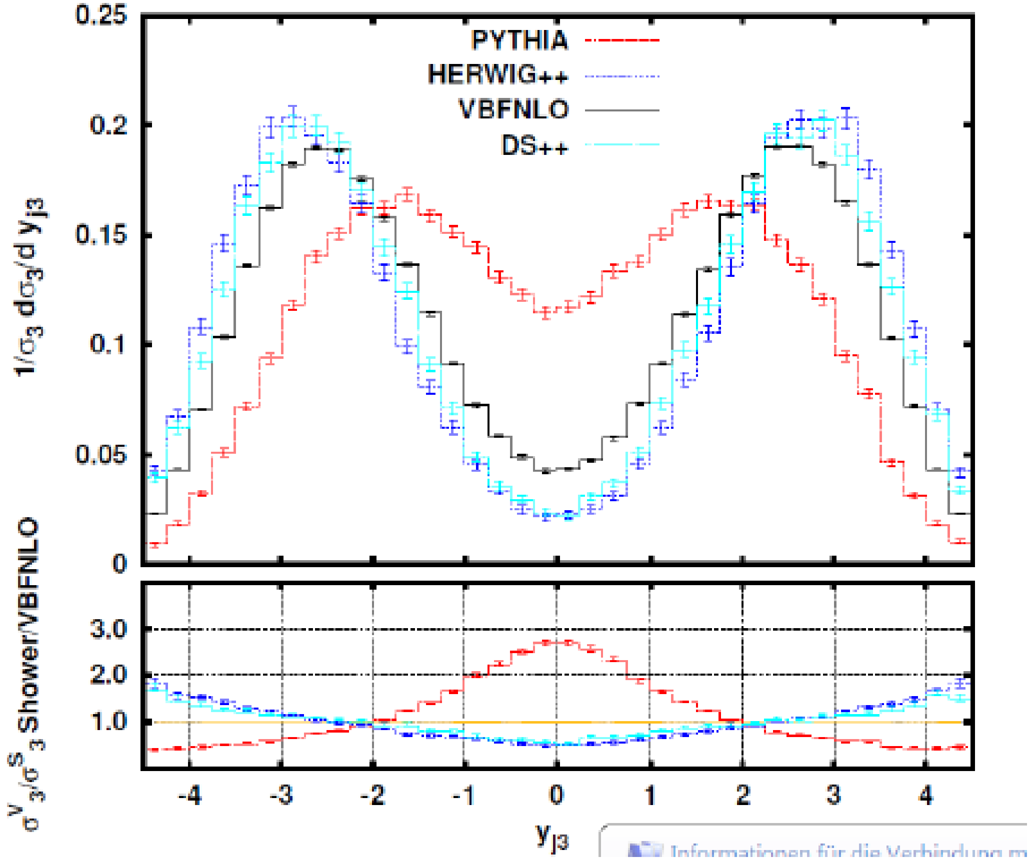
Veto Jets beyond fixed order: Parton Shower interface

Interface of NLO calculations with Herwig and PYTHIA via Powheg Box was implemented by Franziska Schissler

- How well can "veto jets" be modeled directly by parton shower approach?
- Differences between basic shower models
  (PYTHIA vs. default Herwig shower vs. dipole shower)
- Improvements when adding true NLO corrections

Veto jet distribution: LO $qq \to qqh$ matrix elements

Schissler thesis, 2014



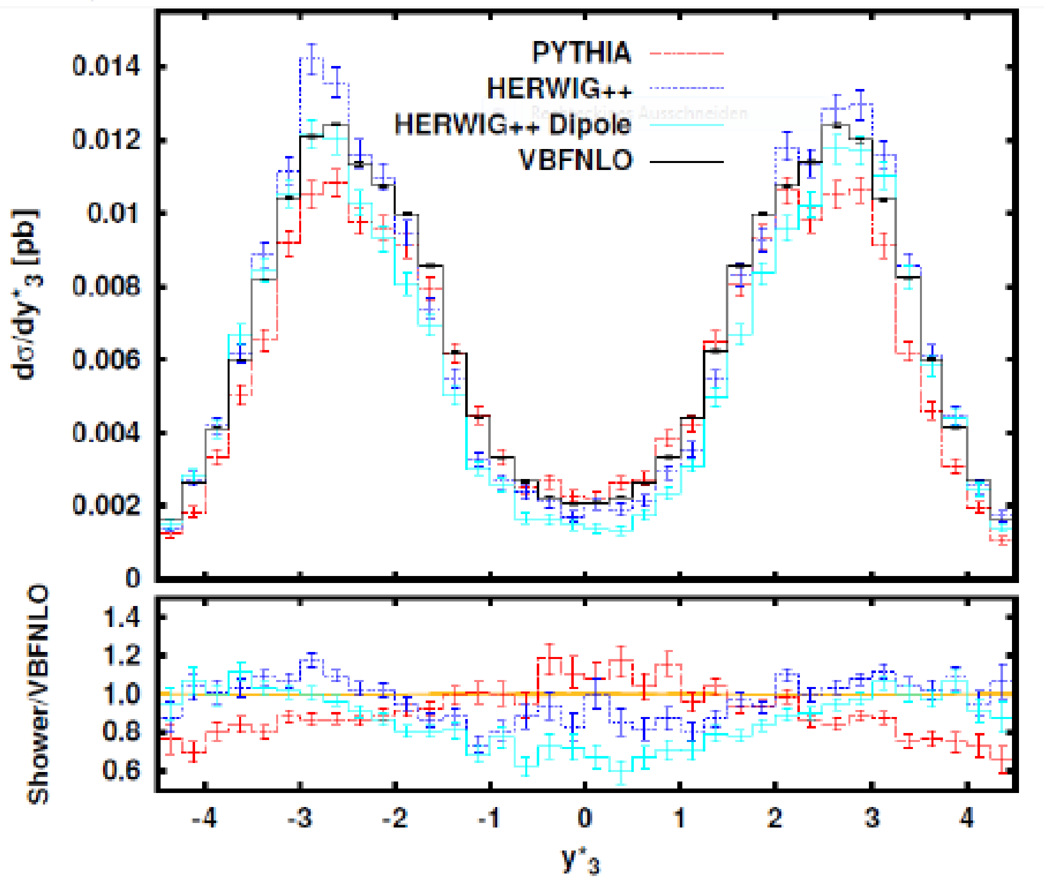
Pure parton-shower generation of central jets does not produce reliable results

Collinear approximation inherent in PS approach is not valid in veto region for VBF events

Extra parton must be included in hard matrix element

Veto jet distribution: VBF $Wjjj$ production at LO

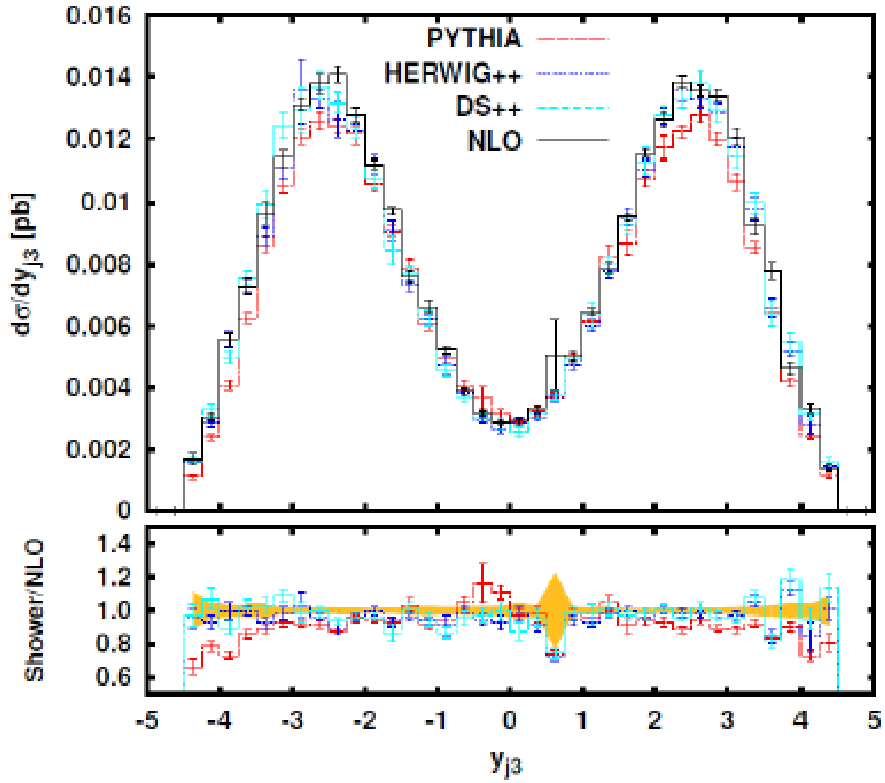
Schissler,DZ arXiv:1302.2884



Inclusion of third parton at ME level produces reasonable agreement between NLO Vjj calculations and parton shower programs

Veto jet distribution: VBF $hjjj$ production at NLO

Jäger, Schissler,DZ arXiv:1405.6950



Further improvement with NLO $hjjj$ calculation matched to PS programs

Reliable simulation of veto jet candidates is possible but requires matrix elements with sufficiently high parton multiplicity

NLO QCD Corrections

- Determine VBF/VBS characteristics with sufficient precision to extract couplings from LHC data
- Need QCD (and EW) corrections
- In Karlsruhe we have calculated VBF, VBS and a variety of other processes involving final state EW bosons with NLO QCD precision
- Implemented in the VBFNLO Monte Carlo

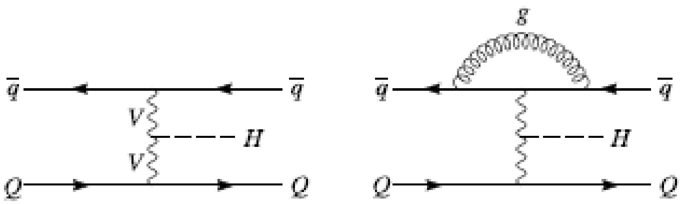
  Publicly available at

  https://www.itp.kit.edu/vbfnlo//wiki/doku.php

Generic features of NLO QCD corrections to VBF and VBS

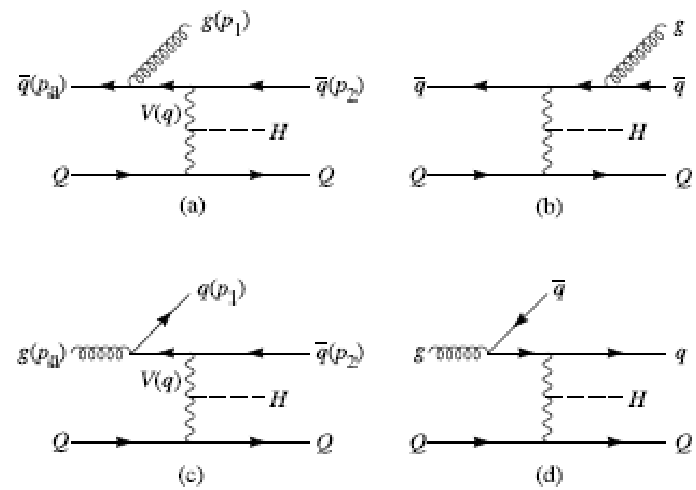
t-channel color singlet exchange $\Longrightarrow$ QCD corrections to different quark lines are independent

Born and vertex corrections to upper line



No t-channel gluon exchange at NLO

real emission contributions: upper line

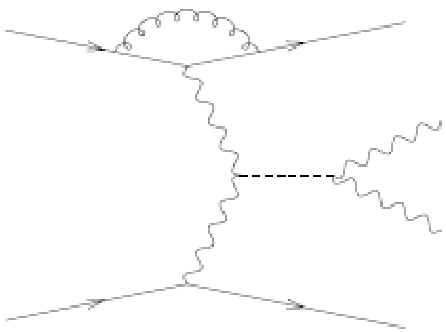


Treat s-channel contributions (here VH production with $V \to jj$ decay)
and QCD processes (e.g. $VVjj$ production at order $\alpha_s^2\alpha^2$) as separate processes.
Neglect interference for identical fermions: small effects in phase space where VBF/VBS is visible
Features are generic for all VBF/VBS processes

Virtual corrections: Higgs production

Most trivial case: Higgs production

Virtual correction is vertex correction only



virtual amplitude proportional to Born

$$\mathcal{M}_V = \mathcal{M}_{\text{Born}} \frac{\alpha_s(\mu_R)}{4\pi} C_F \left(\frac{4\pi\mu_R^2}{Q^2}\right)^{\epsilon} \Gamma(1+\epsilon) \left[-\frac{2}{\epsilon^2} - \frac{3}{\epsilon} + \frac{\pi^2}{3} - 7\right] + \mathcal{O}(\epsilon)$$

- Divergent piece canceled via Catani Seymour algorithm

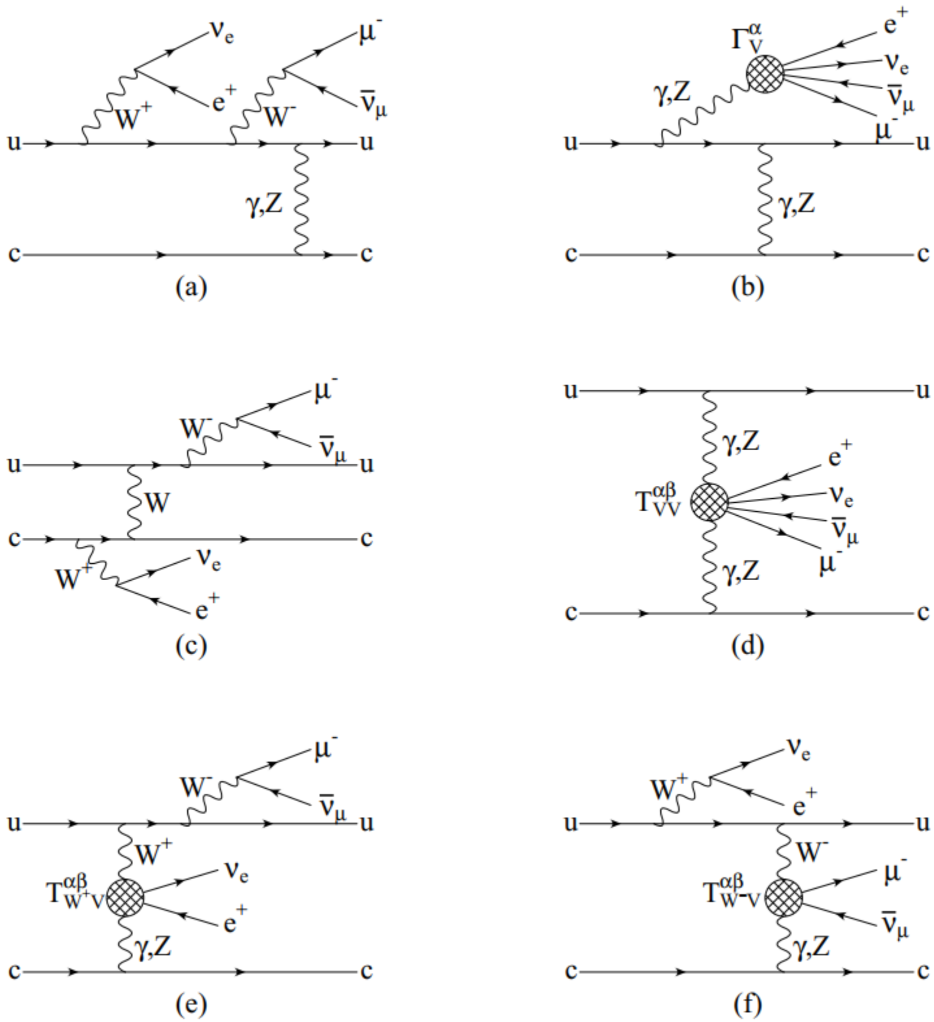
Remaining virtual corrections are accounted for by trivial factor multiplying Born cross section

$$|\mathcal{M}_{\text{Born}}|^2 \left(1 + 2\alpha_s \frac{C_F}{2\pi} c_{\text{virt}}\right)$$

- Factor 2 for corrections to upper and lower quark line
- Same factor to Born cross section absorbs most of the virtual corrections for other VBF processes

Weak boson scattering: $qq \to qqWW$, $qqZZ$, $qqWZ$ at NLO

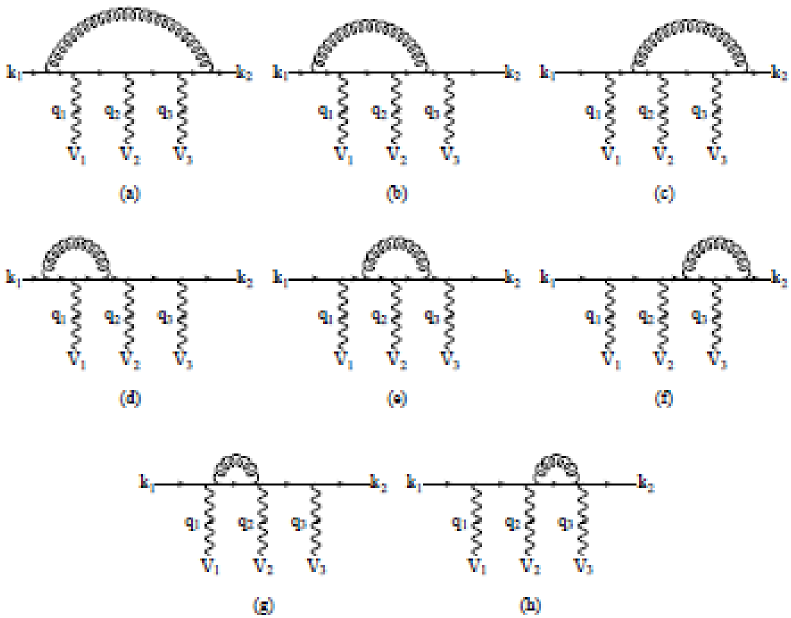
- example: WW production via VBF with leptonic decays: $pp \to e^+\nu_e\mu^-\bar{\nu}_\mu + 2j$
- Spin correlations of the final state leptons
- All resonant and non-resonant Feynman diagrams included
- NC $\Longrightarrow$ 181 Feynman diagrams at LO
- CC $\Longrightarrow$ 92 Feynman diagrams at LO



Large cancellations between VBS type graphs and V emission off quark lines: observe factor 1000 cancellation due to interference terms

Most complex for virtual: penline corrections

Virtual corrections involve up to pentagons



The external vector bosons correspond to $V \to l_1 \bar{l}_2$ decay currents or quark currents

The sum of all QCD corrections to a single quark line is simple

$$
\begin{aligned}
\mathcal{M}_V^{(i)} &= \mathcal{M}_B^{(i)} \frac{\alpha_s(\mu_R)}{4\pi} C_F \left(\frac{4\pi\mu_R^2}{Q^2} \right)^{\epsilon} \Gamma(1+\epsilon) \\
&\quad \left[-\frac{2}{\epsilon^2} - \frac{3}{\epsilon} + c_{\mathrm{virt}} \right] \\
&\quad + \widetilde{\mathcal{M}}^{(i)}_{V_1 V_2 V_3,\tau}(q_1, q_2, q_3) + \mathcal{O}(\epsilon)
\end{aligned}
$$

- Divergent pieces sum to Born amplitude: canceled via Catani Seymour algorithm
- Use amplitude techniques to calculate finite remainder of virtual amplitudes

Pentagon tensor reduction with Denner-Dittmaier is stable at 0.1% level

Some Phenomenology

Study LHC cross sections within typical VBF cuts

- Identify two or more jets with k_T-algorithm ($D = 0.8$)

$$p_{Tj} \geq 20 \text{ GeV}, \qquad |y_j| \leq 4.5$$

- Identify two highest p_T jets as tagging jets with wide rapidity separation and large dijet invariant mass

$$\Delta y_{jj} = |y_{j_1} - y_{j_2}| > 4, \qquad M_{jj} > 600 \text{ GeV}$$

- Charged decay leptons ($\ell = e,\ \mu$) of W and/or Z must satisfy

$$p_{T\ell} \geq 20 \text{ GeV}, \qquad |\eta_\ell| \leq 2.5, \qquad \triangle R_{j\ell} \geq 0.4,$$
$$m_{\ell\ell} \geq 15 \text{ GeV}, \qquad \triangle R_{\ell\ell} \geq 0.2$$

and leptons must lie between the tagging jets

$$y_{j,min} < \eta_\ell < y_{j,max}$$

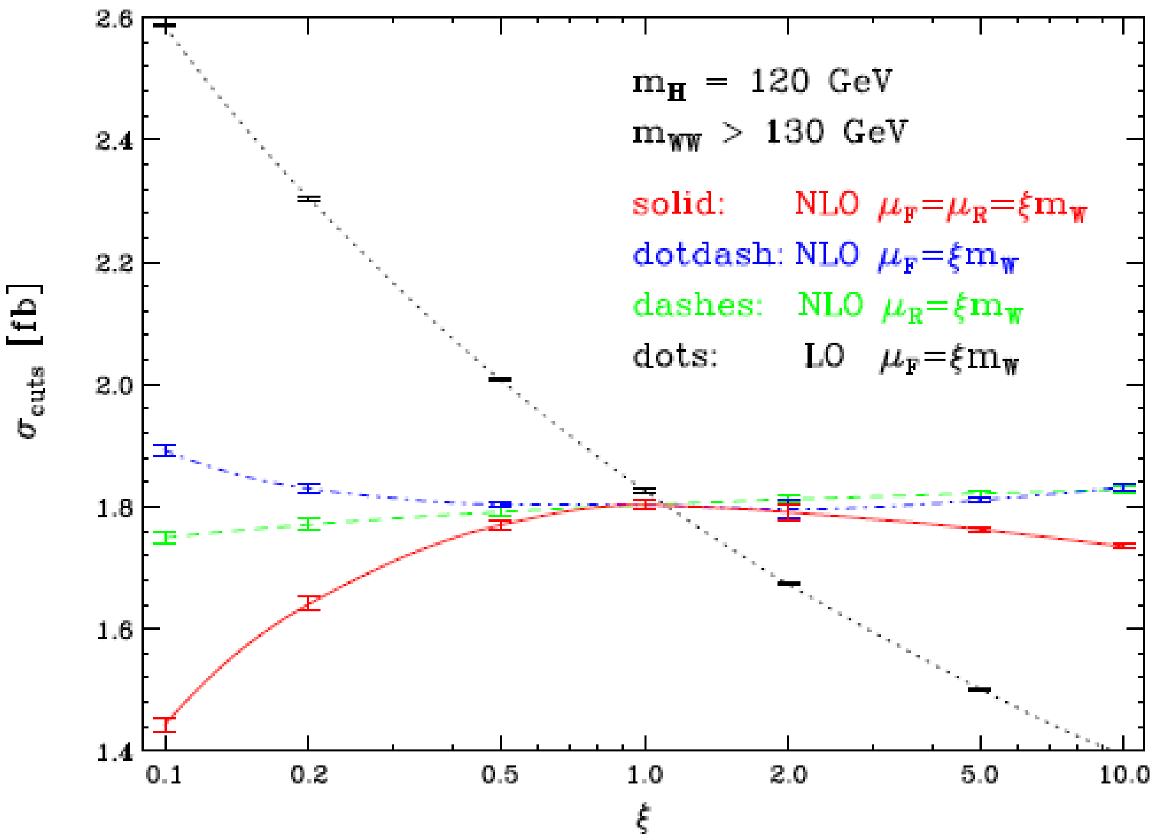
For scale dependence studies we have considered

$\mu = \xi\ m_V$ fixed scale $\qquad$ $\mu = \xi\ Q_i$ weak boson virtuality : $Q_i^2 = 2k_{q_1} \cdot k_{q_2}$

WW production: $pp \to jje^+\nu_e\mu^-\bar{\nu}_\mu X$ @ LHC

Stabilization of scale dependence at NLO

Jäger, Oleari, DZ hep-ph/0603177



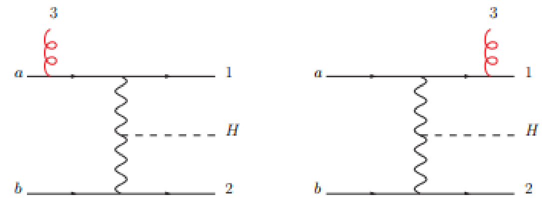
Extension to 3-jet production in VBF/VBS

- NLO QCD corrections to hjjj VBF production available since 2007
- Need NLO QCD corrections to Vjjj and VVjjj
- Interface to parton shower
- Fast tools required for phenomenological studies

Ingredients of the NLO Calculation

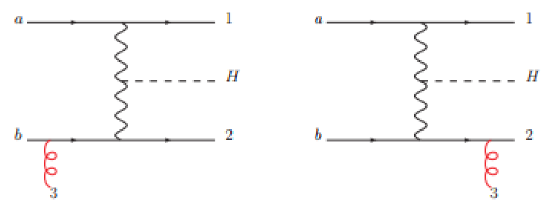
- Born: 3 final state partons + Higgs via VBF

$$\mathcal{M}_B = \delta_{i_2 i_b} t^{a_3}_{i_1 i_a} \left[\mathcal{M}_{B,1a} : \right.$$



$$\left. \right]$$

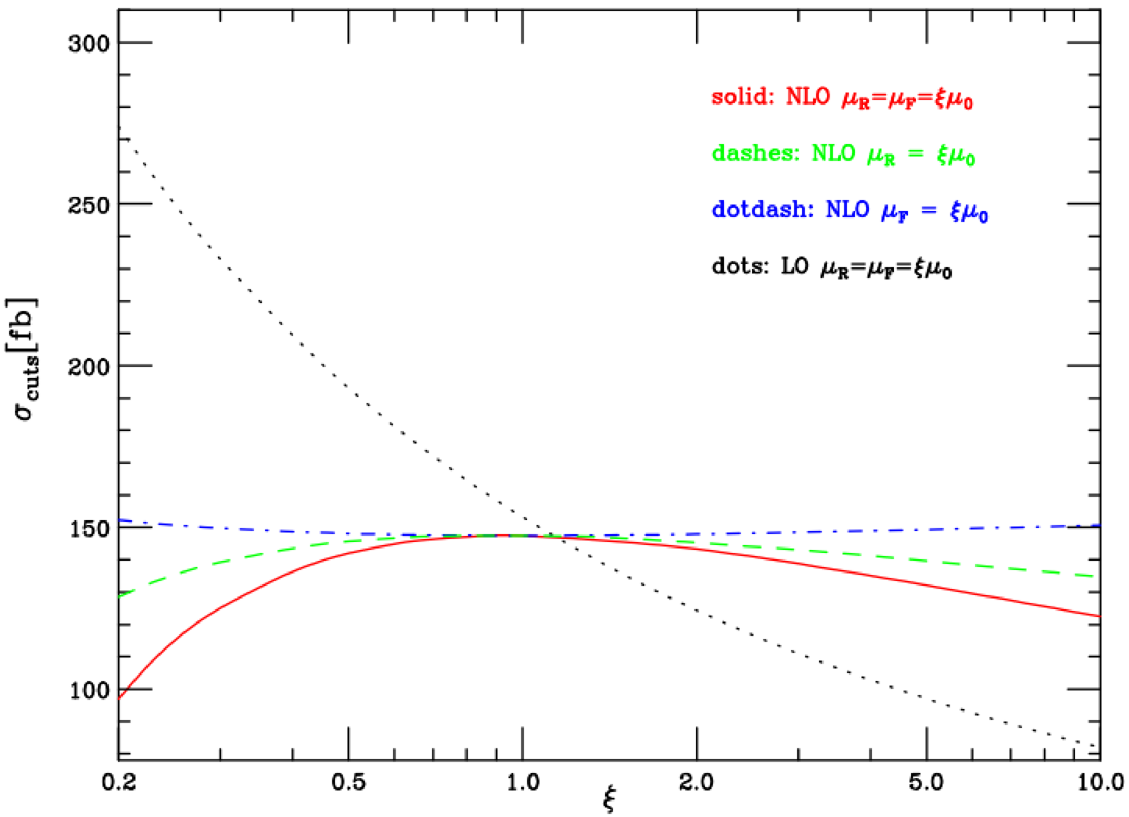
$$+ \ \delta_{i_1 i_a} t^{a_3}_{i_2 i_b} \left[\mathcal{M}_{B,2b} : \right.$$



$$\left. \right]$$

- Catani, Seymour subtraction method
- Real: 4 final state partons + Higgs via VBF
- Virtual: Two classes of gauge invariant subsets
  - Box + Vertex + Propagator
  - Pentagon + Hexagon are small and can be neglected

Total $Hjjj$ Cross Section at the LHC: NLO vs LO

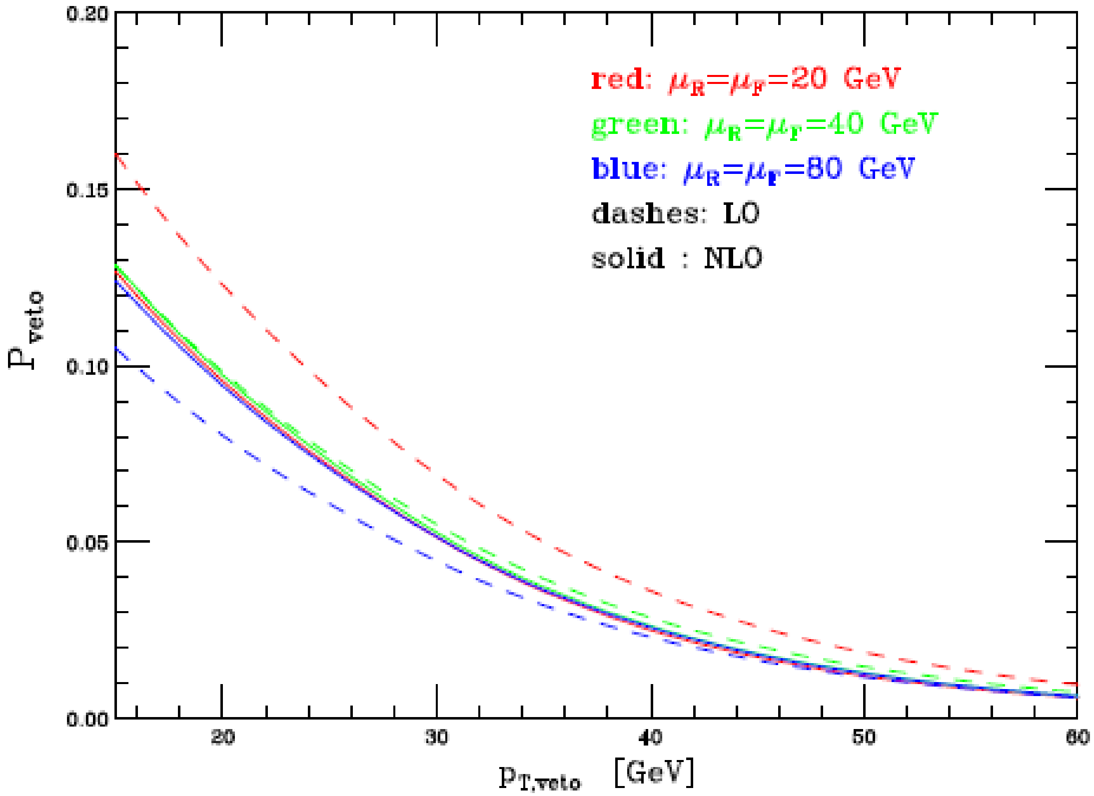


$\mu_0 = 40$ GeV

$\xi = 2^{\mp 1}$ scale variations:

- LO: +26% to −19%
- NLO: less than 5%

Veto Probability for the VBF Signal



$$P_{\text{veto}} = \frac{1}{\sigma_2^{NLO}} \int_{p_{T,veto}}^{\infty} dp_{Tj}^{veto} \frac{d\sigma_3}{dp_{Tj}^{veto}}$$

Scale variations, $p_{T,veto} = 15$ GeV:

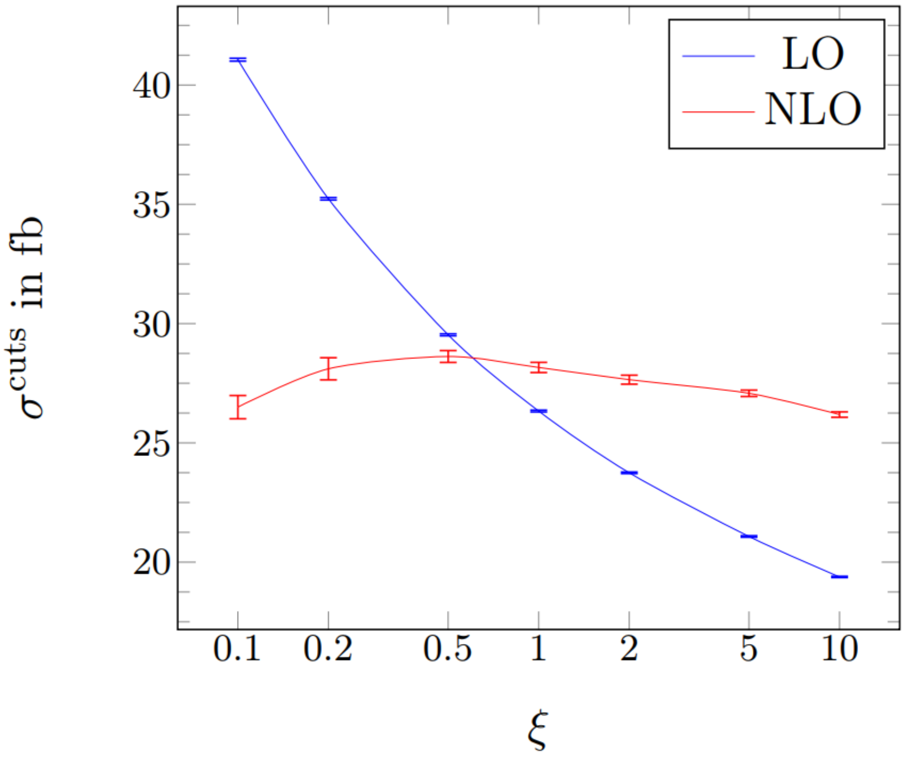
- LO: $+33\%$ to -17%
- NLO: -1.4% to -3.4%

Reliable prediction for perturbative part of veto probability at NLO

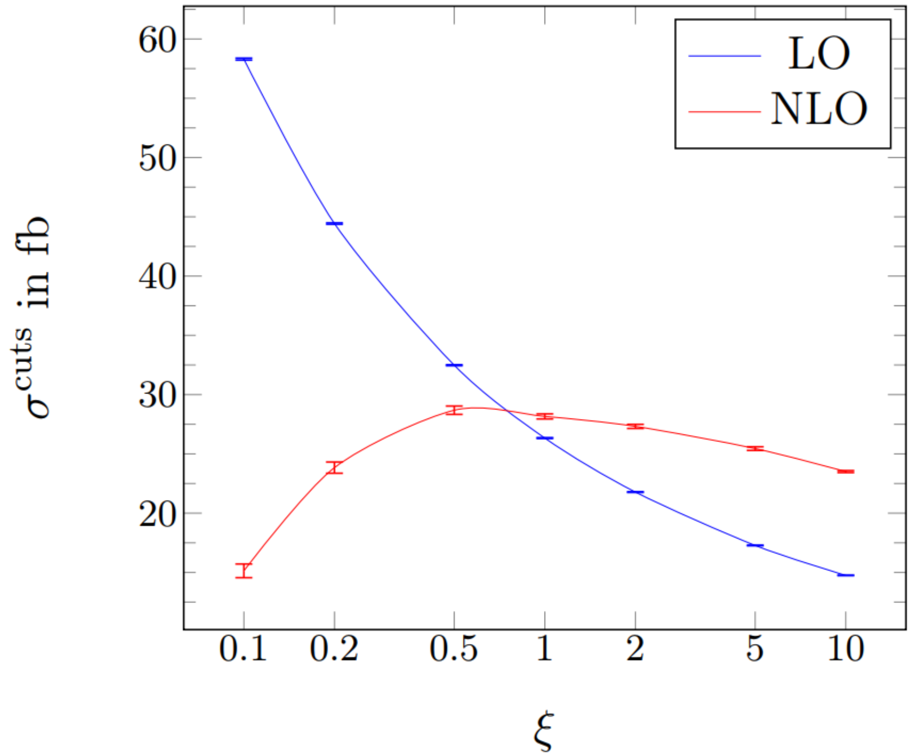
Extension of calculation to Vjjj production

- Thesis Amon Engemann:
  Zjjj at NLO QCD in VBF approximation
- Thesis Belinda Benz:
  extension to Wjjj production
- Future: NLO QCD corrections to VBS processes like WZjjj or same sign WWjjj production
- Interface with Herwig

Scale variation of (Z→ll)jjj cross section



(b) $\mu_F = \text{const.}, \mu_R = \xi\mu_0$

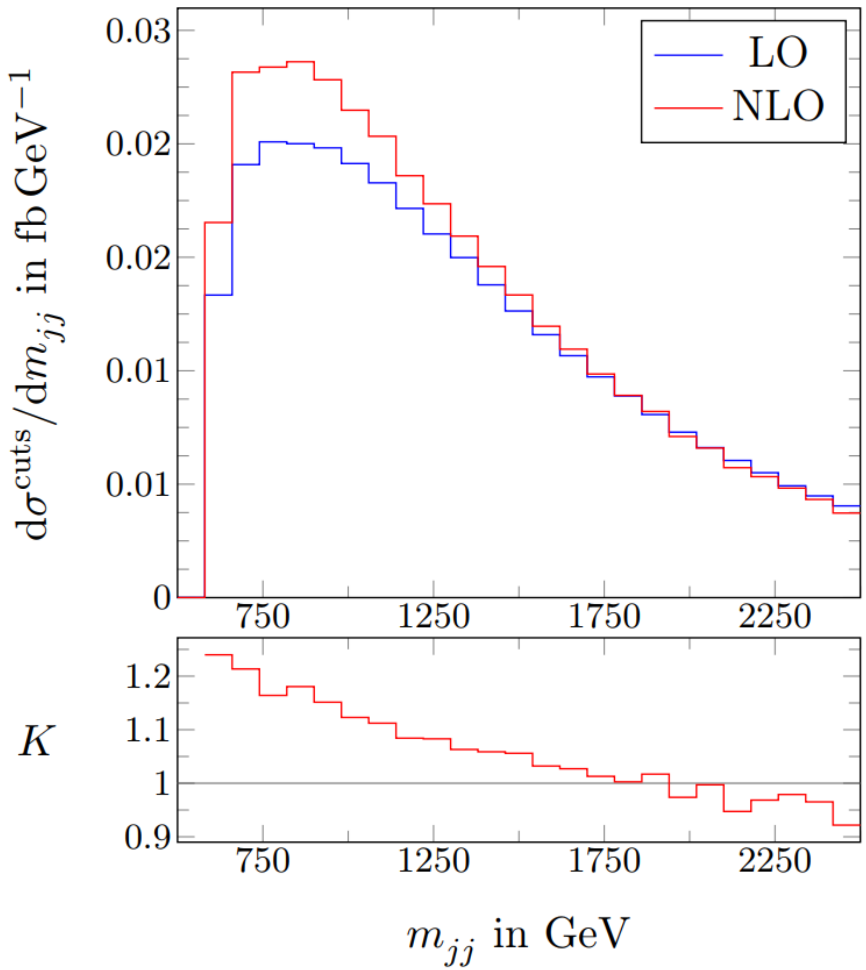


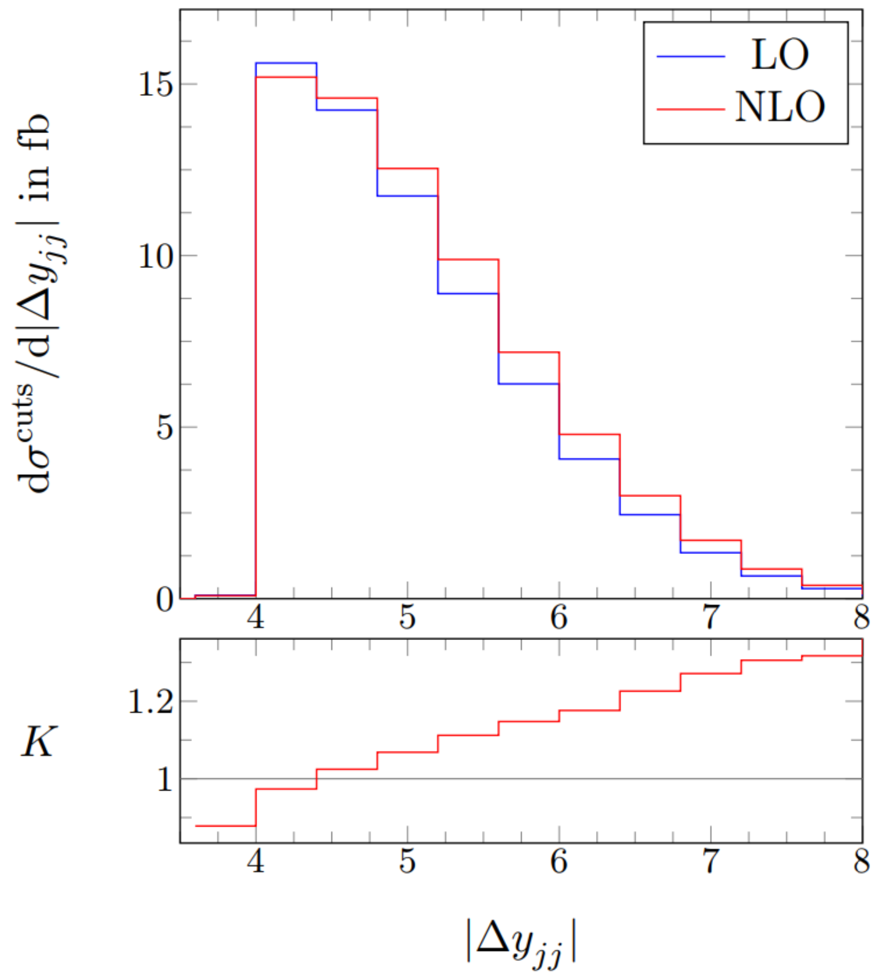
(c) $\mu_F = \mu_R = \xi\mu_0$

Reduced factorization and renormalization scale dependence at NLO QCD

Example shown for fixed scale μ_0 = 100 GeV

Effects on tagging jet pair

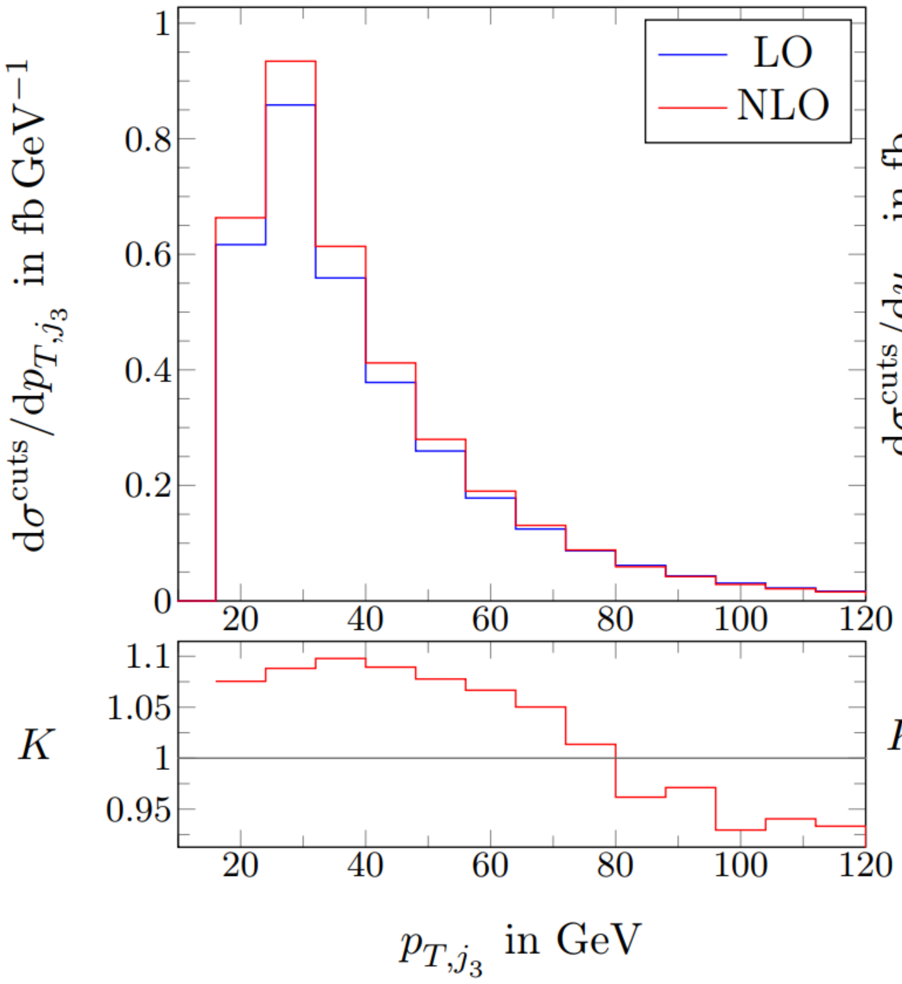


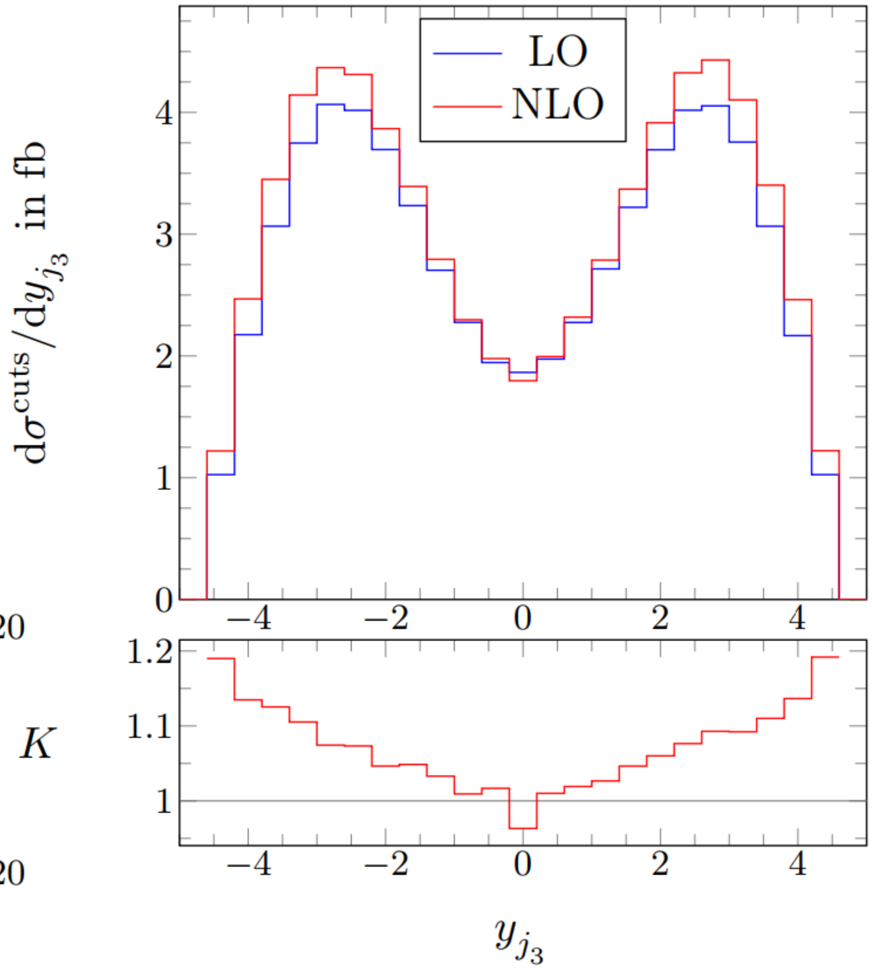


Invariant mass of pair

rapidity separation

Distributions of third jet





Conclusions

- VBF and VBS provide powerful tests of electroweak symmetry breaking
- Jet activity/hadronic activity beyond two leading tagging jets provides a potentially powerful handle on backgound suppression
- Goal is to develop CJV into a precision tool for studying VBF and VBS
- First steps are fast NLO QCD simulations for 3-jet final states: available for VBF production of Hjjj, Zjjj, in work for Wjjj production
- Small team in Karlsruhe (Belinda Benz, Heiko Schäfer-Siebert, DZ) will be joined by Tomas Jezo in fall and collaborates with Tilman Plehn, Simon Plätzer and Terrance Figy