

Anomalous couplings in WZ production beyond NLO QCD

Robin Roth | 14.06.2016

in collaboration with Francisco Campanario, Sebastian Sapeta, Dieter Zeppenfeld

LHCP 2016, LUND



Goal

- test the Standard Model (SM) at the LHC with the highest possible precision
- look for deviations from the SM in a model independent way

Methods

- more precise SM prediction, reduced theory error $\Rightarrow \bar{n}$ NLO
- parametrize beyond-SM effects \Rightarrow Anomalous Couplings (AC) / EFT
- improve analyses \Rightarrow better cuts and observables, dynamical jet veto

Tools

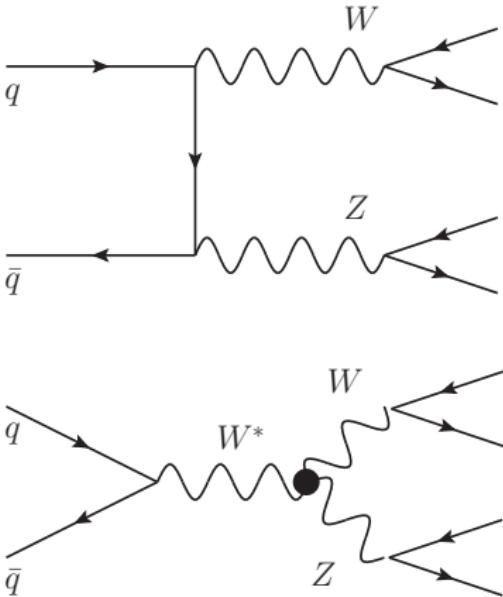
- VBFNLO: diboson production at NLO QCD with AC
- LoopSim: \bar{n} NLO based on VBFNLO input

Why Diboson

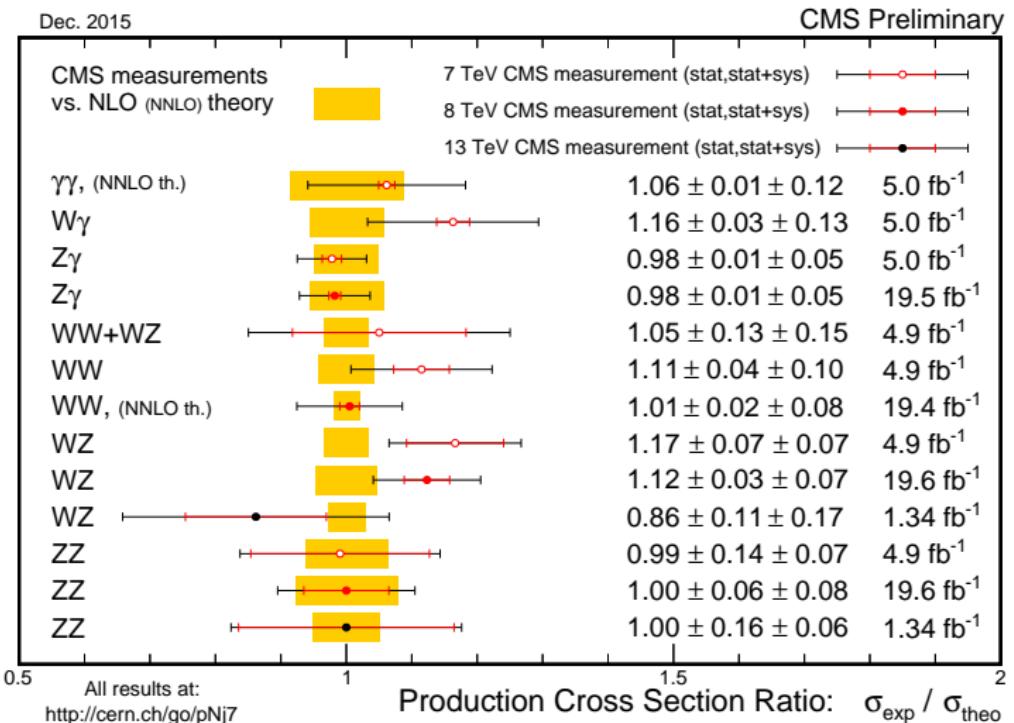
- leptonic decays: "easy" to tag, precise knowledge of final state
- access to triple gauge couplings, deviations in EW sector

Observables

- new resonances
- enhanced production at high energy
 \Rightarrow AC
- m_T, p_{TV}, p_{TI}
- decay angles, spin information



Current state of diboson production at the LHC



SM as Effective Field Theory

- only use SM fields and preserve symmetries
- add higher-dimensional terms to Lagrangian $\mathcal{L} = \mathcal{L}_{\text{SM}} + \sum_i \frac{f_i}{\Lambda^2} \mathcal{O}_i$
- contributions to WWZ vertex at dim 6 from 3 operators:
 $\mathcal{O}_W = (D_\mu \Phi)^\dagger \hat{W}^{\mu\nu} (D_\nu \Phi)$, $\mathcal{O}_{WWW} = \text{Tr} [\hat{W}_{\mu\nu} \hat{W}^{\nu\rho} \hat{W}_\rho^\mu]$,
 $\mathcal{O}_B = (D_\mu \Phi)^\dagger \hat{B}^{\mu\nu} (D_\nu \Phi)$

Relation to κ Framework

- To first order: $\Delta \kappa_\gamma = \frac{M_W^2}{2\Lambda^2} (f_B + f_W)$, $\Delta g_1^Z = \frac{M_Z^2}{2\Lambda^2} f_W, \dots$
- EFT inherently gauge invariant, works consistently beyond LO

Limited Validity of EFT

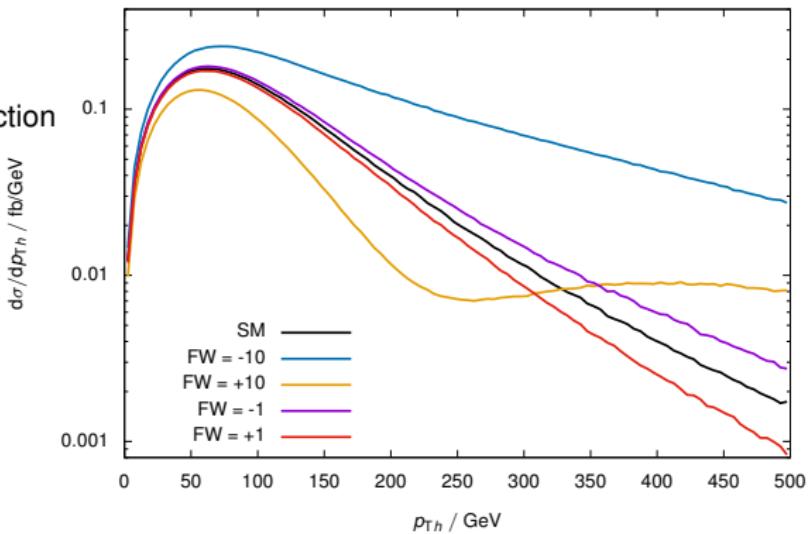
- low-energy expansion of unknown higher-energy model
- only valid if expansion parameter small
validity depends on phase space region/kinematics

Anomalous Couplings

Example operator: $\mathcal{O}_W = (D_\mu \Phi)^\dagger \hat{W}^{\mu\nu} (D_\nu \Phi)$, $\mathcal{L} = \mathcal{L}_{SM} + \frac{f_W}{\Lambda^2} \mathcal{O}_W + \dots$

WWH vertex: $\underbrace{igm_W g^{\mu\nu}}_{SM} - \underbrace{\frac{1}{2} i \frac{f_W}{\Lambda^2} gm_W \left(-g^{\mu\nu} (p_h \cdot p_- + p_h \cdot p_+) + p_h^\nu p_-^\mu + p_h^\mu p_+^\nu \right)}_{\mathcal{O}_W}$

WH production
 $\Lambda = 1 \text{ TeV}$

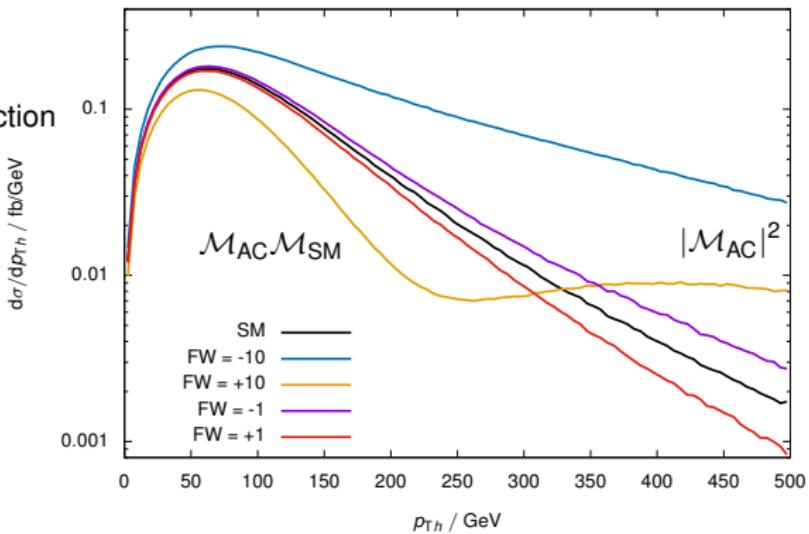


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Idea

- “Giant QCD K-factors beyond NLO”
[\[Rubin, Salam, Sapeta, 1006.2144\]](#)
- merge different multiplicity final states
 $X@\text{NLO} + Xj@\text{NLO} = X@\bar{n}\text{NLO}$
- parton level
- use NLO events, interface to existing Monte Carlos programs

2	$\sigma_0^{(2)}$	$\sigma_1^{(2)}$	\dots		
1	$\sigma_0^{(1)}$	$\sigma_1^{(1)}$	$\sigma_2^{(1)}$	\dots	
0	$\sigma_0^{(0)}$	$\sigma_1^{(0)}$	$\sigma_2^{(0)}$	$\sigma_3^{(0)}$	\dots
	0	1	2	3	\dots

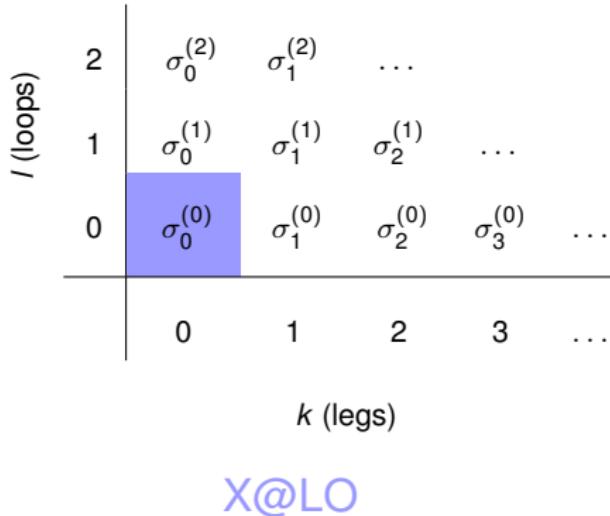
k (legs)

Properties

- misses finite 2-loop contributions
- include dominant contributions from extra emissions, $\mathcal{O}(\alpha_s \ln^2 p_{T\text{jet}} / m_Z)$
- preserve NLO total cross section
- nearly NNLO in high- p_T tails

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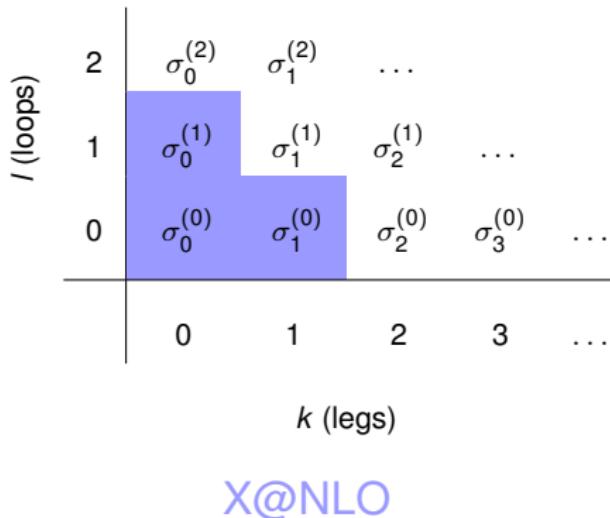


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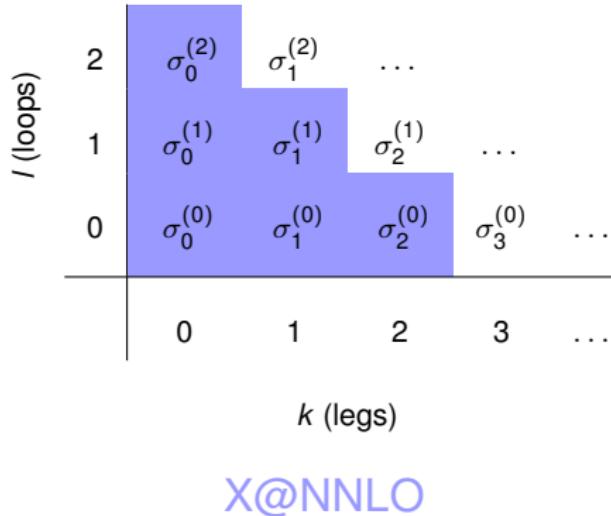


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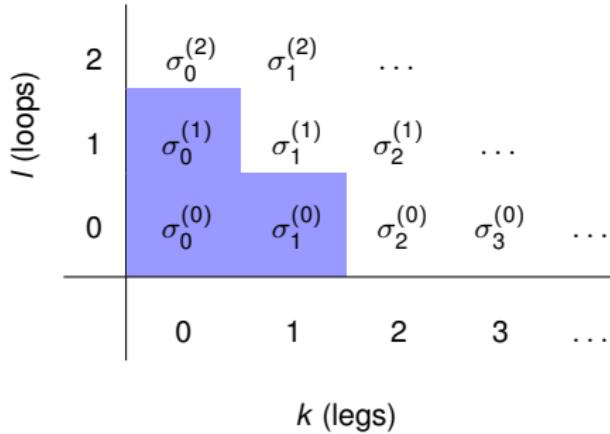


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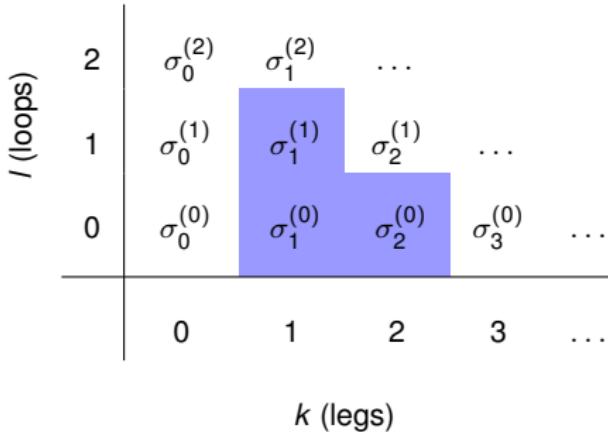
X@NLO

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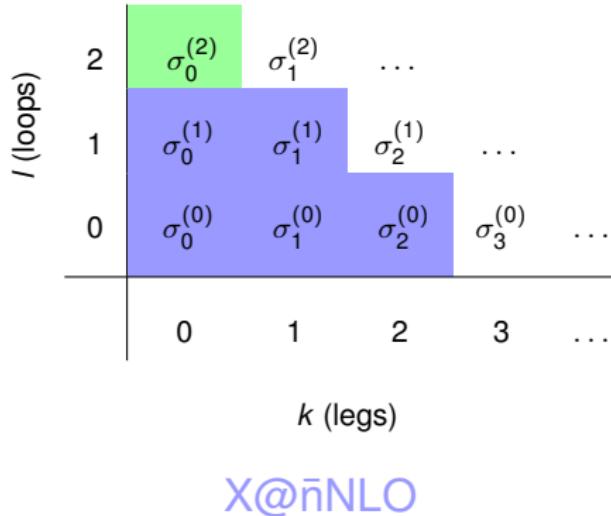
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X+jet@NLO

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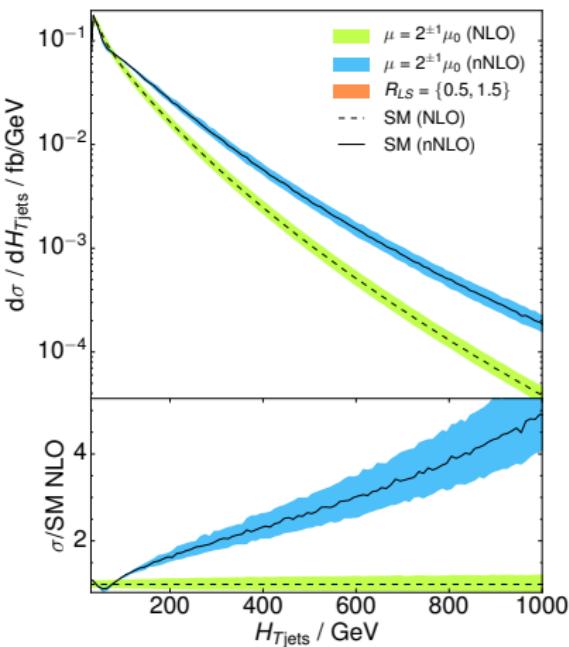
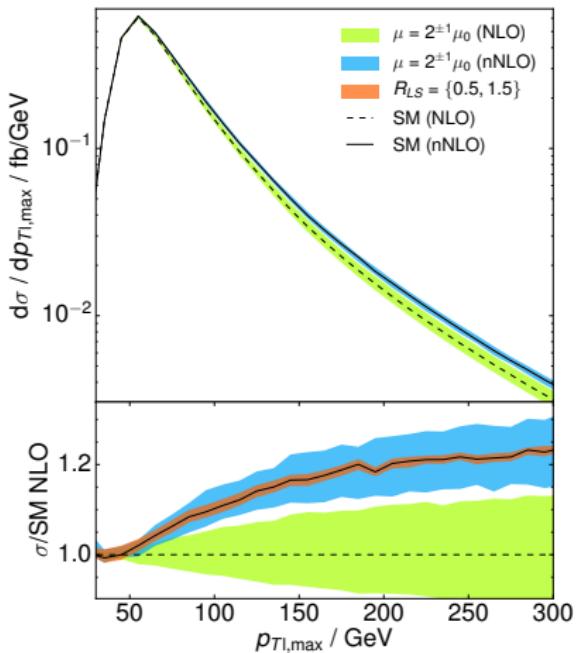


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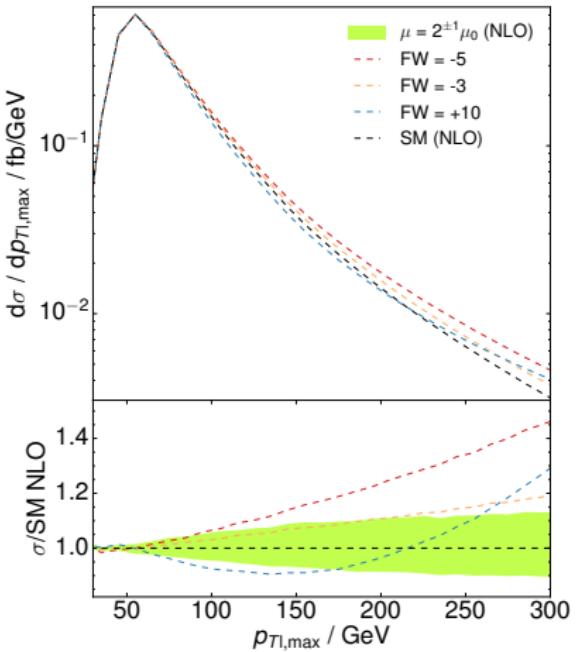
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\bar{n} NLO for WZ production

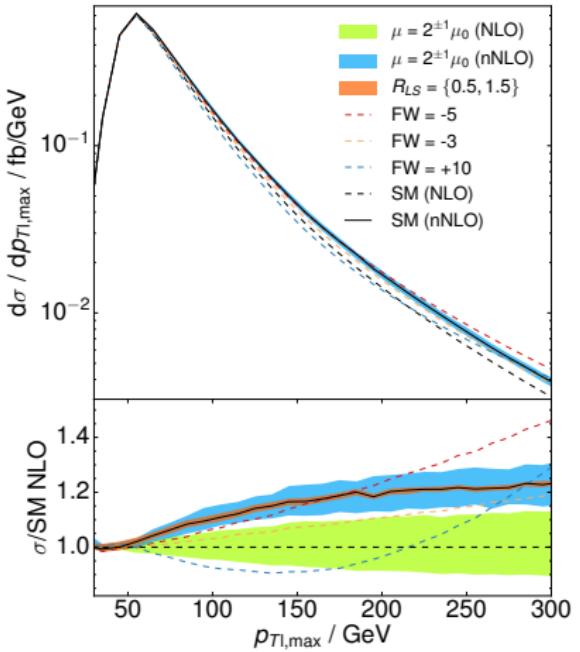
LHC, 13 TeV, inclusive cuts



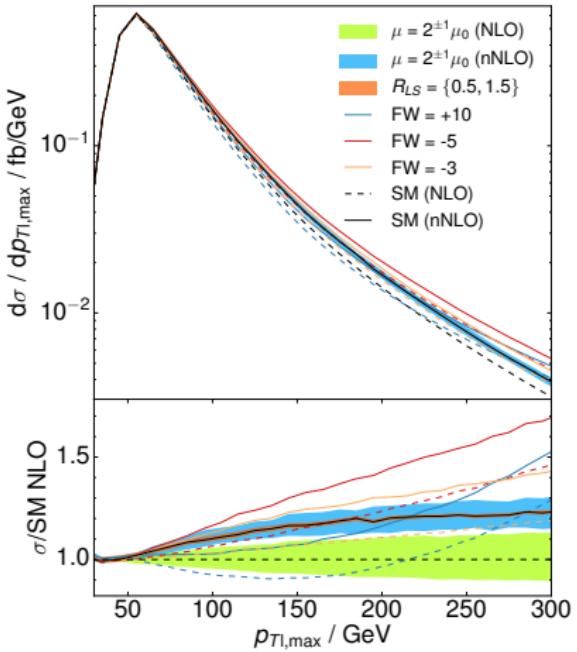
AC for diboson production



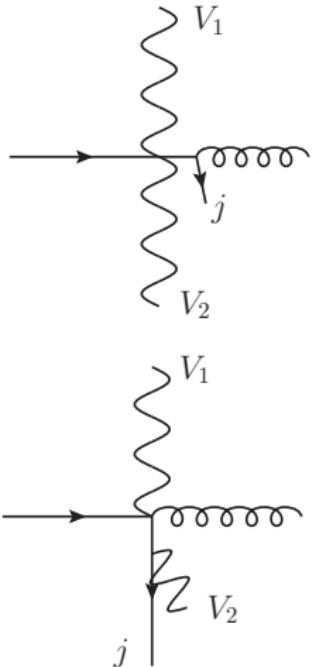
AC for diboson production



AC for diboson production



want $VV + \text{jets}$, not $Vj + V$



Traditional (fixed) jet veto

- don't allow any jets above a fixed p_T threshold
- introduces large logs $\log p_{T\text{veto}}/m_{VV}$
- cuts away relevant phase space:
 $m_{VV} \approx 1 \text{ TeV} \leftrightarrow p_{T\text{jet}} = 50/300 \text{ GeV}$

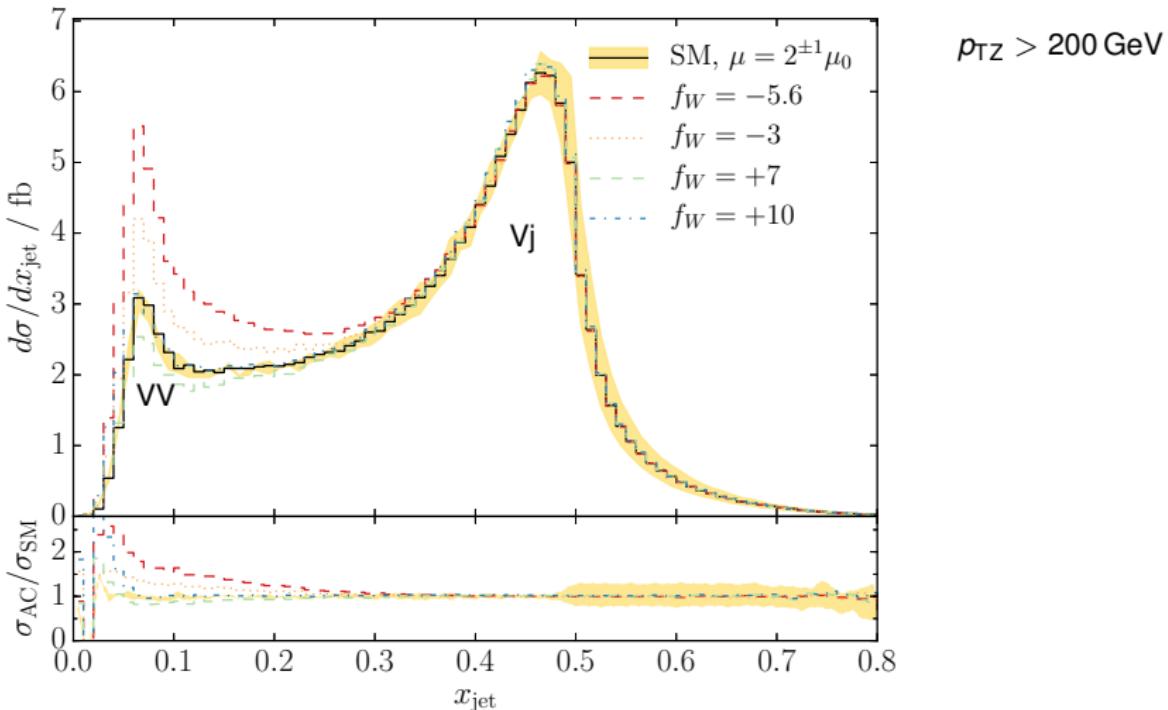
Dynamical veto

- veto scaled depending on overall scale \Rightarrow smaller logs
- allow more QCD radiation in tails of EW distributions

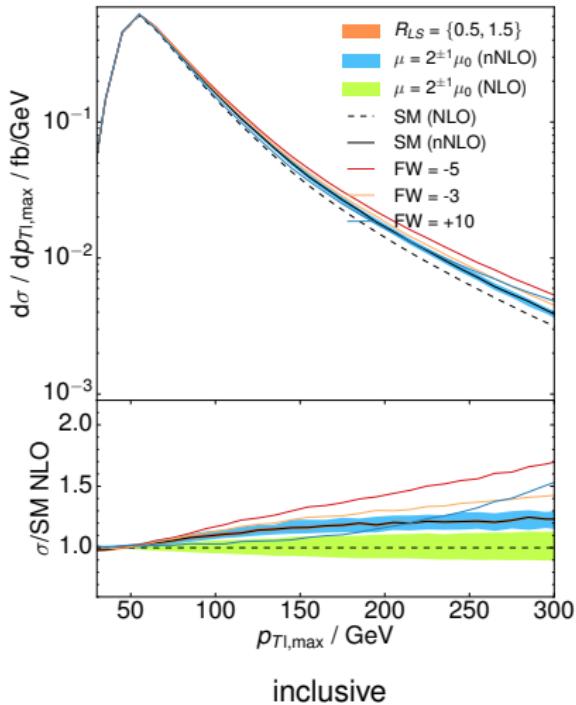
$$x_{\text{jet}} = \frac{\sum_{\text{jets}} E_{T,i}}{\sum_{\text{jets}} E_{T,i} + E_{T,W} + E_{T,Z}}$$

[Campanario, RR, Zeppenfeld, 1410.4840]

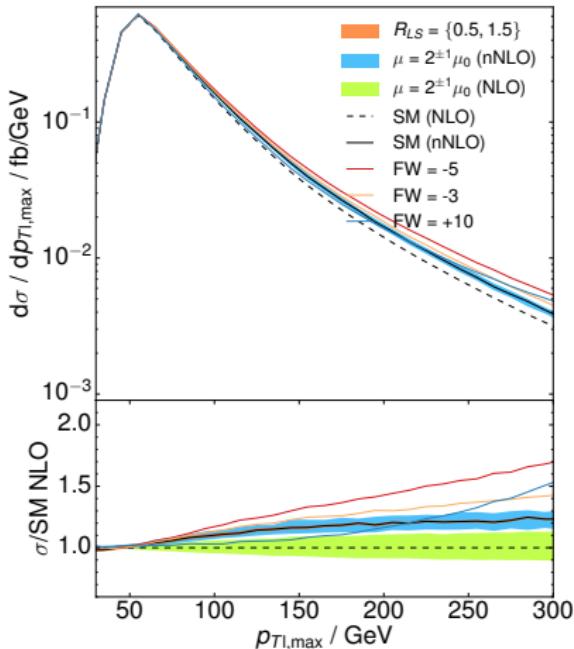
$$\textbf{Observable } x_{\text{jet}} = \frac{\sum_{\text{jets}} E_{\text{T},i}}{\sum_{\text{jets}} E_{\text{T},i} + E_{\text{T},W} + E_{\text{T},Z}}$$



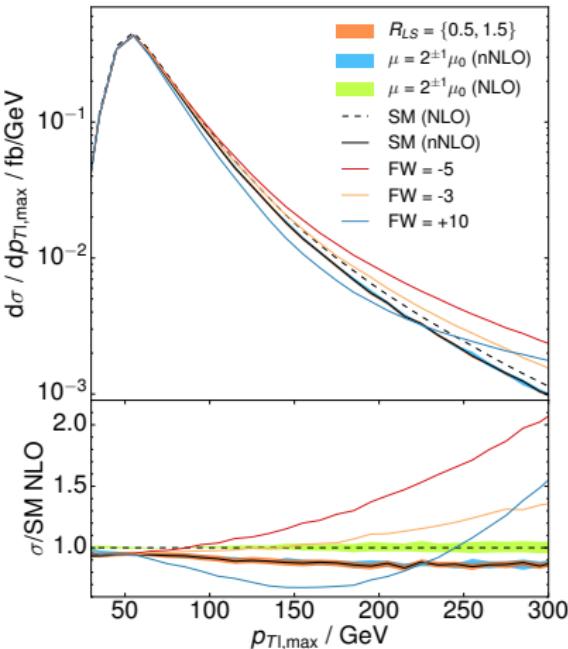
Dynamical veto to improve AC sensitivity



Dynamical veto to improve AC sensitivity



inclusive



$x_{\text{jet}} < 0.2$

Beyond NLO: Loopsim

- method to combine multiplicities consistently at parton level
 $X@\text{NLO} + Xj@\text{NLO} = X@\bar{n}\text{NLO}$
- captures log enhanced terms of real emission
- nearly NNLO in high- p_T region

Anomalous couplings

- diboson production interesting channel to study triple gauge couplings
- validity depends on coupling and phase space region
- increase sensitive \Rightarrow dynamical jet veto

$$x_{\text{jet}} = \frac{\sum_{\text{jets}} E_{T,i}}{\sum_{\text{jets}} E_{T,i} + E_{T,W} + E_{T,Z}}$$

VBFNLO: <https://www.itp.kit.edu/vbfnlo> [0811.4559, 1107.4038, 1404.3940]

VBFNLO [0811.4559, 1107.4038, 1404.3940]

K. Arnold, J. Baglio, J. Bellm, G. Bozzi, M. Brieg, F. Campanario, C. Englert, B. Feigl, J. Frank, T. Figy, F. Geyer, N. Greiner, C. Hackstein, V. Hankele, B. Jäger, N. Kaiser, M. Kerner, G. Klämke, M. Kubocz, M. Löschner, L.D. Ninh, C. Oleari, S. Palmer, S. Plätzer, S. Prestel, M. Rauch, R. Roth, H. Rzehak, F. Schissler, O. Schlimpert, M. Spannowsky, M. Worek, D. Zeppenfeld

- Monte Carlo program for hadron collider cross sections at NLO QCD
- focus on processes with EW bosons: VBF, VV, VVV (+jets)
- includes leptonic decay of vector bosons with full off-shell effects
- anomalous triple/quartic gauge couplings
- efficient by reusing electroweak part of diagrams in terms of leptonic tensors
- BLHA interface to event generators: NLO event output

EFT assumptions

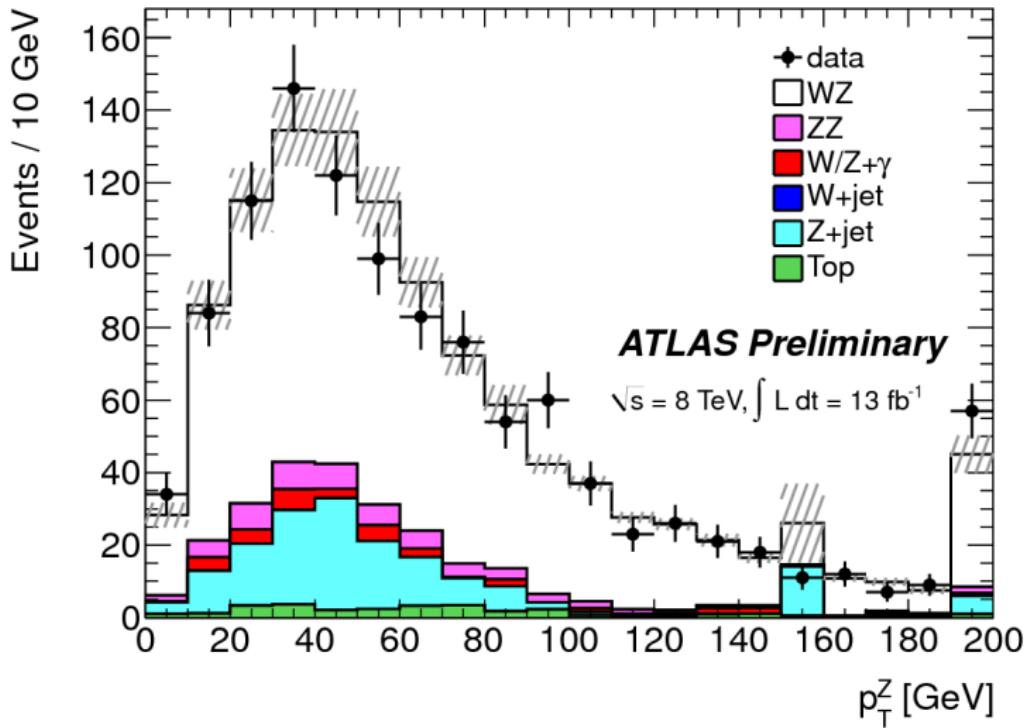
- all NP scales well above observables, no resonances at measurable scales
- f/Λ^2 "small", depends on coupling: $\mathcal{O}(1)$ or $\mathcal{O}(\alpha_{\text{QED}})$

Power counting in Λ

$$\mathcal{M} = \mathcal{M}_{\text{SM}} + \underbrace{\mathcal{M}_{\text{AC}}^{d=6}}_{1/\Lambda^2} + \underbrace{\mathcal{M}_{\text{AC}}^{d=8}}_{1/\Lambda^4}$$

$$|\mathcal{M}|^2 = \underbrace{|\mathcal{M}_{\text{SM}}|^2}_{1/\Lambda^0} + \underbrace{2\text{Re}\mathcal{M}_{\text{SM}}^*\mathcal{M}_{\text{AC}}^{d=6}}_{1/\Lambda^2} + \underbrace{\left|\mathcal{M}_{\text{AC}}^{d=6}\right|^2}_{1/\Lambda^4} + \underbrace{2\text{Re}\mathcal{M}_{\text{SM}}^*\mathcal{M}_{\text{AC}}^{d=8}}_{1/\Lambda^4} + \underbrace{\left|\mathcal{M}_{\text{AC}}^{d=8}\right|^2}_{1/\Lambda^8}$$

- power-counting Λ^{-4} : $|\mathcal{M}_{\text{AC}}^{d=6}|^2$, $\mathcal{M}_{\text{SM}}^*\mathcal{M}_{\text{AC}}^{d=8}$?
- conservative: experimental fit only in range where $|\mathcal{M}_{\text{AC}}|^2 \ll \mathcal{M}_{\text{SM}}^*\mathcal{M}_{\text{SM}}$
- but: \mathcal{M}_{SM} accidentally small (phase space, weak coupling compared to \mathcal{M}_{AC})
 $\Rightarrow \mathcal{M}_{\text{SM}}^*\mathcal{M}_{\text{AC}}$ suppressed, $|\mathcal{M}_{\text{AC}}^{d=6}|^2$ leading $1/\Lambda^4$ term



Cuts

$$p_{\mathrm{T}j} > 30 \text{ GeV}$$

$$p_{\mathrm{T}I} > 15 \text{ GeV}$$

$$\not{p}_{\mathrm{T}} > 30 \text{ GeV}$$

$$|\eta_j| < 4.5$$

$$|\eta_I| < 2.5$$

$$R_{I,j} > 0.4$$

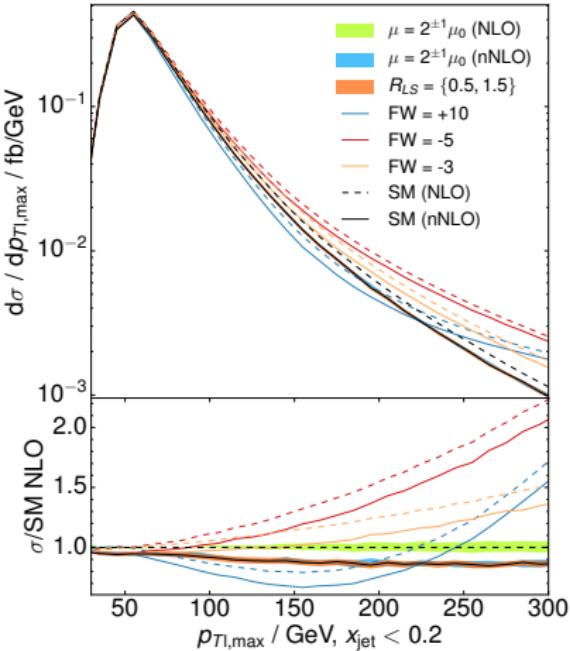
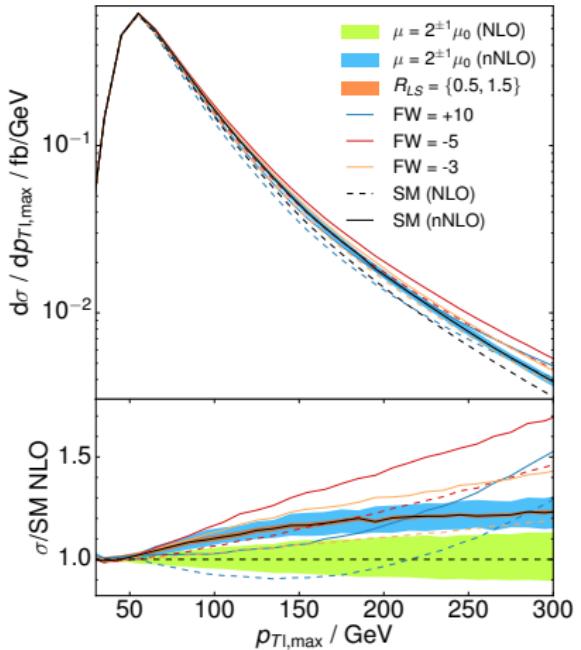
$$60 \text{ GeV} < m_{\parallel} < 120 \text{ GeV}$$

boosted: $p_{\mathrm{T}Z} > 200 \text{ GeV}$

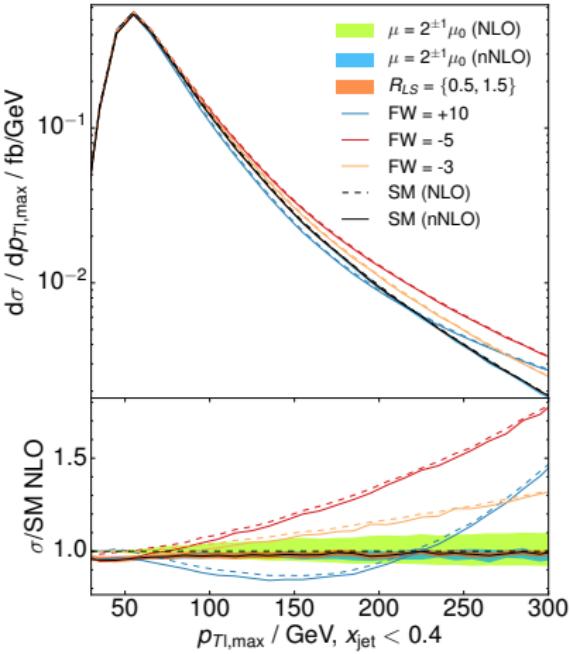
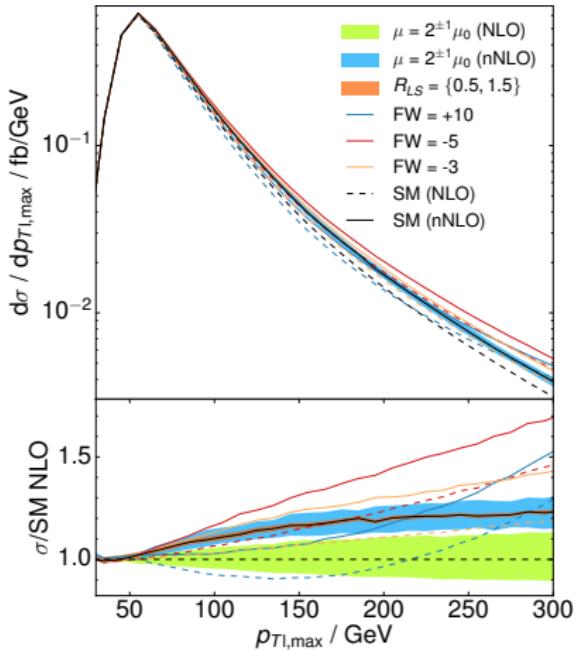
Input values

- EW constants: VBFNLO default
- PDF: NNPDF23

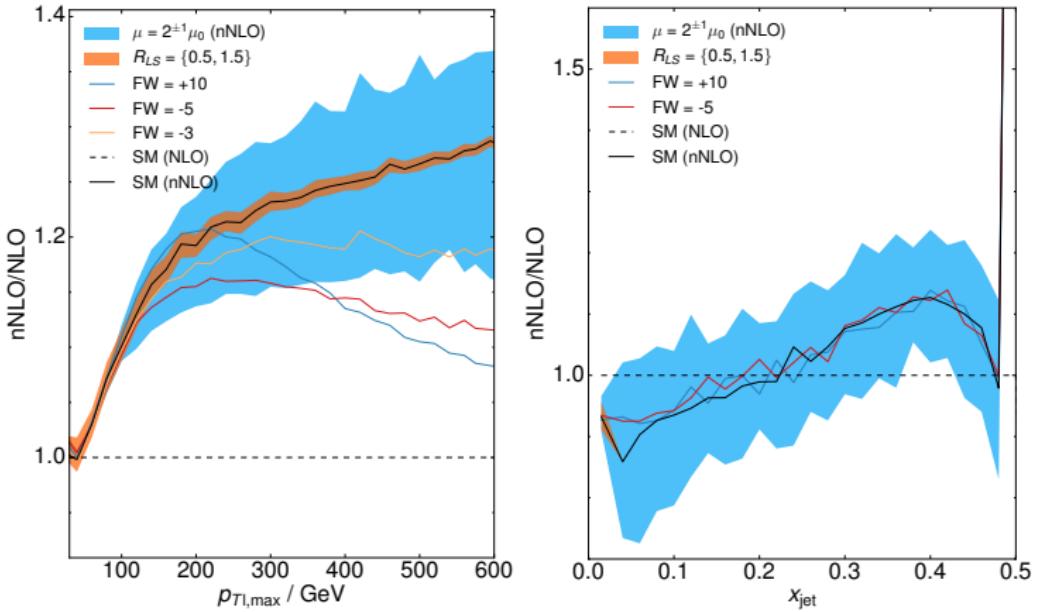
Different x_{jet} cuts



Different x_{jet} cuts



x_{jet} nNLO corrections



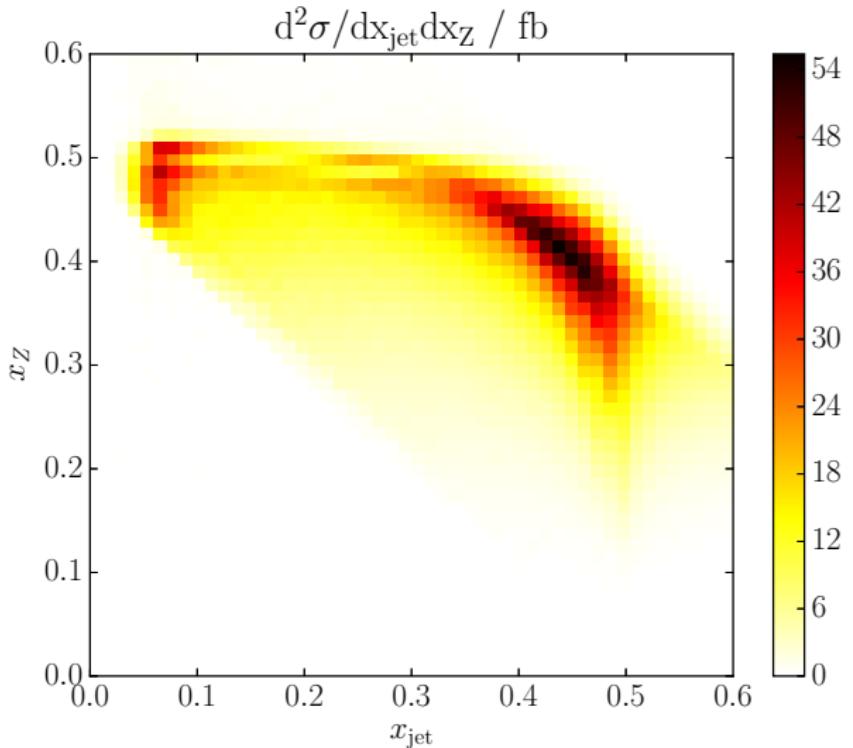
Motivation

- 3 particle final state (WZ)
- the transverse momenta can be parametrized using only two variables
6 d.o.f. ($p_{T,W}$, $p_{T,Z}$, $p_{T,\text{jet}}$) - 2 (total $p_T = 0$) - 1 (no ϕ dependence) - 1 (rescaling at high p_T)
- dalitz-like construction

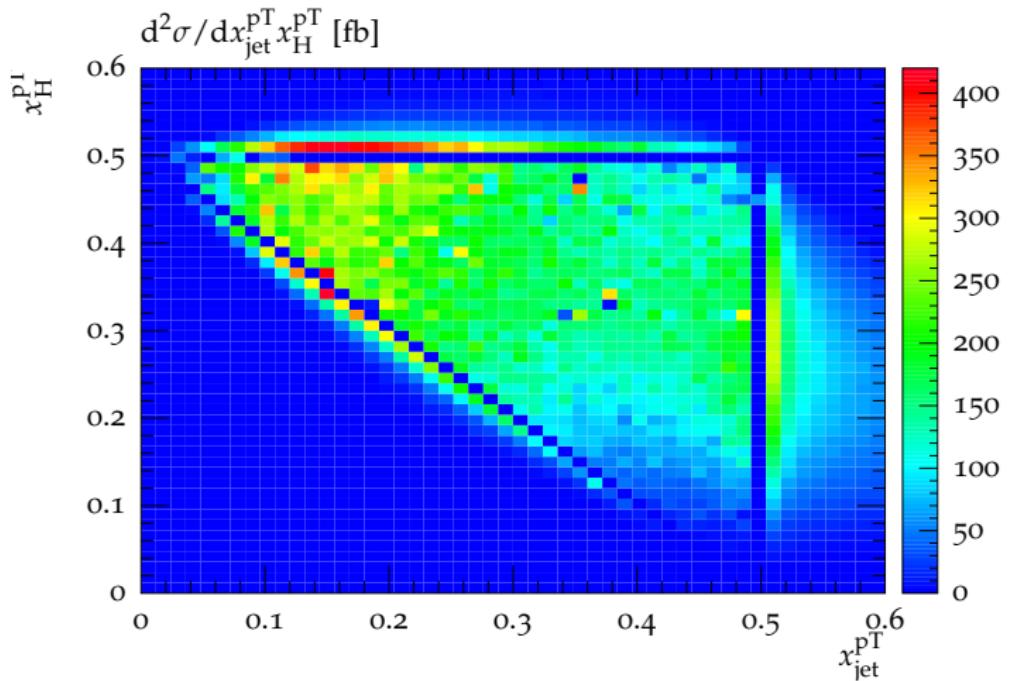
$$x_{\text{jet}} = \frac{\sum_{\text{jets}} E_{T,i}}{\sum_{\text{jets}} E_{T,i} + E_{T,W} + E_{T,Z}}, \quad x_V = \frac{E_{TV}}{\sum_{\text{jets}} E_{T,i} + E_{T,W} + E_{T,Z}}$$
$$x_{\text{jet}} + x_W + x_Z = 1$$
$$x_i \leq 0.5 \quad (\text{at LO only})$$

other choices: p_T instead of E_T , partons instead of jets, ...
Careful not to be (too) infrared-sensitive

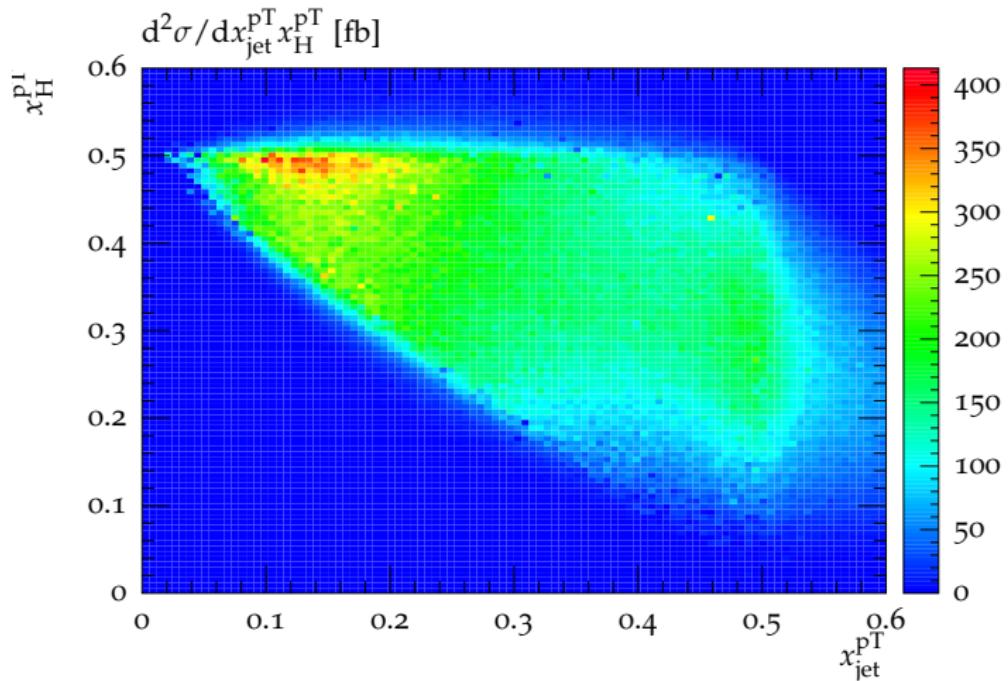
Observable: x_{jet}, x_Z



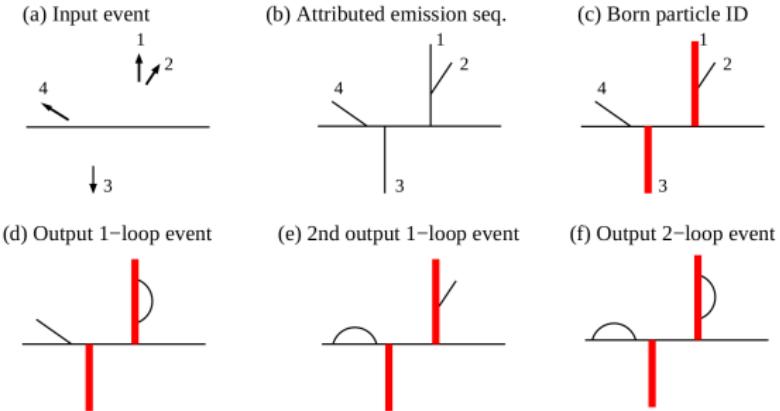
PS effects on x_{jet}



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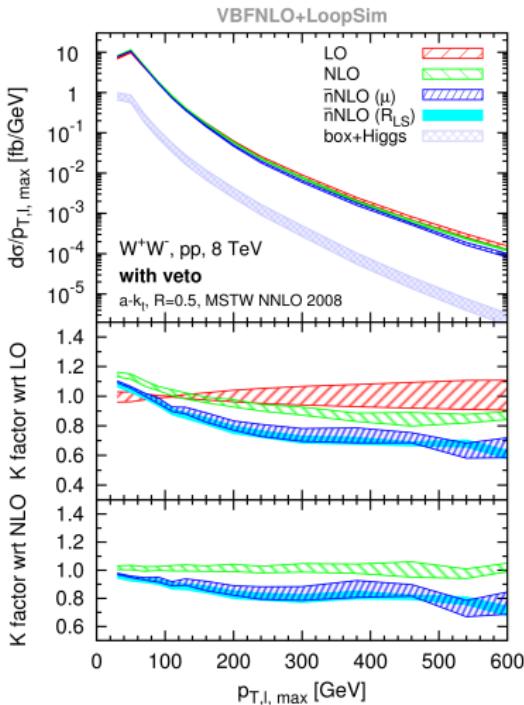
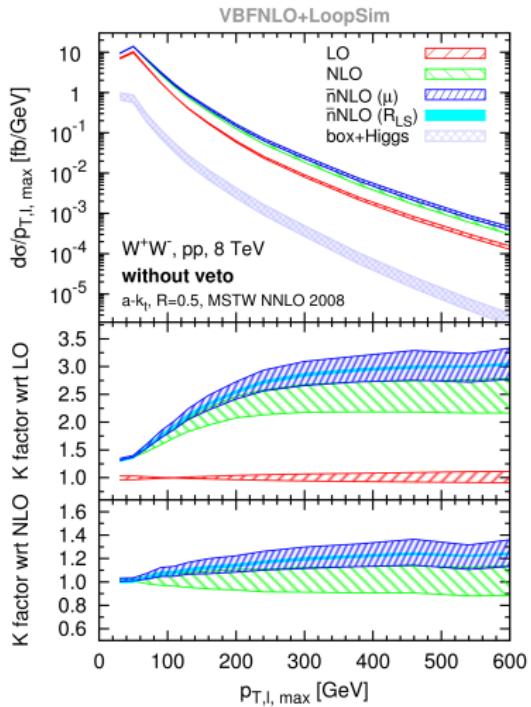


The LoopSim Method – “Looping”



- cluster by distance to get emission sequence (C/A algorithm)
- captures soft/collinear divergences
- subtract divergences by generating looped diagrams with negative weight
- Catani-Seymour like generation of looped kinematics
- Clustering radius R_{LS} gives estimate of dependence on merging
- Scale dependence preserved for additional emissions, overestimates the NNLO scale dependence

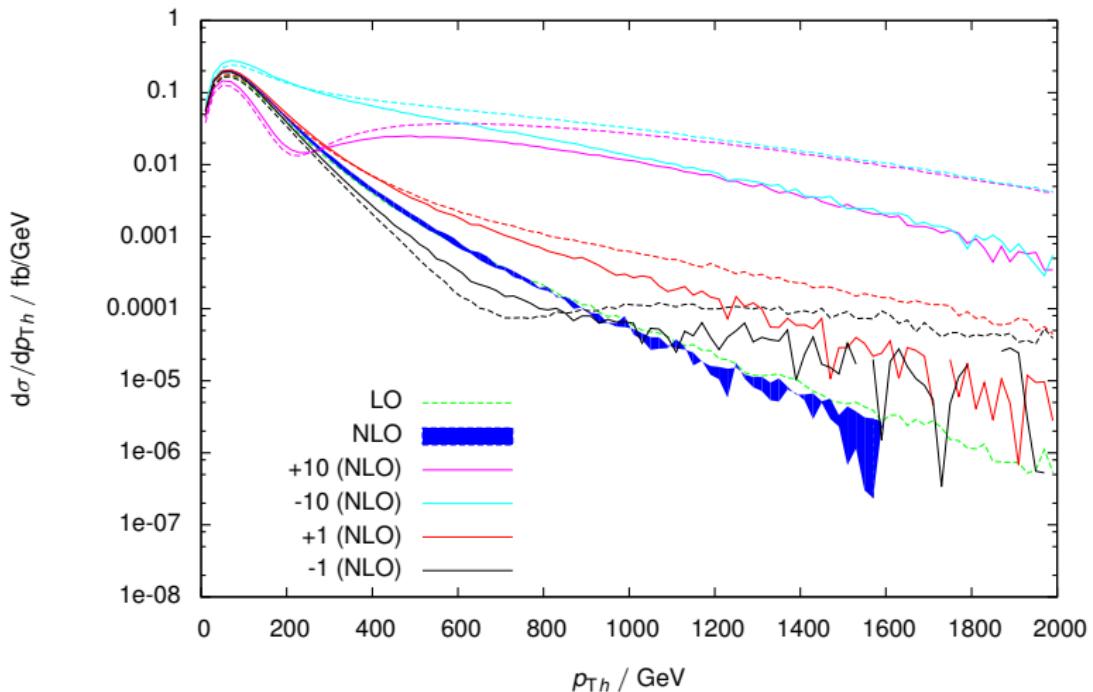
Previous LoopSim results



[Campanario, Rauch, Sapeta, 1309.7293]

Anomalous Couplings

WWh with inclusive cuts and several values of f_W/Λ^2 in TeV^{-2} and no form factor



Anomalous Couplings

with form factor $\left(\frac{\Lambda^2}{\Lambda^2 + m_{WH}^2}\right)^2$, $\Lambda = 2 \text{ TeV}$

