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Anomalous Couplings in WZ production at $\bar{n}$NLO QCD

Robin Roth | 18.06.2015

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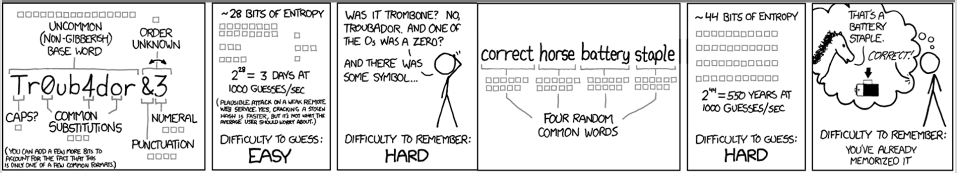

Overview

1. Introduction & Reminder
2. Anomalous Couplings and Additional QCD radiation
   - Motivation
   - Observable: x_{jet}, x_Z
   - R_{ll}
3. LoopSim: n̄NLO QCD
   - The LoopSim Method
   - Preliminary Results of WZ with Anomalous Couplings
4. Technical Issues
   - Statistics
   - Bin Smearing
5. Outlook

Introduction

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Goal

- Test the Standard Model (SM) at the LHC with the highest possible precision
- Look for deviations from the SM in a structured way

Methods

- Improve SM prediction, reduce theory error ($\Rightarrow$ n̄NLO)
- Provide framework to parametrize beyond-SM effects ($\Rightarrow$ AC)
- Help to improve analyses ($\Rightarrow$ better cuts and observables)

Tools

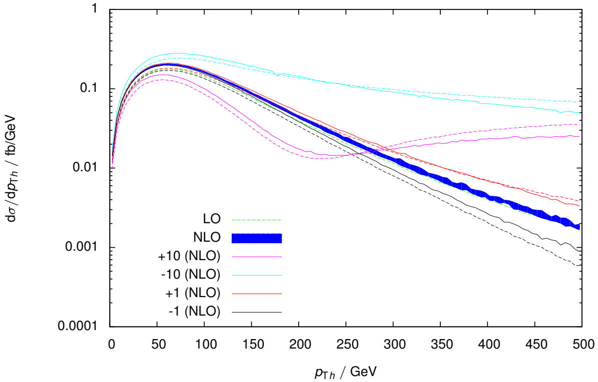
- `VBFNLO`: AC for Diboson Production at NLO QCD
- LoopSim: n̄NLO based on `VBFNLO` input

Anomalous Couplings

- bottom-up Effective Field Theory, constructed from SM fields/symmetries
- add higher-dimension terms to Lagrangian
- allows to parametrize deviations from SM, e.g. in triple/quartic gauge couplings

Example operator: $\mathcal{O}_W = (D_\mu \Phi)^\dagger \hat{W}^{\mu\nu} (D_\nu \Phi), \quad \mathcal{L} = \mathcal{L}_{SM} + \frac{f_W}{\Lambda^2} \mathcal{O}_W + \frac{f_k}{\Lambda^4} \dots$

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



Validity of EFT approach

Assumptions

- New Physics at a high mass scale
- well-behaved couplings (small)

Then EFT provides: most general extension of the SM

Problems

- Conventions/Basis
- Power counting (Λ, p^2)
- Mixing of operators (need complete basis)
- Interplay of different powers:

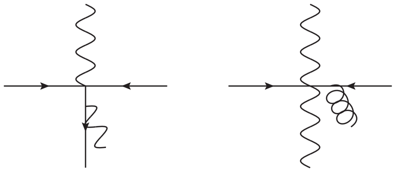
$$\mathcal{M} = \mathcal{M}_{\text{SM}} + \mathcal{M}_{\text{AC}}$$

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

- Include dimension 8? Theory error: $\mathcal{M}_{\text{AC}}^2$?
- Experimental fit only in range where $\mathcal{M}_{\text{AC}}^2 \ll \mathcal{M}_{\text{AC}}\mathcal{M}_{\text{SM}}$

Motivation: Additional Jets in Diboson Production

- [Campanario, RR, Zeppenfeld, arXiv:1410.4840]
- VV production at high p_{T} is mostly Vj with a second soft vector boson
- Anomalous Couplings scale with $s = m_{VV}$
  $\Rightarrow$ focus on phase space with high m_{VV}, little energy in jets
- traditional fixed jet veto brings terms $\log \frac{p_{\mathrm{T\,veto}}}{m_{VV}}$



Observable: x_{jet}, x_Z

Motivation

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

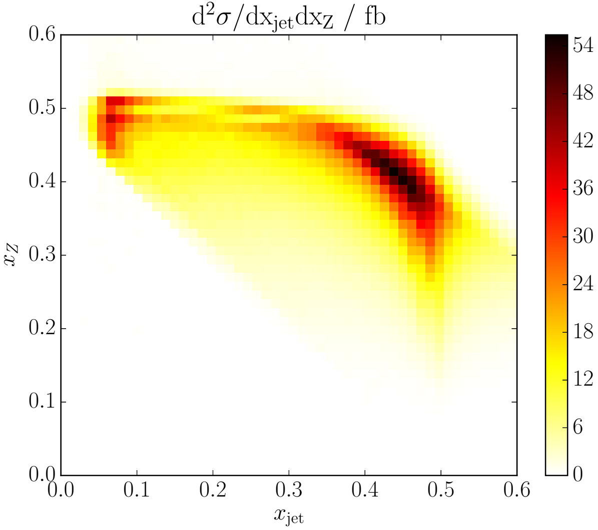
$$x_{\text{jet}} = \frac{\sum_{\text{jets}} \mathrm{E}_{\mathrm{T},i}}{\sum_{\text{jets}} \mathrm{E}_{\mathrm{T},i} + \sum_{W,Z} \mathrm{E}_{\mathrm{T},i}}, \quad x_V = \frac{E_{TV}}{\sum_{\text{jets}} \mathrm{E}_{\mathrm{T},i} + \sum_{W,Z} \mathrm{E}_{\mathrm{T},i}}$$

$$x_{\text{jet}} + x_W + x_Z = 1$$

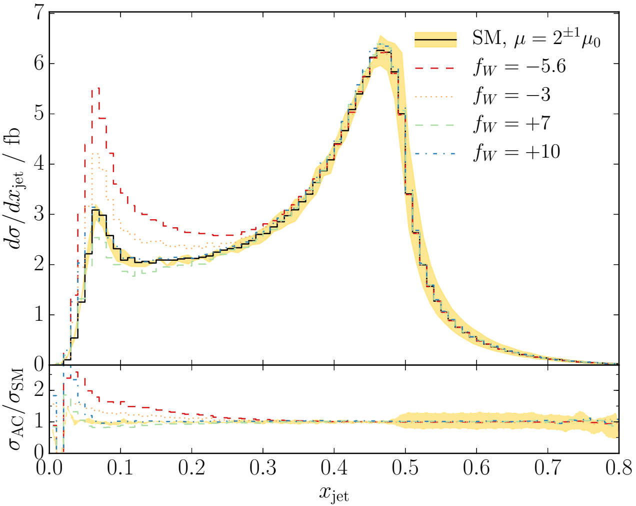
$$x_i \leq 0.5 \quad \text{(at LO only)}$$

other choices: p_T instead of E_T, partons instead of jets, . . .

Observable: x_{jet}, x_{Z}



Observable: x_{jet}, x_Z



The R_{ll} cut and Anomalous Couplings

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- R_{ll}: $\Delta R^2 = \Delta\phi^2 + \Delta\eta^2$, separation of leptons

$$\vec{p} = \begin{pmatrix} p_\mathrm{T}\cos\phi \\ p_\mathrm{T}\sin\phi \\ p_\mathrm{T}\sinh\eta \end{pmatrix}, \quad |\vec{p}| = p_\mathrm{T}\cosh\eta$$

Relation to invariant mass of two particles to R_{ll}

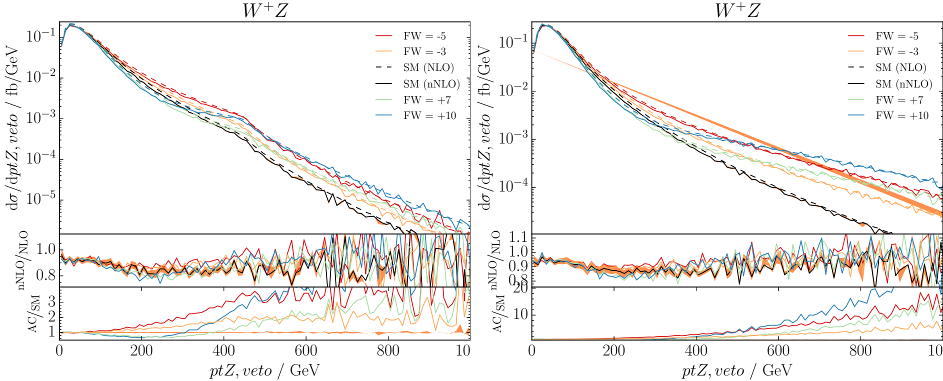
- Assumption: massless/relativistic products of boosted massive particle

$$\begin{aligned} m^2 &= 2p_1 \cdot p_2 = 2\left(E_1 E_2 - \vec{p}_1 \cdot \vec{p}_2\right) = \\ &= 2\left(p_{\mathrm{T}1}p_{\mathrm{T}2}\cosh\eta_1\cosh\eta_2 - p_{\mathrm{T}1}p_{\mathrm{T}2}\left(\cos\phi_1\cos\phi_2 + \sin\phi_1\sin\phi_2 + \sinh\eta_1\sinh\eta_2\right)\right) \\ &= 2p_{\mathrm{T}1}p_{\mathrm{T}2}\left(\cosh(\eta_1 - \eta_2) - \cos(\phi_1 - \phi_2)\right) \\ &\approx 2\frac{pt_Z}{2}\frac{pt_Z}{2}\left(1 + \frac{1}{2}\Delta\eta^2 - 1 + \frac{1}{2}\Delta\phi^2\right) = \boxed{\frac{1}{4}pt_Z^2\Delta R^2} \end{aligned}$$

for M_Z and $R_{ll} = 0.4$: $pt_Z = 450\,\mathrm{GeV}$

Sensitive on Decay angle and thus Z polarization!

R_{ll} and Anomalous Couplings



The LoopSim Method

Goal

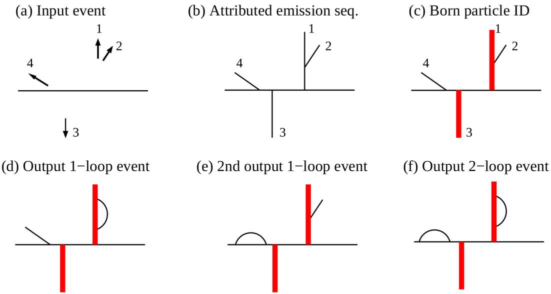
- Merge different multiplicity final state
- include dominant contributions from extra emissions, possibly log enhanced
- Work on parton level, no shower needed
- preserve NLO total cross section
- use NLO events, interface to existing Monte Carlos programs

X@nNLO

- X@NLO
- Xj@NLO
- loop Xj@NLO and remove double counting
- missing: finite

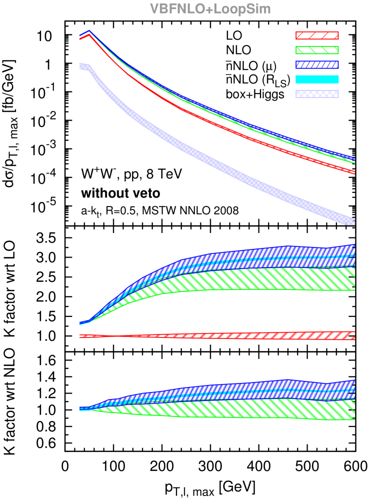
- Inspired by CKKW matching
- [Rubin, Salam, Sapeta arXiv:1006.2144]

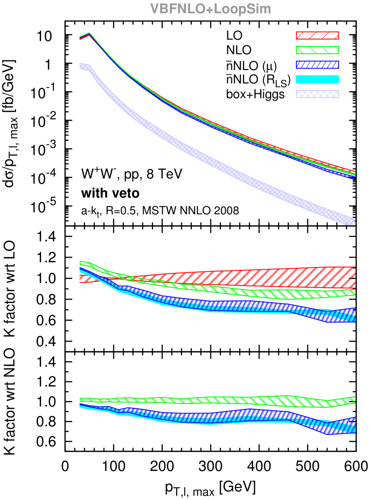
The LoopSim Method



- 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, arXiv:1309.7293]

LoopSim with VBFNLO

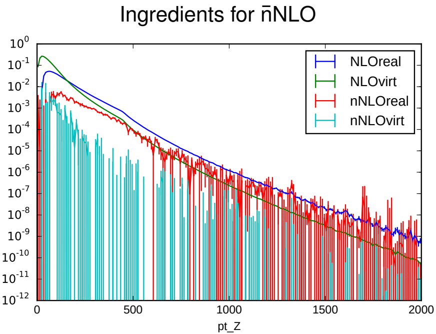
Interfacing with LoopSim

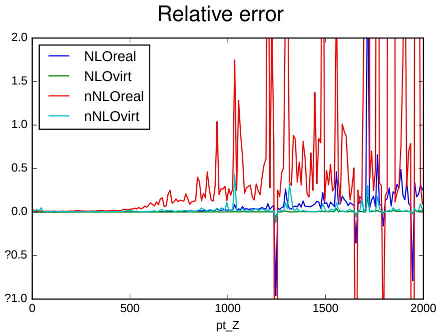
- VBFNLO produces event sample
- LoopSim generates looped events from sample
- run analysis on those final events

Issues

- no flavour information from VBFNLO (summed over)
- need very inclusive sample (no jet cut) to fill all of phase space
- Consistent scale choice over all samples needed

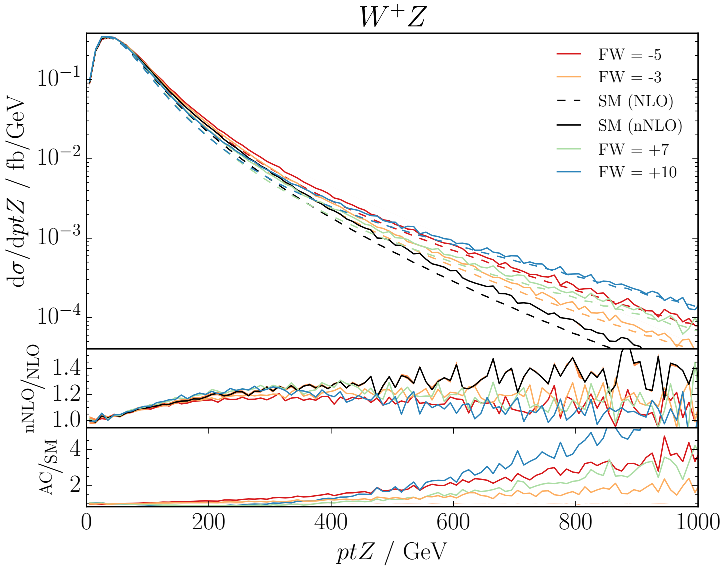
practical LoopSim



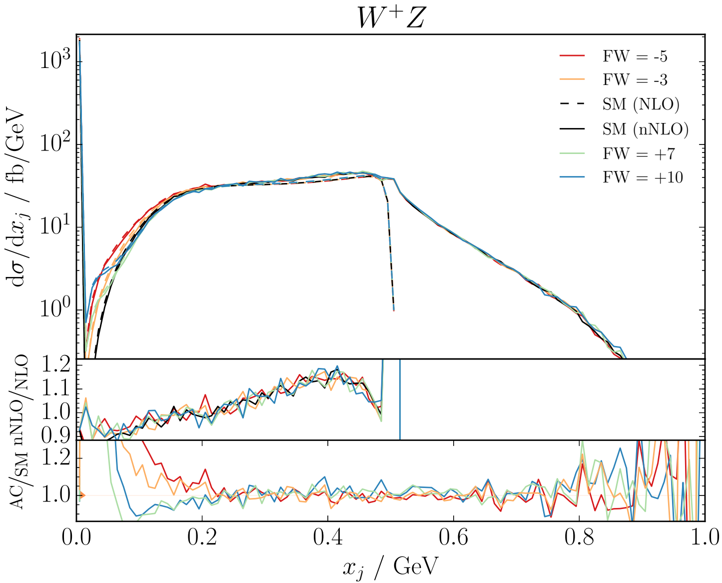


- LoopSim slower than bare VBFNLO run by a factor 8
- interest not in phase space region with highest cross section but tails

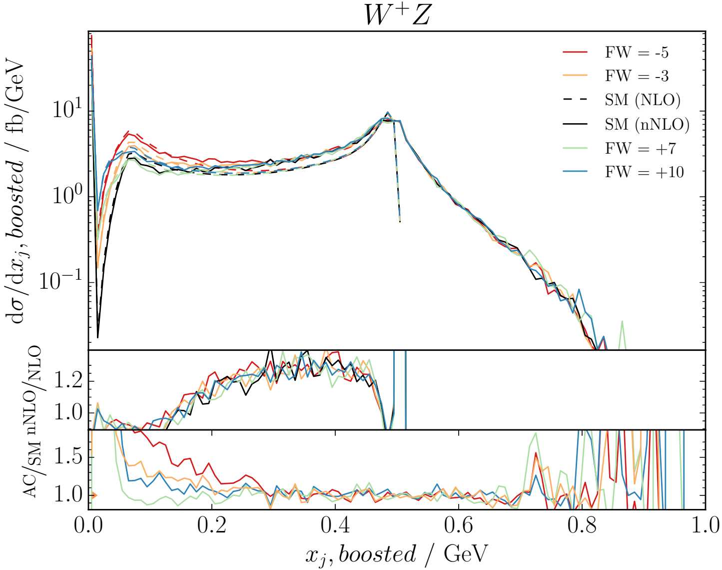
Preliminary Results



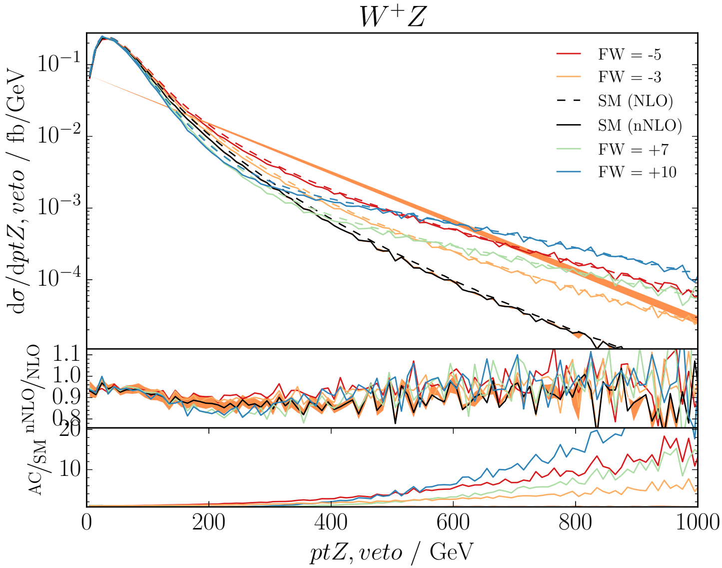
Preliminary Results



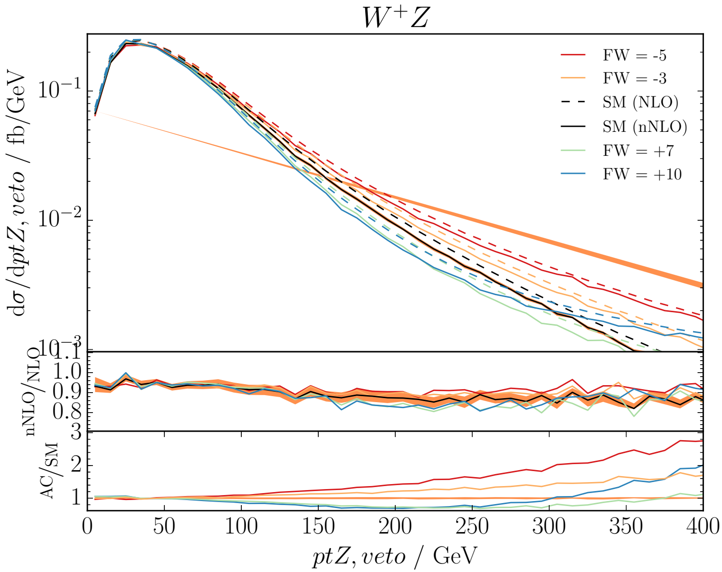
Preliminary Results



LoopSim: n̄NLO QCD


W^+Z
$d\sigma/dptZ, veto$ / fb/GeV
10^{-1}
10^{-2}
10^{-3}
10^{-4}
FW = -5
FW = -3
SM (NLO)
SM (nNLO)
FW = +7
FW = +10
nNLO/NLO
1.1
1.0
0.9
0.8
AC/SM
20
10
0
200
400
600
800
1000
$ptZ, veto$ / GeV

Preliminary Results



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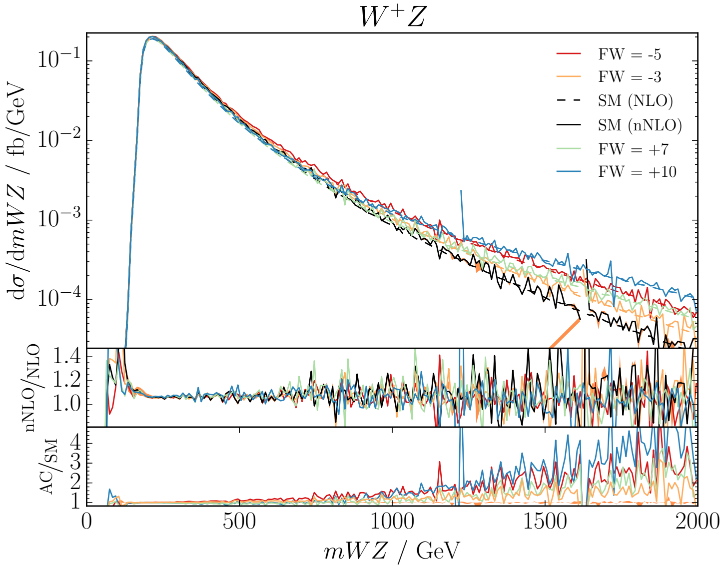

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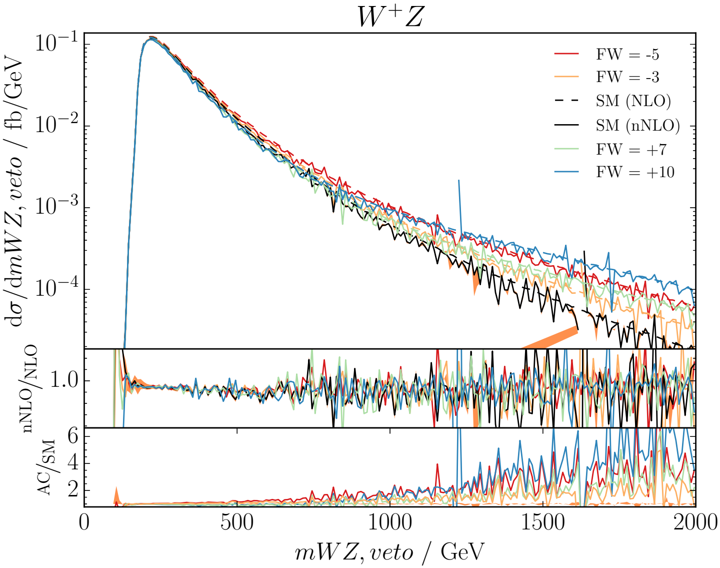
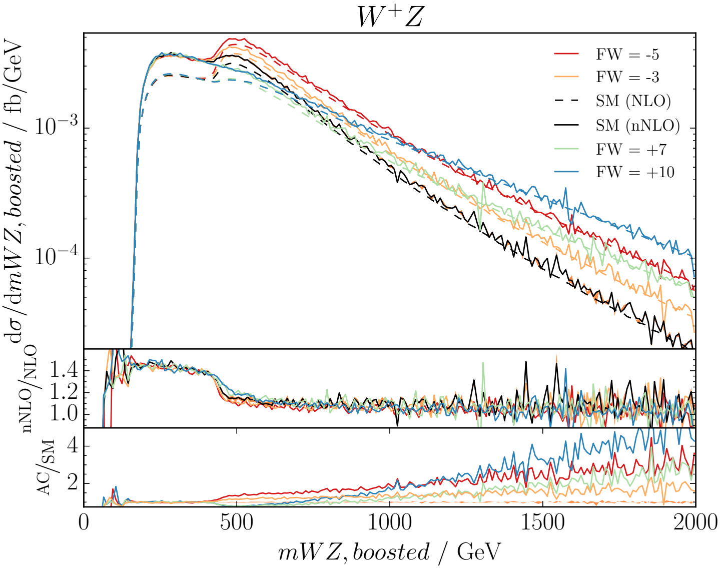


Preliminary Results



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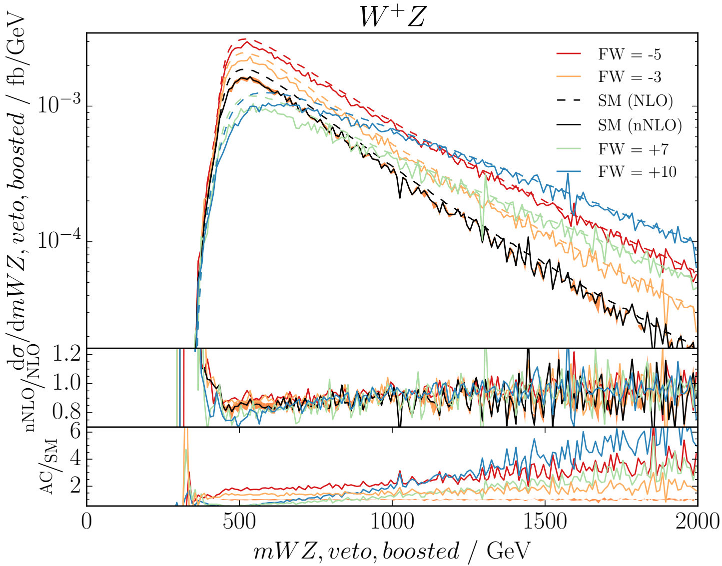
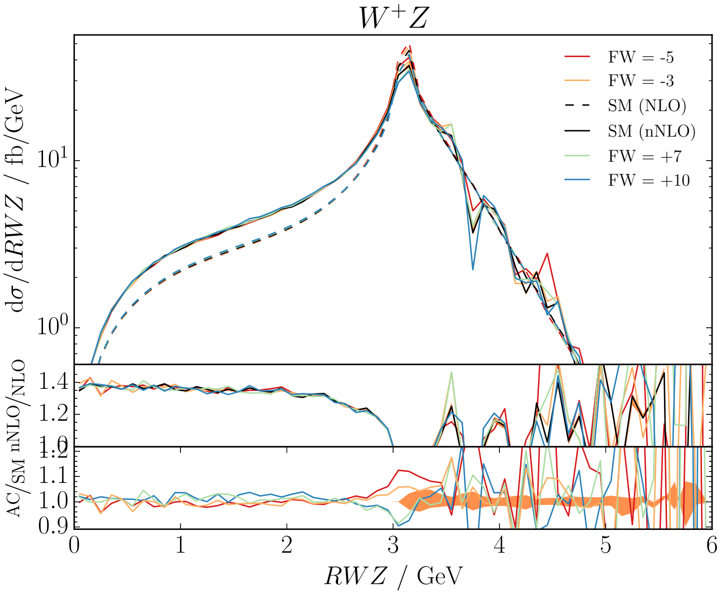


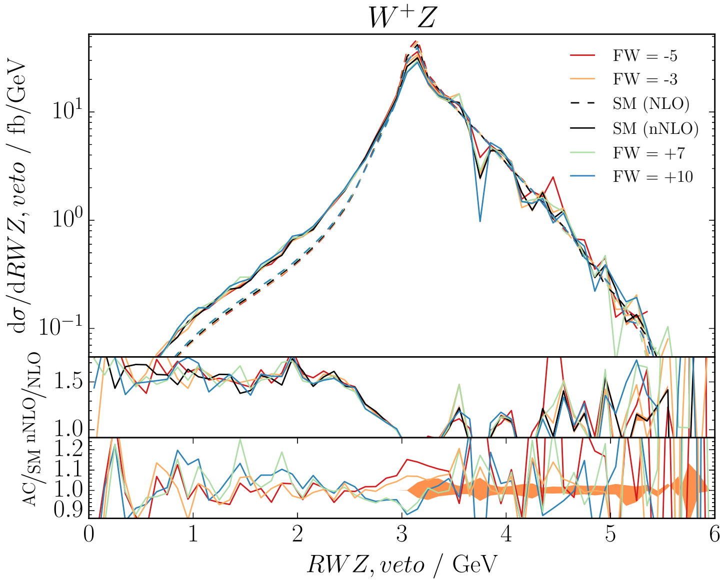
LoopSim: n̄NLO QCD

Preliminary Results

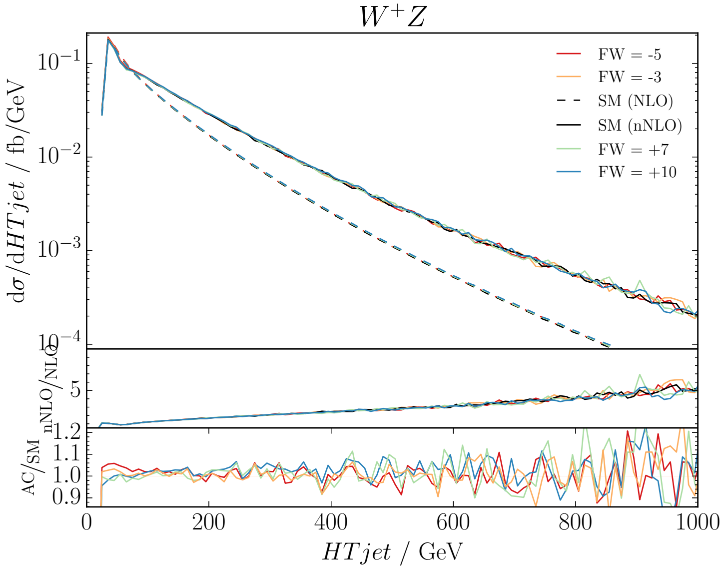


LoopSim: n̄NLO QCD

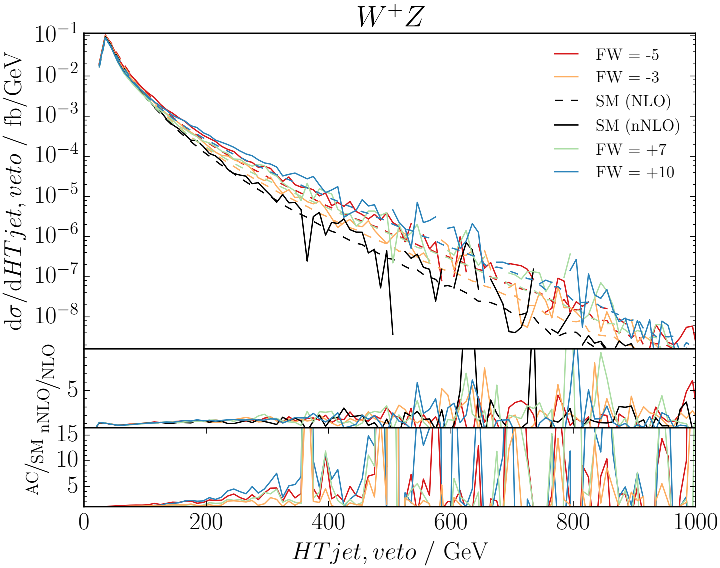
Preliminary Results



Preliminary Results



Preliminary Results



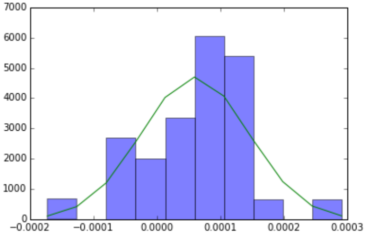
Combine histograms of N runs

- have: observables of N runs
- want: central value and error
- assumption: Gaussian distribution of individual runs

$$\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i - \mu)^2}$$

$$\sigma_{\text{MC}} = \sqrt{\left(\frac{1}{N}\sum_{i=1}^{N}x_i^2\right) - \left(\frac{1}{N}\sum_{i=1}^{N}x_i\right)^2}$$

$$\sigma_{\text{mean}} = \frac{\sigma_{\text{MC}}}{\sqrt{N}}$$



Standard deviation ⇔ Standard error of the mean

Bin Smearing

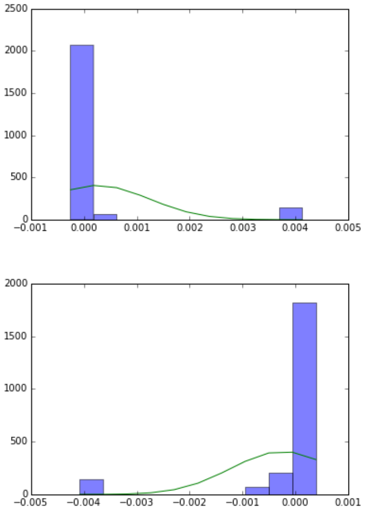
Problem

- large cancellations between events (real/subtraction, real/looped)
- small momentum changes (tilde kinematics)
- events close to bin boundary can end up in different bins
- increased error in both bins

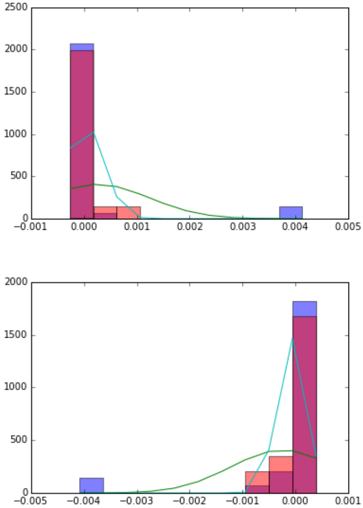
Solution

- count events close to bin boundaries in both bins
- need smooth function to transition from 100% Bin1 to 100% Bin2

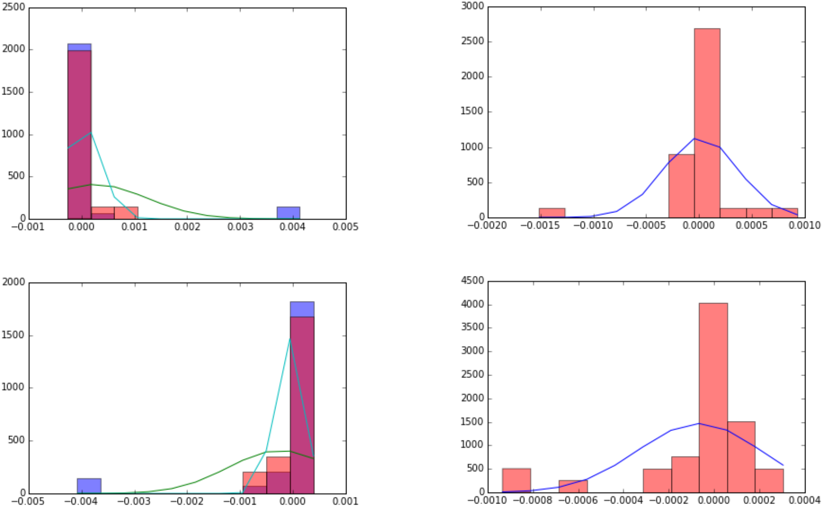
Bin Smearing



Bin Smearing



Bin Smearing



Optimizing Monte Carlo integration

Monaco, our Monte Carlo core

- based on Vegas
- importance sampling, choose points proportional to weight

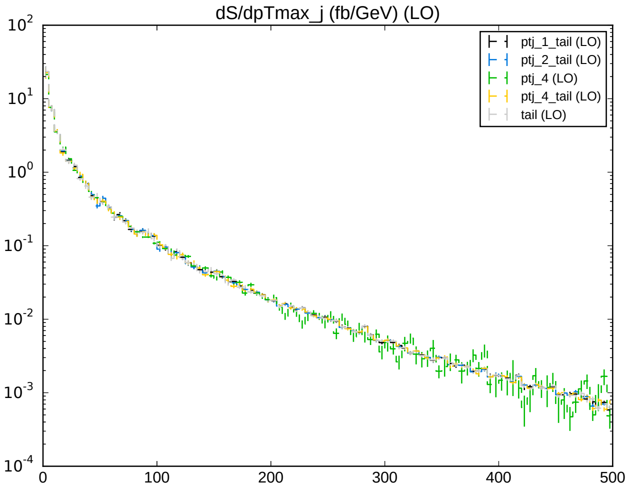
Problem

- Monaco tries to reduce error on total cross section
- for LoopSim: want high statistics in tails, not soft jets

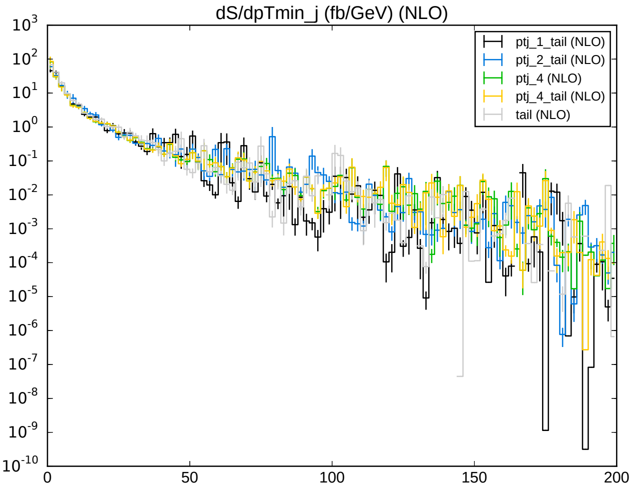
Solution

- "Cheat" Monaco
- function to integrate: $\sigma(p_i) \cdot rew(p_i)$
- $rew(p_i) = {H_T}^4 \cdot \left\{ \left(\frac{pt_{\text{jet},\text{min}}}{pt_{\text{jet},\text{analysiscut}}} \right)^n, 1 \right\}$, where $n = 1, 2, 4$ and $H_T = \sum_{\text{jets}} p_{T,i}$

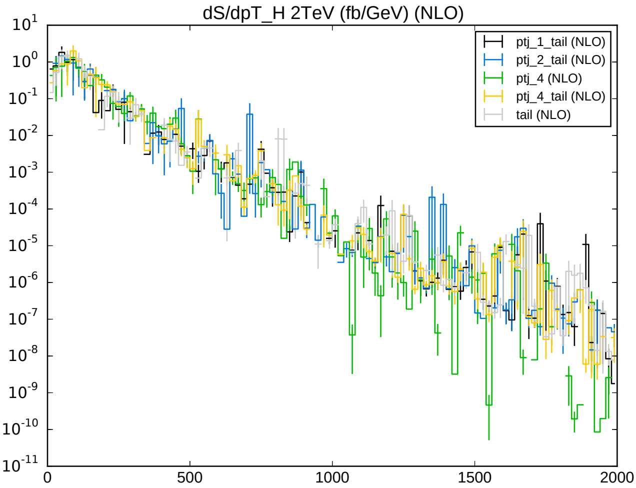
Monaco Cheating



Monaco Cheating



Monaco Cheating

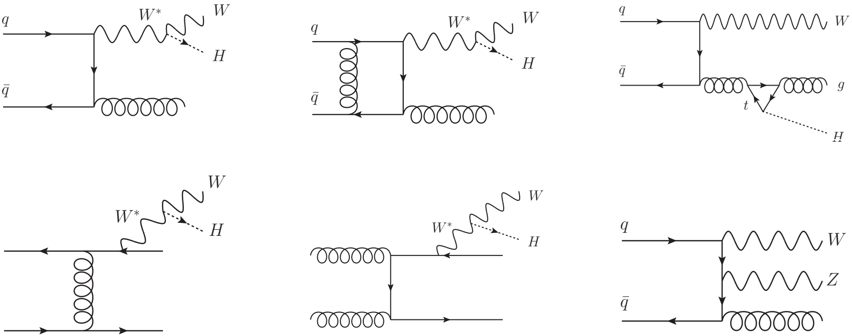


Outlook

- merge WZjj@NLO for WZ@n̄n̄NLO
- compare LoopSim to other merging schemes (Herwig/Matchbox, ...)
- validate with existing differential NNLO calculations (*WH*, $\gamma\gamma$?)
- estimate missing two-loop term $\sim \alpha_s^2 \sigma_{\mathrm{LO}}$ for a class of processes
- better observables for anomalous couplings, search strategies for LHC

Backup

Introduction & Reminder WHj Production



Cross sections of WZj

	inclusive				boosted			
	W^+Z		W^+Zj		W^+Z		W^+Zj	
N_{jets}	LO	NLO	LO	NLO	LO	NLO	LO	NLO
0	14.00	16.74			0.492	0.397		
1		11.28	11.31	8.391		1.242	1.248	0.554
2				6.223				1.094

$\sqrt{s} = 14\,\text{TeV}$, jet algorithm: anti-$k_t$ with $R = 0.4$

$\mu_0 = \frac{1}{2}\left(\sum_{\text{partons}} p_{T,i} + \sum_{W,Z}\sqrt{p_{T,i}^2 + m_i^2}\right)$

Cuts

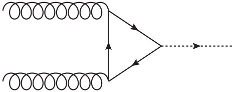
$p_{T\,l} > 20\,\text{GeV}$ $\quad p_{T\,j} > 30\,\text{GeV}$ $\quad \not{p}_T > 30\,\text{GeV}$

$|\eta_j| < 4.5$ $\quad |\eta_l| < 2.5$ $\quad R_{l(l,j)} > 0.4$

$m_{ll} > 15\,\text{GeV}$ $\quad R_{ll} > 0.4$

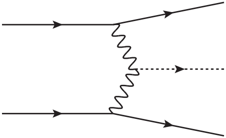
boosted: $p_{T\,Z} > 200\,\text{GeV}$

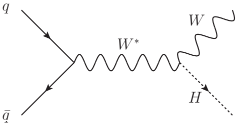
Higgs at LHC



Gluon Fusion

Vector Boson Fusion

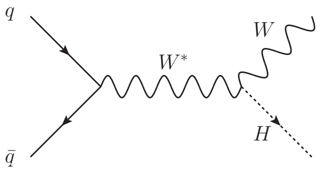




Higgsstrahlung

WH at LHC

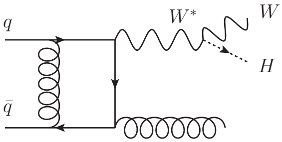
- small cross section $\Rightarrow$ large BR most interesting
- WH, H $\rightarrow b\bar{b}$ has large background from W + jets
- improve S/B using boosted Higgs, fat jet, subjet analysis
- current status:
  CMS WH $\rightarrow Wb\bar{b}$: 2.1σ excess
  ATLAS exclusion down to 1.4 σ_{SM}
- useful for BSM decay modes
- WWH coupling
- best channel for H $\rightarrow b\bar{b}$

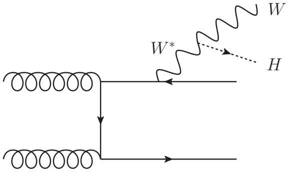


WHj NLO

- NLO QCD: virtual and real contributions
- numerical integration with different phase spaces: need to be finite individually
- Catani-Seymour dipole subtraction

$$\sigma^{NLO} = \int_m \mathrm{d}\sigma^V + \int_{m+1} \mathrm{d}\sigma^R$$
$$= \int_m \left(\mathrm{d}\sigma^V + \int_1 \mathrm{d}\sigma^A\right) + \int_{m+1} \left(\mathrm{d}\sigma^R - \mathrm{d}\sigma^A\right)$$





Anomalous Couplings

- use effective field theory to describe physics entering at a higher scale
- new operators with dimensionful couplings $\mathcal{L}_{\text{EFT}} = \sum_i \frac{f_i}{\Lambda^{d-4}} \mathcal{O}_i^{(d)}$
- dimension 6 operators affecting the WWH vertex:

$$\mathcal{O}_W = (D_\mu \Phi)^\dagger \hat{W}^{\mu\nu} (D_\nu \Phi)\,, \quad \mathcal{O}_{WW} = \Phi^\dagger \hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \Phi \quad \text{(CP even)}$$

$$\mathcal{O}_{\tilde{W}} = (D_\mu \Phi)^\dagger \widetilde{\hat{W}}^{\mu\nu} (D_\nu \Phi)\,, \quad \mathcal{O}_{\tilde{W}W} = \Phi^\dagger \widetilde{\hat{W}}_{\mu\nu} \hat{W}^{\mu\nu} \Phi \quad \text{(CP odd)}$$

f_W/Λ^2 (TeV^{-2})	cross section (fb)			$p_{Th} < 200\,\text{GeV}$		
	LO	NLO	K	LO	NLO	K
0	25.0	28.6	1.14	21.5	24.8	1.15
1	22.9	25.9	1.13	20.5	23.1	1.13
−1	28.0	30.7	1.09	22.7	25.5	1.13
10	52.3	34.6	0.66	13.6	15.5	1.14
−10	103.5	82.7	0.80	36.0	40.0	1.11

Event selection and cross sections

$\sqrt{s} = 14$ TeV, $\mathrm{R_{jj}} = 0.8$, k_T-alg., $\mathrm{R_{jl}} = 0.6$

$\mathrm{m_h} = 126$ GeV, $p_{T,j} = 30$ GeV, $p_{T,l} = 20$ GeV

$\mu_R = \mu_F = \mathrm{m_Z}$, $|\eta_j| < 4.5$, $|\eta_l| < 2.5$

Process	LO (fb)	NLO (fb)	K-Factor
W^+H	56	76	1.37
W^-H	32	45	1.41
W^+Hj	25	28	1.10
W^-Hj	15	17	1.15
W^+Hjj	11		
W^-Hjj	6		

- included: $\mathrm{BR}\left(W^+ \to e^+\nu\right) = 10.84\%$
- not included: $\mathrm{BR}\left(H \to b\bar{b}\right) = 57\%$