Karlsruhe Institute of Technology

Anomalous couplings in WZ production beyond NLO QCD

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in collaboration with Francisco Campanario, Sebastian Sapeta, Dieter Zeppenfeld

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Motivation

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

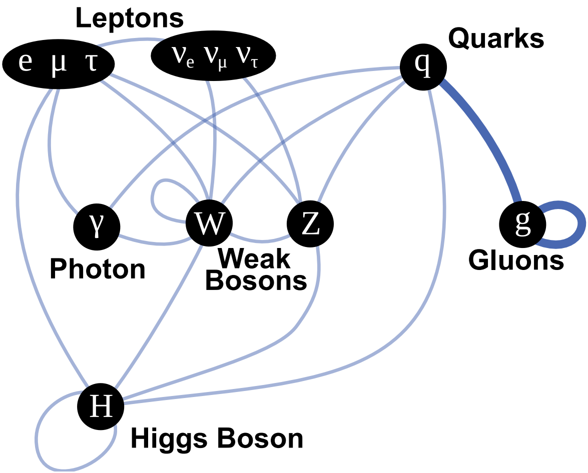
Methods

- 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

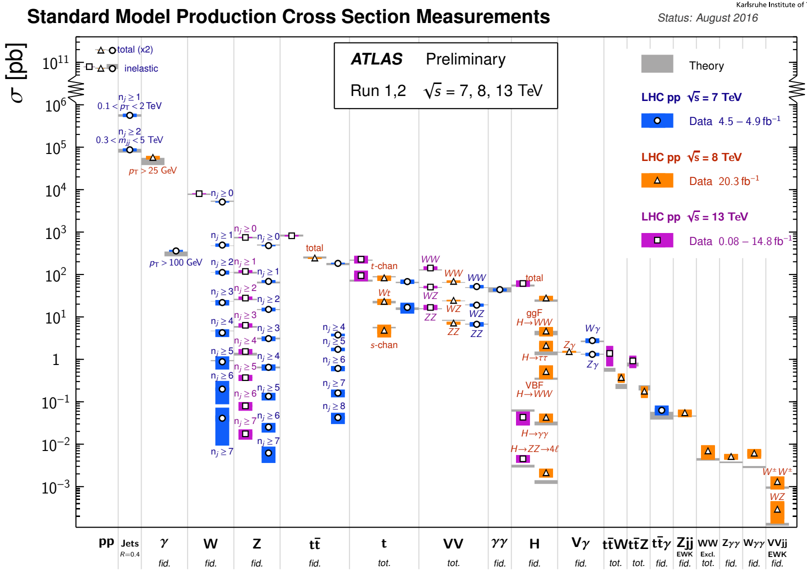
Tools

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

The Standard Model of Particle Physics



LHC Cross Sections



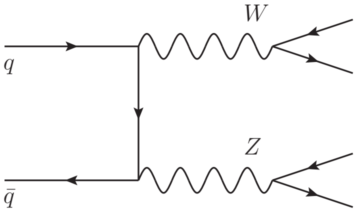
Diboson production at the LHC

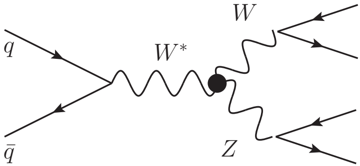
Why Diboson

- 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
- $m_T, p_{T\,V}, p_{T\,l}$
- decay angles, spin information

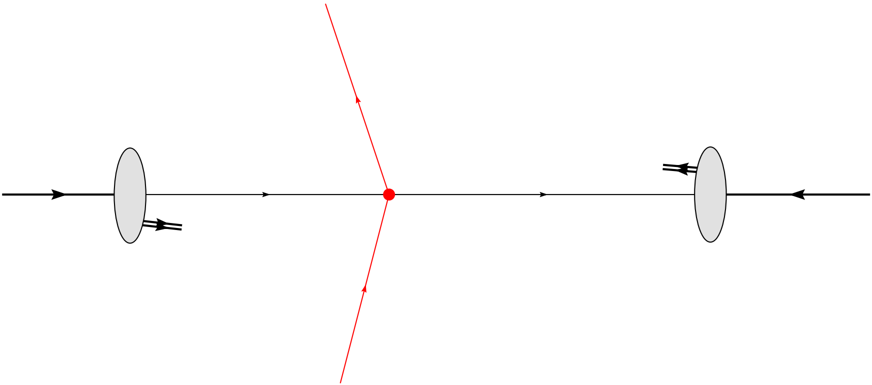




Hadron collision

Stefan Gieseke, Monte Carlo lectures

Hadron collision



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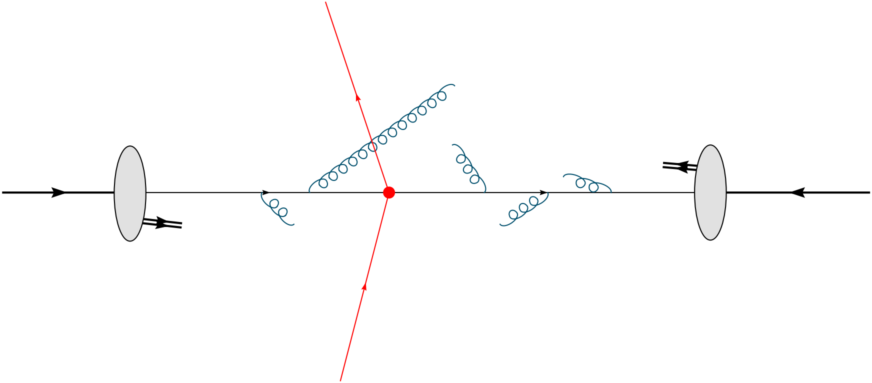

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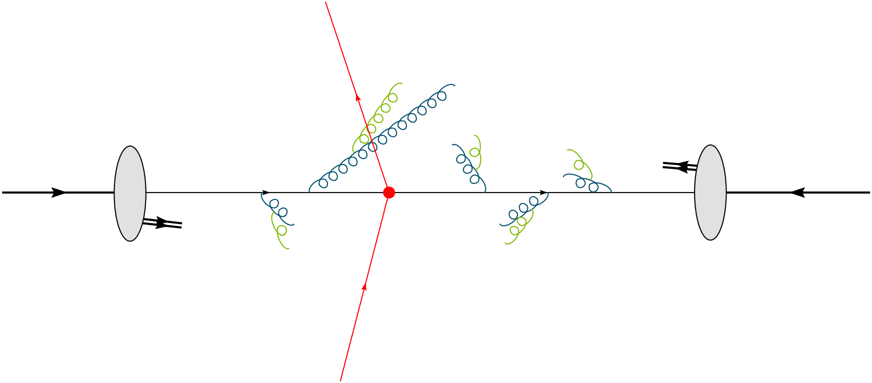

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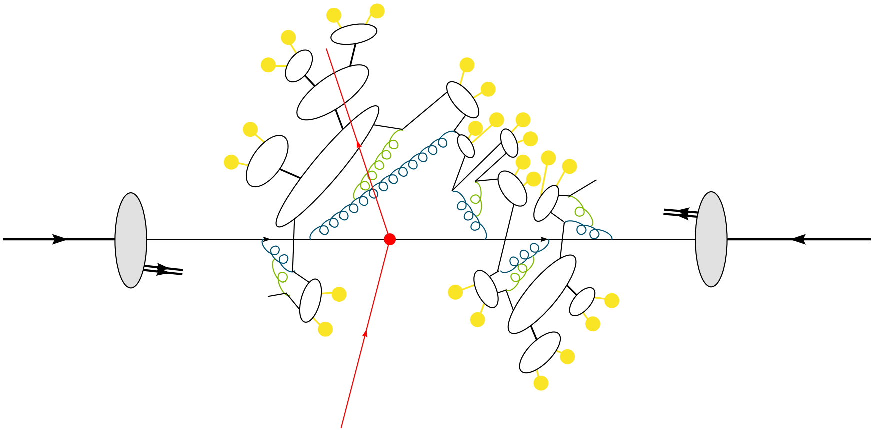

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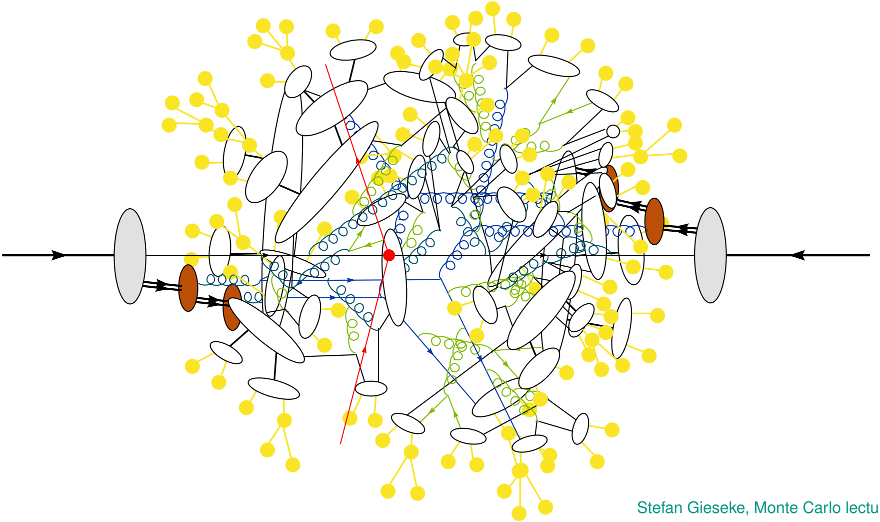

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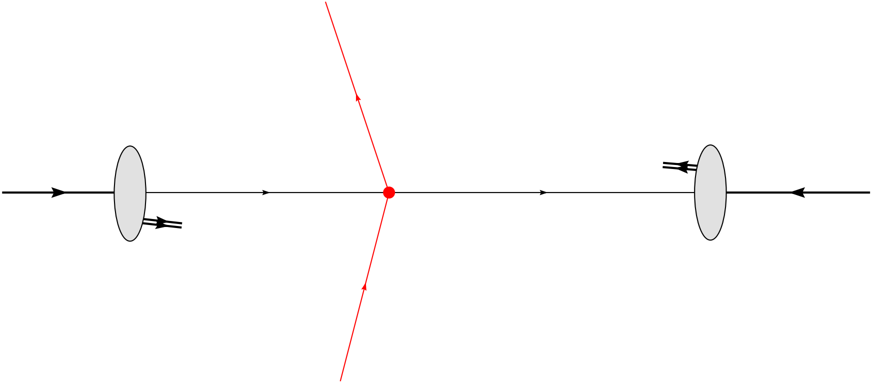

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Fixed Order Calculations

Perturbation Theory

- exact solution of interacting theory not know
- start from free particles and consider interactions as perturbations
- couplings ($\alpha = \frac{g^2}{4\pi}$) small
- expand in powers of the couplings
- Leading Order (= Born), NLO, ...

NLO Contributions

- Real emission (extra leg)
  - soft or collinear emissions divergent
  - at LO: jet definition/cuts

$\propto \frac{1}{p_g \cdot p_q} \propto \frac{1}{E_q E_g (1 - \cos\theta)}$

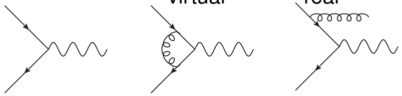
- Virtual (extra loop)
  - divergent for small loop momenta

KLN Theorem: Divergences cancel

Amplitude

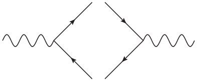
LO NLO

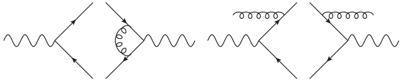
virtual real



Squared Amplitude

LO





virtual real

LoopSim

Idea

- “Giant QCD K-factors beyond NLO” [Rubin, Salam, Sapeta, 1006.2144]
- merge different multiplicity final states X@NLO + Xj@NLO = X@n̄NLO
- parton level
- use NLO events, interface to existing Monte Carlos programs

Properties

- preserve NLO total cross section
- exact tree-level and one-loop
- only singular two-loop contributions
- include dominant contributions from extra emissions, $\mathcal{O}(\alpha_s \ln^2 p_{\mathrm{Tjet}}/m_Z)$
- nearly NNLO in high-p_T tails

l (loops)					
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)

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X@LO

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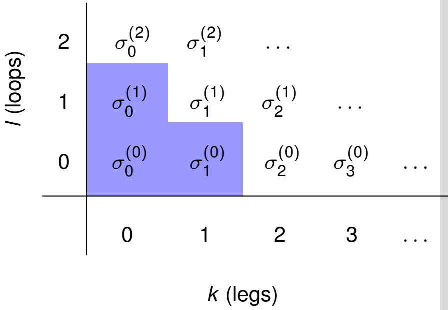

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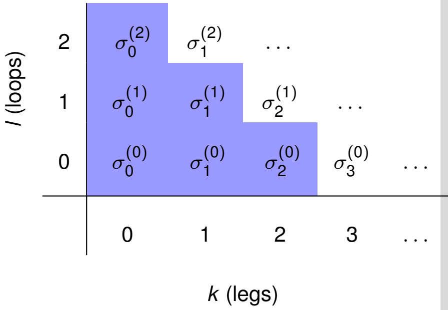

X@NNLO

LoopSim

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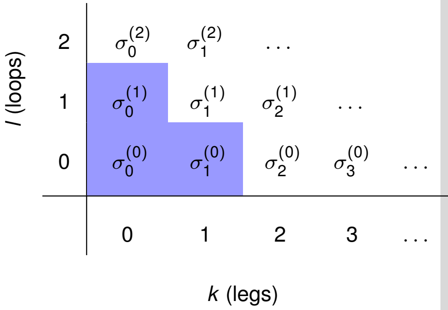

X@NLO

LoopSim

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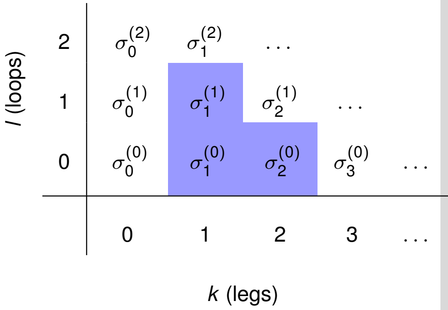

X+jet@NLO

LoopSim

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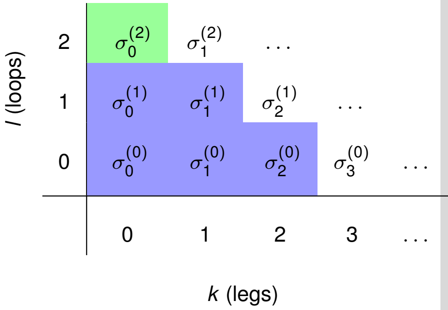
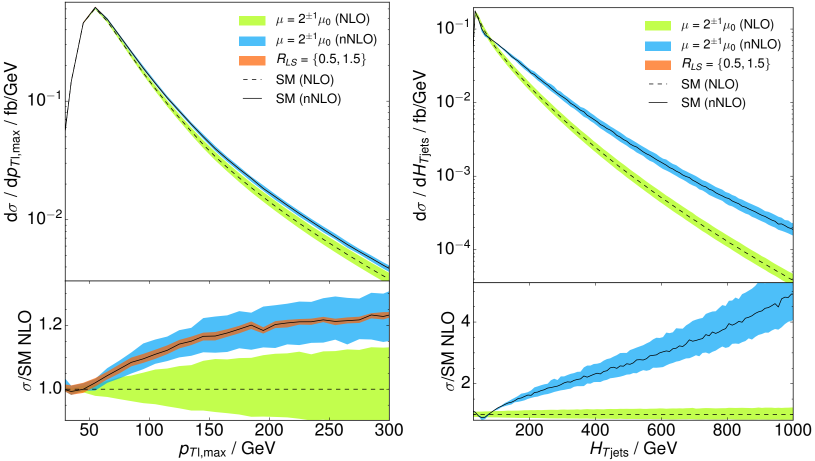


X@n̄NLO

n̄NLO for WZ production

$e^+\nu_e\,\mu^+\mu^-$ + X, LHC@13 TeV, inclusive cuts



Anomalous Couplings

SM as Effective Field Theory

- assume there are fields beyond the SM at a high mass scale Λ
- describe effects at lower (electro-weak) energy scales
- add higher-dimensional terms to Lagrangian $\mathcal{L} = \mathcal{L}_{\text{SM}} + \sum_i \frac{f_i}{\Lambda^2} \mathcal{O}_i$

Building Blocks (SM Fields and Symmetries)

- Higgs field Φ
- (covariant) derivative ∂^μ, D^μ
- fermion fields ψ
- field strength tensors $G^{\mu\nu}$, $W^{\mu\nu}$, $B^{\mu\nu}$

Contributions to WWZ vertex

At dimension 6 only 3 linear independent operators (assuming C, P conservation)

$$\mathcal{O}_W = (D_\mu \Phi)^\dagger \, \hat{W}^{\mu\nu} \, (D_\nu \Phi) \,,$$
$$\text{O}_{WWW} = \text{Tr}\left[\hat{W}_{\mu\nu} \hat{W}^{\nu\rho} \hat{W}_\rho^\mu \right] ,$$
$$\text{O}_B = (D_\mu \Phi)^\dagger \, \hat{B}^{\mu\nu} \, (D_\nu \Phi)$$

Validity of EFT approach

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

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

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

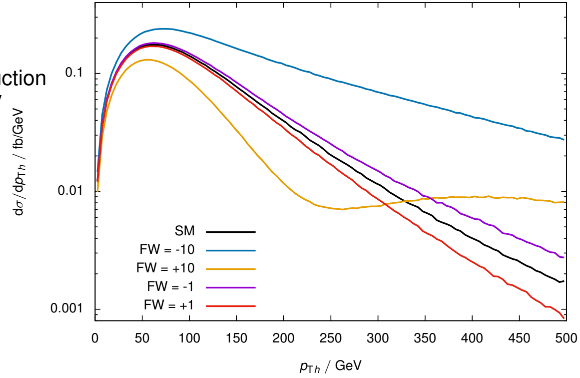
- power-counting Λ^{-4}: $\left|\mathcal{M}_{\text{AC}}^{d=6}\right|^2$, $\mathcal{M}_{\text{SM}}^*\mathcal{M}_{\text{AC}}^{d=8}$?
- conservative: experimental fit only in range where $|\mathcal{M}_{\text{AC}}|^2 \ll \mathcal{M}_{\text{SM}}^*\mathcal{M}_{\text{AC}}$
- but: $\mathcal{M}_{\text{SM}}$ accidentally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

Anomalous Couplings

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

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

WH production
$\Lambda = 1$ TeV



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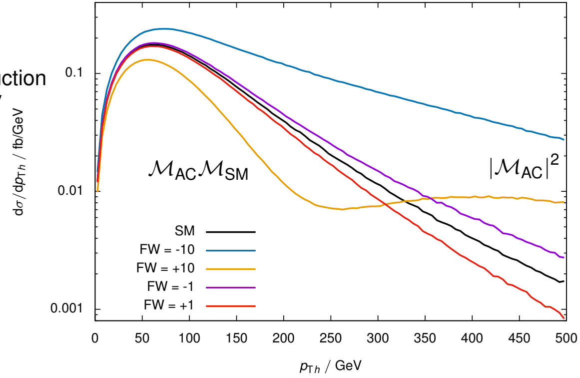
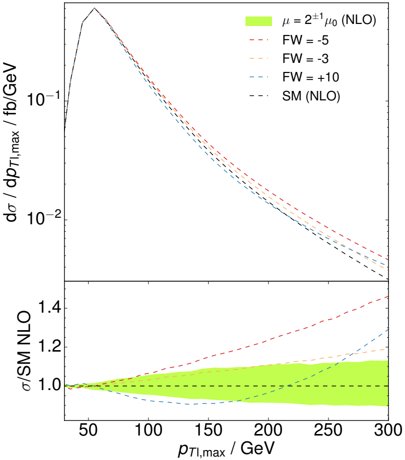


AC for WZ production



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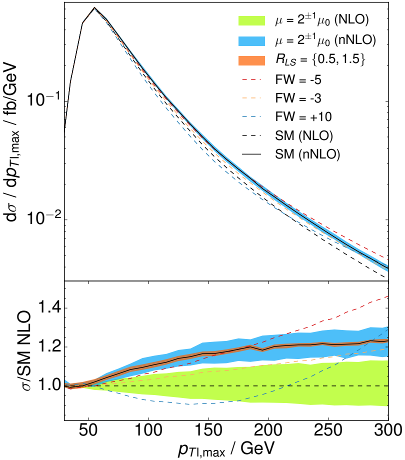

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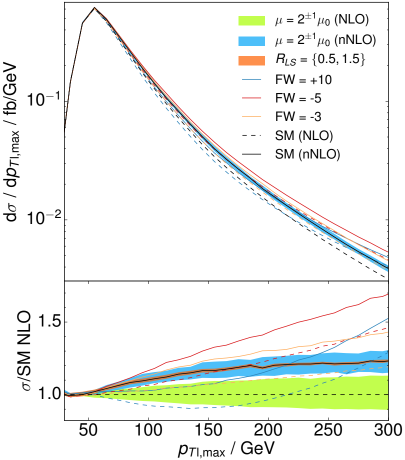
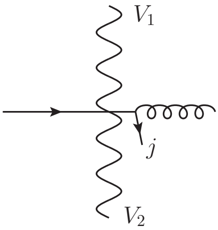
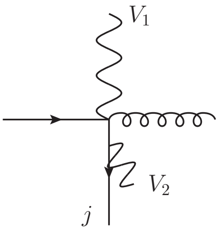


Jet vetos

want VV + jets, not Vj + V





Traditional (fixed) jet veto

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

Dynamical veto

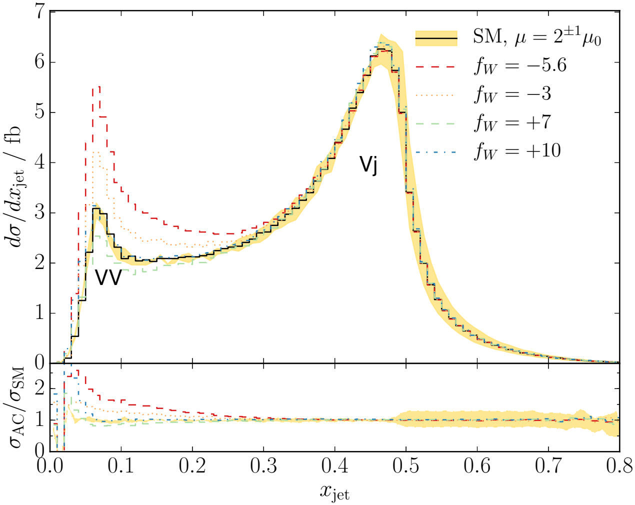
[Campanario, RR, Zeppenfeld, 1410.4840]

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

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

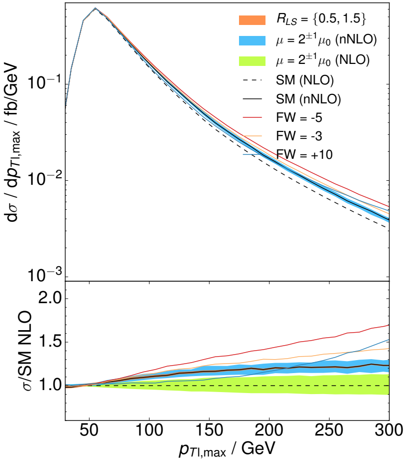
$$E_\mathrm{T} = E\,\frac{|\vec{p}_\mathrm{T}|}{|\vec{p}|}, \text{ alternatively } m_\mathrm{T}, p_\mathrm{T}$$

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



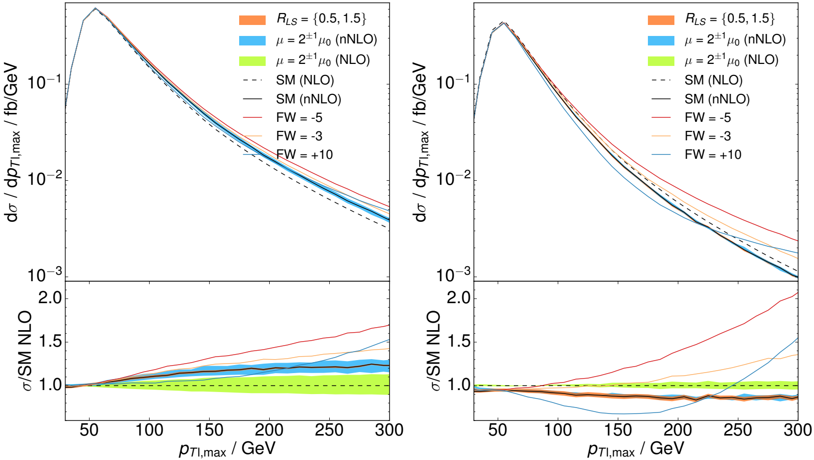
$p_{TZ} > 200$ GeV

Dynamical veto to improve AC sensitivity



inclusive

Dynamical veto to improve AC sensitivity



inclusive

$x_{jet} < 0.2$

Conclusion

Pushing the SM Frontier

- current default: NLO QCD, $O(10\%)$ theory uncertainty
- improve precision, LoopSim, NNLO, N^3LO
- matching to parton shower, improving non-perturbative physics

Anomalous couplings in diboson production

- diboson production interesting channel to study triple gauge couplings
- EFT validity depends on coupling and phase space region

Interplay between precision and new physics

- higher orders might look similar to anomalous couplings
- increase sensitive to new physics $\Rightarrow$ dynamical jet veto

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