Karlsruhe Institute of Technology

QCD Corrections to LHC Cross Sections

Robin Roth | 24.02.2016

INSTITUTE FOR THEORETICAL PHYSICS

Overview

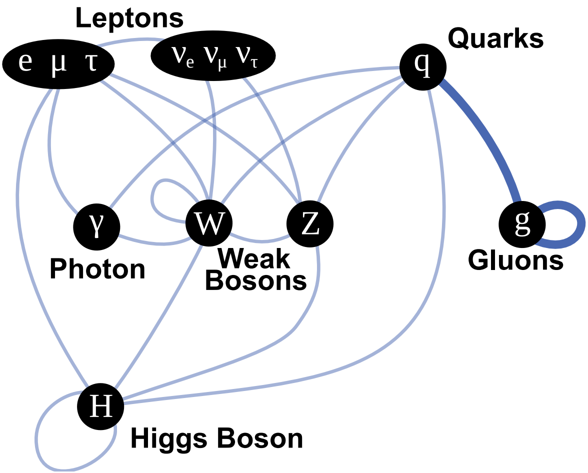
1. Calculation of LHC cross sections

2. Precise Predictions
   - Next-to-leading order
   - Beyond NLO: LoopSim

3. Physics beyond the Standard Model
   - Effective Field Theory

4. Phenomenology
   - Diboson production
   - Dynamical jet vetos

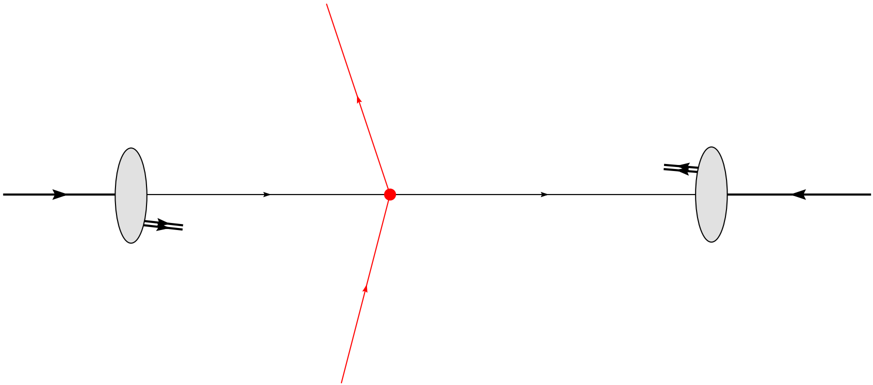
The Standard Model of Particle Physics



Hadron collision

Stefan Gieseke, Monte Carlo lectures

Hadron collision



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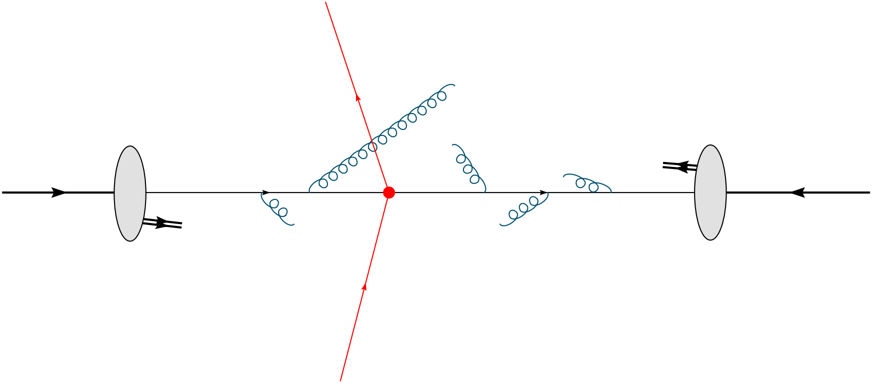

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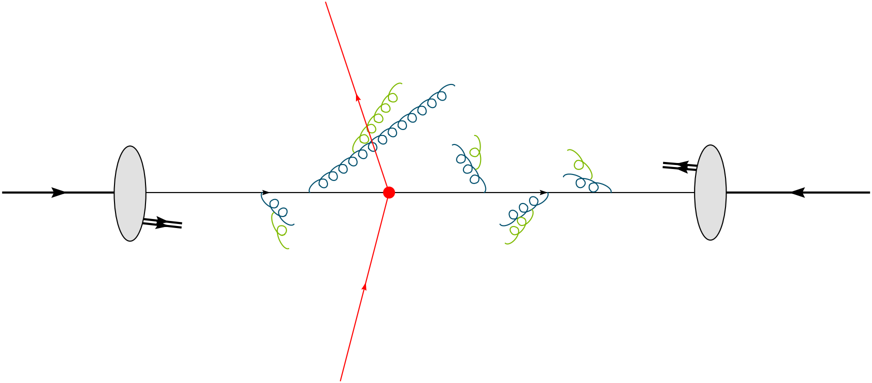

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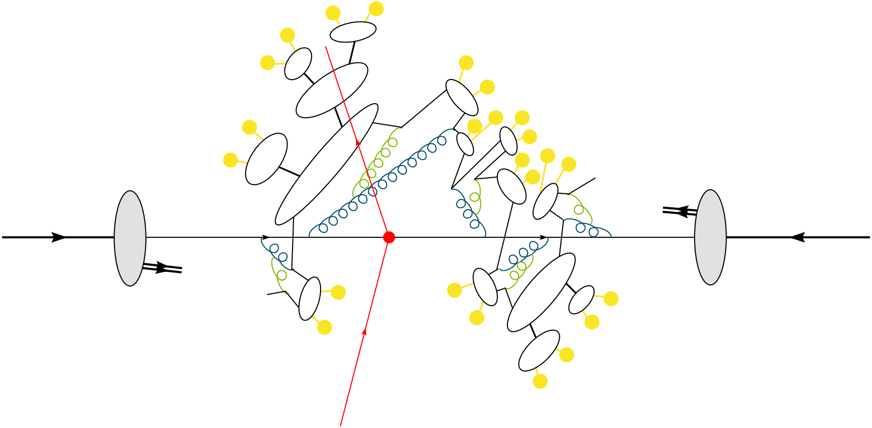

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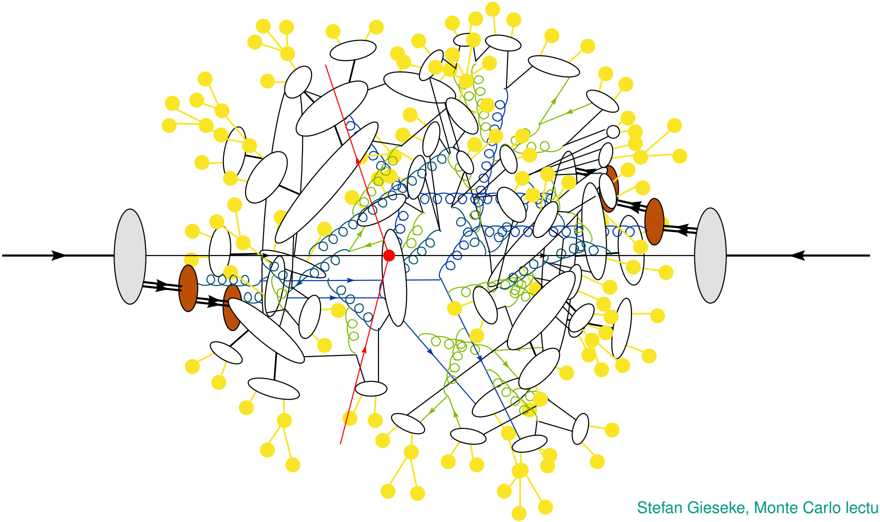

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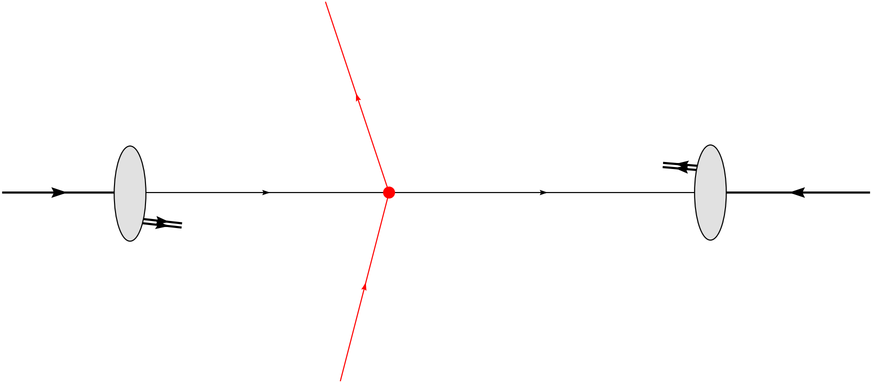


Stefan Gieseke, Monte Carlo lectures

Cross sections

Measurements

- rates of specific event types
- $\dot{\mathrm{N}} = \underbrace{L}_{\text{Luminosity}} \cdot \underbrace{\sigma}_{\text{cross section}}$
- process: set of final state particles
- total cross section σ_{tot}
- differential cross section $\mathrm{d}\sigma$: dependence on kinematics, p_{T}, η, φ

Calculation

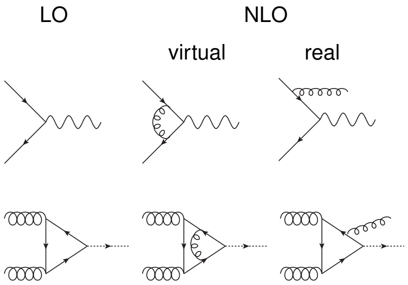
$$\mathrm{d}\sigma = \frac{1}{2\hat{\mathrm{s}}} \mathrm{d}\Phi_{\mathrm{X}} \, |\mathcal{M}|^2$$

- ignored for this presentation: connecting partons to hadrons
- $\mathrm{d}\Phi_{\mathrm{X}}$: integration of final state momenta
- $\mathcal{M}$: amplitude, transition from initial- to final state particles
- Feynman diagrams visualize contributions to amplitude

Perturbation Theory Language

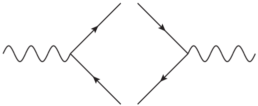
Perturbation Theory

- 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, ...

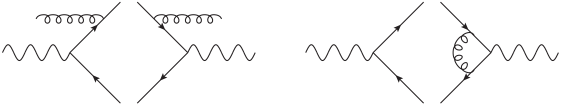


NLO contributions

LO:



NLO:



Real

- soft or collinear emissions divergent
- at LO: jet definition/cuts

Virtual

- divergent for small loop momenta

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

KLN Theorem: Divergences cancel

Canceling Divergences

- infra-red (IR) divergences not physical
- IR-safe observables: don't depend on the IR details

Total cross section

- integral over final state phase space
- parametrize using a regulator
- cancel divergences analytically

Differential cross section

- not integrated
- analytical structure depends on observable/cuts ⇒ complicated
- divergences process-independent
- cancel them with subtraction terms ⇒ Catani-Seymour, Antenna, . . .

$$\sigma_{\text{NLO}} = \int \mathrm{d}\Phi_{\mathrm{X+jet}} \left[\widetilde{\sigma}_{\text{real}} - \sigma_{\mathrm{A}}\right] + \int \mathrm{d}\Phi_{\mathrm{X}} \left[\widetilde{\sigma}_{\text{virt}} + \int \sigma_{\mathrm{A}}\right]$$

Multiple loops and legs

$$d\sigma = \frac{1}{2\hat{s}} \sum_{k} d\Phi_{X+k} \left| \sum_{l} \mathcal{M}^{(l)}_{X+k} \right|^2$$

- k: number of additional external legs
- l: number of loops
- $k + l$: order in α
- leading order (LO): $(k, l) = (0, 0)$
- next-to-leading order (NLO): $(k, l) = \{(0, 0), (0, 1), (1, 0)\}$

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

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LO

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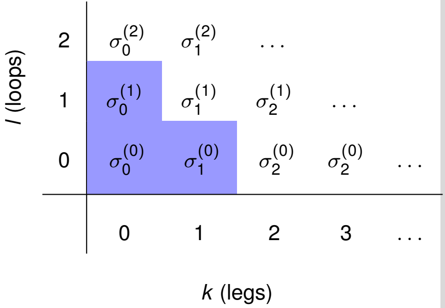

NLO

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k (legs)

NNLO

LoopSim

Idea [1006.2144]

- approximate NNLO
  without calculating 2-loop-diagrams
- divergences of 2-loop-terms must cancel
  $\Rightarrow$ cancel them numerically
- use existing NLO monte carlos

Accuracy

- misses finite 2-loop contributions
- includes log enhanced terms
- preserves total NLO cross section
- nearly NNLO in high-p_T tails

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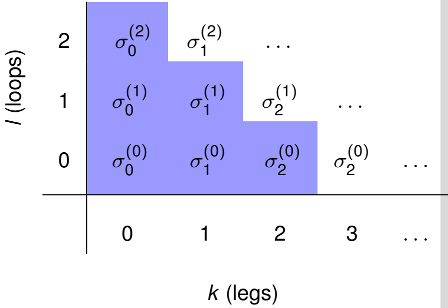

X@NNLO

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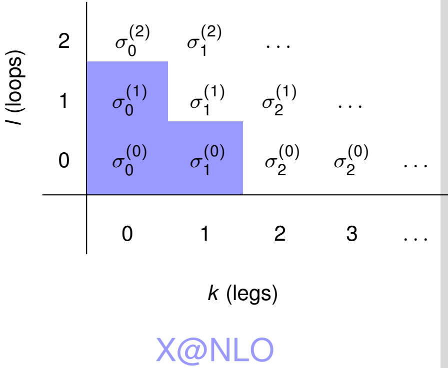

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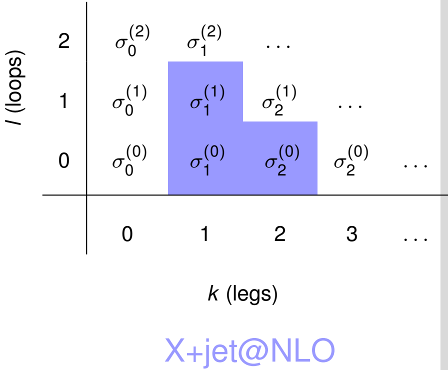

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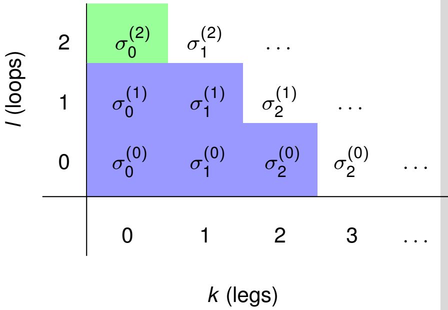


X@n̄NLO

Physics beyond the SM

Motivation: Dark Matter, unification of forces, hierarchy problem

Concrete models

- additional particles (=fields)
- new gauge groups, Supersymmetry

SM as Effective Field Theory

- only use SM fields and symmetries
- add higher-dimensional terms to Lagrangian (dim 6, 8) $\mathcal{L}_{\text{EFT}} = \frac{f_i}{\Lambda^2}\mathcal{O}_i$

Limited Validity EFT

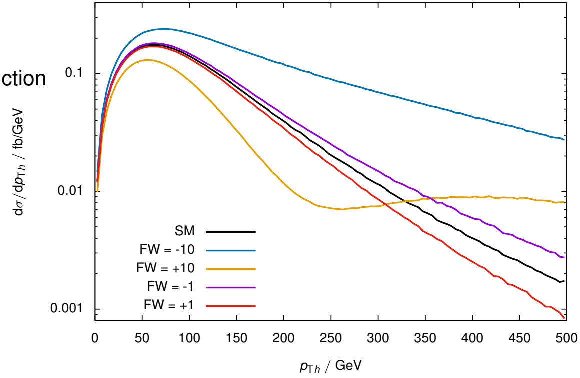
- low-energy expansion of unknown higher-energy model
- only valid if expansion parameter small
  validity depends on phase space region

Anomalous Couplings

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

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

WH production



VBFNLO

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

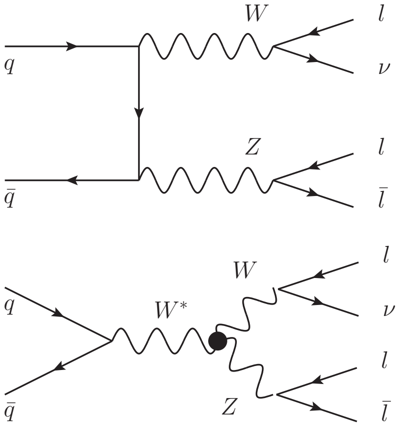
Diboson production at the LHC

Why Diboson

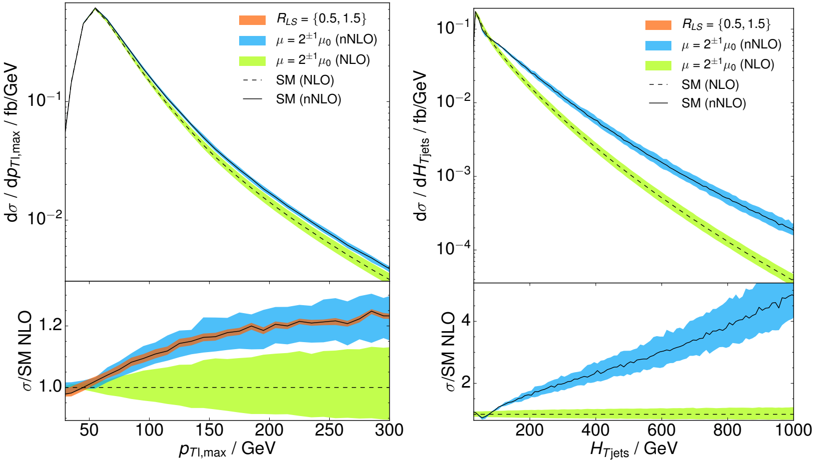
- leptonic decays: “easy” to tag, precise knowledge of final state
- access to triple gauge couplings, deviations in EW sector

Observables

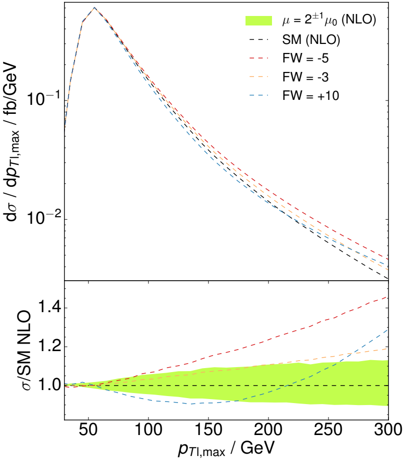
- m_{VV}: new resonances? AC?
- θ^*: angular/spin information



n̄NLO for diboson production



AC for diboson production



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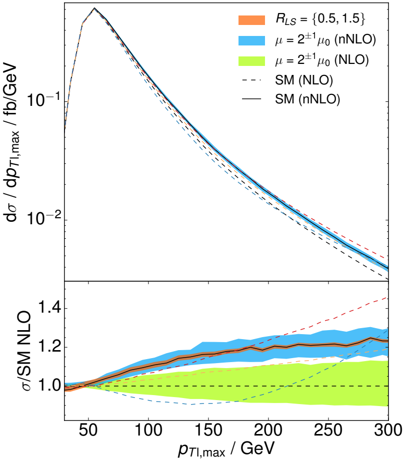

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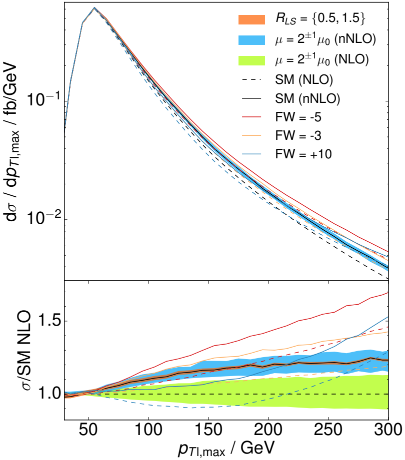
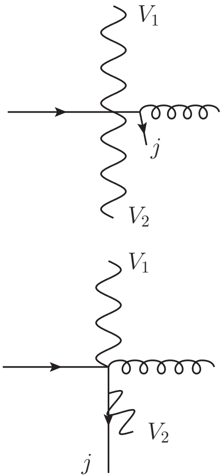


Jet vetos

want VV + jets, not Vj + V



Traditional (fixed) jet veto

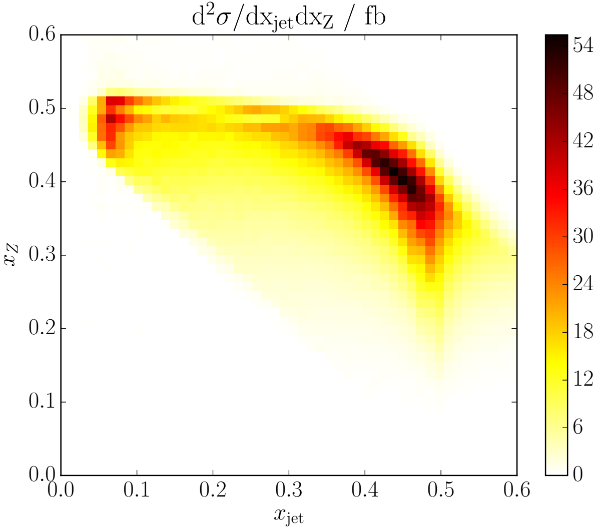
- don't allow any jets above a p_{T} threshold
- introduces large logs $\log p_{\mathrm{T\,veto}}/m_{VV}$
- cuts away relevant phase space: $m_{VV} \approx 1\,\mathrm{TeV} \leftrightarrow pt_{\mathrm{jet}} = 50/300\,\mathrm{GeV}$

Dynamical veto

- scale veto depending on overall scale $\Rightarrow$ no logs
- allow more QCD radiation in tails of EW distributions

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

Observable: x_{jet}



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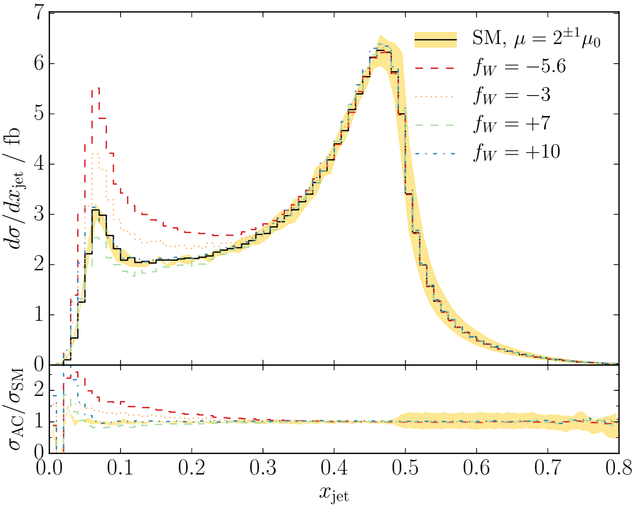
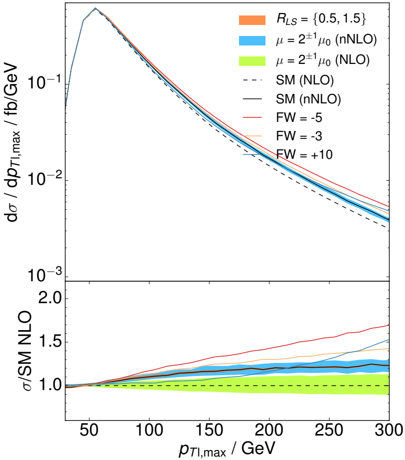


Dynamical veto to improve AC sensitivity



inclusive

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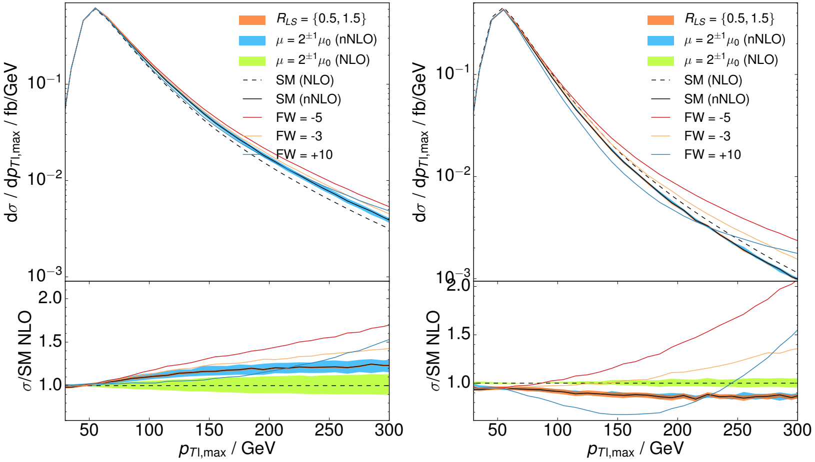

inclusive

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

Conclusion

Pushing the SM Frontier

- current default: NLO QCD, $O(10\%)$ theory uncertainty
- higher order in perturbation theory (NNLO, N^3LO)
- matching parton shower to fixed order
- improving non-perturbative physics

Beyond the Standard Model

- concrete models: SUSY, 2HDM, W', ...
- Effective Field Theory
  parametrize deviations from Standard Model
  $\Rightarrow$ Poster Genessis Perez: Effective Lagrangian for Vector Boson Scattering

Interplay between precision and new physics

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

Event Selection

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Cuts

$p_{T\,l} > 15\,\text{GeV}$ $\quad p_{T\,j} > 30\,\text{GeV}$ $\quad \not{p}_T > 30\,\text{GeV}$

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

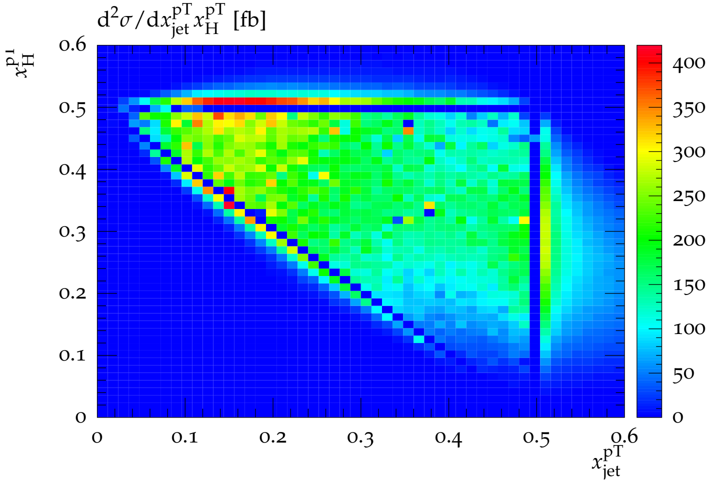
$60\,\text{GeV} < m_{ll} < 120\,\text{GeV}$

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

Input values

- EW constants: VBFNLO default
- PDF: NNPDF23

PS effects on x_{jet}



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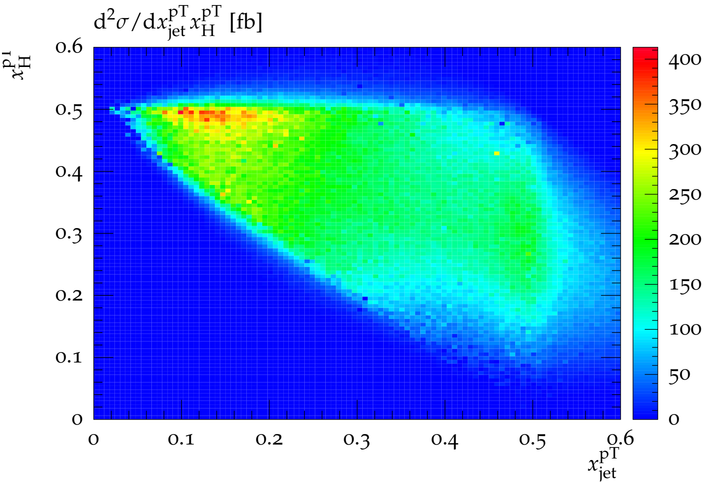
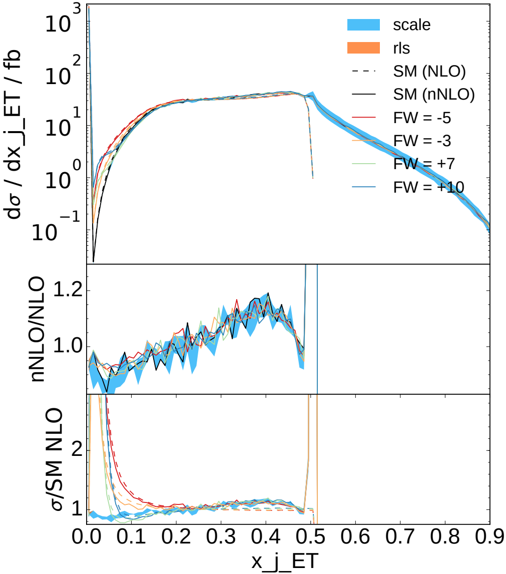


x_{jet} n̄NLO corrections



Validity of EFT approach

Best way to check validity: Do expansion of UV theory, but:

- don't know UV theory/explicit expansion
- don't even know scale/couplings

EFT assumptions

- all NP scales are well above our observables, no resonances at measurable scales
- coupling $\alpha_{\text{NP}} < 4\pi$
  could be small $\approx \alpha_{\text{QED}}$ or large $O(1)$
- f/Λ^2 "small"

Potential pitfalls

- is dim 6 the leading term? What about dim-8?
- consider only AC-SM-interference or also AC^2?
- are tree-level AC predictions sufficient?

Validity of EFT approach

Power counting in Λ

$$\mathcal{M} = \mathcal{M}_{\text{SM}} + \underbrace{\mathcal{M}_{\text{AC6}}}_{1/\Lambda^2} + \underbrace{\mathcal{M}_{\text{AC8}}}_{1/\Lambda^4}$$

$$|\mathcal{M}|^2 = \underbrace{\mathcal{M}^2_{\text{SM}}}_{1/\Lambda^0} + \underbrace{2\text{Re}\mathcal{M}^*_{\text{AC6}}\mathcal{M}_{\text{SM}}}_{1/\Lambda^2} + \underbrace{\mathcal{M}^2_{\text{AC6}}}_{1/\Lambda^4} + \underbrace{2\text{Re}\mathcal{M}^*_{\text{AC8}}\mathcal{M}_{\text{SM}}}_{1/\Lambda^4} + \underbrace{\mathcal{M}^2_{\text{AC8}}}_{1/\Lambda^8}$$

- power-counting Λ^{-4}: $\mathcal{M}^2_{\text{AC6}}$, $\mathcal{M}^*_{\text{AC8}}\mathcal{M}_{\text{SM}}$?
- conservative: experimental fit only in range where $\mathcal{M}^2_{\text{AC}} \ll \mathcal{M}_{\text{AC}}\mathcal{M}_{\text{SM}}$
- but: $\mathcal{M}_{\text{SM}}$ accidentally small (phase space, weak coupling compared to $\mathcal{M}_{\text{AC}}$) $\Rightarrow \mathcal{M}^*_{\text{AC}}\mathcal{M}_{\text{SM}}$ suppressed, $\mathcal{M}^2_{\text{AC6}}$ leading term

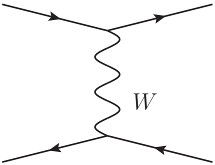
Limitation of dim 6 operators for anomalous couplings

- no neutral triple gauge couplings (come at dim. 8)
- only some (linear combinations) of quartic gauge couplings

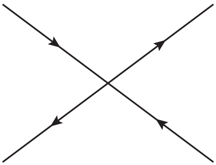
Anomalous couplings – EFT approach

Effective Field Theory

- top-down: take a theory at a high scale, integrate out heavy degrees of freedom, get description of low-scale physics with less degrees of freedom
  weak interaction → Fermi theory / four-fermion-vertices
  Soft-Collinear Effective Theory
- bottom-up: make minimal assumptions about high scale physics, consider all allowed low-scale effects and measure them
  anomalous couplings

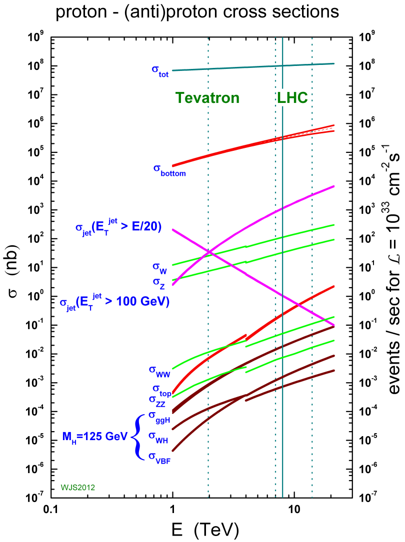


$\propto \frac{g^2/2}{m_W^2}$



$\propto \frac{f}{\Lambda^2} \left(= \frac{4G_F}{\sqrt{2}}\right)$

Predictions for processes at the LHC



Observable: x_{jet}, x_Z

Motivation

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

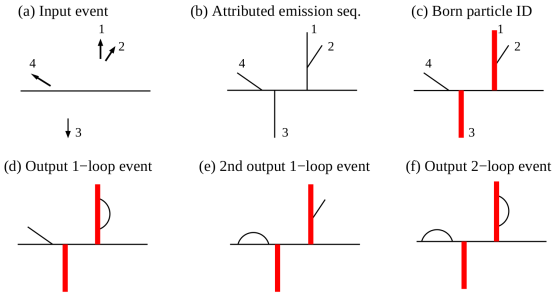
$$x_{\text{jet}} = \frac{\sum_{\text{jets}} E_{T,i}}{\sum_{\text{jets}} E_{T,i} + E_{T,W} + E_{T,Z}}, \quad x_V = \frac{E_{TV}}{\sum_{\text{jets}} E_{T,i} + E_{T,W} + E_{T,Z}}$$

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

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

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

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

LoopSim with VBFNLO

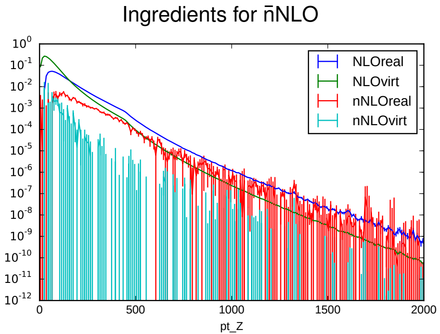
Interfacing with LoopSim

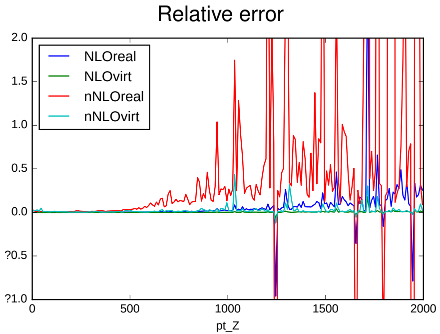
- VBFNLO produces event sample
- LoopSim generates looped events from sample
- run analysis on those final events

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

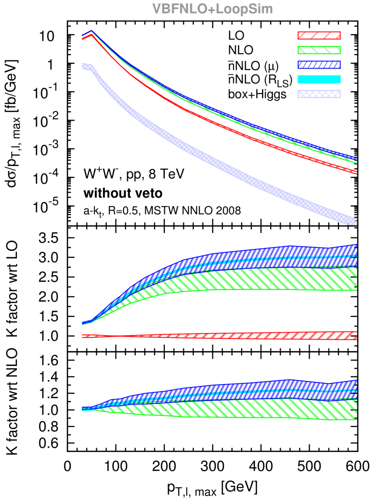
practical LoopSim





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

Previous LoopSim results



[Campanario, Rauch, Sapeta, 1309.7293]