Karlsruhe Institute of Technology

Higher Order Corrections to Diboson Production and anomalous Triple Gauge Couplings

Robin Roth | 01.09.2016

in collaboration with Francisco Campanario, Sebastian Sapeta, Dieter Zeppenfeld

XII Quark Confinement & the Hadron Spectrum, Thessaloniki, Greece

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

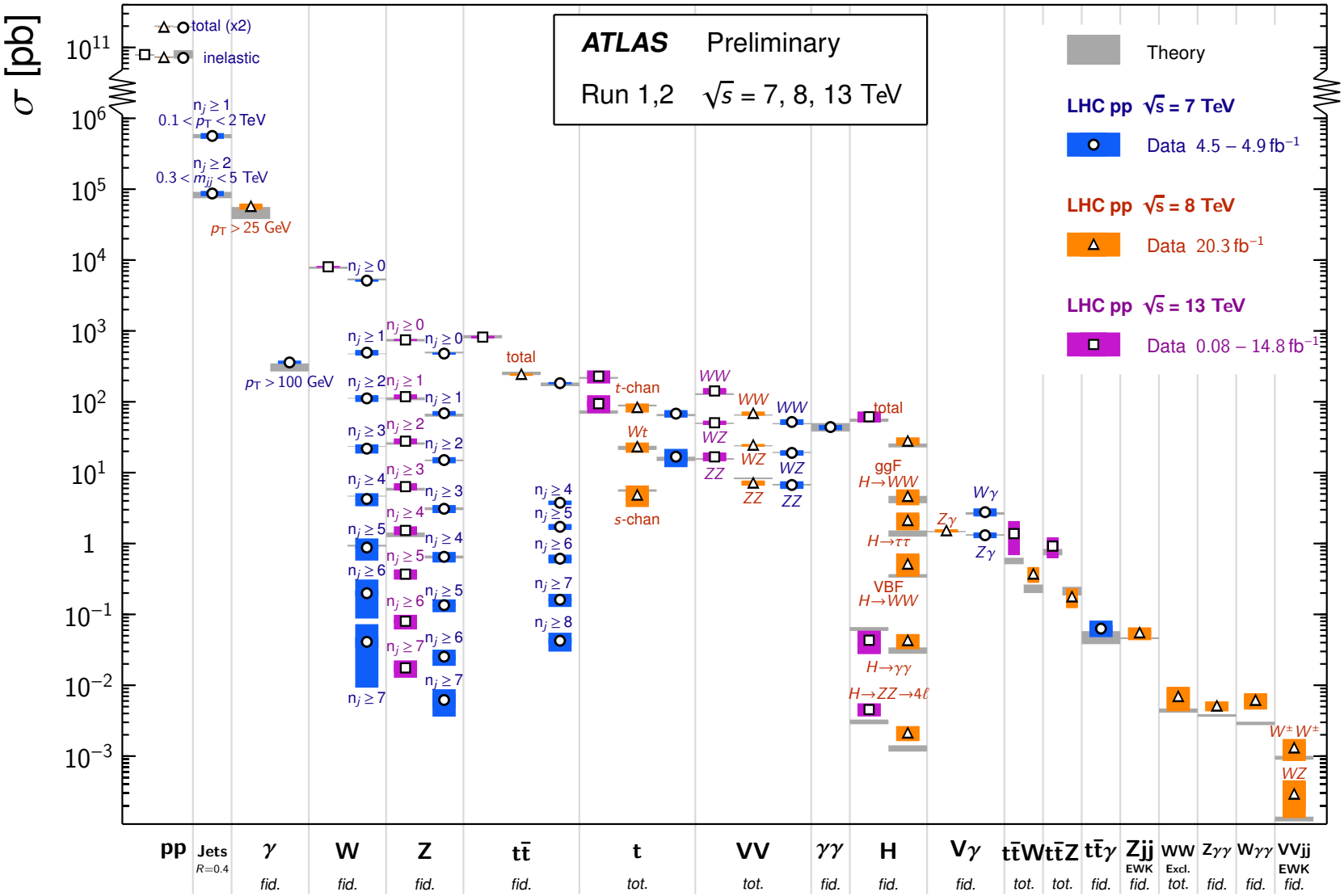
Tools

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

LHC Cross Sections

Standard Model Production Cross Section Measurements

Status: August 2016



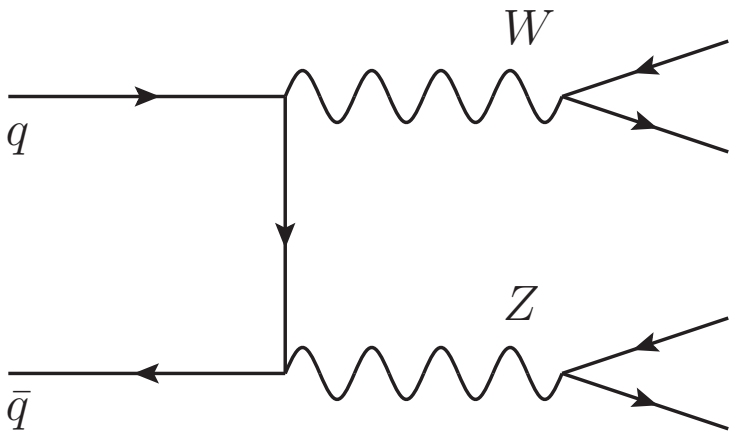
Diboson production at the LHC

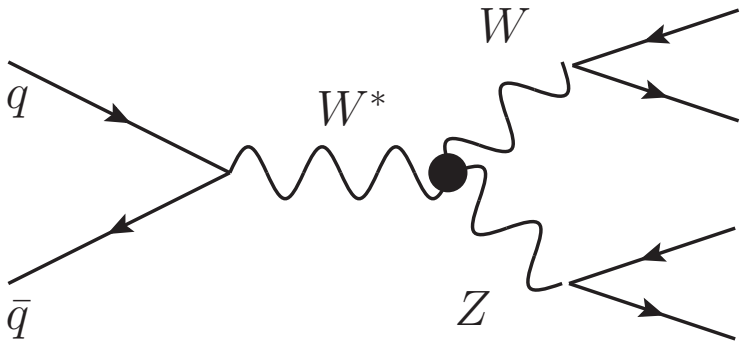
Why Diboson

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





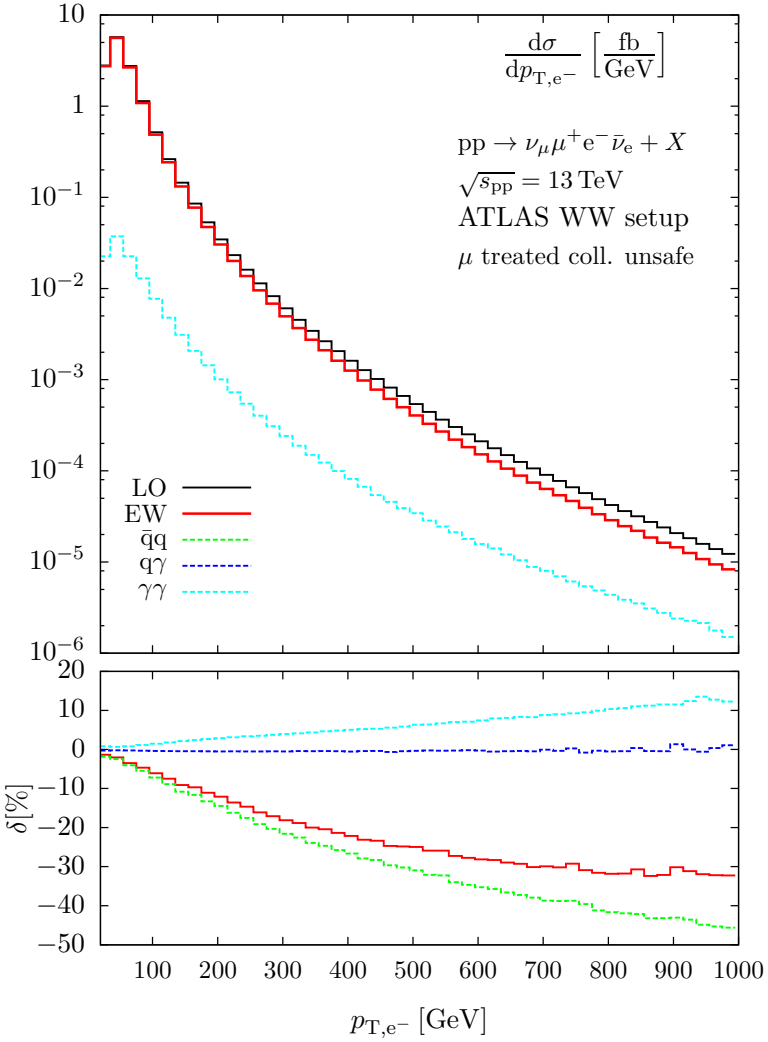
Corrections to diboson production

- NLO QCD first reliable prediction and scale variation uncertainty
  LO only depends on factorization scale
- NNLO QCD needed for precision measurements
  first order to include all partonic channels
  now available for all diboson processes [Grazzini, Kallweit et al.; Ellis et al.;]
  corrections to gg initial state large [Caola, Melnikov, et al.]
  coming soon: more differential results, public codes
- NLO EW sizeable in tails of distributions
  work ongoing towards automation and combination with QCD corrections
  [Baglio et al.; Bierweiler, Kühn et al.; Biedermann et al.; Denner, Dittmaier et al.]
- matching to parton shower:
  established schemes for NLO QCD
  first results for DY NNLO QCQ + PS [Hoeche, Li, Prestel; Karlberg, Re, Zanderighi]

Recent results

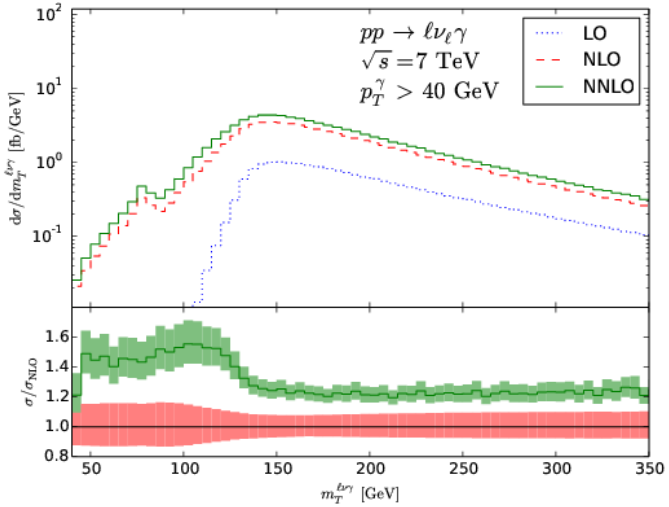
EW corrections to WW production

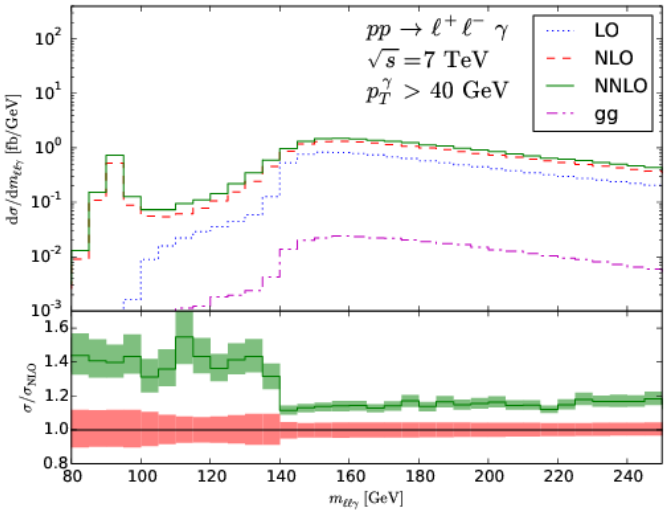
[Biedermann, Billoni, Denner, Dittmaier, Hofer, Jäger, Salfelder, 1605.03419]



NNLO QCD corrections to $V\gamma$ production

[Grazzini, Kallweit, Rathlev, 1601.06751]





Anomalous Couplings

SM as Effective Field Theory

- only use SM fields and preserve symmetries
- add higher-dimensional terms to Lagrangian $\mathcal{L} = \mathcal{L}_{\text{SM}} + \sum_i \frac{f_i}{\Lambda^2} \mathcal{O}_i$

Building Blocks

- 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:

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

Limited Validity of EFT

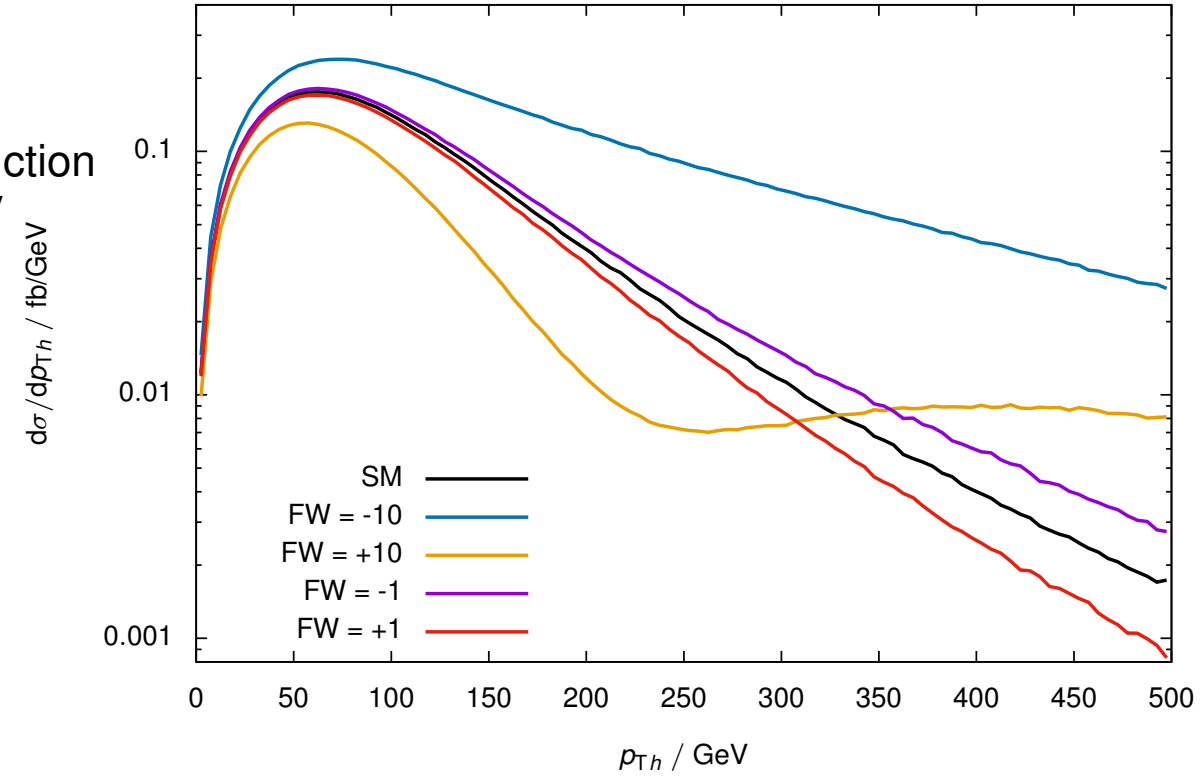
- low-energy expansion of unknown higher-energy model
- only valid if expansion parameter small
  validity depends on phase space region/kinematics

Anomalous Couplings

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

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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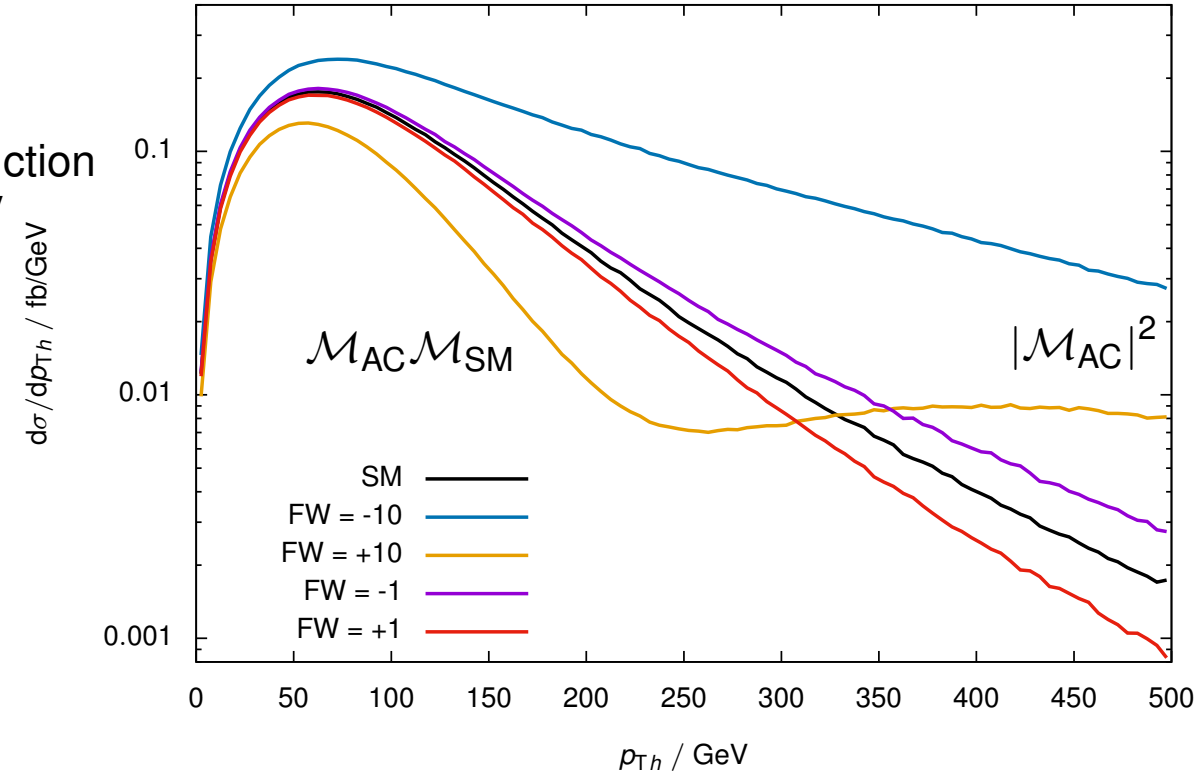

LoopSim

Idea

- "Giant QCD K-factors beyond NLO" [Rubin, Salam, Sapeta, 1006.2144]
- merge different multiplicity final states X@NLO + Xj@NLO = X@$\bar{n}$NLO
- 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, $\mathcal{O}(\alpha_s \ln^2 p_{T\text{jet}}/m_Z)$
- nearly NNLO in high-p_T tails

l (loops) \ k (legs)	0	1	2	3	...
2	$\sigma_0^{(2)}$	$\sigma_1^{(2)}$	...		
1	$\sigma_0^{(1)}$	$\sigma_1^{(1)}$	$\sigma_2^{(1)}$	...	
0	$\sigma_0^{(0)}$	$\sigma_1^{(0)}$	$\sigma_2^{(0)}$	$\sigma_3^{(0)}$	...

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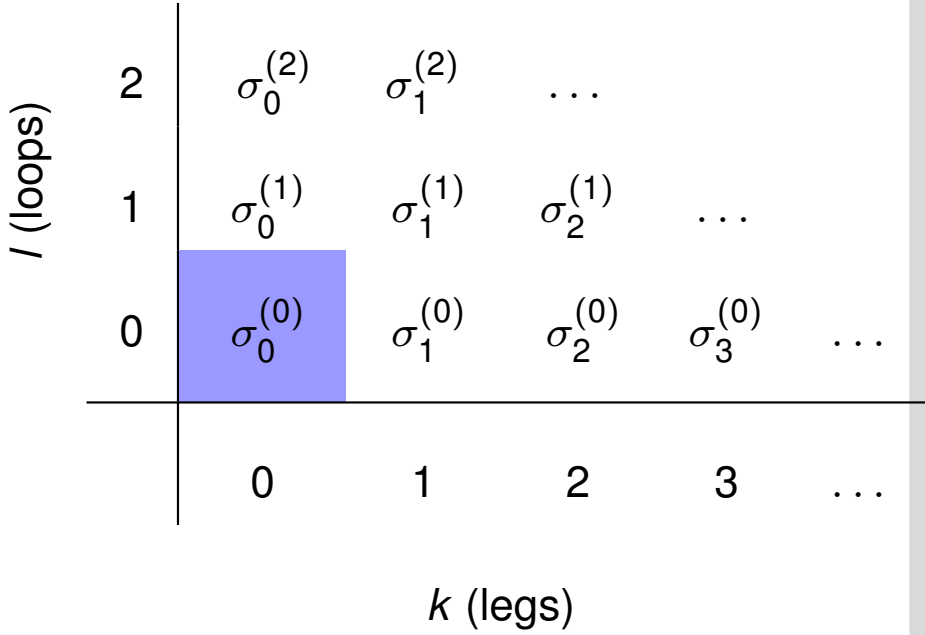

X@LO

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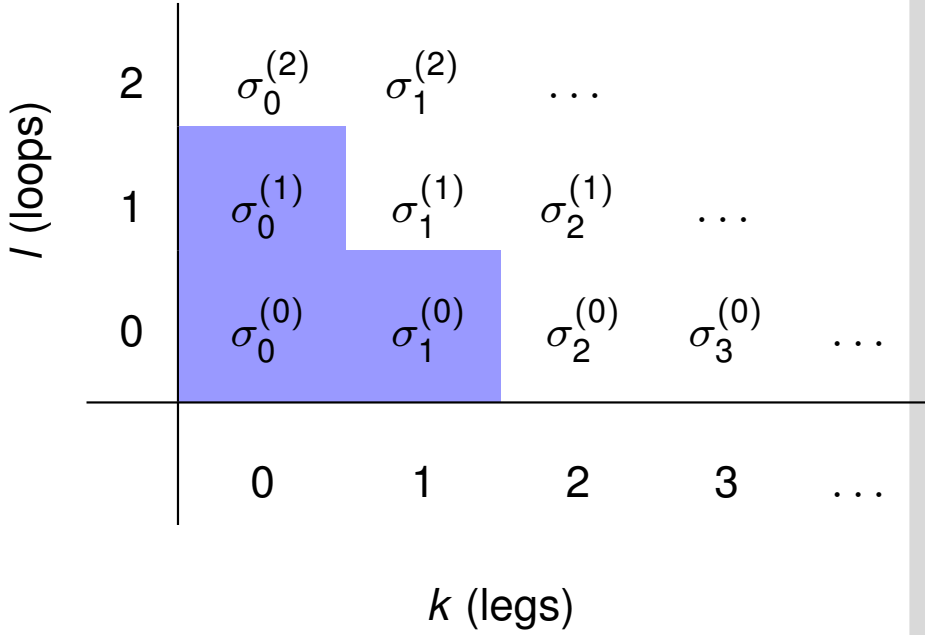

X@NLO

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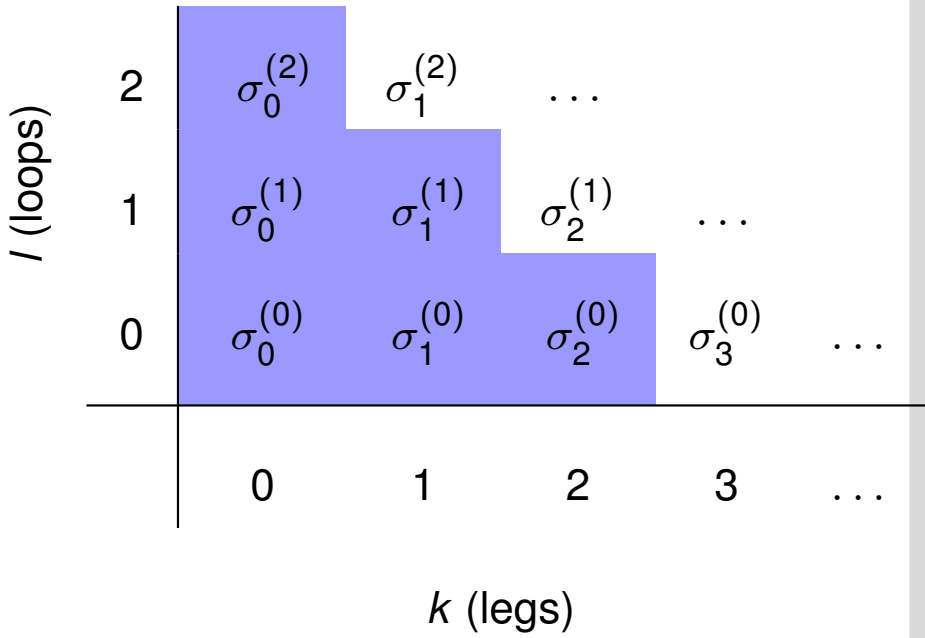

X@NNLO

LoopSim

Idea

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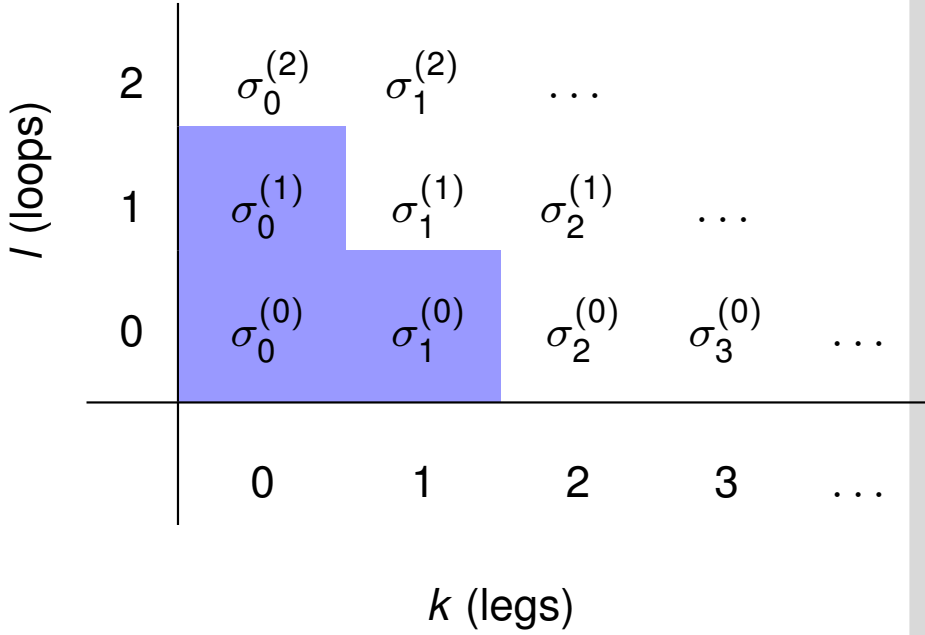

X@NLO

LoopSim

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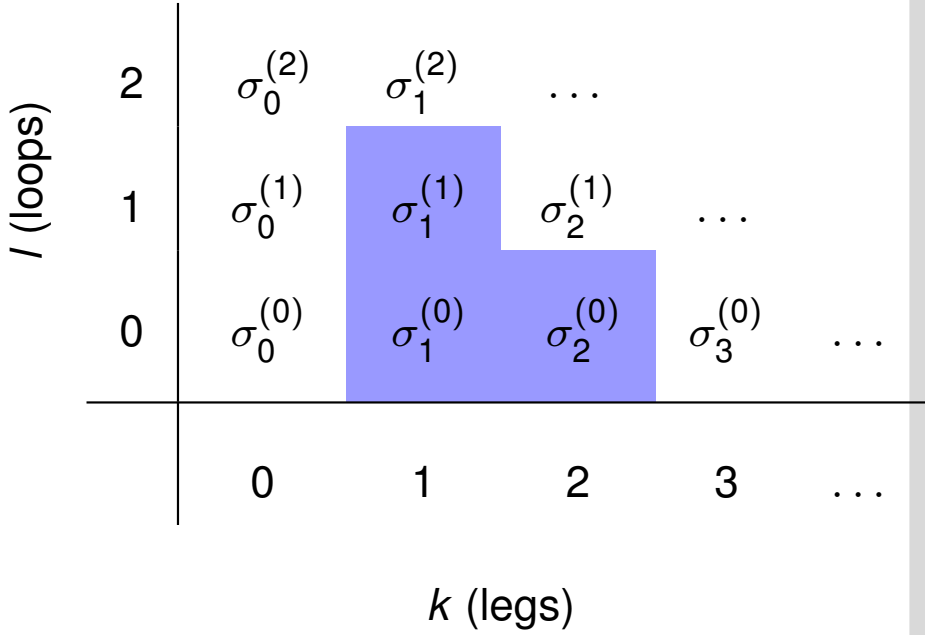

X+jet@NLO

LoopSim

Idea

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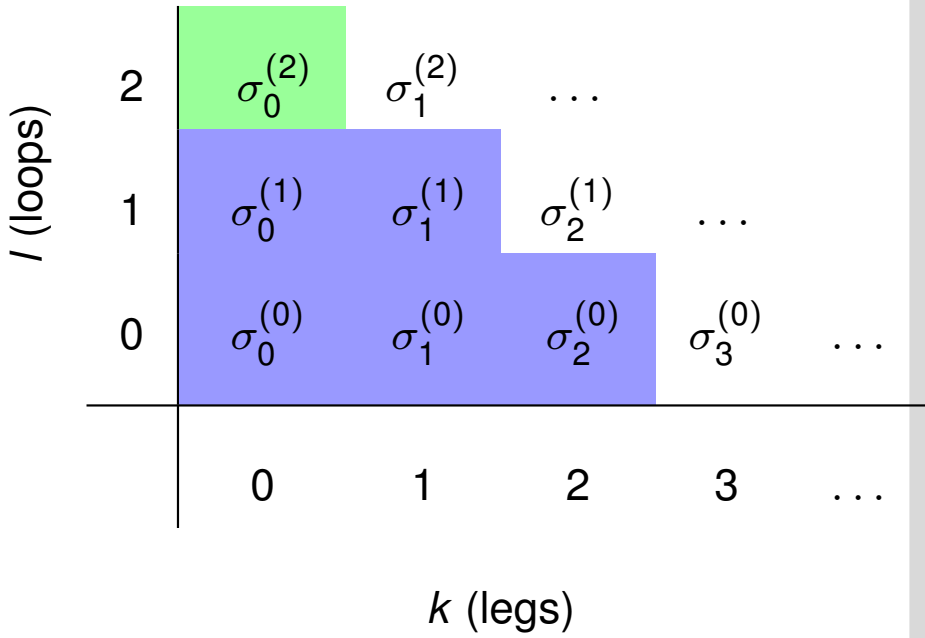
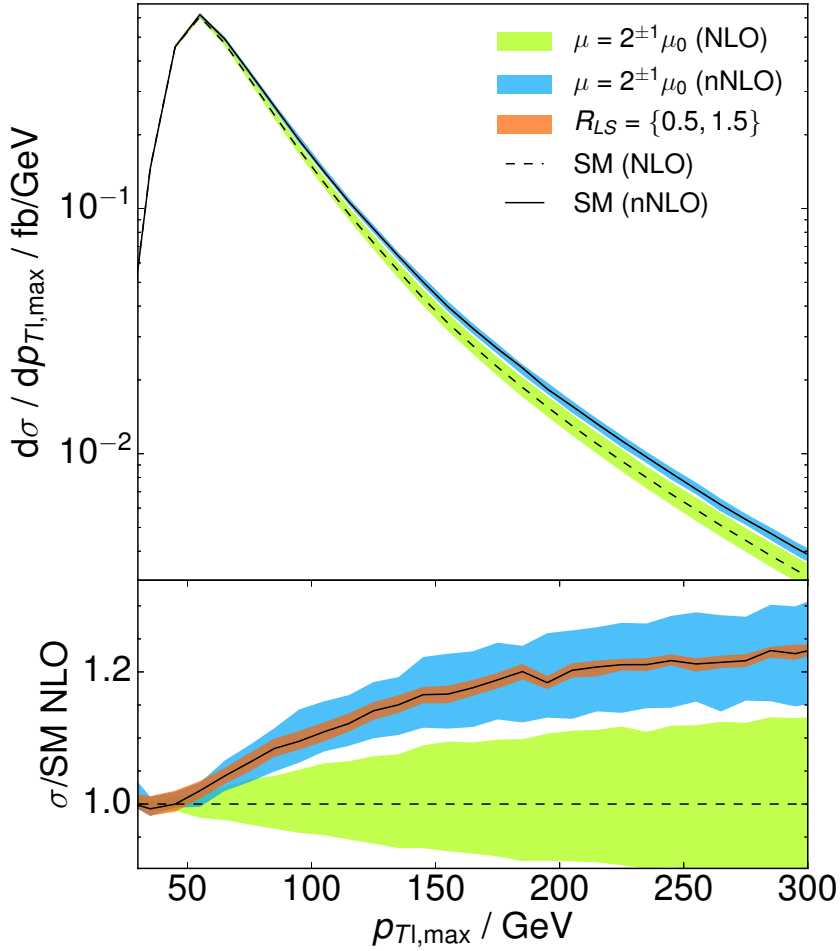
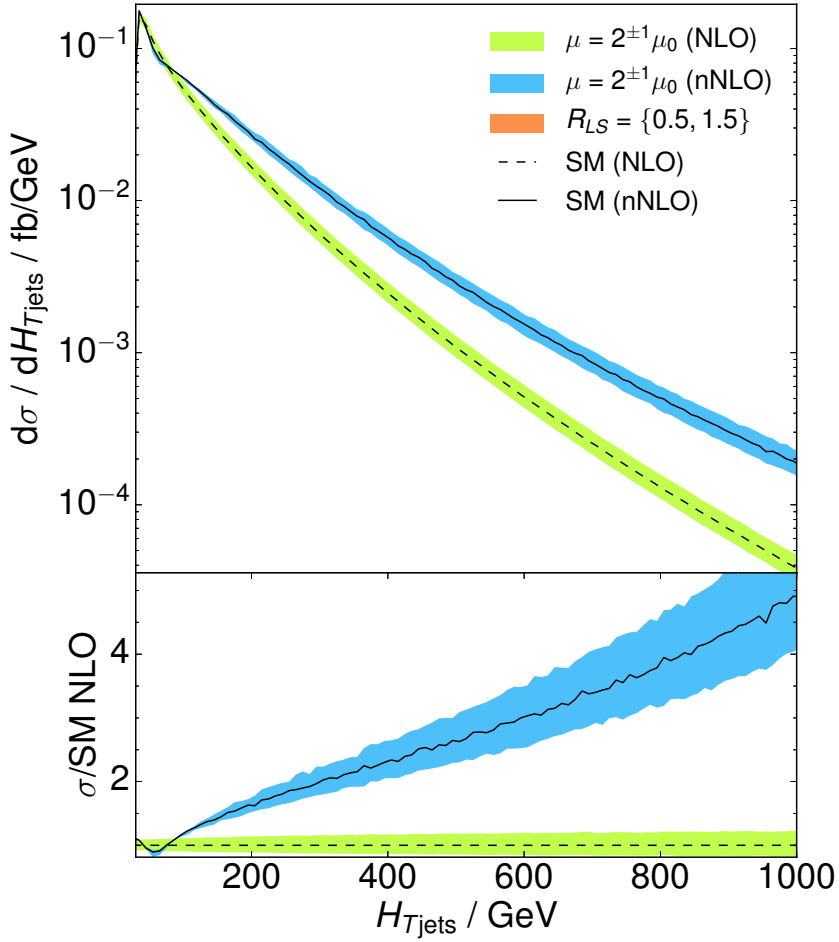


X@n̄NLO

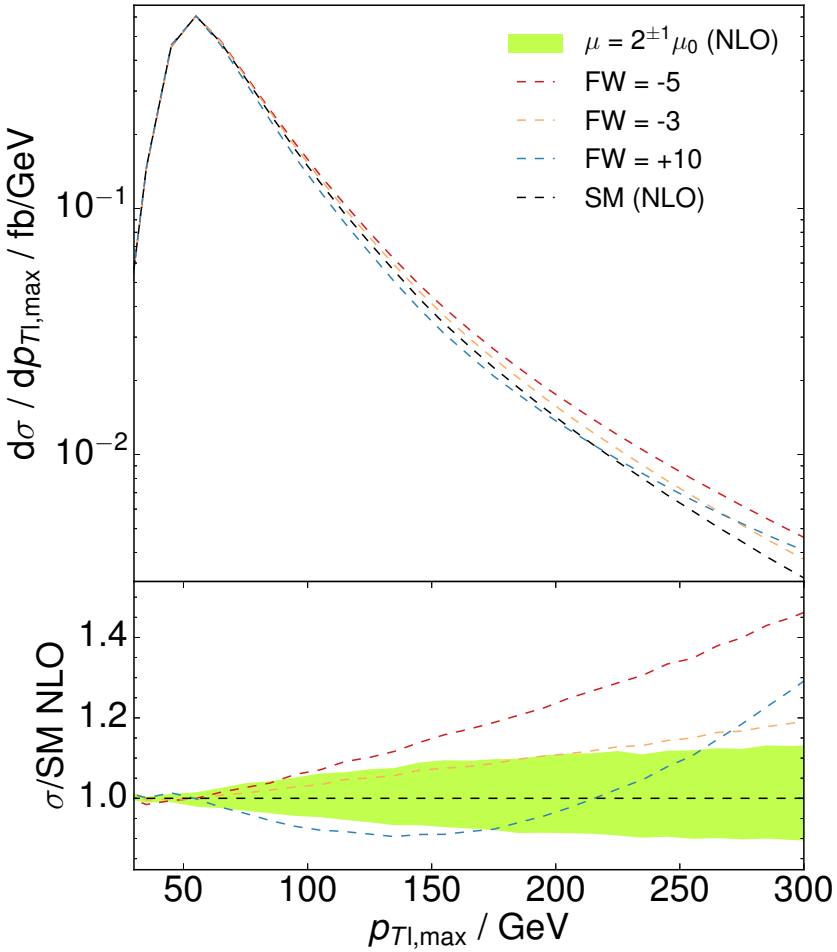
n̄NLO for WZ production

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





AC for diboson production



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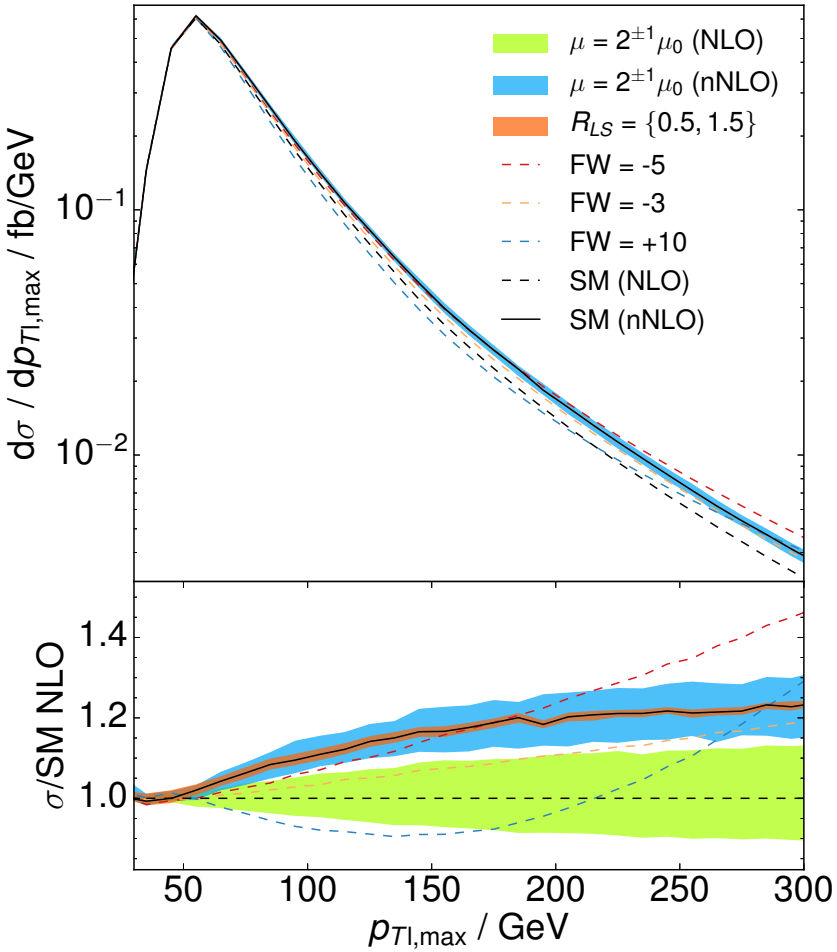

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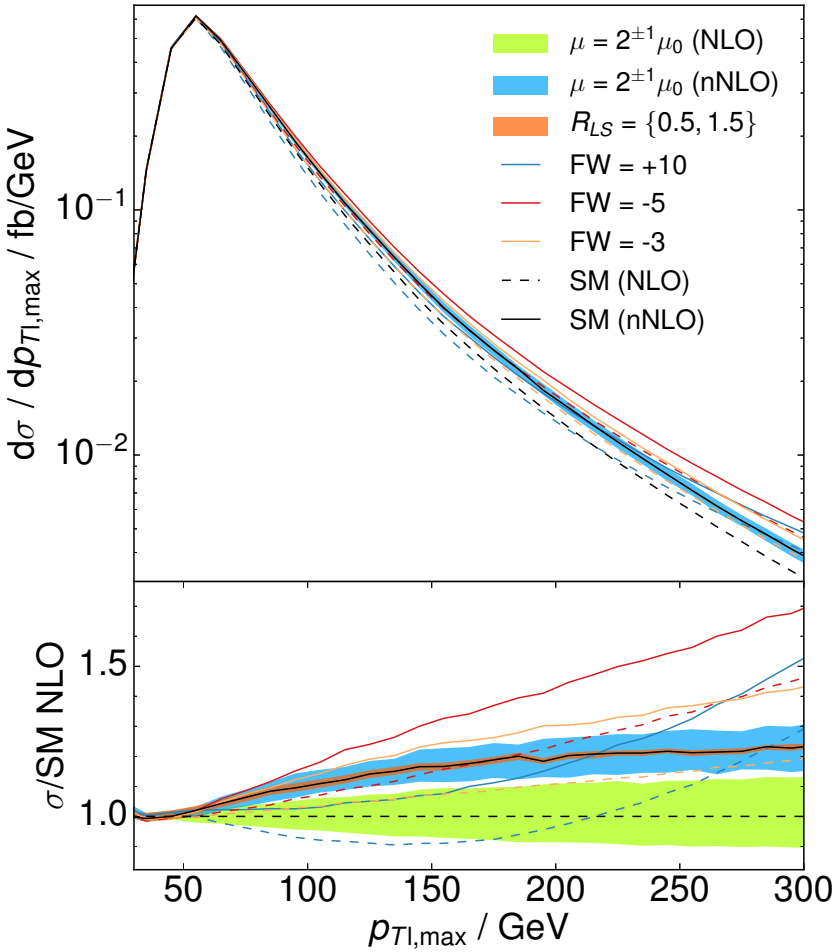
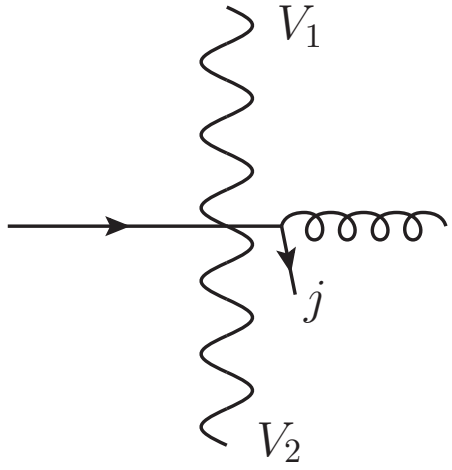
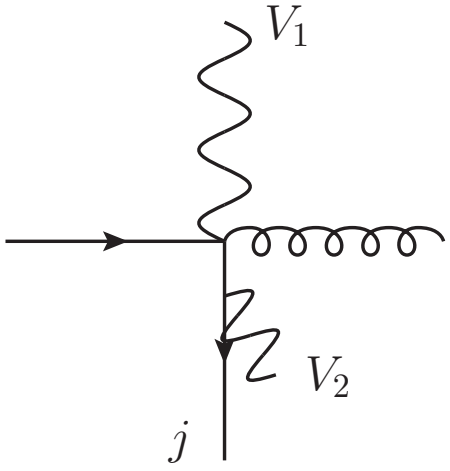


Jet vetos

want VV + jets, not Vj + V





Traditional (fixed) jet veto

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

Dynamical veto

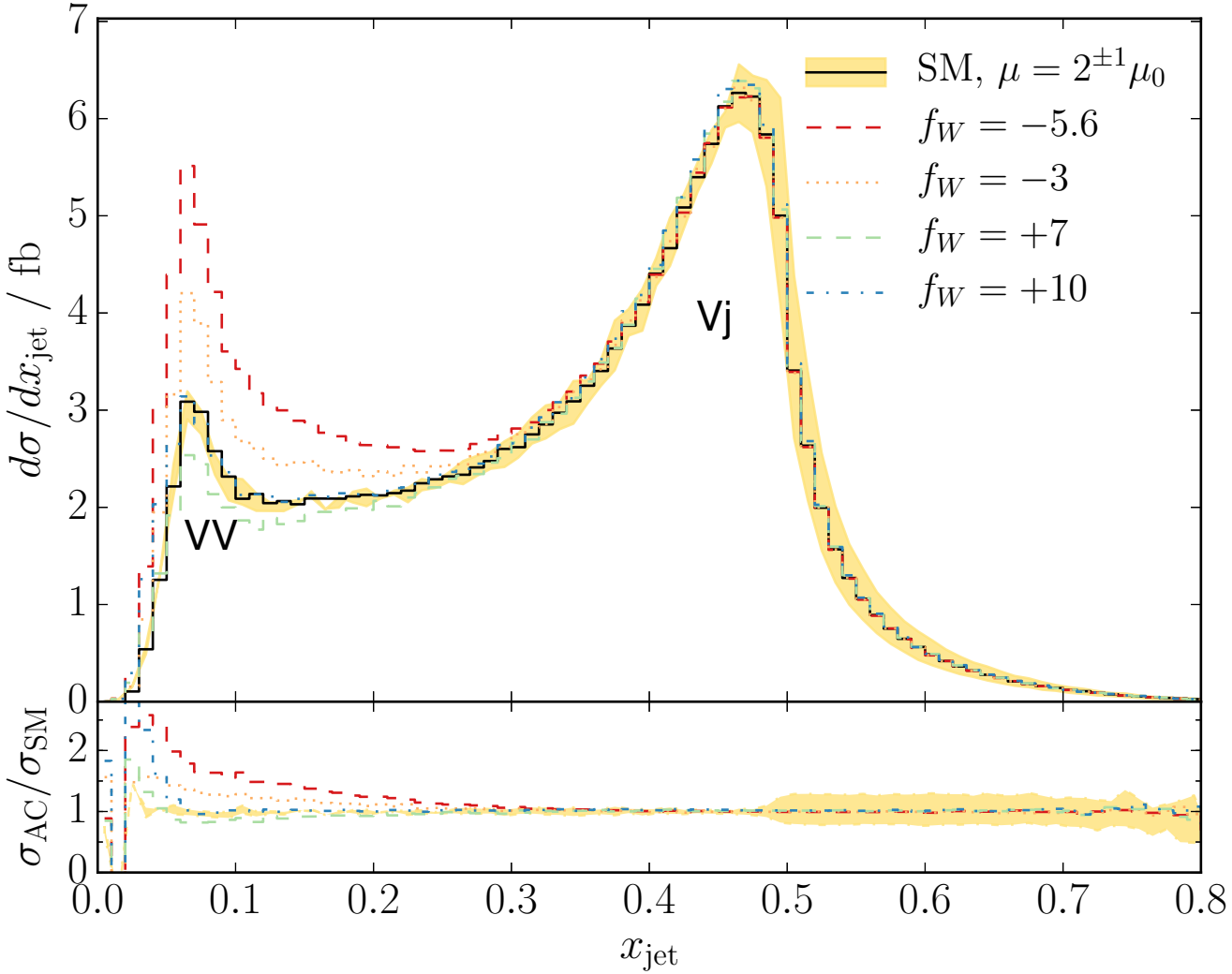
[Campanario, RR, Zeppenfeld, 1410.4840]

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

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

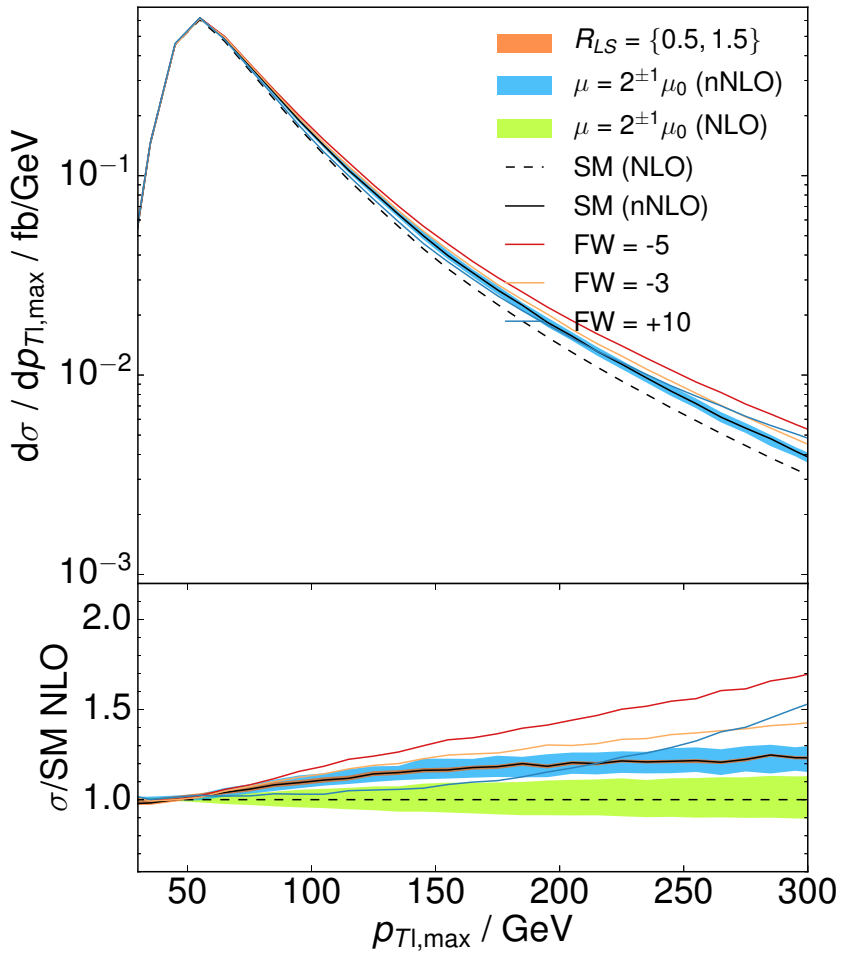
$$\mathrm{E}_{\mathrm{T}} = E\,\frac{|\vec{p}_{\mathrm{T}}|}{|\vec{p}|}$$

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



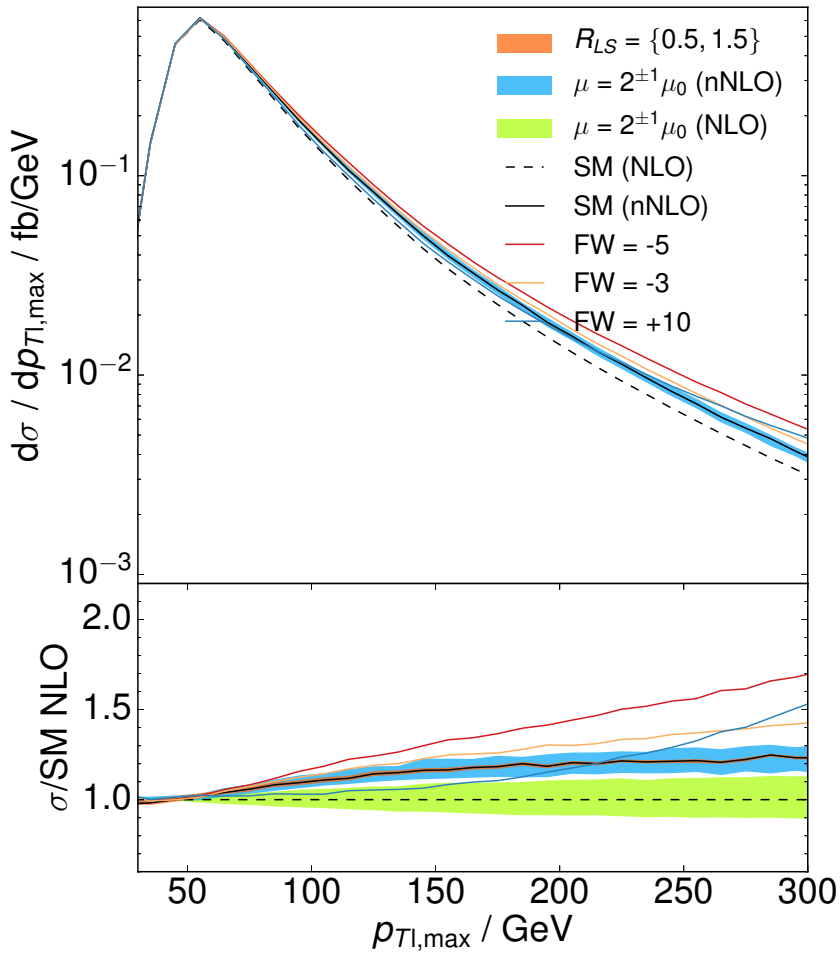
$p_{TZ} > 200\,\text{GeV}$

Dynamical veto to improve AC sensitivity

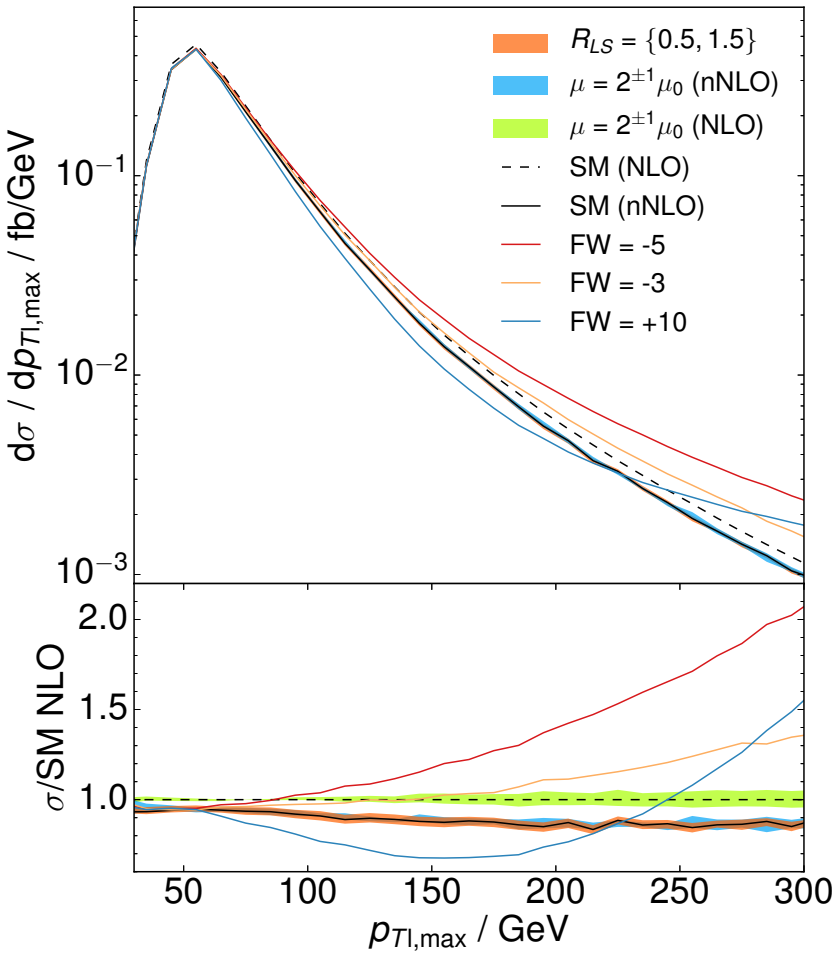


inclusive

Dynamical veto to improve AC sensitivity



inclusive



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

Conclusion

Beyond NLO: Loopsim

- method to combine multiplicities consistently at parton level
  X@NLO + Xj@NLO = X@$\bar{n}$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

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

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 $\mathcal{O}(\alpha_{\text{QED}})$

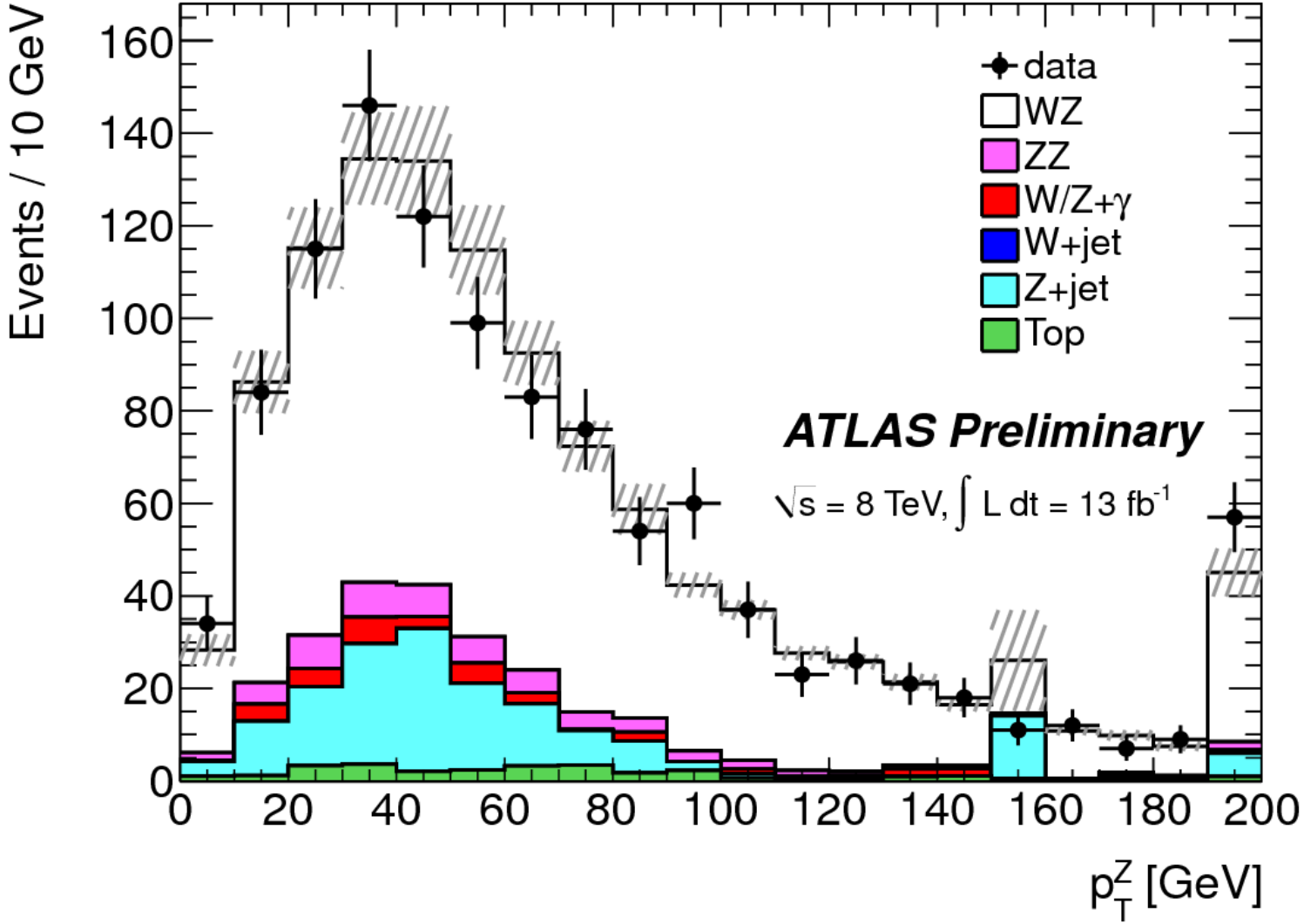
Power counting in Λ

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

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

- 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 $|\mathcal{M}_{\text{AC}}|^2 \ll \mathcal{M}_{\text{SM}}^*\mathcal{M}_{\text{SM}}$
- but: $\mathcal{M}_{\text{SM}}$ accidentally small (phase space, weak coupling compared to $\mathcal{M}_{\text{AC}}$) $\Rightarrow \mathcal{M}_{\text{SM}}^*\mathcal{M}_{\text{AC}}$ suppressed, $\left|\mathcal{M}_{\text{AC}}^{d=6}\right|^2$ leading $1/\Lambda^4$ term

ATLAS WZ p_{TZ}


Events / 10 GeV
160
140
120
100
80
60
40
20
0
0
20
40
60
80
100
120
140
160
180
200
p_T^Z [GeV]
data
WZ
ZZ
W/Z+γ
W+jet
Z+jet
Top
ATLAS Preliminary
$\sqrt{s}$ = 8 TeV, $\int$ L dt = 13 fb^{-1}

Event Selection

Cuts

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

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

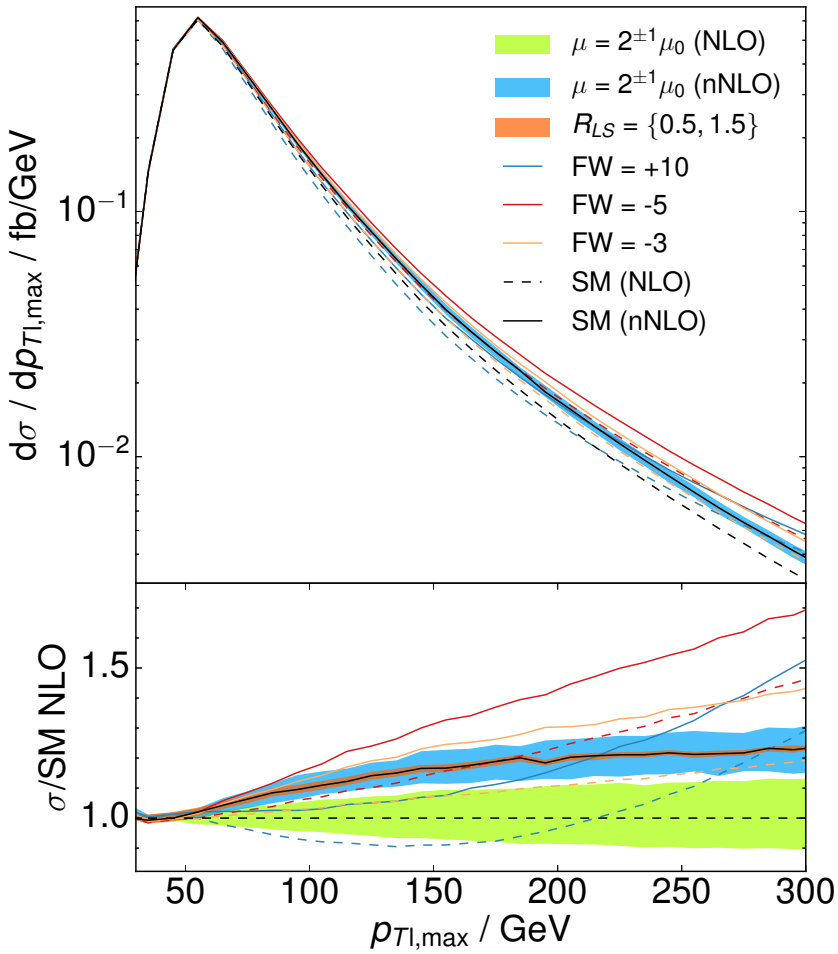
$60\,\mathrm{GeV} < m_{ll} < 120\,\mathrm{GeV}$

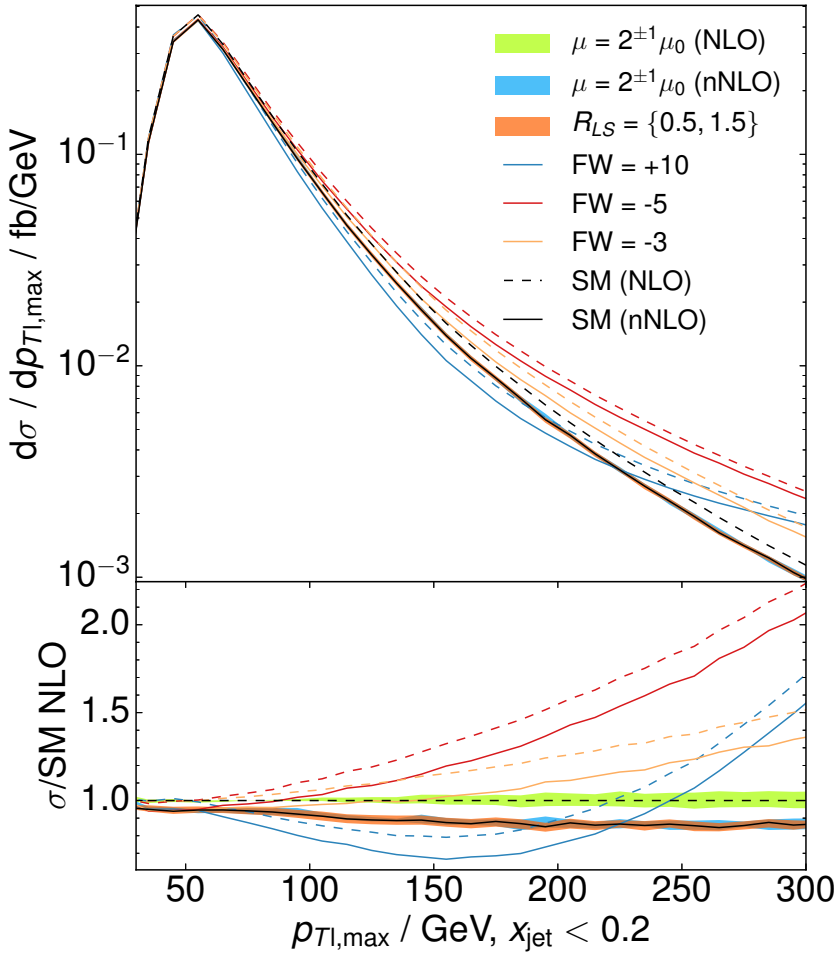
boosted: $p_{\mathrm{T}Z} > 200\,\mathrm{GeV}$

Input values

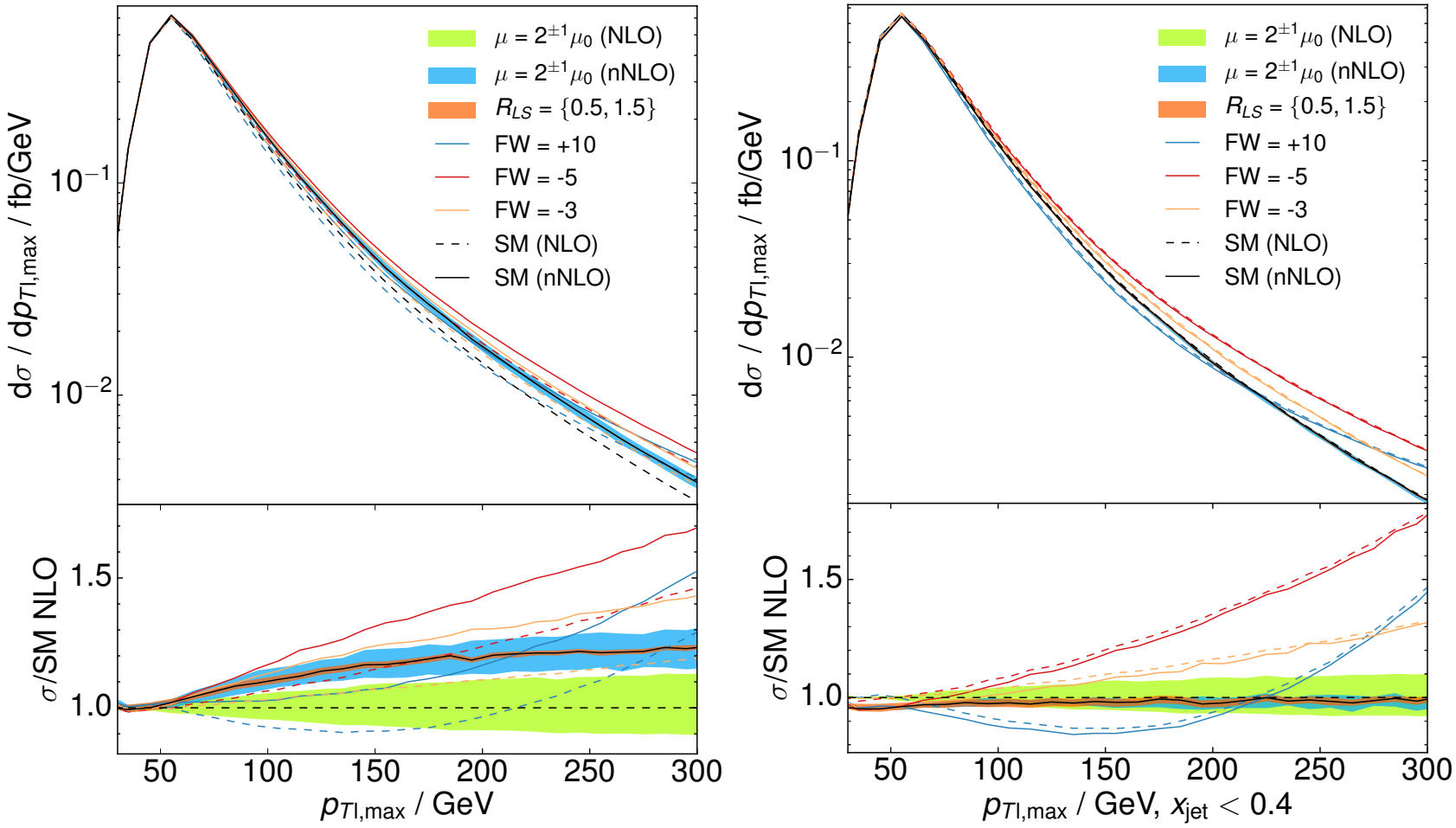
- EW constants: VBFNLO default
- PDF: NNPDF23

Different x_{jet} cuts

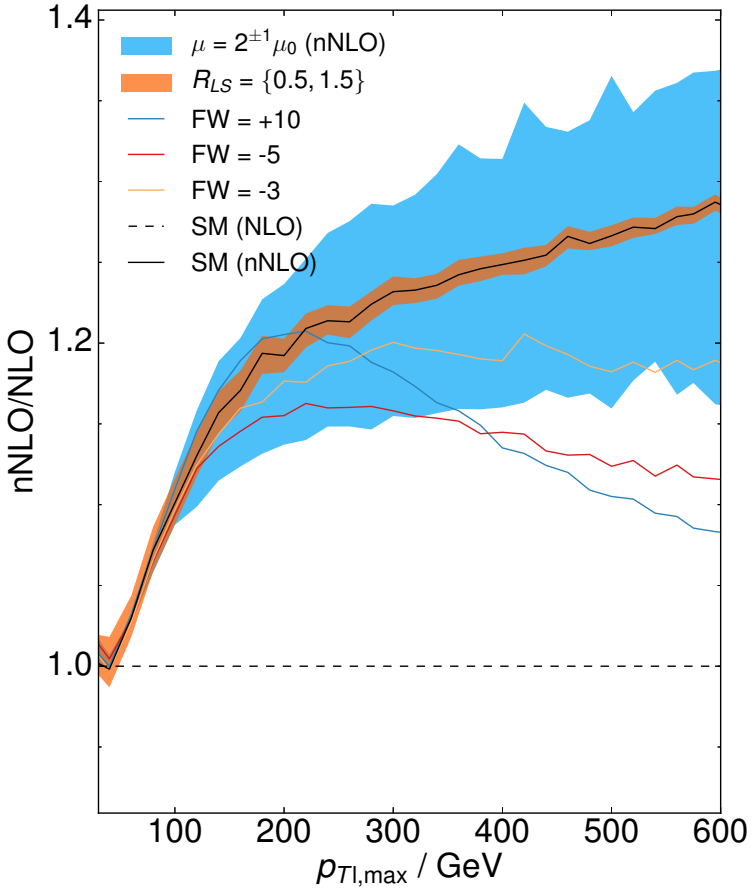


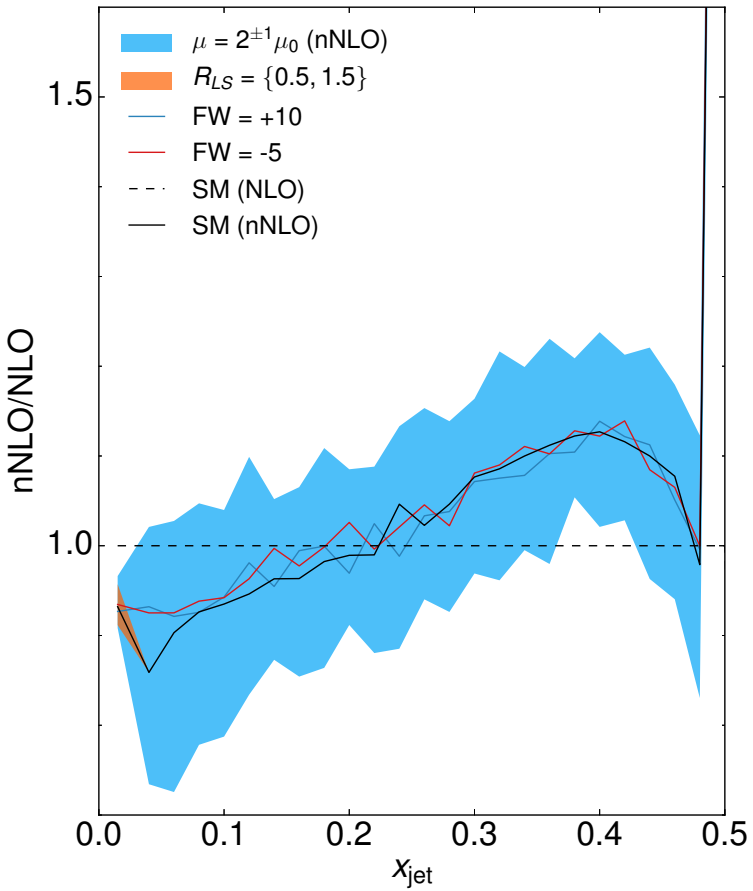


Different x_{jet} cuts



x_{jet} n̄NLO corrections





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. ($p_{\text{TW}}, p_{\text{TZ}}, p_{\text{Tjet}}$)- 2 (total $p_{\text{T}} = 0$) - 1 (no ϕ dependence) - 1 (rescaling at high p_{T})
- dalitz-like construction

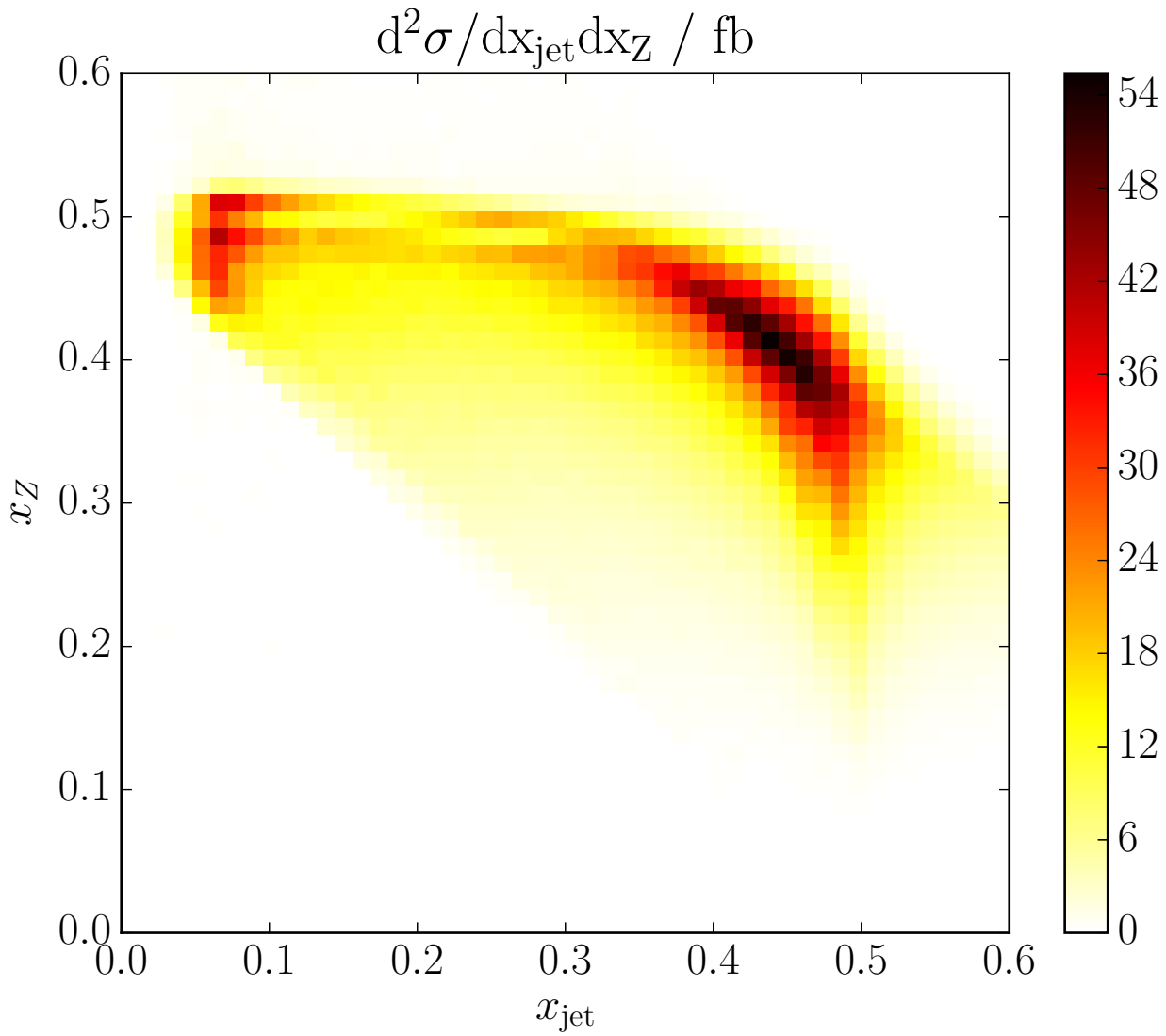
$$x_{\text{jet}} = \frac{\sum_{\text{jets}} \text{E}_{\text{T},i}}{\sum_{\text{jets}} \text{E}_{\text{T},i} + \text{E}_{\text{T},W} + \text{E}_{\text{T},Z}}, \quad x_V = \frac{E_{TV}}{\sum_{\text{jets}} \text{E}_{\text{T},i} + \text{E}_{\text{T},W} + \text{E}_{\text{T},Z}}$$

$$x_{\text{jet}} + x_{\text{W}} + x_{\text{Z}} = 1$$

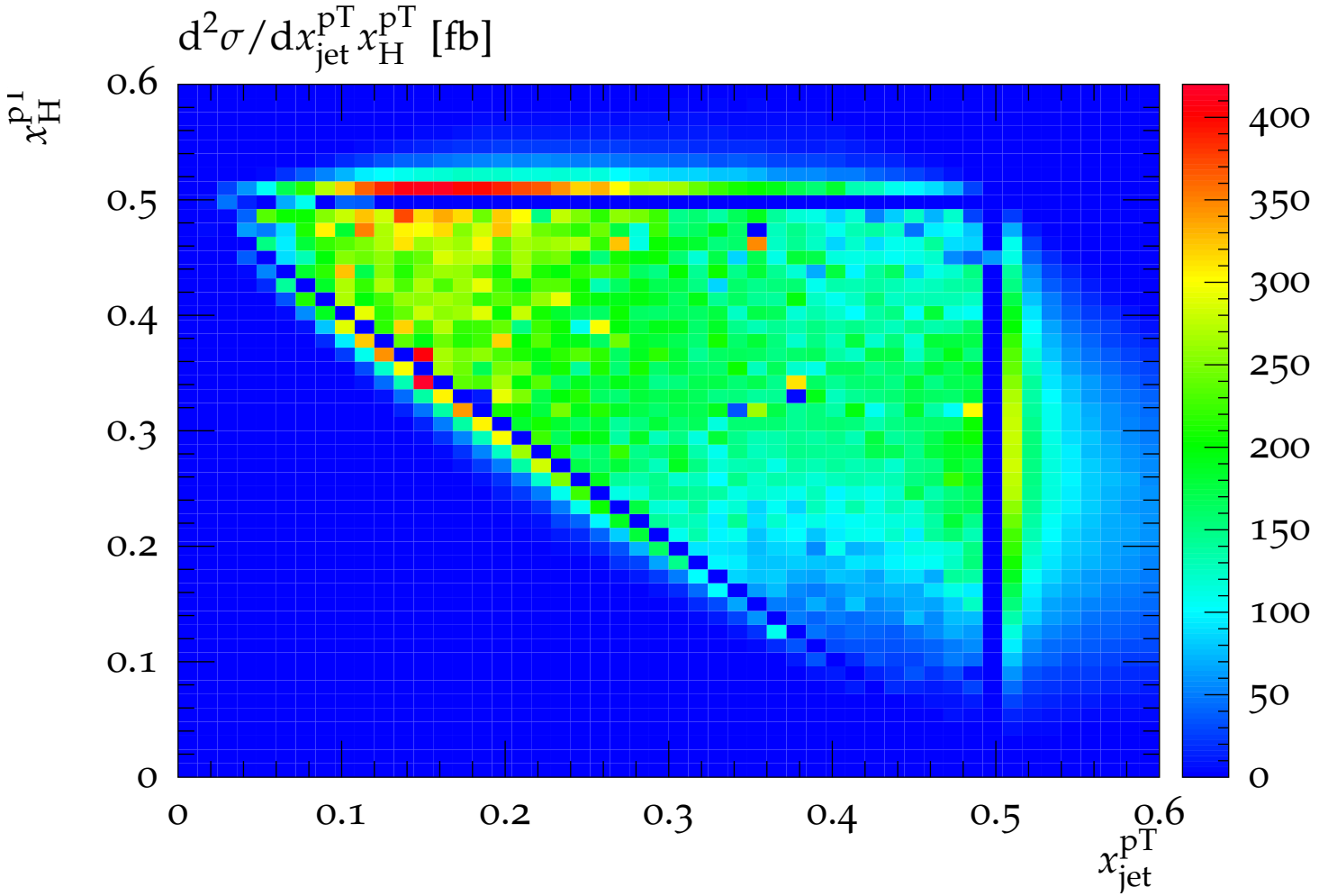
$$x_i \leq 0.5 \quad \text{(at LO only)}$$

other choices: p_{T} instead of E_{T}, partons instead of jets, ...
Careful not to be (too) infrared-sensitive

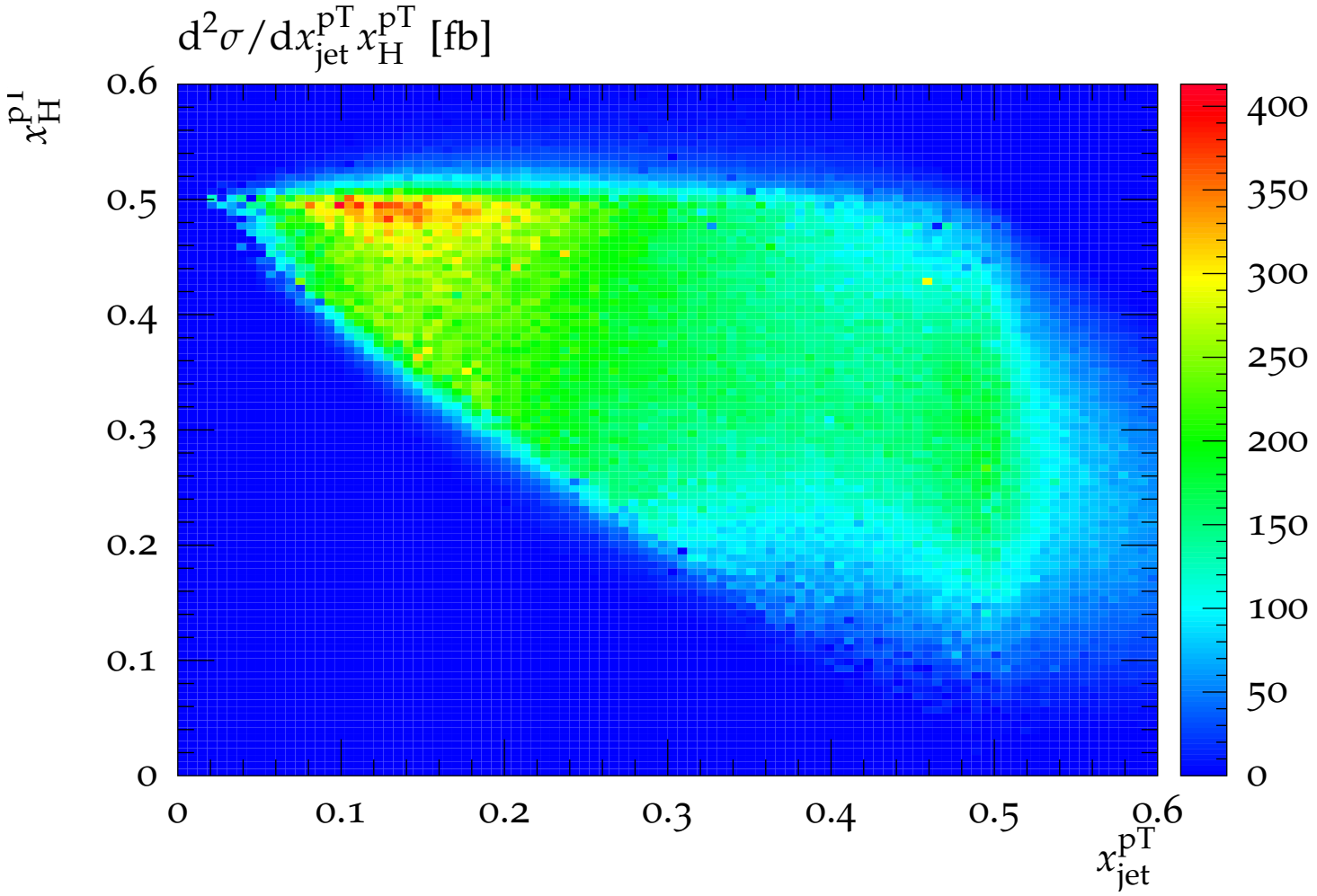
Observable: x_{jet}, x_Z



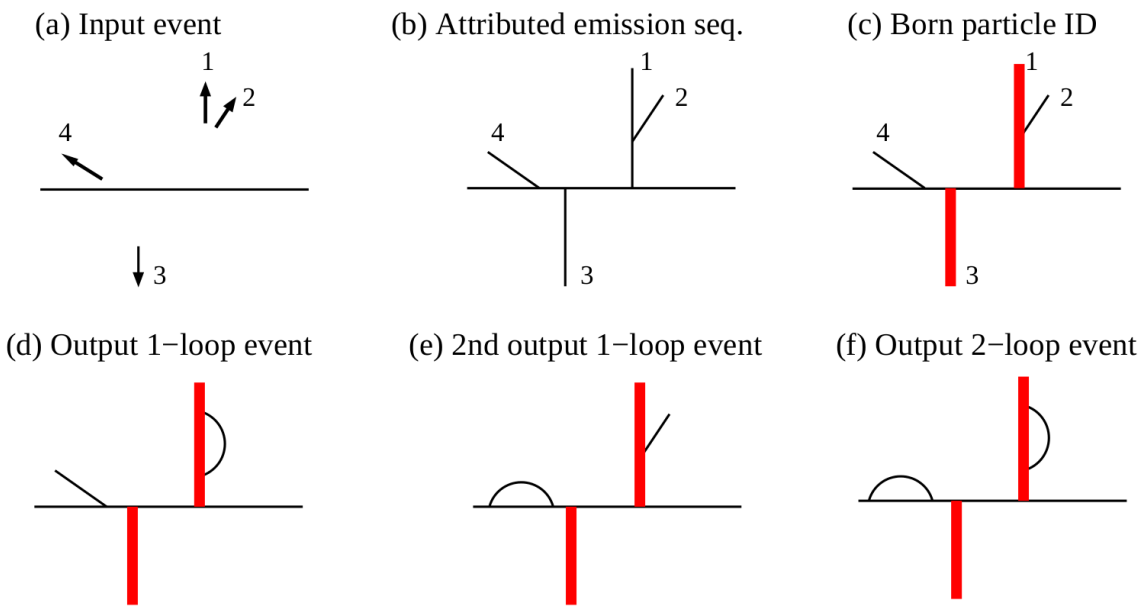
PS effects on x_{jet}



PS effects on x_{jet}

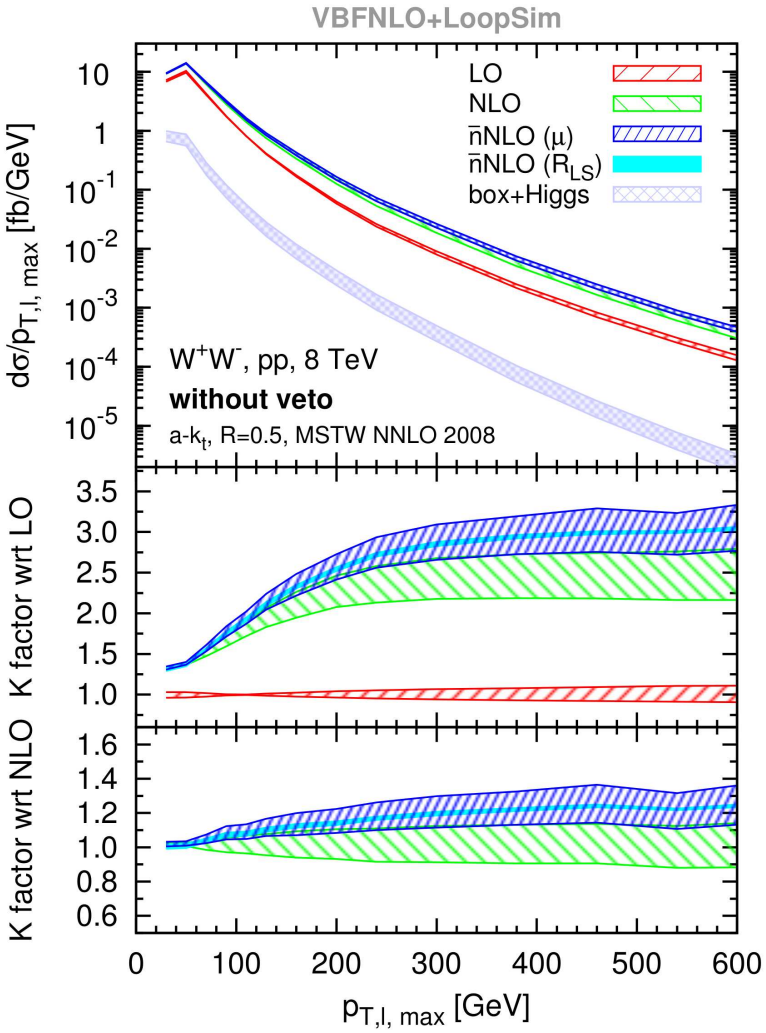


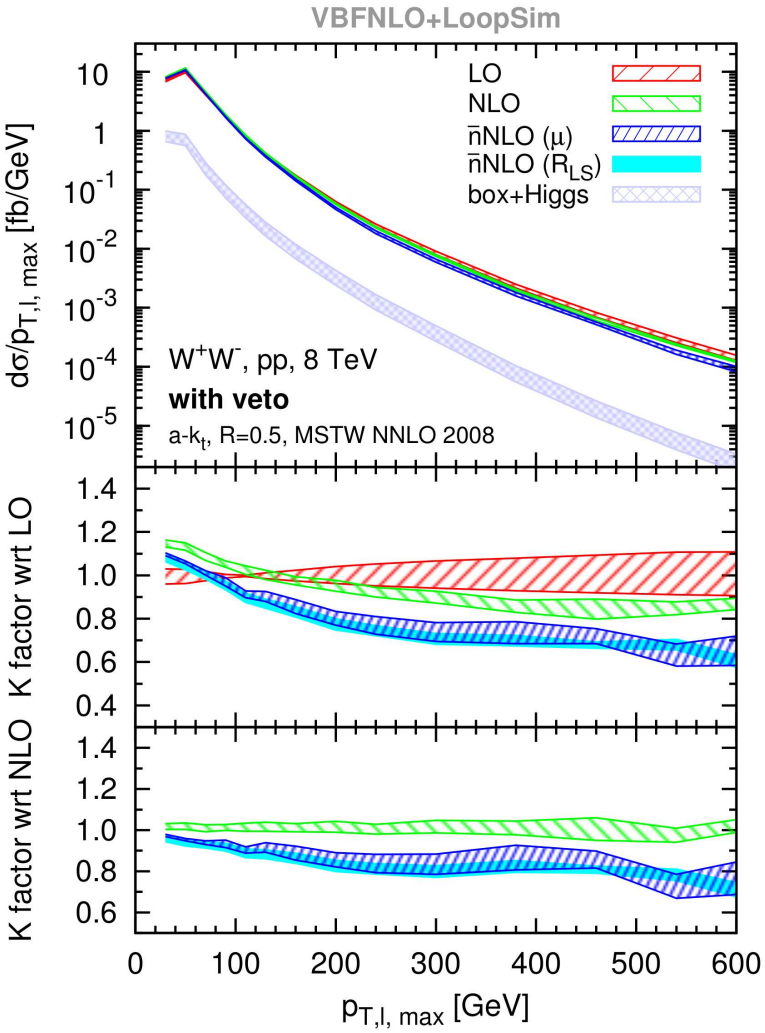
The LoopSim Method – “Looping”



- 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

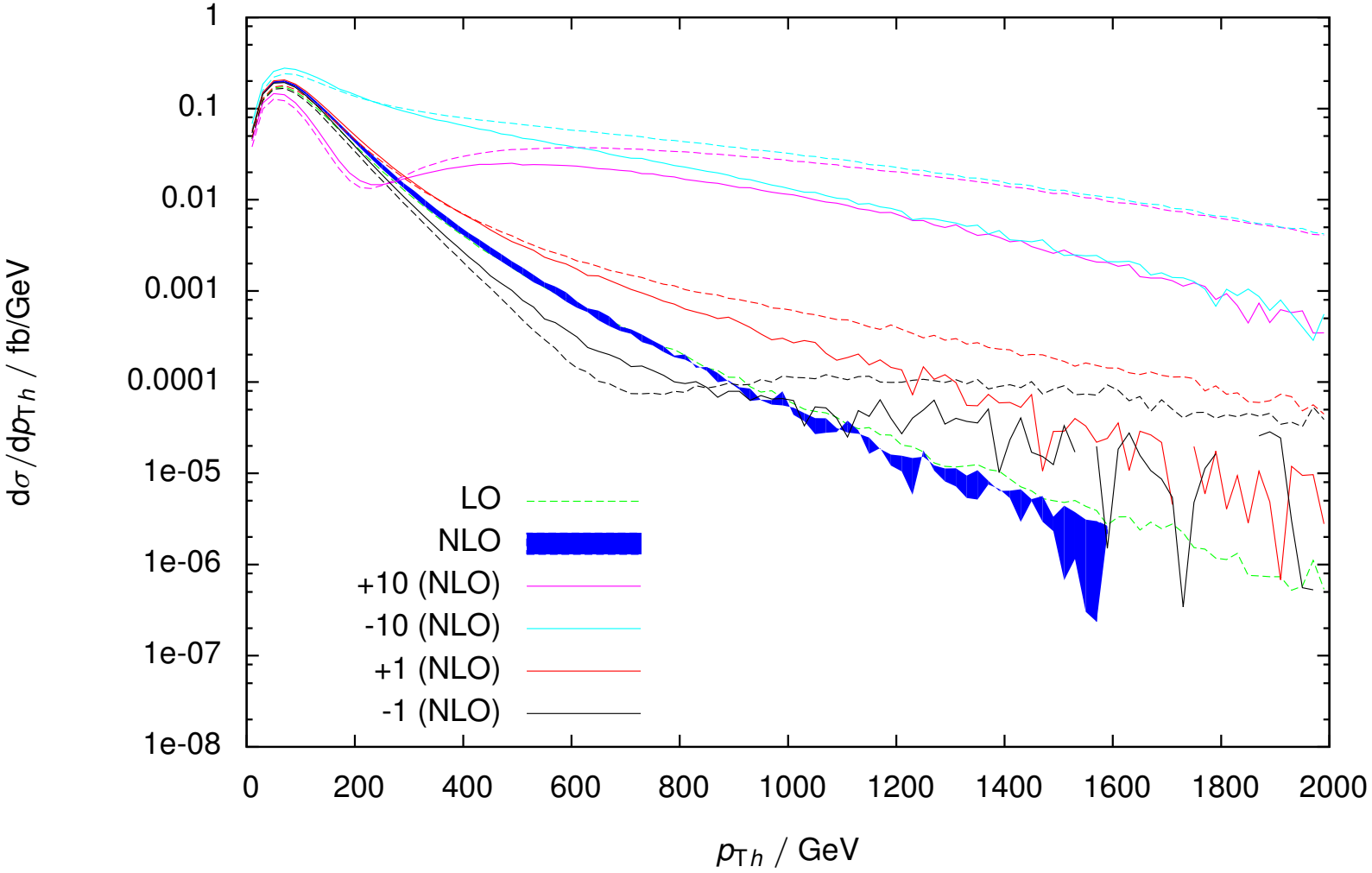




[Campanario, Rauch, Sapeta, 1309.7293]

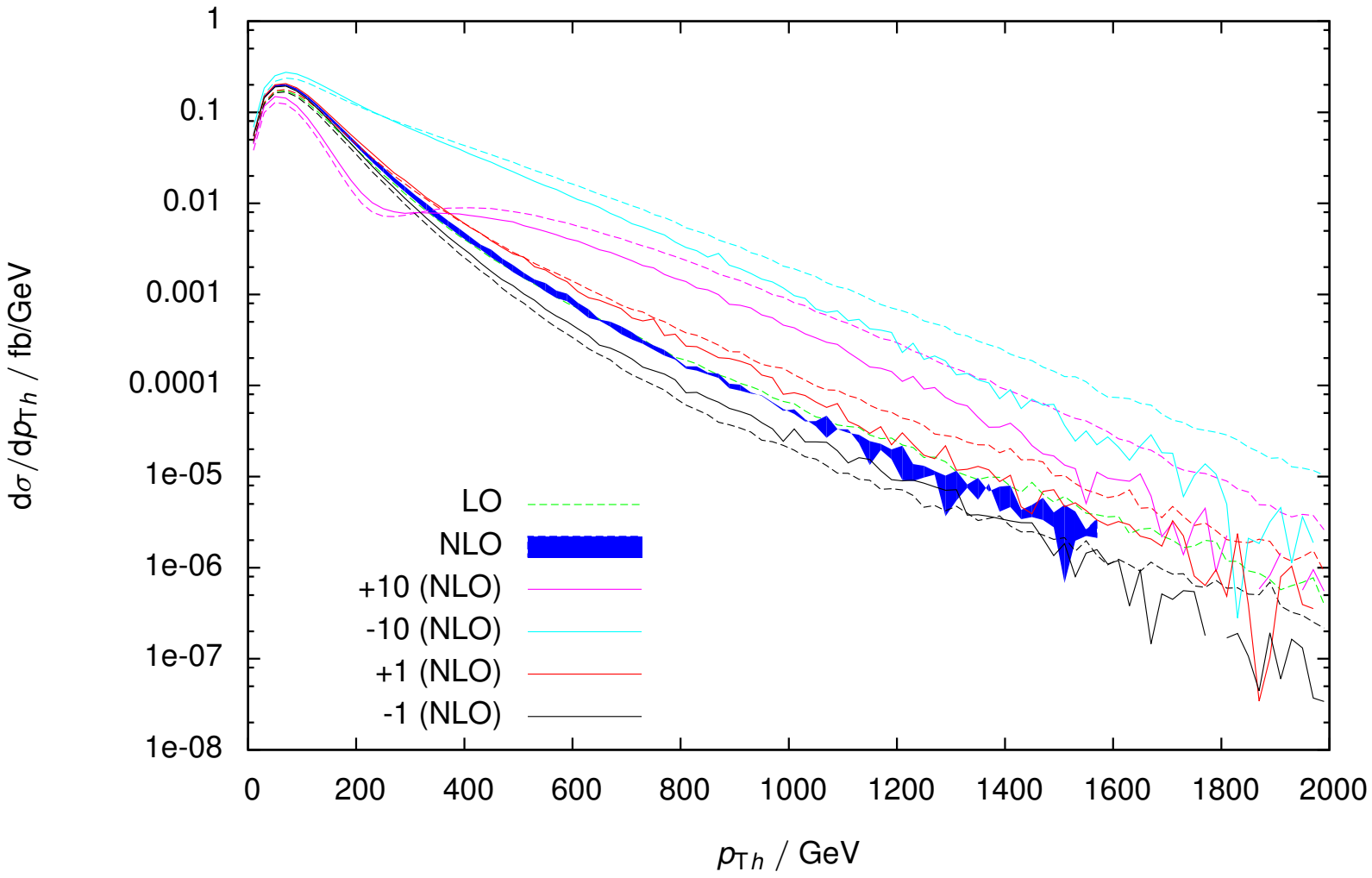
Anomalous Couplings

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



Anomalous Couplings

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



Current state of diboson production at the LHC