TECHNISCHE UNIVERSITÄT DRESDEN

Fakultät Mathematik und Naturwissenschaften Institut für Kern- und Teilchenphysik

MC simulations of vector-boson production processes

Recent methodological developments

Frank Siegert

Standard Model at LHC 2014, Madrid, 9 April

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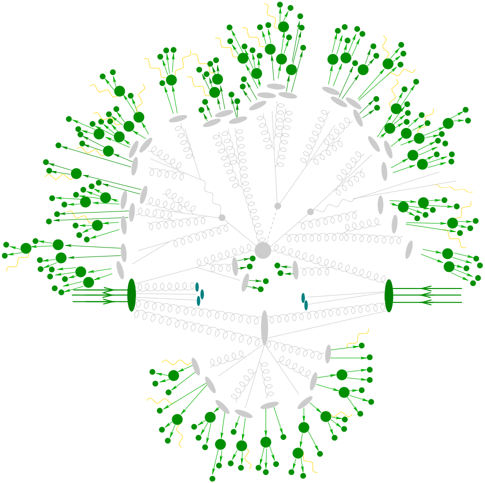
Introduction: Monte-Carlo event generators



- We want:
  Simulation of $pp \to$ full hadronised final state
- MC event representation
- We know from first principles:
  - Hard scattering at fixed order in perturbation theory (**Matrix Element**)
  - Approximate resummation of QCD corrections to all orders (**Parton Shower**)
- Hadronisation/Underlying event

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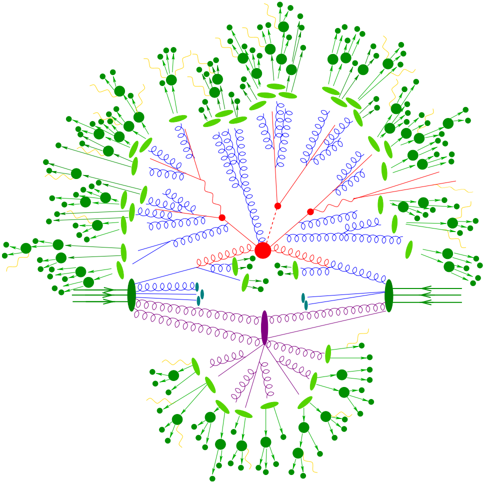

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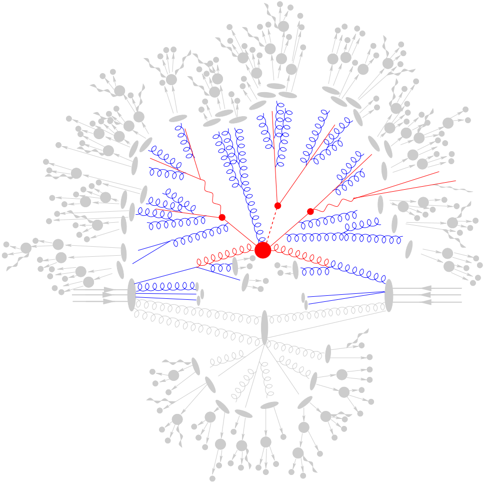

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Outline

- Improving parton showers at fixed order
- (Applications in V+jets)
- Applications in VV+jets
- Finite loop^2 contributions
- Applications in VVV+jets

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Parton shower corrections: Classification

NLO+PS matching

- Parton shower on top of NLO prediction (e.g. inclusive W production)
- Objectives:
  - avoid double counting in real emission
  - preserve inclusive NLO accuracy

ME+PS@LO merging

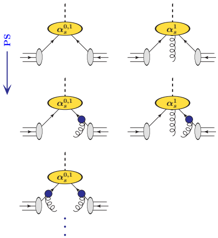
- Multiple LO+PS simulations for processes of different jet multi (e.g. W, Wj, Wjj, . . .)
- Objectives:
  - combine into one inclusive sample by making them exclusive
  - preserve resummation accuracy

⇓ ⇓

Combination: MEPS@NLO

- Multiple NLO+PS simulations for processes of different jet multiplicity e.g. W, Wj, Wjj, . . .
- Objectives:
  - combine into one inclusive sample
  - preserve NLO accuracy for jet observables

NLO+PS matching in a nutshell



Basic idea

- “double-counting” between emission in real ME and parton shower
- ME is better than PS $\rightarrow$ subtract PS contribution first
- but: shower unitary $\rightarrow$ add “integrated” PS contribution back for NLO accuracy

Reminder + notation: NLO subtraction

$$\mathrm{d}\sigma^{(\mathrm{NLO})} = \mathrm{d}\Phi_B \left[\mathcal{B} + \tilde{\mathcal{V}} + \sum_{\{ij\}} \mathcal{I}^{(\mathrm{S})}_{(ij)} \right] + \mathrm{d}\Phi_R \left[\mathcal{R} - \sum_{\{ij\}} \mathcal{D}^{(\mathrm{S})}_{ij} \right]$$

NLO+PS formalism

- shower subtraction terms $\mathcal{D}^{(\mathrm{A})}_{ij}$

$$\mathrm{d}\sigma^{(\mathrm{NLO\ sub})} = \mathrm{d}\Phi_B \; \bar{\mathcal{B}}^{(\mathrm{A})} + \mathrm{d}\Phi_R \left[\mathcal{R} - \sum_{\{ij\}} \mathcal{D}^{(\mathrm{A})}_{ij} \right]$$

$$\text{with } \bar{\mathcal{B}}^{(\mathrm{A})} = \mathcal{B} + \tilde{\mathcal{V}} + \sum_{\{ij\}} \mathcal{I}^{(\mathrm{S})}_{(ij)} + \sum_{\{ij\}} \int \mathrm{d}t \left[\mathcal{D}^{(\mathrm{A})}_{ij} - \mathcal{D}^{(\mathrm{S})}_{ij} \right]$$

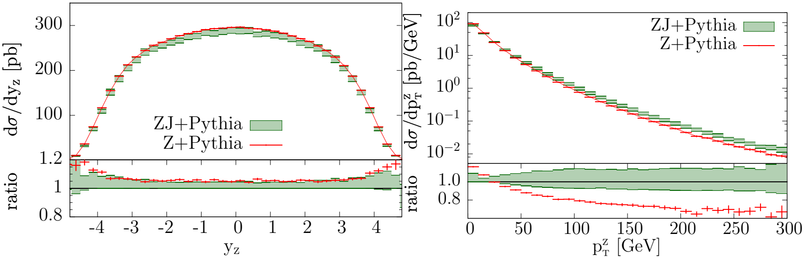
- apply PS resummation using $\mathcal{D}^{(\mathrm{A})}_{ij}$ as splitting kernels

Master formula for NLO+PS up to first emission

$$\mathrm{d}\sigma^{(\mathrm{NLO+PS})} = \mathrm{d}\Phi_B\, \bar{\mathcal{B}}^{(\mathrm{A})}\left[\underbrace{\Delta^{(\mathrm{A})}(t_0,\mu_Q^2)}_{\text{unresolved}} + \underbrace{\sum_{\{ij\}}\int_{t_0}^{\mu_Q^2}\mathrm{d}t\,\frac{\mathcal{D}_{ij}^{(\mathrm{A})}}{\mathcal{B}}\Delta^{(\mathrm{A})}(t,\mu_Q^2)}_{\text{resolved, singular}}\right] + \mathrm{d}\Phi_R\,\underbrace{\left[\mathcal{R}-\sum_{\{ij\}}\mathcal{D}_{ij}^{(\mathrm{A})}\right]}_{\text{resolved, non-singular}\equiv\mathcal{H}^{(\mathrm{A})}}$$

- To $\mathcal{O}(\alpha_s)$ this reproduces $\mathrm{d}\sigma^{(\mathrm{NLO})}$
- Event generation: $\bar{\mathcal{B}}^{(\mathrm{A})}$ or $\mathcal{H}^{(\mathrm{A})}$ seed event according to their XS
  - First line ("$\mathbb{S}$-event"): from one-step PS with $\Delta^{(\mathrm{A})}$
    $\Rightarrow$ emission (resolved, singular) or no emission (unresolved) above t_0
  - Second line ("$\mathbb{H}$-event"): kept as-is $\rightarrow$ resolved, non-singular term
- Resolved cases: Subsequent emissions can be generated by ordinary PS
- Exact choice of $\mathcal{D}_{ij}^{(\mathrm{A})}$ will specify MC@NLO vs. POWHEG vs. S-MC@NLO ...

Z+jet with MINLO

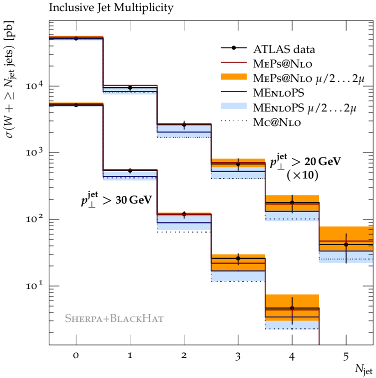


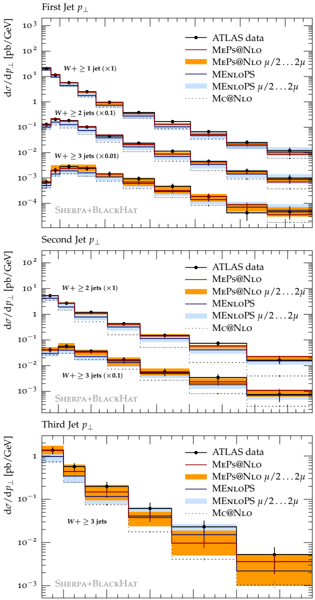
- POWHEG simulation for $pp \to Z$+1 jet, supplemented with CKKW-style scales and Sudakov form factors
  $\Rightarrow$ inclusive simulation possible
- inclusive observables agree with $pp \to Z$ (within perturbative unc's)
- improved description of 1-jet observables: NLO for $p_\perp^Z$

Applications in single vector boson production

Höche, Krauss, Schönherr, FS (2012)

W+jets with ME+PS@NLO





- Comparison to ATLAS measurement
  Phys.Rev. D85 (2012), 092002
- Significant reduction of ME+PS@NLO scale uncertainties in "NLO" multiplicities
- Improved agreement with data

Precise predictions for $pp \to \ell\ell\nu\nu$ + jets

- As signal: SM measurements, vector-boson scattering, anomalous couplings, ...
- As background: Higgs production, BSM searches
- Higgs analyses in exclusive $0, 1, 2$-jet bins ($\Rightarrow$ jet vetoes)
  - $\to$ Better control over backgrounds (WW^* vs. $t\bar{t}$)
  - $\to$ Disentangle production modes ($gg \to H$ vs. VBF)

Non-trivial theoretical issues

- Precise predictions for jet production $\Rightarrow$ beyond inclusive NLO QCD
- Exclusive jet bins $\Rightarrow$ Sudakov effects, resummation
- Offshell WW^* production $\Rightarrow$ non-resonant and interference effects
- Loop-induced processes like $gg \to WW^*$ sizeable in Higgs signal regions

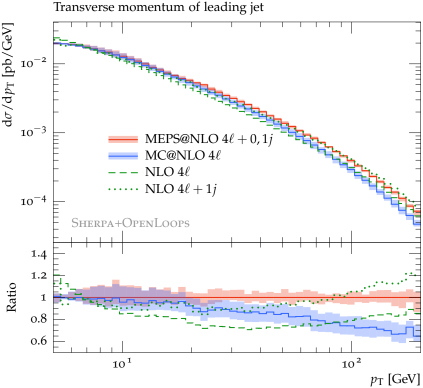
Toolkit

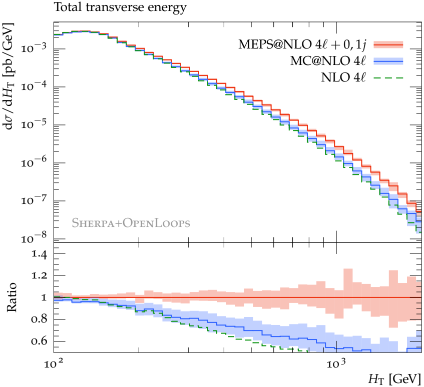
- SHERPA including its automated dipole subtraction and merging a la ME+PS@NLO
- OPENLOOPS automated 1-loop QCD matrix elements — Cascioli, Maierhöfer, Pozzorini (2011)
- COLLIER for fast and stable tensor integral reduction — Denner, Dittmaier, Hofer (in prep.)

$\Rightarrow$ State-of-the-art QCD NLO automation

Basic WW^* analysis

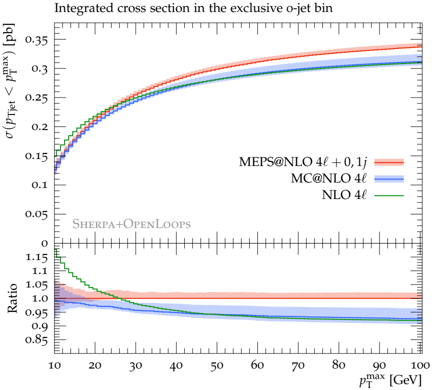
$p_{\perp,\ell} > 25$ GeV, $|\eta_\ell| < 3.5$, $\not{E}_T > 25$ GeV, anti-k_t jets with $R = 0.4$

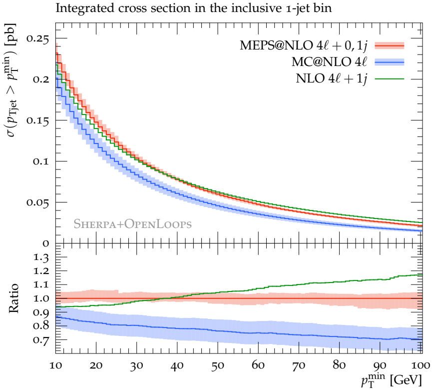




- NLO 4ℓ and S-MC@NLO 4ℓ only LO accurate, underestimate hard $p_\perp$ tail
- Resummation necessary for $p_\perp \to 0$ (Sudakov logs)
  - NLO $4\ell \sim 20\%$ effects at $p_\perp = 5$ GeV
  - NLO $4\ell + 1j$ partially includes logs $\Rightarrow$ reduced effect
- Harder tails in fixed-order due to μ_R not dynamic with jet $p_\perp$
- H_T sensitive to combination of different jet multiplicities $\Rightarrow$ merging crucial

Basic WW^* analysis





Exclusive 0-jet bin

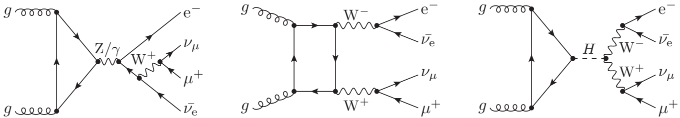
- Few-% agreement between S-MC@NLO 4ℓ and ME+PS@NLO
- Moderate Sudakov effects in comparison of NLO 4ℓ and S-MC@NLO 4ℓ
- Low uncertainties $\rightarrow$ good control wrt higher orders/logs

Inclusive 1-jet bin

- Sizable differences between S-MC@NLO 4ℓ and ME+PS@NLO, similar to jet $p_\perp$
- NLO $4\ell + 1j$ excess in tail due to α_s scale differences again

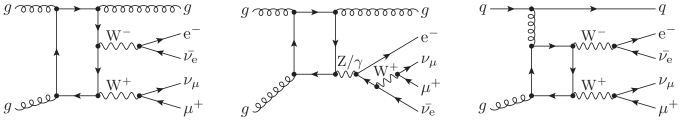
0-jet production: Examples for $gg \to 4\ell$ diagrams

- finite subset of NNLO contributions: squared quark loops like $gg \to 4\ell$
- relevant at LHC due to gluonic initial states, particularly in Higgs signal regions



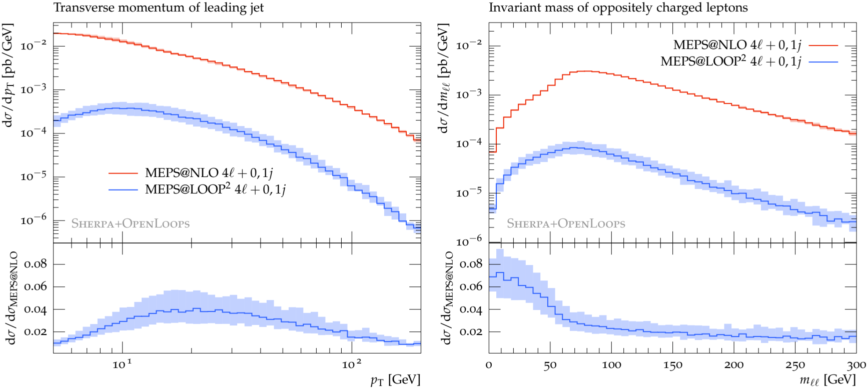
1-jet production

- example diagrams (requirement: vector bosons coupling to pure quark loop)



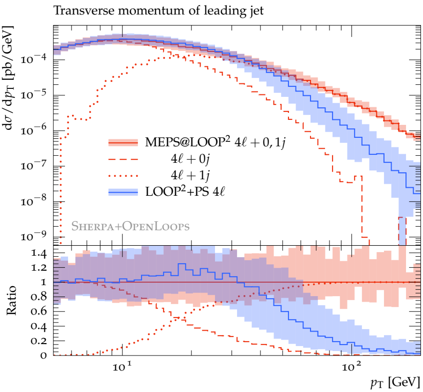
- first merging of 0-jet and 1-jet squared-loop contributions
- tree-level merging techniques since all MEs are finite
- shower on top of $gg \to 4\ell \Rightarrow$ consistency requires MEs for qg, $\bar{q}g$ and $q\bar{q}$ initial states

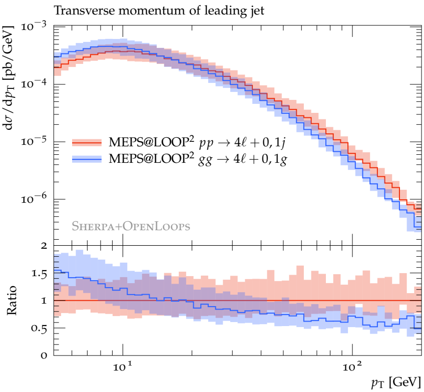
Impact of LOOP^2 contributions



- Inclusive contribution of a few %
- Shape distortions: more significant impact in Higgs signal region (e.g. low $m_{\ell\ell}$)

Features of LOOP^2 contributions





Merging effects

- Inclusion of LOOP^2 $4\ell + 1j$ in merging: harder $p_\perp$ spectrum
- Significant reduction of uncertainties (wrt resummation scale) in high-$p_\perp$ region

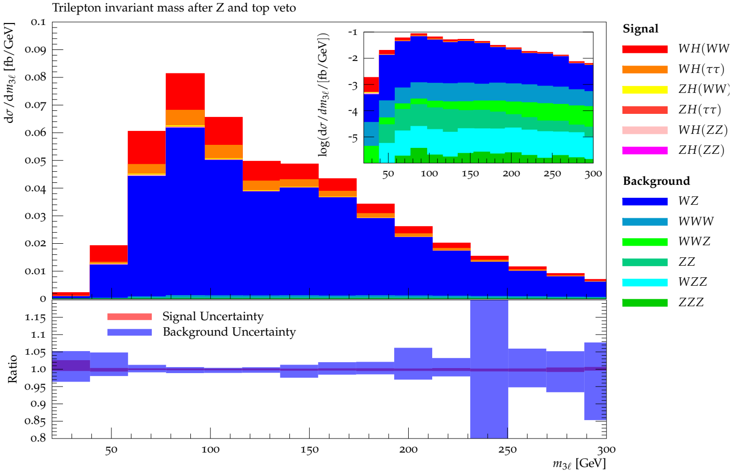
Non-gluonic initial states

- Inclusion of quark-channels $\to$ harder tail
- Naturally, lower Sudakov suppression without quark splittings
- Shape distortion
  $\Rightarrow$ opposite effects in 0/1 jet bins

Applications in triple vector-boson production

Höche, Krauss, Pozzorini, Schönherr, Thompson, Zapp (2014)

- trilepton analysis for associated Higgs production
- various Higgs signals and multi-boson backgrounds taken into account
- signals and dominant backgrounds (WZ, WWW) with MEPS@NLO including +0,1 jets
  $\Rightarrow$ uncertainty reduction to few-% level



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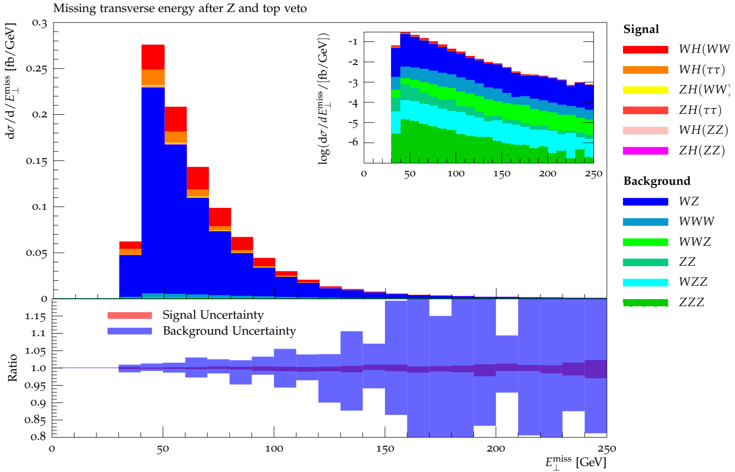


Summary

- recent conceptual developments in MC simulations of vector-boson production
- state of the art: multijet merging of NLO+PS matched simulations
  $\rightsquigarrow$ **cf. Stefan's talk tomorrow!**
- application to single-, di- and triple-boson production:
  improved agreement with data, reduced uncertainties
- inclusion of loop^2: finite, gauge-invariant part of NNLO contributions
  $\rightarrow$ shape distortions in 4ℓ production relevant for Higgs background
- Sherpa 2.x with ME+PS@NLO available publically

Thank you!

Backup material

MC@NLO

Frixione, Webber (2002)

$\mathcal{D}^{(\mathrm{A})}$ **= PS splitting kernels**

+ Shower algorithm for Born-like events easy to implement
– "Non-singular" piece $\mathcal{R} - \sum_{ij} \mathcal{D}_{ij}^{(\mathrm{A})}$ is actually singular:
  - Collinear divergences subtracted by splitting kernels ✓
  - Remaining soft divergences as they appear in non-trivial processes at sub-leading N_c ✗

Workaround: $\mathcal{G}$-function dampens soft limit in non-singular piece
$\Leftrightarrow$ Loss of formal NLO accuracy
(but heuristically only small impact)

S-MC@NLO

Höche, Krauss, Schönherr, FS (2011)

$\mathcal{D}^{(\mathrm{A})}$ **= Subtraction terms** $\mathcal{D}^{(\mathrm{S})}$

+ "Non-singular" piece fully free of divergences
– Splitting kernels in shower algorithm become negative

Solution: Weighted $N_C = 3$ one-step PS based on subtraction terms

$\Downarrow$

Used in SHERPA

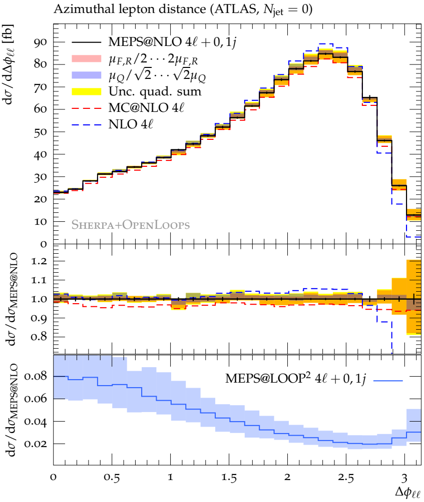
Rivet implementation of Higgs analyses

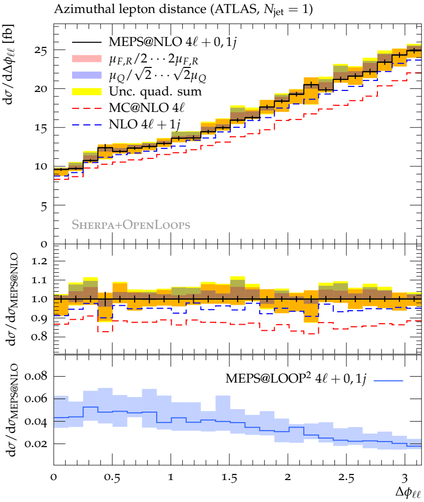
- 8 separate analyses: $\{$ATLAS,CMS$\}$ $\times$ $\{$0-jet, 1-jet$\}$ $\times$ $\{$signal region, control region$\}$
- Differential predictions in relevant observables: $p_\perp^j$, $m_{\ell\ell}$, $\Delta\phi_{\ell\ell}$, m_T

Findings

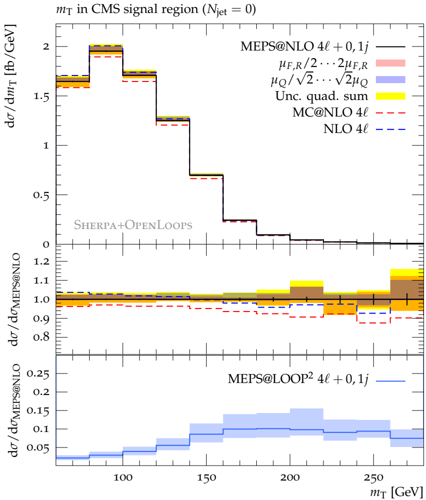
- Different simulation levels agree well in 0-jet bin (where they are NLO accurate)
- Fixed-order agrees with matched/merged predictions in most regions $\to$ Sudakov logs not dominant, except e.g. $\Delta\phi_{\ell\ell} \to \pi$
- Pure MC@NLO predictions underestimates rate in 1-jet bins
- Uncertainty bands for best prediction (ME+PS@NLO) from $\mu_{R,F} \oplus \mu_Q$ variations at the few-% level

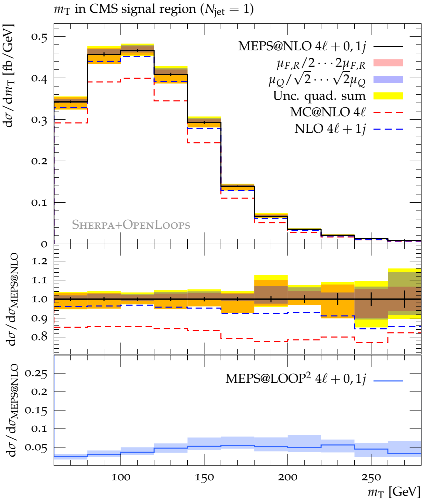
Example from ATLAS analysis





Example from CMS analysis





Signal/control cross sections in exclusive jet bins

- Relevant for background extrapolation from control to signal region in data-driven methods
- Example: ATLAS analysis

0-jet bin	NLO $4\ell\ (+1j)$	S-MC@NLO 4ℓ	MEPS@NLO $4\ell + 0, 1j$	MEPS@LOOP^2 $4\ell + 0, 1j$
σ_S [fb]	$34.28(9)\ ^{+2.1\%}_{-1.6\%}$	$32.52(8)\ ^{+2.1\%}_{-0.8\%}\ ^{+1.2\%}_{-0.7\%}$	$33.81(12)\ ^{+1.4\%}_{-2.2\%}\ ^{+2.0\%}_{-0.4\%}$	$1.98(2)\ ^{+23\%}_{-16.5\%}\ ^{+27\%}_{-20\%}$
σ_C [fb]	$55.76(9)\ ^{+2.0\%}_{-1.7\%}$	$52.28(9)\ ^{+1.4\%}_{-0.7\%}\ ^{+1.4\%}_{-1.1\%}$	$54.18(15)\ ^{+1.4\%}_{-1.9\%}\ ^{+2.5\%}_{-0.4\%}$	$2.41(2)\ ^{+22\%}_{-17\%}\ ^{+27\%}_{-18\%}$
1-jet bin	**NLO $4\ell\ (+1j)$**	**S-MC@NLO 4ℓ**	**MEPS@NLO $4\ell + 0, 1j$**	**MEPS@LOOP^2 $4\ell + 0, 1j$**
σ_S [fb]	$8.99(4)\ ^{+4.9\%}_{-9.5\%}$	$8.02(4)\ ^{+8.5\%}_{-6.4\%}\ ^{+0\%}_{-3.1\%}$	$9.37(9)\ ^{+2.6\%}_{-2.7\%}\ ^{+2.5\%}_{-0.0\%}$	$0.46(1)\ ^{+40\%}_{-18\%}\ ^{+2.2\%}_{-6.3\%}$
σ_C [fb]	$26.50(8)\ ^{+6.4\%}_{-12.5\%}$	$24.58(8)\ ^{+6.1\%}_{-6.5\%}\ ^{+1.2\%}_{-3.0\%}$	$28.32(13)\ ^{+3.1\%}_{-4.7\%}\ ^{+4.1\%}_{-0.0\%}$	$0.79(1)\ ^{+33\%}_{-20\%}\ ^{+15\%}_{-7\%}$

- Merged sample reproduces individual NLO cross sections well
- Combined uncertainty on ME+PS@NLO best prediction around $3(5)\%$ in 0(1)-jet bin
- LOOP^2 effects larger in **S**ignal than in **C**ontrol region

Comparison of different simulation levels

NLO simulations	**0-jet**	**1-jet**	**2-jet**
NLO 4ℓ	NLO	LO	-
NLO $4\ell + 1j$	-	NLO	LO
S-MC@NLO 4ℓ	NLO+PS	LO+PS	PS
S-MC@NLO $4\ell + 1j$	-	NLO+PS	LO+PS
MEPS@NLO $4\ell + 0, 1j$	NLO+PS	NLO+PS	LO+PS
LOOP^2 simulations	**0-jet**	**1-jet**	**2-jet**
LOOP^2 4ℓ	LO	-	-
LOOP^2 $4\ell + 1j$	-	LO	-
LOOP^2+PS 4ℓ	LO+PS	PS	PS
LOOP^2+PS $4\ell + 1j$	-	LO+PS	PS
MEPS@LOOP^2 $4\ell + 0, 1j$	LO+PS	LO+PS	PS