TECHNISCHE UNIVERSITÄT DRESDEN

Fakultät Mathematik und Naturwissenschaften Institut für Kern- und Teilchenphysik

Precise Monte-Carlo predictions for Higgs searches

Frank Siegert

Göttingen, 11 July 2014

There is a Higgs!

The LHC Higgs physics program

- Higgs properties
  - Mass
  - Spin
  - CP
  - (Width?)
- Higgs couplings
  - Production mechanisms
  - Branching fractions

  $\rightarrow$ measure as many couplings to vector bosons and fermions as possible
- Beyond the Standard Model
  - Can we find more than one Higgs boson?
  - What is the one we discovered?

Higgs physics will remain an active field for a while!

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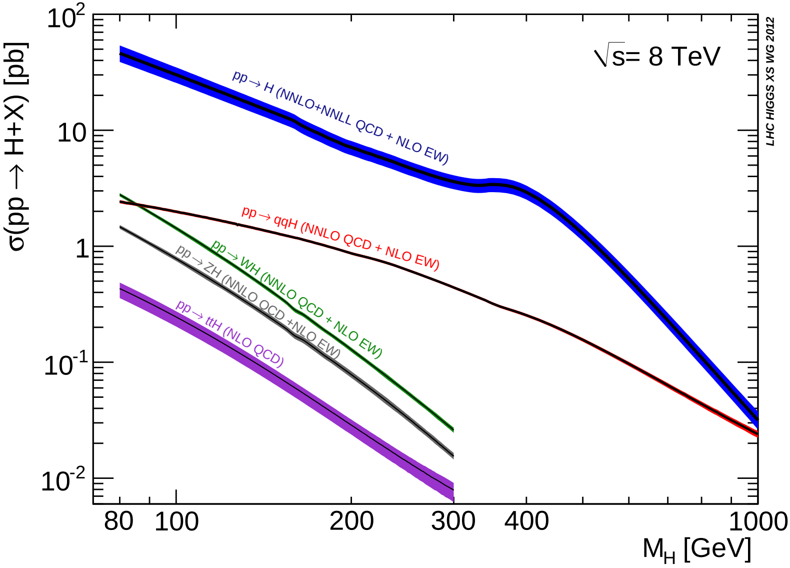
Higgs production mechanisms



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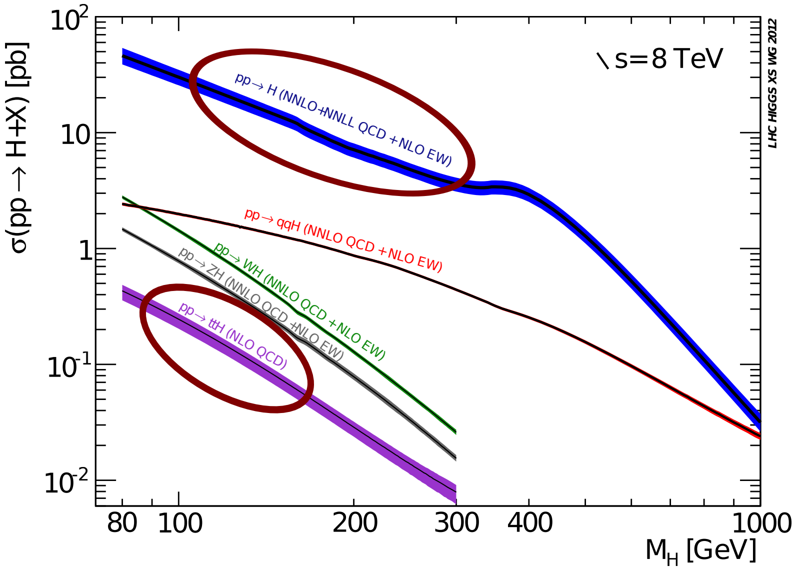
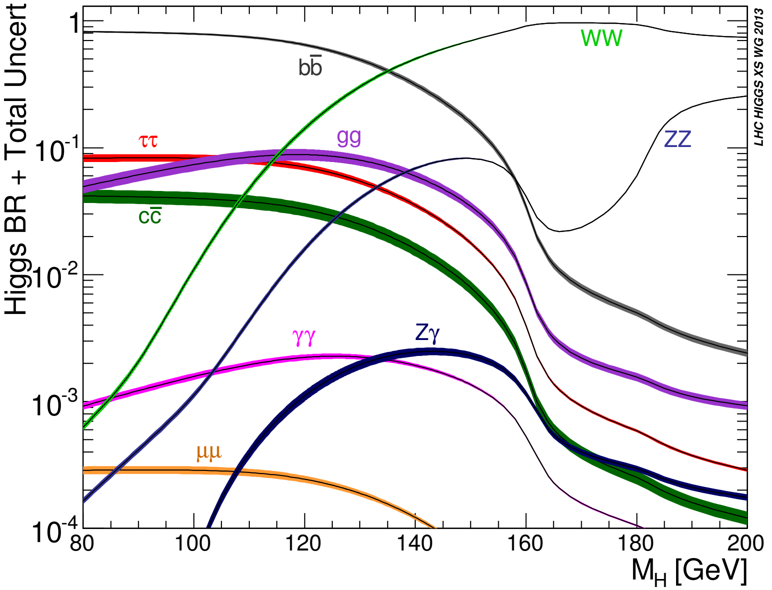


Higgs decay branching ratios



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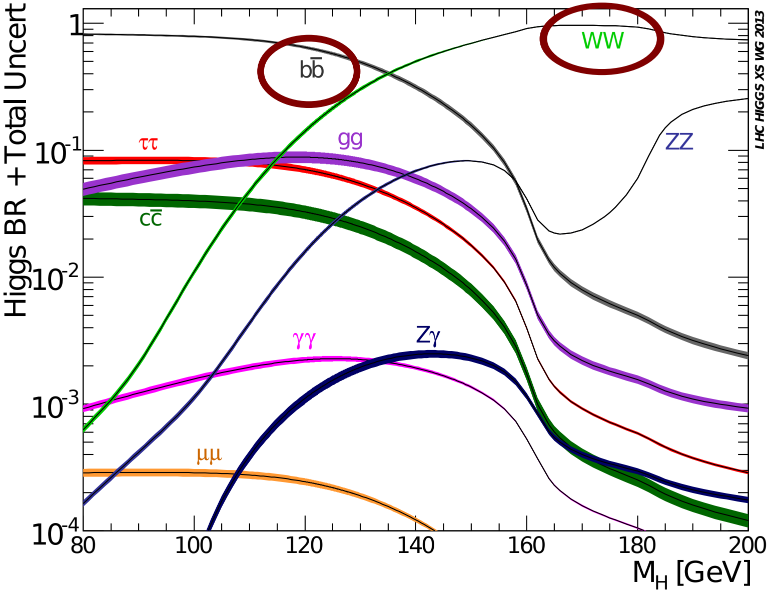

Monte-Carlo event generators in Higgs physics

- optimisation of analysis strategy before data is unblinded
- direct subtraction of backgrounds using simulation
- extrapolation from control to signal region in data-driven approaches
- cheat easily by looking into the event record

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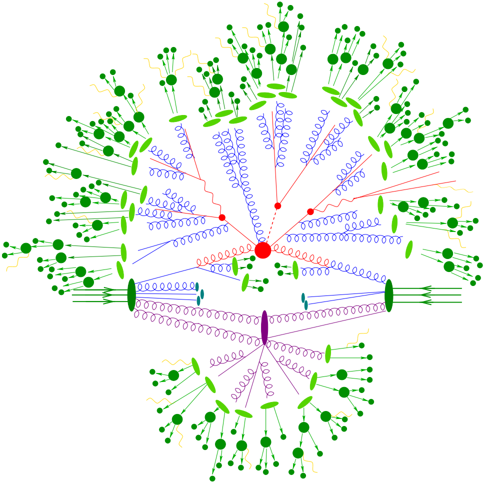
Modern Monte-Carlo event generation



- MC event representation for full event
- Precision improvements in perturbative aspects:
  - Hard scattering at fixed order in perturbation theory (**Matrix Element**)
  - Approximate resummation of QCD corrections to all orders (**Parton Shower**)

  and their combination!
- Gray bits: Hadronisation/Underlying event (ignored today)

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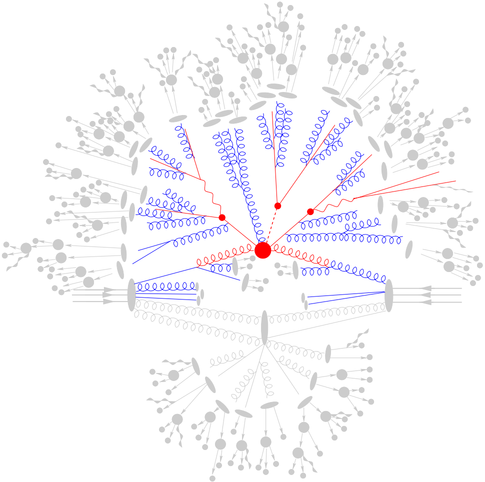

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NLO+PS matching

- 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
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$\Downarrow$ $\Downarrow$

Combination: ME+PS@NLO

- Multiple NLO+PS simulations for processes of different jet multiplicity e.g. W, Wj, Wjj, ...
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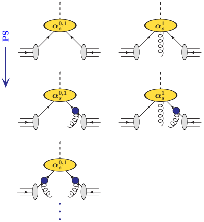
NLO+PS matching in a nutshell



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 $\mathcal{D}^{(\mathrm{A})}_{ij}$

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

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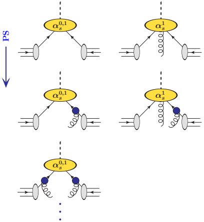

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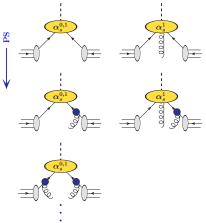

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Master formula for NLO+PS up to first emission

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

$$+\ \mathrm{d}\Phi_R\ \underbrace{\Bigg[\mathcal{R}-\sum_{\{ij\}}\mathcal{D}_{ij}^{(\mathrm{A})}\Bigg]}_{\text{resolved, non-singular}\equiv\mathcal{H}^{(\mathrm{A})}}$$

- To $\mathcal{O}(\alpha_s)$ this reproduces $\mathrm{d}\sigma^{(\mathrm{NLO})}$
- Exact choice of $\mathcal{D}_{ij}^{(\mathrm{A})}$ will specify MC@NLO vs. POWHEG vs. S-MC@NLO …

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$pp \to t\bar{t}b\bar{b}$ as background to $pp \to t\bar{t}H[\to b\bar{b}]$

Motivation

- direct investigation of Higgs couplings to fermions
  without detour of Higgs–gluon or Higgs–photon couplings
- background reduction compared to $pp \to H[\to b\bar{b}]$

LHC status

- ATLAS preliminary results ATLAS-CONF-2014-011
  - $20.3\,\mathrm{fb}^{-1}$ data at $\sqrt{s} = 8\,\mathrm{TeV}$
  - single- and dilepton channel in top decays
  - signal strength relative to SM expectation: $\mu = 1.7 \pm 1.4$
- CMS preliminary results CMS-PAS-HIG-14-010
  - $19.5\,\mathrm{fb}^{-1}$ data at $\sqrt{s} = 8\,\mathrm{TeV}$
  - single- and dilepton channel in top decays
  - signal strength relative to SM expectation: $\mu = 0.67^{+1.35}_{-1.33}$

Experimental challenges

- four b-quarks in the final state
  $\to$ difficult Higgs reconstruction due to combinatorics
- strong contamination from background contributions:
  - reducible: $t\bar{t}jj$ or $t\bar{t}c\bar{c}$ with misidentified jets
  - irreducible: $t\bar{t}b\bar{b}$ continuum

Theoretical challenges for background calculations

- many coloured particles in $pp \to t\bar{t}b\bar{b}$, $t\bar{t}jj$ or $t\bar{t}c\bar{c}$
  - large QCD corrections/uncertainties
  - complicated higher-order calculations
- several mass scales

Fixed NLO QCD calculations

(with massless b-quarks)

- Bredenstein, Denner, Dittmaier, Pozzorini (2009); Id. (2010)
- Bevilacqua, Czakon, Papadopoulos, Pittau, Worek (2009)
- $\Rightarrow$ large NLO/LO factor of $K \approx 1.8$

Massive & matched calculation

Cascioli, Maierhöfer, Moretti, Pozzorini, FS (2013)

- NLO QCD calculation using automated tools in common framework:
  - SHERPA — Gleisberg, Höche, Krauss, Schönherr, Schumann, Winter, FS (2008)
    tree-level matrix elements, dipole subtraction, parton shower matching
  - OPENLOOPS — Cascioli, Maierhöfer, Pozzorini (2011)
    virtual corrections
  - COLLIER — Denner, Dittmaier, Hofer (in prep.)
    tensor integral reduction
- full b-quark mass dependence in 4-flavour-scheme
- matching to SHERPA's parton shower — Höche, Krauss, Schönherr, FS (2011)

$\leadsto$ unexpected new contribution "discovered"

Simulation setup

- 4-flavour-scheme with finite b-mass and corresponding MSTW2008 PDFs + α_s
- top quarks treated as stable particles
  but LO decays could be included automatically with spin correlations
- renormalisation scale

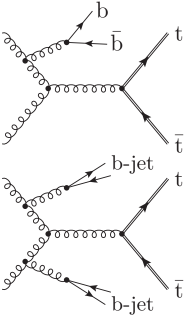
$$\mu_R^4 \sim \prod_{i=t,\bar{t},b,\bar{b}} E_{\mathrm{T},i}$$

- factorisation and resummation scale

$$\mu_F \sim \mu_Q \sim \frac{1}{2}(E_{\mathrm{T},t} + E_{\mathrm{T},\bar{t}})$$

Analysis

- jet reconstruction using anti-k_t algorithm with $R = 0.4$
- "(idealised) experimental" b-tagging:
  b-jet = jet with at least one b-quark constituent
  $\to$ allows for quasi-collinear $b\bar{b}$-pairs
- require ≥ 2 b-jets with $p_\perp > 25\,\mathrm{GeV}$ and $|\eta| < 2.5$
- Higgs signal region selection: $m_{bb} > 100\,\mathrm{GeV}$

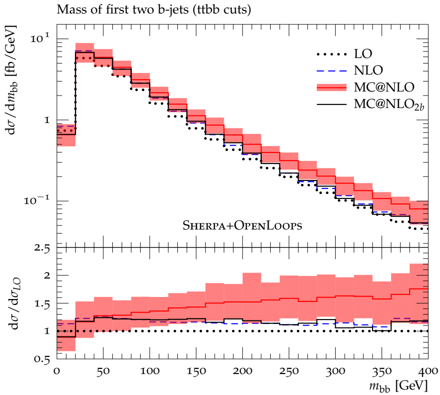


Total cross sections

	ttb	ttbb	ttbb$(m_{bb} > 100)$
σ_{LO} [fb]	$2644^{+71\%}_{-38\%}{}^{+14\%}_{-11\%}$	$463.3^{+66\%}_{-36\%}{}^{+15\%}_{-12\%}$	$123.4^{+63\%}_{-35\%}{}^{+17\%}_{-13\%}$
σ_{NLO} [fb]	$3296^{+34\%}_{-25\%}{}^{+5.6\%}_{-4.2\%}$	$560^{+29\%}_{-24\%}{}^{+5.4\%}_{-4.8\%}$	$141.8^{+26\%}_{-22\%}{}^{+6.5\%}_{-4.6\%}$
σ_{NLO}/σ_{LO}	1.25	1.21	1.15
$\sigma_{\text{S-MC@NLO}}$ [fb]	$3313^{+32\%}_{-25\%}{}^{+3.9\%}_{-2.9\%}$	$600^{+24\%}_{-22\%}{}^{+2.0\%}_{-2.1\%}$	$181.0^{+20\%}_{-20\%}{}^{+8.1\%}_{-6.0\%}$
$\sigma_{\text{S-MC@NLO}}/\sigma_{NLO}$	1.01	1.07	1.28
$\sigma^{2b}_{\text{S-MC@NLO}}$ [fb]	3299	552	146
$\sigma^{2b}_{\text{S-MC@NLO}}/\sigma_{NLO}$	1.00	0.99	1.03

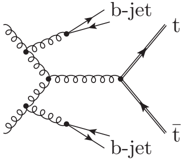
- uncertainty estimates from μ_R and $\mu_F \oplus \mu_Q$ variations
- large enhancement of S-MC@NLO prediction in $m_{bb} > 100$ GeV region!

A closer look at high m_{bb}

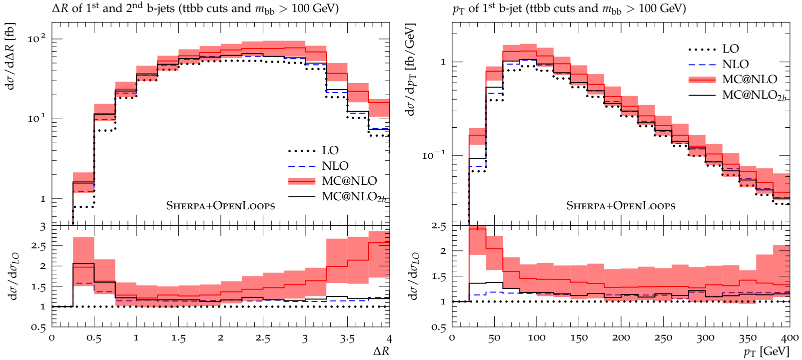


- clear enhancement of S-MC@NLO prediction at high m_{bb}
- caused by double quasi-collinear $g \to b\bar{b}$ splitting

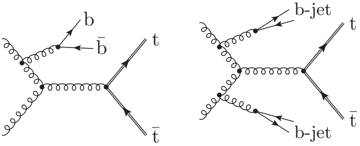
  (technical test: absent if $g \to b\bar{b}$ switched off in PS $\rightsquigarrow$ black line)



- contribution very relevant for Higgs search region $m_{bb} > 100$ GeV exceeds Higgs signal :(
- can only be simulated precisely due to massive and PS matched calculation!



- topology of enhancement:
  back-to-back b-jets with smallest $p_\perp$ to reach $m_{bb} > 100$ GeV
  $\Rightarrow$ completely consistent with expectation from double splitting picture



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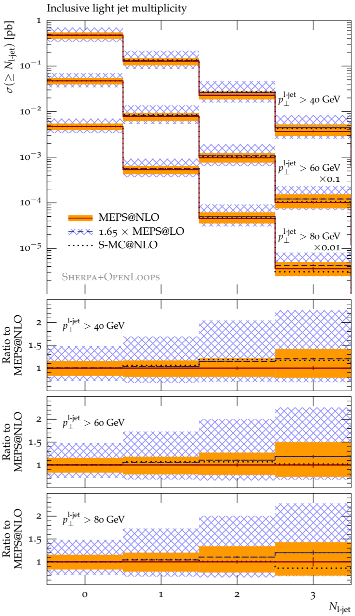
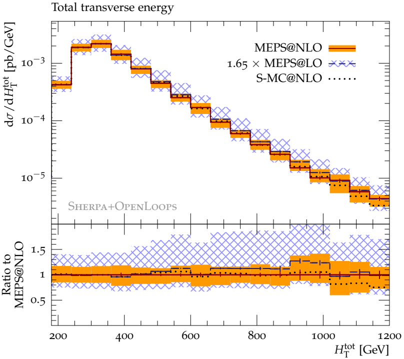
Results for ME+PS@NLO $t\bar{t}$+jets





ME+PS@NLO simulation for
$t\bar{t} + 0, 1, 2$jets@NLO

Höche, Krauss, Maierhöfer, Pozzorini, Schönherr, FS (2014)

- uncertainties reduced in particular in $+0, 1, 2$-jet bins
- BSM search region $H_T^{\text{tot}} > 500$ GeV significantly improved
- TODO:
  not yet combined with $pp \to t\bar{t}b\bar{b}$!

$pp \to \ell\ell\nu\nu$ + jets as background for $pp \to H[\to WW]$

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

Background to $H \to WW^* \to \ell^+\nu\ell^-\bar{\nu}$ + jets

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

Cascioli, Höche, Krauss, Maierhöfer, Pozzorini, FS; arXiv: 1309.0500

Toolkit

- SHERPA including its automated dipole subtraction and merging a la MEPS@NLO
- OPENLOOPS automated 1-loop QCD matrix elements Cascioli, Maierhöfer, Pozzorini; arXiv:1111.5206
  including the COLLIER tensor integral reduction Denner, Dittmaier, Hofer; in prep.

Phenomenological setup: $pp \to e^- \bar{\nu}_e \mu^+ \nu_\mu$ + jets

- Predictions for LHC $\sqrt{s} = 8$ TeV, using CT10 PDFs
- QCD NLO accuracy for $\ell\ell\nu\nu + 0, 1$ jets
- Squared quark-loop contributions merged for $+0, 1$ jets
- Full off-shell, interference and spin-correlation effects
- NLO+PS matching to the parton shower, MEPS@NLO merging into inclusive sample

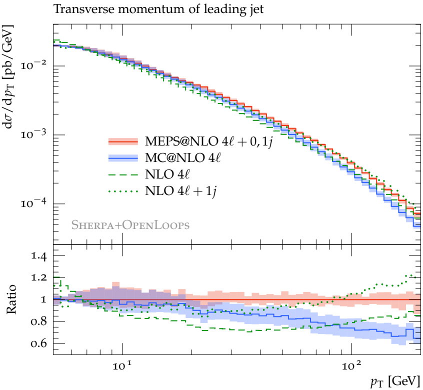
- Central scale choice: $\mu_0 = \frac{1}{2}(E_{T,W^+} + E_{T,W^-})$
- CKKW-like scale prescription in merged jet emissions: $\alpha_s(k_\perp)$
- Independent factor-2 variations of $\mu_{F,R}$ and factor-$\sqrt{2}$ of resummation scale μ_Q

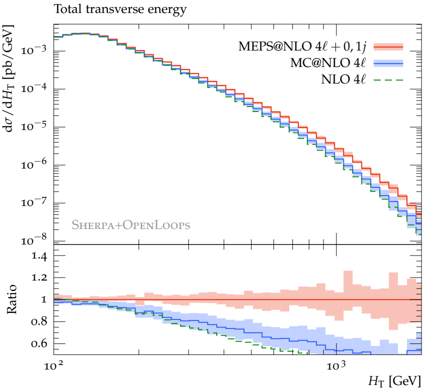
Comparison of different simulation levels

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

Basic WW^* analysis

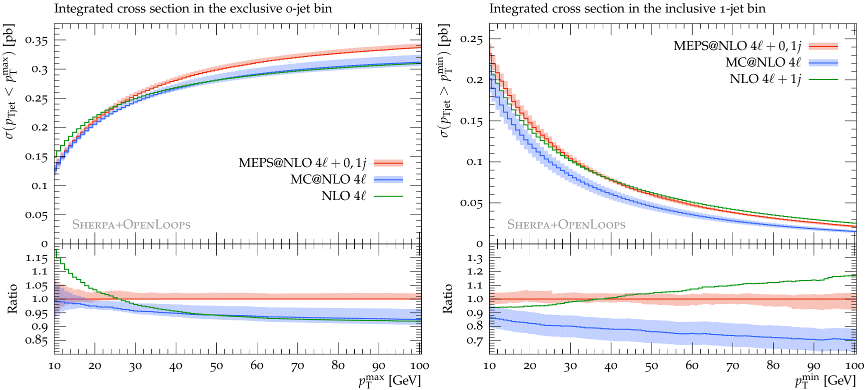
$p_{\perp,\ell} > 25$ GeV, $|\eta_\ell| < 3.5$, $\not{E}_T > 25$ GeV, anti-k_t jets with $R = 0.4$





- 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

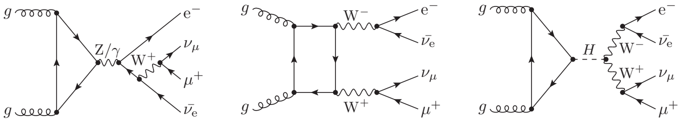
- Few-% agreement between S-MC@NLO and ME+PS@NLO
- Moderate Sudakov effects in comparison of NLO 4ℓ and S-MC@NLO 4ℓ
- Low uncertainties $\rightarrow$ good control wrt higher orders/logs

Inclusive 1-jet bin

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

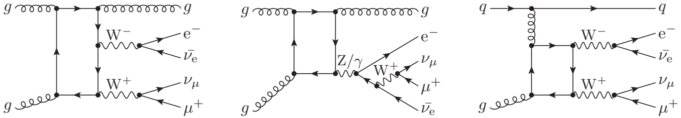
0-jet production: Examples for $gg \to 4\ell$ diagrams

- 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



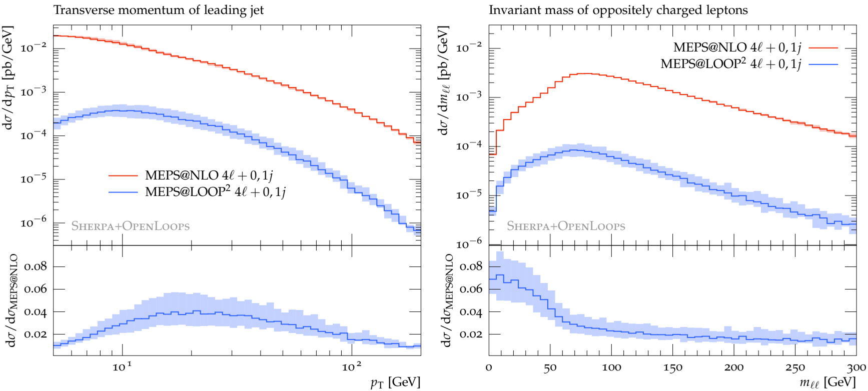
1-jet production

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



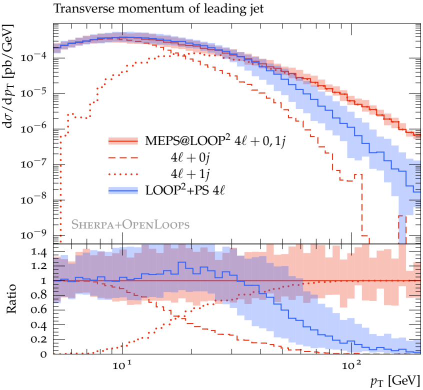
- first merging of 0-jet and 1-jet squared-loop contributions
- tree-level merging techniques since all MEs are finite
- shower on top of $gg \to 4\ell \Rightarrow$ consistency requires MEs for qg, $\bar{q}g$ and $q\bar{q}$ initial states

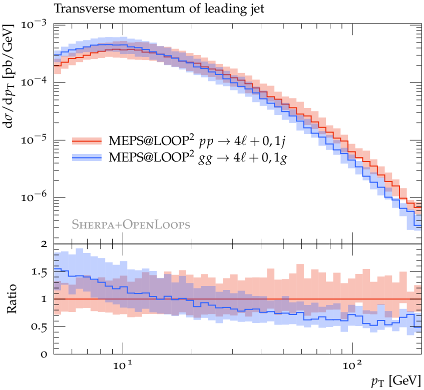
Impact of LOOP^2 contributions



- 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

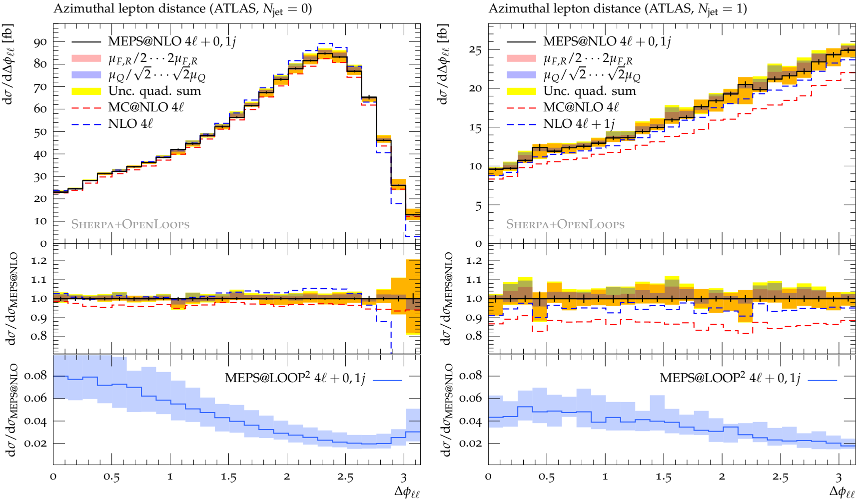
Rivet implementation of Higgs analyses

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

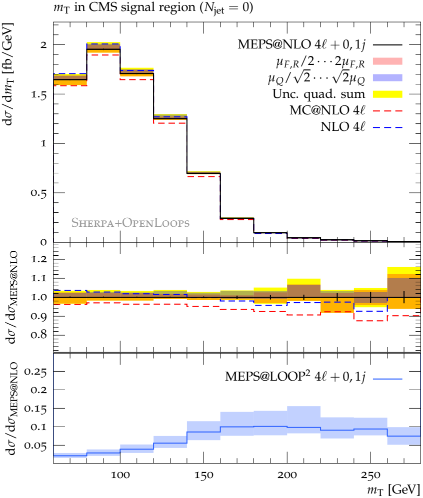
Findings

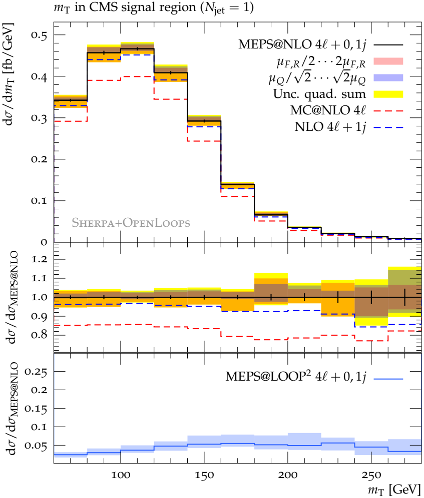
- Different simulation levels agree well in 0-jet bin (where they are NLO accurate)
- Fixed-order agrees with matched/merged predictions in most regions → Sudakov logs not dominant, except e.g. $\Delta\phi_{\ell\ell} \to \pi$
- Pure S-MC@NLO predictions underestimates rate in 1-jet bins
- Uncertainty 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

Summary

- Higgs measurements depend on precise Monte-Carlo predictions, e.g. for background modelling

- Main background to $pp \to t\bar{t}H[\to b\bar{b}]$ under control by NLO+PS matched $pp \to t\bar{t}b\bar{b}$ calculation with massive b-quarks
- Surprising: large contribution from double collinear configurations in Higgs analyses

- $pp \to 4\ell$ continuum background to $pp \to H[\to WW]$ calculated with ME+PS@NLO
- Uncertainties reduced to few-% level simultaneously in $4\ell + 0j$ and $4\ell + 1j$ bin
- Finite loop^2 contributions taken into account in merged approach for $4\ell + 0, 1j$

Outlook for Higgs backgrounds

- Consistent combination of $t\bar{t}H[\to b\bar{b}]$ backgrounds
  - S-MC@NLO prediction for $t\bar{t}b\bar{b}$
  - ME+PS@NLO prediction for $t\bar{t} + 0, 1, 2j$
- Extension to $4\ell + 0, 1, 2j$ for high precision in VBF search region
  $\to$ complement with NLO+PS matched $pp \to WWbb$ for top contributions