Four Top Final States

Fixed Order NLO(QCD) vs. NLO(QCD)+PS

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P H Collaborative Research Center TRR 257
Particle Physics Phenomenology after the Higgs Discovery

Research Training Group Physics of the Heaviest Particles at the LHC

RWTH AACHEN UNIVERSITY

TTK Institute for Theoretical Particle Physics and Cosmology

Why four tops?

- Four top production is an extremely rare process with an estimated cross section

  $\sigma_{tt\bar{t}\bar{t}}^{NLO(QCD+EW)+NLL'} = 13.4^{+1.0}_{-1.8}\ fb$ at $\sqrt{s} = 13\ TeV$

  van Beekveld, Kulesza, Valero '22

- 2 → 12 process - complicated to model in theory and measure in experiment
  - Good test for QCD corrections and parton shower effects

- Sensitive to many new physics models
  - Study modifications in the Higgs sector e.g. two-Higgs-doublet models
  - Top philic models → new BSM heavy resonances decaying to top quark pairs

Four tops - Theory Status

First NLO QCD predictions for 4 stable tops: General idea about the size of the NLO QCD calculations.
Bevilacqua, Worek '12 / Maltoni, Pagani, Tsinikos '16

Complete-NLO predictions for 4 stable tops with sub-leading effects: All the non-vanishing contributions of $\mathcal{O}(\alpha_s^i \alpha^j)$ with $i + j = 4, 5$ are taken into account without any approximation. Top quark decays are omitted.
Frederix, Pagani, Zaro '18

NLO QCD matched to parton shower (NLO+PS): Besides NLO QCD corrections, the inclusion of subleading EW production channels at LO accuracy was also considered. LO spin correlated effects in top quark decays were also studied for the first time.
Ježo, Kraus '22

Threshold resummation for the production of four top quarks: Results for the total cross section for 4-top production at next-to-leading logarithmic (NLO + NLL') accuracy. Top quark decays are not included.
van Beekveld, Kulesza, Valero '22

NLO QCD predictions in perturbative QCD in the 4 lepton channel: Higher-order QCD effects in both the production and decays of the top quarks are taken into account.
Dimitrakopoulos, Worek '24

Observation of four top production

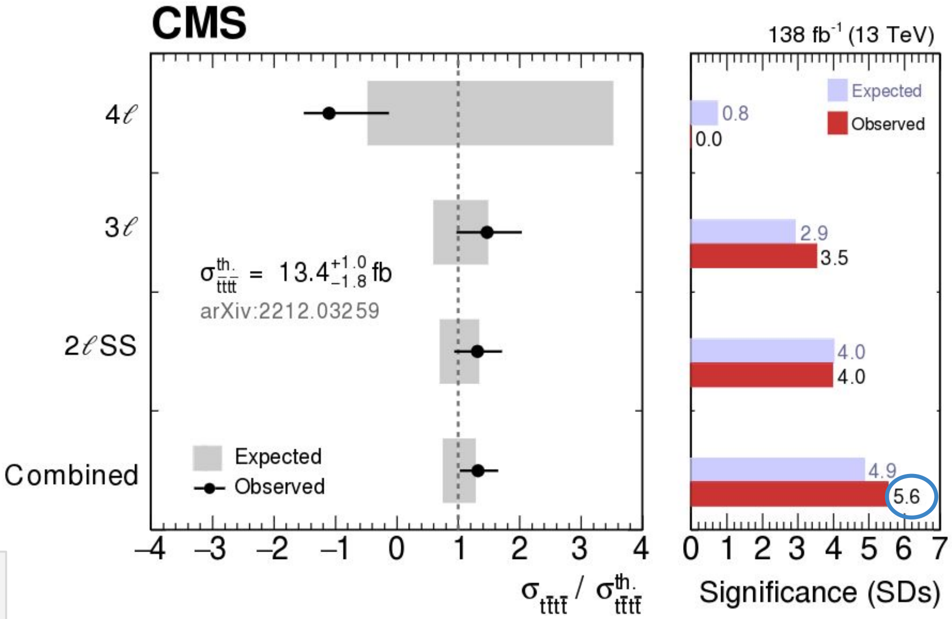
Discovery of four top production in 2023

CMS: arXiv:2305.13439
ATLAS: arXiv:2303.15061

Three different signal regions were taken into account:

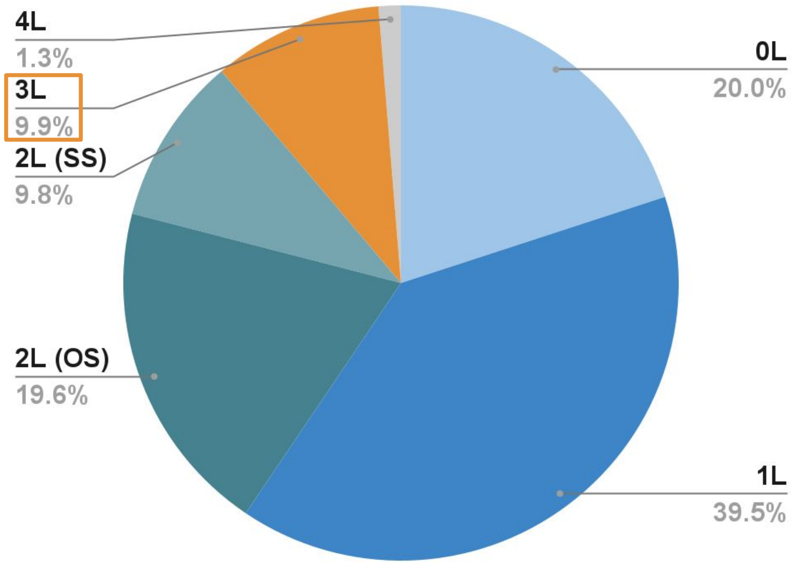
- 4-lepton channel
- 3-lepton channel
- 2lSS channel

Observed significance of 5.6σ for CMS



CMS: arXiv:2305.13439

Branching ratios in four-top production



4 top BRs
Manganelli, Quinnan '22

➔ $t \to Wb$: Top quark decays almost entirely through weak interaction to a *W* boson and a bottom quark with a branching ratio of ~ 100%

➔ W boson decays to either a pair of lepton with its corresponding neutrino or a pair of two quarks

$$Br(W \to l\nu_l) \approx 10.8\%$$
$$\sum_{qq'} Br(W \to q\bar{q}') \approx 67.6\%$$

Goal of this study

- **Compare NLO-FO to NLO+PS → Which observables and regions of phase space are sensitive to parton showers?**

- **What are the effects of including matrix element corrections in NLO+PS predictions?**

Fixed Order vs. Parton Showers

Fixed order

- Four tops:
  $\mathcal{O}(\alpha_S^4\ \alpha_{EW}^8)$@LO & $\mathcal{O}(\alpha_S^5\ \alpha_{EW}^8)$@NLO(QCD)
  Only one extra emission @NLO
- Hard and wide-angle emissions well described
- Problems with soft and/or collinear emissions (large logarithms)

Parton Showers

- Emissions to all orders
- Does not describe wide-angle emissions
- Collinear and soft-collinear emissions well described

Best of both worlds → Matching to PS

Fixed Order vs. Matching to PS

Fixed order - NLO(QCD)

- Full off-shell predictions for *tt* & *tt+X (X = j, γ, Z, H, W, bb)*
- For more complicated final states → full NWA approximation
- NLO at production and in decay of resonant particle
  → NLO *W* and *t* widths

HELAC-NLO
G. Bevilacqua, M. Czakon, M. V. Garzelli, A. van Hameren, A. Kardos, C. G. Papadopoulos, R. Pittau, M. Worek '11

Matching to PS

- DR contributions + approximate finite width effects for heavy resonances - Breit-Wigner smearing
- NLO only at the production stage
  → LO *W* and *t* widths
- PS - approximate higher orders at the production and decays

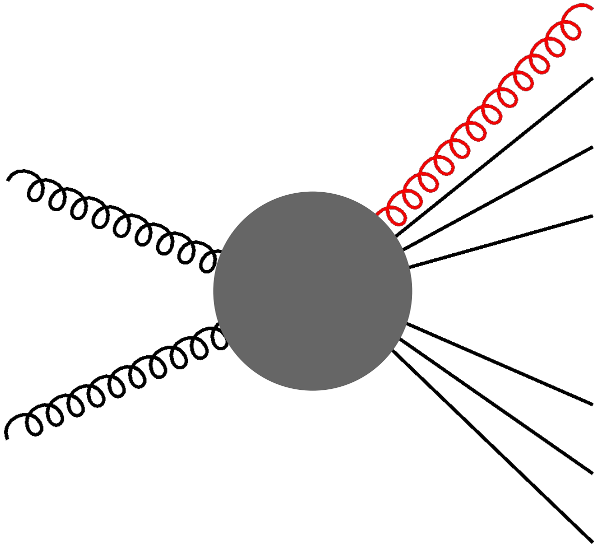
MadGraph5_aMC@NLO
J. Alwall, R. Frederix, S. Frixione, V. Hirschi, F. Maltoni, O. Mattelaer, H.-S. Shao, T. Stelzer, P. Torrielli, M. Zaro '14

POWHEG BOX
P. Nason '04
S. Frixione, P. Nason, C. Oleari '07
S. Alioli, P. Nason, C. Oleari, E. Re '10

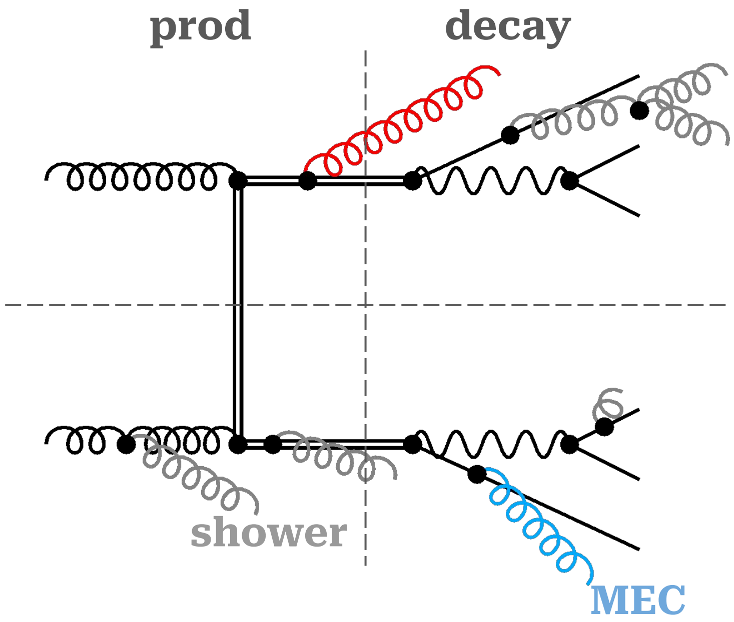
Pythia8 *arXiv:2203.11601*

Fixed Order vs. Matching to PS

Fixed order - Full off-shell NLO(QCD)



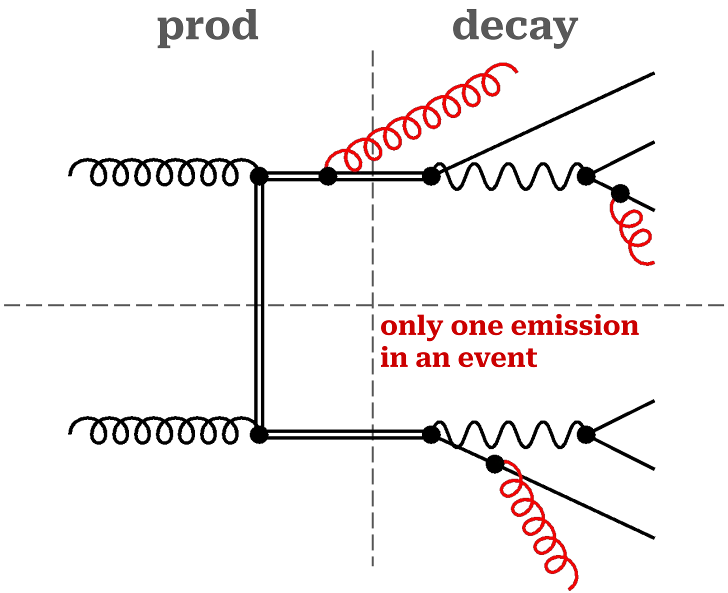
Matching to PS - NLO(QCD)+PS



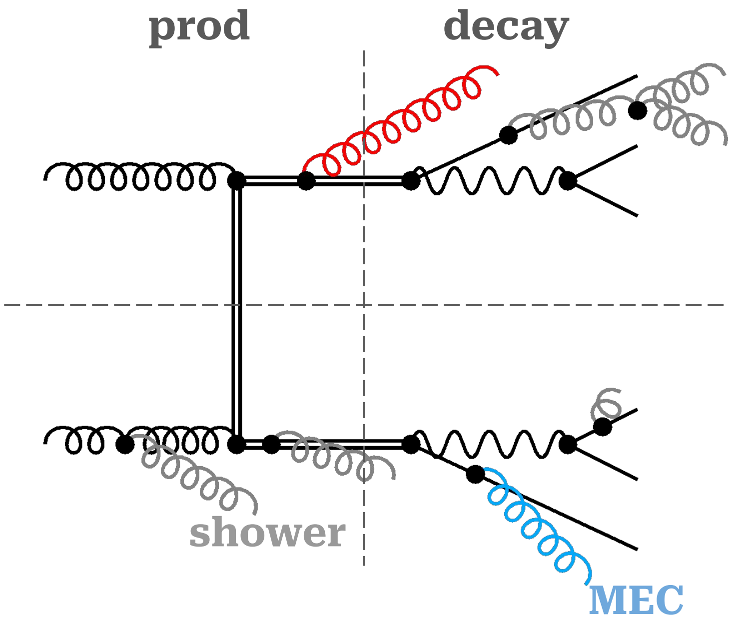
Diagrams created via FeynGame: *Harlander, Klein, Lipp '20*

Fixed Order vs. Matching to PS

Fixed order - NWA NLO(QCD)



Matching to PS - NLO(QCD)+PS



Diagrams created via FeynGame: *Harlander, Klein, Lipp ‘20*

Fixed Order vs. Matching to PS

Fixed order - NLO

- NLO accurate spin correlations
- Uncertainties calculated for the production and decay, i.e. in the fiducial phase space regions → dependent on decays and cuts

Matching to PS - NLO+PS

- LO spin correlations at most
- Scale uncertainties are calculated pre-decays → independent of decays and phase space cuts

Reconstructed tops

Stable tops

$$\mu_R = \mu_F = \mu_0 = \frac{1}{4} E_T$$

$$E_T = \sqrt{m_t^2 + p_T^2(t_1)} + \sqrt{m_t^2 + p_T^2(t_2)} + \sqrt{m_t^2 + p_T^2(\bar{t}_1)} + \sqrt{m_t^2 + p_T^2(\bar{t}_2)}$$

- Additional uncertainty: Matching scale

Matrix Element Corrections : Pythia8

Interface to MC@NLO or POWHEG
Stefano Frixione, Simone Amoroso, Stephen Mrenna '23

- no MEC settings
  - `SpaceShower:MEcorrections = off`
  - `TimeShower:MEcorrections = off`
- Decay MEC settings
  - `SpaceShower:MEcorrections = off`
  - `TimeShower:MEcorrections = on`
  - `TimeShower:MEextended = off`
  - `TimeShower:MEafterFirst = on/off`

`On` : use equivalent ME
`Off` : use exactly matching ME

Relevant exact MEC : $t \to bWg$ & $V \to qqg$

Off → ensure no double counting

`On` : MEC to emissions after the first, for dipole ends that did not yet radiate

MEC to *t*-processes : Status

- **Matrix element corrections in the Pythia8 parton shower in the context of matched simulations at next-to-leading order**
  Stefano Frixione, Simone Amoroso, Stephen Mrenna '23

  tt : dilepton channel

  Up to 20% impact on the shape of distributions. Recommendation of applying MECs.

- **Matrix Element Corrections in top quark decays for the ttW process**
  Rikkert Frederix, Leif Gellersen, Jasmina Nasufi '24

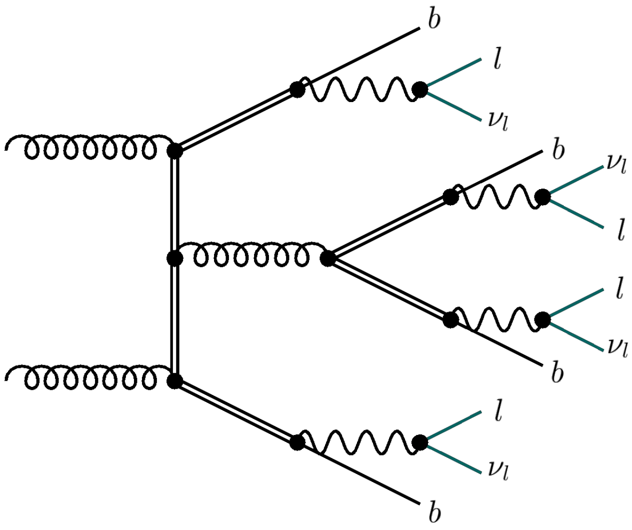
  ttW : 3-lepton and 2SS lepton channels

  MECs contribute up to 6% in some observables and regions.

- **In our study**
  tttt : 4- and 3-lepton channels

The 4-lepton Channel

$$p\ p \rightarrow l^- \bar{\nu}_l l^+ \nu_l l^- \bar{\nu}_l l^+ \nu_l\ \bar{b}\ b\ \bar{b}\ b$$



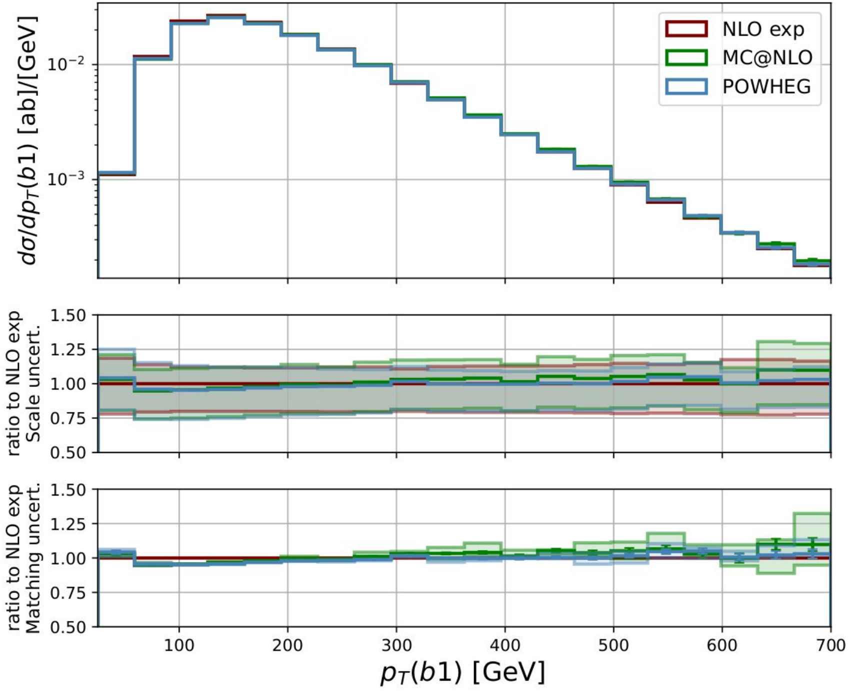
4 leptons: Integrated Cross Section

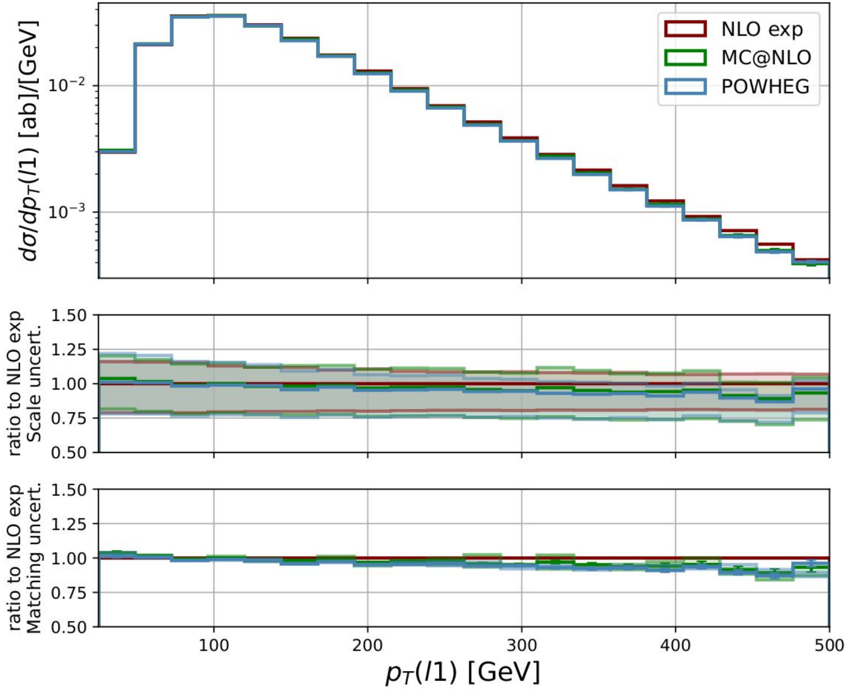
setup	value [ab]	$+\delta^{scale}$	$-\delta^{scale}$	$+\delta^{matching}$	$-\delta^{matching}$	value/NLO_{exp}
NLO_{exp}	5.170(3)	+12%	−20%	–	–	–
MC@NLO - no MECs	4.892(8)	+15%	−21%	+1.4%	−0.6%	0.9462
MC@NLO - with MECs	5.082(8)	+15%	−21%	+1.2%	−0.6%	0.9830
POWHEG - no MECs	4.821(6)	+15%	−21%	+0.0%	−0.5%	0.9325
POWHEG - with MECs	5.024(6)	+15%	−21%	+0.0%	−0.5%	0.9718

- Agreement of results within uncertainties
- MEC effect ~4% → better agreement with NLO-FO
- Scale uncertainties are of the same order for NLO-FO and NLO+PS
- Matching uncertainties 1%

4 leptons: Differential Distributions

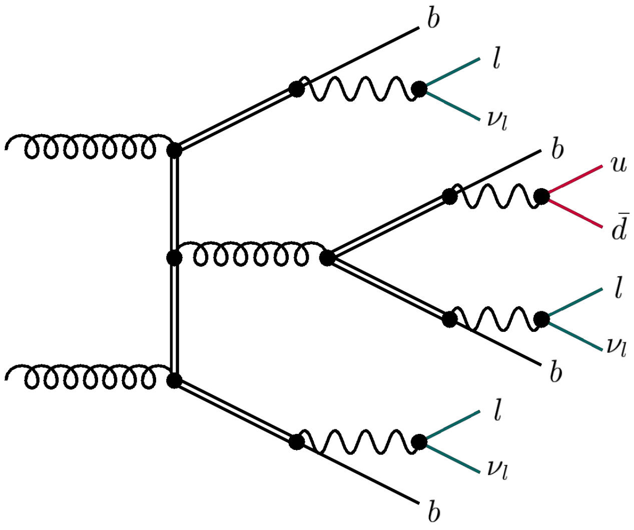
Comparison of NLO-FO to NLO+PS (POWHEG & MC@NLO) with MEC





The 3-lepton Channel

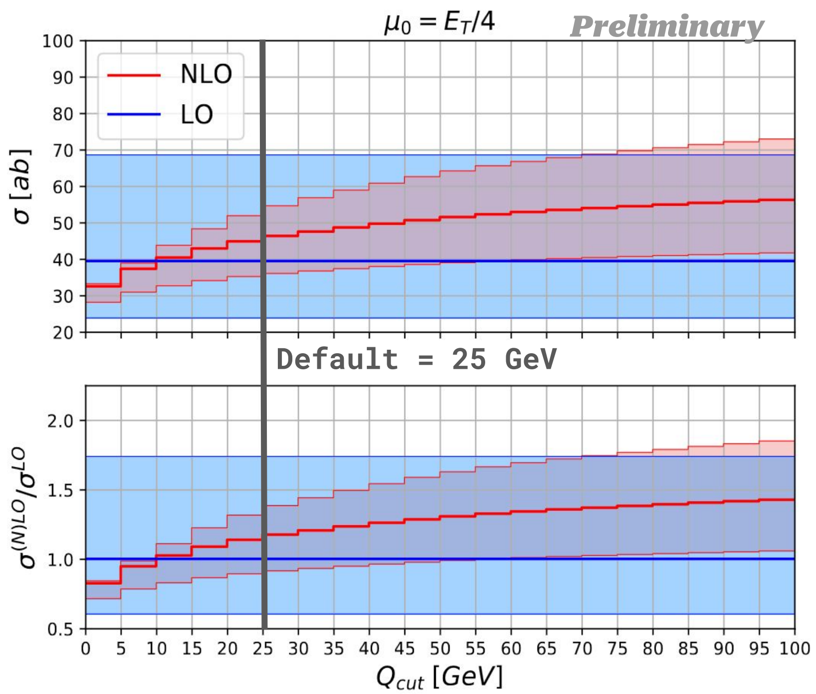
$$p\,p \to l^-\bar{\nu}_l l^+\nu_l l^-\bar{\nu}_l\ q\ \bar{q}\ \bar{b}\ b\ \bar{b}\ b$$

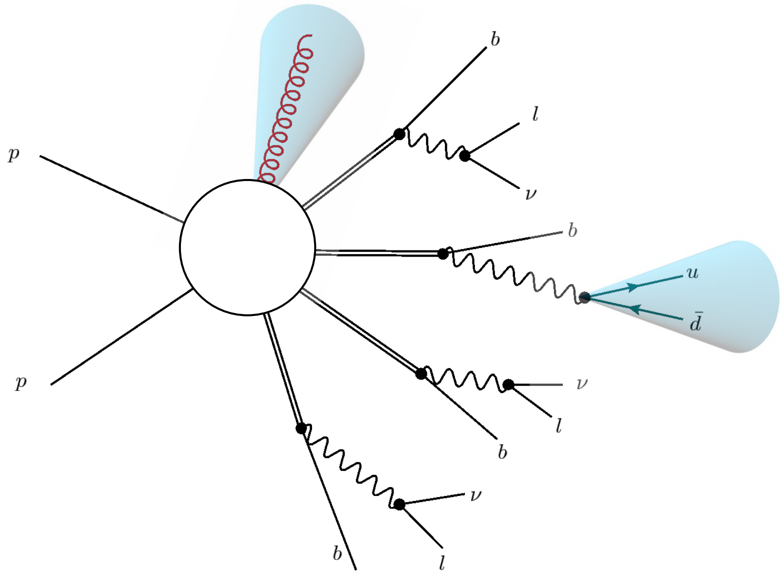


3 leptons : FO concerns

- We require at least one light-jet pair to have an invariant mass close to m_W

$$|M_{jj} - m_W| < Q_{cut}$$





- K factor is *1.5* when Q_{cut} = *100* GeV and *1.8* if no restriction is applied (no Q_{cut})

3 leptons : NLO+PS concerns

- Up to 8 (5) b-jets and 11 (3) l-jets in NLO+PS (NLO-FO)
- Identifying light-jets and b-jets from the hard process
  - With $|M_{jj} - m_W|$ minimisation for light-jets
  - MC truth for light- and b-jets
- *W* width → systematic uncertainties
- Applying a Q_{cut} to NLO+PS results
  - From NLO-FO: necessary to control perturbative convergence (size of NLO corrections and scale uncertainties)
  - From NLO+PS: effect of cut not visible as the scale uncertainties are based on production only → Underestimation of scale uncertainties in NLO+PS results?

3 leptons : Integrated Cross Section

Setup	σ_i^{NLO} [ab]	$+\delta_{scale}$	$-\delta_{scale}$	$\sigma_i^{\mathrm{NLO+PS}}/\sigma_{\mathrm{exp}}^{\mathrm{NLO}}$
	no Q_{cut}			
$\mathrm{NLO}_{\mathrm{exp}}$	70.19(7)	+42%	−30%	–
MC Truth MC@NLO - no MECs	64.7(2)	+14%	−21%	0.9222
MC Truth MC@NLO - with MECs	67.2(2)	+14%	−21%	0.9576
no jet ID MC@NLO - no MECs	72.6(2)	+14%	−21%	1.0340
no jet ID MC@NLO - with MECs	73.0(2)	+14%	−21%	1.0393
	$Q_{cut} = 25$ GeV			
$\mathrm{NLO}_{\mathrm{exp}}$	44.91(3)	+18%	−23%	–
MC Truth MC@NLO - with MECs	38.9(1)	+15%	−21%	0.8658

~4% (MC Truth MC@NLO - no MECs ↔ with MECs)

~0.5% (no jet ID MC@NLO - no MECs ↔ with MECs)

~8% (MC Truth MC@NLO - with MECs ↔ no jet ID MC@NLO - with MECs)

- 8% difference due to vetoing events with 0 light jets from *W* decay and less than 4 *b*-jets from the hard process
- Effect of MEC more pronounced in MC truth

3 leptons : Integrated Cross Section

Setup	σ_i^{NLO} [ab]	$+\delta_{scale}$	$-\delta_{scale}$	$\sigma_i^{\mathrm{NLO+PS}}/\sigma_{\mathrm{exp}}^{\mathrm{NLO}}$
		no Q_{cut}		
$\mathrm{NLO_{exp}}$	70.19(7)	+42%	−30%	–
MC Truth MC@NLO - no MECs	64.7(2)	+14%	−21%	0.9222
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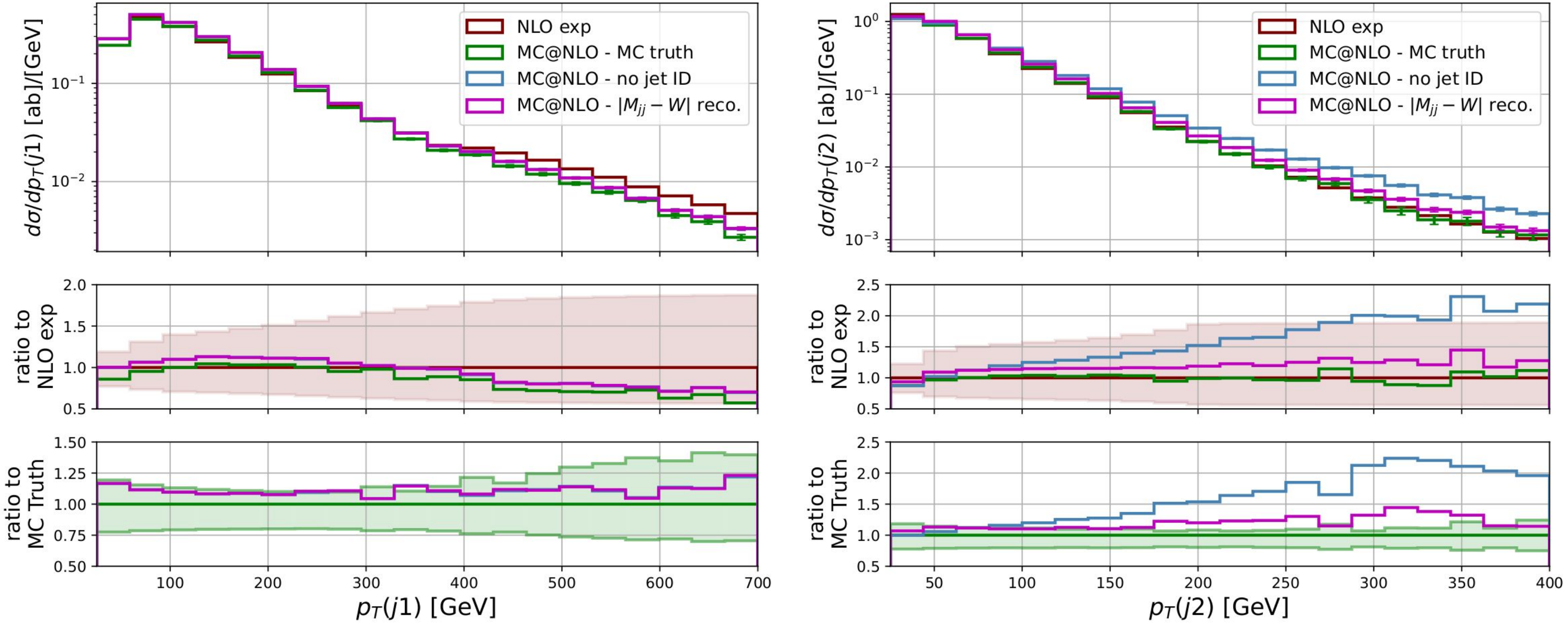
no jet ID MC@NLO - with MECs	73.0(2)	+14%	−21%	1.0393
		Q_{cut} = 25 GeV		
$\mathrm{NLO_{exp}}$	44.91(3)	+18%	−23%	–
MC Truth MC@NLO - with MECs	38.9(1)	+15%	−21%	0.8658

- Scale uncertainties calculated in the fiducial phase-space regions
- Scale uncertainties identical to 4-lepton channel → based on production
- Scale uncertainties unaffected by Q_{cut}

preliminary

3 leptons : Differential Distributions - no Q_{cut}

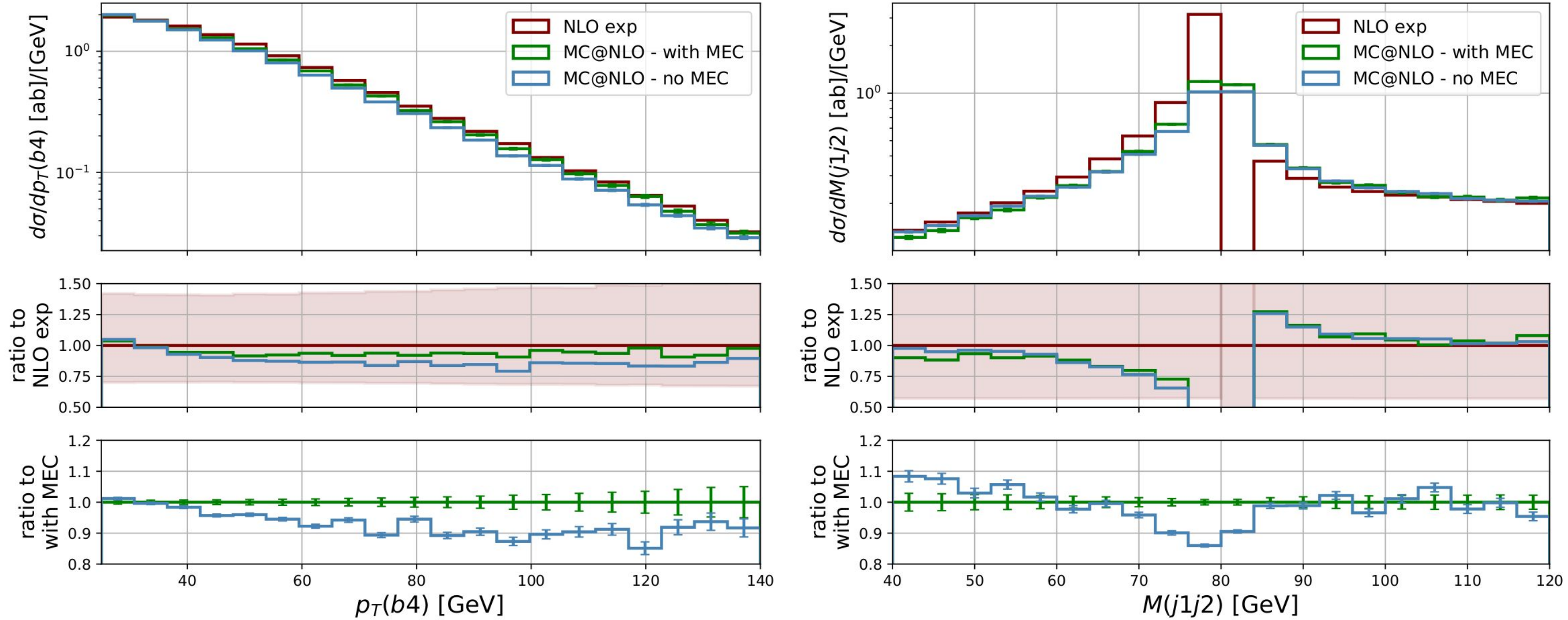
Comparison of FO to MC@NLO- Light-jet identification - including MEC



preliminary

3 leptons : Differential Distributions - no Q_{cut}

Comparison of MC@NLO to FO with and without MEC - MC Truth



Summary and Conclusions

In both channels

- Inclusion of MEC in NLO+PS:
    - 10%-15% difference in some regions and observables ($p_T(b)$, $M(b_1 b_2)$, $M(b_3 b_4)$, $M(j_1 j_2)$)
    - MECs partially recover higher order effects in the decays at the integrated level and for the majority of observables → better agreement with NLO-FO results
- Agreement between MC@NLO and POWHEG results

4lepton-channel

- Agreement between NLO+PS and FO-NLO within theoretical uncertainties
- Scale uncertainties in NLO+PS are similar to those in FO-NLO

3lepton-channel

- Discrepancy between NLO+PS and FO-NLO in light-jet kinematics
- Scale uncertainties in NLO+PS are different from those in FO-NLO

Are the scale uncertainties properly estimated in NLO-FO and NLO+PS?
Is Q_{cut} really needed for predictions at NLO + PS ?

Outlook

- Currently: Improve definition and identification of light- and b-jets from *W* and *t* decays
  - Potentially look towards machine learning methods

    SPANet *A. Shmakov , M.J. Fenton, T. Ho, S. Hsu, D. Whiteson and P. Baldi ’21*
- Long term goal
  - Apply MECs to the *ttH* process in the dilepton channel
  - Comparison to full off-shell prediction @NLO and to NWA@NLO
  - Study the impact on the extraction of the Y_t Yukawa coupling at the differential cross-section level using observables sensitive to Y_t

Back-up Transparencies

Theory & Setup

Fixed Order - Process Description

NLO production & LO decays

$$d\sigma^{\rm NLO}_{\rm full} = d\sigma^{\rm NLO}_{tt\bar{t}\bar{t}} \times \frac{d\Gamma^0_t}{\Gamma^{\rm NLO}_t} \times \frac{d\Gamma^0_{\bar{t}}}{\Gamma^{\rm NLO}_t} \times \frac{d\Gamma^0_t}{\Gamma^{\rm NLO}_t} \times \frac{d\Gamma^0_{\bar{t}}}{\Gamma^{\rm NLO}_t} + d\sigma^{\rm LO}_{tt\bar{t}\bar{t}} \times \frac{d\Gamma^1_t}{\Gamma^{\rm NLO}_t} \times \frac{d\Gamma^0_{\bar{t}}}{\Gamma^{\rm NLO}_t} \times \frac{d\Gamma^0_t}{\Gamma^{\rm NLO}_t} \times \frac{d\Gamma^0_{\bar{t}}}{\Gamma^{\rm NLO}_t}$$

$$+ d\sigma^{\rm LO}_{tt\bar{t}\bar{t}} \times \frac{d\Gamma^0_t}{\Gamma^{\rm NLO}_t} \times \frac{d\Gamma^1_{\bar{t}}}{\Gamma^{\rm NLO}_t} \times \frac{d\Gamma^0_t}{\Gamma^{\rm NLO}_t} \times \frac{d\Gamma^0_{\bar{t}}}{\Gamma^{\rm NLO}_t} + d\sigma^{\rm LO}_{tt\bar{t}\bar{t}} \times \frac{d\Gamma^0_t}{\Gamma^{\rm NLO}_t} \times \frac{d\Gamma^0_{\bar{t}}}{\Gamma^{\rm NLO}_t} \times \frac{d\Gamma^1_t}{\Gamma^{\rm NLO}_t} \times \frac{d\Gamma^0_{\bar{t}}}{\Gamma^{\rm NLO}_t}$$

$$+ d\sigma^{\rm LO}_{tt\bar{t}\bar{t}} \times \frac{d\Gamma^0_t}{\Gamma^{\rm NLO}_t} \times \frac{d\Gamma^0_{\bar{t}}}{\Gamma^{\rm NLO}_t} \times \frac{d\Gamma^0_t}{\Gamma^{\rm NLO}_t} \times \frac{d\Gamma^1_{\bar{t}}}{\Gamma^{\rm NLO}_t} \,.$$

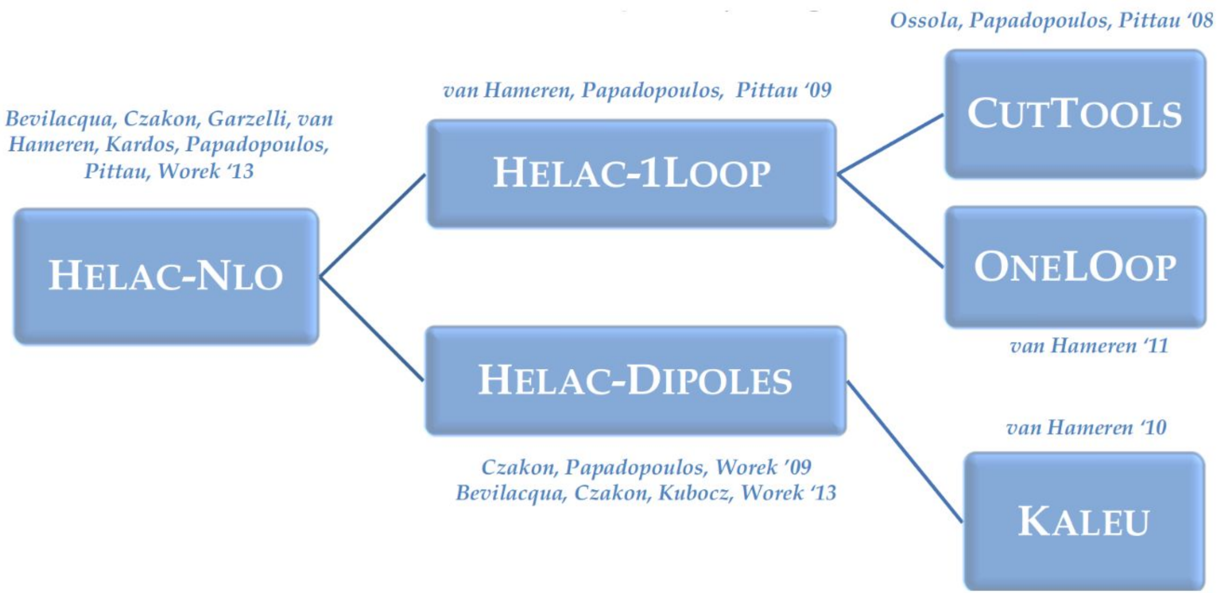
LO production & NLO decays

Expansion of $d\sigma = d\sigma_{tt\bar{t}\bar{t}} \times \frac{d\Gamma_t}{\Gamma_t} \times \frac{d\Gamma_t}{\Gamma_t} \times \frac{d\Gamma_{\bar{t}}}{\Gamma_t} \times \frac{d\Gamma_{\bar{t}}}{\Gamma_t}$

$$\left.\begin{aligned} d\sigma_{tt\bar{t}\bar{t}} &= d\sigma^{(0)}_{tt\bar{t}\bar{t}} + \alpha_s d\sigma^{(1)}_{tt\bar{t}\bar{t}} + \mathcal{O}(\alpha_s^2) \\ d\Gamma_t &= d\Gamma^{(0)}_t + \alpha_s d\Gamma^{(1)}_t + \mathcal{O}(\alpha_s^2) \\ \Gamma^{\rm NLO}_t &= \Gamma^{(0)}_t + \alpha_s \Gamma^{(1)}_t \end{aligned}\right\} d\sigma^{\rm NLO}_{\rm exp} = d\sigma^{\rm NLO} = d\sigma^{\rm NLO}_{\rm full} \times \left(\frac{\Gamma^{\rm NLO}_t}{\Gamma^{\rm LO}_t}\right)^4 - d\sigma^{\rm LO} \times \frac{4(\Gamma^{\rm NLO}_t - \Gamma^{\rm LO}_t)}{\Gamma^{\rm LO}_t}$$

default

HELAC-NLO



- The output is saved in Les Houches & ROOT Ntuple files *https://arxiv.org/abs/hep-ph/0609017, https://arxiv.org/abs/1310.7439*
- It can be further analysed by adding new cuts, changing the renormalization and factorization scales, using different PDF set

Computational Setup

Parameters

$$G_\mu = 1.1663787 \cdot 10^{-5}\ \text{GeV}^{-2}\,, \qquad m_t = 172.5\ \text{GeV}\,,$$

$$m_W = 80.379\ \text{GeV}\,, \qquad m_Z = 91.1876\ \text{GeV}\,.$$

W and t decay widths

$$\Gamma_t^{\text{LO}} = 1.4806\ \text{GeV} \qquad \Gamma_W^{\text{LO}} = 2.04526\ \text{GeV}$$

$$\Gamma_t^{\text{NLO}} = 1.3535983\ \text{GeV} \qquad \Gamma_W^{\text{NLO}} = 2.0972\ \text{GeV}$$

W width reweighing - for the 4 lepton channel

$$\left(\frac{BR^{NLO}(W^\pm \to l_i\nu_i)}{BR^{LO}(W^\pm \to l_i\nu_i)}\right)^4 = 0.903843211$$

Computational Setup

Renormalisation and factorisation scales

- Dynamical scale $\mu_0 = E_T/4$
- Scale variation

$$\left(\frac{\mu_R}{\mu_0}, \frac{\mu_F}{\mu_0}\right) = \{(2,1)\,,(0.5,1)\,,(1,2)\,,(1,1),(1,0.5),(2,2),(0.5,0.5)\}$$

Cuts

$$p_{T,\ell} > 25 \text{ GeV}\,, \qquad |y_\ell| < 2.5\,, \qquad \Delta R_{\ell\ell} > 0.4\,,$$
$$p_{T,b} > 25 \text{ GeV}\,, \qquad |y_b| < 2.5\,, \qquad \Delta R_{bb} > 0.4\,,$$
$$p_{T,j} > 25 \text{ GeV}\,, \qquad |y_j| < 2.5\,, \qquad \Delta R_{bj} > 0.4\,.$$

Matching to PS - Computational Setup

Shower starting scale

- For MC@NLO:

  $\mu_Q = E_T/2$, variation by factors of 2 and 0.5

- For POWHEG:

$$h_{\mathrm{damp}} = \frac{H_T}{4} \,, \qquad h_{\mathrm{bornzero}} = 5 \,,$$

$$(h_{\mathrm{damp}}, h_{\mathrm{bornzero}}) = \left\{ \left(\frac{H_T}{4}, 5\right), \left(\frac{H_T}{4}, 2\right), \left(\frac{H_T}{4}, 5\right), \left(\frac{H_T}{8}, 10\right), \left(\frac{H_T}{2}, 5\right) \right\}$$

MEC - Equivalent & Exact MEs

`flag` **TimeShower:MEextended** `(default =` **on**`)`

Use matrix element corrections also for *1 → n* and *2 → n* processes where no matrix elements are encoded, by an attempt to match on to one of the *1 → 2* processes that are implemented. This should at least provide relevant mass dampening for massive radiators and recoilers

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→ Pre-calculated set of ME*, if the exact 1 → 2 ME relevant for the process does not exist (is not already calculated), approximate by an "equivalent" one

https://pythia.org/latest-manual/TimelikeShowers.html
** hep-ph/0010012*

colour	spin	γ_5	example	codes
$1 \to 3 + \bar{3}$	—	—	(eikonal)	6 – 9
$1 \to 3 + \bar{3}$	$1 \to \frac{1}{2} + \frac{1}{2}$	$1, \gamma_5, 1 \pm \gamma_5$	$Z^0 \to q\bar{q}$	11 – 14
$3 \to 3 + 1$	$\frac{1}{2} \to \frac{1}{2} + 1$	$1, \gamma_5, 1 \pm \gamma_5$	$t \to bW^+$	16 – 19
$1 \to 3 + \bar{3}$	$0 \to \frac{1}{2} + \frac{1}{2}$	$1, \gamma_5, 1 \pm \gamma_5$	$H^0 \to q\bar{q}$	21 – 24
$3 \to 3 + 1$	$\frac{1}{2} \to \frac{1}{2} + 0$	$1, \gamma_5, 1 \pm \gamma_5$	$t \to bH^+$	26 – 29
$1 \to 3 + \bar{3}$	$1 \to 0 + 0$	1	$Z^0 \to \tilde{q}\bar{\tilde{q}}$	31 – 34
$3 \to 3 + 1$	$0 \to 0 + 1$	1	$\tilde{q} \to \tilde{q}'W^+$	36 – 39
$1 \to 3 + \bar{3}$	$0 \to 0 + 0$	1	$H^0 \to \tilde{q}\bar{\tilde{q}}$	41 – 44
$3 \to 3 + 1$	$0 \to 0 + 0$	1	$\tilde{q} \to \tilde{q}'H^+$	46 – 49
$1 \to 3 + \bar{3}$	$\frac{1}{2} \to \frac{1}{2} + 0$	$1, \gamma_5, 1 \pm \gamma_5$	$\tilde{\chi} \to q\bar{\tilde{q}}$	51 – 54
$3 \to 3 + 1$	$0 \to \frac{1}{2} + \frac{1}{2}$	$1, \gamma_5, 1 \pm \gamma_5$	$\tilde{q} \to q\tilde{\chi}$	56 – 59
$3 \to 3 + 1$	$\frac{1}{2} \to 0 + \frac{1}{2}$	$1, \gamma_5, 1 \pm \gamma_5$	$t \to \tilde{t}\tilde{\chi}$	61 – 64
$8 \to 3 + \bar{3}$	$\frac{1}{2} \to \frac{1}{2} + 0$	$1, \gamma_5, 1 \pm \gamma_5$	$\tilde{g} \to q\bar{\tilde{q}}$	66 – 69
$3 \to 3 + 8$	$0 \to \frac{1}{2} + \frac{1}{2}$	$1, \gamma_5, 1 \pm \gamma_5$	$\tilde{q} \to q\tilde{g}$	71 – 74
$3 \to 3 + 8$	$\frac{1}{2} \to 0 + \frac{1}{2}$	$1, \gamma_5, 1 \pm \gamma_5$	$t \to \tilde{t}\tilde{g}$	76 – 79
$1 \to 8 + 8$	—	—	(eikonal)	81 – 84

Table 1: The processes that have been calculated, also with one extra gluon in the final state. Colour is given with 1 for singlet, 3 for triplet and 8 for octet. See the text for an explanation of the γ_5 column and further comments.

Matching to PS - MC Truth

Access to mother-daughter information and jet constituents

History defined from the production vertex up to the final state

1. **Light- and b-jets distinguished with `jet.bTagged()`**
2. **Identify l-jets with a light-quark from *W* using the mother-daughter history**
3. **Identify b-jets with a b-quark from *t* using mother-daughter history**

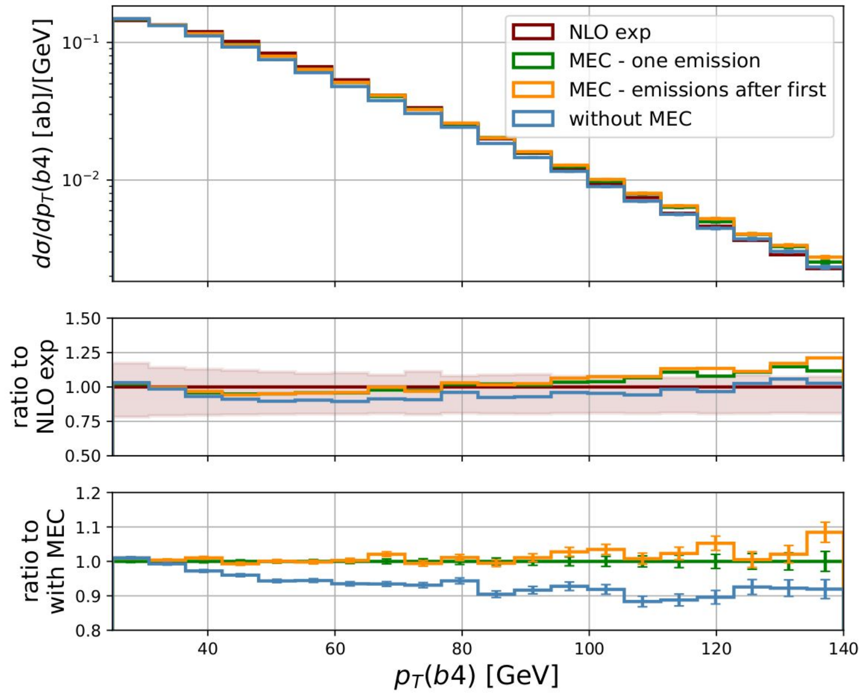
   On 2,3 : if a gluon is found in the history the flavoured quark constituent of the jet is excluded as being from the hard process
4. **For the real emission contribution:**
   a. b-jets: Identify b-jets whose immediate mother is a gluon or b-quark in the initial state, or whose immediate mother is an intermediate b-quark
   b. l-jets: if no b-jets of the case above → consider the remaining hardest light jet
5. **Event vetoed when**
   a. Total b-jets identified = 5 & l-jets from $W < 2$
   b. l-jets from W = 0
   c. Total b-jets identified < 4 } Exact constraint from FO
   d. Total l-jets < 2 }

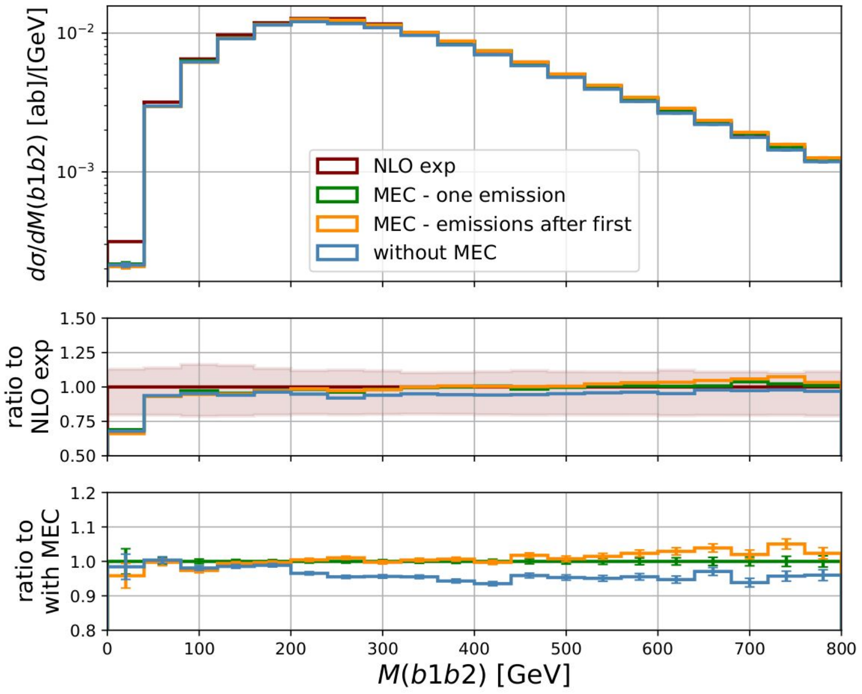
Results

preliminary

4 leptons: Differential Distributions

Comparison of MC@NLO to FO with and without MEC

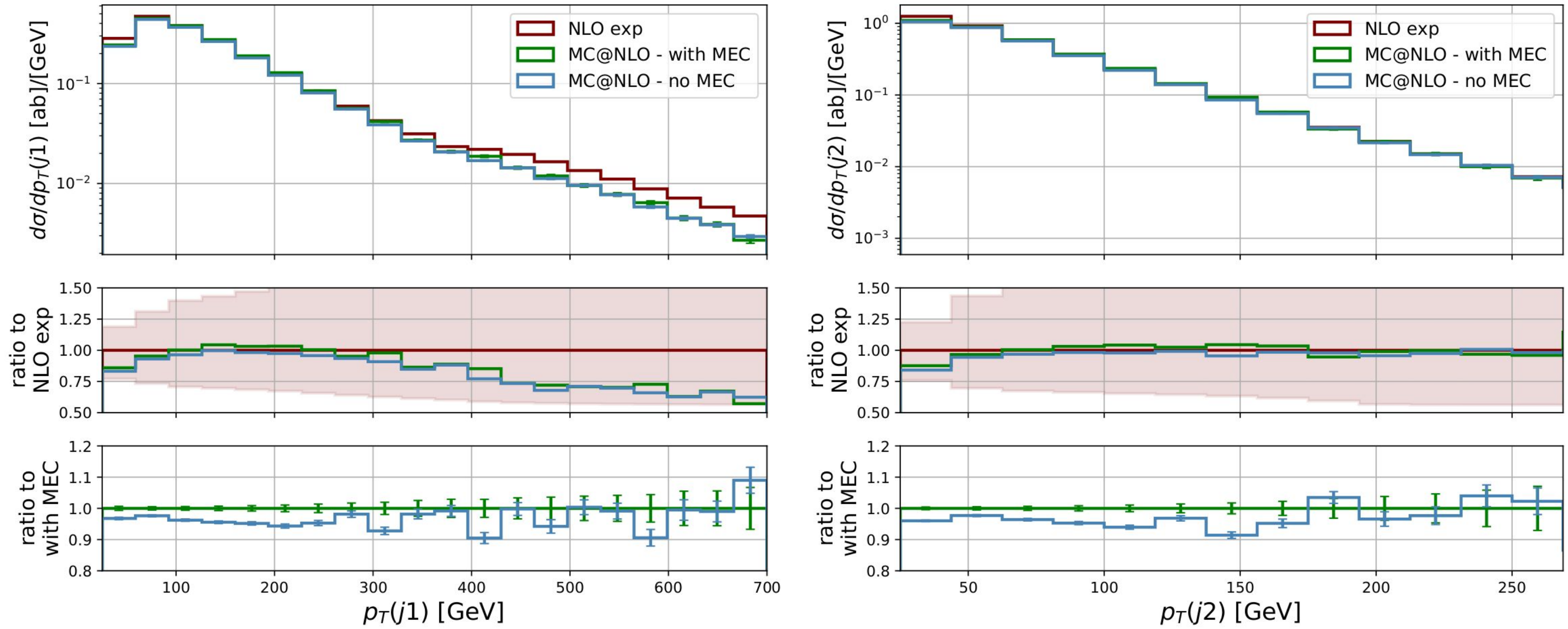




preliminary

3 leptons : Differential Distributions - no Q_{cut}

Comparison of MC@NLO to FO with and without MEC - MC Truth



3 leptons : POWHEG - no shower

Comparison of POWHEG without ISR or FSR to FO