Status and perspectives

on

loop-induced processes

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ATLAS–CMS Monte Carlo Generators Workshop

Disclaimer

I am an author of the SHERPA event generator, but I will try to keep that bias out of the following summary.

This review cannot be exhaustive, but I will focus on most important processes/process classes and recent developments/tools.

I will restrict myself to published results, with the implicit understanding that modern automated one-loop programs can calculate these processes without a dedicated publication.

Introduction

- Common signature $gg \to$ EW bosons
  exceptions e.g. same sign top production etc.
- Distinguish two cases
  1) Loop-induced as sole production mode, e.g. $gg \to h$
     $\to$ few cases with EFT approximation
  2) Tree-level production in $q\bar{q}$ dominant
     $\to$ gauge invariant subset of NNLO calculation
     $\to$ no guarantee that dominant part of NNLO correction
- Important production mechanism even if tree-level production exists
  $\to$ scales with $gg/q\bar{q}$ luminosities
- Implementations available in many parton level gens (MCFM, etc.)
  $\to$ will focus on particle level implementations
- when $q\bar{q}$ exists, then part of NNLO codes (for VV, VH etc.)
- Generally known only at LO, at most estimates of NLO corrections

Higgs production in gluon fusion

- for inclusive *ggh* coupling HEFT working well, correction to loop-induced flat and incorporated in every implementation
- for $pp \to h + n$ jets HEFT good enough to be reweighted $\to \mathcal{O}(1)$ corrections throughout phase space

$\Rightarrow$ can be incorporated in all the multijet merged at NLO machinery available for HEFT

- available in MadGraph, OpenLoops, GoSam

Hirschi, Mattelaer JHEP10(2015)146

Process Single boson + jets		Syntax	Cross section (pb) $\sqrt{s} = 13$ TeV	$\Delta_{\hat{\mu}}$	Δ_{PDF}	Ref.
a.1	$pp \to H$	`p p > h [QCD]`	17.79 ± 0.060	$^{+31.3\%}_{-23.1\%}$	$^{+0.5\%}_{-0.9\%}$	[49]
a.2	$pp \to Hj$	`p p > h j [QCD]`	12.86 ± 0.030	$^{+42.3\%}_{-27.7\%}$	$^{+0.6\%}_{-0.9\%}$	[49]
a.3	$pp \to Hjj$	`p p > h j j QED=1 [QCD]`	6.175 ± 0.020	$^{+61.8\%}_{-35.6\%}$	$^{+0.7\%}_{-0.9\%}$	[49]
†d.1	$pp \to Hjjj$	`p p > h j j j QED=1 [QCD]`	2.519 ± 0.005	$^{+75.1\%}_{-39.8\%}$	$^{+0.6\%}_{-0.6\%}$	[62]

Higgs production in gluon fusion

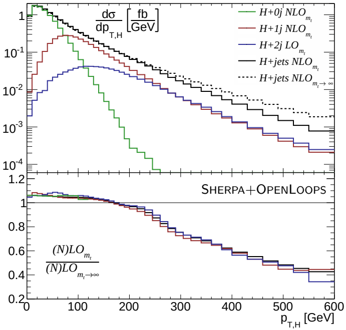
Buschmann, Goncalves, Kuttimalai, MS, Krauss, Plehn JHEP02(2015)038

$pp \to H$ + jets production (ggF)

- correction factor/weight

$$r_t^{(n)} = \frac{|\mathcal{M}^{(n)}(m_t)|^2}{|\mathcal{M}^{(n)}(m_t \to \infty)|^2}$$

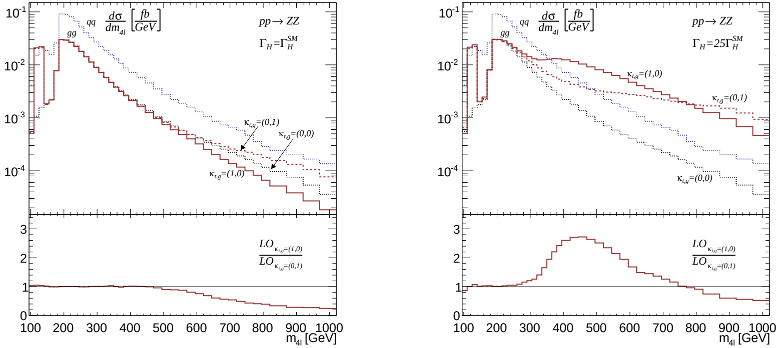
- loops from OpenLoops
- construct MEPs@Nlo from reweighted S-Mc@Nlo
- factorised approach for unknown top mass dependence in V_n, otherwise exact NLO mass dependence



$$\mathrm{d}\sigma_n = \mathrm{d}\Phi_n \, r_t^{(n)} \left[\mathrm{B}_n + \mathrm{V}_n + \int \mathrm{d}\Phi_1 \, \mathrm{D}_n\right] \widetilde{\mathrm{PS}}_n + \mathrm{d}\Phi_{n+1} \left[r_t^{(n+1)} \mathrm{R}_n - r_t^{(n)} \mathrm{D}_n\right]$$

Interference in Higgs production

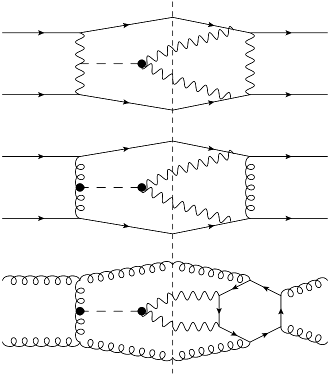
Buschmann, Goncalves, Kuttimalai, MS, Kraus, Plehn JHEP02(2015)038

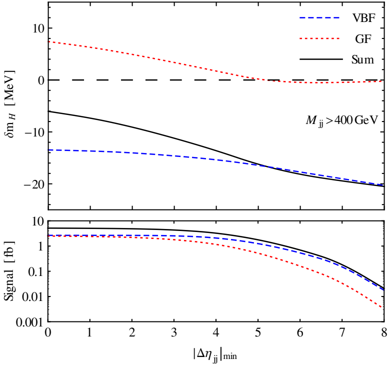


investigate new physics in $pp \to 4\ell$, $q\bar{q}$ @ NLO, gg @ LO
parametrised in κ framework, SM: $(\kappa_t, \kappa_g) = (1, 0)$

Interference in Higgs production

Coradeschi, de Florian, Dixon, Fidanza, Höche, Ita, Li, Mazzitelli PRD92(2015)013004



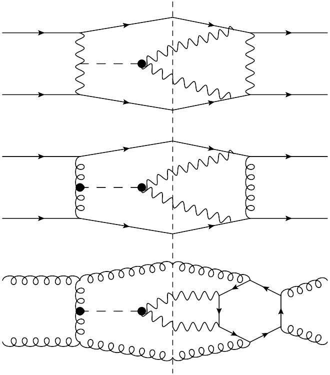


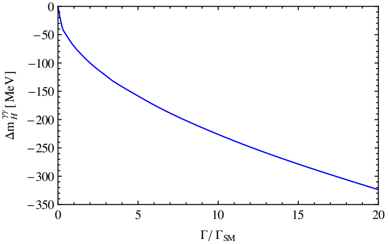
mass shift in $m_{\gamma\gamma}$ in VBF/GF–background interference

quickly increases with Γ_H

Interference in Higgs production

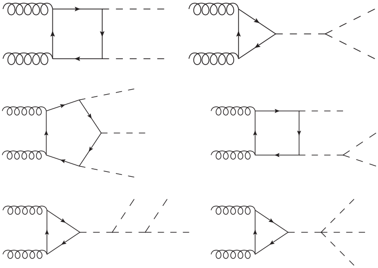
Coradeschi, de Florian, Dixon, Fidanza, Höche, Ita, Li, Mazzitelli PRD92(2015)013004



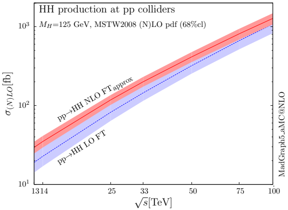


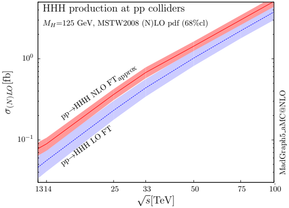
mass shift in $m_{\gamma\gamma}$ in VBF/GF–background interference quickly increases with Γ_H

Double/Triple Higgs production in gluon fusion



Maltoni, Vryonidou, Zaro JHEP11(2014)079

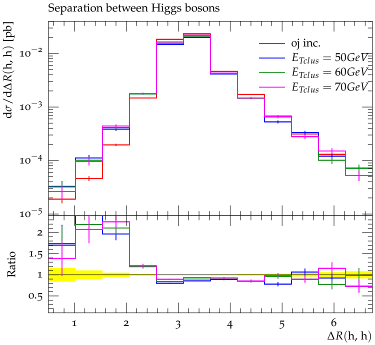


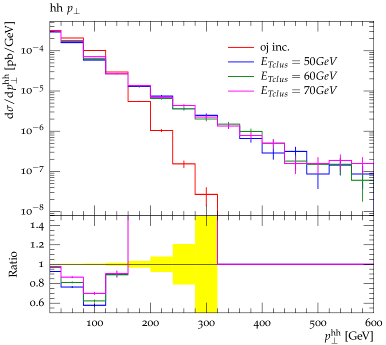


- reweight in $\mathrm{d}\Phi_B$ with r_t^B, in $\mathrm{d}\Phi_R$ with r_t^R
- factorised approach for virtual corrections

Double Higgs production in gluon fusion

Maierhöfer, Papaefstathiou JHEP03(2014)126





- LO merging for $pp \to hh + 0, 1$ jets in MLM scheme
- use exact loop-induced, no reweighting
- using Herwig+++OpenLoops

Associated Higgs production

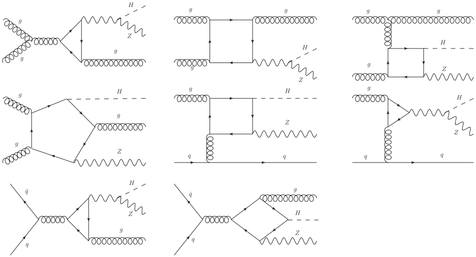
- only $gg \to HZ$, $gg \to HZg$, $gq \to HZq$ and $gg \to H\gamma g$
- relative size of contribution strongly dependent on observable

Hirschi, Mattelaer JHEP10(2015)146

Process		Syntax	Cross section (pb)	$\Delta_{\hat{\mu}}$	Δ_{PDF}	Ref.
Double bosons + jet			$\sqrt{s} = 13$ TeV			
*b.3	$pp \to H\gamma j$	`p p > h a j [QCD]`	$4.225 \pm 0.006 \cdot 10^{-3}$	$^{+38.6\%}_{-25.9\%}$	$^{+0.4\%}_{-0.7\%}$	[52]
*b.4	$gg \to HZ$	`g g > h z [QCD]`	$6.537 \pm 0.030 \cdot 10^{-2}$	$^{+29.4\%}_{-21.3\%}$	$^{+1.0\%}_{-1.1\%}$	[53]
*b.5	$gg \to HZg$	`g g > h z g [QCD]`	$5.465 \pm 0.020 \cdot 10^{-2}$	$^{+46.0\%}_{-29.4\%}$	$^{+1.2\%}_{-1.3\%}$	[52]

Associated Higgs production

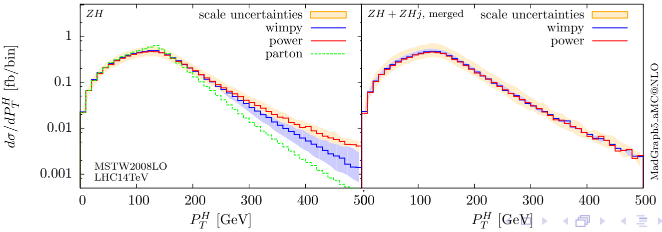
Hespel, Maltoni, Vryonidou JHEP06(2015)065



MLM merge loop-induced ZH production

$gg \to ZH$

$gg \to ZHg$ and $gq \to ZHq$

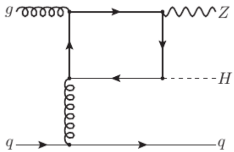


Associated Higgs production

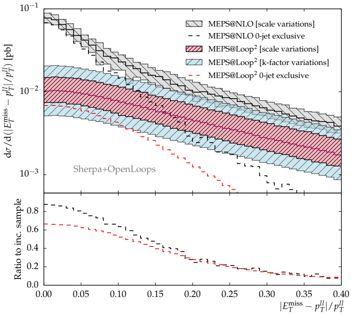
Goncalves, Krauss, Kuttimalai, Maierhöfer PRD92(2015)7,073006

$pp \to \ell\ell\, H$ + jets production

- MEPS@NLO for $q\bar{q}$
  MEPS@LOOP^2 for gg
- care for $qg \to ZHq$:



→ part of NLO ZHj
→ in loop-induced as gauge inv. subset of NNLO ZHj



$pp \to Z[\to \ell\ell\,]H[\to \text{inv}]$ + jets

Associated Higgs production

Goncalves, Krauss, Kuttimalai, Maierhöfer PRD92(2015)7,073006

$pp \to \ell\ell\, H$ + jets production

- MEPS@NLO for $q\bar{q}$
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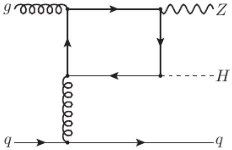
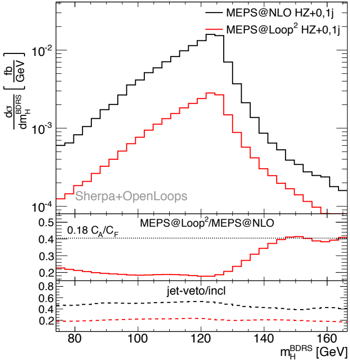


$\to$ part of NLO ZHj
$\to$ in loop-induced as gauge inv. subset of NNLO ZHj



$pp \to Z[\to \ell\ell]\, H[\to b\bar{b}]$ + jets

Vector boson pair production

- relative size of contribution strongly dependent on observable, but typically $< 10\%$

Hirschi, Mattelaer JHEP10(2015)146

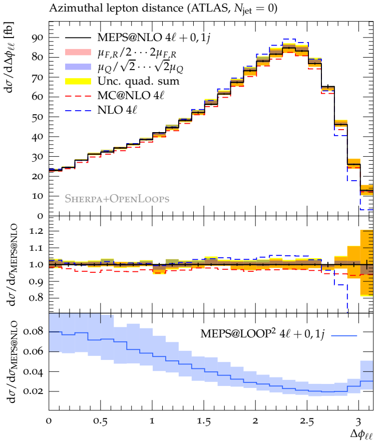
Process Double bosons + jet		Syntax	Cross section (pb) $\sqrt{s} = 13$ TeV	$\Delta_{\hat{\mu}}$	Δ_{PDF}	Ref.
b.6	$gg \to ZZ$	`g g > z z [QCD]`	1.313 ± 0.004	$^{+27.1\%}_{-20.1\%}$	$^{+0.7\%}_{-1.0\%}$	[42]
⋆b.7	$gg \to ZZg$	`g g > z z g [QCD]`	0.6361 ± 0.002	$^{+45.4\%}_{-29.1\%}$	$^{+1.0\%}_{-1.2\%}$	[54]
b.8	$gg \to Z\gamma$	`g g > z a [QCD]`	1.265 ± 0.0007	$^{+30.2\%}_{-22.2\%}$	$^{+0.6\%}_{-1.0\%}$	[42]
⋆b.9	$gg \to Z\gamma g$	`g g > z a g [QCD]`	0.4604 ± 0.001	$^{+43.7\%}_{-28.4\%}$	$^{+0.8\%}_{-1.1\%}$	[55]
b.10	$gg \to \gamma\gamma$	`g g > a a [QCD]`	$5.182 \pm 0.010 \cdot 10^{+2}$	$^{+72.3\%}_{-43.4\%}$	$^{+1.0\%}_{-1.3\%}$	[42]
⋆b.11	$gg \to \gamma\gamma g$	`g g > a a g [QCD]`	19.22 ± 0.030	$^{+59.7\%}_{-35.7\%}$	$^{+0.7\%}_{-1.0\%}$	[56]
b.12	$gg \to W^+W^-$	`g g > w+ w- [QCD]`	4.099 ± 0.010	$^{+26.5\%}_{-19.7\%}$	$^{+0.7\%}_{-1.0\%}$	[57]
⋆b.13	$gg \to W^+W^-g$	`g g > w+ w- g [QCD]`	1.837 ± 0.004	$^{+45.2\%}_{-29.0\%}$	$^{+0.9\%}_{-1.1\%}$	[58]

Vector boson pair production

Cascioli, Höche, Krauss, Maierhöfer, Pozzorini, Siegert arXiv:1309.5912

$pp \to 4\ell + 0, 1$ jets
and $pp \to 2\ell 2\nu + 0, 1$ jets

- MEPS@NLO for $q\bar{q}$
  MEPS@LOOP^2 for gg
- includes loop-induced
  $gg \to 4\ell$,
  $gg \to 4\ell + g$, $gq \to 4\ell + q$,
  $q\bar{q} \to 4\ell + g$



Vector boson pair production

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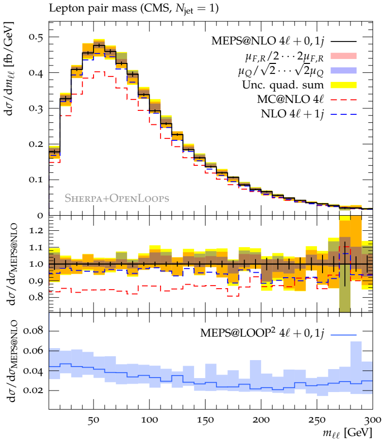
$pp \to 4\ell + 0, 1$ jets
and $pp \to 2\ell 2\nu + 0, 1$ jets

- MEPS@NLO for $q\bar{q}$
  MEPS@LOOP^2 for gg
- includes loop-induced
  $gg \to 4\ell$,
  $gg \to 4\ell + g$, $gq \to 4\ell + q$,
  $q\bar{q} \to 4\ell + g$



Multiboson production

- many process, generally very small cross section

Hirschi, Mattelaer JHEP10(2015)146

Process		Syntax	Cross section (pb)	$\Delta_{\hat{\mu}}$	Δ_{PDF}	Ref.
Triple bosons			$\sqrt{s} = 13$ TeV			
*c.1	$pp \to HHH$	`p p > h h h [QCD]`	$3.968 \pm 0.010 \cdot 10^{-5}$	$^{+31.8\%}_{-22.6\%}$	$^{+1.4\%}_{-1.4\%}$	[59]
†c.2	$gg \to HHZ$	`g g > h h z [QCD]`	$5.260 \pm 0.009 \cdot 10^{-5}$	$^{+31.2\%}_{-22.2\%}$	$^{+1.3\%}_{-1.3\%}$	[–]
†c.3	$gg \to HZZ$	`g g > h z z [QCD]`	$1.144 \pm 0.004 \cdot 10^{-4}$	$^{+31.1\%}_{-22.2\%}$	$^{+1.2\%}_{-1.3\%}$	[–]
†c.4	$gg \to HZ\gamma$	`g g > h z a [QCD]`	$6.190 \pm 0.020 \cdot 10^{-6}$	$^{+29.3\%}_{-21.2\%}$	$^{+1.0\%}_{-1.2\%}$	[–]
†c.5	$pp \to H\gamma\gamma$	`p p > h a a [QCD]`	$6.058 \pm 0.004 \cdot 10^{-6}$	$^{+30.3\%}_{-21.8\%}$	$^{+1.1\%}_{-1.3\%}$	[–]
*c.6	$gg \to HW^+W^-$	`g g > h w+ w- [QCD]`	$2.670 \pm 0.007 \cdot 10^{-4}$	$^{+31.0\%}_{-22.2\%}$	$^{+1.2\%}_{-1.3\%}$	[60]
†c.7	$gg \to ZZZ$	`g g > z z z [QCD]`	$6.964 \pm 0.009 \cdot 10^{-5}$	$^{+30.9\%}_{-22.1\%}$	$^{+1.2\%}_{-1.3\%}$	[–]
†c.8	$gg \to ZZ\gamma$	`g g > z z a [QCD]`	$3.454 \pm 0.010 \cdot 10^{-6}$	$^{+28.7\%}_{-20.9\%}$	$^{+0.9\%}_{-1.1\%}$	[–]
*c.9	$gg \to Z\gamma\gamma$	`g g > z a a [QCD]`	$3.079 \pm 0.005 \cdot 10^{-4}$	$^{+28.0\%}_{-20.9\%}$	$^{+0.7\%}_{-1.0\%}$	[61]
†c.10	$gg \to ZW^+W^-$	`g g > z w+ w- [QCD]`	$8.595 \pm 0.020 \cdot 10^{-3}$	$^{+26.9\%}_{-19.5\%}$	$^{+0.6\%}_{-0.6\%}$	[–]
†c.12	$gg \to \gamma W^+W^-$	`g g > a w+ w- [QCD]`	$1.822 \pm 0.005 \cdot 10^{-2}$	$^{+28.7\%}_{-20.9\%}$	$^{+0.9\%}_{-1.1\%}$	[–]

Tools

Process specific tools:

- gg2VV+HERWIG/PYTHIA — Kauer JHEP12(2013)082
  - $gg \to 2\ell 2\nu$, 4ℓ

⋮

General tools:

- MADGRAPH+HERWIG/PYTHIA — Hirschi, Mattelaer JHEP10(2015)146
  - all on-shell $2 \to 2$ and $2 \to 3$ processes, some $2 \to 4$ in SM
  - MLM merging possible with PYTHIA6
- SHERPA+OPENLOOPS — several publications
  - all off-shell $2 \to 2$ and $2 \to 3$, e.g. $gg \to 4\ell g$
  - MEPS@LOOP^2 merging possible

Timings – MadGraph

Timing for 10k unweighted events (number of phase space points needed)

Helicity sum	Monte-Carlo	Exact	
Loop Reduction	CutTools	CutTools	TIR
Survey			
$pp \to hj$	13m (125k)	32m (260k)	**9m (260k)**
$pp \to hjj$	**2d4h (1.2M)**	16d10h (5.4M)	9d13h (5.4M)*
$gg \to zz$	**1h06m (34k)**	12h50m (255k)	1h44m (255k)
$gg \to zhg$	**11h13m (110k)**	1d8h (516k)	1d4h (516k)*
Refine			
$pp \to hj$	1h43m (385k)	23m (431k)	**6m (431k)**
$pp \to hjj$	**7d17h (2.18M)**	75d1h (20.6M)	51d19h (20.6M)*
$gg \to zz$	**7h20m (407k)**	4d13h (4.55M)	23h07m (5.78M)
$gg \to zhg$	**23h03m (277k)**	2d22h (1.13M)	3d14h (1.4M)*

Hirschi, Mattelaer JHEP10(2015)146

Timings – OpenLoops

Timing per phase space point using Collier

Process	ms/point	Process	ms/point	Process	ms/point
$gg \to h$	0.11	$gg \to hh$	1.3		
$gg \to hg$	1.6	$gg \to hhg$	47	$gg \to \gamma g$	2.7
$gg \to hgg$	50			$gg \to \gamma gg$	117
$gg \to he^+e^-$	2.0	$gg \to e^+e^-$	0.28	$gg \to e^+e^-\gamma$	4.3
$gg \to he^+e^-g$	61	$gg \to e^+e^-g$	4.9	$gg \to e^+e^-\gamma g$	128

Process	ms/point	Process	ms/point
$gg \to e^+e^-\mu^+\mu^-$	8.9	$gg \to e^+\nu_e\mu^-\bar{\nu}_\mu$	2.0
$gg \to e^+e^-\mu^+\mu^-g$	238	$gg \to e^+\nu_e\mu^-\bar{\nu}_\mu g$	72
$gg \to e^+e^-e^+e^-$	25	$gg \to e^+\nu_e e^-\bar{\nu}_e$	6.2
$gg \to e^+e^-e^+e^-g$	638	$gg \to e^+\nu_e e^-\bar{\nu}_e g$	202

Conclusion

- all processes in SM available by several tools
  process specific, MadGraph+Herwig/Pythia, Sherpa+OpenLoops, Sherpa+GoSam
- improve EFT used otherwise
  include important subleading process where $q\bar{q}$ channel exists, gg has different properties
  calculate signatures inaccessible otherwise
- NLO corrections are two-loop, usually with many mass scales
  $\rightarrow$ generally not available
- NLO K-factors are estimated to be large ≈ 2
- selected BSM processes appeared in the literature
- timings/efficiencies vary between tools

Thank you for your attention!