High multiplicity NLO with NJet and Sherpa

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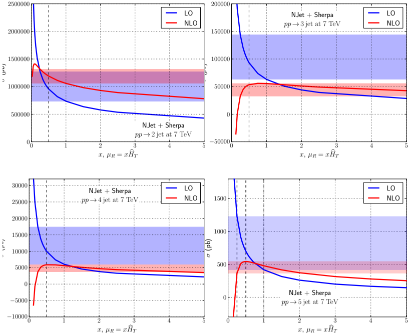
NLO results provide more accurate predictions and theoretical uncertainties for multi-jet backgrounds in new physics searches.

NLO vs LO

- Reduced theoretical uncertainty

NLO automation

- Great advances in the recent years
- High-multiplicity still remains a challenge



— LO
— NLO

NJet public C++ library

Multi-parton matrix elements in massless QCD

[https://bitbucket.org/njet/njet] [arXiv:1209.0100]

Features

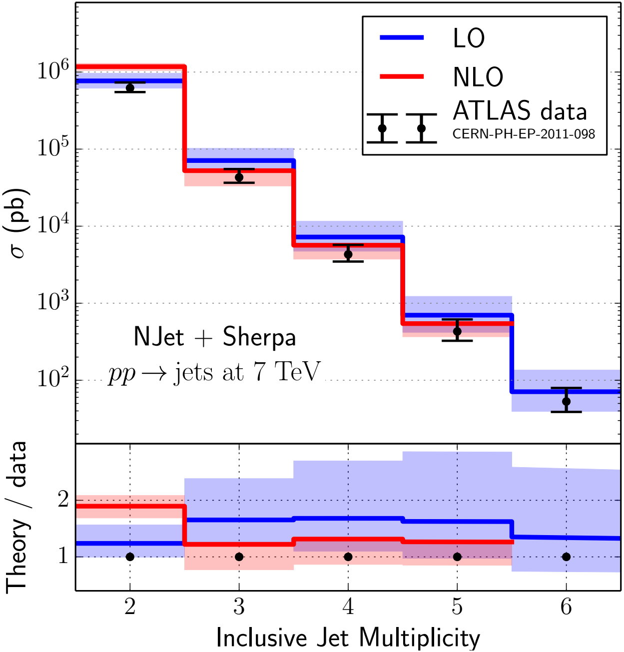
- Full colour-summed amplitudes for up to 5 outgoing partons
- Reliable accuracy estimate and rescue system
- BLHA interface for MC generators

New in NJet 2.0[1]

- $W^\pm/Z/\gamma$ with up to **5 jets** and $\gamma\gamma$ with up to **4 jets**.
- Leading/Subleading colour splitting.
- Hardware vectorization for scaling test.
- BLHA2 support.

[1] beta available from https://bitbucket.org/njet/njet/downloads

NJet+Sherpa: total XS for 2, 3, 4, 5 jets at 7 TeV vs ATLAS measurements



Cuts

anti-kt $R = 0.4$

$p_T^{\text{1st}} > 80$ GeV

$p_T^{\text{other}} > 60$ GeV

$|\eta| < 2.8$

NLO

$\mu_R = \mu_F = \hat{H}_T/2$

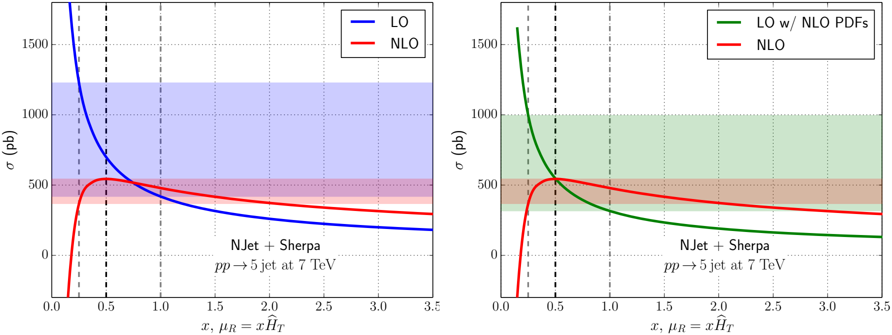
vars. $\hat{H}_T/4$ and $\hat{H}_T$

$\alpha_s(M_Z) = 0.118$

NNPDF23 PDF set

NJet+Sherpa: 5 jets at 7 TeV, scale variations

ATLAS cuts, NNPDF23 PDF set, $\alpha_s(M_Z) = 0.118$



$$\sigma_5^{\text{7TeV-LO}}(\mu = \hat{H}_T/2) = 0.699(0.004)^{+0.530}_{-0.280}\ \text{nb}$$

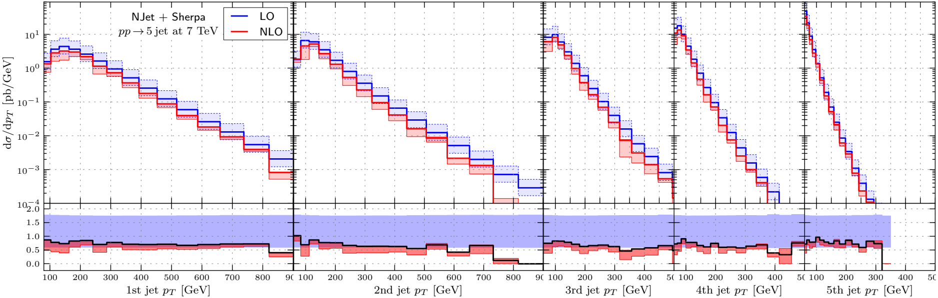
$$\sigma_5^{\text{7TeV-NLO}}(\mu = \hat{H}_T/2) = 0.544(0.016)^{+0.0}_{-0.177}\ \text{nb}$$

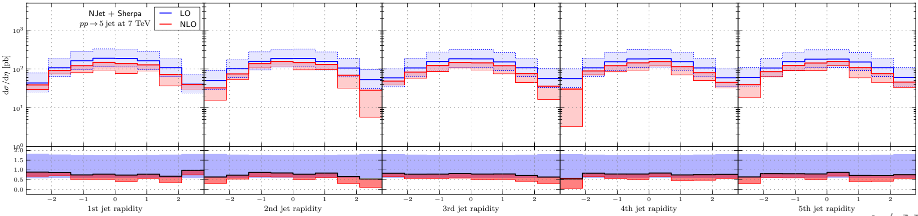
$$\sigma_5^{\text{8TeV-LO}}(\mu = \hat{H}_T/2) = 1.044(0.006)^{+0.770}_{-0.413}\ \text{nb}$$

$$\sigma_5^{\text{8TeV-NLO}}(\mu = \hat{H}_T/2) = 0.790(0.021)^{+0.0}_{-0.313}\ \text{nb}$$

NJet+Sherpa: 5 jets at 7 TeV, p_T and η distributions

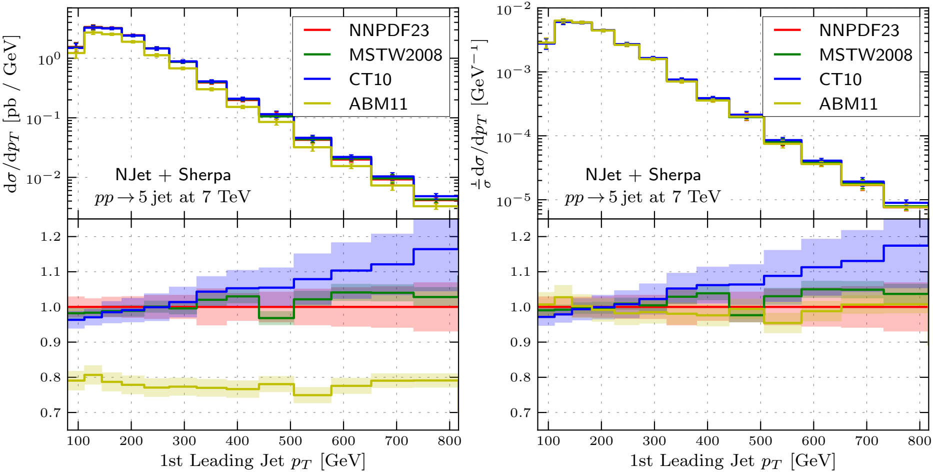
ATLAS cuts, NNPDF23 PDF set, $\alpha_s(M_Z) = 0.118$



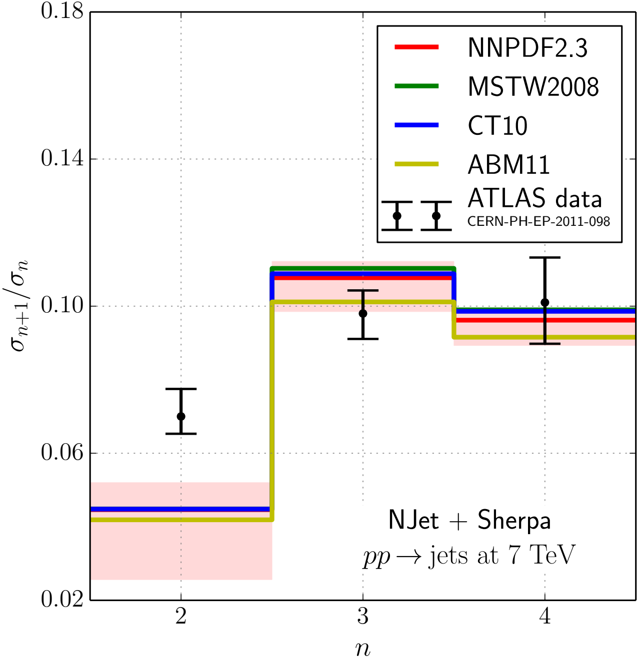


NJet+Sherpa: 5 jets at 7 TeV, PDF uncertainties

ATLAS cuts, $\alpha_s(M_Z) = 0.118$, $\boxed{\text{PDF uncertainty} \approx 3\%}$



Right plot — distributions normalized to total cross-section.



Cuts

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$p_T^{\text{other}} > 60$ GeV

$|\eta| < 2.8$

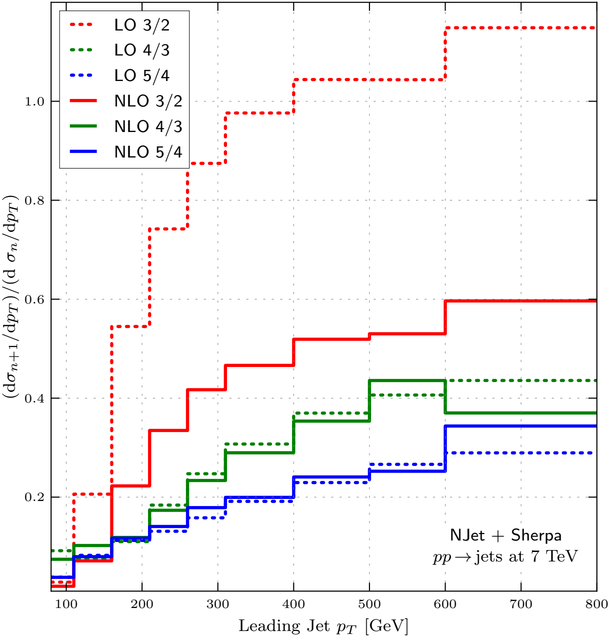
NLO

$\mu_R = \mu_F = \hat{H}_T/2$

vars. $\hat{H}_T/4$ and $\hat{H}_T$ (shown for NNPDF)

$\alpha_s(M_Z) = 0.118$

NJet+Sherpa: p_T for jets ratios at 7 TeV



Cuts

anti-kt $R = 0.4$

$p_T^{\text{1st}} > 80$ GeV

$p_T^{\text{other}} > 60$ GeV

$|\eta| < 2.8$

NLO

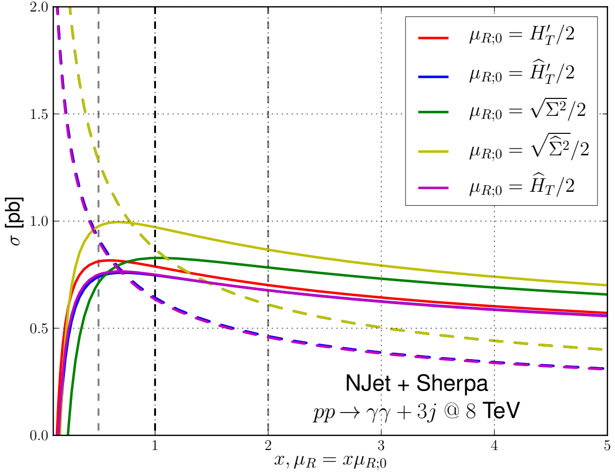
$\mu_R = \mu_F = \hat{H}_T/2$

vars. $60\%, 12\%, 9\%$ (not shown)

$\alpha_s(M_Z) = 0.118$

NNPDF23 PDF set

NJet+Sherpa: $\gamma\gamma + 3j$ at 8 TeV, scale variations, CT10nlo PDF



$$\sigma^{LO}_{\gamma\gamma+3j}(\widehat{H}'_T/2) = 0.643(0.003)^{+0.278}_{-0.180}\,\mathrm{pb}$$
$$\sigma^{NLO}_{\gamma\gamma+3j}(\widehat{H}'_T/2) = 0.785(0.010)^{+0.027}_{-0.085}\,\mathrm{pb}$$

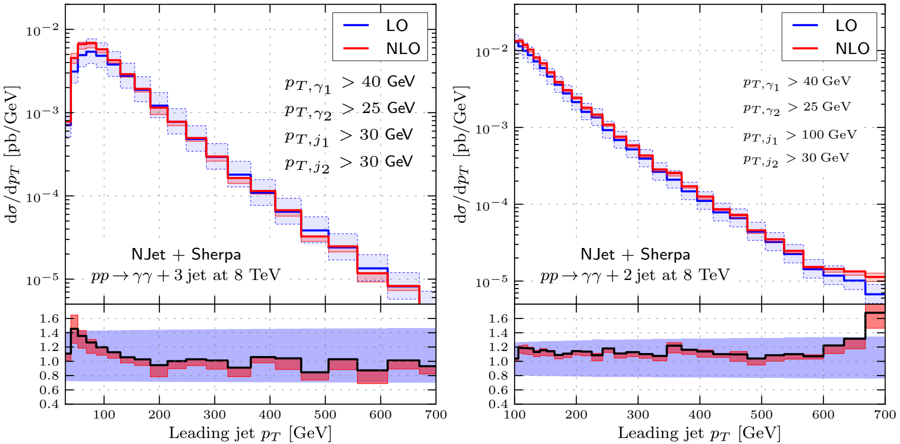
Cuts

$p_{T,j} > 30$ GeV
$|\eta_j| \leq 4.7$
$p_{T,\gamma_1} > 40$ GeV
$p_{T,\gamma_2} > 25$ GeV
$|\eta_\gamma| \leq 2.5$
$R_{\gamma,j} = 0.5$
$R_{\gamma,\gamma} = 0.45$

Scales

$$\widehat{H}_T = \sum_{i\in\{\gamma,\,\text{partons}\}} p_{T,i}$$
$$\widehat{H}'_T = m_{\gamma\gamma} + \sum_{i\in\text{partons}} p_{T,i}$$
$$\widehat{\Sigma}^2 = m^2_{\gamma\gamma} + \sum_{i\in\text{partons}} p^2_{T,i}$$
$$H'_T = m_{\gamma\gamma} + \sum_{i\in\text{jets}} p_{T,i}$$
$$\Sigma^2 = m^2_{\gamma\gamma} + \sum_{i\in\text{jets}} p^2_{T,i}$$

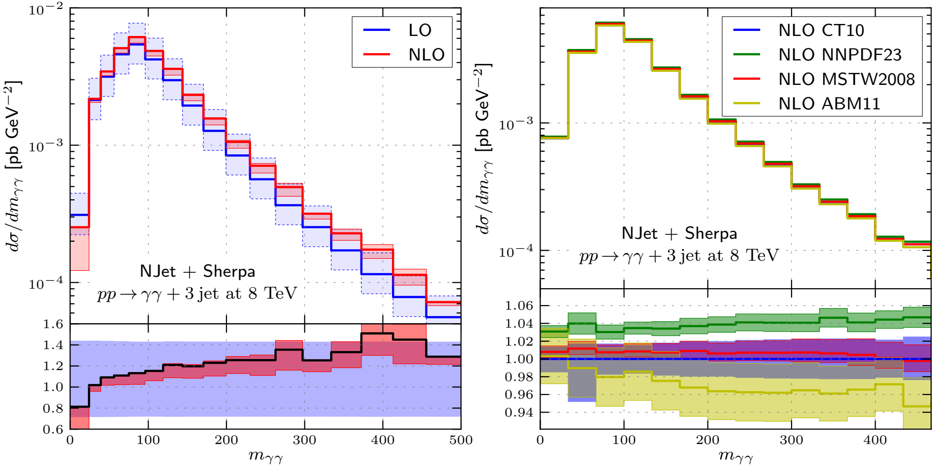
NJet+Sherpa: $\gamma\gamma + 3j$ at 8 TeV, leading p_T cut dependence



p_{T,j_1} cut dependence in leading jet p_T distribution.

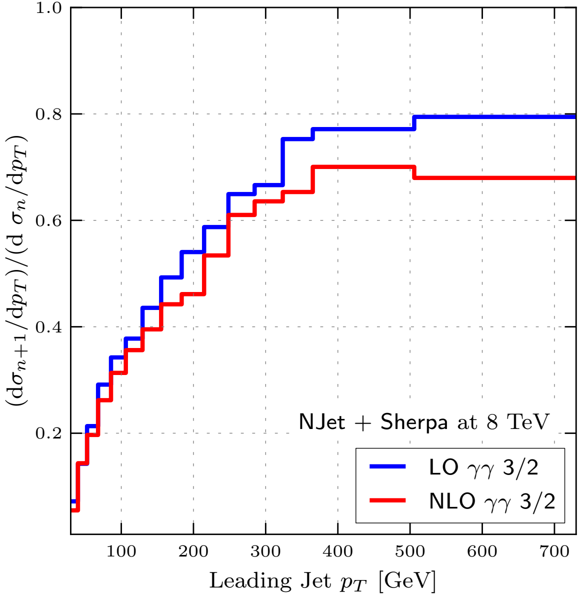
NJet+Sherpa: $\gamma\gamma + 3j$ at 8 TeV, $m_{\gamma\gamma}$ distribution and PDF uncertainties

PDF uncertainty ≈ 3–6%



Di-photon invariant mass distribution

NJet+Sherpa: p_T for $\gamma\gamma +$ jets $3/2$ ratio at 8 TeV



Ratio

$\mu_R = \mu_F = \widehat{H}'_T/2$

$R_{3/2}^{LO} = 0.314(0.002)$

$R_{3/2}^{NLO} = 0.276(0.004)$

Scale

Different scales agree within 8% for $R_{3/2}$

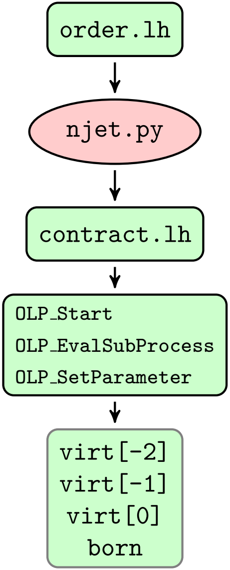
Hard process ingredients

$$\sigma^{\mathrm{NLO}} = \int_n \left(\boxed{d\sigma_n^{\mathrm{B}}} + \underset{\text{bottleneck}}{\boxed{d\sigma_n^{\mathrm{V}}}} + \int_1 \boxed{d\sigma_{n+1}^{\mathrm{S}}} \right) + \int_{n+1} \left(\underset{\text{bottleneck}}{\boxed{d\sigma_{n+1}^{\mathrm{R}} - d\sigma_{n+1}^{\mathrm{S}}}} \right)$$

Calculation ingredients

1. NJet — One-loop virtual matrix elements
   - QCDLoop, libqd, libVc
2. Sherpa MC — Born, Integrated sub, Real + sub
   - Comix, FastJet, LHAPDF, ROOT
3. Linked with BLHA interface

Binoth Les Houches Accord interface to One Loop matrix elements



BLHA

- Simple uniform interface between Monte-Carlo and One Loop providers

BLHA in NJet 2.0

- Support BLHA1 and BLHA2
- Control all settings via order file
- Provide colour/spin-correlated trees
- Provide leading/subleading colour and desymmetrized amplitudes

BLHA in Sherpa

- NJet 2.0 trees tested with *ad hoc* BLHA2 in Sherpa
- Official interface for custom trees would be useful

Loop amplitudes

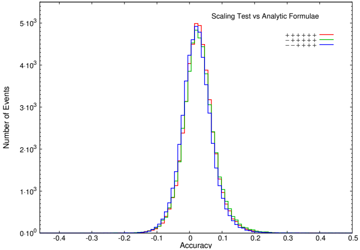
- Loop amplitudes lose accuracy in special kinematic regions
- Tracking these regions gets harder with more legs

NJet strategy

- Use universal scaling test to detect catastrophic cancellations
- Re-evaluate failed points in higher precision

Scaling test

- Evaluate twice and compare
- Parallelized with SSE (libVc)
- Overall $< 10\%$ slowdown



Advanced methods for computing Loop amplitudes

- Generalized unitarity
- Trees from Berends-Giele recursion

Time per phase-space point for dominating channels

$$\mathsf{T}(n) \sim 2^n n^6 \boxed{n!}, \qquad n \text{ – number of legs}$$

Getting rid of the factorial

- Desymmetrizing final states (no need for MC support)
- Separate integration of leading/subleading colour (MC support would improve automation)

Observation

- Squared amplitudes are totally symmetric over final state gluons
- Gluon phase space integration is a symmetric operator

Idea

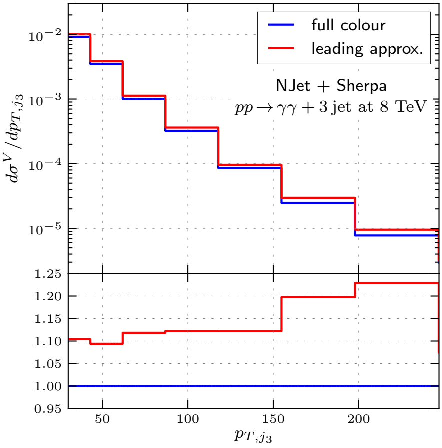
- Replace squared amplitudes with something simpler
  (specialized **full colour** sum, no change on the MC side)

Example:

$$\iiint_a^b \boxed{(x^2y + x^2z + xy^2 + xz^2 + y^2z + yz^2)}\, dx\, dy\, dz = \iiint_a^b \boxed{6x^2y}\, dx\, dy\, dz$$

Get the same result $n_g!/2$ times cheaper

	$gg \to 3g$	$gg \to 4g$	$gg \to 5g$
Standard sum	0.22 s	6.19 s	171.31 s
De-symmetrized	0.07 s	0.50 s	2.76 s
Speedup	$\times 3$	$\times 12$	$\times 60$



Subleading colour

- Order of magnitude slower
- Order of magnitude smaller
- Often cannot be ignored

Separate integration

- Full colour $5{-}10$ times **faster**

Disadvantages

- Manual (no MC support)
- μ_R dep. has to be corrected
- Not standardized in BLHA

ROOT NTuples output

[arXiv:1003.1241]

Store in NTuples:

- Can change scales and/or PDFs during analysis
- Easy to create **APPLgrid**'s
- Takes a lot of disk space
- Needs custom software for full flexibility

Analyze on-the-fly:

- Easy to set-up
- No need to save events
- Can use standard tools: **Rivet**
- Scale changes and PDF variations are **very expensive**

Possible improvements

- Use several Rivet analyses with different μ_R and μ_F in a single run would allow to do simple NLO calculations on-the-fly.
- Interface for custom analysis codes providing information similar to what is passed to NTuples (extend Rivet interface?)

Five final state QCD partons limit

- Using **Comix** instead of **AMEGIC** allows to get approximately $1{-}2$ final state partons more.
- Bottleneck not in speed but in **memory consumption**. Especially for "Process" generation.
- Using **Min/Max_N_Quarks** helps a bit, but still couldn't generate "Process" directory for $Z + 5$ jets.
- Are "Process" directories compatible between different minor **Sherpa** releases?

Summary

- High multiplicity calculations remain a challenge
- First NLO results for 5 jets and $\gamma\gamma + 3$ jets at LHC
- NJet 2.0 with improved speed and new processes

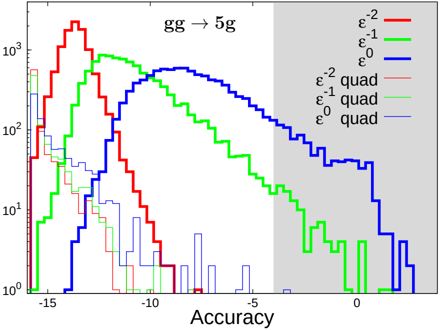
Wishlist for Sherpa

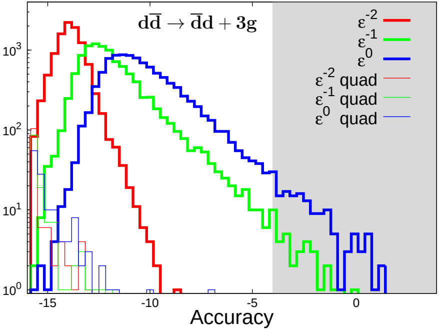
- Support of BLHA2 features (accuracy, trees, etc)
- Leading/Subleading colour splitting support
- More flexibility in on-the-fly analysis (scales, PDFs, grids)
- Less memory demanding Comix “Process” generation

Bonus material

Scaling test of 5 jet amplitudes

Left: 7 gluon squared amplitude. Right: 4 quarks + 3 gluons.





Thick lines – double precision.

Thin lines – fixed with quadruple precision.

Evaluation times

Full colour and helicity sum time per point [clang, Xeon 3.30 GHz].

process	T_{sd}[s]	$T_{4\text{ dig.}}$[s] (%)
$4\,g$	0.030	0.030 (0.00)
$\bar{u}u{+}2g$	0.032	0.032 (0.00)
$\bar{u}u\bar{d}d$	0.011	0.011 (0.00)
$\bar{u}u\bar{u}u$	0.022	0.022 (0.00)

process	T_{sd}[s]	$T_{4\text{ dig.}}$[s] (%)
$5\,g$	0.22	0.22 (0.22)
$\bar{u}u{+}3g$	0.34	0.35 (0.06)
$\bar{u}u\bar{d}d{+}g$	0.11	0.11 (0.00)
$\bar{u}u\bar{u}u{+}g$	0.22	0.22 (0.03)

process	T_{sd}[s]	$T_{4\text{ dig.}}$[s] (%)
$6\,g$	6.19	6.81 (1.37)
$\bar{u}u{+}4g$	7.19	7.40 (0.38)
$\bar{u}u\bar{d}d{+}2g$	2.05	2.06 (0.08)
$\bar{u}u\bar{u}u{+}2g$	4.08	4.15 (0.21)
$\bar{u}u\bar{d}d\bar{s}s$	0.38	0.38 (0.00)
$\bar{u}u\bar{d}d\bar{d}d$	0.74	0.74 (0.00)
$\bar{u}u\bar{u}u\bar{u}u$	2.16	2.17 (0.02)

process	T_{sd}[s]	$T_{4\text{ dig.}}$[s] (%)
$7\,g$	171.3	276.7 (8.63)
$\bar{u}u{+}5g$	195.1	241.2 (3.25)
$\bar{u}u\bar{d}d{+}3g$	45.7	48.8 (0.88)
$\bar{u}u\bar{u}u{+}3g$	92.5	101.5 (1.29)
$\bar{u}u\bar{d}d\bar{s}sg$	7.9	8.1 (0.23)
$\bar{u}u\bar{d}d\bar{d}dg$	15.8	16.2 (0.29)
$\bar{u}u\bar{u}u\bar{u}ug$	47.1	48.6 (0.41)

All times include two evaluations for the scaling test.