Multi-jet production at NLO with NJet

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NLO QCD calculations

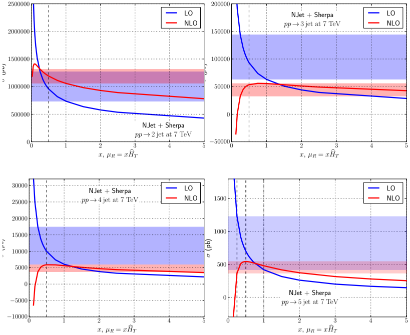
NLO results provide more accurate predictions and theoretical uncertainties for multi-jet backgrounds in new physics searches.

NLO vs LO

- Reduced theoretical uncertainty

NLO automation

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



— LO

— NLO

NLO setup

Hard process ingredients

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

Complicated pieces

1. Virtual matrix elements [NJet, QCDLoop]
    - Integration over loop momentum
    - A number of new competing advanced methods
2. Real + subtraction [Sherpa, Comix]
    - Tree-like
    - Difficult phase-space integration
3. Linked with BLHA interface

NJet version 2.0[1]

Multi-parton matrix elements in massless QCD [arXiv:1209.0100]

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

New in version 2.0

- $W^{\pm}/Z/\gamma$ with up to **5 jets** and $\gamma\gamma$ with up to **4 jets**.
- Leading/Subleading colour splitting.
- Hardware vectorization for scaling test.
- BLHA2 support.
- Fast analytic amplitudes for 2 and 3 jets.

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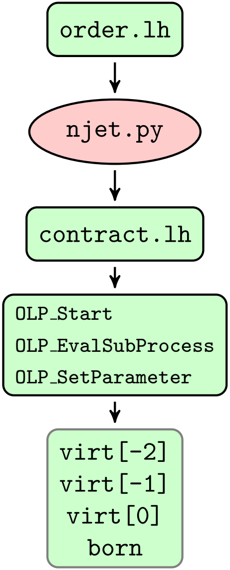
[1] available from project homepage `https://bitbucket.org/njet/njet`

Binoth Les Houches Accord interface to One Loop matrix elements



BLHA

- Simple uniform interface
  between Monte-Carlo (MC)
  and One Loop Providers (OLP)
  [arXiv:1001.1307, arXiv:1308.3462]

BLHA in NJet 2.0

- Support BLHA1 and BLHA2
- Provide colour/spin-correlated trees
- Provide leading/subleading colour and desymmetrized amplitudes

BLHA extensions

- Control all settings via order file
- Single point of interaction with OLP

Dealing with complexity of multi-leg NLO

Advanced methods for computing amplitudes

- On-shell methods to avoid unphysical degrees of freedom
  (amplitudes from trees, rational terms from massive loop cuts)
- Efficient recursive construction of building blocks
- Relations between primitive amplitudes

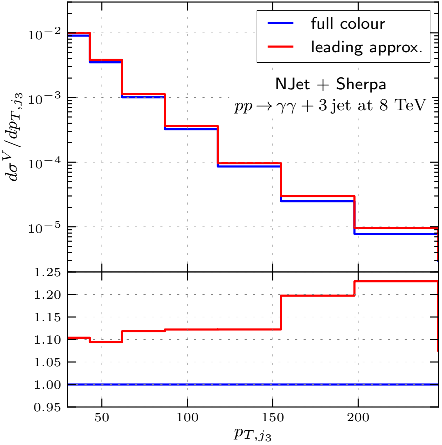
Time per phase-space point for dominating channels

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

Getting rid of the factorial (offload to MC)

- Desymmetrizing final states (available in NJet)
- Separate integration of leading/subleading colour (available in NJet)
- Colour-dressed approach (available in Sherpa/COMIX)

Why split into leading/subleading colour (at high multiplicity)



Subleading colour

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

Separate integration

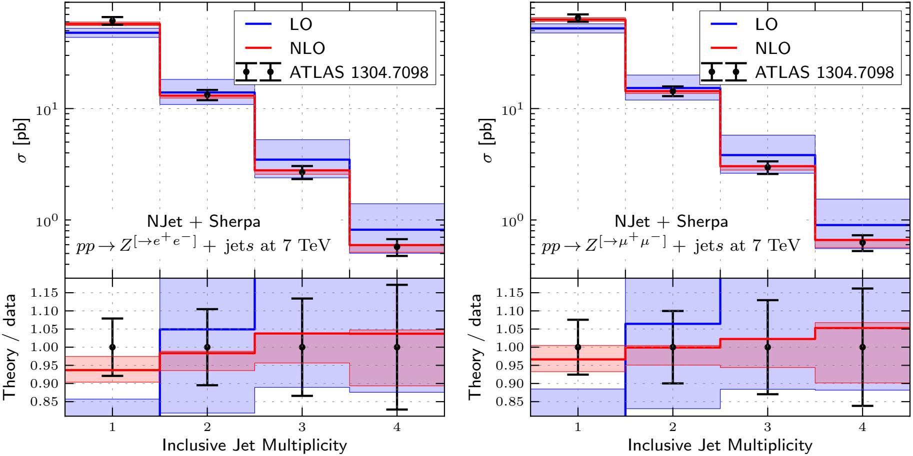
- Full colour $5-10$ times **faster**

Disadvantages

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

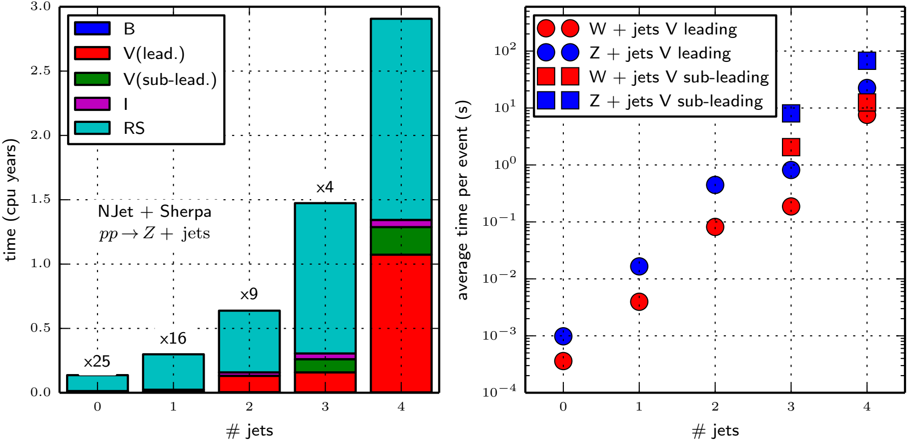
Example: $Z+$jets production with NJet+Sherpa

ATLAS cuts. Agreement with [1304.1253] and [1108.2229]



Example: timing of $W/Z +$ jets production with NJet+Sherpa

Time spent in different parts of NLO calculation



Efficient use of results is crucial

High multiplicity calculations are **expensive**

- Typical 5 final state calculations take $\sim 10^5$ CPU $\cdot$ hours.
- Do not want to run it more than once.

Layered computation set-up

- Save generated events in ROOT NTuples. [arXiv:1003.1241]
- Analyze later (still several days per analysis).
- Interpolation grids with **APPLgrid** for fast PDF convolution and scale variations. [arXiv:1312.4460]

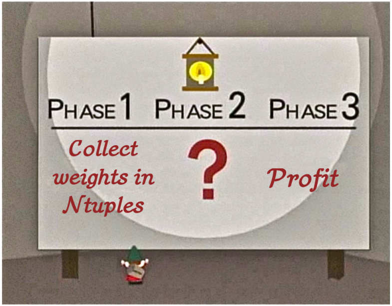
Saving events for further analysis

NLO calculations are expensive and we need to use the results as efficiently as possible.

ROOT NTuples output

[arXiv:1003.1241]

- Save weigths, PDFs, scheme dependence
- Compact compressed storage
- Can change scales/PDFs during analysis
- Several jet algorithms at low cost

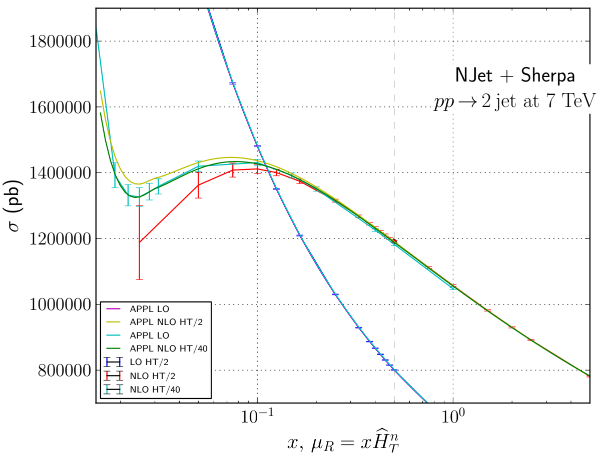


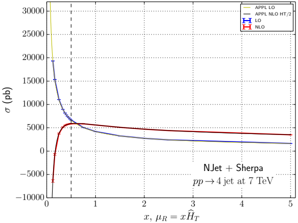
Interpolation grids to speed-up PDF convolution

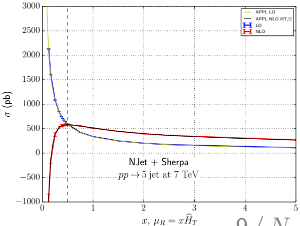
APPLgrid – interpolation grids in Q, x_1, x_2 for each bin in histogram.

NTuples: ~ 1000 GB space, ~ 30 hours to analyze, completely generic

APPLgrid: ~ 1 GB space, ~ 0.1 hour to analyze, specific observable/binning





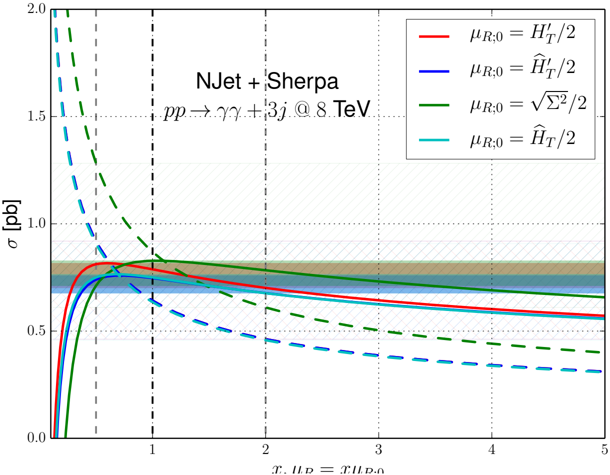


Analysis methods comparison

On-the-fly:	**NTuples:**	**APPLgrid:**
+ **Zero** disk space cost	− **High** disk space cost	+ Low disk space cost
−− Scale/PDF vars. **Extremely high** CPU cost	± Scale/PDF vars. moderate CPU cost	++ Scale/PDF vars. **low** CPU cost
− Flexibility low	++ Flexibility **high**	− Flexibility low
+ Can use standard tools: **Rivet**	− Needs custom software	− Needs custom software

Most important for high-multiplicity fixed order NLO are flexibility and cheap scale/PDF variations: NTuples+APPLgrid

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



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

$$\widehat{H}_T = \sum_{i \in \{\gamma, \text{partons}\}} p_{T,i}$$

$$\widehat{H}'_T = m_{\gamma\gamma} + \sum_{i \in \text{partons}} p_{T,i}$$

$$H'_T = m_{\gamma\gamma} + \sum_{i \in \text{jets}} p_{T,i}$$

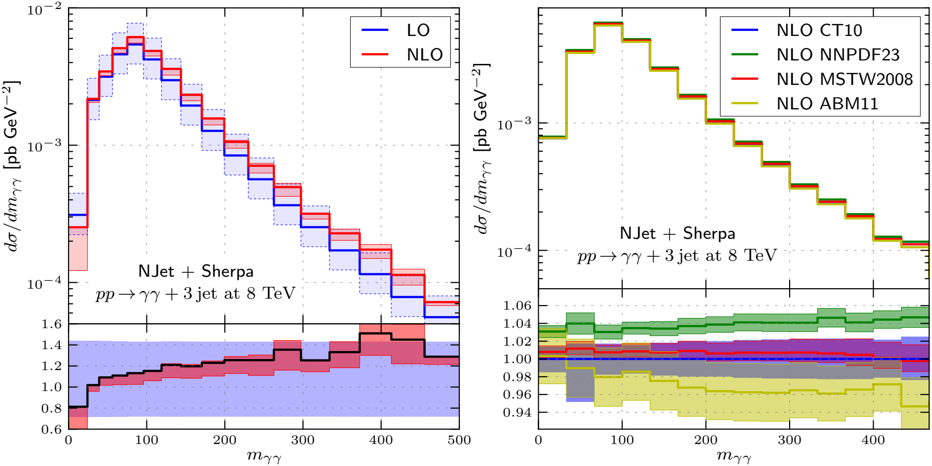
$$\Sigma^2 = m^2_{\gamma\gamma} + \sum_{i \in \text{jets}} p^2_{T,i}$$

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

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

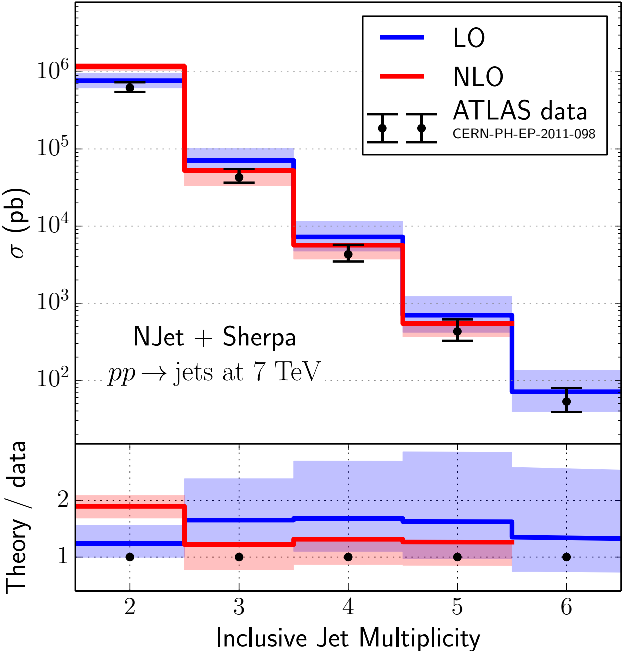
NJet+Sherpa: $\gamma\gamma + 3j$ at 8 TeV, $m_{\gamma\gamma}$ distribution and PDF uncertainties

PDF uncertainty ≈ 3–6%



Di-photon invariant mass distribution

NJet+Sherpa: 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

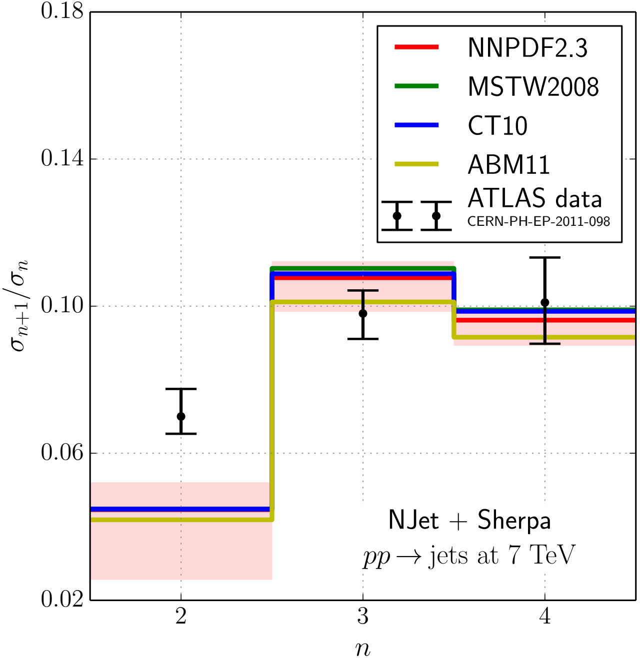
$\mu_R = \mu_F = \hat{H}_T/2$

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

$\alpha_s(M_Z) = 0.118$

NNPDF23 PDF set

NJet+Sherpa: jets ratios at 7 TeV with different PDFs vs ATLAS data



Cuts

anti-kt $R = 0.4$

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

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

$|\eta| < 2.8$

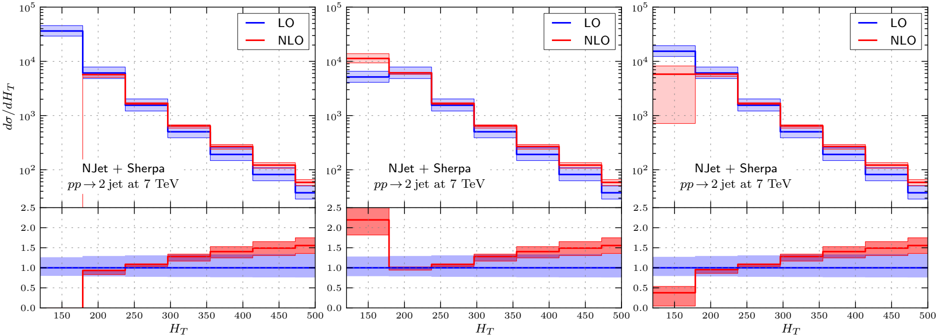
NLO

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

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

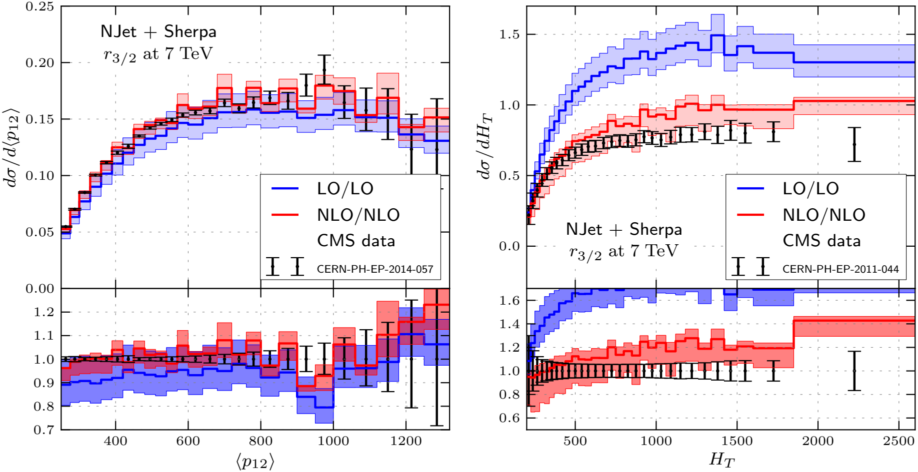
$\alpha_s(M_Z) = 0.118$

Dijet phase-space cuts choices



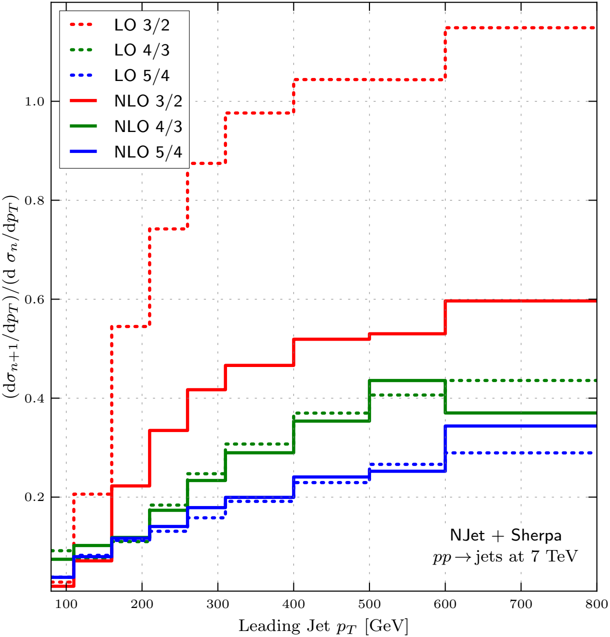
- **Left** symmetric p_T cuts: $p_{T,1} > 60$ GeV, $p_{T,2} > 60$ GeV
  doesn't work for NLO (negative XS)
- **Middle** asymmetric p_T cuts: $p_{T,1} > 80$ GeV, $p_{T,2} > 60$ GeV
  doesn't give full NLO accuracy (LO is symmetric)
- **Right** symmetric $H_{T,2}$ cuts: $p_{T,1} + p_{T,2} > 140$ GeV
  seems to work best

3/2 jet ratios compared with CMS data



$\langle p_{T,12}\rangle = H_{T,2}/2$ results in smaller K-factor than H_T

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

Conclusions

Summary

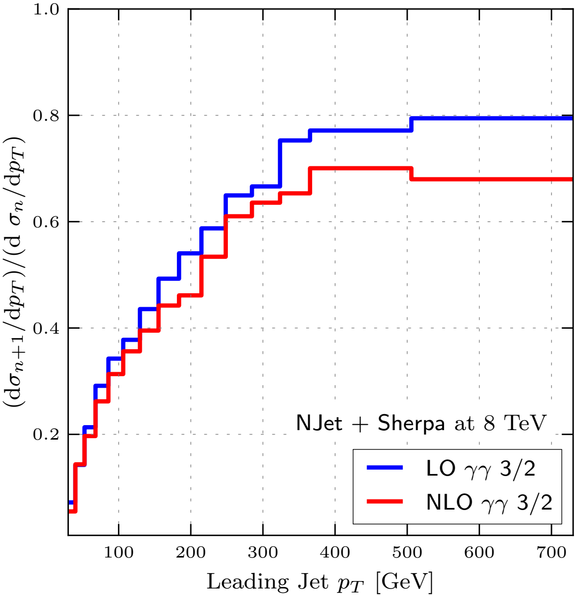
- NJet library version 2 with improved speed and new processes
- Multi-leg NLO workflow with NTuples and APPLgrid
- NJet+Sherpa: $pp \to$ 3, 4, 5 jets at NLO at 7 and 8 TeV
  $pp \to \gamma\gamma +$ 2, 3 jets at NLO at 8 TeV
- $3/2$ ratio is sensitive to cuts and observable definition,
  $4/3$ and $5/4$ ratios are more stable

Outlook

- Today: fully automated 4 final state predictions at NLO
- In a few years: routine calculations with $5/6$ final states

Bonus material

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



Ratio

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

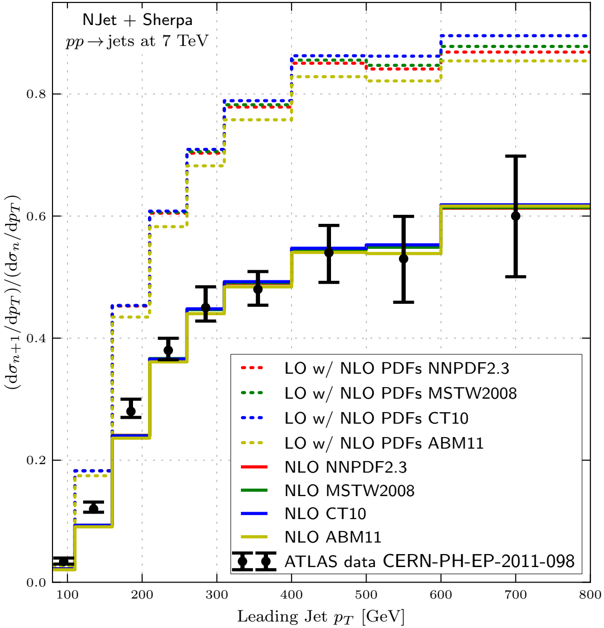
$R^{LO}_{3/2} = 0.314(0.002)$

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

Scale

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

NJet+Sherpa: p_T for 3/2 ratio at 7 TeV with diff. PDFs vs ATLAS data



Cuts

anti-kt $R = 0.6$

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

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

$|\eta| < 2.8$

NLO

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

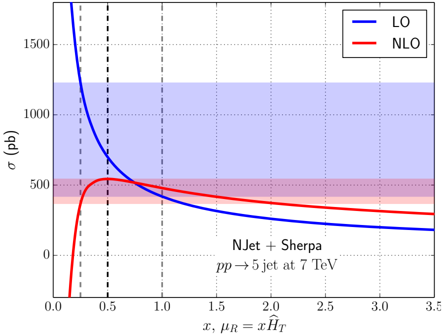
$\alpha_s(M_Z) = 0.118$

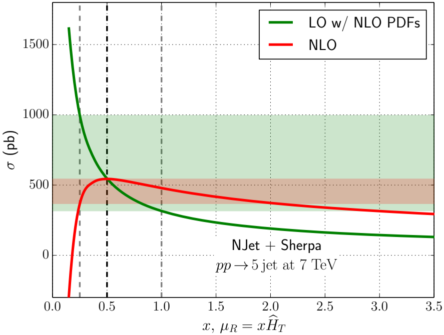
α_s from 3/2 ratios

[ATLAS-CONF-2013-041]
[CMS-QCD-11-003]

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

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





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

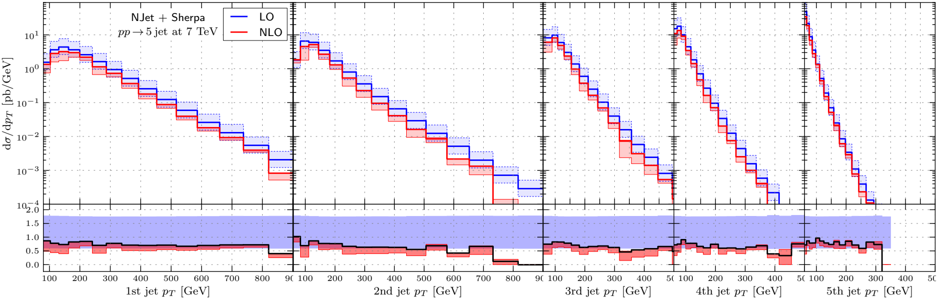
$$\sigma_5^{\text{7TeV-NLO}}(\mu = \hat{H}_T/2) = 0.544(0.016)^{+0.0}_{-0.177}\ \text{nb}$$

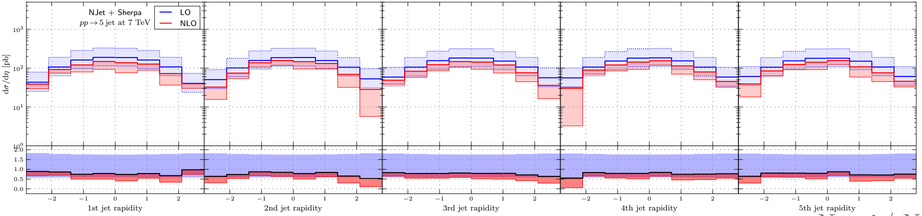
$$\sigma_5^{\text{8TeV-LO}}(\mu = \hat{H}_T/2) = 1.044(0.006)^{+0.770}_{-0.413}\ \text{nb}$$

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

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

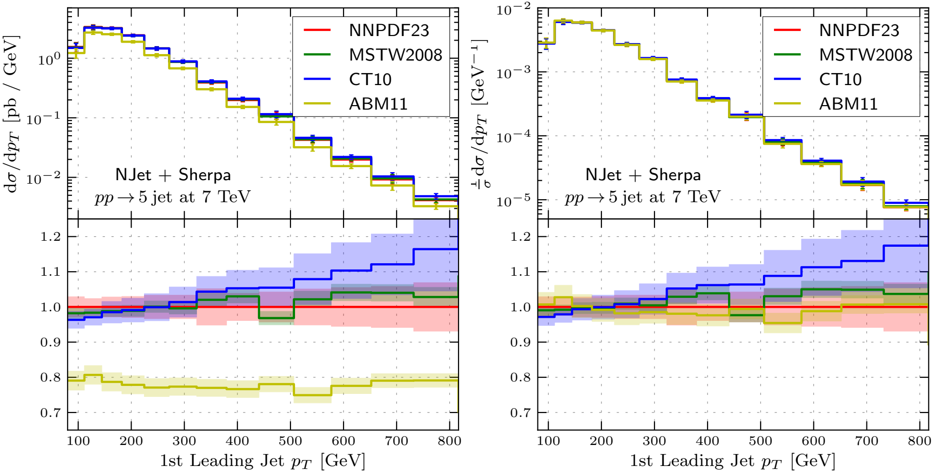
ATLAS cuts, NNPDF23 PDF set, $\alpha_s(M_Z) = 0.118$





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

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



Right plot — distributions normalized to total cross-section.