High multiplicity QCD at NLO

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Outline

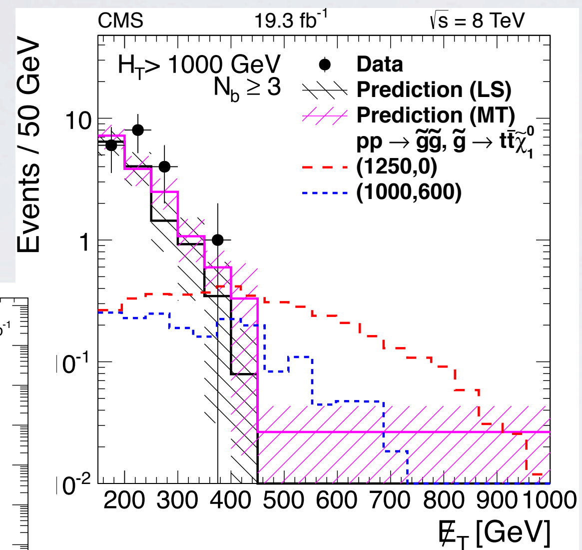
- On-shell methods for loop amplitudes
- NLO computations with NJET + SHERPA
- pp $\to$ 5 jets

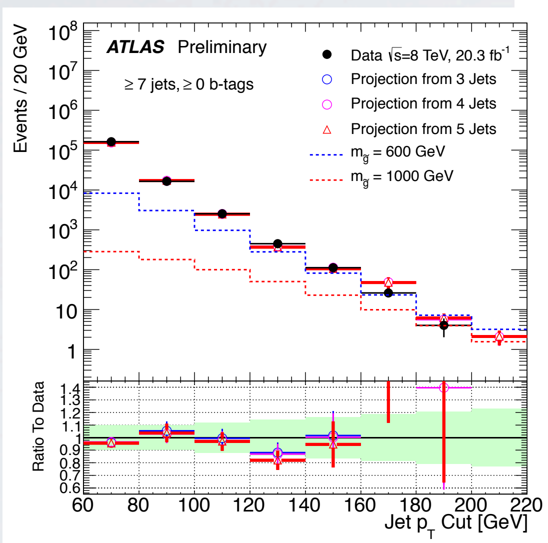
  SB, Biedermann, Uwer, Yundin [arXiv:1309.6585]
- pp $\to \gamma\gamma$ + 3 jets

  SB, Guffanti, Yundin [arXiv:1312.5927]

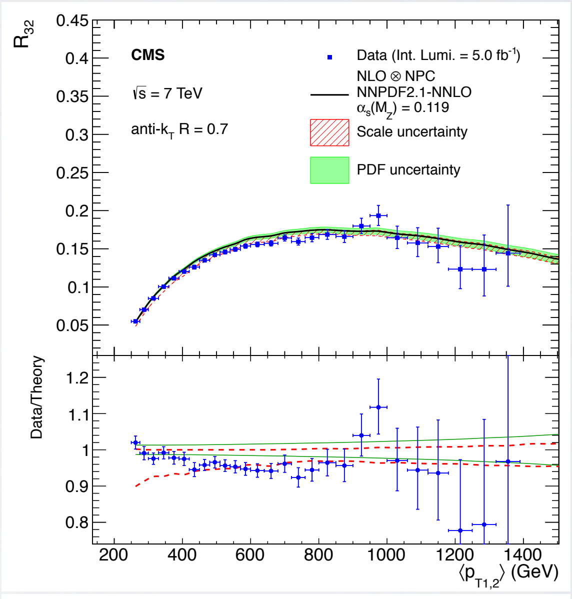
Multi-jet production

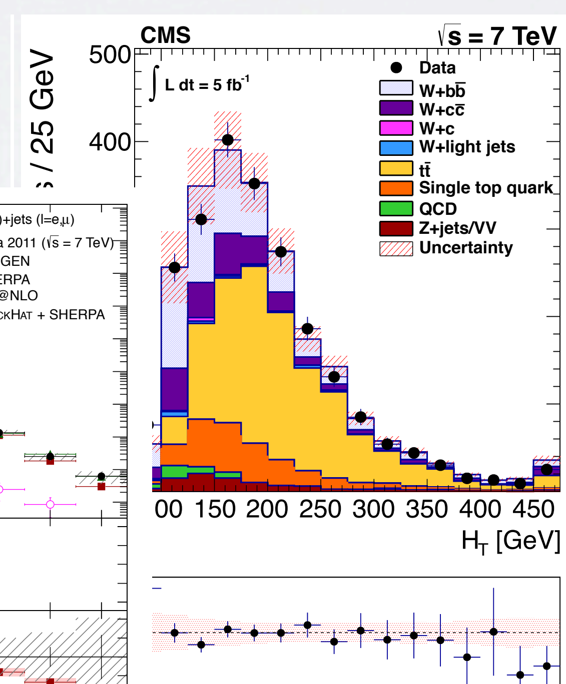
BSM searches

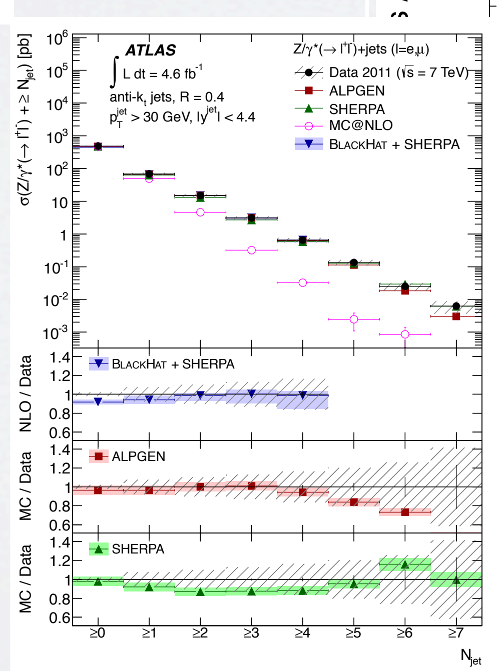




Strong coupling measurements







Precision QCD

Next-to-leading order

everything fixed order today

LO PDFs

LO α_s

$$\sigma^{\rm LO}_{hh\to X} = \sum_{i,j} \int f^{\rm LO}_{i/h_1} f^{\rm LO}_{j/h_2} \otimes \int_n \alpha_s^{n-2} d\sigma^{\rm B}_{ij\to X}$$

$$\sigma^{\rm NLO}_{hh\to X} = \sum_{i,j} \int f^{\rm NLO}_{i/h_1} f^{\rm NLO}_{j/h_2} \otimes \left(\int_n \alpha_s^{n-2} \left(d\sigma^{\rm B}_{ij\to X} + \alpha_s d\sigma^{\rm V}_{ij\to X} \right) + \int_{n+1} \alpha_s^{n-1} d\sigma^{\rm R}_{ij\to X} \right)$$

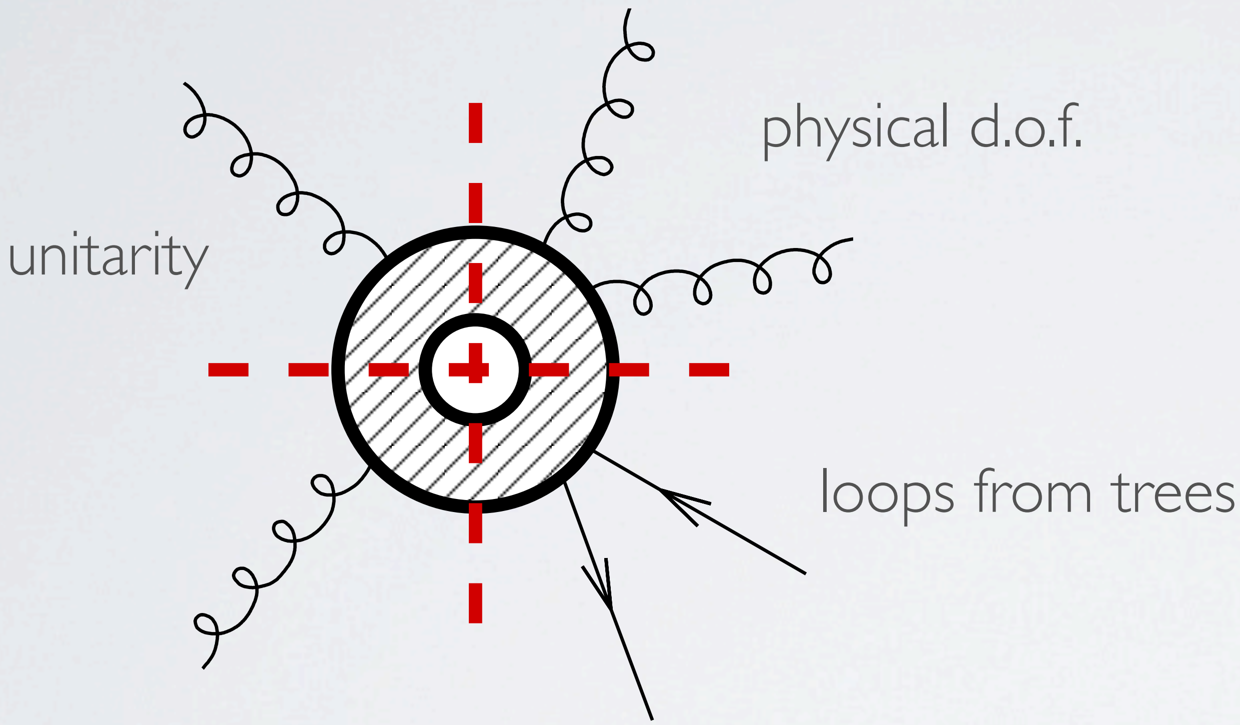
NLO α_s

kinematics

colour

$$d\sigma^{\rm V} = d\Phi \sum_{\text{colours},ij} \sum_{\text{spins},s} 2{\rm Re} \left([A_i^{(0)}(s)]^\dagger \cdot C_{i,j} \cdot A_j^{(1)}(s) \right)$$

On-shell amplitudes in gauge theory



simple final expressions

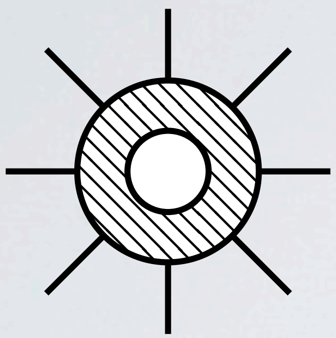
$$\mathrm{MHV}(i^-, j^-) = \frac{\langle ij\rangle^4}{\langle 12\rangle\langle 23\rangle\cdots\langle n1\rangle}$$

Parke, Taylor (1986)

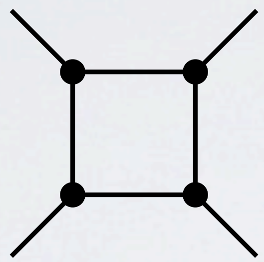
colour ordered primitive amplitudes

fixed external legs and propagators

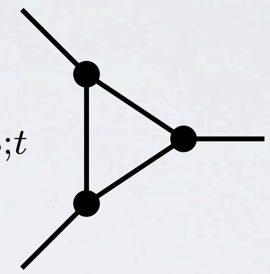
One-loop amplitudes



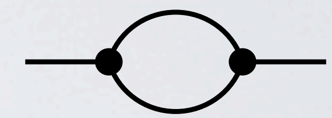
$= \sum_{t\in\text{boxes}} c_{4;t}$



$+ \sum_{t\in\text{triangles}} c_{3;t}$



$+ \sum_{t\in\text{bubbles}} c_{2;t}$



$$A_n^{(1)} = \sum_{p=2}^{4} \sum_{1\le<i_1<\cdots<i_p\le n} c_{p;i_1\ldots i_p} \int \frac{d^D k}{(2\pi)^D} \frac{1}{l_{i_1} l_{i_2} \cdots l_{i_p}}$$

$$l_i = k - p_{1,i}$$

Unitarity and Discontinuities

$$1 = SS^\dagger = (1+iT)(1-iT^\dagger) \Rightarrow TT^\dagger = i(T^\dagger - T)$$

$$A = \langle i|T|f\rangle \qquad 1 = \sum \int d\text{LIPS}|k\rangle\langle k|$$

Cutkosky rules:
imaginary part obtained from

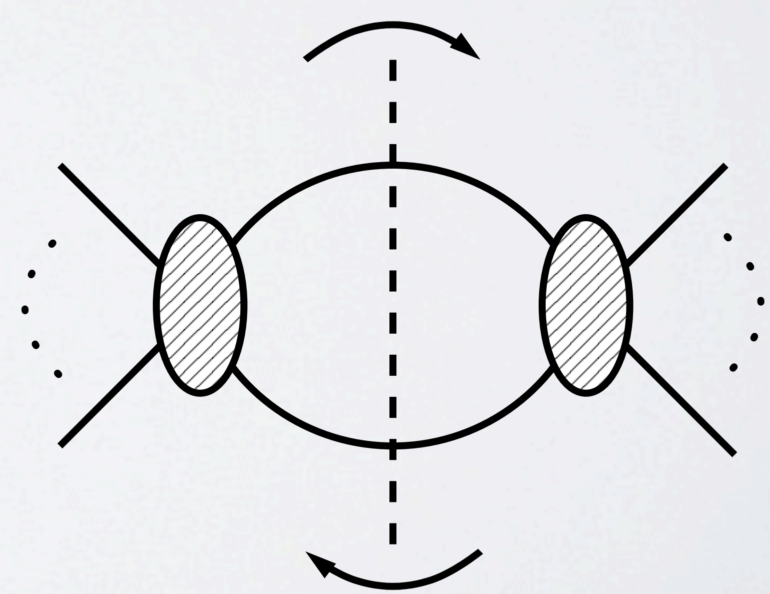
$$\frac{1}{k^2 + iO^+} \longrightarrow i\delta^{(+)}(k^2)$$

$$\Rightarrow \text{Disc}_{P_{i,j-1}}(A^{(1)}) = \sum \int d\text{LIPS}(k, P_{i,j-1})\delta^{(+)}(k)\delta^{(+)}(k - P_{i,j-1})$$
$$A^{(0)}(k, p_i, \ldots, p_{j-1}, -k - P_{i,j-1})A^{(0)}(k + P_{i,j-1}, p_j, \cdots, p_{i-1}, -k)$$

Classic S-matrix theory - perform dispersion integral to obtain full amplitude

Modern unitarity method - use cuts to find coefficient of basis integrals

Bern, Dixon, Dunbar, Kosower (1994)



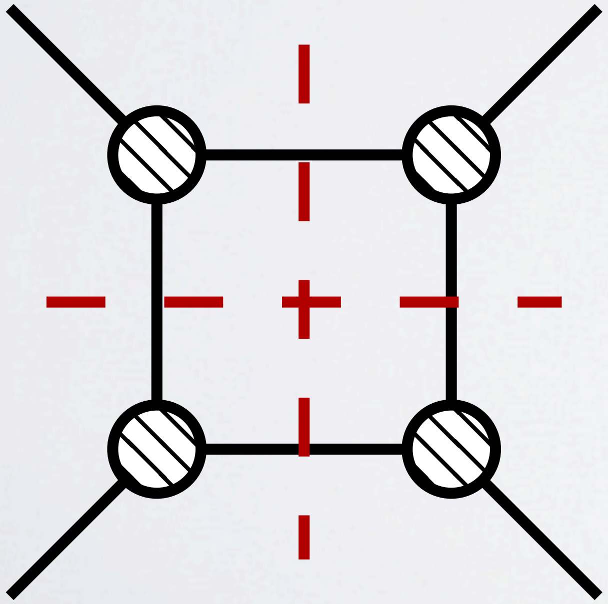
Generalized Unitarity

generalized discontinuities: put more propagators on-shell

$$A_n^{(1)}|_{\text{cut}(1234)} = \sum_{p=2}^{4} \sum_{1\leq<i_1<\cdots<i_p\leq n} c_{p;i_1\ldots i_p} \int \frac{d^Dk}{(2\pi)^D} \frac{l_1^2 l_2^2 l_3^2 l_4^2 \delta^{(+)}(l_1^2)\delta^{(+)}(l_2^2)\delta^{(+)}(l_3^2)\delta^{(+)}(l_4^2)}{l_{i_1} l_{i_2} \cdots l_{i_p}}$$

$$= c_{4;1234}\; I_{4;1234}|_{\text{cut}(1234)}$$

$$= \frac{I_{4;1234}|_{\text{cut}(1234)}}{n_s} \sum_{s\in\mathcal{Z}(l_i^2)} A^{(0)}(-l_1^{(s)},1,l_2^{(s)})A^{(0)}(-l_2^{(s)},2,l_3^{(s)})A^{(0)}(-l_3^{(s)},3,l_4^{(s)})A^{(0)}(-l_4^{(s)},4,l_1^{(s)})$$



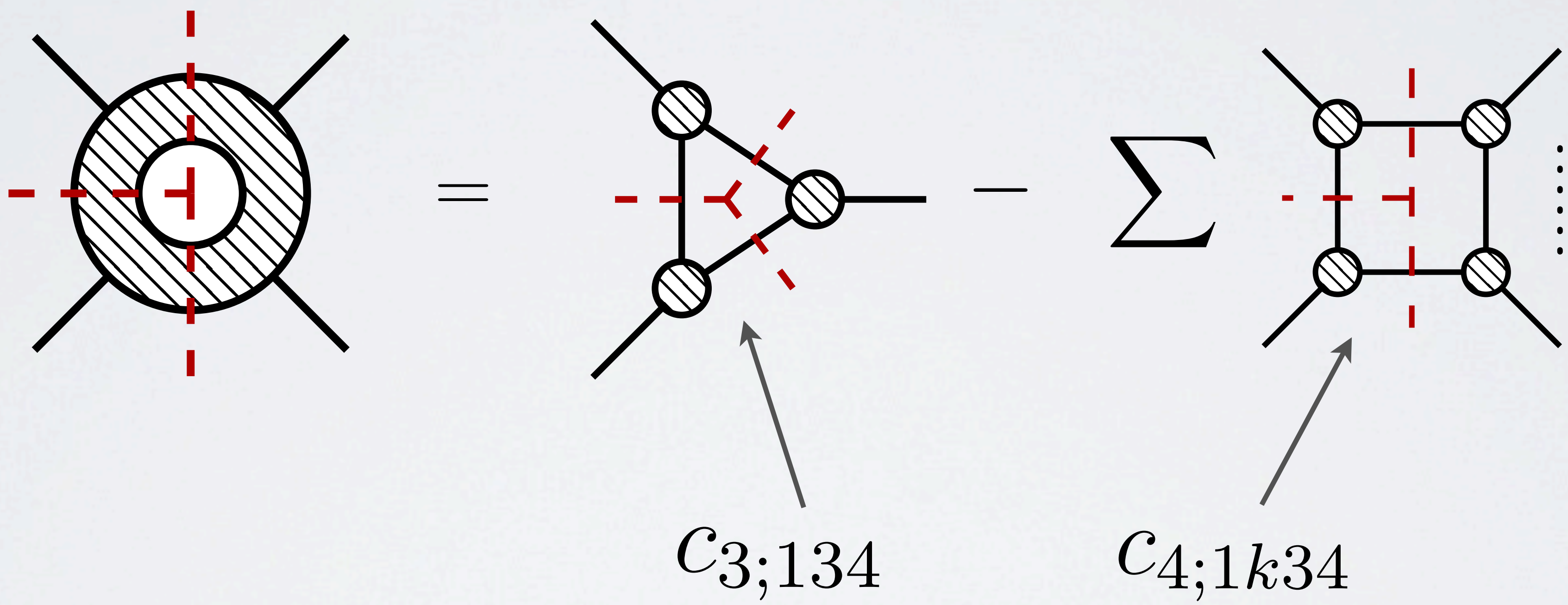
isolate integral coefficients

complex momentum solutions

Britto, Cachazo, Feng (2004)

Generalized Unitarity

top down: subtract leading singularities
and perform further multiple cuts



1-d integral: drop box contribution and find direct formula for triangle coefficient from product of 3 trees

Forde (2007)

$c_{p;i_1 \ldots i_p}$ rational functions - algebraic procedure

Integrand reduction

Ossola, Papadopoulos, Pittau (2006)

Ellis, Giele, Kunszt, (2007)

$$A_n^{(1)} = \sum_{p=2}^{4} \sum_{1 \le < i_1 < \cdots < i_p \le n} c_{p;i_1 \ldots i_p} \int \frac{d^D k}{(2\pi)^D} \frac{1}{l_{i_1} l_{i_2} \cdots l_{i_p}} \rightarrow A_n^{(1)} = \sum_{p=2}^{4} \sum_{1 \le < i_1 < \cdots < i_p \le n} \int \frac{d^D k}{(2\pi)^D} \frac{\Delta_{p;i_1 \ldots i_p}(k)}{l_{i_1} l_{i_2} \cdots l_{i_p}}$$

$$\Delta_{4;1234}(k) = c_{4;1234} + c'_{4;1234}\, k \cdot \omega_{1234}$$

introduce spurious vectors
to span loop space

$$\Delta_{4;1234}(\bar{k}, \mu_{11}) = c^{[0]}_{4;1234} + c^{[1]}_{4;1234}\, \bar{k} \cdot \omega_{1234}$$
$$+ \mu_{11} \left(c^{[2]}_{4;1234} + c^{[3]}_{4;1234}\, \bar{k} \cdot \omega_{1234} \right) + \mu_{11}^2 c^{[4]}_{4;1234}$$

dimensional regulated (with mass shift)

Giele, Kunszt, Melnikov (2008)

SB (2009)

stable numerical algorithm -purely algebraic

Loop integrals: QCDLoop/FF (Ellis, Zanderighi), OneLoop (Van Hameren), ...

Dealing with colour

$SU(N_c)$ colour matrices

$$\mathcal{A}_n^{(L)} = \sum_j c_j^{(L)} A_{n;j}^{(L)}$$

partial amplitude

$$\sum_{\text{colours}} \left(c_i^{(L_1)}\right)^T c_j^{(L_2)} = \mathcal{C}_{ij}^{(L_1,L_2)}(N_c)$$

$$d\sigma^{\mathrm{B}}(s) = d\Phi \sum_{i,j} [A_{n;j}^{(0)}(s)]^\dagger \mathcal{C}_{ij}^{(0,0)} A_{n;j}^{(0)}(s) \qquad d\sigma^{\mathrm{V}}(s) = d\Phi \sum_{i,j} [A_{n;j}^{(0)}(s)]^\dagger \mathcal{C}_{ij}^{(0,1)} A_{n;j}^{(1)}(s)$$

partial amplitudes are a linear combination of primitive amplitudes

$$A_{n;j}^{(L)} = \sum_k a_{k,j} A_n^{[m]} + b_{k,j} A_n^{[f]}$$

Dealing with colour

Feynman diagram matching algorithm

Ellis, Kunszt, Melnikov, Zanderighi [1105.4319]

Ita, Ozeren [1111.4193]

SB, Biedermann, Uwer, Yundin [1209.0100]

diagrams

$$A_{n;j}^{(L)} = \sum_{i=1}^{N} D_i = \sum_{i=1}^{\widehat{N}} C_i K_i$$

invert to find independent set of primitives

$$P_i = \sum_{j=1}^{\widehat{N}} M_{ij} K_i$$

matching matrix {0,+1,-1}

match topology only

4-gluon vertex not needed

diagrams symmetries reduce independent set of primitives (e.g. Furry's theorem)

combinatorical approaches: Melia [1304.7809,1312.0599]; Schuster [1311.6296]; Weinzierl, Reuschle [1310.0413]

Dealing with colour

Process	$N_{\text{pri}}^{[0]}$	$N_{\text{pri}}^{[m]}$	$N_{\text{pri}}^{[f]}$
$8\,g$	720	2520	2520
$\bar{u}u + 6\,g$	720	5040	1800
$\bar{u}u\bar{d}d + 4\,g$	360	3360	671
$\bar{u}u\bar{d}d\bar{s}s + 2\,g$	120	1344	194
$\bar{u}u\bar{d}d\bar{s}s\bar{c}c$	30	384	65

large numbers of primitive amplitudes for high multiplicity

use phase space symmetry to reduce computational cost

$$\sigma^V_{gg\to n(g)} = \int \mathrm{d}PS_n \, A^{(0)\dagger} \cdot \mathcal{C}_{n!\times(n+1)!/2} \cdot A^{(1)}$$

$$= (n-2)! \int \mathrm{d}PS_n \, A^{(0)\dagger} \cdot \mathcal{C}^{\mathrm{dsym}}_{n!\times(n+1)} \cdot A^{(1),\mathrm{dsym}}$$

factor of **(final state gluons)!/2**

retain full colour information

Automation with NJET

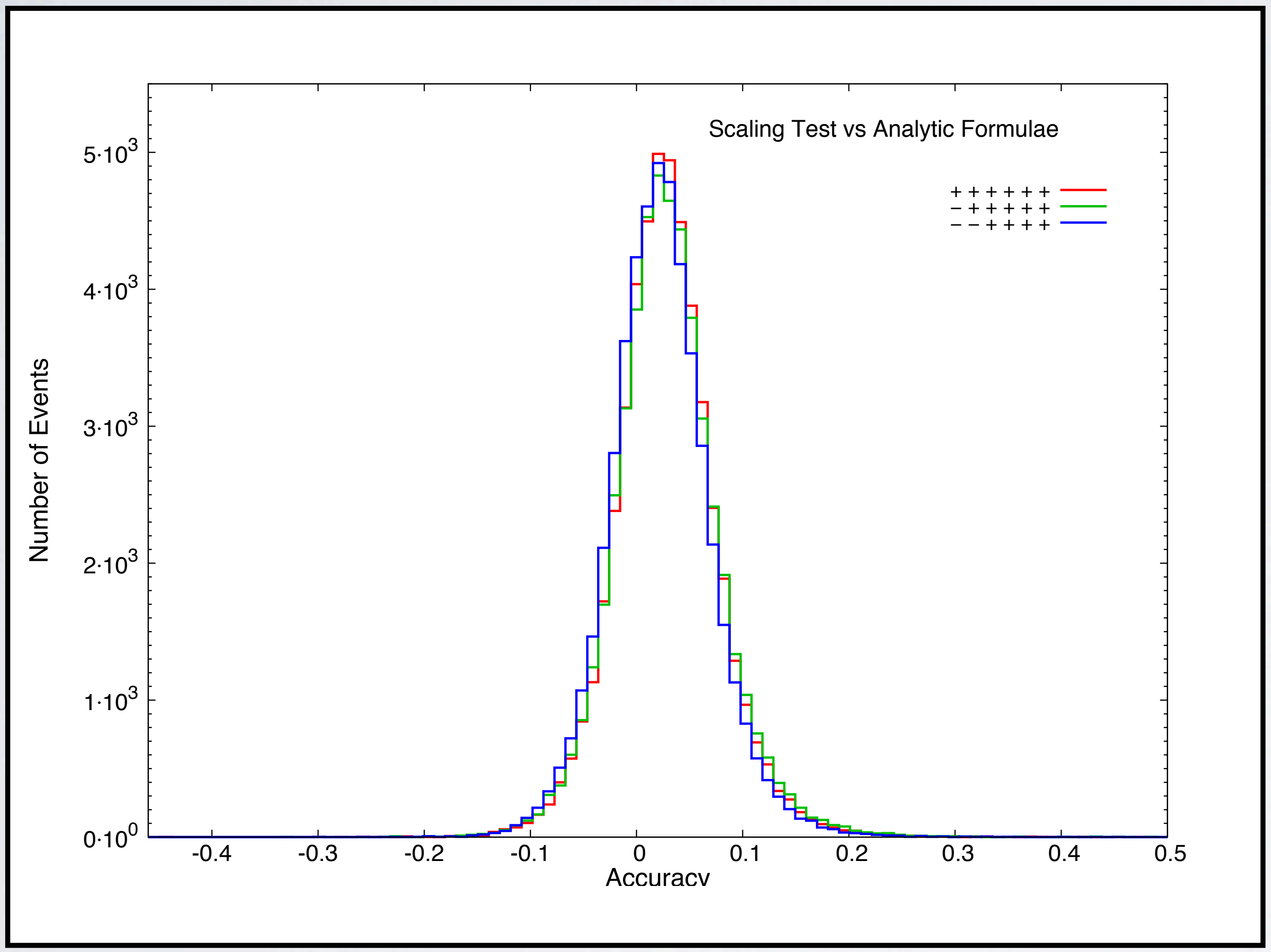
Numerical implementation in C++

Trees	off-shell recursion (Berends-Giele)
Loops	generalized unitarity
Colour	full (via primitive matching), de-symmetrized, leading/sub-leading
Interface	Binoth Les Houches Accord (python)

building on NGLUON [1011.2900]

SB, Biedermann, Uwer, Yundin [1209.0100]

Accuracy



$$\text{accuracy} = \log_{10}\left(\frac{A_{\text{NJET}}(s_1)+A_{\text{NJET}}(s_2)}{2(A_{\text{NJET}}(s_1)-A_{\text{NJET}}(s_2))}\right) - \log_{10}\left(\frac{A_{\text{NJET}}(1)+A_{\text{analytic}}}{2(A_{\text{NJET}}(1)+A_{\text{analytic}})}\right)$$

dimension scaling test

$$A(p_i, m_i, \mu_R) = x^{4-n} A(xp_i, xm_i, x\mu_R) := A_{\text{NJET}}(x)$$

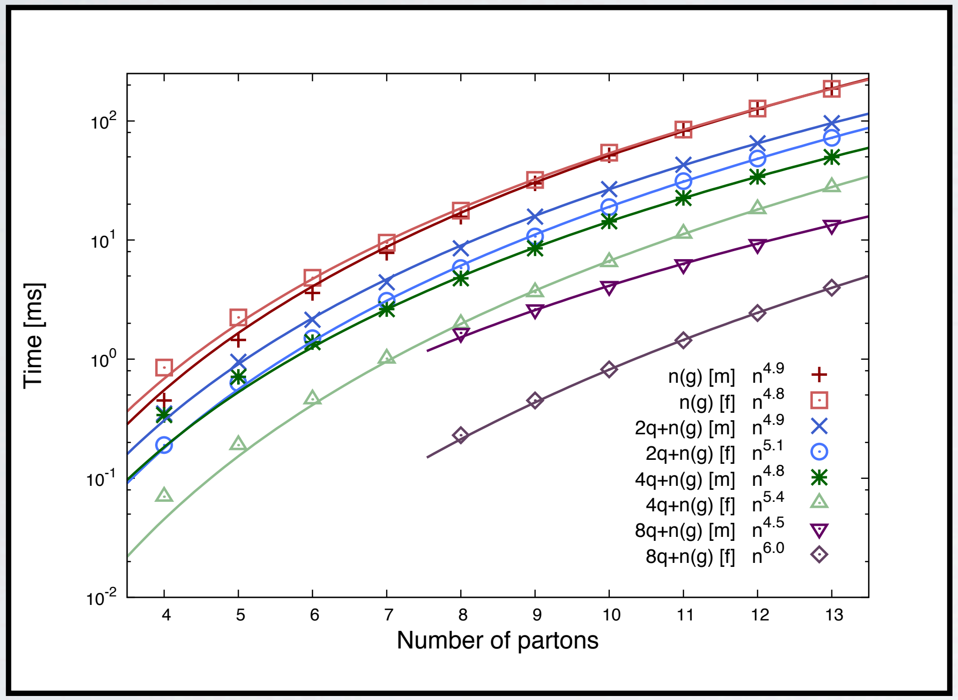
$$\#\text{digits} = \log_{10}\left(\frac{A_{\text{NJET}}(s_1)+A_{\text{NJET}}(s_2)}{2(A_{\text{NJET}}(s_1)-A_{\text{NJET}}(s_2))}\right)$$

2 calls for the price of 1 using explicit vectorization with Vc

reliable but statistical: add ~2 digits on min. accuracy

Performance

primitives scale ~n^6 for n $\lesssim$ 20



process	T_{sd}[s]	$T_{4\text{ digits}}$[s]	(% fixed)
4g	0.030	0.030	(0.00)
2u2g	0.032	0.032	(0.00)
2u2d	0.011	0.011	(0.00)
4u	0.022	0.022	(0.00)

process	T_{sd}[s]	$T_{4\text{ digits}}$[s]	(% fixed)
5g	0.22	0.22	(0.22)
2u3g	0.34	0.35	(0.06)
2u2d1g	0.11	0.11	(0.00)
4u1g	0.22	0.22	(0.03)

process	T_{sd}[s]	$T_{4\text{ digits}}$[s]	(% fixed)
6g	6.19	6.81	(1.37)
2u4g	7.19	7.40	(0.38)
2u2d2g	2.05	2.06	(0.08)
4u2g	4.08	4.15	(0.21)
2u2d2s	0.38	0.38	(0.00)
2u4d	0.74	0.74	(0.00)
6u	2.16	2.17	(0.02)

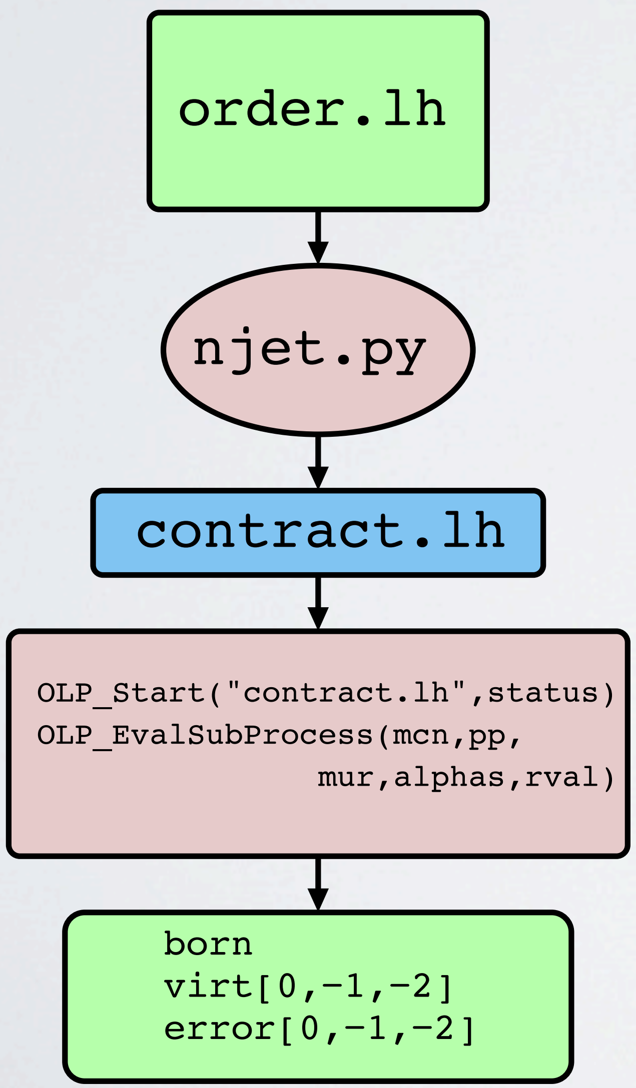
process	T_{sd}[s]	$T_{4\text{ digits}}$[s]	(% fixed)
7g	171.3	276.7	(8.63)
2u5g	195.1	241.2	(3.25)
2u2d3g	45.7	48.8	(0.88)
4u3g	92.5	101.5	(1.29)
2u2d2s1g	7.9	8.1	(0.23)
2u4d1g	15.8	16.2	(0.29)
6u1g	47.1	48.6	(0.41)

full colour sums a few seconds for 2⟶4

	$gg \to 2g$	$gg \to 3g$	$gg \to 4g$	$gg \to 5g$
standard sum	0.03	0.22	6.19	171.31
de-symmetrized	0.03	0.07	0.57	3.07

Monte-carlo interface

- BLHA - Binoth Les Houches Accord ([1001.1307], updated [1308.3462])



order file

```
# OLE_order for 5jet production


MatrixElementSquareType  CHsummed
CorrectionType           QCD
IRregularisation         CDR
AlphasPower              5
# process list
21 21 -> 21 21 21 21 21
1 -1 -> 21 21 21 21 21
1 -1 -> 21 -2 2 21 21
1 -1 -> 21 -1 1 21 21
1 -1 -> 21 -2 2 -3 3
1 -1 -> 21 -2 2 -2 2
1 -1 -> 21 -1 1 -1 1
```

contract file

```
# OLE_order for 5jet production
# Generated file. Do not edit by hand.
# Signed by NJet 3900867518.
# 12 1 1e-05 0.01 0 1 1 1 1 0 3 5
MatrixElementSquareType CHsummed | OK
CorrectionType QCD | OK
IRregularisation CDR | OK
AlphasPower 5 | OK
# process list
21 21 -> 21 21 21 21 21 | 1 1 # 70 120 4 64 0 (-2 -1 3 4 5 6 7)
1 -1 -> 21 21 21 21 21 | 1 2 # 71 120 4 9 0 (-1 -2 3 4 5 6 7)
1 -1 -> 21 -2 2 21 21 | 1 3 # 72 6 4 9 0 (-1 -2 4 5 3 6 7)
1 -1 -> 21 -1 1 21 21 | 1 4 # 73 6 4 9 0 (-1 -2 4 5 3 6 7)
1 -1 -> 21 -2 2 -3 3 | 1 5 # 74 1 4 9 0 (-1 -2 4 5 6 7 3)
1 -1 -> 21 -2 2 -2 2 | 1 6 # 75 4 4 9 0 (-1 -2 4 5 6 7 3)
1 -1 -> 21 -1 1 -1 1 | 1 7 # 76 4 4 9 0 (-1 -2 4 5 6 7 3)
```

NJET + Sherpa

$$\sigma_n^{\text{NLO}} = \sigma^{\text{LO}} + \int_n d\sigma_n^{\text{V}} + \int_n d\sigma_n^{\text{I+fac.}} + \int_{n+1} \left(d\sigma_{n+1}^{R} - d\sigma_{n+1}^{S}\right)$$

NJET v2.0

leading/sub-leading colour

de-symmetrized colour sums

$pp \to \leq 5j$

$pp \to \gamma\gamma + 4j$

$pp \to W^{[\to l^\pm \nu_l]} + \leq 5j$

$pp \to Z/\gamma^{*\;[\to l^+ l^-]} + \leq 5j$

$pp \to \gamma + \leq 4j$

$pp \to \gamma\gamma + \leq 4j$

Sherpa MC v2.0.0

Comix [Gleisberg, Hoeche (2008)]

CS subtraction [Gleisberg, Krauss (2007)]

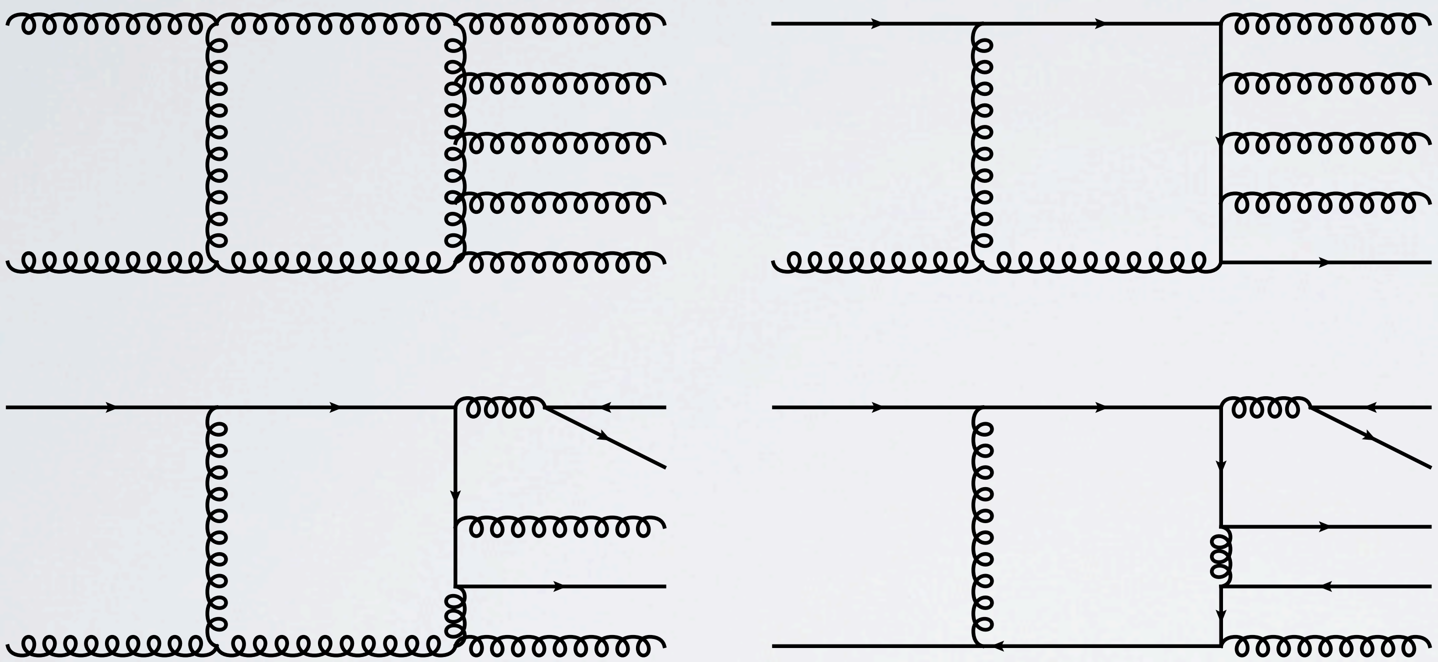
ROOT Ntuple event generation

also:

FastJet [Caccari, Salam, Soyez (2008)]

LHAPDF [Whalley, Bourilkov, Group (2005)]

Multi-jet production at the LHC



full colour

$N_f = 5$ flavour scheme

no top loops

ATLAS cuts [1107.2092]

$p_{T,j_1} > 80$ GeV $p_{T,j} > 60$ GeV $|\eta_j| < 2.8$

anti-kt $R = 0.4$ $\mu_R = \mu_F = \widehat{H}_T/2$

NLO QCD corrections

$pp \to \leq 3j$ Nagy (NLOJet++) [hep-ph/0307268]

$pp \to \leq 4j$ Bern et al. (BlackHat) [1112.3940]

SB, Biedermann, Uwer, Yundin [1209.0098]

$pp \to \leq 5j$ SB, Biedermann, Uwer, Yundin [1309.6585]

Virtual matrix elements

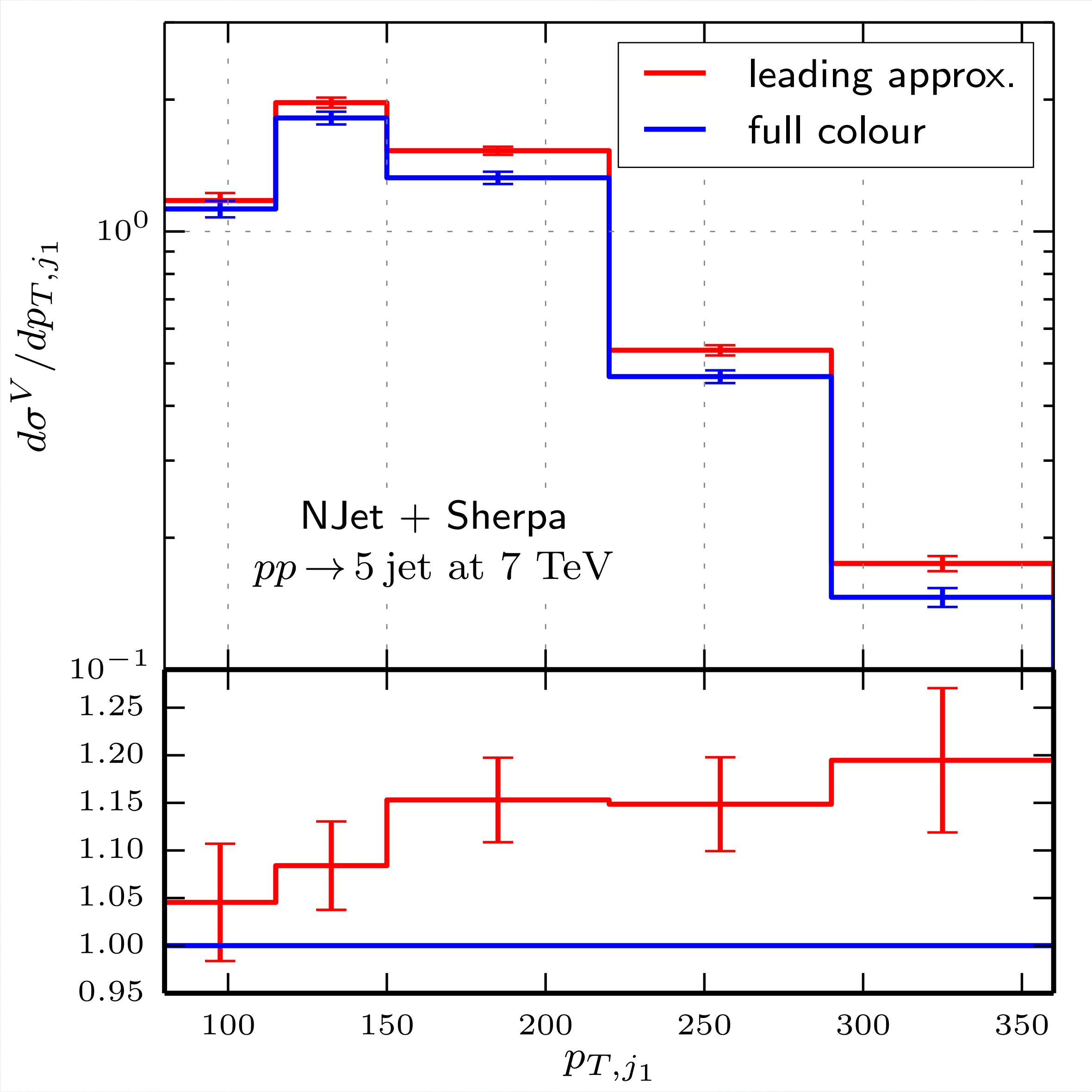
leading part: best case of de-sym. and leading colour

fermion loops included in sub-leading part

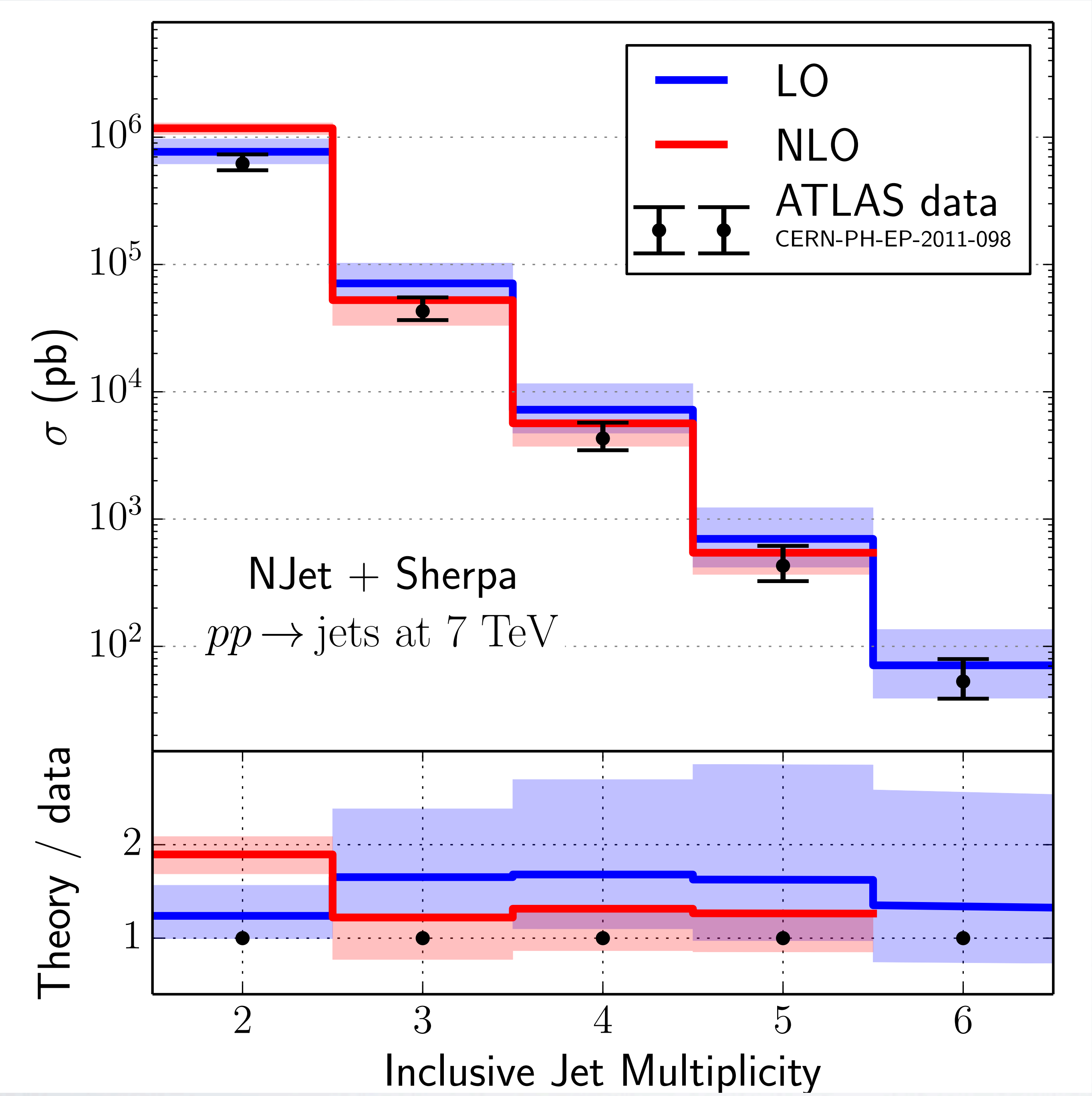
Virtual part	Time per event	QP	QP2	OP
leading	17 s	2%	0.5%	0.01%
subleading	112 s	2.5%	1%	0.05%

average evaluation time on cluster

possibility to switch to octuple precision - not necessary in practice



Total cross-sections



$$\sigma_5^{\text{7TeV-LO}}(\mu = \widehat{H}_T/2) = 0.699(0.004)^{+0.530}_{-0.280}\ \text{nb},$$
$$\sigma_5^{\text{7TeV-NLO}}(\mu = \widehat{H}_T/2) = 0.544(0.016)^{+0.0}_{-0.177}\ \text{nb}.$$

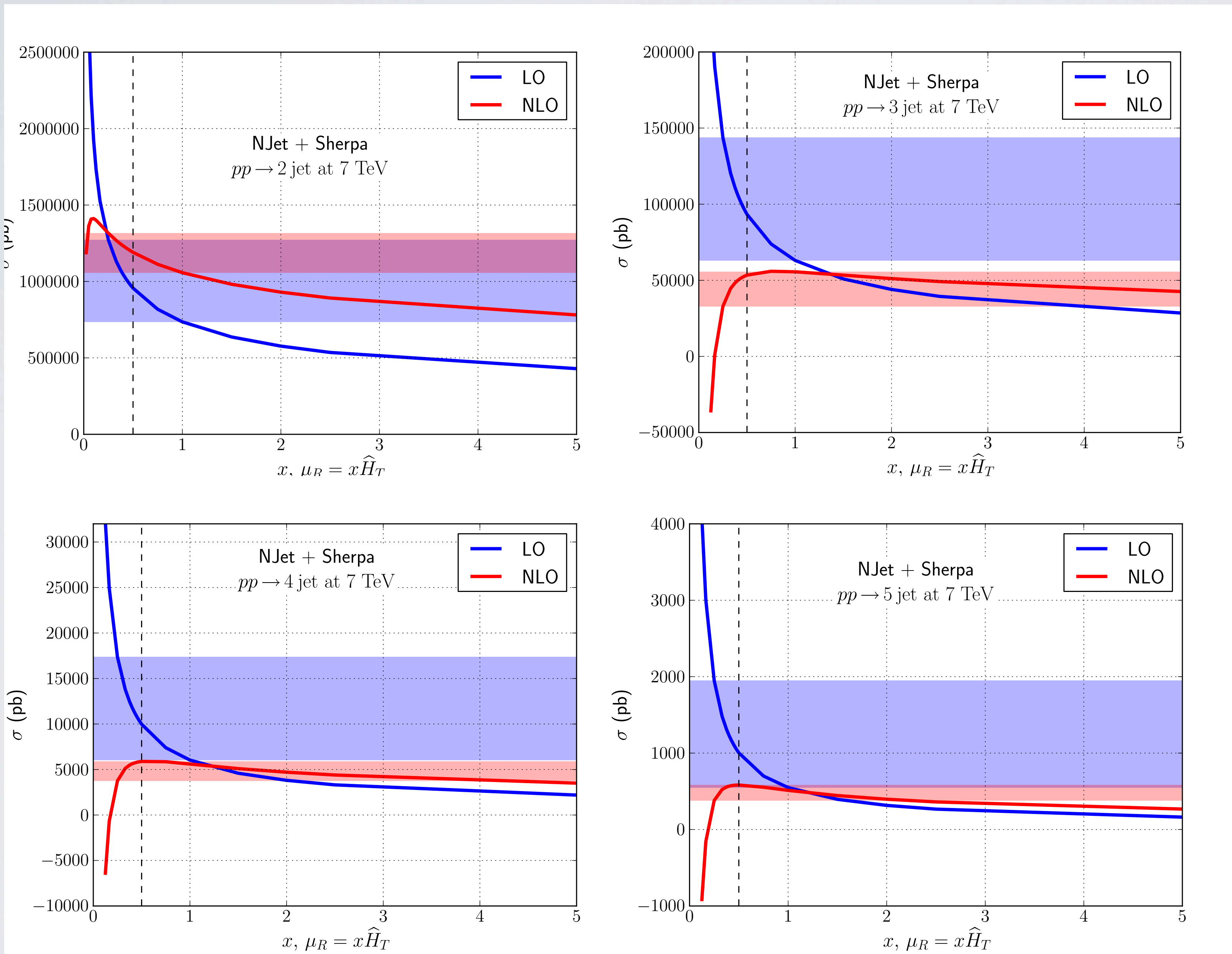
NNPDF2.1 LO

$\alpha_s(M_Z) = 0.119$

NNPDF2.3 NLO

$\alpha_s(M_Z) = 0.118$

Scale dependence



LO PDF: MSTW2008lo

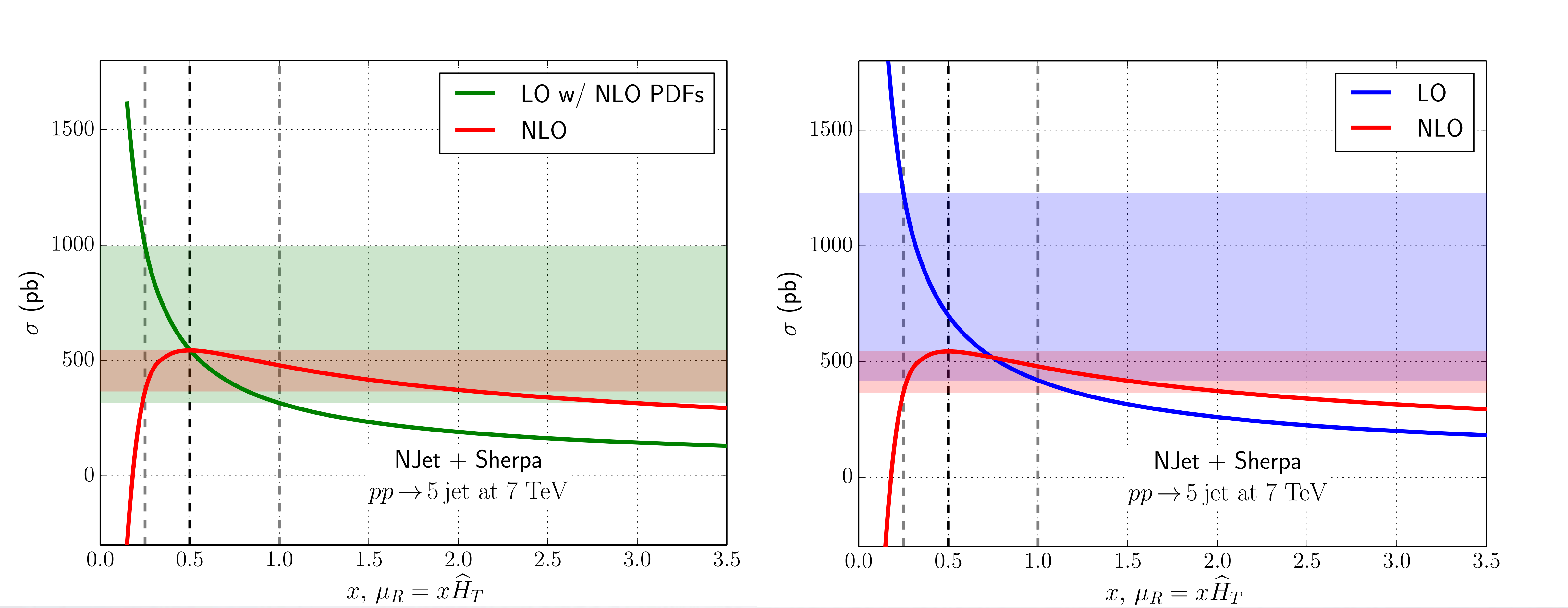
$$\alpha_s(M_Z) = 0.139$$

NLO PDF: MSTW2008nlo

$$\alpha_s(M_Z) = 0.120$$

Dynamical scale attempting include large logarithms

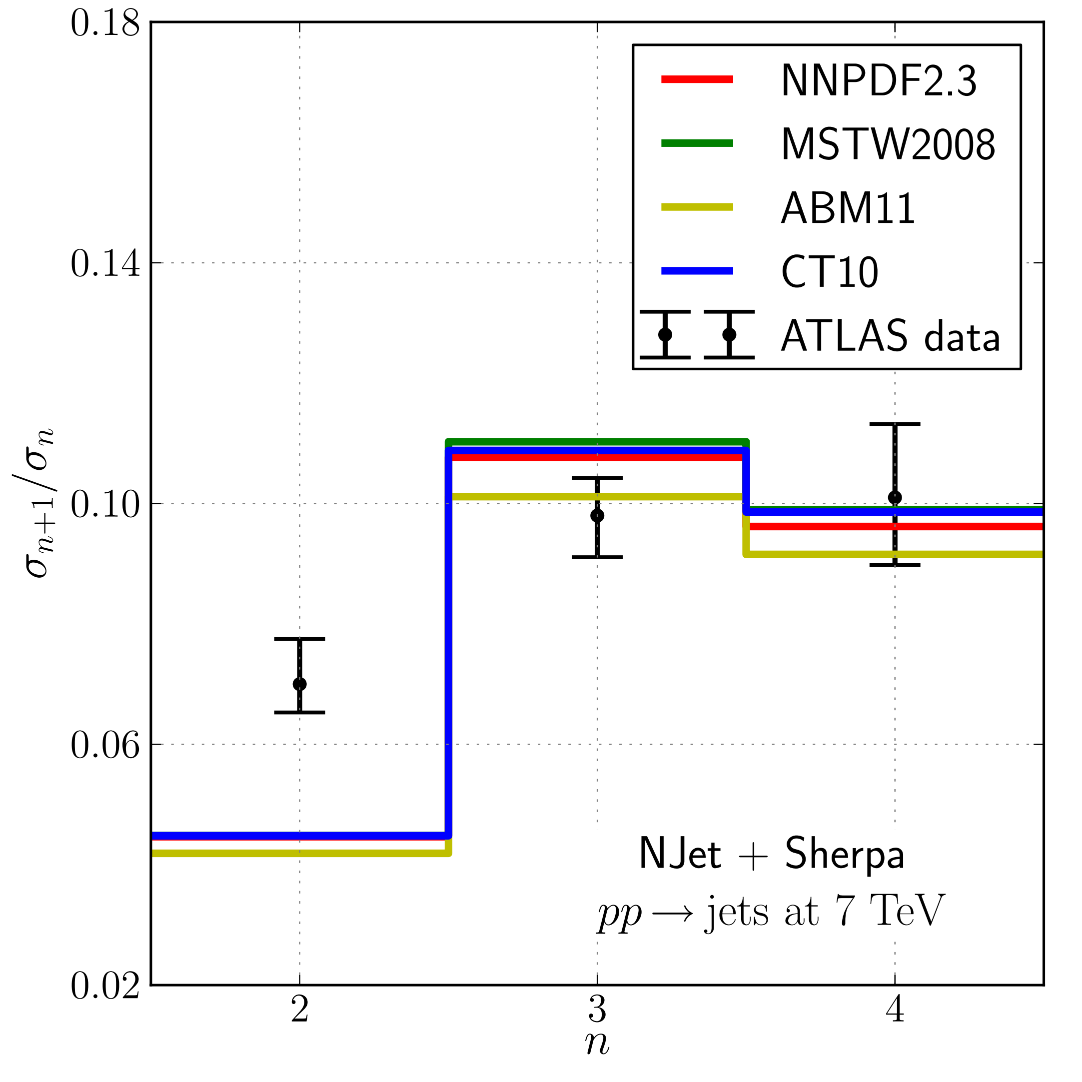
Scale dependence



Majority of NLO corrections are coming from 2-loop running of α_s

Jet Ratios

Reliable quantities for both theory and experiment



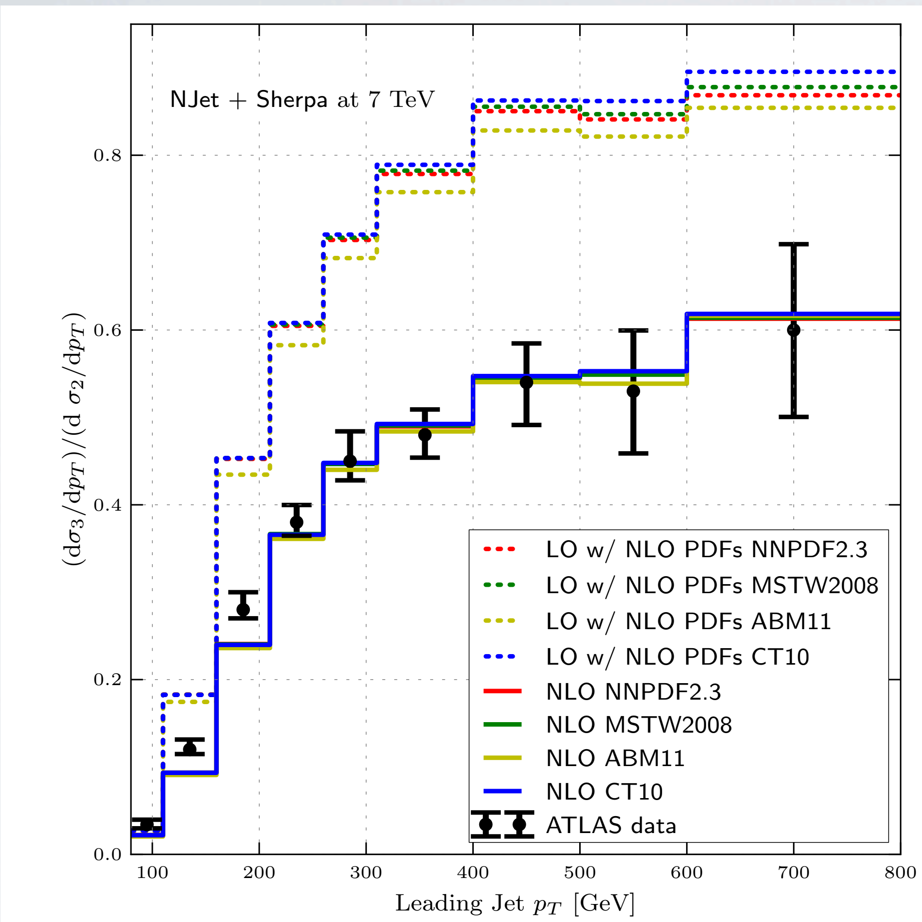
fixed order NLO good for di-jets with asymmetric cuts

c.f. large NLO K-factors Rubin, Salam, Sapeta [1006.2144]

e.g. α_s determination [1304.7498; CMS-QCD-11-003]

$$\alpha_S(M_Z) = 0.1148 \pm 0.0014\,(\text{exp.}) \pm 0.0018\,(\text{PDF}) \pm 0.0050\,(\text{theory})$$

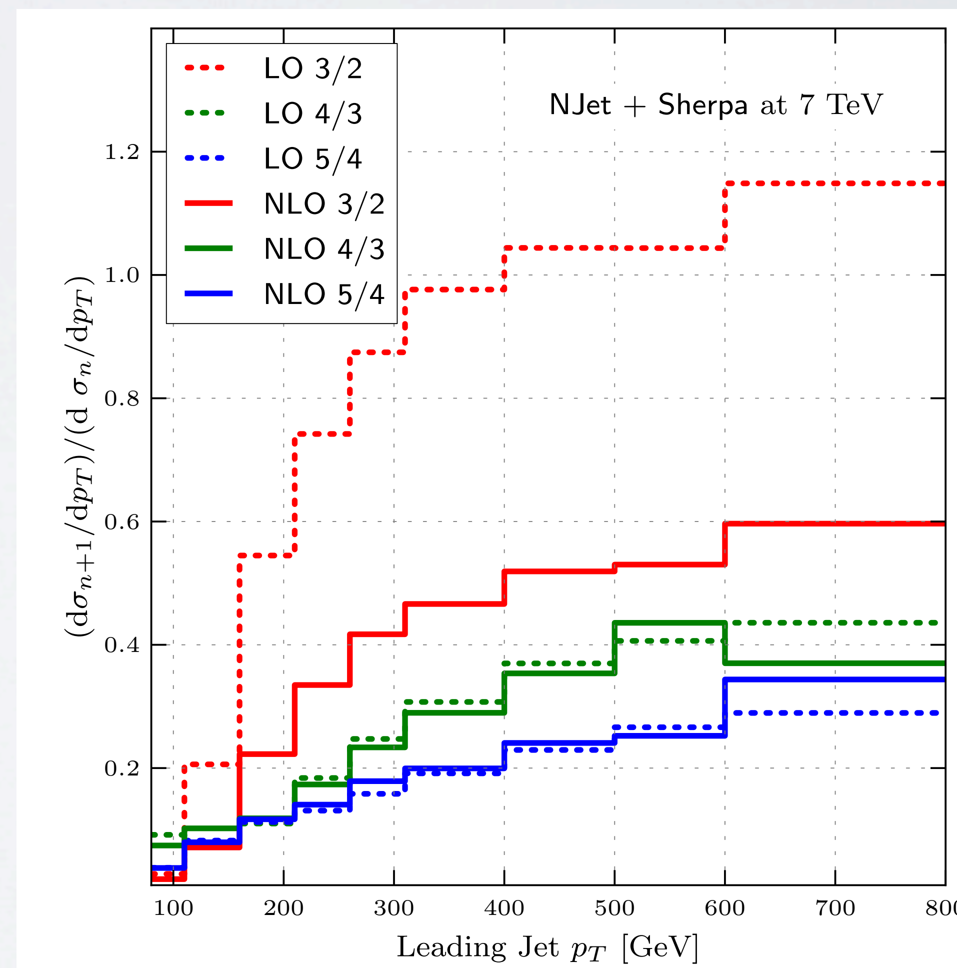
Jet Ratios



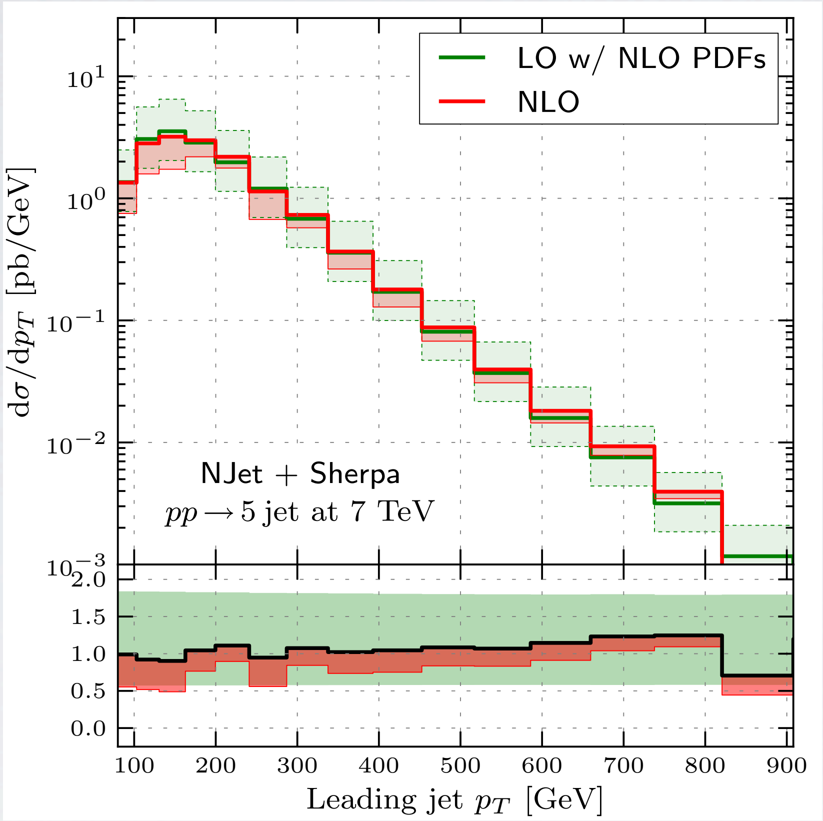
large NLO corrections to 3/2 ratio

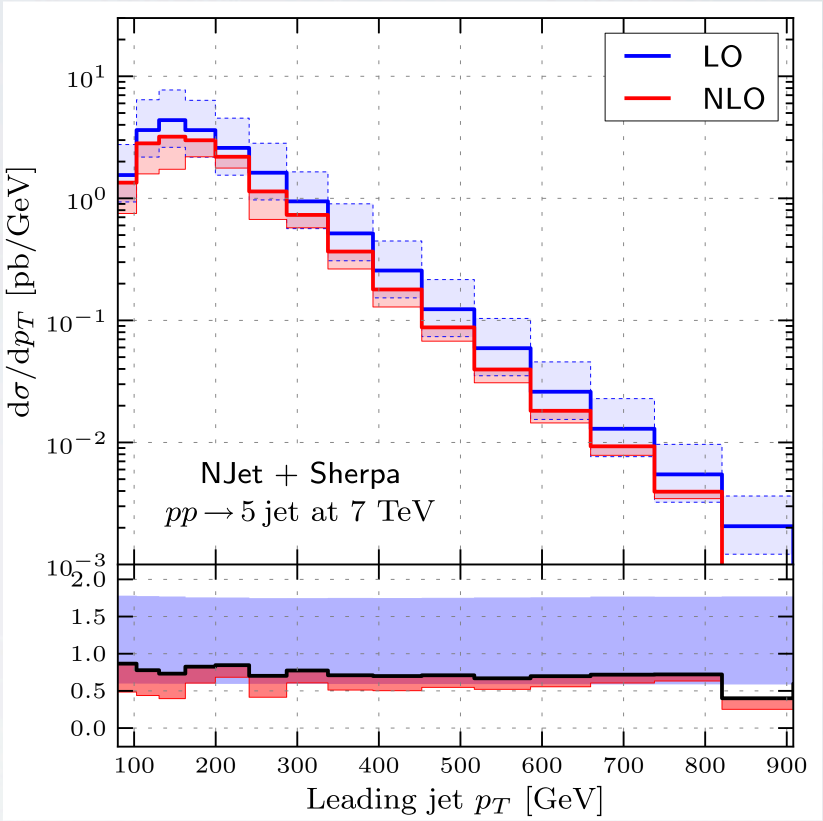
all PDF sets in good agreement with data

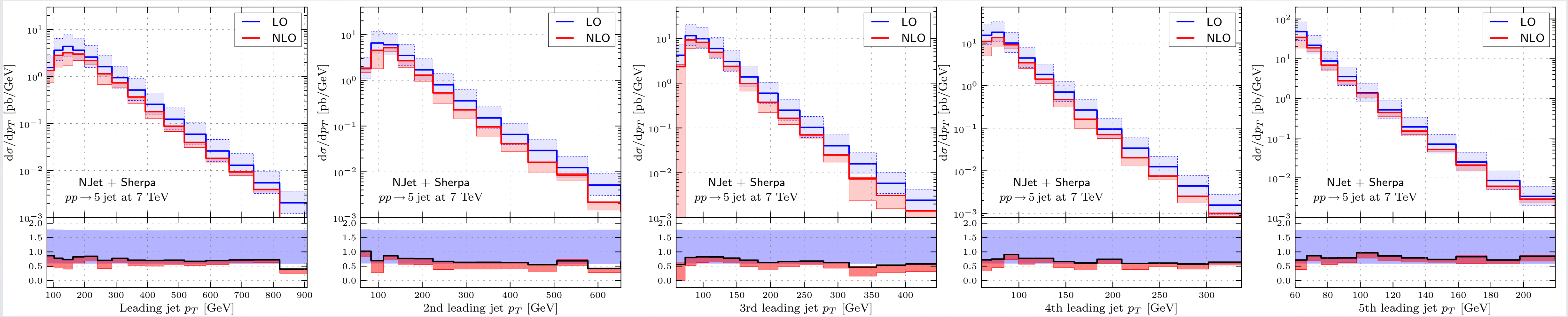
4/3 and 5/4 ratios more stable QCD corrections



p_T distributions



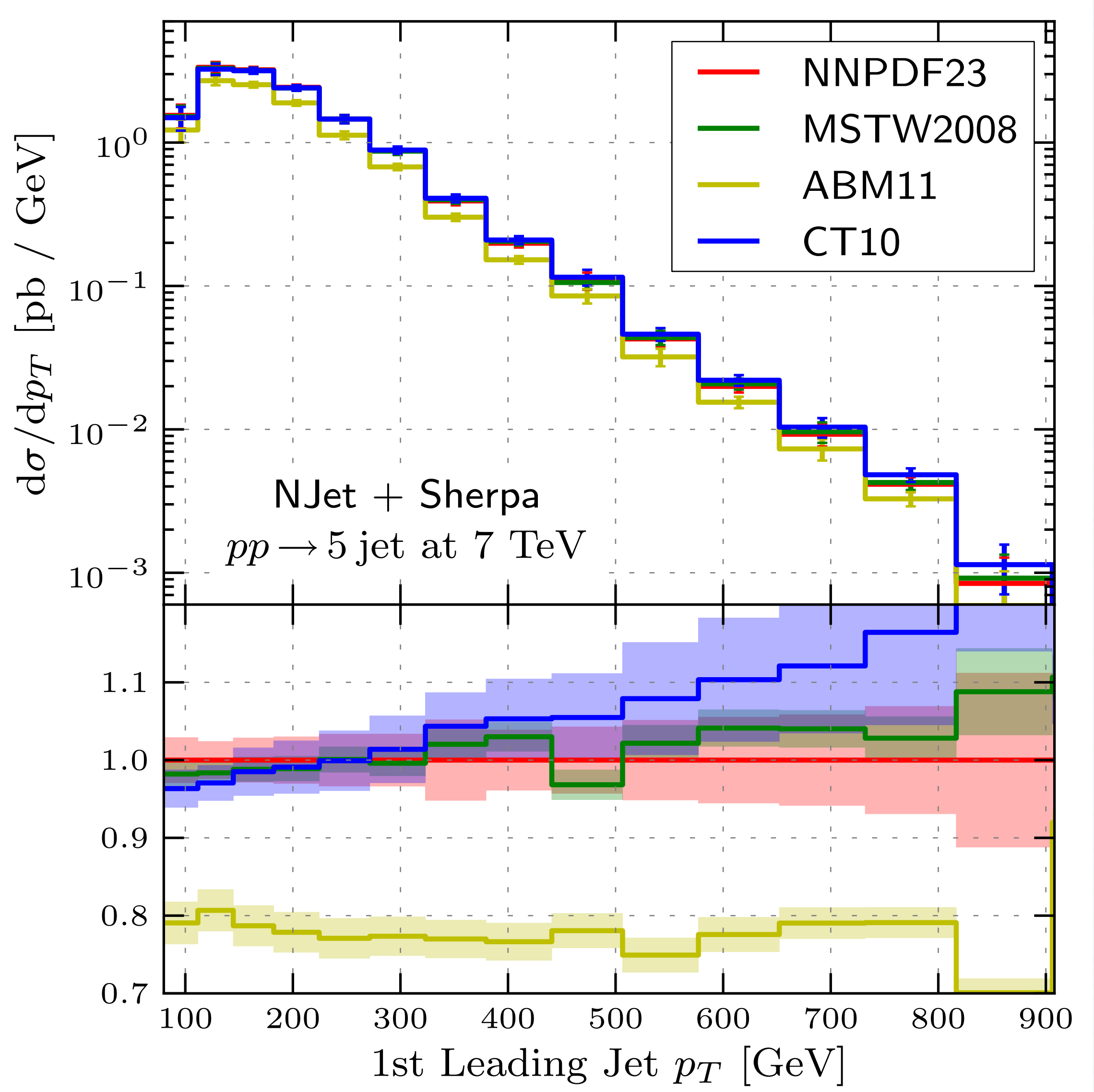




more distributions at https://bitbucket.org/njet/njet/wiki/Results/Physics

PDF dependence

Generally weak dependence on the choice of PDF fit (excluding choice for $\alpha_s(M_Z)$)



comparison using all sets with

$\alpha_s(M_Z) = 0.118$

some dependence on p_T

significant deviation in normalization of ABM11

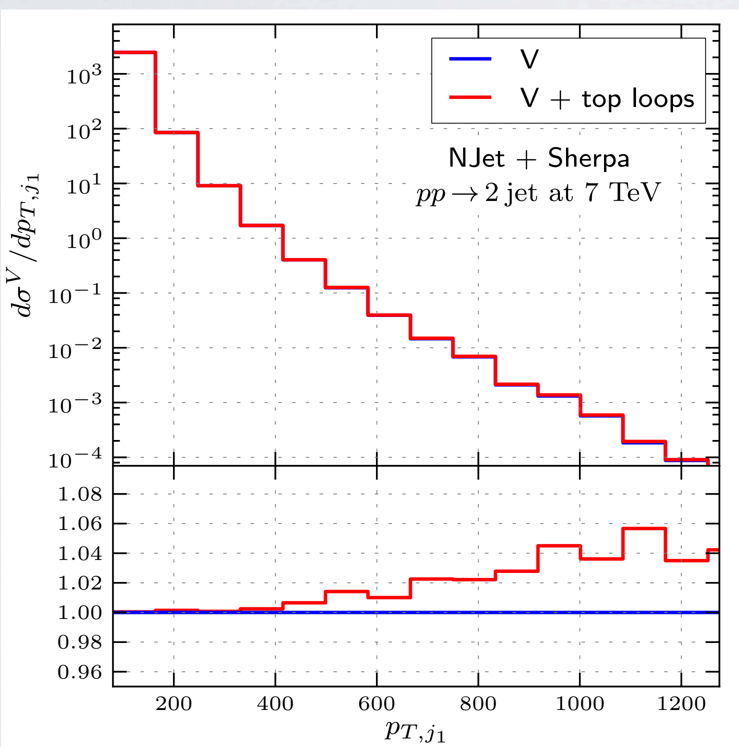
Heavy quark loops

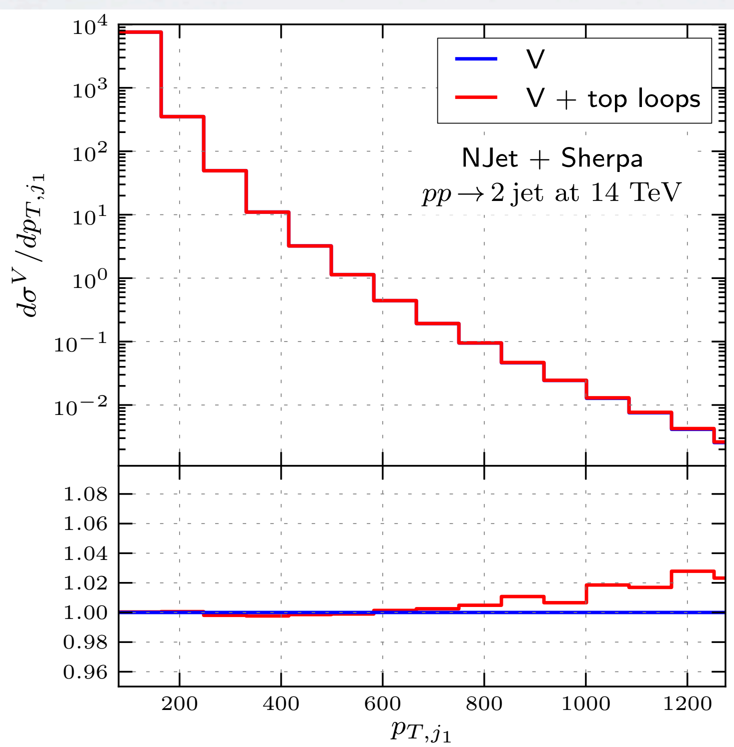
preliminary

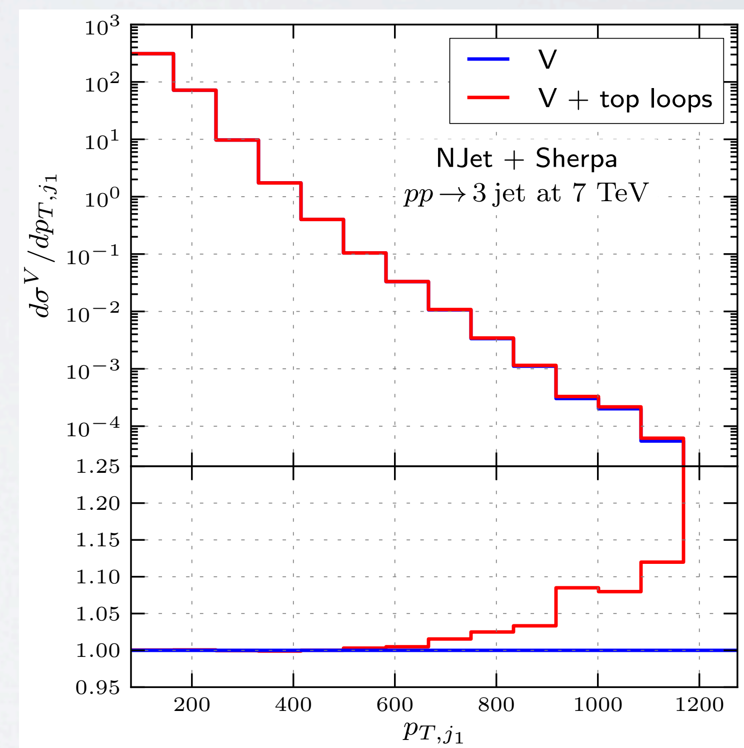
top quark loop effects are small (<1%)

di-jets seem to have additional kinematic suppression

matrix elements checked against MadLoop







corrections grow at very large p_T - still negligible

Efficient Event Generation

- Leading/sub-leading expansion - sample dominant contributions more often
- Separate contributions by number of fermion lines
- ROOT Ntuples - make the most out of the integration run
    - Re-weighting PDFs and renormalization/factorization scales (also jet algorithms with suitable event generation)
- APPLgrid - extremely fast and flexible analysis (very useful for PDF error analyses)

Tancredi et al. [0911.2985]

Vector boson production

Validation/feasibility test only

$$W^{\pm}[\to e^{\pm}\nu_e] + \leq 4j$$

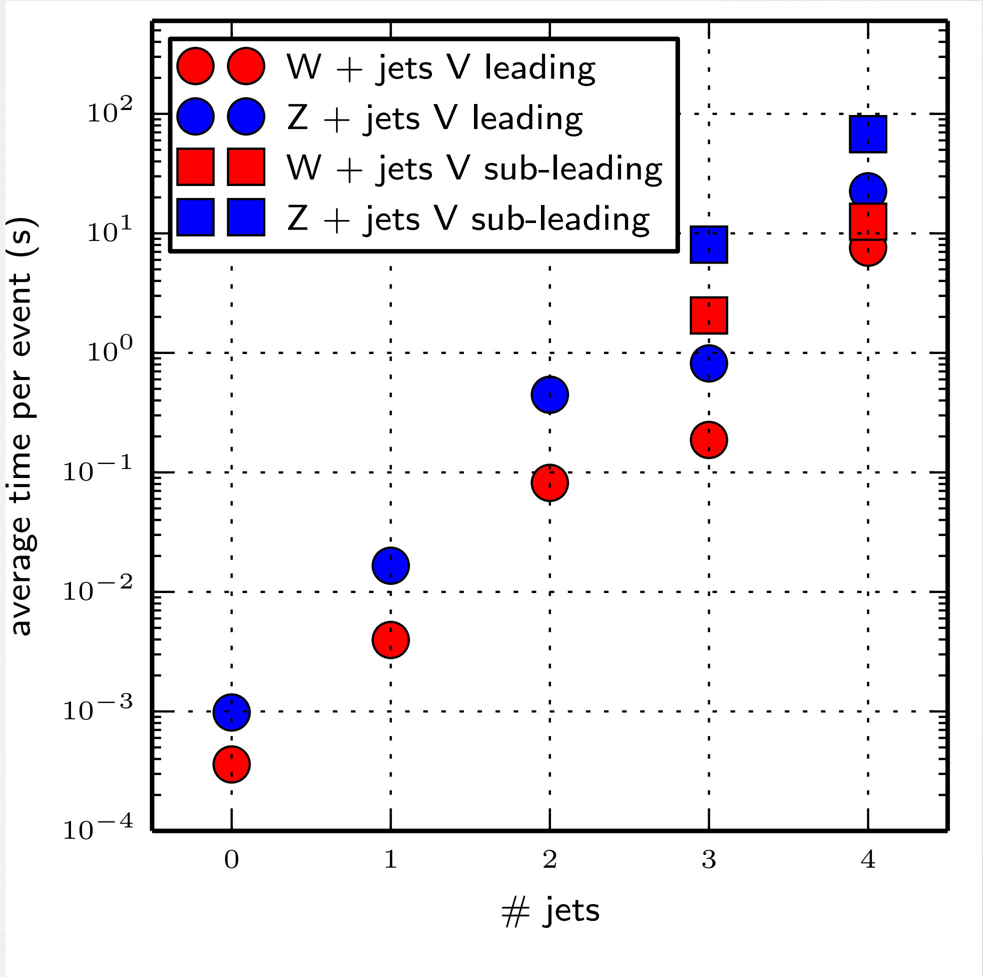
$$Z/\gamma^{*}[\to e^{+}e^{-}] + \leq 4j$$

good agreement on total cross sections

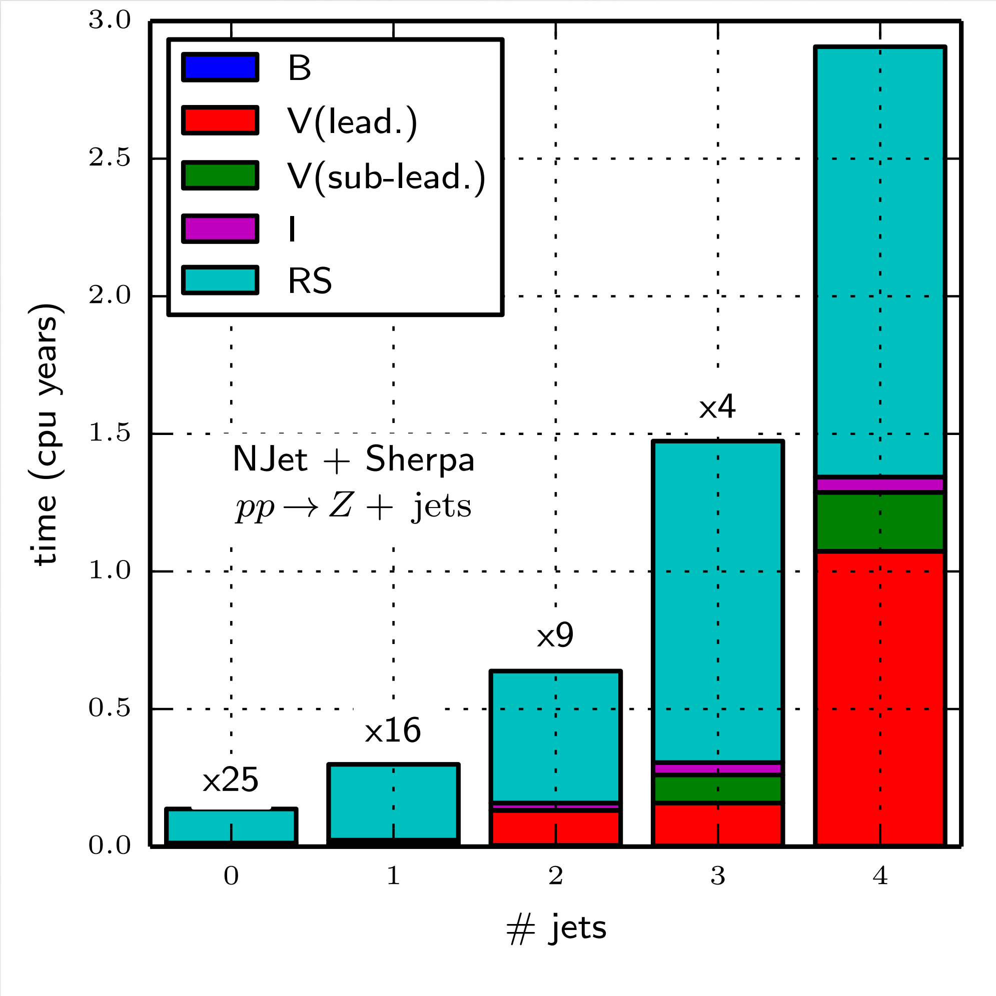
comparison with

Bern et al. [1304. 1253]

$$pp \to \leq W^{\pm} + 5j$$



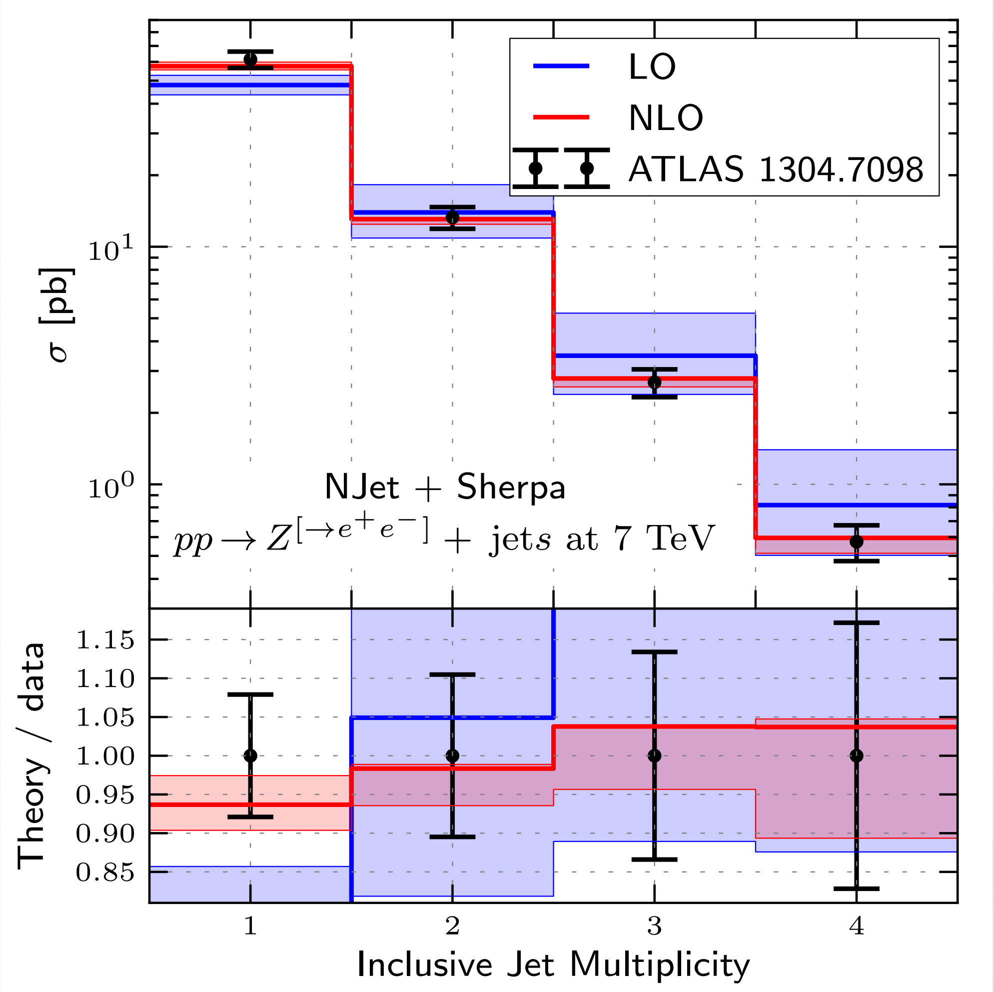
Vector boson production



ATLAS JHEP 1307 (2013) 032 [1304.7098]

Ita, Bern, Dixon, Febres Cordero, Kosower, Maitre [1108.2229]

$$Z/\gamma^*[\to e^+e^-]+ \leq 4j$$



$p_{T,j} > 30$ GeV

$|\eta_j| < 4.4$

$p_{T,e} > 20$ GeV

$66 < m_{ee} < 116$ GeV

$|\eta_e| < 2.47 \qquad 1.37 < |\eta_e| < 1.52$

anti-kt $R = 0.4$

$$\mu_R = \mu_F = \left(\sqrt{m_{ee}^2 + p_{T,ee}^2} + \widehat{H}_T\right)/2$$

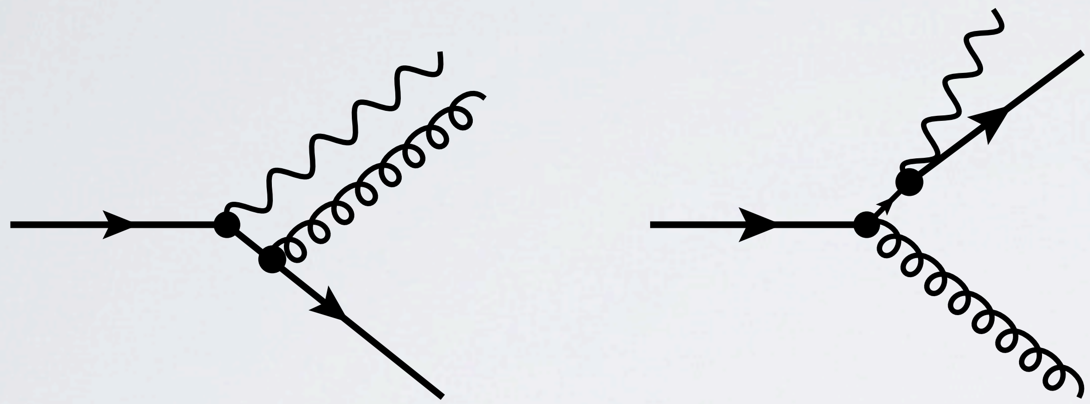
Di-photon plus jets

Backgrounds to Higgs measurements $pp \to H \to \gamma\gamma$

$pp \to \gamma\gamma$	NNLO	Catani, Cieri, de Florian, Ferrera, Grazzini [1110.2375]
$pp \to \gamma\gamma + 1j$	NLO	Gehrmann, Greiner, Heinrich [1303.0824] Del Duca, Maltoni, Nagy, Trocsanyi [hep-ph/0303012]
$pp \to \gamma\gamma + 2j$	NLO	Gehrmann, Greiner, Heinrich [1308.3660] Bern, Dixon, Febres Cordero, Hoeche, Ita, Kosower, Lo Presti, Maitre [1312.0592]
$pp \to \gamma\gamma + 3j$	NLO	SB, Guffanti, Yundin [1312.5927]

Isolating hard photons

[Frixione (1998)]



Infra-red safe definition of a hard photon must include QCD partons

Smooth cone isolation

- keep soft gluons
- discard partons collinear to photon

$$E_{\mathrm{hadronic}}(r_\gamma) \leq \epsilon\, p_{T,\gamma} \left(\frac{1-\cos r_\gamma}{1-\cos R} \right)^n$$

no need for fragmentation functions

$pp \to \gamma\gamma + \text{jets}$ at NLO

SB, Guffanti, Yundin [1312.5927]

$p_{T,j} > 30\,\text{GeV}$ $\quad |\eta_j| \leq 4.7$

$p_{T,\gamma_1} > 40\,\text{GeV}$ $\quad p_{T,\gamma_2} > 25\,\text{GeV}$ $\quad |\eta_\gamma| \leq 2.5$

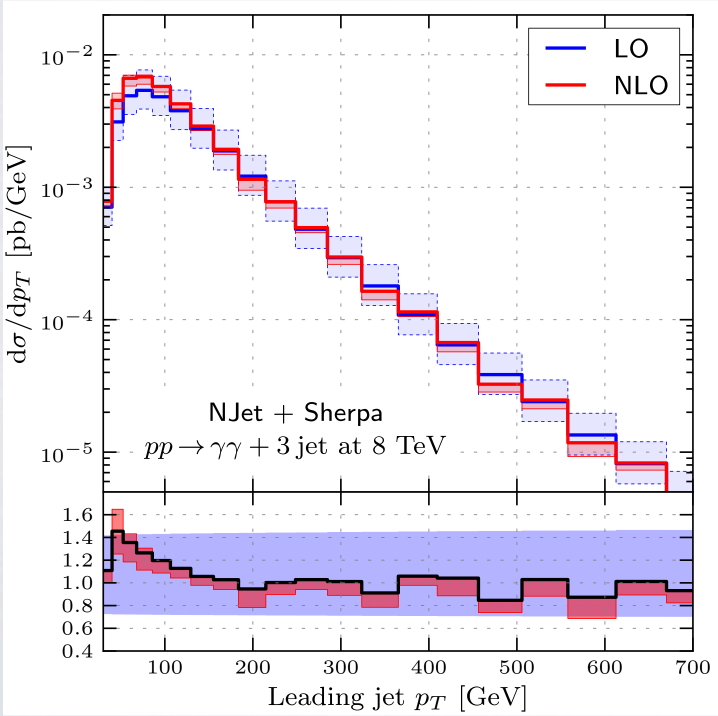
$R_{\gamma,j} = 0.5$ $\quad R_{\gamma,\gamma} = 0.45$

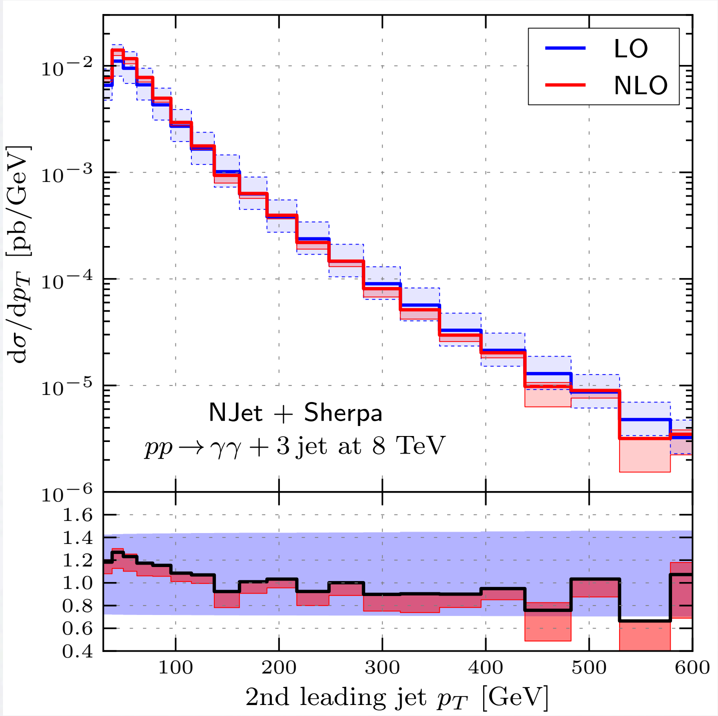
anti-kT $R = 0.5$ (FastJet)

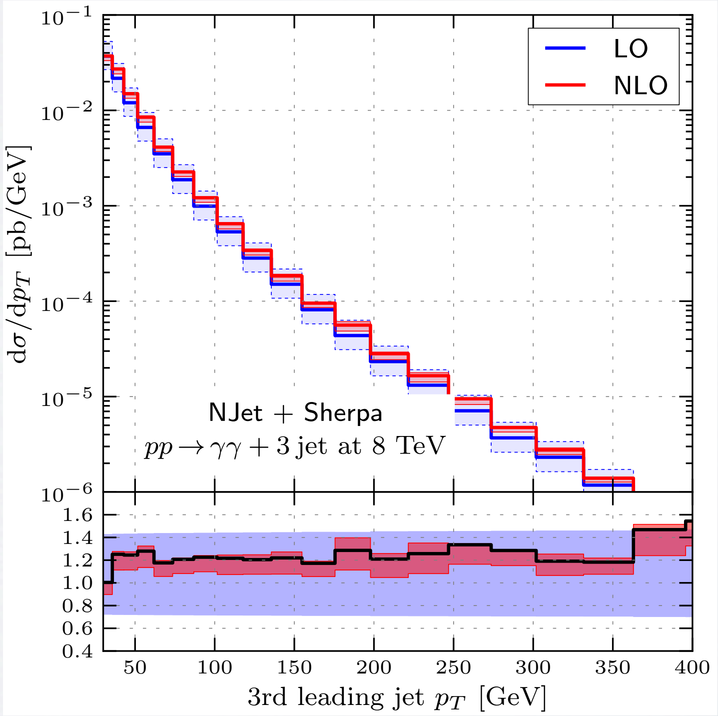
Frixione smooth cone photon isolation $\quad \epsilon = 0.05,\ R = 0.4 \text{ and } n = 1$

CT10 NLO PDF set

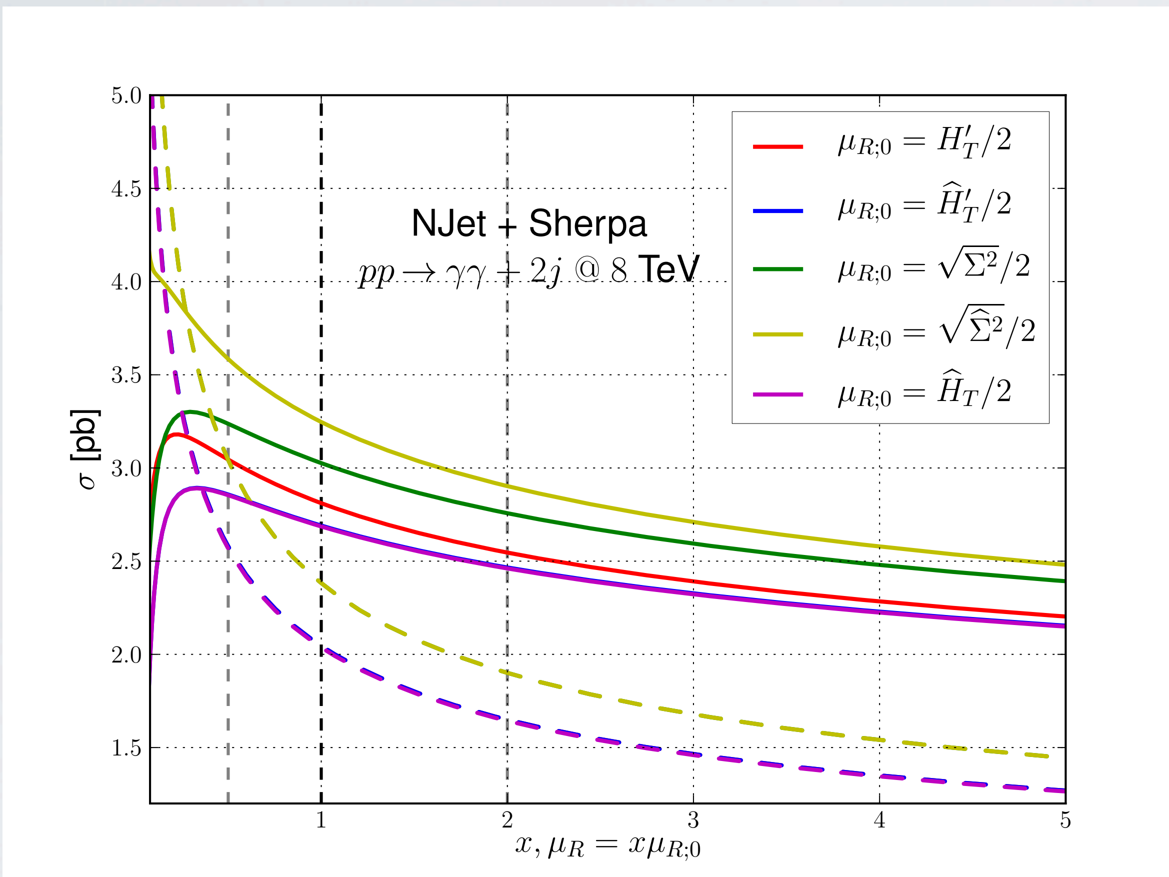
$$\sigma^{LO}_{\gamma\gamma+3j}(\widehat{H}'_T/2) = 0.643(0.003)^{+0.278}_{-0.180}\,\text{pb} \qquad \sigma^{NLO}_{\gamma\gamma+3j}(\widehat{H}'_T/2) = 0.785(0.010)^{+0.027}_{-0.085}\,\text{pb}$$

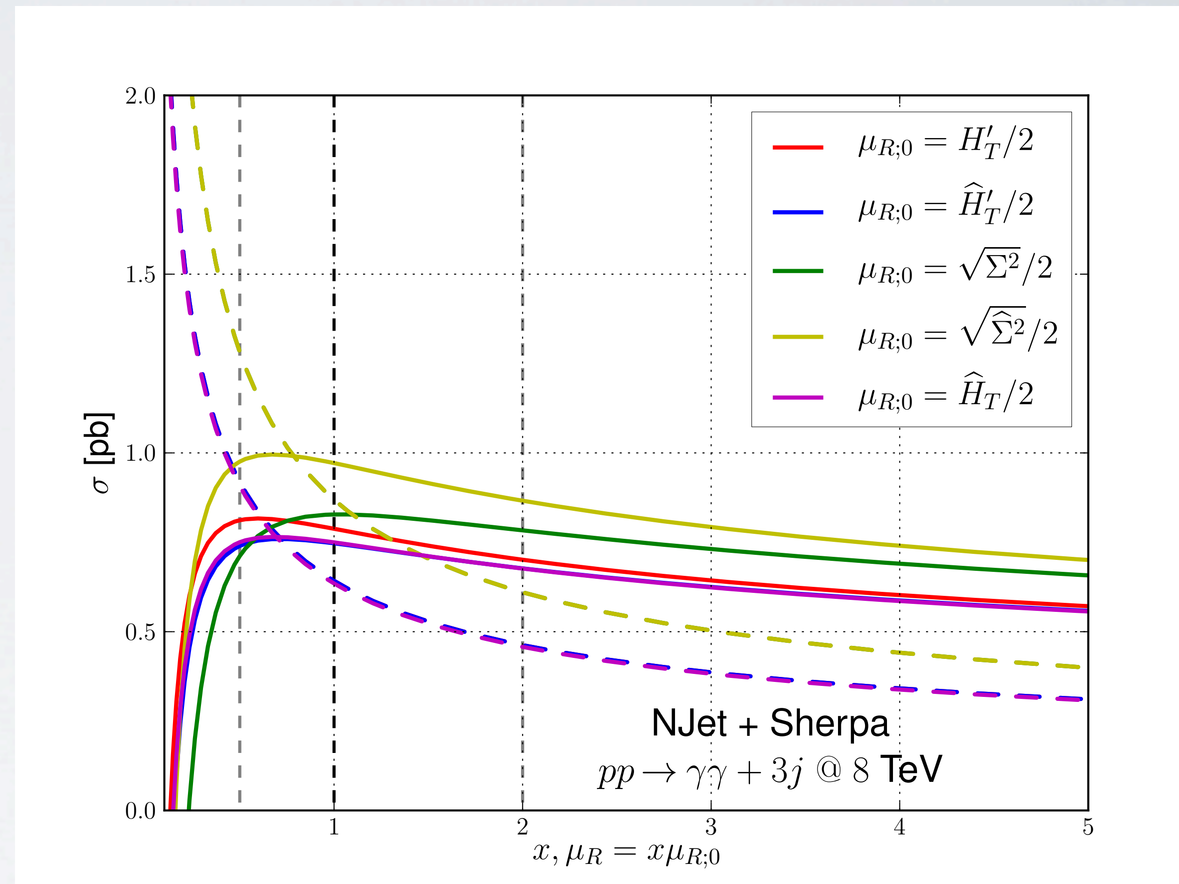






Scale dependence





NLO predictions reduce uncertainty from 50% to 20%

Fairly wide range of predictions with different dynamical scales

Scale dependence

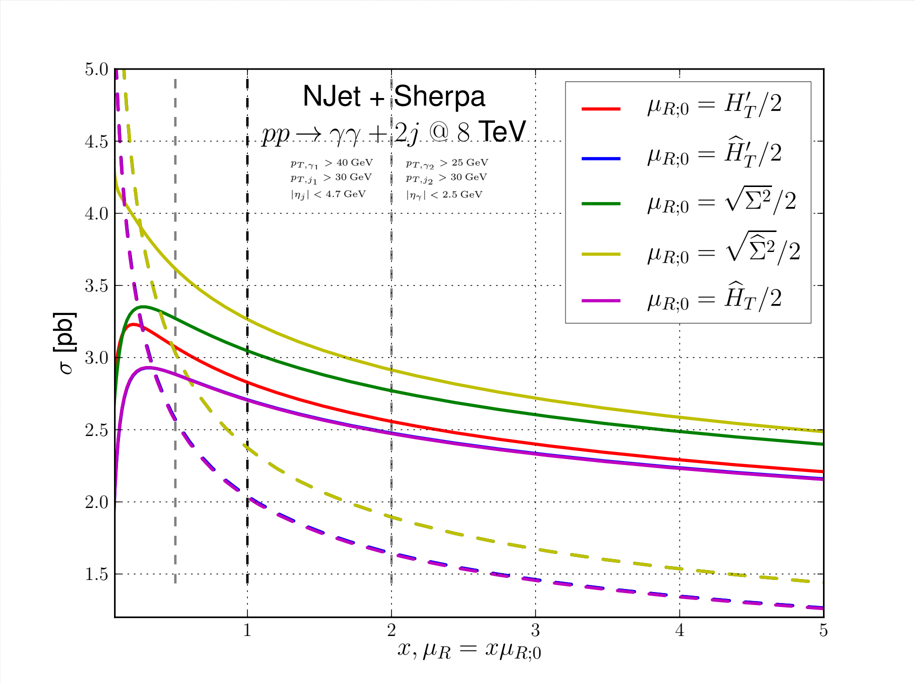
$$\widehat{H}_T = p_{T,\gamma_1} + p_{T,\gamma_2} + \sum_{i \in \text{partons}} p_{T,i}$$

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

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

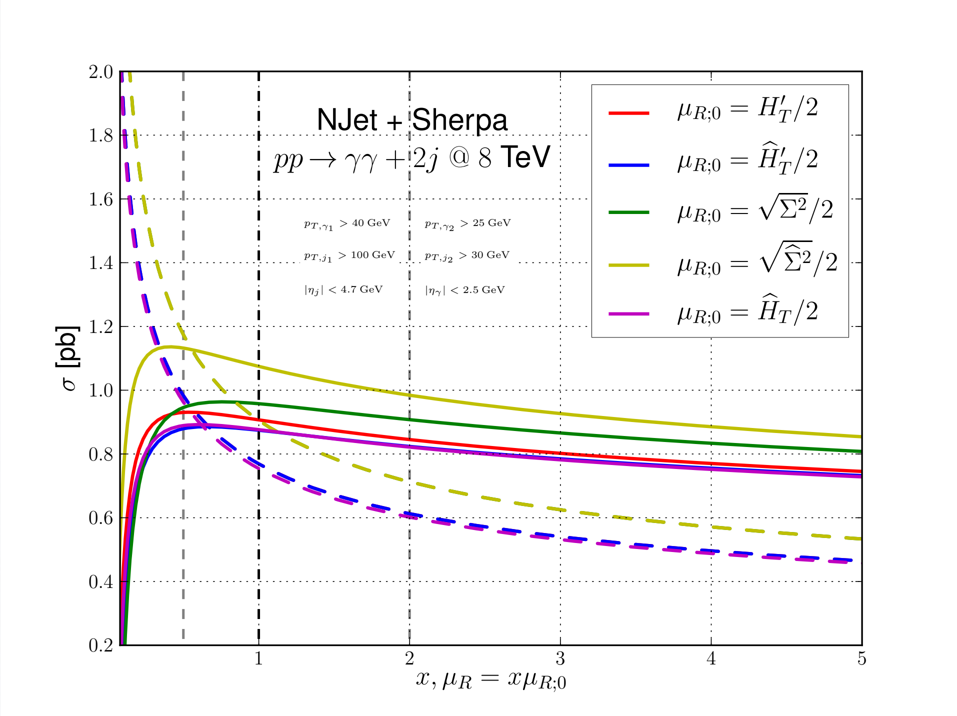
$$H'_T = m_{\gamma\gamma} + \sum_{i \in \text{jets}} p_{T,i}$$

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

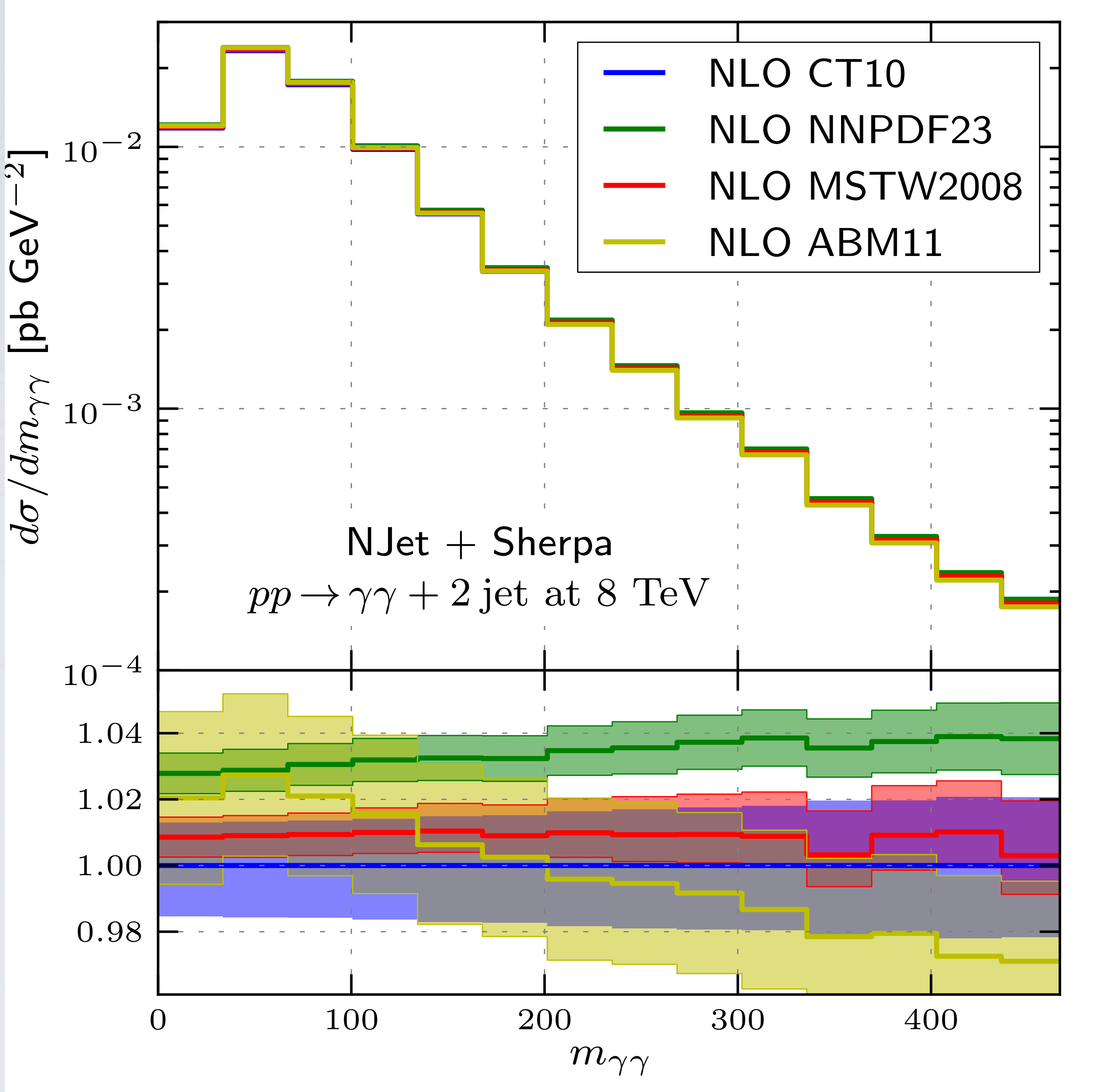


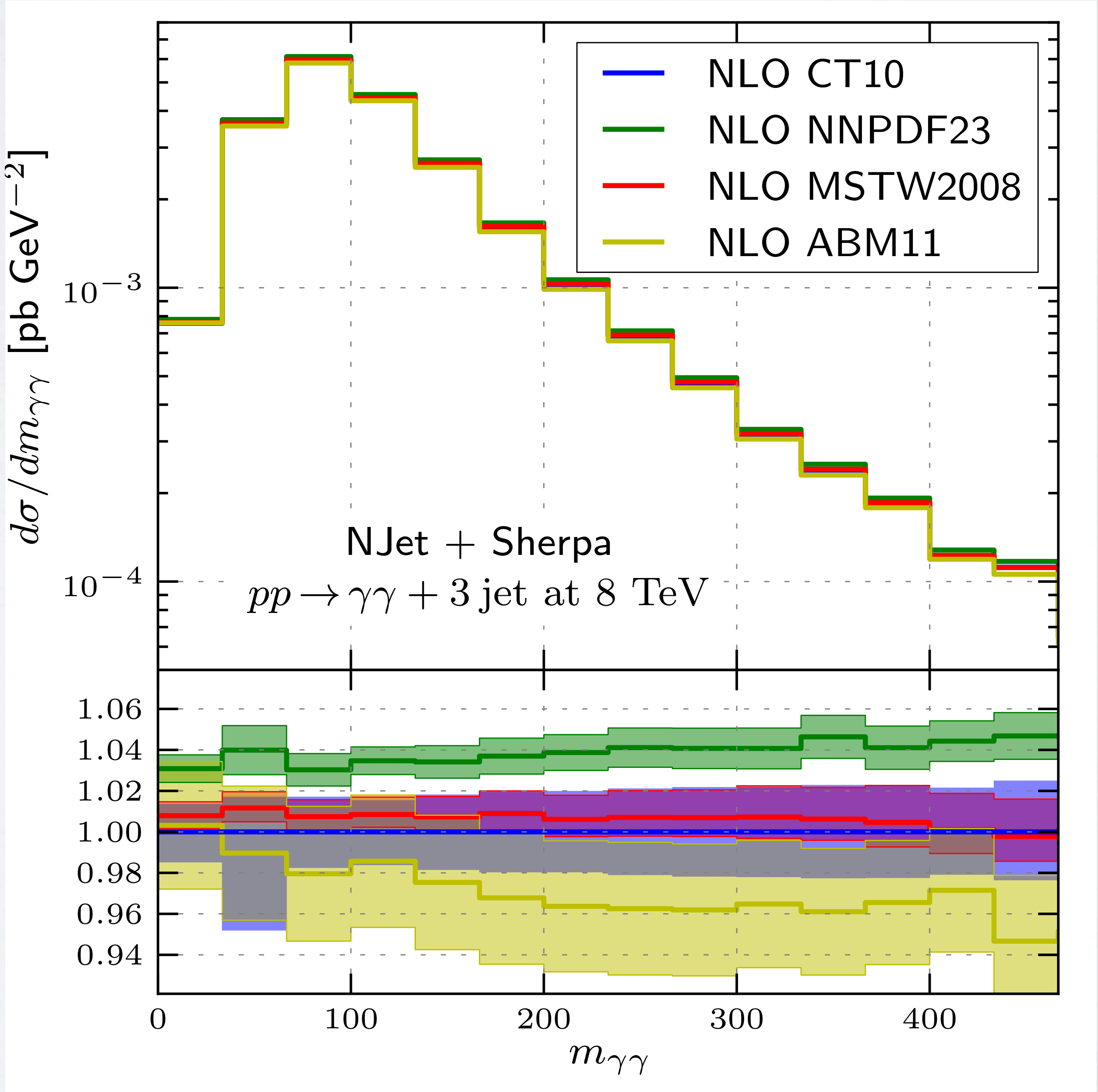
$p_{T,j_1} > 30$ GeV

$p_{T,j_1} > 100$ GeV



PDF dependence





Conclusions

- On-shell methods do a good job at keeping theoretical complexity of high-multiplicity amplitudes under control
- NLO computations with NJET + SHERPA https://bitbucket.org/njet/njet/
- First computations of NLO QCD corrections to $pp \to 5j$ and $pp \to \gamma\gamma + 3j$
- Precision QCD for 13 TeV / 14 TeV LHC runs (as well as current data)
  - matching/merging with parton shower (still hard for pure jets)