Fast grid technologies for Higher Order QCD calculations

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Preface

- Theoretical uncertainties (proton PDFs, scales μ_R, μ_F) often the dominant systematic on many important physics processes at the LHC
  - Searches for new massive particles; Higgs production; limiting precision on fundamental quantities, α_s, M(Z) …
- Improved precision data being matched by more sophisticated theoretical predictions - at least NLO; NNLO now becoming available
- Use cases such as inclusion of a calculation in a PDF fit require the evaluation of the cross section many, many times with different PDFs, different scales, different couplings …
- Higher order calculations require cancellation of divergences in numerical phase space integration with non-trivial kinematic selections
  - Typically require very long computation times, days, weeks on large CPU farms

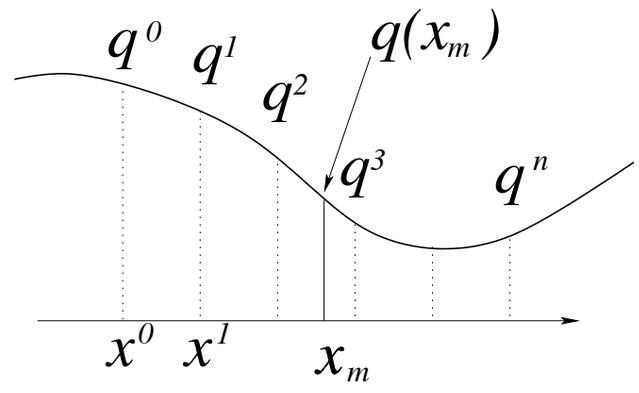
- One solution is to store the perturbative coefficients of the (N)NLO QCD calculations of final state observables in look up tables or grids
  - Run the full calculation once, store the coefficients
  - Allows the subsequent convolution with the PDF to be performed *a-posteriori*, with any PDF, choice of scales, choice of α_s, etc

- Fast *a-posteriori* convolution typically **only a few milliseconds** rather than weeks
- Typically reproduces the caclulation to 10^{-4} - 10^{-5} accuracy

Recap of the Numerical Technique

- For a calculation of a cross section from $m = 1 \ldots N$ weights, w_m , from a Monte Carlo integration with momentum fraction x_m , form the product

$$\sum_m w(x_m) q(x_m)$$



- Can interpolate the function $q(x_m)$

$$q(x_m) \approx \sum_i q^{(i)} I^{(i)}(x_m - x^{(i)})$$

- such that

$$\begin{aligned} \sum_m w(x_m) q(x_m) &\approx \sum_i q^{(i)} \sum_m w(x_m) I^{(i)}(x_m - x^{(i)}) \\ &\approx \sum_i q^{(i)} W^{(i)} \end{aligned}$$

- For a calculation of a cross section with $m = 1 \ldots N$ weights, from a Monte Carlo integration with momentum transfer Q^2

$$\begin{aligned} d\sigma &= \sum_p \sum_{m=1}^{N} w_m^{(p)} \left(\frac{\alpha_s(Q_m^2)}{2\pi} \right)^p q(x_m, Q_m^2) \\ &= \sum_p \sum_{ij} q(x_{(i)}, Q_{(j)}^2) \left(\frac{\alpha_s(Q_{(j)}^2)}{2\pi} \right)^p \sum_m^N w_m^{(p)} I_i^x(x_m) I_j^{Q^2}(Q_m^2) \\ &= \sum_p \sum_{ij} q(x_{(i)}, Q_{(j)}^2) \left(\frac{\alpha_s(Q_{(j)}^2)}{2\pi} \right)^p W_{ij}^{(p)} \end{aligned}$$

Proton-Proton Collisions

- For pp collisions need an extra dimension for the PDF of the second colliding hadron

$$d\sigma \quad = \quad \sum_{p} \sum_{m=1}^{N} w_m^{(p)} \left(\frac{\alpha_s(Q_m^2)}{2\pi} \right)^p \; q_1(x_{1m}, Q_m^2) \; q_2(x_{2m}, Q_m^2)$$

- But there is an implicit summation over parton flavours. Make use of symmetries in the matrix elements to use a vector of $k = 1 \ldots M$ independent weights such that

$$\sum_{ij=q,\bar{q},g} w_{ij} q_{1i}(x_1) q_{2j}(x_2) = \sum_{k=1}^{M} w^{(k)} F^{(k)}(x_1, x_2)$$

- so that

$$d\sigma \quad = \quad \sum_{p} \sum_{k=1}^{M} \sum_{m=1}^{N} w_m^{(p)(k)} \left(\frac{\alpha_s(Q_m^2)}{2\pi} \right)^p F_m^{(k)}(x_{1m}, x_{2m}, Q_m^2)$$

- Which can be placed on a grid in the same way as for DIS

- So from the summation, everything is down to the quality of the interpolation of the pdf at the grid nodes
  - It is s **pure quadrature technique** and is not, in principle subject to statistical fluctuation, or put another way …
  - Each **individual** weight gets added to the grid, and should be well approximated **individually**

Timeline of grid technology

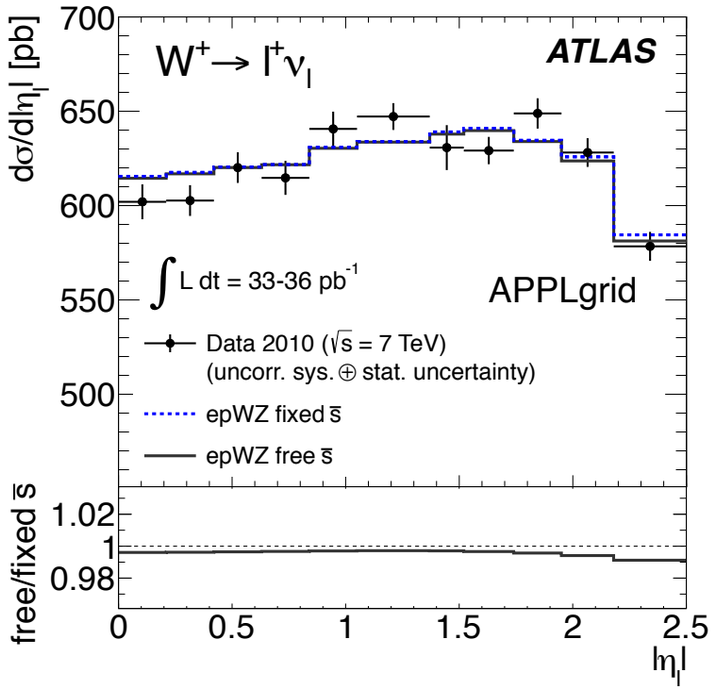
2000	**First implementation of grid technique for DIS at H1**- Markus Wobisch DESY-THESIS-2000-049
2001	**First basic fit in DIS using jets H1** -EPJ C19, 289 (2001)
2004	**First full fit in DIS using jets from ZEUS** - PRD 67 0120071 (2003)
2005	**APPLgrid for jets in hadron-hadron collisions** - Carli, Salam, Siegert - C++, fully open source - user code for grid generation available - arbitrary scale variation
< 2006	**fastNLO implementation for DIS and jets in hadron-hadron** with NLOjet++ and threshold corrections fro Kidonakis et al, Kluge Rabbertz, Wobisch - Separate Fortran routines for only precomputed grids - limited precomputed scale choices - No user grid generation
Nov 2009	**APPLgrid for jets in hadron-hadron - first full release** - custom sparse memory structure for more efficient storage - arbitrary beam energy scaling - fastNLO interface - **First implementation of non-jet cross sections - MCFM interface for inclusive W and Z production at NLO**
2010	**APPLgrid for other processes in hadron-hadron** - Extension to heavy flavours in MCFM QQ - ttbar, bbbar, ccbar
Aug 2012	**fastNLO 2 + toolkit produced** - New C++ interface and user grid generation code made available
Jun 2013	**APPLgrid for other processes in hadron-hadron** - Extension to essentially **all remaining processes in MCFM**, including Z, W + jets, W+c etc
July 2013	APPLgrid Native interface to Sherpa - **All NLO QCD** in Sherpa
Dec 2013	APPLgrid modifications for MCFM integrated into official MCFM 6.7 MCgrid APPLgrid interface to Sherpa - **All NLO QCD in Sherpa** from within Rivet
June 2014	AMCfast - AMC@NLO interterface to APPLgrid - **All NLO QCD in aMC@NLO**
Sept 2015	**fastNLO Interface to DiffTop**
Early 2015	**fastNLO integration with Sherpa** using the MCgrid APPLgrid - Sherpa interface
	Watch this space ...

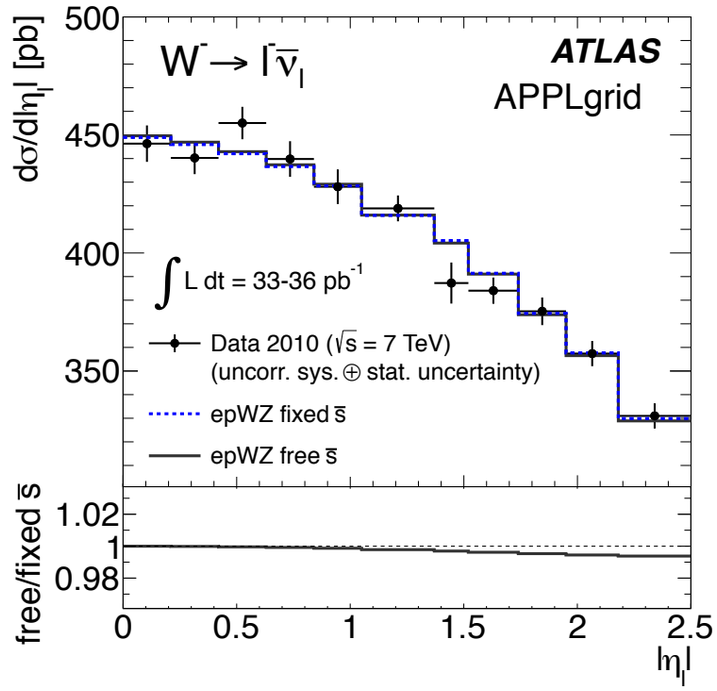
Timeline of grid technology (and major landmarks)

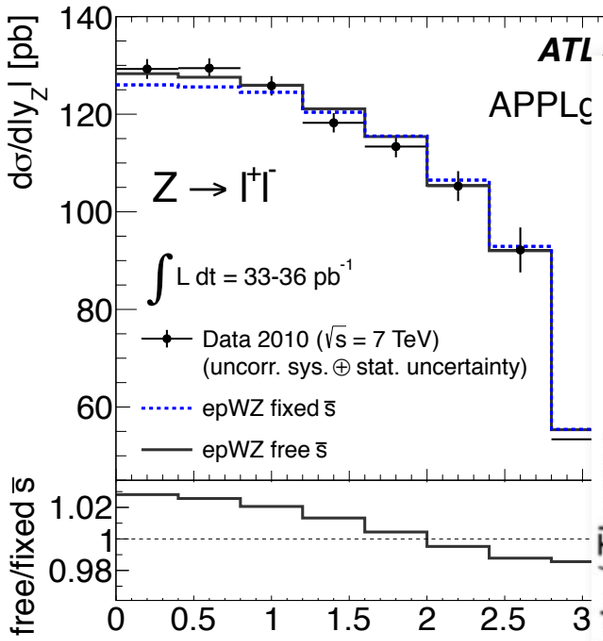
Oct 2015	**Initiated the APPLfast - NNLO project** (of which more later)	
March 2016	**Implementation of the photon density within the photon** Implementation with APPLgrid and aMCFast - Stefano Carrazza	
May 2016	**APFELgrid - modified grids using APFEL evolution** Valerio Bertone, Stefano Carrazza, Nathan P. Hartland	
July 2016	**NNLOJET z+jets cross section** A. Gehrmann-De Ridder, T. Gehrmann, E.W.N. Glover, A. Huss, T. A. Morgan	***
late 2016	**top pair production at NNLO interfaced to fastNLO** Michael Czakon, David Heymes and Alexander Mitov	
August 2016	**First public APPLfast status report - Z + jets closure announced**	
Nov 2016	**NNLOJET inclusive jet cross section** J. Currie, E.W.N. Glover, J. Pires	***
March 2017	**APPLfast - first studies of major production campaign announced**	
March 2017	**APPLfast NNLO inclusive jets - closure announced**	
May 2017	**NNLOJET inclusive dijet cross section** J. Currie, A. Gehrmann-De Ridder, T. Gehrmann, E.W.N. Glover, A. Huss, J. Pires	***
June 2017	**today …**	

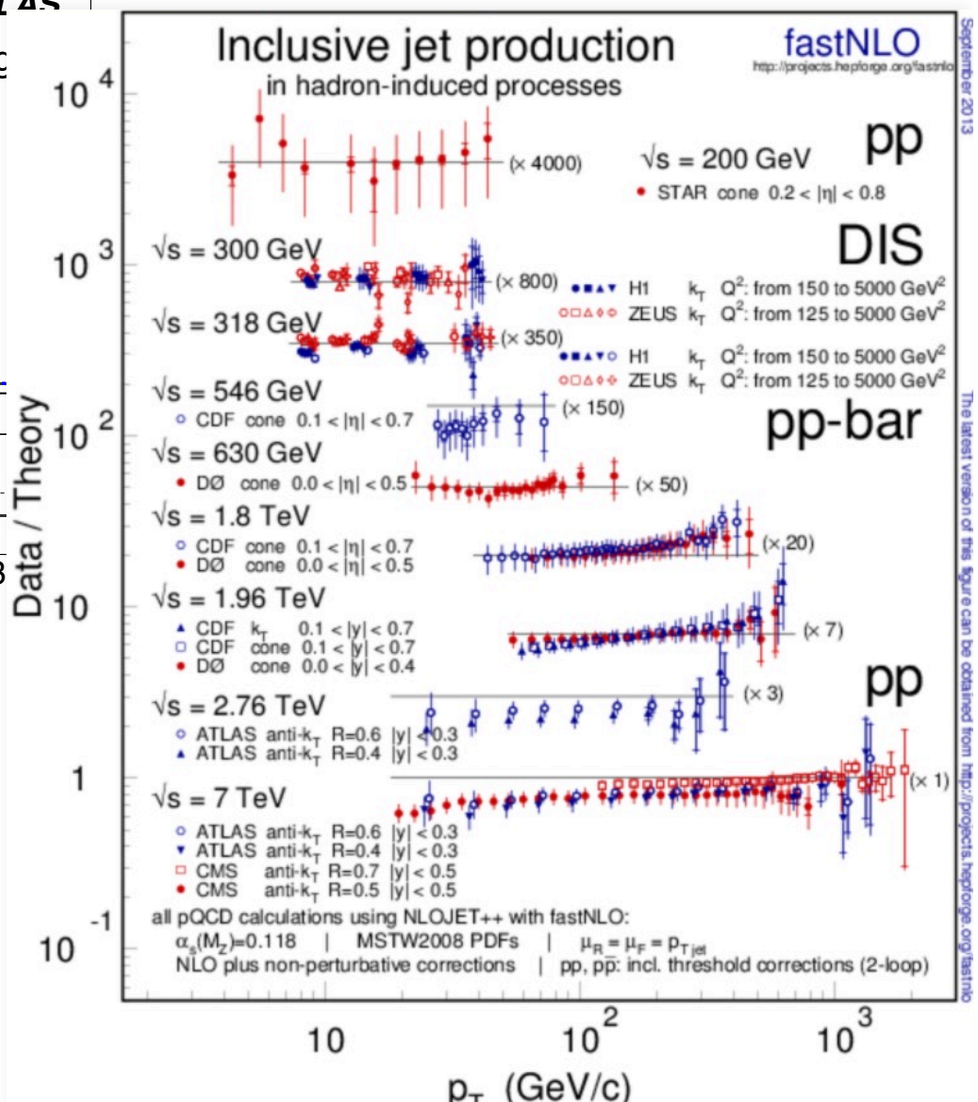
Available processes at NLO

- Essentially all of NLO QCD is available with both fastNLO or APPLgrid
- Implementation in Sherpa, aMC@NLO (aMCfast), MCFM
  - Jet production, in DIS And pp, inclusive, dijet, threejet
  - Inclusive W±, Z production
  - Inclusive heavy flavour
  - Heavy flavour with W, Z etc
  - Photon distributions in the proton - thanks to Stefano Carrazza
  - …
- Now implementing NNLO …









APPLfast-NNLO

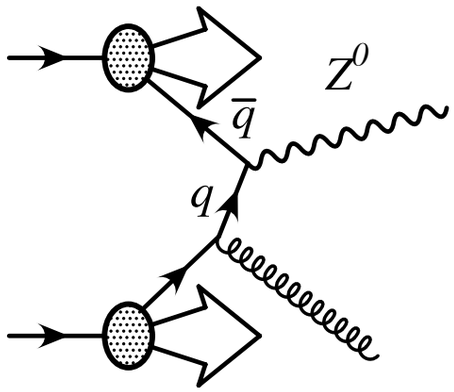
Daniel Britzger[†], Claire Gwenlan[‡], Alex Huss[§]
(Tom Morgan*), Joao Pires[a], Klaus Rabbertz[b], Mark Sutton[c]

DESY[†], Oxford[‡], ETH Zurich[§],
IPPP Durham*, MPP Munchen[a], Karlsruhe[b], Sussex[c]

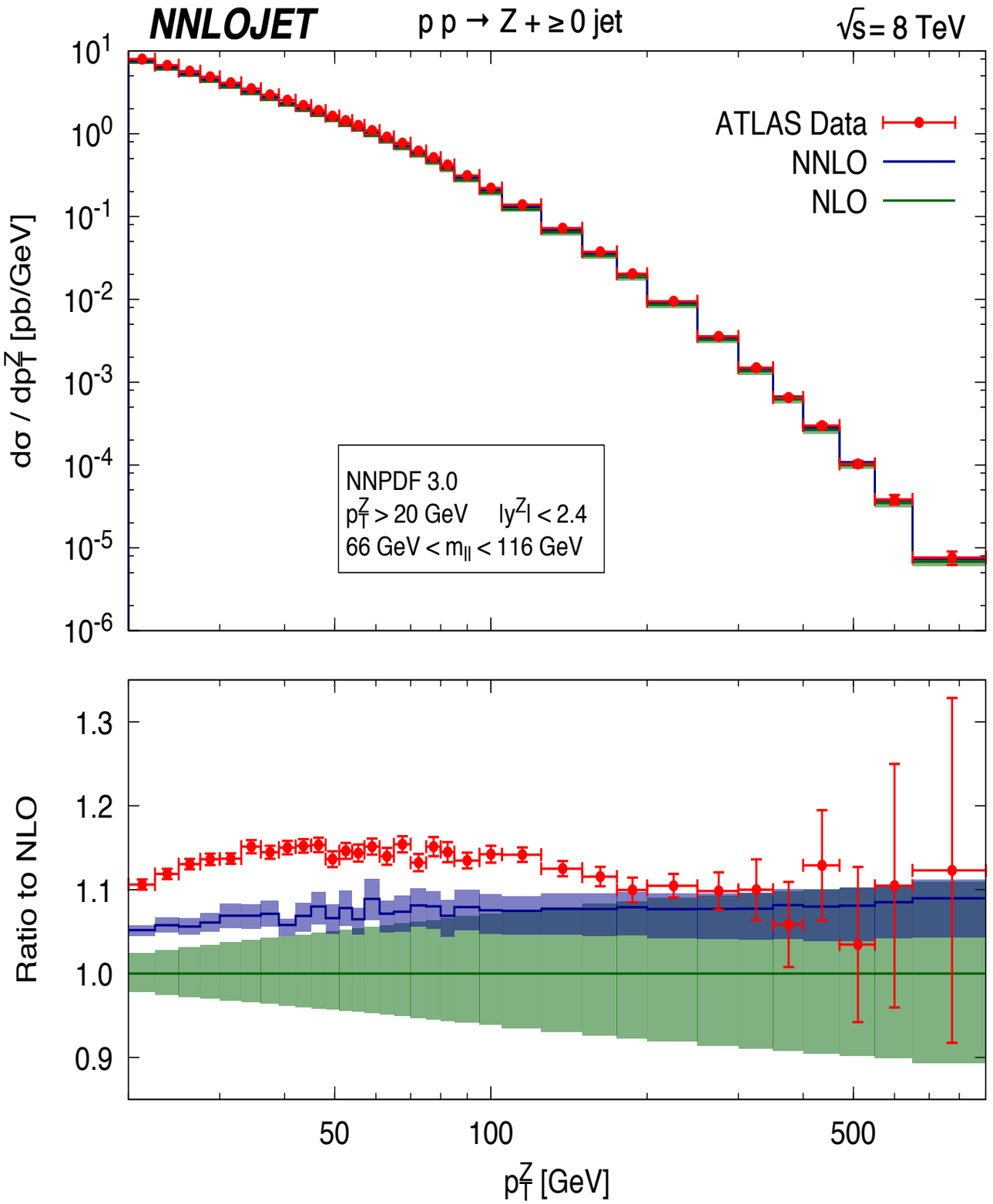
Work supported by the IPPP Associateship program

APPLfast-NNLO interface to NNLOJET

- Aim is to act as an interface to NNLOJET to provide grids usable for PDF fits etc to the wider community
- Make use of the semi-automated calculation of cross sections in NNLOJET
  - Gehrmann-De Ridder et al arXiv: 1607.01749

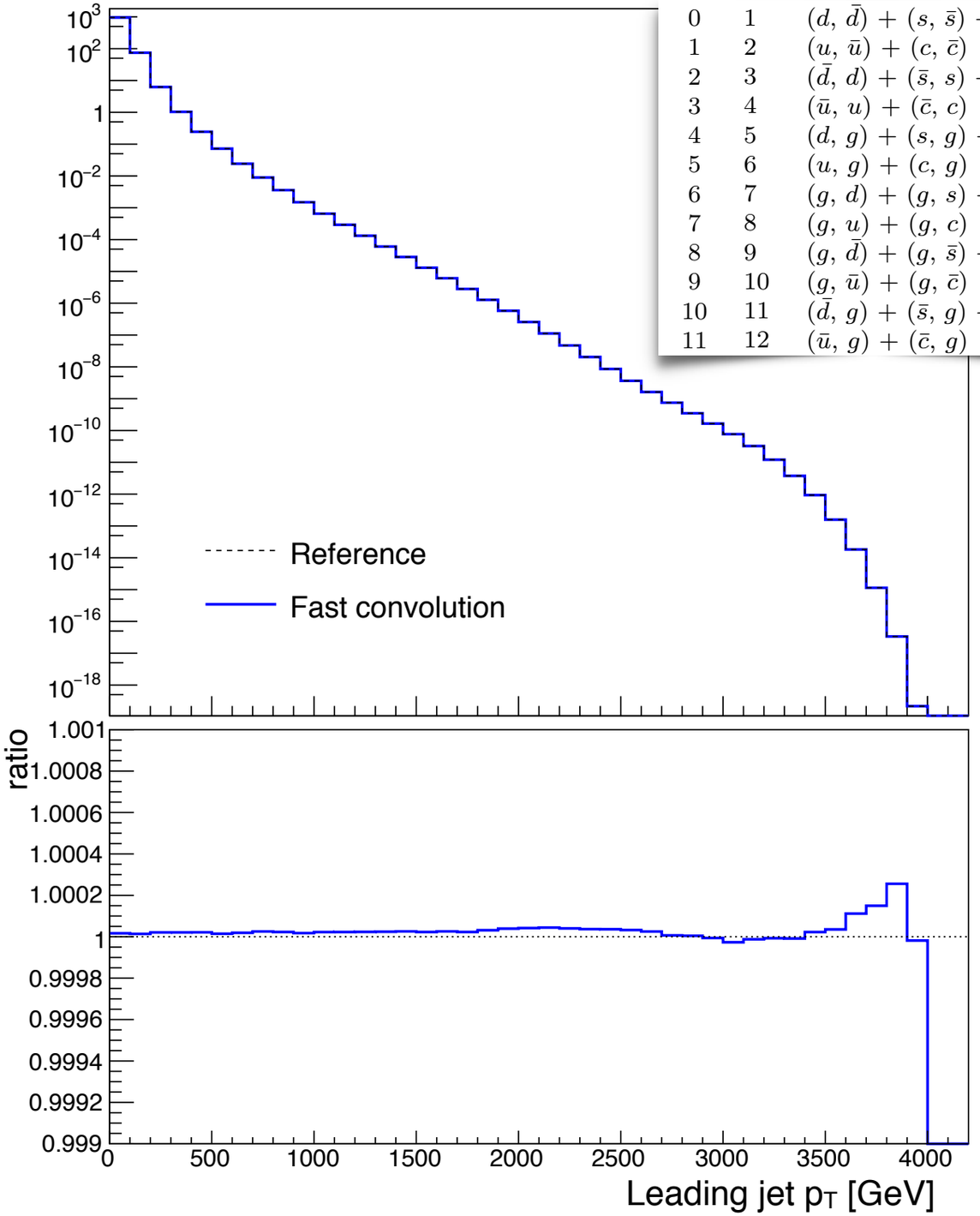


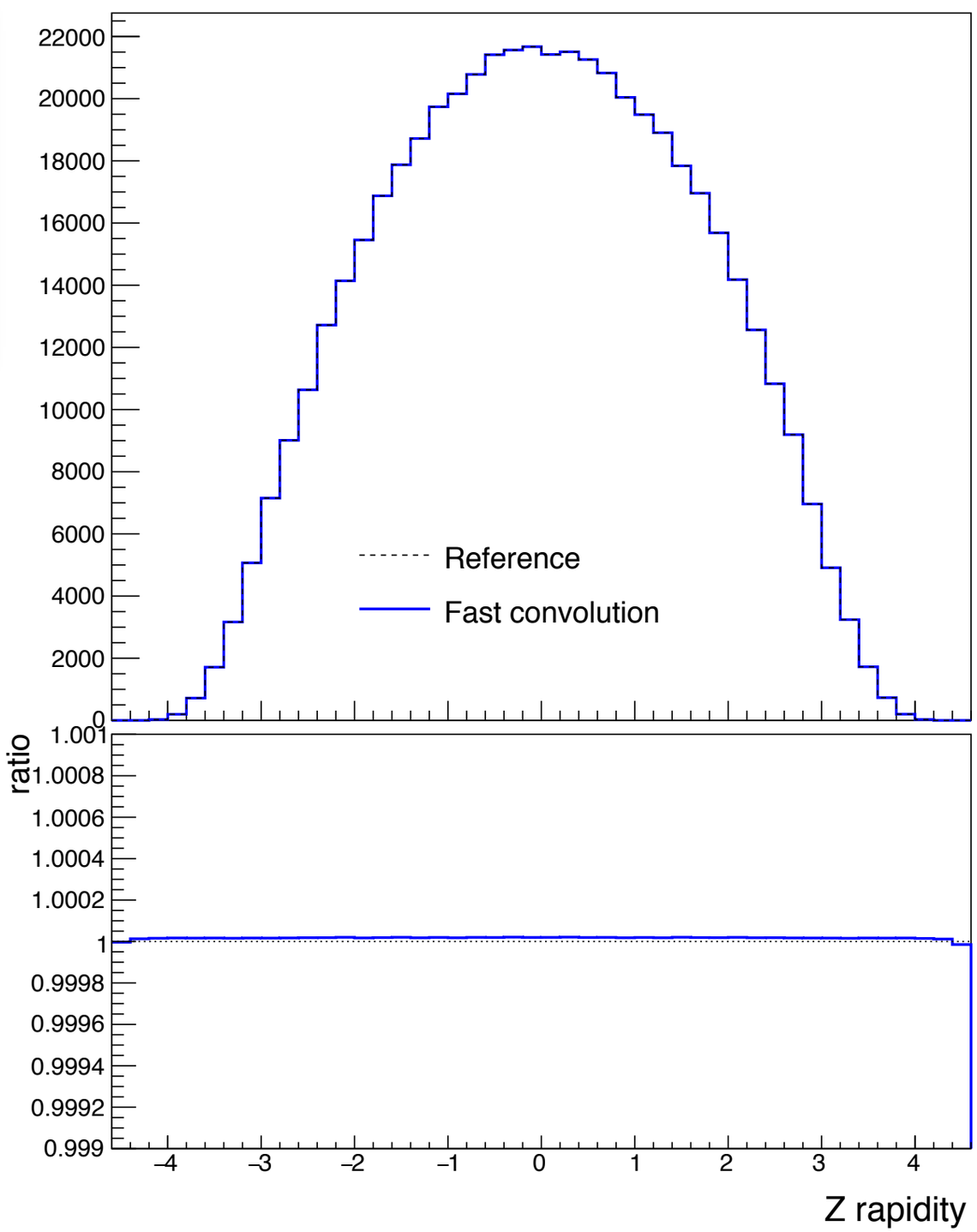
- APPLfast-NNLO …
- Project personnel from both fastNLO and APPLgrid together with developers from the NNLOJET developers
  - Implementing a single combined interface for the NNLO calculation with the fast grid technology
  - Developing a generic interface applicable for all available processes



Z + jets at Leading order - fast convolution closure

0	1	$(d, \bar{d}) + (s, \bar{s}) + (b, \bar{b})$
1	2	$(u, \bar{u}) + (c, \bar{c})$
2	3	$(\bar{d}, d) + (\bar{s}, s) + (\bar{b}, b)$
3	4	$(\bar{u}, u) + (\bar{c}, c)$
4	5	$(d, g) + (s, g) + (b, g)$
5	6	$(u, g) + (c, g)$
6	7	$(g, d) + (g, s) + (g, b)$
7	8	$(g, u) + (g, c)$
8	9	$(g, \bar{d}) + (g, \bar{s}) + (g, \bar{b})$
9	10	$(g, \bar{u}) + (g, \bar{c})$
10	11	$(\bar{d}, g) + (\bar{s}, g) + (\bar{b}, g)$
11	12	$(\bar{u}, g) + (\bar{c}, g)$





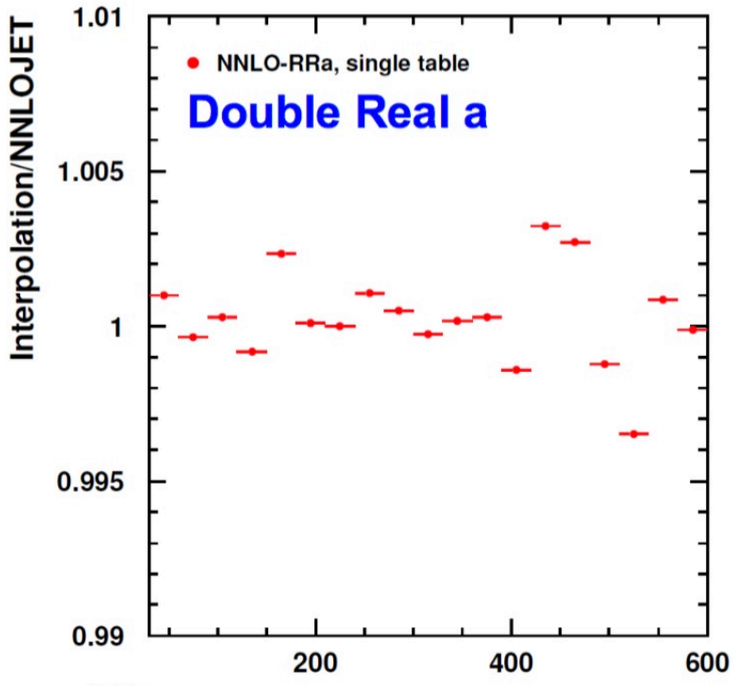
- Note the ± 0.1 % maximum range in ratio plots
- As always, Leading Order component well reproduced - usual issues near the edges of the phase space

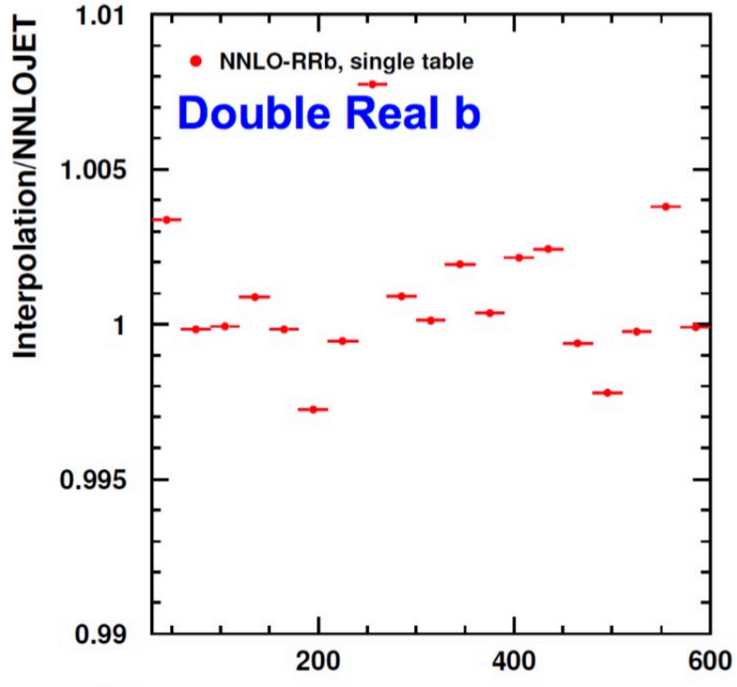
Z + jets - closure tests at NNLO

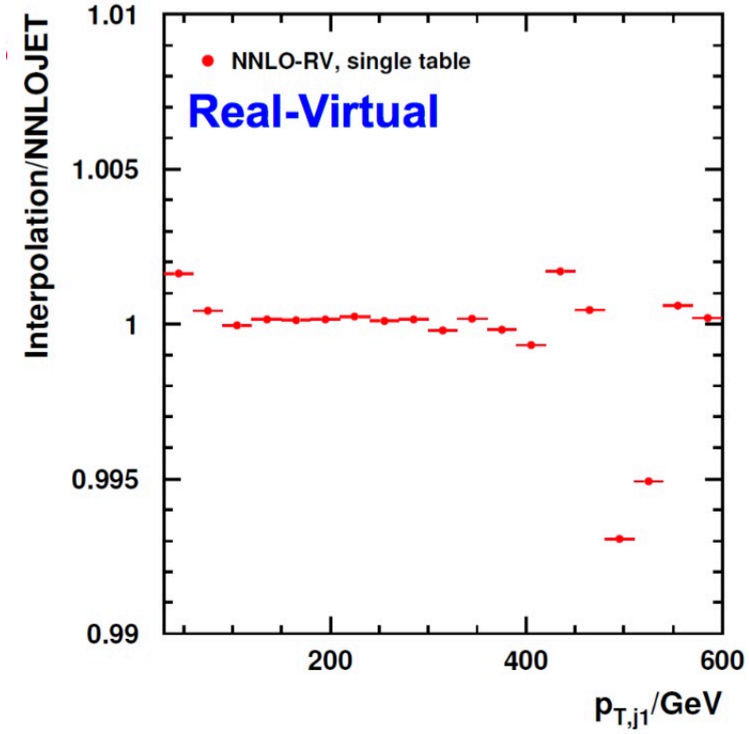
- Note increased ± 1% y-axis range
- Generally agreement to aound the per mille level

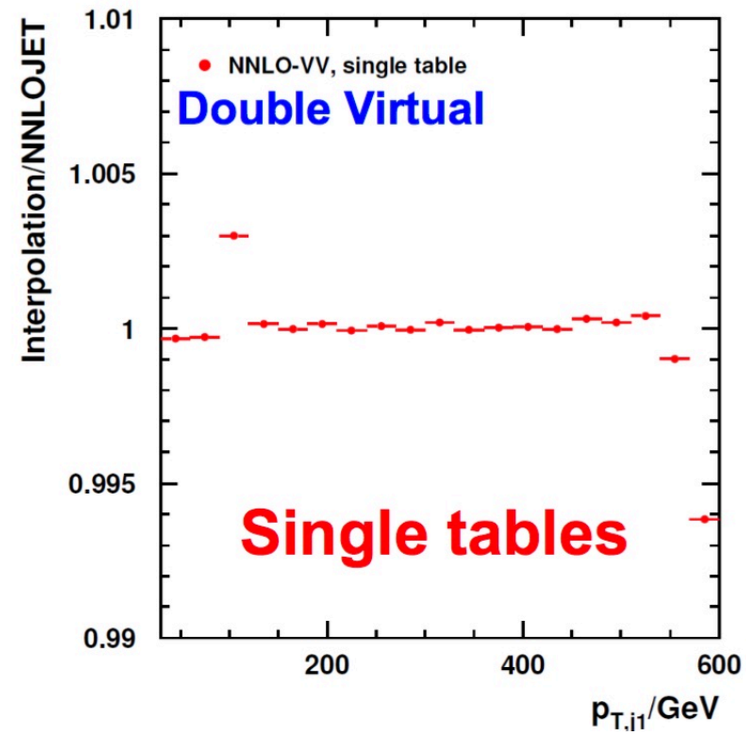
- Double Real contribution in computed in two parts here

- Some inevitable large fluctuations
  - Incomplete cancelation between bins
  - Taken care of during the global proceedure to combine the grids for the final cross section

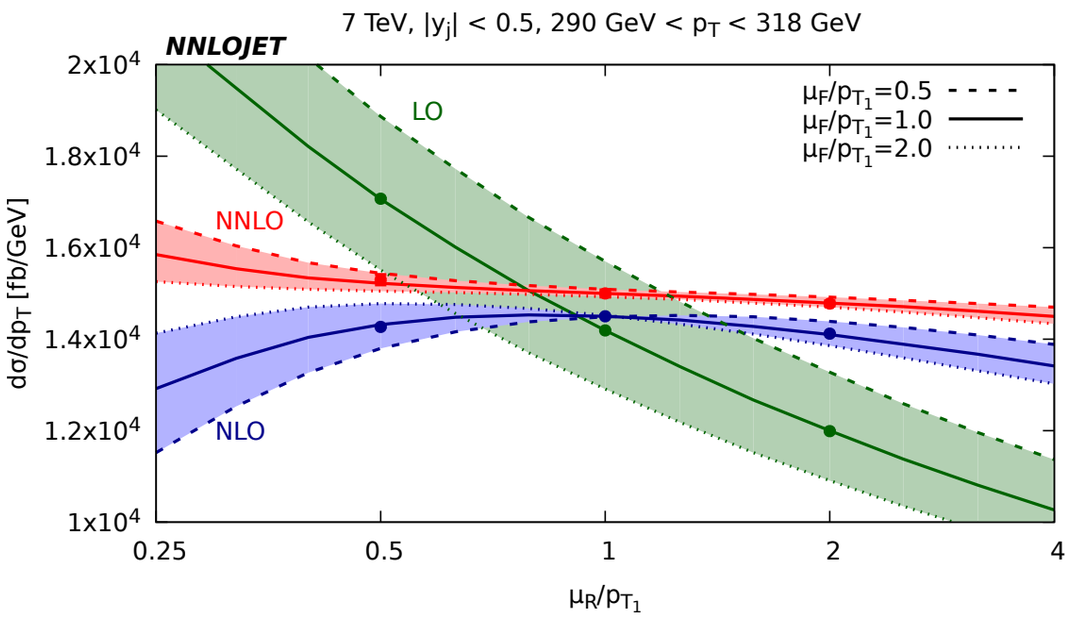




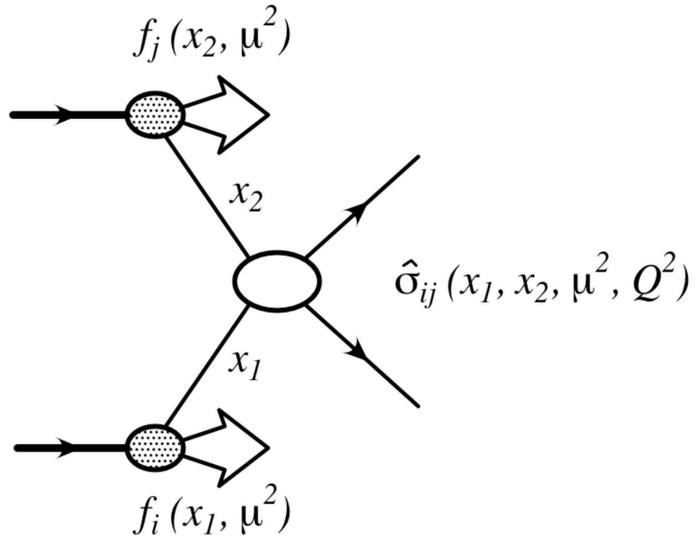




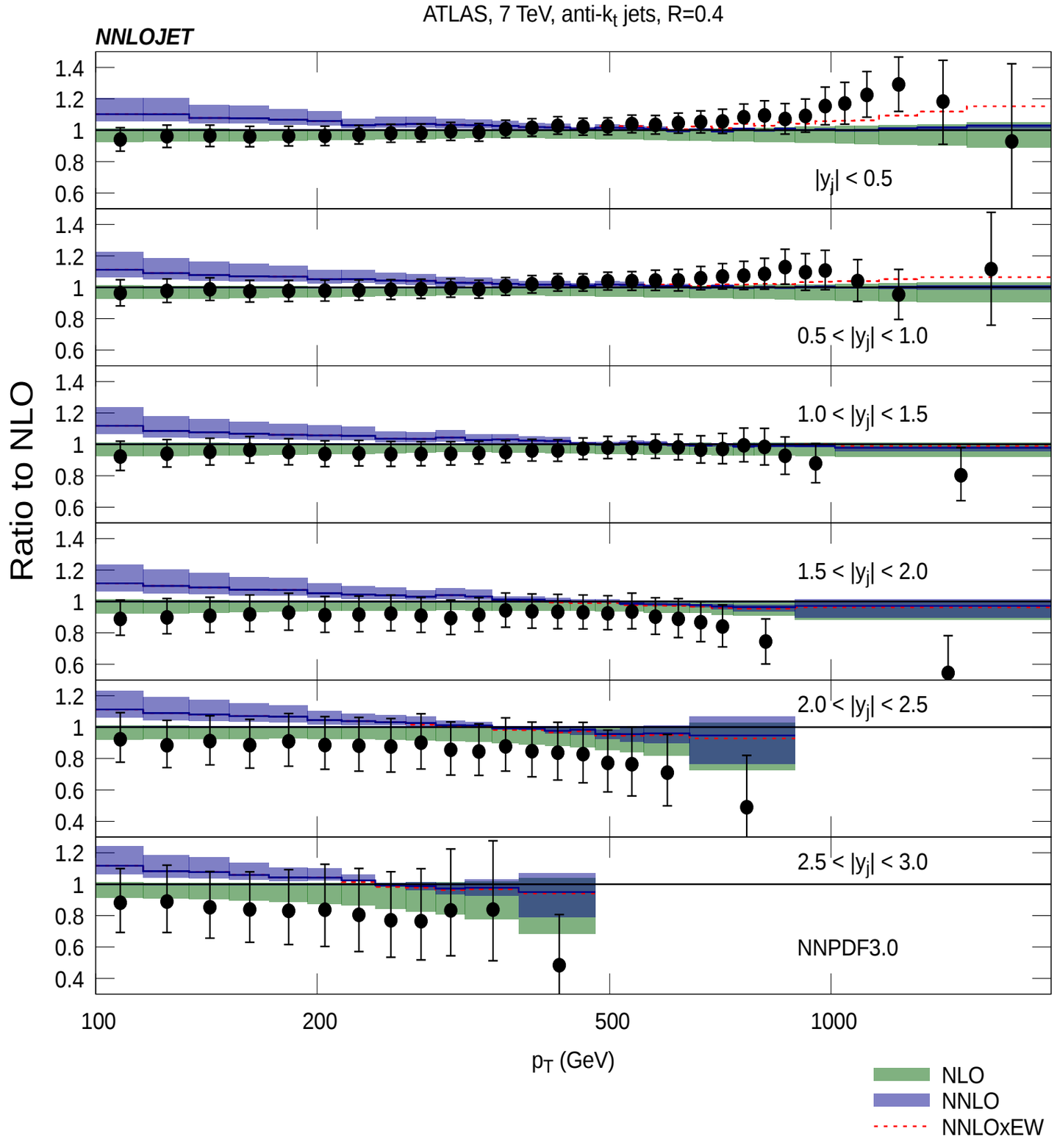
Inclusive jet production



- NNLO QCD predictions for single jet inclusive production at the LHC
  - J. Currie, E.W.N. Glover, J. Pires **arXiv: 1611.01460**



- For initial linited statistics grid validation studies, use scale choice, $\mu_R = \mu_F = p_{T\,lead}$



Jet production technicalities

- Leading order - 25 internal processes

0	1 6 13	$(g,\, g)$
1	2 9	$(d,\, g) + (u,\, g) + (s,\, g) + (c,\, g) + (b,\, g)$
2	3 10 18 22	$(d,\, \bar{d}) + (u,\, \bar{u}) + (s,\, \bar{s}) + (c,\, \bar{c}) + (b,\, \bar{b})$
3	4 11	$(g,\, d) + (g,\, u) + (g,\, s) + (g,\, c) + (g,\, b)$
4	5 12 19 24	$(\bar{d},\, d) + (\bar{u},\, u) + (\bar{s},\, s) + (\bar{c},\, c) + (\bar{b},\, b)$
5	7 14	$(g,\, \bar{d}) + (g,\, \bar{u}) + (g,\, \bar{s}) + (g,\, \bar{c}) + (g,\, \bar{b})$
6	8 15	$(\bar{d},\, g) + (\bar{u},\, g) + (\bar{s},\, g) + (\bar{c},\, g) + (\bar{b},\, g)$
7	16	$(d,\, \bar{d}) + (d,\, \bar{u}) + (d,\, \bar{s}) + (d,\, \bar{c}) + (d,\, \bar{b}) + (u,\, \bar{d}) + (u,\, \bar{u}) + (u,\, \bar{s}) + (u,\, \bar{c}) + (u,\, \bar{b}) + (s,\, \bar{d}) + (s,\, \bar{u}) + (s,\, \bar{s}) + (s,\, \bar{c}) + (s,\, \bar{b}) + (c,\, \bar{d}) + (c,\, \bar{u}) + (c,\, \bar{s}) + (c,\, \bar{c}) + (c,\, \bar{b}) + (b,\, \bar{d}) + (b,\, \bar{u}) + (b,\, \bar{s}) + (b,\, \bar{c}) + (b,\, \bar{b})$
8	17	$(d,\, d) + (d,\, u) + (d,\, s) + (d,\, c) + (d,\, b) + (u,\, d) + (u,\, u) + (u,\, s) + (u,\, c) + (u,\, b) + (s,\, d) + (s,\, u) + (s,\, s) + (s,\, c) + (s,\, b) + (c,\, d) + (c,\, u) + (c,\, s) + (c,\, c) + (c,\, b) + (b,\, d) + (b,\, u) + (b,\, s) + (b,\, c) + (b,\, b)$
9	20	$(\bar{d},\, \bar{d}) + (\bar{d},\, \bar{u}) + (\bar{d},\, \bar{s}) + (\bar{d},\, \bar{c}) + (\bar{d},\, \bar{b}) + (\bar{u},\, \bar{d}) + (\bar{u},\, \bar{u}) + (\bar{u},\, \bar{s}) + (\bar{u},\, \bar{c}) + (\bar{u},\, \bar{b}) + (\bar{s},\, \bar{d}) + (\bar{s},\, \bar{u}) + (\bar{s},\, \bar{s}) + (\bar{s},\, \bar{c}) + (\bar{s},\, \bar{b}) + (\bar{c},\, \bar{d}) + (\bar{c},\, \bar{u}) + (\bar{c},\, \bar{s}) + (\bar{c},\, \bar{c}) + (\bar{c},\, \bar{b}) + (\bar{b},\, \bar{d}) + (\bar{b},\, \bar{u}) + (\bar{b},\, \bar{s}) + (\bar{b},\, \bar{c}) + (\bar{b},\, \bar{b})$
10	21	$(\bar{d},\, d) + (\bar{d},\, u) + (\bar{d},\, s) + (\bar{d},\, c) + (\bar{d},\, b) + (\bar{u},\, d) + (\bar{u},\, u) + (\bar{u},\, s) + (\bar{u},\, c) + (\bar{u},\, b) + (\bar{s},\, d) + (\bar{s},\, u) + (\bar{s},\, s) + (\bar{s},\, c) + (\bar{s},\, b) + (\bar{c},\, d) + (\bar{c},\, u) + (\bar{c},\, s) + (\bar{c},\, c) + (\bar{c},\, b) + (\bar{b},\, d) + (\bar{b},\, u) + (\bar{b},\, s) + (\bar{b},\, c) + (\bar{b},\, b)$
11	23	$(d,\, d) + (u,\, u) + (s,\, s) + (c,\, c) + (b,\, b)$
12	25	$(\bar{d},\, \bar{d}) + (\bar{u},\, \bar{u}) + (\bar{s},\, \bar{s}) + (\bar{c},\, \bar{c}) + (\bar{b},\, \bar{b})$

- And at NLO - 150 internal processes

0	26 31 38 45 84 89 98 109 120 127 134	$(g,\, g)$
1	27 34 41 51 61 70 78 87 92 94 105 116 123 130 145 155 165 173 181 189	$(d,\, g) + (u,\, g) + (s,\, g) + (c,\, g) + (b,\, g)$
2	28 35 42 48 58 68 76 95 106 117 124 131 139 149 159 167 175 183	$(d,\, \bar{d}) + (u,\, \bar{u}) + (s,\, \bar{s}) + (c,\, \bar{c}) + (b,\, \bar{b})$
3	29 36 43 53 63 72 80 85 90 96 107 118 125 132 143 153 163 171 179 187	$(g,\, d) + (g,\, u) + (g,\, s) + (g,\, c) + (g,\, b)$
4	30 37 44 52 62 71 79 97 108 119 126 133 140 150 160 169 177 185	$(\bar{d},\, d) + (\bar{u},\, u) + (\bar{s},\, s) + (\bar{c},\, c) + (\bar{b},\, b)$
5	32 39 46 57 67 75 83 86 91 99 110 121 128 135 144 154 164 172 180 188	$(g,\, \bar{d}) + (g,\, \bar{u}) + (g,\, \bar{s}) + (g,\, \bar{c}) + (g,\, \bar{b})$
6	33 40 47 56 66 74 82 88 93 100 111 122 129 136 146 156 166 174 182 190	$(\bar{d},\, g) + (\bar{u},\, g) + (\bar{s},\, g) + (\bar{c},\, g) + (\bar{b},\, g)$
7	49 59 101 112 138 148 158	$(d,\, d) + (d,\, u) + (d,\, s) + (d,\, c) + (d,\, b) + (u,\, d) + (u,\, u) + (u,\, s) + (u,\, c) + (u,\, b) + (s,\, d) + (s,\, u) + (s,\, s) + (s,\, c) + (s,\, b) + (c,\, d) + (c,\, u) + (c,\, s) + (c,\, c) + (c,\, b) + (b,\, d) + (b,\, u) + (b,\, s) + (b,\, c) + (b,\, b)$
8	50 60 102 113 137 147 157	$(d,\, \bar{d}) + (d,\, \bar{u}) + (d,\, \bar{s}) + (d,\, \bar{c}) + (d,\, \bar{b}) + (u,\, \bar{d}) + (u,\, \bar{u}) + (u,\, \bar{s}) + (u,\, \bar{c}) + (u,\, \bar{b}) + (s,\, \bar{d}) + (s,\, \bar{u}) + (s,\, \bar{s}) + (s,\, \bar{c}) + (s,\, \bar{b}) + (c,\, \bar{d}) + (c,\, \bar{u}) + (c,\, \bar{s}) + (c,\, \bar{c}) + (c,\, \bar{b}) + (b,\, \bar{d}) + (b,\, \bar{u}) + (b,\, \bar{s}) + (b,\, \bar{c}) + (b,\, \bar{b})$
9	54 64 103 114 142 152 162	$(\bar{d},\, d) + (\bar{d},\, u) + (\bar{d},\, s) + (\bar{d},\, c) + (\bar{d},\, b) + (\bar{u},\, d) + (\bar{u},\, u) + (\bar{u},\, s) + (\bar{u},\, c) + (\bar{u},\, b) + (\bar{s},\, d) + (\bar{s},\, u) + (\bar{s},\, s) + (\bar{s},\, c) + (\bar{s},\, b) + (\bar{c},\, d) + (\bar{c},\, u) + (\bar{c},\, s) + (\bar{c},\, c) + (\bar{c},\, b) + (\bar{b},\, d) + (\bar{b},\, u) + (\bar{b},\, s) + (\bar{b},\, c) + (\bar{b},\, b)$
10	55 65 104 115 141 151 161	$(\bar{d},\, \bar{d}) + (\bar{d},\, \bar{u}) + (\bar{d},\, \bar{s}) + (\bar{d},\, \bar{c}) + (\bar{d},\, \bar{b}) + (\bar{u},\, \bar{d}) + (\bar{u},\, \bar{u}) + (\bar{u},\, \bar{s}) + (\bar{u},\, \bar{c}) + (\bar{u},\, \bar{b}) + (\bar{s},\, \bar{d}) + (\bar{s},\, \bar{u}) + (\bar{s},\, \bar{s}) + (\bar{s},\, \bar{c}) + (\bar{s},\, \bar{b}) + (\bar{c},\, \bar{d}) + (\bar{c},\, \bar{u}) + (\bar{c},\, \bar{s}) + (\bar{c},\, \bar{c}) + (\bar{c},\, \bar{b}) + (\bar{b},\, \bar{d}) + (\bar{b},\, \bar{u}) + (\bar{b},\, \bar{s}) + (\bar{b},\, \bar{c}) + (\bar{b},\, \bar{b})$
11	69 77 168 176 184	$(d,\, d) + (u,\, u) + (s,\, s) + (c,\, c) + (b,\, b)$
12	73 81 170 178 186	$(\bar{d},\, \bar{d}) + (\bar{u},\, \bar{u}) + (\bar{s},\, \bar{s}) + (\bar{c},\, \bar{c}) + (\bar{b},\, \bar{b})$

Jet production

- Double virtual - 93 internal processes

0	270 279 288 301 312 323 336 347 358	(g, g)
1	271 280 289 299 310 321 337 348 359	$(g, d) + (g, u) + (g, s) + (g, c) + (g, b)$
2	272 281 290 302 313 324 338 349 360	$(g, \bar{d}) + (g, \bar{u}) + (g, \bar{s}) + (g, \bar{c}) + (g, \bar{b})$
3	273 282 291 304 315 326 331 342 353	$(d, d) + (d, u) + (d, s) + (d, c) + (d, b) + (u, d) + (u, u) + (u, s) + (u, c) + (u, b) +$ $(s, d) + (s, u) + (s, s) + (s, c) + (s, b) + (c, d) + (c, u) + (c, s) + (c, c) + (c, b) + (b, d) +$ $(b, u) + (b, s) + (b, c) + (b, b)$
4	274 283 292 305 316 327 330 341 352	$(d, \bar{d}) + (d, \bar{u}) + (d, \bar{s}) + (d, \bar{c}) + (d, \bar{b}) + (u, \bar{d}) + (u, \bar{u}) + (u, \bar{s}) + (u, \bar{c}) + (u, \bar{b}) +$ $(s, \bar{d}) + (s, \bar{u}) + (s, \bar{s}) + (s, \bar{c}) + (s, \bar{b}) + (c, \bar{d}) + (c, \bar{u}) + (c, \bar{s}) + (c, \bar{c}) + (c, \bar{b}) + (b, \bar{d}) +$ $(b, \bar{u}) + (b, \bar{s}) + (b, \bar{c}) + (b, \bar{b})$
5	275 284 293 297 308 319 339 350 361	$(d, g) + (u, g) + (s, g) + (c, g) + (b, g)$
6	276 285 294 306 317 328 335 346 357	$(\bar{d}, d) + (\bar{d}, u) + (\bar{d}, s) + (\bar{d}, c) + (\bar{d}, b) + (\bar{u}, d) + (\bar{u}, u) + (\bar{u}, s) + (\bar{u}, c) + (\bar{u}, b) +$ $(\bar{s}, d) + (\bar{s}, u) + (\bar{s}, s) + (\bar{s}, c) + (\bar{s}, b) + (\bar{c}, d) + (\bar{c}, u) + (\bar{c}, s) + (\bar{c}, c) + (\bar{c}, b) + (\bar{b}, d) +$ $(\bar{b}, u) + (\bar{b}, s) + (\bar{b}, c) + (\bar{b}, b)$
7	277 286 295 307 318 329 334 345 356	$(\bar{d}, \bar{d}) + (\bar{d}, \bar{u}) + (\bar{d}, \bar{s}) + (\bar{d}, \bar{c}) + (\bar{d}, \bar{b}) + (\bar{u}, \bar{d}) + (\bar{u}, \bar{u}) + (\bar{u}, \bar{s}) + (\bar{u}, \bar{c}) + (\bar{u}, \bar{b}) +$ $(\bar{s}, \bar{d}) + (\bar{s}, \bar{u}) + (\bar{s}, \bar{s}) + (\bar{s}, \bar{c}) + (\bar{s}, \bar{b}) + (\bar{c}, \bar{d}) + (\bar{c}, \bar{u}) + (\bar{c}, \bar{s}) + (\bar{c}, \bar{c}) + (\bar{c}, \bar{b}) + (\bar{b}, \bar{d}) +$ $(\bar{b}, \bar{u}) + (\bar{b}, \bar{s}) + (\bar{b}, \bar{c}) + (\bar{b}, \bar{b})$
8	278 287 296 303 314 325 340 351 362	$(\bar{d}, g) + (\bar{u}, g) + (\bar{s}, g) + (\bar{c}, g) + (\bar{b}, g)$
9	298 309 320 332 343 354	$(d, \bar{d}) + (u, \bar{u}) + (s, \bar{s}) + (c, \bar{c}) + (b, \bar{b})$
10	300 311 322 333 344 355	$(\bar{d}, d) + (\bar{u}, u) + (\bar{s}, s) + (\bar{c}, c) + (\bar{b}, b)$

- Real-virtual - 54 internal processes

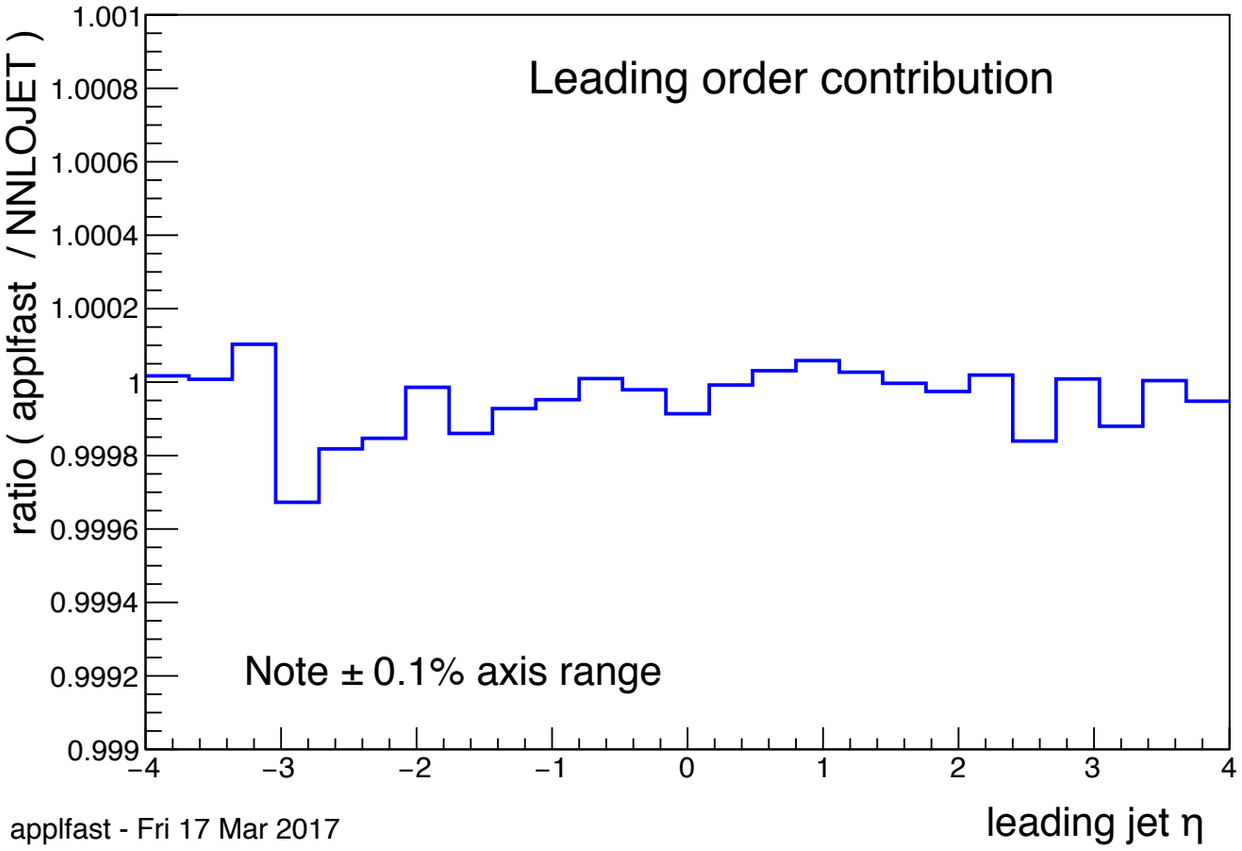
0	216 221 230 241 258 269	(g, g)
1	217 222 228 239 253 264	$(g, d) + (g, u) + (g, s) + (g, c) + (g, b)$
2	218 223 231 242 257 268	$(g, \bar{d}) + (g, \bar{u}) + (g, \bar{s}) + (g, \bar{c}) + (g, \bar{b})$
3	219 224 226 237 251 262	$(d, g) + (u, g) + (s, g) + (c, g) + (b, g)$
4	220 225 232 243 256 267	$(\bar{d}, g) + (\bar{u}, g) + (\bar{s}, g) + (\bar{c}, g) + (\bar{b}, g)$
5	227 238 248 259	$(d, \bar{d}) + (u, \bar{u}) + (s, \bar{s}) + (c, \bar{c}) + (b, \bar{b})$
6	229 240 252 263	$(\bar{d}, d) + (\bar{u}, u) + (\bar{s}, s) + (\bar{c}, c) + (\bar{b}, b)$
7	233 244 249 260	$(d, d) + (d, u) + (d, s) + (d, c) + (d, b) + (u, d) + (u, u) + (u, s) + (u, c) + (u, b) + (s, d) + (s, u) + (s, s) +$ $(s, c) + (s, b) + (c, d) + (c, u) + (c, s) + (c, c) + (c, b) + (b, d) + (b, u) + (b, s) + (b, c) + (b, b)$
8	234 245 250 261	$(d, \bar{d}) + (d, \bar{u}) + (d, \bar{s}) + (d, \bar{c}) + (d, \bar{b}) + (u, \bar{d}) + (u, \bar{u}) + (u, \bar{s}) + (u, \bar{c}) + (u, \bar{b}) + (s, \bar{d}) + (s, \bar{u}) + (s, \bar{s}) +$ $(s, \bar{c}) + (s, \bar{b}) + (c, \bar{d}) + (c, \bar{u}) + (c, \bar{s}) + (c, \bar{c}) + (c, \bar{b}) + (b, \bar{d}) + (b, \bar{u}) + (b, \bar{s}) + (b, \bar{c}) + (b, \bar{b})$
9	235 246 254 265	$(\bar{d}, d) + (\bar{d}, u) + (\bar{d}, s) + (\bar{d}, c) + (\bar{d}, b) + (\bar{u}, d) + (\bar{u}, u) + (\bar{u}, s) + (\bar{u}, c) + (\bar{u}, b) + (\bar{s}, d) + (\bar{s}, u) + (\bar{s}, s) +$ $(\bar{s}, c) + (\bar{s}, b) + (\bar{c}, d) + (\bar{c}, u) + (\bar{c}, s) + (\bar{c}, c) + (\bar{c}, b) + (\bar{b}, d) + (\bar{b}, u) + (\bar{b}, s) + (\bar{b}, c) + (\bar{b}, b)$
10	236 247 255 266	$(\bar{d}, \bar{d}) + (\bar{d}, \bar{u}) + (\bar{d}, \bar{s}) + (\bar{d}, \bar{c}) + (\bar{d}, \bar{b}) + (\bar{u}, \bar{d}) + (\bar{u}, \bar{u}) + (\bar{u}, \bar{s}) + (\bar{u}, \bar{c}) + (\bar{u}, \bar{b}) + (\bar{s}, \bar{d}) + (\bar{s}, \bar{u}) + (\bar{s}, \bar{s}) +$ $(\bar{s}, \bar{c}) + (\bar{s}, \bar{b}) + (\bar{c}, \bar{d}) + (\bar{c}, \bar{u}) + (\bar{c}, \bar{s}) + (\bar{c}, \bar{c}) + (\bar{c}, \bar{b}) + (\bar{b}, \bar{d}) + (\bar{b}, \bar{u}) + (\bar{b}, \bar{s}) + (\bar{b}, \bar{c}) + (\bar{b}, \bar{b})$

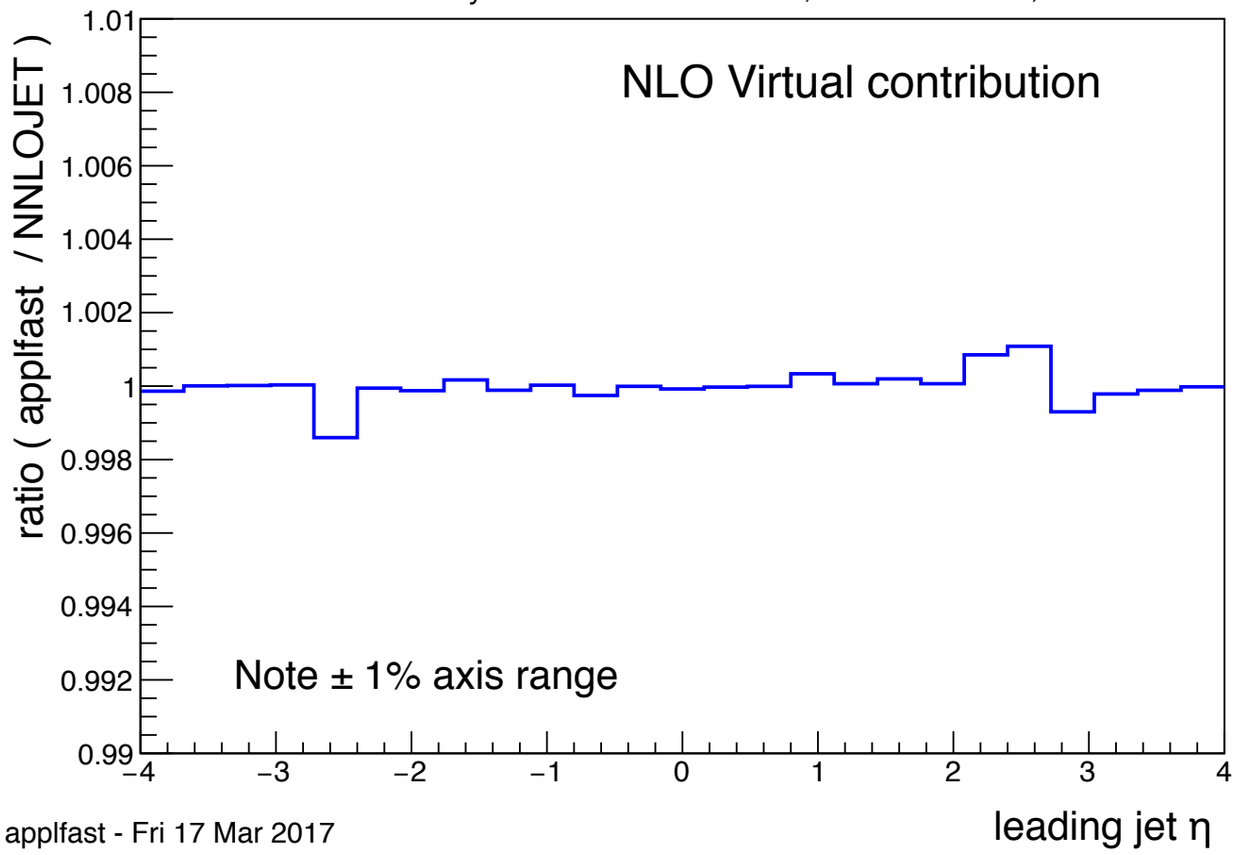
- Double real - 25 internal processes

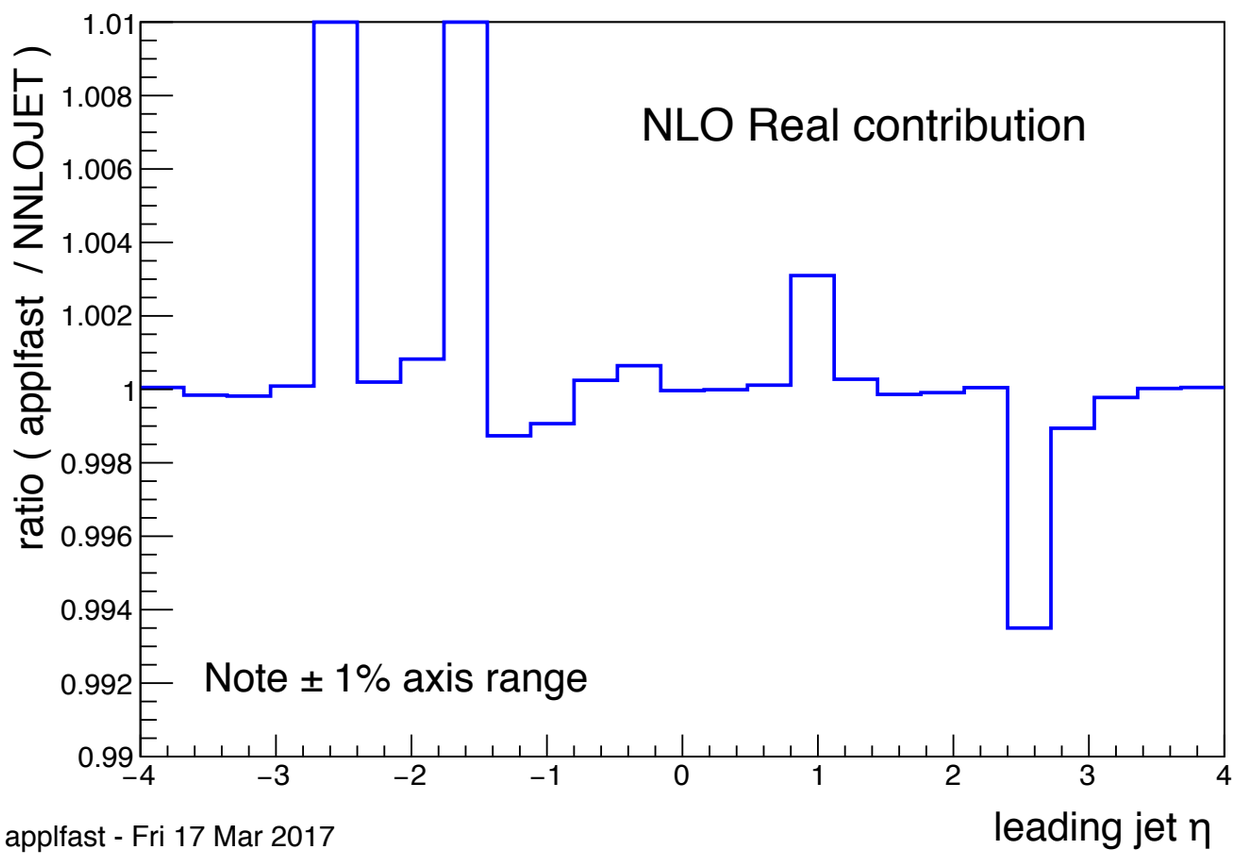
0	191 196 209	(g, g)
1	192 202	$(d, g) + (u, g) + (s, g) + (c, g) + (b, g)$
2	193 199 210	$(d, \bar{d}) + (u, \bar{u}) + (s, \bar{s}) + (c, \bar{c}) + (b, \bar{b})$
3	194 204	$(g, d) + (g, u) + (g, s) + (g, c) + (g, b)$
4	195 203 213	$(\bar{d}, d) + (\bar{u}, u) + (\bar{s}, s) + (\bar{c}, c) + (\bar{b}, b)$
5	197 208	$(g, \bar{d}) + (g, \bar{u}) + (g, \bar{s}) + (g, \bar{c}) + (g, \bar{b})$
6	198 207	$(\bar{d}, g) + (\bar{u}, g) + (\bar{s}, g) + (\bar{c}, g) + (\bar{b}, g)$
7	200 211	$(d, d) + (d, u) + (d, s) + (d, c) + (d, b) + (u, d) + (u, u) + (u, s) + (u, c) + (u, b) + (s, d) + (s, u) + (s, s) + (s, c) + (s, b) + (c, d) +$ $(c, u) + (c, s) + (c, c) + (c, b) + (b, d) + (b, u) + (b, s) + (b, c) + (b, b)$
8	201 212	$(d, \bar{d}) + (d, \bar{u}) + (d, \bar{s}) + (d, \bar{c}) + (d, \bar{b}) + (u, \bar{d}) + (u, \bar{u}) + (u, \bar{s}) + (u, \bar{c}) + (u, \bar{b}) + (s, \bar{d}) + (s, \bar{u}) + (s, \bar{s}) + (s, \bar{c}) + (s, \bar{b}) + (c, \bar{d}) +$ $(c, \bar{u}) + (c, \bar{s}) + (c, \bar{c}) + (c, \bar{b}) + (b, \bar{d}) + (b, \bar{u}) + (b, \bar{s}) + (b, \bar{c}) + (b, \bar{b})$
9	205 214	$(\bar{d}, d) + (\bar{d}, u) + (\bar{d}, s) + (\bar{d}, c) + (\bar{d}, b) + (\bar{u}, d) + (\bar{u}, u) + (\bar{u}, s) + (\bar{u}, c) + (\bar{u}, b) + (\bar{s}, d) + (\bar{s}, u) + (\bar{s}, s) + (\bar{s}, c) + (\bar{s}, b) + (\bar{c}, d) +$ $(\bar{c}, u) + (\bar{c}, s) + (\bar{c}, c) + (\bar{c}, b) + (\bar{b}, d) + (\bar{b}, u) + (\bar{b}, s) + (\bar{b}, c) + (\bar{b}, b)$
10	206 215	$(\bar{d}, \bar{d}) + (\bar{d}, \bar{u}) + (\bar{d}, \bar{s}) + (\bar{d}, \bar{c}) + (\bar{d}, \bar{b}) + (\bar{u}, \bar{d}) + (\bar{u}, \bar{u}) + (\bar{u}, \bar{s}) + (\bar{u}, \bar{c}) + (\bar{u}, \bar{b}) + (\bar{s}, \bar{d}) + (\bar{s}, \bar{u}) + (\bar{s}, \bar{s}) + (\bar{s}, \bar{c}) + (\bar{s}, \bar{b}) + (\bar{c}, \bar{d}) +$ $(\bar{c}, \bar{u}) + (\bar{c}, \bar{s}) + (\bar{c}, \bar{c}) + (\bar{c}, \bar{b}) + (\bar{b}, \bar{d}) + (\bar{b}, \bar{u}) + (\bar{b}, \bar{s}) + (\bar{b}, \bar{c}) + (\bar{b}, \bar{b})$

Inclusive jets at NLO

- Tests of grid closure of the NLO components
  - Only low statistics runs so far - completely consistent with NLO jet production from numerous sources
  - Even with short warmup, agreement generally better than 0.1%

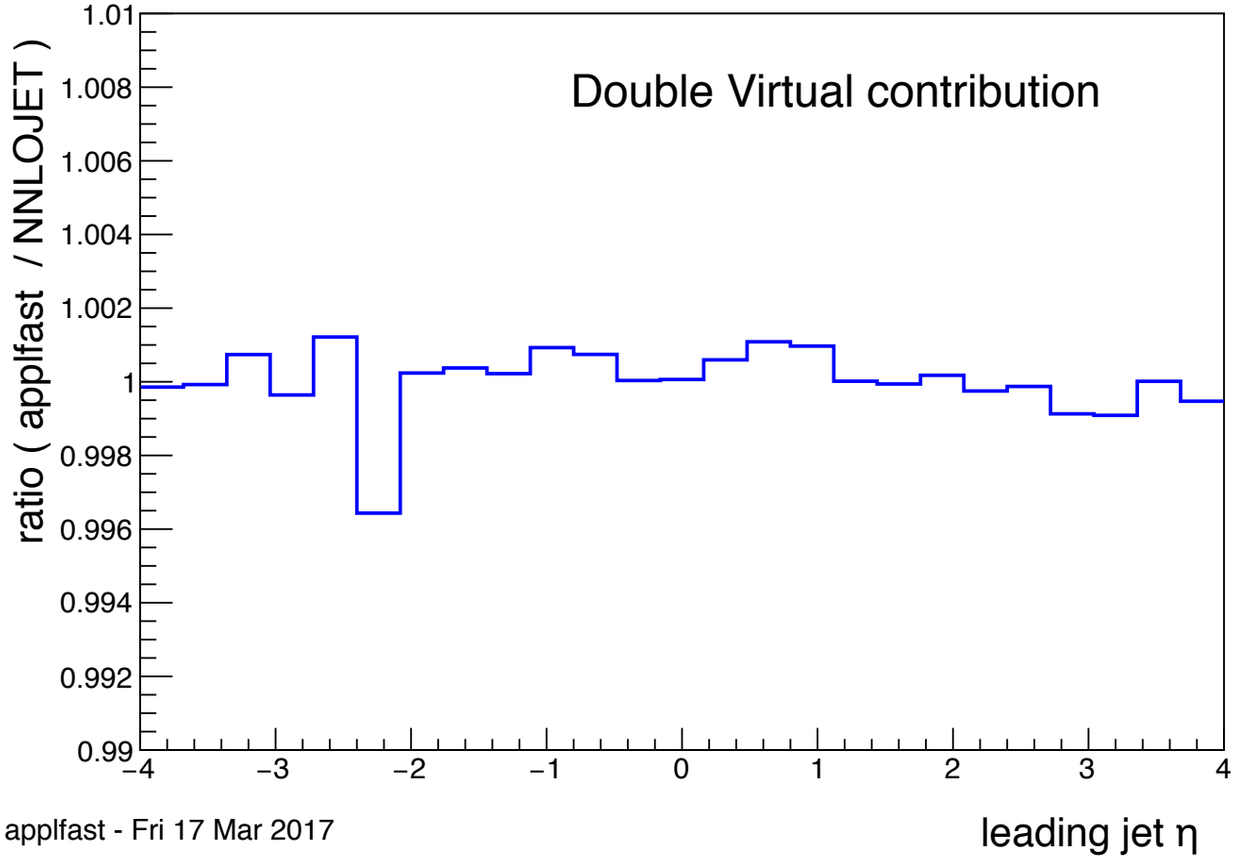


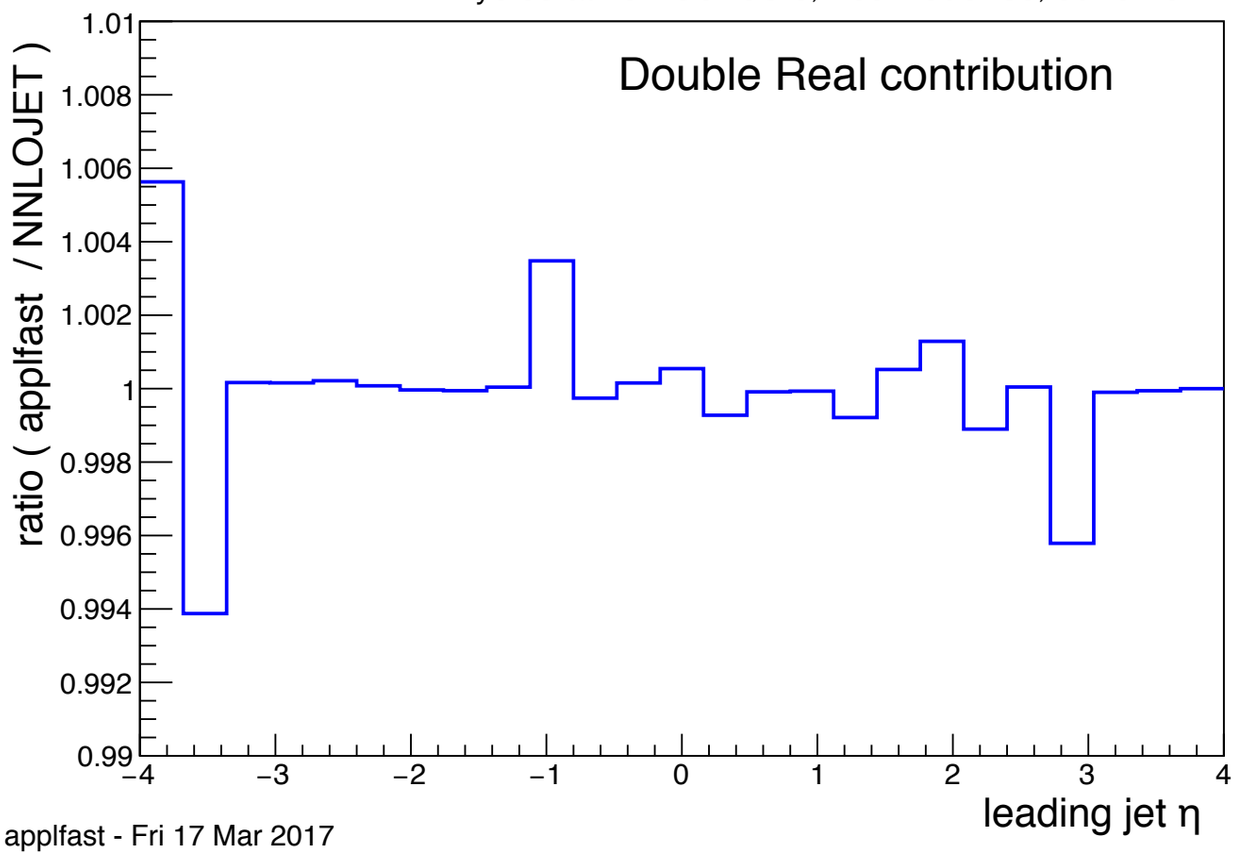


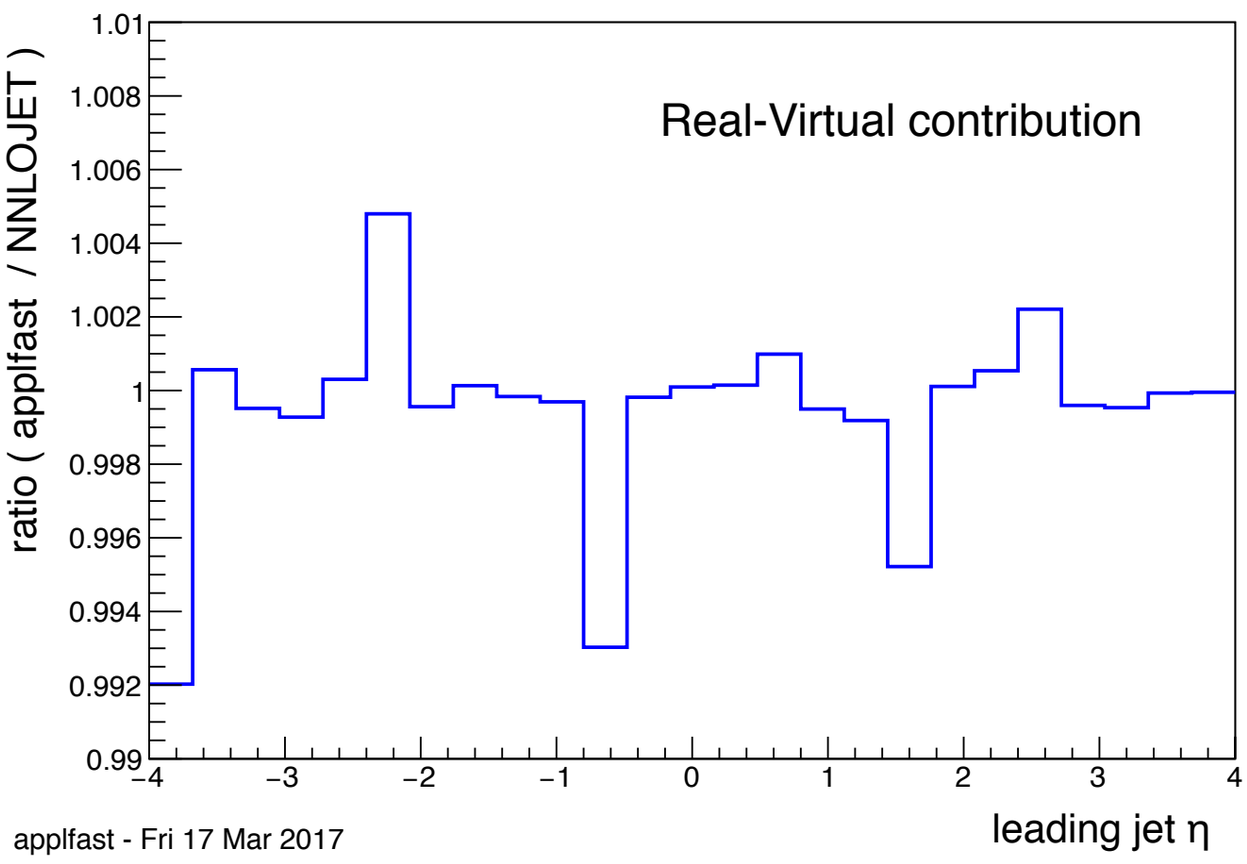


Inclusive jets at NNLO

- Similarly NNLO contributions also generally better than 0.1 %
  - Should improve with longer warmup
- Intend to start larger scale production in the near future







Grid and table distribution

- How do we make grids available ?
  - Currently general grids for specifc processes can be downloaded from the APPLgrid and fastNLO websites.
  - Other sites, such as the Spectrum web site collect grids
  - Many users generate their own grids
  - ATLAS, CMS, MMHT, NNPDF, CTEQ ….
- Getting grids for new processes, typically involves generating your own, or asking other people for the grids that they have produced
- How to find which grids are available ?
- Is there a better way ?

fastNLO

LHC: pp @ sqrt(s) = TeV	
fnl5332g_v23_fix_l1459051	CMS inclusive jets 2015 (anti-kT R=0.7; pT, y); LO, NLO, NP
fnl5362g_v23_fix_l1459051	CMS inclusive jets 2015 (anti-kT R=0.4; pT, y); LO, NLO, NP
	inSPIRE HepData RIVET_ID: Not yet available. Presumably: CMS_2016_I1459051
	Validation plots: fnl5332g NLO NLOxNP
	Validation plots: fnl5362g NLO NLOxNP
LHC: pp @ sqrt(s) = 2.76 TeV	
fnl4332_l1410826	CMS inclusive jets 2013 (anti-kT R=0.7; pT, y); LO, NLO
	inSPIRE HepData RIVET_ID: Not yet available. Presumably: CMS_2015_I1410826
	Validation plots: fnl4332 NLO
LHC: pp @ sqrt(s) = 8 TeV	
fnl3332_l1487277	CMS inclusive jets 2012 (anti-kT R=0.7; pT, |y| < 3.0); LO, NLO
fnl3232e_l1487277_v23_fix	CMS inclusive jets 2012 (anti-kT R=0.7; pT, 3.2 < |y| < 4.7); LO, NLO
	inSPIRE HepData not yet available. RIVET_ID: Not yet available. Presum
	Validation plots to come after HepData are available. fnl3332
	Validation plots to come after HepData are available. fnl3232e_l1487277_v2
LHC: pp @ sqrt(s) = 7 TeV	
fnl2332e_v23_fix_l1298810	CMS inclusive jets 2011 (anti-kT R=0.7; pT, y); LO, NLO, NP
fnl2342e_v23_fix_l1298810	CMS inclusive jets 2011 (anti-kT R=0.5; pT, y); LO, NLO, NP
	inSPIRE HepData RIVET_ID: CMS_2014_I1298810
	Validation plots: fnl2332e NLO NLOxNP NLOxNP(log x-axis)
	Validation plots: fnl2342e NLO NLOxNP NLOxNP(log x-axis)
fnl2732numa_l1230937	CMS 3-jet ratio 2011, numerator (anti-kT R=0.7; pT_1,2); LO, NLO
fnl2732dena_l1230937	CMS 3-jet ratio 2011, denominator (anti-kT R=0.7; pT_1,2); LO, NLO
	inSPIRE HepData no RIVET analysis available
fnl2332d_l1208923	CMS inclusive jets 2011 (anti-kT R=0.7; pT, y); LO, NLO
	inSPIRE HepData RIVET_ID: CMS_2013_I1208923
	Validation plots: fnl2332d NLO
fnl2412e_l1208923	CMS dijet mass 2011 (anti-kT R=0.7; Mjj, y_max); LO, NLO
	inSPIRE HepData RIVET_ID: CMS_2013_I1208923
fnl2622f_l1090423	CMS dijet angular 2011 (anti-kT R=0.5; Chi, Mjj); LO, NLO
	inSPIRE HepData RIVET_ID: CMS_2012_I1090423
	(Note: The data are normalized distributions, while the table produces unnor
fnl2222b_l1087342	CMS inclusive forward jets 2011 (anti-kT R=0.5; pT, eta); LO, NLO
	inSPIRE HepData RIVET_ID: CMS_2012_I1087342
	(Note: Unfortunately, the RIVET analysis mixes forward and forward+central analysis.)
fnl1016_l1082936	ATLAS inclusive jets 2010 (anti-kT R=0.4; pT, y); LO, NLO, THC-2loop
	inSPIRE HepData RIVET_ID: ATLAS_2012_I1082936
	(Note: Unfortunately, the RIVET analysis mixes all together, inclusive jets an into one analysis.)
fnl1015_l1082936	ATLAS inclusive jets 2010 (anti-kT R=0.6; pT, y); LO, NLO, THC-2loop
	inSPIRE HepData RIVET_ID: ATLAS_2012_I1082936
	(Note: Unfortunately, the RIVET analysis mixes all together, inclusive jets an into one analysis.)
fnl1014_l902309	CMS inclusive jets 2010 (anti-kT R=0.5; pT, y); LO, NLO, THC-2loop, NPC,
fnl1014_cv21_l902309	CMS inclusive jets 2010 (anti-kT R=0.5; pT, y); LO, NLO; NLOJet++-2.0.1 &
	inSPIRE HepData RIVET_ID: CMS_2011_S9086218
fnl2412c_l895742	CMS dijet mass 2010 (anti-kT R=0.7; pT, y_max)
	inSPIRE HepData no RIVET analysis available

APPLgrid

LHC: pp @ sqrt(s) = 2.76TeV

ATLAS inclusive jets (2011 data 0.2pb^{-1})
arXiv:1304.4739v1 Inclusive jets anti-kT: Tables 4-10 (R=0.4) and 11-17 (R=0.6)
hepdata
grid tarball contains
`atlas-incldijets-arxiv-1304.4739/r04/atlas-incljets-eta[1-7].root (R=0.4)`
`atlas-incldijets-arxiv-1304.4739/r06/atlas-incljets-eta[1-7].root (R=0.6)`

LHC: pp @ sqrt(s) = 7TeV

ATLAS inclusive jets (2010 data 17nb^{-1})
arXiv:1009.5908v2 Inclusive jets anti-kT: Tables 1-3 (R=0.4) and 4-6 (R=0.6)
hepdata
grid tarball contains
`atlas-incljets-arxiv-1009.5908v2/r04/atlas-incljets-eta[1-5].root (R=0.4)`
`atlas-incljets-arxiv-1009.5908v2/r06/atlas-incljets-eta[1-5].root (R=0.6)`

ATLAS inclusive jets (2010 data 37pb^{-1})
arXiv:1112.6297 Inclusive jets anti-kT: Tables 5-11 (R=0.4) and 12-18 (R=0.6)
hepdata
grid tarball contains
`atlas-incljets-arxiv-1112.6297/r04/atlas-incljets-eta[1-7].root (R=0.4)`
`atlas-incljets-arxiv-1112.6297/r06/atlas-incljets-eta[1-7].root (R=0.6)`

ATLAS inclusive dijets (2010 data 37pb^{-1})
arXiv:1112.6297 Inclusive dijets anti-kT: Tables 19-27 (R=0.4) and 28-36 (R=0.6)
hepdata
grid tarball contains
`atlas-incldijets-arxiv-1112.6297/r04/atlas-incldijets-eta[1-9].root (R=0.4)`
`atlas-incldijets-arxiv-1112.6297/r06/atlas-incldijets-eta[1-9].root (R=0.6)`

NB: the grids for the 3.0 < y* < 3.5 interval for both R=0.4 and R=0.6 are missing

ATLAS inclusive dijets (2011 data 4.5fb^{-1})
arXiv:1312.3524 Inclusive dijets anti-kT: Tables 4-9 (R=0.4) and 10-15 (R=0.6)
hepdata
grid tarball contains
`atlas-incldijets-arxiv-1312.3524/r04/atlas-incldijets-y[0-5].root (R=0.4)`
`atlas-incldijets-arxiv-1312.3524/r06/atlas-incldijets-y[0-5].root (R=0.6)`

NB: requires applgrid-1.4.56 or later.
The cross sections in the paper scale both the renormalisation and factorisation scales by an additional factor of exp(0.3*y*)

ATLAS inclusive jets (2011 data 4.5fb^{-1}) **NEW !!**
arXiv:1410.8857 Inclusive jets anti-kT: Tables 3-8 (R=0.4) and 9-14 (R=0.6)
hepdata
grid tarball contains
`atlas-incljets-arxiv-1410.8857/r04/atlas-incljets-y[0-5].root (R=0.4)`
`atlas-incljets-arxiv-1410.8857/r06/atlas-incljets-y[0-5].root (R=0.6)`

NB: requires applgrid-1.4.56 or later.

ATLAS W+, W- data (2010 data 35pb^{-1})
arXiv:1109.5141 W plus data, W minus data for the asymmetry, vs lepton rapidity: Tables 24 (W- -> l nubar) and 25 (W+ -> lbar nu)
hepdata
grid tarball contains
`atlas-Wpm-arxiv-1109.5141/Wplus/atlas-Wplus-rapidity.root`
`atlas-Wpm-arxiv-1109.5141/Wminus/atlas-Wminus-rapidity.root`

ATLAS Z0 data (2010 data 35pb^{-1})
arXiv:1109.5141 Z0 rapidity distribution: Table 23 (Z0 -> llbar)
hepdata
grid tarball contains
`atlas-Z0-arxiv-1109.5141/Z0/atlas-Z0-rapidity.root`

Yes there is …

- Have a new, broad agreement between members of the PDF fitting community to share grid and table resources
- Establishing a new package on hepforge
- Aim is ..
  - Users register to be allowed to upload to the upload directory of the package
  - Users **upload grids** and a **conrresponding standard configuration** file
  - Automatic program runs …
    - Reads in the configuration file
    - Renames grid files to standard form, stores in internal database
    - Updates database, book keeping, web pages

- Agnostic to **type of data** being managed - as long as the it conforms to the configuration information

- Grids can then be published, inspected or downloaded, automatically
  - Will at some point provide a lightweight user interface for the automated interaction with the package - should the final user not wish to access the information themselves

- A single access point for finding out which grids are available, and from which they can be obtained should make configuration of fitting (and other) jobs more straightforward

Technicalities and involvement

- So far we have agreement between
  - APPLgrid and fastNLO developers
  - CMS and ATLAS, H1
  - xFitter, CTEQ MMHT

- In addition we have agreement from HEPDATA that in principle a link, back to the relevant grids in the HEPDATA web page can be implemented
  - Should be possible to download the data set and the grids for the calculation from one place

- Iterating on the exact data and format needed for the grid configuration

Proof of concept table generation …

grid and table distribution

Test page for testing the grid table making tools

Available results

table generation proof of concept

atlas inclusive jets at 7 TeV - r06 - y4
arXiv:1410.8857 atlas inclusive jets at 7 TeV, full description with lots of information. can be spread over line
hepdata
grid tarball contains
atlas inclusive jets at 7 TeV - r06 - y3
arXiv:1410.8857 atlas inclusive jets at 7 TeV, full description with lots of information. can be spread over line
hepdata
grid tarball contains
atlas inclusive jets at 7 TeV - r06 - y2
arXiv:1410.8857 atlas inclusive jets at 7 TeV, full description with lots of information. can be spread over line
hepdata
grid tarball contains
atlas inclusive jets at 7 TeV - r06 - y1
arXiv:1410.8857 atlas inclusive jets at 7 TeV, full description with lots of information. can be spread over line
hepdata
grid tarball contains
atlas inclusive jets at 7 TeV - r06 - y0
arXiv:1410.8857 atlas inclusive jets at 7 TeV, full description with lots of information. can be spread over line
hepdata
grid tarball contains
atlas inclusive jets at 7 TeV - r04 - y2
arXiv:1410.8857 atlas inclusive jets at 7 TeV, full description with lots of information. can be spread over line
hepdata
grid tarball contains
atlas inclusive jets at 7 TeV - r04 - y1
arXiv:1410.8857 atlas inclusive jets at 7 TeV, full description with lots of information. can be spread over line
hepdata
grid tarball contains
atlas inclusive jets at 7 TeV - r04 - y0
arXiv:1410.8857 atlas inclusive jets at 7 TeV, full description with lots of information. can be spread over line
hepdata
grid tarball contains

Outlook

- The NNLOJET calculation for many processes is available …
  - Provides a common interface for multifarious physics processes - Inclusive Z production Z+jet, W inclusive, Inclusive Higgs production, DIS jets, multijets in e+e- …
- The APPLfast-NNLO proof of concept development is starting to mature tp a usable package
  - Proof of concept validated with common interface for both APPLgrid and fastNLO at LO, NLO and NNLO order for Z+jets, inclusive jets in pp and DIS etc …
- Large scale production launched for Z+jets in pp collisions, DIS jets
  - More processes currently under development: inclusive Z production, inclusive jets …
  - Working on completion of correct combination of large scale production results
- Looking forward to completion of the validation for many new NNLO grids to provide a veritable smörgåsbord of physics processes of the highest order.
- A new cross-comminuty project is being initiated to allow the more straightforward and direct sharing of grids and tables
- We gratefully acknowledge support from the IPPP Associateship program and from Baden-Württemberg HPC through the BwUniCluster and BwForCluster.