Interpolation grids in NNLO for DIS jets and determination of the strong coupling constant using inclusive jets

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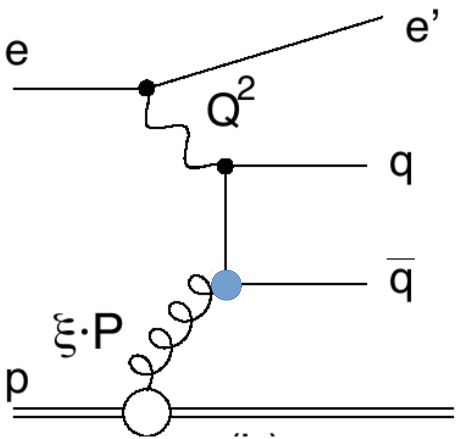
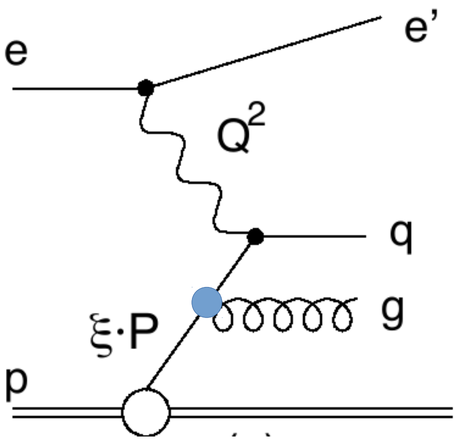
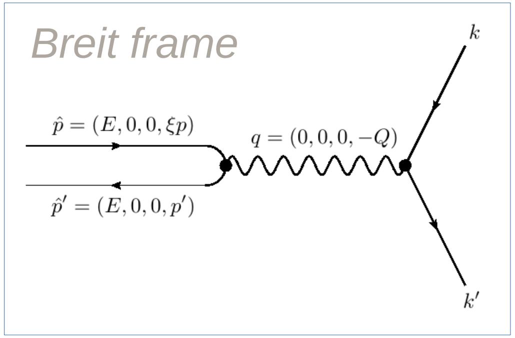
Jet production in DIS



Boson-gluon fusion



QCD Compton



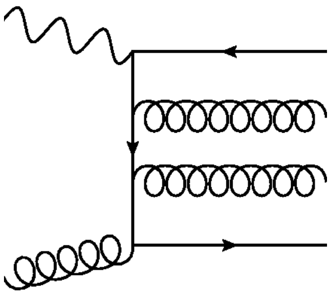
Jets in DIS measured in Breit frame

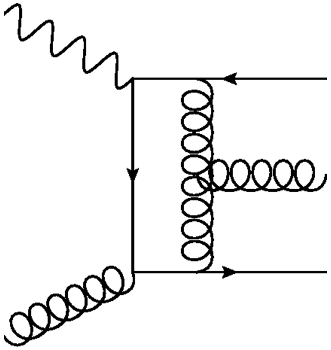
- Virtual boson collides 'head-on' with parton from proton: ep → 2 jets
- Boson-gluon fusion dominant process
  QCD compton important only for high-p_T jets (high-x)

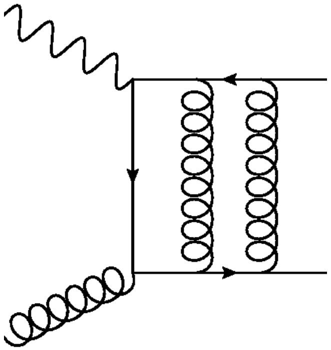
Jet measurements are sensitive to α_s and gluon density at LO
→ valuable phenomenological applications

DIS jet production in NNLO

J. Currie, et al. [RPL 117 (2016) 042001]
J. Currie, et al. [JHEP 1707 (2017) 018]


Double-real


Real-virtual


Double-virtual

A bit of history

- 1973 asymptotic freedom of QCD
  [PRL 30(1973) 1343 & 1346]
- 1993 NLO studies of DIS jet cross sections
  [Phys. Rev. D49 (1994) 3291]
- 2016 NNLO corrections for DIS jets
  [Phys. Rev. Lett. 117 (2016) 042001], [arXiv:1703.05977]

Antenna subtraction

- Cancellation of IR divergences with local subtraction terms
- Contributions for each order:
  LO = LO
  NLO = Real (R) + Virtual (V)
  NNLO = VV + RV + RRa + RRb

Jet production in DIS

NNLO predictions confronted with data

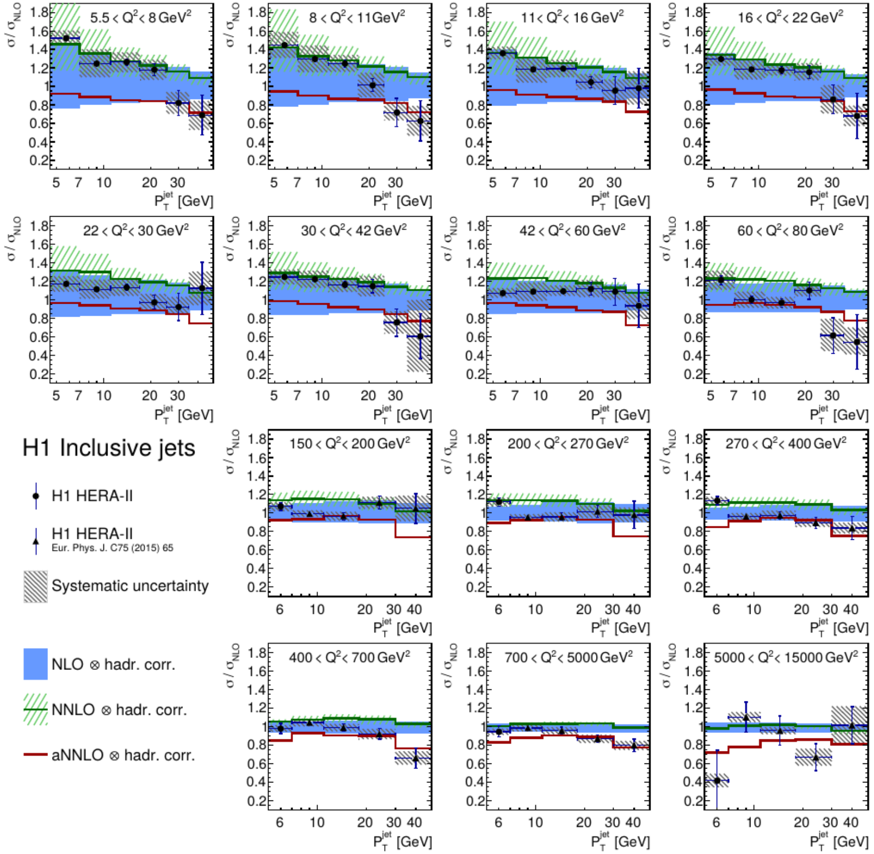
- NNLO proved to provide good description of HERA data over entire kinematic reach
- NNLO turns out to be crucial at lower scales (low Q^2, low p_T^{jet})
- Significant reduction of scale uncertainty w.r.t. NLO,
  particularly at higher scales

For phenomenological applications

- NNLO predictions must be repeated sufficiently fast, with differing paramters

→ Fast interpolation grids

Eur.Phys.J.C77 (2017) 4, 215

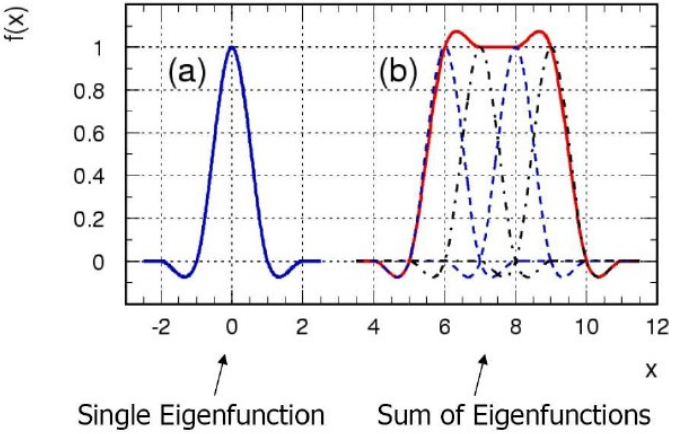


Technique of interpolation grids

Motivation

- phenomenological studies rely on sufficiently fast repetition of theoretical predictions

→ higher-order pQCD predictions: often 'slow'

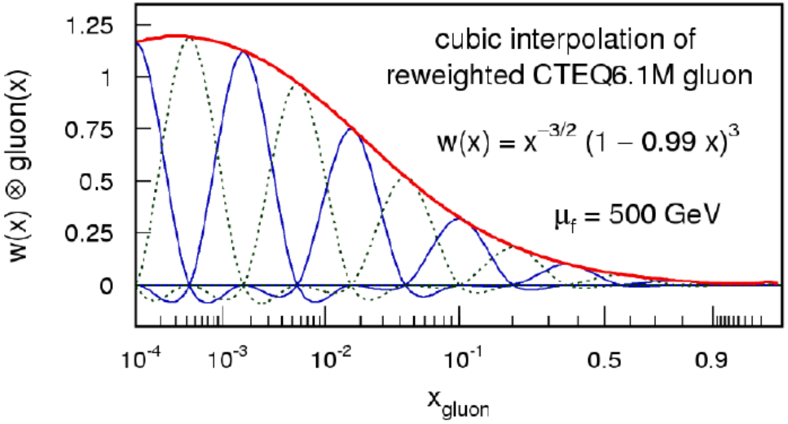


fastNLO and APPLgrid concept

- Introduce interpolation kernel (unit operator; lagrange polynomials):
  Set of functions f(x) around n discrete x-nodes
- Single PDF is replaced by set of interpolation kernels

$$f_a(x) \cong \sum_i f_a(x_i) \cdot E^{(i)}(x)$$

- Improve interpolation by reweighting PDF



Scale dependence

- Similar interpolation procedure also for scales
- Two approaches implemented
  'fixed scales': μ_R and μ_F are specified during grid generation
  'flexible scale':Coefficients are fully independent on μ_R and μ_F

Measurements under consideration

Inclusive jet and dijet cross section

- H1 & ZEUS

Data taking periods

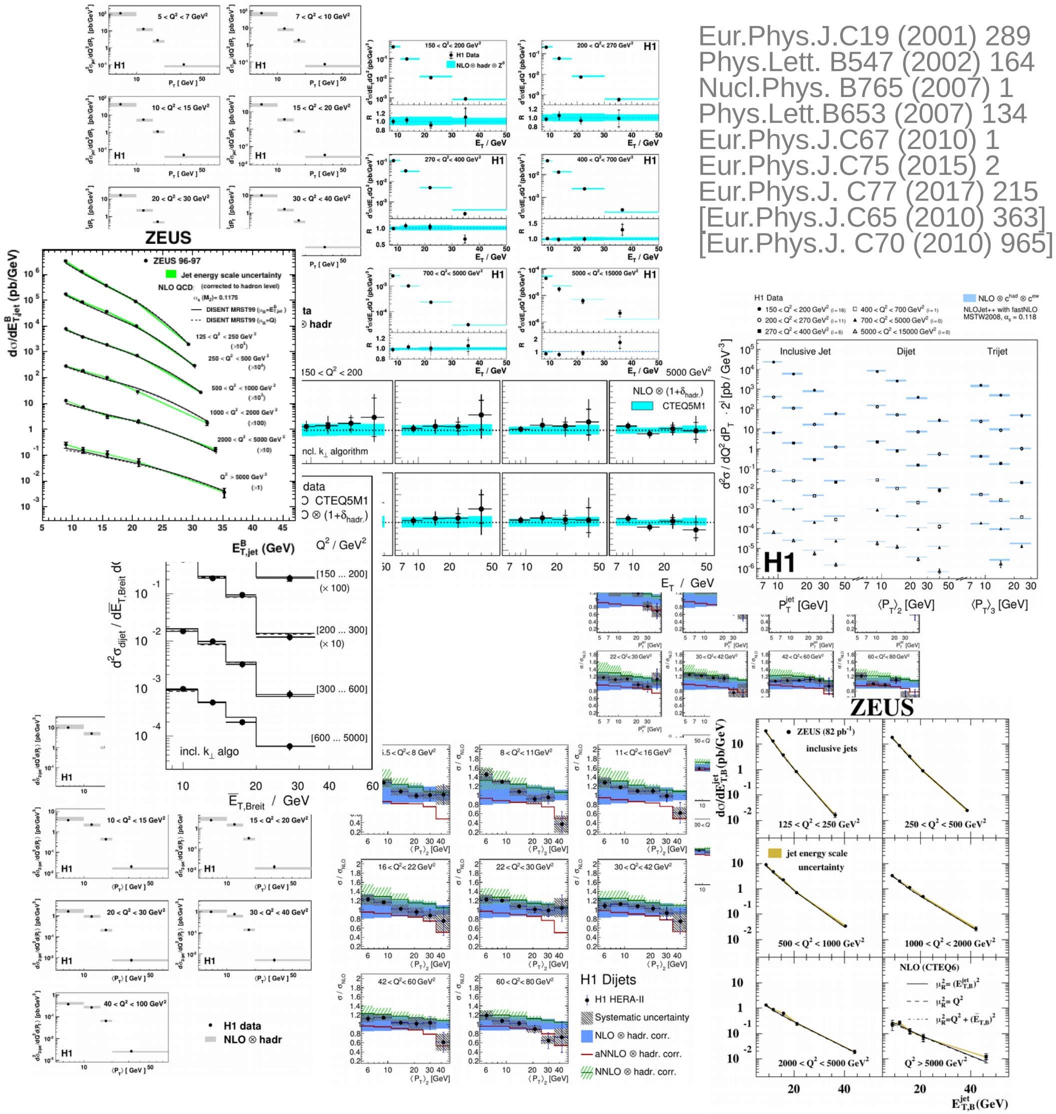
  - HERA-I (1996/97): $\sqrt{s} \sim 301$ GeV
  - HERA-I (1998/2000): $\sqrt{s} \sim 319$ GeV
  - HERA-II (2003/2007): $\sqrt{s} \sim 319$ GeV

Kinematic range(s)

  - low-Q^2 ($Q^2 < 100$ GeV^2)
  - high-Q^2 ($Q^2 > 100$ GeV^2)

Inclusive jets and dijet

  - jets: k_T-algo, R=1.0
  - 'all' inclusive jet data sets will be made available in NNLO
  - dijets: selection of data sets, because some dijet definitions are infrared sensitive in NNLO ($p_{T,min}^{jet1} = p_{T,min}^{jet2}$)



Eur.Phys.J.C19 (2001) 289
Phys.Lett. B547 (2002) 164
Nucl.Phys. B765 (2007) 1
Phys.Lett.B653 (2007) 134
Eur.Phys.J.C67 (2010) 1
Eur.Phys.J.C75 (2015) 2
Eur.Phys.J. C77 (2017) 215
[Eur.Phys.J.C65 (2010) 363]
[Eur.Phys.J. C70 (2010) 965]

Workflow for production of NNLO grids

1. Preprocessing:

- Check of interpolation quality
- Short test jobs to check interpolation settings (& optimise if necessary)

O(10 h)

2. NNLOJET Warm-up:

- Vegas integration optimisation
- 1 long (multi-core) job per process

O(100 h)

3. APPLgrid/fastNLO Warm-up:

- Adapt x- and scale-grids to accessed phase space
  (exact strategy differs between APPLgrid & fastNLO)
- Only phase space provided from NNLOJET → significant speed-up

O(100 h)

4. Interpolation grid production:

O(300k h)

- Thousands of parallel jobs

5. Postprocessing:

1) Statistical evaluation and combination of all single NNLOJET file — O(h)
2) Merge grid-files with weights from step 1) — O(50 h)
3) MergeJob to combine all grids and estimate statistical uncertainty — O(min)

6. Validate, validate, and validate

O(y)

Grid closure: dijet cross sections

- fastNLO grid vs. native NNLOJET run

Trade-off(s)

- accuracy vs. …

- file-size of grid(s)
- Memory consumption during production
- speed when evaluating grid
- functionality (scale choice)

→ flexible scale choice (p_T, Q^2)
→ Goal: closure better than 0.1%
0.1% is numerical precision of the data tables

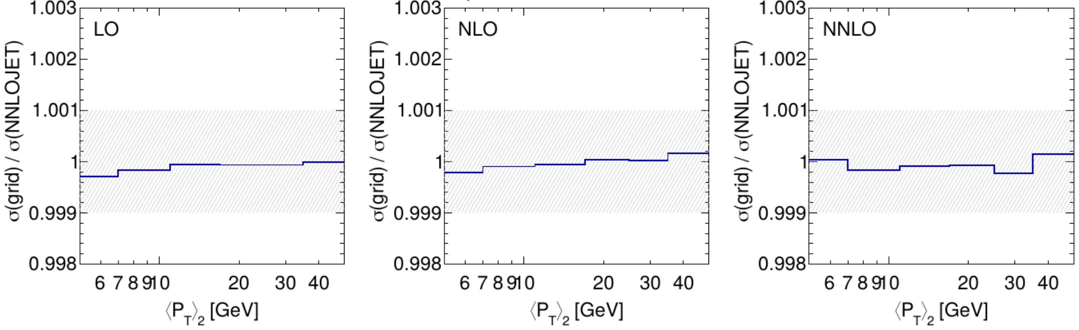
Closure

- significantly better than 0.1%
- LO, NLO look equivalent:
  Grid (mainly) reproduces stat. fluctuations
- at NNLO:
  due to imperfect closure (O(0.01%)) grid does not exactly look like (N)LO, but incorporates some stat. fluctuations
  → closure still < 0.1%
  → closes better with full statistics (up to x7800)

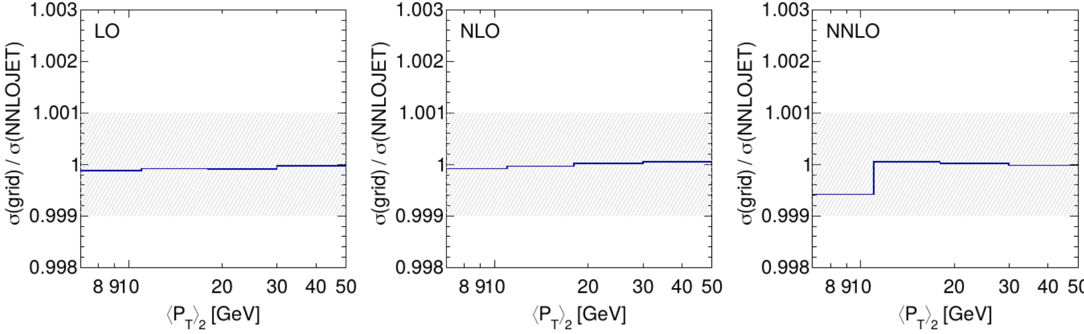
Dijet cross section: dσ/d<p_T>$_2$

- 'single run' for each contribution
  `NLO  = LO+V+R`
  `NNLO = LO+V+R+VV+RV+RRa+RRb`
  → limited statistics only!

Dijets, dσ/d<p_T>2 , 22 < Q^2 < 30 GeV²



Dijets, dσ/d<p_T>2 , 150 < Q^2 < 200 GeV²



Applgrid and fastNLO

New tool to convert

- fastNLO grids → Applgrid(s)
- Applgrid → fastNLO
- fastNLO → fastNLO
- Applgrid → Applgrid

Previous conversion tool

- based on numerical value of grid nodes

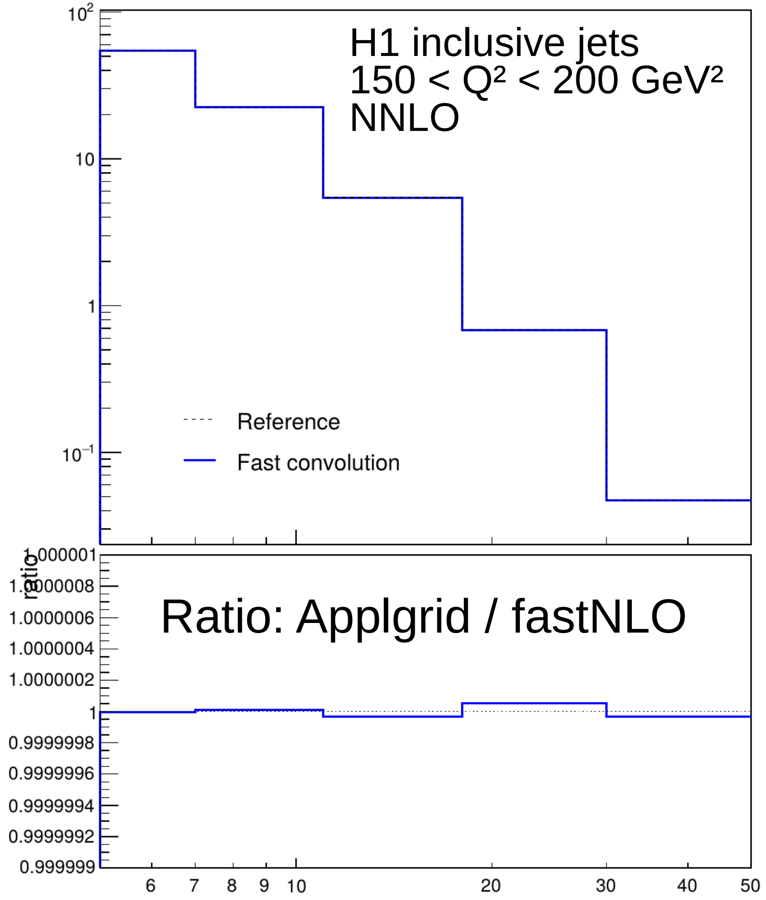
New conversion tool

- Use an existing grid as 'input generator' to a new one

→ perfect clousre, when 'input' and 'output' grid have equivalent node specifications

Many applications

- Conversions between formats
- Reduce file size and improved speed, by reducing functionality/accuracy
  → reduce grid accuracy (less nodes)
  → reduce functionality (fix scale settings)



First Applgrids in DIS

Inclusive jets I

Commonly, the calculation of single inclusive jet cross sections is technically more involved…

- Every single jet has to be counted,
  i.e. every 'event' may have multiple entries in the 'histogram'

- The scale settings:
  if a single jet-dependent quantity/observable shall be used as input to the scale calculation:
  e.g. p_T^{jet}, η^{jet}

  - Event kinematic, and measurement function, must be known prior to calculation of the amplitude

  - Every single phase space point has to be evaluated multiple times, but for different scale settings (e.g. p_T^{jet1}, p_T^{jet2}, ….)

→ ***Inclusive jets are often difficult to implement in generator codes***

Inclusive jets: scale settings

Exploit the scale structure of NNLO predictions

$$\omega = \omega_0 + \log(\mu_F^2)\,\omega_F + \log(\mu_R^2)\,\omega_R + \log^2(\mu_F^2)\,\omega_{FF} + \log^2(\mu_R^2)\,\omega_{RR} + \log(\mu_F^2)\log(\mu_R^2)\,\omega_{RF}$$

For a single phase-space point ('event')

- Calculate amplitude for 6 distinct choices for pairs of (μ_F,μ_R)
  These pairs can be constant, and fairly trivial,…

$$\begin{matrix} \omega_1(\mu_{F,1},\mu_{R,1}) \\ \omega_2(\mu_{F,2},\mu_{R,2}) \\ [...] \\ \omega_6(\mu_{F,6},\mu_{R,6}) \end{matrix} \quad \text{using} \quad \begin{matrix} (\mu_{F,1},\mu_{R,1}) = (e,e) \\ (\mu_{F,2},\mu_{R,2}) = (e^{2,}e) \\ [...] \\ (\mu_{F,6},\mu_{R,6}) = (..,..) \end{matrix} \quad \text{solve:} \quad \begin{pmatrix} \omega_0 \\ \omega_F \\ \omega_R \\ \omega_{FF} \\ \omega_{RR} \\ \omega_{RF} \end{pmatrix} = A^{-1} \begin{pmatrix} \omega_1 \\ \omega_2 \\ \omega_3 \\ \omega_4 \\ \omega_5 \\ \omega_6 \end{pmatrix}$$

- This defines a 6x6 system of linear equations, which is solved by a (constant) inverse matrix

→ This provides the values of ω_0, ω_F, …, ω_{RF}

Once, the parameters ω_0, ω_F, …, ω_{RF} are known...

- the amplitude can be re-evaluated trivially
- scale variations become compuational cheap
- jet observables (e.g. p_T^{jet}) can easily be employed for the scales

- For the grids, the weights ω_0, ω_F, …, ω_{RF} are stored separately in the grids (for later evaluation)

Application I:
Scale dependence of NNLO cross sections

Simultaneous variation of μ_R and μ_F

At lower scales

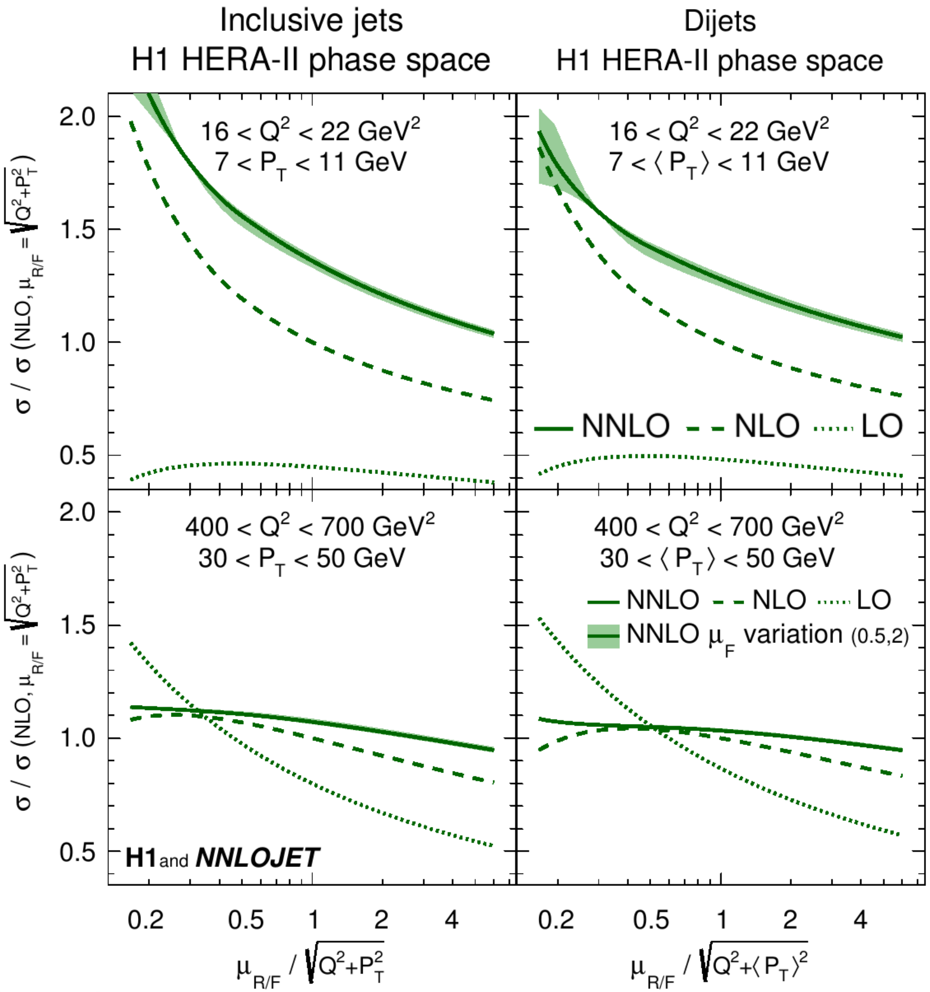
- Significant NNLO k-factors
- NNLO with reduced scale dependence
- Inclusive jets have somewaht higher scale-dependence than dijets

At higher scales

- NNLO with reduced scale dependence

More grid feautures (hot shown)

- PDF choices, PDF uncertainties
- scale choices



EPJ C77 (2017) 791

Application: α_s determination

Determination of αs(MZ) from inclusive jets at HERA

- Exploit all H1 and ZEUS inclusive jet cross section data

χ_2-minimisation

- $\alpha_s(m_Z)$ is a free parameter to NNLO theory prediction σ_i

$$\chi^2 = \sum_{i,j} \log \frac{\varsigma_i}{\sigma_i} (V_{\mathrm{exp}} + V_{\mathrm{had}} + V_{\mathrm{PDF}})^{-1}_{ij} \log \frac{\varsigma_j}{\sigma_j}$$

ς_i	jet data
σ_i	NNLO theory
V	covariance matrices

- NNLO theory is sensitive to $\alpha_s(m_Z)$
- Methodology equivalent to Eur.Phys.J.C77 (2017), 791

Perform fits to

- All <u>inclusive jet data</u> sets from H1 and ZEUS

Determination of $\alpha_s(m_Z)$

Value of $\alpha_s(m_Z)$ from HERA inclusive jet data

H1 inclusive jet cross sections

- See: Eur.Phys.J.C77 (2017) 791

ZEUS inclusive jet cross section

- New!
- Inclusive jets, HERA-I, 1996/97

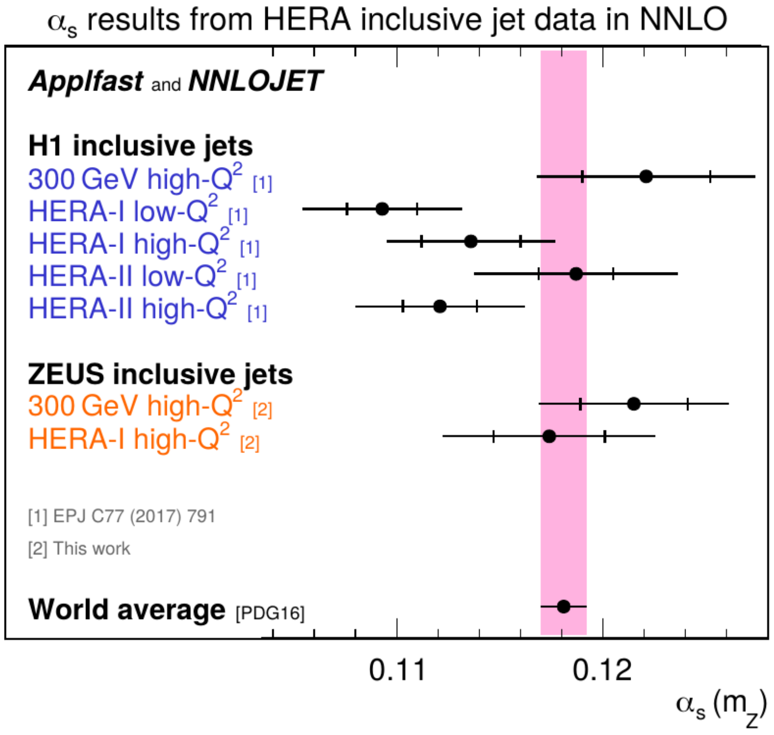
$$0.1213\,(28)_{\rm exp}\,(3)_{\rm had}\,(5)_{\rm PDF}\,(2)_{{\rm PDF}\alpha_s}\,(3)_{\rm PDFset}\,(26)_{\rm scale}$$

- Inclusive jets, HERA-I, 1998-2000

$$0.1181\,(27)_{\rm exp}\,(16)_{\rm had}\,(6)_{\rm PDF}\,(2)_{{\rm PDF}\alpha_s}\,(6)_{\rm PDFset}\,(25)_{\rm scale}$$

ZEUS data are well described by NNLO predictions

- [96/97] χ^2/ndf = 28.6/29
- [98/00] χ^2/ndf = 20.8/29



Determination of $\alpha_s(m_Z)$

Multiple data sets taken together
All H1 data sets

- See: Eur.Phys.J.C77 (2017) 791

Both ZEUS data sets taken together

$$0.1199\,(20)_{\rm exp}\,(8)_{\rm had}\,(6)_{\rm PDF}\,(1)_{{\rm PDF}\alpha_s}\,(5)_{\rm PDFset}\,(26)_{\rm scale}$$

All HERA inclusive jet cross sections

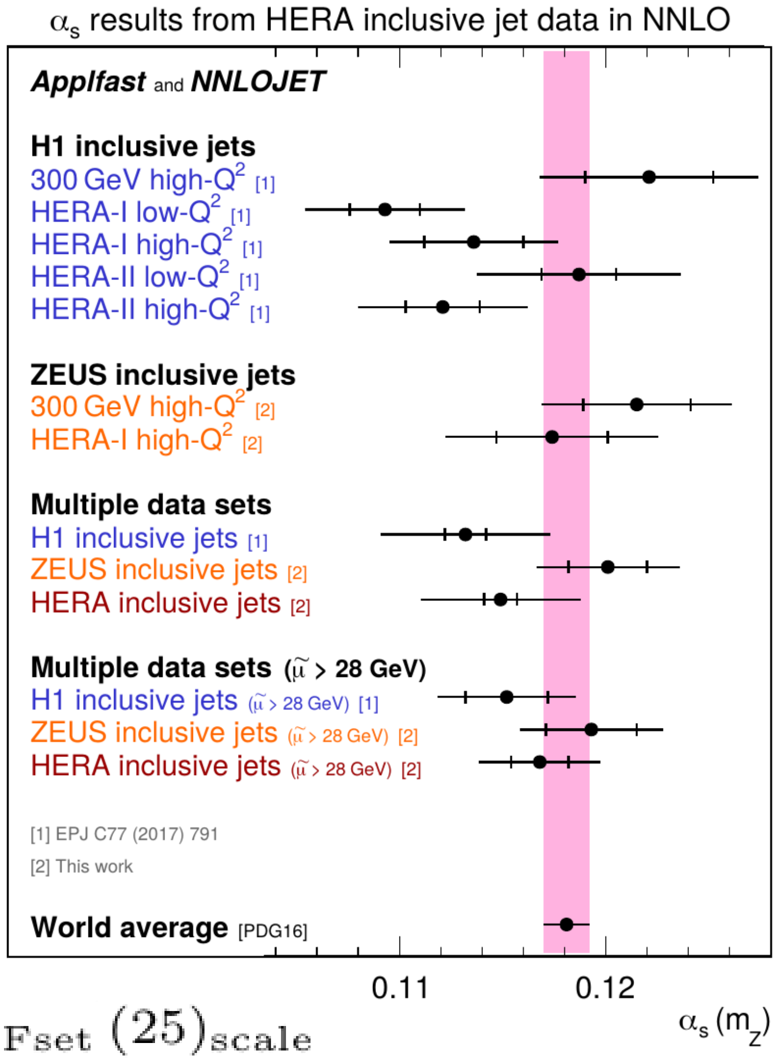
- H1 & ZEUS taken together in a single fit
  consistent jet definition (k_T-jets, R=1)

$$0.1148\,(9)_{\rm exp}\,(5)_{\rm had}\,(4)_{\rm PDF}\,(3)_{{\rm PDF}\alpha_s}\,(2)_{\rm PDFset}\,(38)_{\rm scale}$$

- Excellent description of all inclusive jet data:
  $\chi^2/\mathrm{ndf} = 191.3/193$

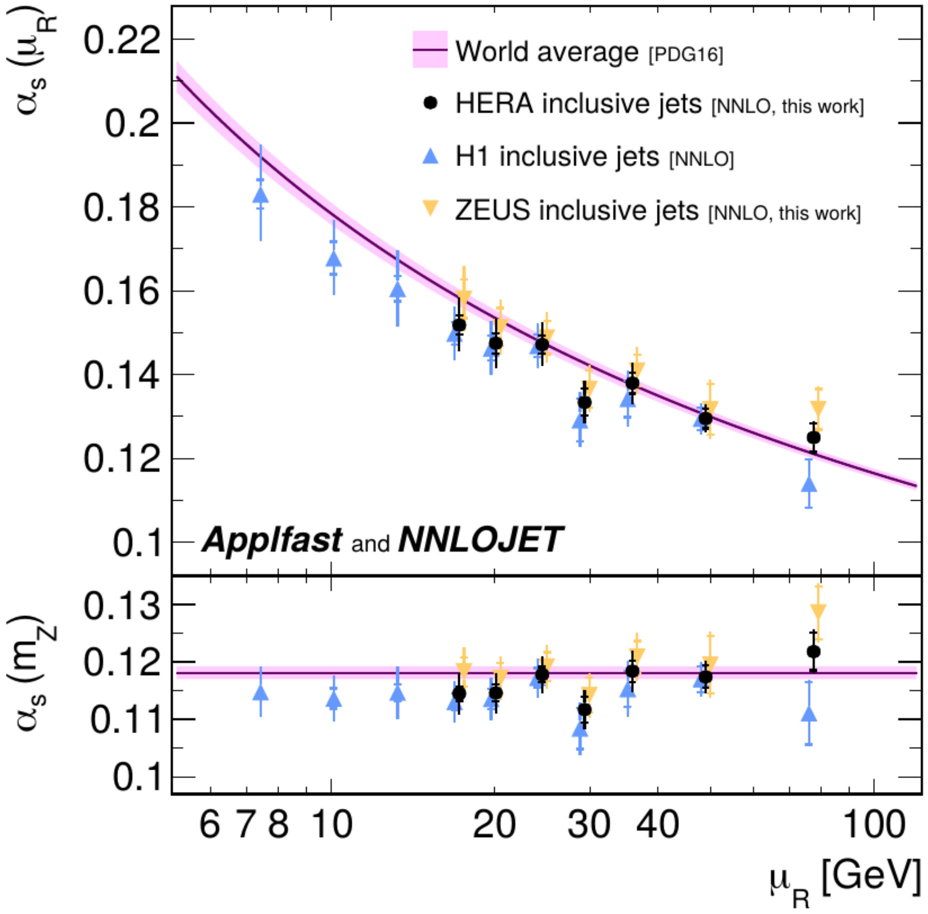
→ High experimental precision.
→ moderate (NNLO) scale uncertainty

- Reduction of scale uncertainty 'achieved' by cutting data a low scales (μ<28GeV)



$$0.1169\,(14)_{\rm exp}\,(7)_{\rm had}\,(3)_{\rm PDF}\,(2)_{{\rm PDF}\alpha_s}\,(3)_{\rm PDFset}\,(25)_{\rm scale}$$

Scale dependence of strong coupling



Determination of α_s at different scales

- Data points are grouped according to their values of μ_R

Results

- all H1 data: EPJ C77 (2017) 791
- all ZEUS data (new)
  approx: $15 < \mu_R < 90$ GeV
  → results consistent with expectation(s)
- H1 and ZEUS well consistent within exp. uncertainty
- HERA (i.e. H1&ZEUS, new)

  → highest precision using a single observable only
  → consistent with expectation

Grid distribution

Grids will be mad publically available

- Dedicated website was set up

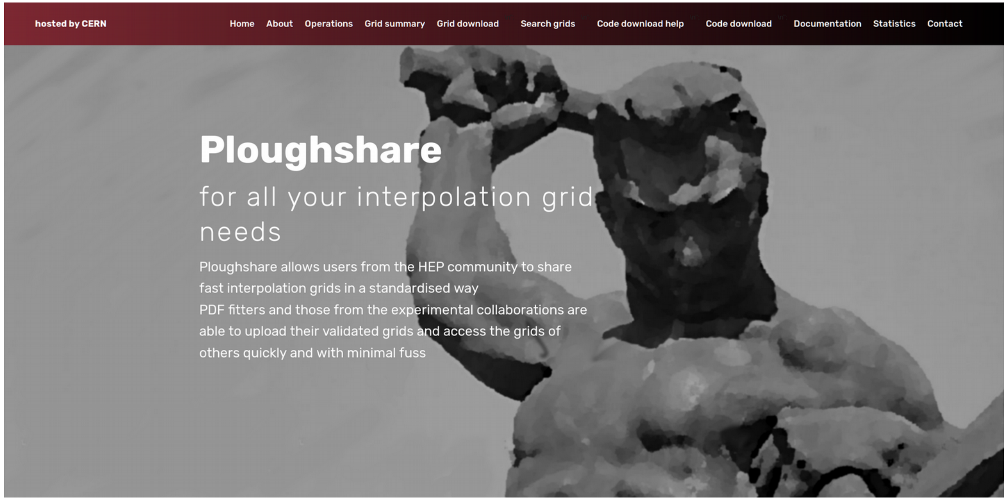
  ploughshare.web.cern.ch

- Inclusive jet and dijet grids
- H1 & ZEUS

- grids in fastNLO format with flexible scale choice

- Also Applgrid files will become available applgrid's are converted fastNLO grids

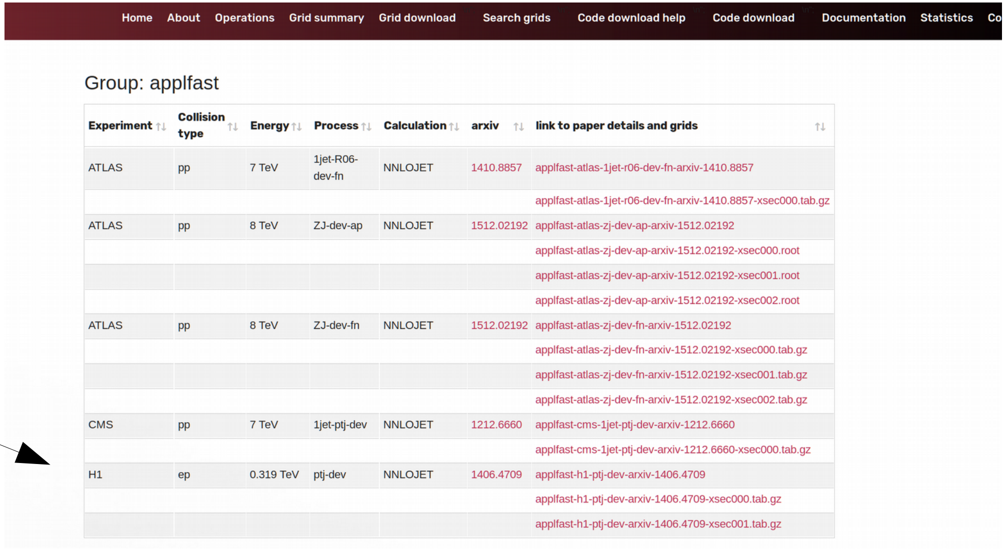
- First grids for testing purposes have already been made public



Ploughshare

for all your interpolation grid needs

Ploughshare allows users from the HEP community to share fast interpolation grids in a standardised way
PDF fitters and those from the experimental collaborations are able to upload their validated grids and access the grids of others quickly and with minimal fuss



Group: applfast

Experiment	Collision type	Energy	Process	Calculation	arxiv	link to paper details and grids
ATLAS	pp	7 TeV	1jet-R06-dev-fn	NNLOJET	1410.8857	applfast-atlas-1jet-r06-dev-fn-arxiv-1410.8857
						applfast-atlas-1jet-r06-dev-fn-arxiv-1410.8857-xsec000.tab.gz
ATLAS	pp	8 TeV	ZJ-dev-ap	NNLOJET	1512.02192	applfast-atlas-zj-dev-ap-arxiv-1512.02192
						applfast-atlas-zj-dev-ap-arxiv-1512.02192-xsec000.root
						applfast-atlas-zj-dev-ap-arxiv-1512.02192-xsec001.root
						applfast-atlas-zj-dev-ap-arxiv-1512.02192-xsec002.root
ATLAS	pp	8 TeV	ZJ-dev-fn	NNLOJET	1512.02192	applfast-atlas-zj-dev-fn-arxiv-1512.02192
						applfast-atlas-zj-dev-fn-arxiv-1512.02192-xsec000.tab.gz
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						applfast-atlas-zj-dev-fn-arxiv-1512.02192-xsec002.tab.gz
CMS	pp	7 TeV	1jet-ptj-dev	NNLOJET	1212.6660	applfast-cms-1jet-ptj-dev-arxiv-1212.6660
						applfast-cms-1jet-ptj-dev-arxiv-1212.6660-xsec000.tab.gz
H1	ep	0.319 TeV	ptj-dev	NNLOJET	1406.4709	applfast-h1-ptj-dev-arxiv-1406.4709
						applfast-h1-ptj-dev-arxiv-1406.4709-xsec000.tab.gz
						applfast-h1-ptj-dev-arxiv-1406.4709-xsec001.tab.gz

Summary

Interpolation grids for DIS jets have been calculated using NNLOJET

- All HERA running periods: 820GeV, HERA-I, HERA-II
- H1 and ZEUS measurements
- Inclusive jet and dijet cross sections
- low-Q^2 and high-Q^2 kinematic regions

Grid features

- flexible scale choice (Q^2, pTjet, <pT>)
- High numerical accuracy, at moderate file sizes and fast convolution speed
- O(1M) CPU hours have been spent

Grids are made publically available on ploughshare.web.cern.ch

H1 grids have been used in EPJ C77 (2017) 791
ZEUS grids have now been exploited for α_s determination

Strong coupling from all of HERA inclusive jet data

$$\alpha_s(m_Z) = 0.1169\ (14)_{\mathrm{exp}}\ (25)_{\mathrm{scale}}$$