

Application of the APPLfast grid interface to NNLOJET and determination of α_s at NNLO from DIS jet cross sections

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A. Huss (CERN), K. Rabbertz (KIT), M. Sutton (Sussex)



- Interpretation of experimental data requires reasonably fast theory
- Often: Repeated computation of same cross section:
 - ➔ Different PDF sets; PDF uncertainties
 - ➔ Variations of renormalisation & factorisation scales μ_R, μ_F
 - ➔ Variation of $\alpha_s(M_Z)$
 - ➔ SM parameter fits (→ e.g. with xFitter, see talk by C. Gwenlan)
- Jet cross section calculations at NLO were slow
 - ➔ Initial reason for interpolation grids
- Nowadays NNLO in general very demanding!
 - ➔ More than ever need fast re-evaluations of higher order cross sections for varied input parameters
 - ➔ Use interpolation grids like from APPLgrid or fastNLO

APPLgrid, Carli et al., Eur. Phys. J. C, 2010, 66, 503.
fastNLO, Britzger et al., arXiv:1208.3641.



What is APPLfast?

- Started as joint project of NNLOJET, APPLgrid, and fastNLO authors at QCD@LHC in London, 2015



- Developed common interface between NNLOJET and fast interpolation grid technology

➔ The least obtrusive as possible for NNLOJET

➔ No grids → no timing penalty

➔ As similar as possible for APPLgrid & fastNLO

➔ Simpler maintenance

➔ Usable from other theory programs



X. Chen, J. Cruz-Martinez, J. Currie, R. Gauld, A. Gehrmann-De Ridder, T. Gehrmann, E.W.N. Glover, A. Huss, I. Majer, T. Morgan, J. Niehuis, J. Pires, D. Walker

Common framework for NNLO corrections using antenna subtraction

Characteristics:

- Parton-level event generator
- Based on antenna subtraction
- Test & validation framework
- Interface to APPLfast

Processes:

- ▶ $pp \rightarrow (Z \rightarrow \ell^+ \ell^-) + 0, 1 \text{ jets}$
- ▶ $pp \rightarrow (W^\pm \rightarrow \ell \nu) + 0, 1 \text{ jets}$
- ▶ $pp \rightarrow H + 0, 1 \text{ jets, VBF}$
 $\hookrightarrow \gamma\gamma, \ell^+ \ell^- \gamma, 4\ell, \dots$
- ▶ $pp \rightarrow \text{dijets}$
- ▶ $ep \rightarrow 1, 2 \text{ jets}$
- ▶ $e^+ e^- \rightarrow 3 \text{ jets}$
- ▶ ...

A. Gehrmann-De Ridder, T. Gehrmann, N. Glover, A. Huss, T. Morgan,
PoS RADCOR2015 (2016) 075, arXiv: 1601.04569.



Interpolation concept

Implemented in APPLgrid & fastNLO

Use interpolation kernel

- Introduce set of n discrete **x-nodes**, x_i 's being equidistant in a function $f(x)$
- Take set of **Eigenfunctions** $E_i(x)$ around nodes x_i

→ Interpolation kernels

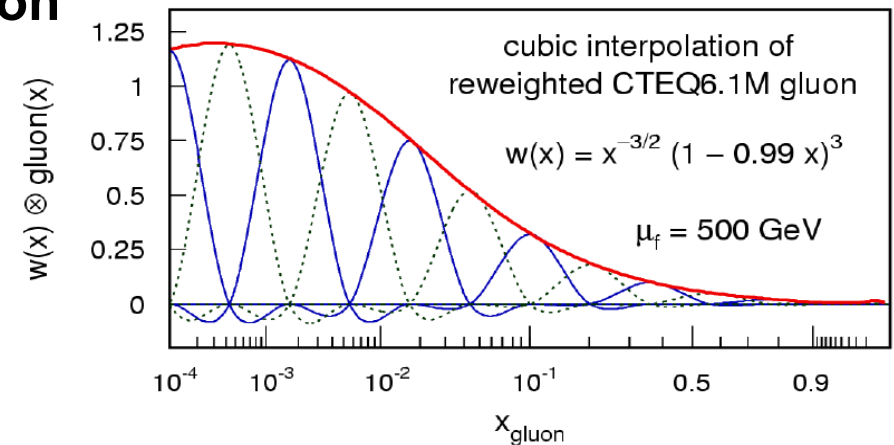
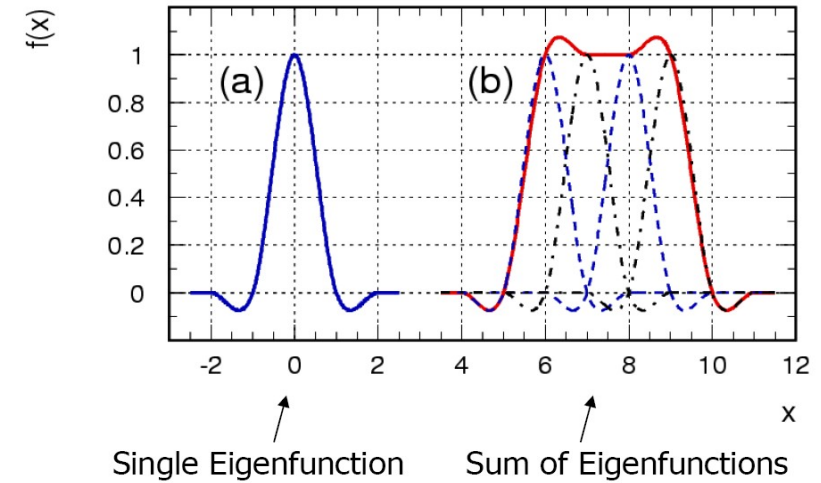
- Actually a rather old idea, see e.g.

C. Pascaud, F. Zomer (Orsay, LAL), LAL-94-42

→ Single PDF is replaced by a linear combination of interpolation kernels

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

- Then the integrals are done only once
- Afterwards only summation required to change PDF



Tabulate the convolution of the perturbative coefficients with the interpolation kernel

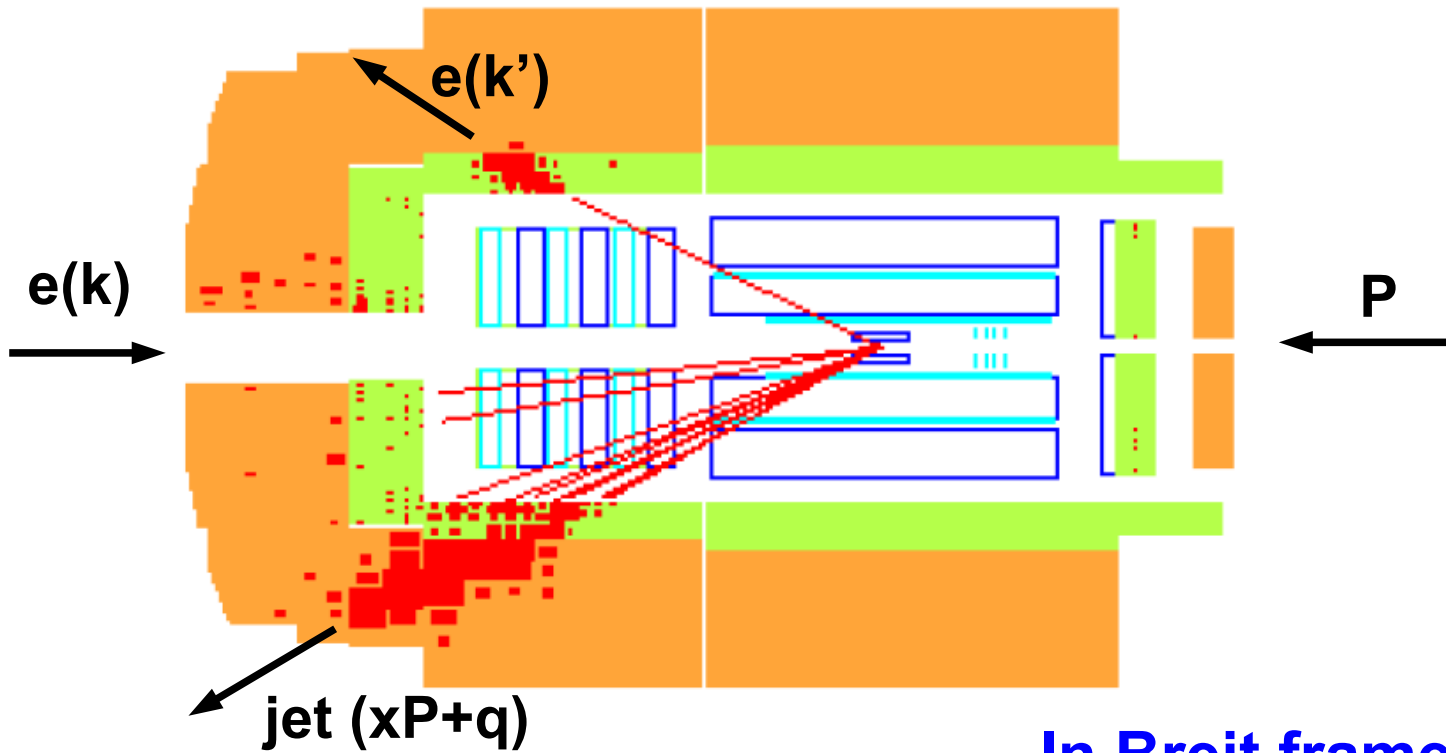


- **1. Preprocessing: Check of interpolation quality**
 - ➔ Short test jobs to check interpolation settings (& optimise if necessary) $O(10 \text{ h})$
- **2. NNLOJET Warm-up: Vegas integration optimisation**
 - ➔ 1 long (multi-core) job per process $O(100 \text{ h})$
- **3. APPLgrid/fastNLO Warm-up: Adapt x- and scale-grids to accessed phase space (exact strategy differs between APPLgrid & fastNLO)**
 - ➔ Only phase space provided from NNLOJET → significant speed-up $O(100 \text{ h})$
- **4. Interpolation grid production:**
 - ➔ Thousands of parallel jobs $O(250 \text{ kh})$
- **5. Postprocessing: Statistical evaluation and combination of all produced grids ...**
 - ➔ Job to combine all grids and estimate statistical uncertainty $O(100 \text{ h})$
- **6. Validate, validate, and validate** $O(? \text{ h})$
- **7. Present final results :-)** 30 min :-)



Application to DIS jets

DIS event in H1 detector



DIS kinematics

$$Q^2 = -q^2$$

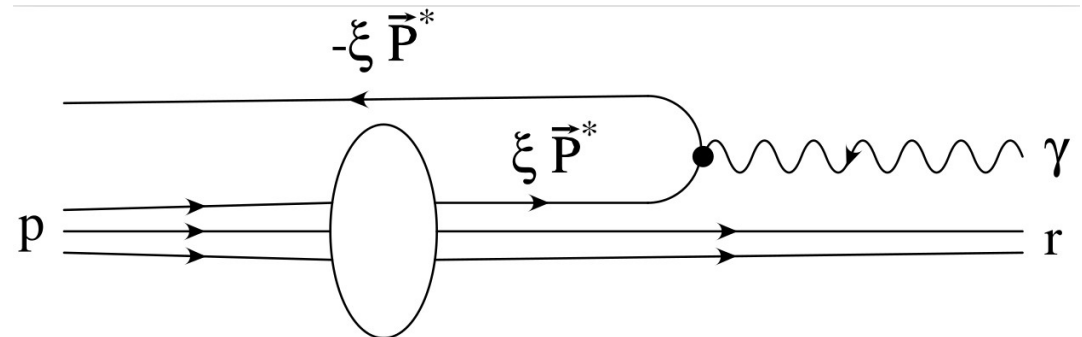
$$= -(k-k')^2$$

$$x = Q^2 / 2P \cdot q$$

In Breit frame of reference

Backscattered quark
in quark-parton-model

No jet pT!

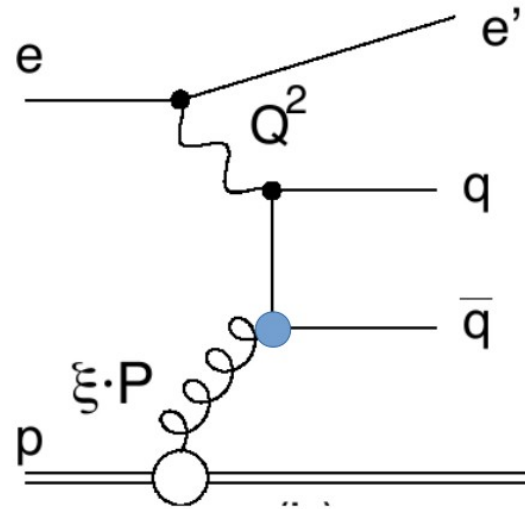




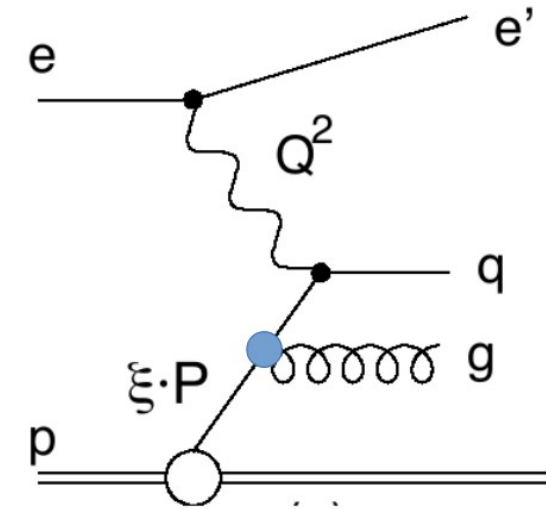
DIS jets in Breit frame

$ep \rightarrow 2 \text{ jets}$

from head-on collision
of virtual boson with
struck quark in proton



Boson-gluon fusion



QCD Compton

Accesses gluon density
→ dominates at low to medium x

Accesses quark density
→ dominates at high p_T (high x)

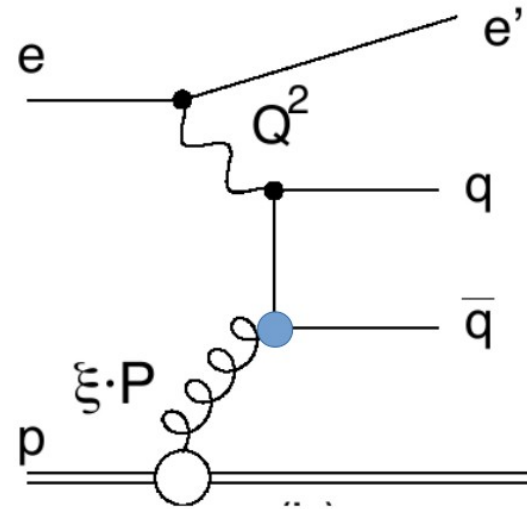
Sensitivity to strong coupling constant α_s and gluon density $g(x, \mu_F^2)$ at LO



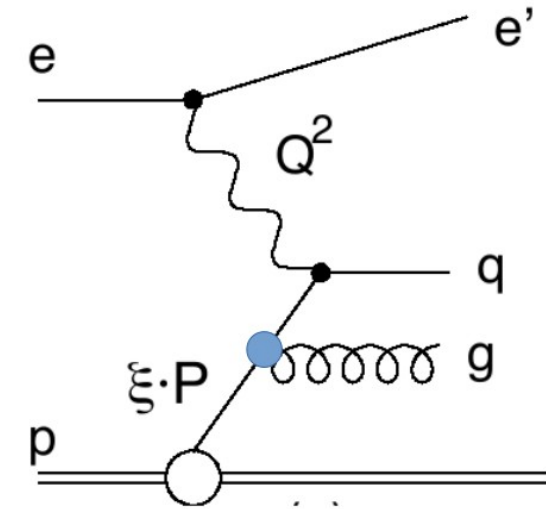
DIS jets in Breit frame

$ep \rightarrow 2 \text{ jets}$

from head-on collision of virtual boson with struck quark in proton



Boson-gluon fusion



QCD Compton

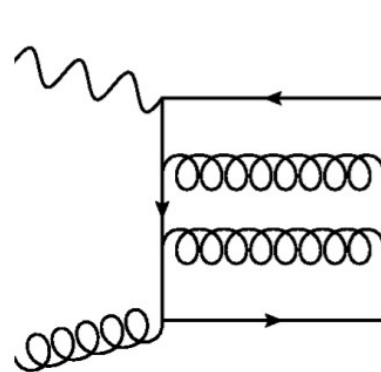
Accesses gluon density

→ dominates at low to medium x

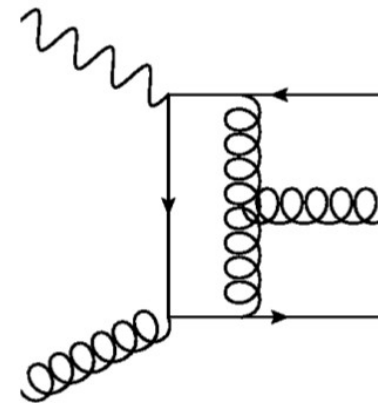
Accesses quark density

→ dominates at high p_T (high x)

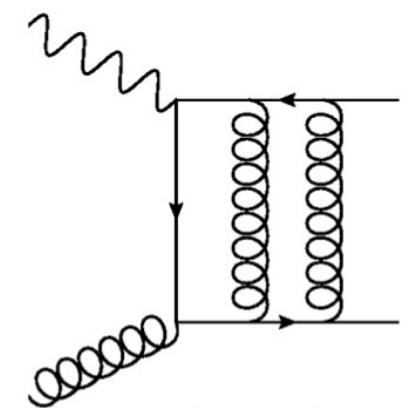
Now with NNLO corrections!



Double-real



Real-virtual



Double-virtual



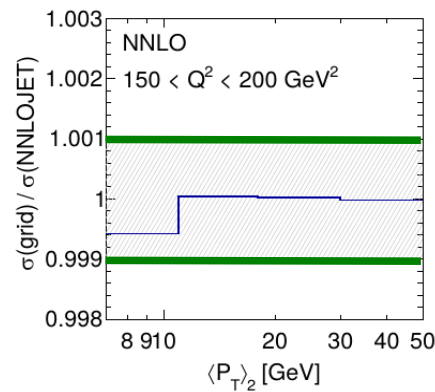
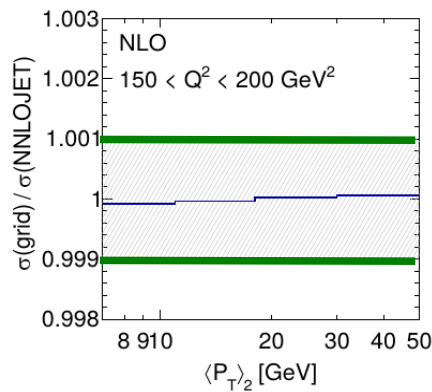
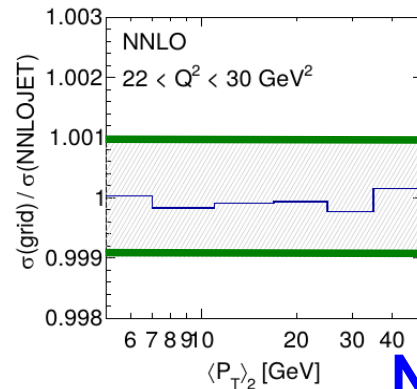
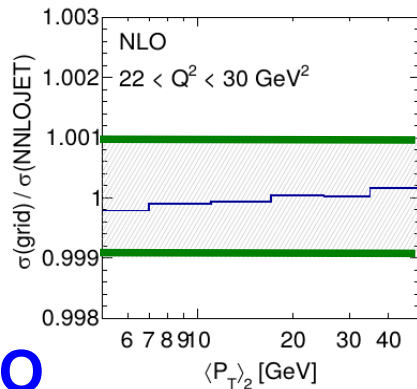
Closure in x for DIS jet grids

Interpolation quality optimisable,
e.g. depends on **observable(!)** and :

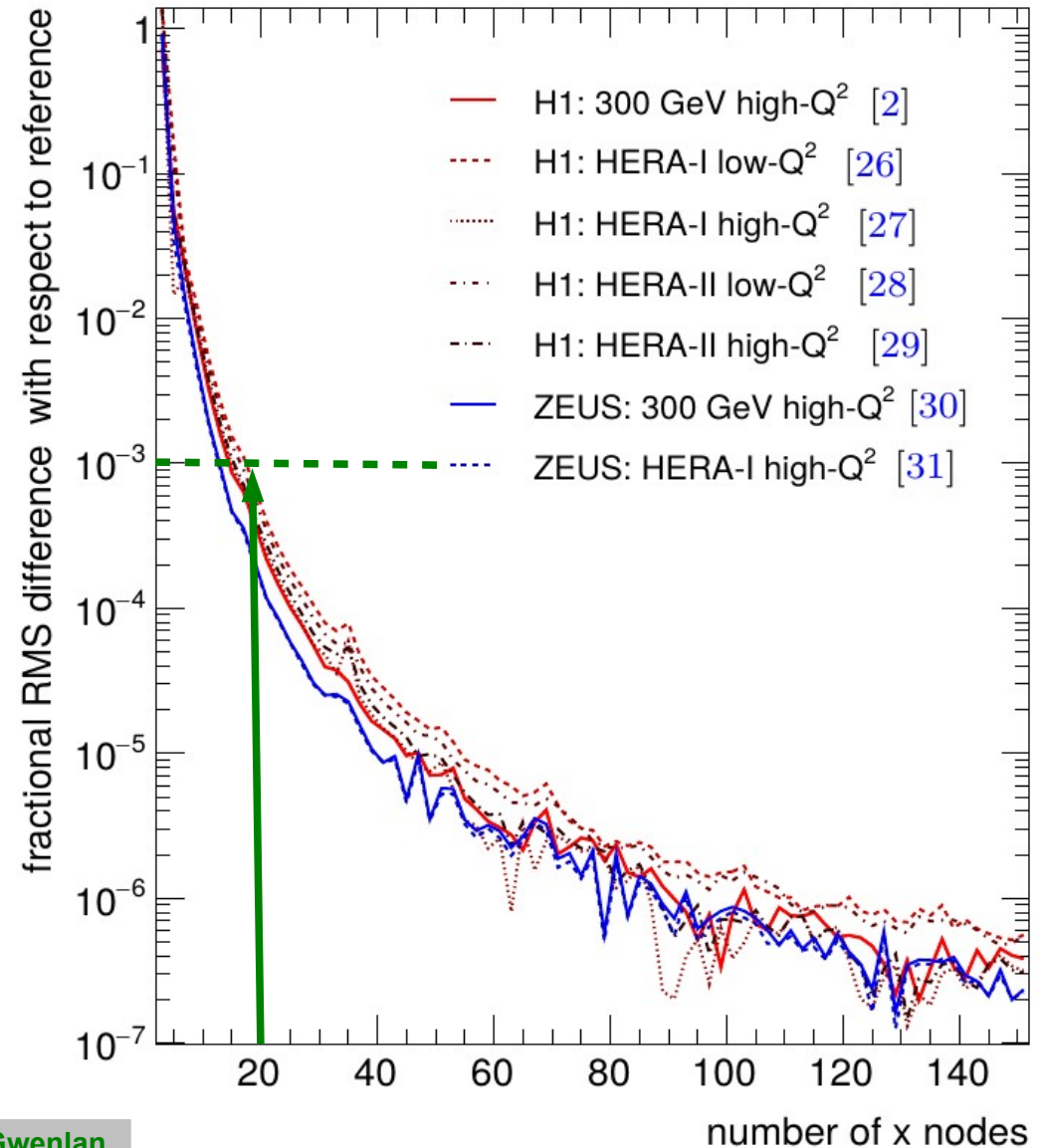
- ➔ Reweighting functions
- ➔ Distribution of x nodes
- ➔ Number of x nodes

NLO

NNLO



With 20 nodes $< 1\%$ deviation!



D. Britzger, J. Currie, A. Gehrmann-De Ridder, T. Gehrmann, N. Glover, C. Gwenlan, A. Huss, T. Morgan, J. Niehuis, J. Pires, K. Rabbertz, M. Sutton, arXiv: 1906.05303.



Scale dependence

Implementation of scale dependence differs between APPLgrid & fastNLO:

APPLgrid:

- Stores one grid per order
- Calculates log terms and convolutions with splitting functions dynamically (HOPPET)
- Computationally more complex, smaller grid sizes

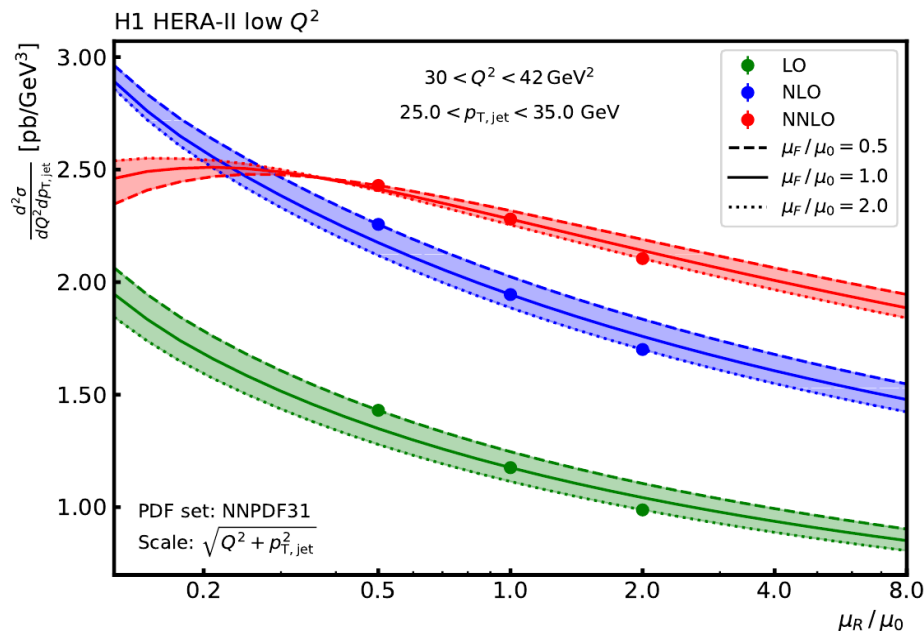
fastNLO:

- Stores one grid per log term per order
- Simpler computation, but larger grid sizes
- Simpler to store alternative scale choice, again increasing grid size

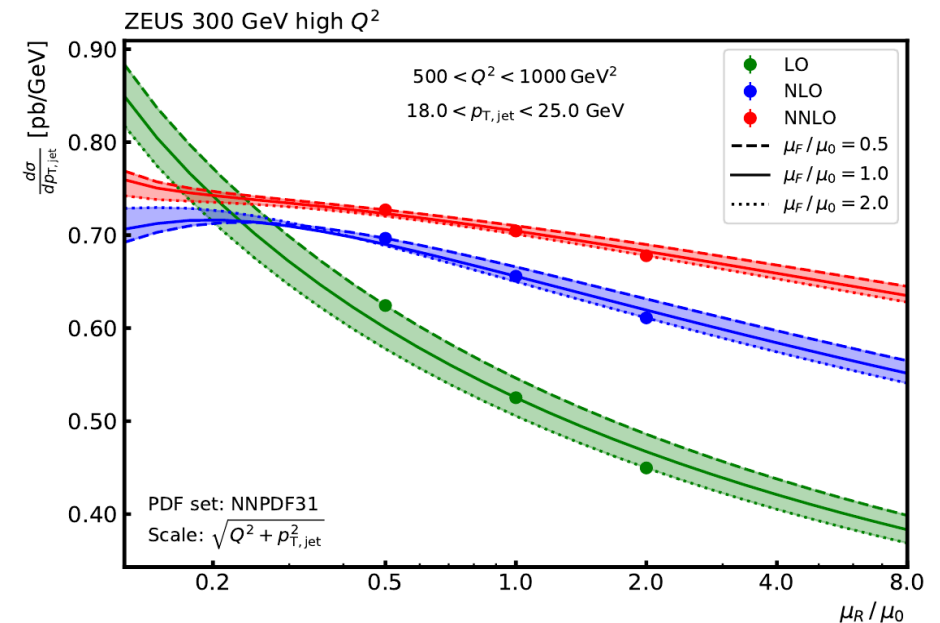
Conversion possible between APPLgrid & fastNLO formats:

- Here: Convert central scale grid from fastNLO production to APPLgrid
- Both implementations of scale dependence agree

H1 low Q^2



ZEUS high Q^2

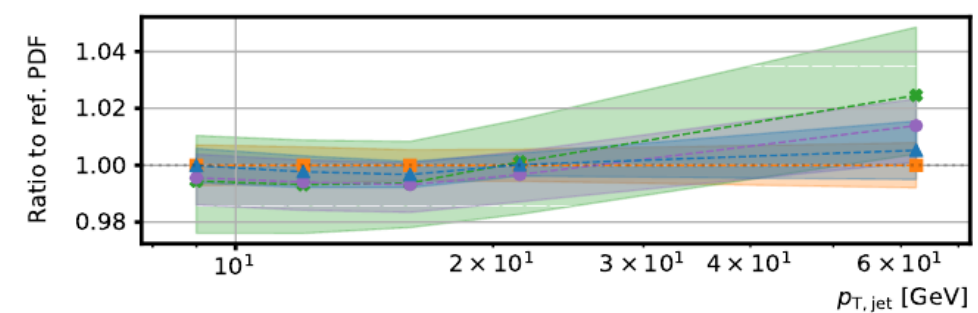
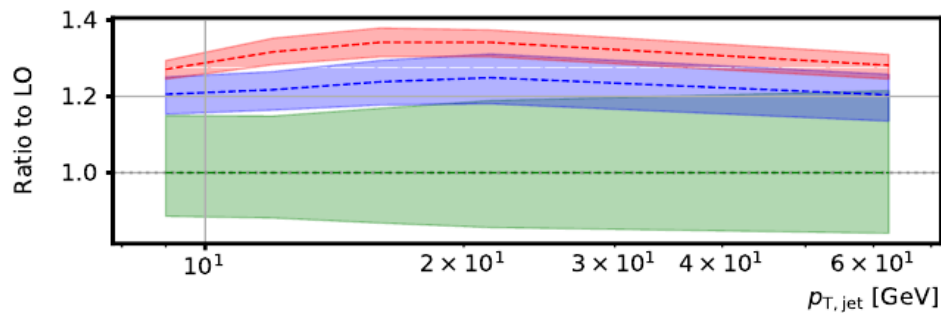
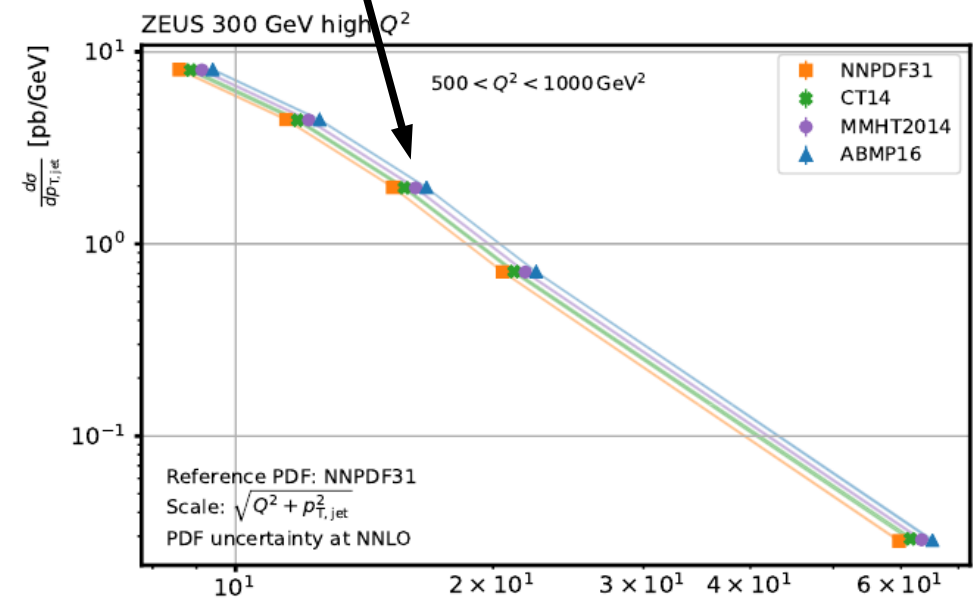
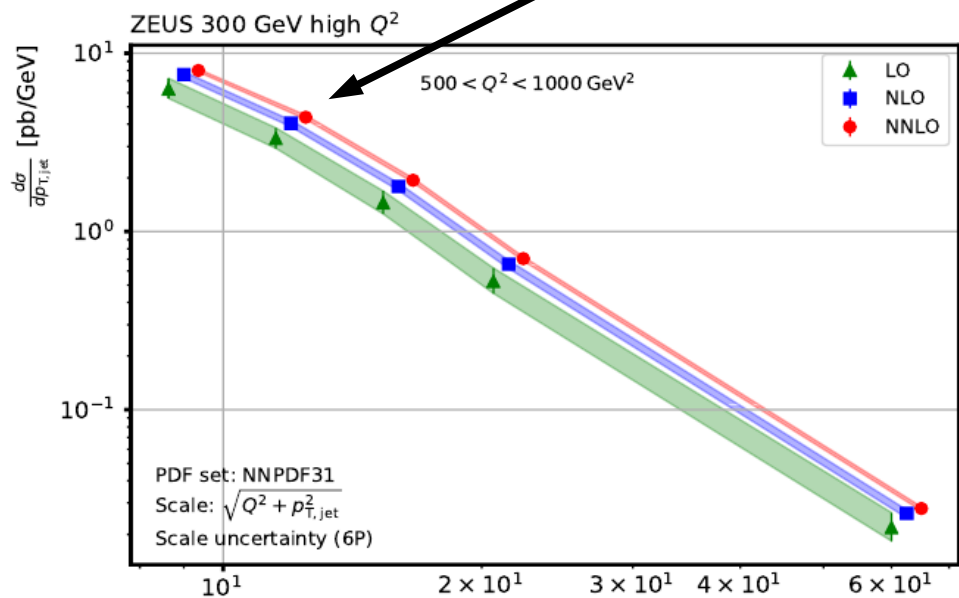




Scale & PDF uncertainty

Grids allow fast re-evaluation for different orders, scales, PDFs etc.; here for one of the new ZEUS inclusive jet datasets

Note: Points are shifted for better visibility





Datasets

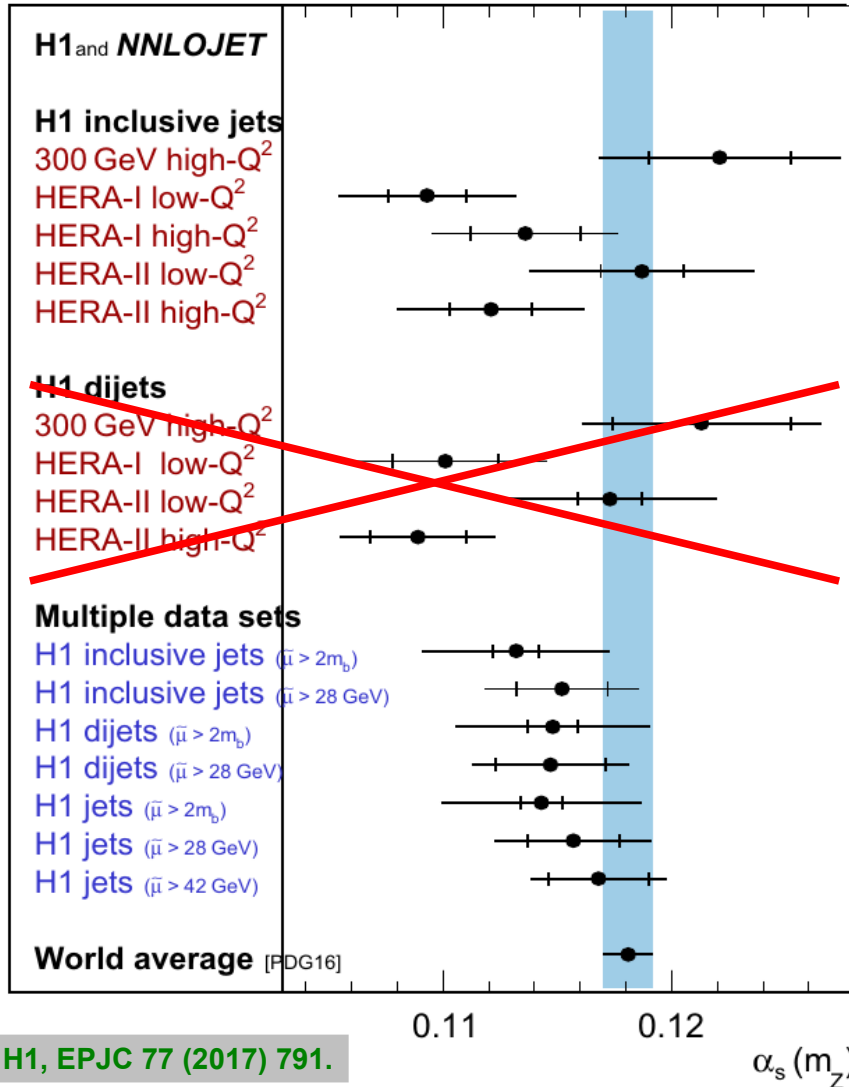
Previously:

- H1 data only
- Inclusive & di-jets
- Normalised

Today:

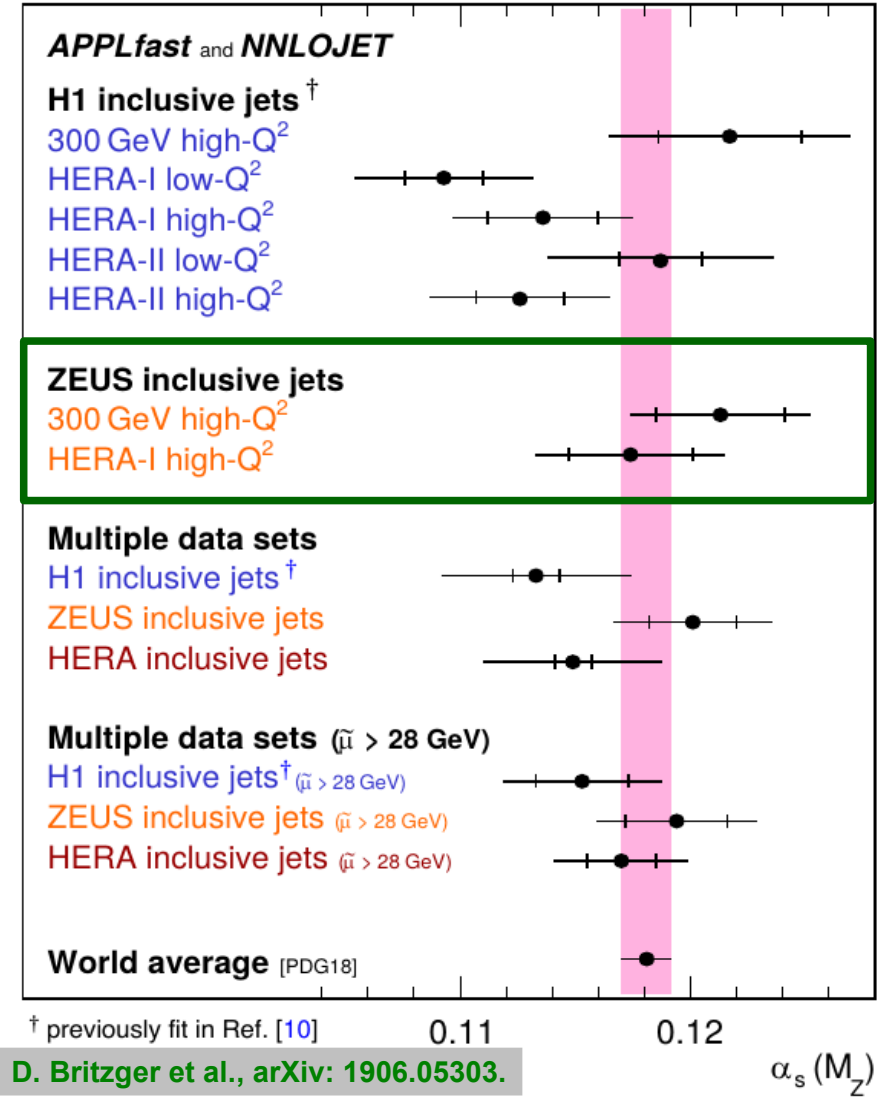
- H1 and ZEUS data
- Inclusive jets only
- Unnormalised
- Some H1 grids with increased stat. precision

α_s results from H1 jet data in NNLO



H1, EPJC 77 (2017) 791.

α_s results from HERA inclusive jet data in NNLO



[†] previously fit in Ref. [10]

D. Britzger et al., arXiv: 1906.05303.



Results

All HERA inclusive jets data points ($\mu_{\text{cut}} > 2 m_b$):

$$\alpha_s(M_Z) = 0.1149 (9)_{\text{exp}} (5)_{\text{had}} (4)_{\text{PDF}} (3)_{\text{PDF}\alpha_s} (2)_{\text{PDFset}} (37)_{\text{scale}}$$

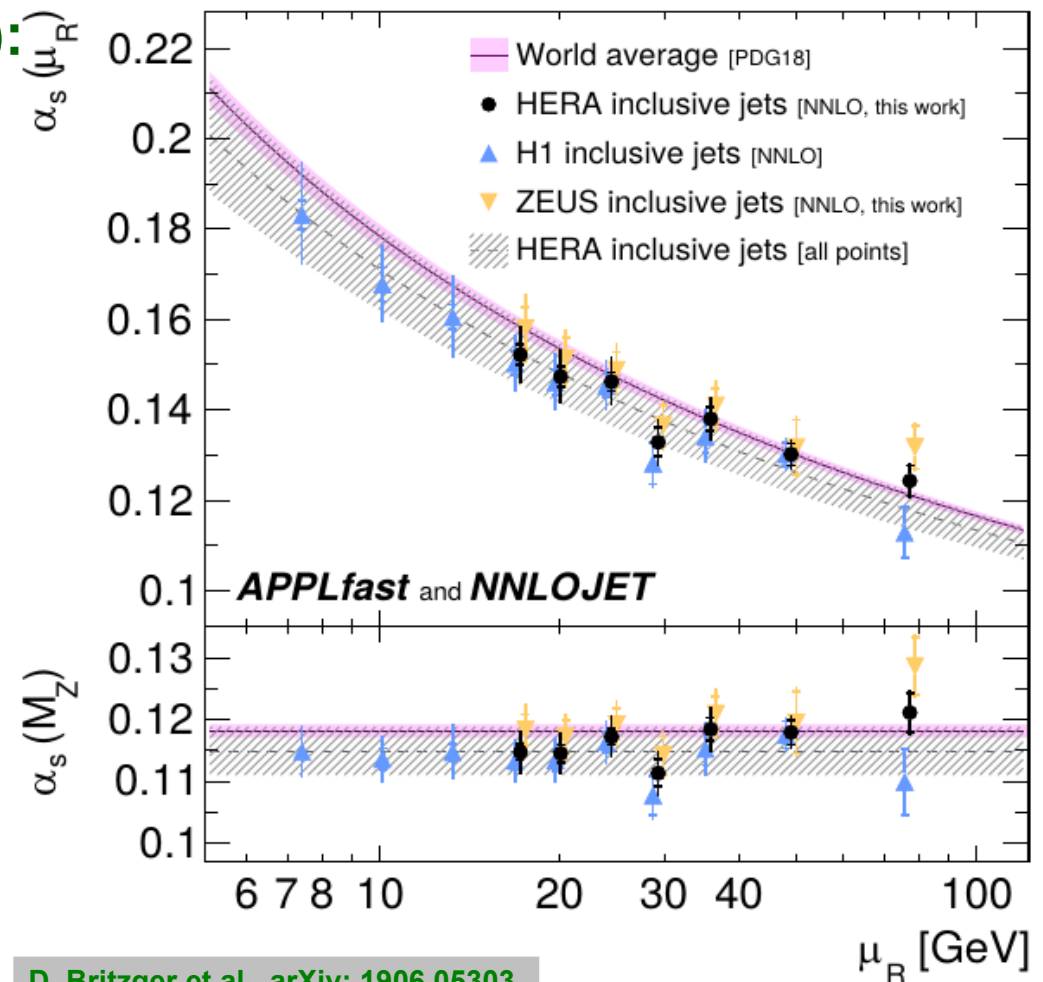
$$\alpha_s(M_Z) = 0.1170 (15)_{\text{exp}} (7)_{\text{had}} (3)_{\text{PDF}} (2)_{\text{PDF}\alpha_s} (3)_{\text{PDFset}} (24)_{\text{scale}}$$

Smallest total uncertainty ($\mu_{\text{cut}} > 28 \text{ GeV}$):

Compatible with world average

Scale still largest uncertainty :-)

Data	μ_{cut} [GeV]	$\alpha_s(M_Z)$	exp	theo	X2/ndof
All	$2 m_b$	0.1149	9	38	183/193
H1	28	0.1153	19	28	44/60
ZEUS	28	0.119 4	24	27	39/43
All > 28	28	0.1170	15	25	86/104



D. Britzger et al., arXiv: 1906.05303.



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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



What is Ploughshare ?

- 1 **Quick to use** - a web based utility for the automated distribution of fast interpolation grids for the high energy physics community.
- 2 **Secure storage** - registered users can upload grid files and corresponding standard format configuration files to describe the grids and physics processes and these are added to a central repository.
- 3 **Automatic distribution** - a standard utility library will be provided to download any required grids automatically in user code.

A utility for the community Ploughshare allows users to share their grids, so it is important that the provenance of the grids is guaranteed. This is achieved by allowing only registered users to upload their validated grids. Subsequently however, anyone is free to download and use the grids as they wish.

Fast operations summary

Navigate quickly to some of the primary operations you might be interested in



Download grids

View all the lovely grids which are available for download



Upload grids

Upload grids using the standard web interface



Download grid code

Get the code for the automated download of multiple grids



Settings

How to set up the automated code for the grid downloads

- ➔ **Repository where registered users can upload grids with some documentation**
- ➔ **Registered(!) user gets FAME or BLAME**
- ➔ **Automated job treats the upload:**
 - ➔ **Add to the appropriate location in the file system**
 - ➔ **Generate relevant lists, and display web pages**
- ➔ **Provides a user interface for automated download with a simple line of code**
- ➔ **Have expression of interest from other stakeholders**
- ➔ **DIS inclusive jet grids at NNLO are downloadable!**



DIS inclusive jet grids at NNLO

General

Search mask

Group Experiment Energy (in TeV) Type (ep, pp etc)

Process (incljets, Z0, Wpm etc) Calculation Order (LO, NLO, NNLO) Arxiv

Search

you selected: type='ep'

applfast-h1-incjets-appl-arxiv-0010054	-H1 inclusive jets 300 GeV high-Q2
applfast-h1-incjets-appl-arxiv-0706.3722	-H1 inclusive jets HERA-I high-Q2
applfast-h1-incjets-appl-arxiv-0911.5678	-H1 inclusive jets HERA-I low-Q2
applfast-h1-incjets-appl-arxiv-1406.4709	-H1 inclusive jets HERA-II high-Q2
applfast-h1-incjets-appl-arxiv-1611.03421	-H1 inclusive jets HERA-II low-Q2
applfast-h1-incjets-fnlo-arxiv-0010054	-H1 inclusive jets 300 GeV high-Q2
applfast-h1-incjets-fnlo-arxiv-0706.3722	-H1 inclusive jets HERA-I high-Q2
applfast-h1-incjets-fnlo-arxiv-0911.5678	-H1 inclusive jets HERA-I low-Q2
applfast-h1-incjets-fnlo-arxiv-1406.4709	-H1 inclusive jets HERA-II high-Q2
applfast-h1-incjets-fnlo-arxiv-1611.03421	-H1 inclusive jets HERA-II low-Q2
applfast-zeus-incjets-appl-arxiv-0208037	-ZEUS inclusive jets Ep=820GeV high-Q2, Rkt=1 aem=1/137
applfast-zeus-incjets-appl-arxiv-0608048	-ZEUS inclusive jets HERA-I high-Q2, Rkt=1 aem=1/137
applfast-zeus-incjets-fnlo-arxiv-0208037	-ZEUS inclusive jets Ep=820GeV high-Q2, Rkt=1 aem=1/137
applfast-zeus-incjets-fnlo-arxiv-0608048	-ZEUS inclusive jets HERA-I high-Q2, Rkt=1 aem=1/137

APPLgrid project

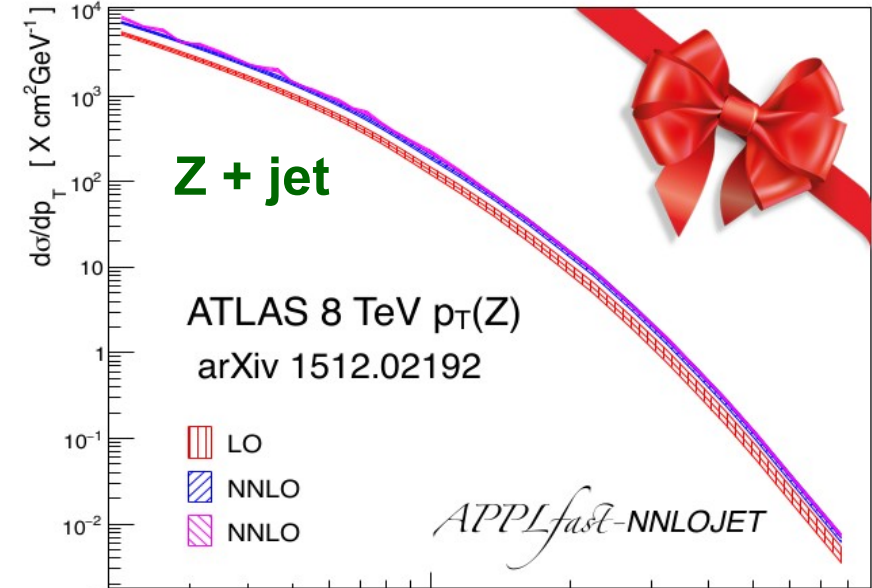
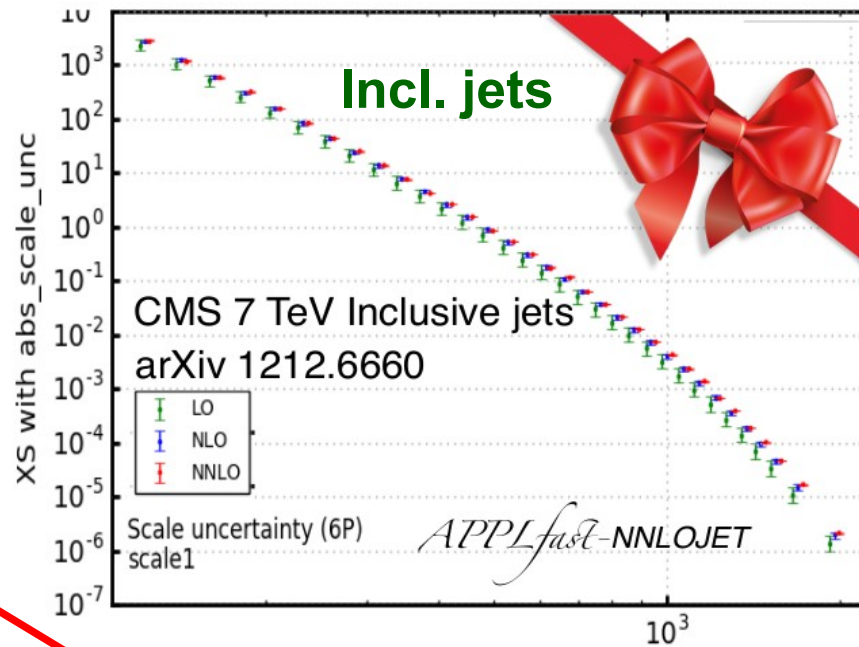
Available in both formats

fastNLO

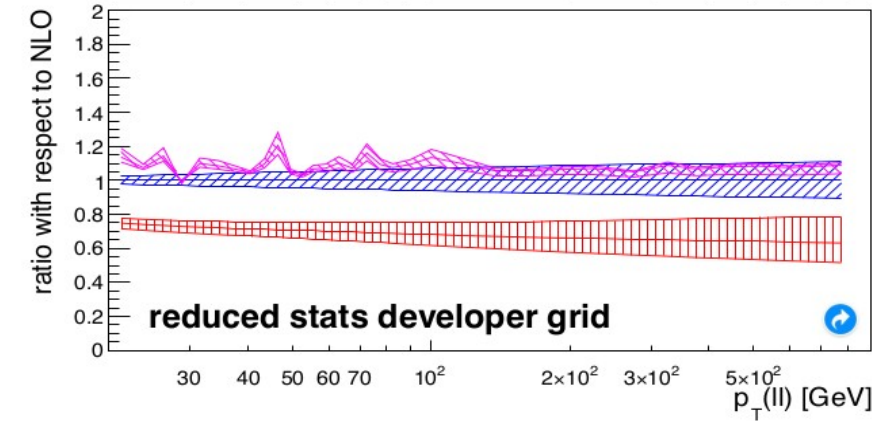
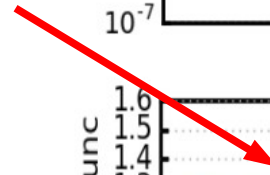


Perspective for pp collisions

- Grid production much more involved: For each event have two x values!**
- ➔ **Grids become substantially larger and need more CPU time for sufficient stat. accuracy**
 - ➔ **Nevertheless first grids for testing available**



Note: Stat. fluctuations



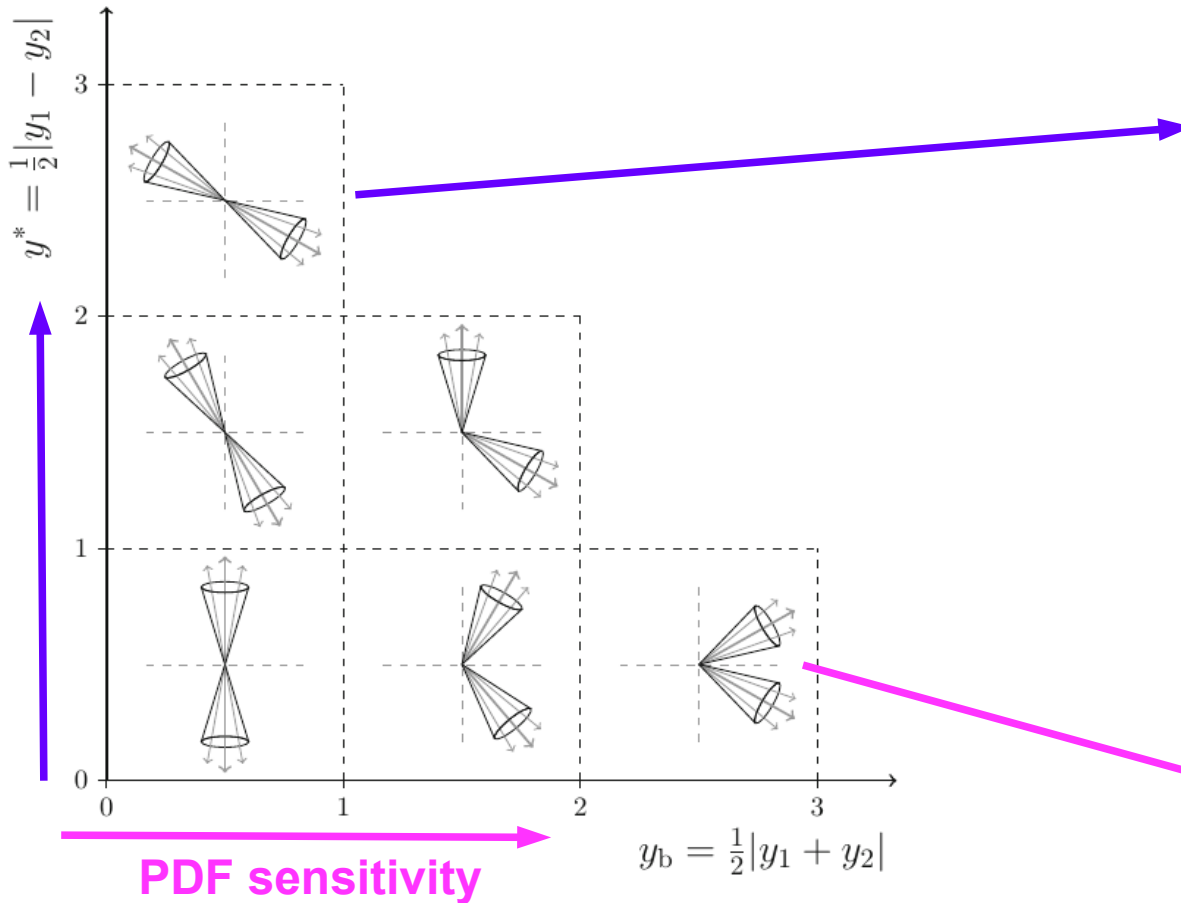
LO, NLO, NNLO scale uncertainty & K factors



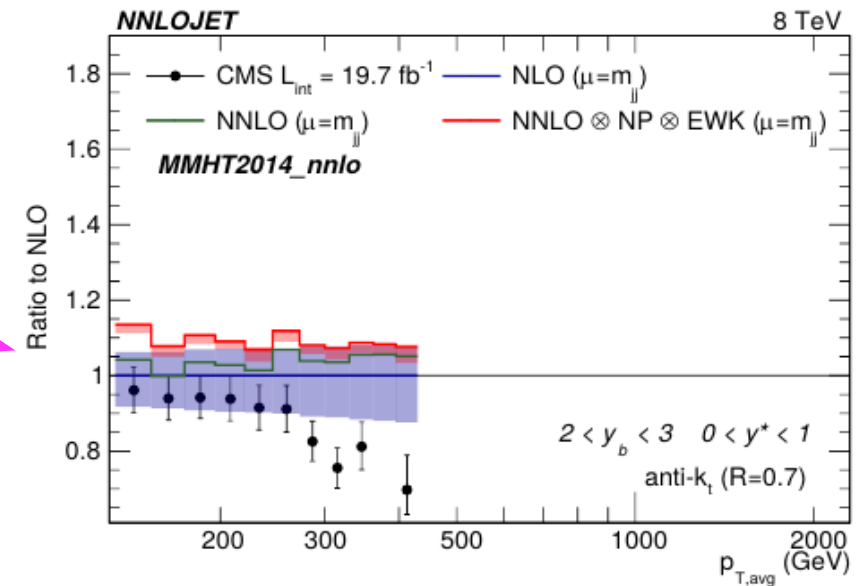
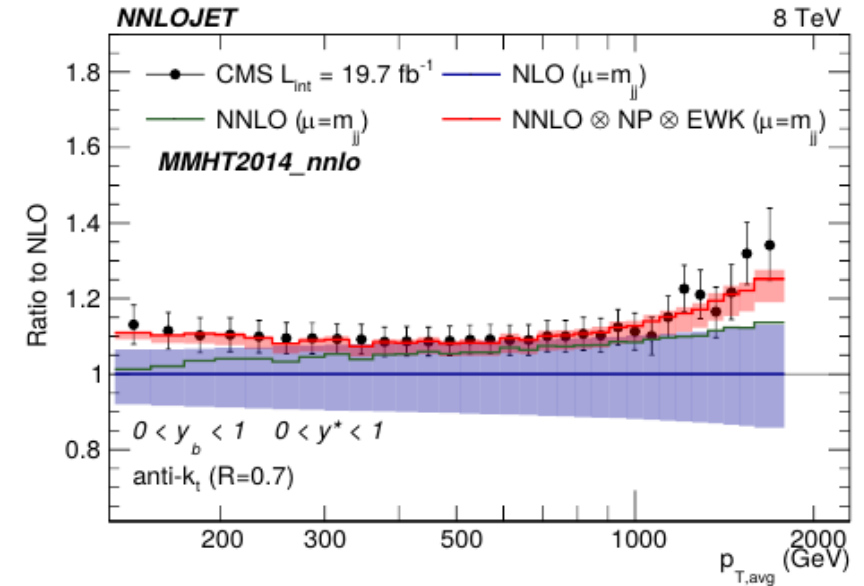
Triple-differential dijets

Triple-differential dijet production

Hard process dependent



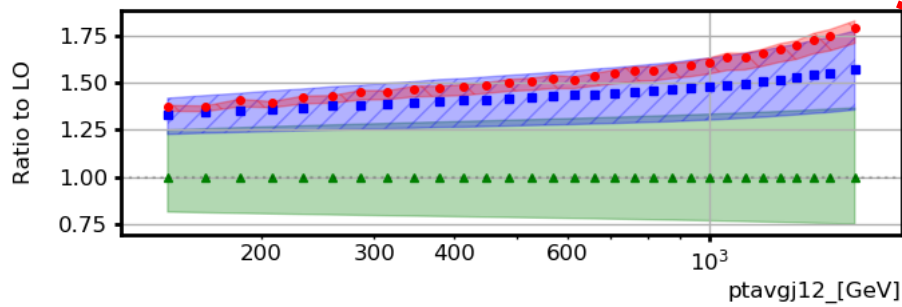
CMS, EPJC 77 (2017) 746, arXiv: 1705.02628.
 A. Gehrmann-De Ridder, T. Gehrmann, N. Glover, A. Huss, J. Pires,
 arXiv: 1905.09047.



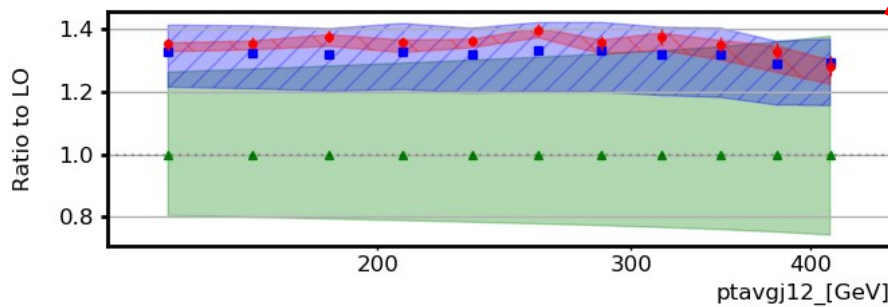


Work in progress: Dijets

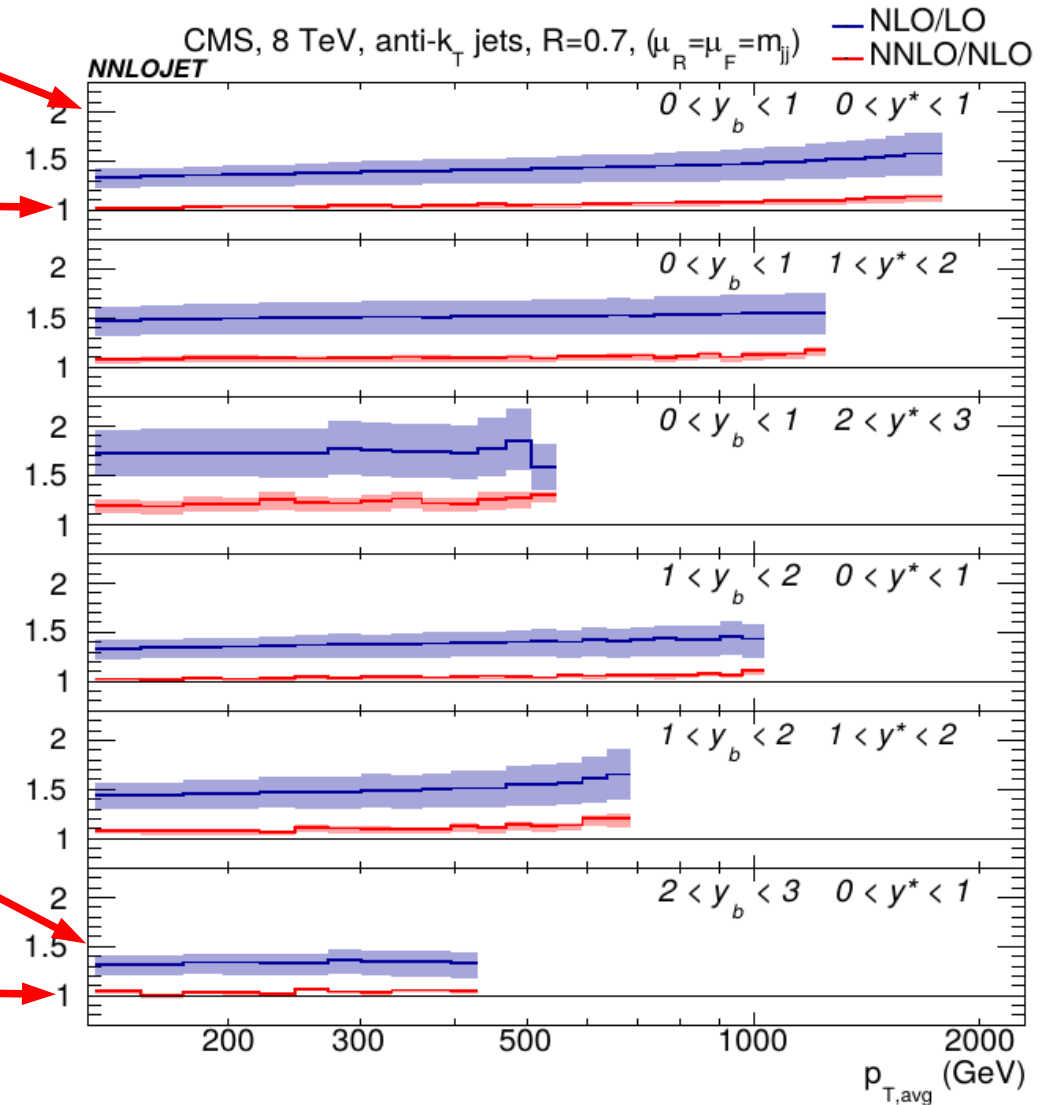
NLO/LO, NNLO/LO



Interpolation table nicely reproduces size and shape of statistically independent NNLOJET original



NLO/LO, NNLO/NLO



Note: y axis scales differ!



- APPLfast grids with DIS jets at NNLO from NNLOJET used
 - ➔ by H1 to determine α_s from inclusive jets and dijets
 - ➔ by HERAPDF team to include jet production in NNLO PDF+ α_s fit
 - ➔ here to determine α_s from all H1 and ZEUS inclusive jet data
- The best overall uncertainty is achieved for $\mu_{\text{cut}} > 28 \text{ GeV}$
$$\alpha_s(M_Z) = 0.1170 \pm 15(\text{exp}) \pm 25(\text{theo})$$
- Grids are publically available on Ploughshare web site
- Grids for pp processes in progress

Thank you for your attention!



Backup



- Storage of scale-independent weights enable full scale flexibility also in NNLO

- Additional logs in NNLO

$$\omega(\mu_R, \mu_F) = \underbrace{\omega_0 + \log(\mu_R^2) \omega_R + \log(\mu_F^2) \omega_F}_{\text{log's for NLO}} + \underbrace{\log^2(\mu_R^2) \omega_{RR} + \log^2(\mu_F^2) \omega_{FF} + \log(\mu_R^2) \log(\mu_F^2) \omega_{RF}}_{\text{additional log's in NNLO}}$$

- Store weights: $w_0, w_R, w_F, w_{RR}, w_{FF}, w_{RF}$ for order α_s^{n+2} contributions

Advantages

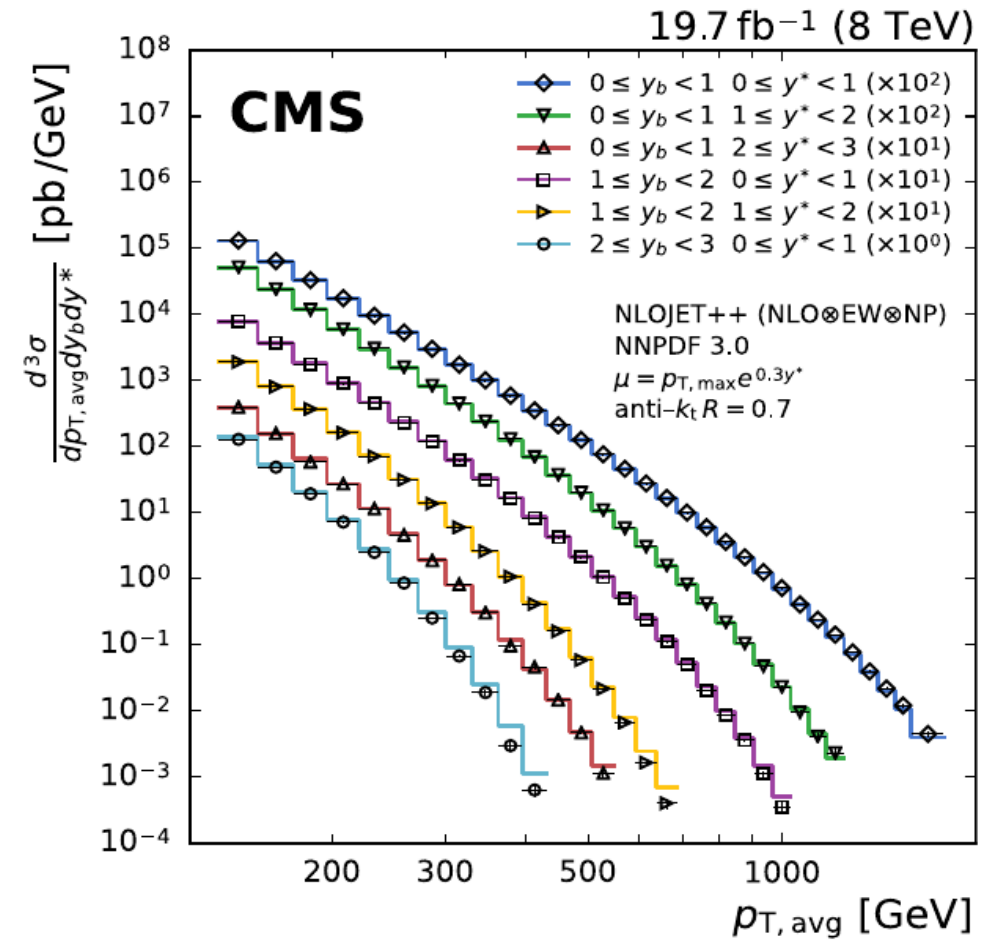
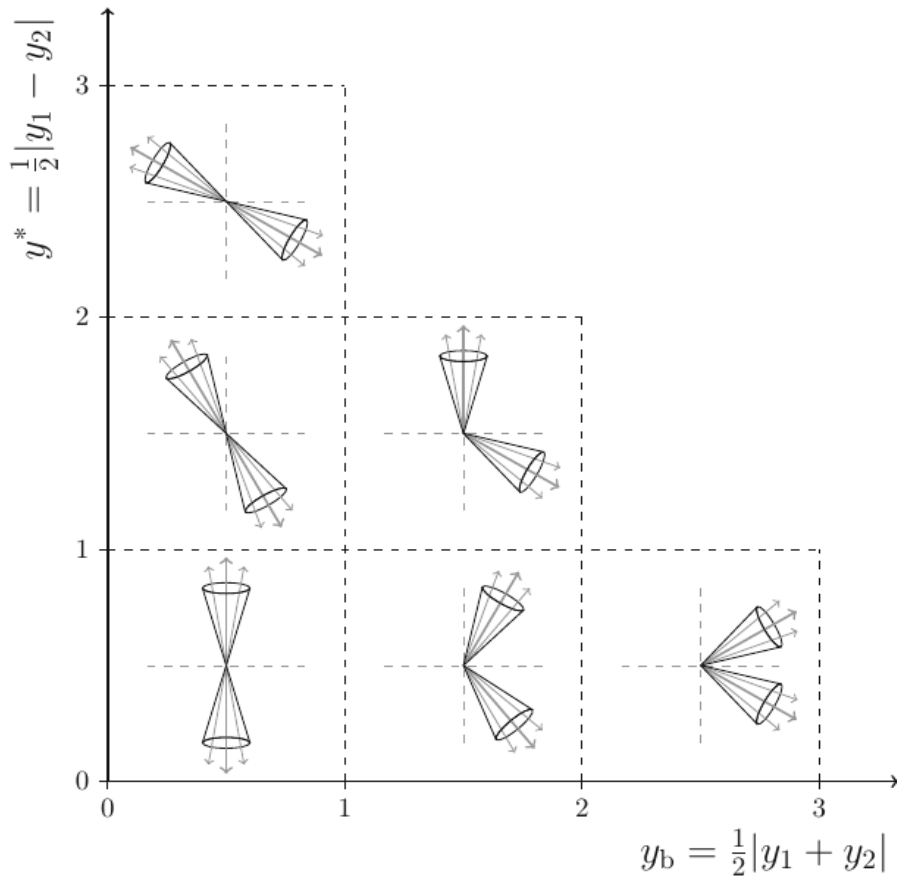
- Renormalization and factorization scale can be varied *independently* and by *any* factor
 - No time-consuming 're-calculation' of splitting functions in NLO necessary
- Only small increase in amount of stored coefficients

Implementation

- Two different observables can be used for the scales
 - e.g.: H_T and $p_{T,max}$
 - or e.g.: p_T and $|y|$
 - ...
- Any function of those two observables can be used for calculating scales



CMS triple-differential dijets



CMS, EPJC 77 (2017) 746, arXiv: 1705.02628.
 A. Gehrmann-De Ridder, T. Gehrmann, N. Glover, A. Huss, J. Pires,
 arXiv: 1905.09047.