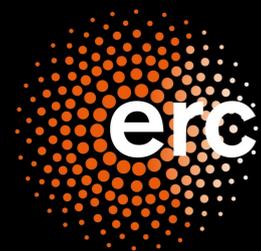
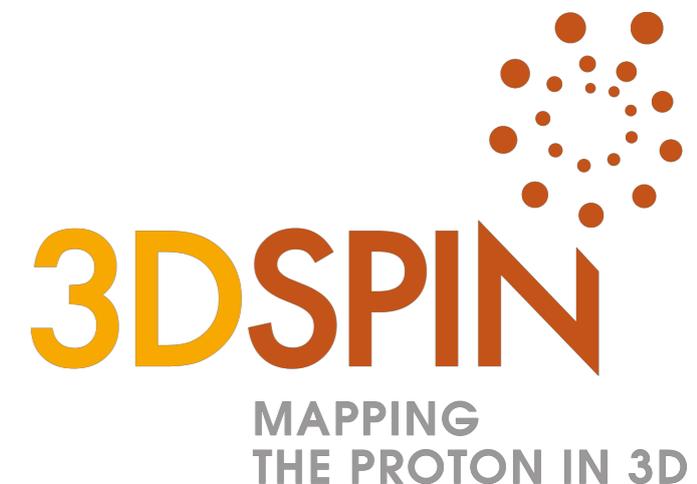


Collinear and TMD distributions

Valerio Bertone
INFN and Università di Pavia



TMDs@JLab 2018
December 19, 2018, Pavia



European Research Council
Established by the European Commission

Outline

- Collinear **unpolarised** distributions:
 - PDFs,
 - FFs.
- Collinear **longitudinally polarised** distributions.
- Collinear **transversely polarised** distributions.
- **q_T dependence:**
 - collinear and TMD frameworks.
 - Theoretical issues.
 - Computational tools.

Collinear unpolarised

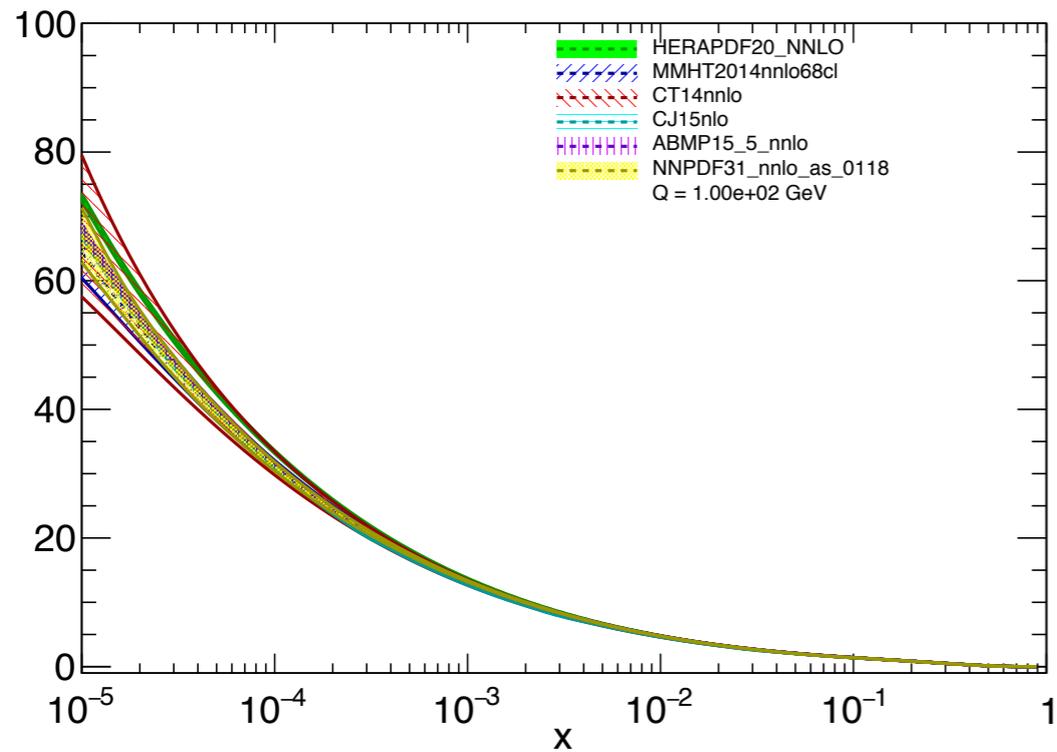
Parton distribution functions

- Great **effort** into the determination of unpolarised PDFs:
 - plenty of **data** available (LHC, Tevatron, HERA, JLab, etc.).
 - refined treatment of the experimental information.
 - Very accurate theoretical **calculations** (NNLO is becoming the standard):
 - DIS, Drell-Yan, jet production, top-pair production, etc,
 - Many **active collaborations** have put effort and experience:
 - ABMP, CJ, CT, (GJR), HERAPDF, NNPDF, MMHT, etc.
 - Many available **public tools**:
 - LHAPDF, APPLgrid, FastNLO, QCDNUM, Hoppet, APFEL, etc.
- Remarkable **consistency** amongst different determinations:
 - just a few blind spots, most noticeably the **very large- x region**.

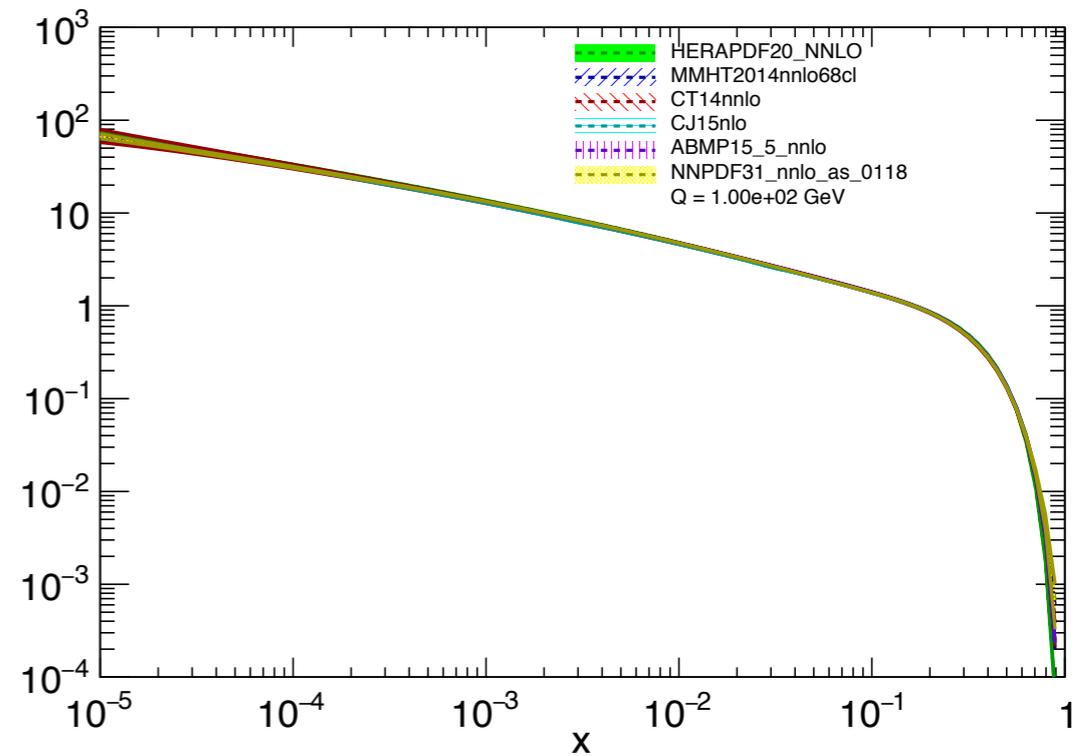
Collinear unpolarised

Parton distribution functions

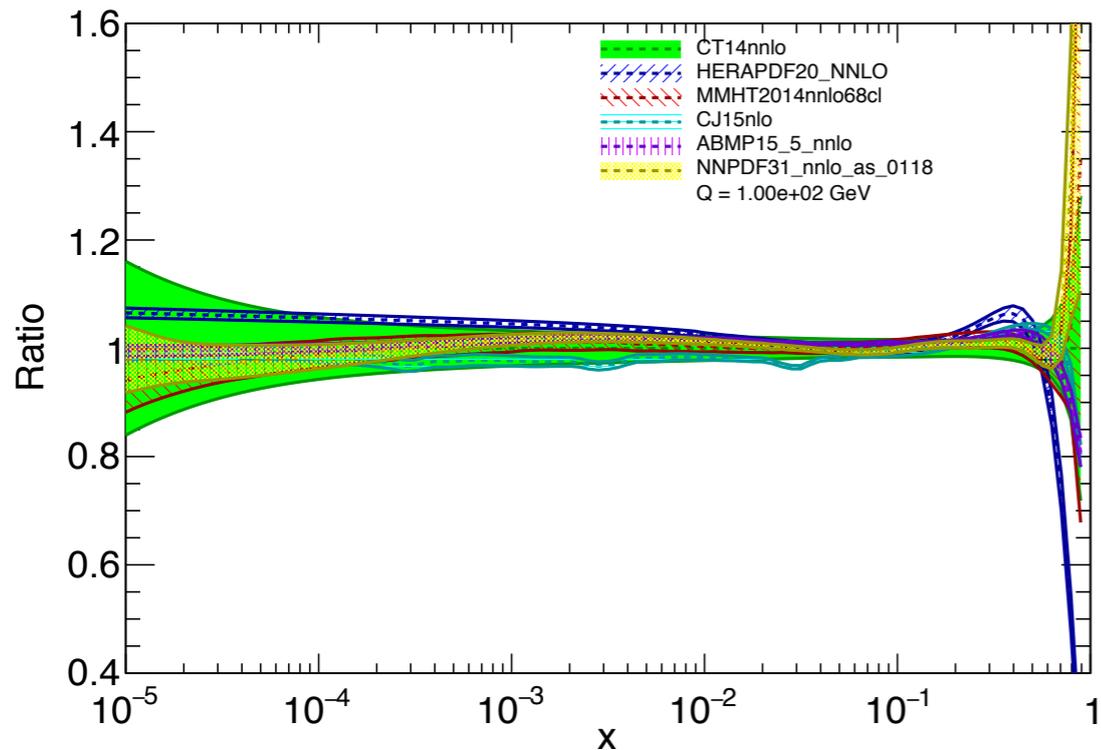
$x\Sigma(x,Q)$, comparison



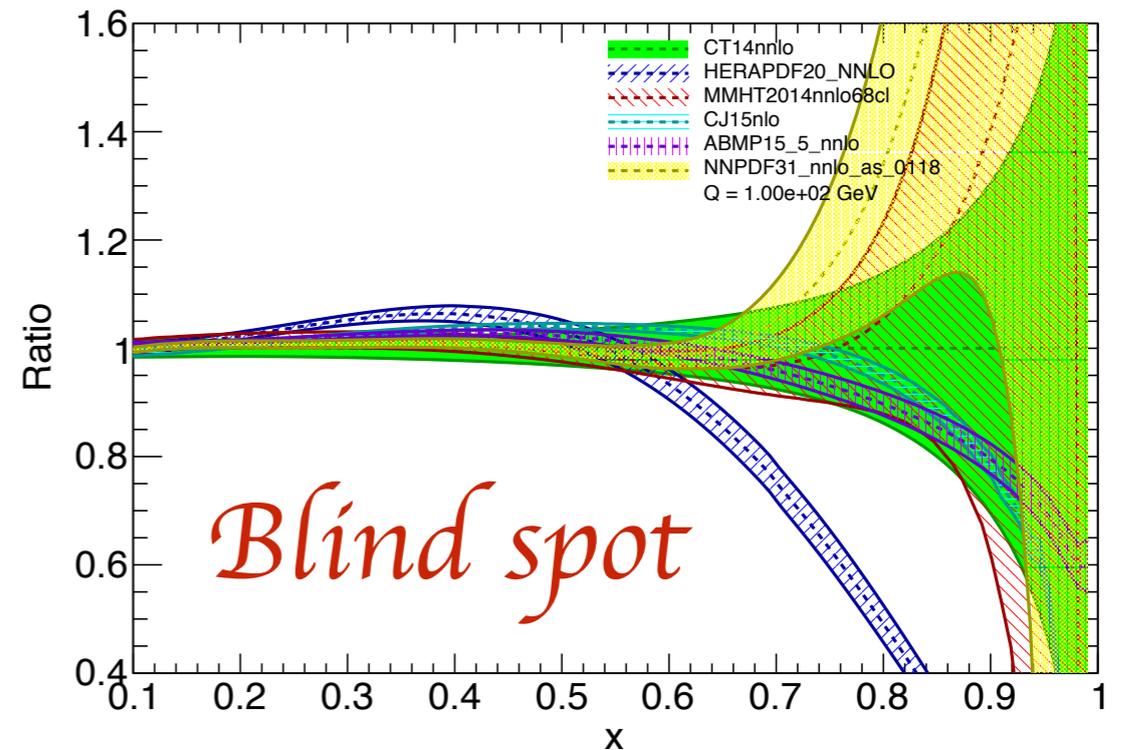
$x\Sigma(x,Q)$, comparison



$x\Sigma(x,Q)$, comparison



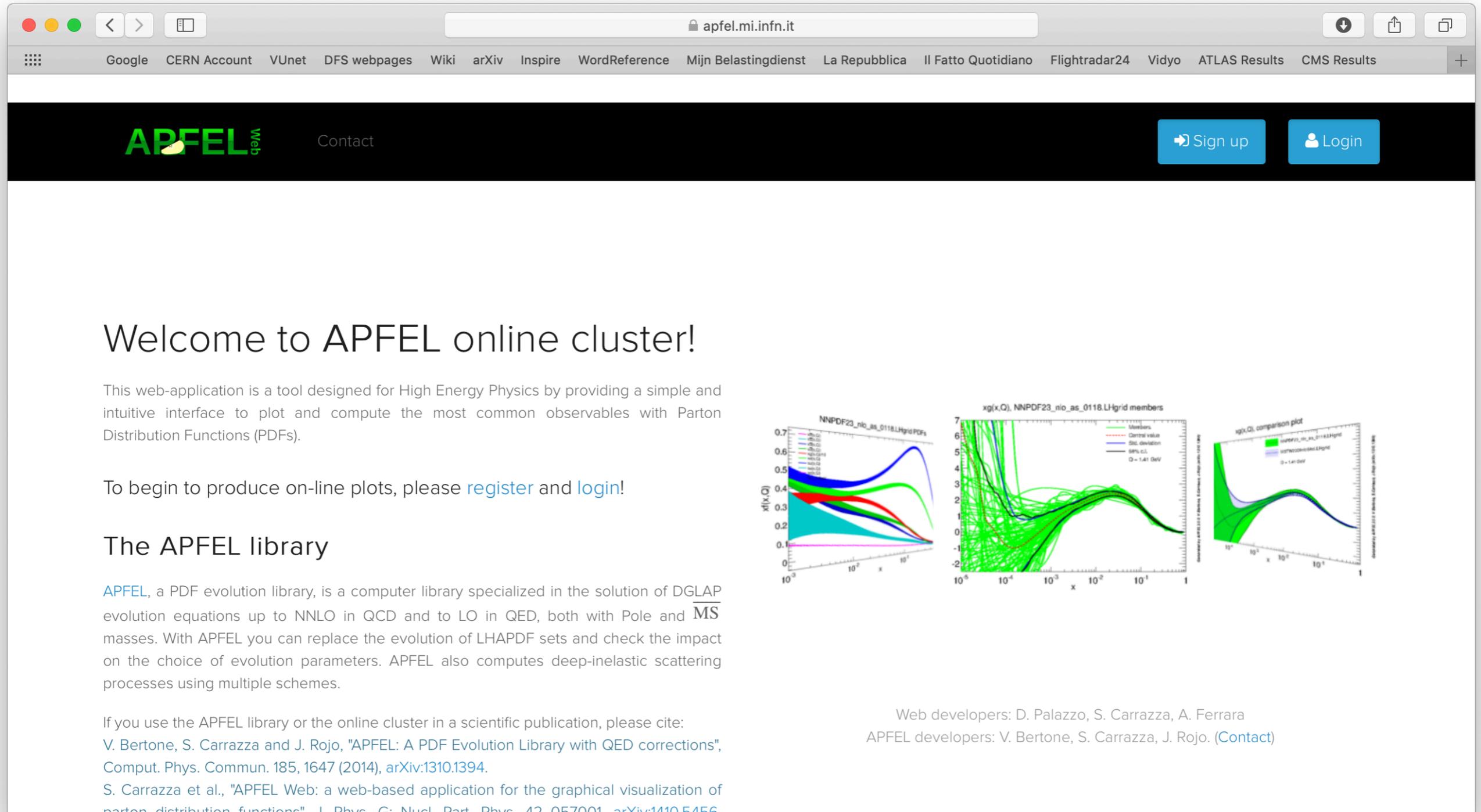
$x\Sigma(x,Q)$, comparison



Collinear unpolarised

Aside: APFEL Web

<https://apfel.mi.infn.it>



Welcome to APFEL online cluster!

This web-application is a tool designed for High Energy Physics by providing a simple and intuitive interface to plot and compute the most common observables with Parton Distribution Functions (PDFs).

To begin to produce on-line plots, please [register](#) and [login](#)!

The APFEL library

APFEL, a PDF evolution library, is a computer library specialized in the solution of DGLAP evolution equations up to NNLO in QCD and to LO in QED, both with Pole and $\overline{\text{MS}}$ masses. With APFEL you can replace the evolution of LHAPDF sets and check the impact on the choice of evolution parameters. APFEL also computes deep-inelastic scattering processes using multiple schemes.

If you use the APFEL library or the online cluster in a scientific publication, please cite:
V. Bertone, S. Carrazza and J. Rojo, "APFEL: A PDF Evolution Library with QED corrections", Comput. Phys. Commun. 185, 1647 (2014), [arXiv:1310.1394](#).
S. Carrazza et al., "APFEL Web: a web-based application for the graphical visualization of parton distribution functions", J. Phys. G: Nucl. Part. Phys. 42 057001, [arXiv:1410.5456](#).

Web developers: D. Palazzo, S. Carrazza, A. Ferrara
APFEL developers: V. Bertone, S. Carrazza, J. Rojo. ([Contact](#))

Collinear unpolarised

Aside: APFEL Web

The screenshot shows the APFEL Web interface. The top navigation bar includes the APFEL logo, a 'Contact' link, and a 'Logout' button. A sidebar on the left contains 'Workspace' (Home, My Profile), 'PDF MANAGER' (My PDF sets, Add PDF set, Import a LHAPDF grid), 'TOOLS' (Plotting Tools), and 'DOWNLOAD RESULTS' (View jobs). The main content area is titled 'Manage your PDF setups' and includes instructions on creating, modifying, or deleting PDF sets. It features a list of PDF sets with checkboxes and 'Modify' and 'Delete' buttons.

Workspace

- Home
- My Profile

PDF MANAGER

- My PDF sets
- Add PDF set
- Import a LHAPDF grid

TOOLS

- Plotting Tools

DOWNLOAD RESULTS

- View jobs

Manage your PDF setups

Create a PDF set

Create, modify or delete your personalized PDF sets. We provide PDFs sets from the LHAPDF5 and LHAPDF6 libraries. You are able to prepare special PDF sets with custom evolution provided by the APFEL library.

[Add PDF set](#) [Import a grid](#)

View details, modify or remove your PDF setups

- HERAPDF20_NNLO (LHAPDF6)
- MMHT2014nnlo68cl (LHAPDF6)
- CT14nnlo (LHAPDF6)
- CJ15nlo (LHAPDF6)
- ABMP15_5_nnlo (LHAPDF6)
- NNPDF31_nnlo_as_0118 (LHAPDF6)

[Modify](#) [Delete](#)

The screenshot shows the APFEL Web interface. The top navigation bar includes the APFEL logo, a 'Contact' link, and a 'Logout' button. A sidebar on the left contains 'Workspace' (Home, My Profile), 'PDF MANAGER' (My PDF sets, Add PDF set, Import a LHAPDF grid), 'TOOLS' (Plotting Tools), and 'DOWNLOAD RESULTS' (View jobs). The main content area is titled 'View and download your jobs' and includes instructions on viewing, modifying, and deleting jobs. It features a table with columns for Image, Label, Status, Date, and Actions.

Workspace

- Home
- My Profile

PDF MANAGER

- My PDF sets
- Add PDF set
- Import a LHAPDF grid

TOOLS

- Plotting Tools

DOWNLOAD RESULTS

- View jobs

View and download your jobs

Jobs usually take few minutes to complete, if this is not the case please contact the [administrators](#).

View, modify and delete your jobs.

Image	Label	Status	Date	Actions
	General_log	Done	Dec. 18, 2018, 9:39 a.m.	Details Clone Erase
	General_ratio_largex	Done	Dec. 18, 2018, 9:37 a.m.	Details Clone Erase
	General_ratio_1	Done	Dec. 18, 2018, 9:34 a.m.	Details Clone Erase
	General1	Done	Dec. 18, 2018, 9:31 a.m.	Details Clone Erase

The screenshot shows the APFEL Web interface. The top navigation bar includes the APFEL logo, a 'Contact' link, and a 'Logout' button. A sidebar on the left contains 'Workspace' (Home, My Profile), 'PDF MANAGER' (My PDF sets, Add PDF set, Import a LHAPDF grid), 'TOOLS' (Plotting Tools), and 'DOWNLOAD RESULTS' (View jobs). The main content area is titled 'Choose a plotting tool and select your PDF set' and includes instructions on choosing a plotting tool and selecting a PDF set. It features a grid of plotting tools for basic plotting and analysis & comparisons.

Workspace

- Home
- My Profile

PDF MANAGER

- My PDF sets
- Add PDF set
- Import a LHAPDF grid

TOOLS

- Plotting Tools

DOWNLOAD RESULTS

- View jobs

Choose a plotting tool and select your PDF set

Some jobs, like PDF luminosities, require some time to be finalized. Check the job status at [View jobs](#) page. The plotting tools can be used for both the LHAPDF libraries: LHAPDF5 and LHAPDF6.

Tools for PDF basic plotting

- Plot PDF Members
- Plot Multiple PDF Flavors

Tools for PDF analysis & comparisons

- Compare PDFs in x
- Compare PDFs in Q^2
- Compare PDF Luminosity
- All PDF Luminosities
- Compare PDF Correlations
- PDF Correlation Matrix

The screenshot shows the APFEL Web interface. The top navigation bar includes the APFEL logo, a 'Contact' link, and a 'Logout' button. A sidebar on the left contains 'Workspace' (Home, My Profile), 'PDF MANAGER' (My PDF sets, Add PDF set, Import a LHAPDF grid), 'TOOLS' (Plotting Tools), and 'DOWNLOAD RESULTS' (View jobs). The main content area is titled 'Tools for theoretical predictions from PDFs' and includes instructions on choosing a plotting tool and selecting a PDF set. It features a grid of plotting tools for theoretical predictions.

Workspace

- Home
- My Profile

PDF MANAGER

- My PDF sets
- Add PDF set
- Import a LHAPDF grid

TOOLS

- Plotting Tools

DOWNLOAD RESULTS

- View jobs

Tools for theoretical predictions from PDFs

- DIS in x
- DIS in Q^2
- APPLgrid Observables LO NLO prediction

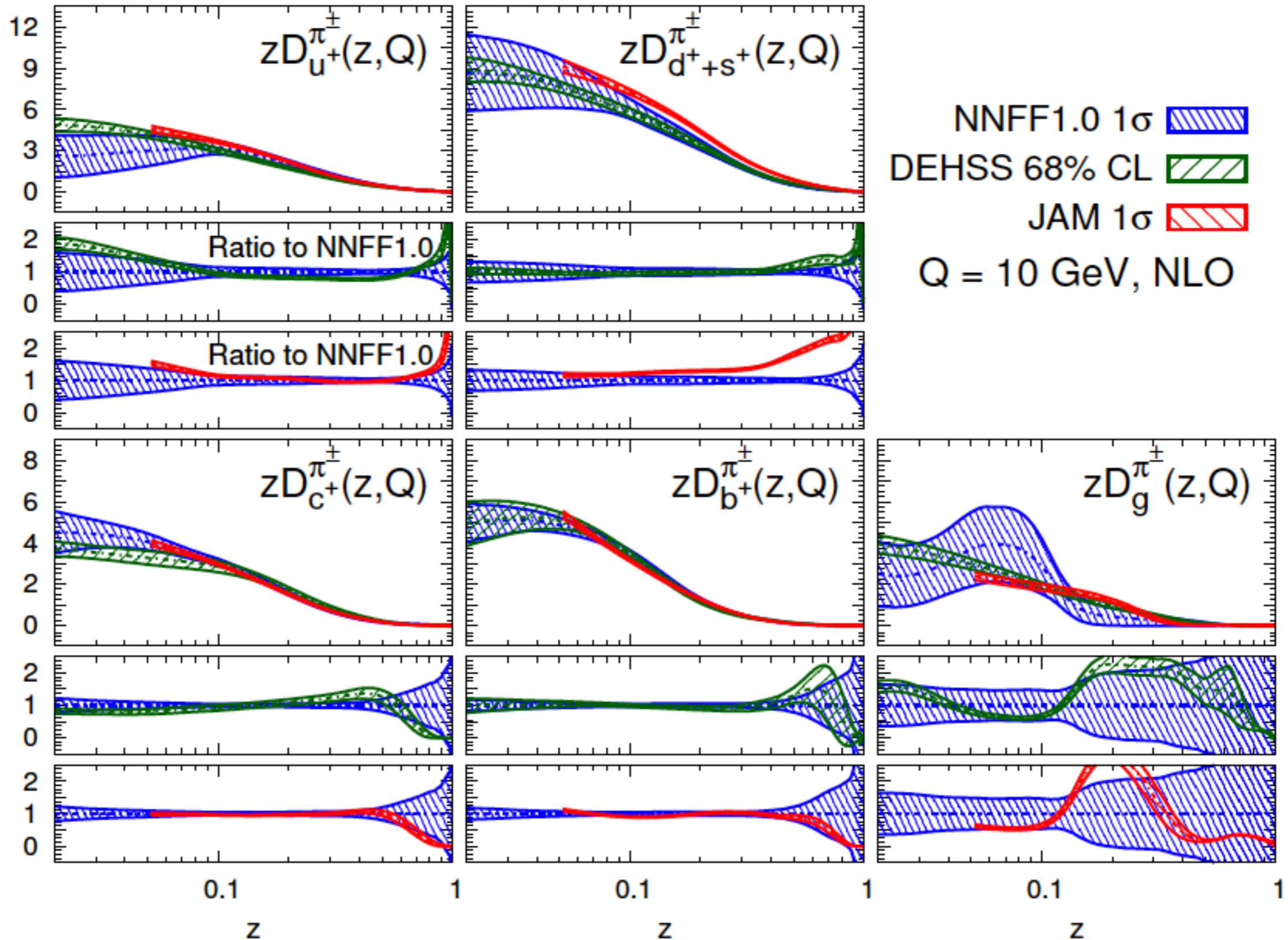
Collinear unpolarised

Fragmentation functions

- Increasing **effort** into the determination of unpolarised FFs:
 - precise **data** available (LHC, Tevatron, RHIC, LEP, BELLE, BABAR).
 - towards a sound treatment of the experimental information.
 - Accurate theoretical **calculations** (NLO is the current standard):
 - (SI)DIS, hadron-hadron collision,
 - Just a few **active collaborations**:
 - DSSV, JAM, NNFF, etc.
 - Not many available **public tools**:
 - LHAPDF (only NNFF), APFEL, QCDNUM.
- Some **fundamental** problems still open:
 - more or less substantial differences depending of the hadronic species.

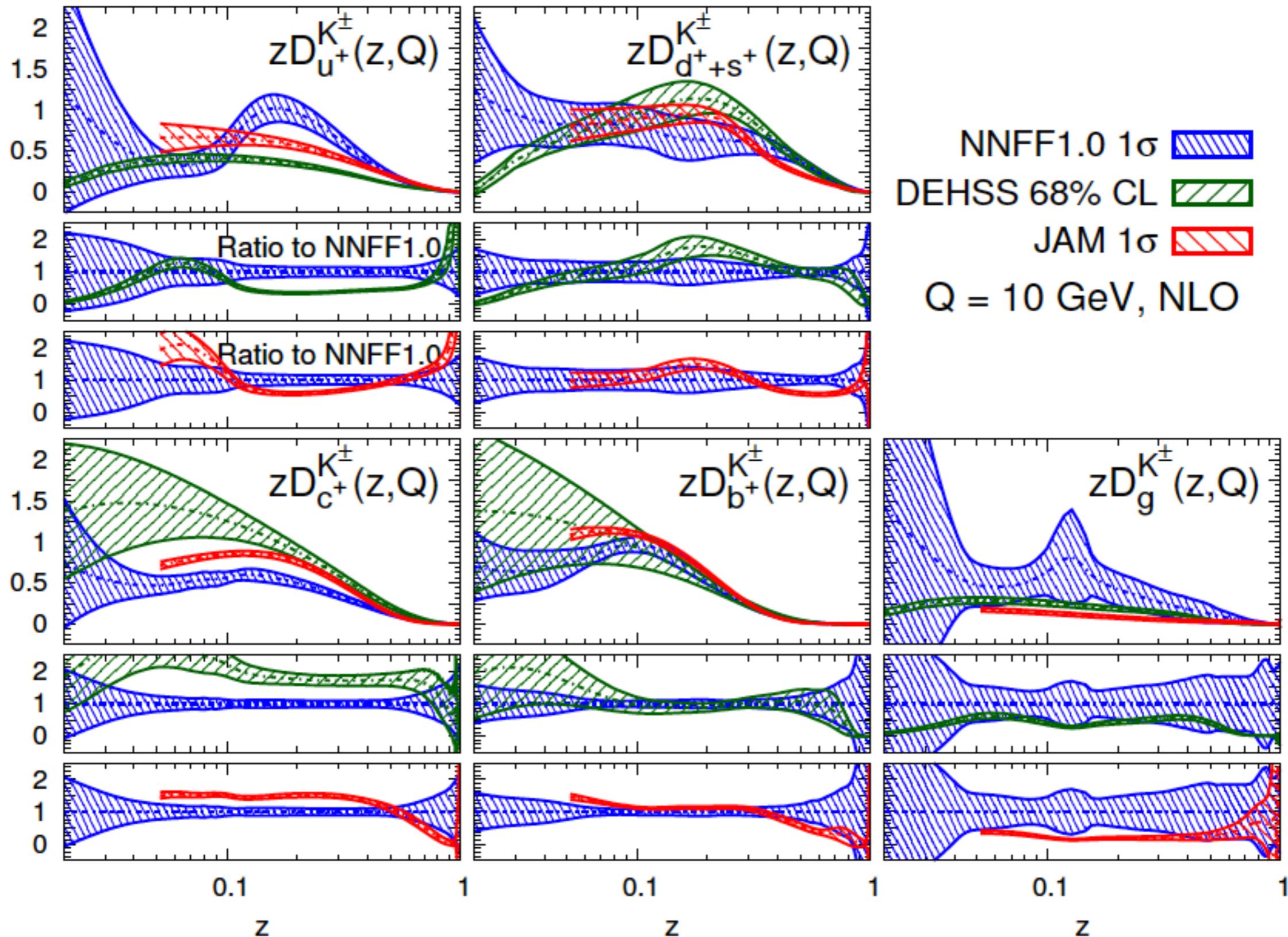
Collinear unpolarised

Fragmentation functions: Pions



Collinear unpolarised

Fragmentation functions: Kaons



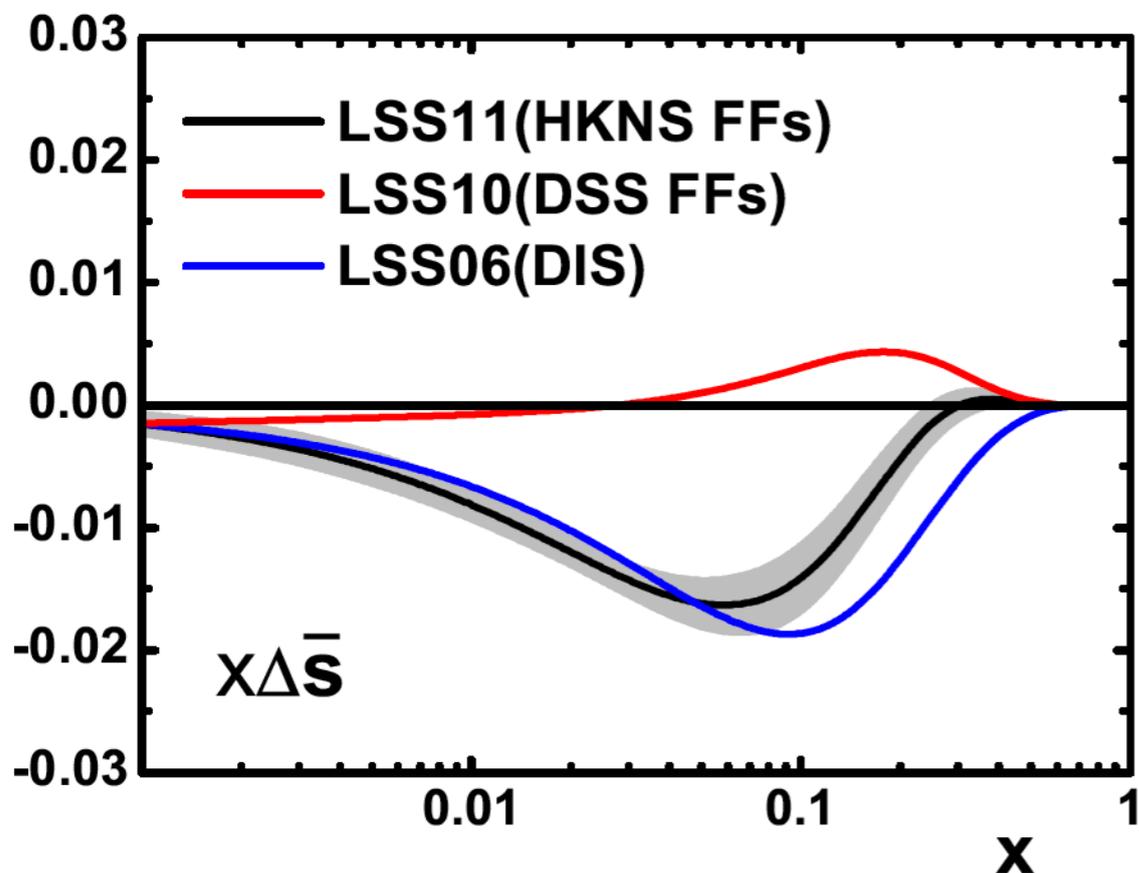
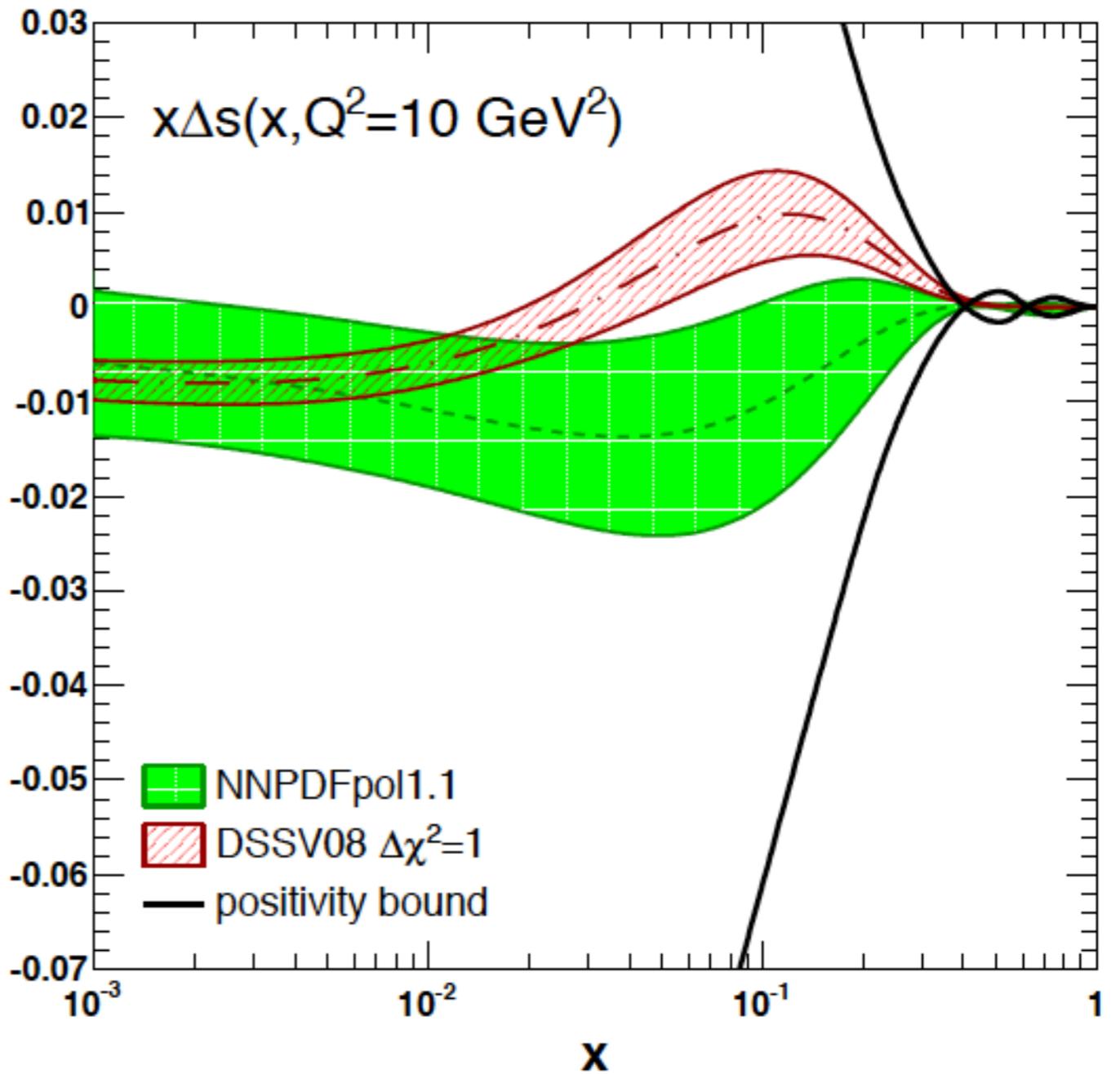
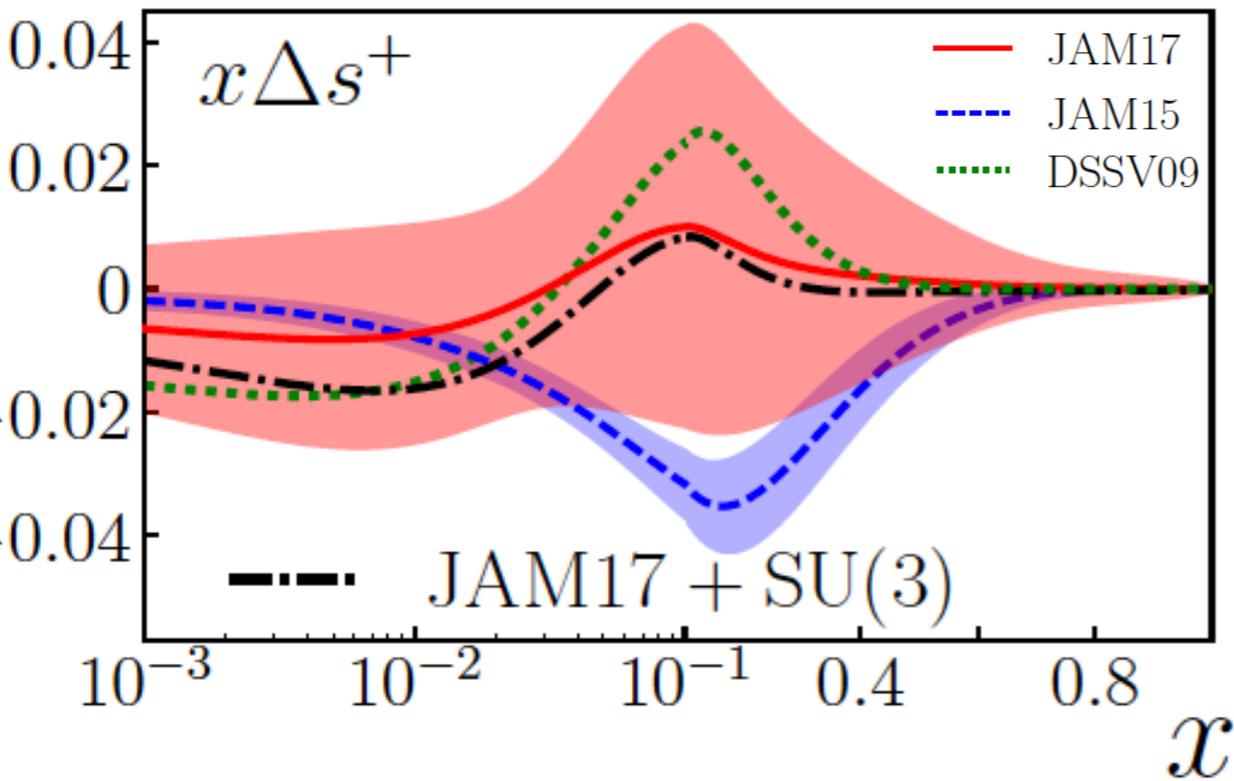
Collinear polarised PDF

Longitudinally polarised

- Not much **effort** into the determination of helicity PDFs:
 - limited experimental **data** available (RHIC, DESY, SLAC, CERN).
 - towards a sound treatment of the experimental information.
 - Accurate theoretical **calculations** (NLO is the current standard):
 - SIA, SIDIS, hadron-hadron collision,
 - A number of **active collaborations**:
 - DEHSS, JAM, NNFF, (HKNS), etc.
 - Very few available **public tools**:
 - APFEL, something else?
- **Lack of agreement** amongst different determinations:
 - specifically, the question of the strangeness.

Collinear polarised PDF

Longitudinally polarised



- The **strange quark distribution** is very sensitive to the FF set used in the analysis.
- A simultaneous fit of PDFs and FFs may help.

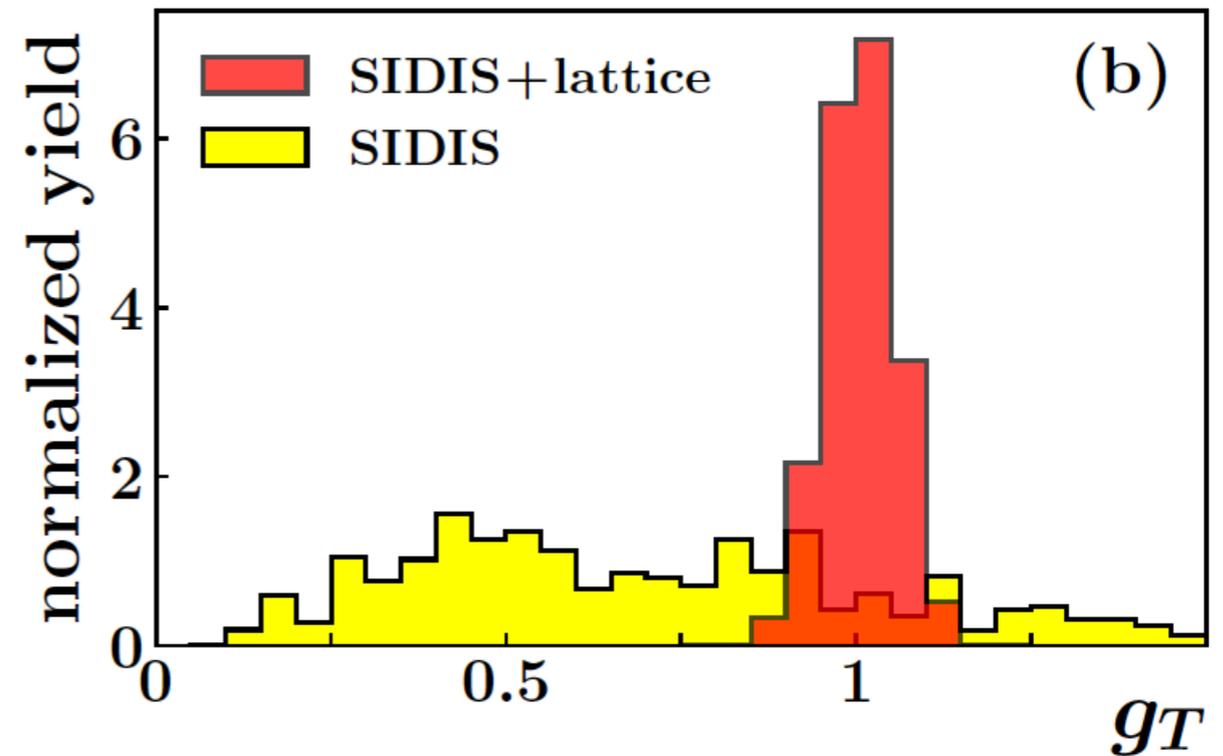
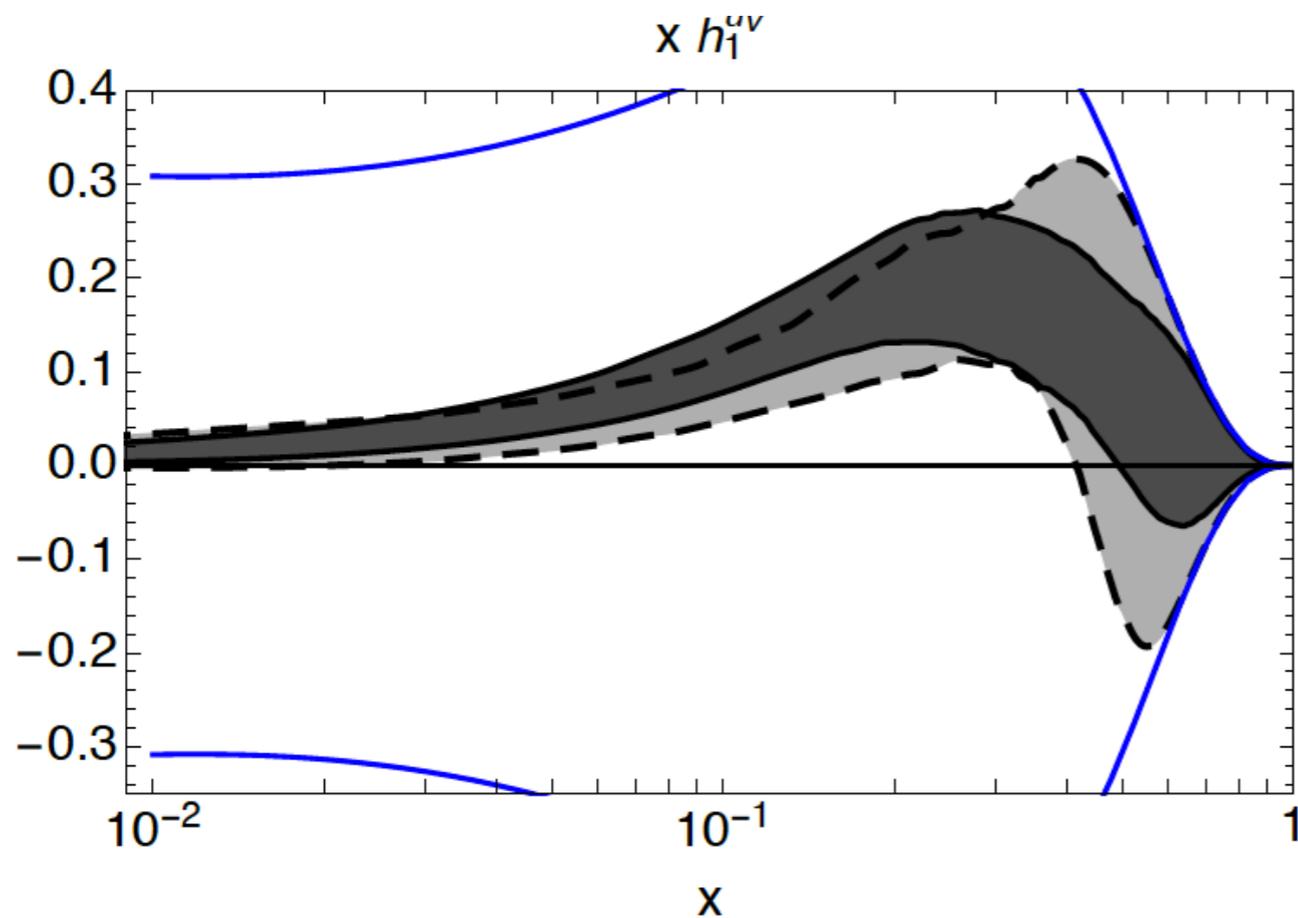
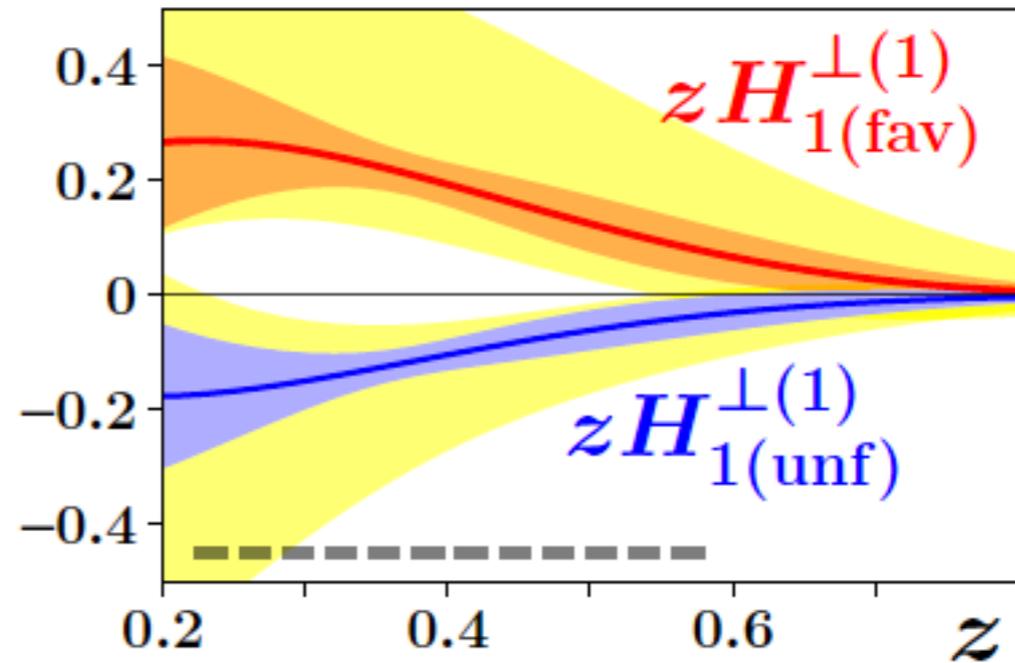
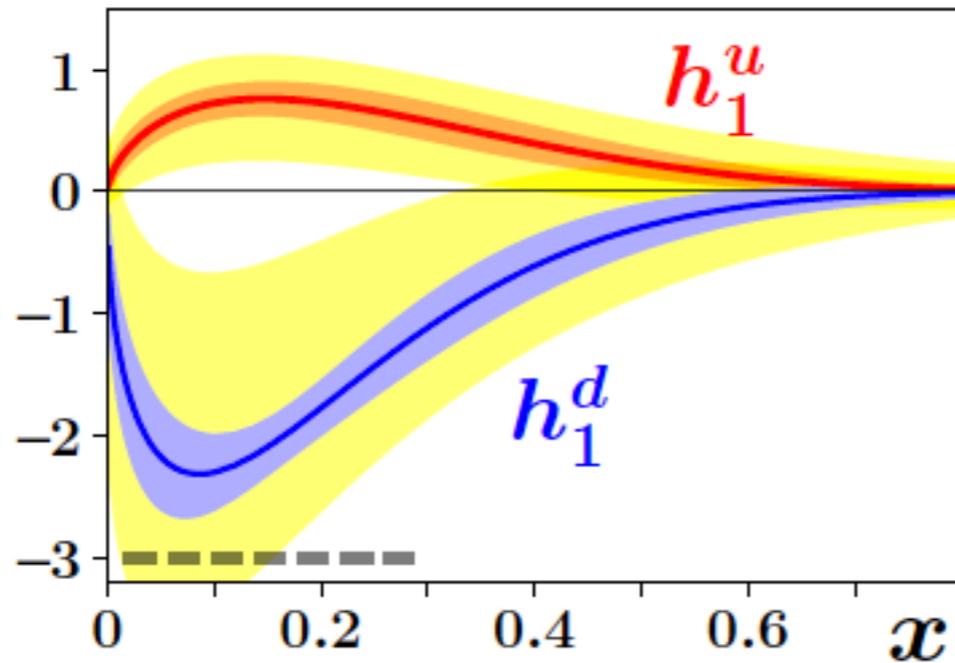
Collinear polarised

Transversely polarised

- Not much **effort** into the determination of transversities:
 - limited experimental **data** available (HERMES, COMPASS, STAR).
 - Is the experimental information fully exploited?
 - Can we trust “lattice data”?
 - No accurate theoretical **calculations** (nothing beyond LO):
 - SIDIS, hadron-hadron collision,
 - A couple of **active collaborations**:
 - Radici & Bacchetta, JAM, someone else.
 - Essentially **no available public tools**:
 - private implementations of the DGLAP evolution in Hoppet and APFEL.
- Some **fundamental** problems still open:
 - specifically, the question of the tensor charge.

Collinear polarised

Transversely polarised

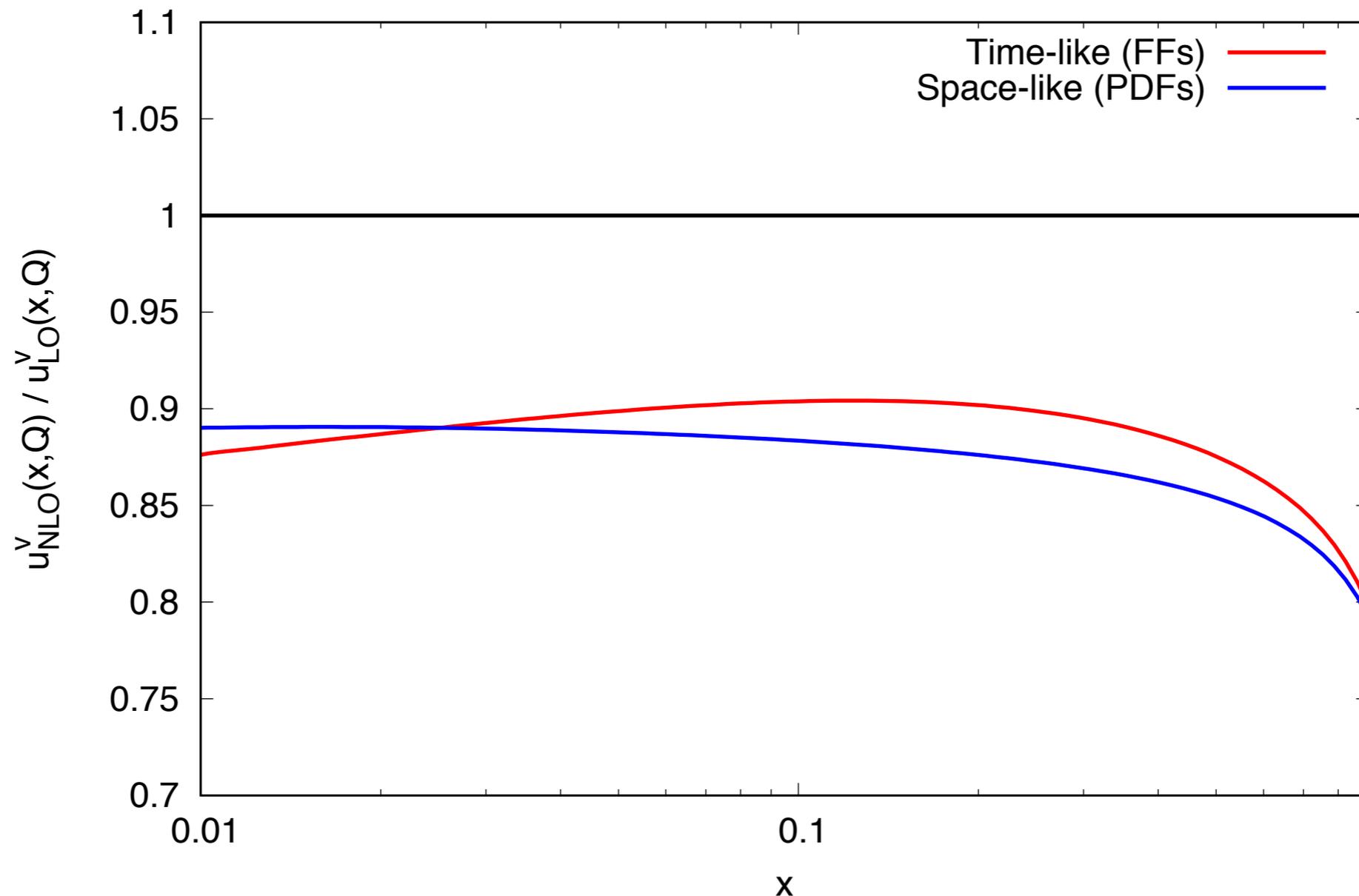


Collinear polarised

Transversely polarised

- LO and **NLO** transversity DGLAP evolution as implemented in APFEL:

Transversity collinear evolution $Q = 10$ GeV



- **Large impact** of the NLO corrections.
- Working on a **fit** accurate at NLO.

q_T dependence

Collinear and TMD frameworks

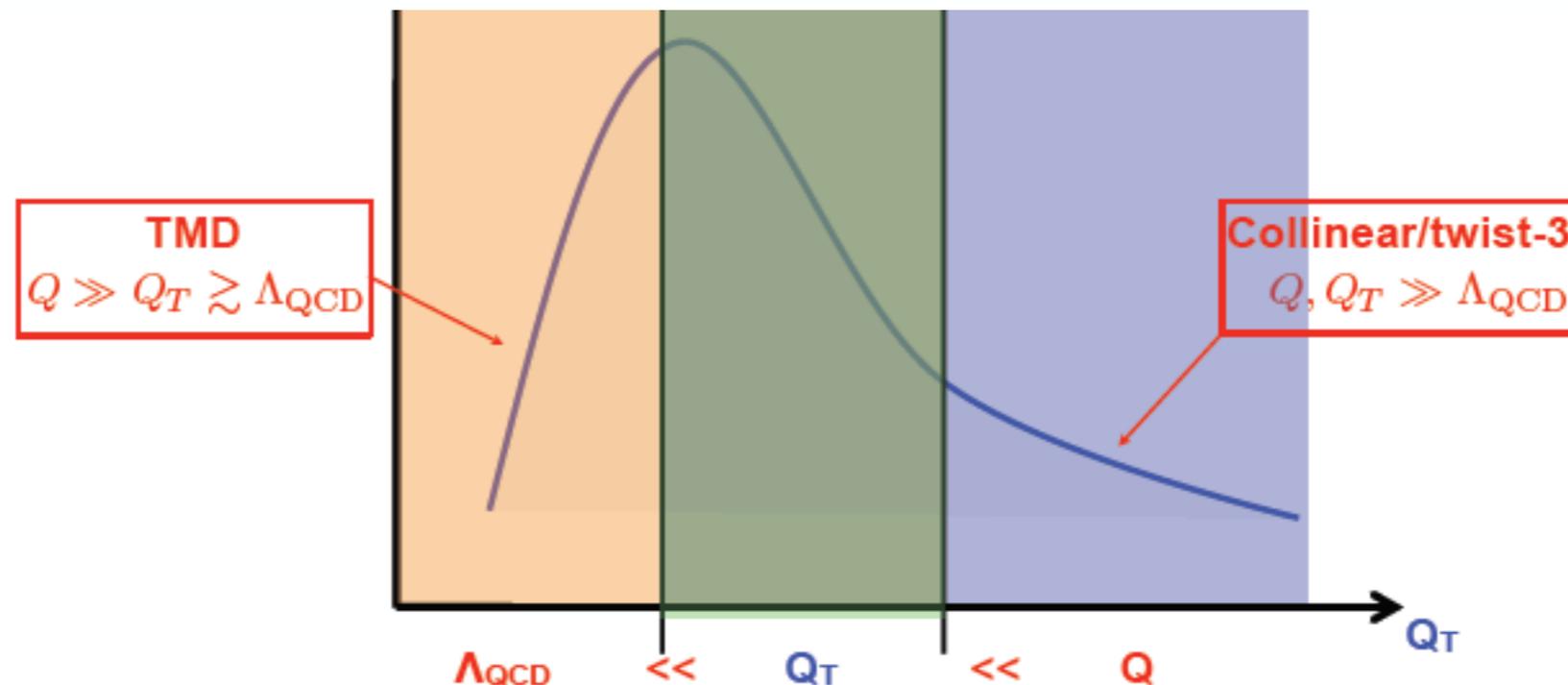
- Referring to **colourless** final-state processes, the description of q_T dependent observables is based on two well-established frameworks:
 - the **TMD** framework for $q_T \ll Q$,
 - the **collinear** framework for $q_T \approx Q$.
- These two regimes can be **matched** leading to *theoretically* possibly accurate predictions over the full range in q_T .
- However, assuming that collinear distributions are determined reliably, the very-low q_T (TMD) region receives **non-perturbative** contributions that need to be determined from data.
- A lot of effort has been put into the determination of the TMD non-perturbative component but still far from a general agreement:
 - different prescriptions (CSS, Parton Branching, Scimemi-Vladimirov, etc.),
 - different perturbative orders and orderings,
 - ...

q_T dependence

Collinear and TMD frameworks

- At **relatively high energies**, the separation between small- and large- q_T regimes is unambiguous:
 - **safe** application of the two frameworks in the respective regions,
 - just some care required in the **transition region** $\Lambda_{\text{QCD}} \ll q_T \ll Q$ that is however well-defined (dependence on the matching prescription),
 - **limited** effect of the TMD non-perturbative contributions.

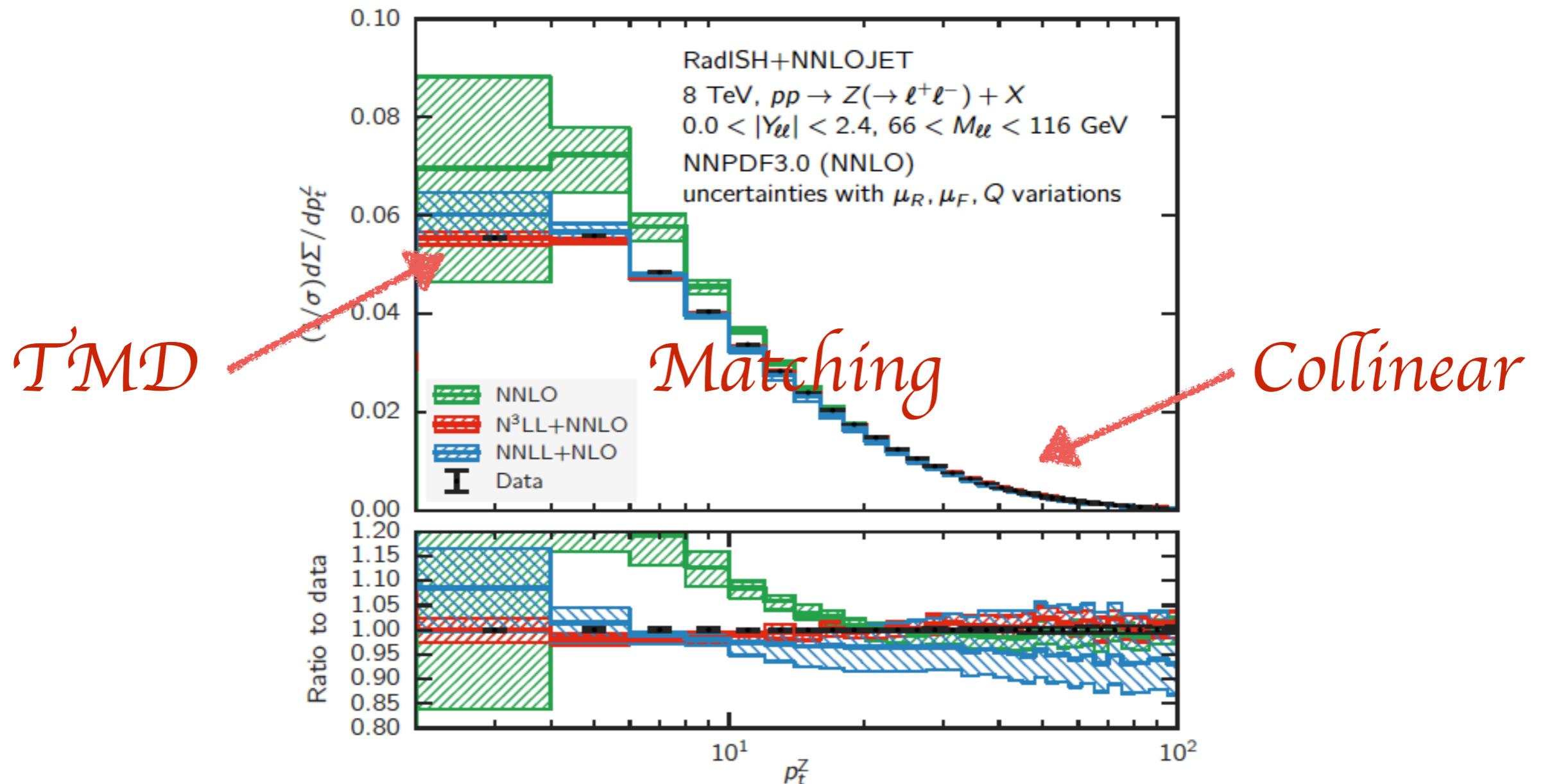
$$d\sigma(m \lesssim q_T \lesssim Q, Q) = W(q_T, Q) + Y(q_T, Q) + \mathcal{O}\left(\frac{m}{Q}\right)^c d\sigma(q_T, Q)$$



q_T dependence

Collinear and TMD frameworks

- Current state-of-the-art: $N^3LL + NNLO$ (no non-pert. effects):



- Excellent description of the precise ATLAS Z-production data.
- Limited impact of possible non-perturbative effects (a few %).
- However, this data can be used to determine the non-pert. component.

q_T dependence

Collinear and TMD frameworks

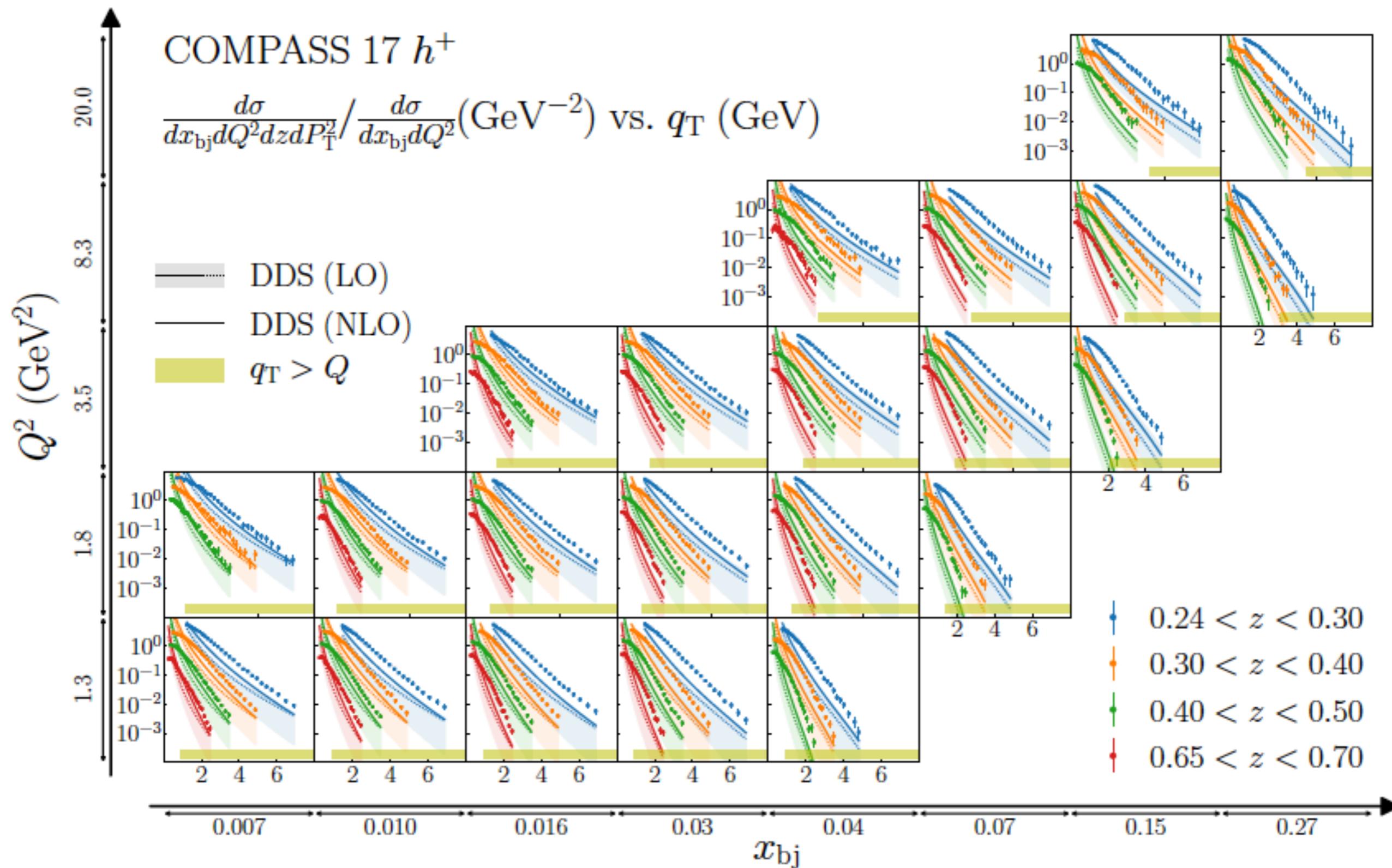
- More complicated situation if Λ_{QCD} and Q are not very far apart:

$$d\sigma(m \lesssim q_T \lesssim Q, Q) = W(q_T, Q) + Y(q_T, Q) + \mathcal{O}\left(\frac{m}{Q}\right)^c d\sigma(q_T, Q)$$

- **SIDIS multiplicity data** from HERMES and COMPASS.
- In these conditions **other effects** may (and do) become relevant:
 - TMD non-perturbative components,
 - higher-twist effects,
 - target-mass corrections,
 - heavy-quark mass corrections,
 - treatment of the DIS inclusive structure functions,
 - ...
- Is it so hopeless to achieve a reasonable description of this data?

q_T dependence

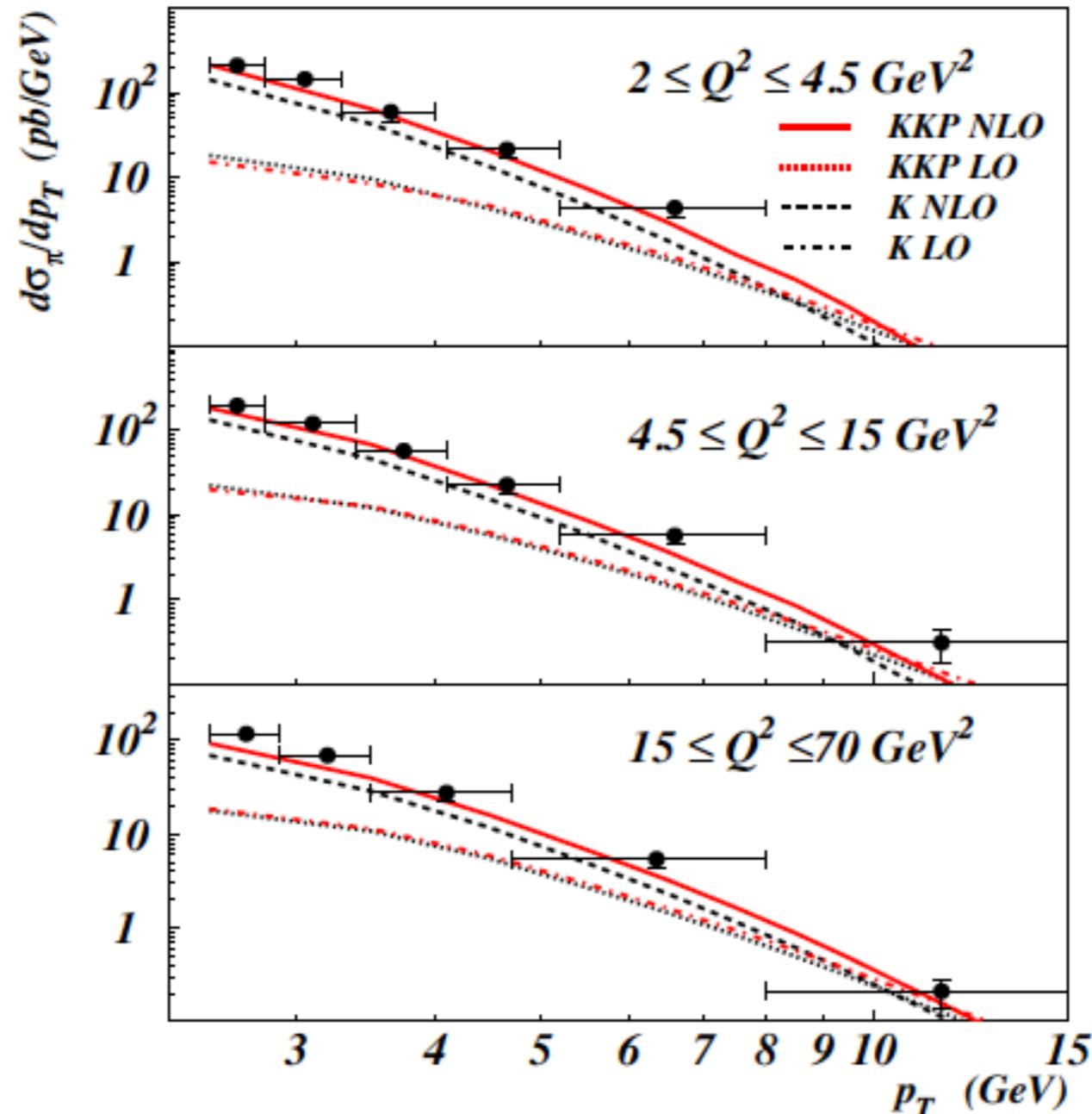
Theoretical issues: utter failure of the NLO fixed order?



q_T dependence

Theoretical issues: utter failure of the NLO fixed order?

- ... possibly not!

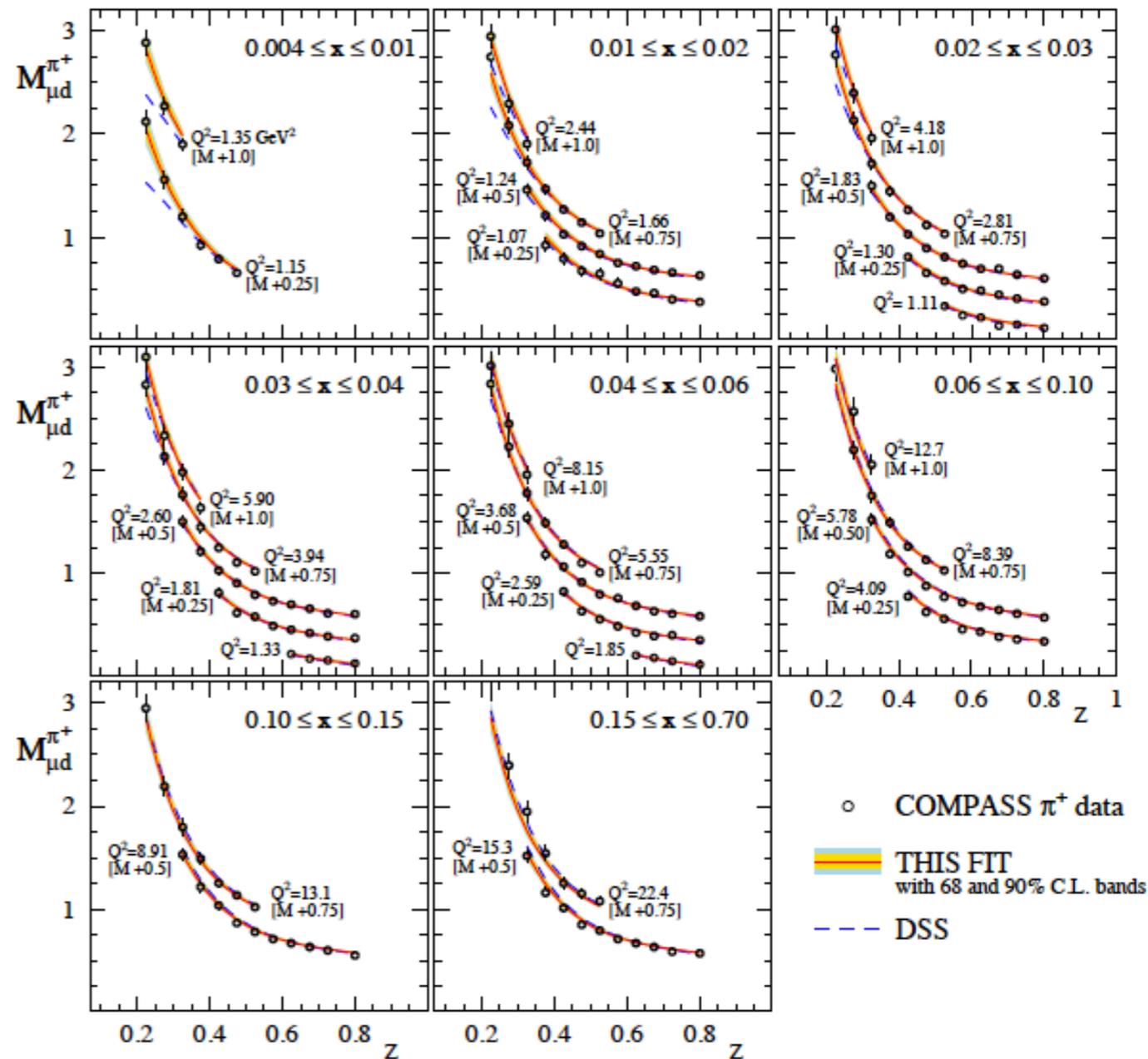
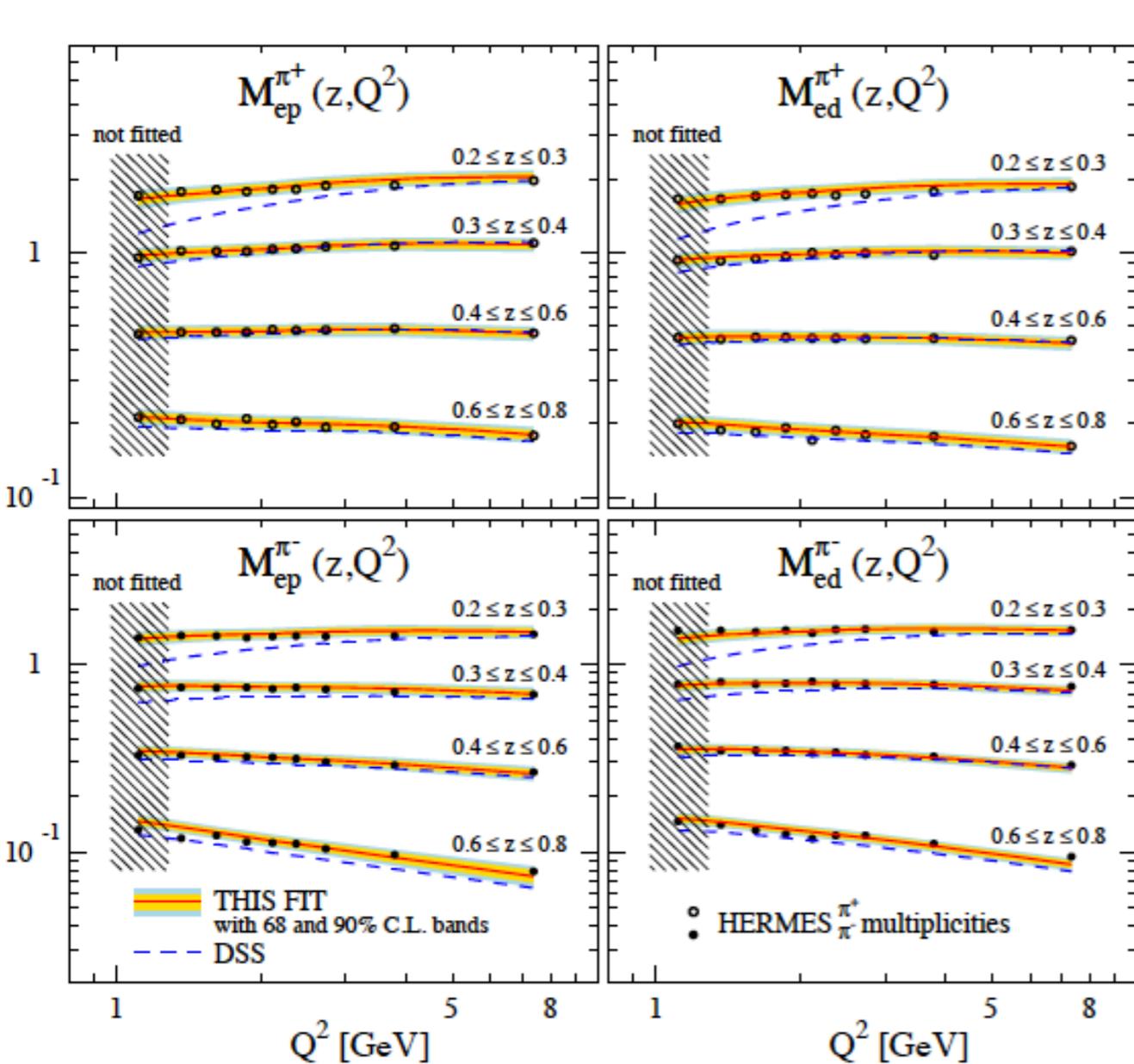


- Back in 2004 Daleo *et al.* showed that NLO corrections were fundamental to describe H1 data.

q_T dependence

Theoretical issues: utter failure of the NLO fixed order?

● ... possibly not!



● q_T **integrated** cross sections are well described by NLO fixed-order

q_T dependence

Computational tools: *arTeMiDe*

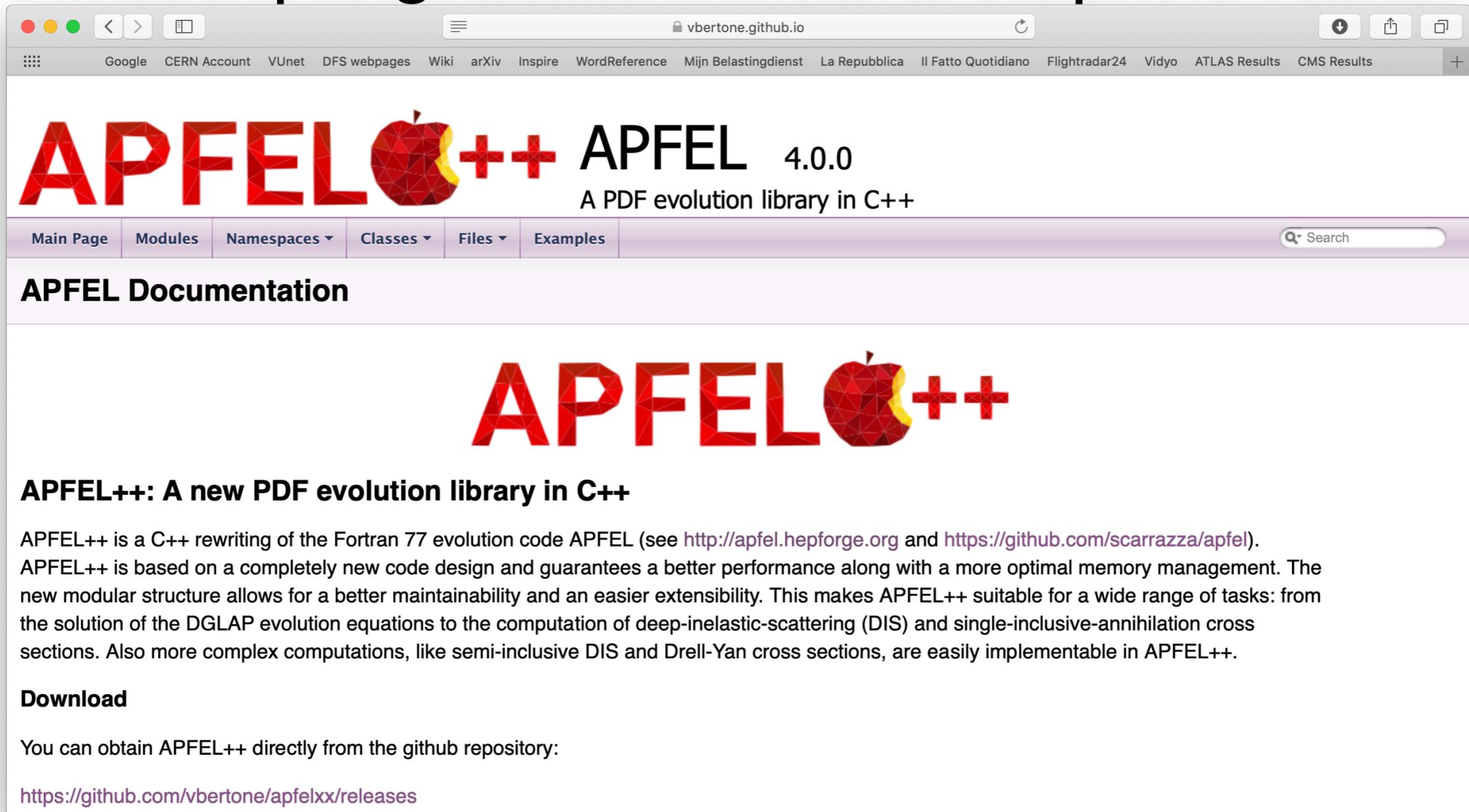
<https://teorica.fis.ucm.es/artemide/>

- Computes low- q_T Drell-Yan cross sections up to NNLL in the “Scimemi-Vladimirov” scheme (modified TMD evolution plus ζ -prescription).

qt dependence

Computational tools: APFEL++

<https://github.com/vbertone/apfelxx>



APFEL++ 4.0.0
A PDF evolution library in C++

Main Page Modules Namespaces Classes Files Examples Search

APFEL Documentation



APFEL++: A new PDF evolution library in C++

APFEL++ is a C++ rewriting of the Fortran 77 evolution code APFEL (see <http://apfel.hepforge.org> and <https://github.com/scarrazza/apfel>). APFEL++ is based on a completely new code design and guarantees a better performance along with a more optimal memory management. The new modular structure allows for a better maintainability and an easier extensibility. This makes APFEL++ suitable for a wide range of tasks: from the solution of the DGLAP evolution equations to the computation of deep-inelastic-scattering (DIS) and single-inclusive-annihilation cross sections. Also more complex computations, like semi-inclusive DIS and Drell-Yan cross sections, are easily implementable in APFEL++.

Download

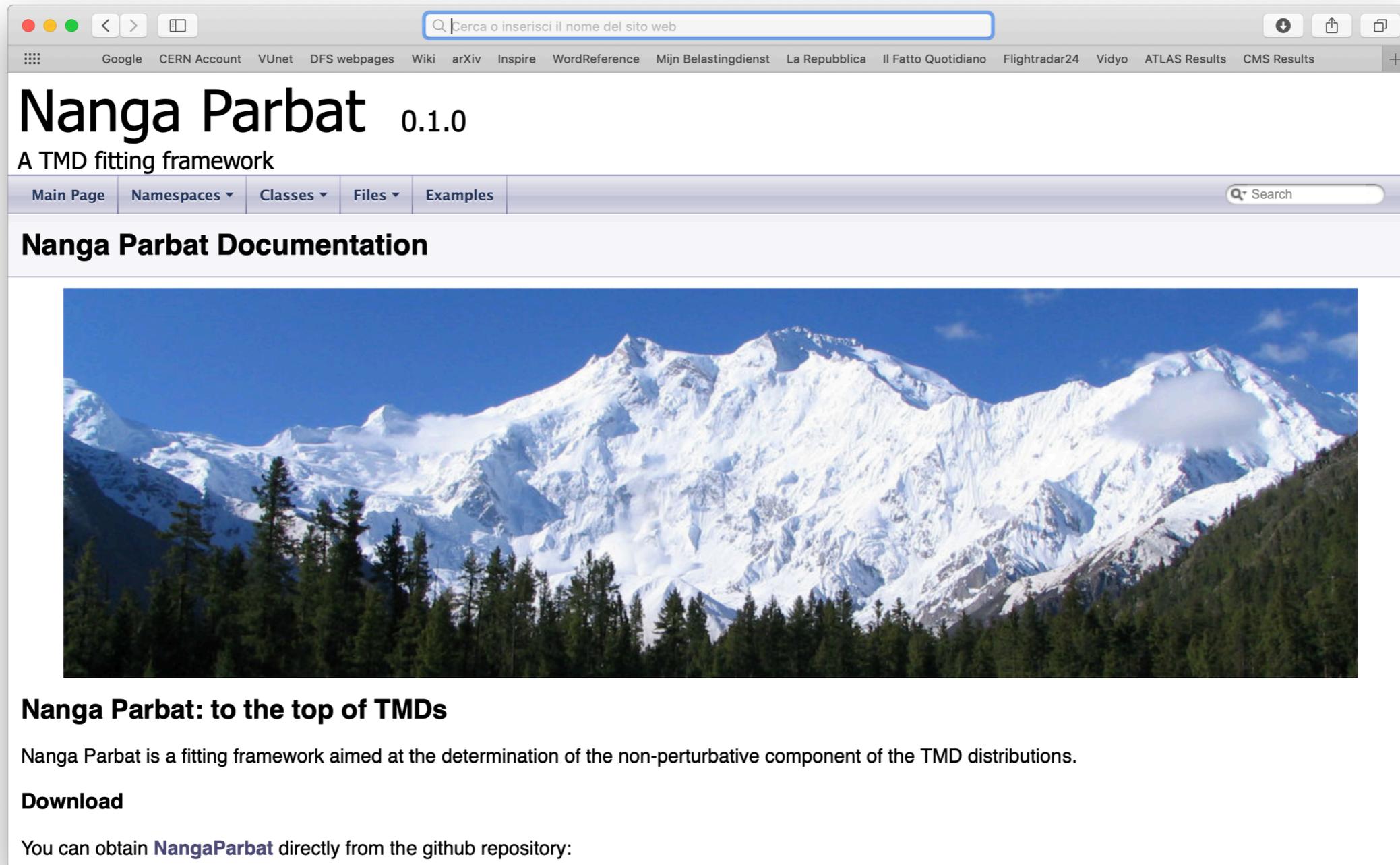
You can obtain APFEL++ directly from the github repository:

<https://github.com/vbertone/apfelxx/releases>

- General framework for the fast computation of convolutions and integrals. C++ evolution of APFEL, used in many studies such as the NNPDF fits.

qt dependance

Computational tools: Nanga Parbat



Nanga Parbat 0.1.0
A TMD fitting framework

Main Page Namespaces Classes Files Examples Search

Nanga Parbat Documentation



Nanga Parbat: to the top of TMDs

Nanga Parbat is a fitting framework aimed at the determination of the non-perturbative component of the TMD distributions.

Download

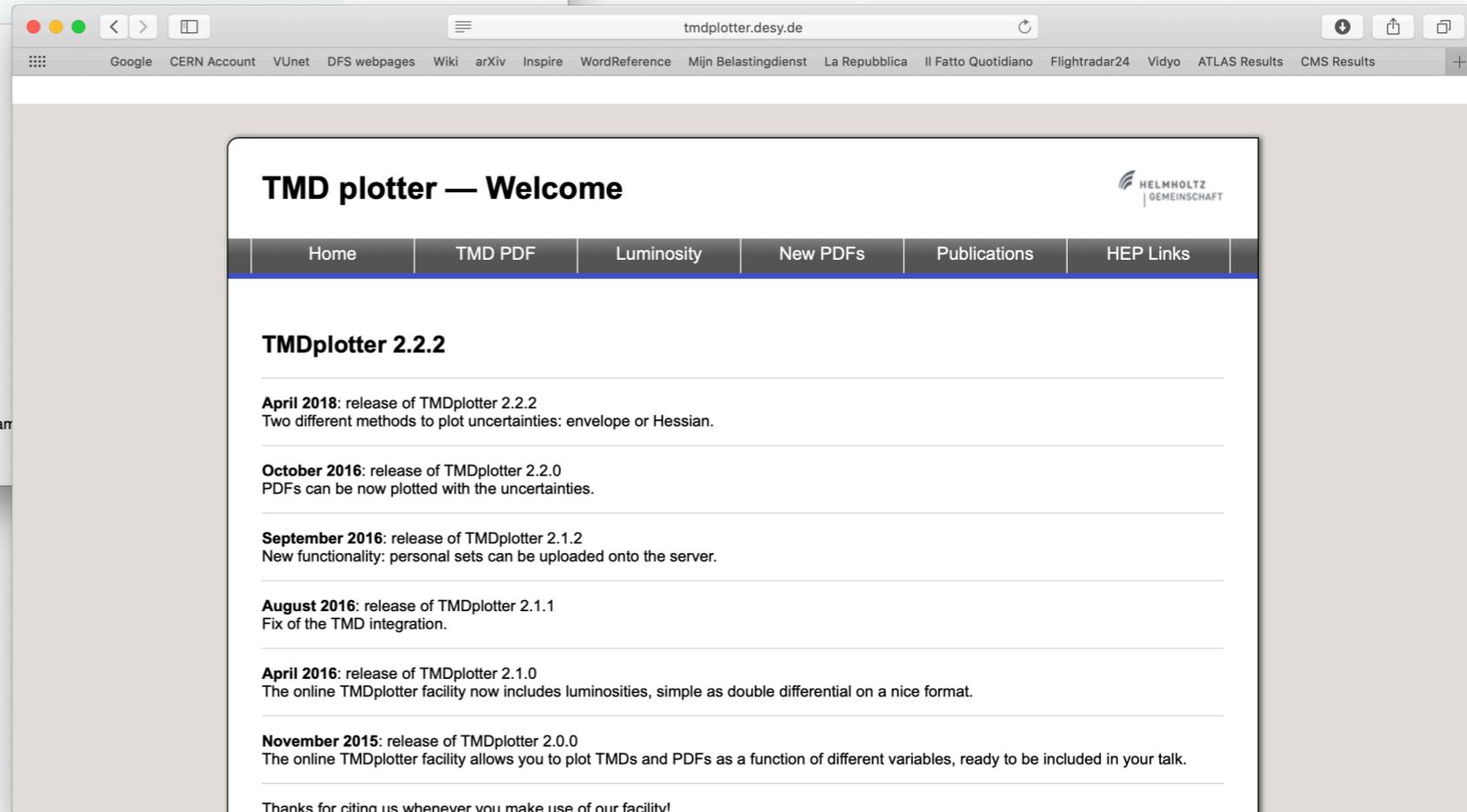
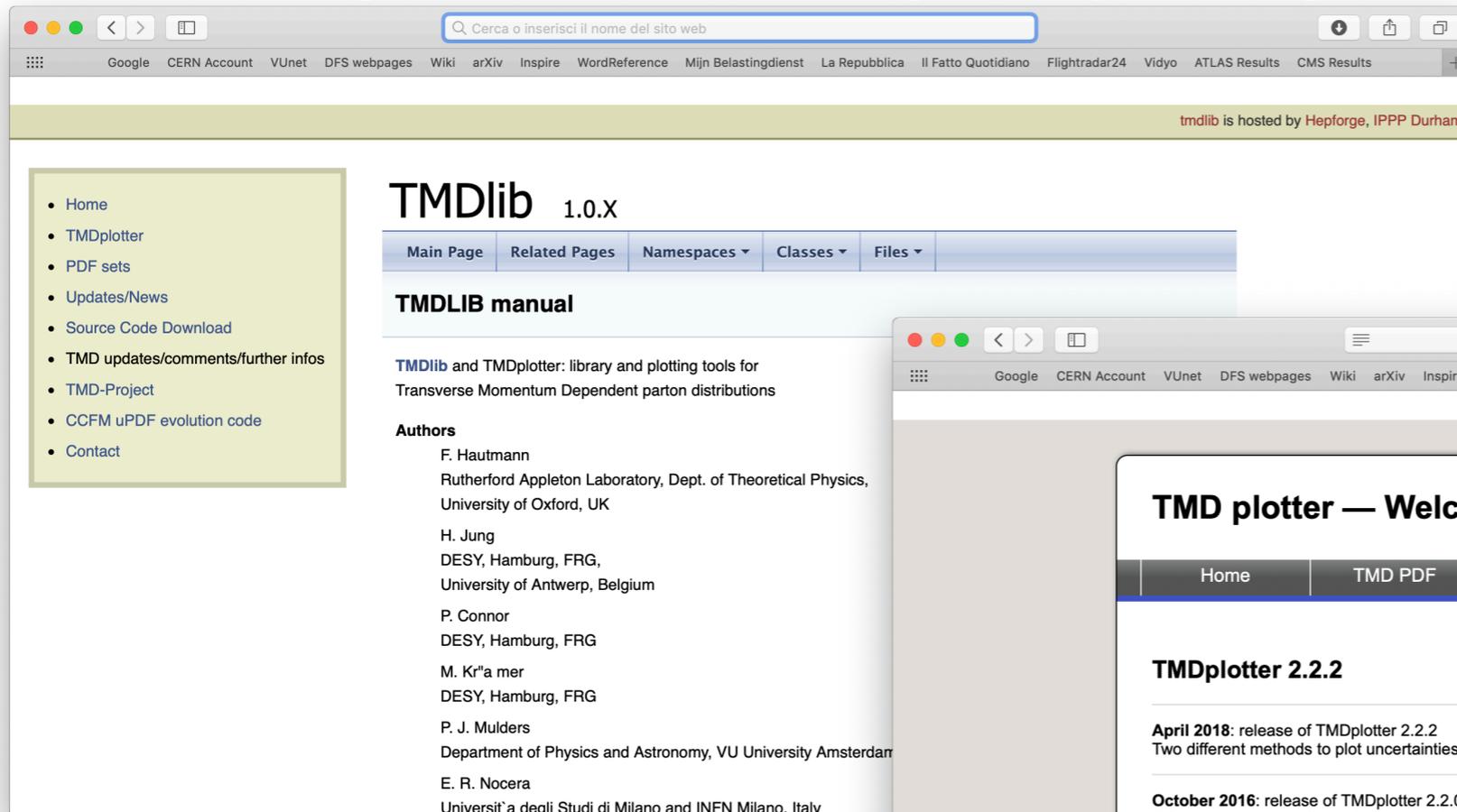
You can obtain [NangaParbat](#) directly from the github repository:

- The TMD fitting framework based on APFEL++ and that is currently being developed by the Pavia's group to extract TMD PDFs and FF.

qt dependance

Computational tools: *TMDlib* and *TMDplotter*

<https://tmdlib.hepforge.org/doxy/html/index.html>



- Library and plotting tools for Transverse Momentum Dependent parton distributions.

Thank you