# Collinear and TMD distributions

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3DSPIN
MAPPING THE PROTON IN 3D

# 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.

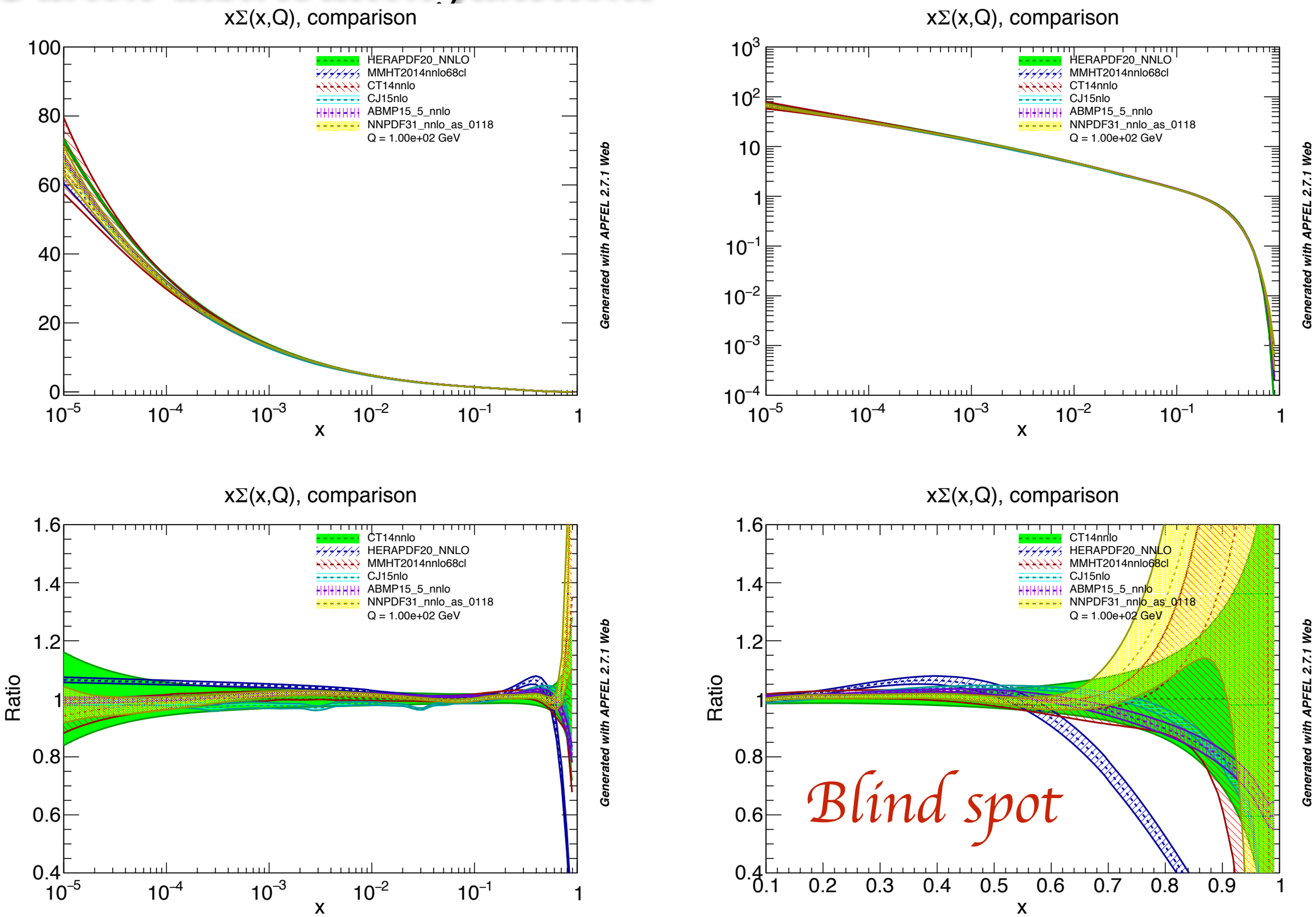
# Collinear unpolarised

*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*



# Collinear unpolarised

## *Aside: APFEL Web*

https://apfel.mi.infn.it

apfel.mi.infn.it

Google CERN Account VUnet DFS webpages Wiki arXiv Inspire WordReference Mijn Belastingdienst La Repubblica Il Fatto Quotidiano Flightradar24 Vidyo ATLAS Results CMS Results

APFEL Web Contact Sign up Login

### Welcome to APFEL online cluster!

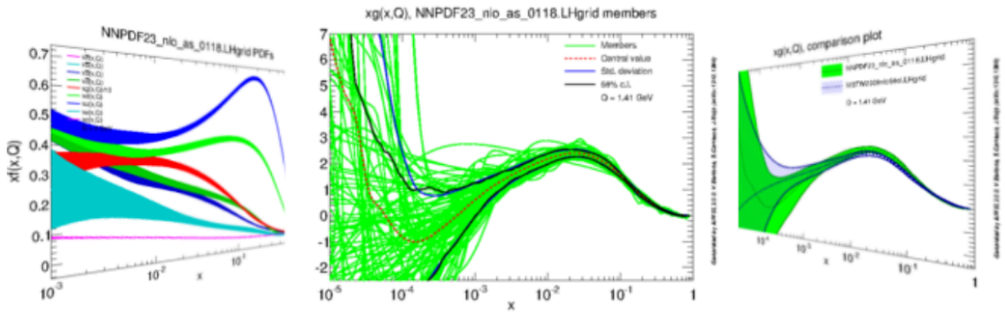
This web-application is a tool designed for High Energy Physics by providing a simple and intuitive interface to plot and compute the most common observables with Parton Distribution Functions (PDFs).

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.

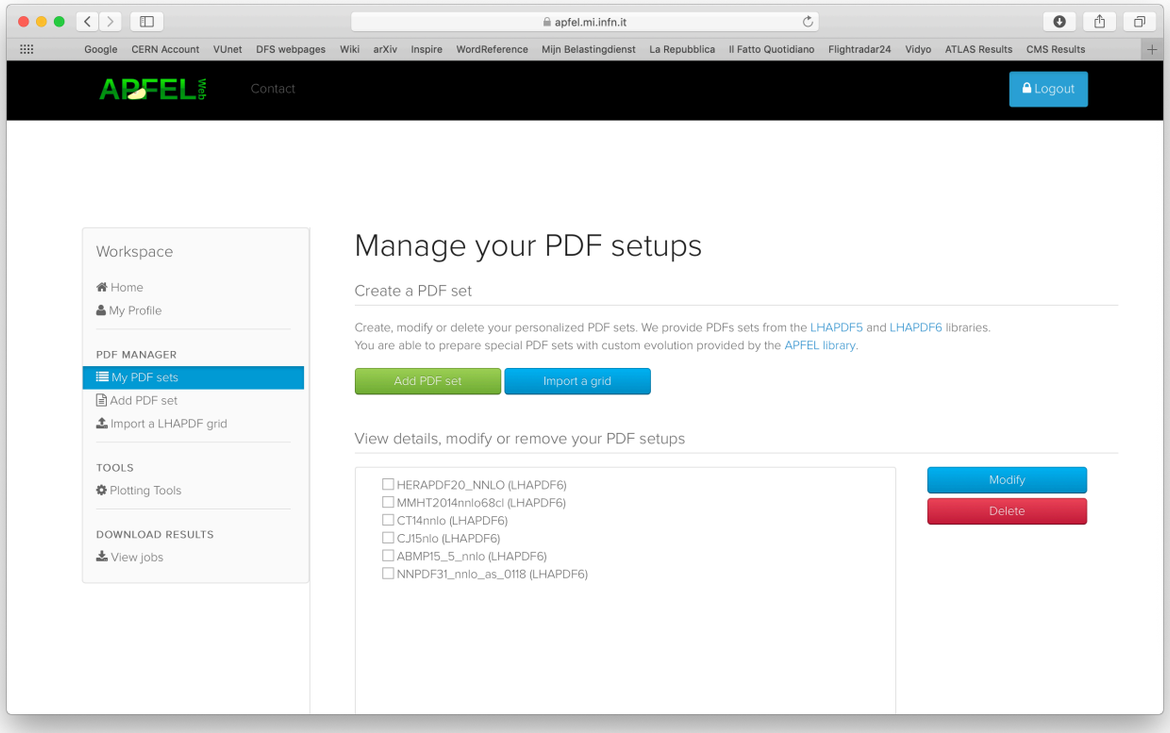
If you use the APFEL library or the online cluster in a scientific publication, please cite:
V. Bertone, S. Carrazza and J. Rojo, "APFEL: A PDF Evolution Library with QED corrections", Comput. Phys. Commun. 185, 1647 (2014), arXiv:1310.1394.
S. Carrazza et al., "APFEL Web: a web-based application for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

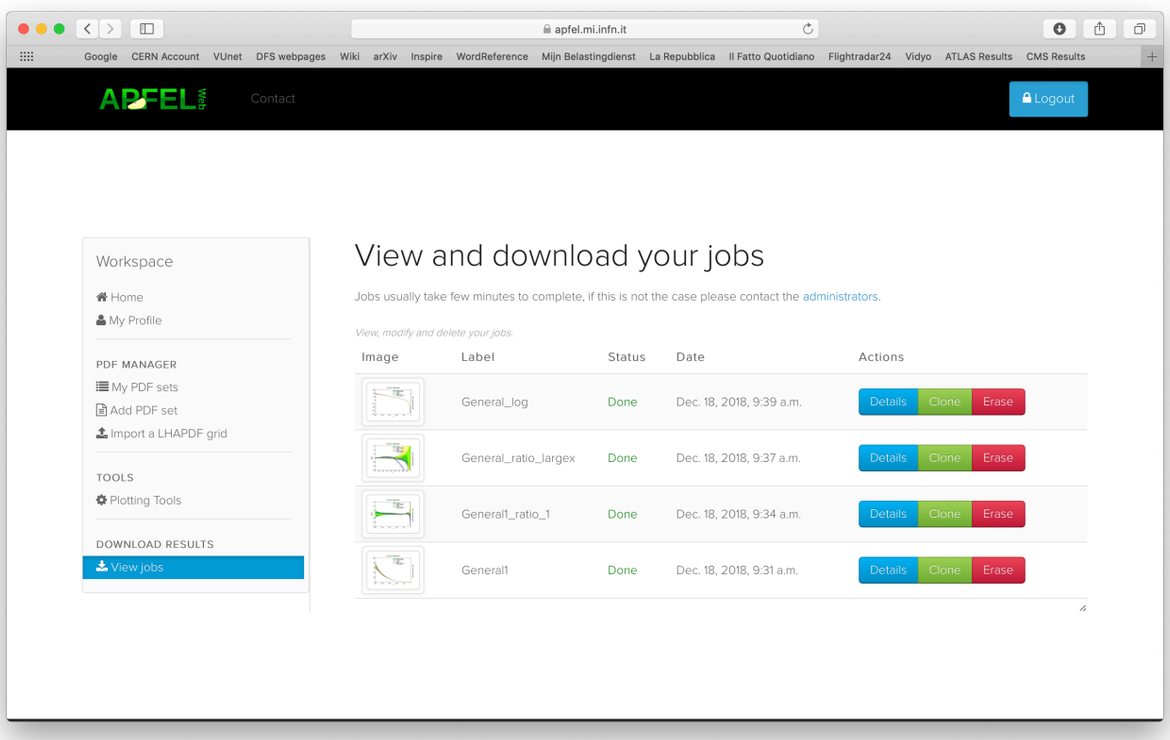


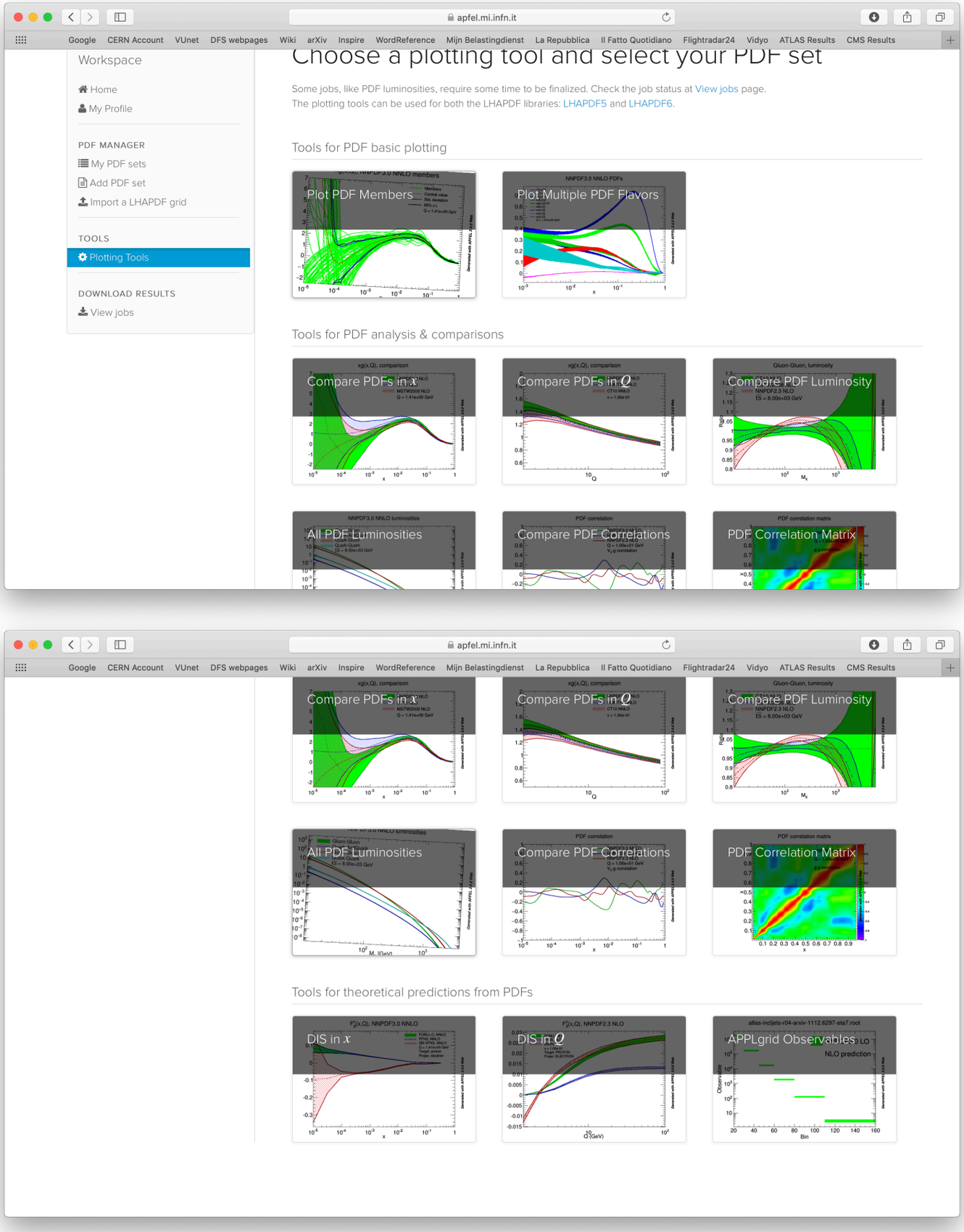

Web developers: D. Palazzo, S. Carrazza, A. Ferrara
APFEL developers: V. Bertone, S. Carrazza, J. Rojo. (Contact)

# Collinear unpolarised

## *Aside: APFEL Web*



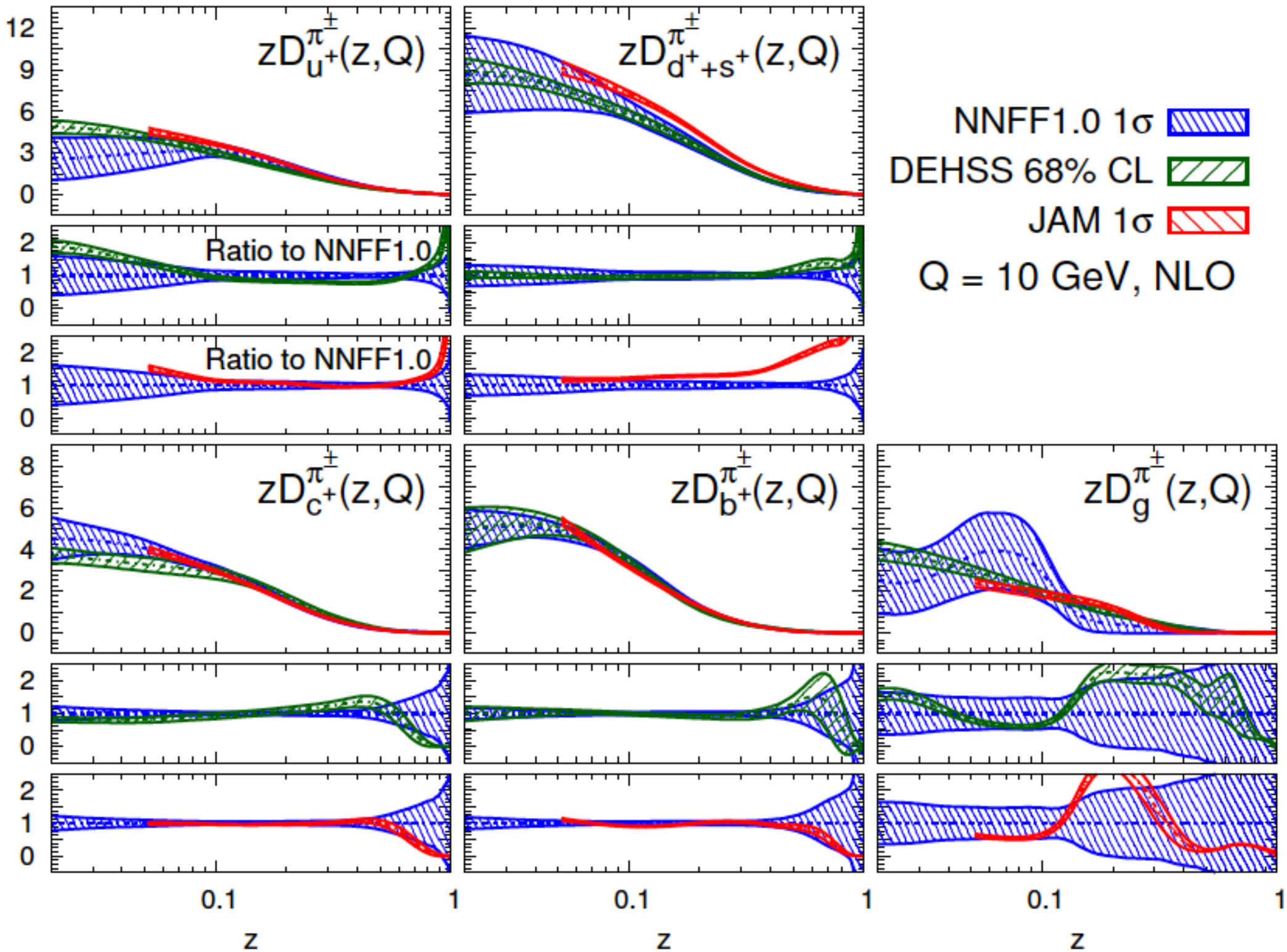
# Collinear unpolarised

*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.

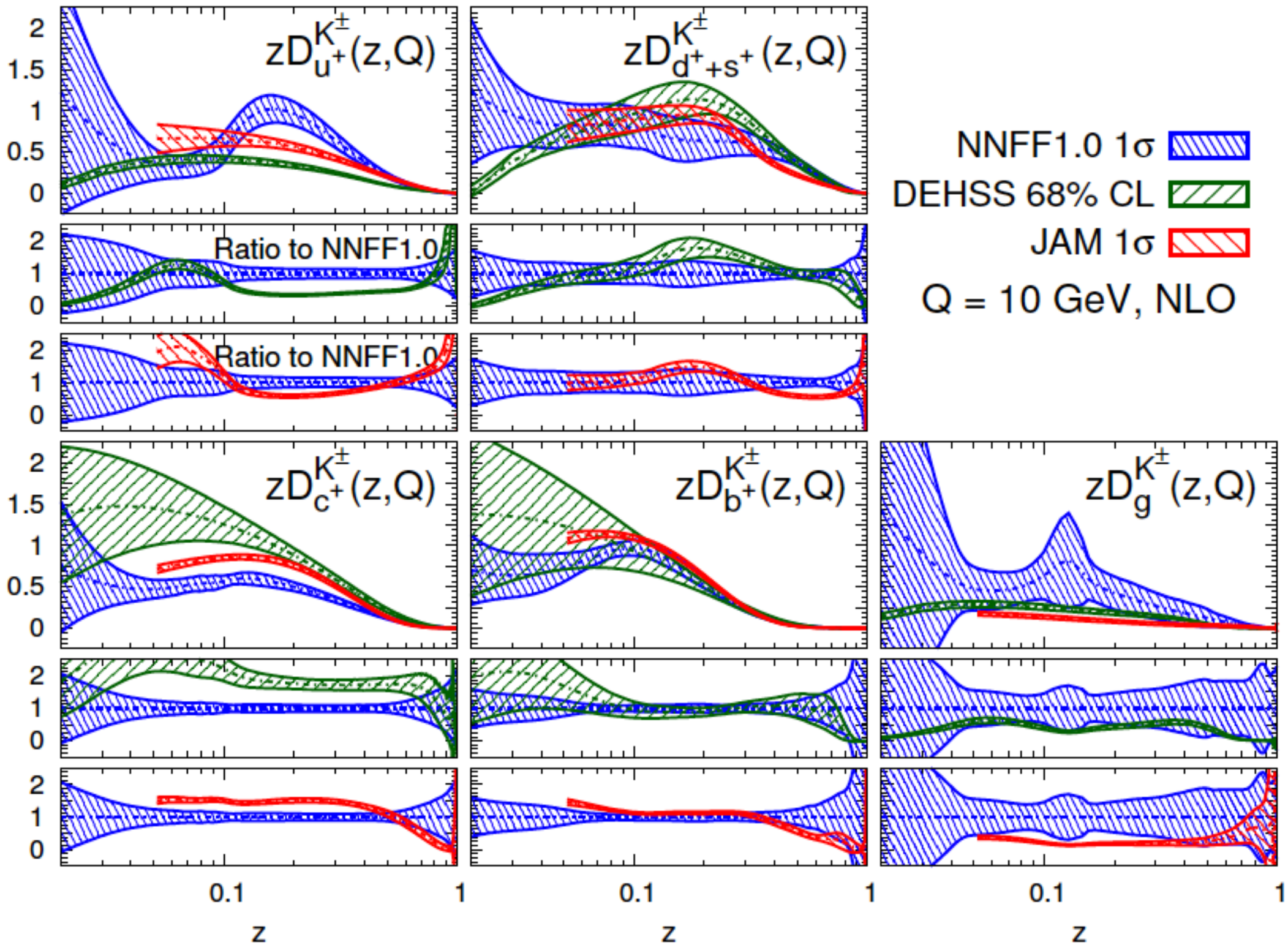
# Collinear unpolarised

*Fragmentation functions: Pions*



# Collinear unpolarised

*Fragmentation functions: Kaons*



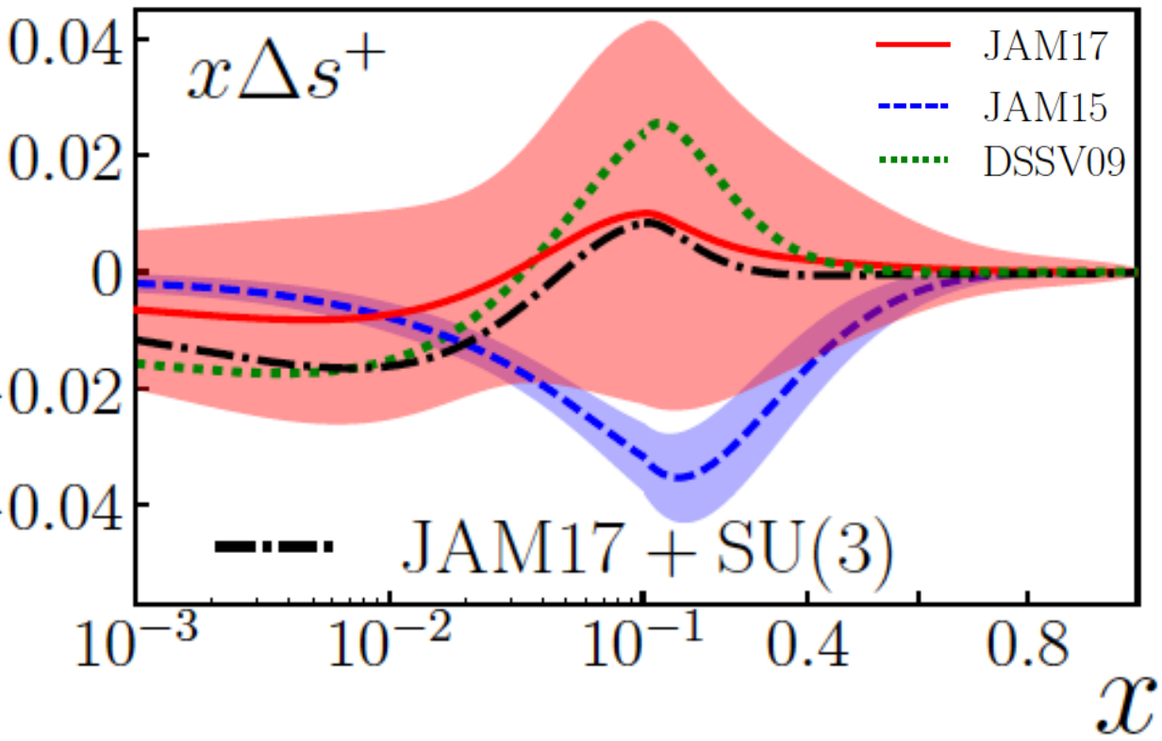
# Collinear polarised PDF

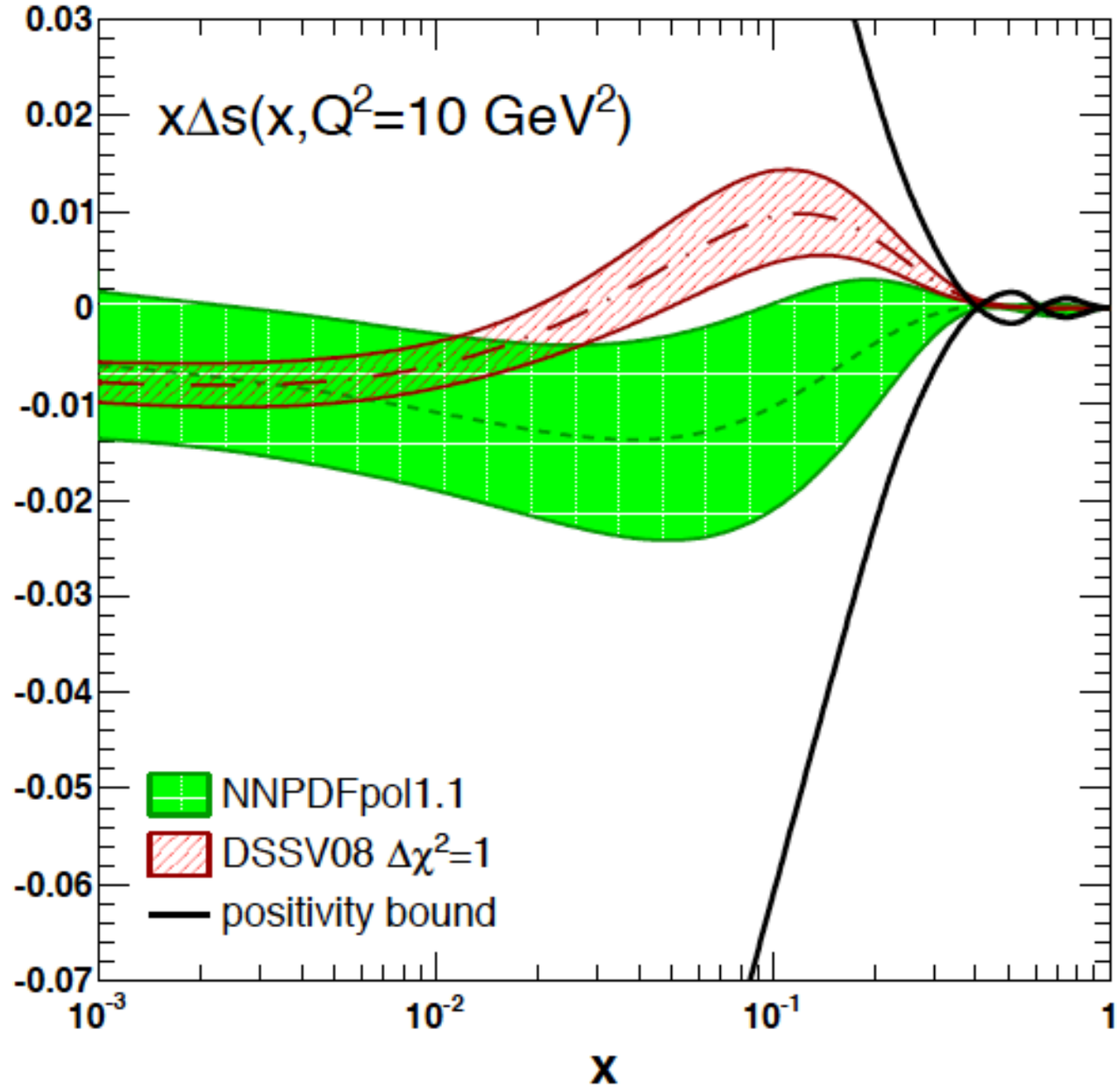
*Longitudinally polarised*

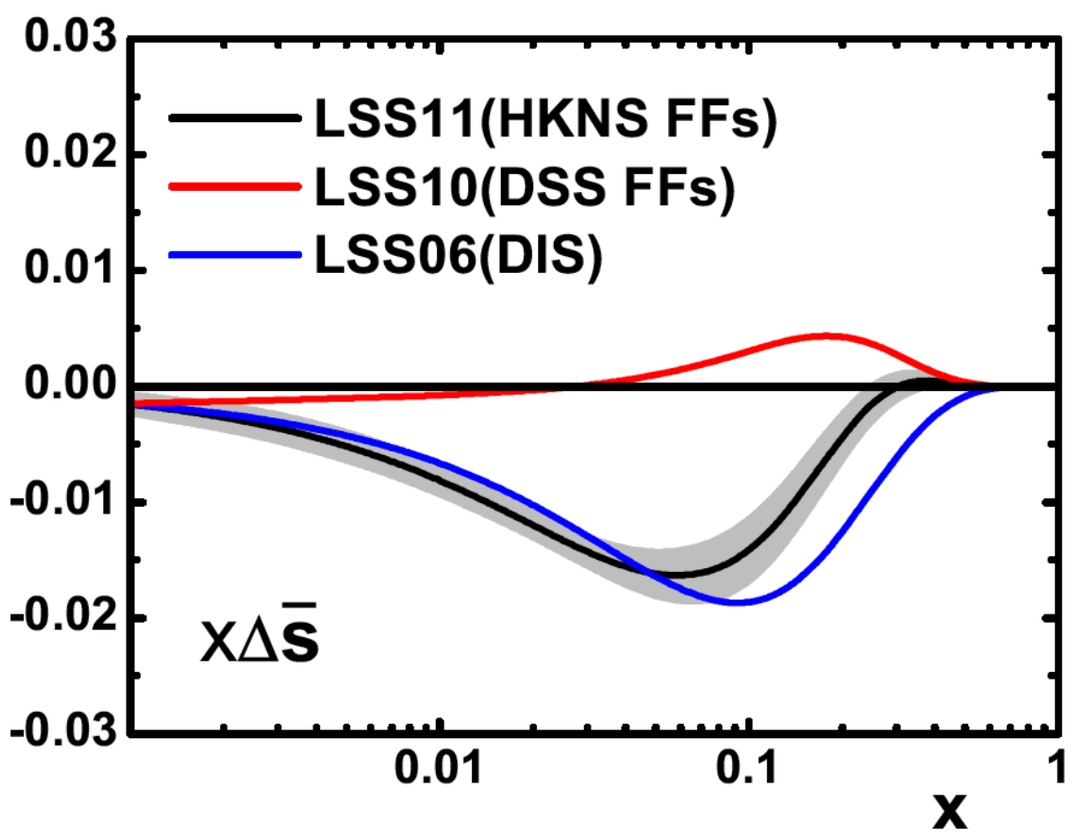
- Not much **effort** into the determination of helicity PDFs:
  - limited experimental **data** available (RHIC, DESY, SLAC, CERN).
    - towards a sound treatment of the experimental information.
  - Accurate theoretical **calculations** (NLO is the current standard):
    - SIA, SIDIS, hadron-hadron 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.

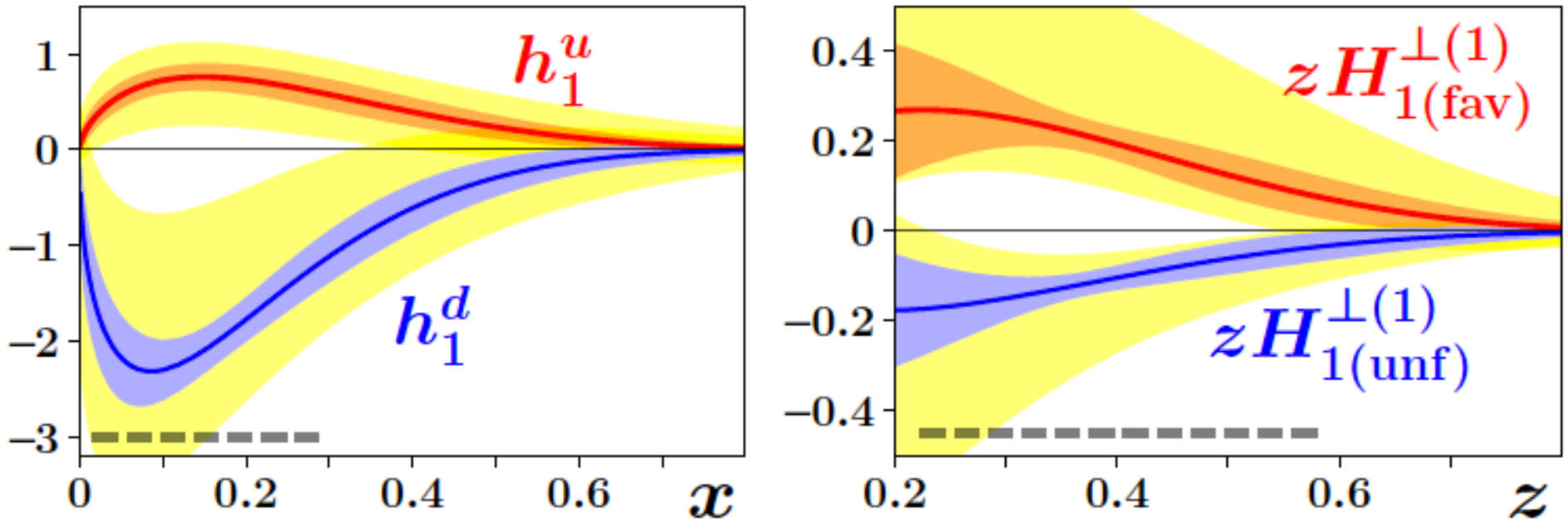
# Collinear polarised

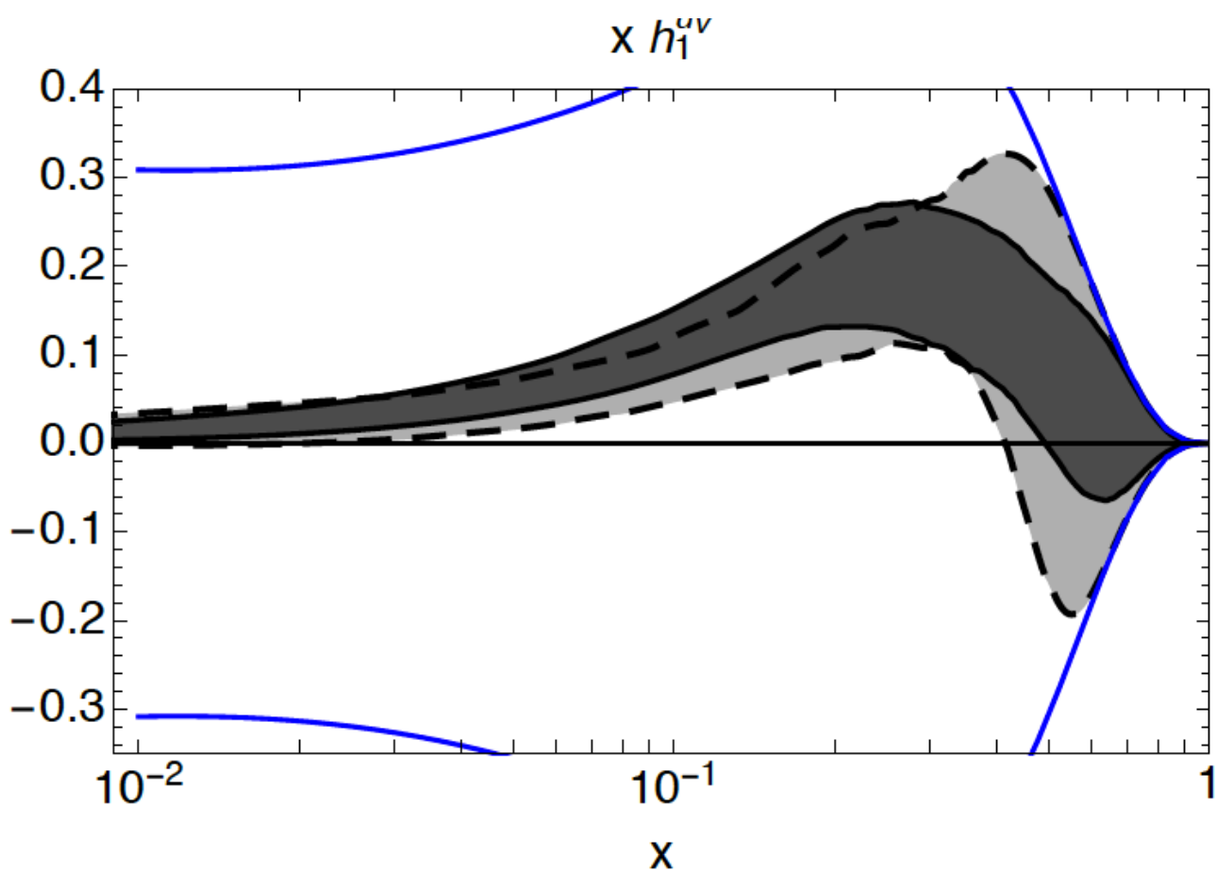
## *Transversely polarised*

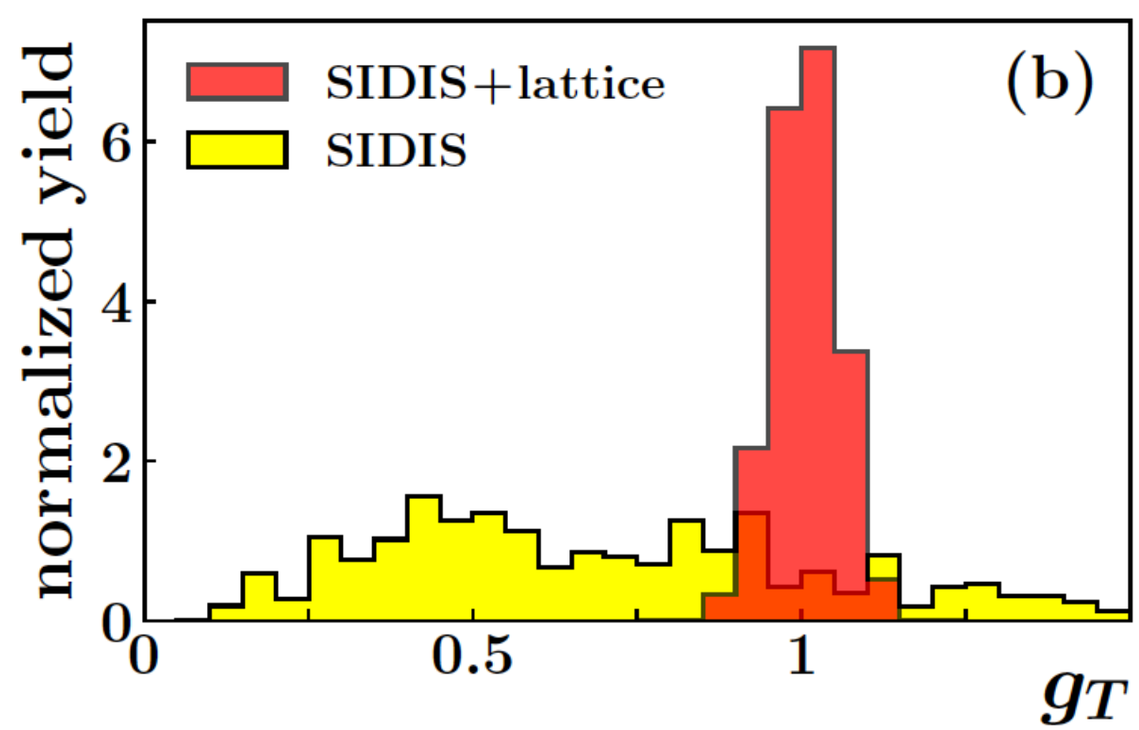
- Not much **effort** into the determination of transversities:
  - limited experimental **data** available (HERMES, COMPASS, STAR).
    - Is the experimental information fully exploited?
    - Can we trust "lattice data"?
  - No accurate theoretical **calculations** (nothing beyond LO):
    - SIDIS, 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*



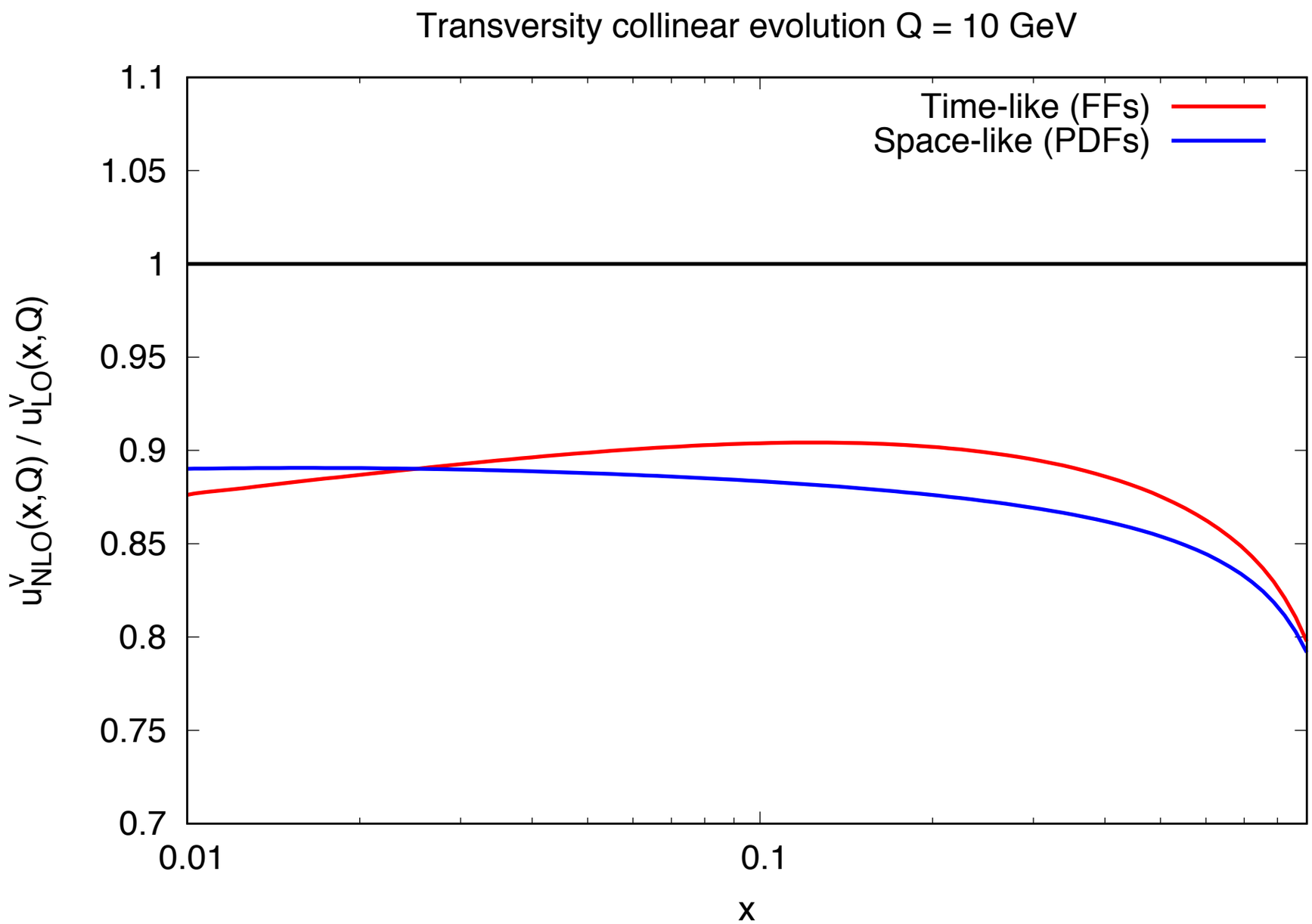



# Collinear polarised

## *Transversely polarised*

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




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

# $q_T$ dependence

## *Collinear and TMD frameworks*

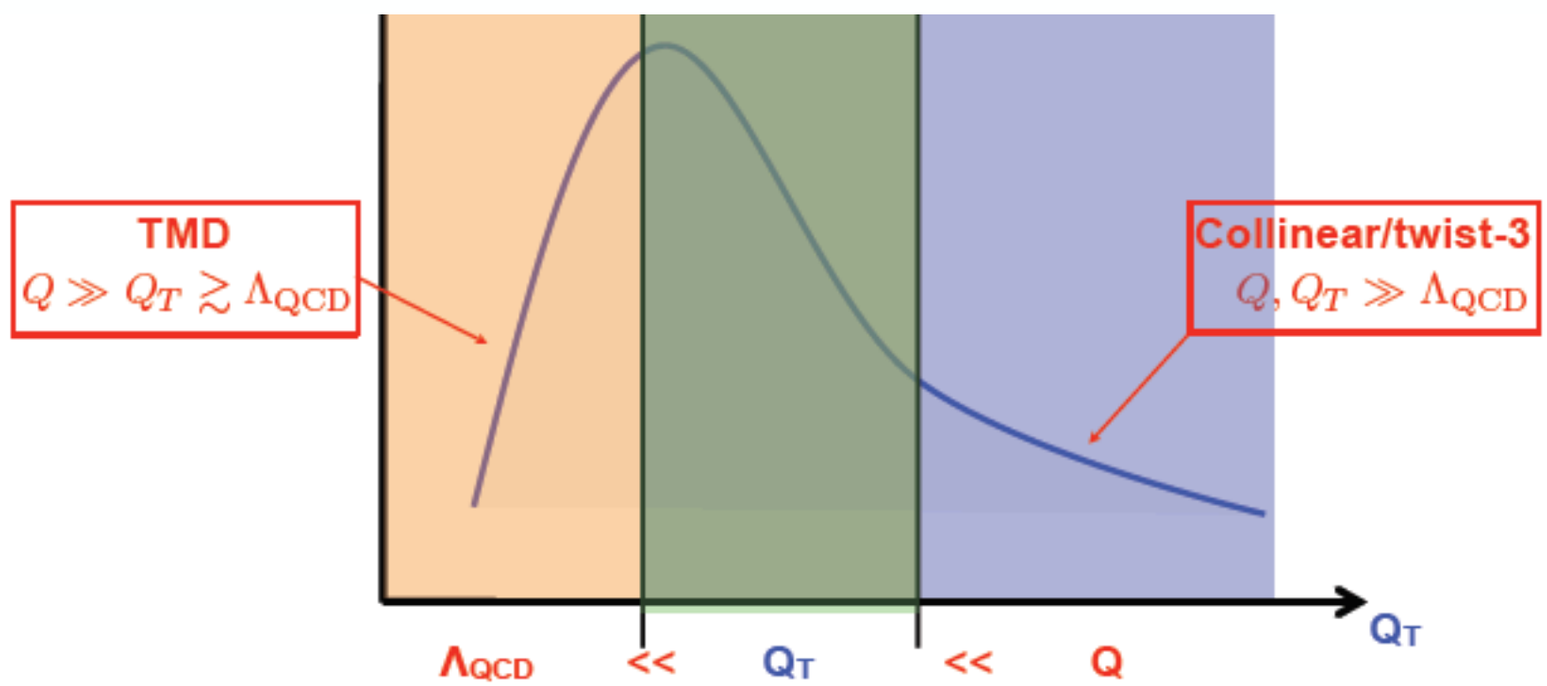
- Referring to **colourless** final-state processes, the description of $q_T$ dependent observables is based on two well-established frameworks:
  - the **TMD** framework for $q_T \ll Q$,
  - the **collinear** framework for $q_T \simeq Q$.
- These two regimes can be **matched** leading to *theoretically* 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** $\Lambda_{QCD} \ll q_T \ll Q$ that is however well-defined (dependence on the matching prescription),
  - **limited** effect of the TMD non-perturbative contributions.

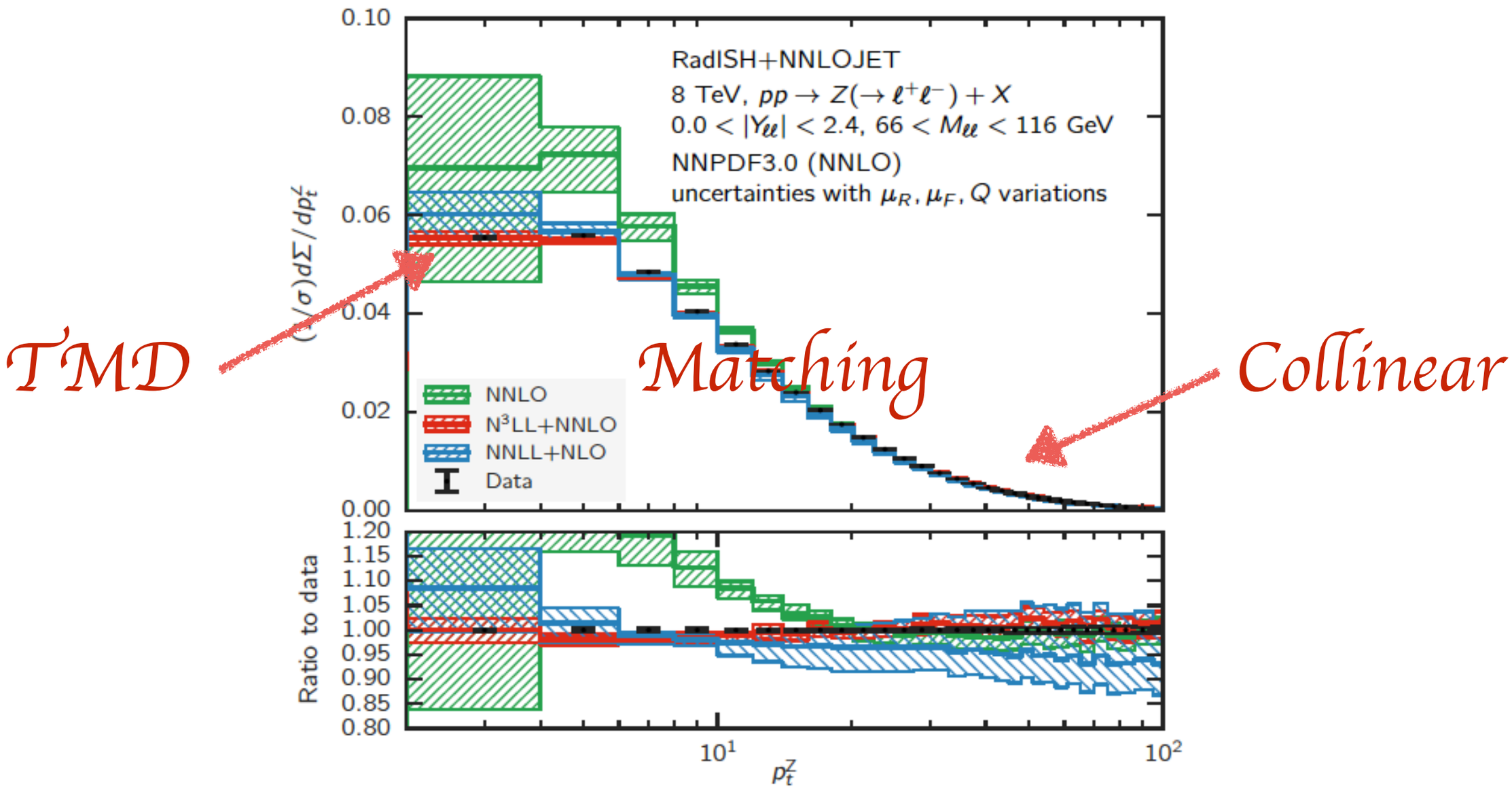
$$d\sigma(m \lesssim q_T \lesssim Q, Q) = W(q_T, Q) + Y(q_T, Q) + O\left(\frac{m}{Q}\right)^c d\sigma(q_T, Q)$$



# $q_T$ dependence

*Collinear and TMD frameworks*

- Current state-of-the-art: N$^3$LL + 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*

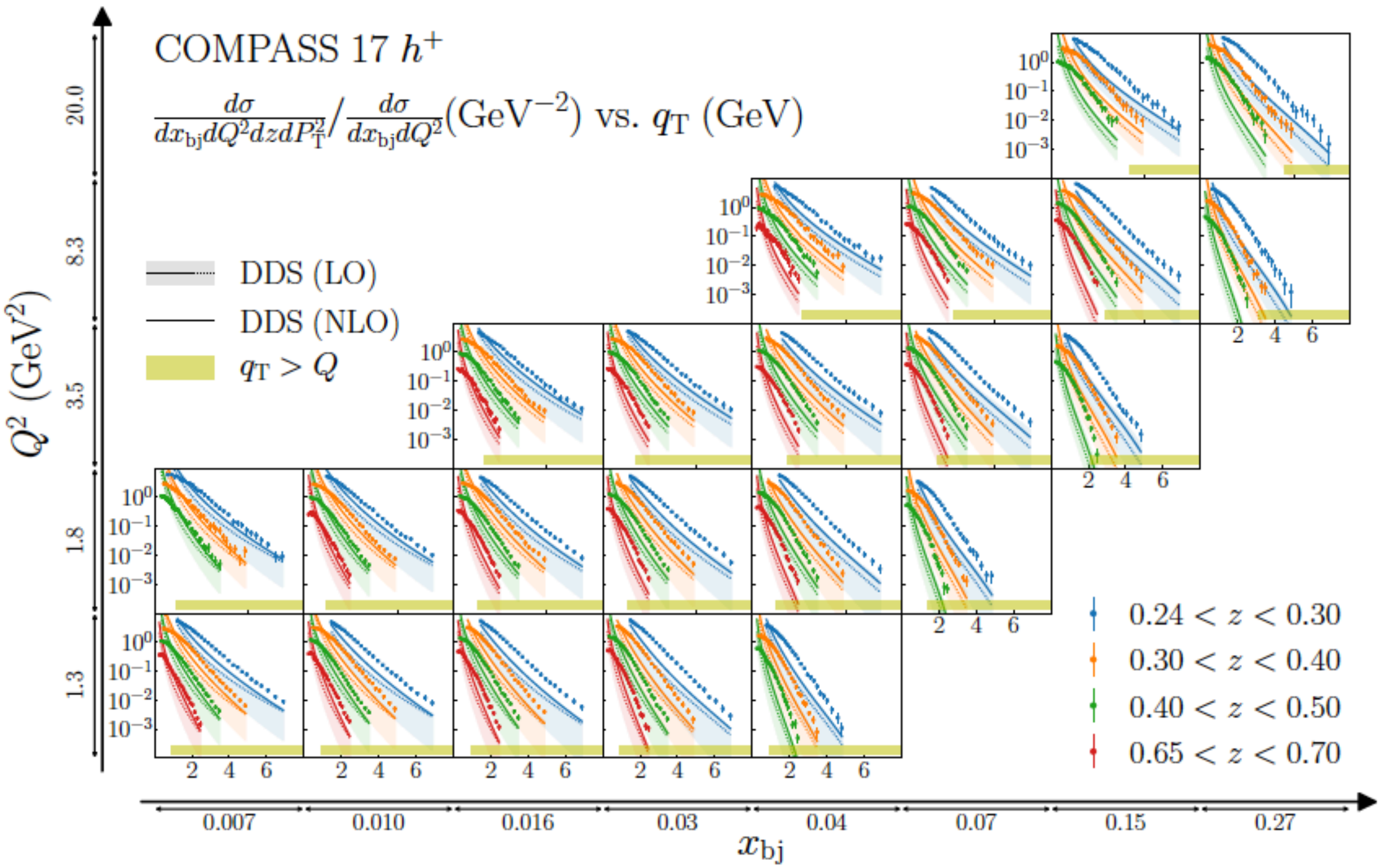
- More complicated situation if $\Lambda_{QCD}$ and $Q$ are not very far apart:

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

  - **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

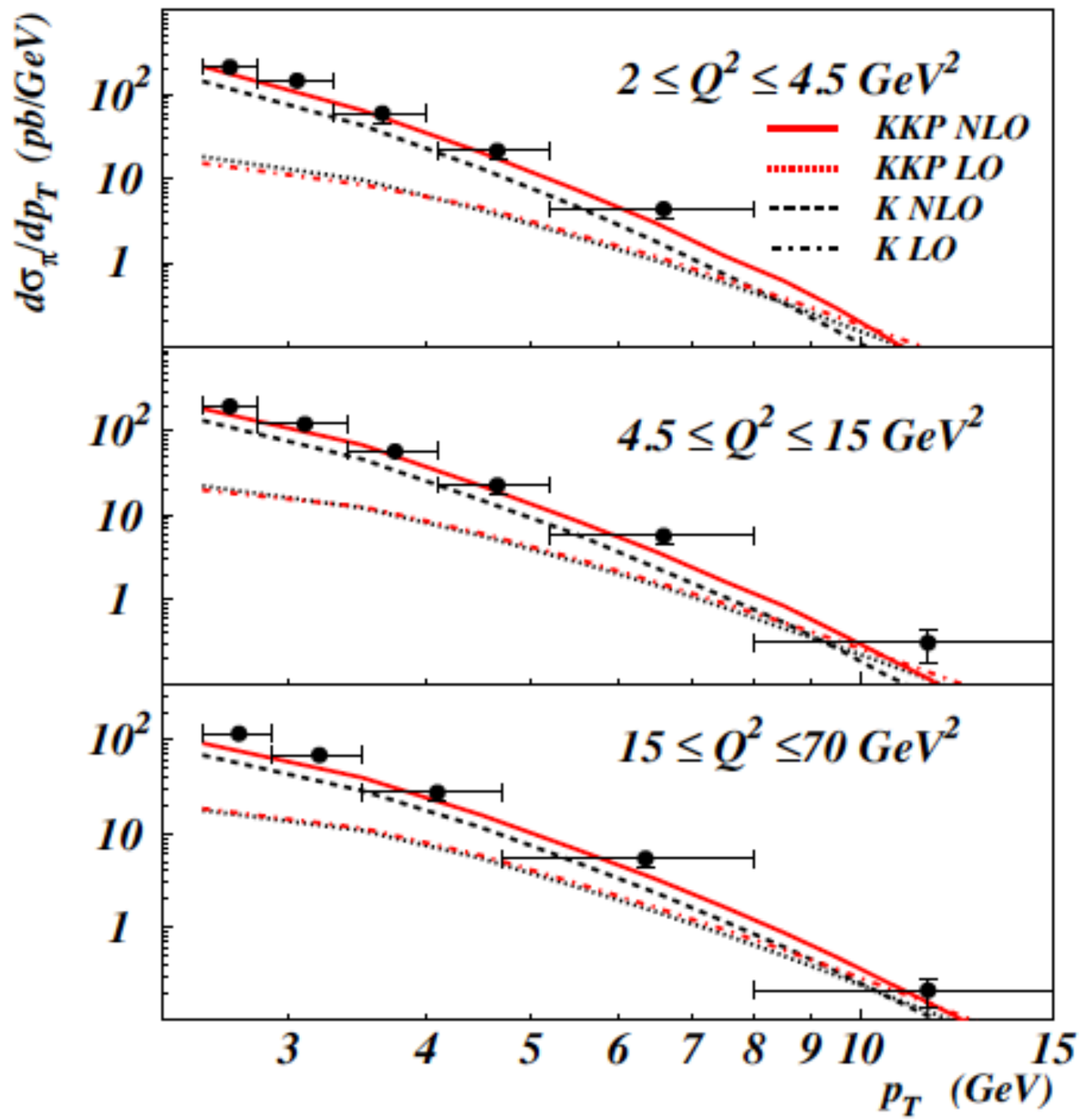
*Theoretical issues: utter failure of the NLO fixed order?*



# $q_T$ dependence

*Theoretical issues: utter failure of the NLO fixed order?*

- … possibly not!

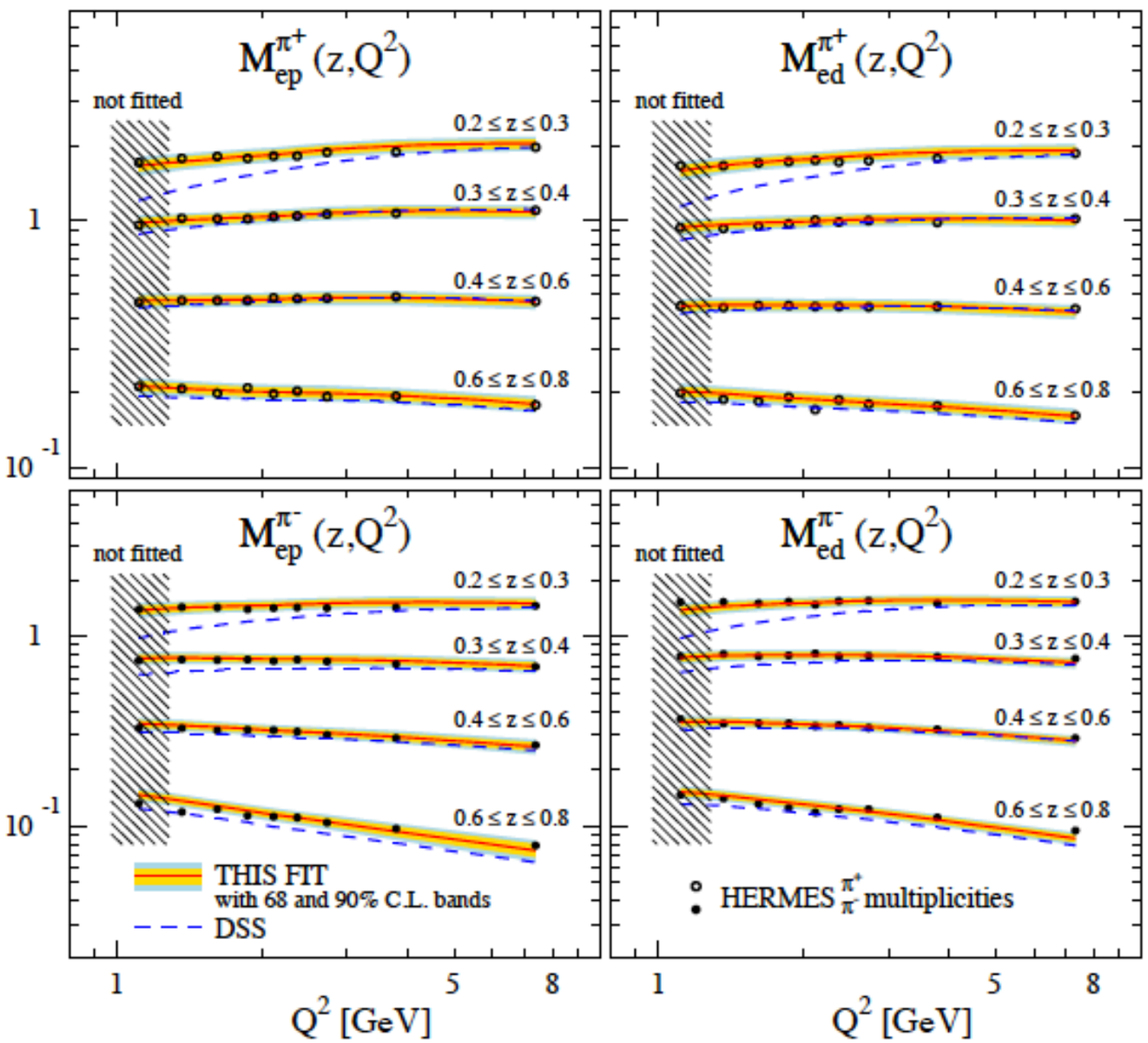


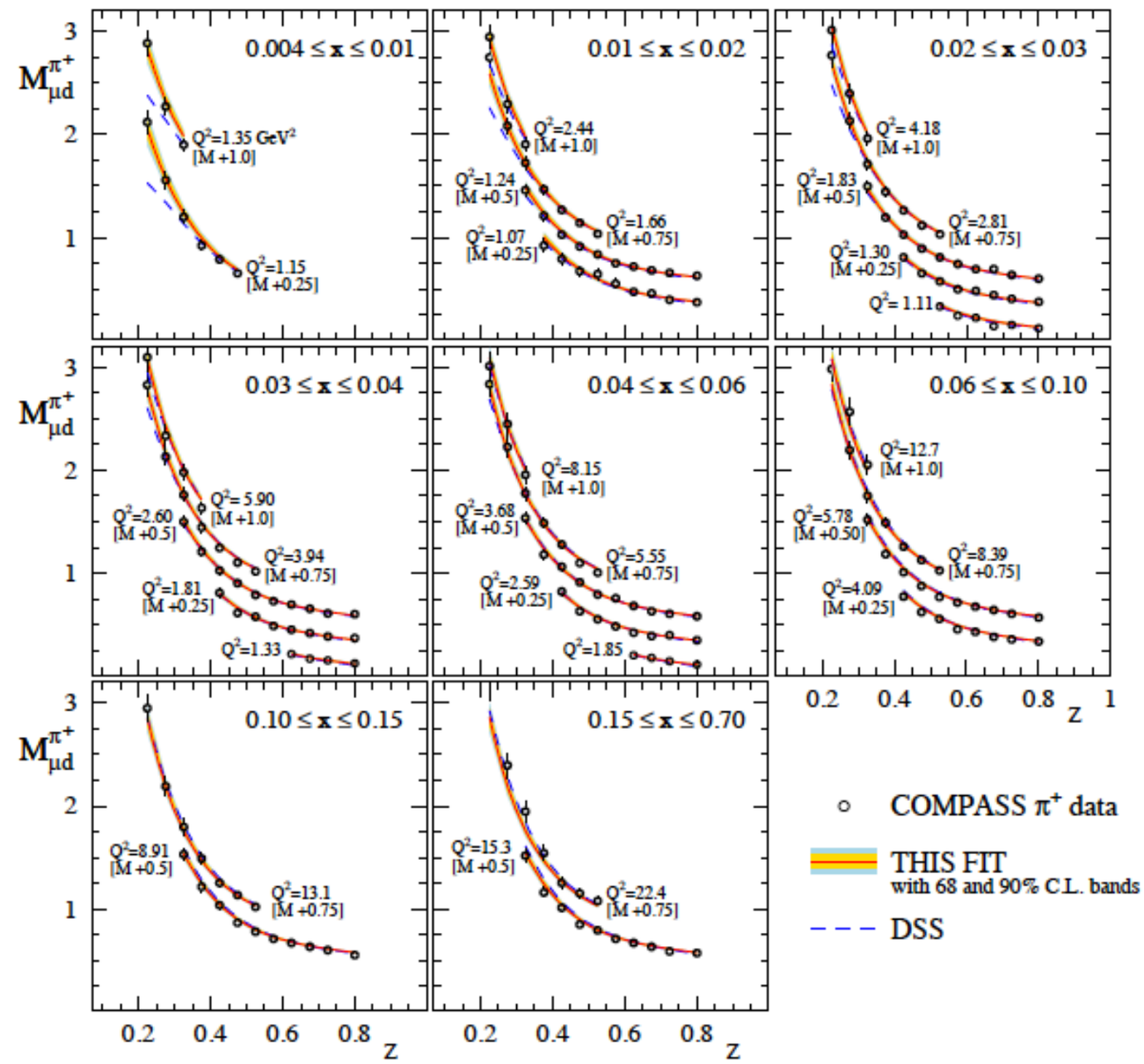

- Back in 2004 Daleo *et al.* showed that NLO corrections were fundamental to describe H1 data.

# $q_T$ dependence

*Theoretical issues: utter failure of the NLO fixed order?*

- … possibly not!



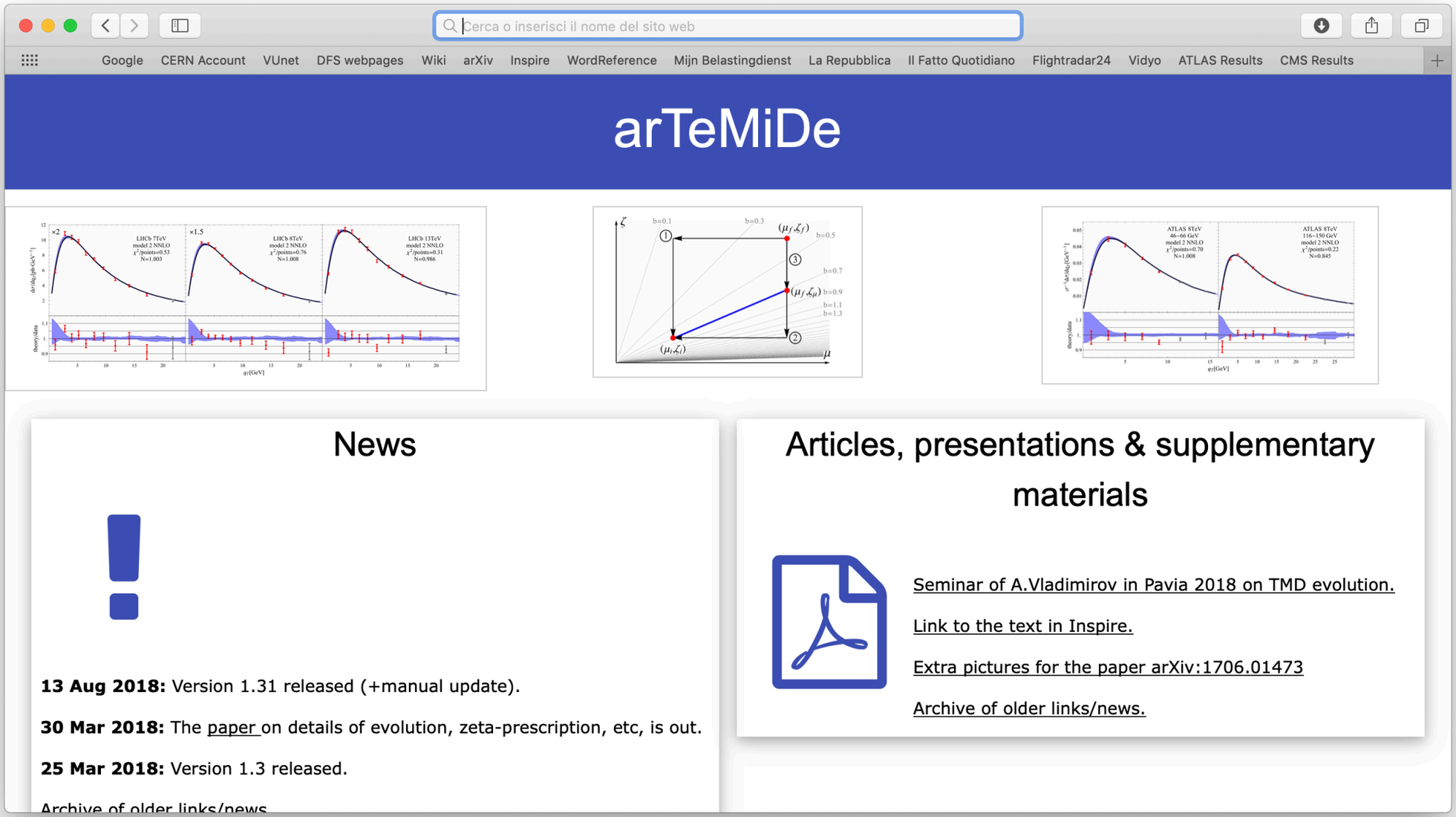




- $q_T$ **integrated** cross sections are well described by NLO fixed-order

# $q_T$ dependence

## *Computational tools: arTeMiDe*

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

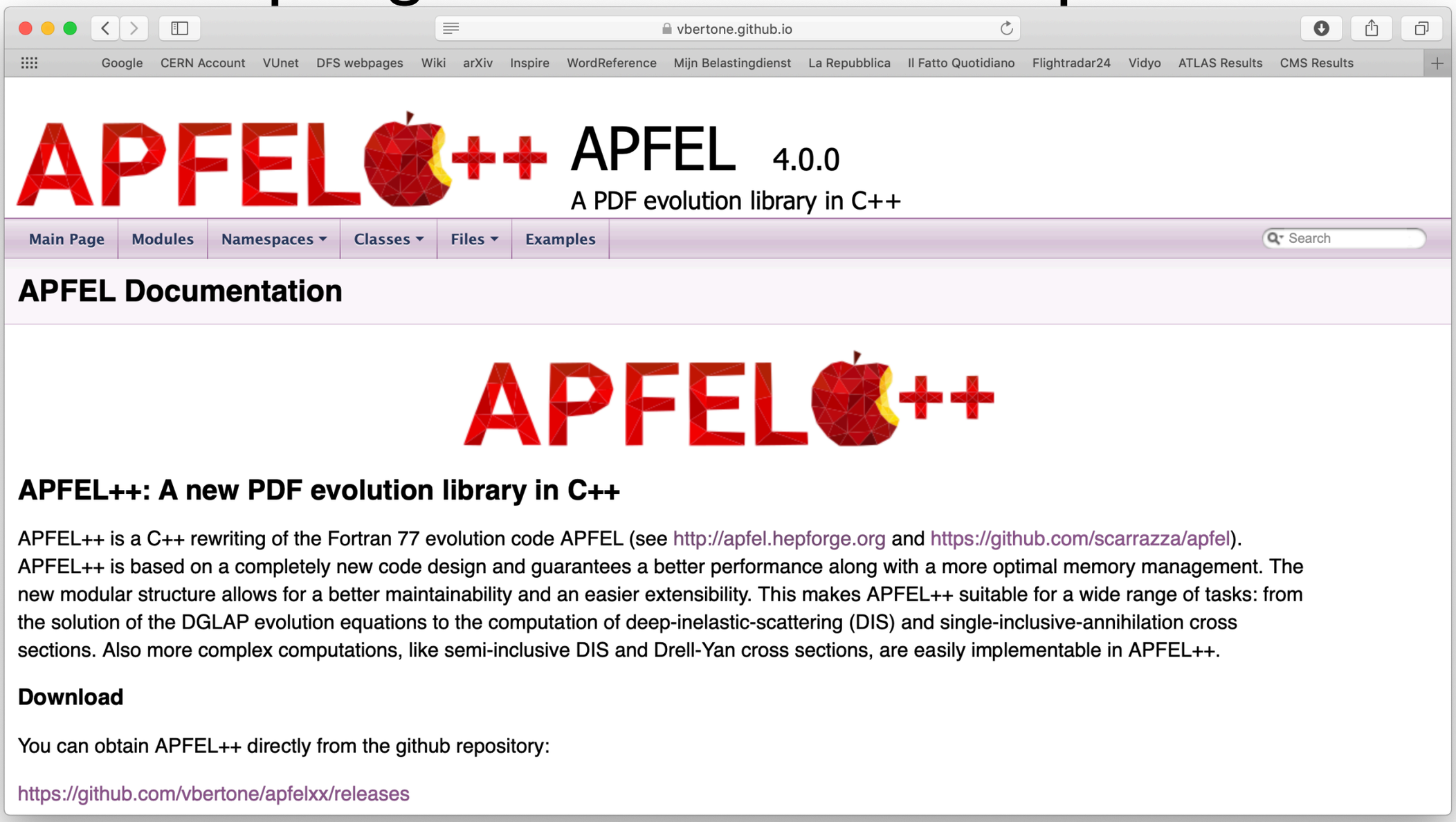



- Computes low-$q_T$ Drell-Yan cross sections up to NNLL in the "Scimemi-Vladimirov" scheme (modified TMD evolution plus $\zeta$-prescription).

# $q_T$ dependence

## *Computational tools: APFEL++*

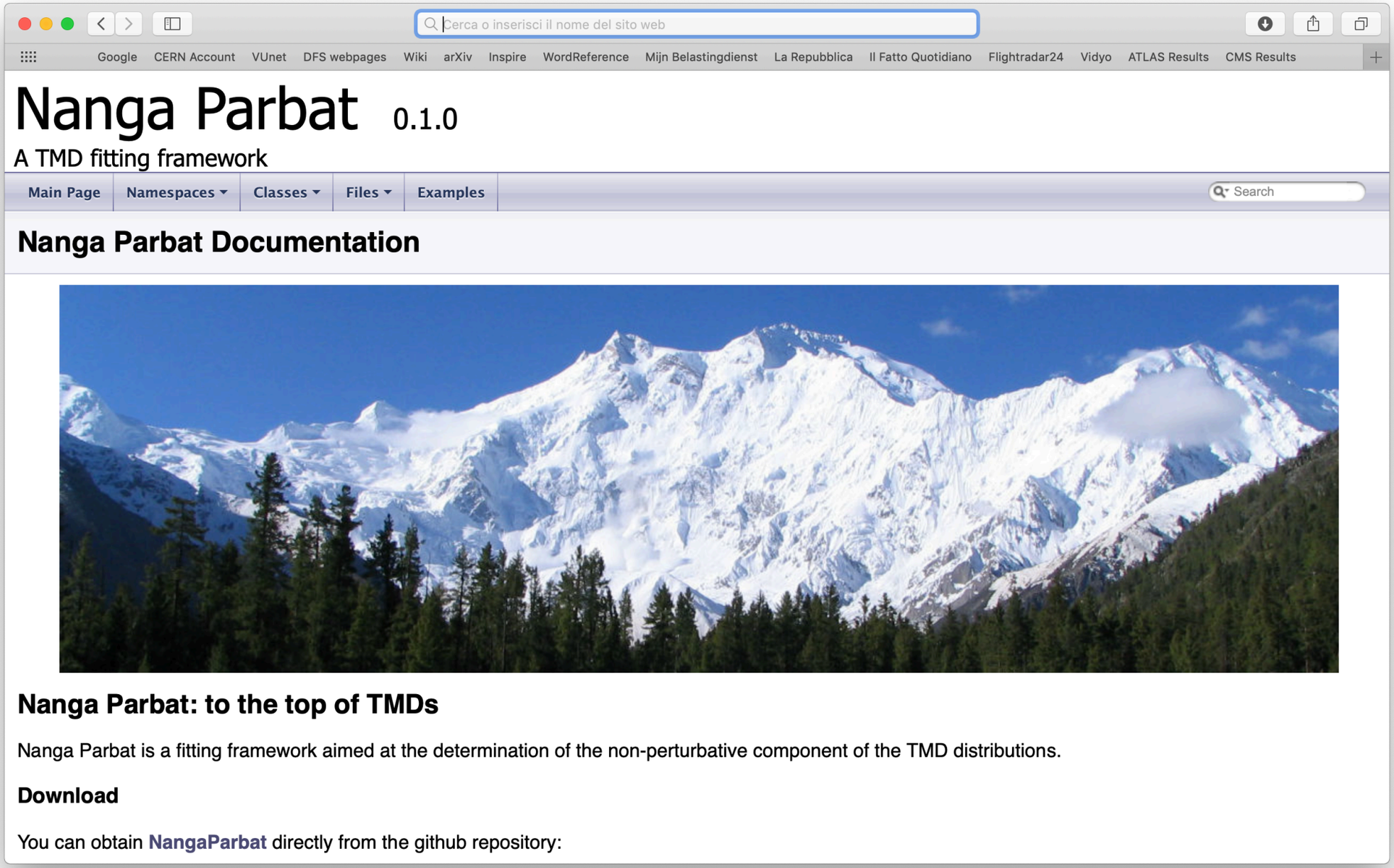
https://github.com/vbertone/apfelxx




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

# $q_T$ dependence

## *Computational tools: Nanga Parbat*

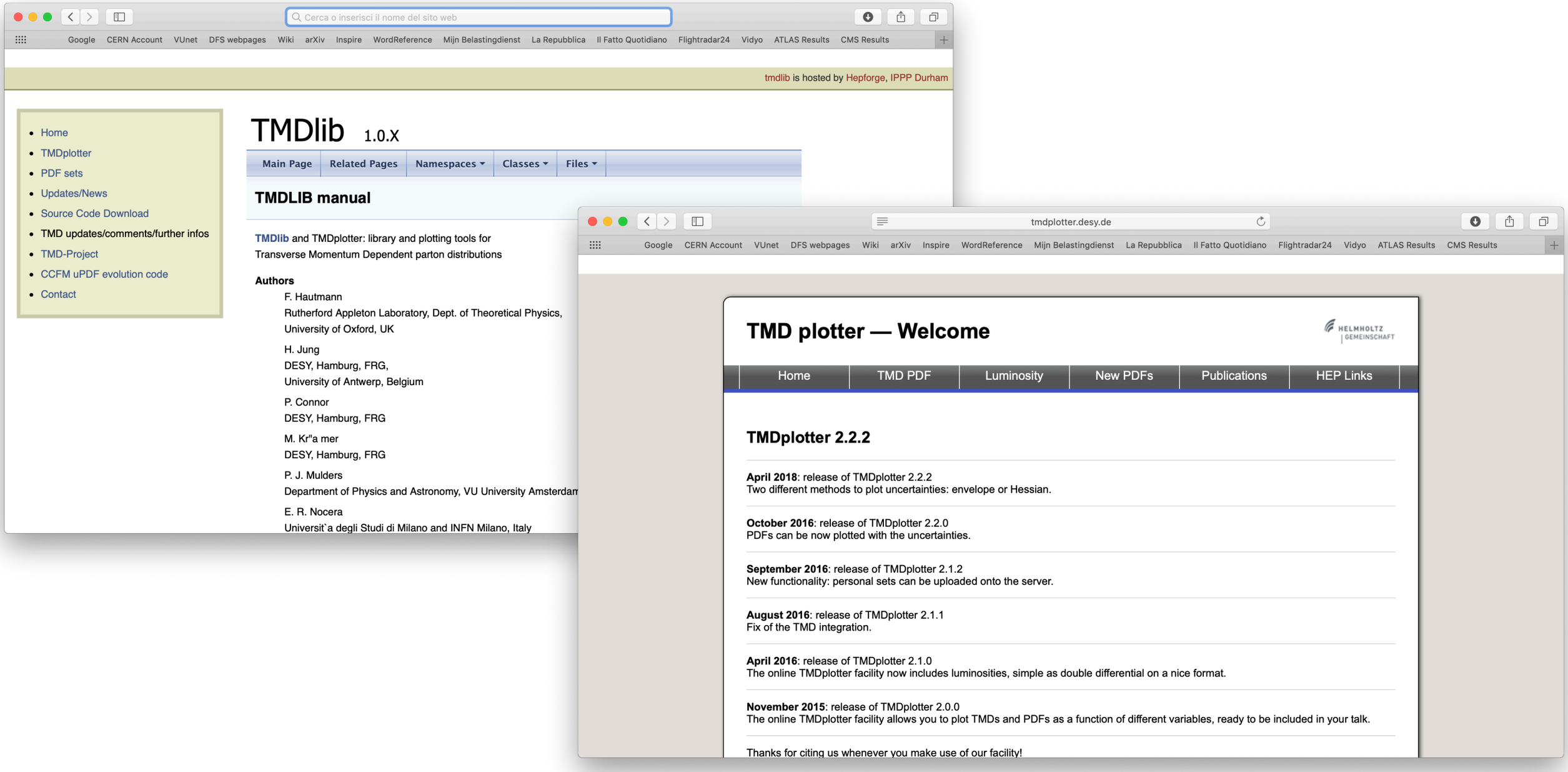



- The TMD fitting framework based on APFEL++ and that is currently being developed by the Pavia's group to extract TMD PDFs and FF.

# $q_T$ dependence

## *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