NNFF1.1h: charged-hadron fragmentation functions with Tevatron and LHC data

Based on V. Bertone *et al.*, *Eur. Phys. J.* C78 (2018), no. 8 651 [arXiv:1807.03310]

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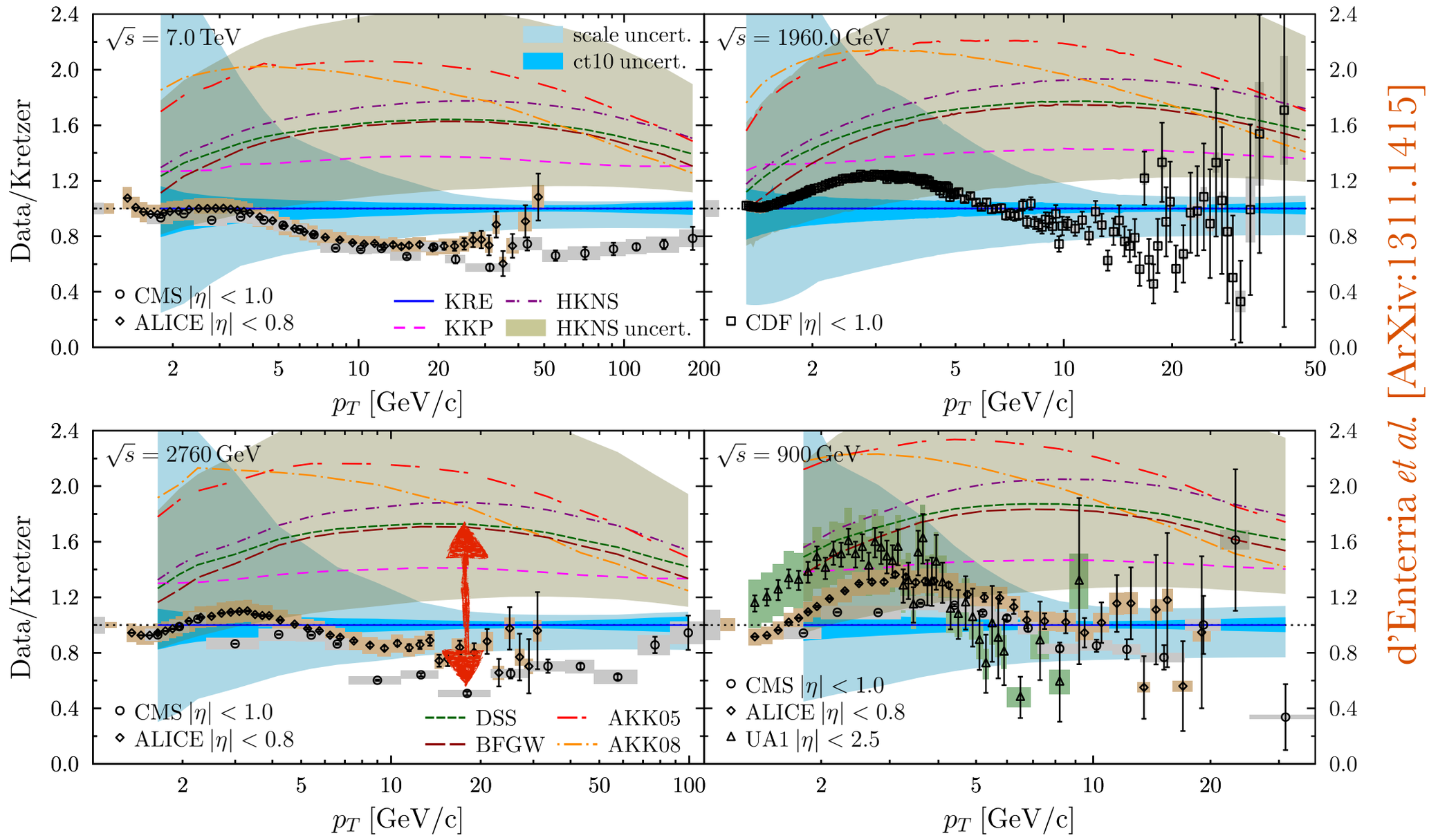
3DSPIN

MAPPING THE PROTON IN 3D

Interesting facts

Why bother about fragmentation functions

Comparison data/theory at NLO for inclusive **charged-hadron p_T spectra**:



d'Enterria *et al.* [ArXiv:1311.1415]

- Large energy data tend to be **overshot** by predictions obtained with most of the current FF sets ⇒ too hard gluon FF at large z?
- Not much progress since then.

Fitting methodology

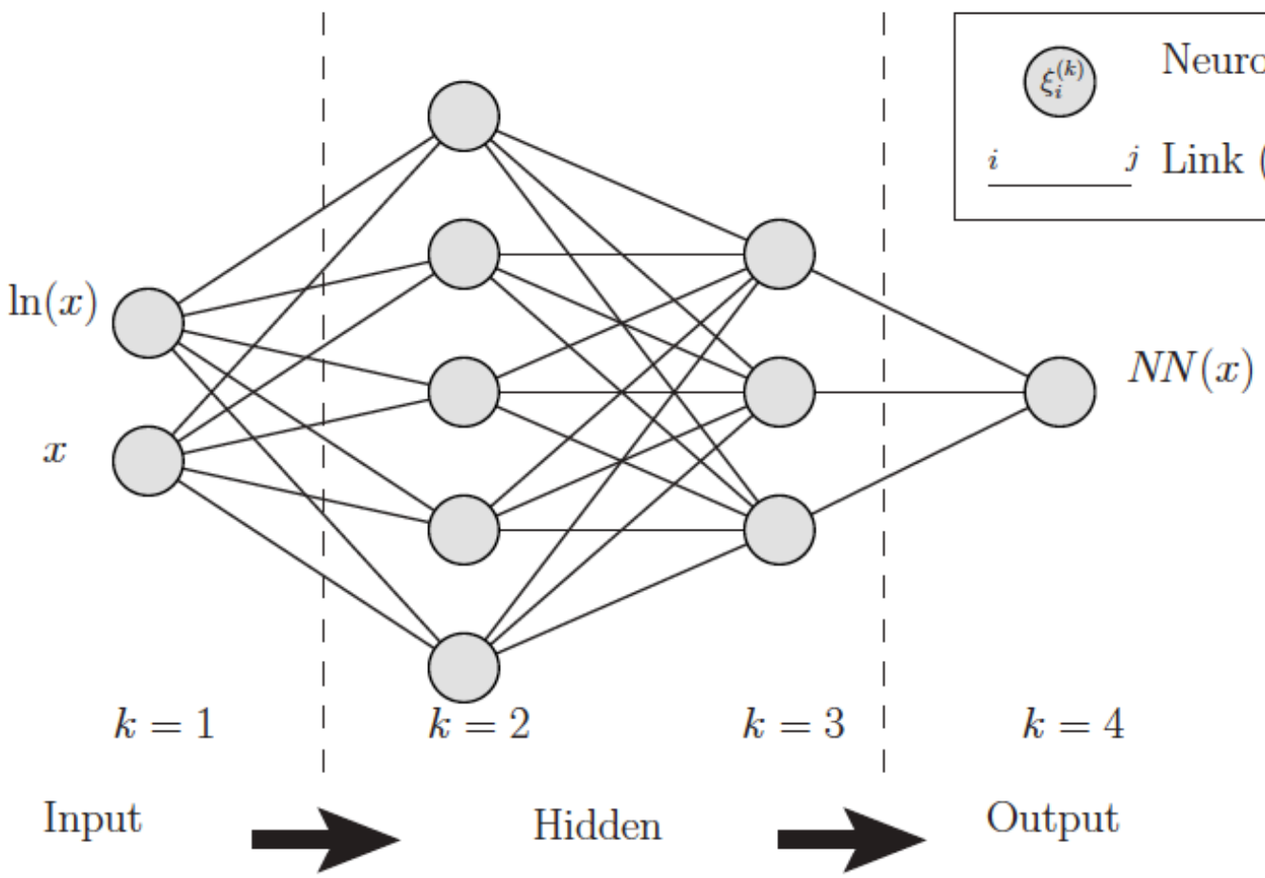
The NNPDF approach in a nutshell

- **Monte Carlo** sampling:
  - construct a set of data replicas which reproduces the statistical features of the original dataset,
  - clear statistical interpretation.
- **Neural network (NN)** parameterisation:
  - flexible functional form parametrised by a large number of parameters.
- **Genetic algorithm/CMA-ES** for the fit:
  - suitable exploration of the parameter space to avoid to fall into local minima of the figure of merit.
- Determination of the best fit by **cross-validation**:
  - exploit the random distribution of the statistical fluctuations in a given MC replica to avoid over-learning.
- So far, successfully used to extract **PDFs** and **FFs**.

Fitting methodology

A word on the parametrisation

- FFs are parametrised in terms of NNs with architecture (2-5-3-1):



$$\xi_i^{(j)} = g\left(\sum_k^{\text{(j-1)th layer}} \xi_k^{(j-1)} \omega_{ki}^{(j)} - \theta_i^{(j)}\right)$$

Activation function:

$$g(x) = \text{sign}(x)\ln(|x|+1)$$

- Each NN has 37 free parameters.
- FFs are expressed as $f_i(x) = \text{NN}_i(x) - \text{NN}_i(1)$
  - The $\text{NN}_i(1)$ term ensures that $f_i(x) \xrightarrow[x\to 1]{} 0$

DGLAP equations

Time-like evolution

- FFs obey the standard **time-like** DGLAP evolution equations:

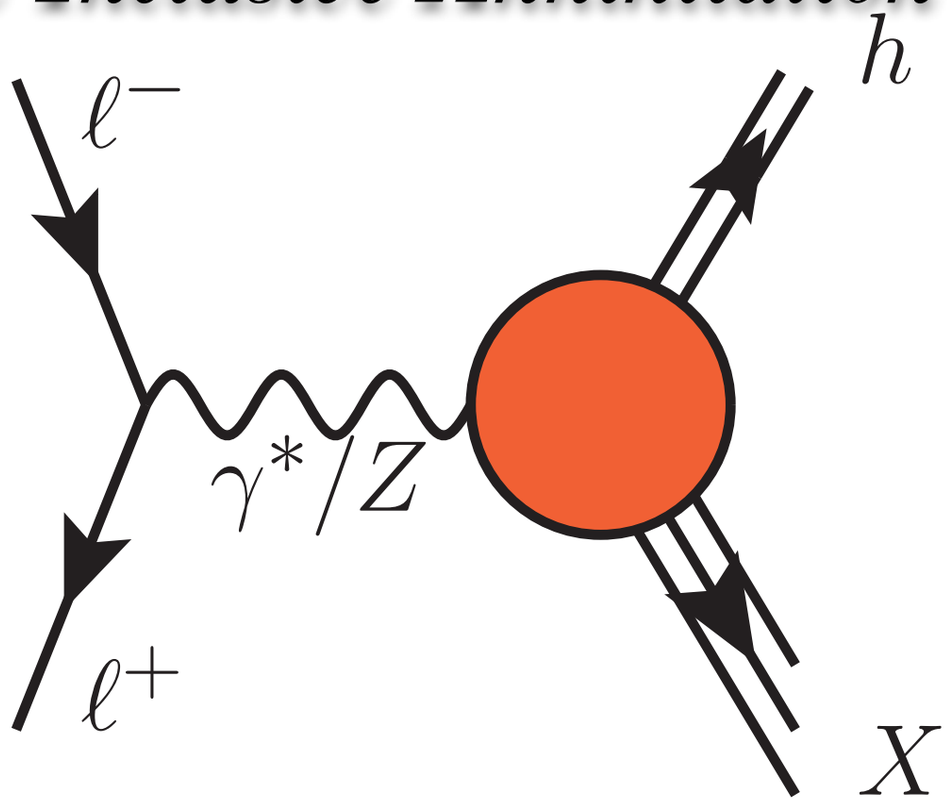
$$\mu^2 \frac{\partial}{\partial \mu^2} D^h_{\rm NS} \quad = \quad P_{\rm NS} \otimes D^h_{\rm NS}$$

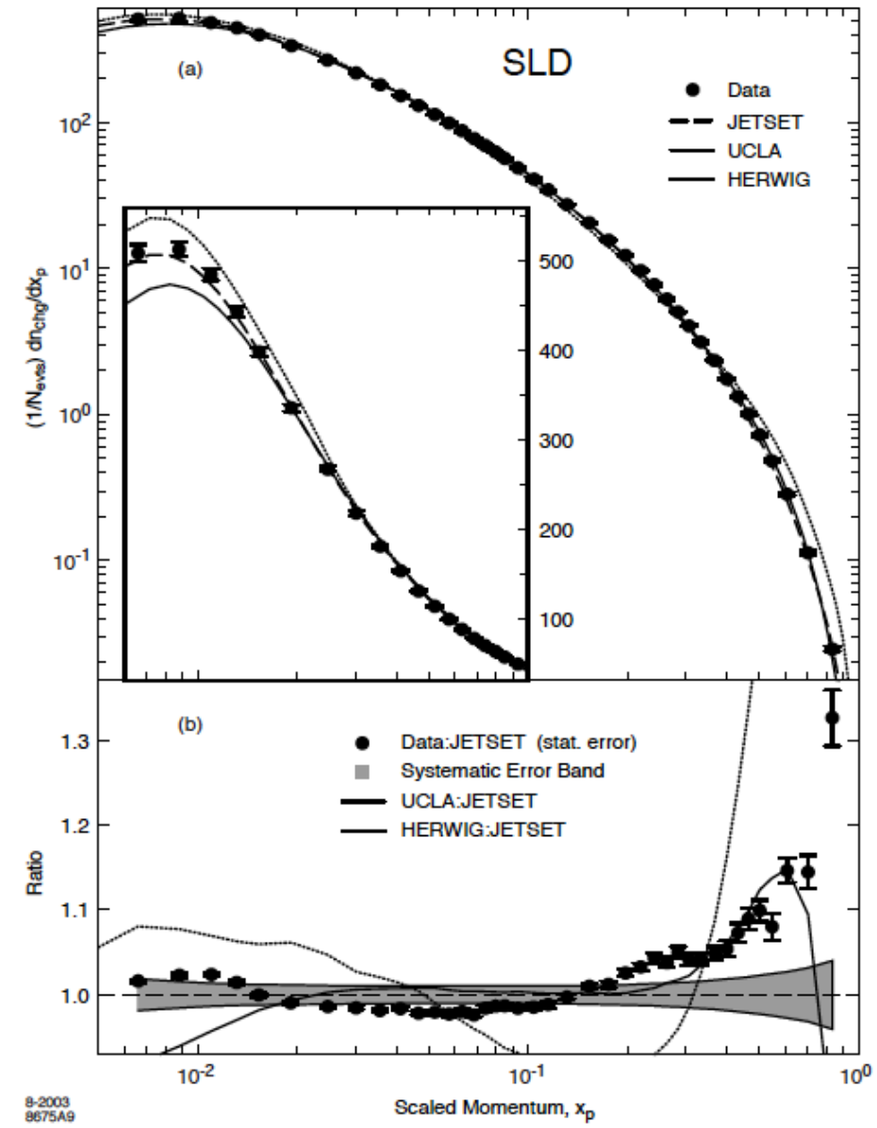
$$\mu^2 \frac{\partial}{\partial \mu^2} \begin{pmatrix} D^h_\Sigma \\ D^h_g \end{pmatrix} \quad = \quad \begin{pmatrix} P_{qq} & P_{qg} \\ P_{gq} & P_{gg} \end{pmatrix} \otimes \begin{pmatrix} D^h_\Sigma \\ D^h_g \end{pmatrix}$$

- Time-like splitting functions known up to NNLO.
  A. Mitov and S. O. Moch [hep-ph/0604160], M. Gluck, E. Reya, and A. Vogt [Phys.Rev. D48 (1993)]
- Numerical implementation in the **APFEL** code:
  V. Bertone, C. Carrazza, J. Rojo [arXiv:1310.1394]
  - careful benchmark against in the the $\mathcal{N}$-space **MELA** code,
    V. Bertone, S. Carrazza, E. R. Nocera [arXiv:1501.00494]
  - perfect agreement with **QCDNUM** (after a correction of a bug in the latter).
    M. Botje [arXiv:1602.08383]

Relevant observables

Single Inclusive Annihilation (SIA)





$$\frac{d\sigma^h}{dz} = \hat{\sigma}_0^h \left[C_q \otimes D_\Sigma^h + C_g \otimes D_g^h + C_{\rm NS} \otimes D_{\rm NS}^h \right]$$

- ✅ **Clean** channel: only FFs involved,
- ✅ **higher-order** corrections to NNLO,
- ✅ **precise data** available.
- ❌ **No flavour separation**,
  - ✅ tagged data for heavy-quark FFs.
- ❌ gluon distribution **suppressed** by α_s.

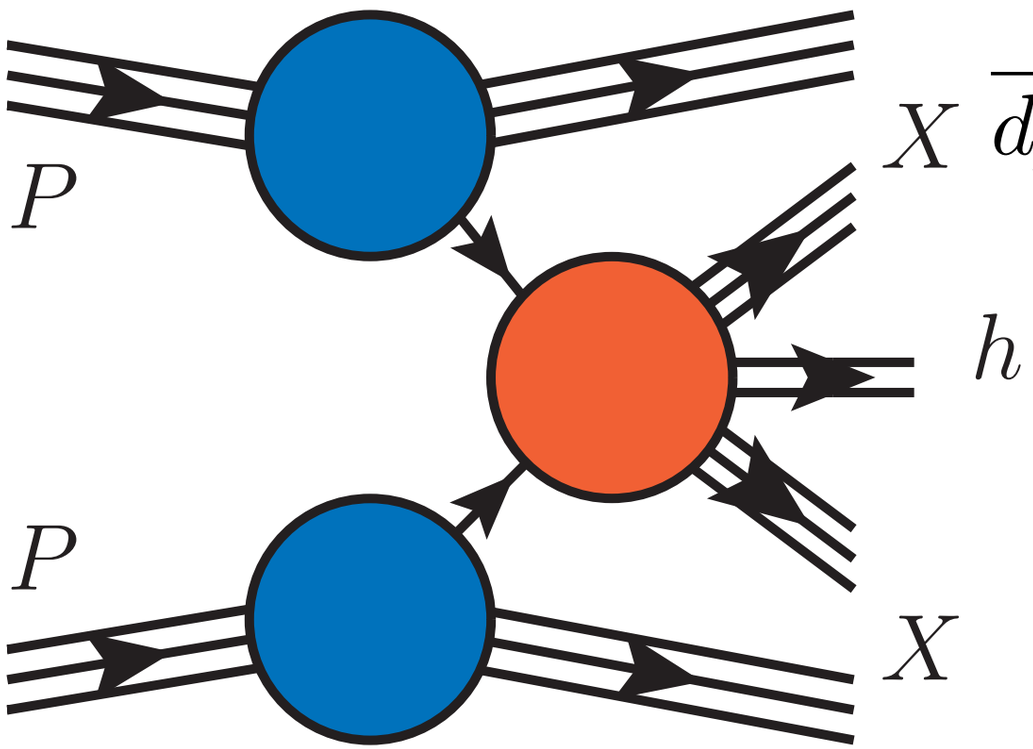
$$D_\Sigma^h = \sum_q \left(D_q^h + D_{\bar{q}}^h \right) = \sum_q D_{q^+}^h$$

$$D_{\rm NS}^h = \sum_q \left(\frac{\hat{e}_q^2}{\langle \hat{e}_q^2 \rangle} - 1 \right) D_{q^+}^h$$

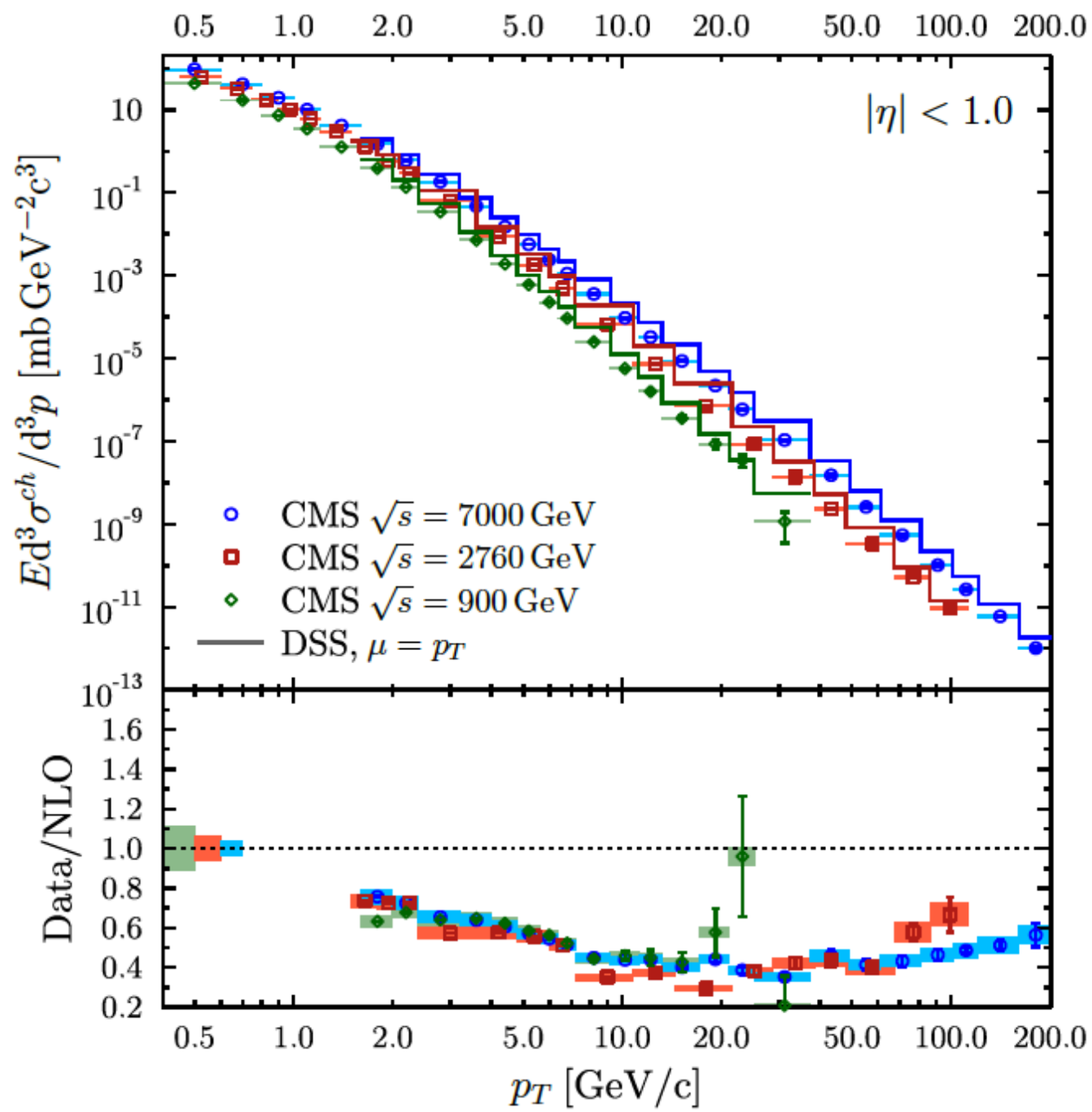
$$C_q, C_{\rm NS} \propto \mathcal{O}(1) \quad \text{while} \quad C_g \propto \mathcal{O}(\alpha_s)$$

Relevant observables

Hadroproduction in proton-proton collisions (pp)



$$\frac{d\sigma^h}{dp_T d\eta} = \sum_{ijk} f_i^{(1)} \otimes f_j^{(2)} \otimes \frac{d\hat{\sigma}_{ijk}}{dp_T d\eta} \otimes D_k^h$$



- ✅ Direct sensitivity to the **gluon FF**,
- ✅ **Scale scan** of FFs ($\mu_F \propto p_T$),
- ✅ Precise data from LHC/Tevatron.
- ❌ Involves both **FFs** and **PDFs**,
- ❌ Known so far up to NLO,
  - ❌ large scale variations at low p_T,
- ❌ cumbersome to compute.

Fit settings

- **Physical parameters**:

$$\alpha_s(M_Z) = 0.118, \quad \alpha_{\rm em}(M_Z) = 1/127, \quad m_c = 1.51 \text{ GeV}, \quad m_b = 4.92 \text{ GeV}$$

- **Parametrisation scale**:

$$Q_0 = 5 \text{ GeV } (> m_c, m_b)$$

  - substantial heavy-quark intrinsic component,
  - heavy-quark FFs parametrised on the same footing as the light FFs.

- **5 independent FFs**:

$$\{D^h_{u^+}, D^h_{s^++d^+}, D^h_{c^+}, D^h_{b^+}, D^h_g\}$$

  - **inclusive SIA data** only constrains three FF combinations,
  - heavy-quark FFs constrained directly by **tagged SIA data**.

- Each FF is parametrised by a **Neural Net** (architecture 2-5-3-1).

- **Kinematic cuts**:

$$z_{\rm min} \leq z \leq z_{\rm max}, \quad z_{\rm min} = \begin{cases} 0.02 & \text{for } \sqrt{s} = M_Z \\ 0.075 & \text{otherwise} \end{cases}, \quad z_{\rm max} = 0.9$$

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contributions $\propto \ln(1 - z)$

$$z_{\rm min} \leq z \leq z_{\rm max}, \quad z_{\rm min} = \begin{cases} 0.02 & \text{for } \sqrt{s} = M_Z \\ 0.075 & \text{otherwise} \end{cases}, \quad z_{\rm max} = 0.9$$

Charged hadron FFs

An overview

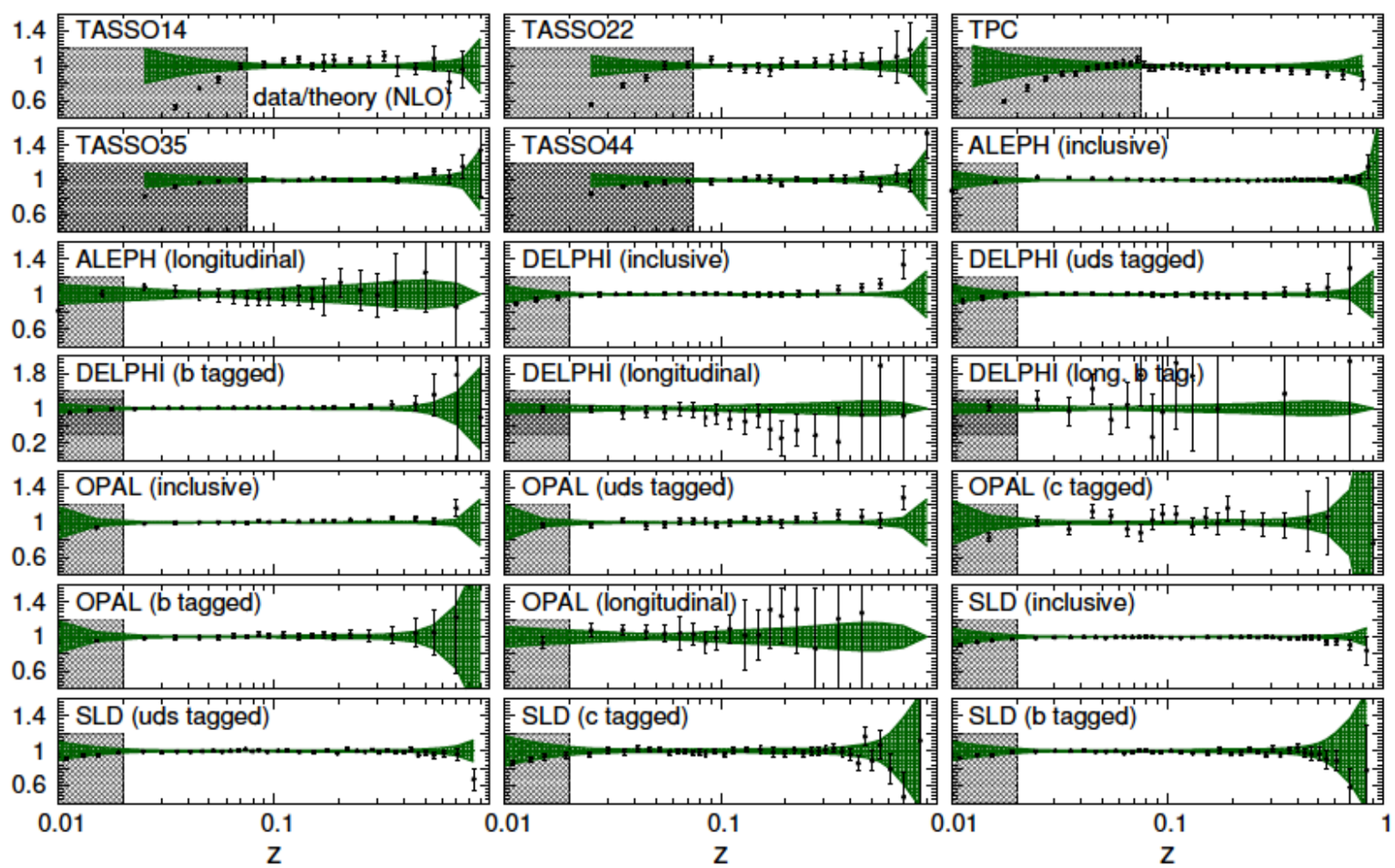
- Many experiments provide data for **charged-hadron** production:
  - this data includes, not only pions, kaons and protons, but **also heavier** (and less abundant) **charged hadrons**.
- Restricting to **SIA experiments**, data is available from:
  - TASSO, TPC, ALEPH, DELPHI, OPAL, SLD.
- Some experiments measure also the **longitudinal** cross section:
  - ALEPH, DELPHI, OPAL.
- Predictions for the longitudinal cross section start at $O(\alpha_s)$:
  - as a consequence it is **not possible to go beyond NLO** (i.e. $O(\alpha_s^2)$) yet.
  - This data provides a strong handle on the **gluon distribution**.

Charged hadron FFs

The NNFF1.0h analysis

E. Nocera [ArXiv:1709.03400]

- General good description of the entire dataset (χ^2 / $N_{\rm dat}$ = 0.83).
- Particularly good the description of the **longitudinal data**.

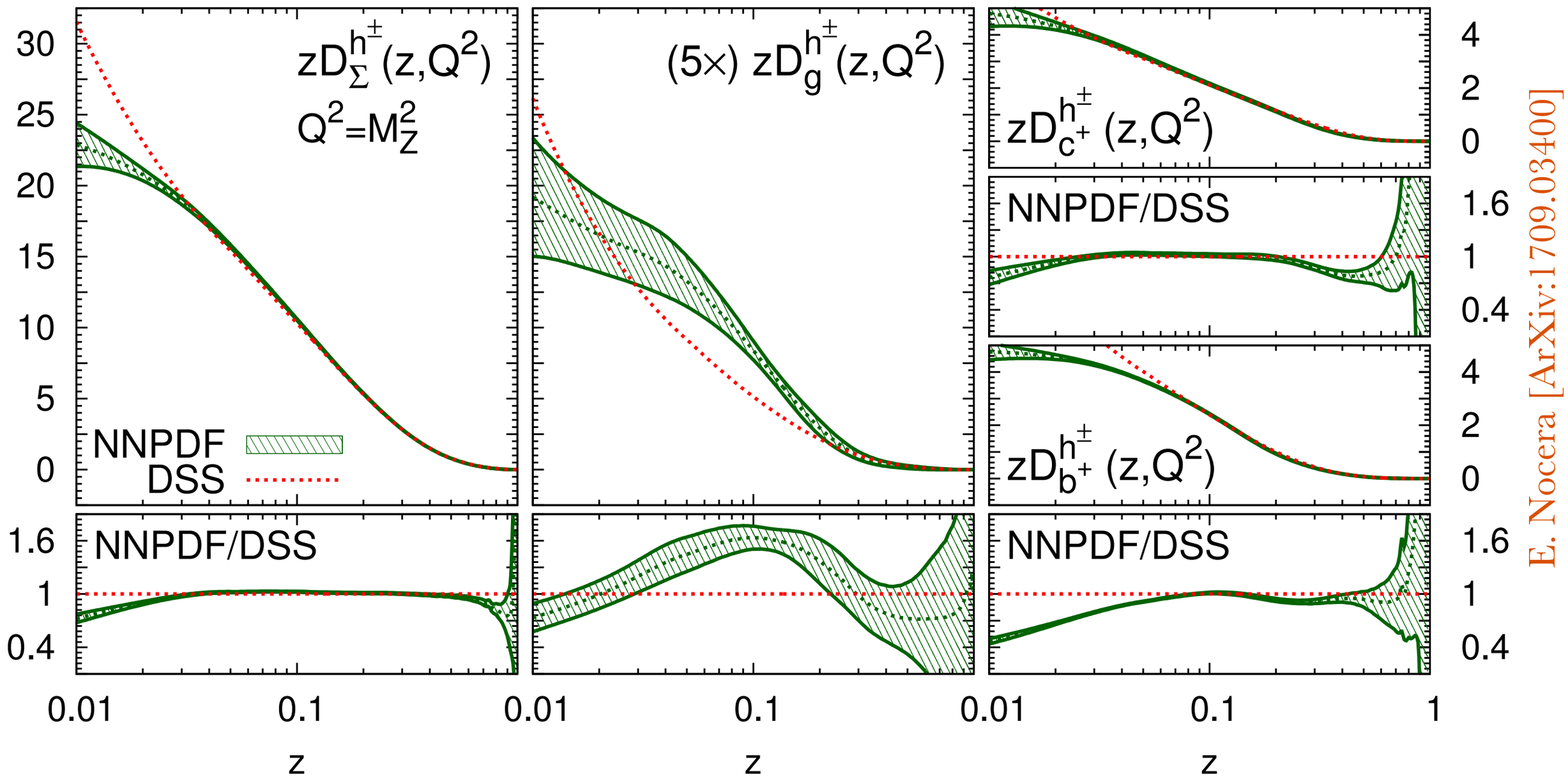


Experiment	Reference	Observable	$\sqrt{s}$ [GeV]	$N_{\rm dat}$	$\chi^2/N_{\rm dat}$
TASSO14	[5]	$\frac{1}{\sigma_{\rm tot}}\frac{d\sigma^{h^\pm}}{dz}$	14.00	15 (20)	1.23
TASSO22	[5]	$\frac{1}{\sigma_{\rm tot}}\frac{d\sigma^{h^\pm}}{dz}$	22.00	15 (20)	0.51
TPC	[6]	$\frac{1}{\sigma_{\rm tot}}\frac{d\sigma^{h^\pm}}{dz}$	29.00	21 (34)	1.65
TASSO35	[5]	$\frac{1}{\sigma_{\rm tot}}\frac{d\sigma^{h^\pm}}{dz}$	35.00	15 (20)	1.14
TASSO44	[5]	$\frac{1}{\sigma_{\rm tot}}\frac{d\sigma^{h^\pm}}{dz}$	44.00	15 (20)	0.68
ALEPH	[7]	$\frac{1}{\sigma_{\rm tot}}\frac{d\sigma^{h^\pm}}{dz}$	91.20	32 (35)	1.04
	[7]	$\frac{1}{\sigma_{\rm tot}}\frac{d\sigma_L^{h^\pm}}{dz}$	91.20	19 (21)	0.36
DELPHI	[8]	$\frac{1}{\sigma_{\rm tot}}\frac{d\sigma^{h^\pm}}{dp_h}$	91.20	21 (27)	0.65
	[8]	$\frac{1}{\sigma_{\rm tot}}\frac{d\sigma^{h^\pm}}{dp_h}\Big\vert_{uds}$	91.20	21 (27)	0.17
	[8]	$\frac{1}{\sigma_{\rm tot}}\frac{d\sigma^{h^\pm}}{dp_h}\Big\vert_{b}$	91.20	21 (27)	0.82
	[9]	$\frac{1}{\sigma_{\rm tot}}\frac{d\sigma_L^{h^\pm}}{dz}$	91.20	20 (22)	0.72
	[9]	$\frac{1}{\sigma_{\rm tot}}\frac{d\sigma_L^{h^\pm}}{dz}\Big\vert_{b}$	91.20	20 (22)	0.44
OPAL	[10]	$\frac{1}{\sigma_{\rm tot}}\frac{d\sigma^{h^\pm}}{dz}$	91.20	20 (22)	2.41
	[10]	$\frac{1}{\sigma_{\rm tot}}\frac{d\sigma^{h^\pm}}{dz}\Big\vert_{uds}$	91.20	20 (22)	0.90
	[10]	$\frac{1}{\sigma_{\rm tot}}\frac{d\sigma^{h^\pm}}{dz}\Big\vert_{c}$	91.20	20 (22)	0.61
	[10]	$\frac{1}{\sigma_{\rm tot}}\frac{d\sigma^{h^\pm}}{dz}\Big\vert_{b}$	91.20	20 (22)	0.21
	[11]	$\frac{1}{\sigma_{\rm tot}}\frac{d\sigma_L^{h^\pm}}{dz}$	91.20	20 (22)	0.31
SLD	[12]	$\frac{1}{\sigma_{\rm tot}}\frac{d\sigma^{h^\pm}}{dp_h}$	91.28	34 (40)	0.75
	[12]	$\frac{1}{\sigma_{\rm tot}}\frac{d\sigma^{h^\pm}}{dz}\Big\vert_{uds}$	91.28	34 (40)	1.03
	[12]	$\frac{1}{\sigma_{\rm tot}}\frac{d\sigma^{h^\pm}}{dz}\Big\vert_{c}$	91.28	34 (40)	0.62
	[12]	$\frac{1}{\sigma_{\rm tot}}\frac{d\sigma^{h^\pm}}{dz}\Big\vert_{b}$	91.28	34 (40)	0.97
Total dataset				471 (527)	0.83

Charged hadron FFs

The NNFF1.0h analysis

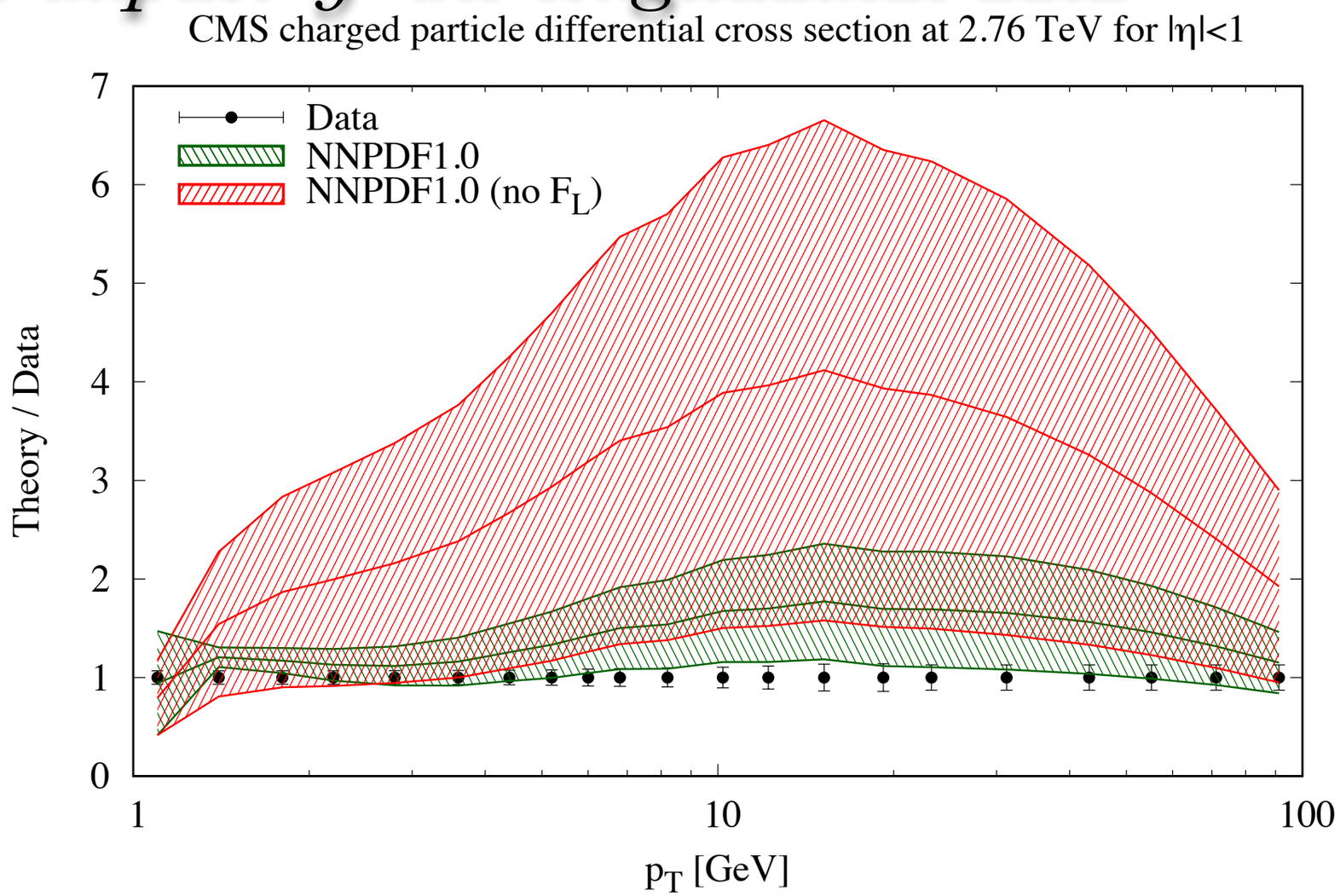
- Charged hadron FFs at the Z-boson mass scale:



- Significant differences w.r.t. DSS, particularly for the gluon.

Charged hadron FFs

Aside: the impact of the longitudinal data



- Strong **sensitivity to the gluon distribution**.
- Very significant impact of the **longitudinal data**:
  - dramatic reduction of the **uncertainty**,
  - **better agreement** with CMS data.
- **LHC** and **Tevatron** data expected to have a big impact on FFs.

Charged hadron FFs

Impact hadroproduction in pp collision data

- **CDF** at the *Tevatron*, and **CMS** and **ALICE** at the *LHC* released charged-hadron p_T spectra at different c.o.m. energies:
  - CMS and ALICE at $\sqrt{s}$ = 900, 2760, and 7000 GeV,
  - CDF at $\sqrt{s}$ = 630, 1800, and 1960 GeV.
  - Sensitivity to the **charged-hadron FFs**, particularly to the **gluon**,
- Hard cross sections currently know to **NLO** (i.e. $O(\alpha_s^3)$).
  - **large scale variations** at low p_T. Consider only data with $\boldsymbol{p_T > 7}$ **GeV**.
  - No CDF data points at 630 GeV survive.
- Include CMS, ALICE, and CDF data in the NNFF1.0 analysis of charged-hadron FFs by means of **Bayesian reweighting**:
  - use **NNPDF3.1** for the PDFs.

Charged hadron FFs

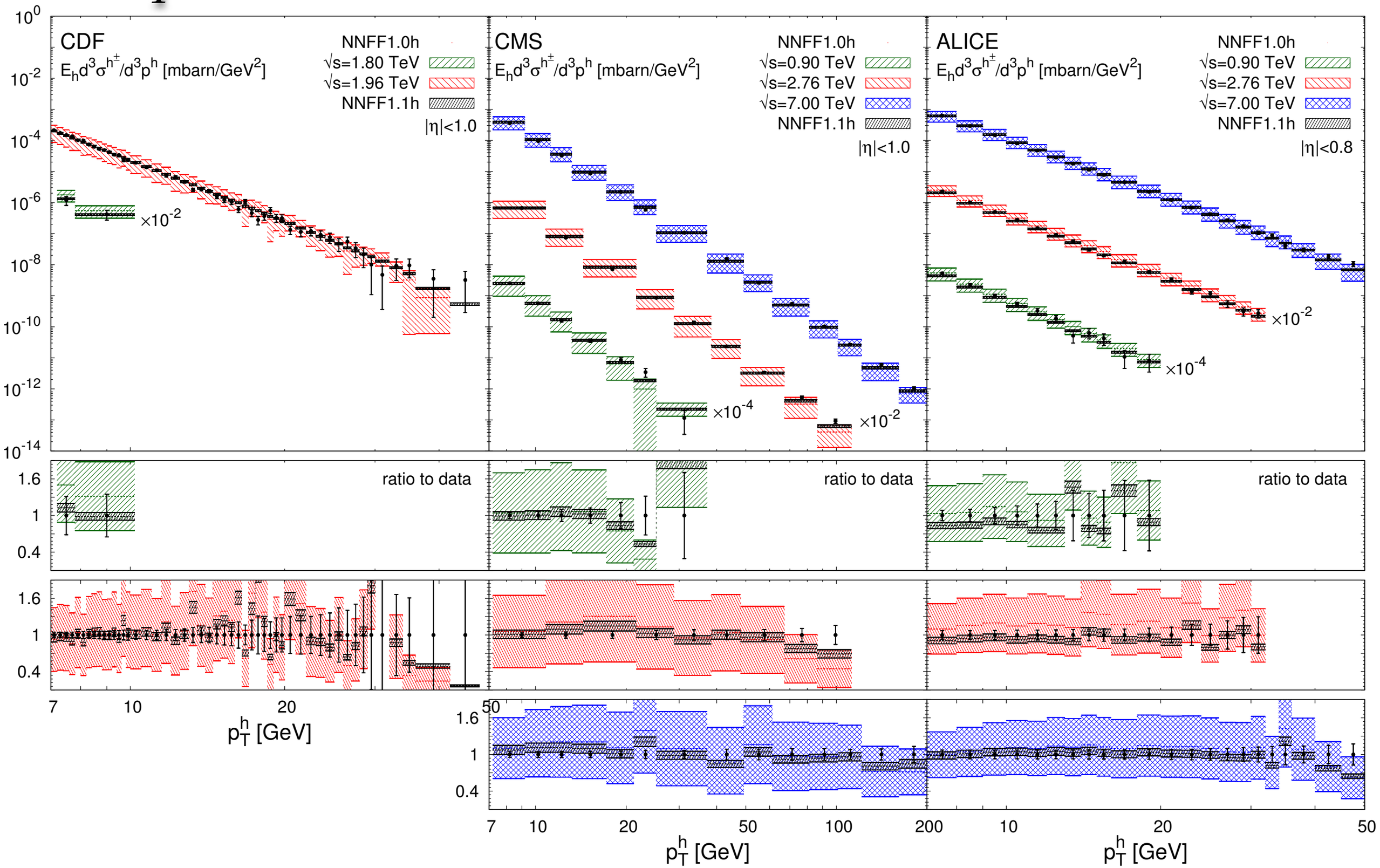
Impact hadroproduction in pp collision data

Process	Experiment	Ref.	$\sqrt{s}$ [TeV]	$N_{\rm dat}$	$\chi^2_{\rm in}/N_{\rm dat}$	$\chi^2_{\rm rw}/N_{\rm dat}$
SIA	various, see Table 1 in [33]			471 (527)	0.83	0.83
pp	CDF	[9]	1.80	2 (49)	3.32	0.20
		[10]	1.96	50 (230)	2.93	1.23
	CMS	[13]	0.90	7 (20)	4.20	0.70
		[14]	2.76	9 (22)	10.6	1.24
		[13]	7.00	14 (27)	12.4	1.64
	ALICE	[15]	0.90	11 (54)	4.94	1.88
		[15]	2.76	27 (60)	13.3	0.82
		[15]	7.00	22 (65)	6.03	0.53
				603 (1054)	6.54 →	1.11

- Substantial improvement of the single χ^2's as well as of the global one:
  - no tension between the different datasets.

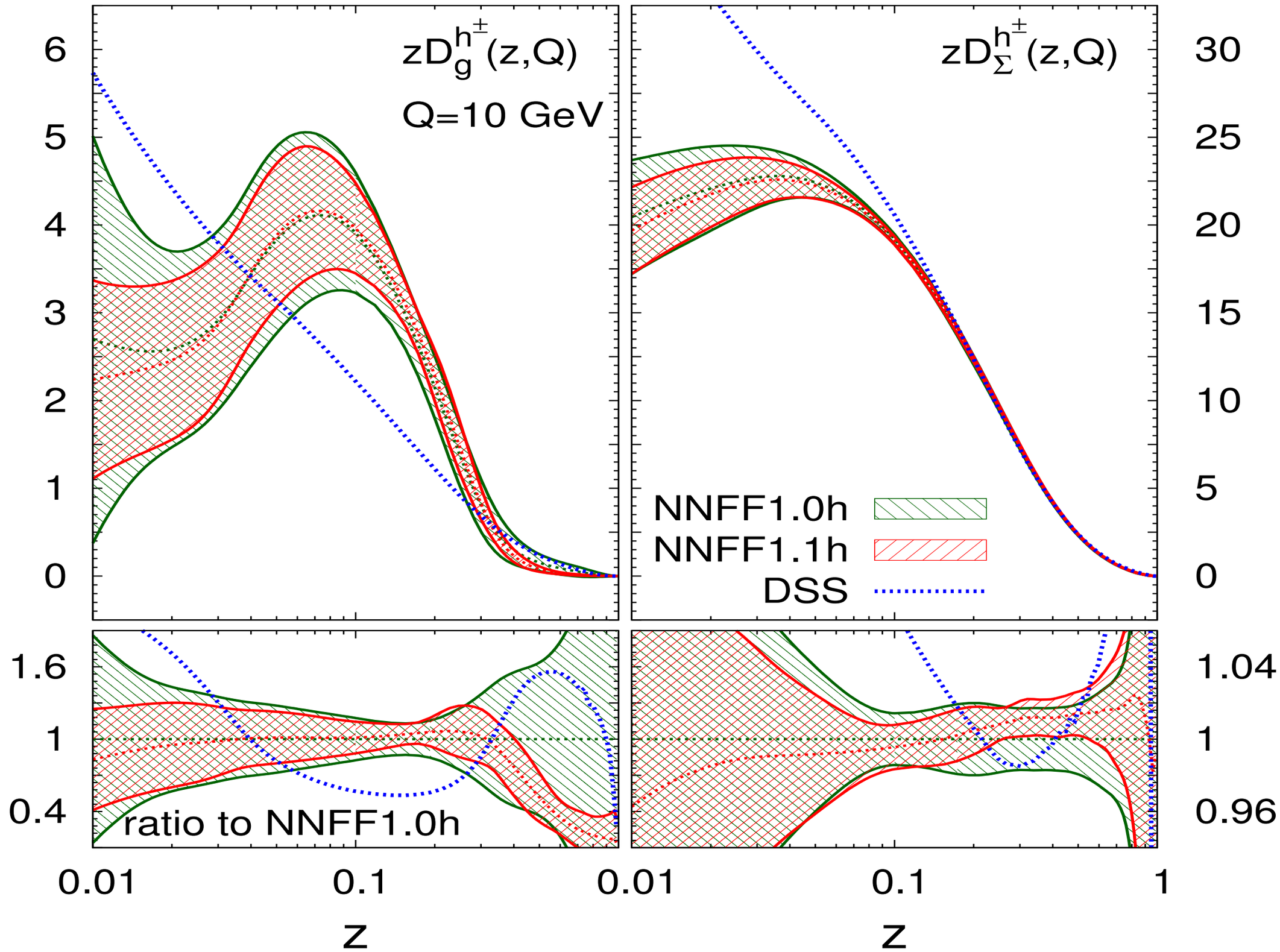
Charged hadron FFs

Comparison to LHC/Tevatron data



Charged hadron FFs

Impact hadroproduction in pp collision data



Charged hadron FFs

Choice of the cut in p_T

- A suitable p_T cut is important to avoid large **higher-order** corrections.
  - behaviour of the χ^2 upon variations of the cut:

Experiment	$p_{T,\mathrm{cut}}^h$ $\sqrt{s}$ [TeV]	5 GeV $\frac{\chi^2_{\mathrm{rw}}}{N_{\mathrm{dat}}}$	5 GeV N_{dat}	6 GeV $\frac{\chi^2_{\mathrm{rw}}}{N_{\mathrm{dat}}}$	6 GeV N_{dat}	7 GeV $\frac{\chi^2_{\mathrm{rw}}}{N_{\mathrm{dat}}}$	7 GeV N_{dat}	10 GeV $\frac{\chi^2_{\mathrm{rw}}}{N_{\mathrm{dat}}}$	10 GeV N_{dat}
CDF	1.80	1.30	7	0.28	4	0.10	2	—	—
	1.96	1.32	60	1.26	55	1.23	50	1.15	35
CMS	0.90	0.93	10	0.67	8	0.70	7	0.80	6
	2.76	1.38	11	1.27	10	1.24	9	1.16	8
	7.00	2.01	17	1.80	15	1.64	14	1.40	13
ALICE	0.90	2.56	15	2.05	13	1.88	11	1.52	8
	2.76	0.61	21	0.72	19	0.82	17	1.08	14
	7.00	0.56	26	0.52	24	0.53	22	0.60	19
Total		1.27	167	1.14	148	1.11	132	1.08	103

Too large χ^2

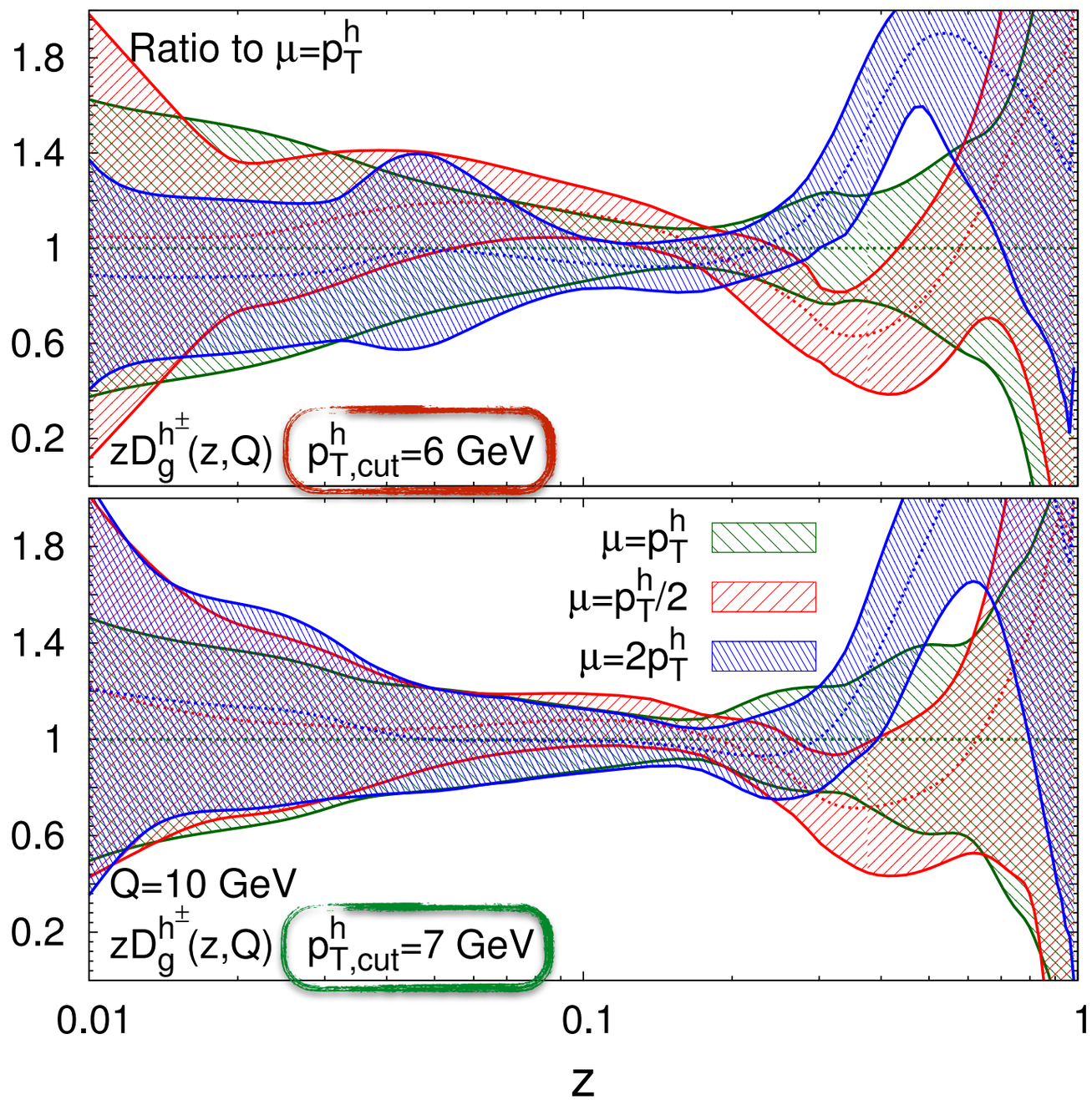
Candidates

Too few points

Charged hadron FFs

Choice of the cut in p_T

- A suitable p_T cut is important to avoid large **higher-order** corrections.
  - stability of the FFs upon scale variations:



- The cut at 7 GeV seems to be optimal:
  - good χ^2,
  - many points survive the cut,
  - good stability of the FFs upon scale variations.

Charged hadron FFs

Compatibility with NNFF1.0

- Charged-hadron FFs can be regarded as:

$$D_i^{h^\pm} = D_i^{\pi^\pm} + D_i^{K^\pm} + D_i^{p/\bar{p}} + D_i^{\mathrm{res}^\pm}$$

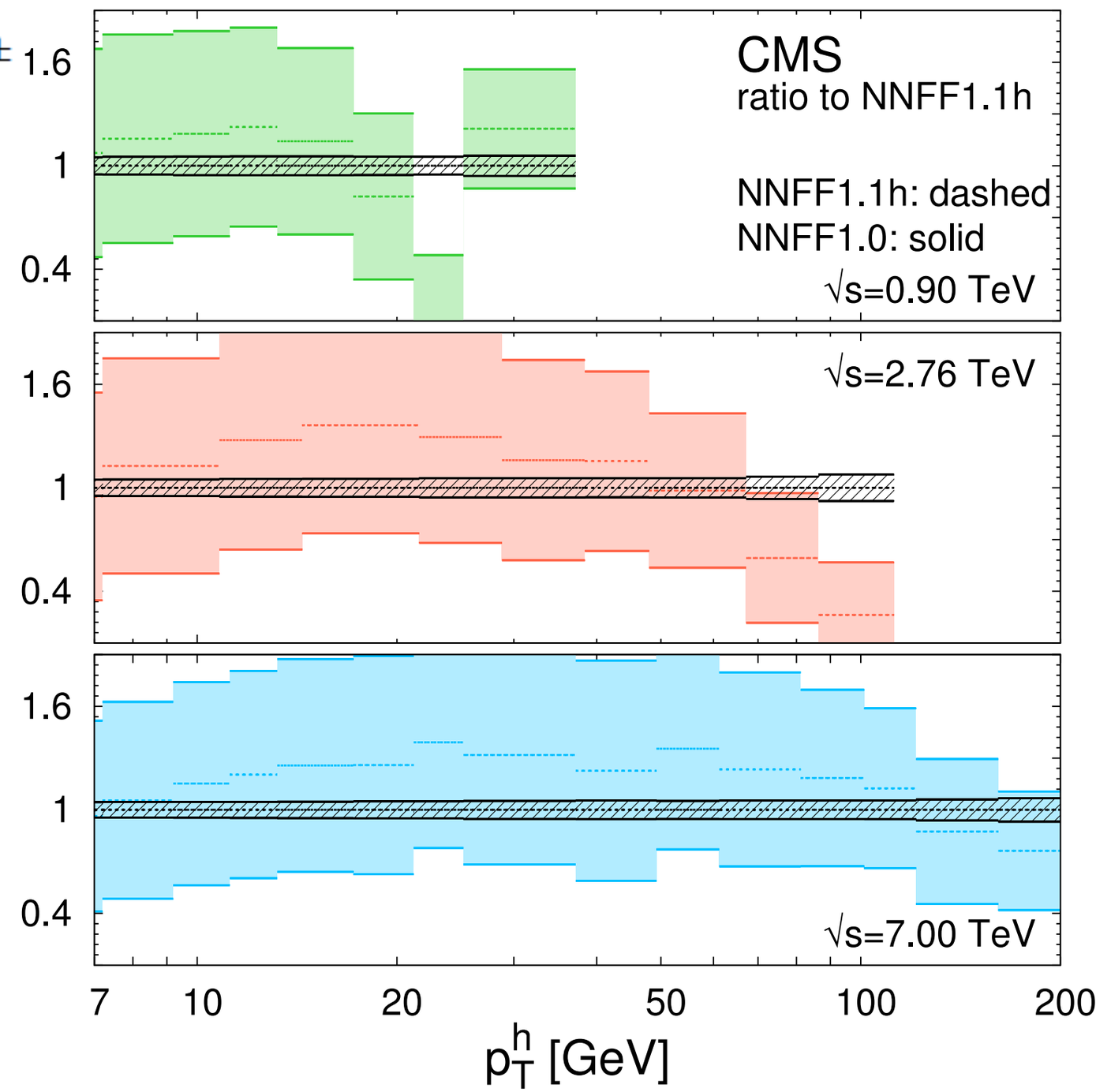
- Therefore:

$$E_h \frac{d^3\sigma^{h^\pm}}{d^3p^h} > \sum_{\mathcal{H}=\pi^\pm,K^\pm,p/\bar{p}} E_h \frac{d^3\sigma^{\mathcal{H}}}{d^3p^h}$$

- Fulfilled within uncertainties.

- The same argument applies to the momentum fractions:

$Q = 5$ GeV i	NNFF1.1h $M_i^{h^\pm}(Q)$	NNFF1.0 $M_i^{\mathrm{light}}(Q)$
g	0.86 ± 0.06	0.80 ± 0.18
u^+	1.24 ± 0.07	1.42 ± 0.12
$d^+ + s^+$	2.05 ± 0.08	2.07 ± 0.27
c^+	1.09 ± 0.03	1.01 ± 0.08
b^+	1.06 ± 0.02	0.98 ± 0.08



Summary

- **First** determination of charged-hadron FFs including both **Tevatron** and **LHC** data (**NNFF1.1h**):
  - **CMS/ALICE** at $\sqrt{s}$ = 0.9, 2.76, 7 TeV, **CDF** at $\sqrt{s}$ = 1.8,1.96 TeV.
  - **148** datapoints in total.
- Inclusion of these datasets by **reweighing** of a pre-existing FF set based on **SIA data only** (**NNFF1.0h**).
- Remarkable **consistency** of these datasets:
  - **simultaneous** inclusion of all of them is possible,
  - very good description of **all single datasets**.
- Strong impact on the **gluon FF**:
  - dramatic reduction of the **uncertainty**, particularly at large z,
  - much **softer** large-z gluon (in agreement with the predictions d'Enterria et. al).
- Consistent results with light-hadron FFs (NNFF1.0).

Backup slides