Parton Distribution studies at AFTER

Juan Rojo
CERN, TH Unit, PH Division
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Outline

- ☑ Neural Network Parton Distributions
- ☑ PDF studies at AFTER
- ☑ Parton Distributions with Intrinsic Charm

NEURAL NETWORK PARTON DISTRIBUTIONS

cross section for the elementary process ij→O, function of M_O, g_{ijO}

strength of the coupling between i,j and O

$$\sigma(pp \to O + X) = \int dx_1\, dx_2 \sum_{i,j} \boxed{f_i(x_1)\, f_j(x_2)}\ \boxed{\hat{\sigma}_{(ij\to O)}}(M_O, g_{ijO}, \ldots)$$

mass of O

N of partons of type "i", "j", carrying a fraction $x_{i,j}$ of the proton momentum

- A theory of particle physics is defined by parameters like M_O, g_{ijO}
- Their extraction, by inverting the above relation, is the ultimate goal of the cross-section measurement (eg. M_Z and $\sin^2\theta_W$ at LEP, and $M_{top,Higgs}$ and y_t at LHC)
- The precision of this extraction is determined by:
  - The precision of the calculation of the elementary cross section in terms of M_O, g_{ijO} **↓ Theory**
  - The precision in the knowledge of the "parton densities" $f_i(x)$ (PDFs) **← Theory + exp**
  - The precision of the cross section measurement, defined by:

MLM LumiDays11

$$\sigma(pp \to O + X) = \frac{N_{events}(O)}{\text{Luminosity}}$$

← exp

← this meeting

3

PDF Uncertainties: The Hessian Method

- Determine best-fit PDF parameters by χ^2 minimization
- **Expand quadratically** around minimum and define 68% CL by a **suitable tolerance**

$$\Delta\chi^2_{\text{global}} \equiv \chi^2_{\text{global}} - \chi^2_{\text{min}} = \sum_{i,j=1}^{n} H_{ij}(a_i - a_i^0)(a_j - a_j^0) \qquad H_{ij} = \frac{1}{2}\frac{\partial^2 \chi^2_{\text{global}}}{\partial a_i \partial a_j}\Big|_{\text{min}}$$

- PDF errors on physical observables can be computed by **linear error propagation**

$$\Delta F = \frac{1}{2}\sqrt{\sum_{k=1}^{n}\left[F(S_k^+) - F(S_k^-)\right]^2},$$

Eigenvectors from Hessian matrix diagonalization

- Used by CT, MSTW, HERAPDF, ABKM, JR (with different variants)
- Drawbacks of Hessian approach:
    - Relies on the **Gaussian approximation** and **linear error propagation**
    - The **determination of tolerance** non-trivial when combining many datasets

PDF Uncertainties: The Monte Carlo Method

- Generate a large number of Monte Carlo replicas of the experimental data with the same underlying probability distribution

$$F_{I,p}^{(\mathrm{art})(k)} = S_{p,N}^{(k)} F_{I,p}^{(\mathrm{exp})} \left(1 + \sum_{l=1}^{N_c} r_{p,l}^{(k)} \sigma_{p,l} + r_p^{(k)} \sigma_{p,s} \right) \quad , \; k = 1, \ldots, N_{\mathrm{rep}} >> 1$$

sys errors — **stat error** — **lumi error** — **random numbers**

- Perform a **PDF determination** on each of these MC replicas

- The set of PDF replicas form a **representation of the probability density in the space of parton distribution functions**

- PDF uncertainties can be propagated to physical cross sections using textbook statistics, no need of linear / gaussian assumptions

Central PDF prediction = Expectation Value of MC sample →

$$\langle \mathcal{O} \rangle = \int \mathcal{O}[f] \, \mathcal{P}(f) \, Df = \frac{1}{N} \sum_{k=1}^{N} \mathcal{O}[f_k]$$

PDF Uncertainty = Standard Deviation of MC sample →

$$\Delta f = \sqrt{ \frac{1}{N} \sum_{k=1}^{N} f_k^2 - \left(\frac{1}{N} \sum_{k=1}^{N} f_k \right)^2 }$$

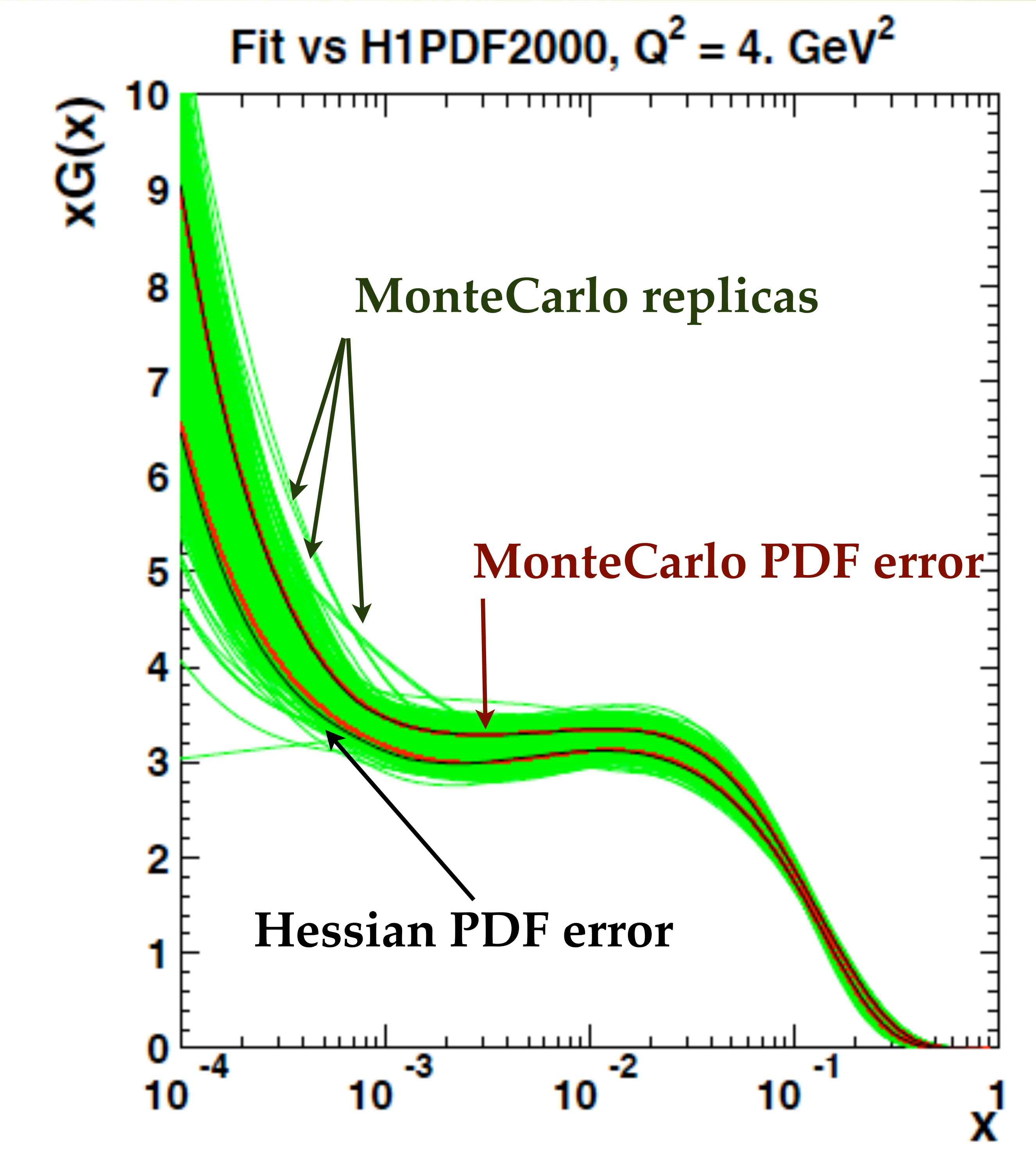
PDF Uncertainties: Hessian vs Monte Carlo

- Hessian and Monte Carlo methods **statistically equivalent** if gaussian quadratic approximation is realistic and no tolerances are introduced

- HERA-LHC workshop proceedings: with the **HERAPDF** framework, Hessian and Monte Carlo methods shown to be **numerically equivalent** in a QCD analysis of H1 data

- **Monte Carlo method more flexible** with deviations from the quadratic approximation and combinations of many experiments

- MC method used by the **NNPDF** analisys, but also studies by **MSTW** and **HERAPDF**



Artificial Neural Networks

- We use **Artificial Neural Networks** as **functions** to represent **PDFs at the starting scale**
- We employ **Multilayer Feed-Forward** Neural Networks trained using **Genetic Algorithms** with the **Cross-Validation Method** for dynamical stopping
- Activation determined by weights and thresholds

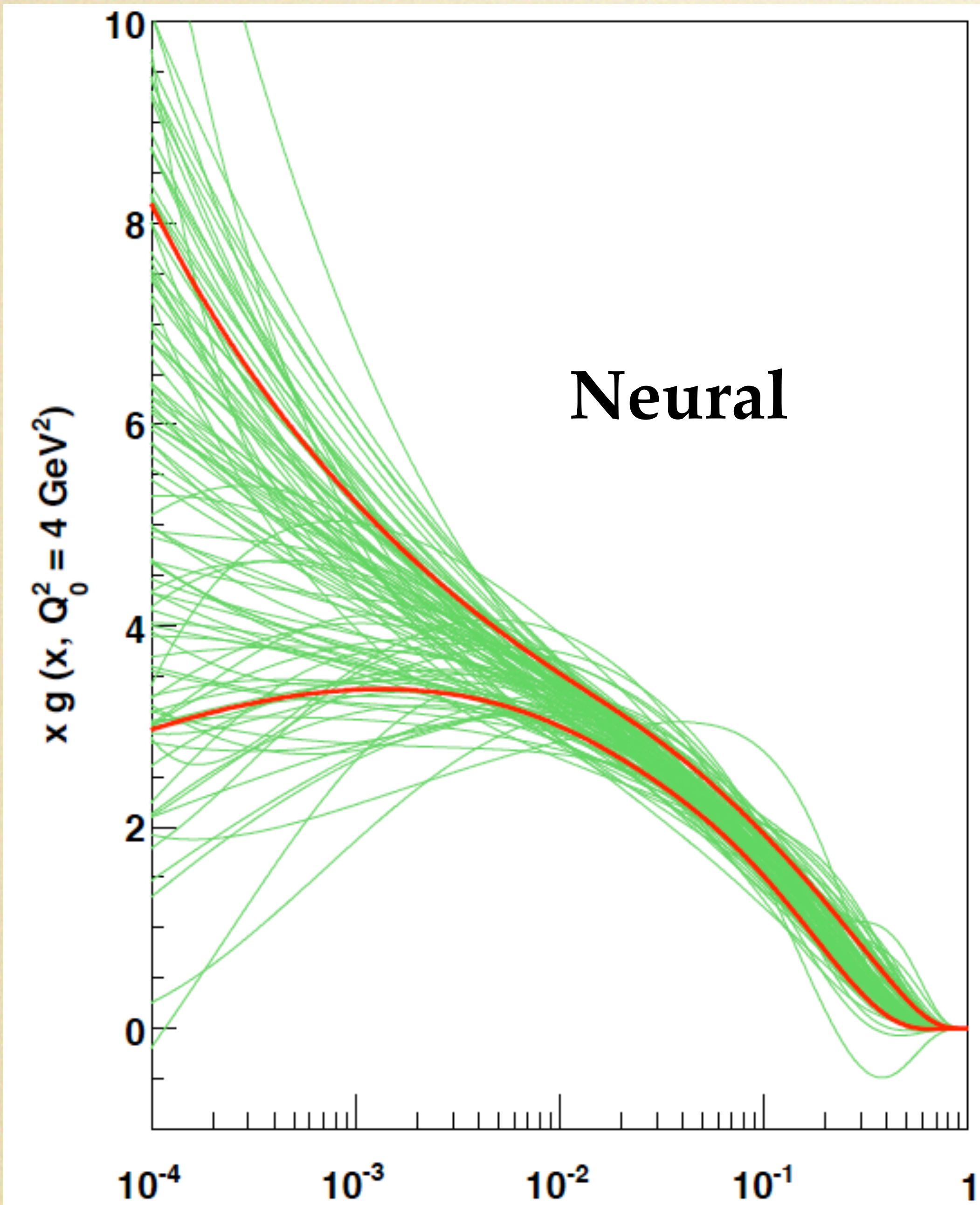
$$\xi_i = g\left(\sum_j \omega_{ij}\xi_j - \theta_i\right), \qquad g(x) = \frac{1}{1+e^{-\beta x}}$$

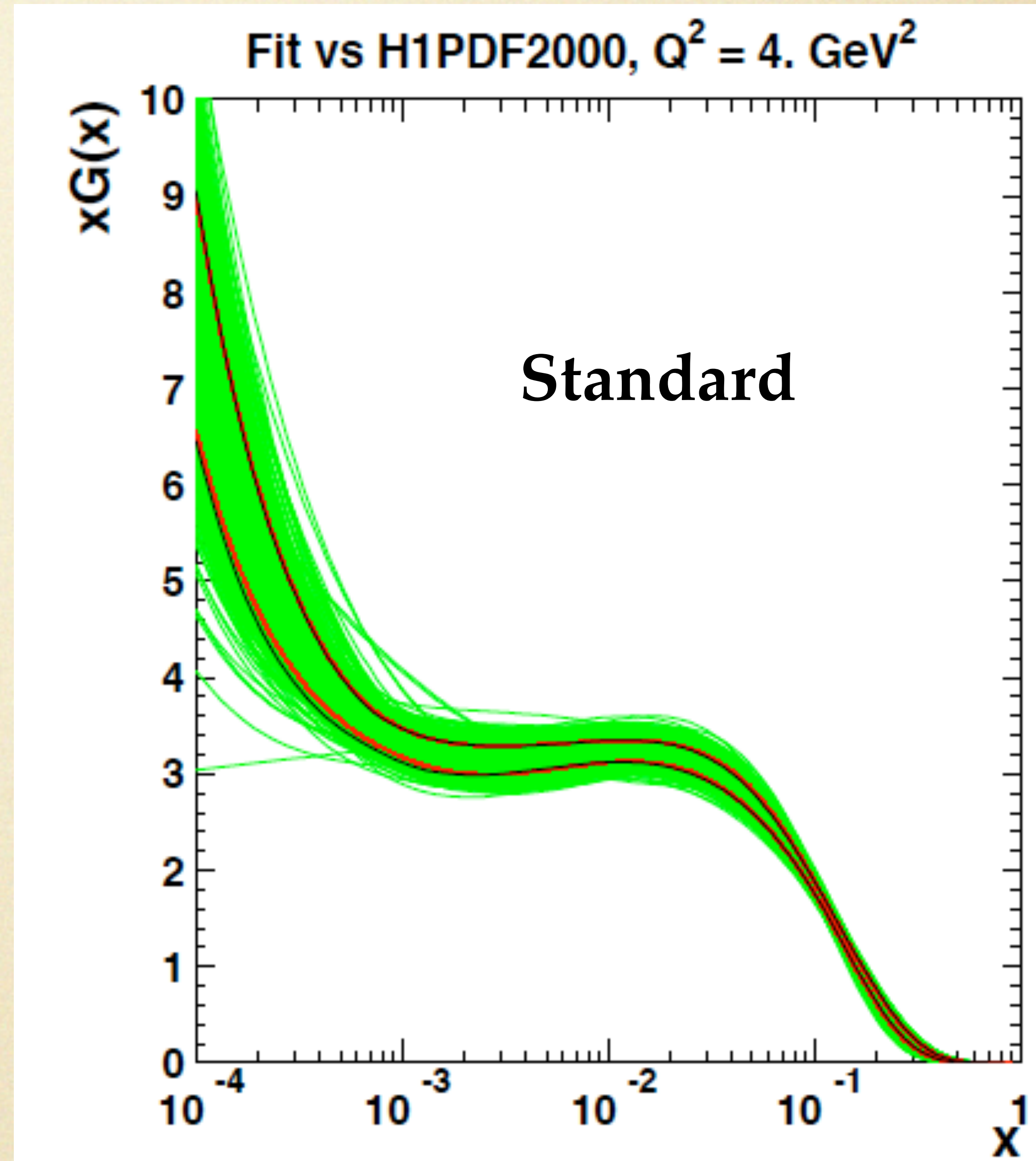
Ex.: 1-2-1 NN:

$$\xi_1^{(3)}(\xi_1^{(1)}) = \frac{1}{1+e^{\theta_1^{(3)} - \frac{\omega_{11}^{(2)}}{1+e^{\theta_1^{(2)}-\xi_1^{(1)}\omega_{11}^{(1)}}} - \frac{\omega_{12}^{(2)}}{1+e^{\theta_2^{(2)}-\xi_1^{(1)}\omega_{21}^{(1)}}}}}$$

- They provide a parametrization which is **redundant** and **robust** against variations

PDF Parametrization Uncertainties: simple polynomials vs Neural Networks

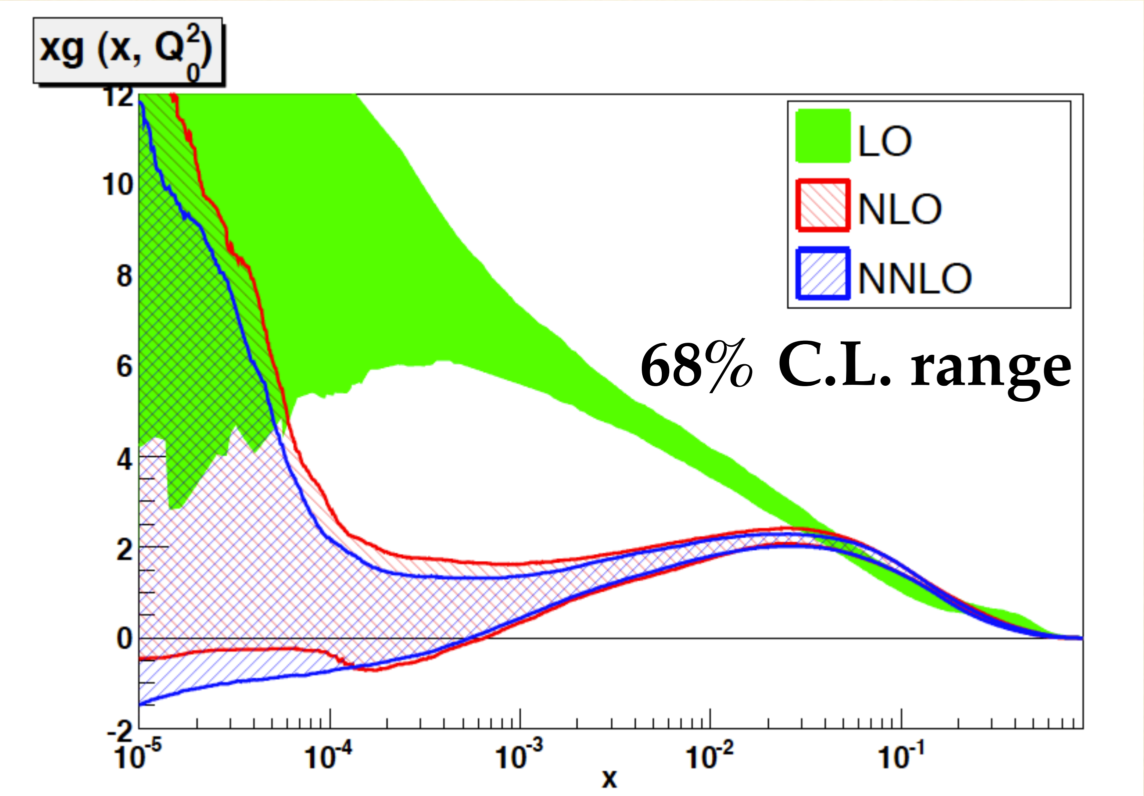


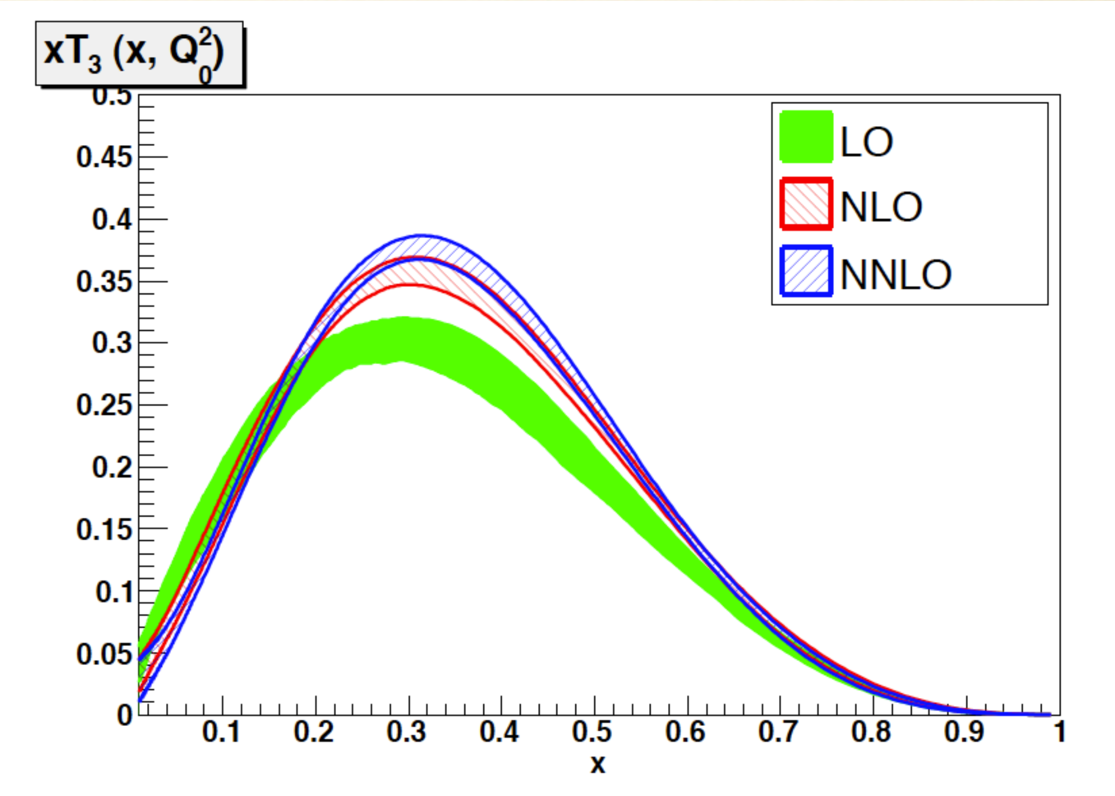


- Standard PDF parametrization with simple polynomials introduce **substantial bias in the PDF determinations**
- Artificial neural networks are a suitable **universal unbiased interpolants**: We want to extract **physical laws from the data**, not get back **the theory bias** we are putting in!

The NNPDF2.1 family

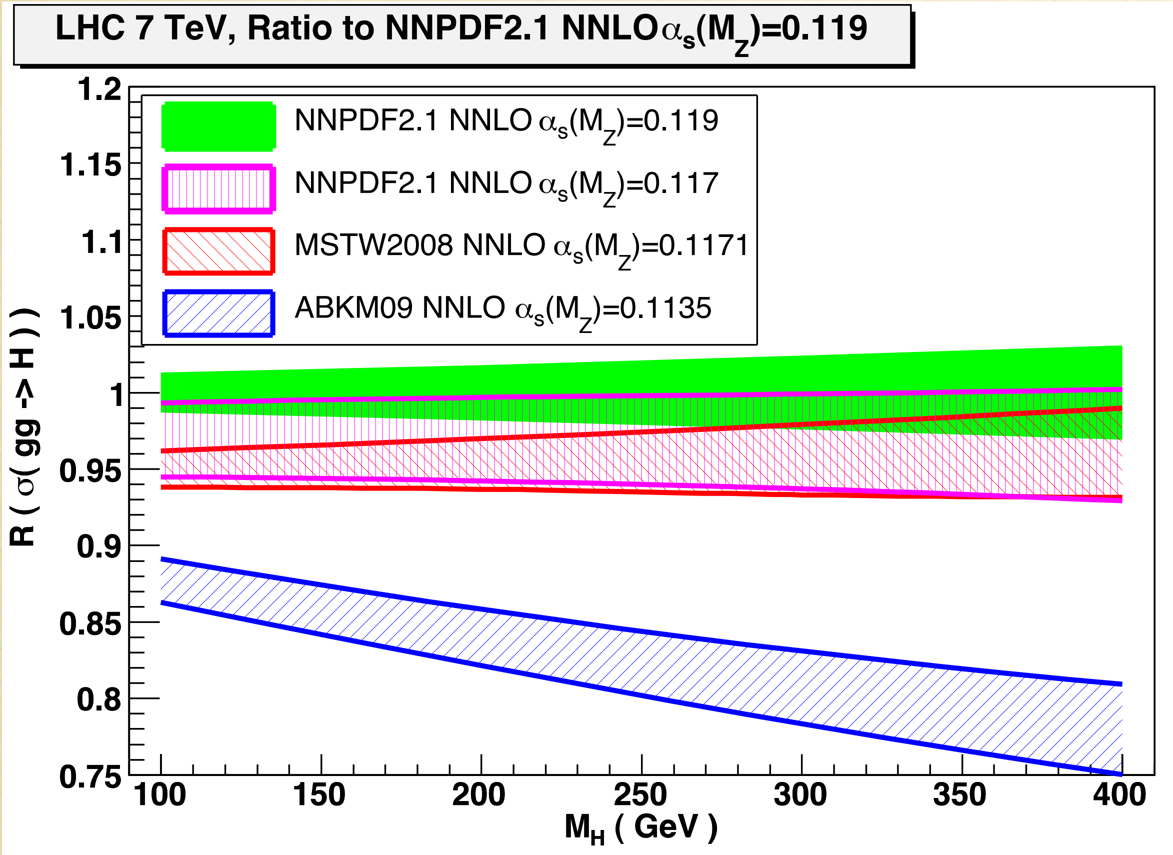
- The NNPDF2.1 family provides LO, NLO and NNLO sets (arXiv:1101.1300,1107.2652)
- Sets with variations of $\alpha_S(M_Z)$, quark masses and dataset are also provided in LHAPDF, as well as FFN sets
- NNPDF2.1 is based on
  - The most updated pre-LHC **dataset**: HERA-I, TeV W/Z and jets, ...
  - The most advanced **methodology**: artificial neural networks, Monte Carlo techniques, Bayesian reweighting, ...
  - The most up-to-date **theory calculations**: exact NLO for all hadronic data, FONLL GM-VFN for heavy quarks in DIS, ...



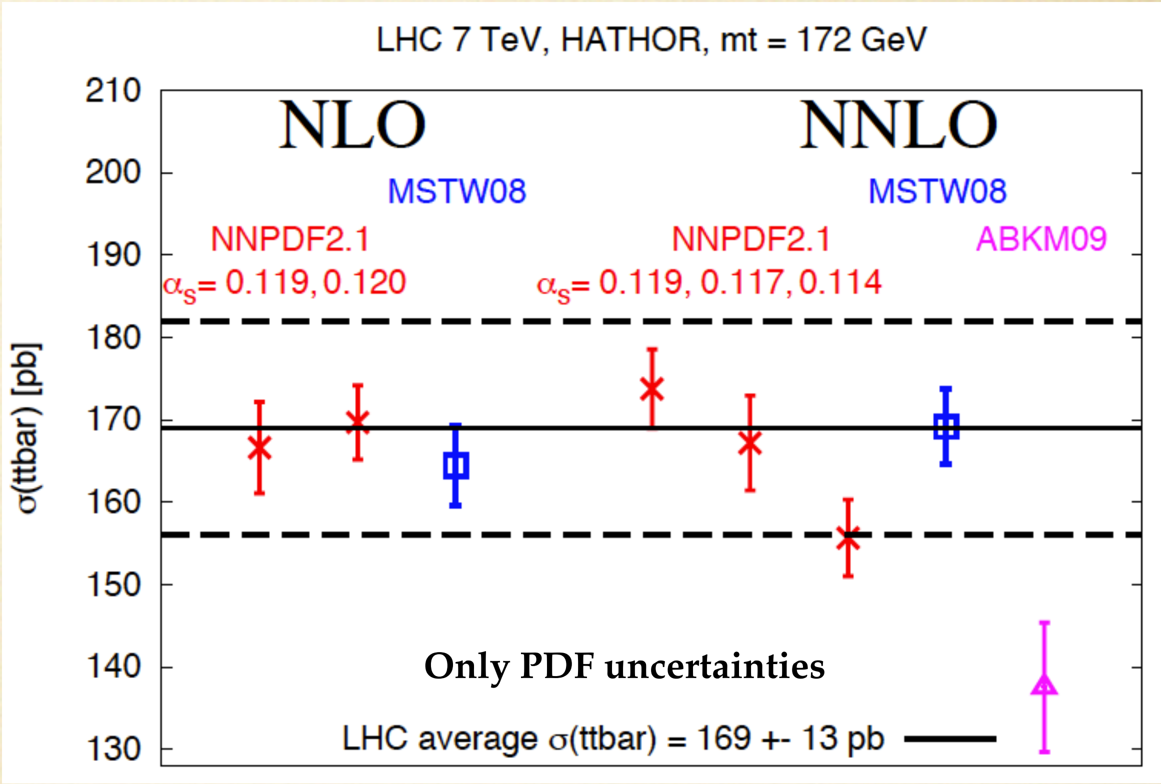


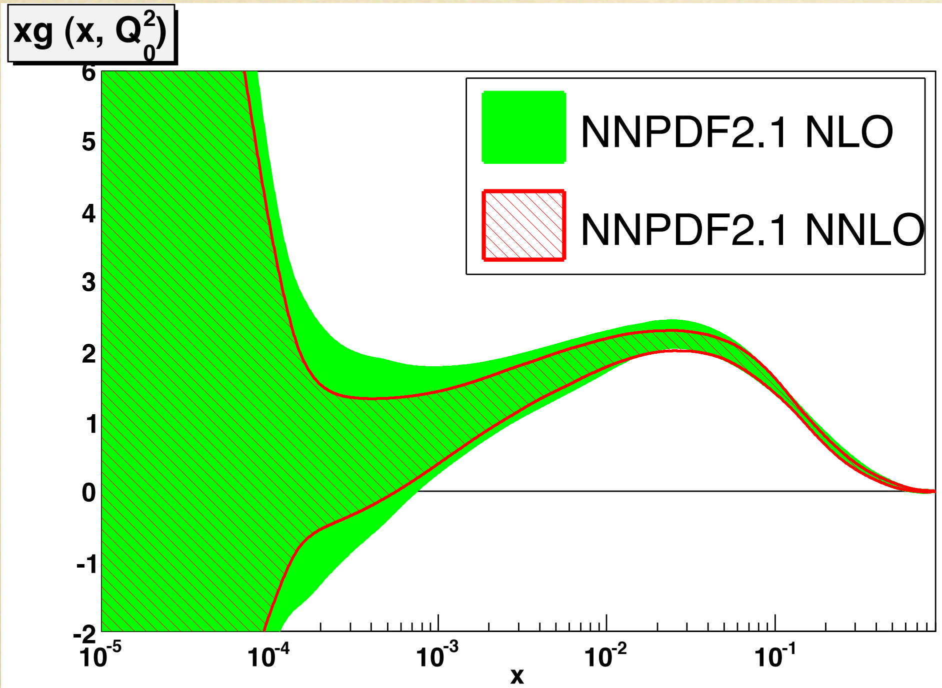
(selected) NNPDF2.1 Phenomenology

Higgs ggF xsec: Agreement of NNLO global sets

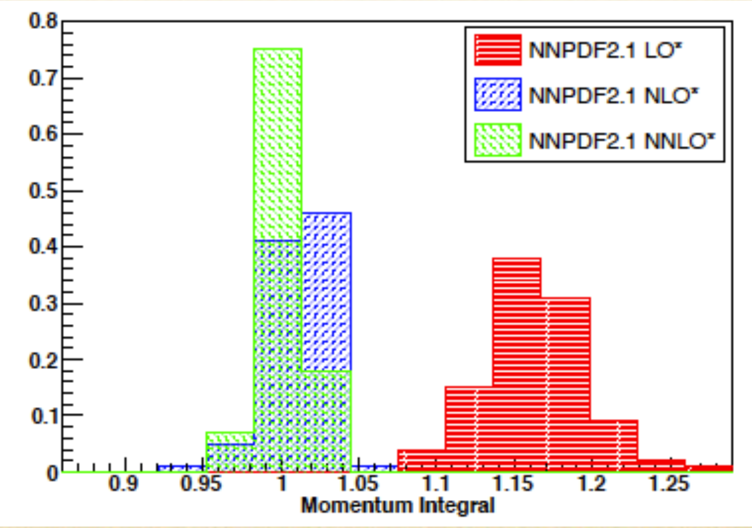


ttbar xsec: towards PDF discrimination with LHC data





PDFs **stable** from NLO to NNLO



Unbiased determination of the **proton momentum** at NNLO

Excellent agreement with QCD expectations

Non-trivial **consistency check** of global PDF analysis

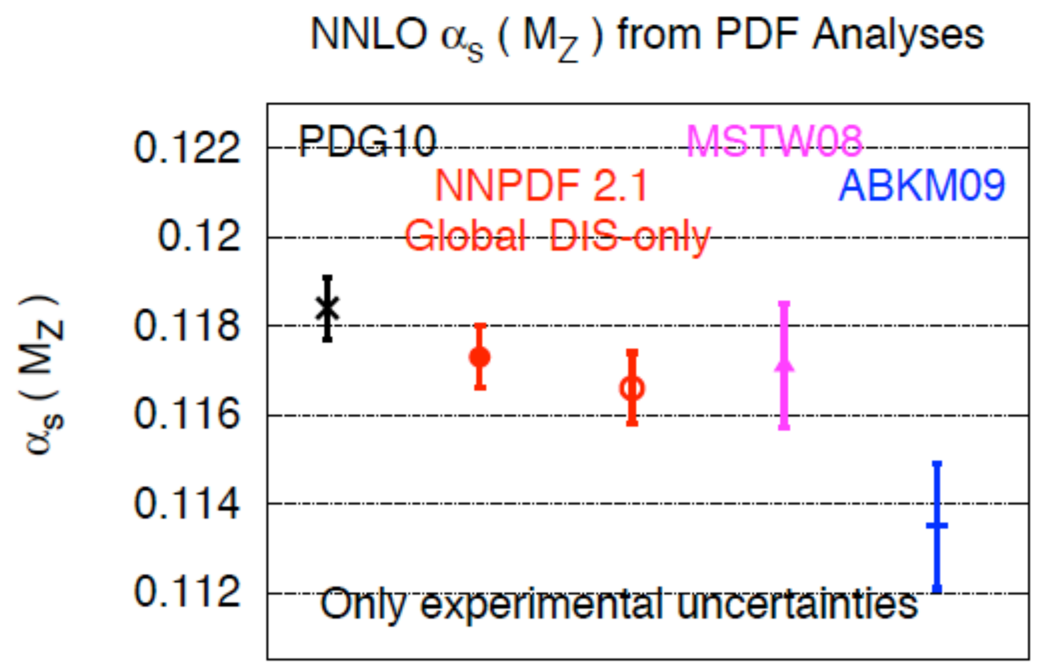
$$[M]\left(Q^2\right) \equiv \int_0^1 dx \left(xg\left(x,Q^2\right) + x\Sigma\left(x,Q^2\right)\right)$$

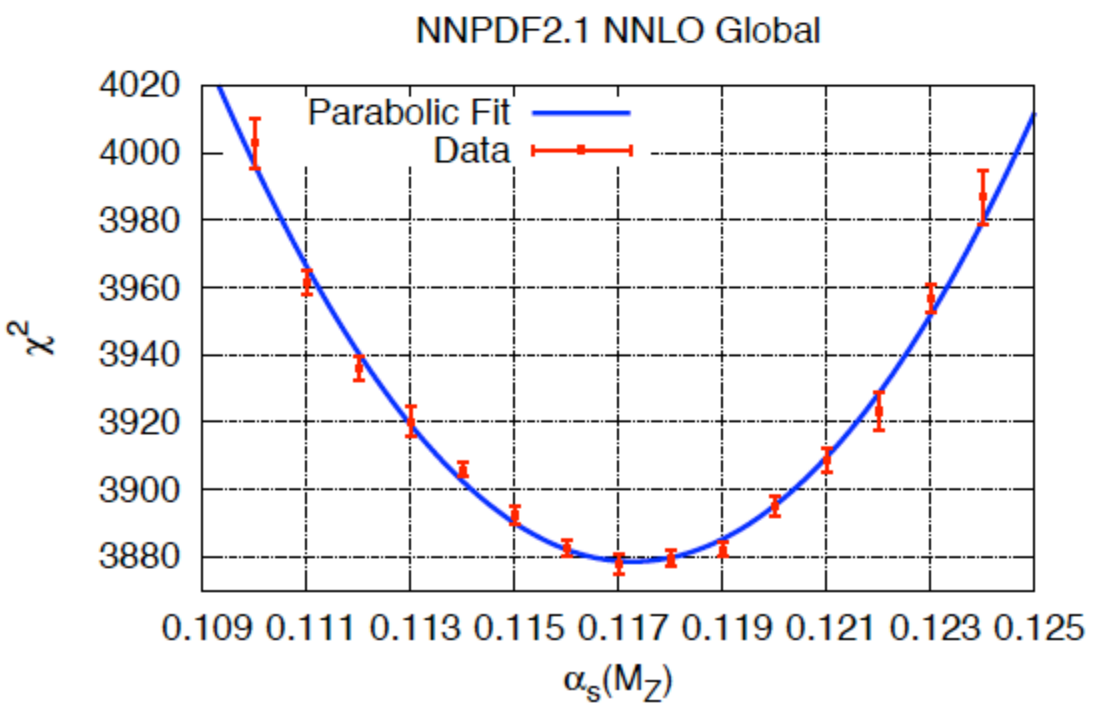
$$[M]_{\rm LO} = 1.161 \pm 0.032\,, [M]_{\rm NLO} = 1.011 \pm 0.018\,, [M]_{\rm NNLO} = 1.002 \pm 0.014$$

Determination of SM parameters

- The NNPDF methodology also very useful for precision determinations of SM parameters from data: **strong coupling, Vcs** (both part of PDG12 averages), **W mass**....

- Good: Small statistical errors from large dataset
- Bad: Bias from PDF parametrization? Dependence on dataset?
- NNLO: $\alpha_s^{\rm NNLO,global}(M_Z) = \mathbf{0.1173 \pm 0.0007}$ reasonable agreement with MSTW08, NNPDF2.1 smallest statistical uncertainties without theoretical bias
- $\alpha_s(M_Z)$ from DIS–only? A bit smaller $\alpha_s^{\rm NLO,dis}(M_Z) = \mathbf{0.1166 \pm 0.0009}$
- Compare with current PDG average $\alpha_s^{\rm PDG}(M_Z) = 0.1184 \pm 0.0007$





NNPDF2.2

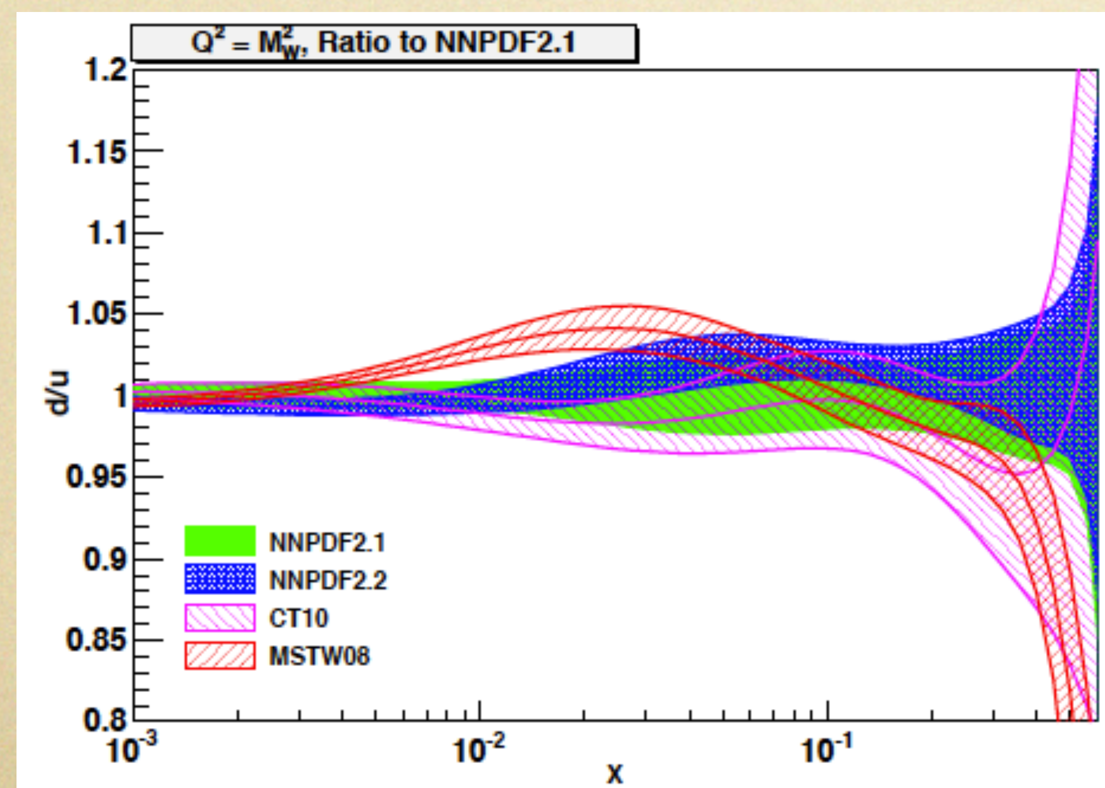
- NNPDF2.2 (**arXiv:1108.1758**) is the **only public PDF set** (available in LHAPDF) with LHC data included
- CMS (arXiv:1103.3470) and ATLAS (arXiv:1103.2929) 36 pb^{-1} W lepton asymmetry data
- Excellent description of all datasets, reduced (anti)quarks PDF uncertainties

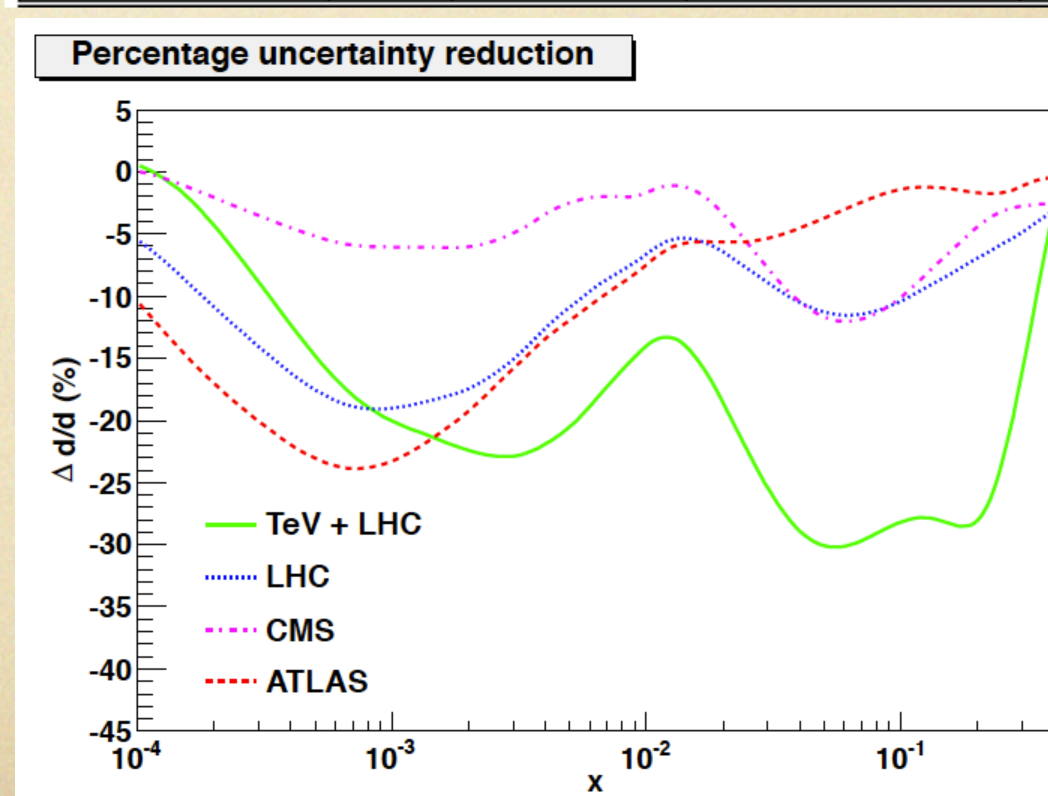
Initial comparison

	N_{dat}	NNPDF2.1	CT10	MSTW08
ATLAS(31pb^{-1})	11	0.76	0.77	3.32
CMS(36pb^{-1}) electron $p_T > 25$ GeV	6	1.83	1.19	1.70
CMS(36pb^{-1}) muon $p_T > 25$ GeV	6	1.24	0.73	0.77

After the fit

Experiment	N_{dat}	NNPDF2.1	NNPDF2.1 LHC	NNPDF2.2
ATLASmuASY	11	[0.77]	0.97	1.07
CMSeASY	6	[1.83]	1.23	1.08
CMSmuASY	6	[1.24]	0.63	0.56
D0eASY	12	[4.39]	[3.46]	1.38
D0muASY	10	[1.48]	[1.17]	0.35





PDF STUDIES AT AFTER

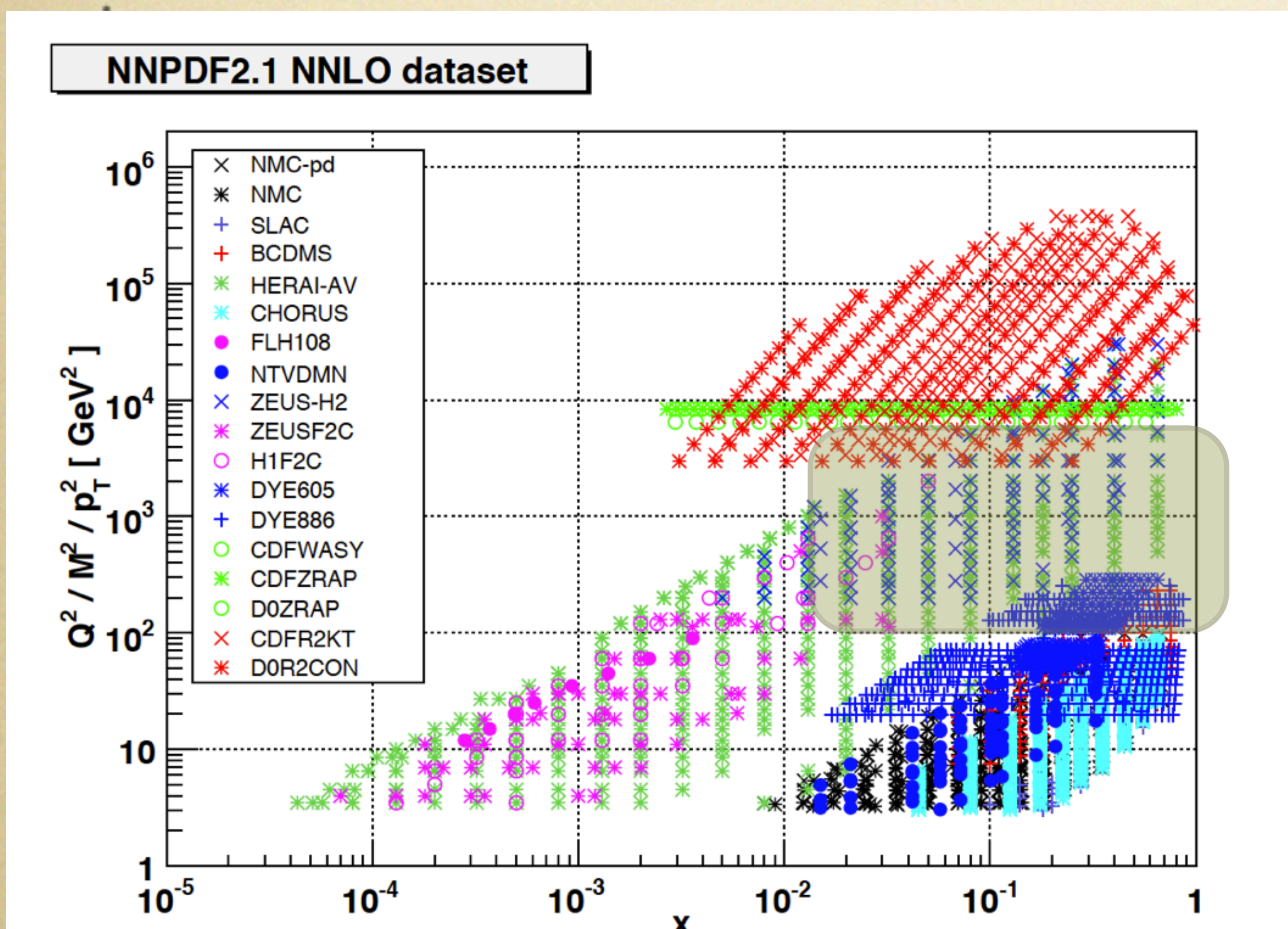
A Fixed Target ExpeRiment using the LHC beams

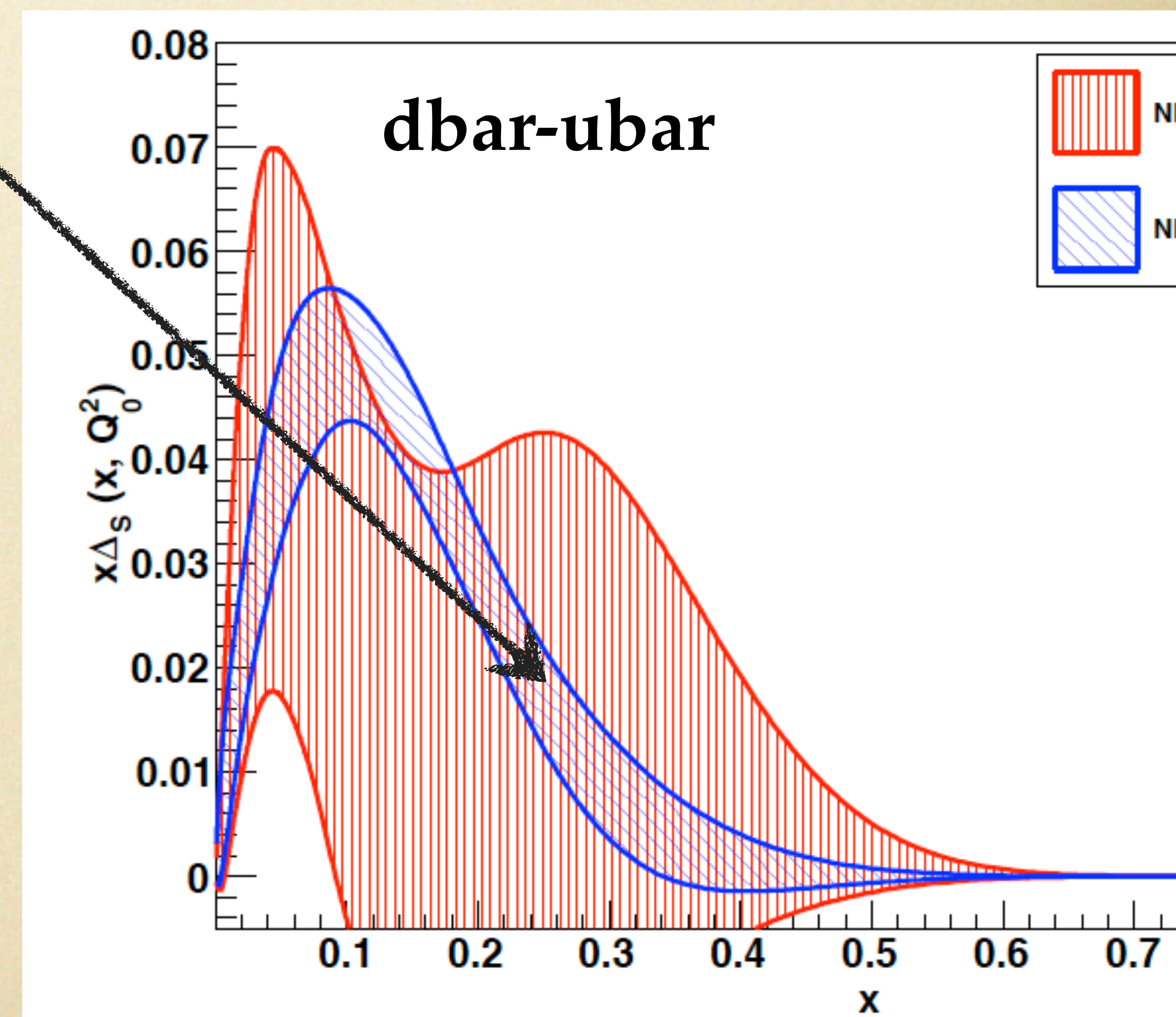
AFTER

- **A F**ixed **T**arget **E**xpe**R**iment at the LHC would collider the LHC beam on proton and nuclear fixed targets
- For 7 TeV the energy of the collision is (**115 GeV**)^2, for 13 TeV one has (**160 GeV**)^2
- Such **fixed target** programs offers several interesting physics studies related to **perturbative QCD and Parton Distributions**
- Relevant processes include **Drell-Yan** production, **open heavy quark** production, **quarkonia, jets, prompt photons**, and **electroweak** boson production
- Rich program in a **clean environment**, with **modern experimental and statistical analysis techniques** as compared to previous FT experiments
- Unique handle to **non perturbative QCD dynamics** like **intrinsic heavy quark** component of the proton

Drell-Yan data in PDF fits

- **Fixed target DY data** are a backbone of global PDF analysis
- They constrain the **quark flavor decomposition for x > 0.01** (Fixed target kinematics)
- However old FT DY data have **large uncertainties**, **no covariance matrix available**, **nuclear targets**,...
- DY FT data taken at a **modern experiment, with robust experimental and statistical analysis techniques**, could complement LHC measurements for **quark PDF constraints**
- Impact of DY data in **NNPDF2.0 set**

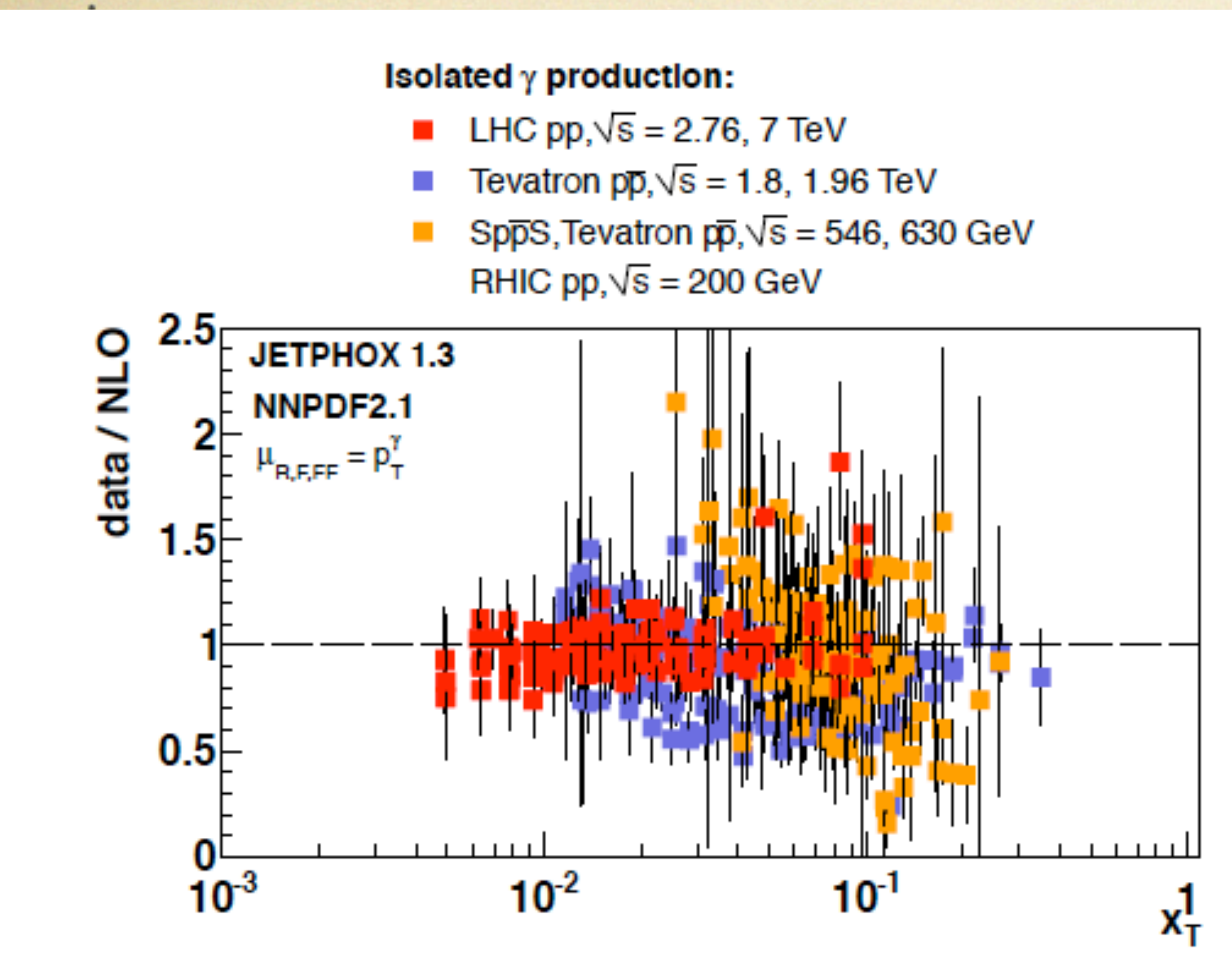


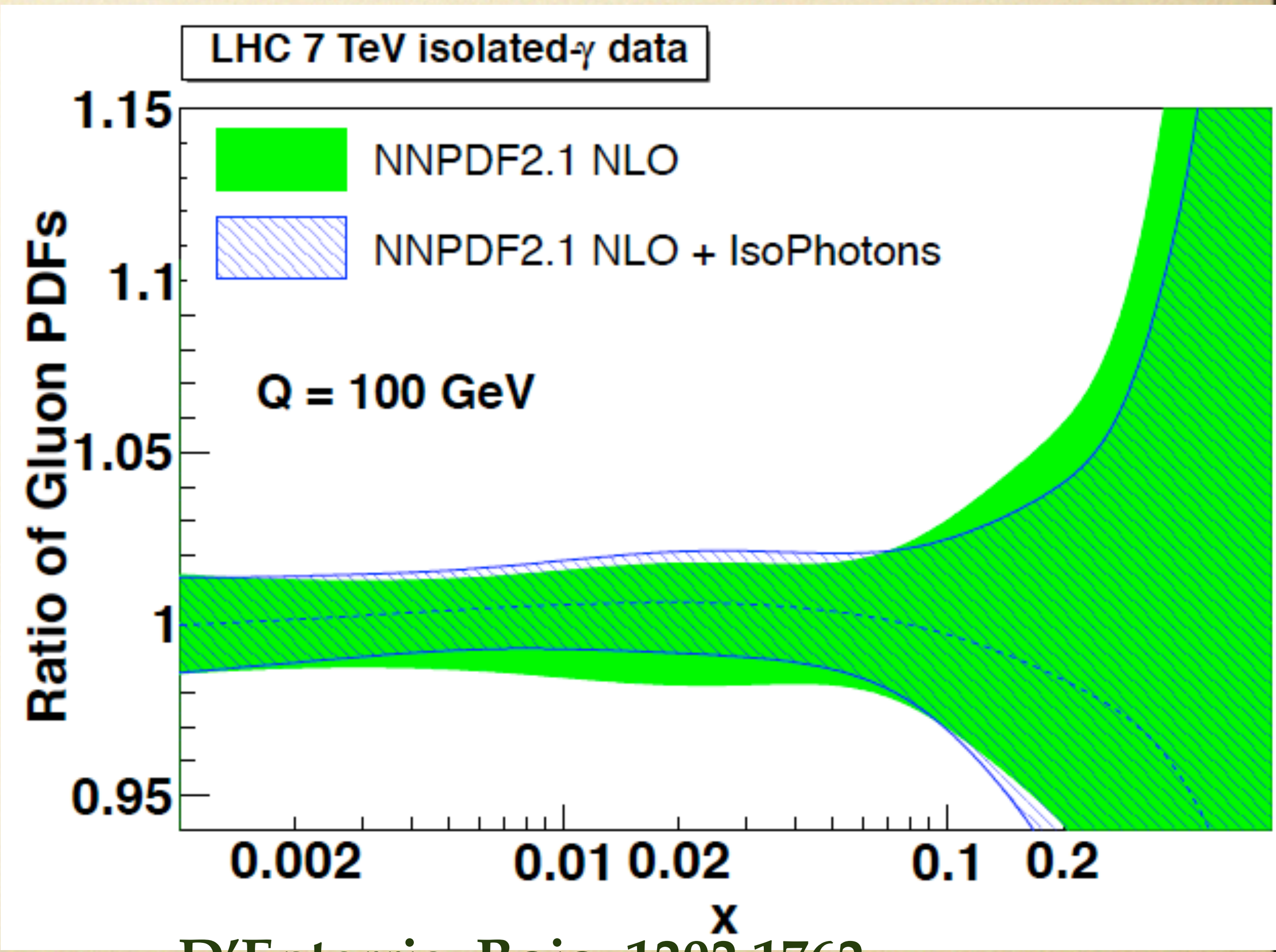


NNPDF, 1002.4407

Prompt Photons

- **Prompt photon production** provides a clean handle on the **gluon PDF**
- **LHC data** on direct photons constrains the **gluon PDF at medium *x***
- Crucial to reduce the fragmentation background with **isolation criteria**
- Also allows studies of perturbative and NP QCD: **intrinsic kT, all order resummations**





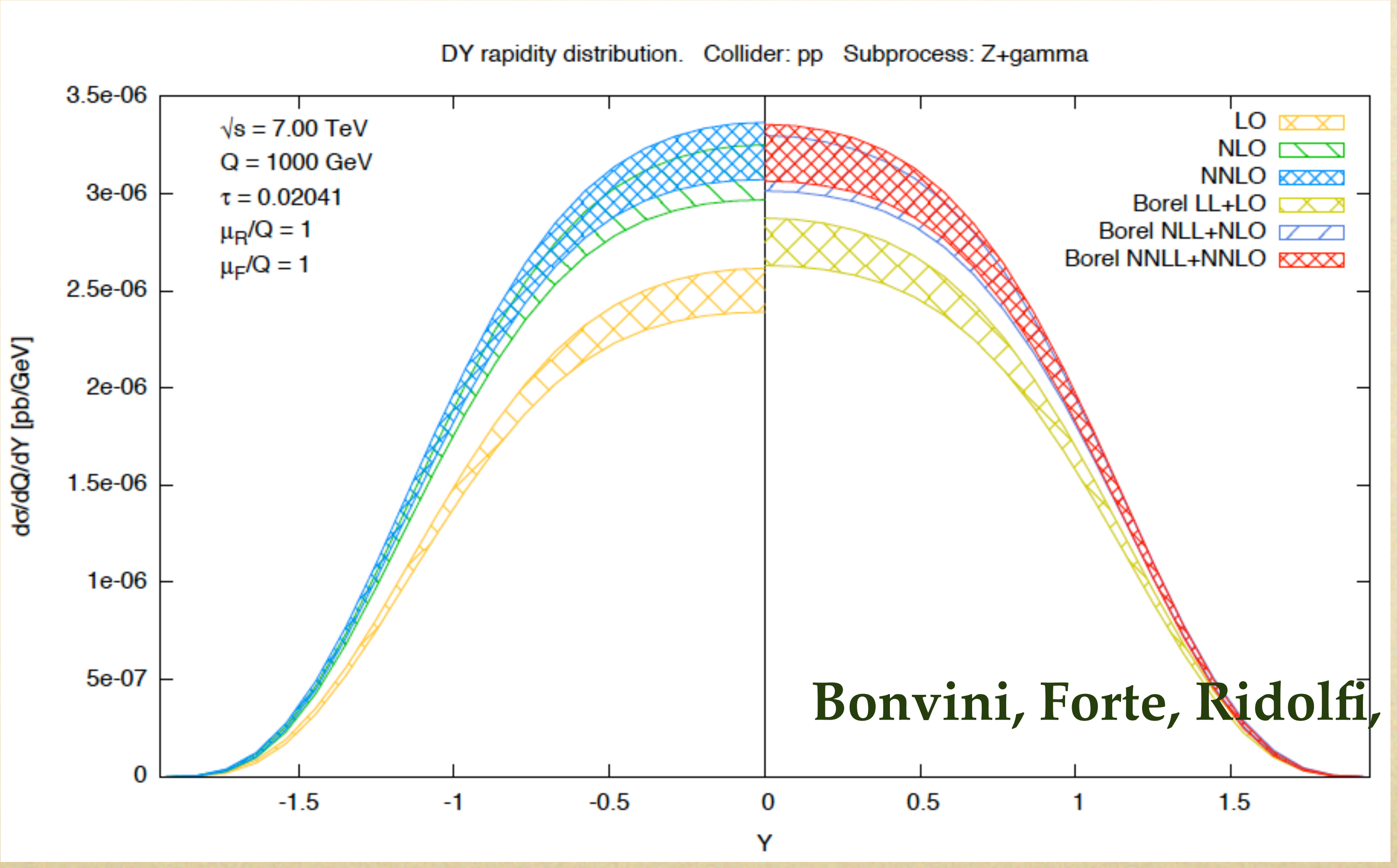
D'Enterria, Rojo, 1202.1762

W and Z production

- **W and Z production at threshold** offer a unique testing ground of perturbative QCD: large logarithms from s**oft gluon radiation** need to be r**esummed to all orders**

$$C^{\rm res}(N, \alpha_s(Q^2)) = g_0(\alpha_s)\, \exp \mathcal{S}\left(\bar{\alpha} \ln \frac{1}{N}, \bar{\alpha}\right),$$
$$\mathcal{S}(\lambda, \bar{\alpha}) = \frac{1}{\bar{\alpha}}\, g_1(\lambda) + g_2(\lambda) + \bar{\alpha}\, g_3(\lambda) + \bar{\alpha}^2\, g_4(\lambda) + \ldots$$

- Direct interplay with **non perturbative dynamics**, and unique source to understand the **convergence of the QCD perturbative expansion**

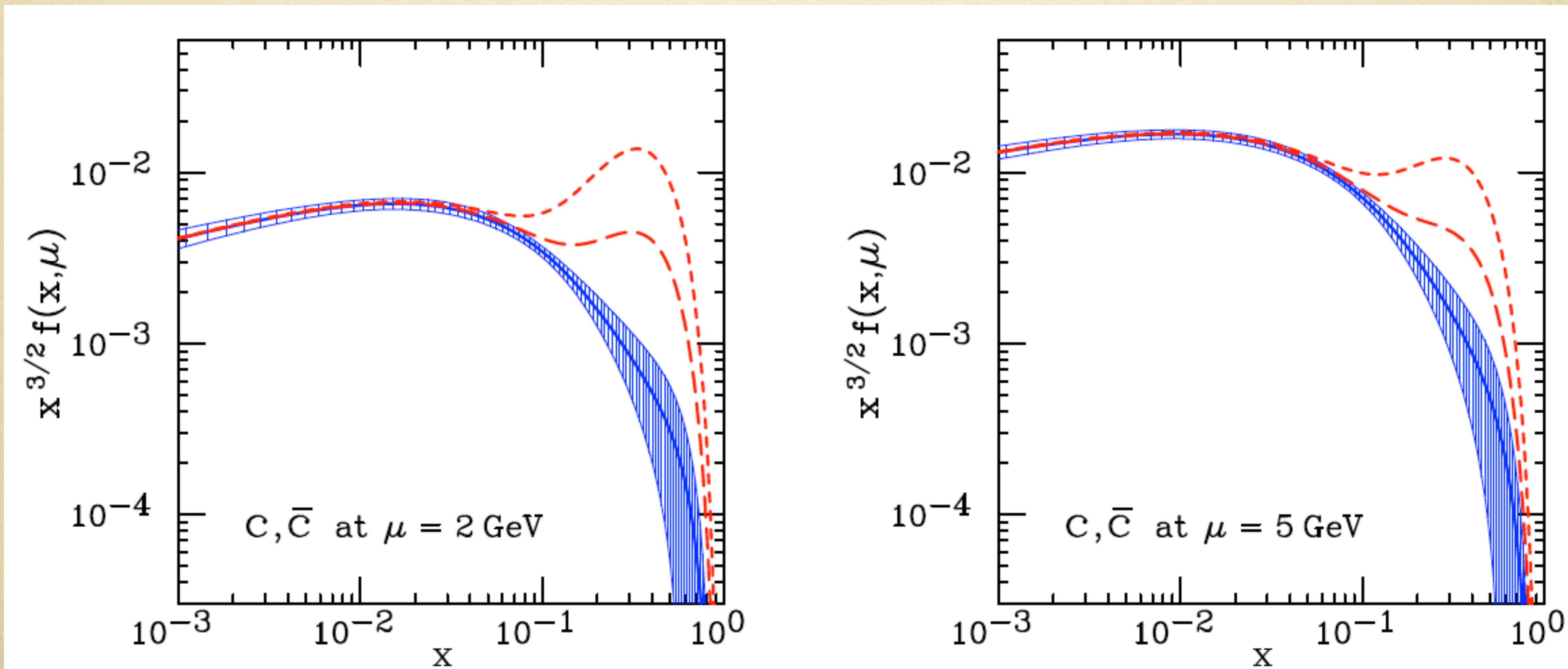


Bonvini, Forte, Ridolfi, 1009.5691

INTRINSIC CHARM

Intrinsic Charm

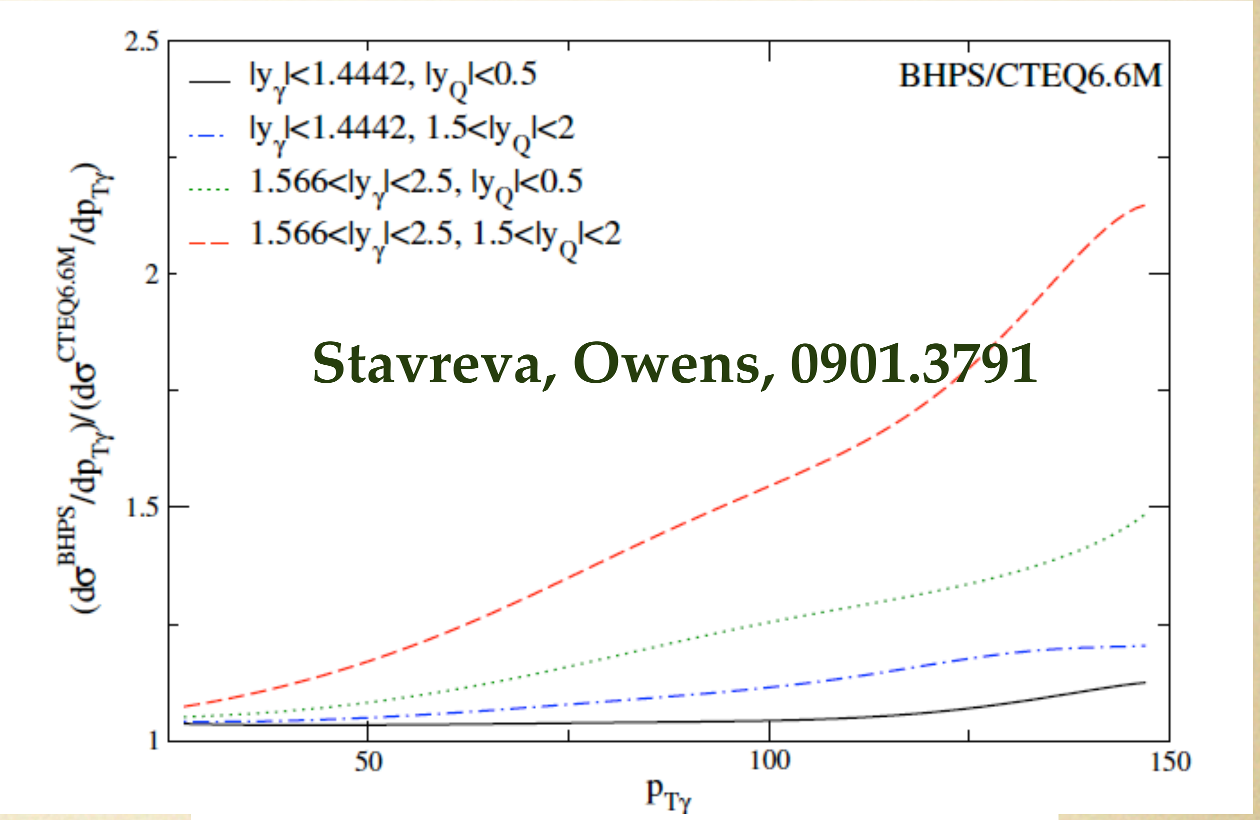
- **Intrinsic Charm** in the proton wave function is motivated by **non perturbative models of hadron structure** in QCD
- Recent phenomenological study by the **CTEQ** collaboration: IC might be **sizable at large x**, a momentum fraction **smaller than 2%** cannot be excluded by current data
- However the CTEQ analysis relies on **a very constrained parametrization** for IC, and no attempt is done to extract the **asymmetry between Intrinsic Charm and AntiCharm,** and the dataset is now outdated, with no constraints from LHC data



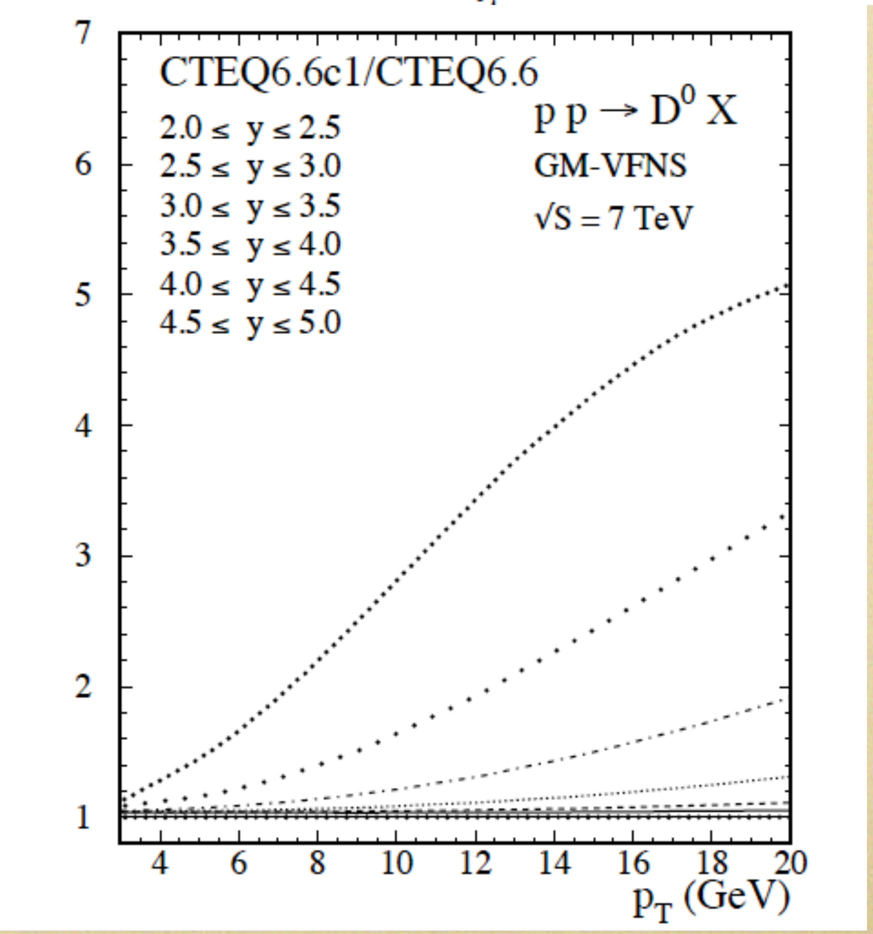
CTEQ6.6c, hep-ph/0701220

Probes of Intrinsic Charm

- Intrinsic Charm could be studies in **Fixed Target charm production Deep-Inelastic scattering** at large-x: suitable for the **AFTER setup**
- At the LHC **production and asymmetries of D mesons** (both for CMS/ATLAS and LHCb regions) would be modified by intrinsic charm
- Relation with **LHCb anomalies in the charm sector**?
- Intrinsic Charm could sizably modify the yields of final states with charm quarks like **gamma+c and Z+c**



Stavreva, Owens, 0901.3791



Kniehl et al, 0901.4130

Probes of Intrinsic Charm

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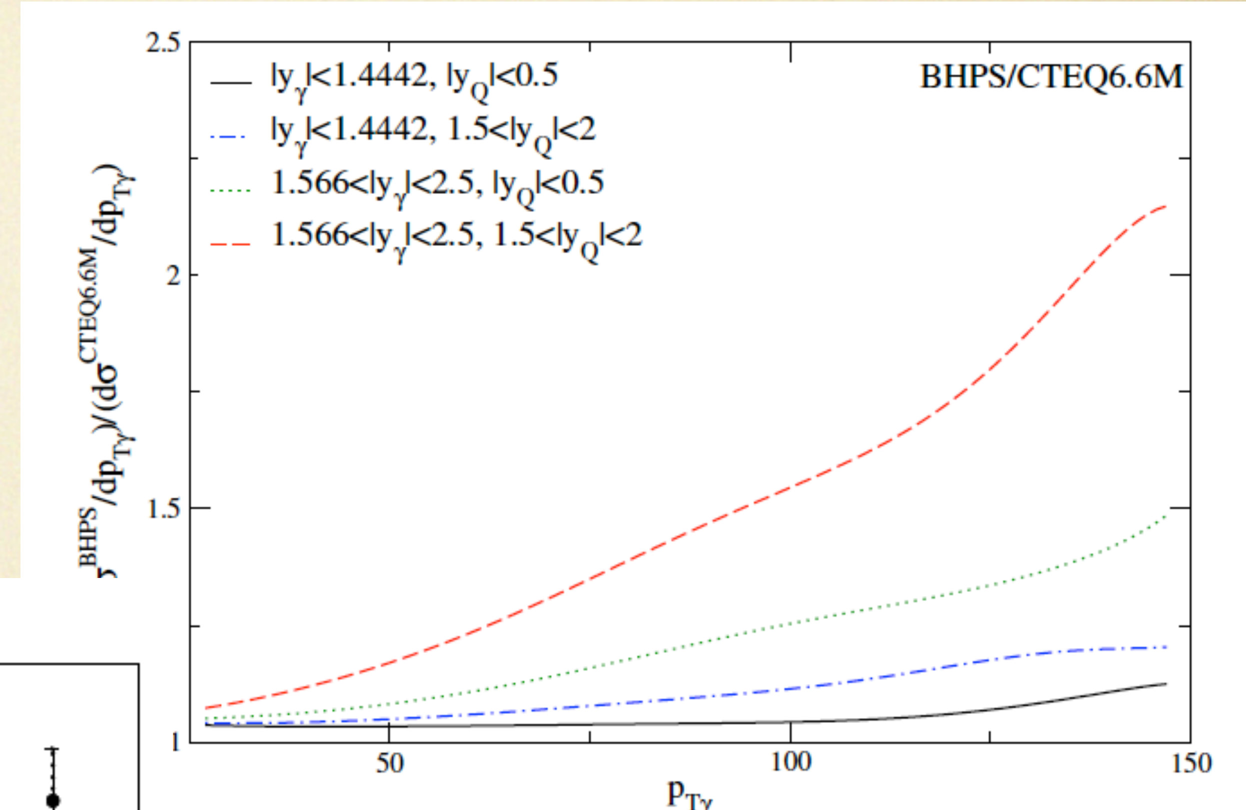
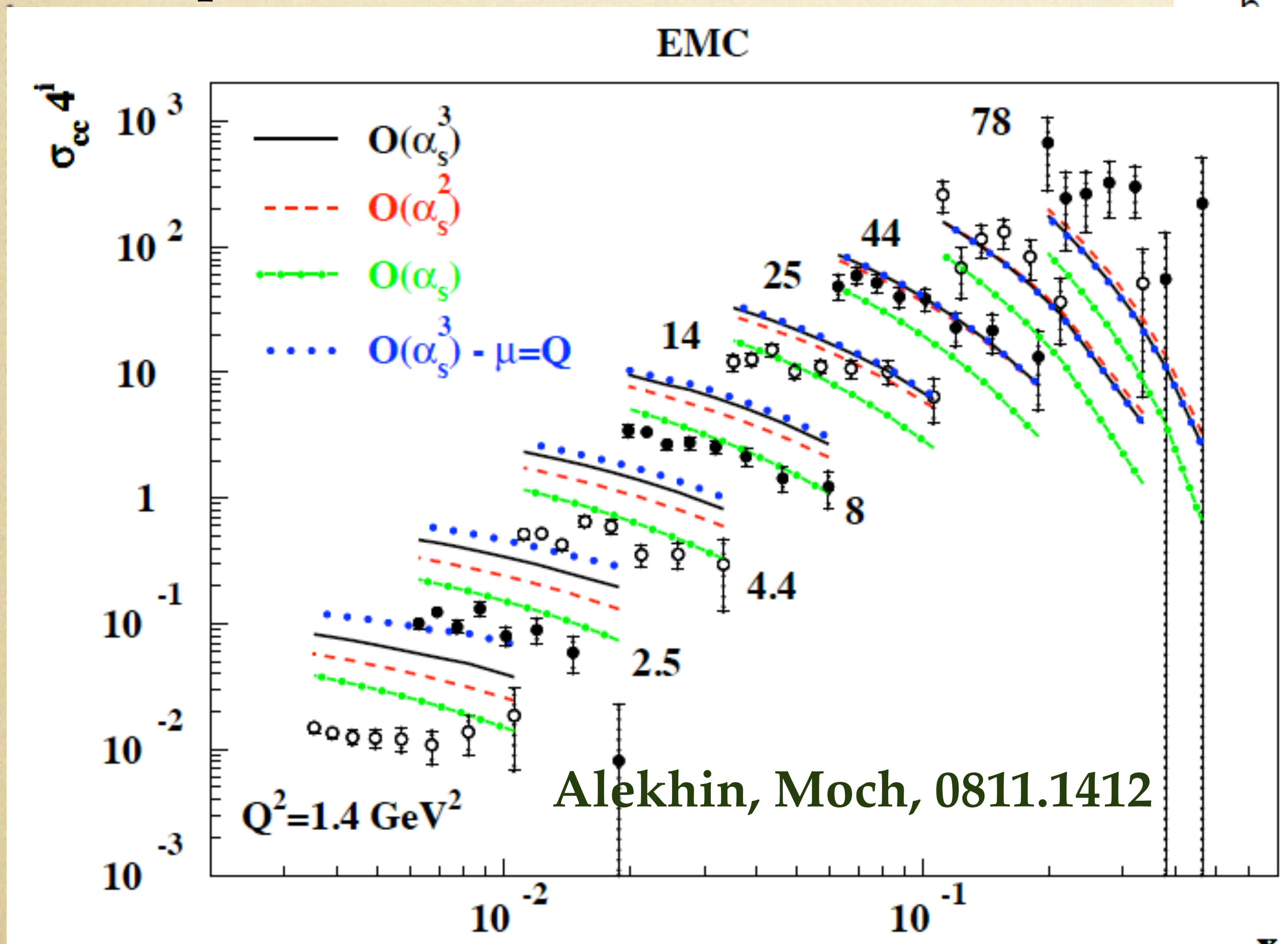
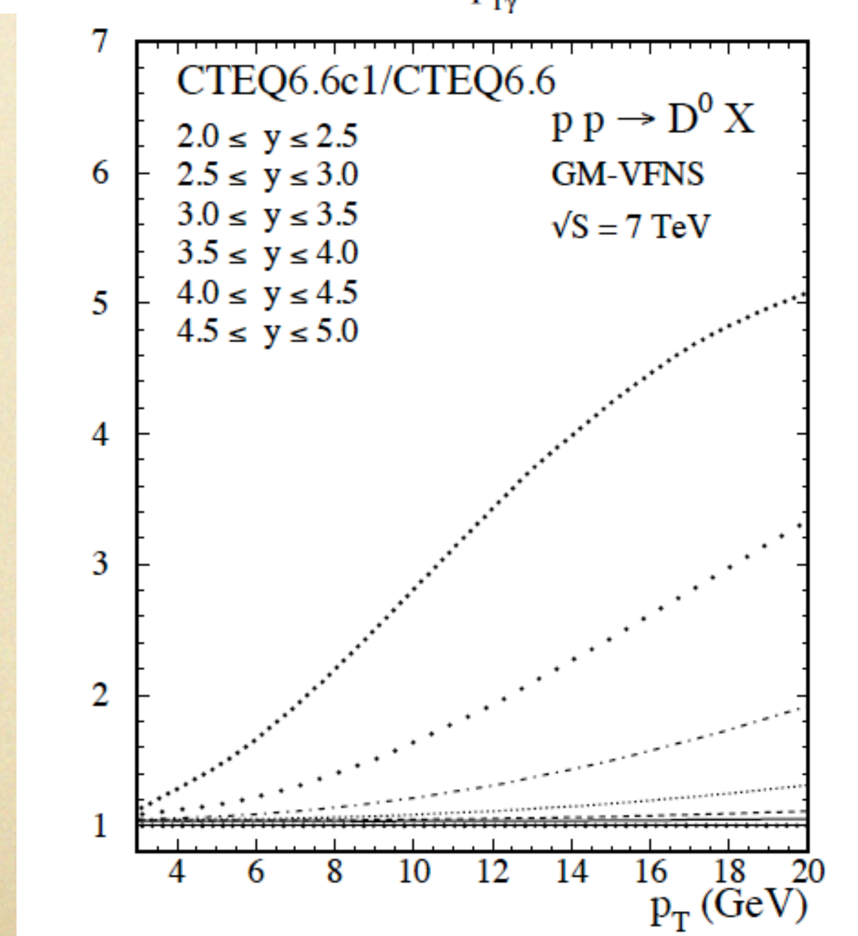






A solution for the EMC anomaly at AFTER?

NNPDF determination of Intrinsic Charm

- The **FONLL GM-VFN scheme** can be generalized to include a **Intrisic Charm component**
  - First, the initial condition in **massless DGLAP evolution for the charm PDF** has to be **parametrized with neural networks**, instead of assuming that it vanishes (**80 new parameters** in the fit!)

$$
\begin{aligned}
c^+(x,Q_0^2) &= (1-x)^{m_{c^+}}\, x^{-n_{c^+}} \mathrm{NN}_{c^+}(x)\ , \\
c^-(x,Q_0^2) &= (1-x)^{m_{c^-}}\, x^{-n_{c^-}} \mathrm{NN}_{c^-}(x) - A_{c^-}\left[x^{r_{c^-}}(1-x)^{t_{c^-}}\right]\ ,
\end{aligned}
$$

- Second, the N_F=3 **massive structure functions** need to account for the scattering of the virtual photon **off a massive quark in the proton**

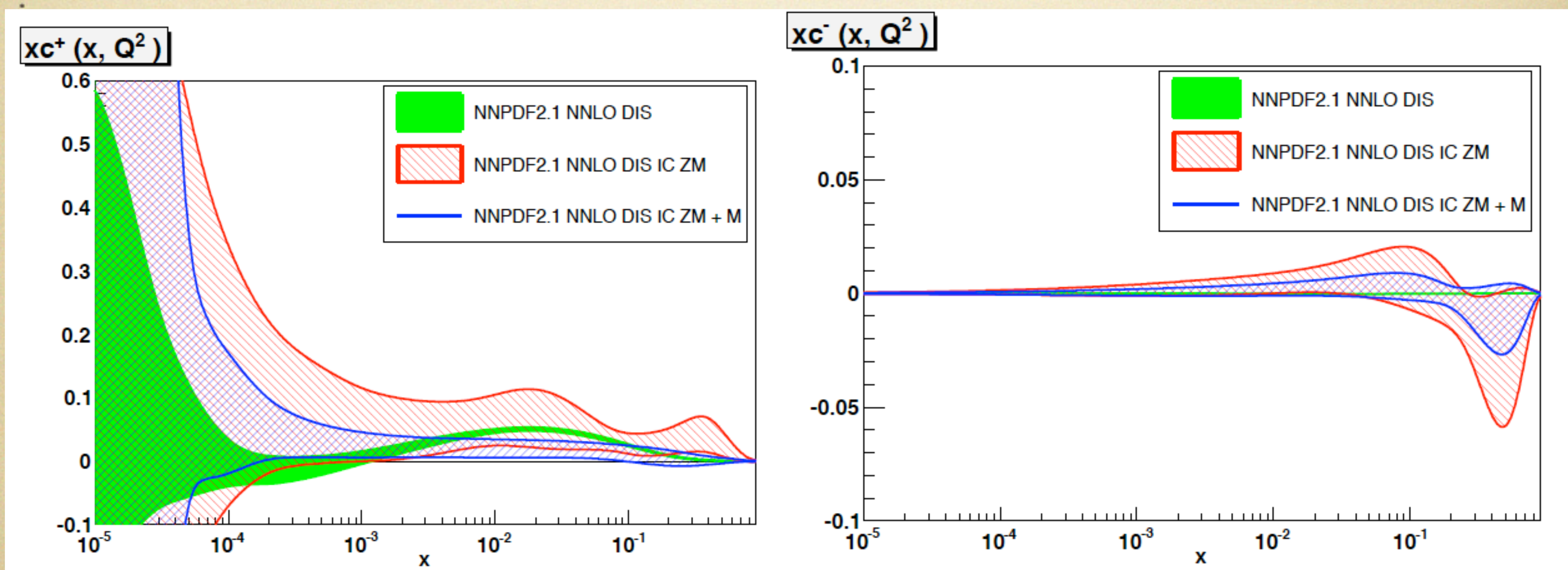
$$
\left.\mathcal{F}_2 = \frac{2Q^2}{S_+\Delta}\frac{1}{2x}F_2\right\} = Q_1(\chi,Q^2) \qquad F_2^c(x,Q^2) = \frac{S_+\Delta}{2Q^2}2xc(\chi,Q^2)
$$

$$
\begin{aligned}
\hat{\mathcal{F}}^{QS^{(0+1)}}_{i=1,2,3}(x,Q^2,\mu^2) &\equiv \mathcal{F}_i^{QS^{(0)}}(x,\mu^2) + \hat{\mathcal{F}}_i^{QS^{(1)}}(x,Q^2,\mu^2) \qquad (8)\\
&= Q_1(\chi,\mu^2) + \frac{\alpha_s(\mu^2)}{2\pi}\int_\chi^1 \frac{d\xi'}{\xi'}\times\left[Q_1\left(\frac{\chi}{\xi'},\mu^2\right)\hat{H}_i^q(\xi',m_1,m_2)\right]\ ,\xi'\equiv\frac{\chi}{\xi}
\end{aligned}
$$

NLO corrections to in Kretzer, Schienbein, hep-ph/9805233

NNPDF determination of Intrinsic Charm

- Extend the NNPDF determination to allow for a **Intrisic Charm component** in the proton (both for total and for IC asymmetry)
- Compare IC obtained when **only ZM evolution** is corrected for IC, with the full treatement including IC in the **FFN structure functions**
- **Consistent GM-VFN formulation** of structure functions with **Intrisic Charm** crucial for quantitative results
- Phenomenological studies at the LHC in progress. **Study also the AFTER setup**?



Summary and outlook

- The NNPDF2 family is the **most updated PDF set** in terms of dataset, theoretical information and methodology
- Several interesting **PDF studies** can be performed at AFTER: constraints on quark PDFs from **DY**, constraints on gluons from **jets and photons**, **intrinsic heavy quarks, ...**
- The threshold region of W,Z production can be throughly studied: stringent test of **all-order QCD resummations**
- An unbiased PDF analysis allows for a **substantial Intrinsic Charm in the proton**, which would have **important phenomenological implication**s, both at LHC and at AFTER