Charm in the Proton

- Intrinsic Charm?
- VFNS with IC
- Fitted Charm
- LHC prospects

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Diffraction Sep 2016
Acireale

Intrinsic Charm?

Standard PDF Paradigm:

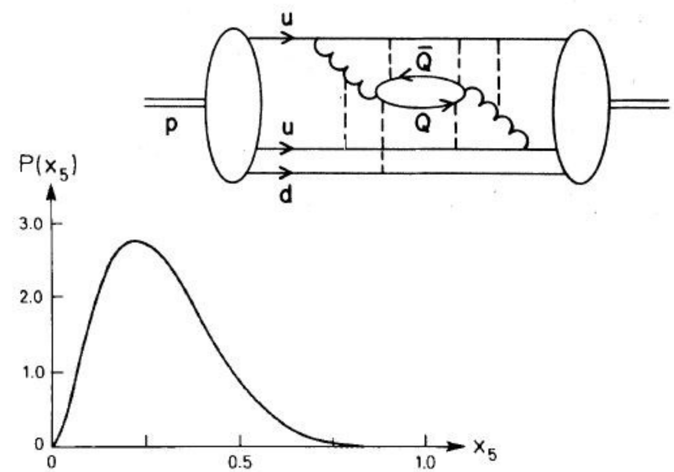
- Light partons: $L = g, u, \bar{u}, d, \bar{d}, s, \bar{s}$: $m_L \ll 1\ GeV$: nonpert: fit PDFs
- Heavy partons: $H = c, \bar{c}, b, \bar{b}, t, \bar{t}$: $m_H \gg 1\ GeV$: generated in pert QCD

But $m_c \simeq 1.5\ GeV$:

nonperturbative ('intrinsic') charm?

BHPS PLB93B (1980) 451

Brodsky et al: arXiv:1504.06287



Test empirically:

fit an unbiased charm PDF!

(in a global PDF fit, e.g. NNPDF)

Technical hitch:

VFNS: $\begin{cases} Q \sim m_c\text{: threshold effects, need mass dependence} \\ Q \gg m_c\text{: large } \ln Q^2/m_c^2 \text{ ; need to resum (DGLAP)} \end{cases}$

Prescriptions: **ACOT**, BMSN, TR, **FONLL**, CSN, **S-ACOT**, TR′, **FNMR**,….

Need to incorporate a fitted charm PDF

VFNS for IC

RDB, Bonvini, Rottoli: JHEP 1511 (2015) 122 (arxiv:1510.02491)

RDB, Bertone, Bonvini, Forte, Groth-Merrild, Rojo, Rottoli:
Phys Lett B754 (2016) 49 (arXiv:1510.00009)

Factorization (DIS)

Notation: PDFs f_p, $p = (l, h)$, $l = \{g, u, \bar{u}, d, \bar{d}, s, \bar{s}\}$, $h = \{c, \bar{c}\}$, ignore $b, \bar{b}, t, \bar{t}$

- $\overline{MS}$ or Massless Factorization : **4FS**

CFP NPB175 (1980) 27

$$F^{(4)}(Q) = \underbrace{C_p^{(4)}\big(0, \alpha_s(Q)\big)}_{\text{no large logs}} \otimes f_p^{(4)}\,(Q) \qquad f_P^{(4)}(Q) = \underbrace{\Gamma_{pp'}^{(4)}(Q, Q_0)}_{\text{resums } \ln Q^2 \text{ (DGLAP)}} \otimes f_{p'}^{(4)}\,(Q_0)$$

- Massive or Decoupling or FFN Factorization : **3FS**

CWZ PRD18 (1978) 242:

Collins PRD58 (1998) 094002

$$F^{(3)}(Q) = \underbrace{C_p^{(3)}\left(\frac{m}{Q}, \alpha_s(q)\right)}_{\text{large logs } \ln Q^2/m^2} \otimes f_p^{(3)}(Q) \qquad f_l^{(3)}(Q) = \underbrace{\Gamma_{ll'}^{(3)}(Q, Q_0)}_{\text{resums light } \ln Q^2 \text{ (DGLAP)}} \otimes f_{l'}^{(3)}\,(Q_0)$$

- Matching:

$$f_p^{(4)}(Q) = \underbrace{K_{pp'}\left(\frac{m}{Q}, \alpha_s(Q)\right)}_{\text{large logs } \ln Q^2/m^2} \otimes f_{p'}^{(3)}\,(Q) \qquad K = 1 + \alpha_s\, k \ln\frac{Q^2}{m^2} + \cdots$$

- **Consistency:**

$$\underbrace{C_{p'}^{(4)}(0, \alpha_s)}_{\text{no large logs}} = \lim_{m\to 0} \underbrace{C_p^{(3)}\left(\frac{m}{Q}, \alpha_s(q)\right)}_{\text{large logs}} \otimes \underbrace{K_{pp'}^{-1}\left(\frac{m}{Q}, \alpha_s(Q)\right)}_{\text{removes large logs!}}$$

The VFNS

- Combine the 3FS with the 4FS:

$$\underbrace{C_p^{(3)}(m,\alpha_s)}_{\text{large logs}} \otimes f_p^{(3)} = \underbrace{C_p^{(3)}(m,\alpha_s)}_{\text{large logs}} \otimes \underbrace{K_{pp'}^{-1}(m,\alpha_s)}_{\textbf{removes}\text{ large logs}} \otimes f_{p'}^{(4)} \equiv \underbrace{C_p^{(4)}(m,\alpha_s)}_{\textbf{no large logs!}} \otimes f_p^{(4)}$$

$C_P^{(4)}(m,\alpha_s)$ has correct behaviour near threshold, but no large logs: $\lim_{m\to 0} C_P^{(4)}(m) = C_P^{(4)}(0)$

ACOT PRD50 (1994) 3102

- FONLL prescription:

CGN hep-ph/9803400

BMSN hep-ph/9612398

$$F = F^{(3)} + F^{(4)} - F^{(3,0)}$$

$F^{(3,0)} = C_p^{(3,0)}(m,\alpha_s) \otimes f_p^{(3)}$ removes the double counting:

$$C_p^{(3,0)}(m,\alpha_s) = \text{"} \lim_{m\to 0} C_p^{(3)}(m,\alpha_s)\text{"} \equiv C_{p'}^{(4)}(0) \otimes K_{p'p}(m)$$

- $Q \sim m_c\ :\ F = F^{(3)} + [F^{(4)} - F^{(3,0)}]$ ⟵ subleading
- $Q \gg m_c\ :\ F = F^{(4)} + [F^{(3)} - F^{(3,0)}]$ ⟵ power suppressed

$$F = [C_p^{(3)}(m,\alpha_s) \otimes K_{pp'}^{-1}(m,\alpha_s) + \cancel{C_{p'}^{(4)}(0,\alpha_s)} - \cancel{C_p^{(3,0)}(m,\alpha_s) \otimes K_{pp'}^{-1}(m,\alpha_s)}] \otimes f_{p'}^{(4)}$$

$$\boxed{\textbf{FONLL} \equiv \textbf{ACOT} \equiv \textbf{VFNS}}$$

order by order in pertbn th

Perturbative Charm: the S-VFNS

- Constraint: no 'Intrinsic' Charm

FLNR arXiv:1001:2312

$f_h^{(3)}$ is scale independent : set $f_c^{(3)} = f_{\bar{c}}^{(3)} = 0$

Charm is then entirely perturbative:

$$f_h^{(4)} = K_{hl}(m,\alpha_s) \otimes f_l^{(3)} \qquad f_l^{(4)} = K_{ll'}(m,\alpha_s) \otimes f_{l'}^{(3)} \qquad \text{(cf matching)}$$

Then $F^{(3)} = C_l^{(3)}(m,\alpha_s) \otimes f_l^{(3)} = C_l^{(3)}(m,\alpha_s) \otimes K_{ll'}^{-1}(m,\alpha_s) \otimes f_{l'}^{(4)}$, so (using FONLL)

$$F_S = \underbrace{[(C_l^{(3)}(m,\alpha_s) - C_l^{(3,0)}(m,\alpha_s)) \otimes K_{ll'}^{-1}(m,\alpha_s) + C_{l'}^{(4)}(0,\alpha_s)] \otimes f_l^{(4)}}_{\text{light}} + \underbrace{C_h^{(4)}(0,\alpha_s) \otimes f_h^{(4)}}_{\text{heavy, but } m_c = 0}$$

Treat all incoming heavy quark lines as massless

KOS hep-ph/0003035

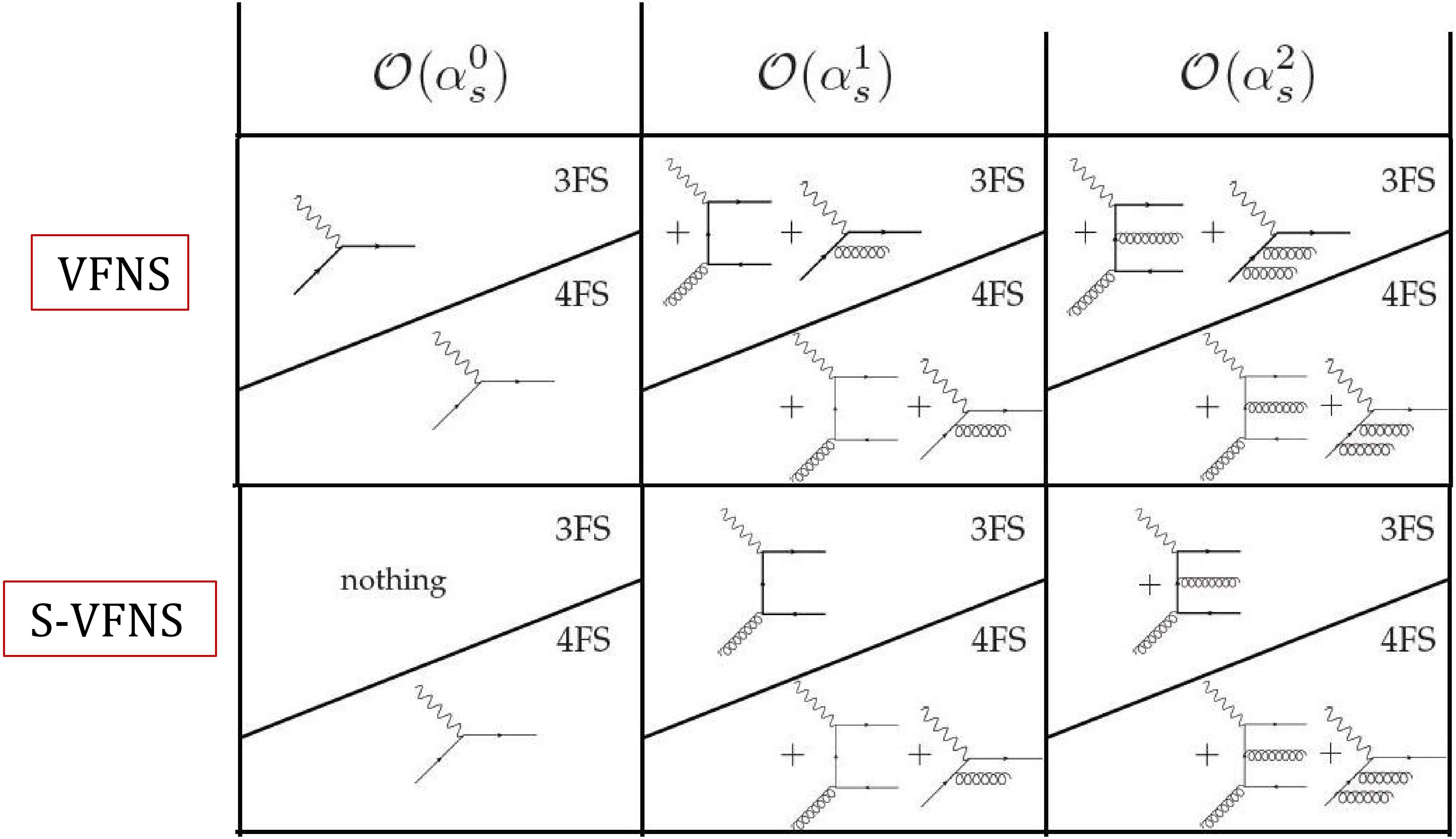
$$\boxed{\text{FLNR} \equiv \text{S-ACOT} \equiv \text{S-VFNS}}$$

- The Intrinsic Charm correction

$$F = F_S + \Delta F$$

$$\Delta F = \underbrace{[C_h^{(4)}(m,\alpha_s) - C_h^{(4)}(0,\alpha_s)]}_{\text{Vanishes if incoming heavy quark lines massless}} \otimes \underbrace{(f_h^{(4)} - K_{hl}(m,\alpha_s) \otimes K_{ll'}^{-1}(m,\alpha_s) \otimes f_{l'}^{(4)})}_{\text{Vanishes if charm is entirely perturbative}}$$

Sample Diagrams



VFNS vs S-VFNS

- if we believe that $f_c^{(3)} = 0$ ('no IC'): use S-VFNS (exact, order by order)
- if we believe that $f_c^{(3)} \sim O(1)$ ('large IC'): use VFNS (exact, order by order)
- if we believe that $f_c^{(3)} \sim O\left(\frac{\Lambda^2}{m_c^2}\right)$ ('small IC'): then

$$\Delta F \sim O\left(\frac{m_c^2}{Q^2}\right) O\left(\frac{\Lambda^2}{m_c^2}\right) \sim O\left(\frac{\Lambda^2}{Q^2}\right)$$

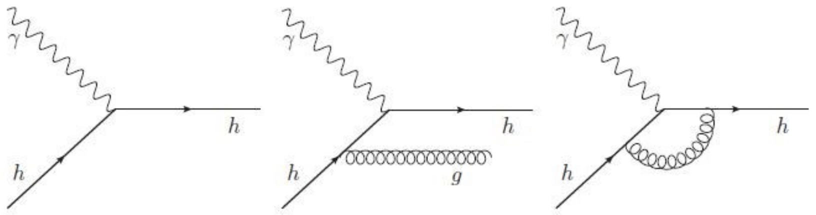
ΔF is a small computable power correction (cf TMC):

S-VFNS is a good approximation: but VFNS is better

With unbiased fitted charm, thus VFNS, need 3FS diagrams with incoming massive quark:

Hoffmann & Moore: Z Phys C20(1983)71

Kretzer & Schienbein: hep-ph/9805233



Fitted Charm

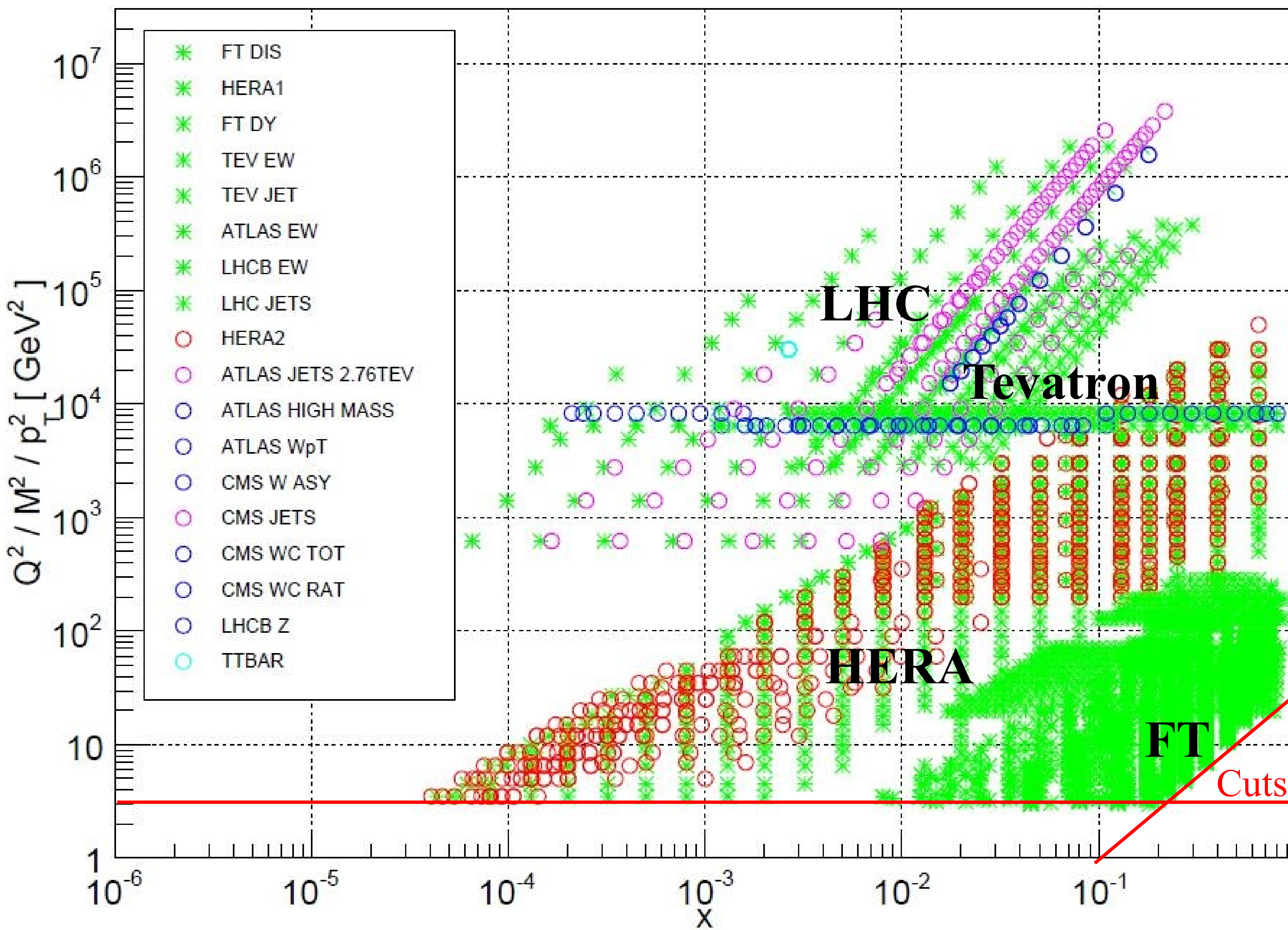
NNPDF: RDB, Bertone, Bonvini, Carrazza, Forte,
Guffanti, Hartland, Rojo, Rottoli: arXiv:1605.06515

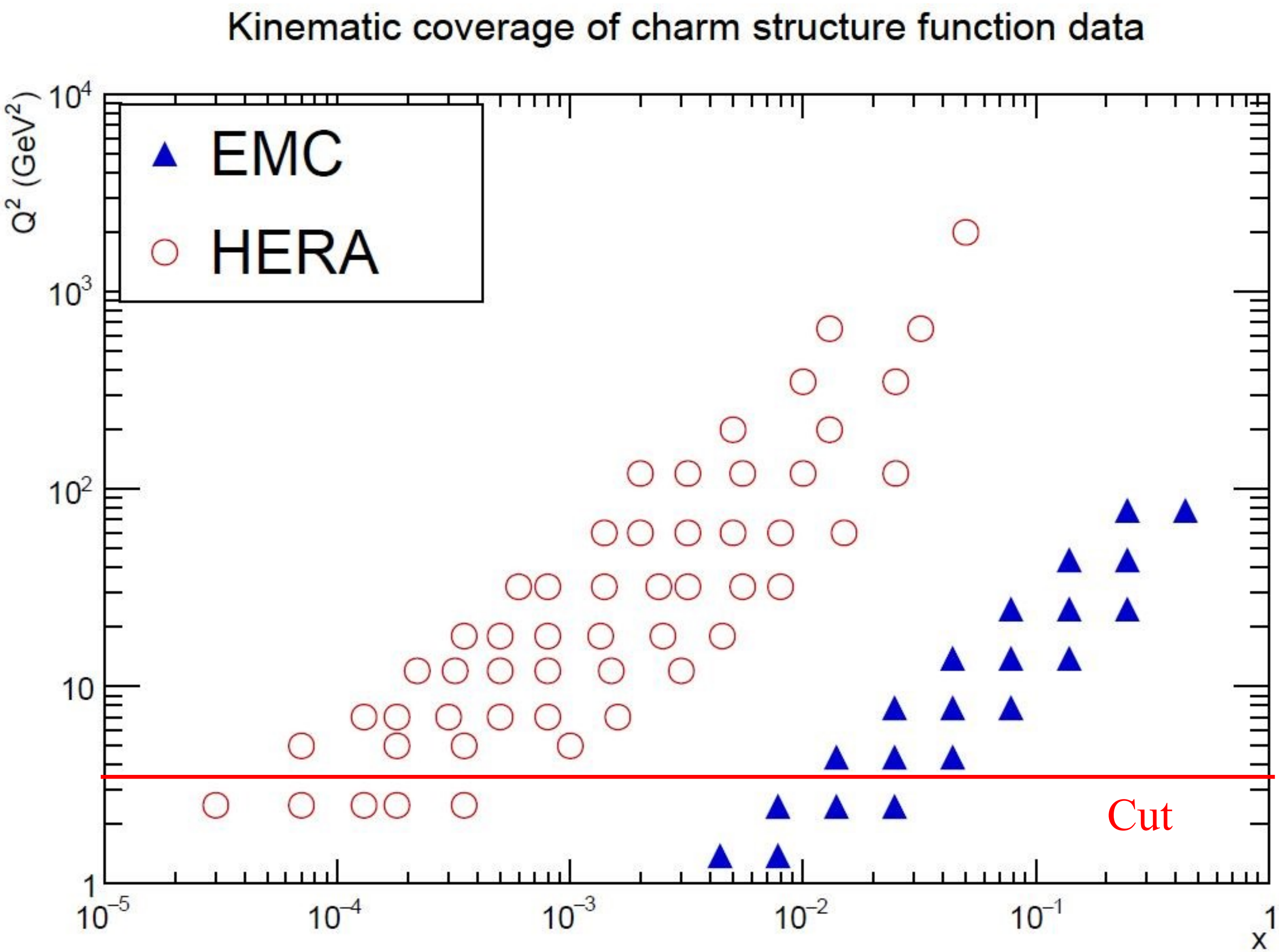
Use NNPDF3.0: NLO VFNS: fitted $g, u \pm \bar{u}, d \pm \bar{d}, s \pm \bar{s}, c + \bar{c}$

296 free parameters, 3866 data pts

$\alpha_s(m_Z) = 0.118,\quad m_c(pole) = 1.47$ GeV (PDG)

NNPDF3.0 NLO dataset





- ▲ EMC F_2^c (J. J. Aubert et al., Nucl. Phys. B213 (1983) 31): difficult? – not included in most fits
- ○ HERA F_2^c (H. Abramowicz et al., Eur.Phys.J. C73 (2013) 2311): easy? – already in NNPDF3.0

Are these data even mutually compatible?

NNPDF3IC vs NNPDF3.0

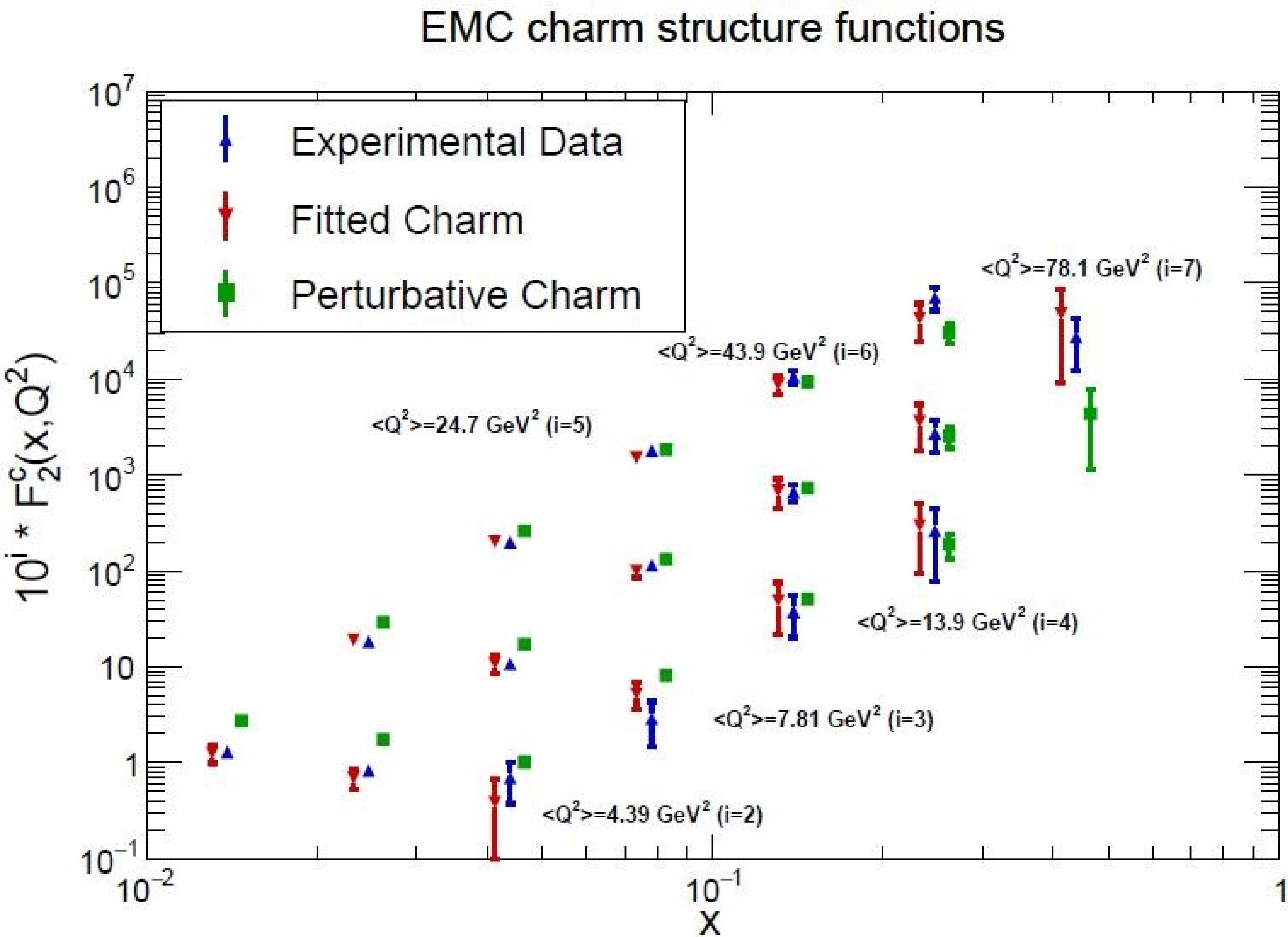
NNPDF3 NLO $m_c = 1.47$ GeV (pole mass)			
Experiment	$N_{\rm dat}$	$\chi^2/N_{\rm dat}$ fitted charm	$\chi^2/N_{\rm dat}$ perturbative charm
NMC	325	1.36	1.34
SLAC	67	1.21	1.32
BCDMS	581	1.28	1.29
CHORUS	832	1.07	1.11
NuTeV	76	0.62	0.62
EMC	16	1.09	[32]
HERA inclusive	1145	1.17	1.19
HERA F_2^c	47	1.14	1.09
DY E605	104	0.82	0.84
DY E866	85	1.04	1.13
CDF	105	1.07	1.07
D0	28	0.64	0.61
ATLAS	193	1.44	1.41
CMS	253	1.10	1.08
LHCb	19	0.87	0.83
$\sigma(t\bar{t})$	6	0.96	0.99
Total	3866	1.159	1.176

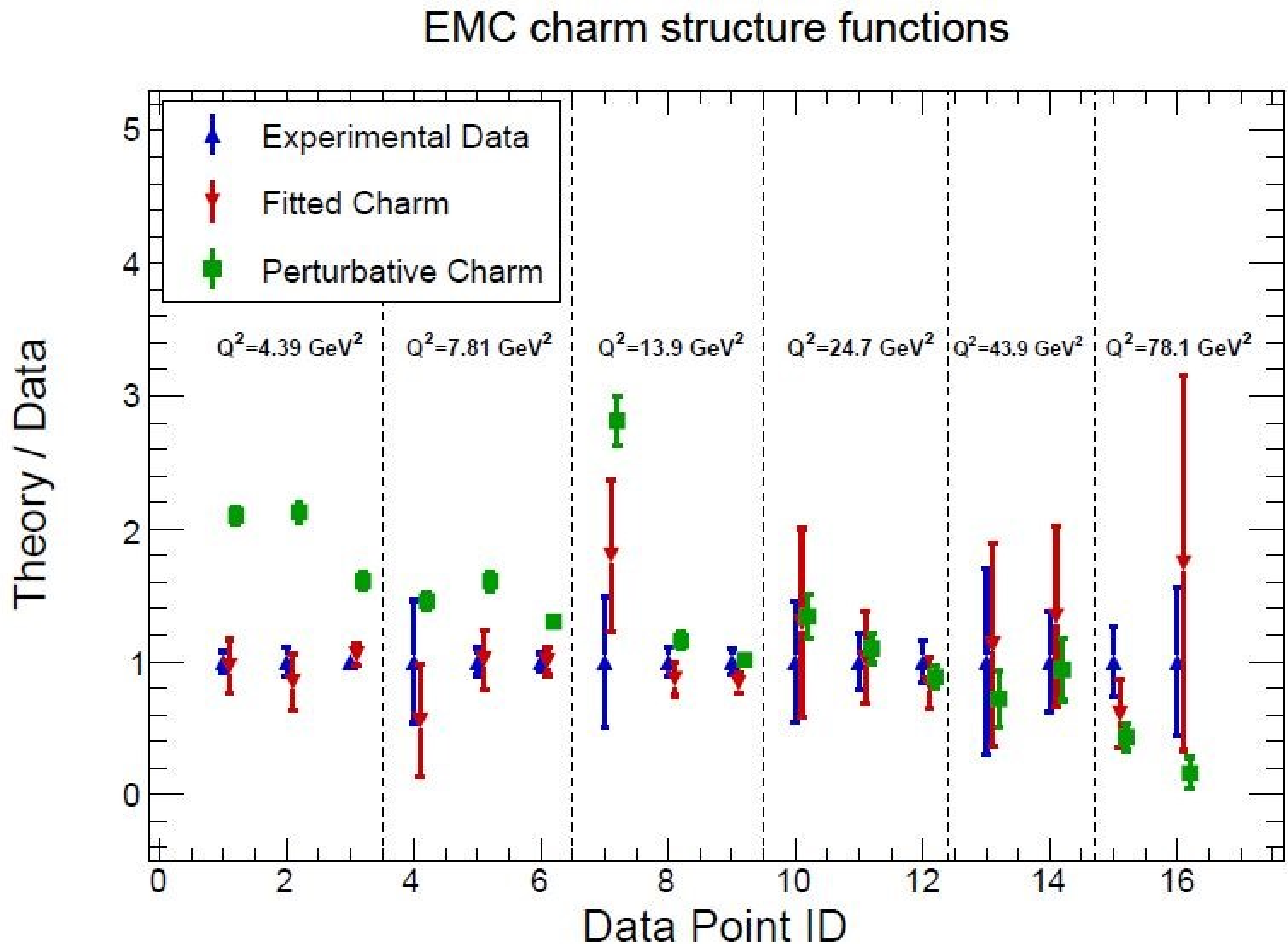
F_2^c

EMC errors 5 times too small?!

Fitting reduces χ^2 by 66pts

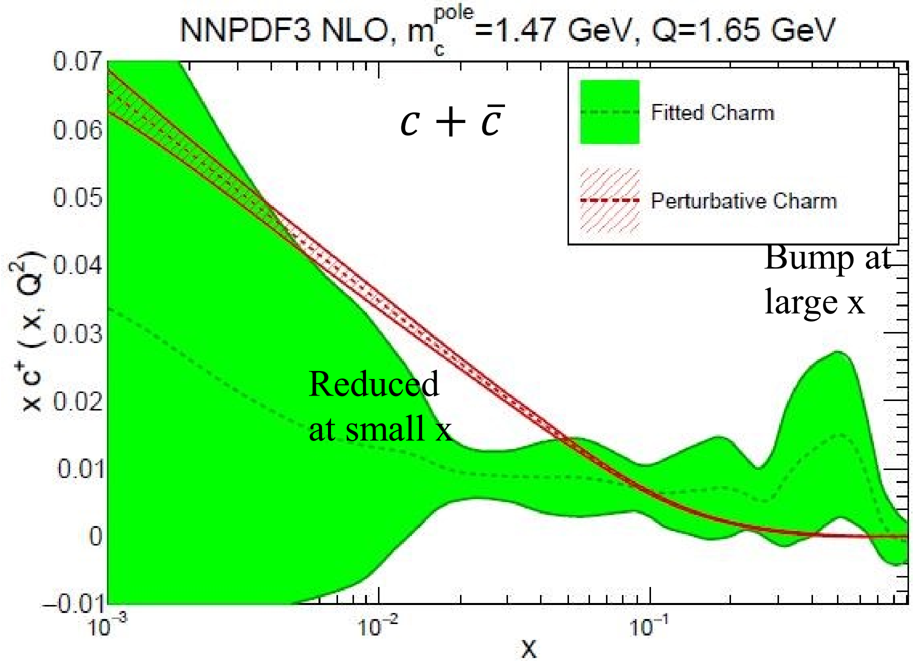
EMC F_2^c data fine - provided charm is fitted!


EMC charm structure functions
Experimental Data
Fitted Charm
Perturbative Charm
$\langle Q^2\rangle$=78.1 GeV^2 (i=7)
$\langle Q^2\rangle$=43.9 GeV^2 (i=6)
$\langle Q^2\rangle$=24.7 GeV^2 (i=5)
$\langle Q^2\rangle$=13.9 GeV^2 (i=4)
$\langle Q^2\rangle$=7.81 GeV^2 (i=3)
$\langle Q^2\rangle$=4.39 GeV^2 (i=2)
$10^i * F_2^c(x,Q^2)$
x



Strong evidence for fitted charm

Perturbative vs Fitted Charm

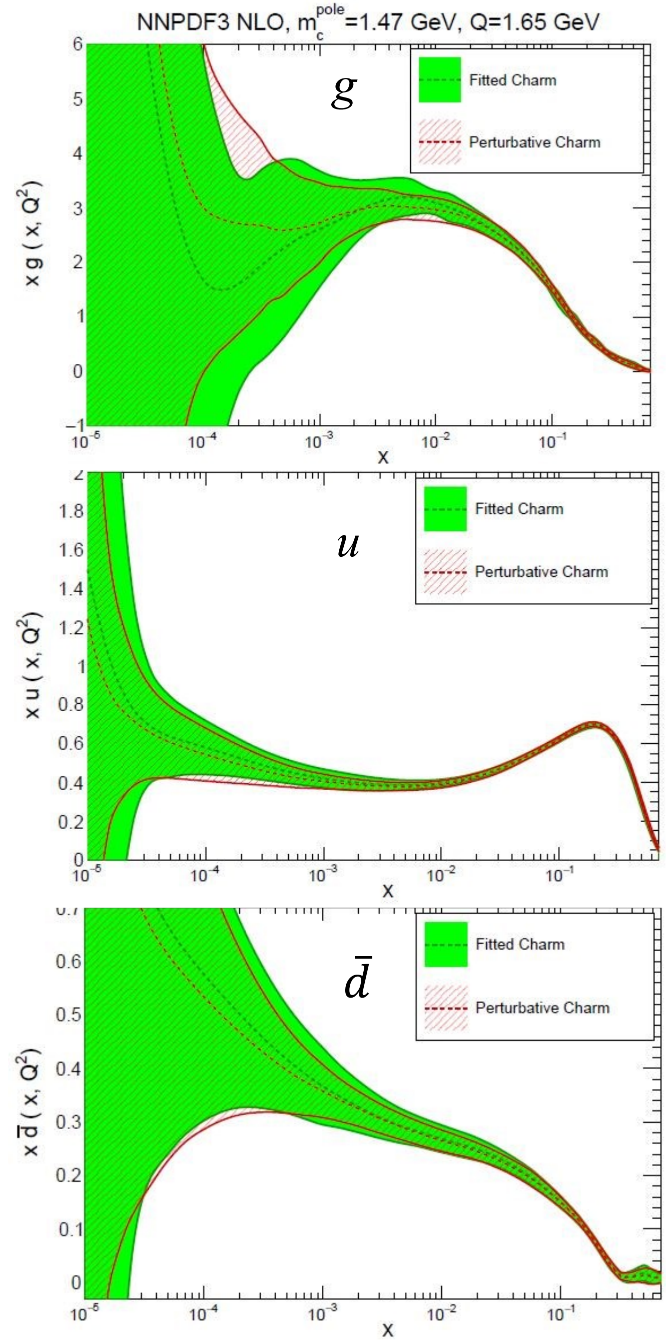


New shape, larger uncertainties

Charm momentum fraction: $C(Q^2) \equiv \int_0^1 dx\, x\, [c(x,Q^2) + \bar{c}(x,Q^2)]$

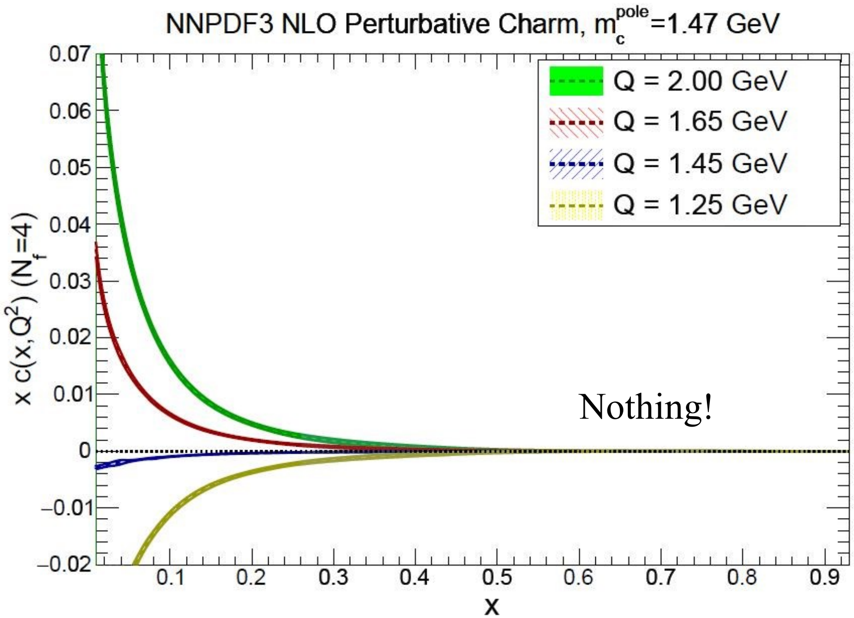
PDF set	$C(Q = 1.65$ GeV$)$
NNPDF3 perturbative charm	$(0.239 \pm 0.003)\%$
NNPDF3 fitted charm	$(0.7 \pm 0.3)\%$
NNPDF3 fitted charm (no EMC)	$(1.6 \pm 1.2)\%$

$\boxed{IC \sim 0.5 \pm 0.3\ \%}$

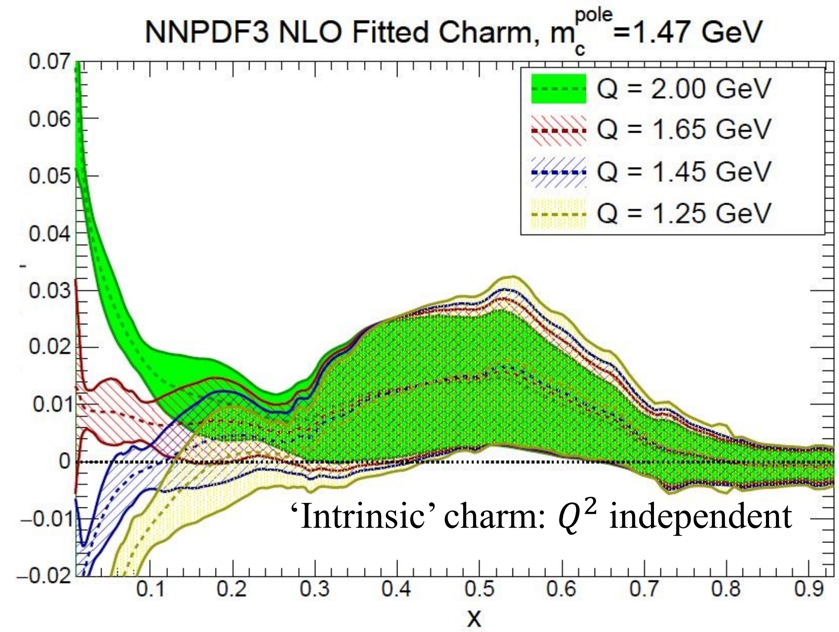


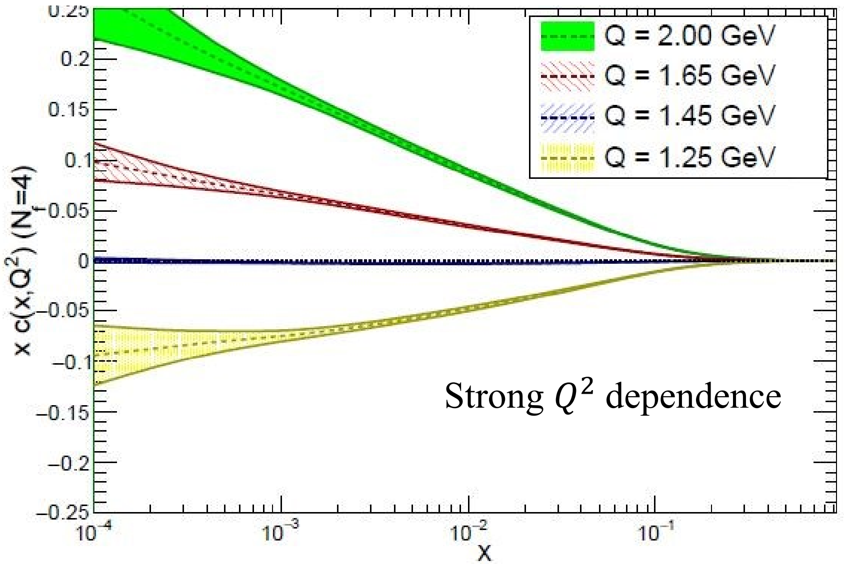
Light partons: essentially unchanged

Perturbative vs Fitted Charm : Q^2 dependence

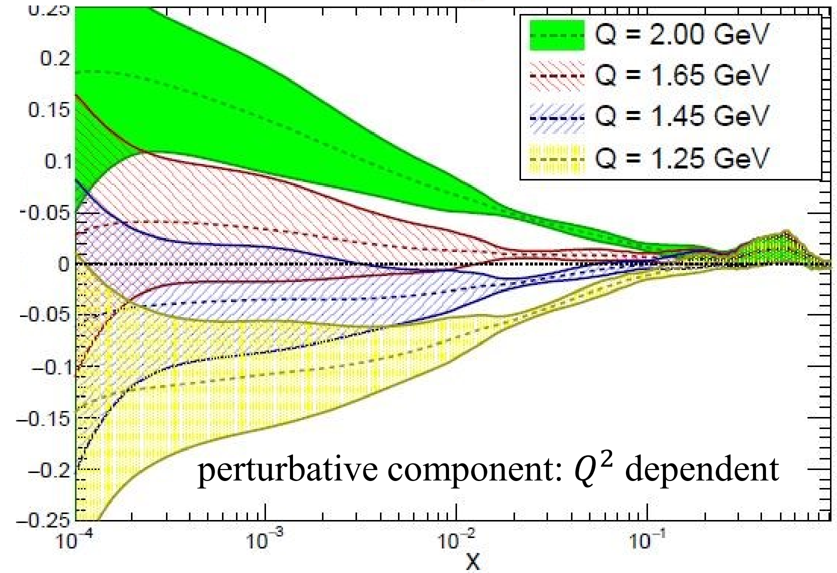


Large x





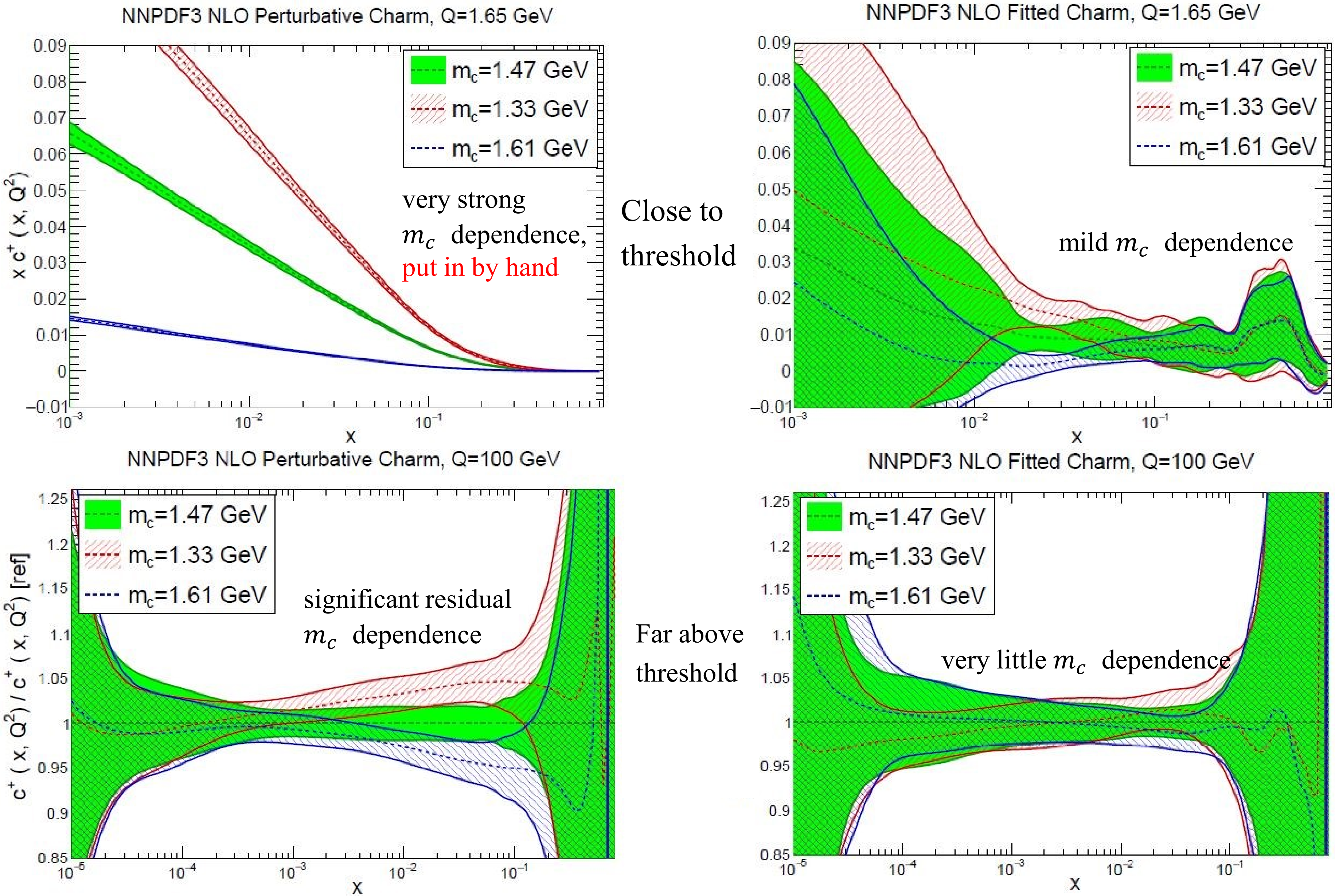
Small x



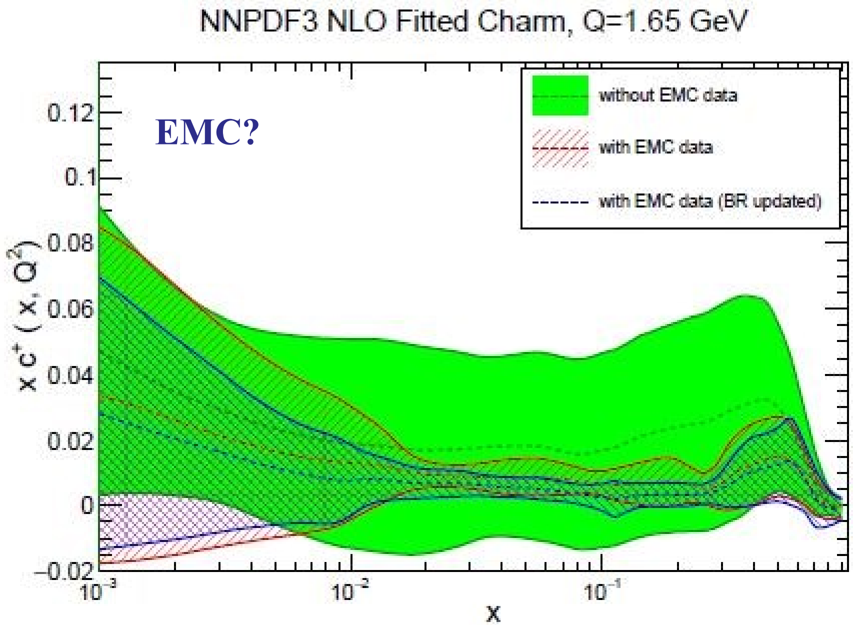
Requires $c = 0$ at $Q = m_c$: constraint put in by hand

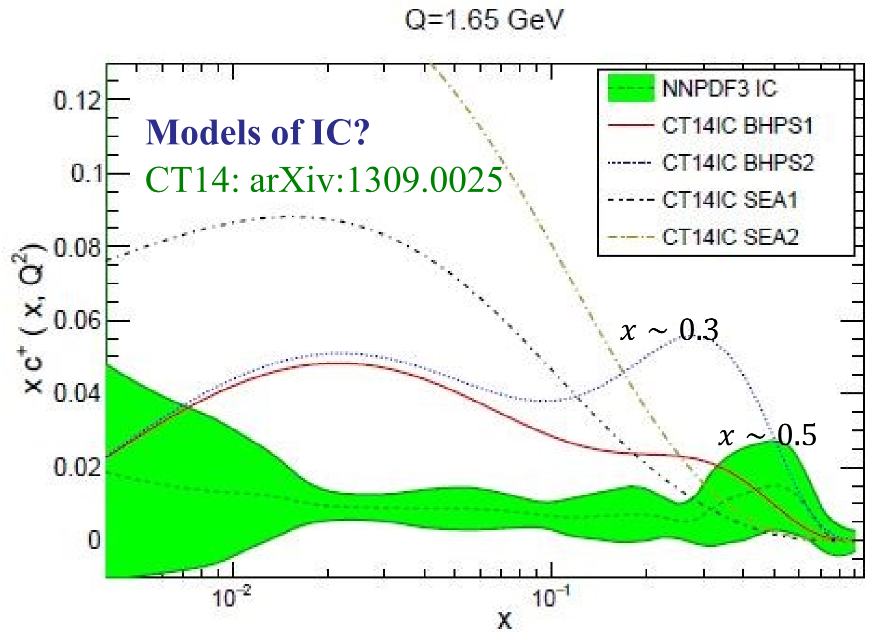
At small x, find $c \simeq 0$ at $Q \simeq 1.5$ GeV: empirical (from fit to data)

Perturbative vs Fitted Charm : m_c dependence

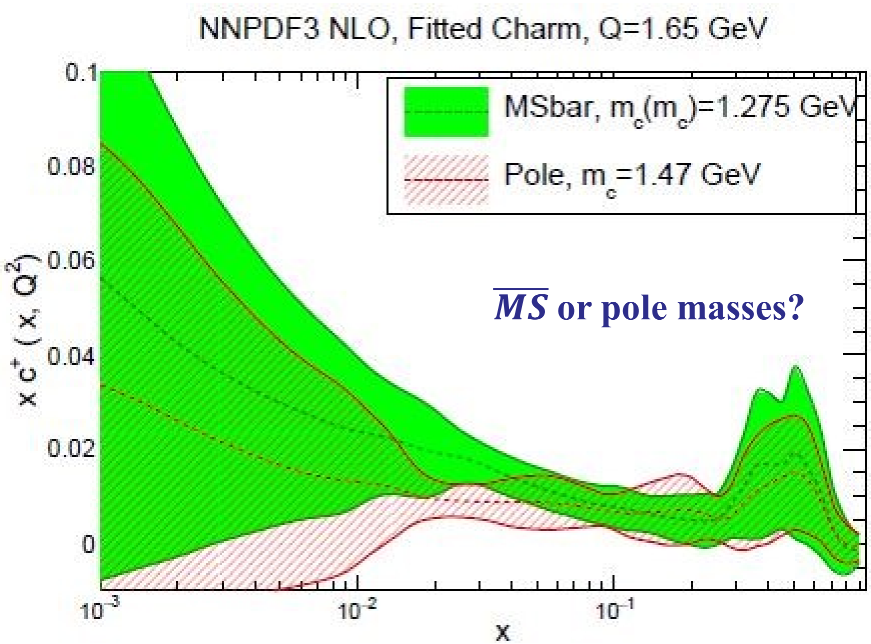


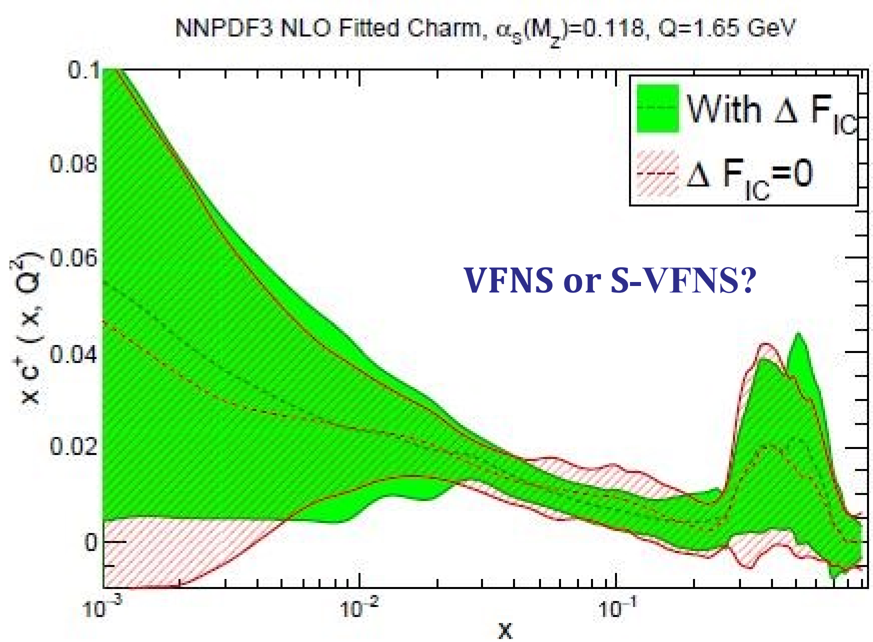
Take care when attempting to determine m_c from a global fit!





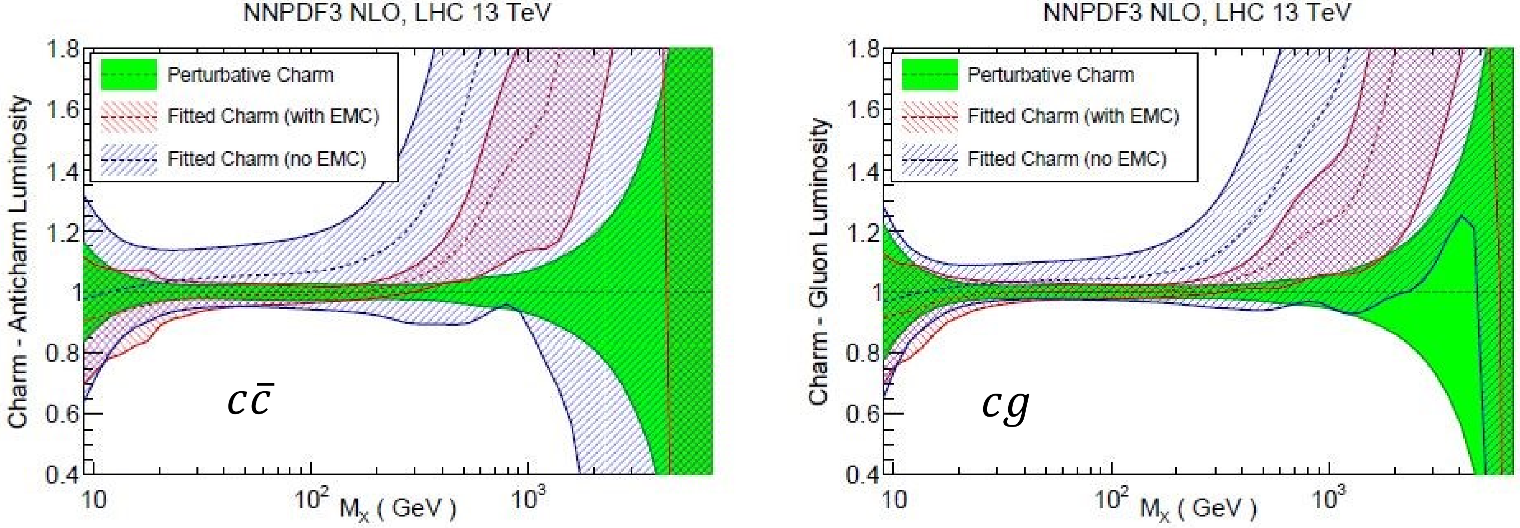
Update BR($D \to \mu\nu$), 8% to 10%: fit improves



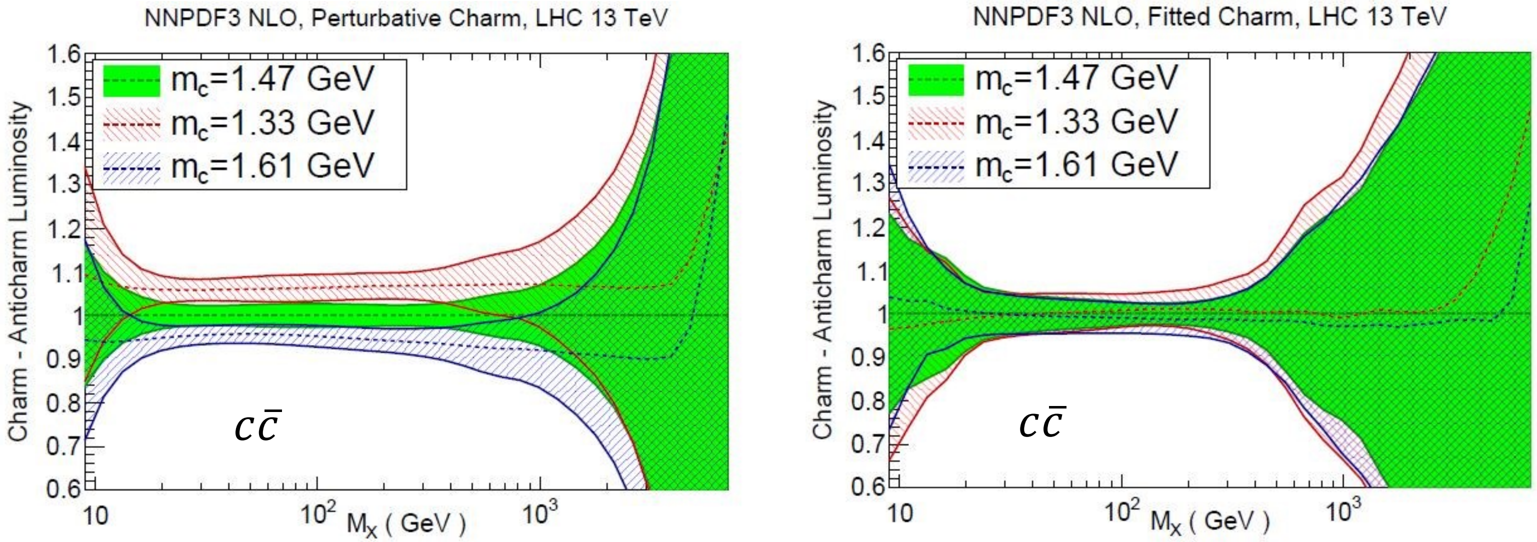


Charm at LHC

Charm Luminosities at LHC

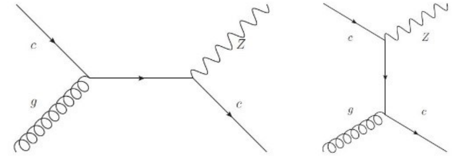


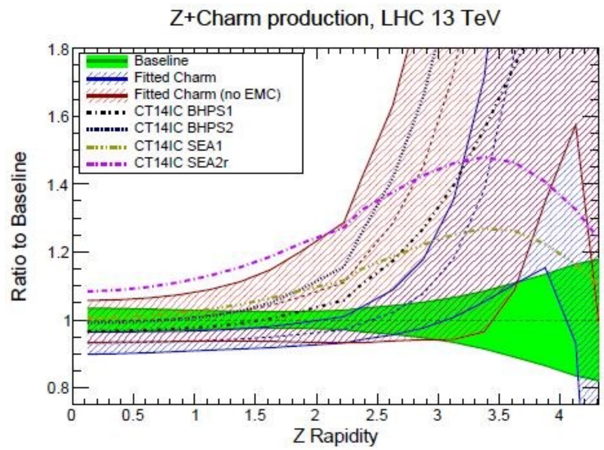
Significant enhancements at high M_X

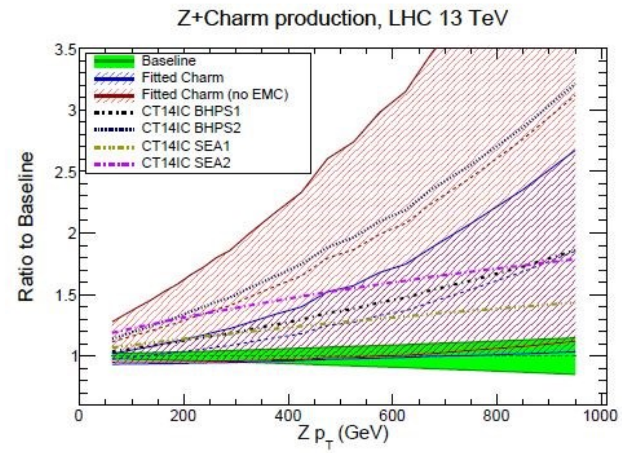


Fitting charm reduces dependence on m_c

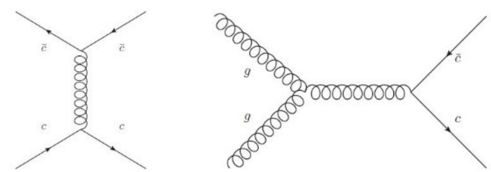
Z+c

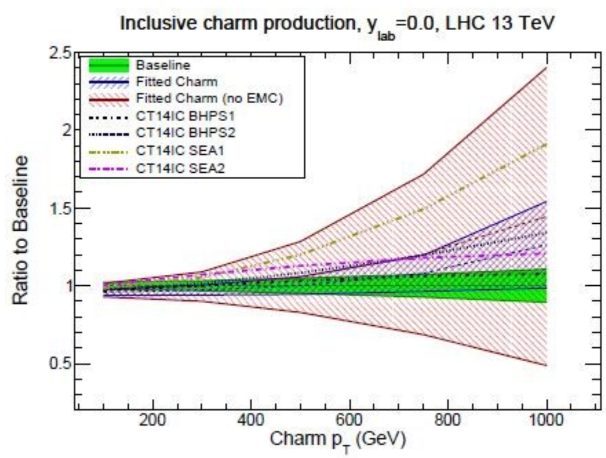


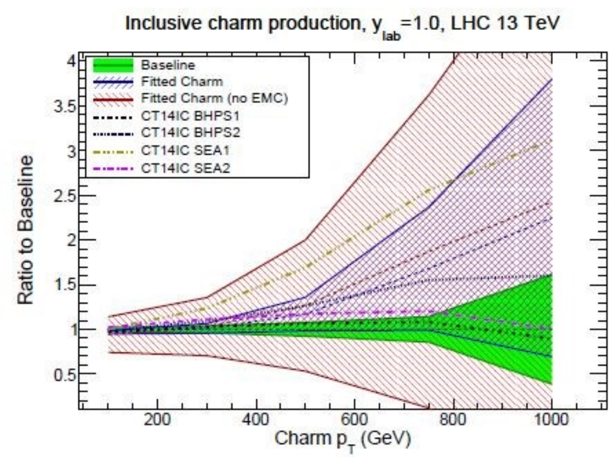




$c\bar{c}$ production



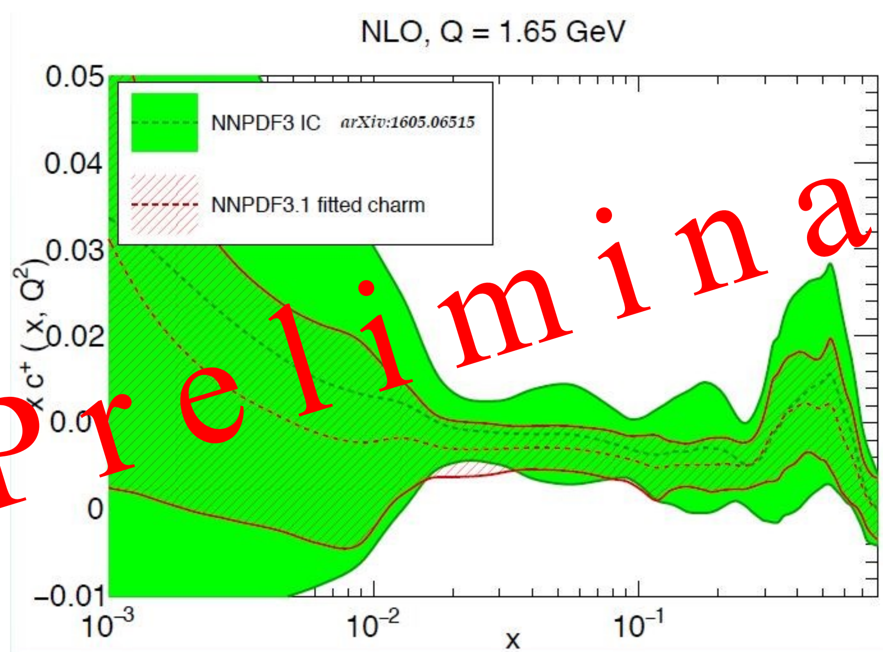




Significant enhancements at high rapidity and high p_T

Meanwhile….new data added for NNPDF3.1

• D0 legacy W asymmetries	Tevatron Run 2	quark flavour separation
• CMS W asymmetry 8 TeV	LHC Run 1	quark flavour separation
• CMS low&hi mass DY 7,8 TeV	LHC Run 1	small & large x quarks
• ATLAS low mass DY 7 TeV	LHC Run 1	small x quarks
• LHCb W,Z rap dist 7,8 TeV	LHC Run 1	small & large x quarks
• ATLAS Z pT 7,8 TeV	LHC Run 1	med x gluon & quarks
• CMS Z (pT,y) 8 TeV	LHC Run 1	med x gluon & quarks
• ATLAS inclusive jets 7 TeV	LHC Run 1	large x gluon
• CMS 8/2.76 TeV jets ratio	LHC Run 1	med & large x gluon
• ATLAS&CMS ttbar diff 8 TeV	LHC Run 1	large x gluon



Summary & Outlook

- Tentative evidence for **IC**: $\sim 0.5 \pm 0.3\%$
- **EMC** F_2^c data a useful constraint
- Fitting charm reduces $\boldsymbol{m_c}$ dependence
- **LHC Run 2**: watch this space!

The NLO PDFs presented here are available in the LHAPDF6 format [121] from the NNPDF HepForge webpage:

https://nnpdf.hepforge.org/html/nnpdf3ic/nnpdf3ic.html

In particular, we make available the following PDF sets:

- PDF sets with fitted charm, for three different values of the pole charm mass:

  NNPDF3_IC_nlo_as_0118_mcpole_1330
  NNPDF3_IC_nlo_as_0118_mcpole_1470
  NNPDF3_IC_nlo_as_0118_mcpole_1610

- PDF sets with identical theory settings as those above, with the only differences being that the charm PDF is perturbatively generated and that the EMC data are excluded, for the same three values of the charm mass:

  NNPDF3_nIC_nlo_as_0118_mcpole_1330
  NNPDF3_nIC_nlo_as_0118_mcpole_1470
  NNPDF3_nIC_nlo_as_0118_mcpole_1610

- A PDF set with fitted charm and the central value of the charm quark pole mass $m_c^{\rm pole} = 1.47$ GeV without the EMC charm data included:

  NNPDF3_IC_nlo_as_0118_mcpole_1470_noEMC

Also similar sets with $\overline{MS}$ masses

Fitted charm PDF sets for general use will be provided with the new **NNPDF3.1** global analysis (later this year)