DETERMINING
THE CHARM PDF

STEFANO FORTE
UNIVERSITÀ DI MILANO & INFN

HF PRODUCTION AT THE LHC

DURHAM, APRIL 20, 2016

CHARM IN CURRENT PDF SETS

DYNAMICALLY GENERATED BY RADIATION FROM LIGHT QUARKS AND GLUONS

QUESTIONS

- DOES CHARM REALLY VANISH BELOW ITS PRODUCTION THRESHOLD?
- WHAT IS THE VALUE OF THE PRODUCTION THRESHOLD SCALE?
- DOES THIS VALUE IT DEPEND ON THE PERTURBATIVE ORDER (IN PRACTICE, IF NOT IN PRINCIPLE?)

ANSWER:
DETERMINE THE CHARM PDF

- THEORY: FONLL WITH A CHARM PDF
  - THE FONLL SCHEME
  - FONLL WITH A CHARM PDF TO $O(\alpha_s)$
  - HIGHER ORDERS AND ACOT
- PHENOMENOLOGY: DETERMINING THE CHARM PDF
  - THE CHARM PDF AND ITS STABILITY
  - "INTRINSIC" AND "PERTURBATIVE" CHARM
  - IMPACT ON THE OTHER PDFS
- PHENOMENOLOGY: CHARM AT THE LHC
  - FITTING THE CHARM MASS
  - CHARM PRODUCTION AT THE LHC
  - IMPACT ON LHC STANDARD CANDLES

THEORY

THE FONLL METHOD

(Cacciari, Greco, Nason, 1998; DIS: sf, Laenen, Nason, Rojo, 2010;
fitted HQ: Ball, Bertone, Bonvini, sf, Groth-Merrild, Rojo, Rottoli, 2016)

BASIC IDEA: COMBINE N^iLL MASSLESS RESUMMED & N^jLO MASSIVE FIXED-ORDER (UNRESUMMED) $\Rightarrow$ EXPAND OUT THE RESUMMED RESULT AND REPLACE THE FIRST j ORDERS WITH THEIR MASSIVE COUNTERPARTS

$$F(x,Q^2) = F^{(3)}(x,Q^2) + F^{(4)}(x,Q^2) - F^{(3,0)}(x,Q^2)$$

$$F^{(3)}(x,Q^2) = x\int_x^1 \frac{dy}{y} \sum_{i=g,q,\bar{q}} C_i^{(3)}\left(\frac{x}{y}, \frac{Q^2}{m_h^2}, \alpha_s^{(3)}(Q^2)\right) f_i^{(3)}(y,Q^2)$$

$$F^{(4)}(x,Q^2) = x\int_x^1 \frac{dy}{y} \sum_{i=g,q,\bar{q},h,\bar{h}} C_i^{(4)}\left(\frac{x}{y}, \alpha_s^{(4)}(Q^2)\right) f_i^{(4)}(y,Q^2)$$

ADVANTAGES

- RELIES ON STANDARD FACTORIZATION & DECOUPLING
- THE RESUMMED AND UNRESUMMED ORDERS CAN BE CHOSEN FREELY & INDEPENDENTLY

COMPLICATIONS

- RESUMMED & FIXED-ORDER CALCULATION ARE PERFORMED IN DIFFERENT RENORMALIZATION & FACTORIZATION SCHEMES: 3F (MASSIVE, DECOUPLING) VS. 4F (MASSLESS)
- MUST MATCH α_s & PDFS

SOLUTION

RE-EXPRESS 3F-SCHEME PDFS & α_s IN TERMS OF THE 4F-SCHEME ONES

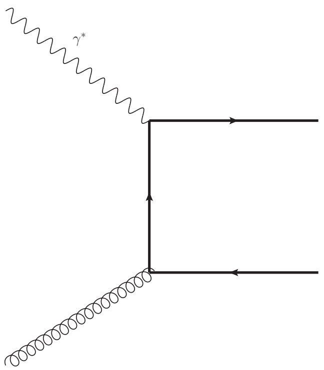
MATCHING CONDITIONS

$$\alpha_s^{(4)}(m_h^2) = \alpha_s^{(3)}(m_h^2) + \mathcal{O}(\alpha_s^3)\,,$$
$$f_i^{(4)}(m_h^2) = \sum_j K_{ij}(m_h^2) \otimes f_j^{(3)}(m_h^2)\,, \qquad i,j = q,\bar{q},g,h,\bar{h}$$

- MATCHING CAN BE DONE AT ANY SCALE, RESULTS SHOULD NOT DEPEND ON IT
- GIVEN K_{ij} AT ONE SCALE, RESULTS AT ANY SCALE CAN BE OBTAINED BY DGLAP+RGE ON LHS & RHS
- $K_{ij}^{(0)} = \delta_{ij}$, RECEIVE CORRECTIONS AT HIGHER ORDERS:
  - $i = j \neq h \Rightarrow$ DIFFERENT NORMALIZATION OF OPERATORS DUE TO # OF QUARKS IN LOOPS, STARTS AT $O(\alpha_s^2)$
  - $i = j = h \Rightarrow$ DIFFERENT NORMALIZATION OF OPERATORS DUE TO ON-SHELL VS $\overline{\text{MS}}$ SUBTRACTION, STARTS AT $O(\alpha_s)$
  - $i \neq j$ OPERATOR MIXING
- MAIN DIFFERENCE:
  - DYNAMICAL CHARM:
    * $f_h^{(3)} = 0$
    * $i = h \Rightarrow$ HEAVY FLAVOR PDF IN TERMS OF LIGHT FLAVOR ONES
    * $i, j \neq h$ INVERT & EXPRESS 3FS PDFS IN TERMS OF 4FS
  - FITTED CHARM:
    * $f_h^{(3)} \neq 0$, SCALE INDEPENDENT
    * INVERT & EXPRESS 3FS PDFS IN TERMS OF 4FS FOR ALL i, j (INCL. HQ)

INCLUDING A CHARM PDF TO $O(\alpha_s)$ (FONLL-A)

DYNAMICAL



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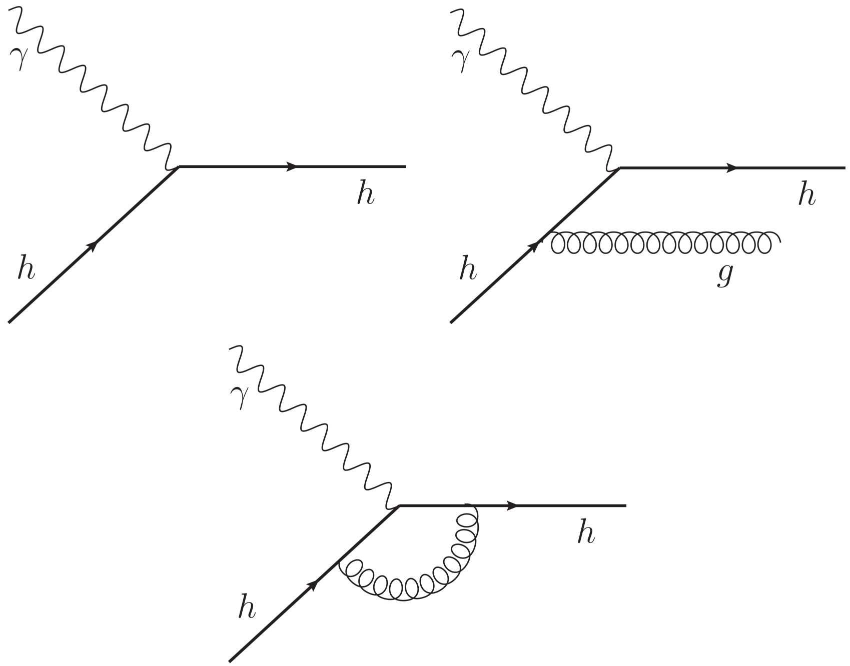


- 4FS: ONLY THE BOUNDARY CONDITION CHANGES
- 3FS: EXTRA CONTRIBUTION:
  $\Delta F_h(x,Q^2) = \sum_{i=h,\bar{h}} \left[C_i^{(3)}\left(\frac{Q^2}{m_h^2}, \alpha_s^{(3)}(Q^2)\right) - C_i^{(3,0)}\left(\frac{Q^2}{m_h^2}, \alpha_s^{(3)}(Q^2)\right)\right] \otimes f_i^{(3)};$
  LO NOW $O(\alpha_s^0) \Rightarrow$ SUBLEADING TERMS PROMOTED TO LEADING

THE CHARM PDF: 3FS VS 4FS

- IN THE 3FS, THE CHARM PDF DOES NOT EVOLVE
- WHEN EXPRESSING 3FS IN TERMS OF 4FS, SCALE DEPENDENCE IS EXPANDED & SUBTRACTED TO FINITE PERTURBATIVE ORDER

$$f_h^{(3)} = f_h^{(4)}(Q^2) - \alpha_s^{(4)}(Q^2)\left(K_{hh}^{(1)}(m_h^2) + P_{qq}^{(0)} L\right) \otimes f_h^{(4)}(Q^2) - \alpha_s^{(4)}(Q^2) L P_{qg}^{(0)} \otimes g^{(4)}(Q^2) + \mathcal{O}(\alpha_s^2)$$

THE HEAVY STRUCTURE FUNCTION TO $O(\alpha_s)$ (FONLL-A)

$$
\begin{aligned}
F_h(x,Q^2) = \sum_{i=h,\,\bar h} \Bigg\{ & C_i^{(3),\,0}\left(\frac{Q^2}{m_h^2}\right) \\
& + \alpha_s^{(4)}(Q^2)\left[C_i^{(3),\,1}\left(\frac{Q^2}{m_h^2}\right) - C_i^{(3),\,0}\left(\frac{Q^2}{m_h^2}\right)\otimes\left(K_{hh}^{(1)}(m_h^2)+P_{qq}^{(0)}L\right)\right]\Bigg\}\otimes f_i^{(4)}(Q^2) \\
& + \alpha_s^{(4)}(Q^2)\left[C_g^{(3),\,1}\left(\frac{Q^2}{m_h^2}\right) - \sum_{i=h,\bar h} C_i^{(3),\,0}\left(\frac{Q^2}{m_h^2}\right)\otimes P_{qg}^{(0)}L\right]\otimes f_g^{(4)}(Q^2) + \mathcal{O}(\alpha_s^2)
\end{aligned}
$$

- COMBINE 4FS PDFs ($f_i^{(4)}$) WITH 3FS COEFFICIENT FUNCTIONS ($C_i^{(3)}$) WITH COLLINEAR LOGS SUBTRACTED $\Rightarrow$ ACOT
- DIFFERS FROM EXPRESSION IN (SF, LAENEN, NASON ROJO, 2010) BY TERMS WHICH BECOME SUBLEADING WHEN CHARM IS DYNAMICAL $\Rightarrow$ S-ACOT
- NOTE NOW FONLL-A INCLUDES 3FS UP TO NLO

THE HEAVY STRUCTURE FUNCTION TO ALL ORDERS

(Ball, Bonvini, Rottoli, 2015)

$$F(x,Q^2) = \sum_{i,j=g,q,\bar{q},h,\bar{h}} \left[C_i^{(3)}\left(\frac{Q^2}{m_h^2}\right) - C_i^{(3,0)}\left(\frac{Q^2}{m_h^2}\right)\right] \otimes K_{ij}^{-1}(Q^2) \otimes f_j^{(4)}(Q^2) + \sum_{i,j=g,q,\bar{q},h,\bar{h}} C_i^{(4)} \otimes f_i^{(4)}(Q^2)$$
$$= \sum_{i,j=g,q,\bar{q},h,\bar{h}} C_i^{(3)}\left(\frac{Q^2}{m_h^2}\right) \otimes K_{ij}^{-1}(Q^2) \otimes f_j^{(4)}(Q^2) \qquad (1)$$

- SIMPLE ALL-ORDER STRUCTURE:
  [3FS (MASSIVE) C.F.] ⊗ [INVERSE MATCHING] (DIVIDES OUT COLLN. LOGS) ⊗ [4FS PDFs]
- THE SUBLEADING "DIFFERENCE" TERM $F^{(d)}(x,Q^2) = F^{(4)}(x,Q^2) - F^{(3,0)}(x,Q^2)$ VANISHES; ONLY SUBLEADING TERMS FROM INTERFERENCE OF MASSIVE C.F. WITH H.O. MASSLESS EVOLUTION

PHENOMENOLOGY

THE NNPDF3IC PDF DETERMINATION

The NNPDF collaboration: Ball, Bertone, Bonvini, Carrazza, sf, Guffanti, Hartland, Rojo, Rottoli

- DATASET: SAME AS NNPDF3.0 (BUT WITH COMBINED INSTEAD OF SEPARATE HERA-II), SUPPLEMENTED BY EMC F_2^c DATA (1983,1987)
- STANDARD NNPDF3 METHODOLOGY, WITH ONE EXTRA PDF: $c = \bar{c}$, PARM. AS ALL OTHER PDFS (NEURAL NET, 37 FREE PARAMETERS)
- FITS PERFORMED WITH $\overline{\text{MS}}$ MASS $m_c = 1.15,\ 1.275,\ 1.4$ GEV (PDG$\pm 5\sigma$); & WITH POLE MASS $m_c = 1.33,\ 1.47,\ 1.61$ GEV (ONE-LOOP CONVERSION); ALSO POLE $m_c = 1.275$ GEV (CROSS-CHECK)
- FONLL-B, BOTH WITH DYNAMICAL AND FITTED CHARM (DEGRADES TO FONLL-A FOR FITTED CHARM)

FIT QUALITY

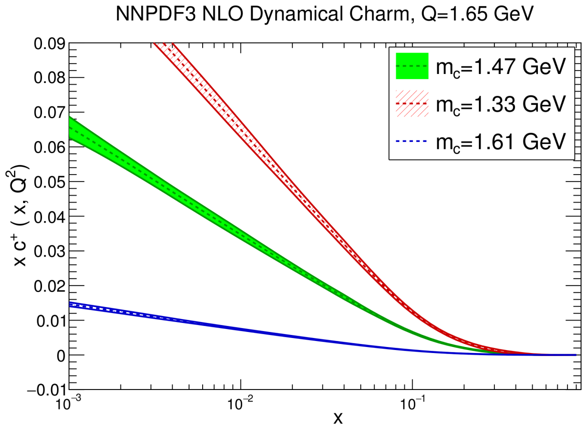
NNPDF3 NLO $m_c = 1.47$ GeV (pole mass)			
Experiment	$N_{\rm dat}$	$\chi^2/N_{\rm dat}$ fitted charm	$\chi^2/N_{\rm dat}$ dynamical charm
NMC	325	1.36	1.34
SLAC	67	1.21	1.32
BCDMS	581	1.28	1.29
CHORUS	832	1.07	1.11
NuTeV	76	0.62	0.62
EMC	16	1.09	- (32)
HERA inclusive	1145	1.17	1.19
HERA F_2^c	47	1.14	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

- WITHOUT FITTED CHARM EMC DATA CANNOT BE FITTED ($\chi^2/dof = 32$); EXCLUDED FROM FINAL FIT
- FIT QUALITY SOMEWHAT BETTER WITH DYNAMICAL CHARM

THE CHARM PDF:
STABILITY

LOW SCALE

DYNAMICAL



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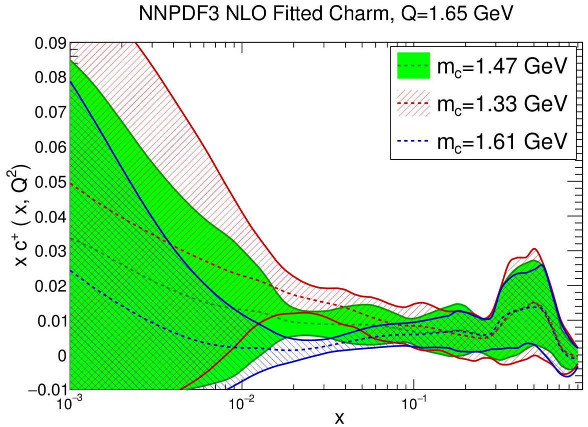
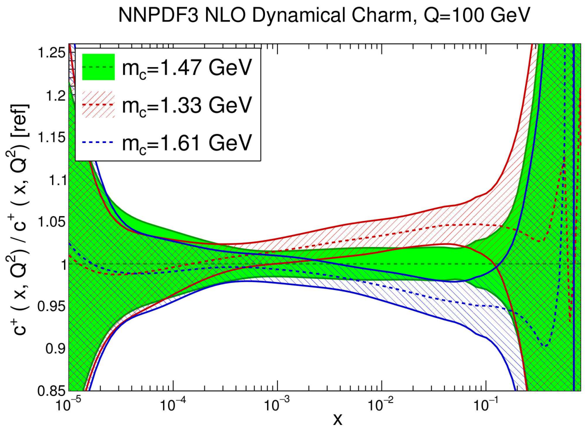
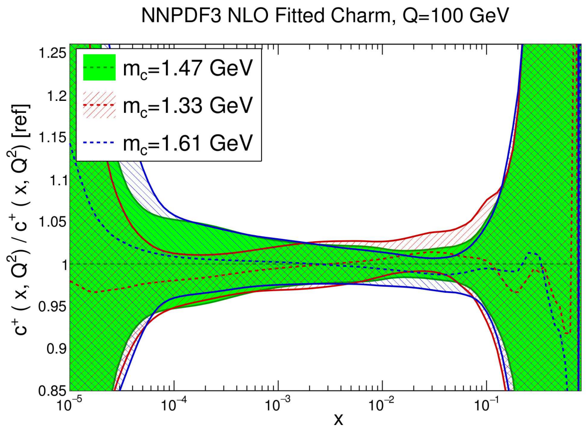


HIGH SCALE



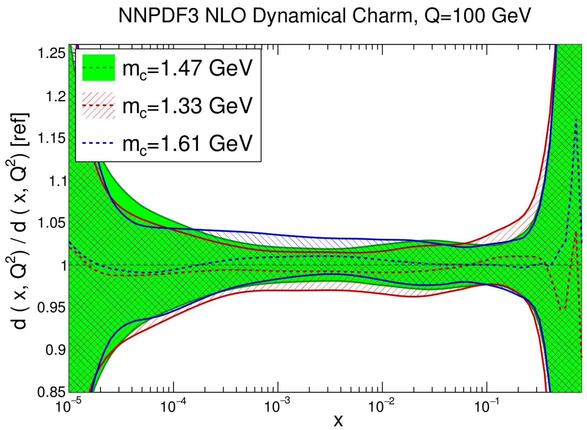


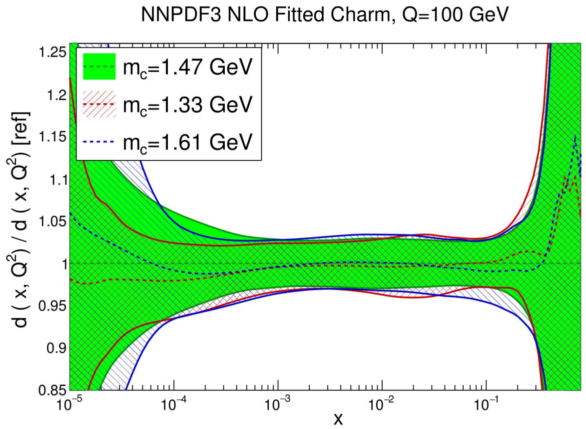
- DYNAMICAL: DEPENDS SIGNIFICANTLY ON THE MASS WHICH SETS THE PHYSICAL THRESHOLD; DEPENDENCE SEEN BOTH AT LOW AND HIGH SCALE;
- FITTED: EXTREMELY STABLE AT ALL SCALES STRUCTURE APPEARS AT LARGE x

STABILITY:
THE LIGHT QUARKS

DOWN

DYNAMICAL





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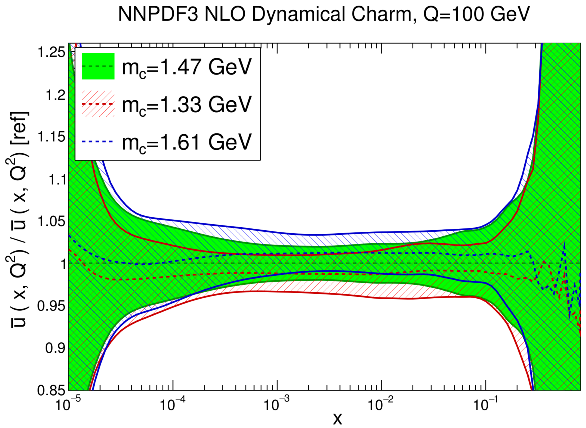

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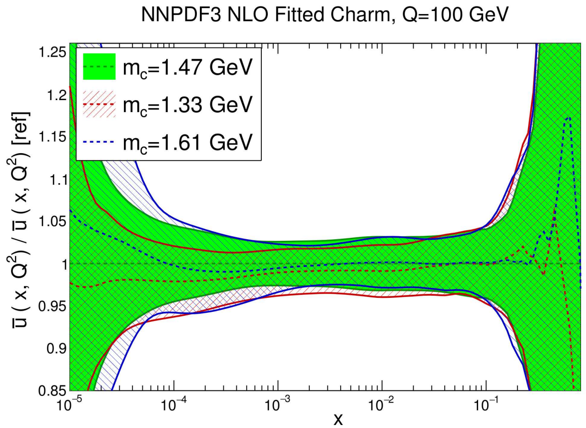
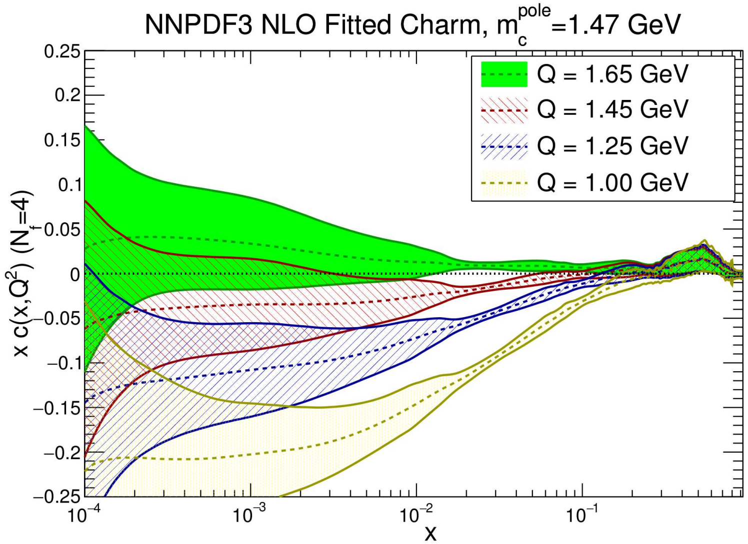


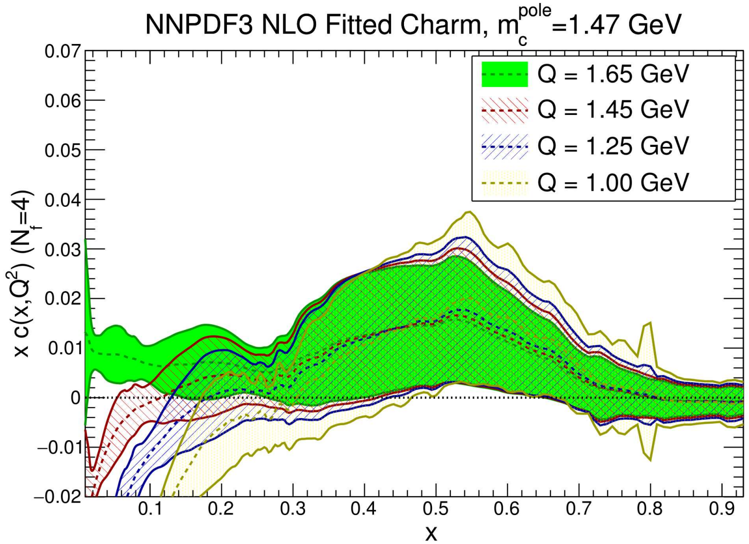
- DYNAMICAL CHARM: LIGHT QUARKS DEPEND (WEAKLY) ON THE MASS WHICH SETS THE PHYSICAL THRESHOLD FOR CHARM, BOTH AT LOW AND HIGH SCALE;
- FITTED CHARM: LIGHT QUARKS BECOME INDEPENDENT OF CHARM MASS AT ALL SCALES
- GLUON LARGELY INSENSITIVE TO CHARM MASS IN ALL CASES

THE CHARM PDF: DYNAMICAL?

SCALE DEPENDENCE

BACKWARD EVOLUTION IN THE 4FS





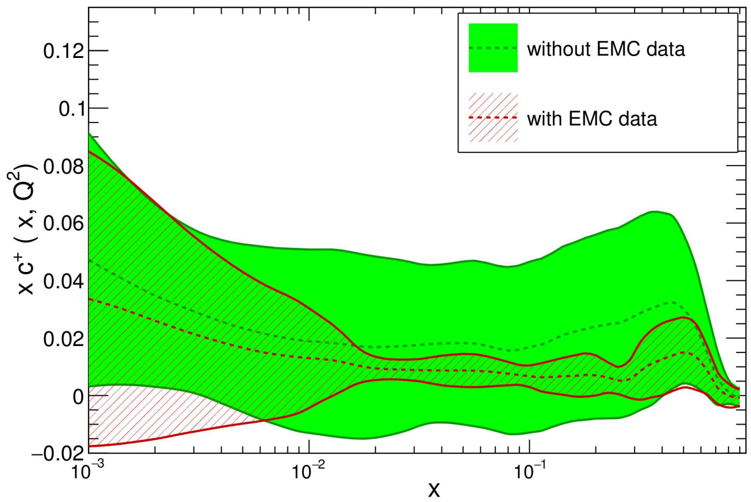
- LARGE x BUMP: ESSENTIALLY SCALE-INDEPENDENT:
  "INTRINSIC", ONE-σ SIGNIFICANCE

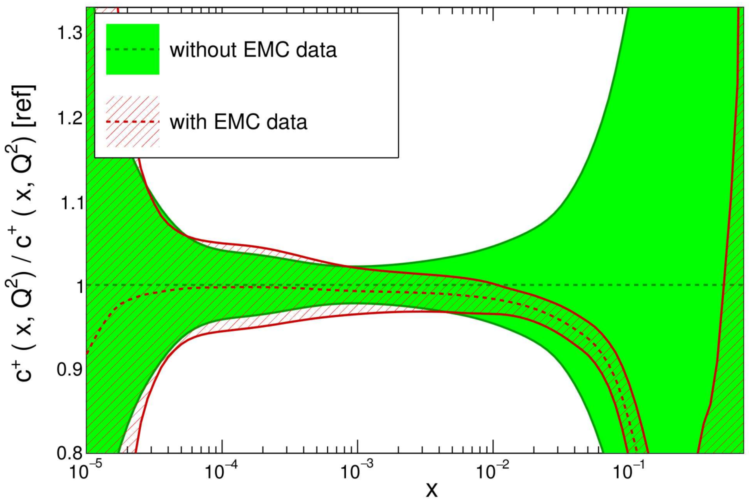
- SMALL x RISE: GOES AWAY AT LOW SCALE, CHARM VANISHES FOR $Q \sim 1.6$ GeV
  (INDEPENDENT OF VALUE OF m_c): "DYNAMICAL" FOR ALL $x \lesssim 0.3$

- AT THE MATCHING SCALE, 3FS PDF REMAINS SCALE-INDEPENDENT $\Rightarrow$
  VANISHING (DYNAMICAL) AT LOW x, POSITIVE BUMP (INTRINSIC) AT LARGE x

THE CHARM PDF: INTRINSIC?

IMPACT OF THE EMC DATA

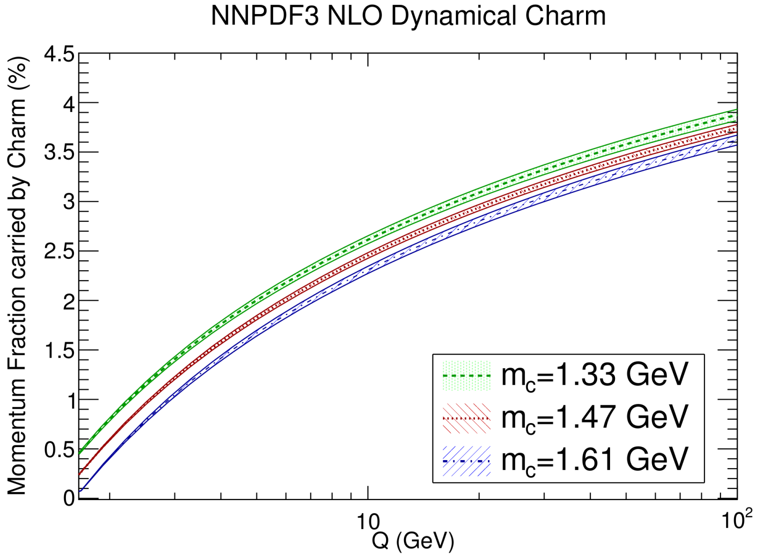


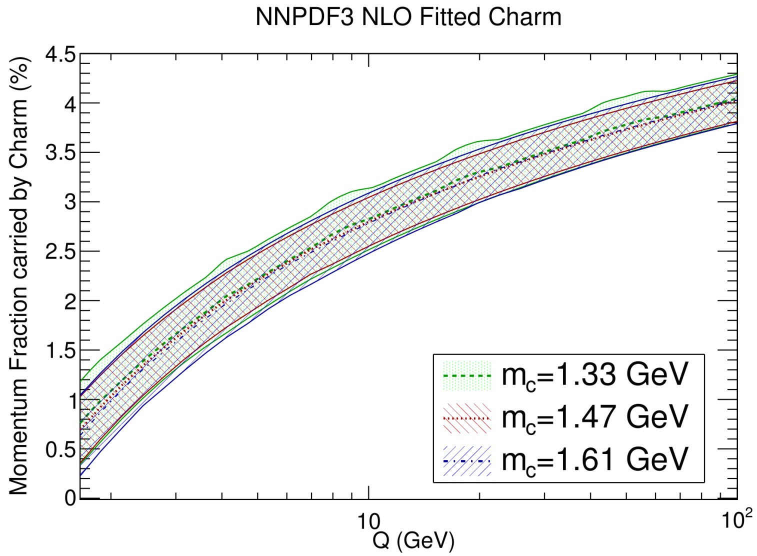


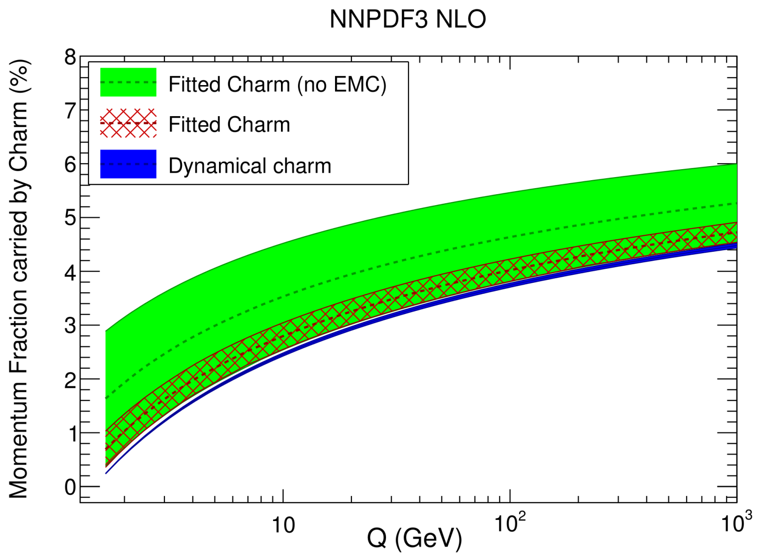
- UNCERTAINTIES LARGER W/O EMC, BUT QUALITATIVE BEHAVIOUR UNCHANGED
- EMC DATA SHOULD BE TAKEN WITH CARE, 10% SYSTEMATICS UNACCOUNTED FOR: YET BUT IMPACT IS QUALITATIVE: χ^2 DOWN FROM ~ 30 TO ~ 1
- WAITING FOR MORE INFORMATION FROM THE LHC

THE CHARM MOMENTUM FRACTION

SCALE DEPENDENCE



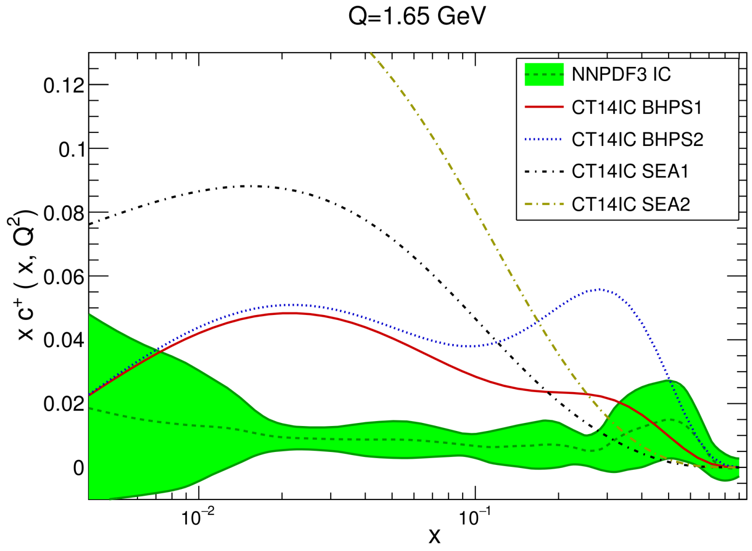


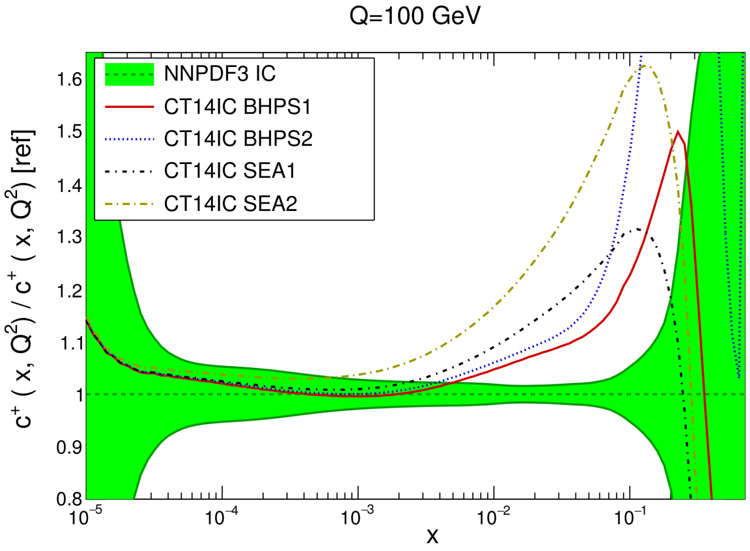


- MASS DEPENDENCE DISAPPEARS IF CHARM FITTED
- LARGER UNCERTAINTY W/O EMC DATA

THE CHARM PDF:

COMPARING TO MODELS

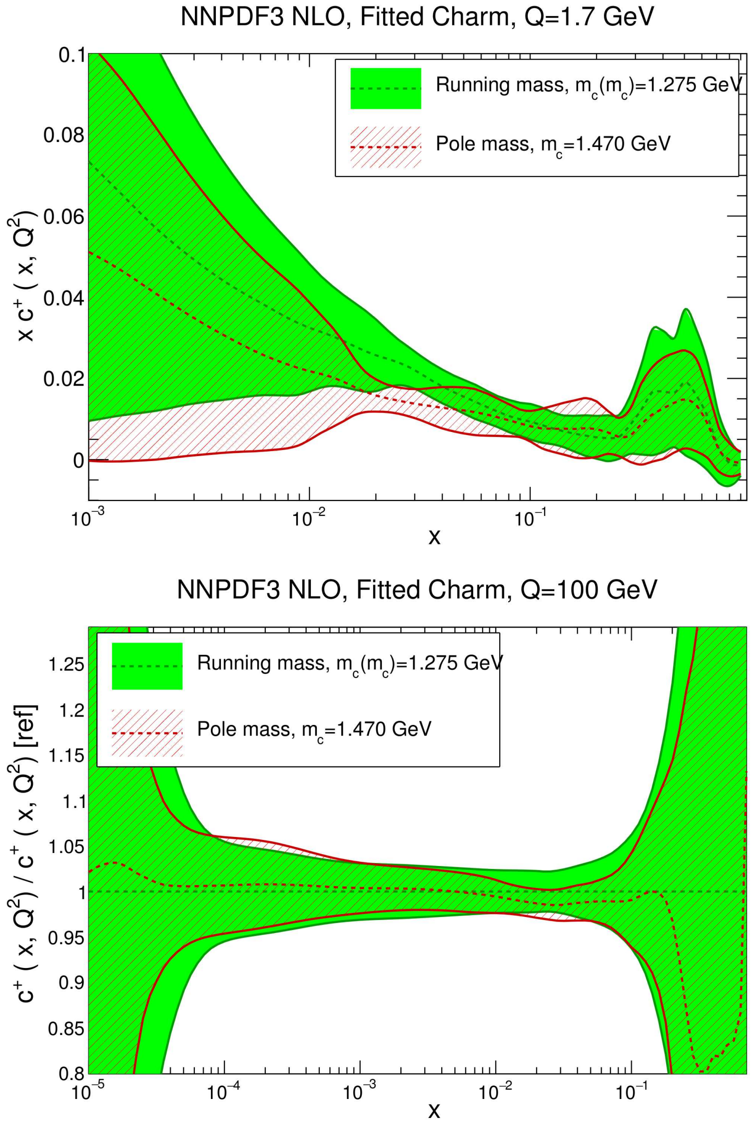




- CT14 PDFs (Dulat, Hou, Gao, Huston, Pumplin, Schmidt, Stump, Yuan, 2013): TWO MODELS "BRODSKY" AND "SEA",
- FOR EACH TWO DIFFERENT NORMALIZATIONS (MOMENTUM FRACTIONS): 0.57% (BHPS1, SEA1); 1.5% (SEA2); 2% (BHPS2)
- AT LOW SCALE, ALL EXCEED OUR FIT FOR LOW $x \lesssim 0.3$
- AT HIGH SCALE, PERTURBATIVE EVOLUTION TAKES OVER AT SMALL x
- AT LARGE x OUR BEST FIT PEAKS AT LARGER x

$\overline{\text{MS}}$ vs. POLE MASSES:

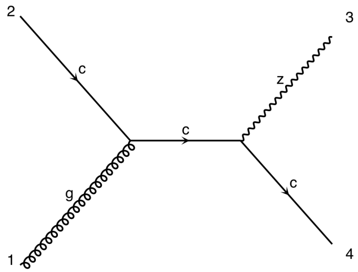
DOES IT MAKE A DIFFERENCE?

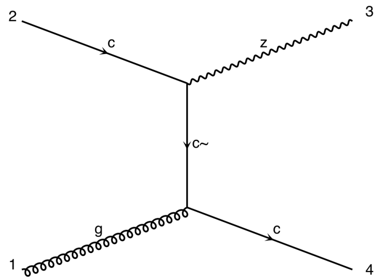


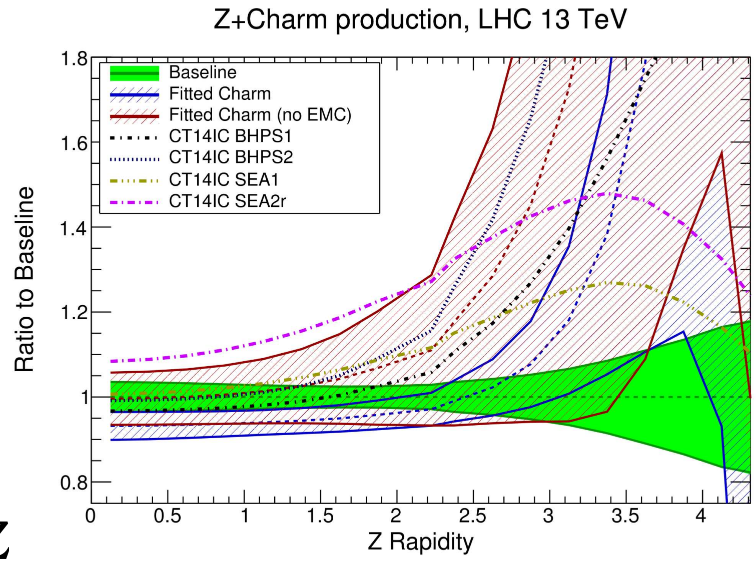
- GOOD CONSISTENCY BETWEEN $\overline{\text{MS}}$ & POLE MASS FITS WITH ONE-LOOP CONVERSION
- FIT QUALITY SOMEWHAT BETTER IN POLE SCHEME

THE IMPACT OF LHC DATA I

ASSOCIATE Zc PRODUCTION





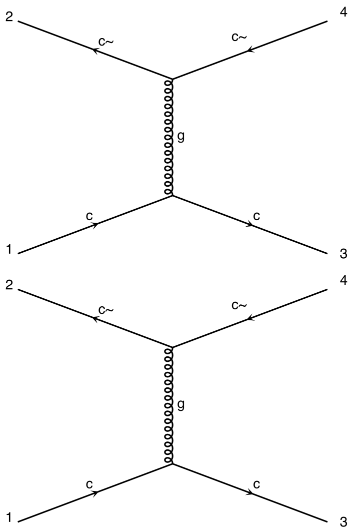


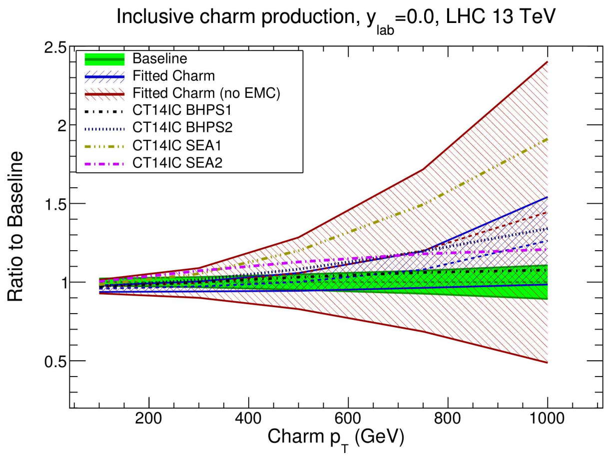
Z

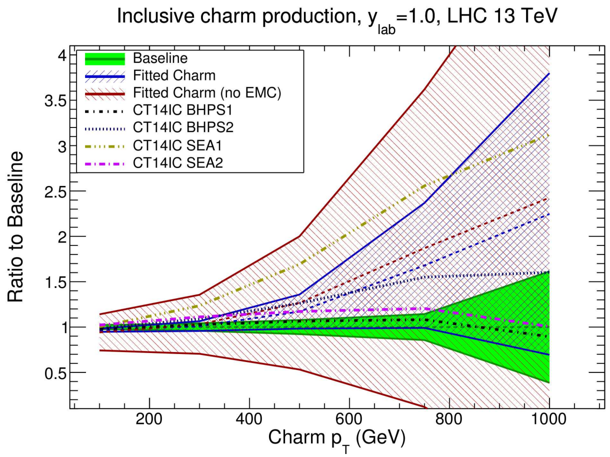
- HIGH SENSITIVITY IN LARGE RAPIDITY REGION
- CAN DISCRIMINATE BETWEEN MODELS & CURRENT FIT

THE IMPACT OF LHC DATA II

CHARM PAIR PRODUCTION





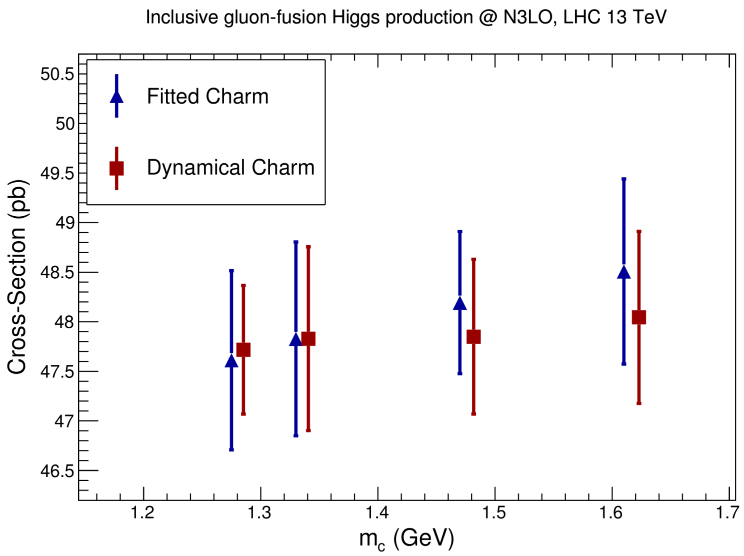


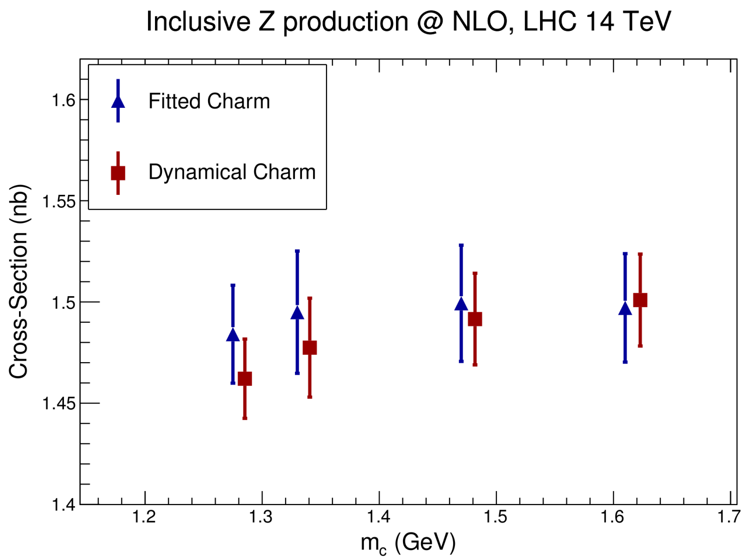
- GLUON CHANNEL DOMINATES AT CENTRAL RAPIDITY & LOW p_T $\Rightarrow$ NO DISCRIMINATION

- LARGE RAPIDITY, p_t $\Rightarrow$ CAN DISCRIMINATE

THE IMPACT OF CHARM ON LHC PHENOMENOLOGY

STANDARD CANDLES





- CONSIDERABLE STABILITY OF STANDARD CANDLES:
  DEPENDENCE ON m_c MUCH SMALLER THAN PDF UNCERTAINTY

- GENERALLY GREATER STABILITY WITH FITTED CHARM

- NO DIFFERENCE IN GLUON-DOMINATED CHANNELS (ALWAYS VERY STABLE)

OUTLOOK

QUESTIONS AND ANSWERS

3FS VS 4FS & CHARM USED FOR DEFINITENESS, APPLY ALSO TO 4FS VS 5FS & BOTTOM

- Q: WHY DOES ONE HAVE TO USE 3F PDFS WITH 3F MES?

  A: BECAUSE THEY CORRESPOND TO DIFFERENT FACTORIZATION & RENORMALIZATION SCHEMES

- Q: HOW BAD IS IT IF ONE USES 3FS ME WITH 4FS PDFS?

  A: THE DGLAP LOGS IN THE HQ PDF ARE DOUBLE-COUNTED, RESULT IS OTHERWISE AS IN FONLL/ACOT

- Q: IS THERE A STRONG DEPENDENCE ON THE HQ MASS?

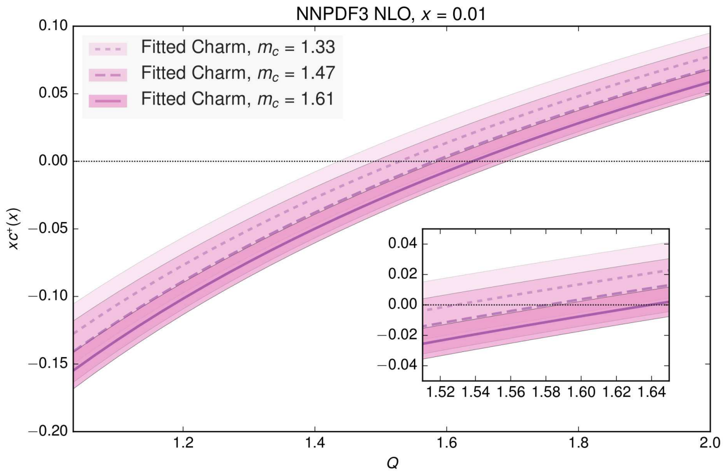
  A: MOST OF THE DEPENDENCE THROUGH EVOLUTION, REABSORBED IN INITIAL PDF

EXTRAS

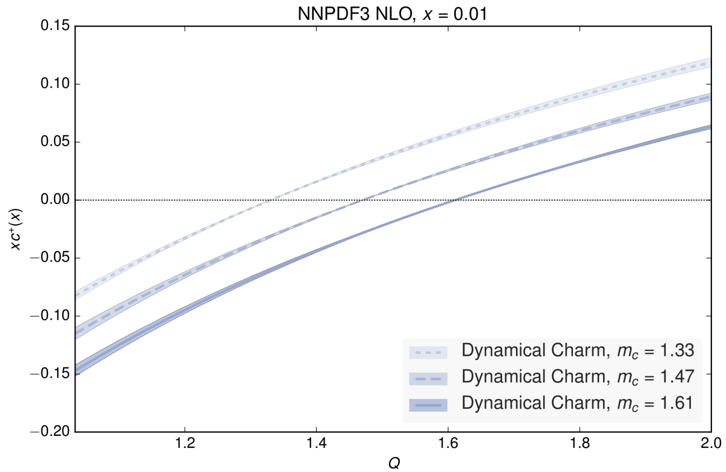
THE VANISHING SCALE:

POSITIVITY

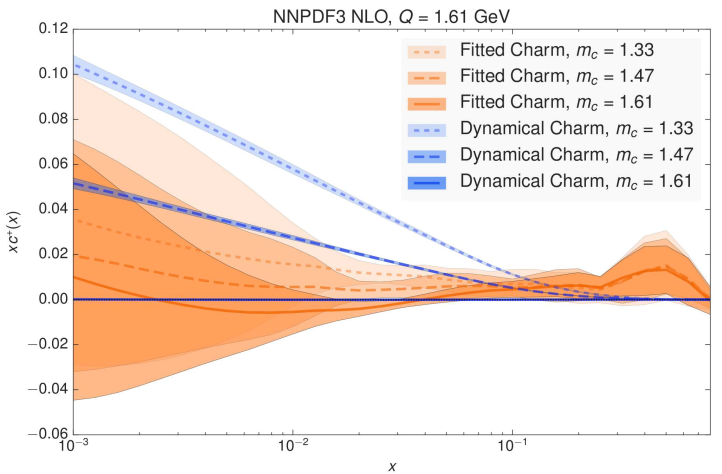
FITTED VS Q, $x = 0.01$



DYNAMICAL VS Q, $x = 0.01$



FITTED VS DYNAMICAL, $Q = 1.6$ GeV



- DYNAMICAL: VANISHING SCALE DEPENDS STRONGLY ON m_c
- FITTED: VANISHING SCALE ESSENTIALLY INDEPENDENT OF m_c
- "“POSITIVITY” PROBLEM OF DYNAMICAL CHARM $\Rightarrow$ SOLVED FOR FITTED CHARM