Heavy Quark Production in the ACOT Scheme at NNLO and N3LO

Fred Olness

SMU

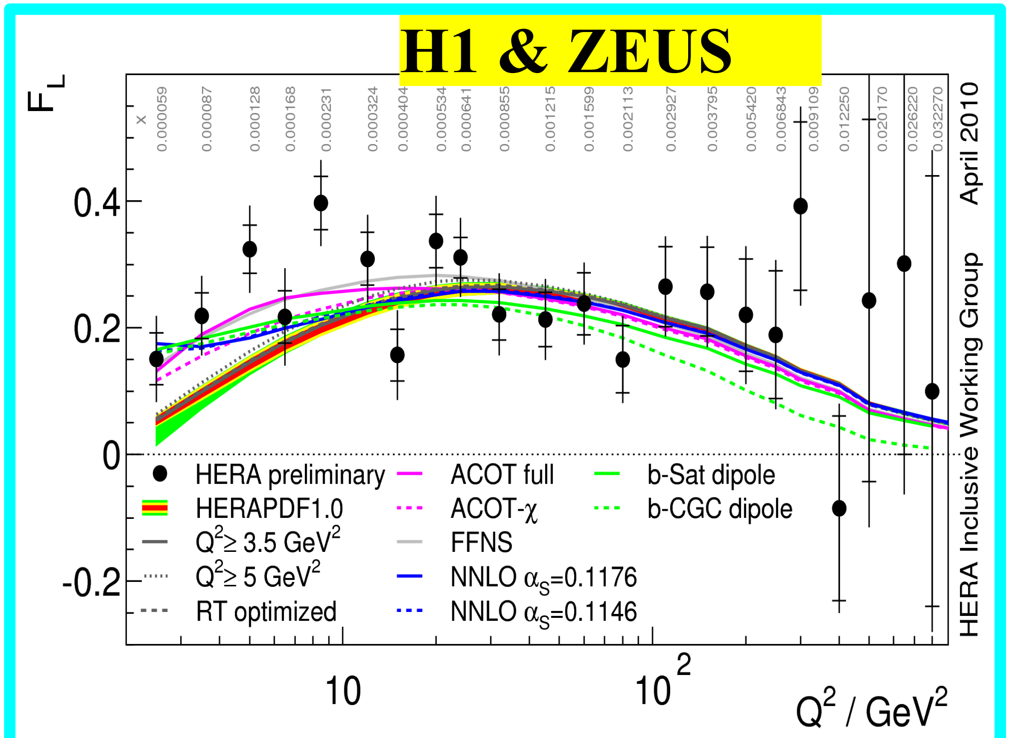
Conspirators:

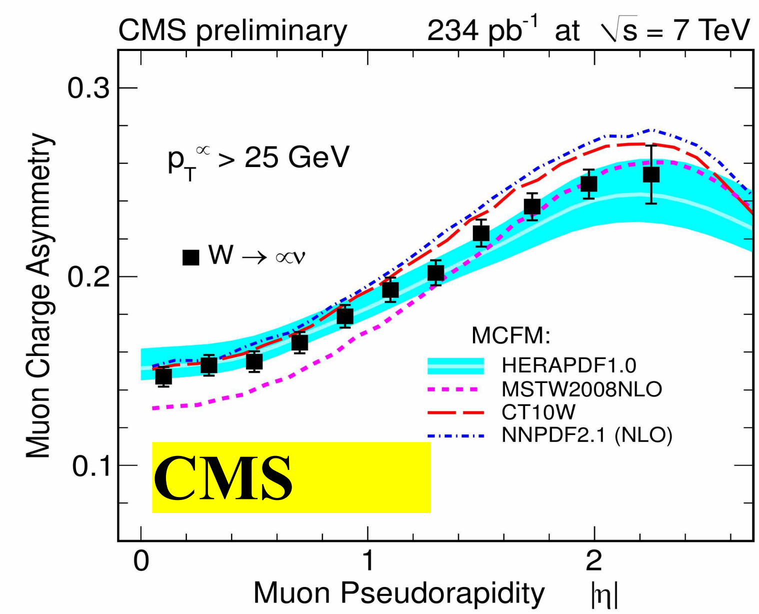
K. Kovarik, I Schienbein, J. Yu, J. Morfin, P. Nadolsky, T.P. Stavreva, A. Kusina, M. Guzzi, J. Gao, Z. Liang J. Owens, C. Keppel, D. Soper ...

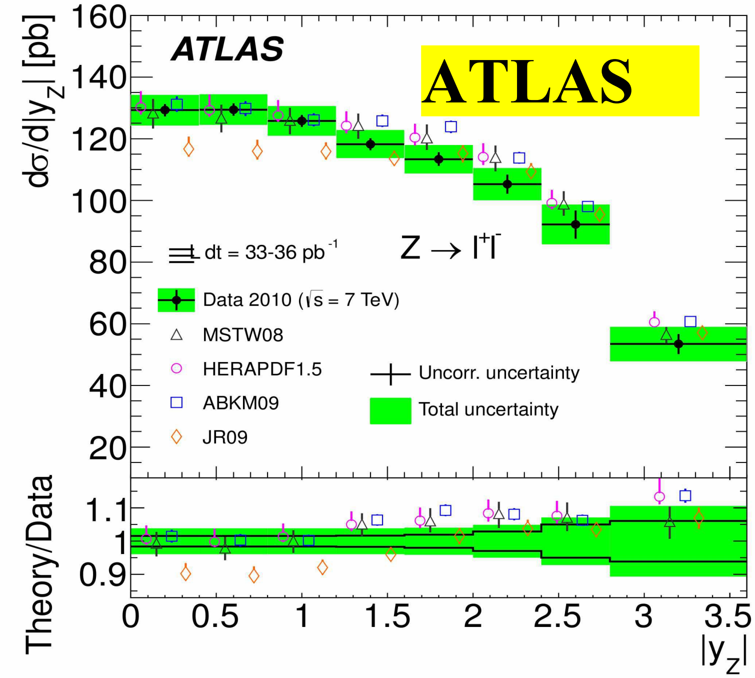
DIS 2012, Bonn
28 March 2012

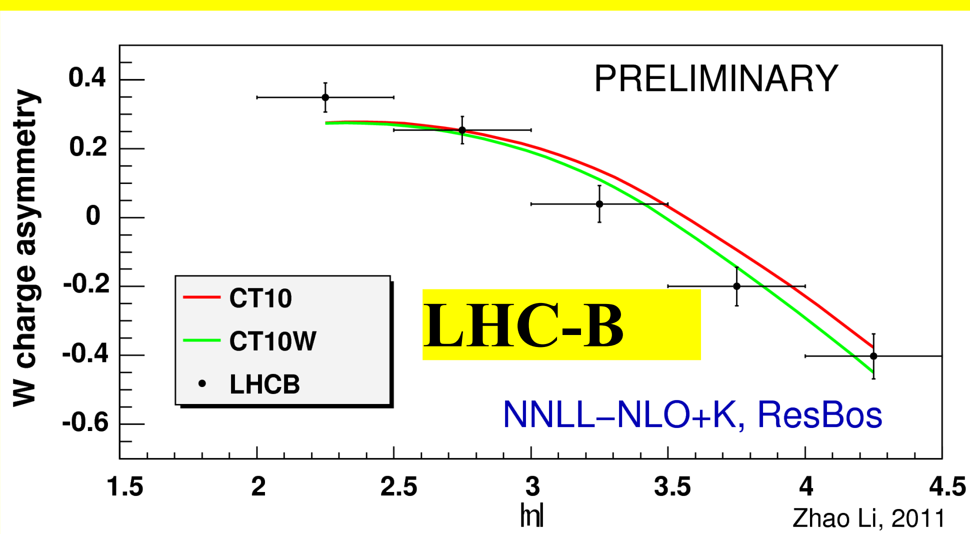
Motivation

Recent Measurements: Requires Theoretical Improvements









Jan Kretzschmar, 7.3.2012 – p.5

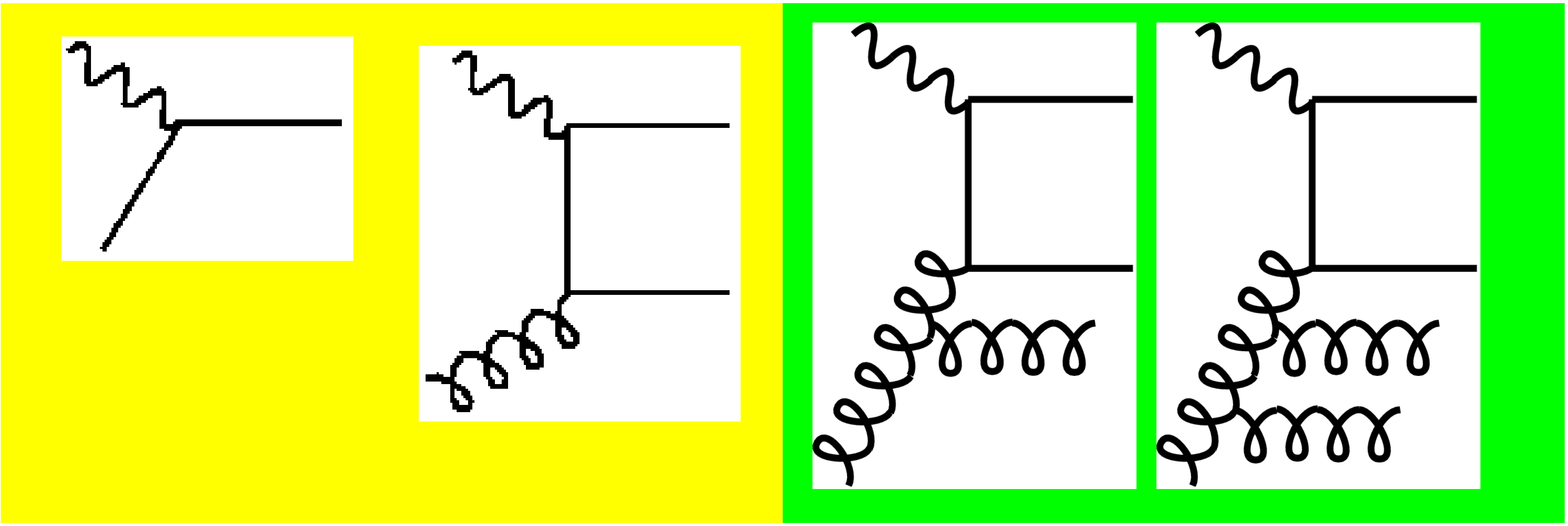
ACOT

@ NNLO + N^3LO

Stavreva, Olness, Schienbein, Jezo, Kusina, Kovarik, Yu
arXiv:1203.0282

ACOT Extension to Higher Orders

LO **NLO** **N2LO** **N3LO**



Full ACOT

Based on the Collins-Wilczek-Zee (CWZ) Renormalization Scheme

... hence, extensible to all orders

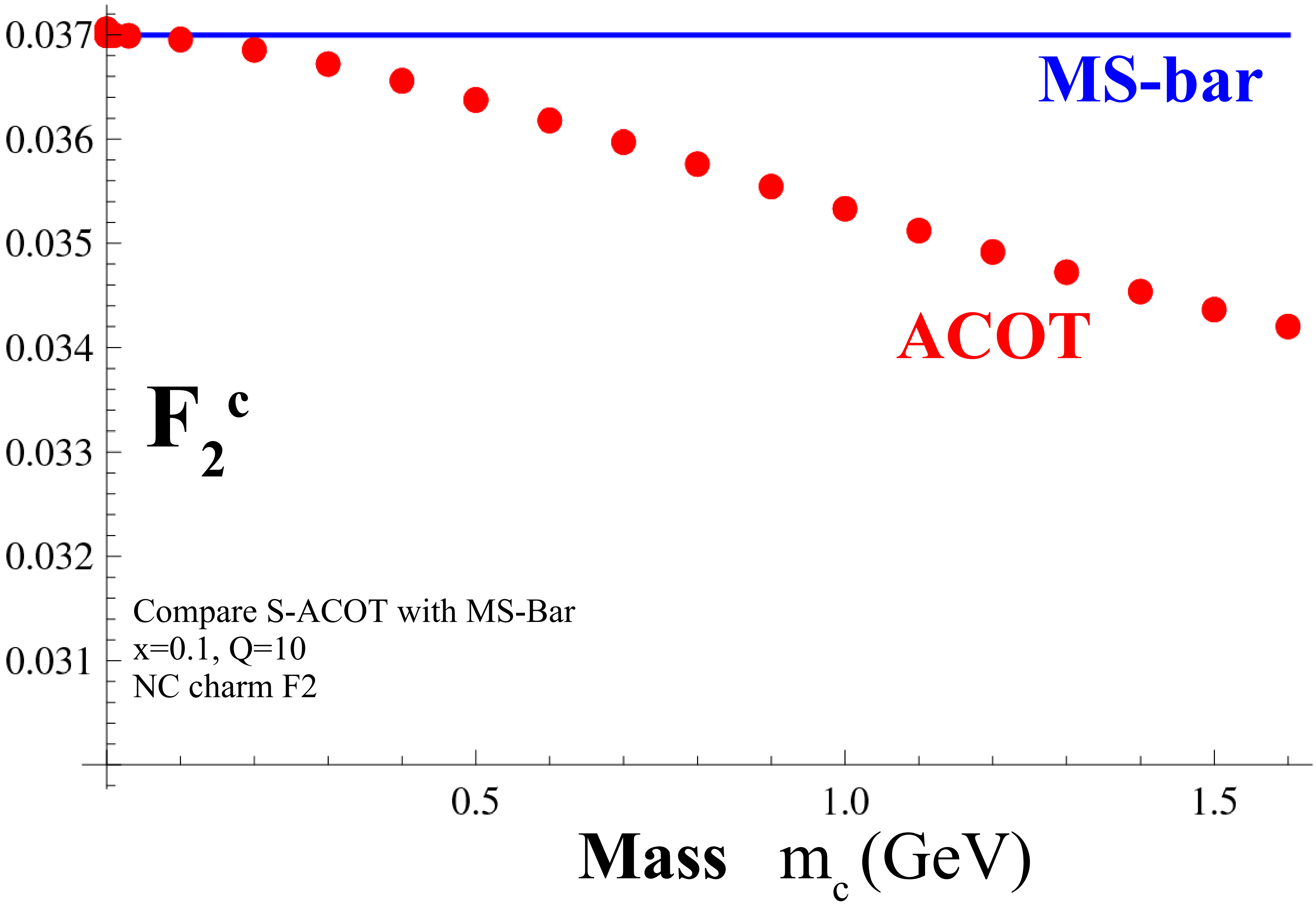
DGLAP kernels & PDF evolution are pure MS-Bar

Subtractions are MS-Bar

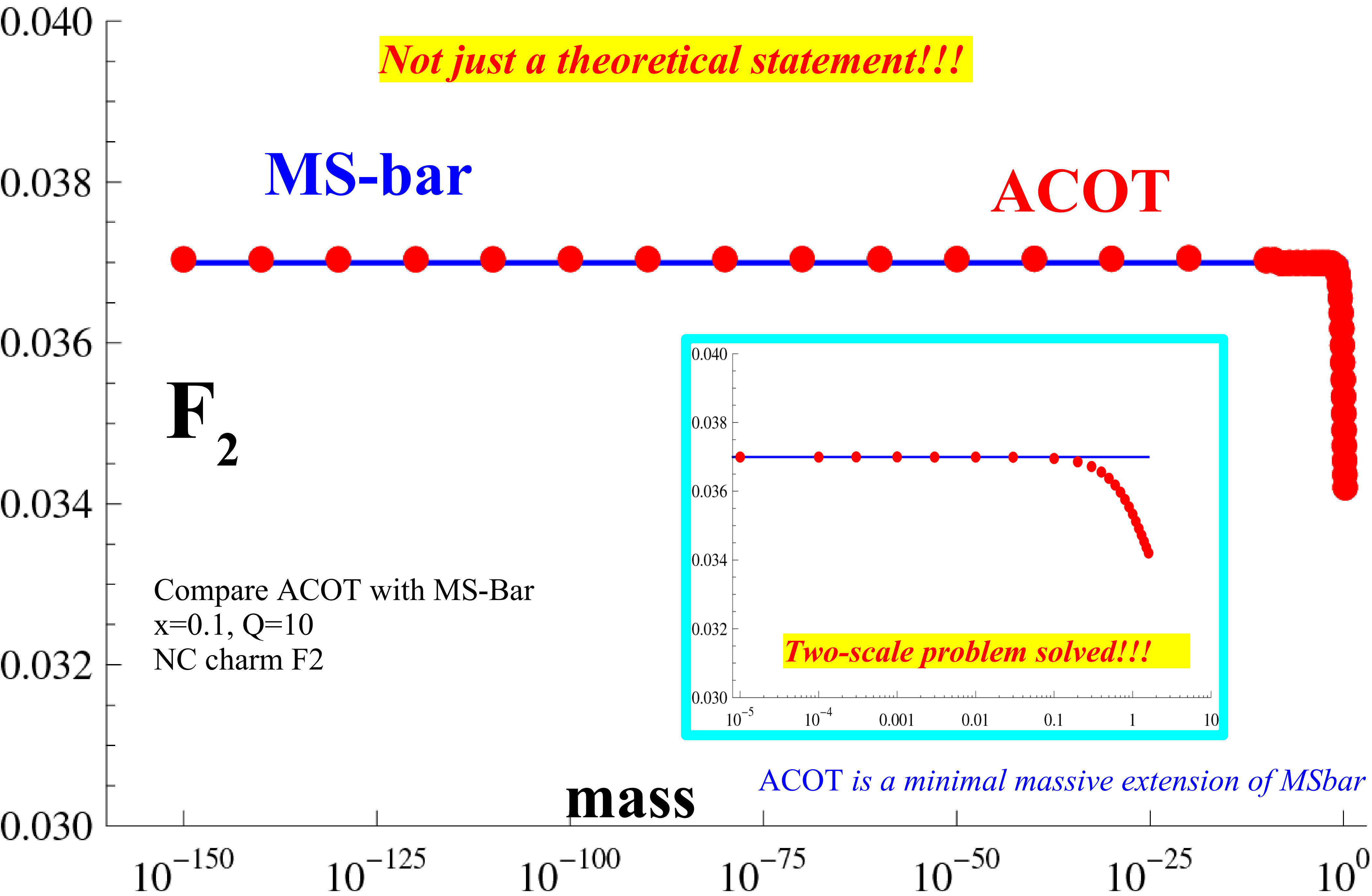
ACOT: $m \rightarrow 0$ limit yields MS-Bar

with no finite renormalization

ACOT m→ 0 limit yields MS-Bar: *No finite renormalization*



ACOT m→ 0 limit yields MS-Bar: *No finite renormalization*



ACOT m→ 0 limit cross check with QCDNUM at NLO

```
PATCH FOR TESTING: HMASS=0=   0.938000023
  IHADRON: SET TO HADRON= 1
  GZ and ZZ are for testing
```

	x	q	F_2	F_L
print x,q, ratios:	0.00319999992	12.2474487	**1.00092636**	**1.0012981**
print x,q, ratios:	0.00499999989	12.2474487	**1.00098575**	**1.00126809**
print x,q, ratios:	0.00800000038	12.2474487	**1.00106943**	**1.00153596**
print x,q, ratios:	0.00319999992	14.1421356	1.00092542	1.00125357
print x,q, ratios:	0.00499999989	14.1421356	1.00097202	1.00121532
print x,q, ratios:	0.00800000038	14.1421356	1.00104411	1.00146055
print x,q, ratios:	0.0130000003	14.1421356	1.00107382	1.0013549
print x,q, ratios:	0.0199999996	14.1421356	1.00114663	1.0014694
print x,q, ratios:	0.0320000015	14.1421356	1.00119237	1.00152525
print x,q, ratios:	0.0500000007	14.1421356	1.00117963	1.00131561
print x,q, ratios:	0.0799999982	14.1421356	1.00098036	1.00123239
print x,q, ratios:	0.00499999989	15.8113883	1.00095999	1.00117694
print x,q, ratios:	0.00800000038	15.8113883	1.0010229	1.00140587
print x,q, ratios:	0.0130000003	15.8113883	1.00104124	1.00130353
	0.0199999996	15.8113883	1.00110599	1.00140934
	0.0320000015	15.8113883	1.00114419	1.00146259
	0.0500000007	15.8113883	1.00113621	1.00125726
	0.0799999982	15.8113883	1.00095108	1.0011996
	0.129999995	15.8113883	1.00055001	1.00103563
print x,q, ratios:	0.25	15.8113883	0.99929117	1.0000816
print x,q, ratios:	0.400000006	15.8113883	0.997267345	0.998376607
print x,q, ratios:	0.00499999989	17.3205081	1.00094852	1.00114569
print x,q, ratios:	0.00800000038	17.3205081	1.00100525	1.00136309
print x,q, ratios:	0.0130000003	17.3205081	1.00101481	1.00118502
print x,q, ratios:	0.0199999996	17.3205081	1.00107357	1.00136459
print x,q, ratios:	0.0320000015	17.3205081	1.00110601	1.00140262

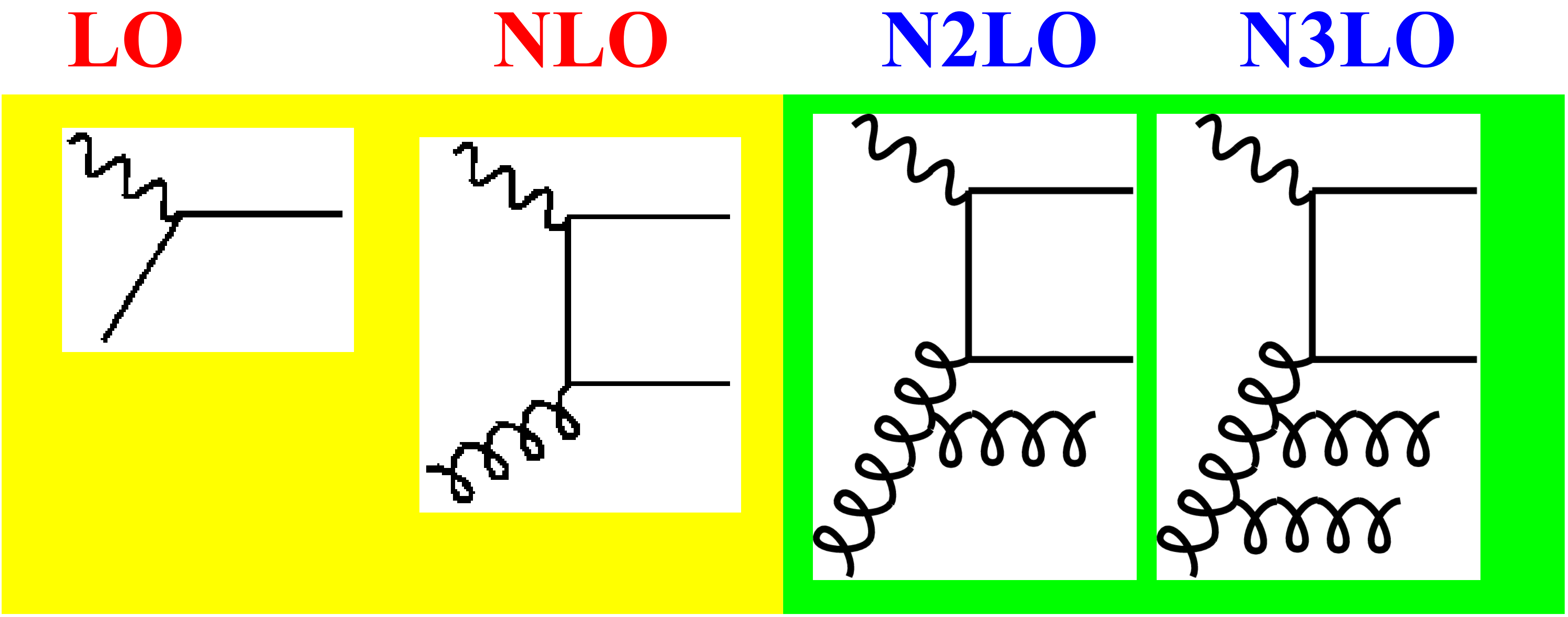
NLO Check with QCDNUM

~1E-3

ACOT

Phase Space & Dynamic Mass

ACOT Extension to Higher Orders



Full ACOT

Extensible to any order

$$\sigma = f(\xi(x, m_{ps}), Q) \otimes \hat{\sigma}(m_{dyn})$$

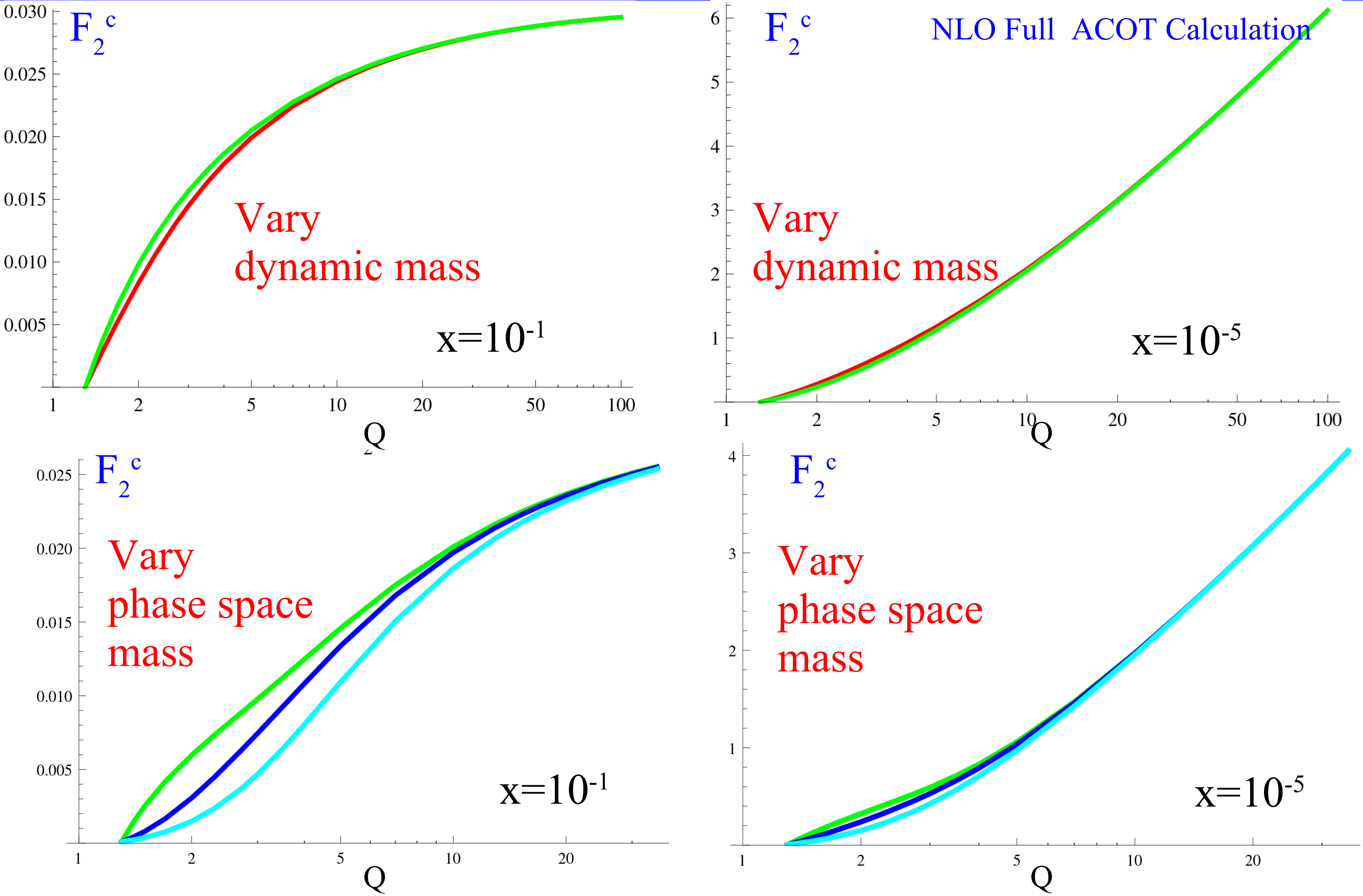
$$\xi(x, m_{ps}) = x \left(1 + \left[\frac{n\, m_{ps}}{Q}\right]^2\right)$$

$$n = \{0, 1, 2\}$$

Distinguish:
"phase space" mass
"dynamic" mass

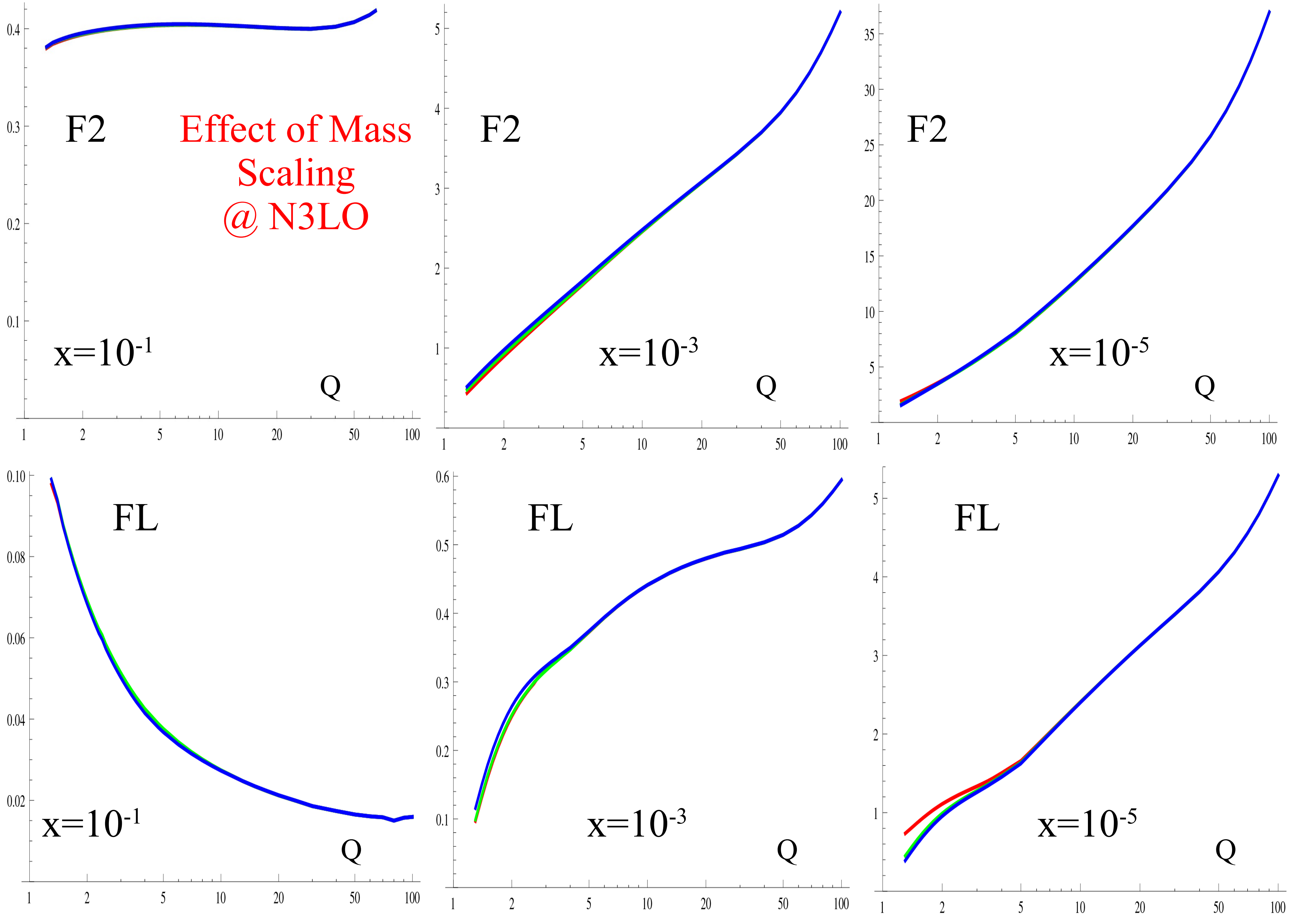
Demonstrate:
1) PS mass dominates
2) Estimated Error small

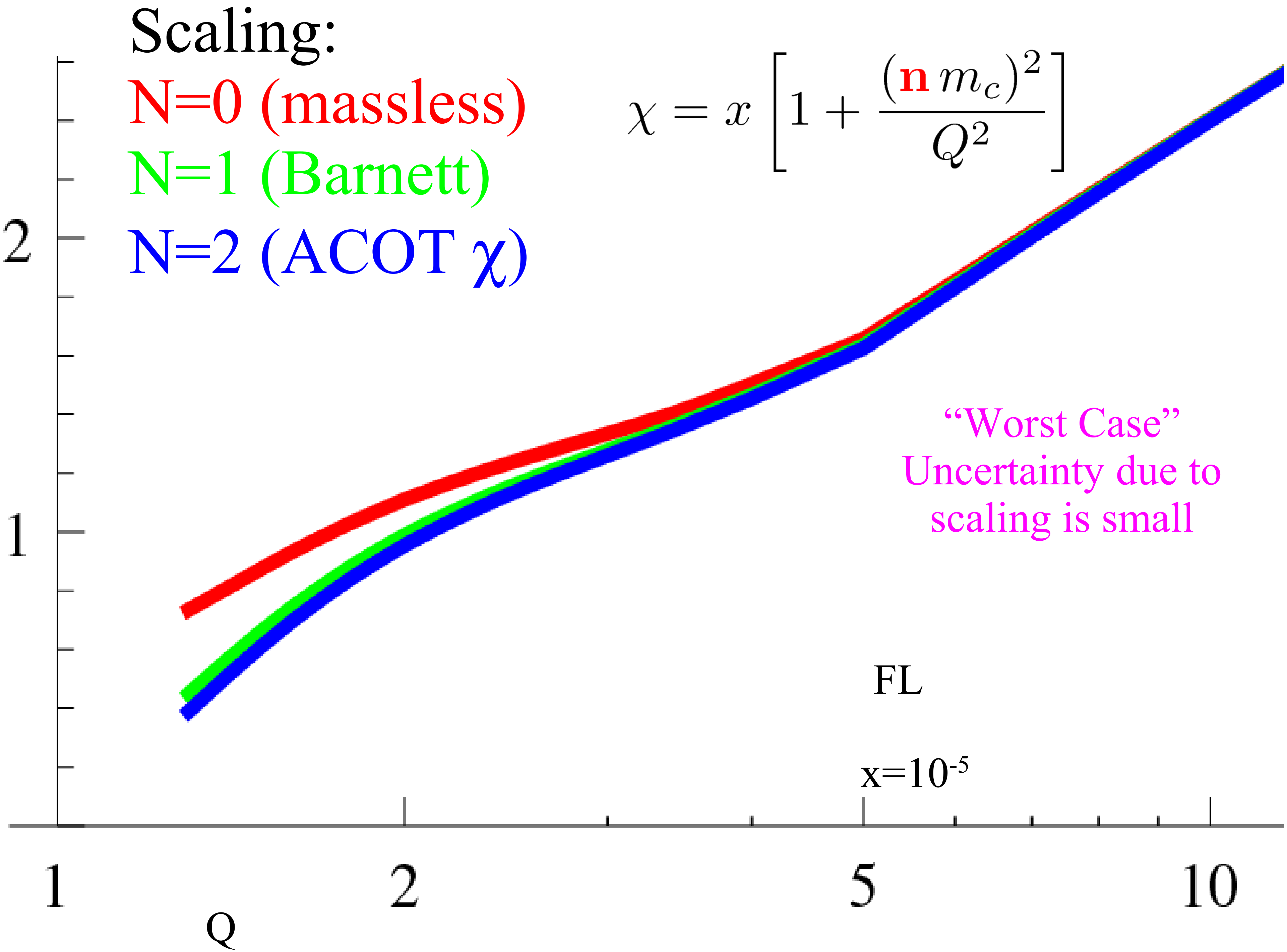
Identify Two Types of Mass Depencence: “dynamic” & “phase space”



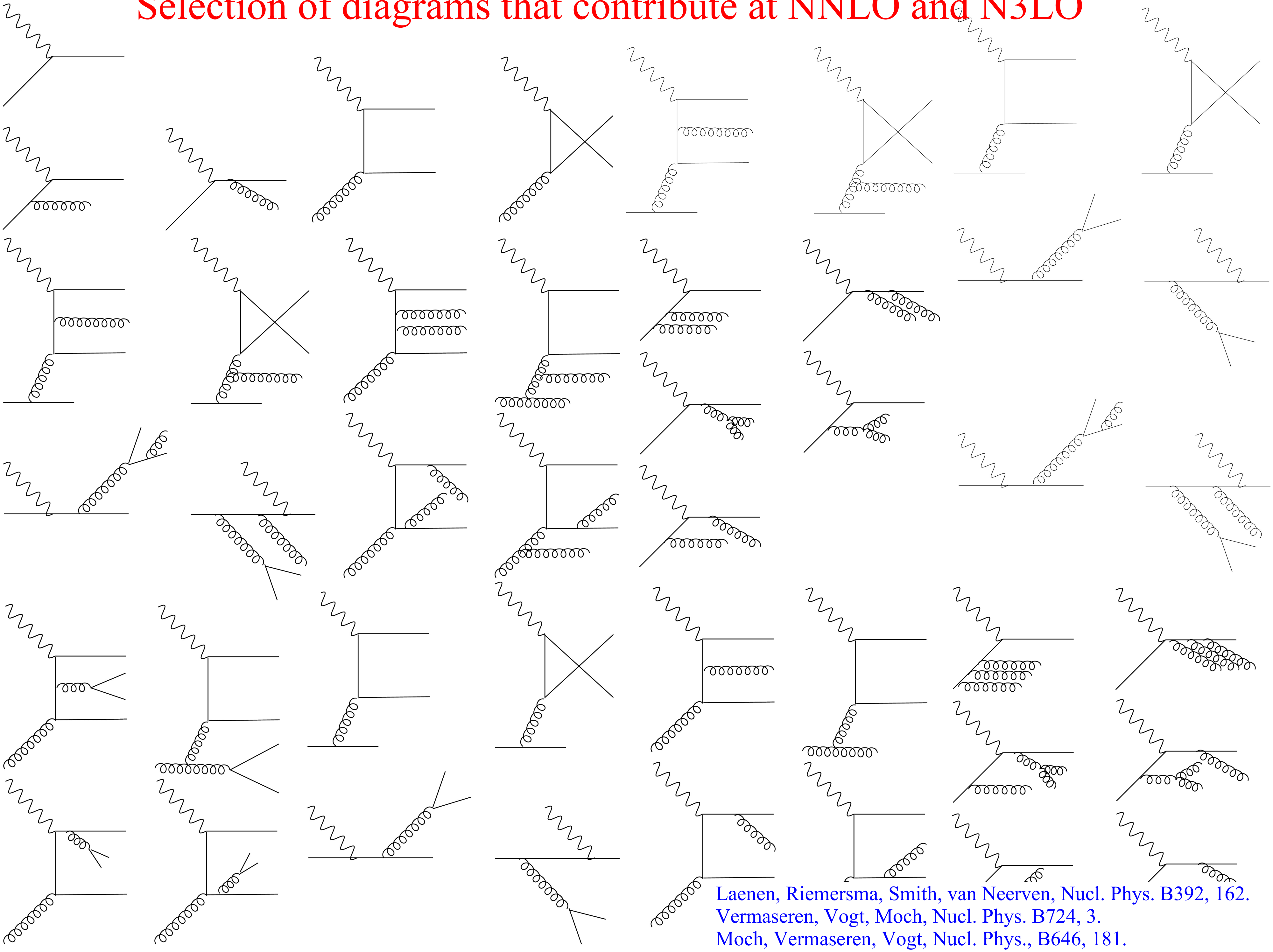
“phase space” mass yields larger variation. Not a proof, but ….

EFFECT OF MASS SCALING @ N3LO (Phase Space Mass)




Scaling:
N=0 (massless)
N=1 (Barnett)
N=2 (ACOT χ)
$\chi = x\left[1 + \frac{(\mathbf{n}\, m_c)^2}{Q^2}\right]$
"Worst Case"
Uncertainty due to
scaling is small
FL
x=10-5
2
1
1
2
5
10
Q

Selection of diagrams that contribute at NNLO and N3LO



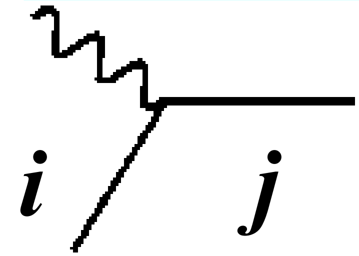
Laenen, Riemersma, Smith, van Neerven, Nucl. Phys. B392, 162.
Vermaseren, Vogt, Moch, Nucl. Phys. B724, 3.
Moch, Vermaseren, Vogt, Nucl. Phys., B646, 181.
Moch, Vermaseren, Vogt, Phys. Lett., B606, 123.
Blumlein, Hasselhuhn, Kovacikova, Moch, Phys.Lett. B700, (2011) 294.

Master formula for decomposing the flavor components

T.P. Stavreva, I Schienbein

$$F = \sum_{i,j}^{6} F^{ij}$$

The Goal: Convert from {s, ns, ps} to {q,g, ...}

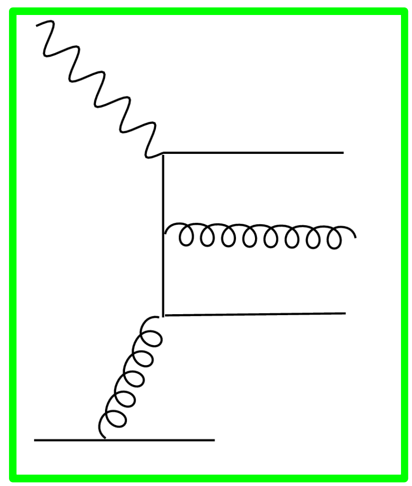


$$x^{-1} F_a^{ij} = q_i^+ \otimes \Big\{ e_i^2 \Big[C_{a,q}^{\rm ns}(n_f = 0)\ \delta_{ij} + C_{a,q}^{\rm ns}(j) - C_{a,q}^{\rm ns}(j-1) \Big] - \langle e^2 \rangle^{(j)}\ C_{a,q}^{\rm ps}(j) - \langle e^2 \rangle^{(j-1)}\ C_{a,q}^{\rm ps}(j-1) \Big\}$$

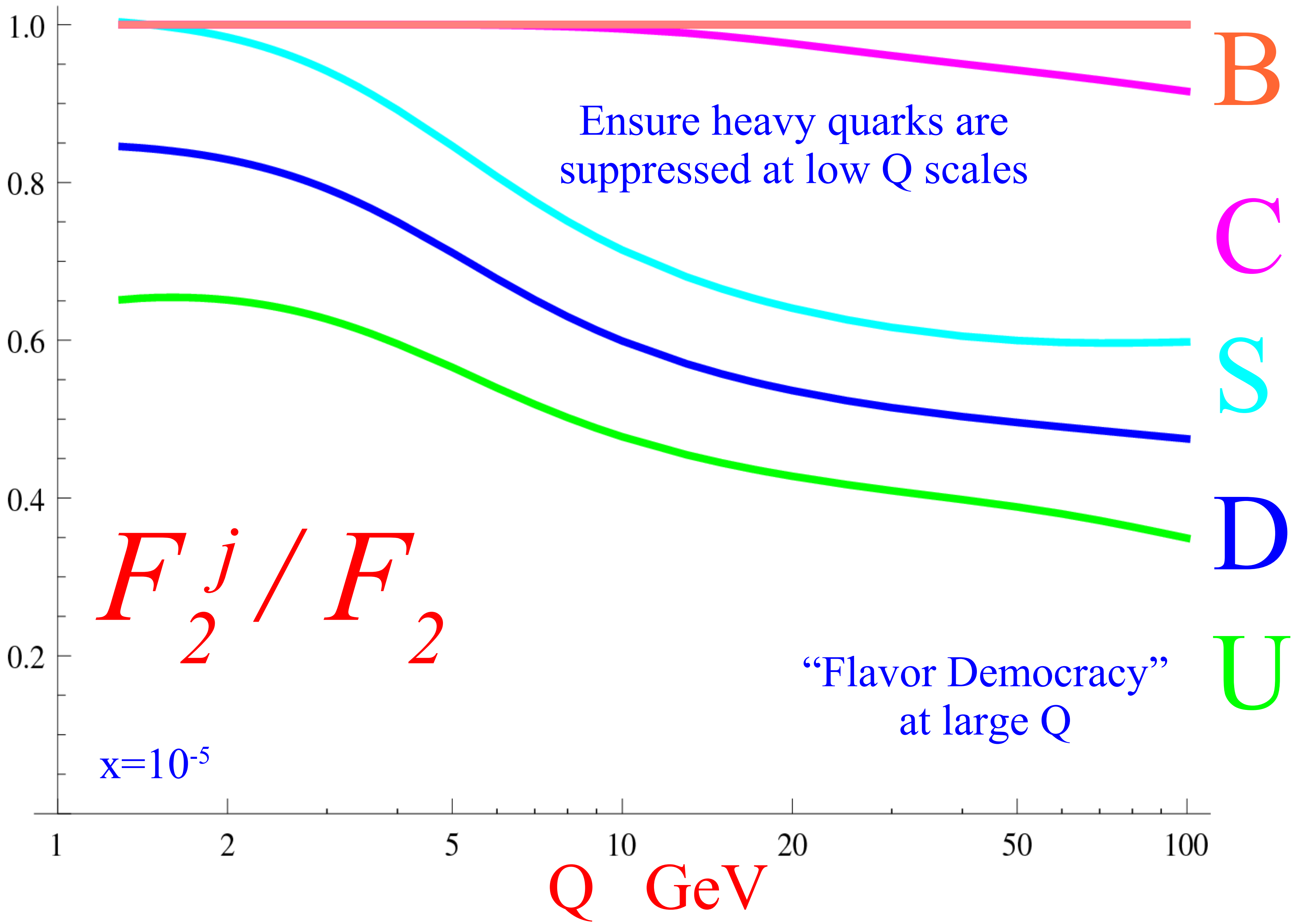
Issues: Flavor separation:

New diagrams at this order

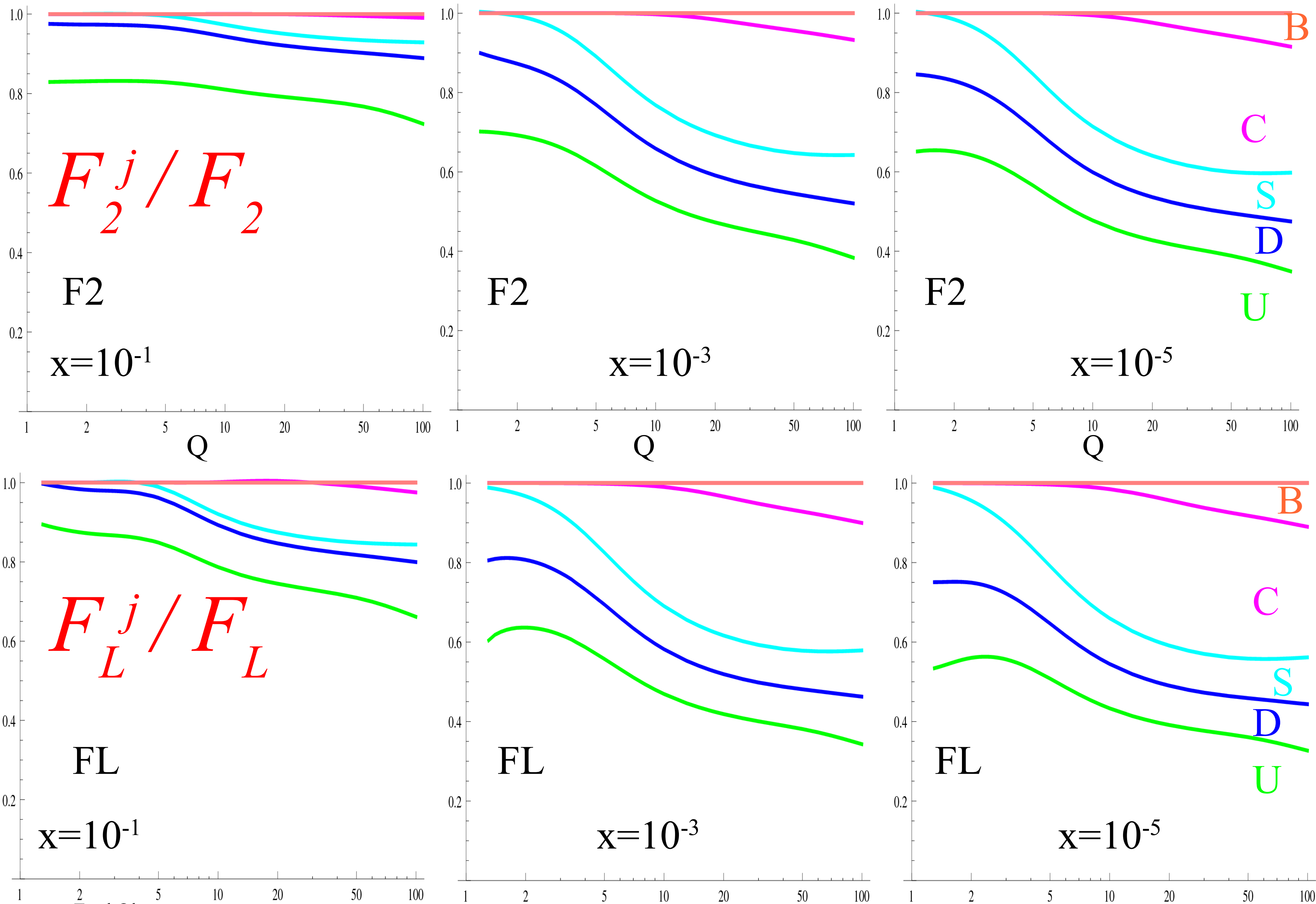
- c,b, goes down beam pipe
- both c & b in final state



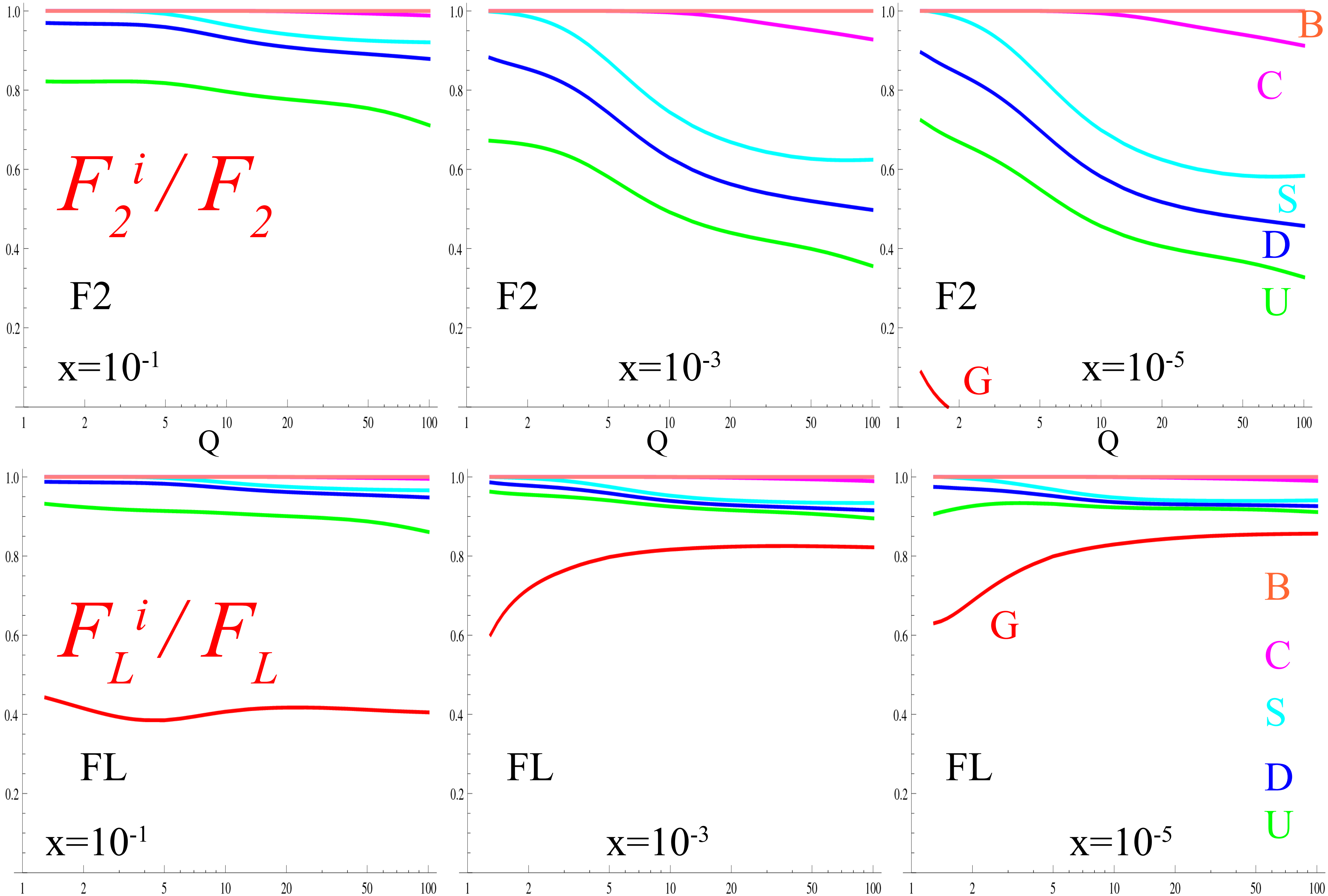
FLAVOR DECOMPOSITION



FLAVOR DECOMPOSITION: Final State Quark:

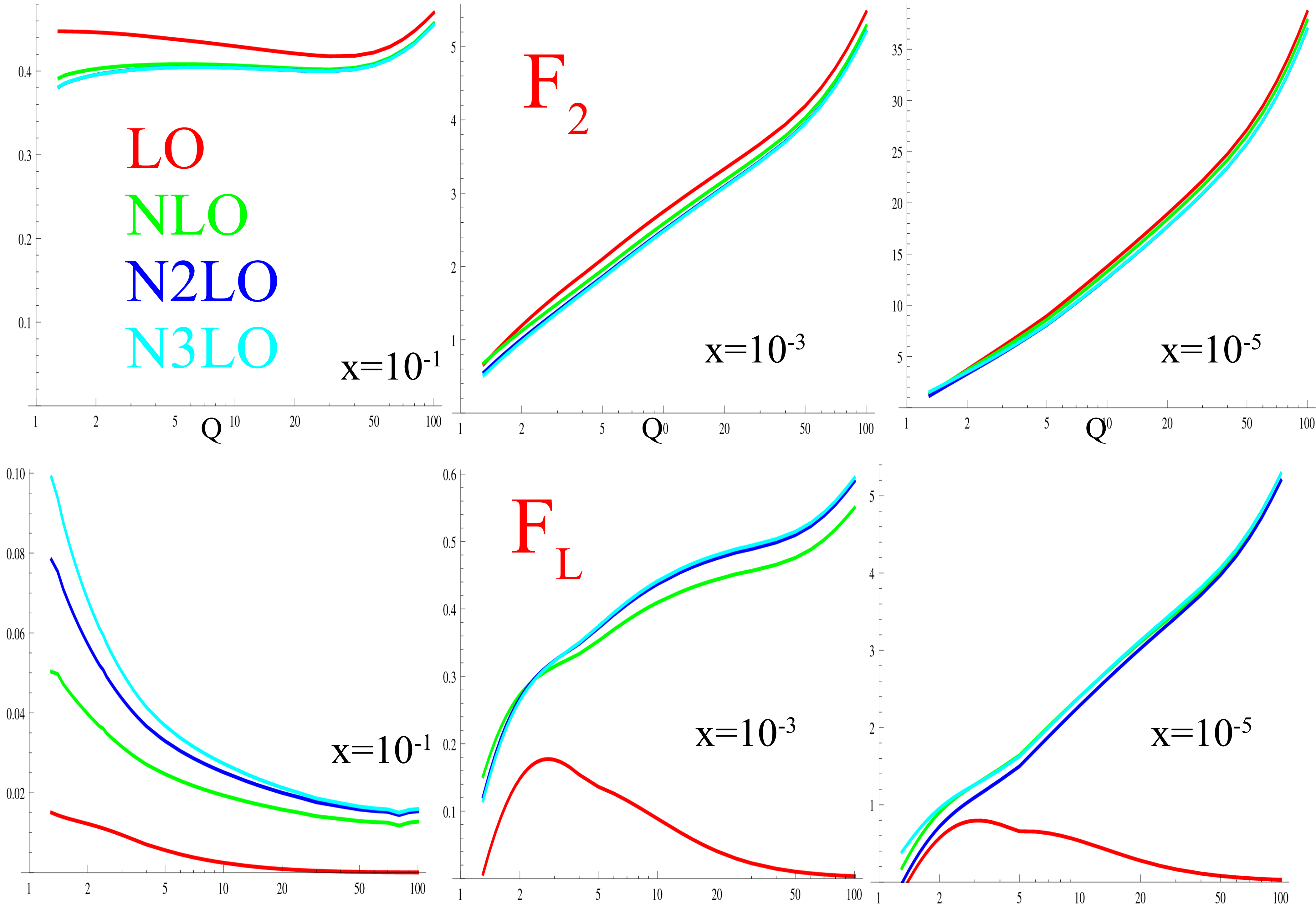


FLAVOR DECOMPOSITION: Initial State Quark:



$F_{2,L}$ @ N3LO

$F_{2,L}$ @ N3LO



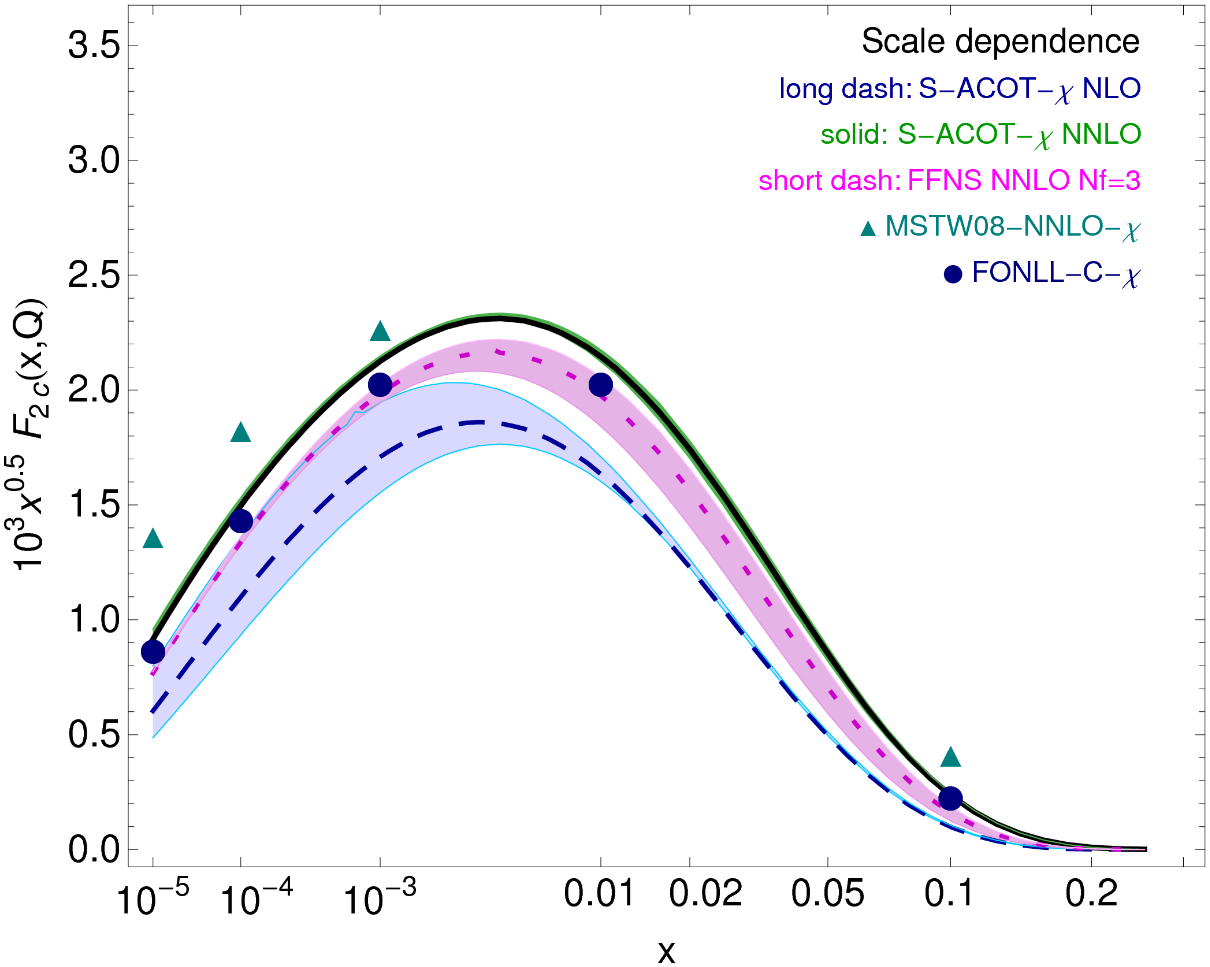
A Complementary Approach

S-ACOT χ at NNLO

led by Marco Guzzi and Pavel Nadolsky

Drastic μ_F-scale reduction in $F_2^c(x, Q^2)$ at NNLO

LH PDFs Q=2 GeV, m_c=1.41 GeV



S-ACOT χ

for Neutral Currents

based on Smith vanNeerven

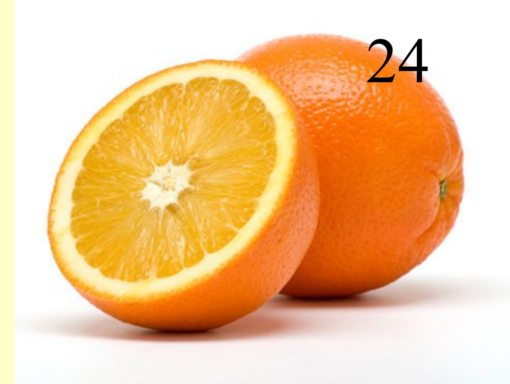
key step for NNLO PDFs

(see Pavel's talk)

By using S-ACOT-χ we obtain a drastic reduction of the theoretical errors compared to the NLO computation.

Comparison

Les Houches
Comparative Studies



Excellent progress in addressing how to compute heavy quarks

The Cast:

ACOT & S-ACOT Codes
Used in CTEQ4HQ, 5HQ, 6HQ

Aivazis, Collins, Olness, Tung,
Phys.Rev.D50:3102-3118,1994.

S-ACOT
CTEQ 6.5 & 6.6

Tung, Lai, Belyaev, Pumplin, Stump, Yuan,
JHEP 0702:053,2007.
Nadolsky, Tung, Phys.Rev.D79:113014,2009.

Thorne-Roberts (TR')
MSTW Fits

Thorne, Phys.Rev.D73:054019,2006.

FONLL:
Used in NNPDF Fits

Forte, Laenen, Nason, Rojo,
Nucl.Phys.B834:116-162,2010.

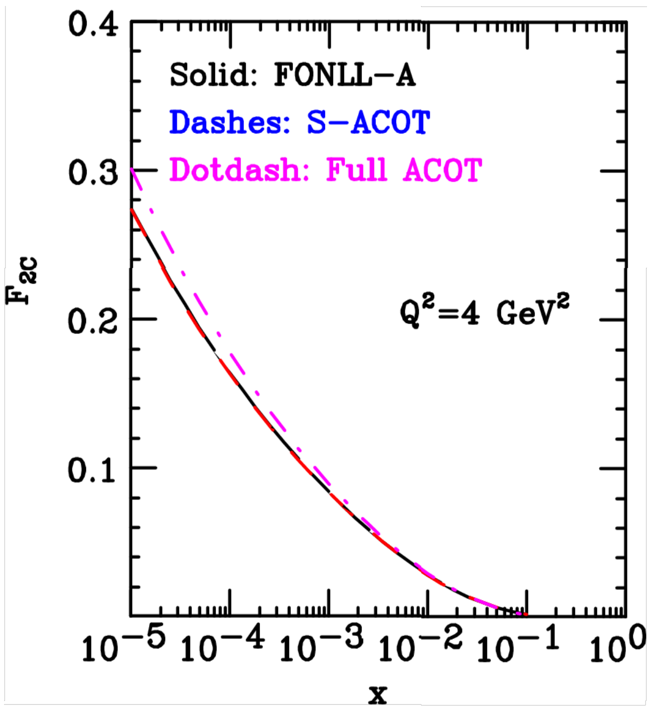
ABKM:

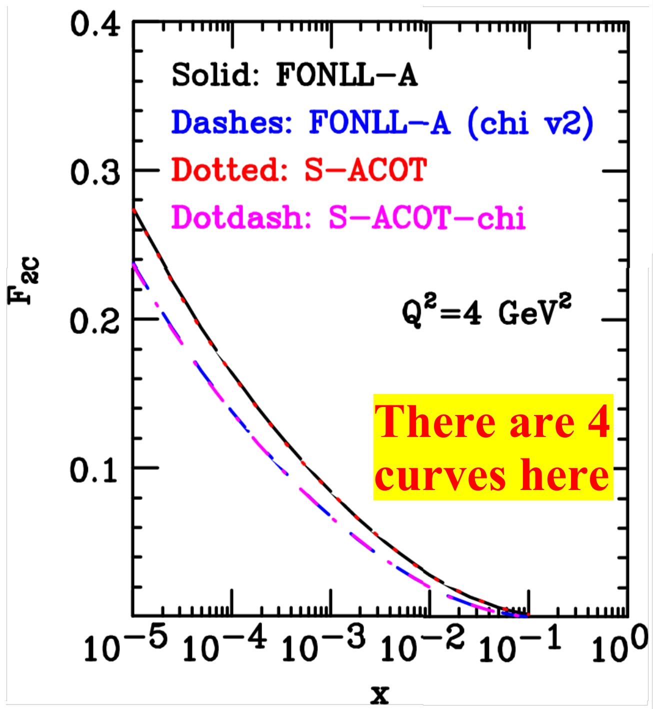
Blumlein, Klein, Moch
Phys.Rev.D81:014032,2010

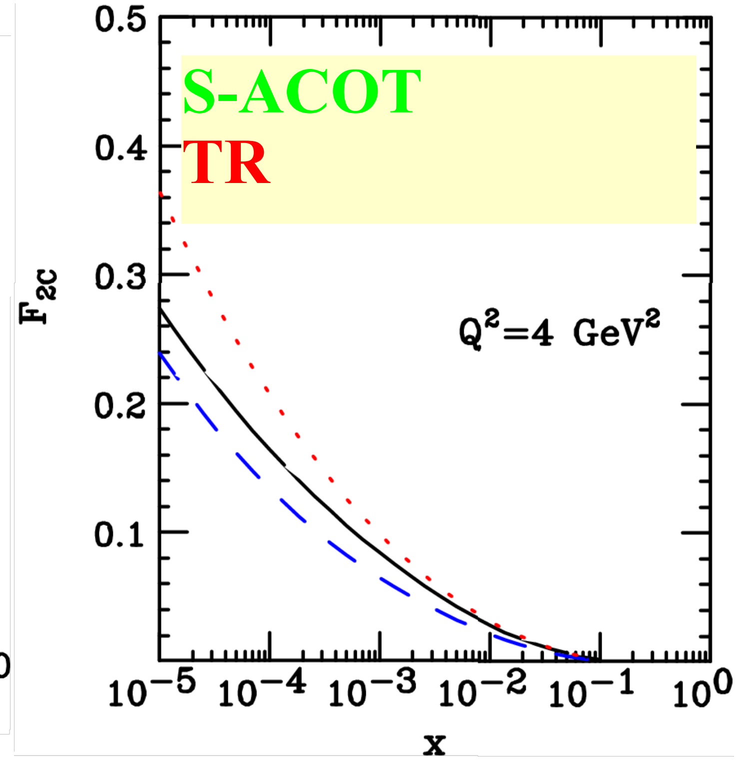
Work is continuing

Many of the above incorporated in HERA-Fitter

Les Houches Report.
J. Rojo, et al., arXiv:1003.1241 [hep-ph]







ACOT & S-ACOT essentially identical

... scheme differences are higher order

FONNL & S-ACOT

Numerically similar

MSTW09

We can quantify <u>theoretical</u> scheme diffferences

The SM and NLO Multileg Working Group: Summary report.

J. Rojo, et al., e-Print: arXiv:1003.1241 [hep-ph]

Differences understood
Should reduce at higher order

Nuclear CTEQ parton distribution functions - Mozilla Firefox

File Edit View History Bookmarks Tools Help

http://projects.hepforge.org/ncteq/

The CTEQ Meta-Page | Nuclear CTEQ parton distri...

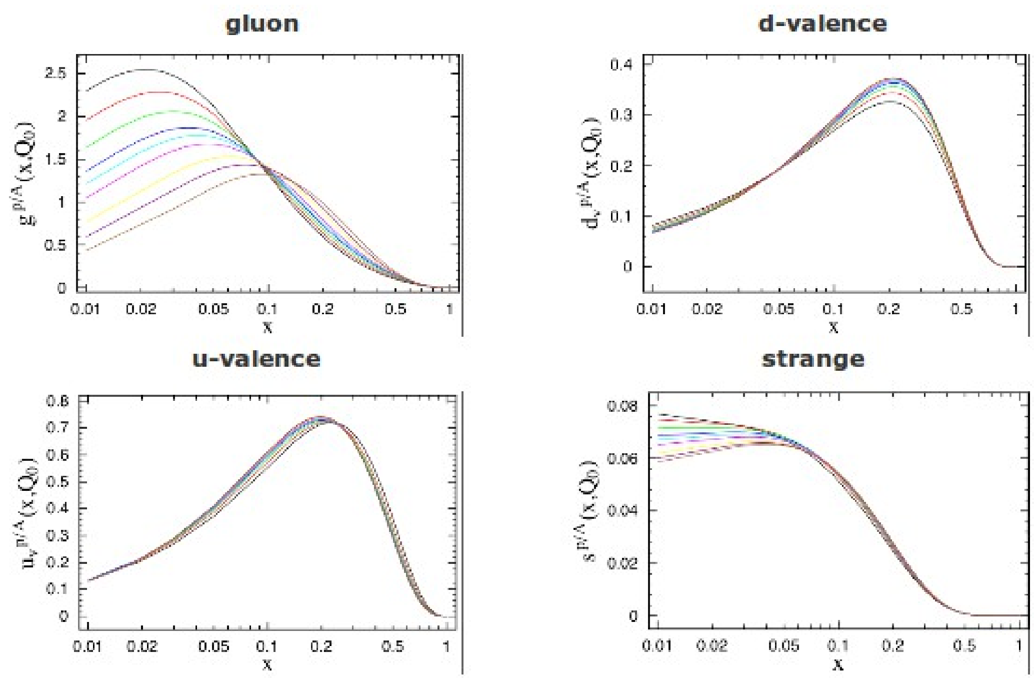
nCTEQ Go! hosted by **CEDAR HepForge**

nCTEQ

nuclear parton distribution functions

- Home
- PDF grids & code
- Papers & Talks
- Subversion
- Tracker
- Wiki

nCTEQ project is an extension of the CTEQ collaborative effort to determine parton distribution functions inside of a free proton. It generalizes the free-proton PDF framework to determine densities of partons in bound protons (hence nCTEQ which stands for nuclear CTEQ). More details on the framework and the first results can be found in arXiv:09072357 [hep-ph].
The effects of the nuclear environement on the parton densities can be shown as modified parton densities



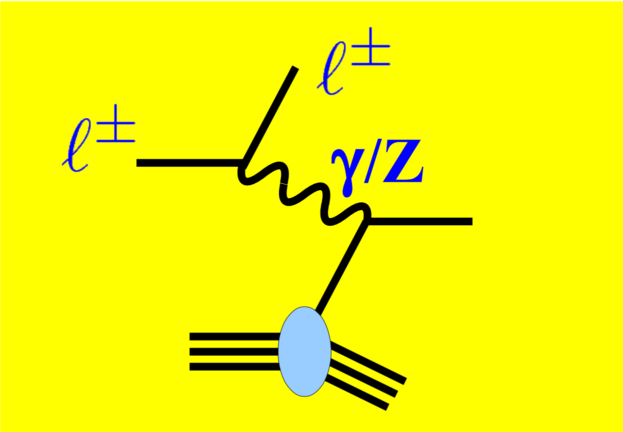
where all black curves stand for free proton PDF and red, green, blue, cyan, pink, yellow, magenta and brown curves show PDF in protons bound in nuclei - from deuterium (red) to lead (brown).

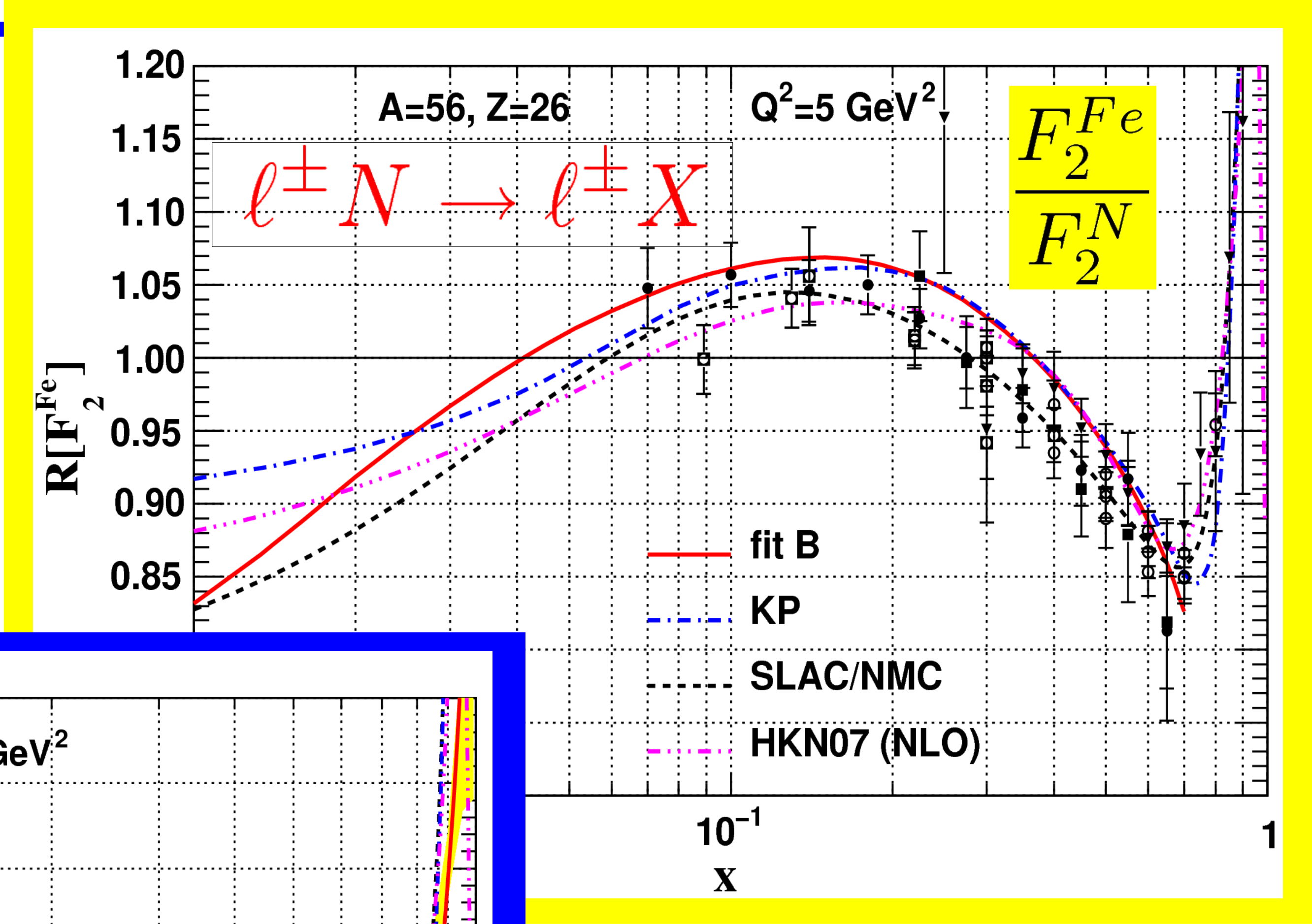
Done

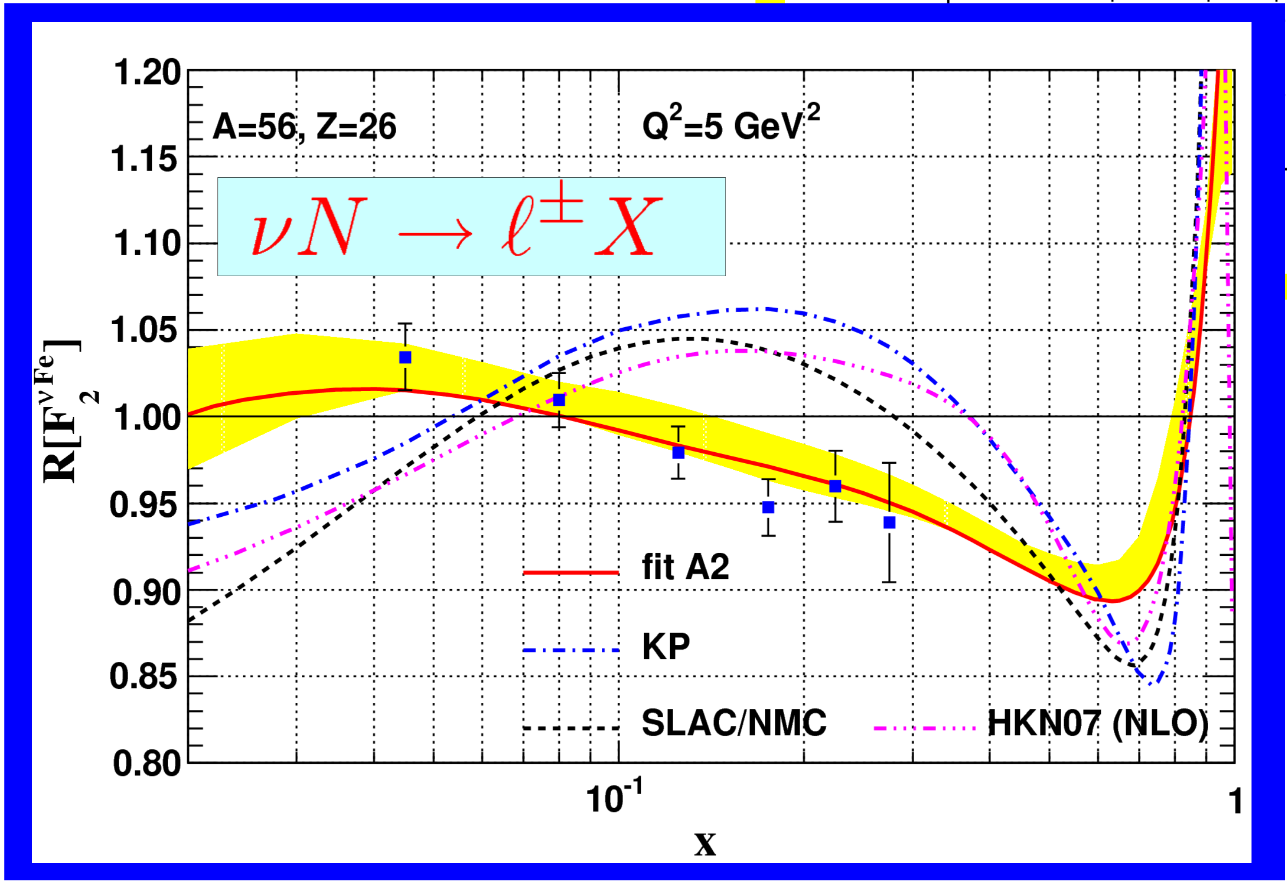
K Kovarik,
I. Schienbein,
J.Y. Yu,
T. Stavreva,
T Jezo,
C. Keppel,
J.G. Morfin,
F. Olness,
J.F. Owens.

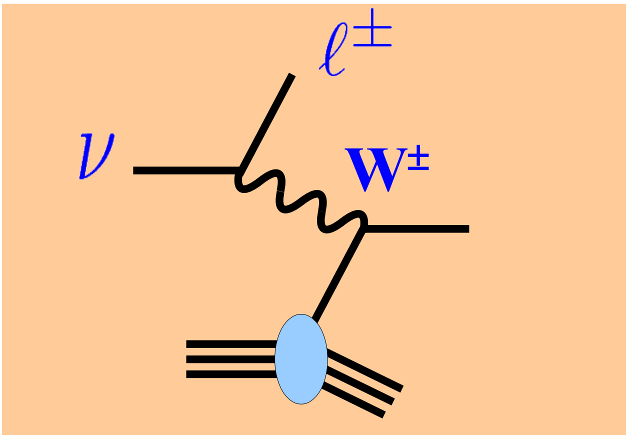
Nuclear Corrections: Compare Neutrino and Charged Lepton DIS

Charged Lepton DIS ⇒









⇐ Neutrino DIS

Conclusion

ACOT at NNLO and N3LO

This technique provides an NNLO & N3LO extension of ACOT

"Phase space" mass is included via rescaling
Dominant effect for LO & NLO

F2: Stable.
LO and NLO have full m-dependence
N2LO and N3LO very similar

FL: More complex as NLO corrections are large (Callan-Gross)
N2LO and N3LO terms converge

Heavy quark terms vanish for low Q;
this moderates mass effects

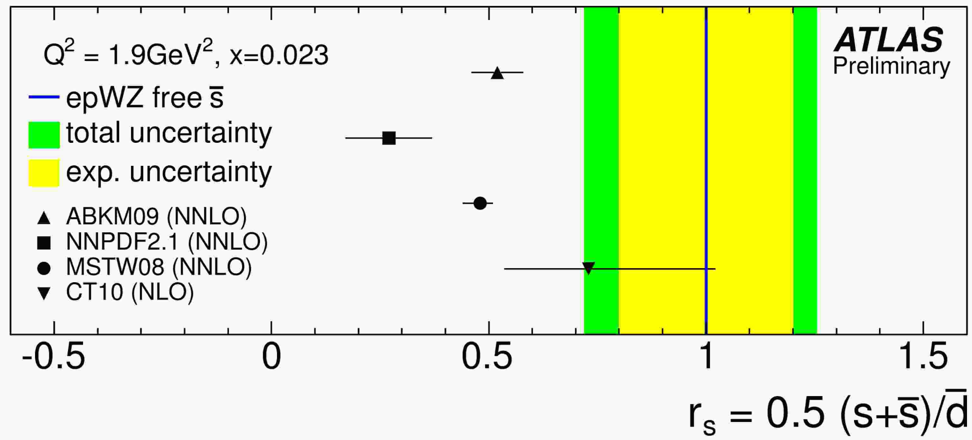
Thanks to: K. Kovarik, A. Kusina, T.P. Stavreva I Schienbein, J.-Y. Yu,
P. Nadolsky, M. Guzzi, J. Owens, J. Morfin, C. Keppel, D. Soper …
& the HERA-PDF Working Group

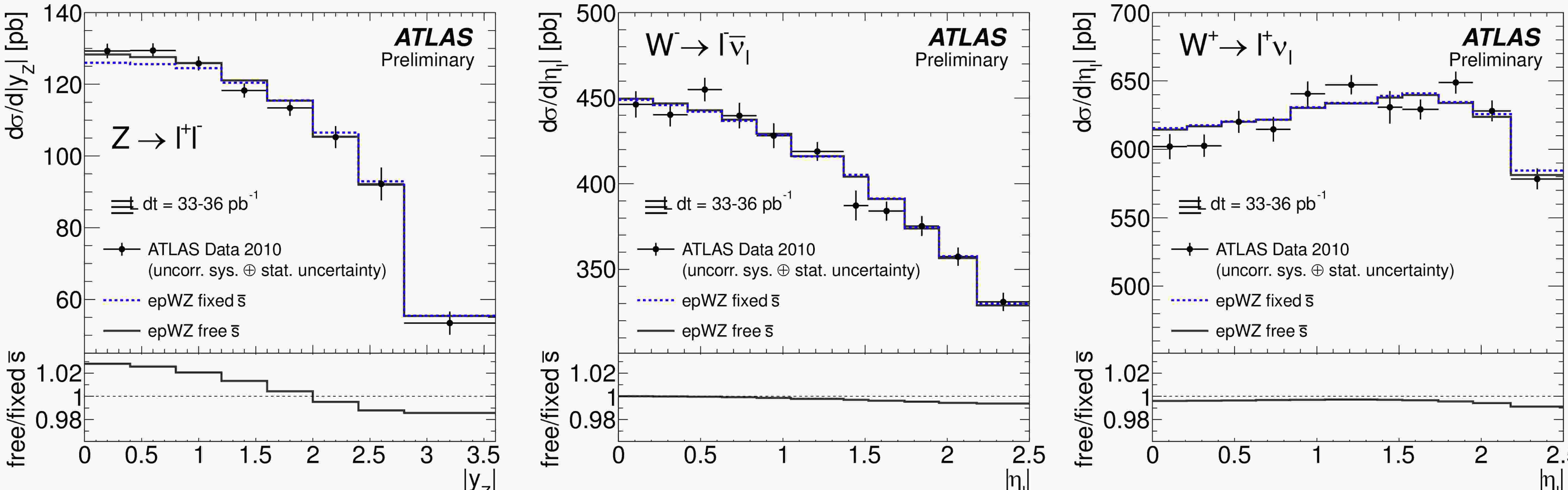
W, Z data sensitivity to strange sea

- ATLAS performed NNLO QCD fit to Z, W^+, W^- + HERA ep DIS cross sections: significant tension for Z observed when suppressing strange by 50% at low scale $1.9\,\mathrm{GeV}^2$

- Fit with free strange sea gives no supression

$$r_s = 1.00 \pm 0.20_{\mathrm{exp}}\,{}^{+0.16}_{-0.20}\,{}_{\mathrm{sys}}$$

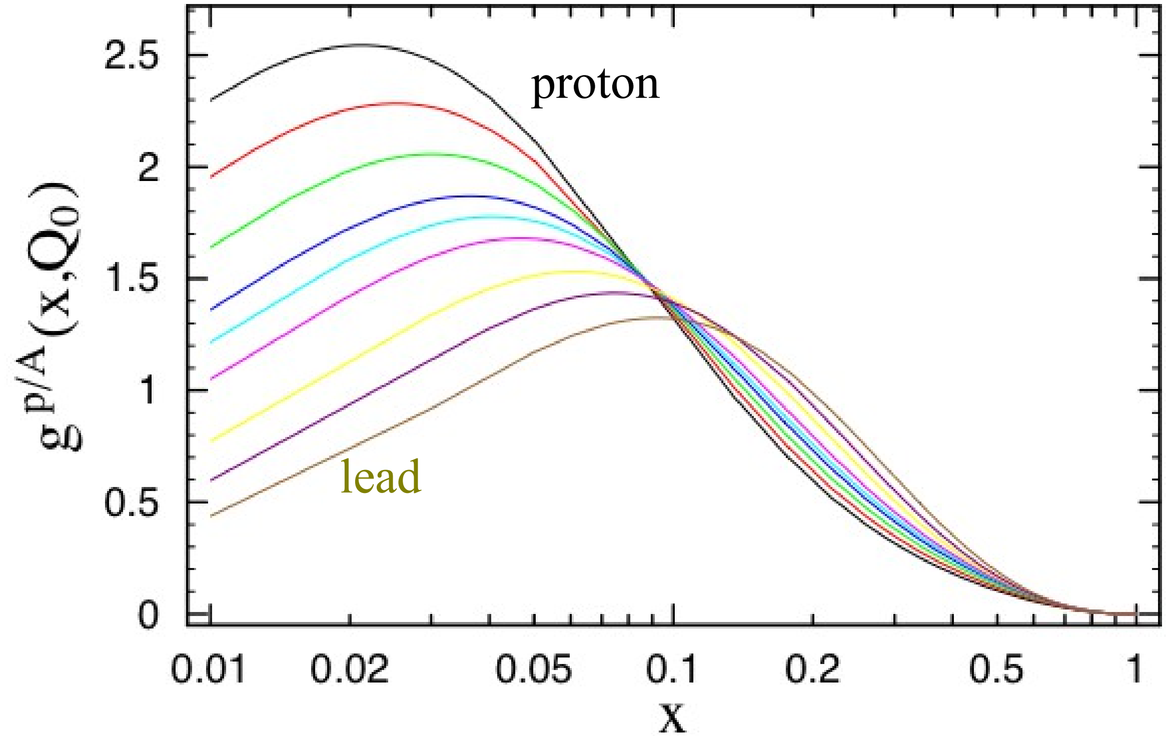




ATLAS-STDM-2011-43 → PRL

nCTEQ Nuclear PDF's

- ✔ CTEQ style global fit extended
  handle various nuclear targets
- ✔ CTEQ Data + nuclear DIS & DY
  [~19 targets; ~2000+ data]
- ✔ A-dependence modeled;
  NLO fits work well

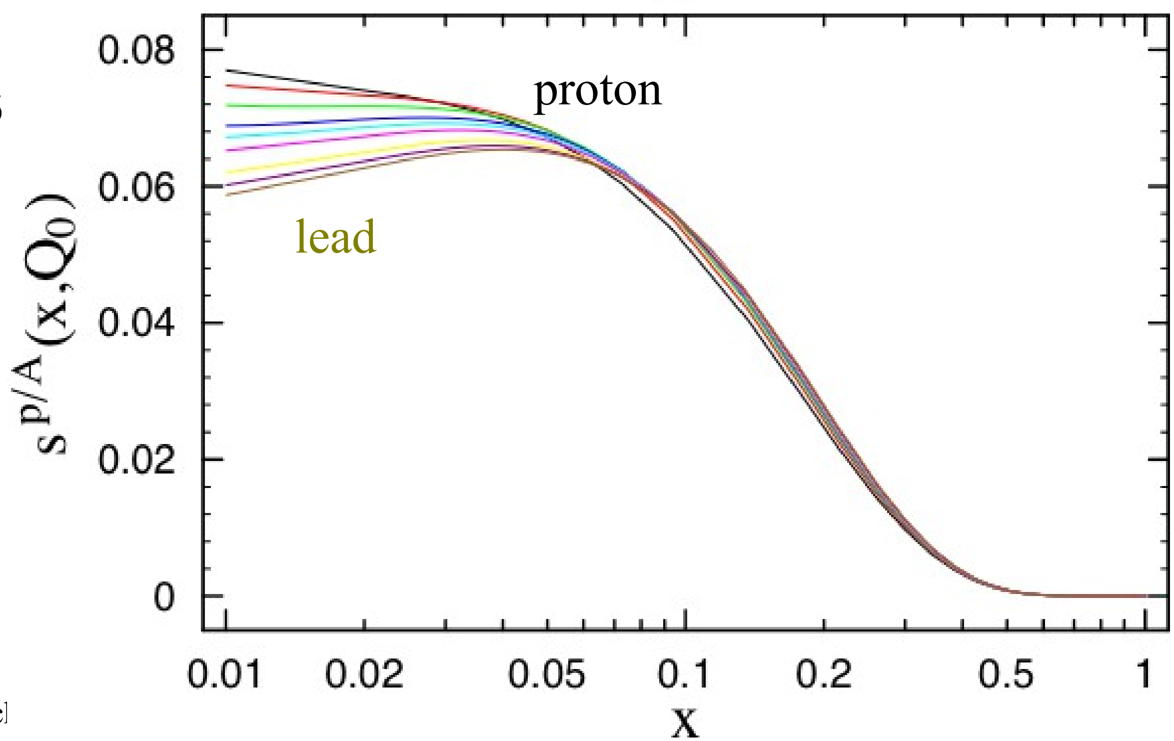


A-Dependent PDFs

$$xf(x) = x^{a_1}(1-x)^{a_2} e^{a_3 x}(1+e^{a_4}x)^{a_5}$$

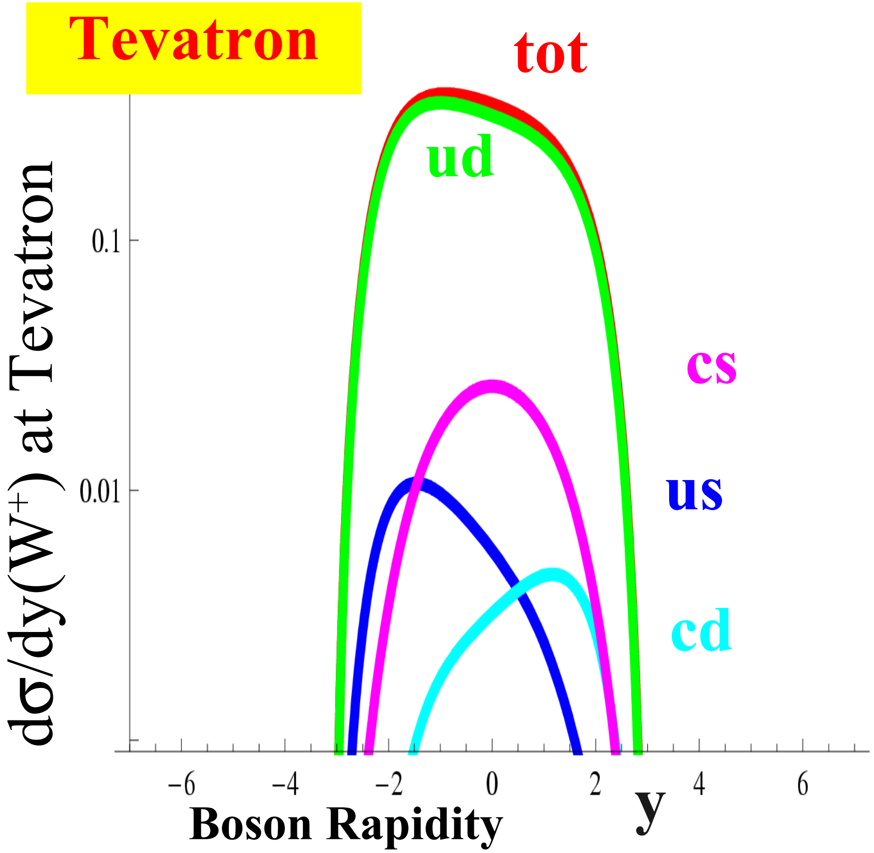
$$a_i \rightarrow a_i(A)$$

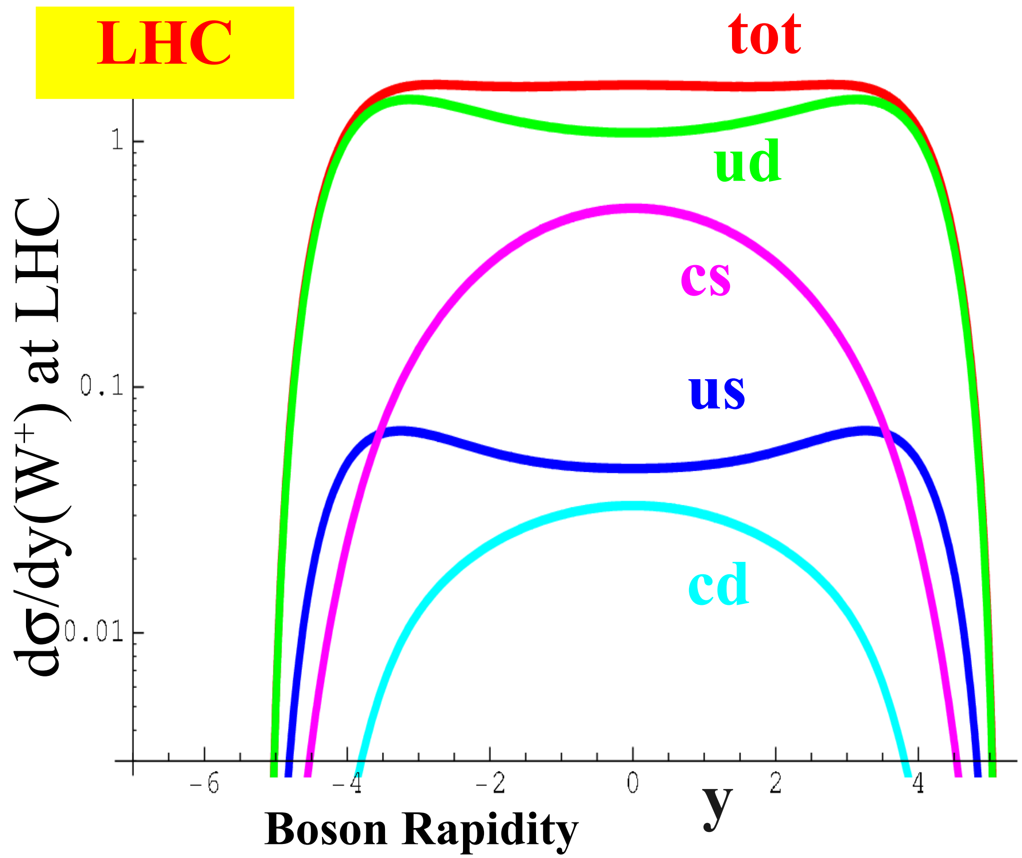
$$a_k = a_{k,0} + a_{k,1}\left(1 - A^{-a_{k,2}}\right)$$



Kovarik, et al., PRD
I. Schienbein, J.Y. Yu, C. Keppel, J.G. Morfin,
F. Olness, J.F. Owens. Phys.Rev.D77:054013,2008.

W Production at LHC: A Benchmark Cross Section

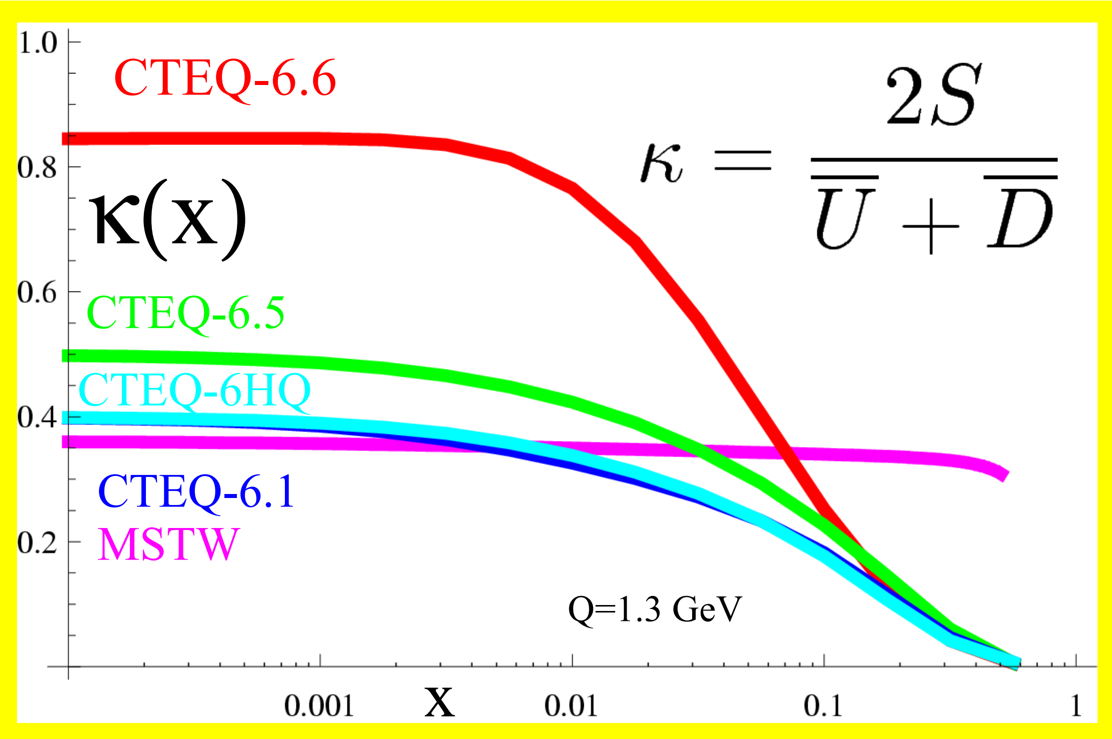




- Larger Energy ⇒ probes PDFs to small momentum fraction x
- Larger Rapidity (y) ⇒ probes PDFs to *really* small x
- Larger fraction of heavy quarks

Heavy Quark components play an increasingly important role at the LHC

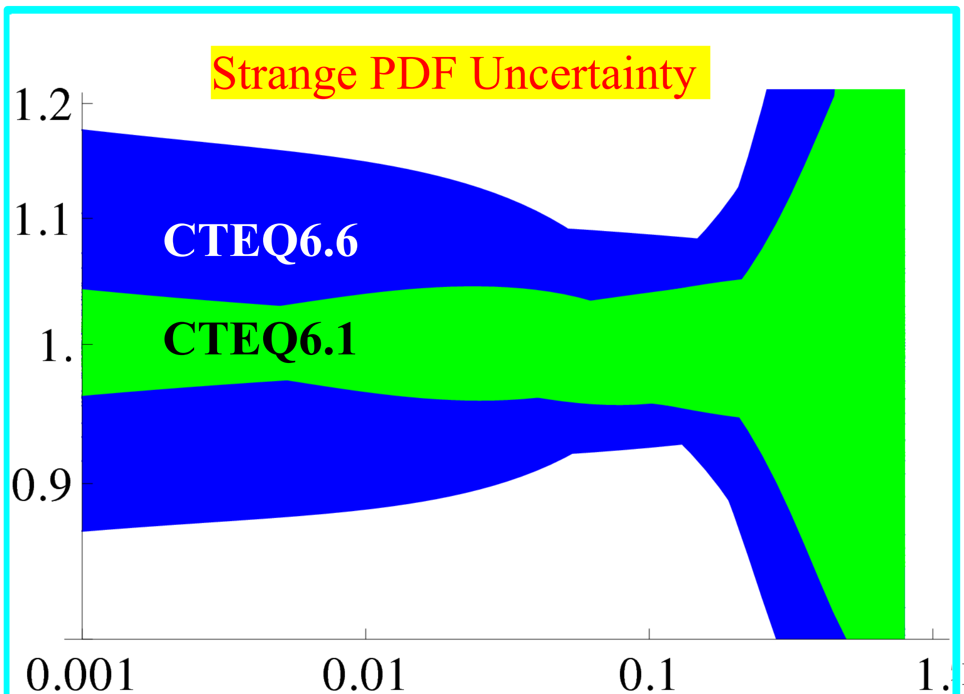
How well do we know the Strange PDF???

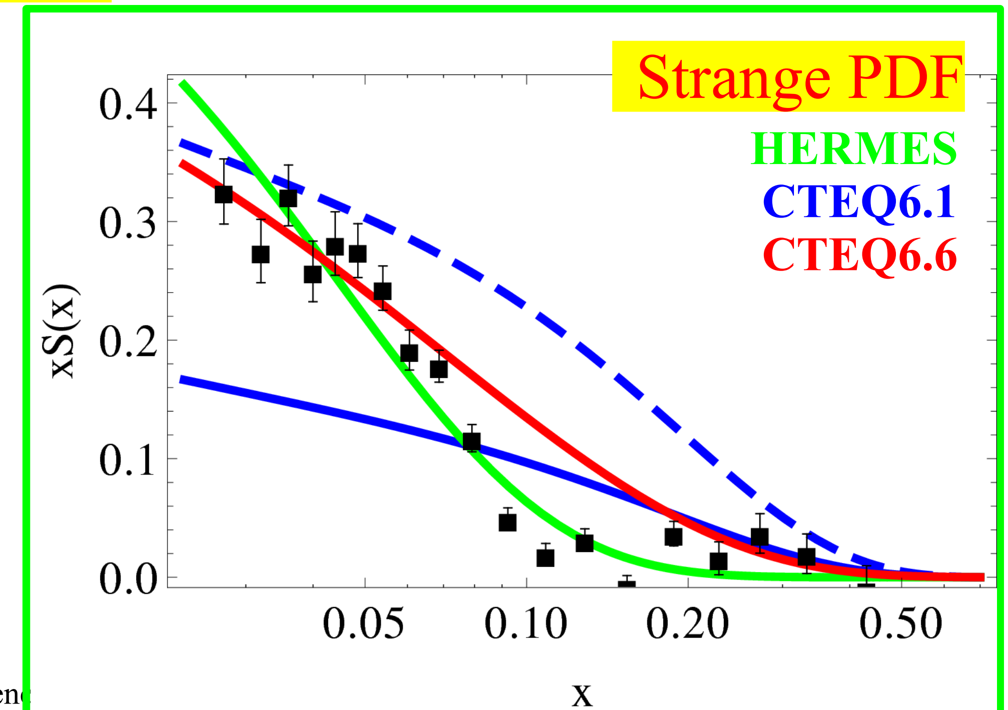


Not so well

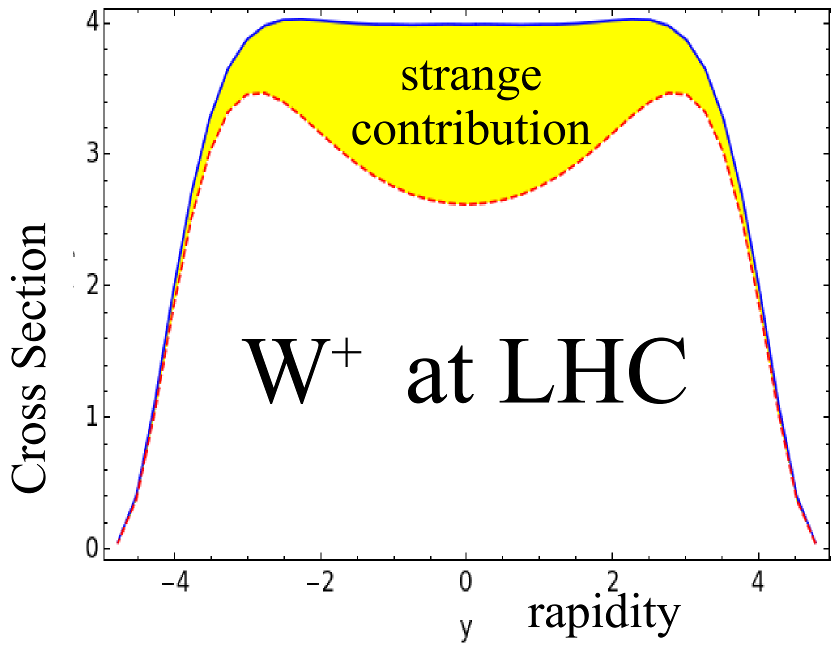
... even after 20 years of PDFs

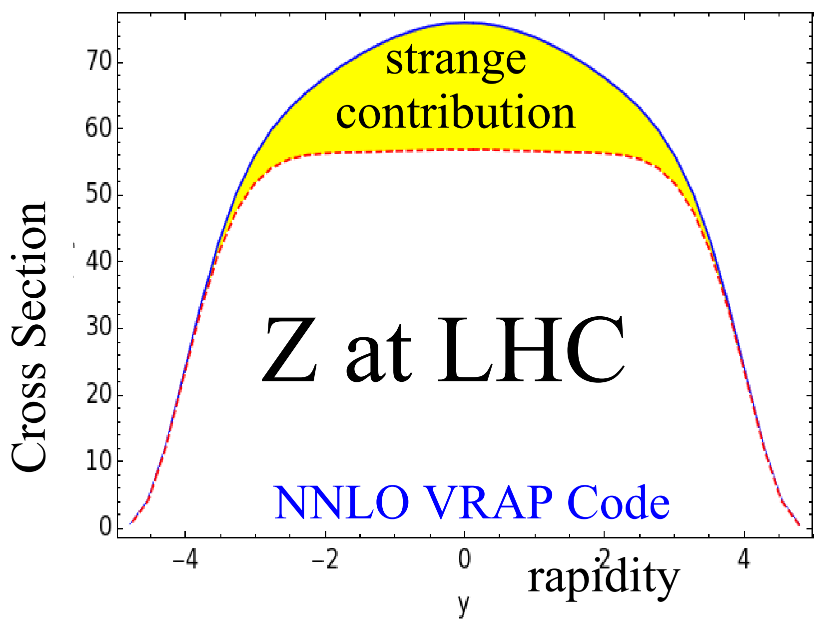
... extra complication:
nuclear corrections

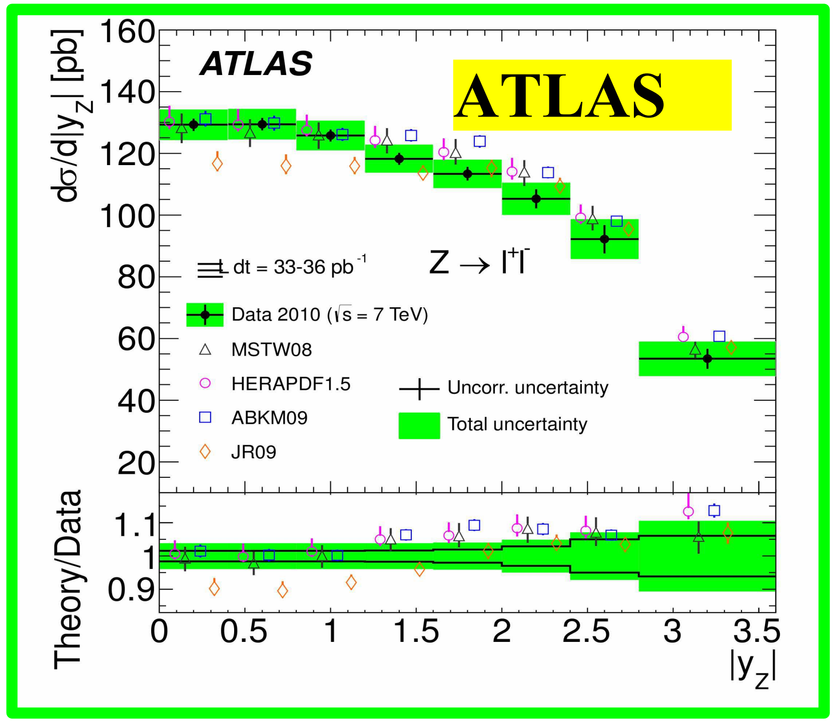


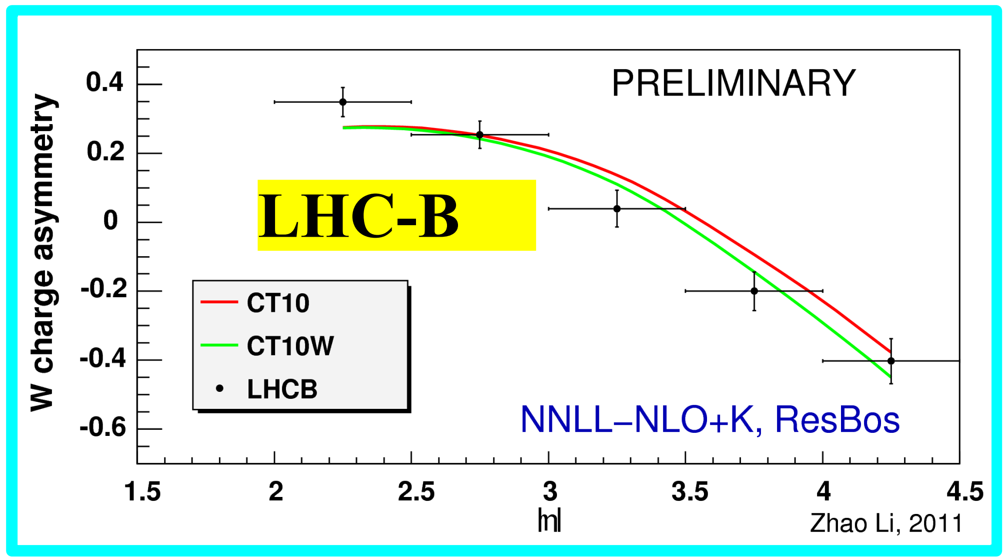


PDF Uncertainties ⇒ S(x) PDF ⇔ W/Z at LHC









NNLO VRAP Code
Anastasiou, Dixon, Melnikov, Petriello,
Phys.Rev.D69:094008,2004.

Kusina, Stavreva, Berge, Olness,
Schienbein, Kovarik, Jezo, Yu, Park
arXiv:1203:1290

y distribution shape can constrain s(x) PDF