QCD in the LHC Era

...

Fred Olness

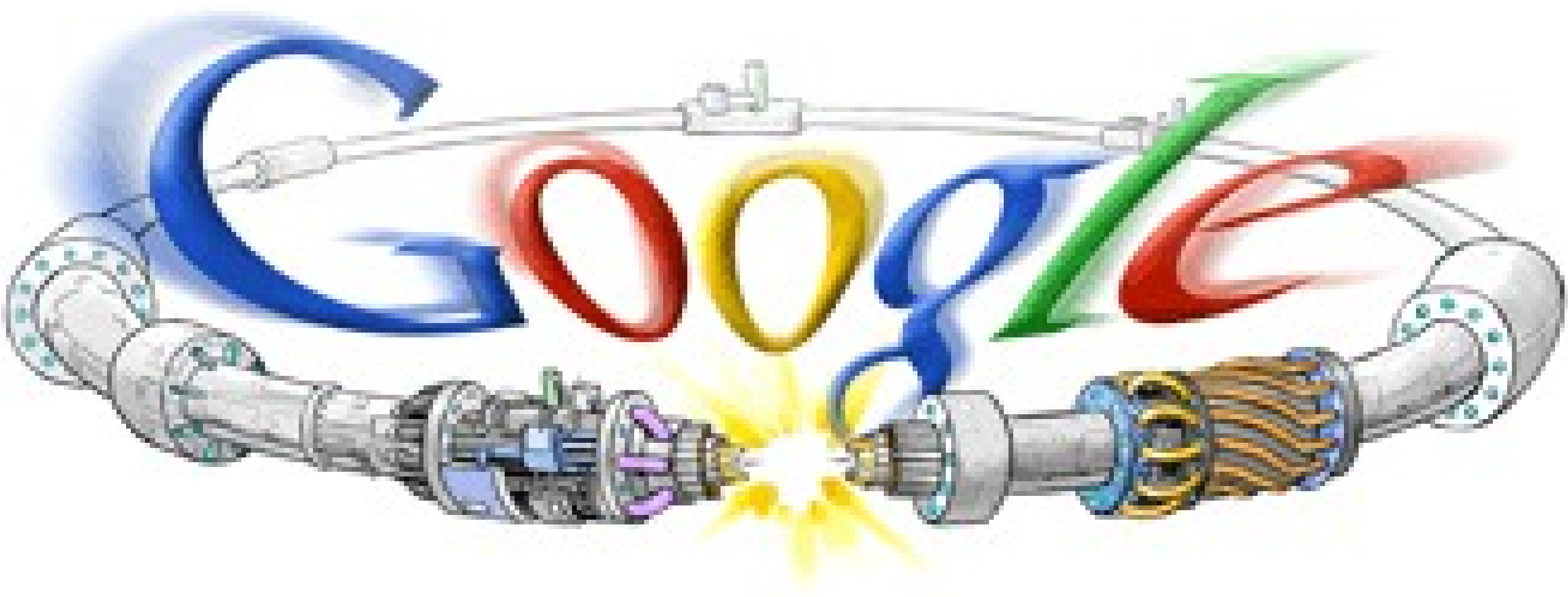
SMU

Conspirators:

A. Kusina,, I. Schienbein, K. Kovarik, J.Y. Yu, T. Stavreva, T. Jezo,
J.G. Morfin, J.F. Owens P. Nadolsky, M. Guzzi, C. Keppel, B. Clark

RPP Grenoble
16 January 2013

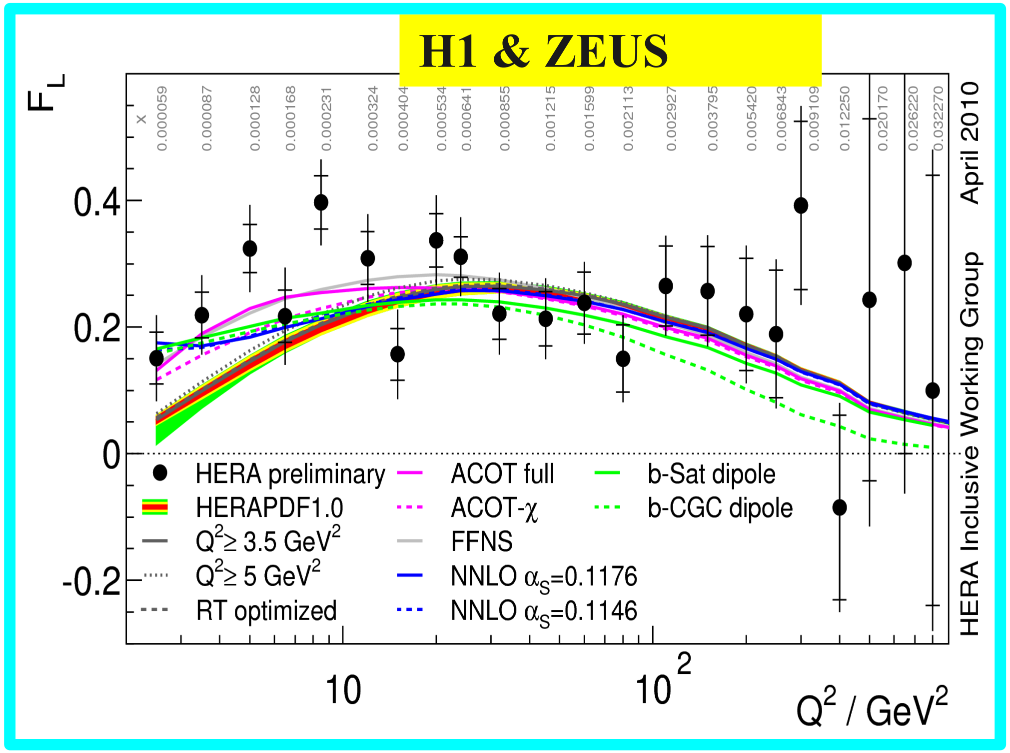
LHC began collisions in 2010

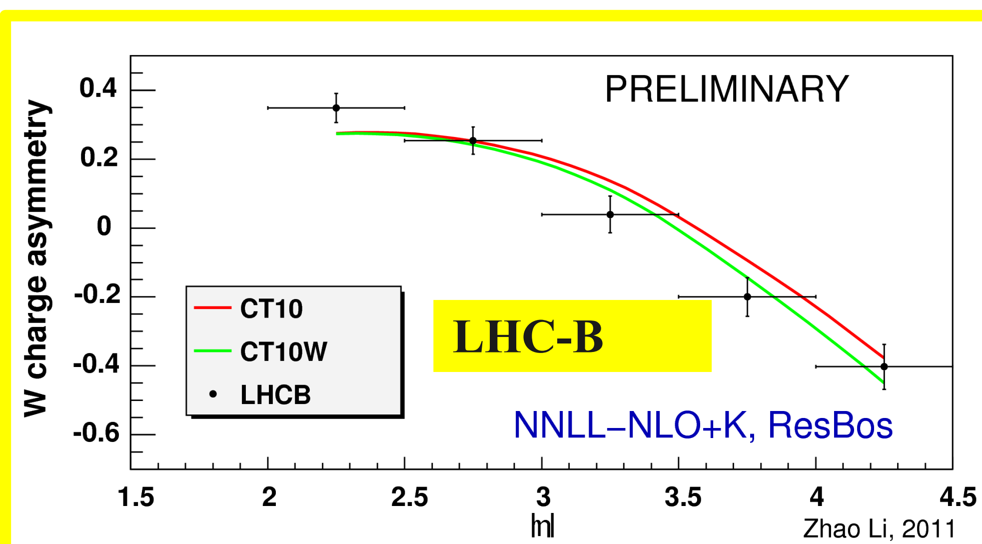


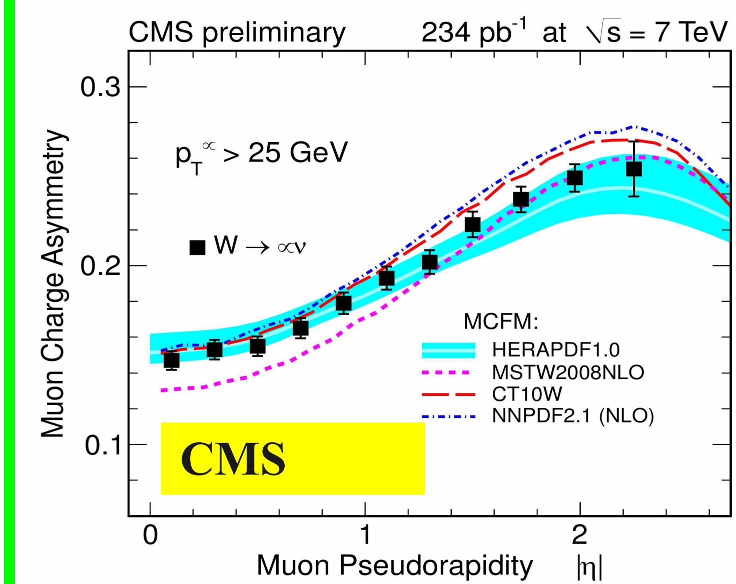
Will the world be absorbed by a black hole?

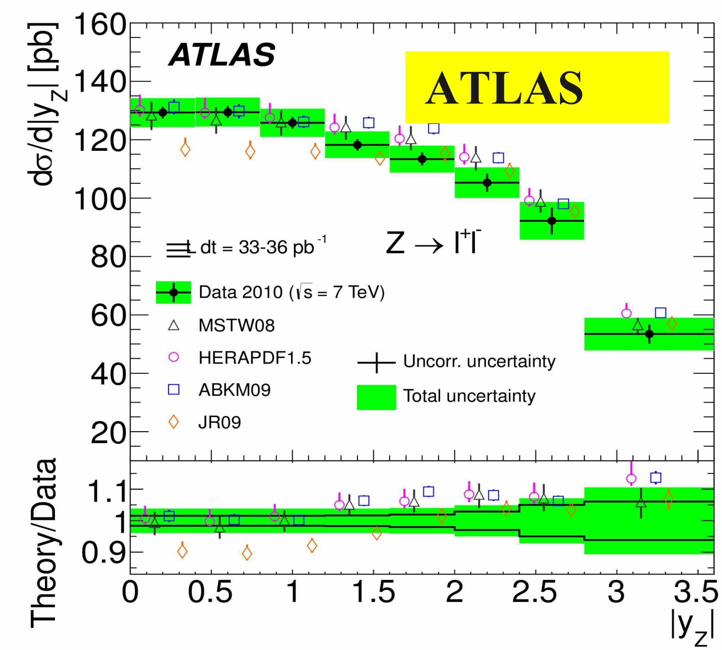
It has been a very good year for Physics!!!!!!

Recent Measurements Spectacular: Requires Theoretical Improvements









Jan Kretzschmar, 7.3.2012 – p.5

Issues we encounter:

1) Multi-scales

2) Nuclear Component

3) Hi precision $\Rightarrow$Hi orders

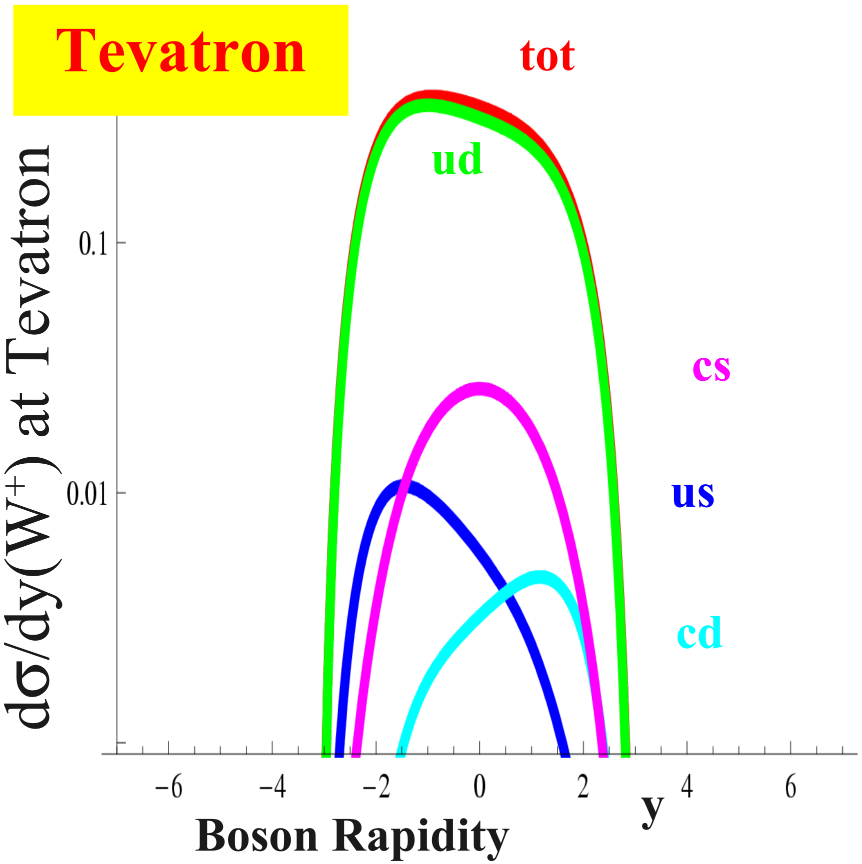
Without a good foundation ...

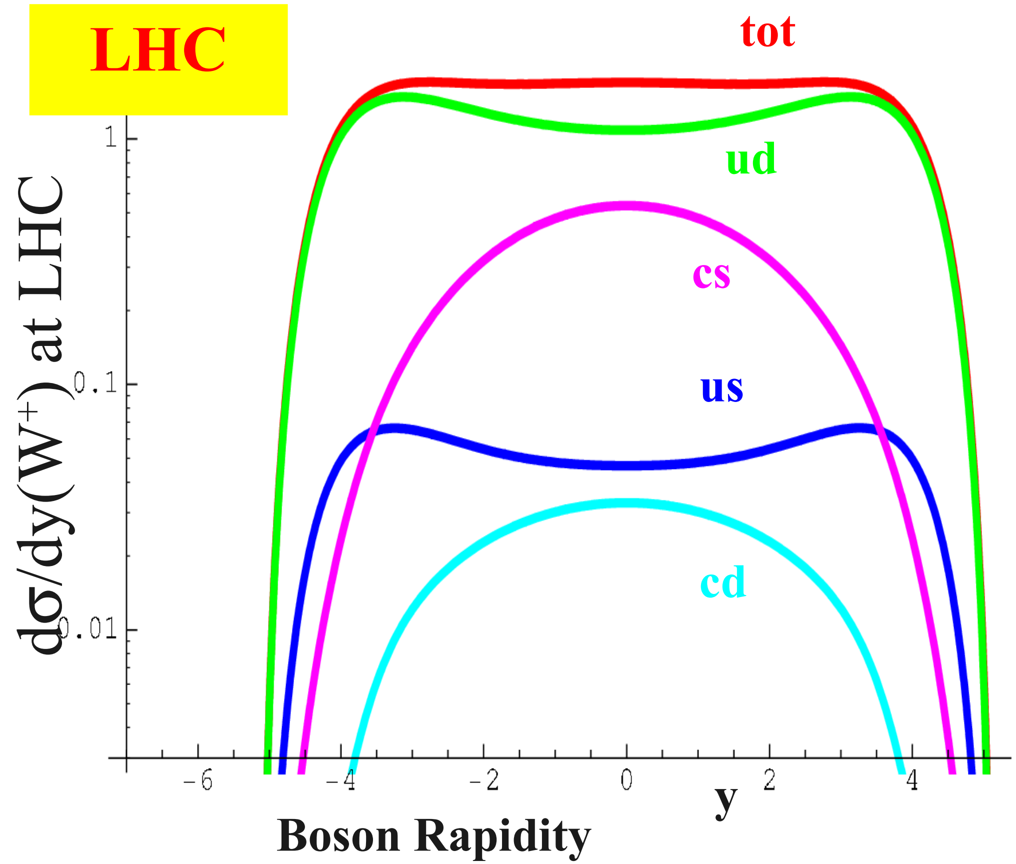
W/Z Production

"Benchmark Calculations"

... things are different at the LHC

W Production at LHC: A Benchmark Cross Section

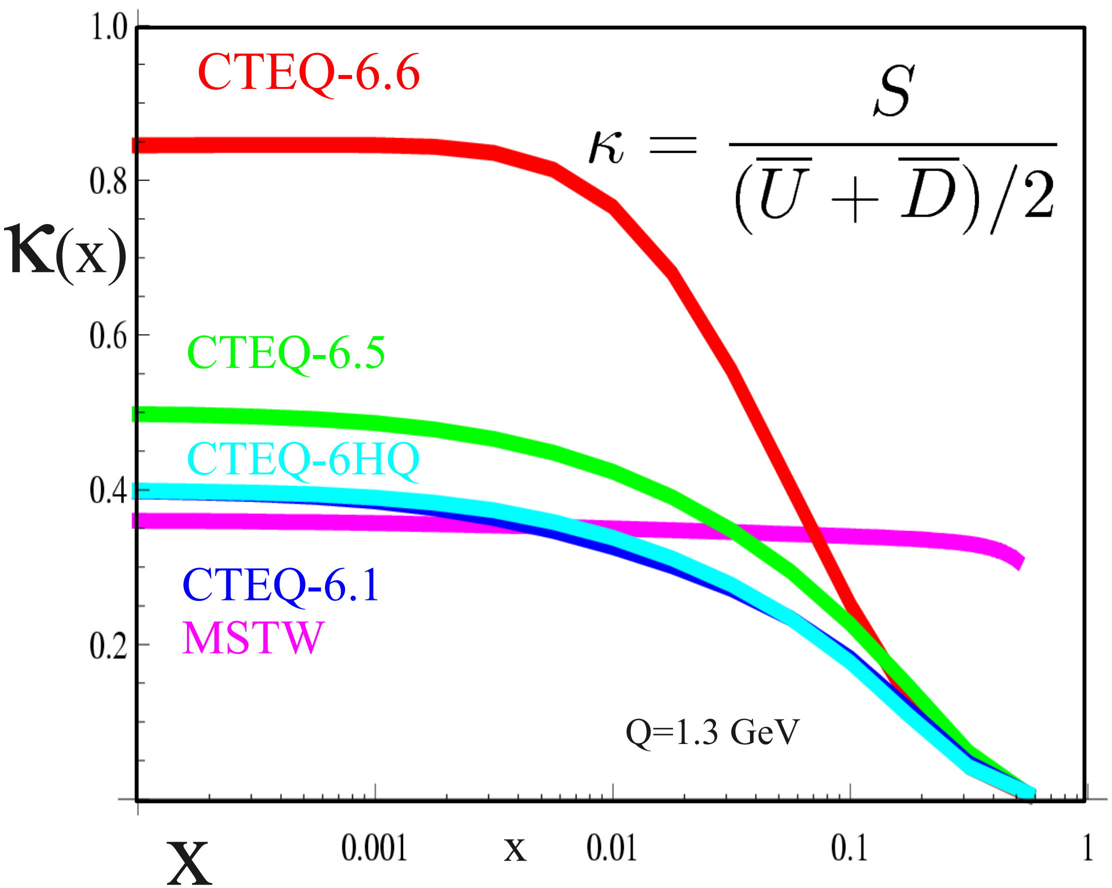


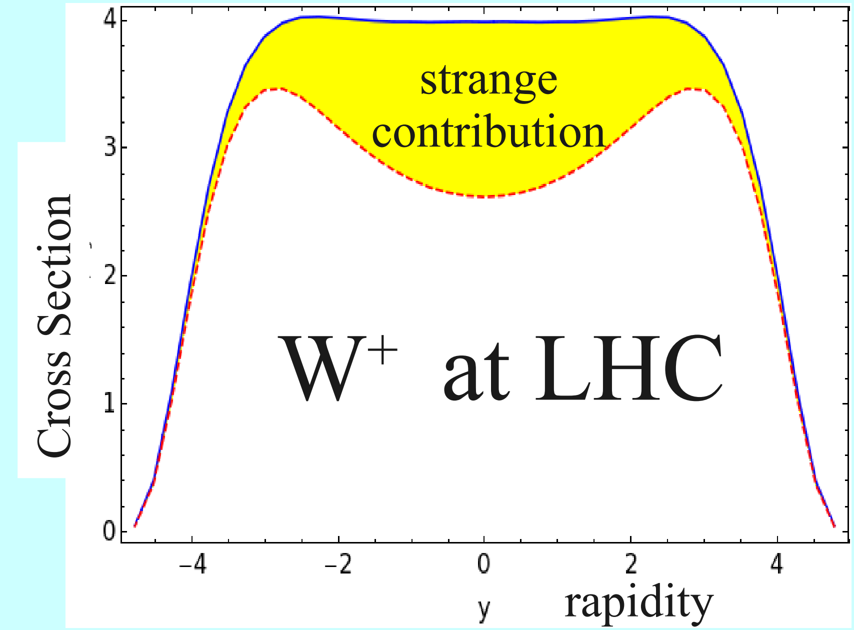


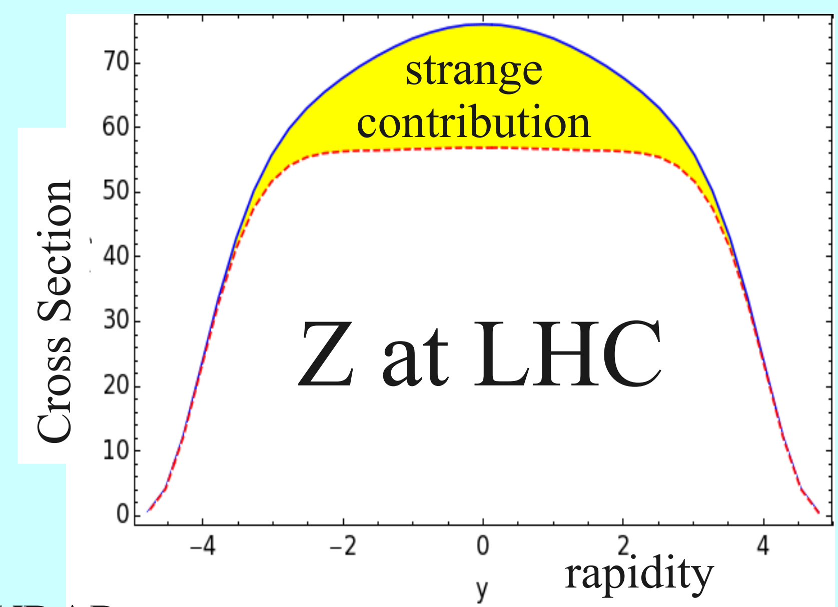
- Larger Energy $\Rightarrow$ probes PDFs to small momentum fraction x
- Larger Rapidity (y) $\Rightarrow$ probes PDFs to *really* small x
- Larger fraction of heavy quarks

Heavy Quark components play an increasingly important role at the LHC

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







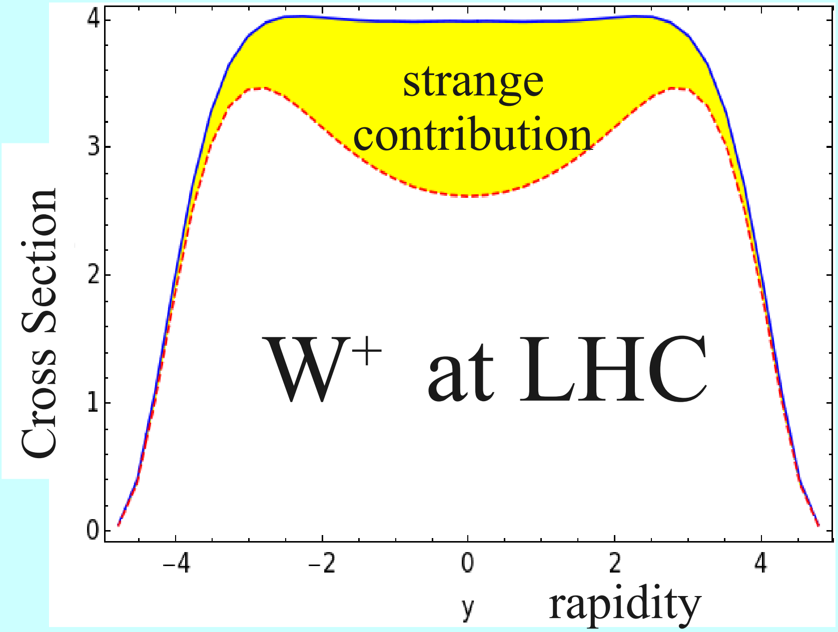
PDF Uncertainties will feed into
LHC "Benchmark" processes

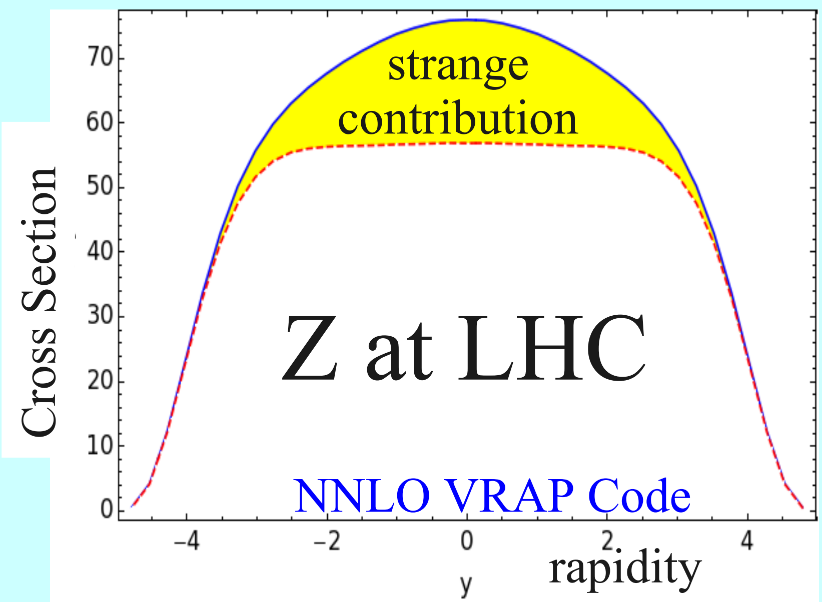
Comparison with new NNPDF sets: Les Houches 2009

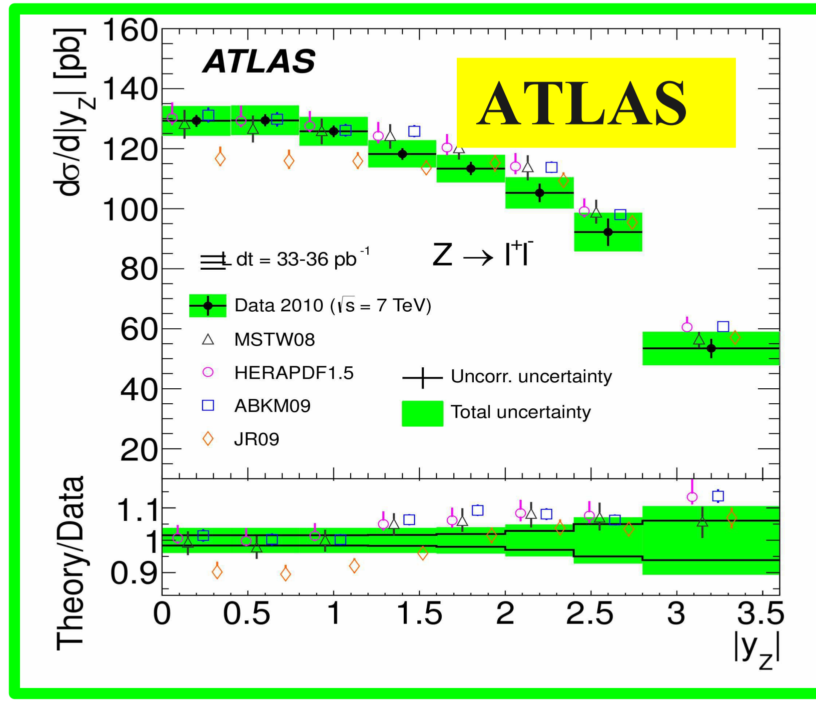
VRAP Code

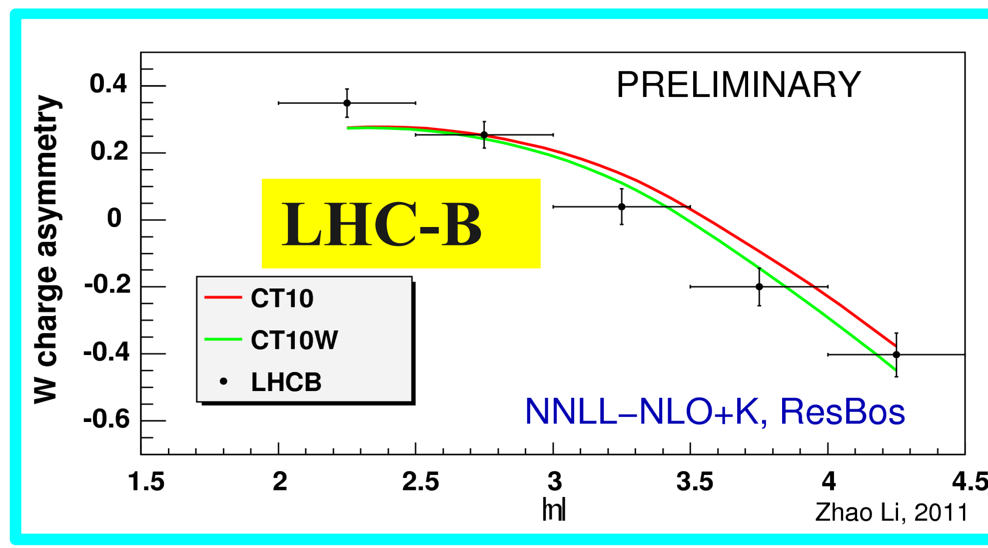
Anastasiou, Dixon, Melnikov, Petriello, Phys.Rev.D69:094008,2004.

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
Phys.Rev. D85 (2012) 094028

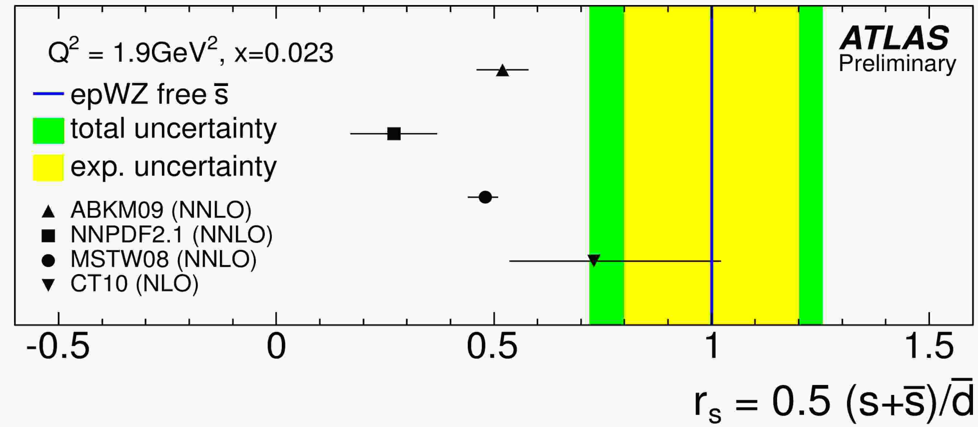
y distribution shape can constrain s(x) PDF

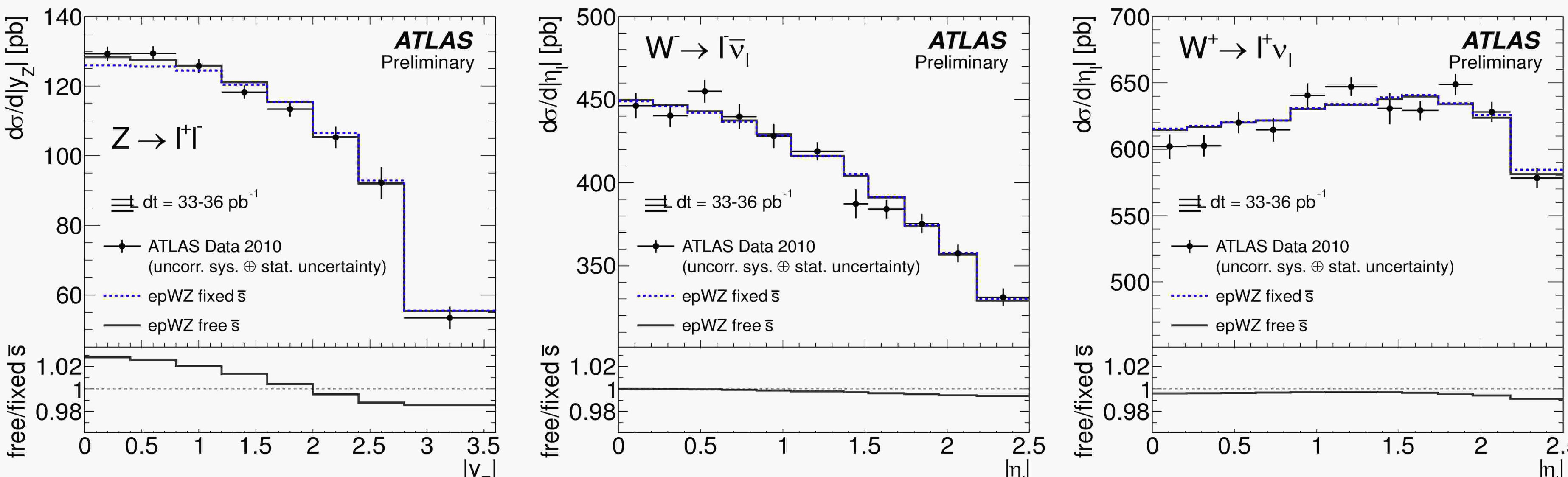
W, Z data sensitivity to strange sea

- 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

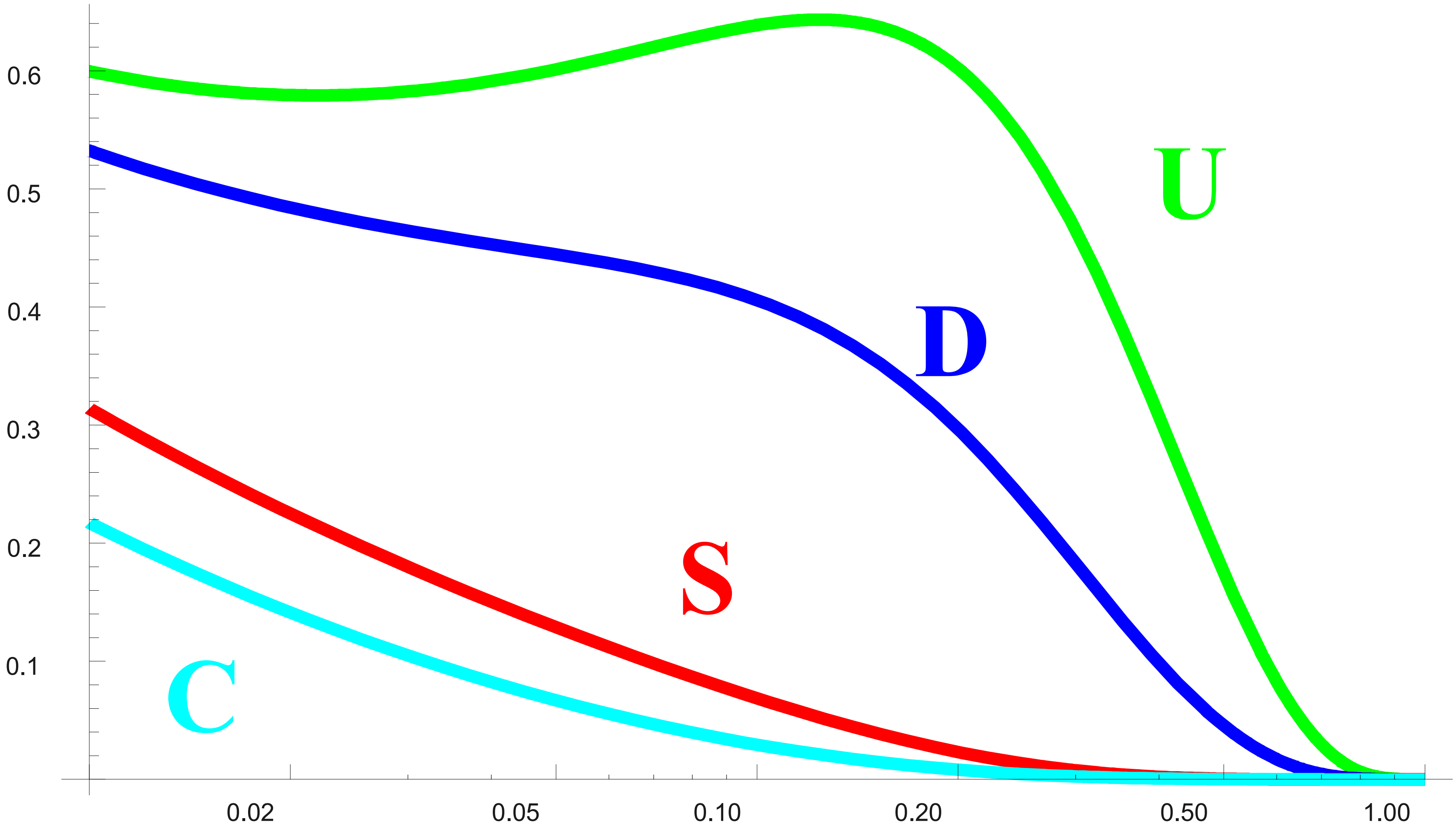
$$\boxed{r_s = 1.00 \pm 0.20_{\mathrm{exp}}\ {}^{+0.16}_{-0.20}\ \mathrm{sys}}$$





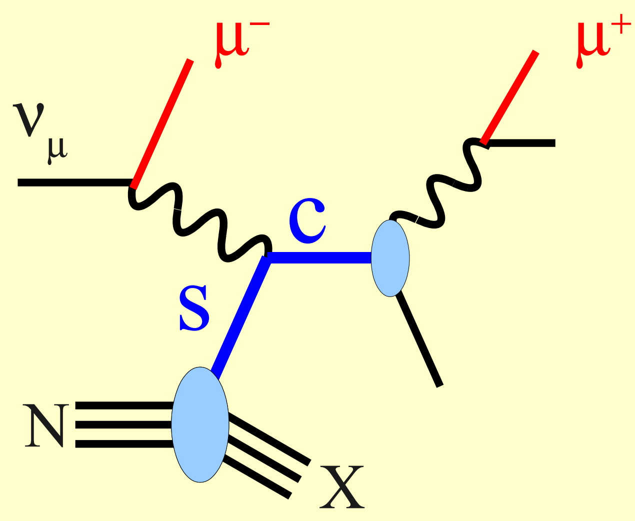
ATLAS-STDM-2011-43 → PRL

What constrains the Strange???

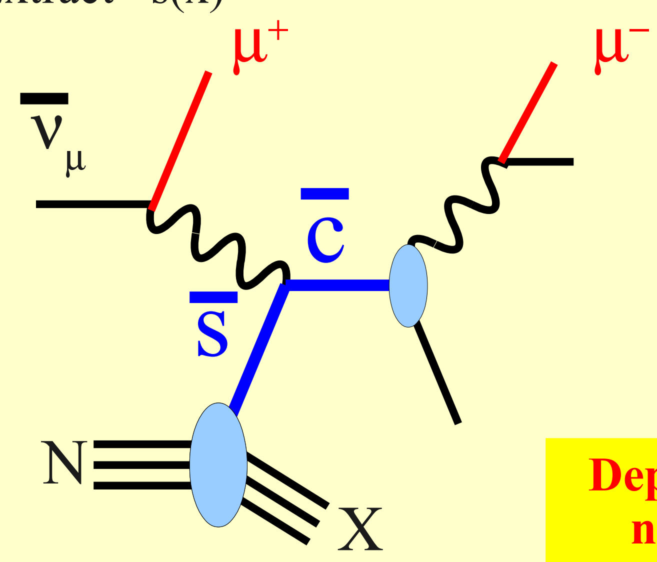


Di-muon production ⇒ Extract s(x) Parton Distribution

Extract s(x)



Extract $\bar{s}(x)$

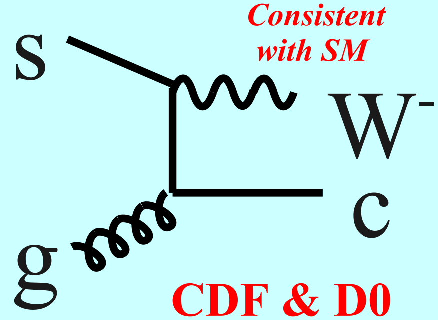


Depends on nuclear corrections

s(x) and $\bar{s}$(x) are essential in extraction of Sinθ_W

Used in CTEQ6 Fits

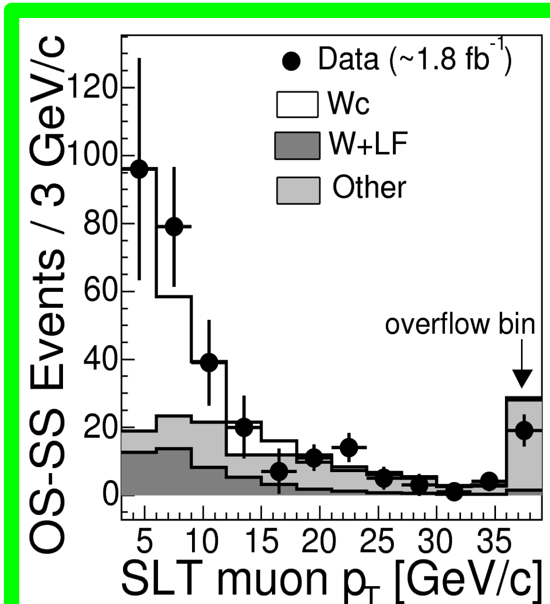
s g→Wc at the Tevatron

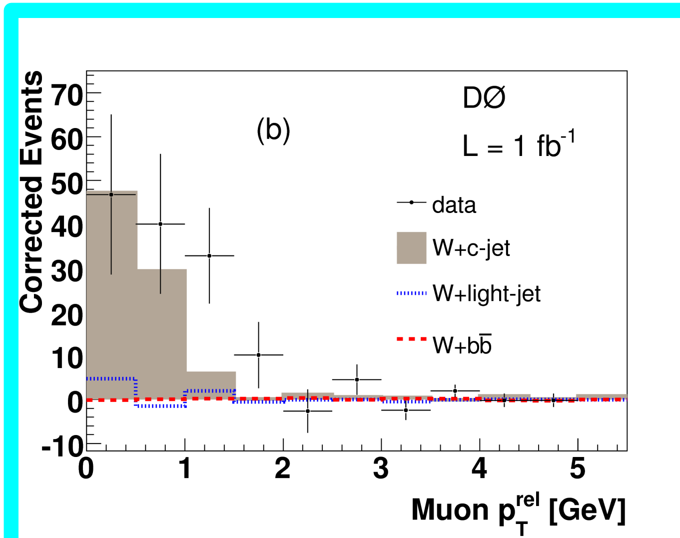


Consistent with SM

CDF & D0

CDF: PRL 100:091803,2008.
D0: PLB666:23,2008.

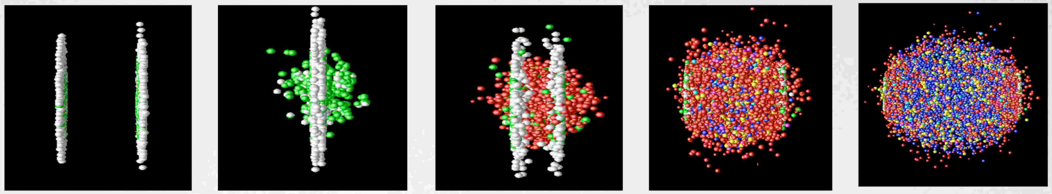




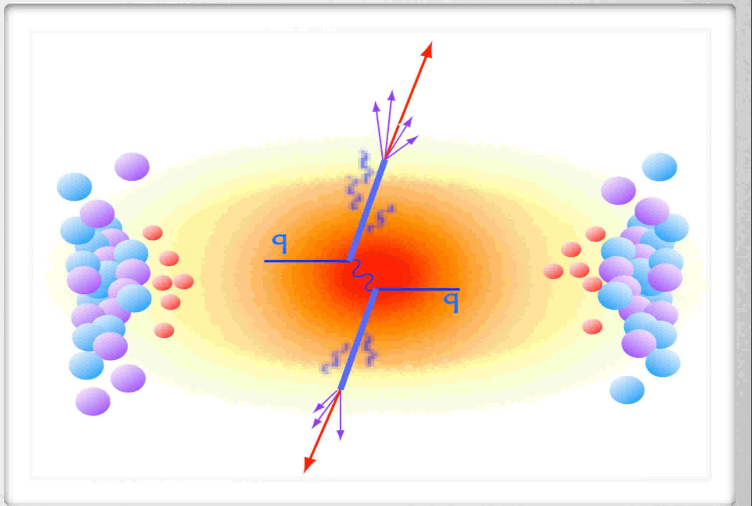
Also a challenge at LHC

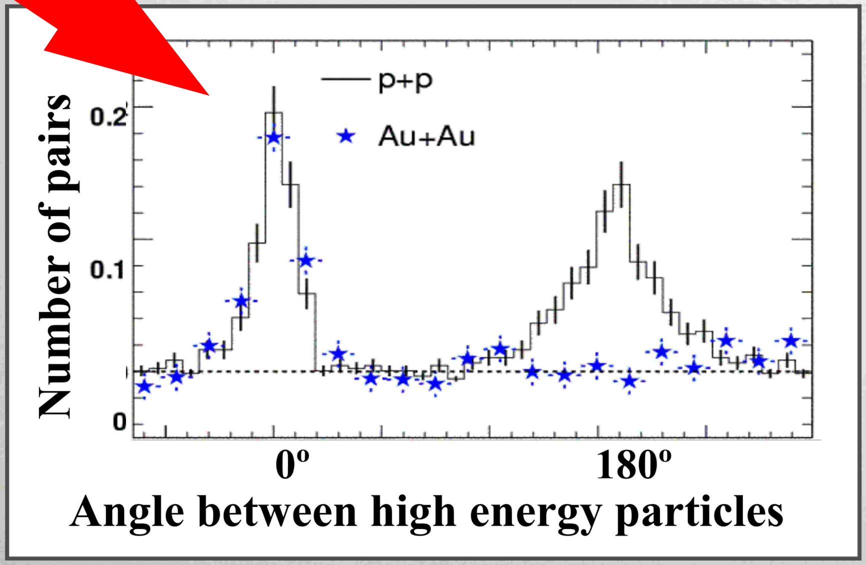
Nuclear Dimension

Will Brooks (ATLAS)
18 December 2009
VIII Latin American Symposium on Nuclear Physics and Applications



- The Relativistic Heavy Ion Collider (RHIC/BNL) has discovered a *new state of matter* in heavy ion collisions
- Experimental evidence indicates it is a hot, dense, strongly interacting system that behaves as a liquid with ultra-low viscosity
- The most compelling evidence that a super-dense medium is formed is ***jet quenching*** - *the disappearance of one of the jets in high-p_T two-jet events:*





- The phenomenon is qualitatively understood, but a number of puzzles remain
- The study of jet quenching in heavy ion collisions at LHC offers many new possibilities:
  - Much wider kinematic range and larger cross sections
  - Well-defined jets
  - Heavy quark jets

Nuclear CTEQ parton distribution functions - Mozilla Firefox

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

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

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nCTEQ

nuclear parton distribution functions

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- PDF grids & code
- Papers & Talks
- Subversion
- Tracker
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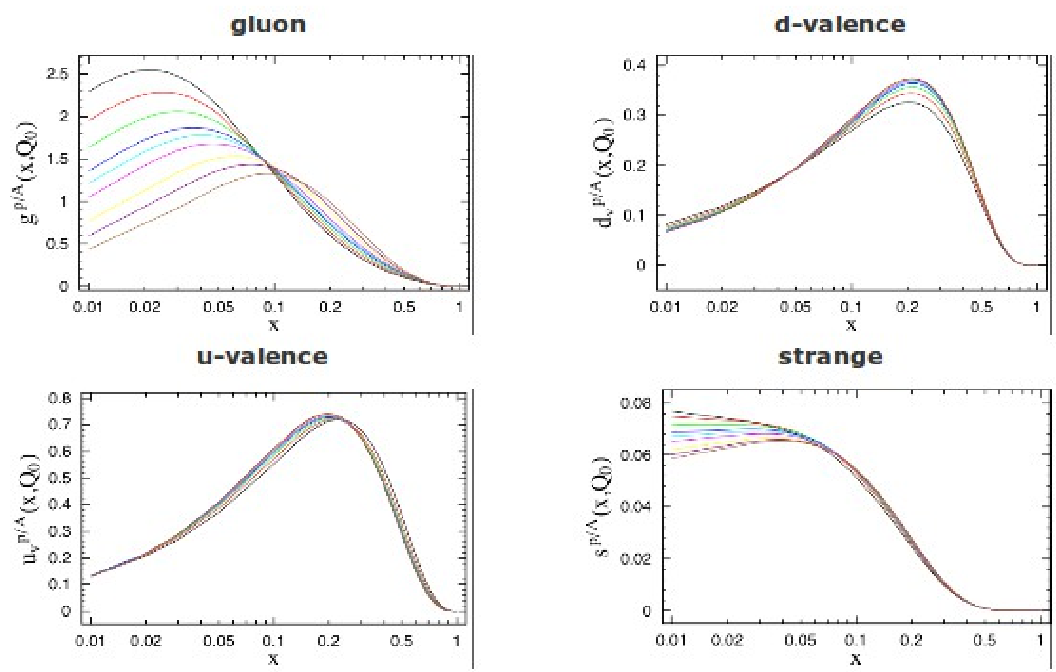
nCTEQ project is an extension of the CTEQ collaborative effort to determine parton distribution functions inside of a free proton. It generalizes the free-proton PDF framework to determine densities of partons in bound protons (hence nCTEQ which stands for nuclear CTEQ). More details on the framework 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).

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

Done

Extended CTEQ Framework

- ✔ CTEQ style global fit extended
  handle various nuclear targets
- ✔ CTEQ Data + nuclear DIS & DY
  [~15 targets; ~2000+ data]
- ✔ A-dependence modeled;
  NLO fits work well

A-Dependent PDFs

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

$$a_i \longrightarrow a_i(A)$$

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

Kovarik, Schienbein, Olness, Yu, Keppel, Morfin, Owens, Stavreva, Phys.Rev.Lett. 106 (2011) 122301

Observable	Experiment	Ref.	# data	χ^2 A1L	χ^2 A1M	χ^2 A1A	ID
F_2^A/F_2^D :							
He/D	SLAC-E139	[18]	18	9.8	6.82	6.28	5141
	NMC-95,re	[19]	16	35.6	16.91	18.31	5124
	Hermes	[20]	92	134.0	72.14	71.05	5156
Li/D	NMC-95	[21]	15	45.0	18.80	19.68	5115
Be/D	SLAC-E139	[18]	17	52.7	21.48	20.75	5138
C/D	EMC-88	[22]	9	10.3	7.29	7.11	5107
	EMC-90	[23]	2	0.2	0.14	0.11	5110
	SLAC-E139	[18]	7	31.3	4.06	4.51	5139
	NMC-95,re	[19]	16	13.9	16.12	16.62	5114
	NMC-95	[21]	15	13.9	7.13	7.26	5113
	FNAL-E665-95	[24]	4	23.4	8.81	8.29	5125
N/D	BCDMS-85	[25]	9	12.1	6.94	7.26	5103
	Hermes	[20]	92	94.5	62.42	58.94	5157
Al/D	SLAC-E049	[26]	18	32.2	20.42	20.38	5134
	SLAC-E139	[18]	17	22.12	6.50	8.05	5136
Ca/D	EMC-90	[23]	2	5.5	1.47	1.37	5109
	SLAC-E139	[18]	7	14.2	2.07	1.53	5140
	NMC-95,re	[19]	15	48.6	12.75	13.74	5121
	FNAL-E665-95	[24]	4	16.2	7.88	7.67	5126
Fe/D	BCDMS-85	[25]	6	5.3	3.91	4.39	5102
	BCDMS-87	[27]	10	35.0	8.58	9.81	5101
	SLAC-E049	[28]	14	8.8	10.39	6.24	5131
	SLAC-E139	[18]	23	43.4	35.14	35.31	5132
	SLAC-E140	[29]	6	16.8	2.93	4.87	5133
Cu/D	EMC-88	[22]	9	7.1	4.24	4.47	5106
	EMC-93(addendum)	[30]	10	14.4	6.13	6.89	5104
	EMC-93(chariot)	[30]	9	9.8	6.18	6.53	5105
Kr/D	Hermes	[20]	84	120.7	64.53	62.98	5158
Ag/D	SLAC-E139	[18]	7	22.5	4.04	2.88	5135
Sn/D	EMC-88	[22]	8	28.3	19.82	20.09	5108
Xe/D	FNAL-E665-92(em cut)	[31]	4	4.0	0.65	0.61	5127
Au/D	SLAC-E139	[18]	18	48.6	8.22	7.89	5137
Pb/D	FNAL-E665-95	[24]	4	20.3	7.77	7.45	5129
$F_2^A/F_2^{A'}$:							
Be/C	NMC-96	[32]	15	14.3	5.87	5.82	5112
Al/C	NMC-96	[32]	15	14.1	5.17	5.19	5111
Ca/C	NMC-95	[19]	20	21.7	31.47	35.73	5120
	NMC-96	[32]	15	19.8	5.39	5.31	5119
Fe/C	NMC-95	[32]	15	25.9	9.54	9.35	5143
Sn/C	NMC-96	[33]	144	312.5	102.82	96.29	5159
Pb/C	NMC-96	[32]	15	13.4	7.31	8.09	5116
C/Li	NMC-95	[19]	20	49.7	21.82	20.37	5123
Ca/Li	NMC-95	[19]	20	38.3	24.62	23.53	5122
$\sigma_{DY}^{pA}/\sigma_{DY}^{pA'}$:							
C/D	FNAL-E7						
Ca/D	FNAL-E7						
Fe/D	FNAL-E7						
W/D	FNAL-E7						
Fe/Be	FNAL-E8						
W/Be	FNAL-E8						
Total:							

Also, other NPDF sets by:
M.Hirai, S.Kumano, T.-H.Nagai,
K.J.Eskola, H.Paukkune, C.A.Salgado,
S.Kulagin, R.Petti

nCTEQ Nuclear PDF's

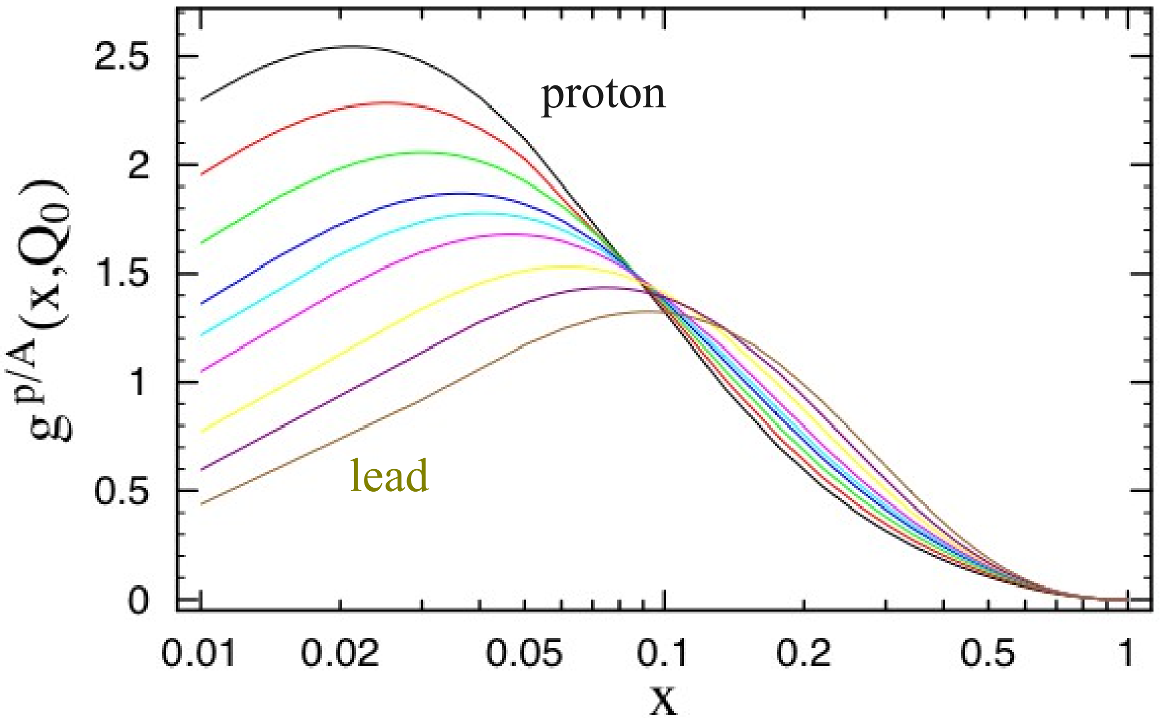
- ✔ CTEQ style global fit extended
  handle various nuclear targets
- ✔ CTEQ Data + nuclear DIS & DY
  [~15 targets; ~2000+ data]
- ✔ A-dependence modeled;
  NLO fits work well

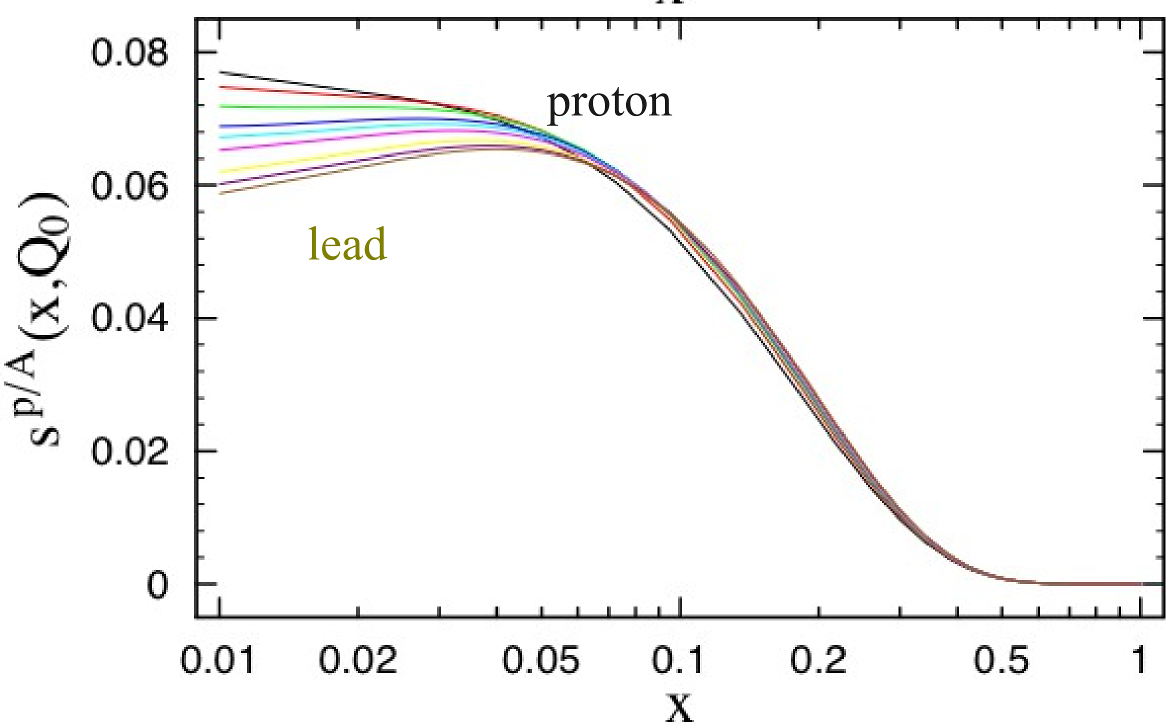
A-Dependent PDFs

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

$$a_i \to a_i(A)$$

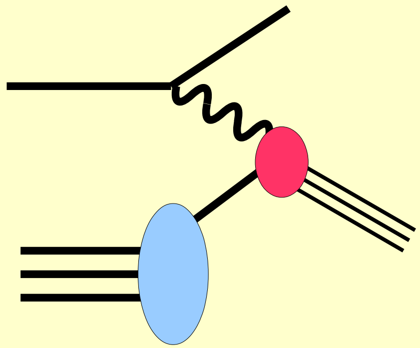
$$a_k = a_{k,0} + a_{k,1}\left(1 - A^{-a_{k,2}}\right)$$



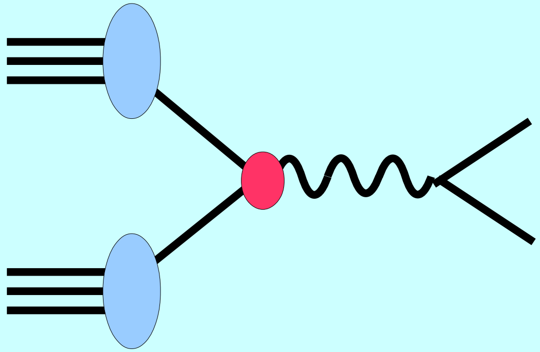


Nuclear PDFs from neutrino deep inelastic scattering.
I. Schienbein, J.Y. Yu, C. Keppel, J.G. Morfin,
F. Olness, J.F. Owens. Phys.Rev.D77:054013,2008.

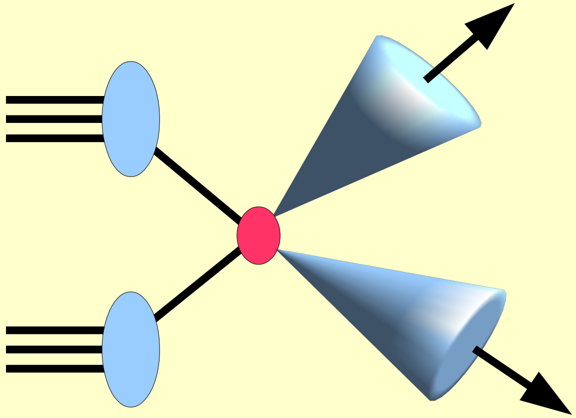
Can LHC Nuclear Data help with Nuclear DIS Corrections????



DIS Production



Drell-Yan



Jet Production

$$F_2^{\nu} \sim [d + s + \bar{u} + \bar{c}]$$
$$F_2^{\bar{\nu}} \sim \left[\bar{d} + \bar{s} + u + c\right]$$

$$F_3^{\nu} = 2\,[d + s - \bar{u} - \bar{c}]$$
$$F_3^{\bar{\nu}} = 2\left[u + c - \bar{d} - \bar{s}\right]$$

$$F_2^{\ell^\pm} \sim \left(\tfrac{1}{3}\right)^2 [d + s] + \left(\tfrac{2}{3}\right)^2 [u + c]$$

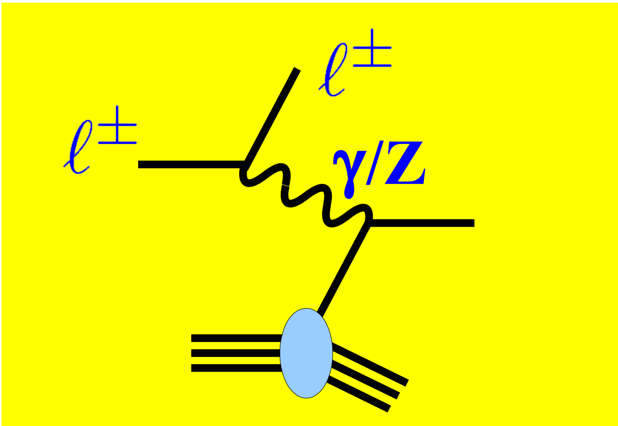
In particular, the DIS combinations have historically been particularly useful

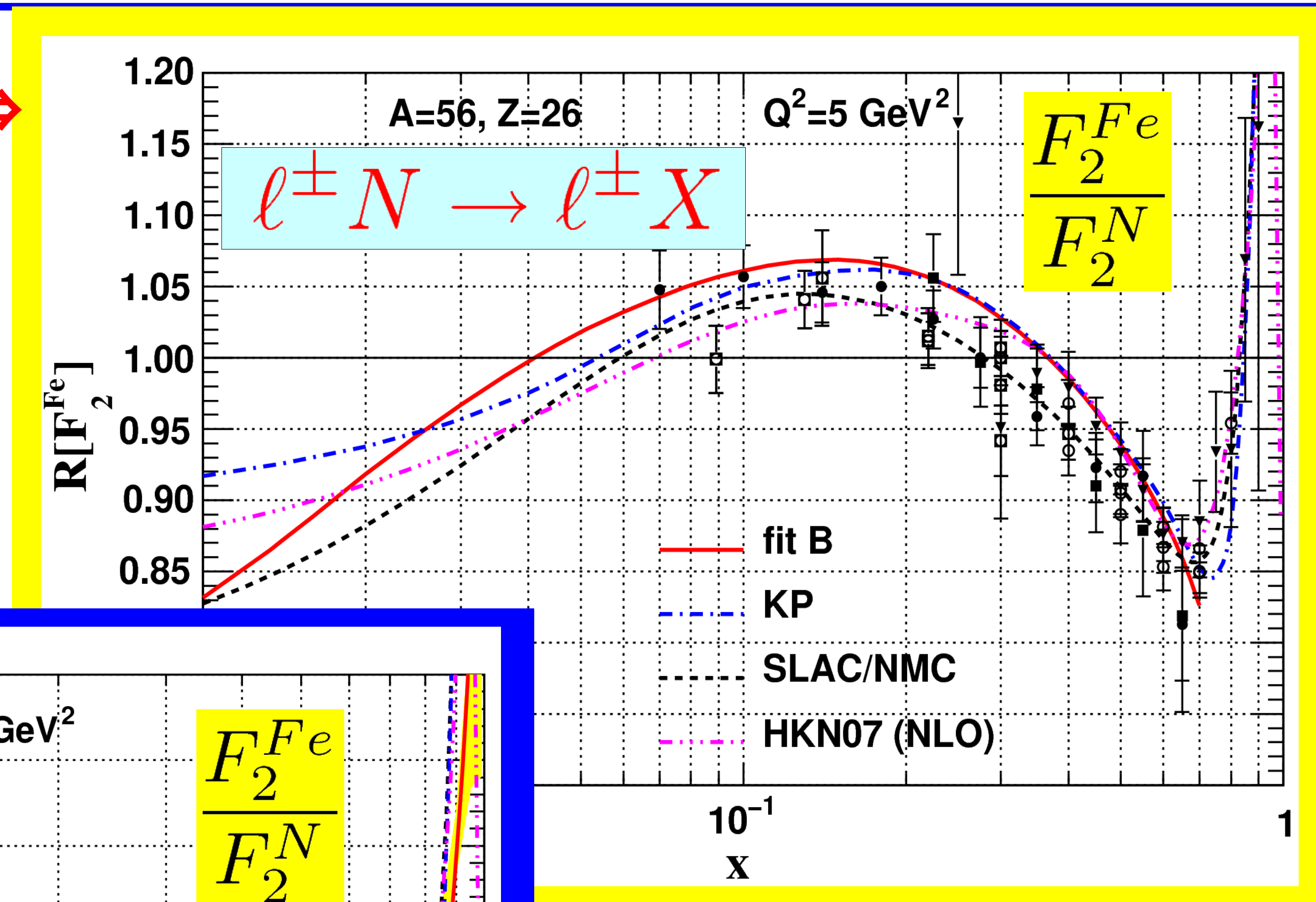
<u>Different</u> linear combinations – key for flavor differentiation

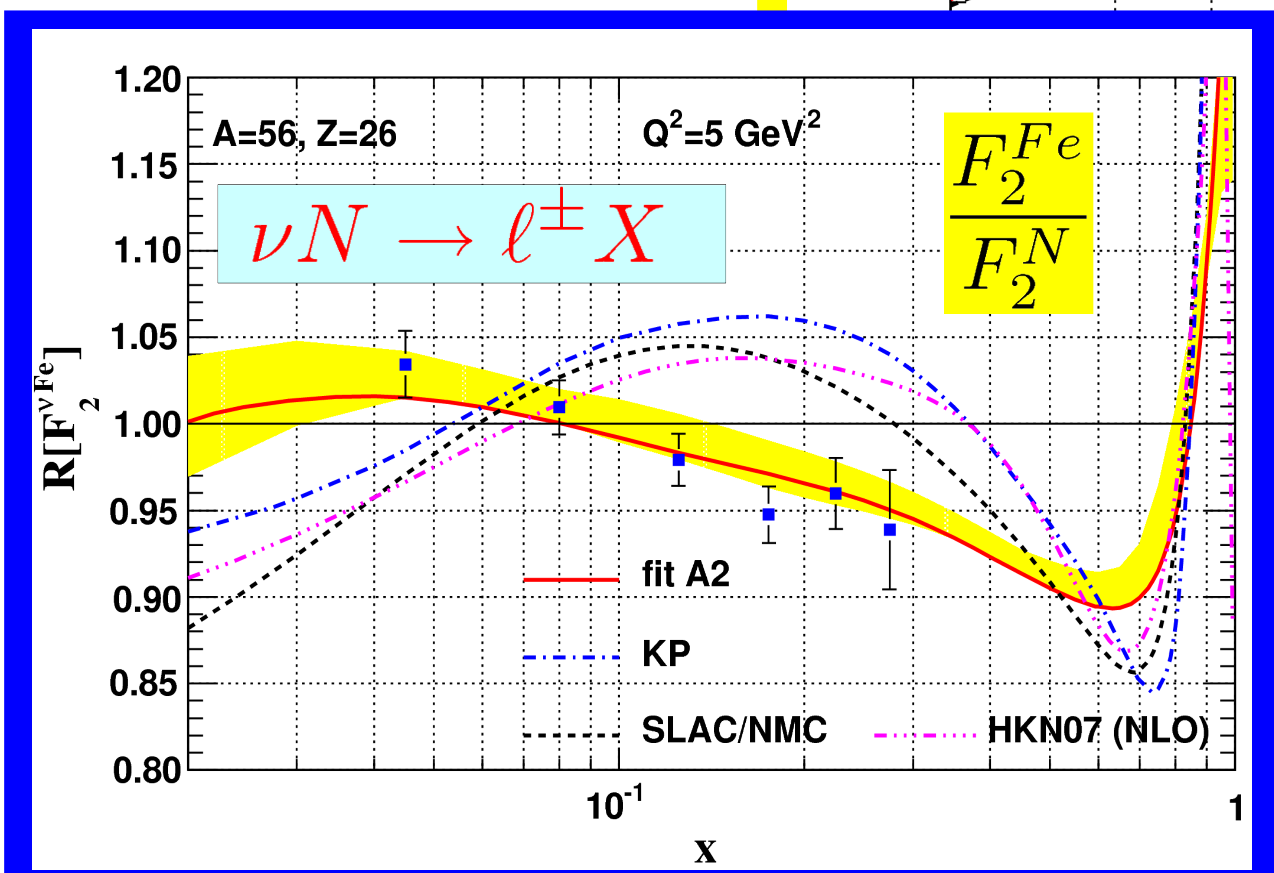
The ν-DIS data typically use heavy targets, and this requires the application of ***<u>nuclear corrections</u>***

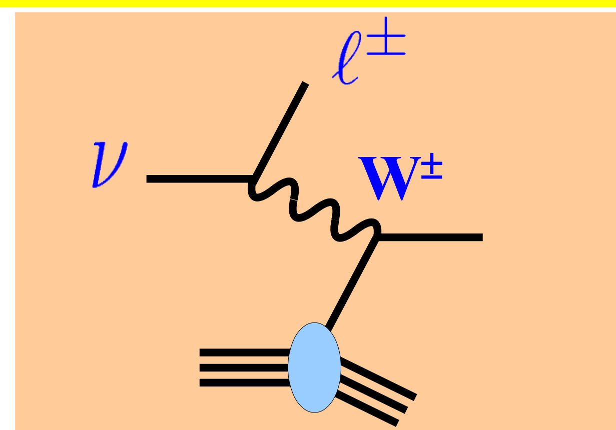
Nuclear Corrections: Compare Neutrino and Charged Lepton DIS

Charged Lepton DIS ⇒









⇐ Neutrino DIS

Nuclear Corrections: Nuclear PDF Uncertainties

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nCTEQ

nuclear parton distribution functions

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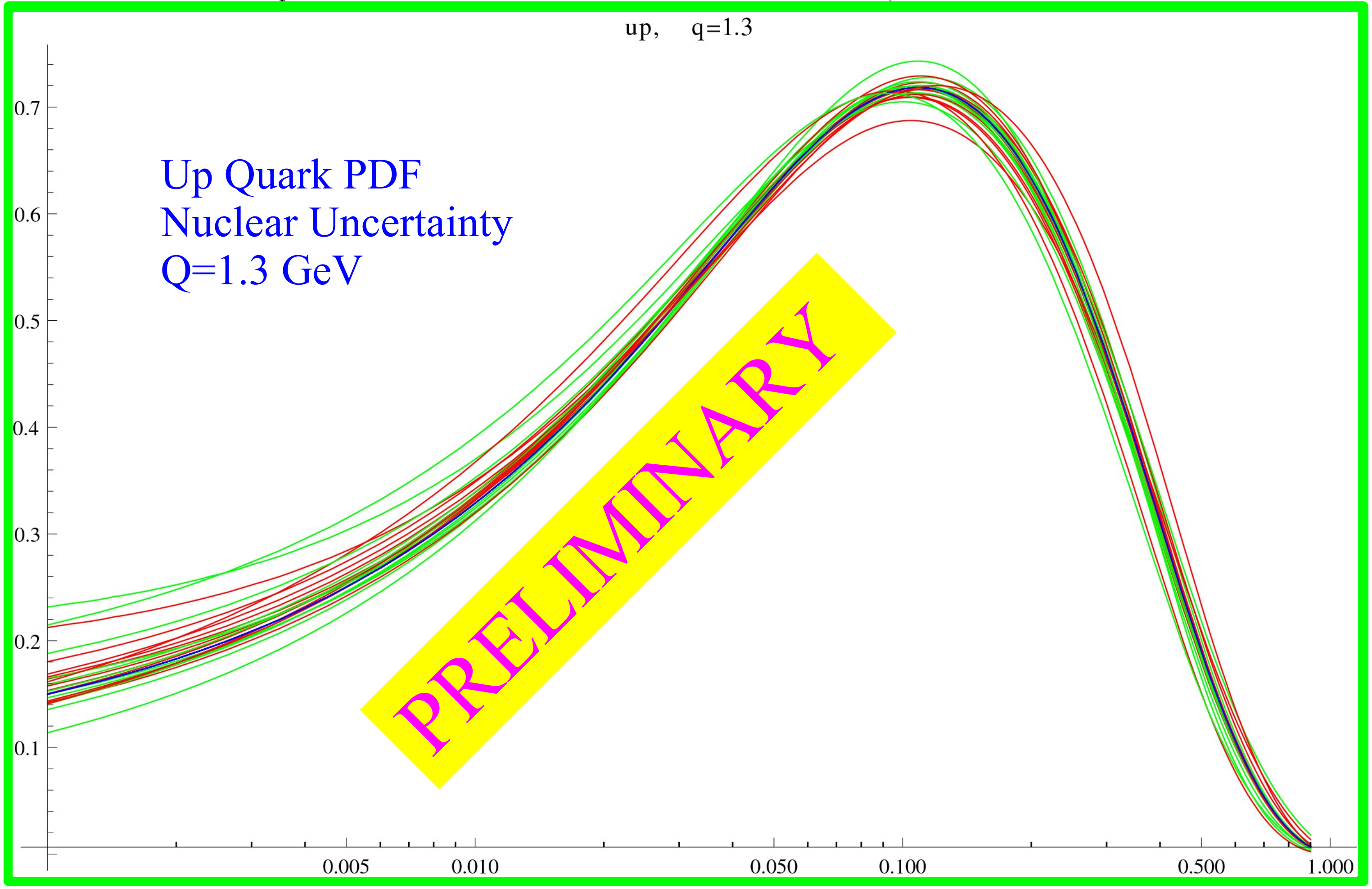


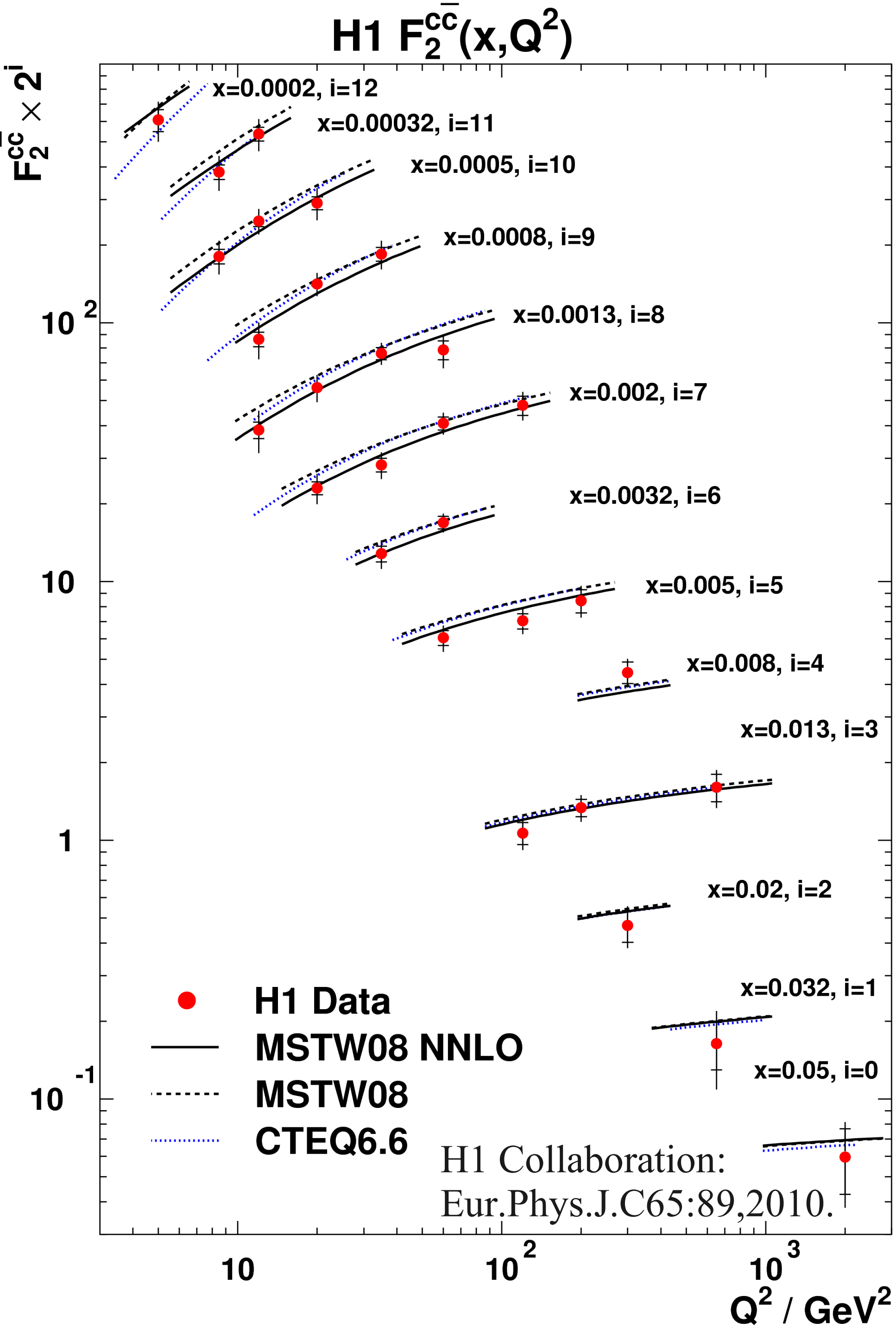
... what about the

Heavy Quarks

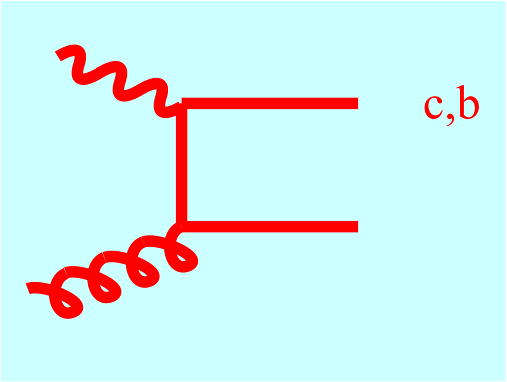
c & *b*

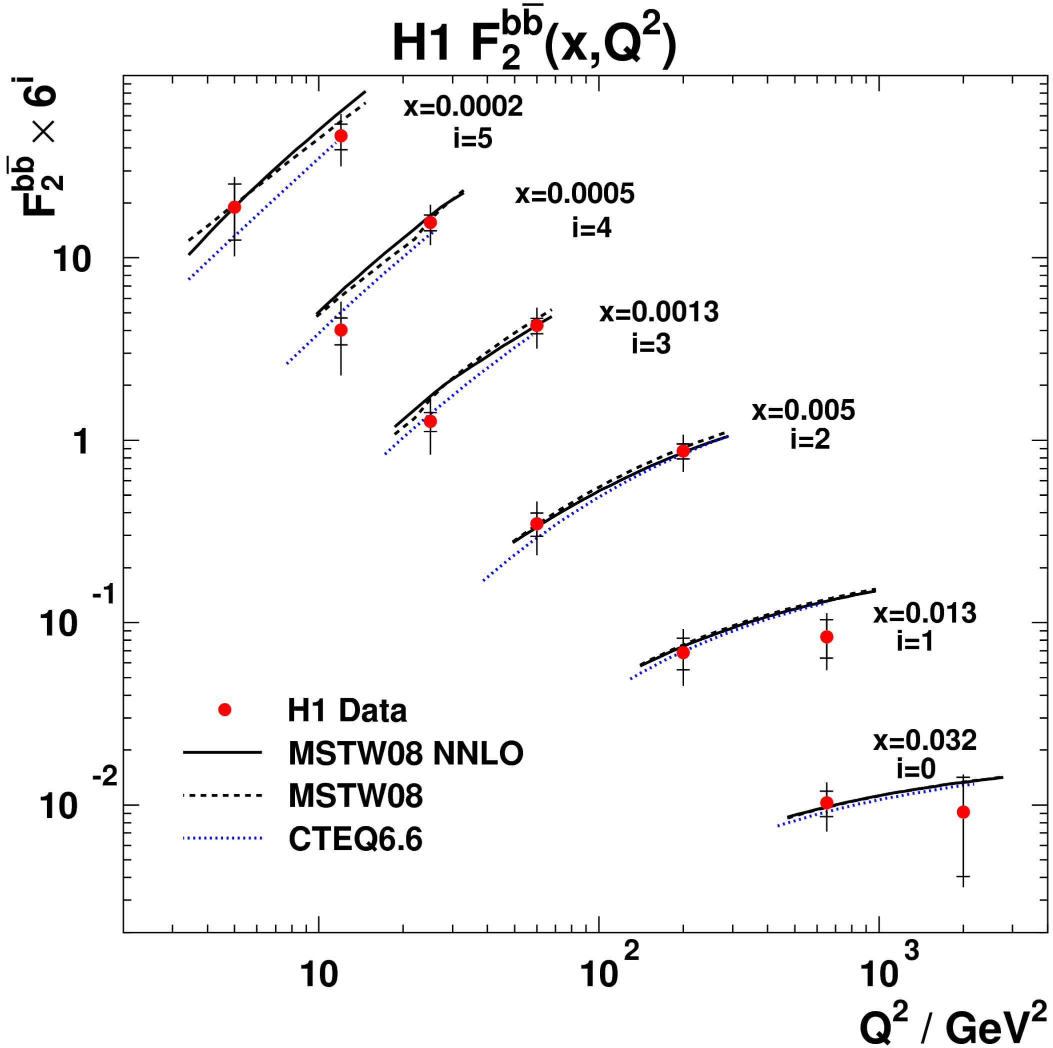
Extrinsic & Intrinsic

Heavy Flavor Components will play prominent role at LHC

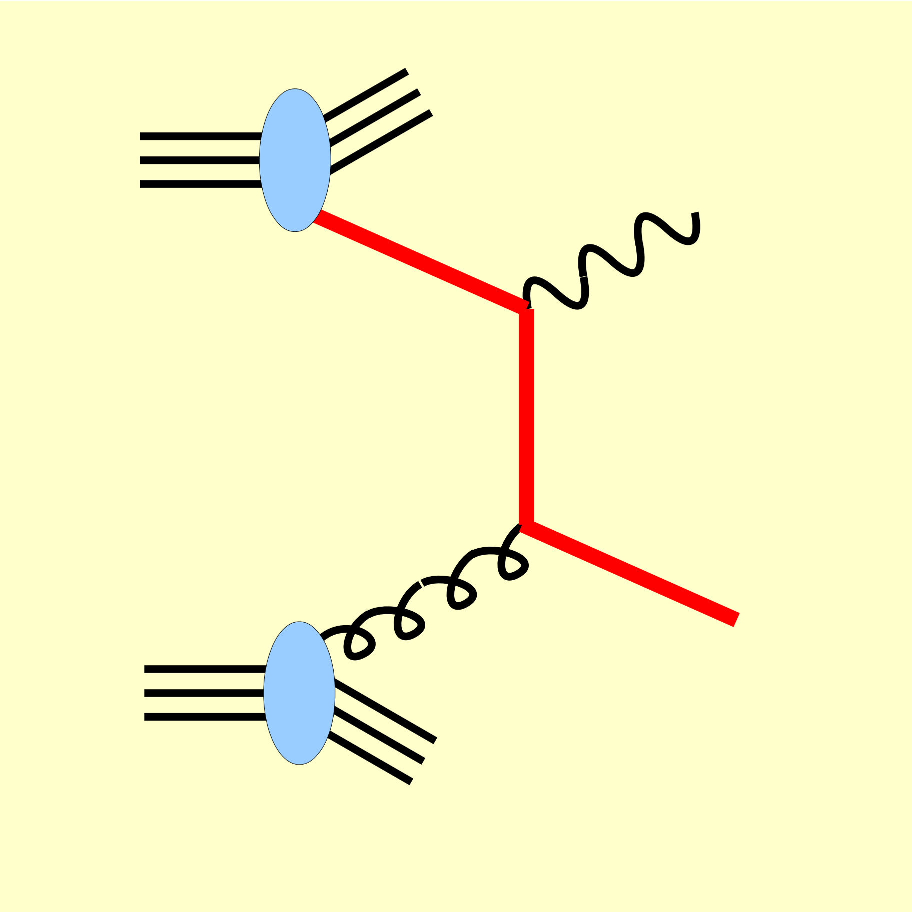


c & b tied to gluon PDFs





How to Access Heavy Flavor Components Directly???



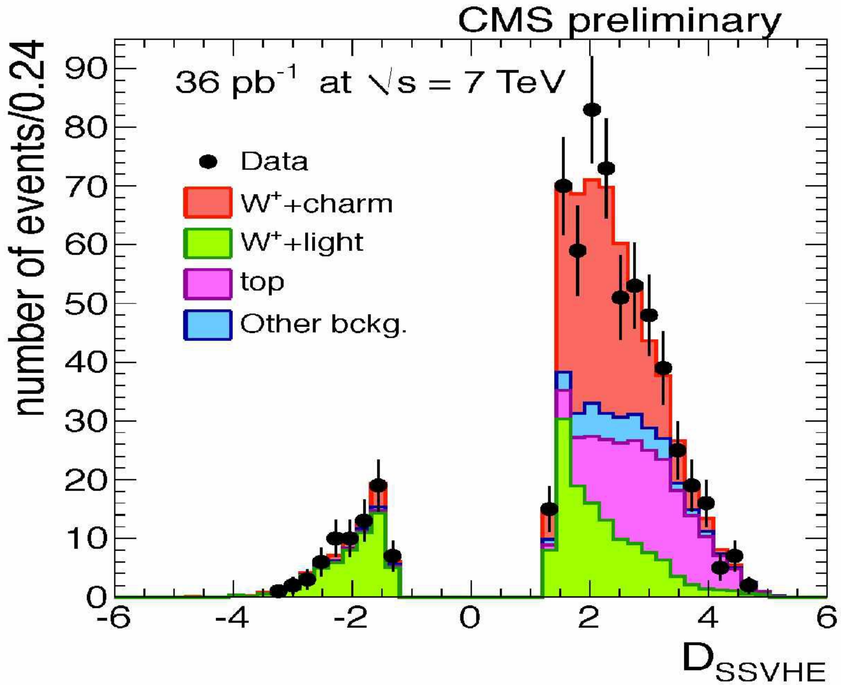
$$c\,g \rightarrow c\,\gamma$$

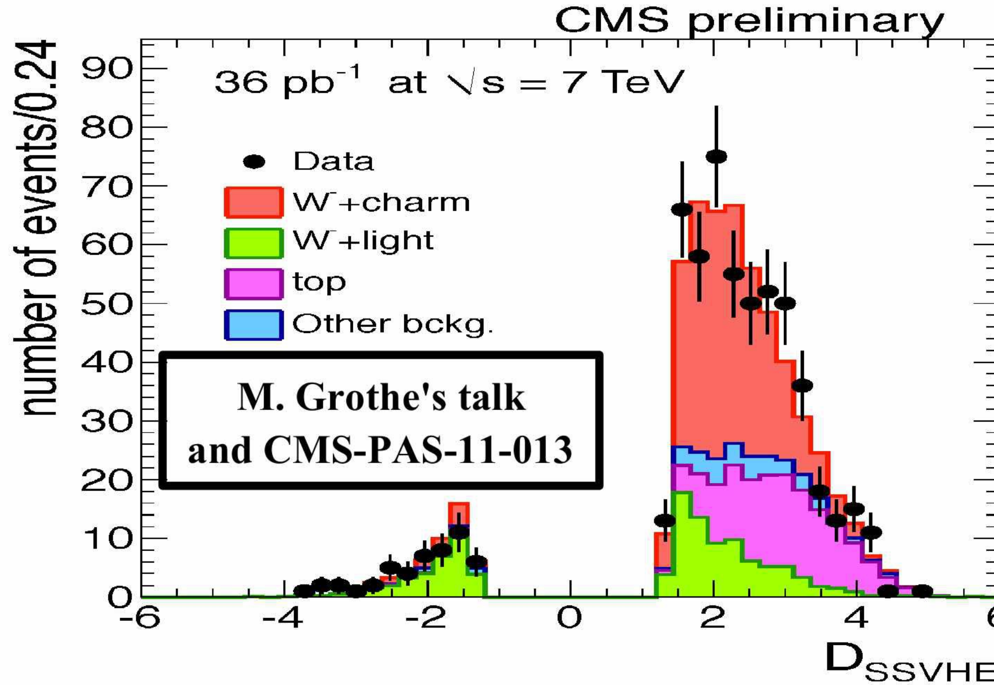
$$b\,g \rightarrow b\,\gamma$$

$$s\,g \rightarrow c\,W$$

$$c\,g \rightarrow b\,W$$

First LHC results on W+charm (CMS)

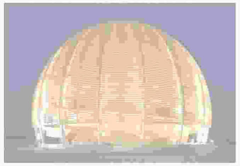




- Sensitive to strange quark PDFs (process dominated by s+g → W + charm):
  - PDF uncertainties from the second quark generation are a potential source of uncertainty for the W mass measurement at the LHC
  - Data-driven control of light-quark and top backgrounds
  - Enormous margin for improvement (only 2010 statistics used), new method (secondary vertex tagging), complementary to the one employed until now at Tevatron (semileptonic charm decay tagging):

$$\underline{For \quad p_T^{jet} > 20 \quad GeV, |\eta^{jet}| < 2.1}:$$

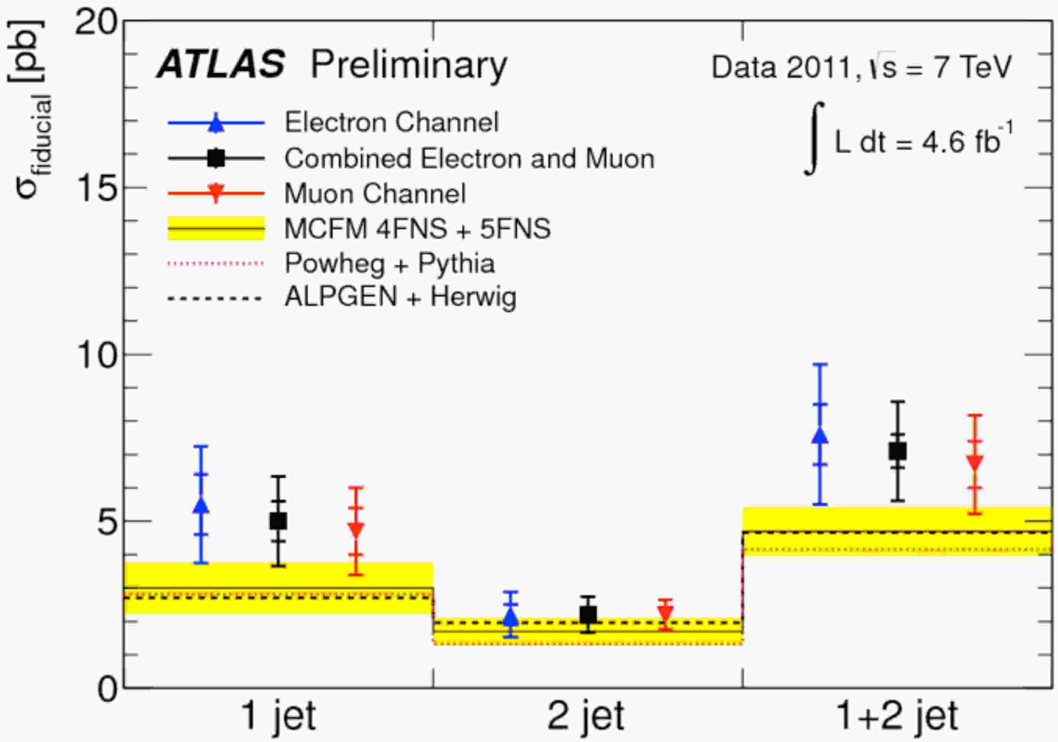
$$\frac{\sigma(W^+ + charm)}{\sigma(W^- + charm)} = 0.92 \pm 0.19(stat.) \pm 0.04(syst.); \quad \frac{\sigma(W + charm)}{\sigma(W + jets)} = 0.142 \pm 0.015(stat.) \pm 0.024(syst.)$$



New D0 and ATLAS Wb results

- Measurements are dominated by jet energy scale uncertainties (not statistics)

ATLAS - 2011



D0

Measured (electron channel)
1.00 ± 0.04 (stat) ± 0.12 (sys) pb
NLO Calculation (MCFM)
1.28 +0.40-0.33 (theory) pb

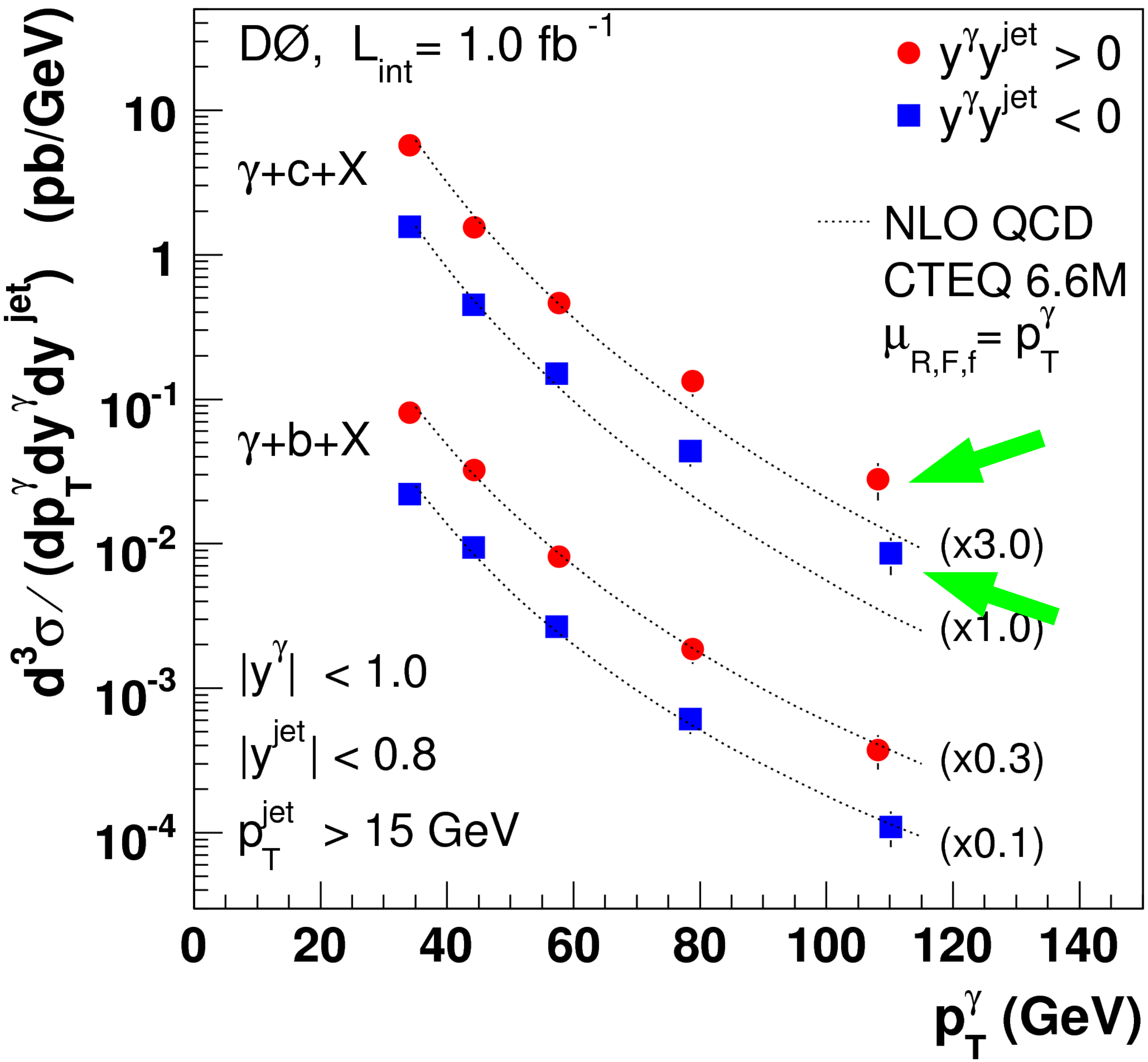
From D0, NLO in agreement with measurement

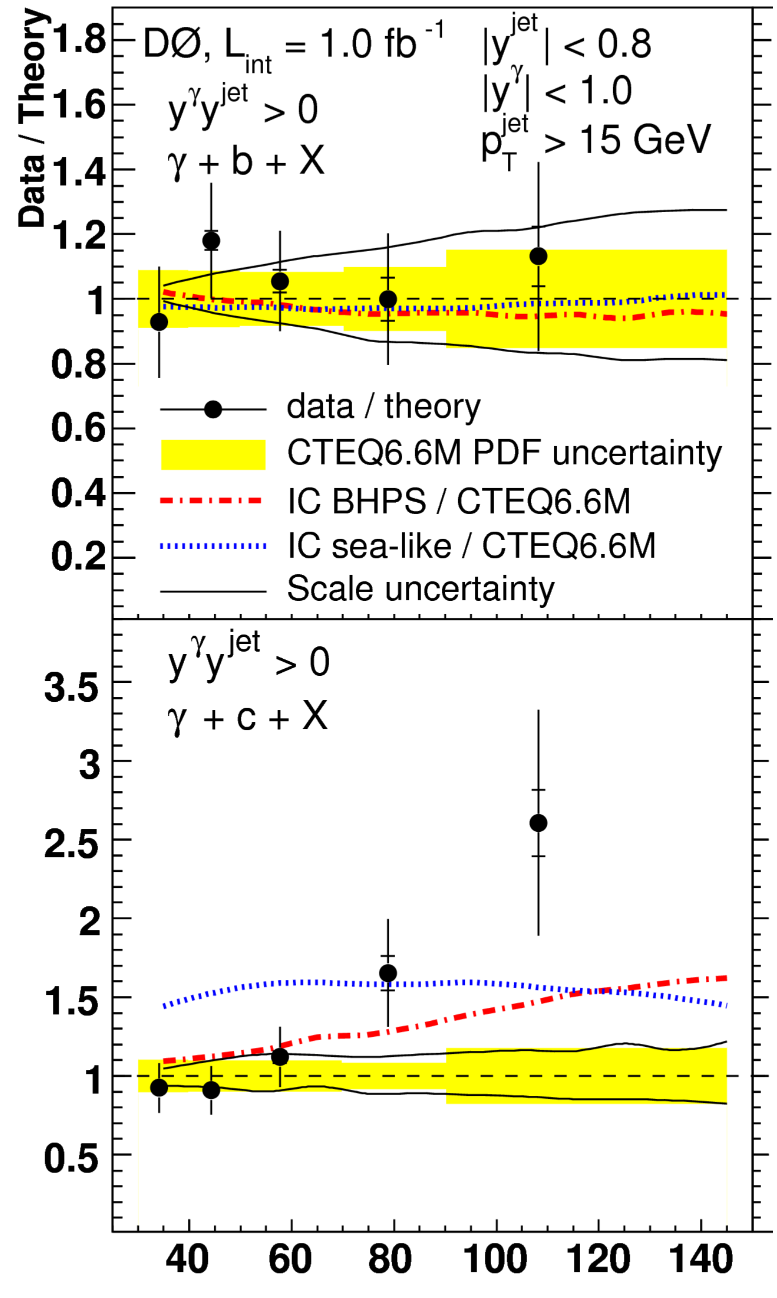
From ATLAS, theory is consistent within 1.5 sigma

Monida Dunford
(Heidelberg U)
Kyoto, November 2012

http://cdsweb.cern.ch/record/1493495

http://arxiv.org/abs/1210.0627

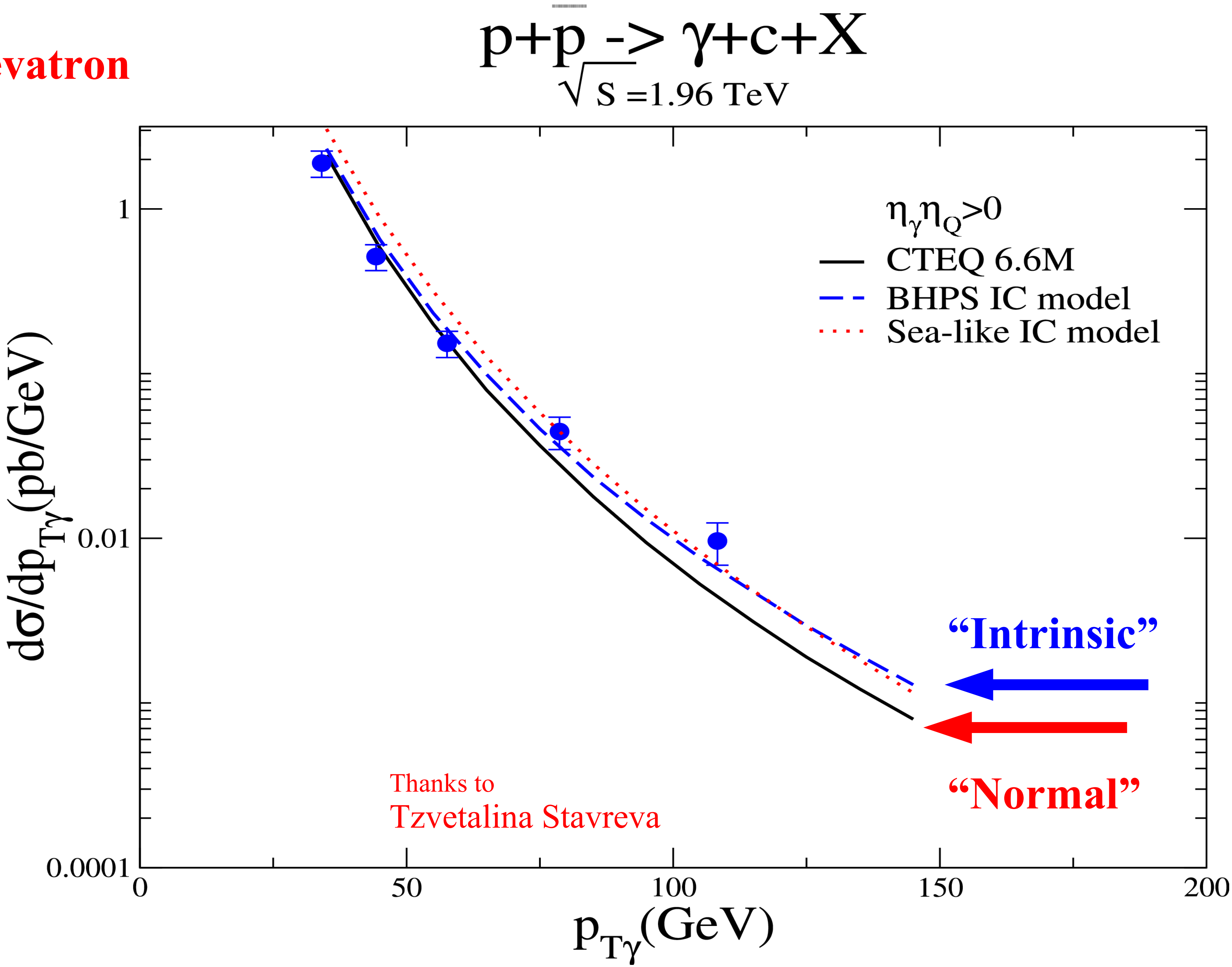




D. Duggan (D0) arXiv:0906.0136

Including "Intrinsic Heavy Quark" Component

Tevatron



T. Stavreva, K. Kovarik, F. Olness, arXiv:1206.2175

T. Stavreva, I. Schienbein, F. Arleo, K. Kovarik, F. Olness, J.Y. Yu, J.F. Owens, JHEP 1101 (2011) 152

Higher Orders

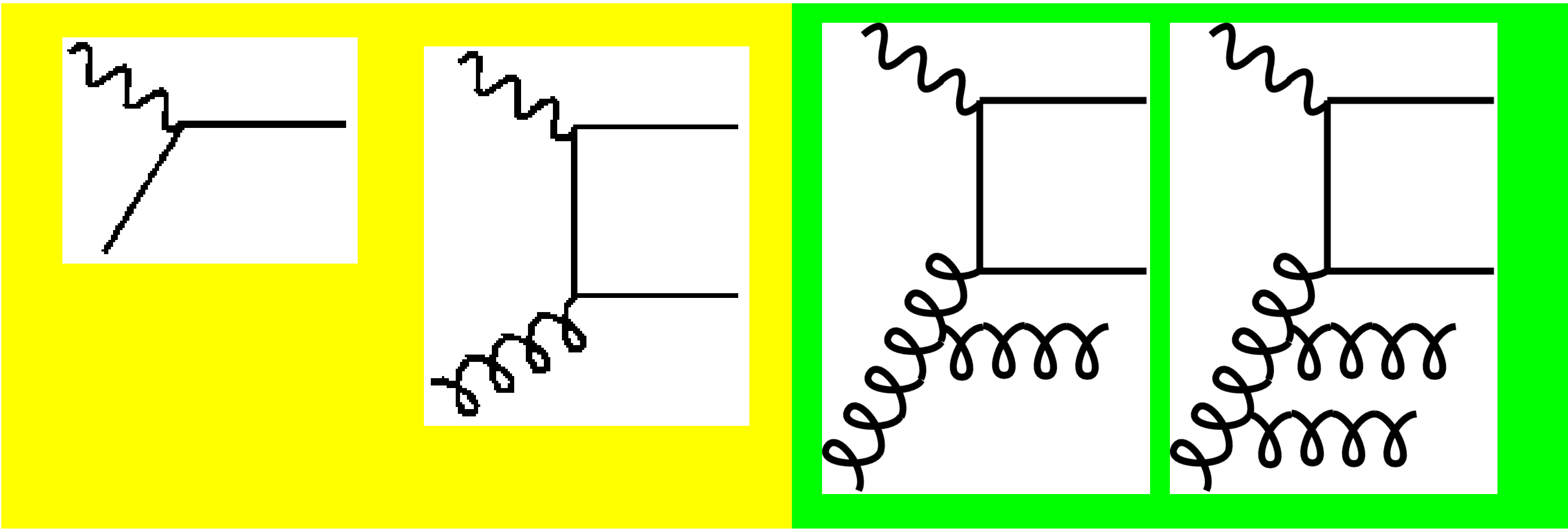
An example...

ACOT@ NNLO + N^3LO

Stavreva, Olness, Schienbein, Jezo, Kusina, Kovarik, Yu
Phys.Rev. D85 (2012) 114014

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

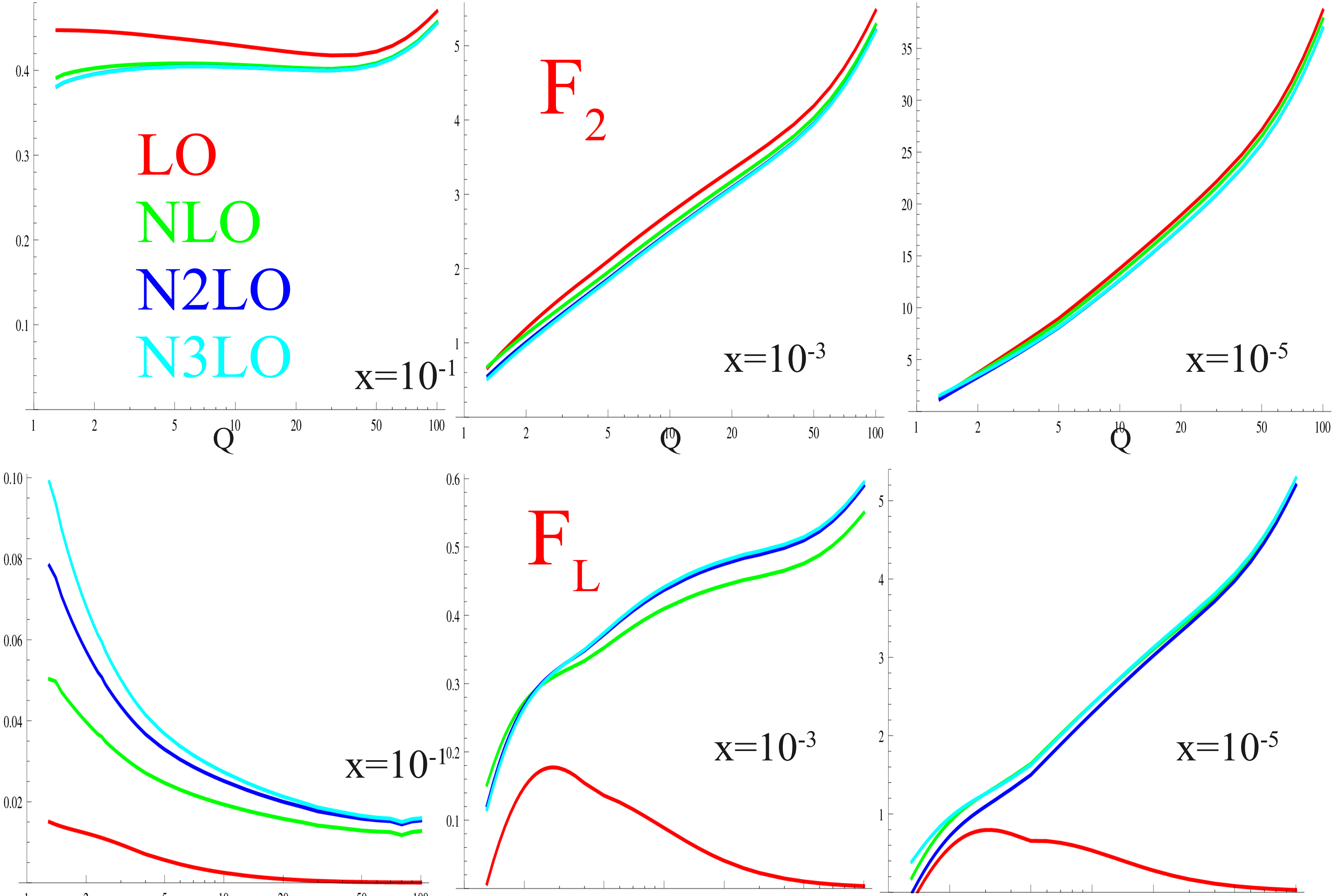
DGLAP kernels & PDF evolution are pure MS-Bar

Subtractions are MS-Bar

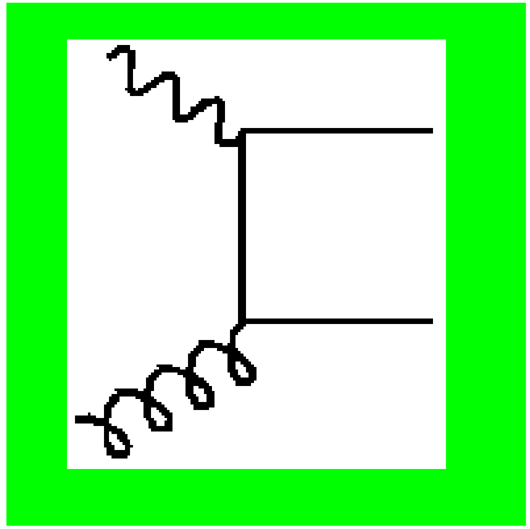
ACOT: $m \to 0$ limit yields MS-Bar

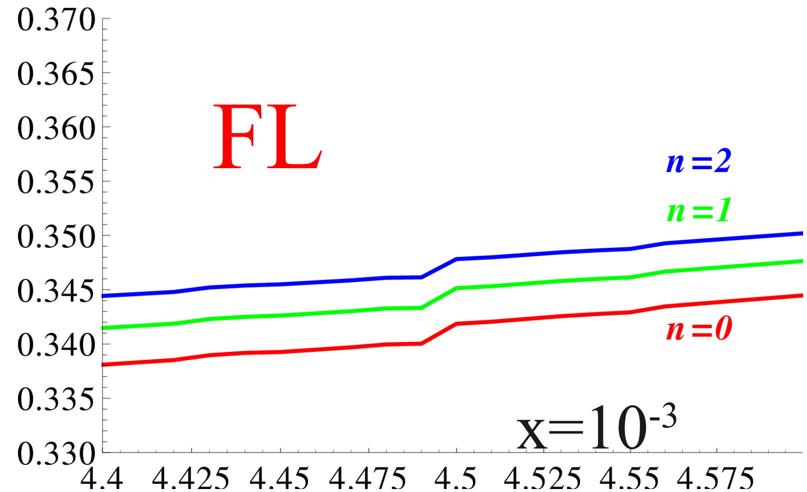
with no finite renormalization

$F_{2,L}$ @ N3LO

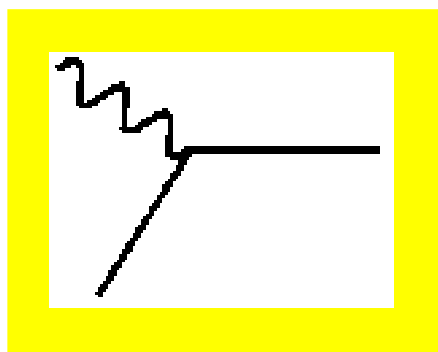


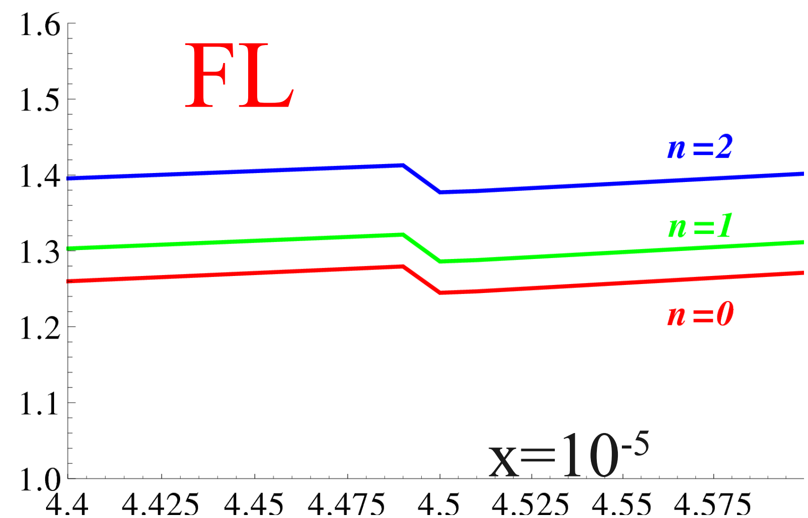
At NNLO+ we have discontinuties. *But QCD Compensates!!!*





Quark & Gluon
have opposite
discontinuities



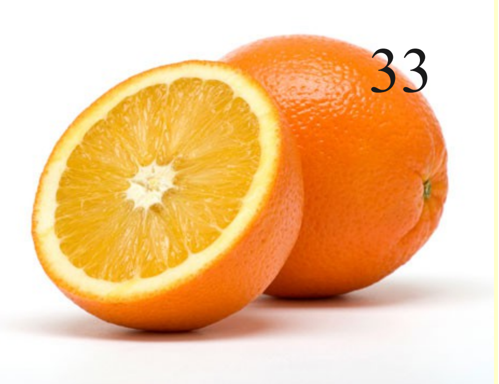


$$\sigma_{TOT}^{N_F+1} = \sigma_{TOT}^{N_F} + \mathcal{O}(\alpha_S^{m+1})$$

... this is really cool!!!

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:

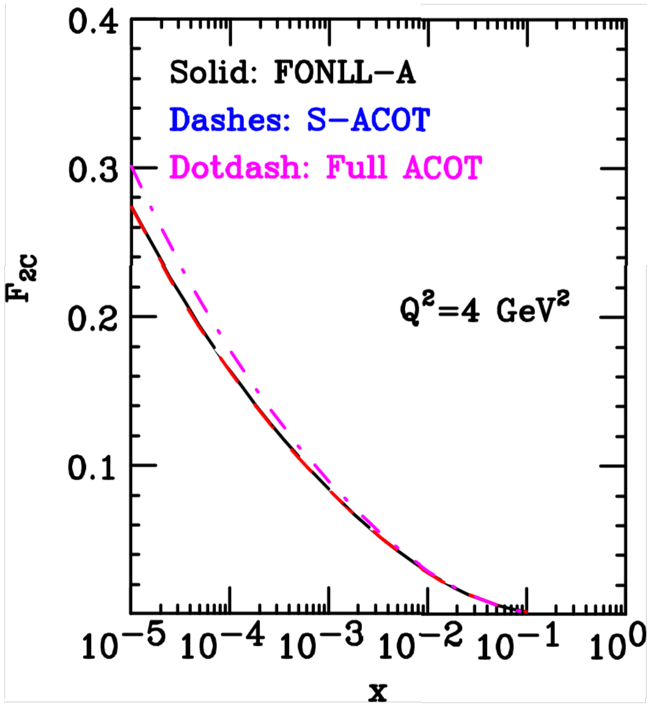
Blumlein, Klein, Moch
Phys.Rev.D81:014032,2010

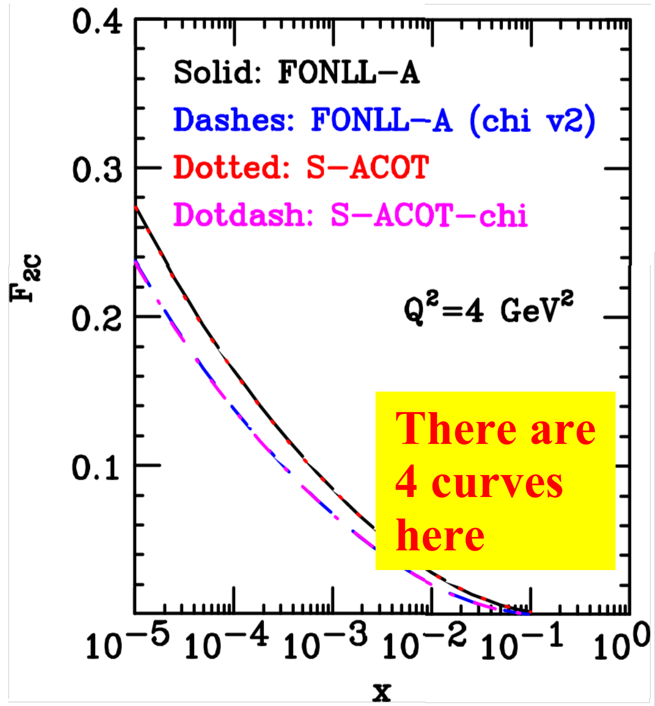
Work is continuing

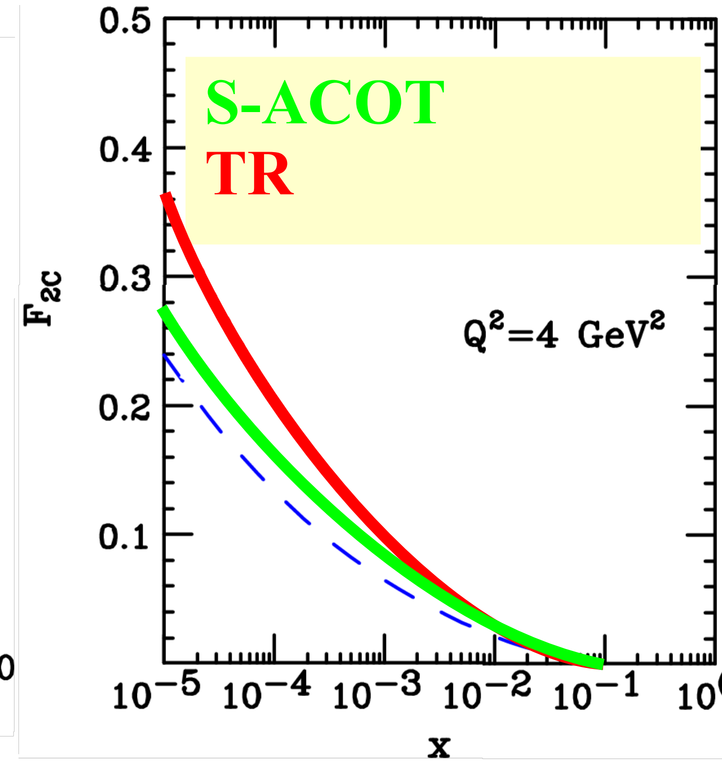
Many of the above incorporated in HERA-Fitter

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

Les Houches Comparative Study







ACOT & S-ACOT essentially identical

... scheme differences are higher order

FONNL & S-ACOT

Numerically similar

MSTW09

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

Differences understood
Should reduce at higher order

The SM and NLO Multileg Working Group: Summary report.
J. Rojo, et al., e-Print: arXiv:1003.1241 [hep-ph]

HERA FITTER

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- More Actions:

HERAFitter

Welcome to HERAFitter Project

HERAFitter is a QCD Fit Package used to determine HERAPDFs and it is part of the HERAPDF project https://www.desy.de/h1zeus.

Downloads of HERAFItter software package

New HERAFitter release is available! The HERAFitter releases can be accessed HERE upon registration. Everyone is free to register.

Registration

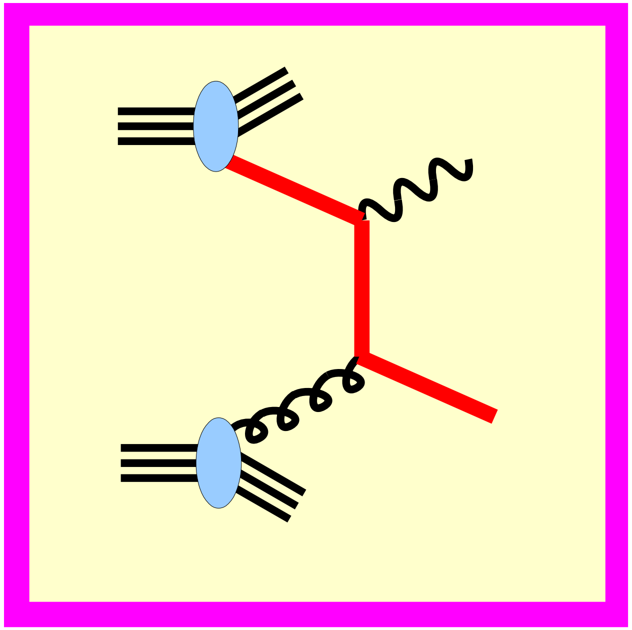
To register, please log in (upper right corner) by creating an account (firstnamelastname, example: JohnSmith) and send your request and login name to `<herafitter-help AT SPAMFREE desy DOT de>`.

HERAFitter Meetings

- User's Meetings: monthly meetings to enhance communication between users and developers (open access)

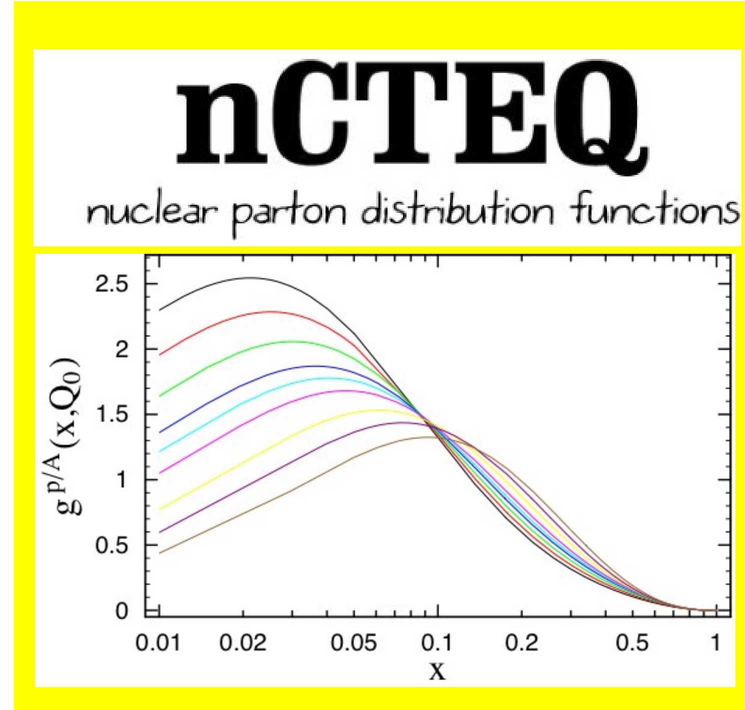
Conclusion

The Challenges

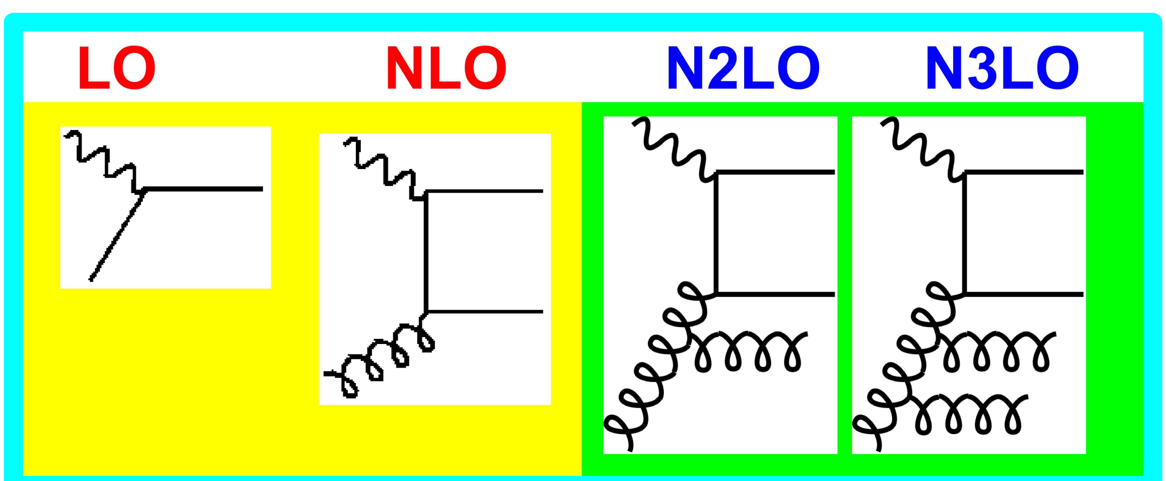


Heavy Quark Issues (Multiscale)

Nuclear Modifications



High Precision / Higher Order Corrections

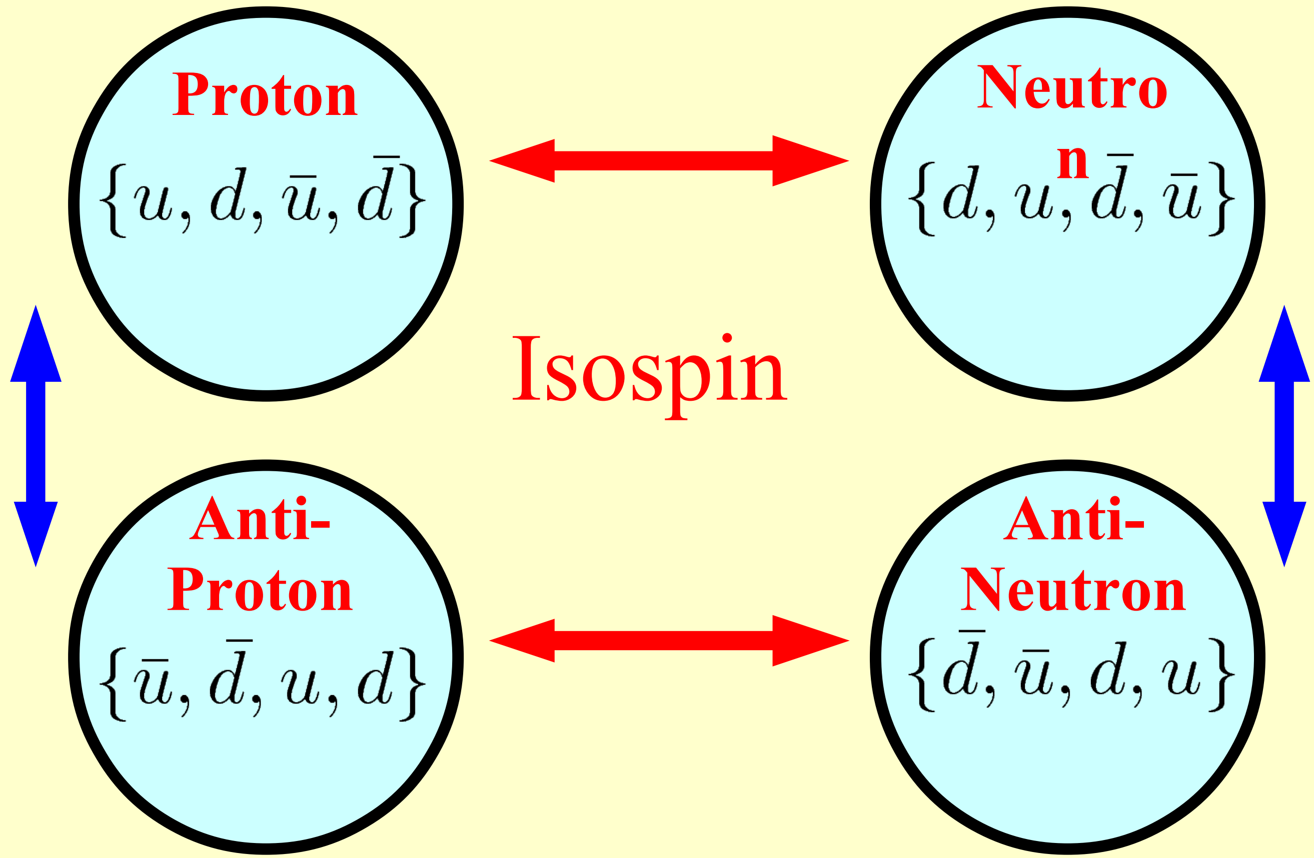


The Future is NOW!

Isospin Symmetry

... taken for granted

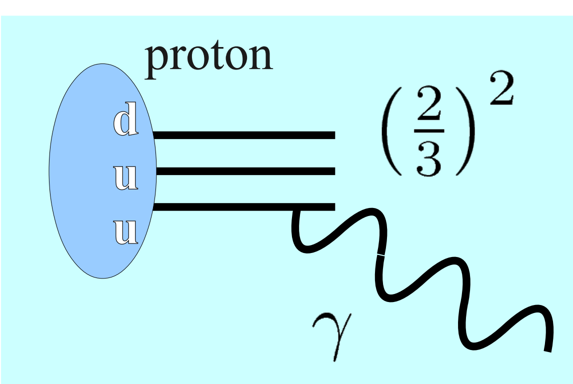
Isospin Symmetry used to relate PDFs

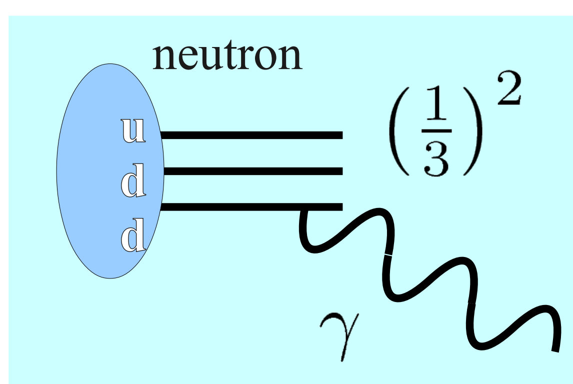


$$q \Leftrightarrow \bar{q}$$

A Review of Target Mass Corrections.
Ingo Schienbein et al,
J.Phys.G35:053101,2008.

MRST, Eur.Phys.J.C39:155-161,2005.

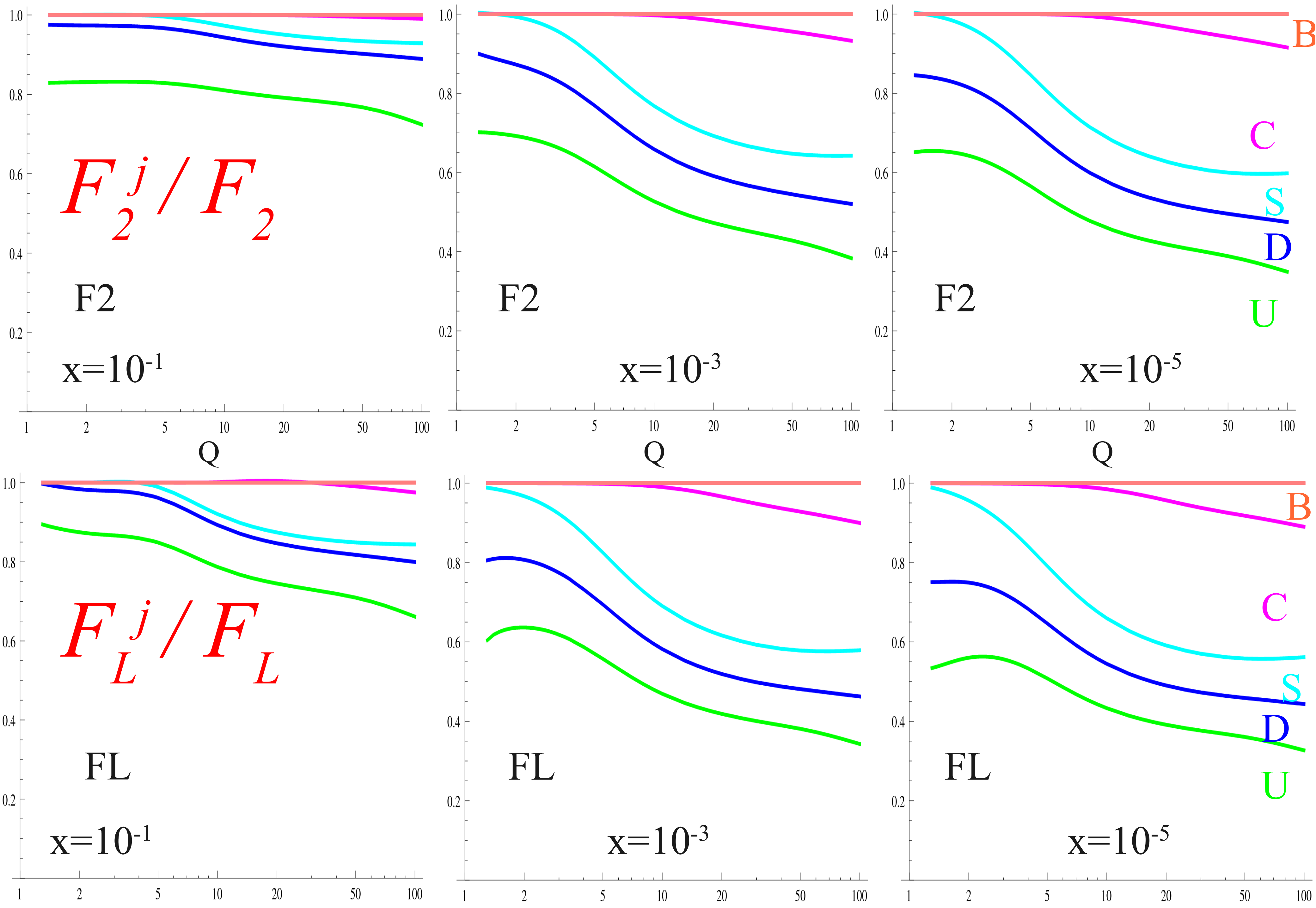




Isospin terms are comparable to NNLO QCD

Fast evolution of parton distributions
Stefan Weinzierlar, Xiv:hep-ph/0203112

FLAVOR DECOMPOSITION: Final State Quark:



Why is F_L so special ???

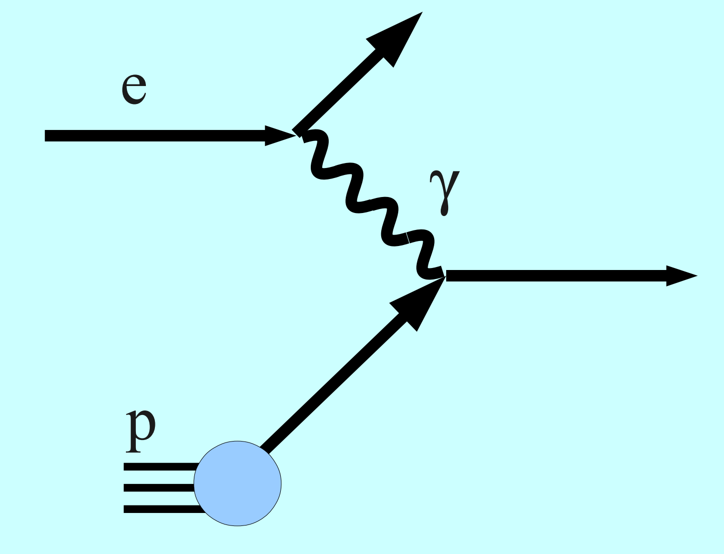
$$\frac{d\sigma^{\nu\,DIS}}{dx\,dy} = (1-y)^2\,\bar{q}(x) + (1-y)\,\phi(x) + q(x)$$

$$\frac{d\sigma^{\nu\,DIS}}{dx\,dy} = (1-y)^2\,F_+(x) + (1-y)\,F_0(x) + F_-(x)$$

$$F_0 = \frac{F_2}{2x} - F_1$$

$$F_0 = 0 \quad\Longrightarrow\quad F_2 = 2xF_1$$

Callan-
Gross



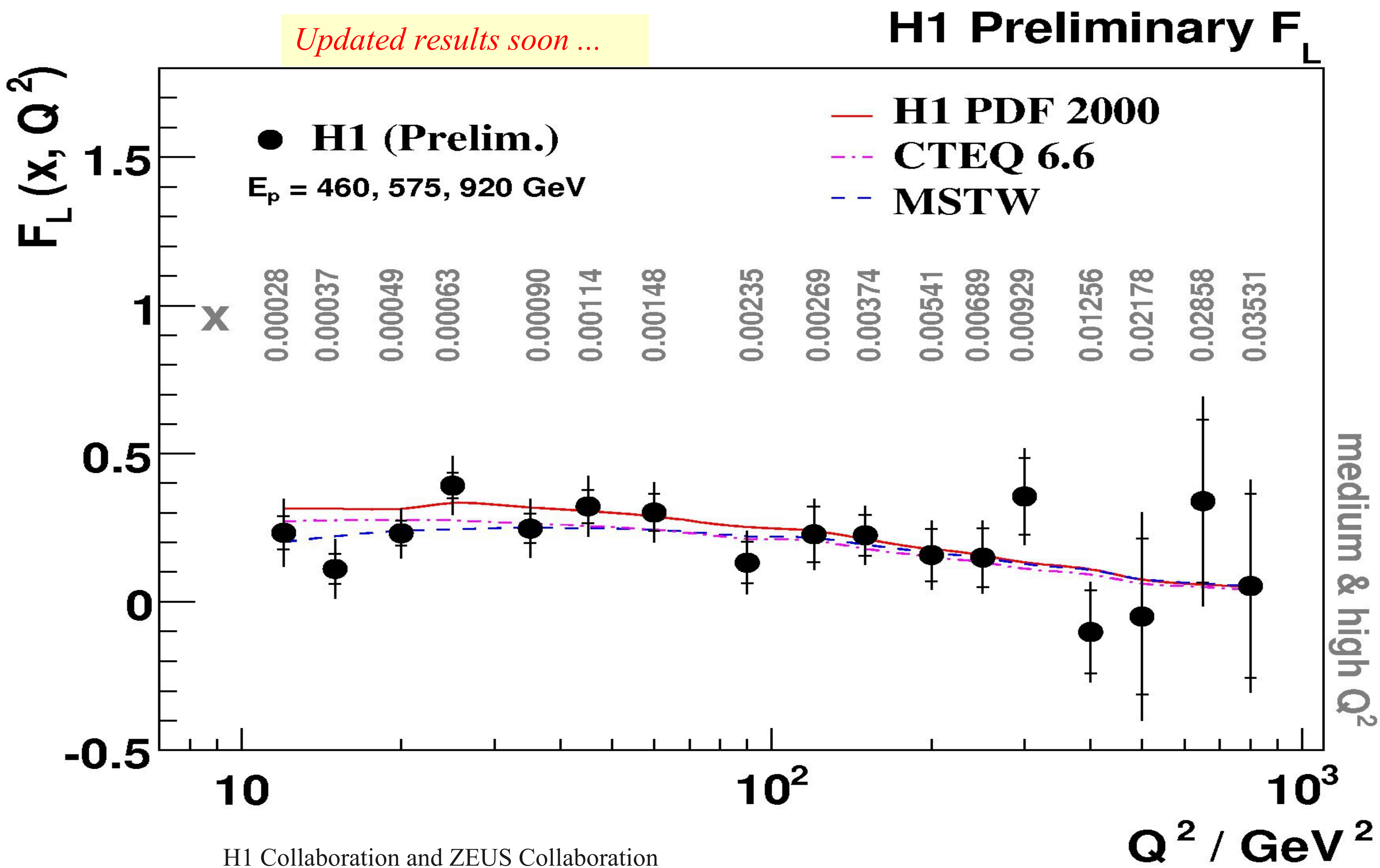
$$F_L \sim \frac{m^2}{Q^2}\,q(x) + \alpha_S\,\{c_g \otimes g(x) + c_q \otimes q(x)\}$$

Masses are importan

Higher Orders are important

New F_L Measurements: New Perspective

Updated results soon ...

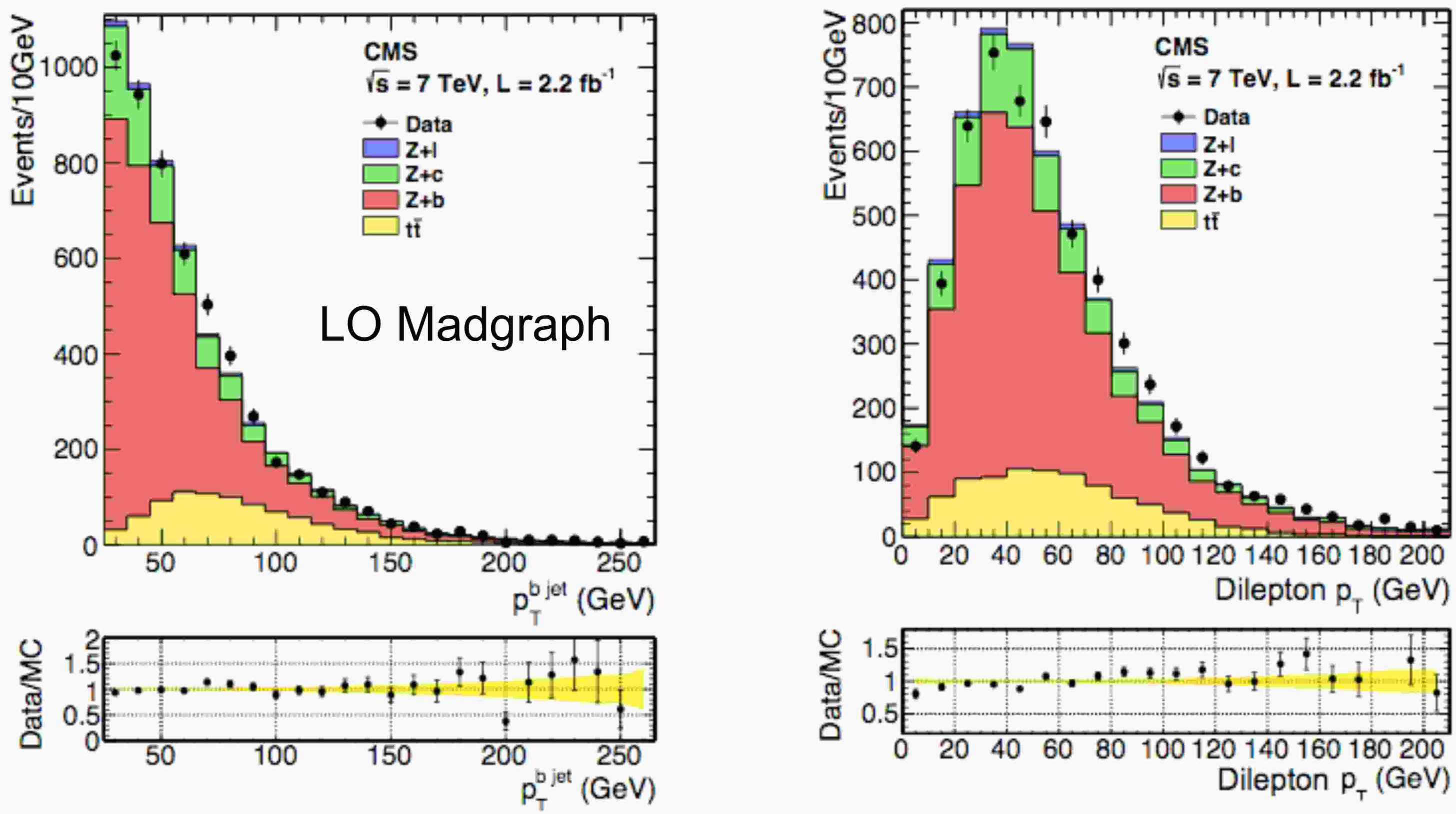


H1 Collaboration and ZEUS Collaboration
(S. Glazov for the collaboration).
Nucl.Phys.Proc.Suppl.191:16-24, 2009.

https://cdsweb.cern.ch/record/1428117

Z+b from CMS

- Compared numerous distributions at 'detector-level' with excellent statistical precision



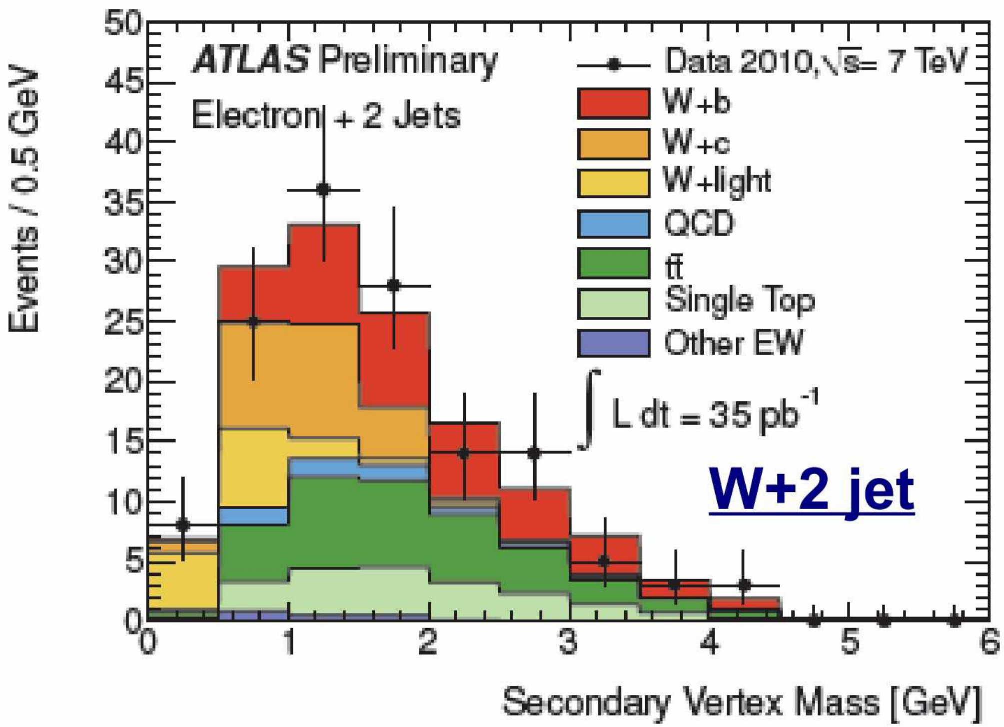
A few differences to data, possibly due to missing higher-order corrections

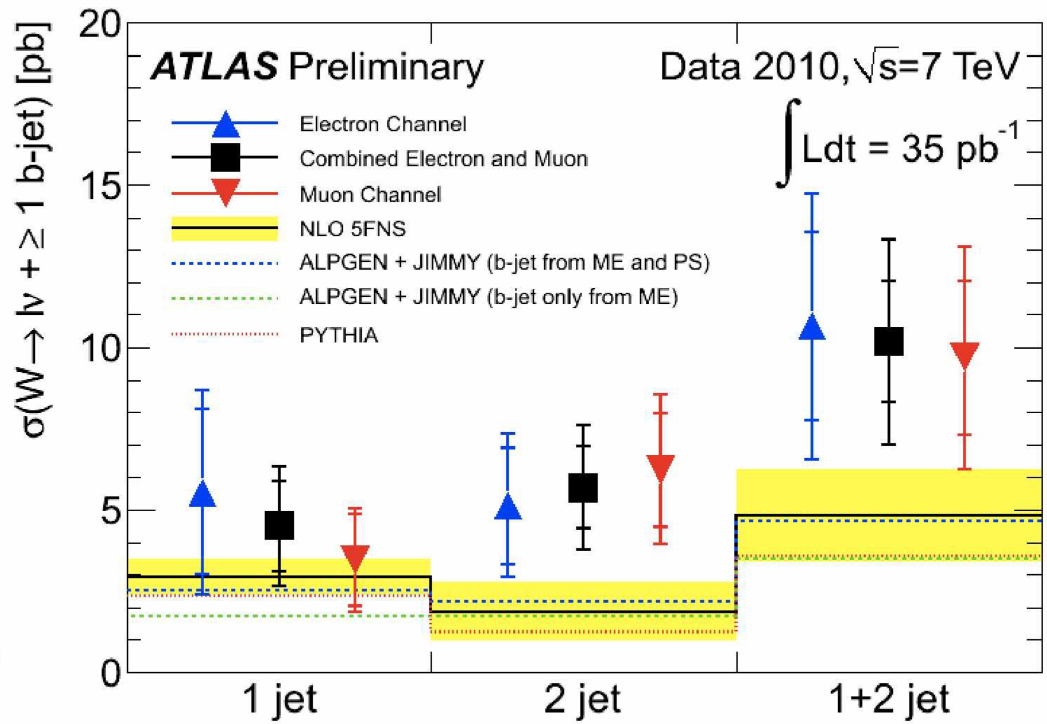
Monida Dunford
(Heidelberg U)
Kyoto, November 2012

First LHC W+b results (ATLAS)

- **Important background for Higgs searches: W+H (H → $b\bar{b}$) at low Higgs masses. Also a background for $t\bar{t}$ and single-top measurements**
- **W+b excess over expectations published by CDF**

A. Messina's talk

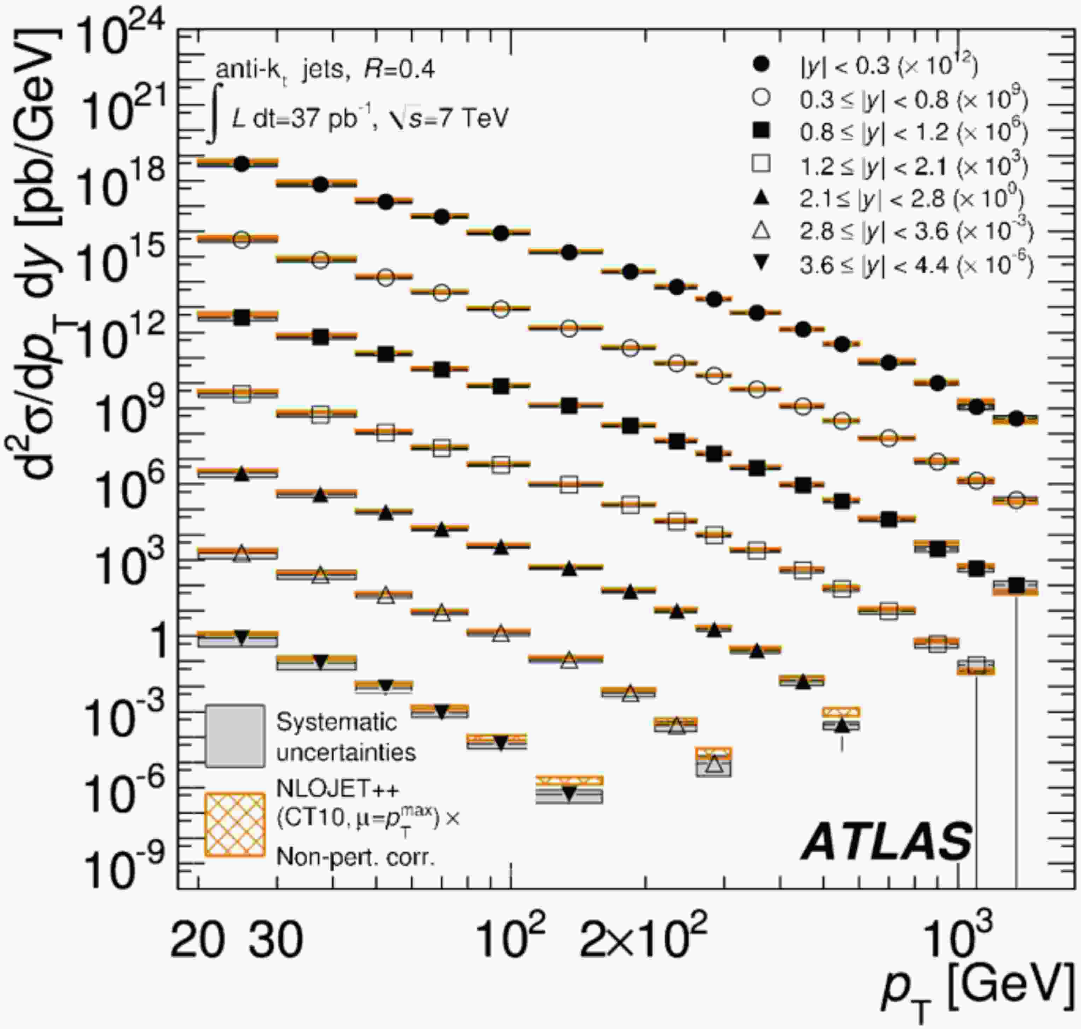




- **Significant decay length (>5.85 σ), fit to the reconstructed mass at secondary vertex**
- **Challenging analysis: it requires significant reduction and control of top backgrounds and W+charm. Analysis performed independently for 1 and 2 b-tags in the event**

Agreement with theoretical predictions at the 1.5 σ level

Inclusive jet cross section

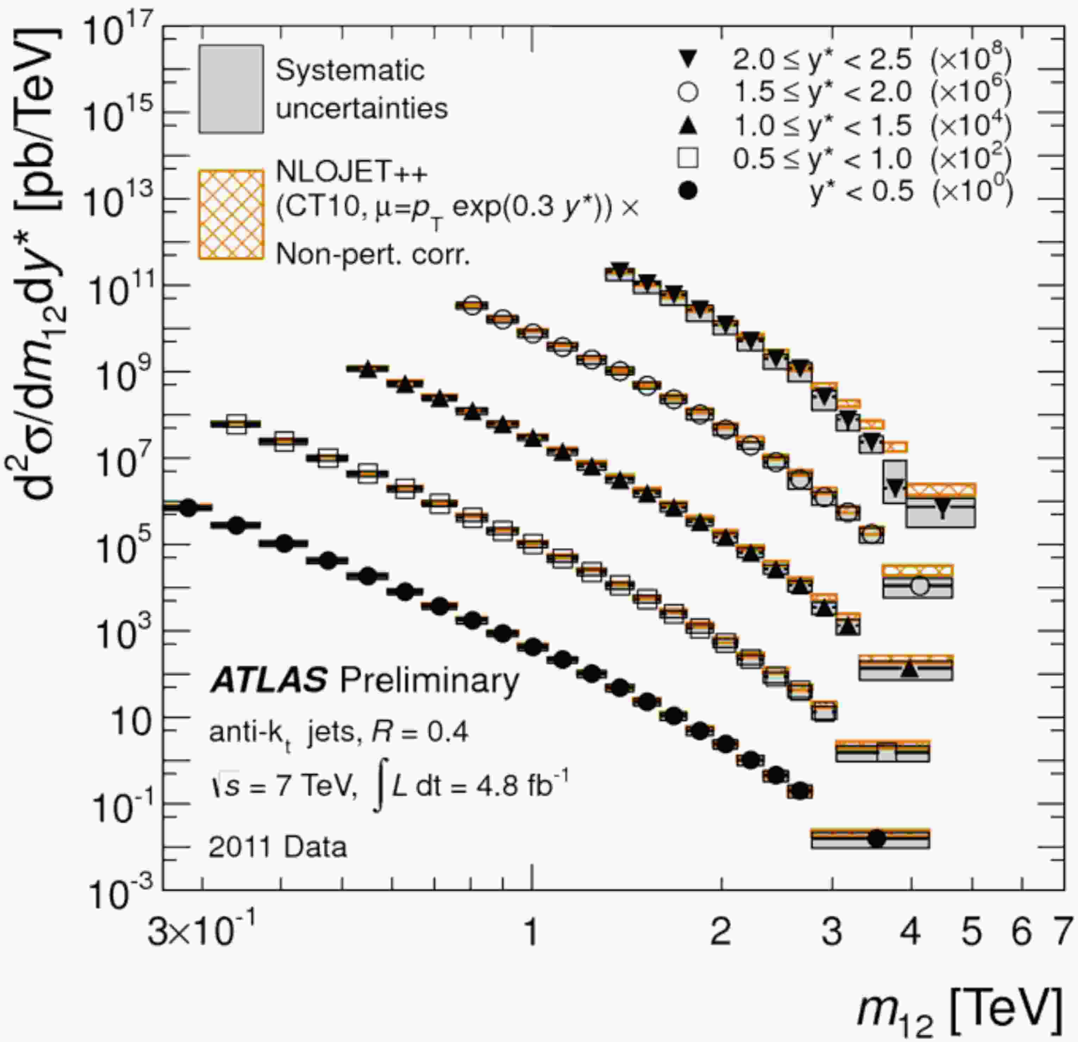


Phys.Rev. D86 (2012) 014022

- Double differential cross section as a function of jet p_T
- Binned in rapidity |y|
- Good agreement with NLOJET++
- Theoretical uncertainties coming from choice of:
  - ★ renormalisation and factorisation scales
  - ★ PDFs
  - ★ alphaS(MZ)
  - ★ Modeling of non-perturbative effects

Dijet production cross section

ATLAS EXPERIMENT
http://atlas.ch



- Double differential cross section as a function of the dijet invariant mass
- Full 2011 dataset
- Dijet mass from 260 GeV to 4.6 TeV
- Binned in y*= |y1-y2|/2
- Good agreement with NLOJET++ and POWHEG +PS

ATLAS-CONF-2012-021