

PDF & nPDF Fits

What happens AFTER the Higgs

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

Les Houches
14 January 2014

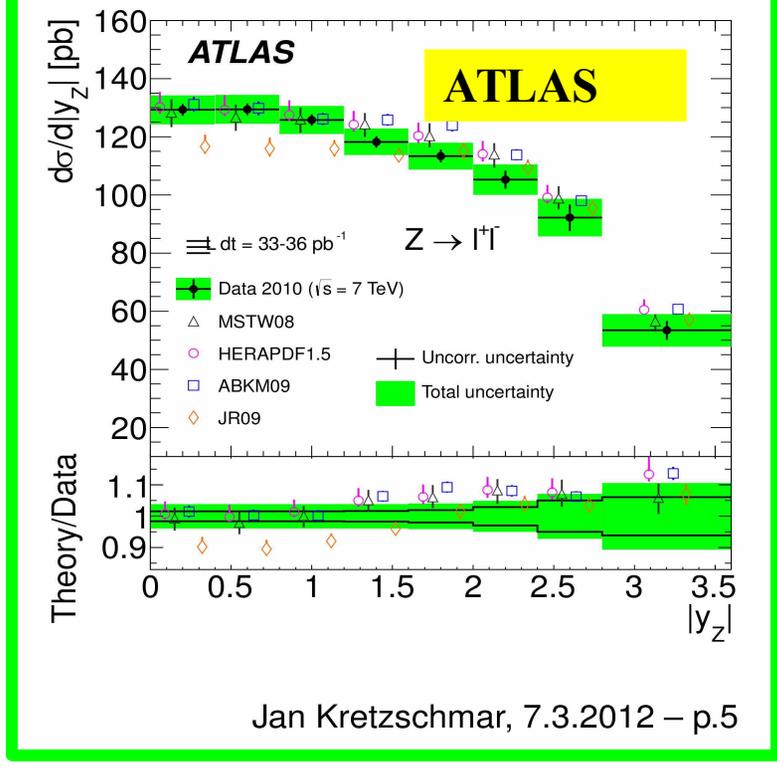
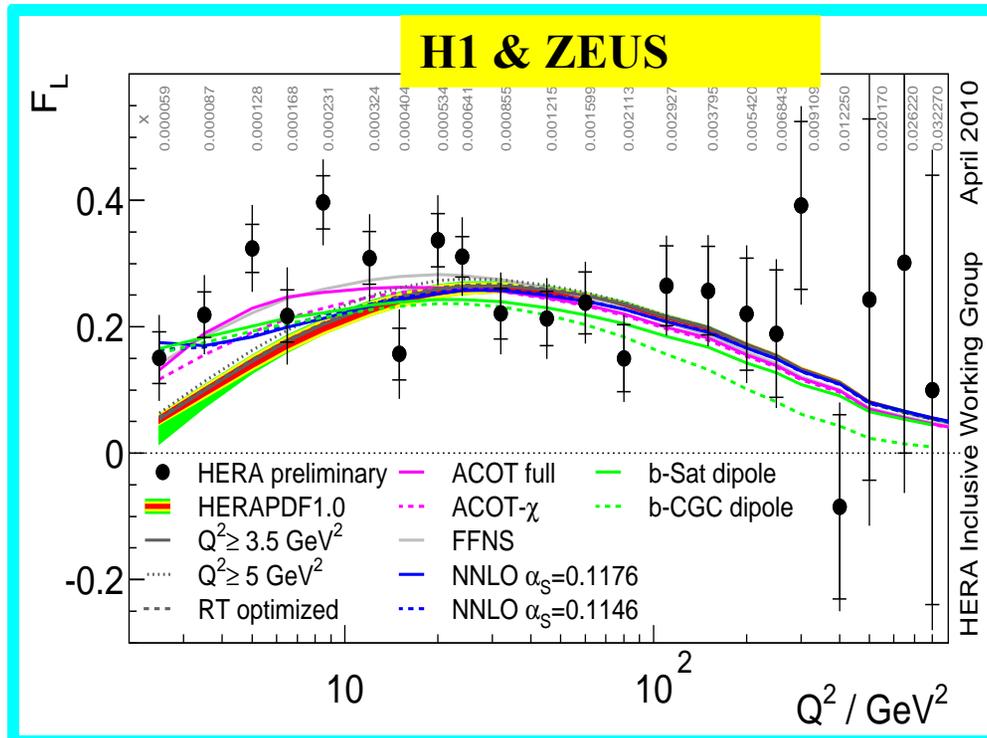
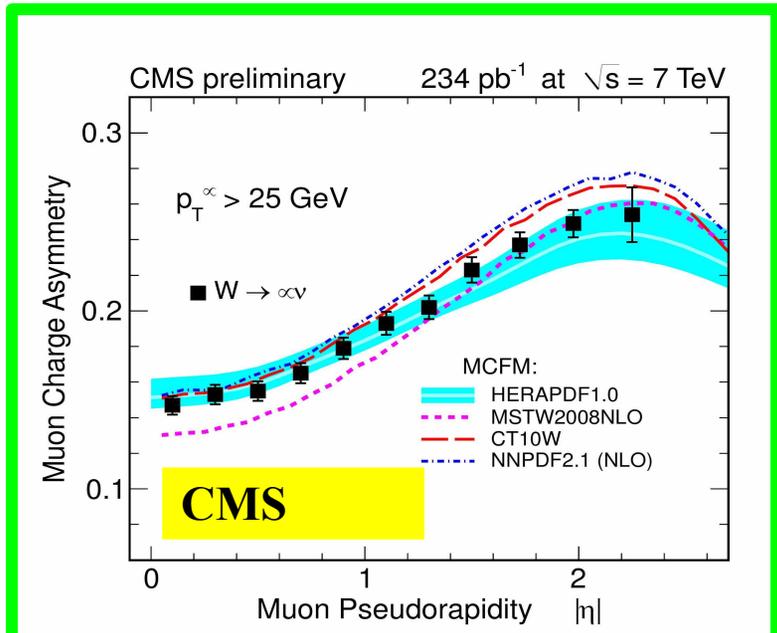
Recent Measurements Spectacular:

ATLAS SUSY Searches* - 95% CL Lower Limits
 Status: SUSY 2013

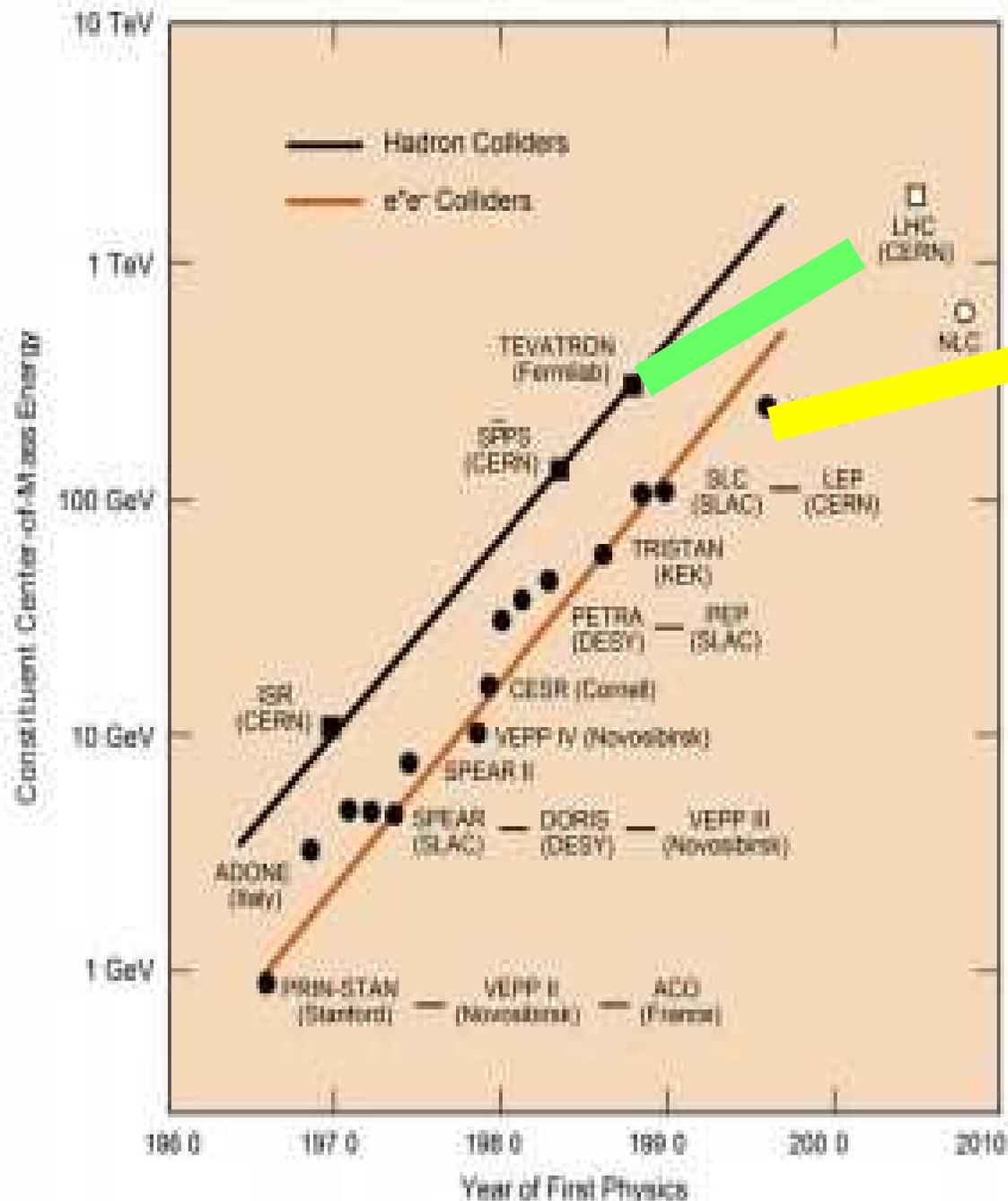
ATLAS Preliminary
 $[L dt = (4.6 - 22.9) \text{ fb}^{-1}$ $\sqrt{s} = 7, 8 \text{ TeV}$

Model	e, μ, τ, γ	Jets	E_{miss}	$[L dt [\text{fb}^{-1}]$	Mass limit	Reference
MSUGRA/CMSM	0	2-6 jets	Yes	20.3	1.7 TeV	m(0)=m(2)
MSUGRA/CMSM	1 e, μ	3-6 jets	Yes	20.3	1.2 TeV	any m(0)
MSUGRA/CMSM	0	7-10 jets	Yes	20.3	1.1 TeV	any m(0)
$\tilde{g}, \tilde{u} \rightarrow q\tilde{q}$	0	2-6 jets	Yes	20.3	740 GeV	$m(\tilde{t}_1) \geq 50 \text{ GeV}$
$\tilde{g}, \tilde{d} \rightarrow q\tilde{q}$	1 e, μ	3-6 jets	Yes	20.3	1.3 TeV	$m(\tilde{t}_1) \geq 50 \text{ GeV}$
$\tilde{g}, \tilde{d} \rightarrow q\tilde{q}(\tau/\nu)/\tilde{\nu}$	1 e, μ	3-6 jets	Yes	20.3	1.18 TeV	$m(\tilde{t}_1) \geq 50 \text{ GeV}, m(\tilde{\nu}) \geq 50 \text{ GeV}$
CMSB (NLSB)	2 e, μ	2-4 jets	Yes	20.3	1.12 TeV	$m(\tilde{t}_1) \geq 50 \text{ GeV}$
CMSB (NLSB)	1, 2 τ	0-2 jets	Yes	4.7	1.24 TeV	lepton-10
CGM (one NLSB)	0	1-6 jets	Yes	4.8	1.07 TeV	$m(\tilde{t}_1) \geq 50 \text{ GeV}$
CGM (w/o NLSB)	1 e, μ	1-6 jets	Yes	4.8	610 GeV	$m(\tilde{t}_1) \geq 50 \text{ GeV}$
CGM (higgsino-like NLSB)	2 e, μ	0-3 jets	Yes	5.8	690 GeV	$m(\tilde{t}_1) \geq 50 \text{ GeV}$
Gravitino LSP	0	mono-jet	Yes	10.5	645 GeV	$m(\tilde{g}) \geq 10^{-1} \text{ eV}$
$\tilde{g} \rightarrow q\tilde{q}$	0	3-6 jets	Yes	20.1	1.2 TeV	$m(\tilde{t}_1) \geq 600 \text{ GeV}$
$\tilde{g} \rightarrow t\tilde{t}$	0	7-10 jets	Yes	20.3	1.1 TeV	$m(\tilde{t}_1) \geq 350 \text{ GeV}$
$\tilde{g} \rightarrow b\tilde{b}$	0-1 e, μ	3-6 jets	Yes	20.1	1.24 TeV	$m(\tilde{t}_1) \geq 400 \text{ GeV}$
$\tilde{g} \rightarrow b\tilde{b}$	0-1 e, μ	3-6 jets	Yes	20.1	1.3 TeV	$m(\tilde{t}_1) \geq 300 \text{ GeV}$
$\tilde{b}_1, \tilde{b}_2 \rightarrow b\tilde{b}$	0	2-6 jets	Yes	20.1	100-620 GeV	$m(\tilde{t}_1) \geq 90 \text{ GeV}$
$\tilde{b}_1, \tilde{b}_2 \rightarrow t\tilde{t}$	2 e, μ (SS)	0-3-6 jets	Yes	20.7	275-430 GeV	$m(\tilde{t}_1) \geq 100 \text{ GeV}$
$\tilde{t}_1 \rightarrow q\tilde{t}$	1-2 e, μ	1-2-6 jets	Yes	4.7	110-167 GeV	$m(\tilde{t}_1) \geq 56 \text{ GeV}$
$\tilde{t}_1 \rightarrow q\tilde{t}$	1-2 e, μ	1-2-6 jets	Yes	20.3	130-220 GeV	$m(\tilde{t}_1) \geq 56 \text{ GeV}$
$\tilde{t}_1 \rightarrow q\tilde{t}$	2 e, μ	0-2 jets	Yes	20.3	225-525 GeV	$m(\tilde{t}_1) \geq 200 \text{ GeV}, m(\tilde{\nu}) \geq 50 \text{ GeV}$
$\tilde{t}_1 \rightarrow q\tilde{t}$	2 e, μ	0-2 jets	Yes	20.1	150-580 GeV	$m(\tilde{t}_1) \geq 200 \text{ GeV}, m(\tilde{\nu}) \geq 50 \text{ GeV}$
$\tilde{t}_1 \rightarrow q\tilde{t}$	1 e, μ	1-6 jets	Yes	20.7	200-610 GeV	$m(\tilde{t}_1) \geq 50 \text{ GeV}$
$\tilde{t}_1 \rightarrow q\tilde{t}$	1 e, μ	1-6 jets	Yes	20.7	320-660 GeV	$m(\tilde{t}_1) \geq 50 \text{ GeV}$
$\tilde{t}_1 \rightarrow q\tilde{t}$	0	2-6 jets	Yes	20.5	90-200 GeV	$m(\tilde{t}_1) \geq 50 \text{ GeV}$
$\tilde{t}_1 \rightarrow q\tilde{t}$	2 e, μ (Z)	1-6 jets	Yes	20.7	500 GeV	$m(\tilde{t}_1) \geq 100 \text{ GeV}$
$\tilde{t}_1 \rightarrow q\tilde{t}$	3 e, μ (Z)	1-6 jets	Yes	20.7	271-520 GeV	$m(\tilde{t}_1) \geq 100 \text{ GeV}$
$\tilde{t}_1 \rightarrow q\tilde{t}$	2 e, μ	0	Yes	20.3	85-315 GeV	$m(\tilde{t}_1) \geq 50 \text{ GeV}$
$\tilde{t}_1 \rightarrow q\tilde{t}$	2 e, μ	0	Yes	20.3	125-450 GeV	$m(\tilde{t}_1) \geq 50 \text{ GeV}, m(\tilde{\nu}) \geq 50 \text{ GeV}$
$\tilde{t}_1 \rightarrow q\tilde{t}$	2 e, μ	0	Yes	20.7	100-300 GeV	$m(\tilde{t}_1) \geq 50 \text{ GeV}, m(\tilde{\nu}) \geq 50 \text{ GeV}$
$\tilde{t}_1 \rightarrow q\tilde{t}$	3 e, μ	0	Yes	20.7	315 GeV	$m(\tilde{t}_1) \geq 50 \text{ GeV}, m(\tilde{\nu}) \geq 50 \text{ GeV}$
$\tilde{t}_1 \rightarrow q\tilde{t}$	1 e, μ	2-6 jets	Yes	20.3	285 GeV	$m(\tilde{t}_1) \geq 50 \text{ GeV}, m(\tilde{\nu}) \geq 50 \text{ GeV}$
Direct $\tilde{t}_1 \tilde{t}_1^*$ prod. long-lived \tilde{t}_1	Disapp. trk	1 jet	Yes	20.3	270 GeV	$m(\tilde{t}_1) \geq 160 \text{ MeV}, \tau(\tilde{t}_1) \geq 0.2 \text{ ns}$
Stable stopped \tilde{t}_1 hadron	0	1-5 jets	Yes	22.9	180-300 GeV	$m(\tilde{t}_1) \geq 100 \text{ GeV}, 10^{-6} \text{ s} < \tau(\tilde{t}_1) < 1000 \text{ s}$
GMSB, stable $\tilde{t}_1 \rightarrow \tau(e, \mu) + (e, \mu)$	1-2 μ	0	Yes	15.9	475 GeV	$10^{-6} \text{ s} < \tau(\tilde{t}_1) < 1000 \text{ s}$
GMSB, $\tilde{t}_1 \rightarrow \tau(e, \mu) + \nu$	1-2 μ	0	Yes	4.7	230 GeV	$10^{-6} \text{ s} < \tau(\tilde{t}_1) < 1000 \text{ s}$
$\tilde{g}, \tilde{u} \rightarrow q\tilde{q}$ (RPV)	1 μ , displ. vtx	0-3-6 jets	Yes	20.3	1.0 TeV	$1.5 \times 10^{-15} \text{ s} < \tau(\tilde{u}) < 108 \text{ GeV}$
LFV $\tilde{g} \rightarrow \tilde{g} + X, \tilde{t}_1 \rightarrow \tilde{t}_1 + \mu$	2 e, μ	0	Yes	4.6	1.61 TeV	$\tilde{a}_{11} = 0.10, \tilde{a}_{22} = 0.05$
LFV $\tilde{g} \rightarrow \tilde{g} + X, \tilde{t}_1 \rightarrow \tilde{t}_1 + \tau$	1 e, μ	0	Yes	4.6	1.3 TeV	$\tilde{a}_{11} = 0.10, \tilde{a}_{22} = 0.05$
Bi-linear RPV CMSM	1 e, μ	7 jets	Yes	4.7	1.2 TeV	$m(0)=m(2), \tau_{\tilde{t}_1} < 1 \text{ mm}$
$\tilde{t}_1 \tilde{t}_1^* \rightarrow W\tilde{t}_1 \tilde{t}_1^* \rightarrow ee\nu, e\nu\nu$	4 e, μ	0	Yes	20.7	300 GeV, $A_{222} = 0$	$m(\tilde{t}_1) \geq 300 \text{ GeV}, A_{222} = 0$
$\tilde{t}_1 \tilde{t}_1^* \rightarrow W\tilde{t}_1 \tilde{t}_1^* \rightarrow \tau\nu\nu, e\nu\nu$	3 e, μ, τ	0	Yes	20.7	350 GeV	$m(\tilde{t}_1) \geq 300 \text{ GeV}, A_{222} = 0$
$\tilde{g} \rightarrow q\tilde{q}$	0	6-7 jets	Yes	20.3	916 GeV	$\text{BR}(\tilde{g} \rightarrow \text{BR}(\tilde{g}) - \text{BR}(\tilde{g})) < 0\%$
$\tilde{g} \rightarrow t\tilde{t}, \tilde{t}_1 \rightarrow b\tilde{t}$	2 e, μ (SS)	0-3-6 jets	Yes	20.7	860 GeV	$\text{BR}(\tilde{g} \rightarrow \text{BR}(\tilde{g}) - \text{BR}(\tilde{g})) < 0\%$
Scalar gluon pair, sgluon $\rightarrow q\tilde{q}$	0	4 jets	Yes	4.6	100-267 GeV	ind. limit from 110.2693
Scalar gluon pair, sgluon $\rightarrow t\tilde{t}$	2 e, μ (SS)	1-6 jets	Yes	14.3	500 GeV	$m(\tilde{t}_1) \geq 80 \text{ GeV}, \text{limit of } 687 \text{ GeV for DB}$
WW interaction (SS, GMSB)	0	mono-jet	Yes	10.5	705 GeV	$m(\tilde{t}_1) \geq 80 \text{ GeV}, \text{limit of } 687 \text{ GeV for DB}$

*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1 σ theoretical signal cross section uncertainty.



What Physics is AFTER the Higgs Discovery???



Hadron colliders

Intersecting Storage Rings	CERN, 1971–1984
Super Proton Synchrotron	CERN, 1981–1984
ISABELLE	BNL, cancelled in 1983
Tevatron	Fermilab, 1987–2011
Relativistic Heavy Ion Collider	BNL, 2000–present
Superconducting Super Collider	Cancelled in 1993
Large Hadron Collider	CERN, 2009–present
High Luminosity Large Hadron Collider	Proposed, CERN, 2020–
Very Large Hadron Collider	Theoretical

The Parton Model and Factorization

$$\sigma_{P\gamma \rightarrow c} = f_{P \rightarrow a} \otimes \hat{\sigma}_{a\gamma \rightarrow c}$$

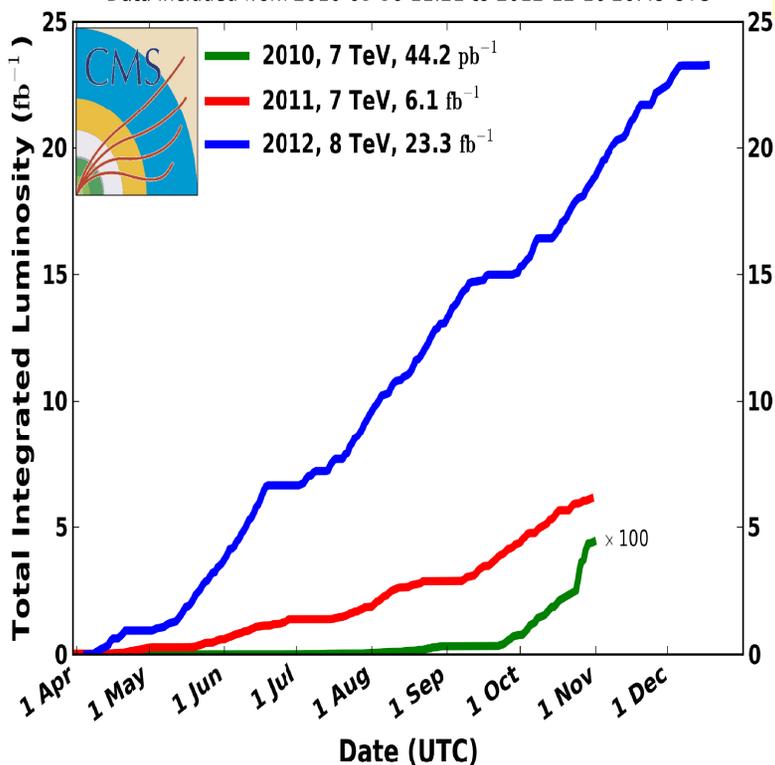
Experimental Observables

Theoretical Calculations

WHAT ABOUT PDF'S ???

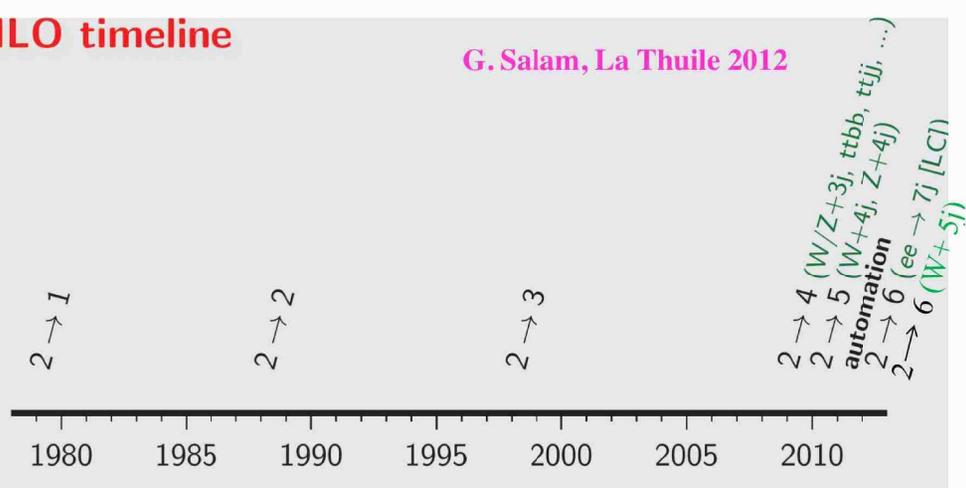
CMS Integrated Luminosity, pp

Data included from 2010-03-30 11:21 to 2012-12-16 20:49 UTC

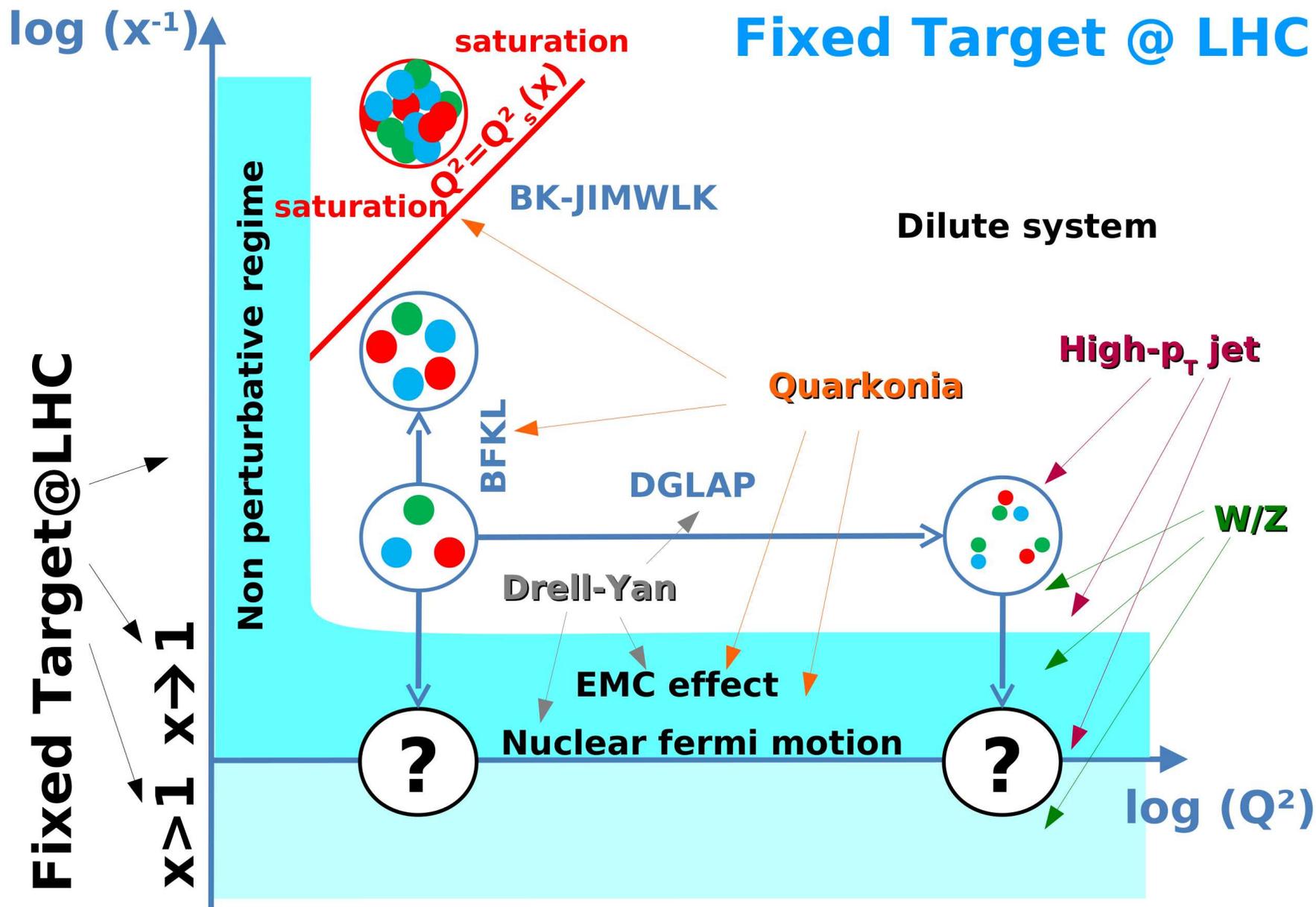


NLO timeline

G. Salam, La Thuile 2012



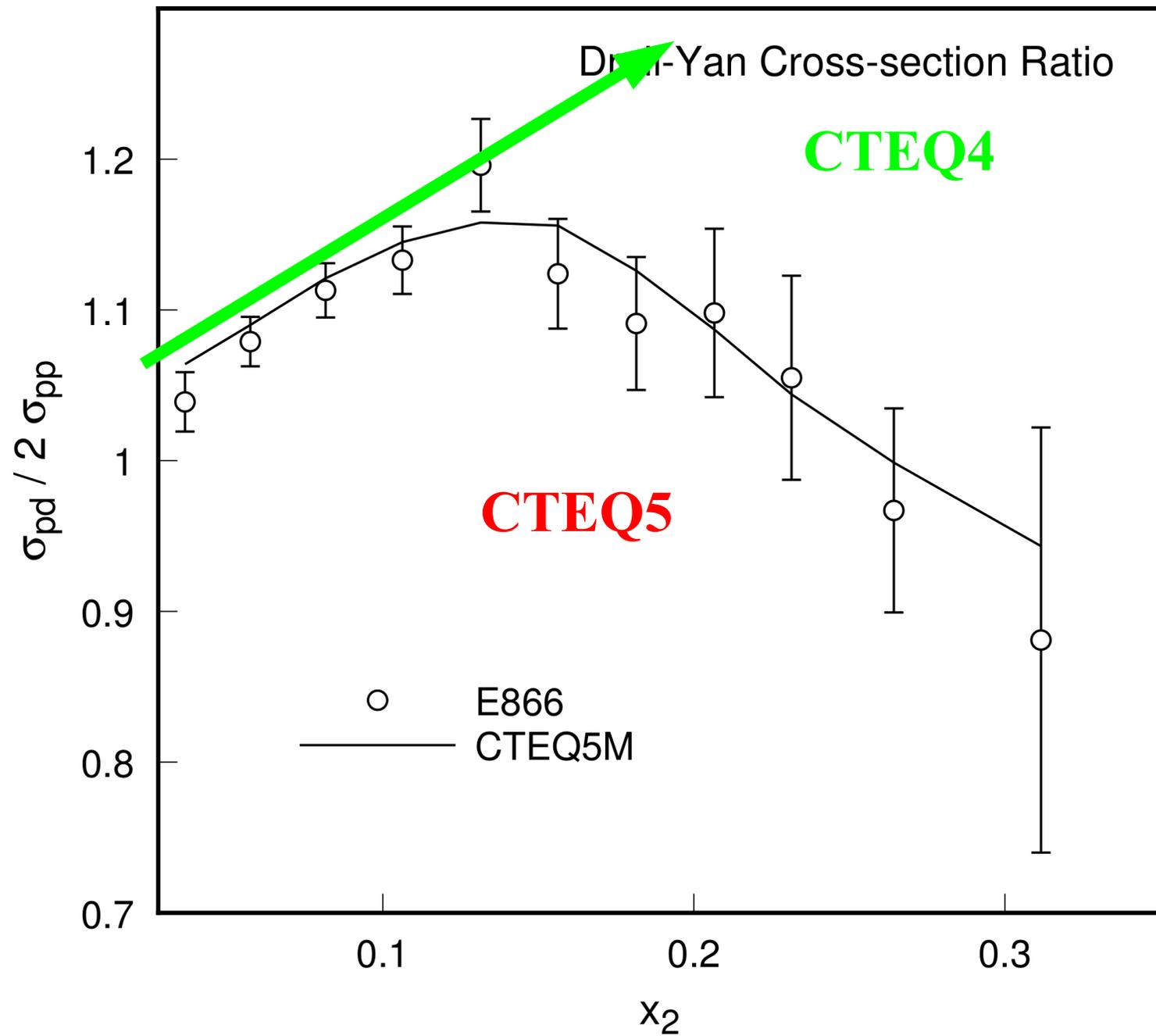
Fixed Target @ LHC



Fixed Target@LHC

$x > 1$ $x \rightarrow 1$

How one experiment can make a difference



Some issues we encounter:

- 1) Nuclear Corrections
- 2) Heavy Quarks & Intrinsic Components
- 3) High X
- 4) Isospin Symmetry

Without a good foundation ...



W/Z Production

“Benchmark Calculations”

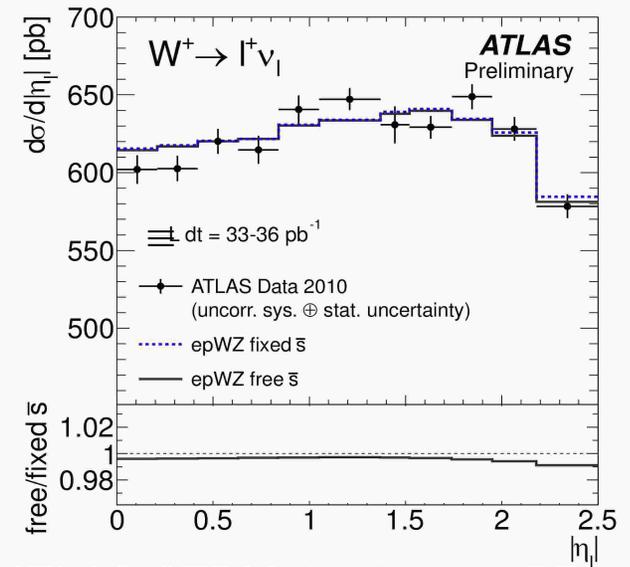
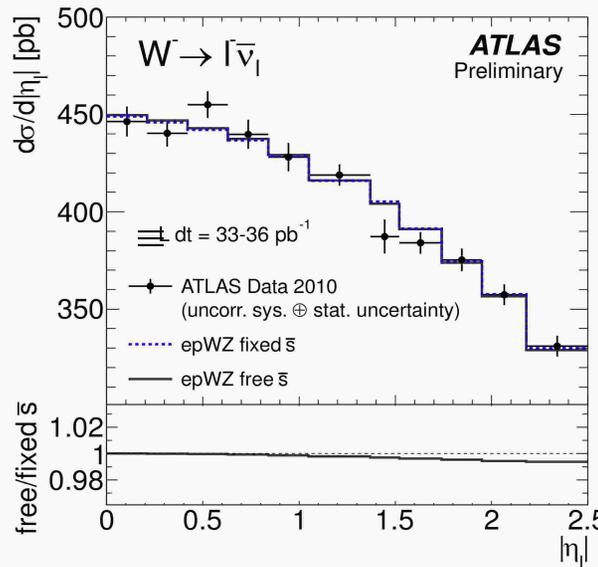
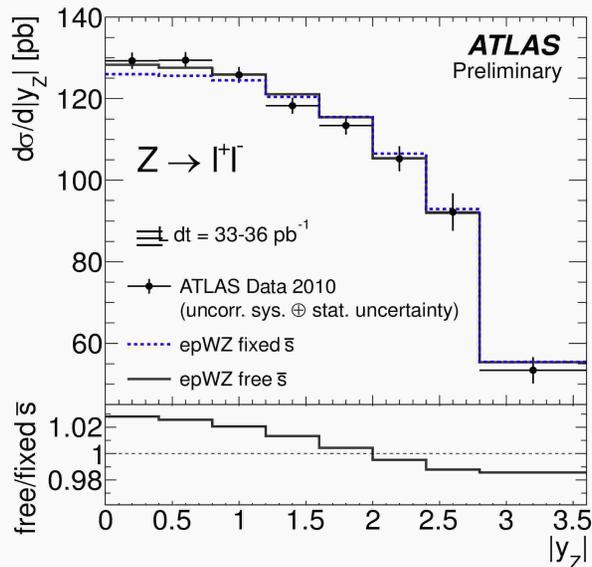
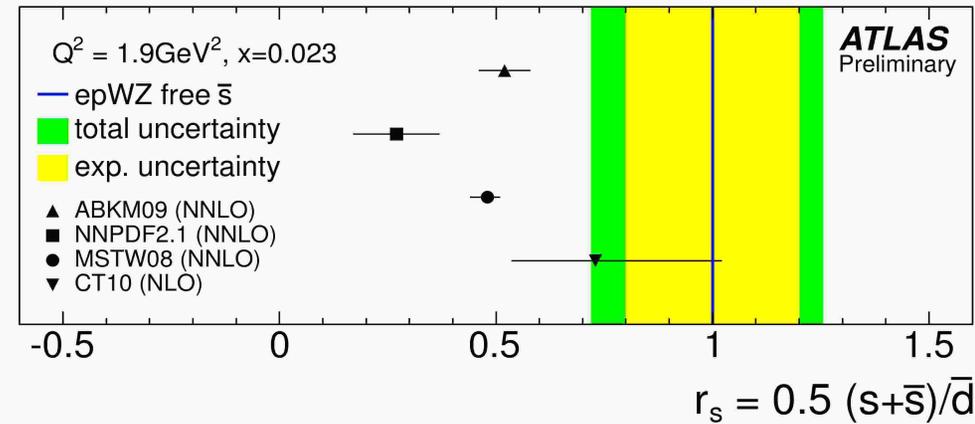
...influence of Fixed-Targets at LHC

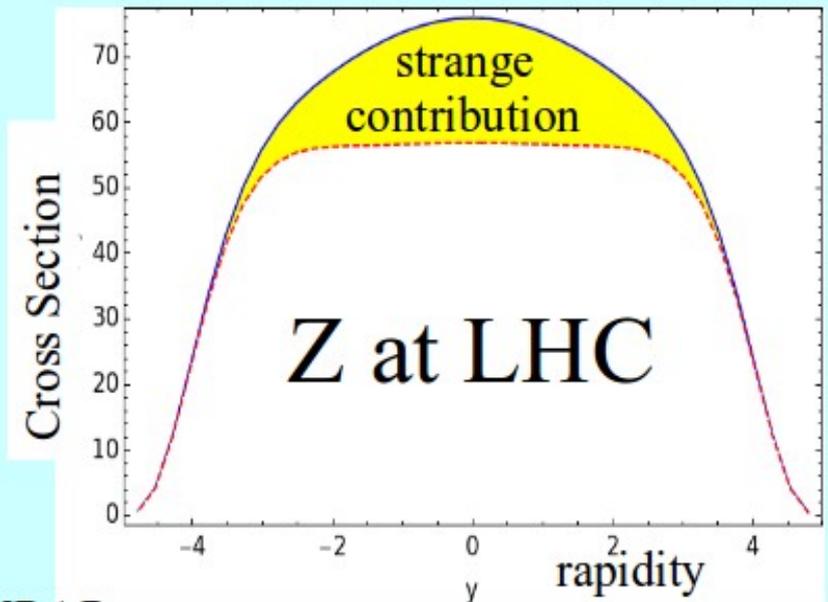
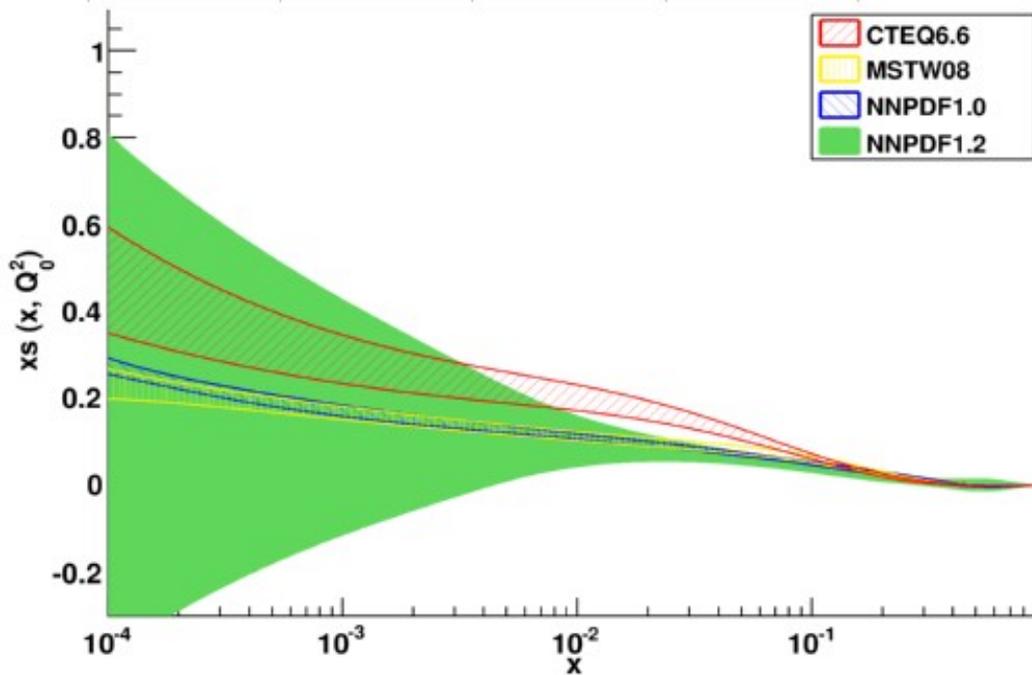
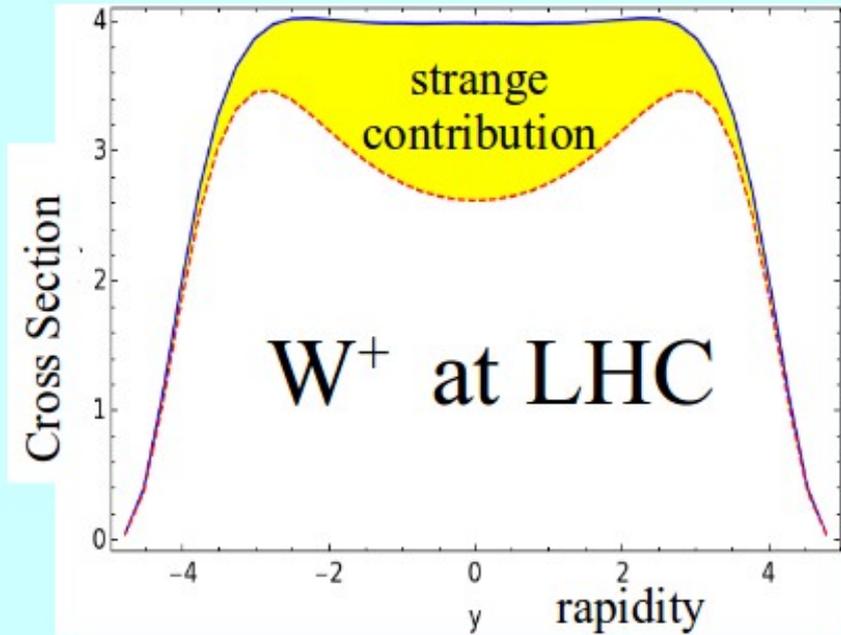
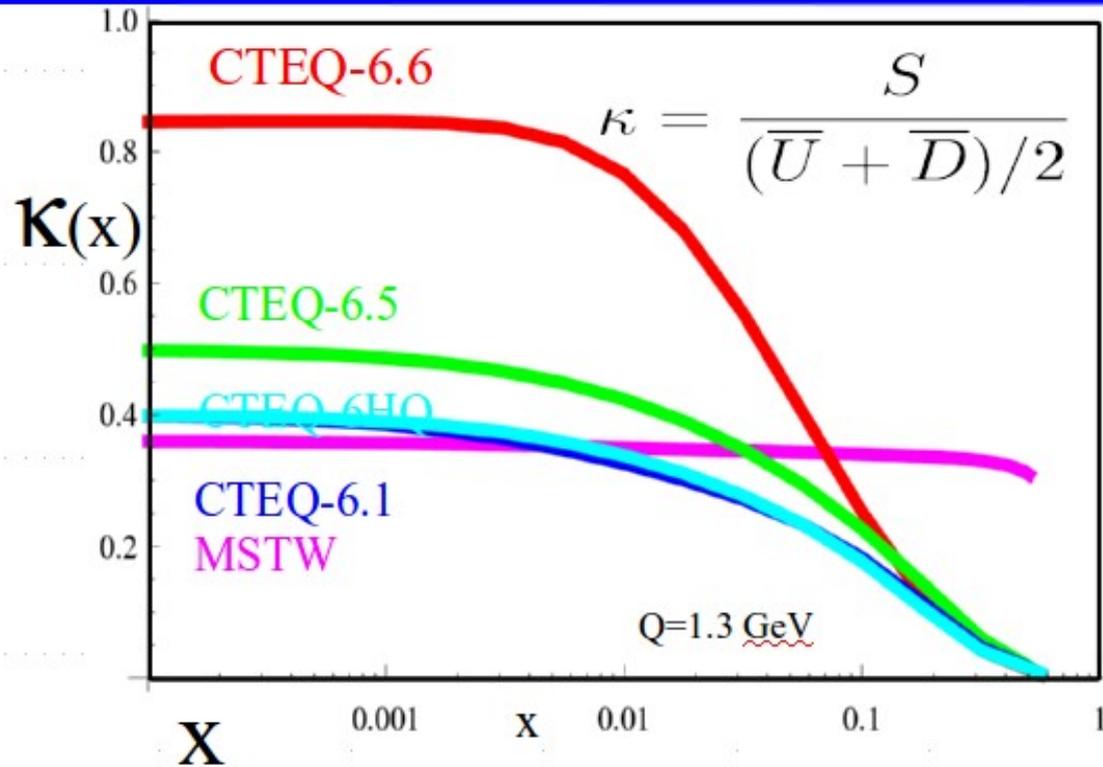
An example

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 GeV^2
- Fit with free strange sea gives no suppression

$$r_s = 1.00 \pm 0.20_{\text{exp}} \begin{matrix} +0.16 \\ -0.20 \text{ sys} \end{matrix}$$



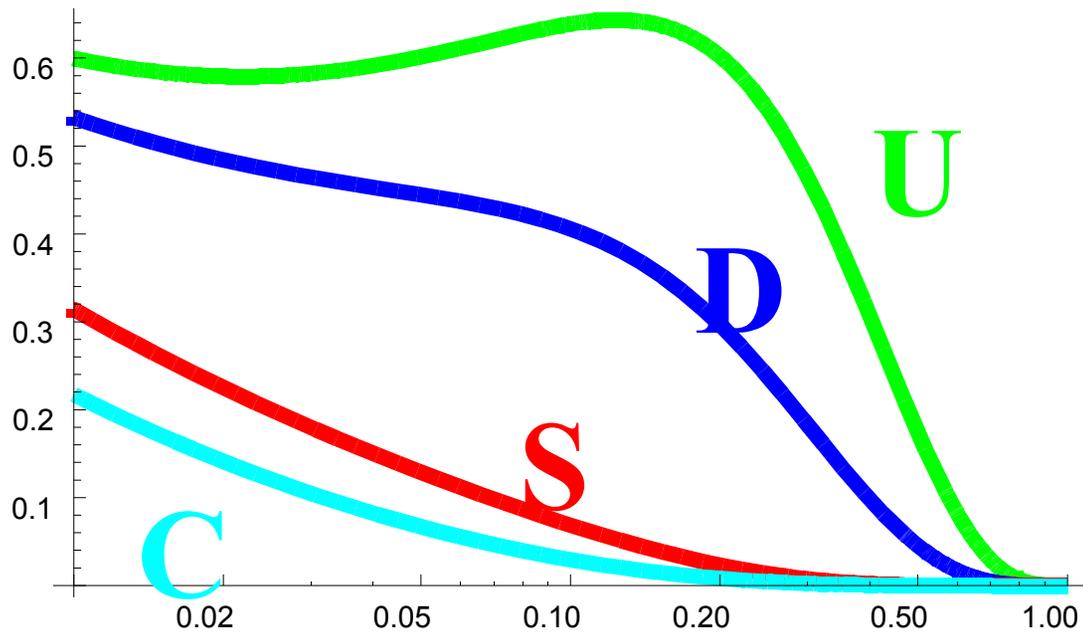


VRAP
Code

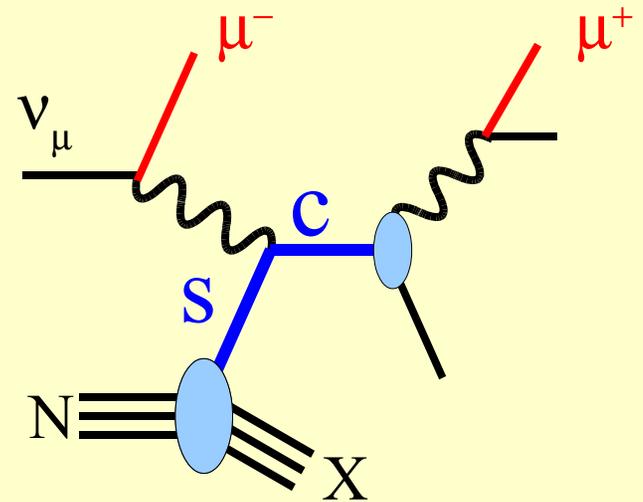
Anastasiou, Dixon, Melnikov, Petriello,
Phys.Rev.D69:094008,2004.

What constrains the Strange???

Not much



Neutrino Di-muon production



**Depends on
nuclear
corrections**

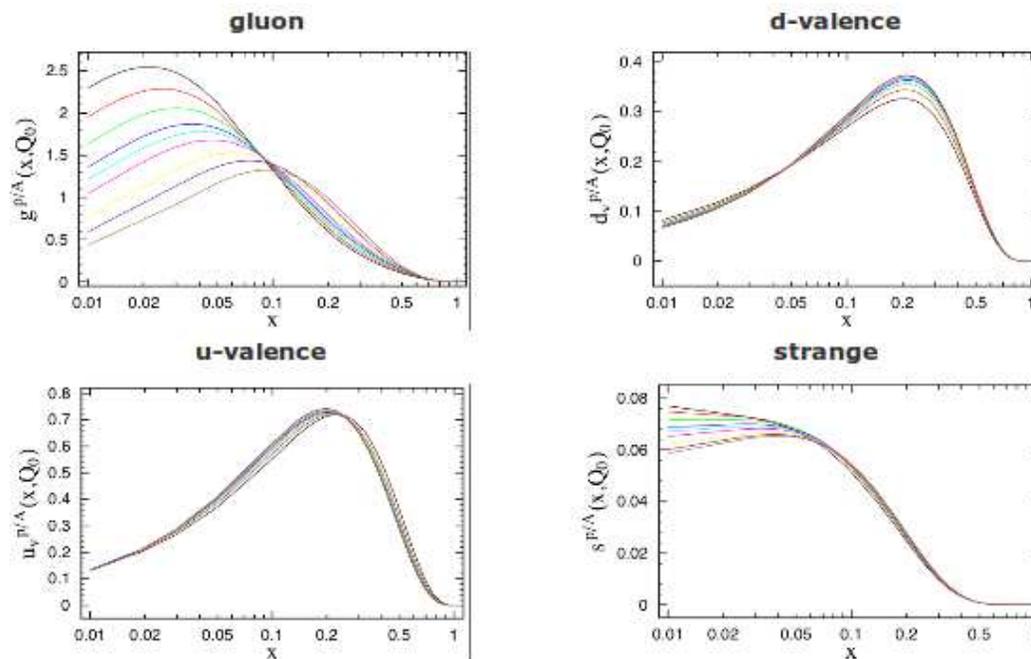
nCTEQ

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 \[hep-ph\]](https://arxiv.org/abs/09072357).

The effects of the nuclear environment 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.

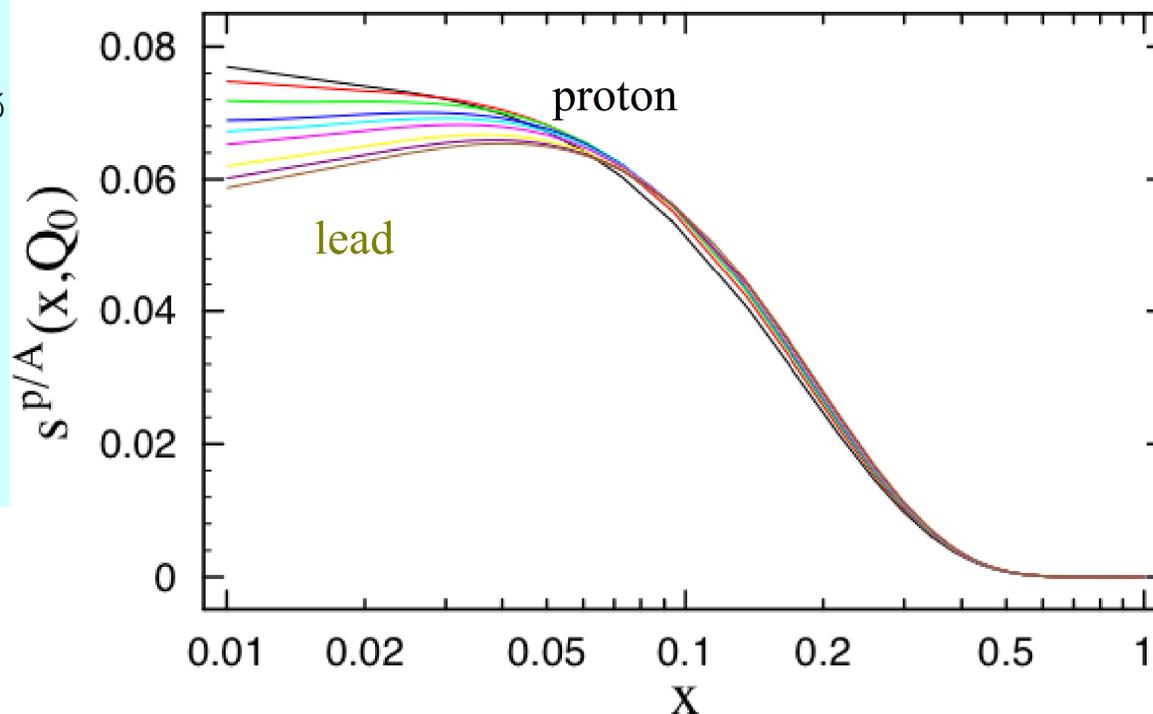
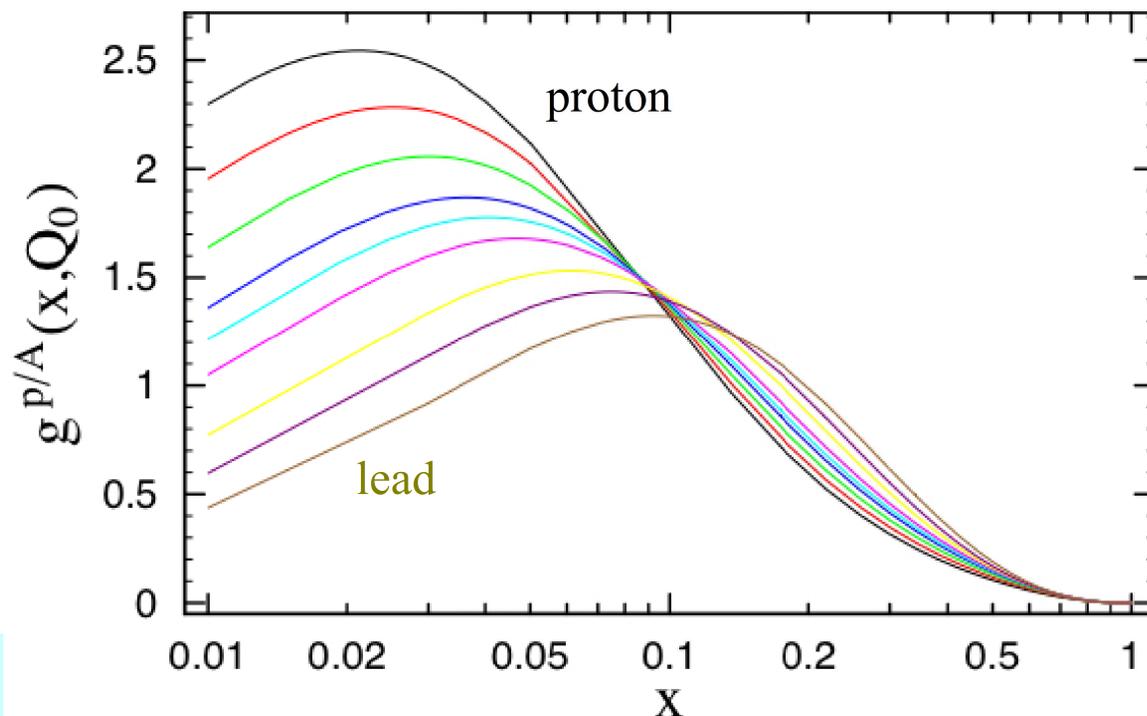
- ✓ CTEQ style global fit extended
handle various nuclear targets
- ✓ CTEQ Data + nuclear DIS & DY
[~15 targets; ~2000+ data]
- ✓ A-dependence modeled;
NLO fits work well

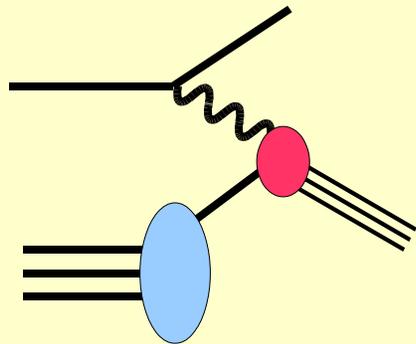
A-Dependent PDFs

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

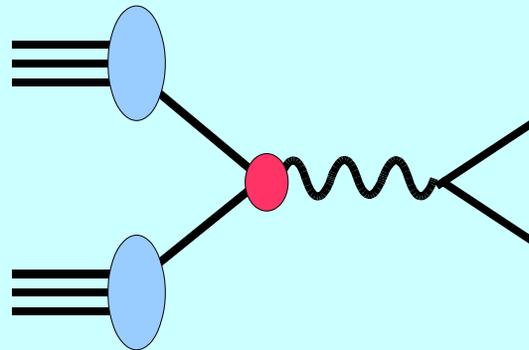
$$a_i \rightarrow a_i(A)$$

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

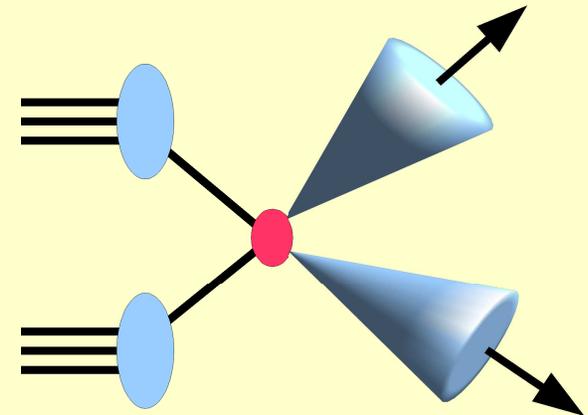




DIS Production



Drell-Yan



Jet Production

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

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

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

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

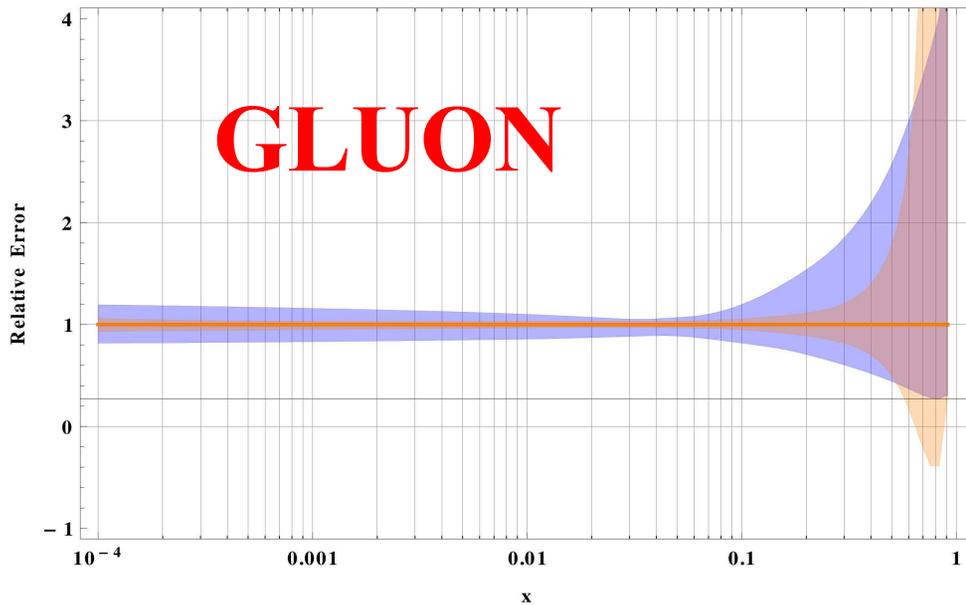
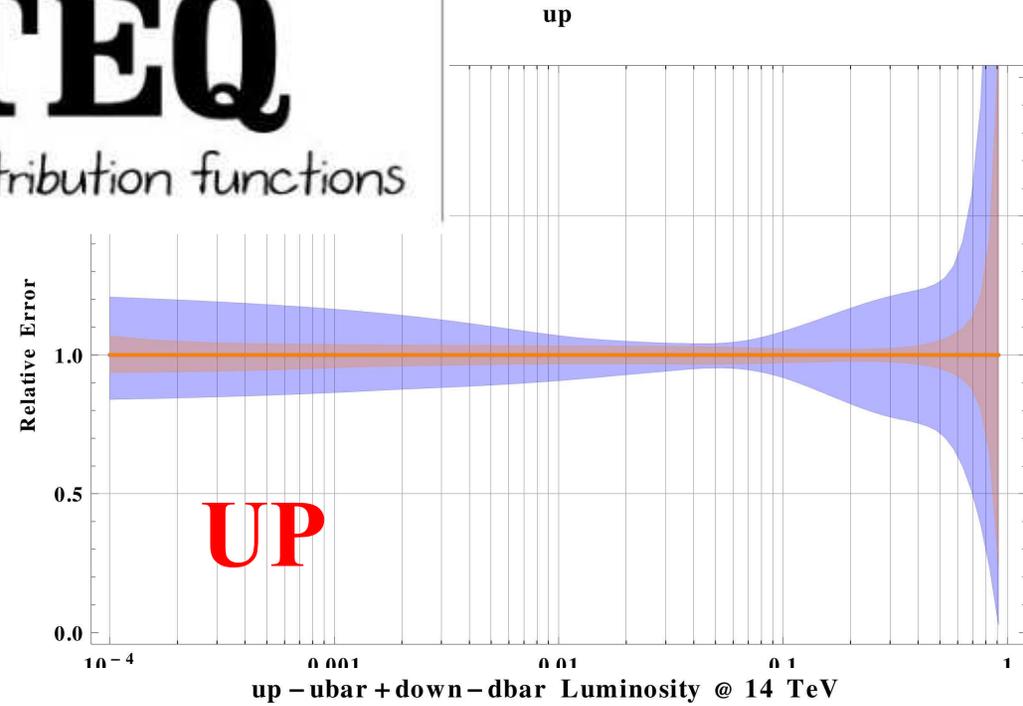
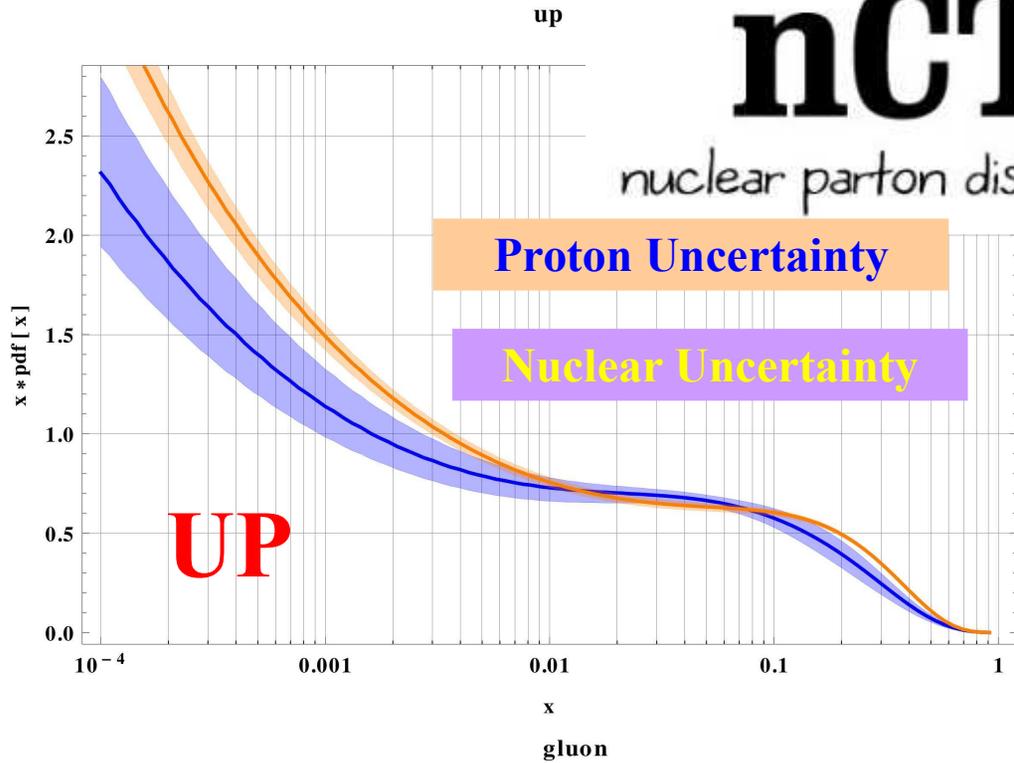
$$F_2^{\ell^\pm} \sim \left(\frac{1}{3}\right)^2 [d + s] + \left(\frac{2}{3}\right)^2 [u + c]$$

Different linear combinations – key for flavor differentiation

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

nCTEQ

nuclear parton distribution functions



Target	ρ (g.cm ⁻³)	A	\mathcal{L} ($\mu\text{b}^{-1}.\text{s}^{-1}$)	$\int \mathcal{L}$ (pb ⁻¹ .yr ⁻¹)
Sol. H ₂	0.09	1	26	260
Liq. H ₂	0.07	1	20	200
Liq. D ₂	0.16	2	24	240
Be	1.85	9	62	620
Cu	8.96	64	42	420
W	19.1	185	31	310
Pb	11.35	207	16	160

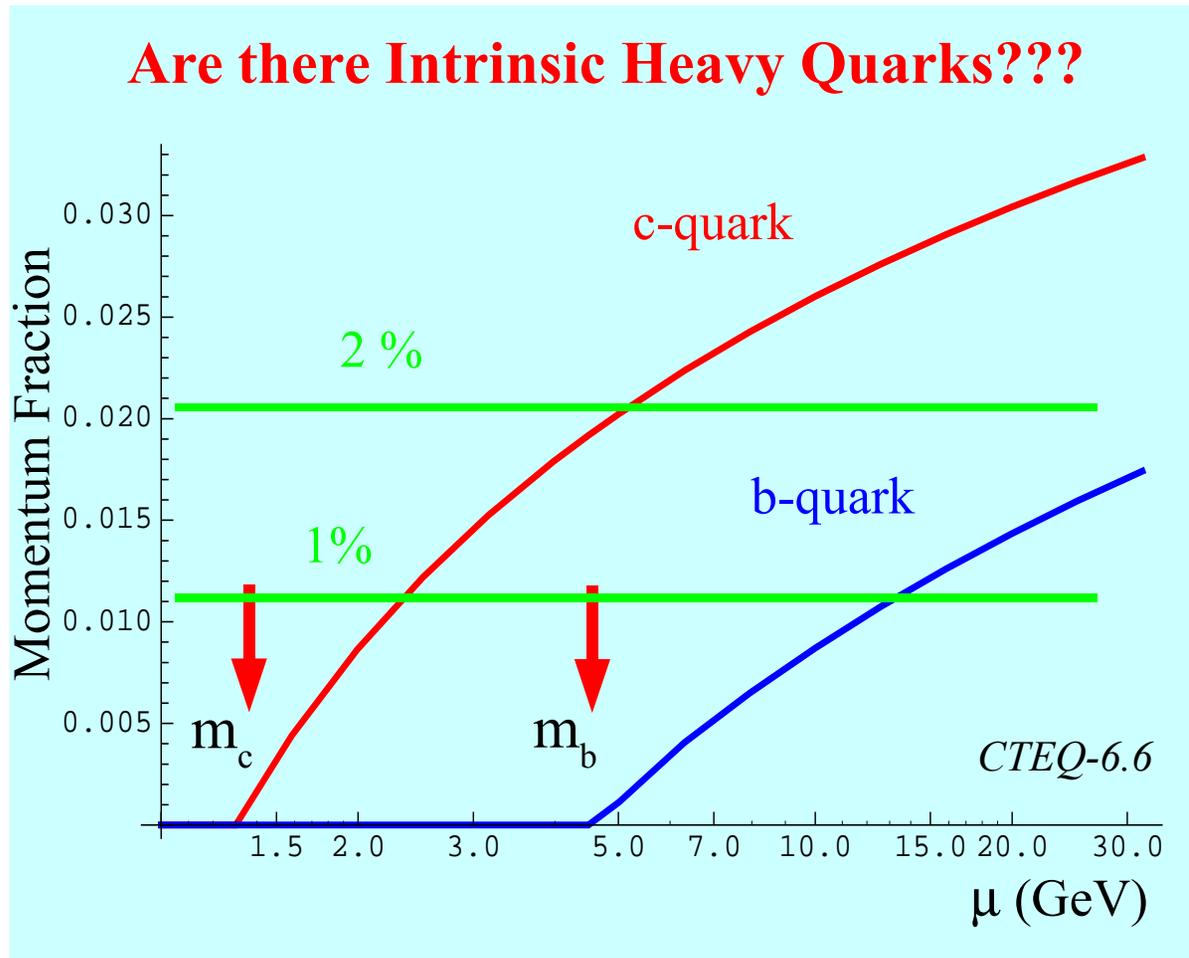
... what about the

Heavy Quarks

c & b

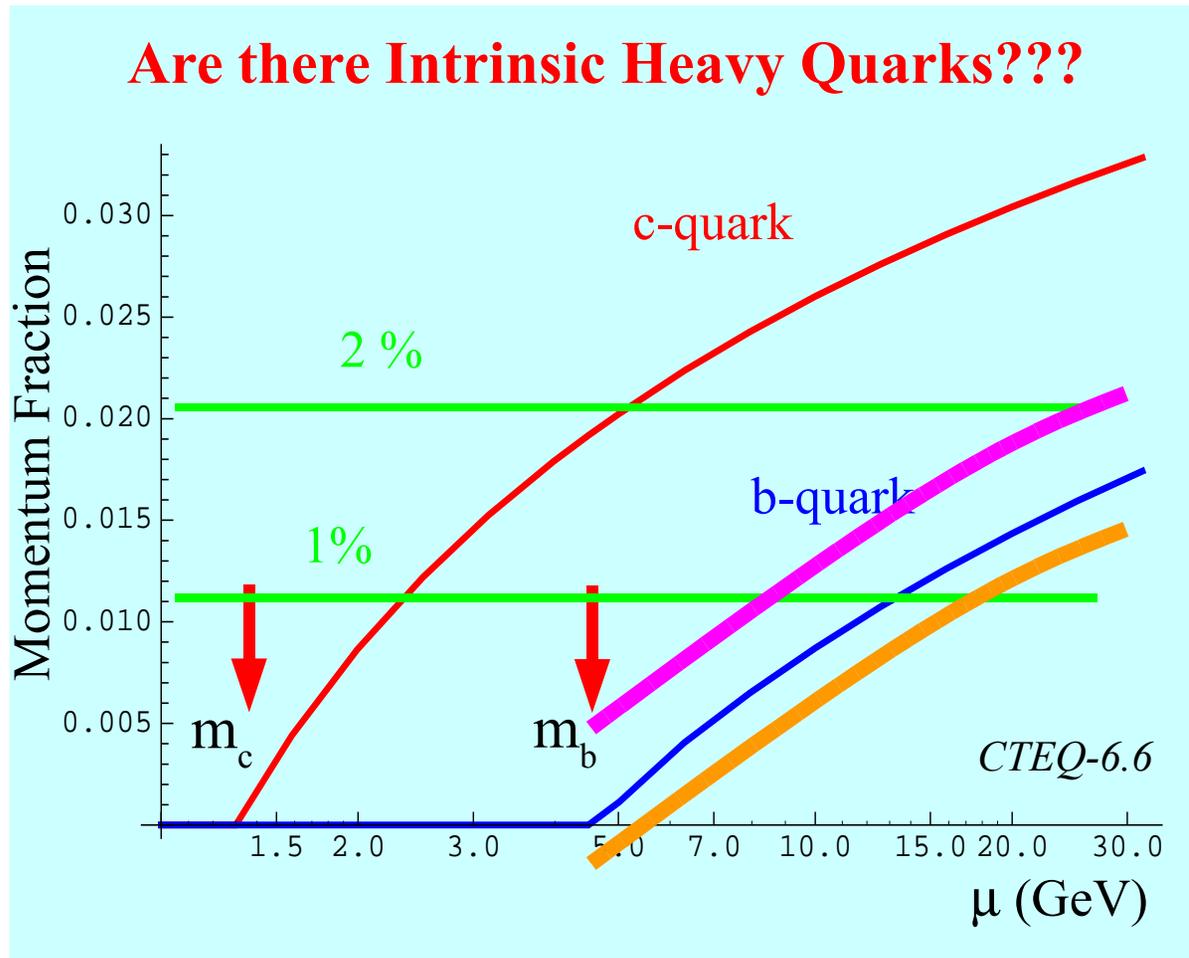
Extrinsic & Intrinsic

Are there Intrinsic Heavy Quarks??? Do they matter???



- * Most sensitive near threshold
- * What happens if we allow the evolution to determine charm?

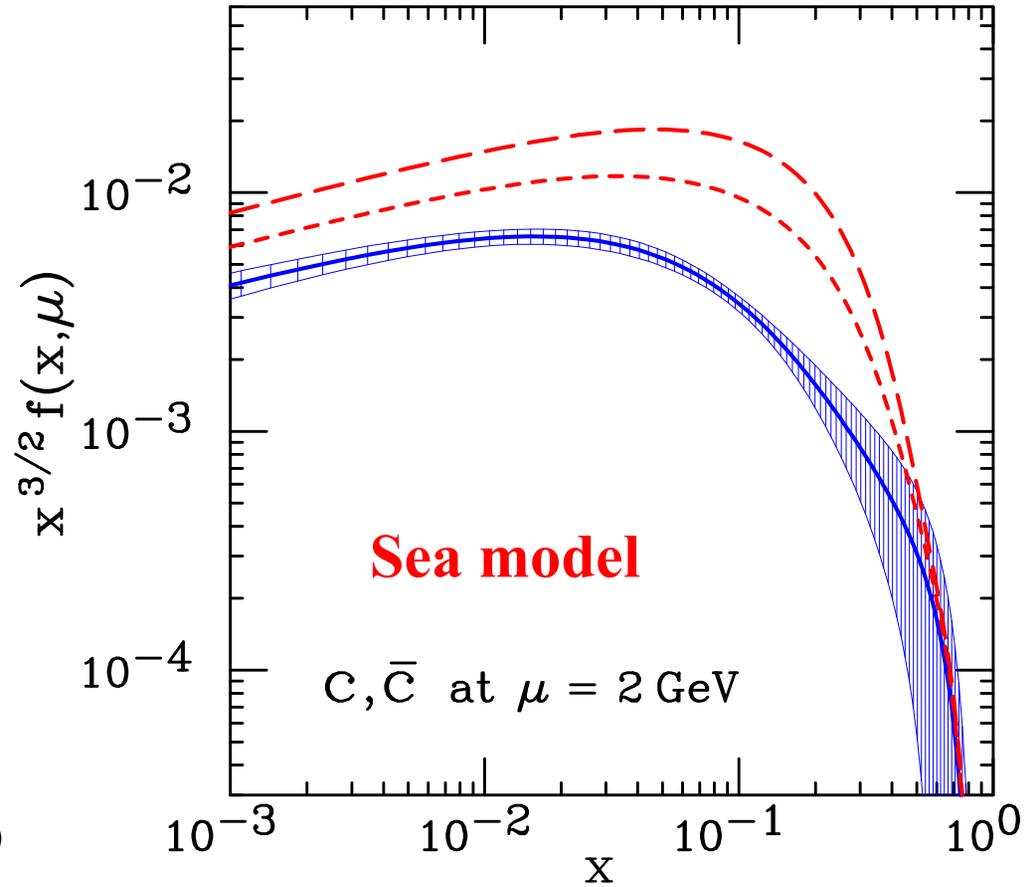
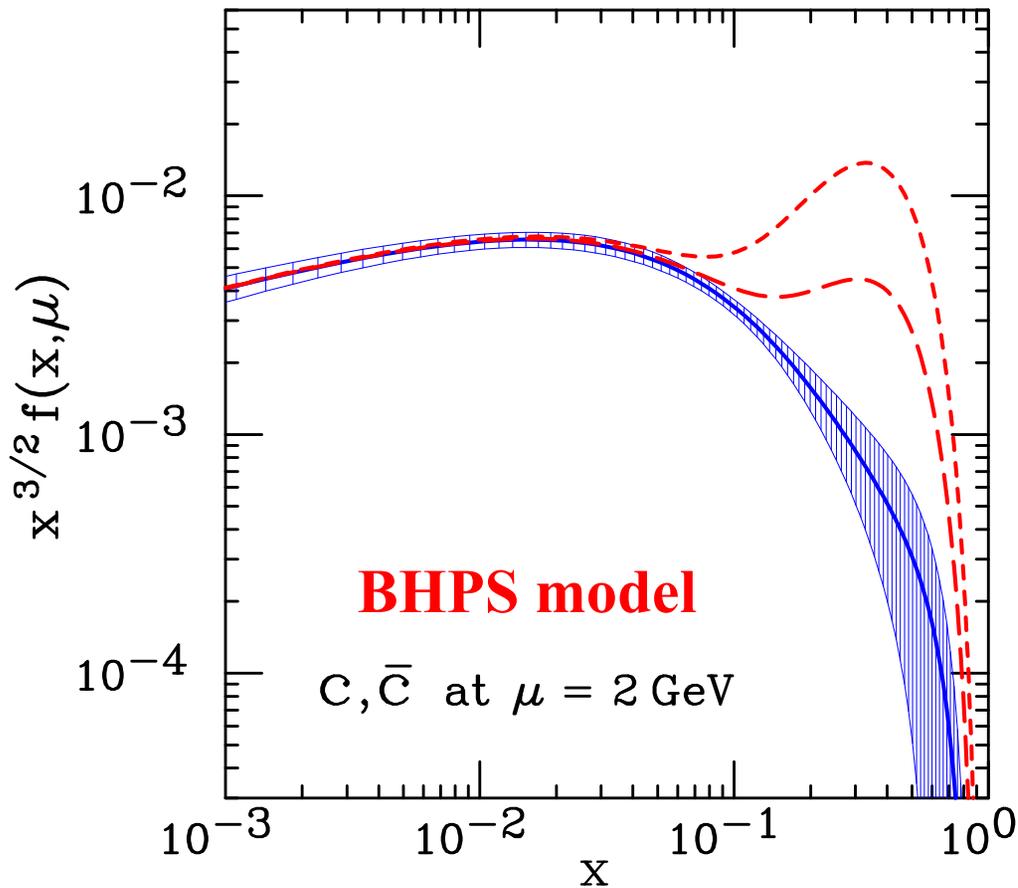
Are there Intrinsic Heavy Quarks??? Do they matter???



- * Most sensitive near threshold
- * What happens if we allow the evolution to determine charm?

Zero: No intrinsic charm
 Positive: Intrinsic charm
 Negative: Inconsistent

What might intrinsic charm look like???



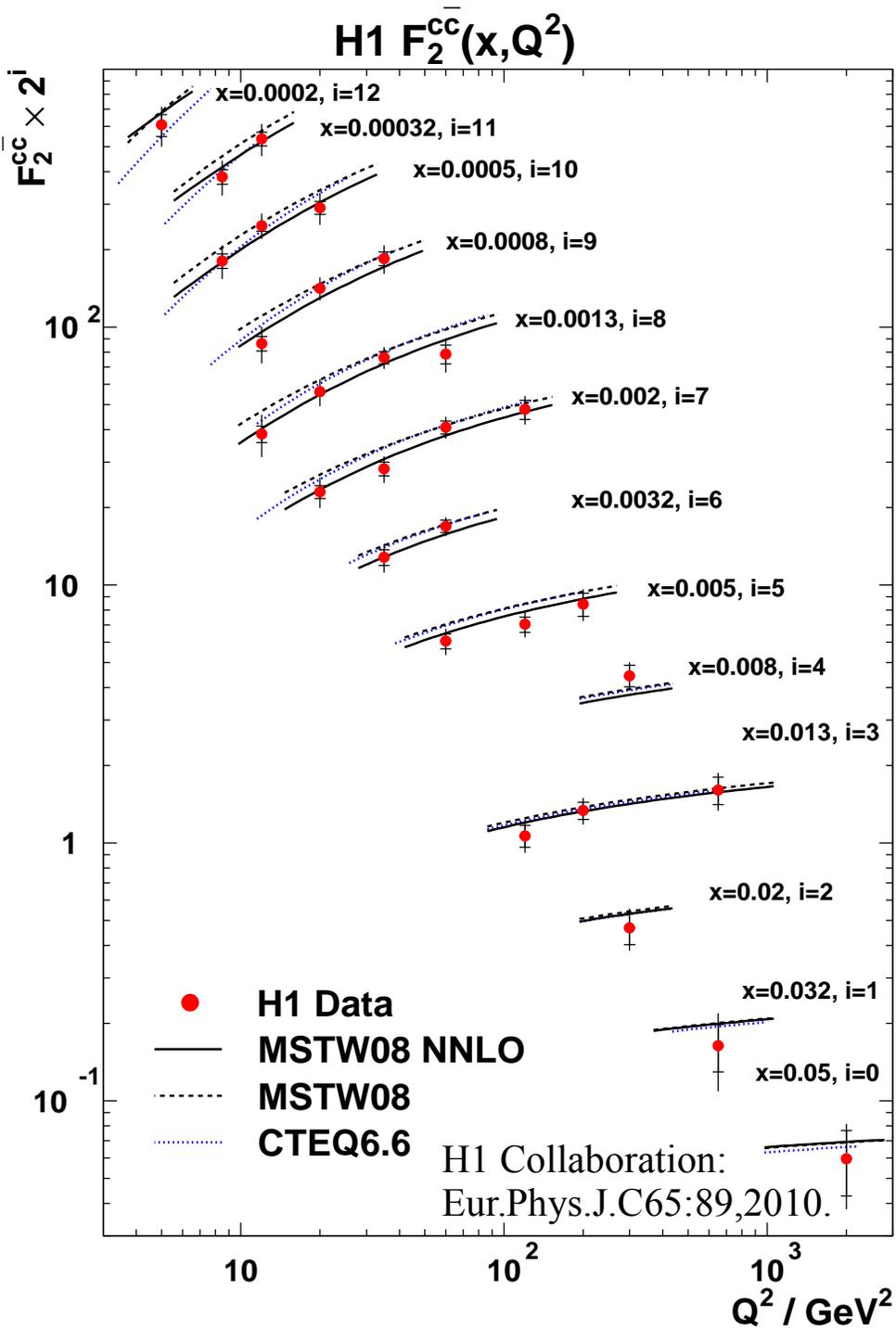
Add 1% or 2% momentum fraction
 in intrinsic component

Note, structure persists to higher
 (e.g., $Q \sim 100 \text{ GeV}$) scales

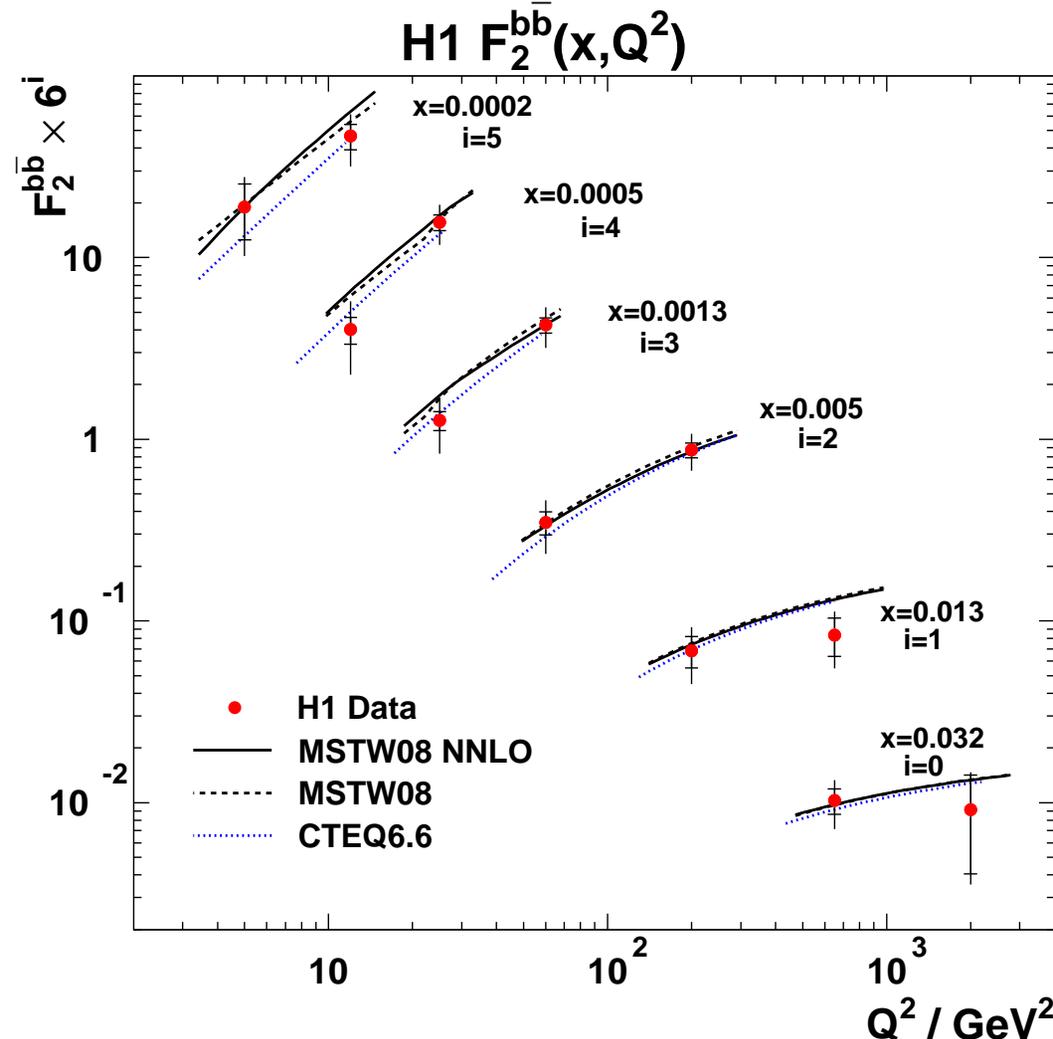
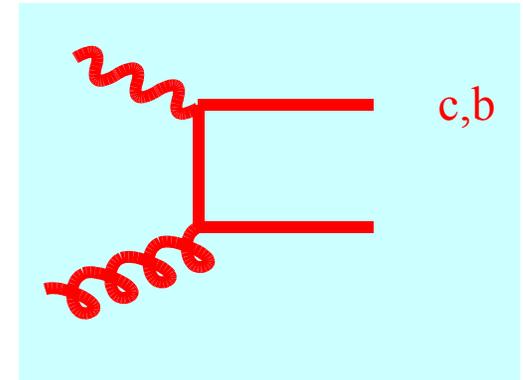
BHPS MODEL:

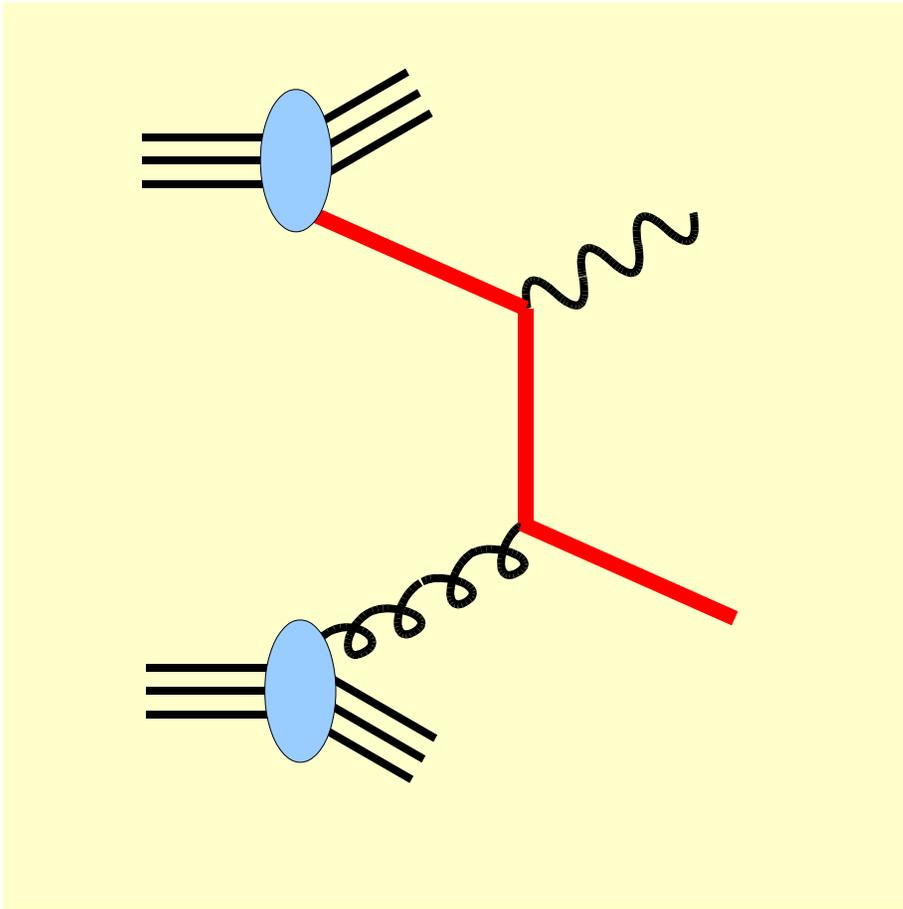
The Intrinsic Charm of the Proton.
 Brodsky, Hoyer, Peterson, Sakai,
 Phys.Lett.B93:451-455,1980.

The Charm Parton Content of the Nucleon.
 J. Pumplin, et al., Phys.Rev.D75:054029,2007.



**c & b
tied to
gluon PDFs**





Direct Photon: Can it constrain the gluon???

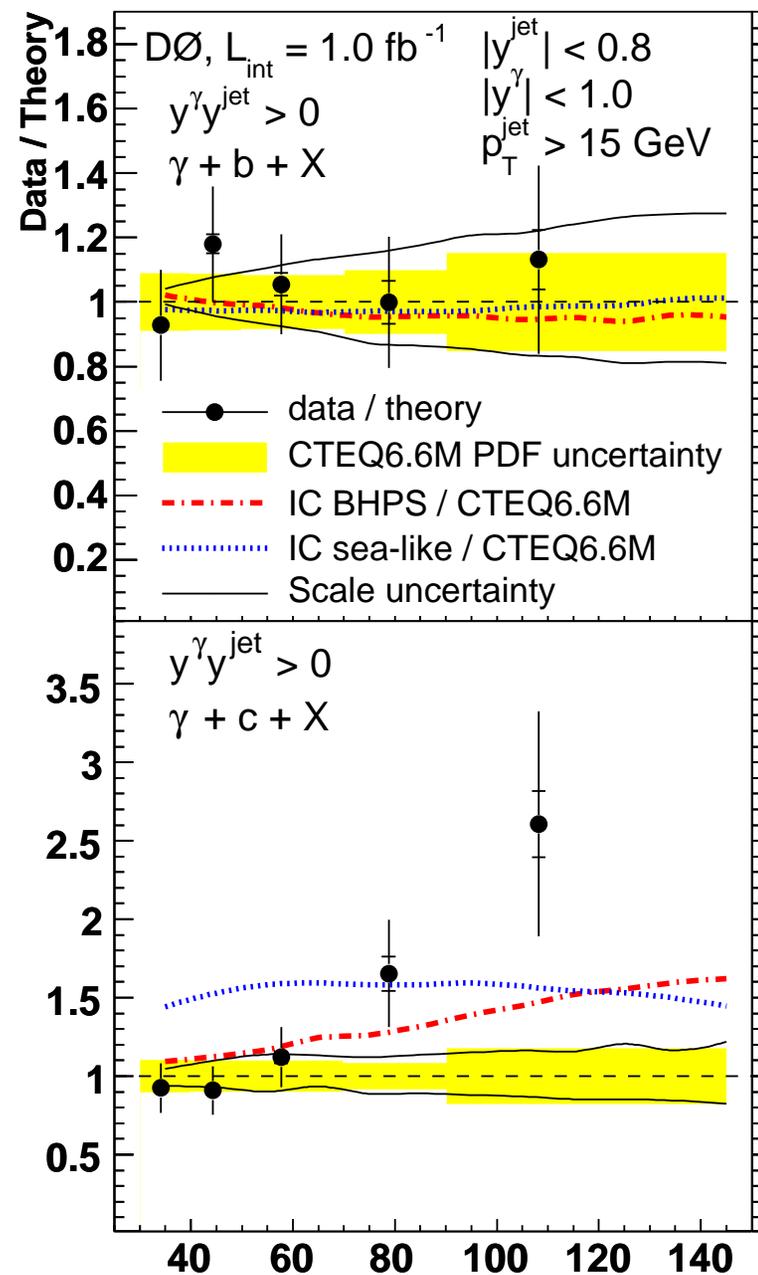
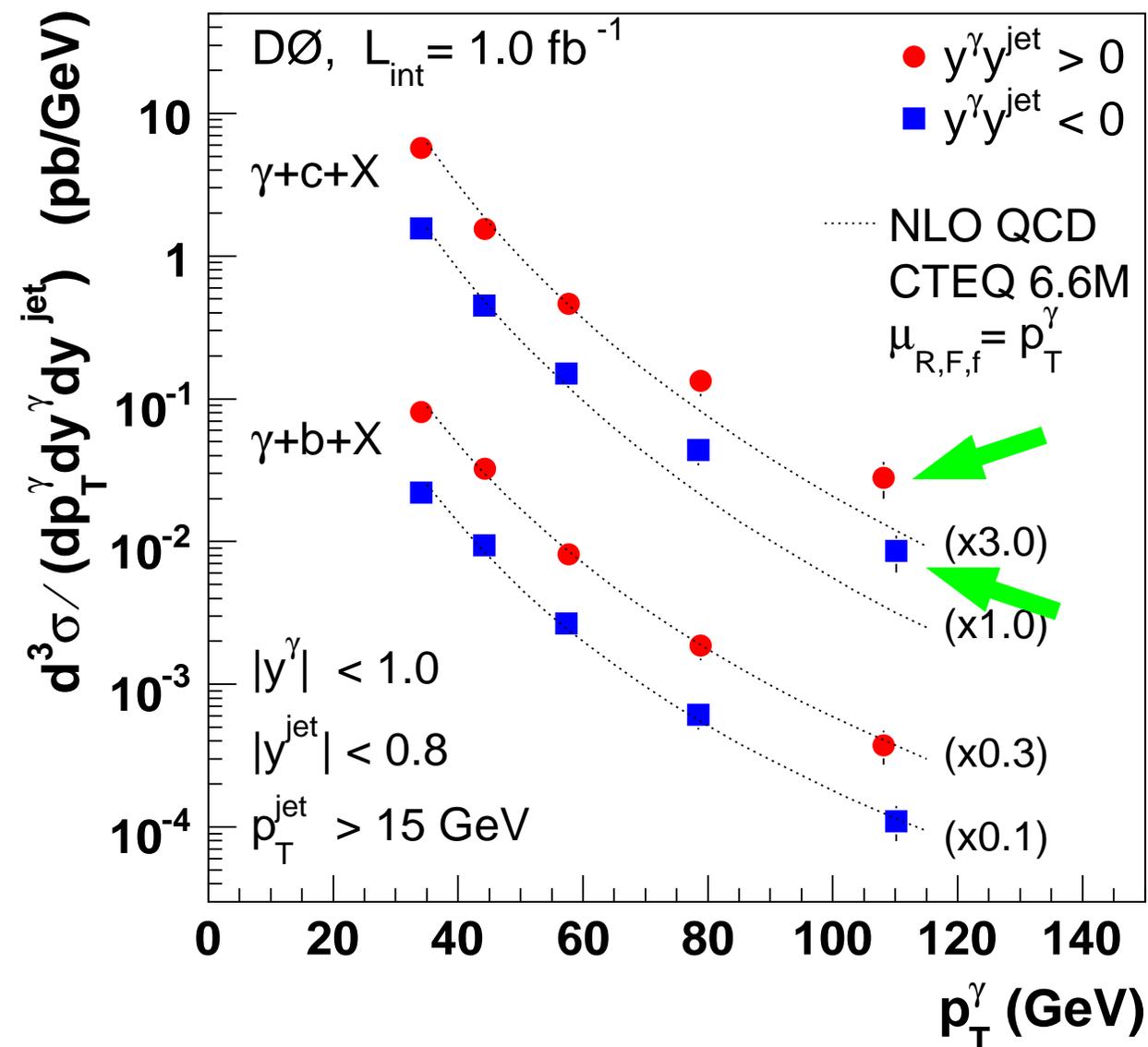
Test Heavy Quark PDF resummation

$$c \quad g g \rightarrow c \quad \gamma$$

$$b \quad g g \rightarrow b \quad \gamma$$

$$s \quad g g \rightarrow c \quad W$$

$$c \quad g g \rightarrow b \quad W$$

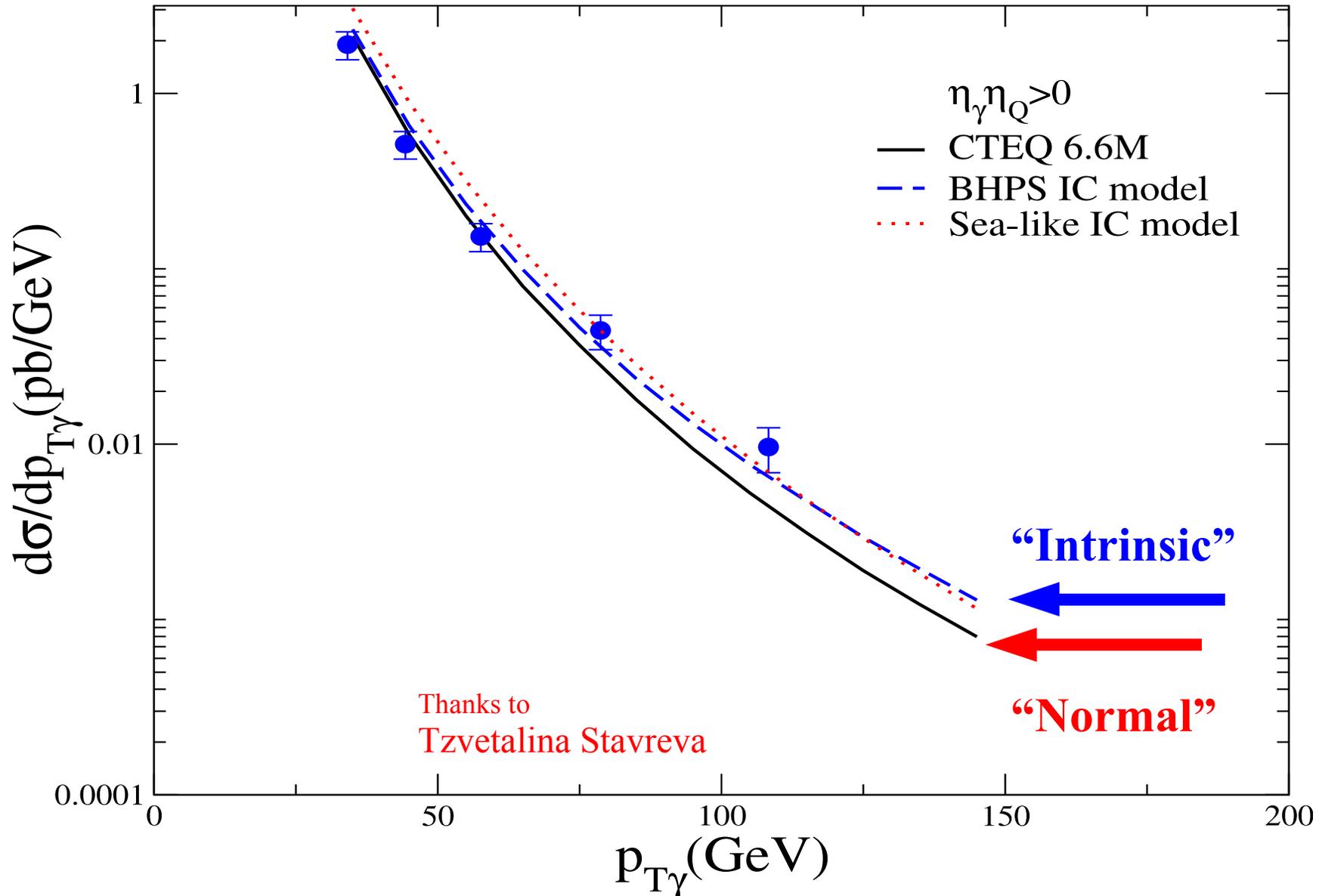


Including “Intrinsic Heavy Quark” Component

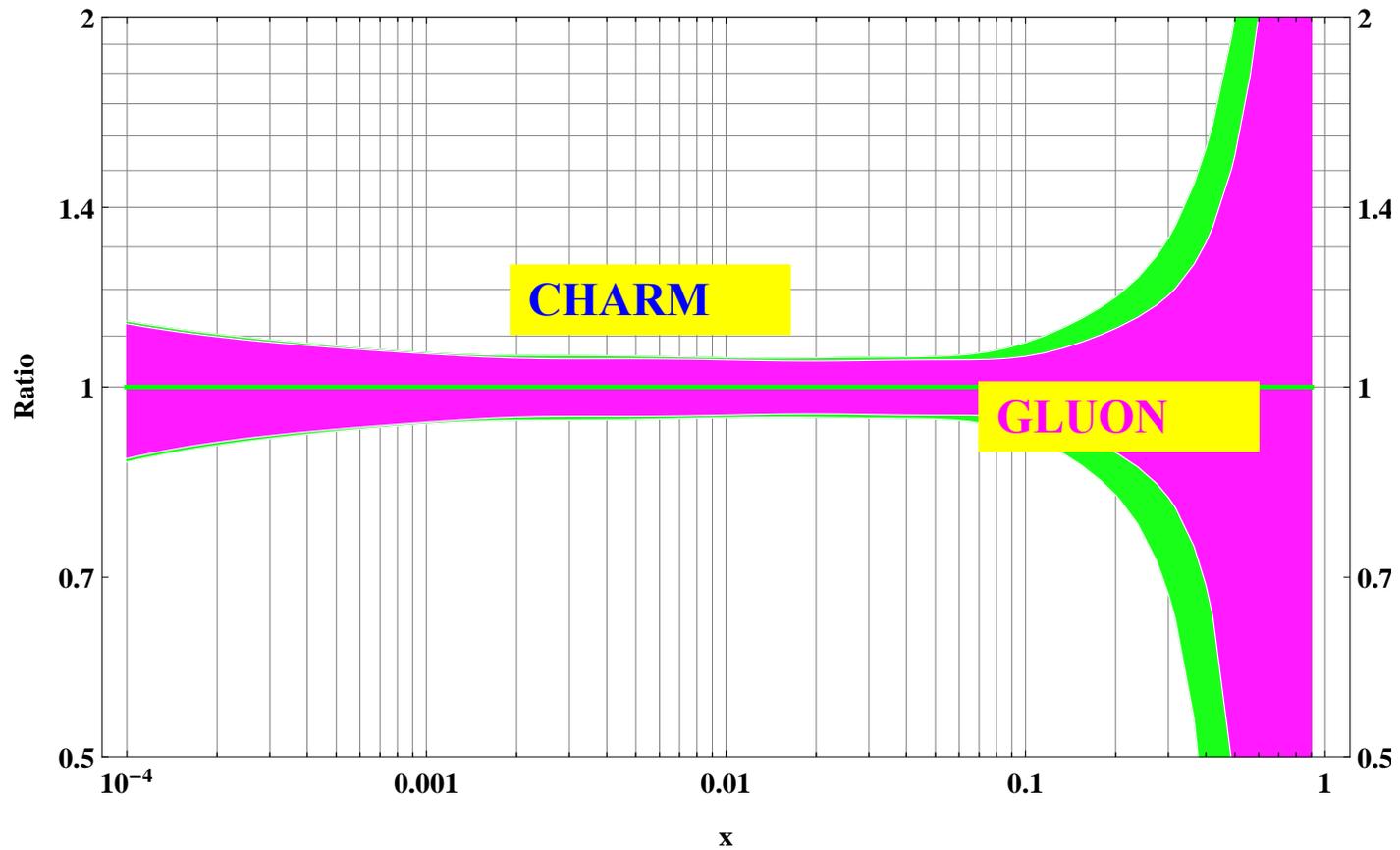
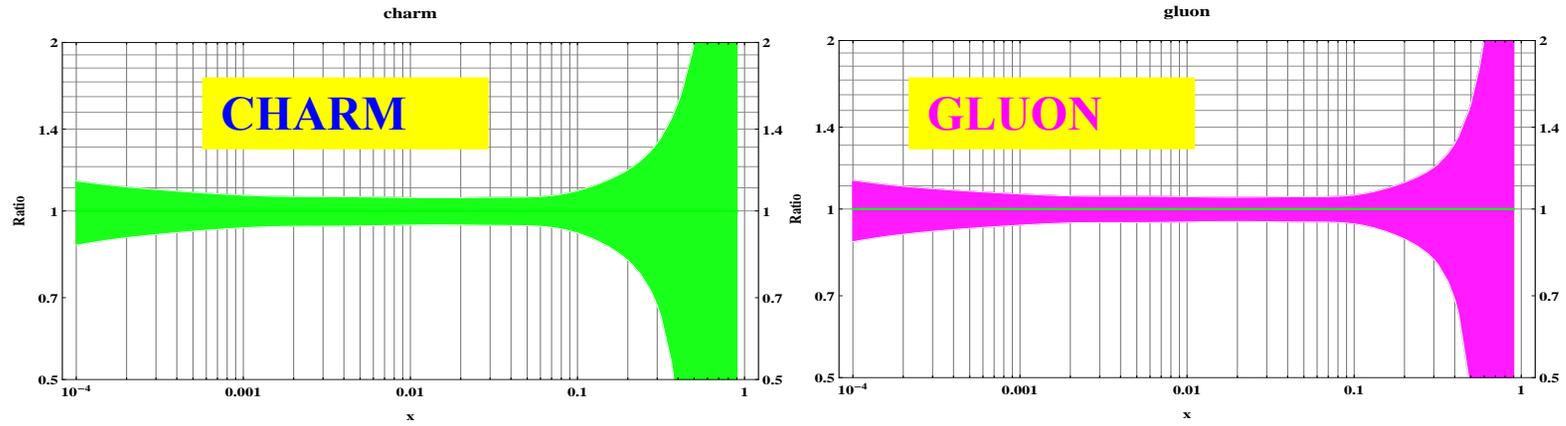
Tevatron

$$p+p \rightarrow \gamma+c+X$$

$$\sqrt{S} = 1.96 \text{ TeV}$$

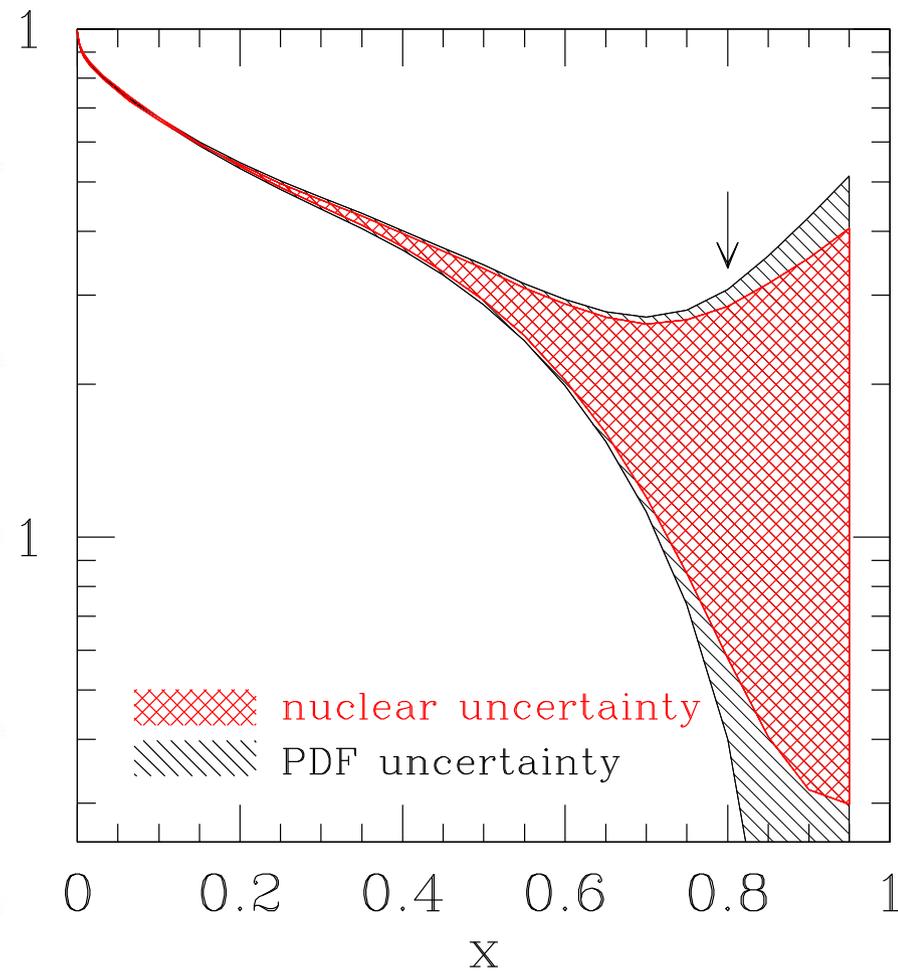
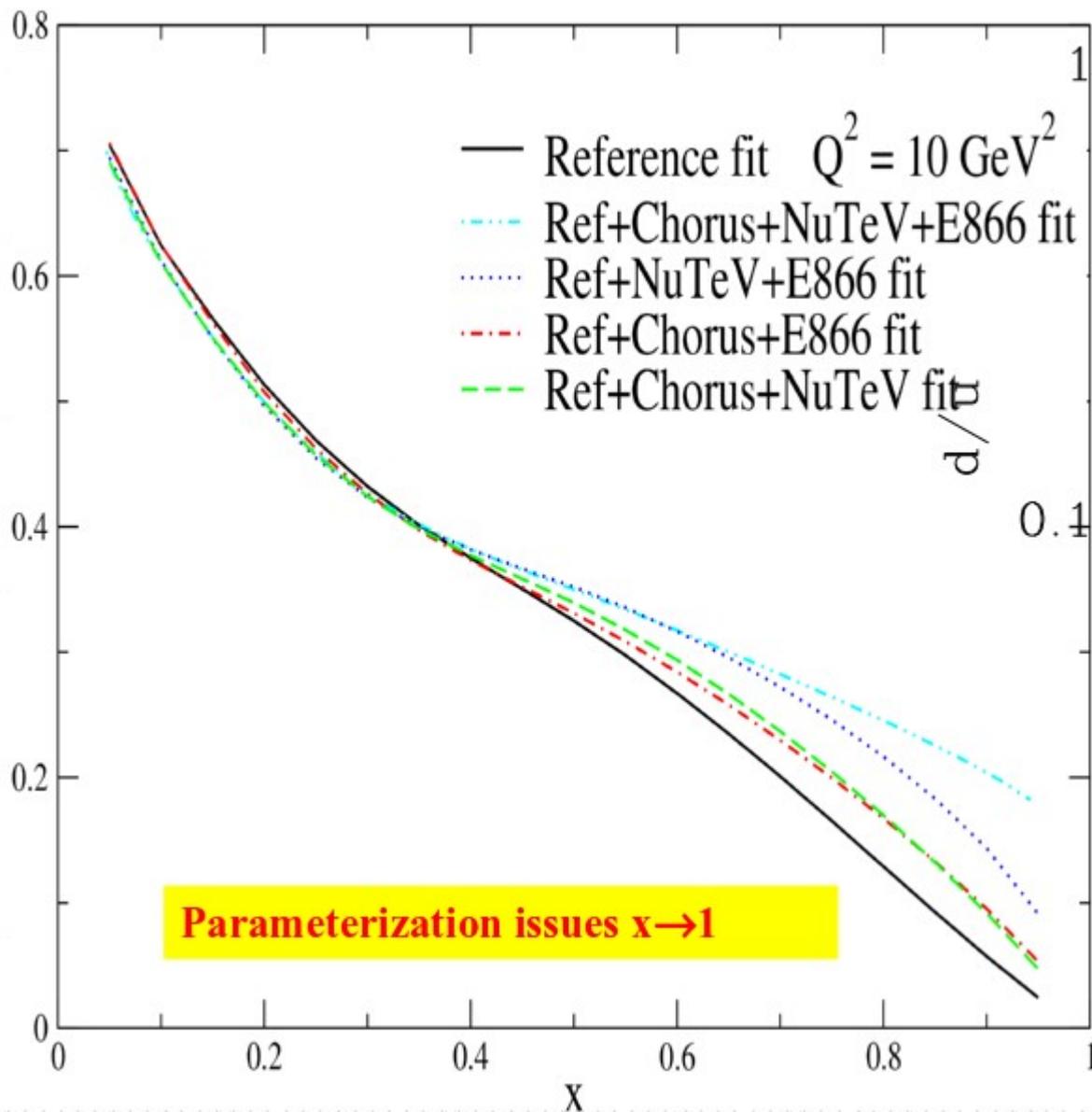


Charm PDF Uncertainty & Relation to Gluon



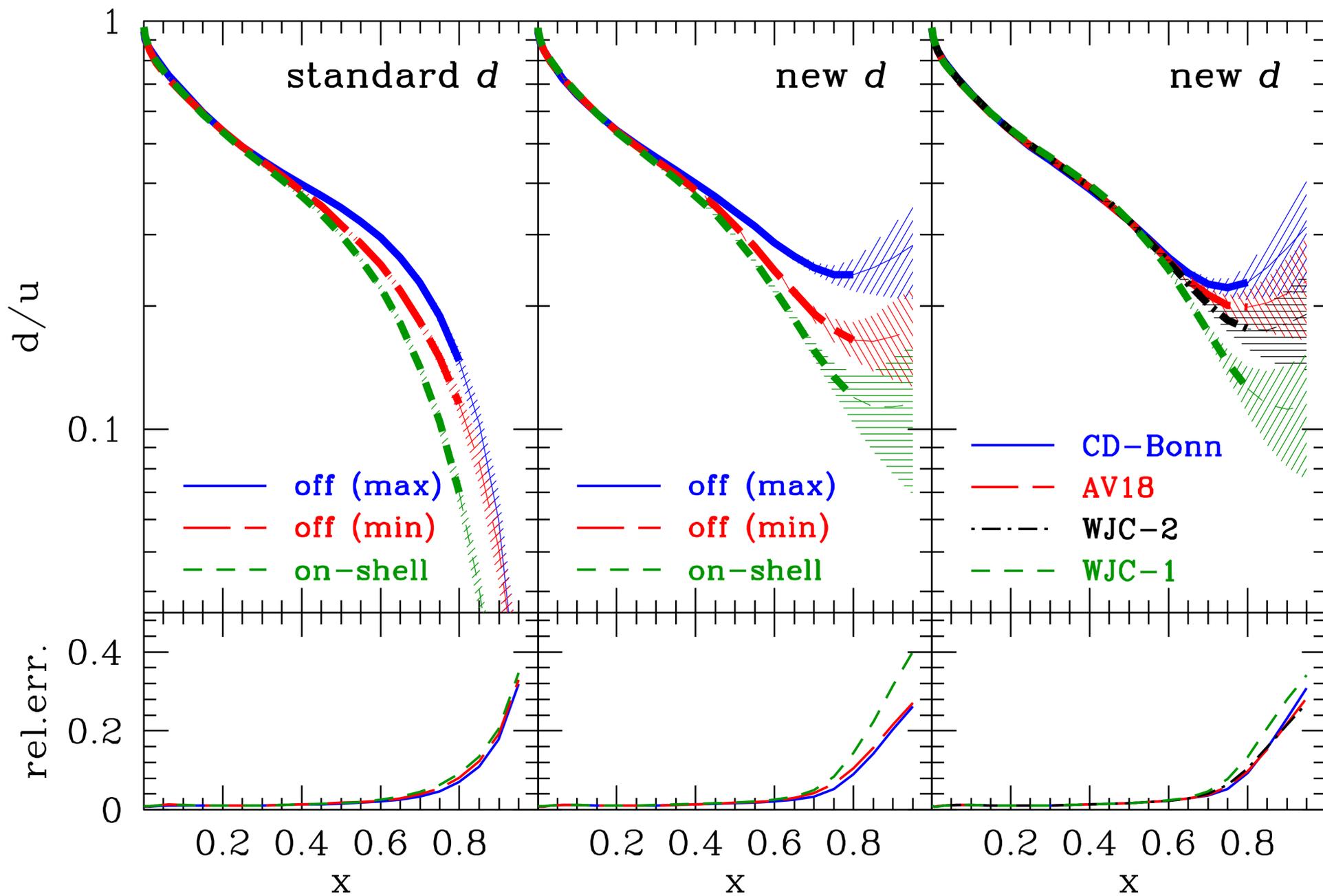
III-X

Tension between data sets: Example: d/u ratio at high x



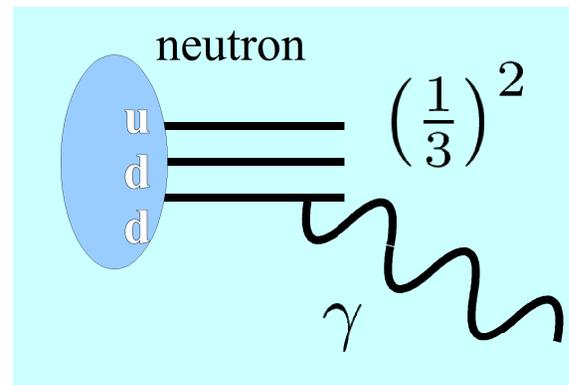
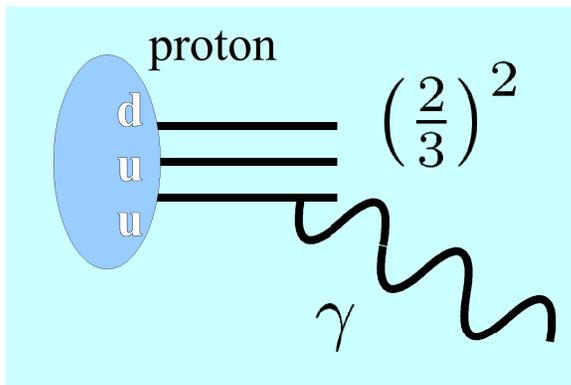
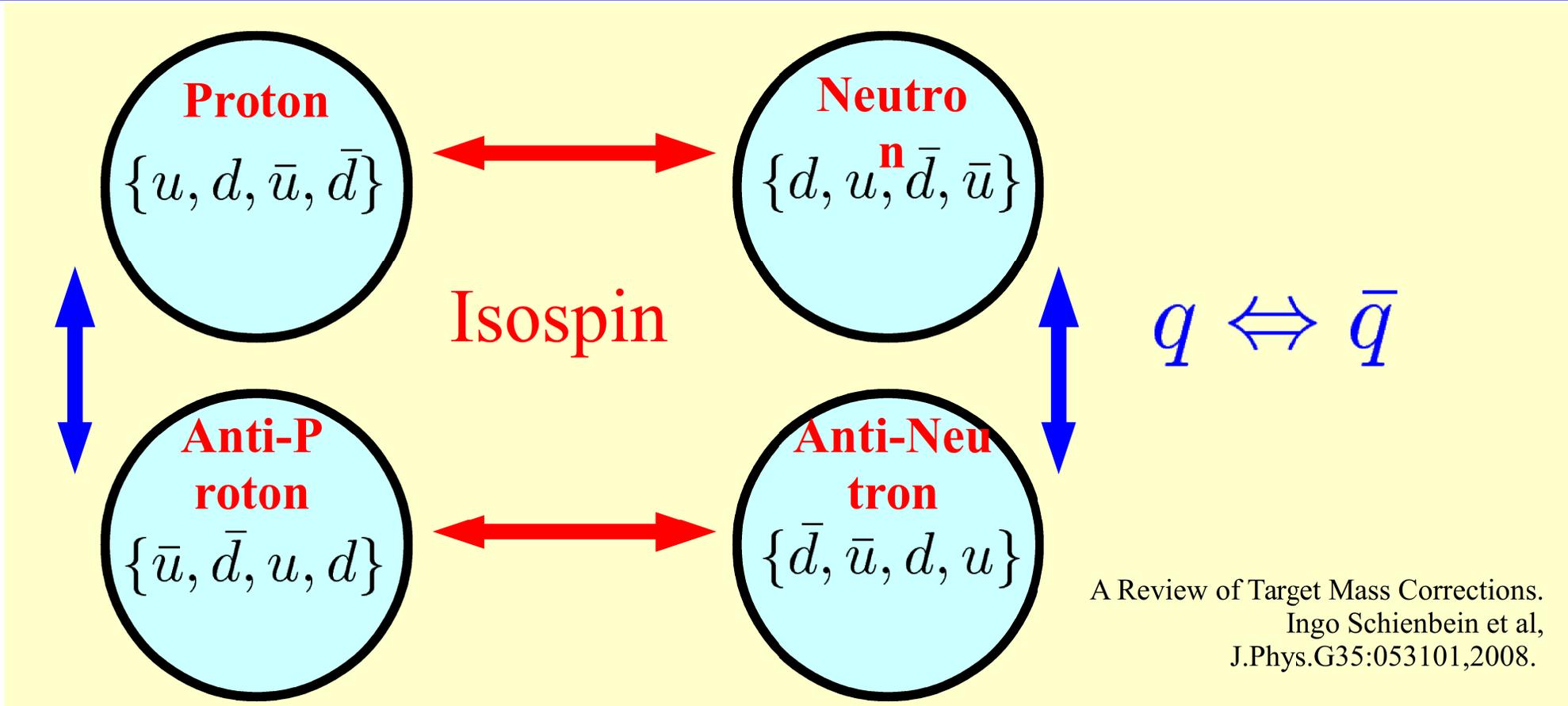
What about $x > 1$ for nuclear PDF?

d/u at Hi-X: Lots to choose from



Isospin Symmetry

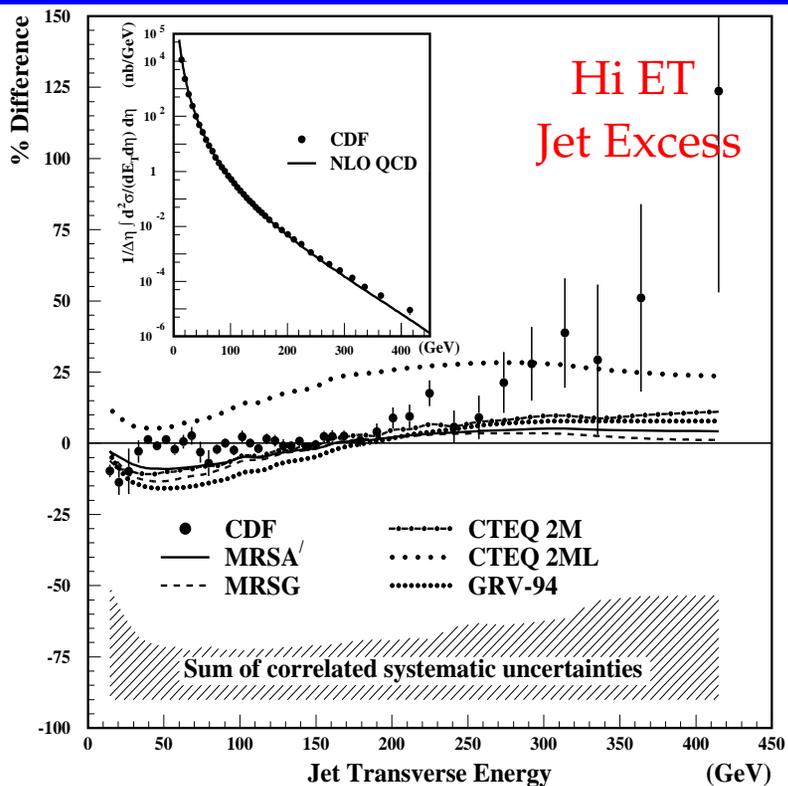
... taken for granted



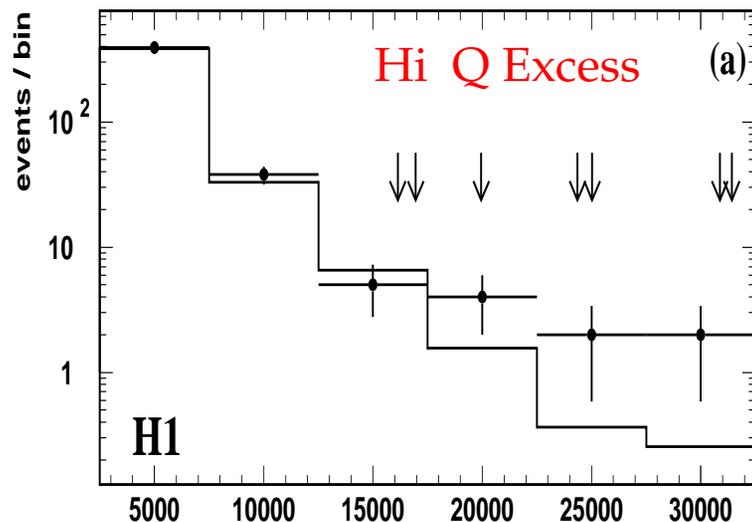
Isospin terms are comparable to NNLO QCD

Why Do We
Need
Independent
Experiments

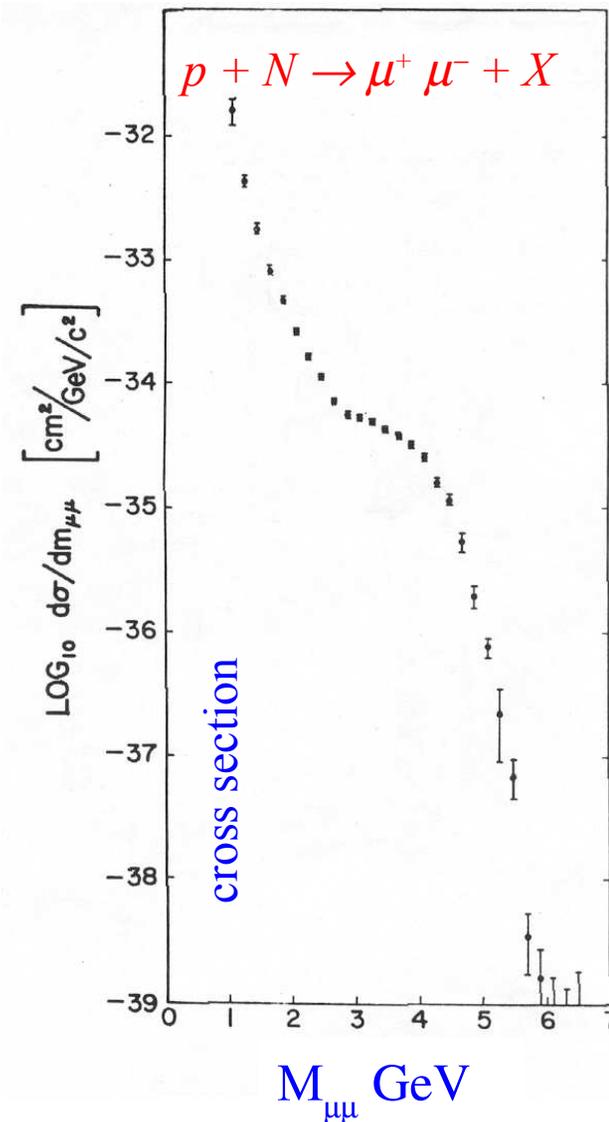
Can you find the Nobel Prize???



CDF Collaboration, PRL 77, 438 (1996)



H1 Collaboration, ZPC74, 191 (1997) Q_e^2 (GeV²)
 ZEUS Collaboration, ZPC74, 207 (1997)



Conclusion

Combination of high statistics, variety of nuclear targets,
and large kinematic range allow ...

PDF Precision:

Flavor Differentiation
TMD PDFs, Generalized PDFs

Nuclear Effects:

Corrections (EMC Effect)
Phenomena (Saturation, Recombination)
Isospin Symmetry & Deuteron corrections

Heavy Quarks:

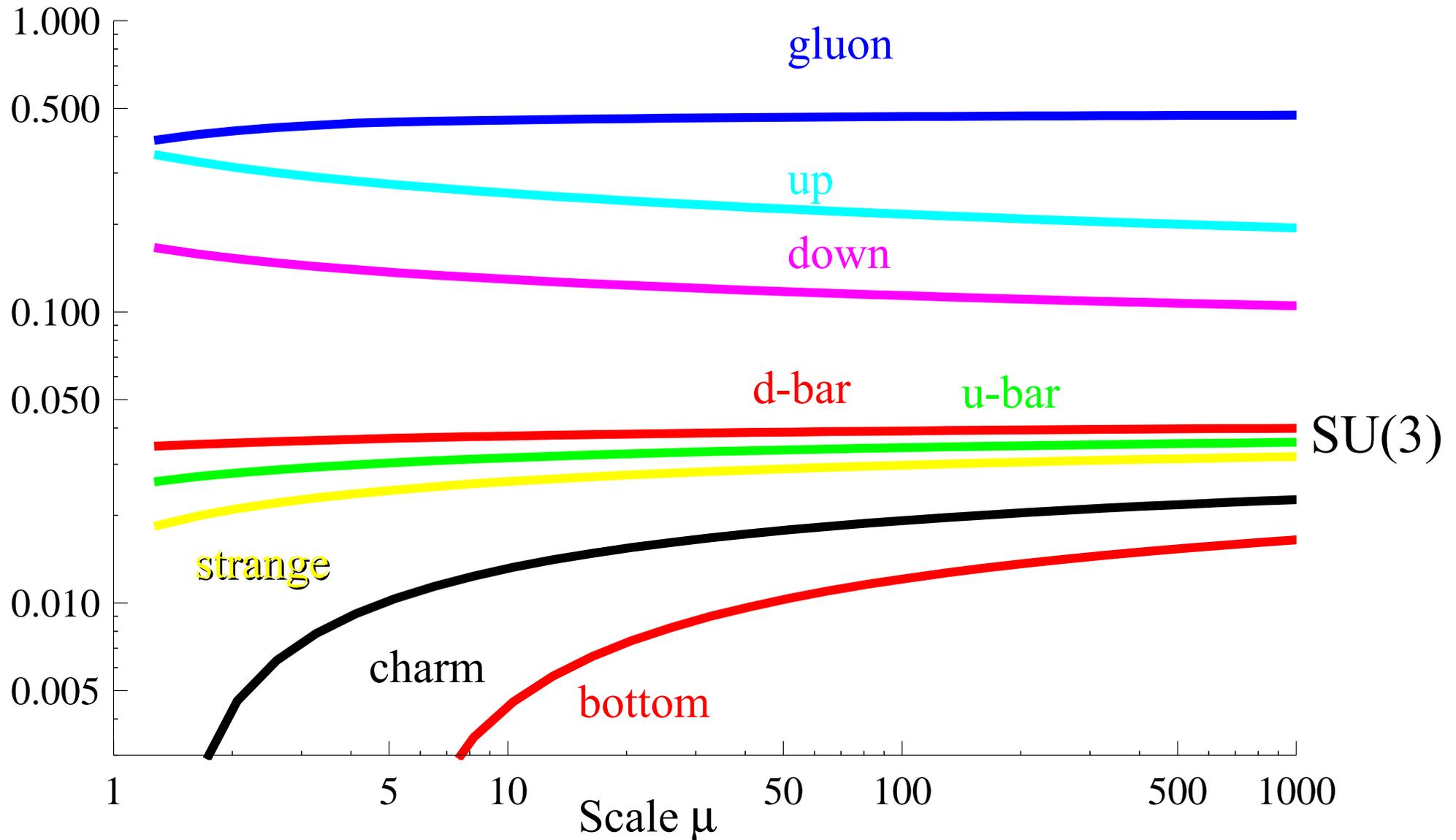
Log(m/Q) resummation & Intrinsic HQs

High X

Higher Twist, Fermi Motion, $x > 1$

PDF Momentum Fractions vs. scale μ

Momentum Fraction



Scaling violations are essential feature of PDFs