"How Strange is the Proton?

Neutrinos DIS and the Strange Quark Asymmetry

A collection of interesting puzzles

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LANL P-25 Seminar
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Why are we interested in the Proton structure?

* Because it's there!

    What is the structure of hadrons?

    What is the character of the QCD theory?

    ... the other forces are comparatively weak

* Because we need this information

    for any hadron-induced process.

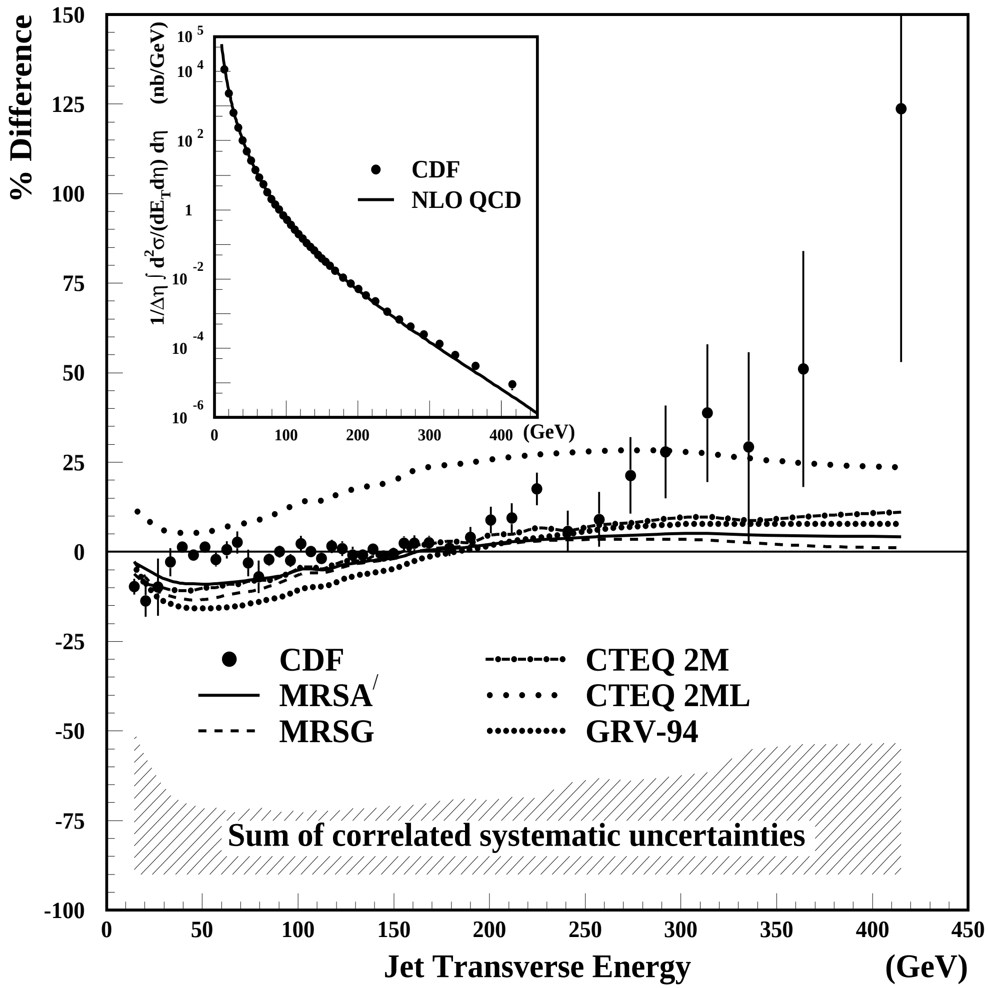
Compare these machines:

LEP	e^+e^-	$\sqrt{s} = 200$ GeV
HERA	ep	$\sqrt{s} = 314$ GeV
RHIC	NN	$\sqrt{s} = N \times 100$ GeV
Tevatron	p - p-bar	$\sqrt{s} = 2000$ GeV
LHC	pp	$\sqrt{s} = 14{,}000$ GeV

The Search For New Physics

1996: Excess High E_T Jets at Tevatron

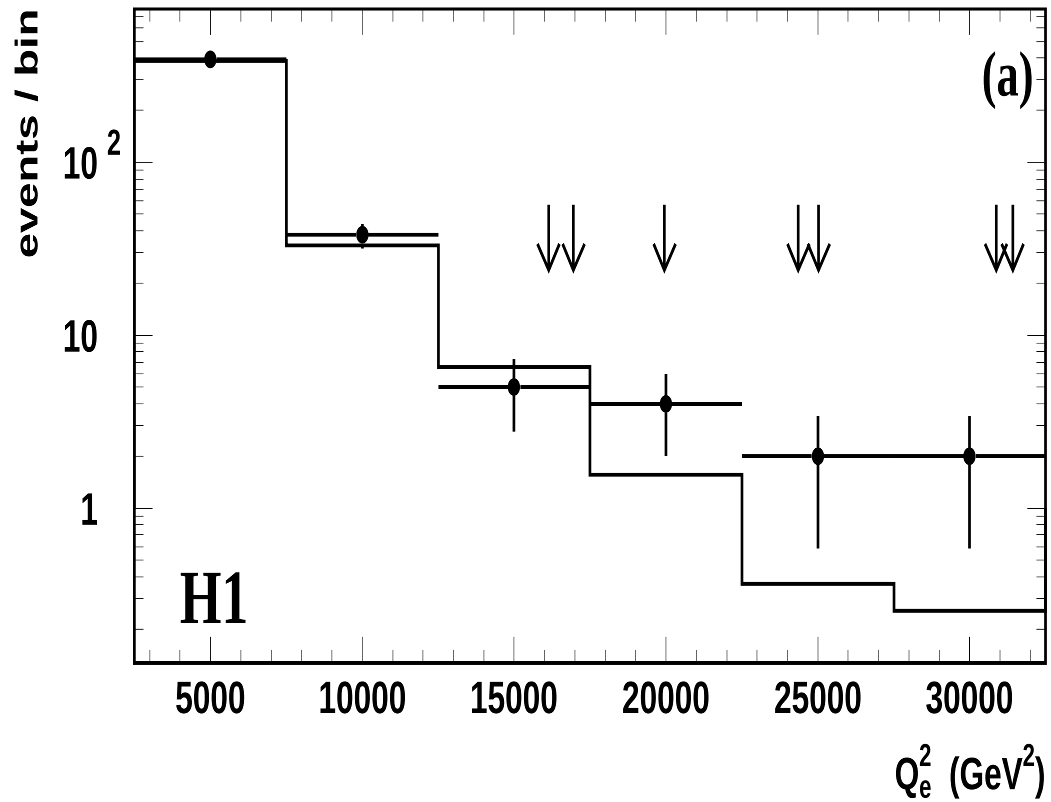
Is this a sign of compositeness?



CDF Collaboration
PRL 77, 438 (1996)

1997: Excess DIS events at large $\{x,Q^2\}$

Is this a sign of lepto-quarks?

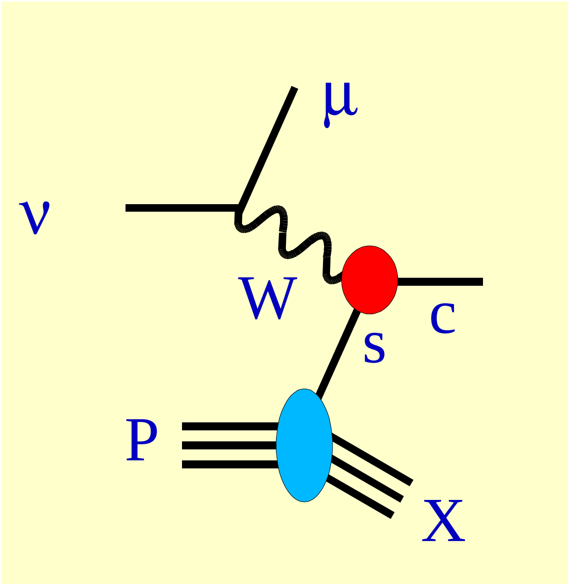


H1 Collaboration, ZPC74, 191 (1997)
ZEUS Collaboration, ZPC74, 207 (1997)

Precision PDF's are essential

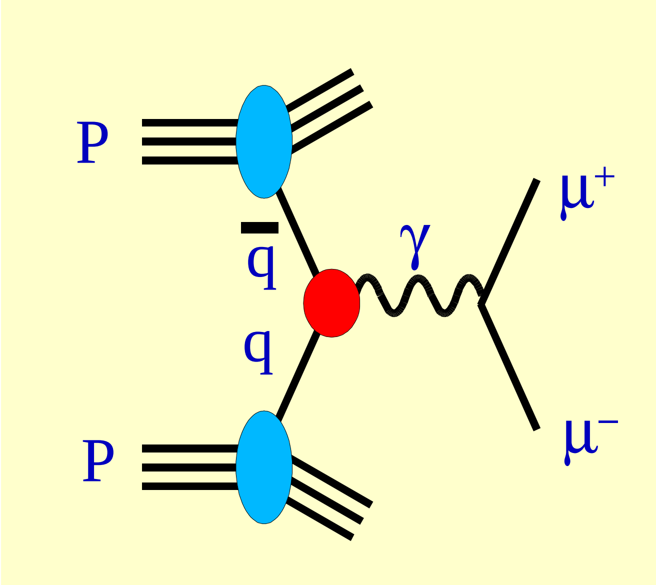
The Basic Processes

Deeply Inelastic Scattering (DIS)



$$\sigma_{DIS} = f_{P\to s} \otimes \hat{\sigma}_{s\to c}$$

Drell- Yan (DY)



$$\sigma_{DY} = f_{P\to q} \otimes f_{P\to \bar{q}} \otimes \hat{\sigma}_{q\bar{q}\to \mu^+\mu^-}$$

Use data to extract PDF, then make predictions for other processes

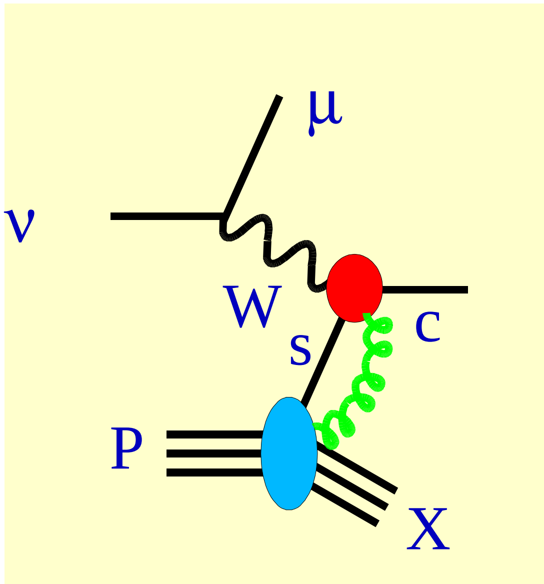
Factorization: Convolution of independent probabilities

$\tau_{INT} < \tau_{HAD}$: If $\tau_{INT} \sim 1/Q$ and $\tau_{HAD} \sim 1/M$, then $\Rightarrow Q/M > 1$

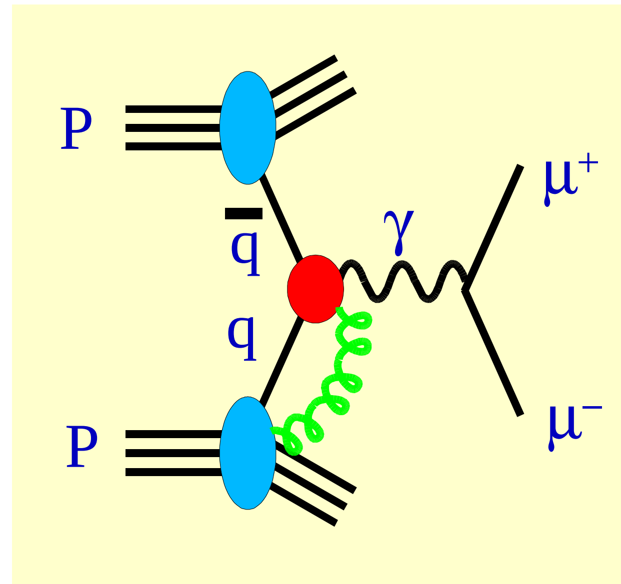
What if $Q/M \leq 1$??? Higher Twist

What about Higher Twist???

Deeply Inelastic Scattering (DIS)



Drell- Yan (DY)



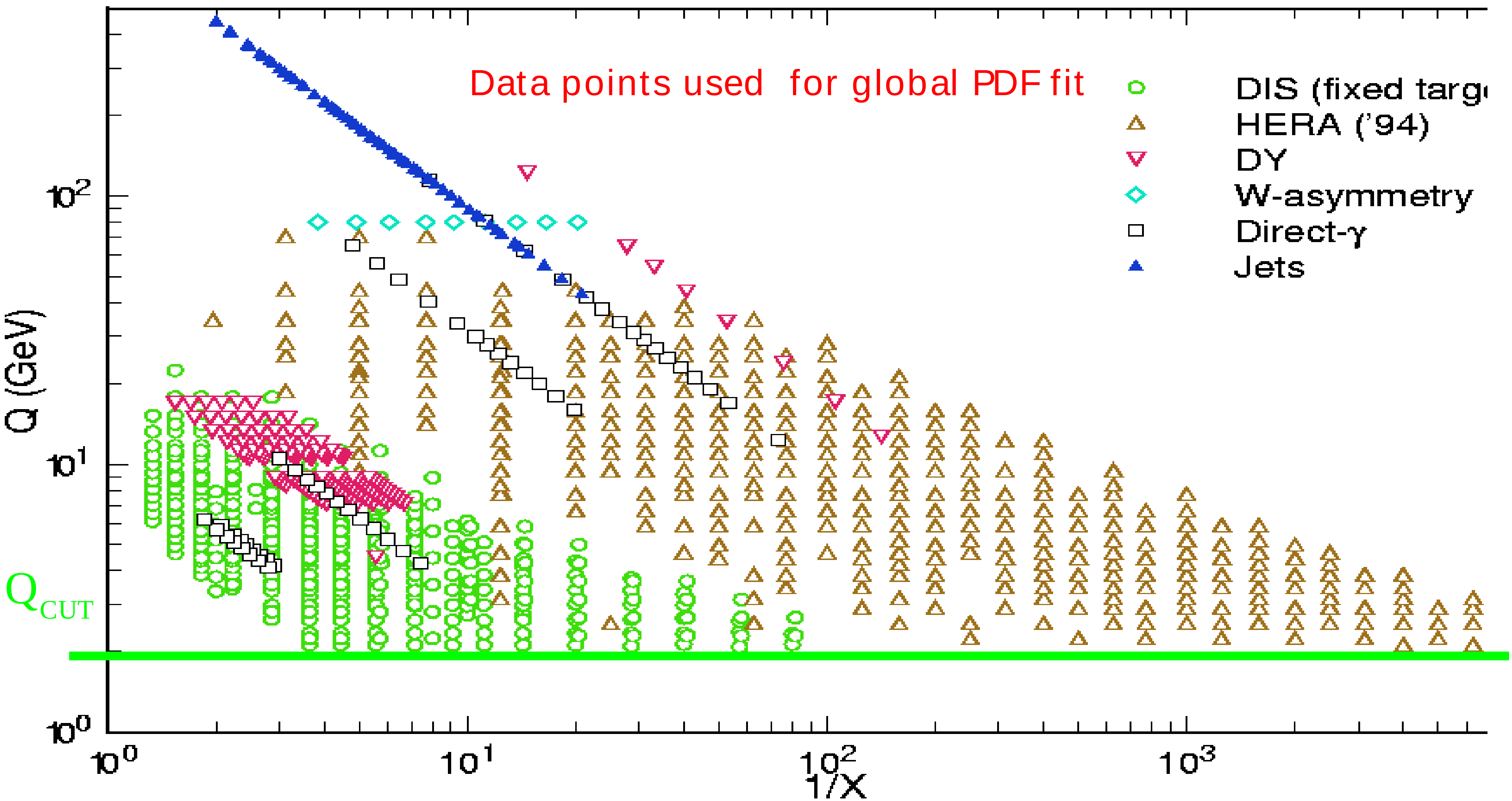
$$\sigma_{DIS} = f_{P\to s} \otimes \hat{\sigma}_{s\to c}$$

$$\sigma_{DY} = f_{P\to q} \otimes f_{P\to \bar{q}} \otimes \hat{\sigma}_{q\bar{q}\to \mu^+ \mu^-}$$

- Factorization breaks down
- Lose Universality
- No “First Principles” model

  ... sometimes parameterized as a $1/Q^2$ correction

What data are used in global fit to extract PDF's

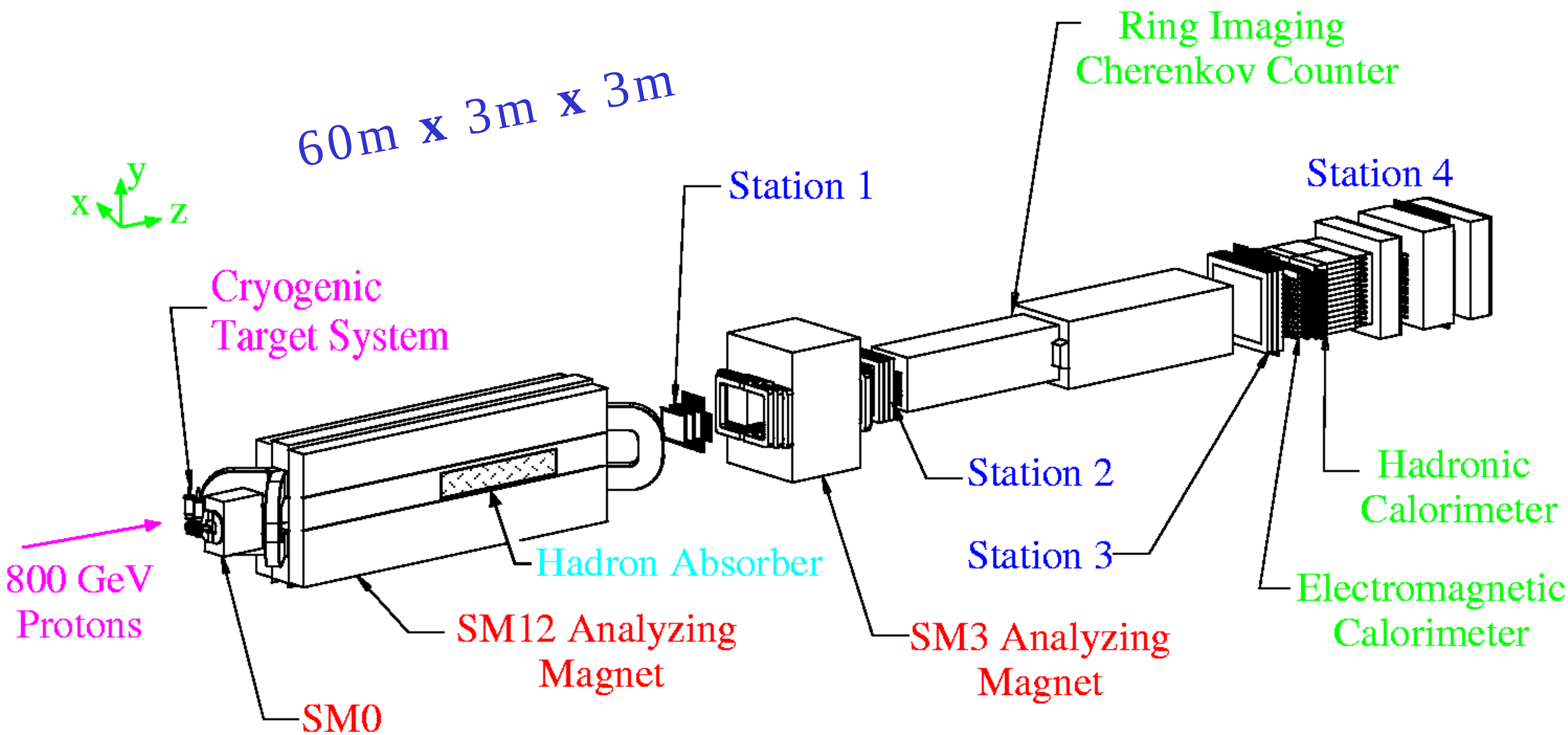


* Precision data essential to PDF, and hence, "new physics" searches
* **Both** Fixed Target and Collider data needed to map out full {x,Q} space
* Note “cuts” in {x,Q} space; many data points outside these cuts

Moral

Extended theoretical understanding of the "higher twist" region would allow us to include the wealth of data available in this region.

Drell0Yan: Fermilab E866/ NuSea Detector



- Forward x_F, high mass μ-pair spectrometer
- Liquid hydrogen and deuterium targets
- Two acceptance defining magnets (SM0, SM12)
- Also used solid W, Be, Fe targets

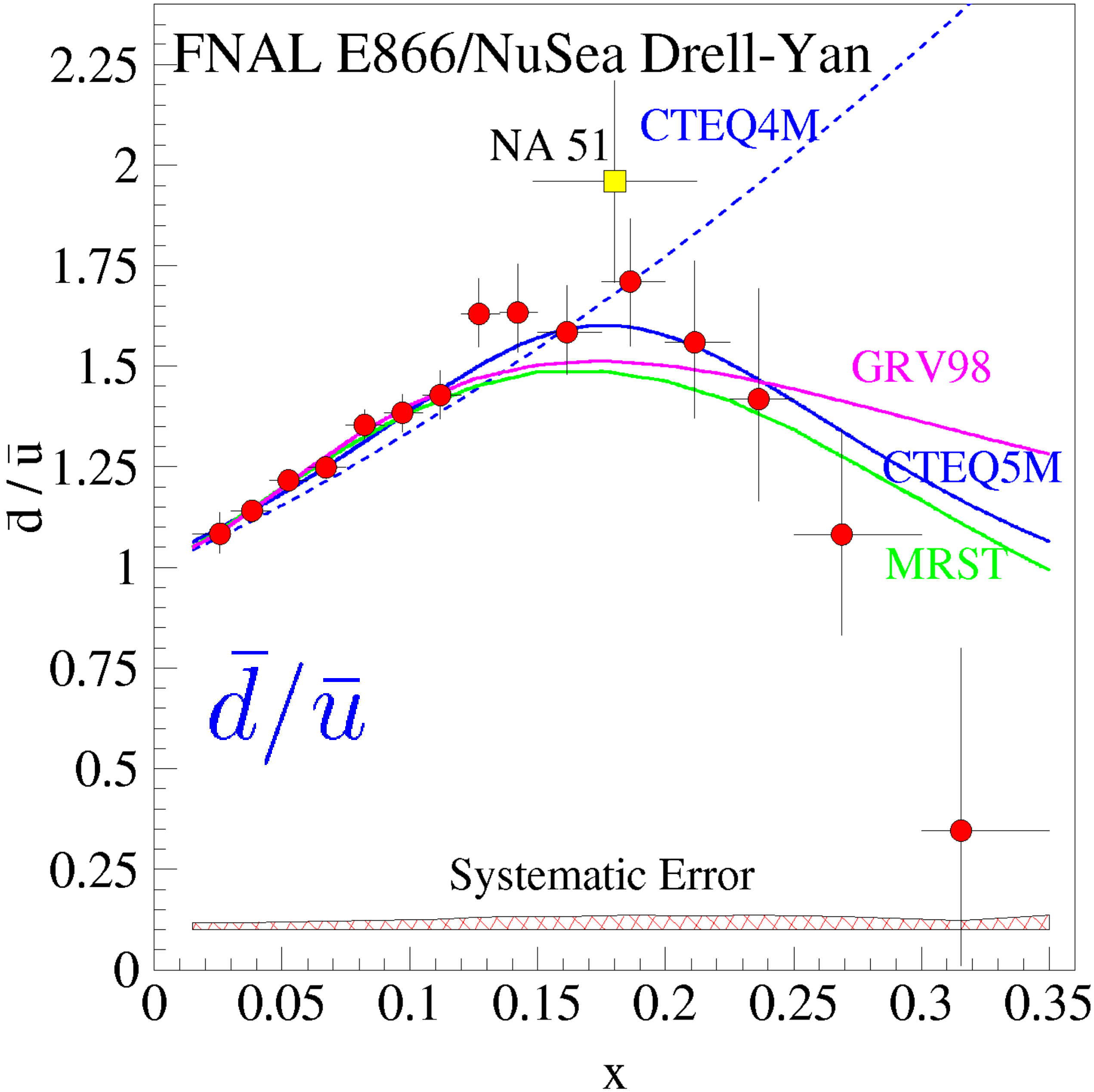
- Beam dump (4.3m Cu)
- Hadronic absorber (13.4 I_0- Cu, C, CH_2)
- Momentum analyzing magnet (SM3)
- Three tracking stations
- Muon identifier wall & 4^{th} tracking

Donald Isenhower (ACU) DIS'04

E866 quark sea distributions:

Examine ratio of deuterium to hydrogen

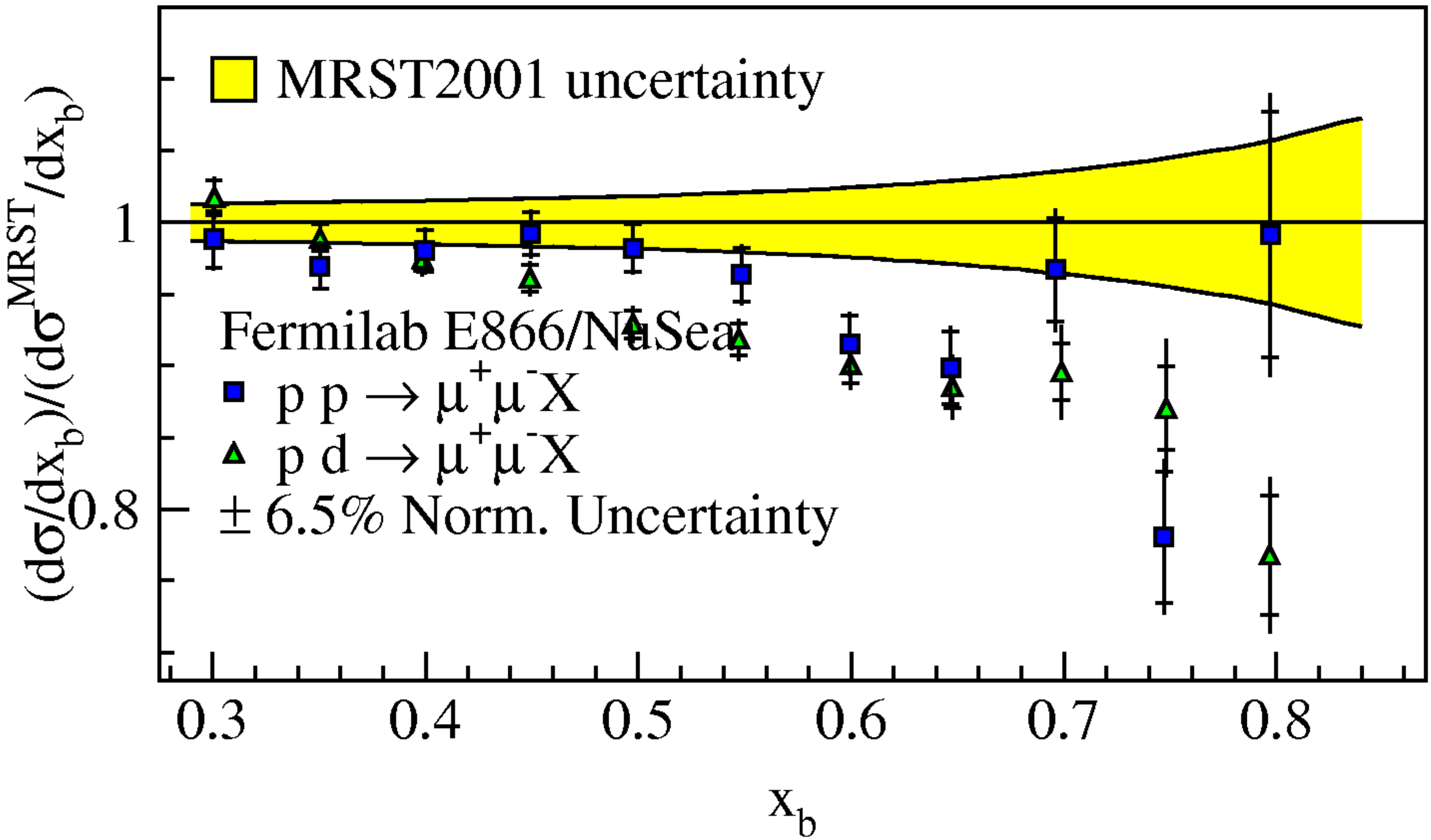
$$\left.\frac{\sigma^{pd}}{2\sigma^{pp}}\right|_{x_b \gg x_t} \approx \frac{1}{2}\left[1 + \frac{\bar{d}(x_t)}{\bar{u}(x_t)}\right]$$



Even for a "mature" analysis, new data can have a large impact

Donald Isenhower (ACU)
DIS'04

Drell- Yan Cross Section in large x limit

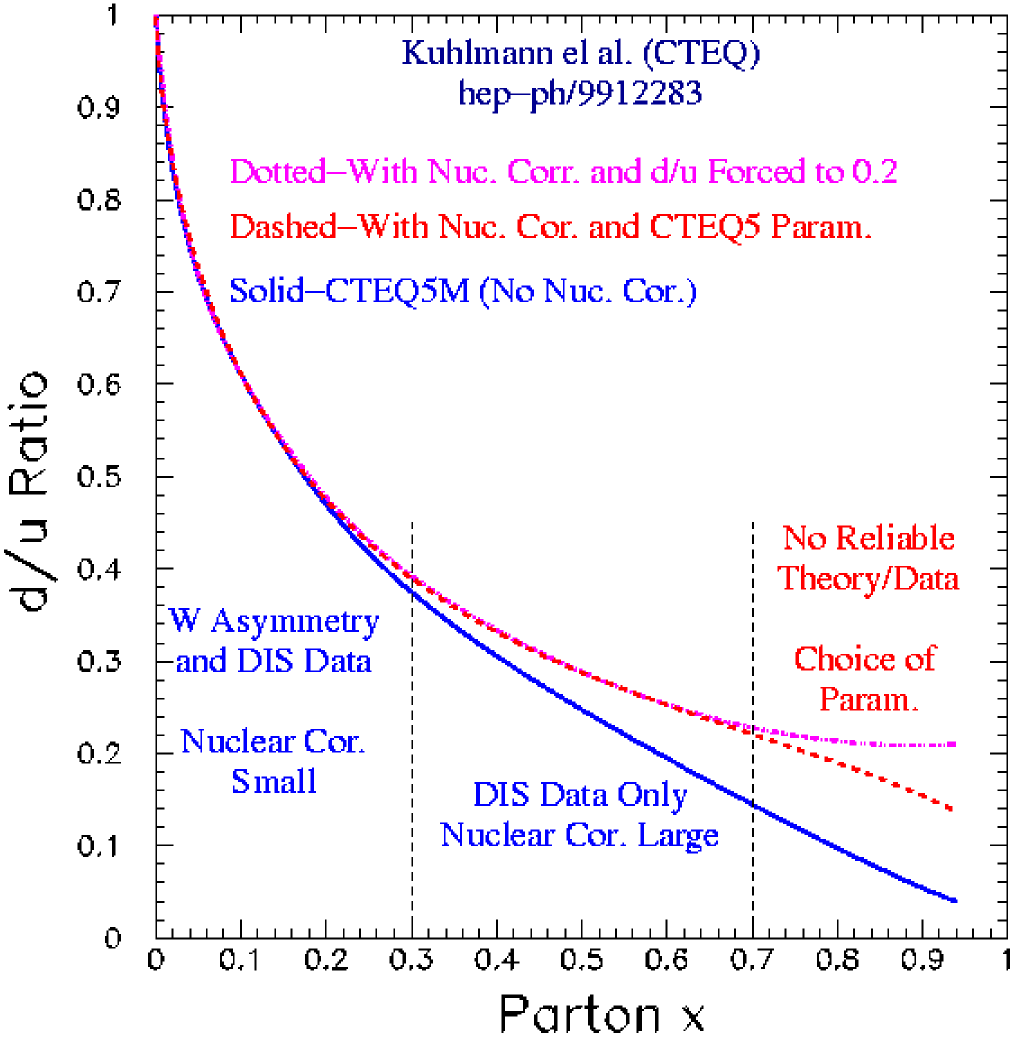


$d\sigma \sim (4u + d)$ in large x limit

Theory over estimates data in this limit

J. C. Webb, et al. [NuSea Collaboration], hep-ex/0302019

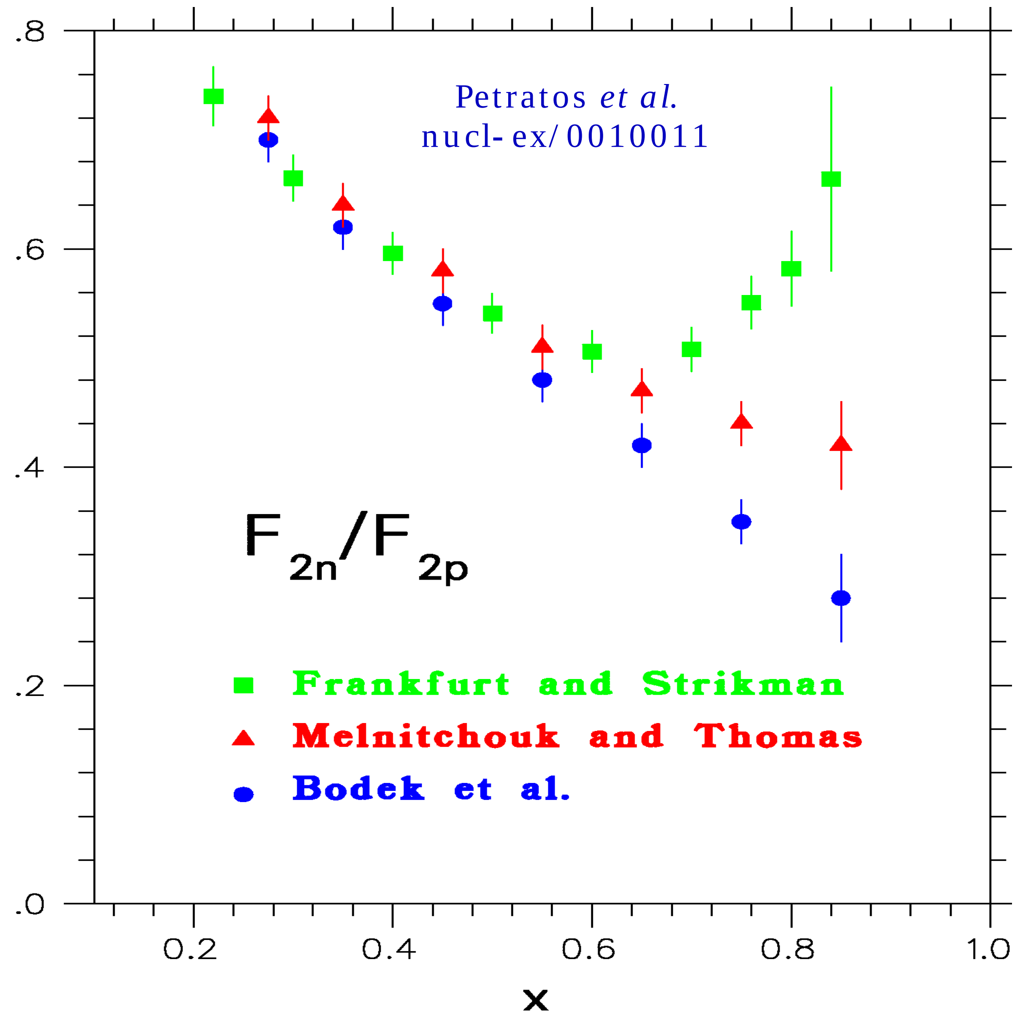
Proton Valence Structure: d/u for large x



For large x, nuclear binding/Fermi motion corrections are important

Even Deuterion has large effects

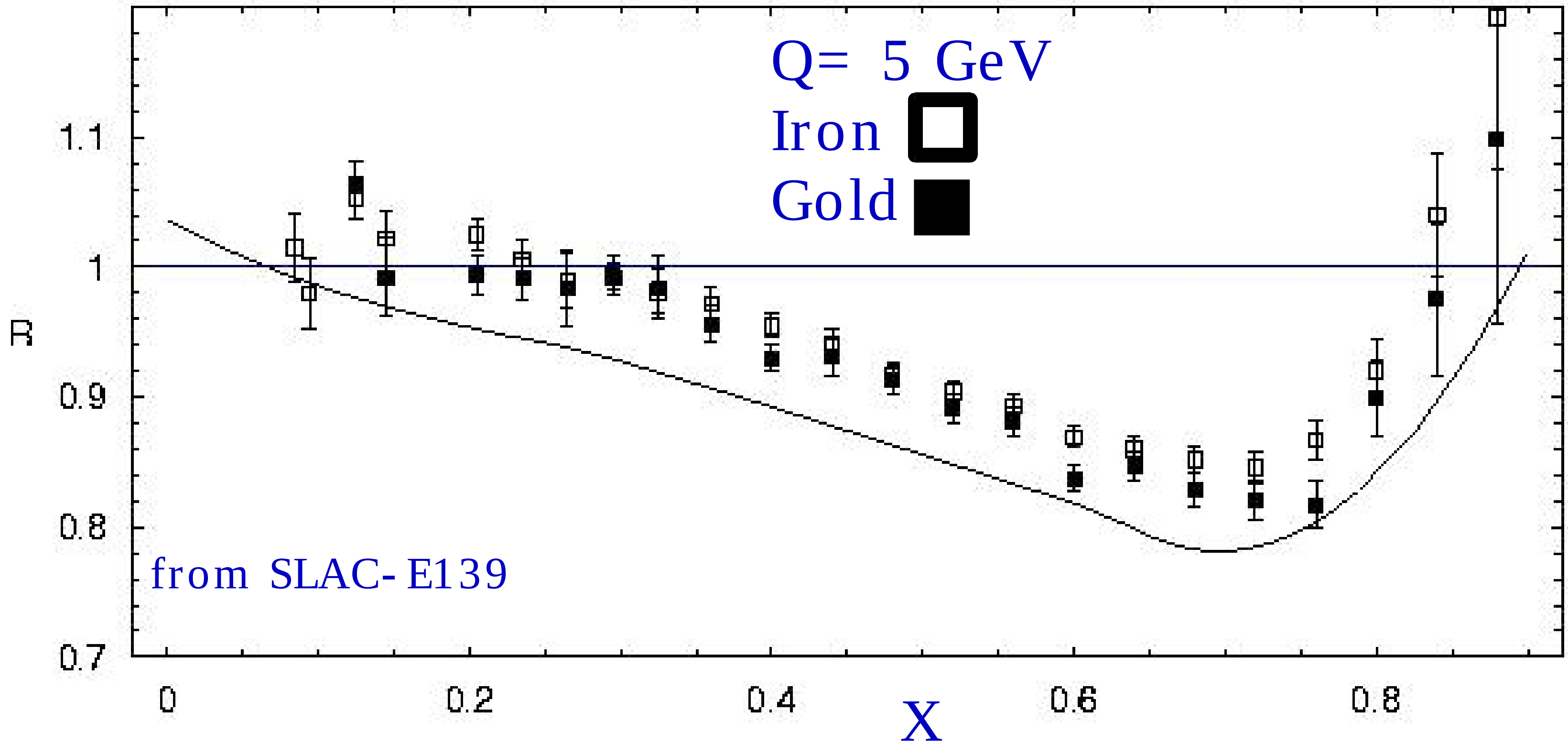
Lots of models to choose from



Donald Isenhower (ACU)
DIS'04

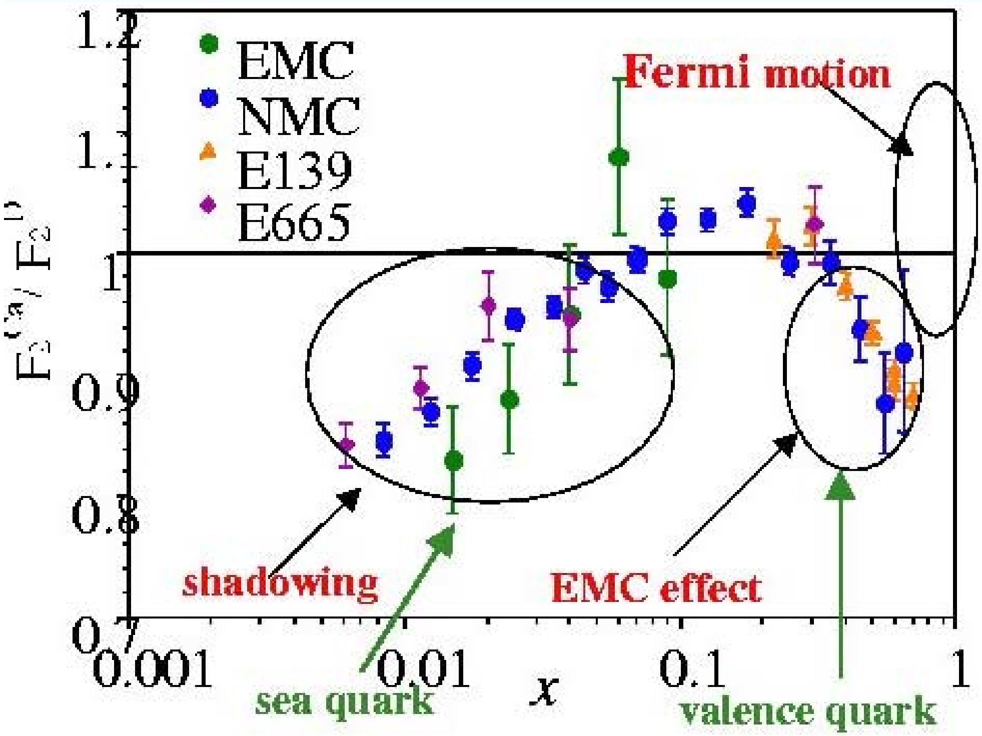
$$R(x,Q) = \frac{F_2^A(x,Q)}{A\ F_2^N(x,Q)}$$

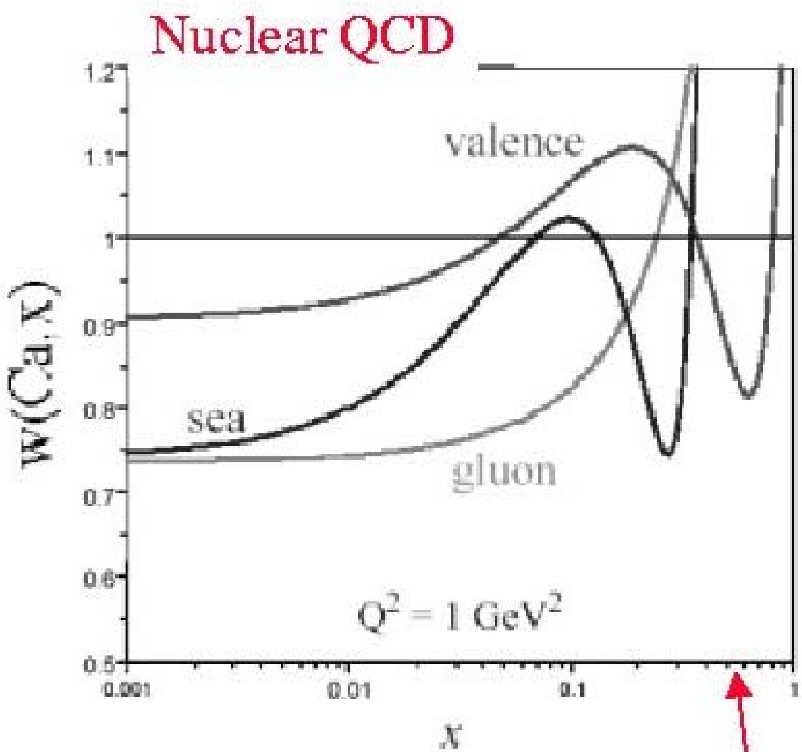
Measures the extent to which nuclei are not a Σ of free nucleons



We're simplying parameterizing our ignorance

Knowledge of Nuclear Effects with Neutrinos: essentially NON-EXISTENT





F_2 / nucleon changes as a function of A. Measured in μ/e - A **not in ν – A**

Good reason to consider nuclear effects are DIFFERENT in ν - A.

- **Presence of axial-vector current.**
- **SPECULATION: Much stronger shadowing for ν -A but somewhat weaker "EMC" effect.**
- **Different nuclear effects for valance and sea --> different shadowing for xF_3 compared to F_2.**
- **Different nuclear effects for d and u quarks.**

MINERνA (Main INjector ExpeRiment ν- A)

Assume 4.0×10^{20} in LE ν beam, 8×10^{20} in ME, 1.5×10^{20} in HE and and 2.5×10^{20} in HEbar

ν_μ Event Rates in 3 fiducial tons of CH

Process	CC	NC	CCbar
Quasi-elastic	835 K	275 K	105 K
Resonance	1605 K	495 K	130 K
Transition	2000 K	635 K	230 K
DIS	4080 K	1215 K	455 K
Coherent	85 K	43 K	20 K
TOTAL	**8600 K**	**2665 K**	**940 K**

Typical Fiducial Volume =
3-5 tons CH, 0.6 ton C, ≈ 1 ton Fe and ≈ 1 ton Pb

8.6 - 14.3 M ν events in CH
1.0 - 1.5 M $\bar{\nu}$ events in CH
1.4 M ν events in C
2.9 M ν events in Fe
2.9 M ν events in Pb

16 Million total CC events in a 4 - year run

Examples of available statistics

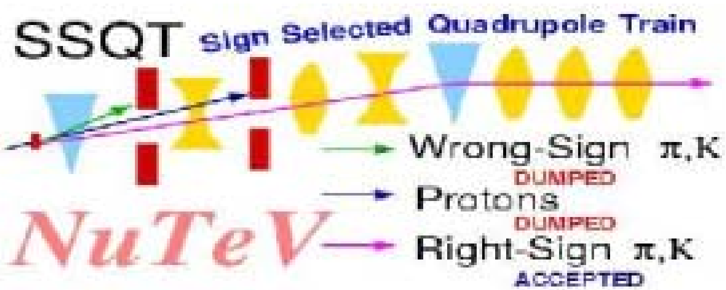
Transition Region	**2 M events**
DIS and Structure Functions	**4 M DIS events (W > 2, Q > 1)**
Nuclear PDF's and Effects	**C:1.4 M, Fe: 2.9 M and Pb: 2.9 M**

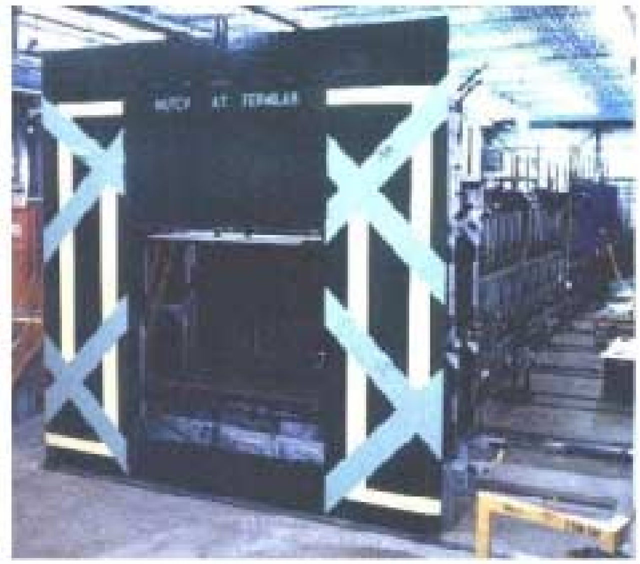
Moral

For the global analysis,
we prefer to reduce nuclear data
to the isoscalar case;
but this reduction is not trivial

The NuTeV experiment at FNAL

ν-N DIS, sign-selected beam $\langle E_\nu \rangle \sim 120$ GeV
and continuous test beam calibration





Data taken during 1996-97

Hadronic energy: $\delta E/E \sim 0.4\%$

$\sigma E/E \sim (2.4 + 87/\sqrt{E})\%$

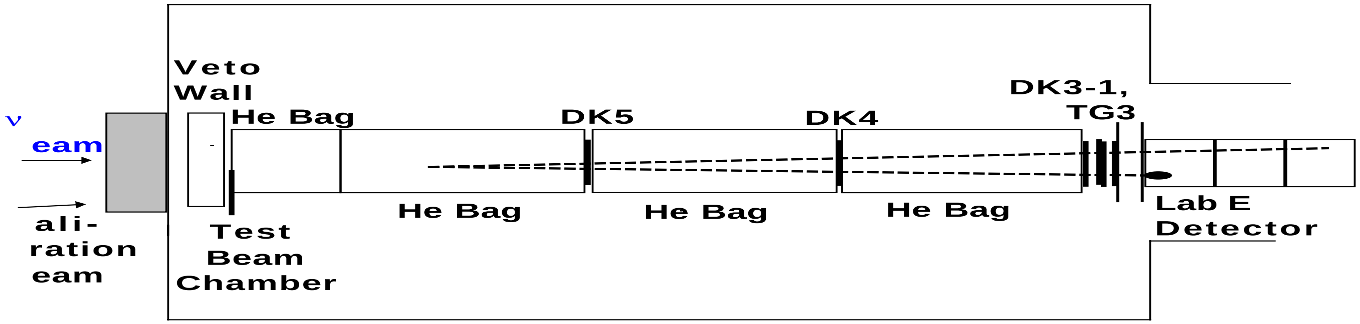
μ momentum

$\delta P/P \sim 1\%$

$\sigma P/P \sim 11\%$

Relative scale (E,P) <0.5%

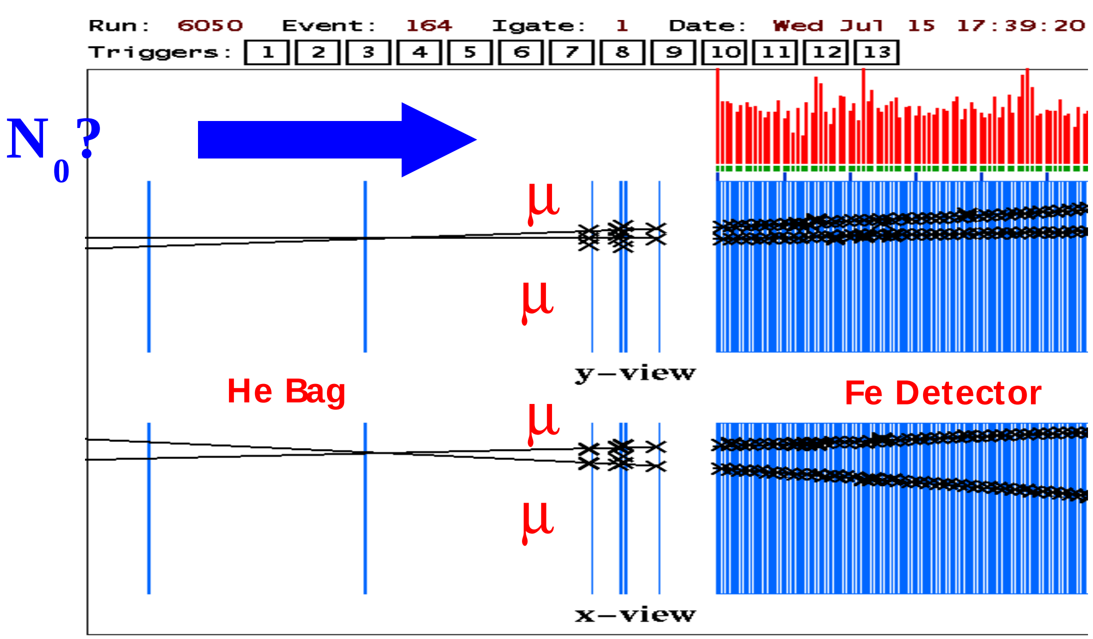
Anomalous μμ events in Neutrino-Induced DIS



Todd Adams
NuTeV Collaboration

PRL 87:041801 (2001)

Could this be evidence for an heavy neutral lepton?

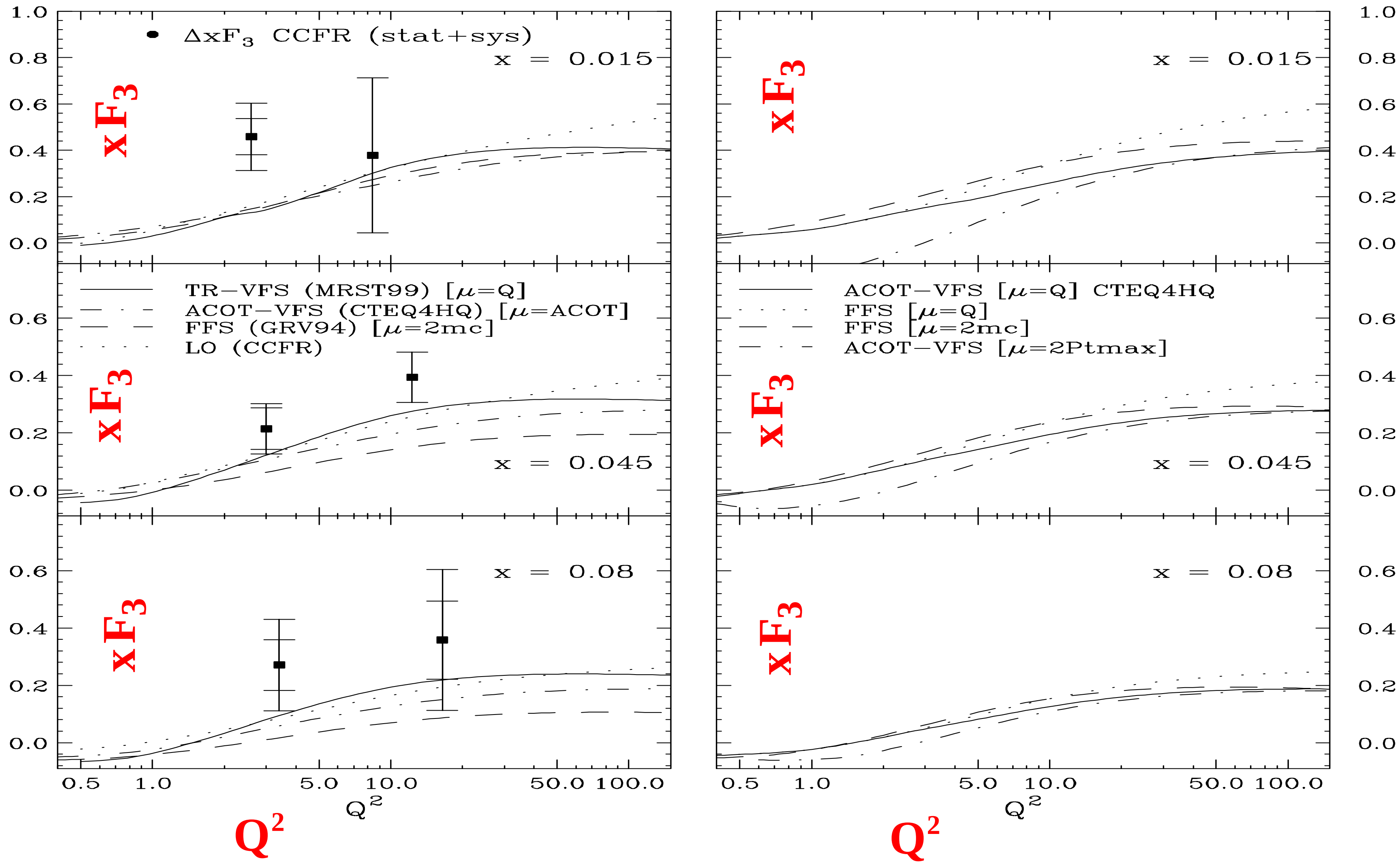


Three μμ events observed

< 0.07 μμ event expected

$N^0 \rightarrow \mu\mu\nu$???

δxF_3 Structure Function

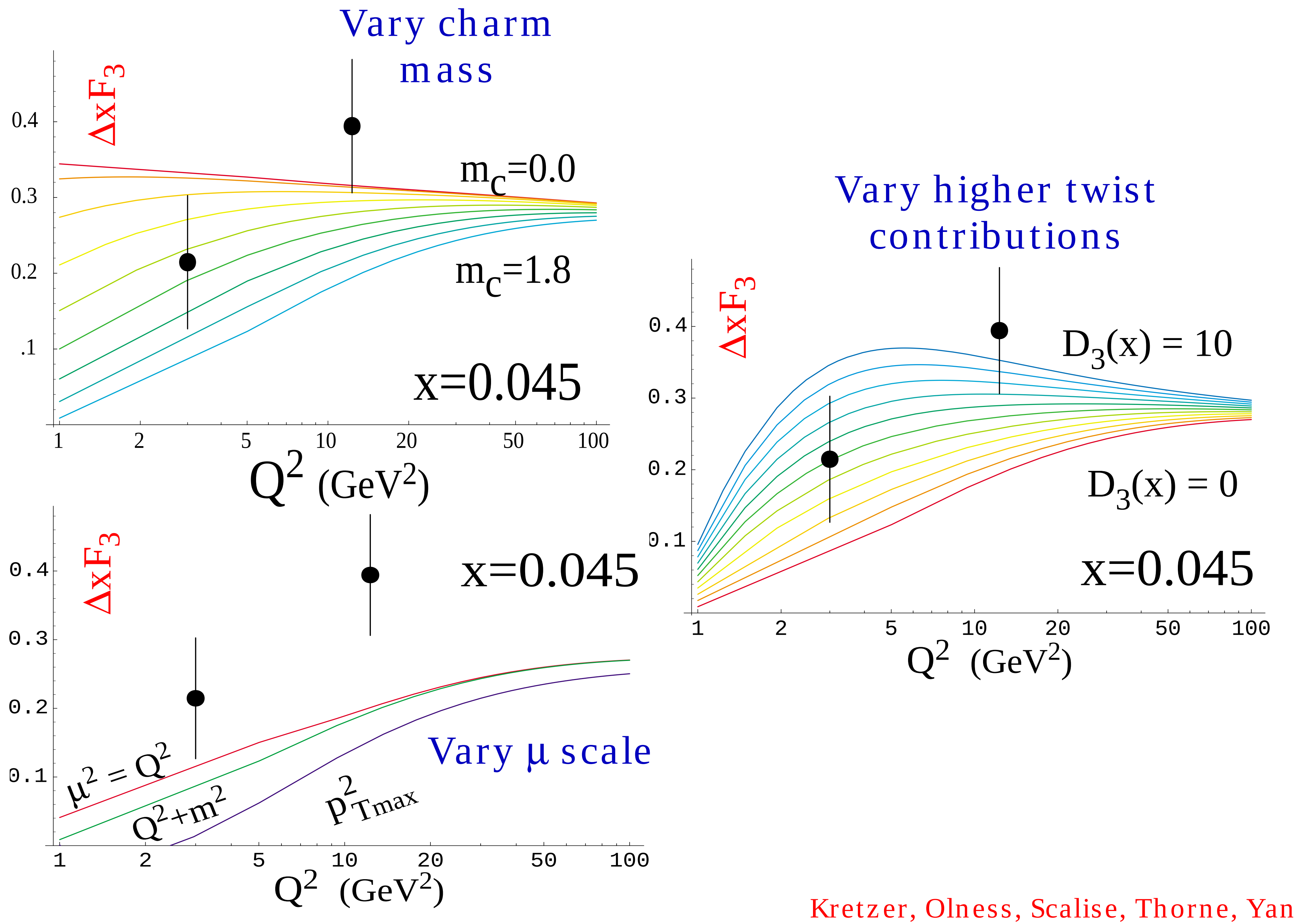


$$\Delta xF_3 \sim 4\,x\,(\,s - c\,)$$

Un- Ki Yang
NuTeV Collaboration

PRL 86:2742 (2001)

Can we make the problem go away?



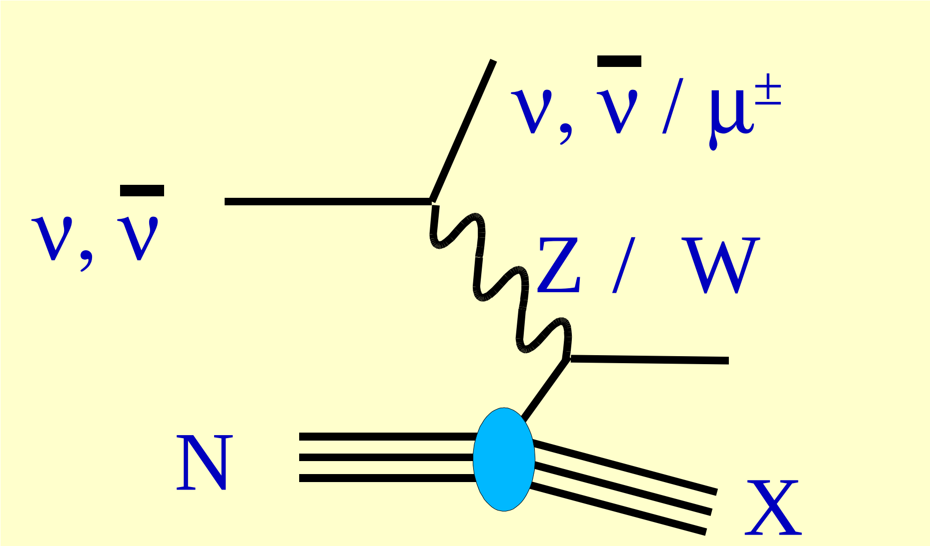
Kretzer, Olness, Scalise, Thorne, Yang
PRD64: 033003, 2001

Question?

$$\Delta x F_3 \sim 4x(s - c)$$

Could something strange be happening with the heavy quarks?

Electroweak Mixing Angle Measurement



Paschos-Wolfenstein Relation:

$$R^{-} \equiv \frac{\sigma(\nu_\mu N \rightarrow \nu_\mu X) - \sigma(\overline{\nu}_\mu N \rightarrow \overline{\nu}_\mu X)}{\sigma(\nu_\mu N \rightarrow \mu^- X) - \sigma(\overline{\nu}_\mu N \rightarrow \mu^+ X)}$$

$$\approx \left(\frac{1}{2} - sin^2\theta_W\right)$$

NuTeV Result: $\sin^2\theta_W^{(on-shell)} = 0.2277 \pm 0.0031(stat) \pm 0.0009(syst)$

Standard Model Fit:

$\sin^2\theta_W^{(on-shell)} = 0.2227 \pm 0.0004$ **LEP EWWG**

A 3 σ difference

G.P. Zeller, (NuTeV) et al., PRL 88: 091802 (2002); PRD 65: 111103 (2002)

Contributions to Experimental Uncertainty

SOURCE OF UNCERTAINTY	$\delta\sin^2\theta_W$	δR^ν	$\delta R^{\overline{\nu}}$
Data Statistics	0.00135	0.00069	0.00159
Monte Carlo Statistics	0.00010	0.00006	0.00010
TOTAL STATISTICS	0.00135	0.00069	0.00159
$\nu_e, \overline{\nu}_e$ Flux	0.00039	0.00025	0.00044
Energy Measurement	0.00018	0.00015	0.00024
Shower Length Model	0.00027	0.00021	0.00020
Counter Efficiency, Noise, Size	0.00023	0.00014	0.00006
Interaction Vertex	0.00030	0.00022	0.00017
TOTAL EXPERIMENTAL	0.00063	0.00044	0.00057
Charm Production, Strange Sea	0.00047	0.00089	0.00184
Charm Sea	0.00010	0.00005	0.00004
$\sigma^{\overline{\nu}}/\sigma^\nu$	0.00022	0.00007	0.00026
Radiative Corrections	0.00011	0.00005	0.00006
Non-Isoscalar Target	0.00005	0.00004	0.00004
Higher Twist	0.00014	0.00012	0.00013
R_L	0.00032	0.00045	0.00101
TOTAL MODEL	0.00064	0.00101	0.00212
TOTAL UNCERTAINTY	0.00162	0.00130	0.00272

TABLE I. Uncertainties for both the single parameter $\sin^2\theta_W$ fit and for the comparison of R^ν and $R^{\overline{\nu}}$ with model predictions.

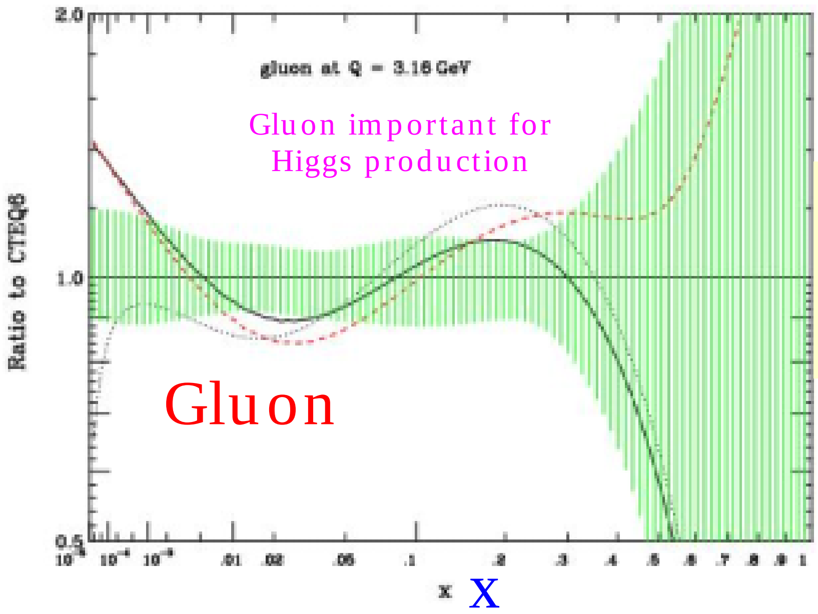
Largest model uncertainty arises from charm production and s(x)

s and s-bar difference can have large effect

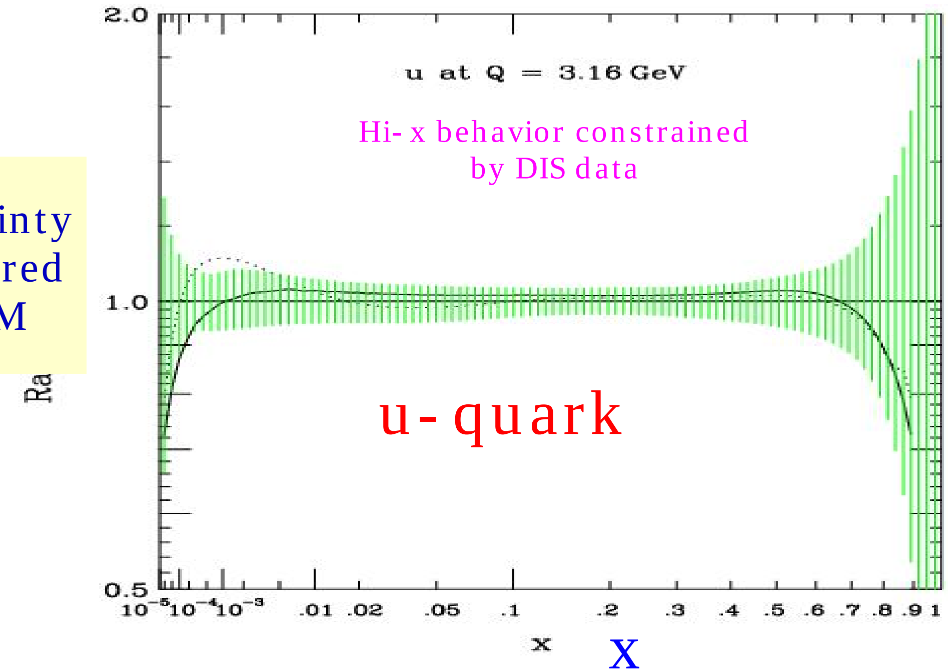
... relative uncertainty is reduced for combination

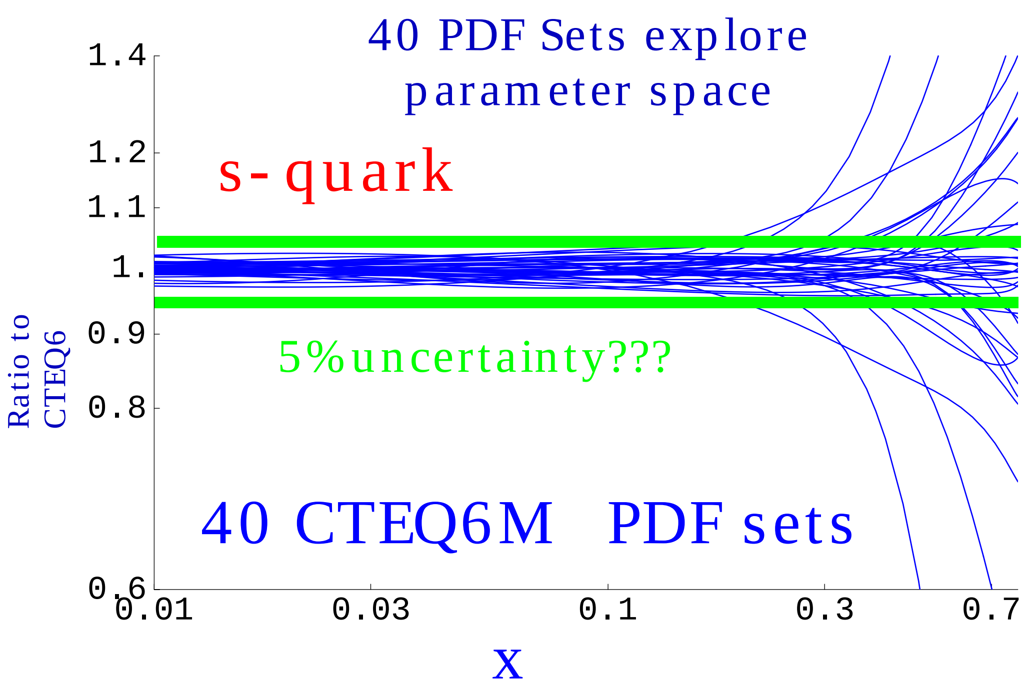
G.P. Zeller, (NuTeV) et al., PRL 88: 091802 (2002); PRD 65: 111103 (2002)

What is relative uncertainty on PDFs' ???



PDF Uncertainty band compared to CTEQ6M





Previously, s(x) was tied to u-bar and d-bar via kappa:

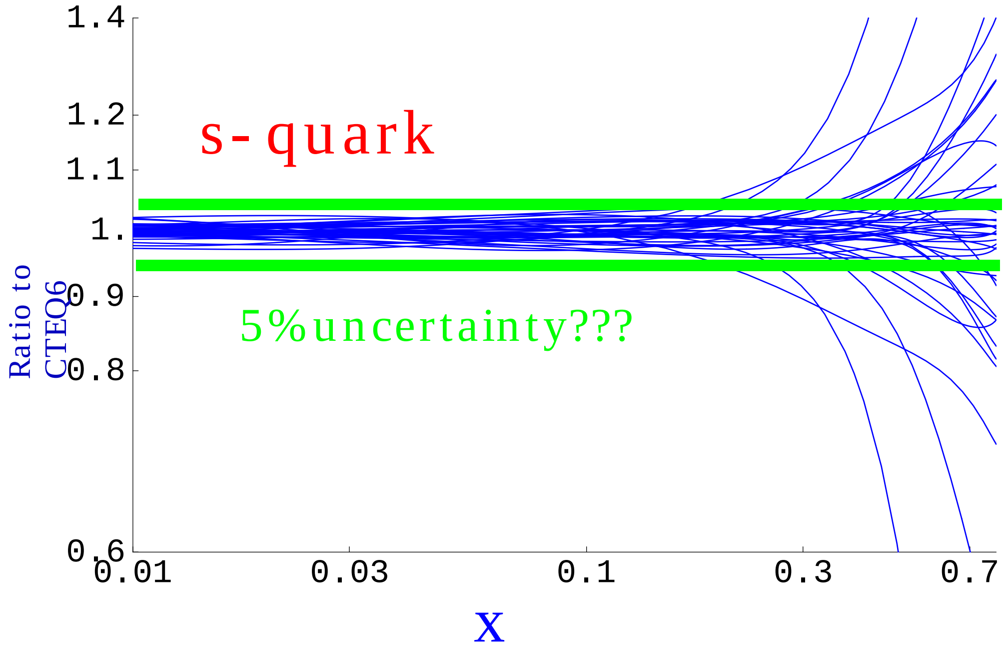
$$s(x) = \bar{s}(x) = \kappa \, \frac{\bar{u}(x) + \bar{d}(x)}{2}$$

Question: Do we really know the s-quark PDF to 5%???

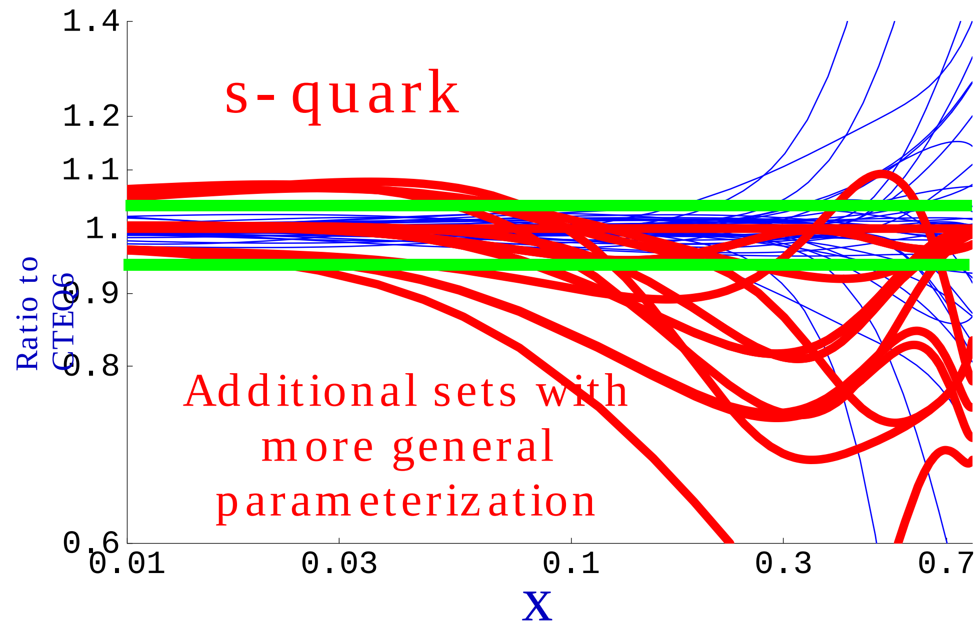
CTEQ6: Pumplin, Stump, Huston, Lai, Nadolsky, Tung, JHEP 0207, 012 (2002)

What is true uncertainty on s-quark PDF???

40 CTEQ6M PDF sets



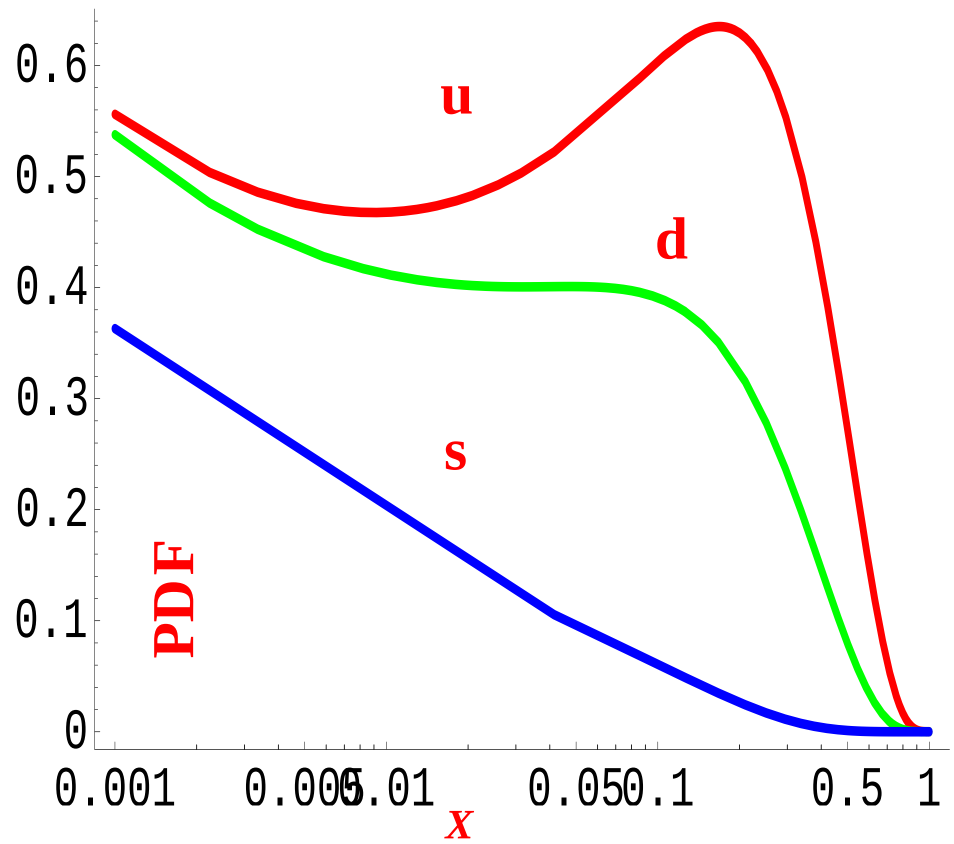
Closer to the true error

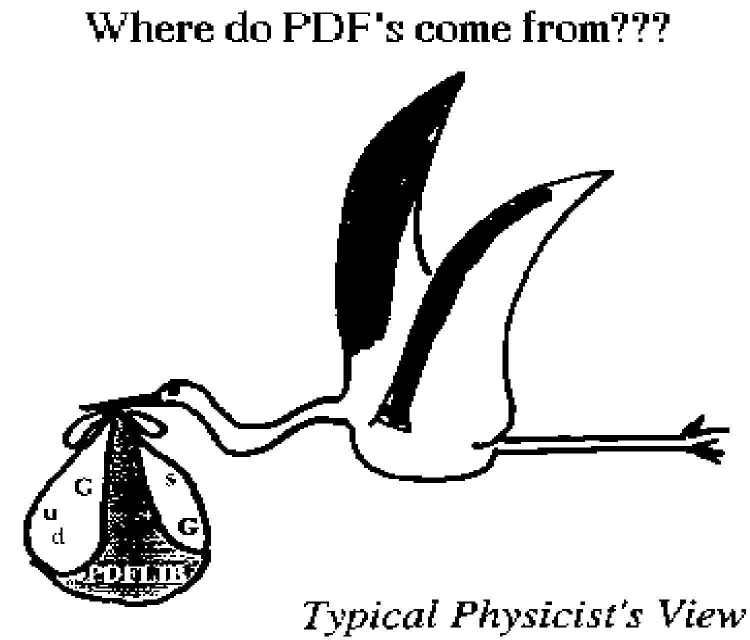


Curves shown are examples;
this is not an exhaustive set

Warning: The Director General has determined the band of PDF's can greatly underestimate the true uncertainty

Where does s(x) come from???





Drawing by Heidi Schellman

Inclusive Structure Funtions:

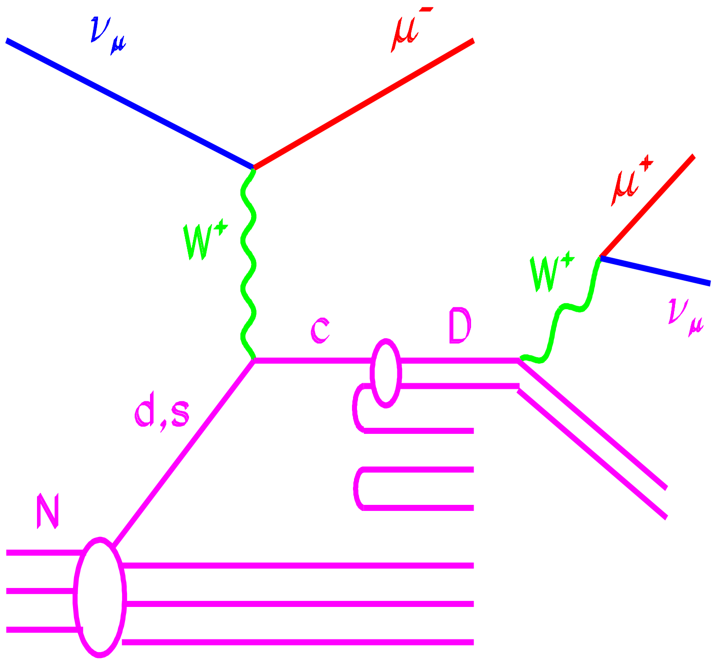
Yield s(x) in combination

Must extract s(x)
from under other PDF's

$$F_2 \cong x\,(u + \bar{u} + d + \bar{d} + s + \bar{s} + c + \bar{c} + \ldots)$$

... we can do better ...

Dimuons are ideal signal of s(x)



di- muon	NuTeV	CCFR	Combined
Neutrino	5012	5030	10042
Anti- Nu	1458	1060	2518

* High stats & high precision data
* Best constraints on strange quark

$$\frac{d\sigma^{+}_{\mu^\pm\mu^\mp}}{dx\,dy} = \int d\Gamma\, d\Omega\ \frac{d\sigma_{\mu^\mp c}}{dx\,dy\,d\Gamma} \otimes D_c(\Gamma) \otimes \Delta_c(\Omega)\Big|_{E_{\mu^\pm}>5\ GeV}$$

Di- muon cross- section

Charm Production cross- section

Fragmentation Function

Decay Distribution

M. Goncharov et al., NuTeV Collaboration PRD 64:110226 (2001)

Global Fit

χ^2 / DOF	CTEQ6M	Constrained	Mixed	Free
CCFR Nu	1.02	0.85	0.79	0.72
CCFR Nu-bar	0.58	0.54	0.59	0.59
NuTeV Nu	1.81	1.70	1.55	1.44
NuTeV Nu-bar	1.48	1.30	1.15	1.13
BCDMS F2p	1.11	1.11	1.11	1.11
BCDMS F2d	1.10	1.10	1.10	1.11
H1 96/97	0.94	0.95	0.94	0.94
H1 98/99	1.02	1.03	1.03	1.03
ZEUS 96/97	1.14	1.14	1.14	1.15
NMC F2p	1.52	1.50	1.51	1.49
NMC F2d/F2p	0.91	0.91	0.91	0.91
MC F2d/F2p <Q^2>	1.05	1.07	1.06	1.03
CCFR F2	1.70	1.71	1.81	1.88
CCFR F3	0.42	0.42	0.44	0.42
E605	0.82	0.82	0.82	0.83
NA51	0.62	0.61	0.52	0.52
CDF ℓ Asym	0.82	0.83	0.82	0.82
E866	0.39	0.40	0.39	0.38
D0 Jets	0.71	0.65	0.70	0.67
CDF Jets	1.48	1.48	1.48	1.47
TOTAL	2173	2144	2142	2133

Total of 1991 data points

Reasonable χ^2 values

(CTEQ6 did not fit di-muon data)

More parameters, lower value of χ^2

Only di-muon data is sensitive to s(x) !!!

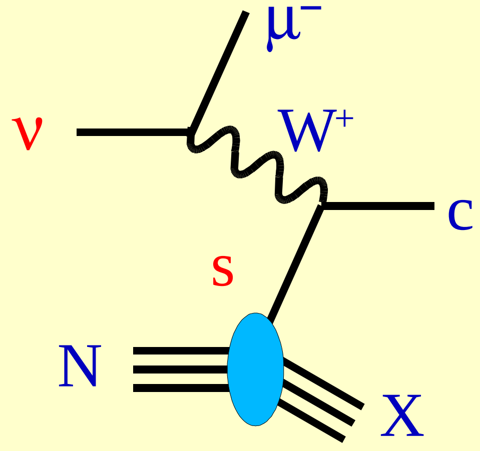
∴

Idea: ν and ν-bar data separately determine s and s-bar distributions

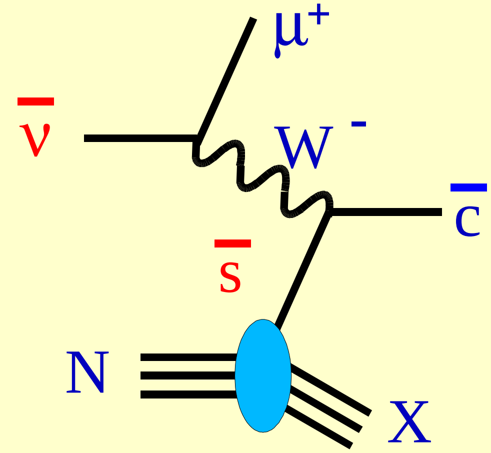
PRELIMINARY

CTEQ6: J. Pumplin, et al., JHEP 0207:012,2002

Sign-selected beam separates ν and $\bar{\nu}$: Extract s and $\bar{s}$



$s(x)$ proportional to ν



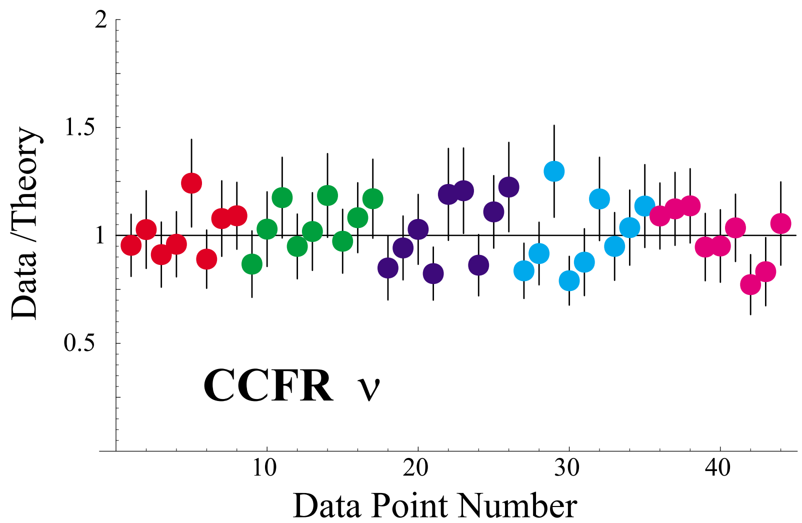
$\bar{s}(x)$ proportional to $\bar{\nu}$

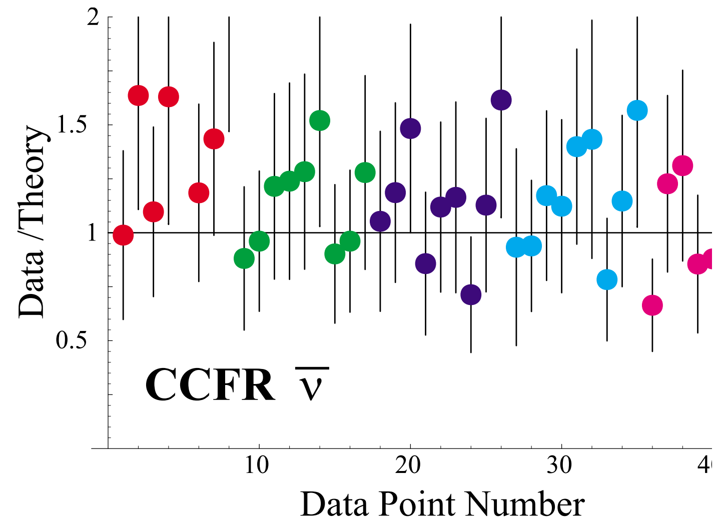
* Other data sets are insensitive to $s(x)$

* Caution: ensure quark number sum rule is satisfied

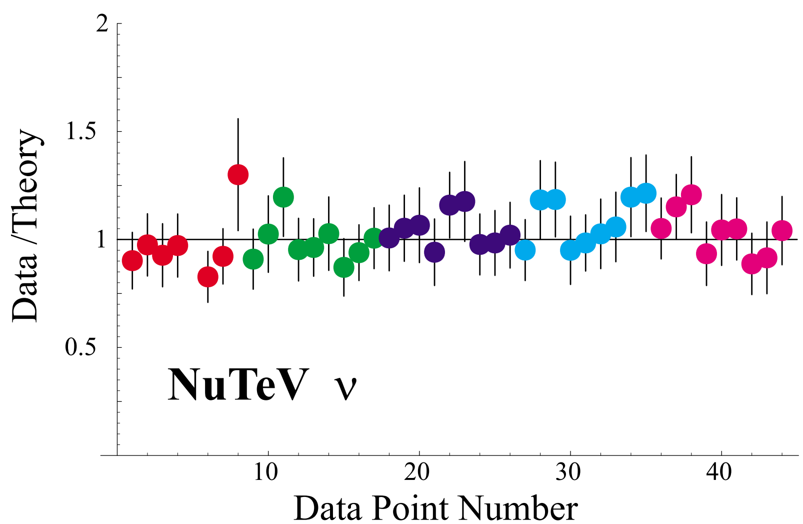
$$\int dx\left[s(x)-\bar{s}(x)\right]=0$$

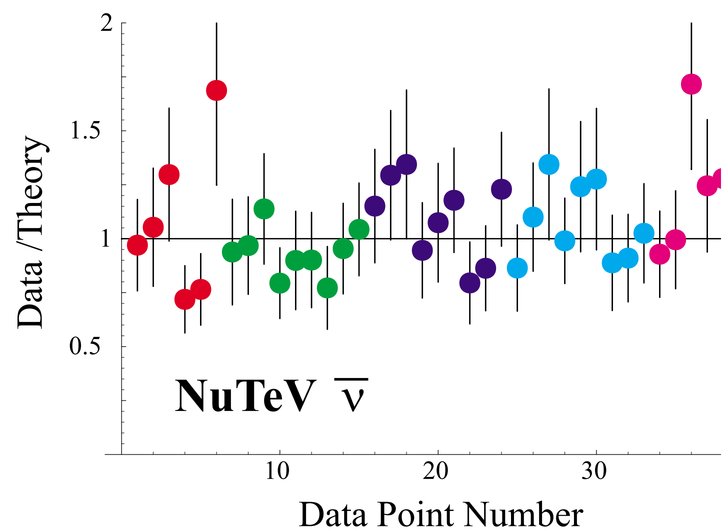
How good is the fit? (Data - Theory)/ Theory Plots





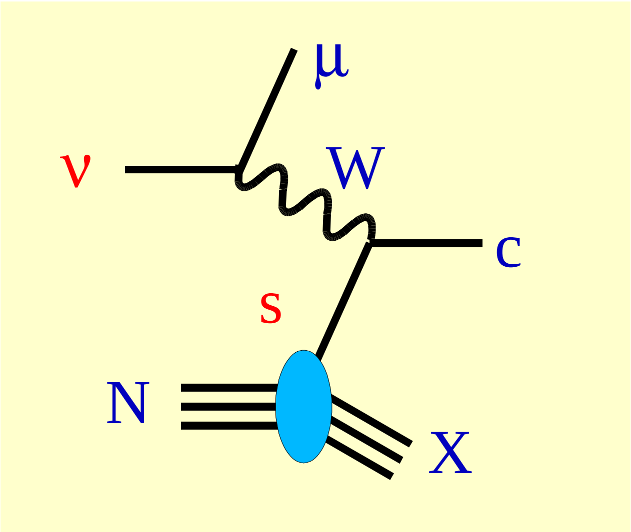
PRELIMINARY

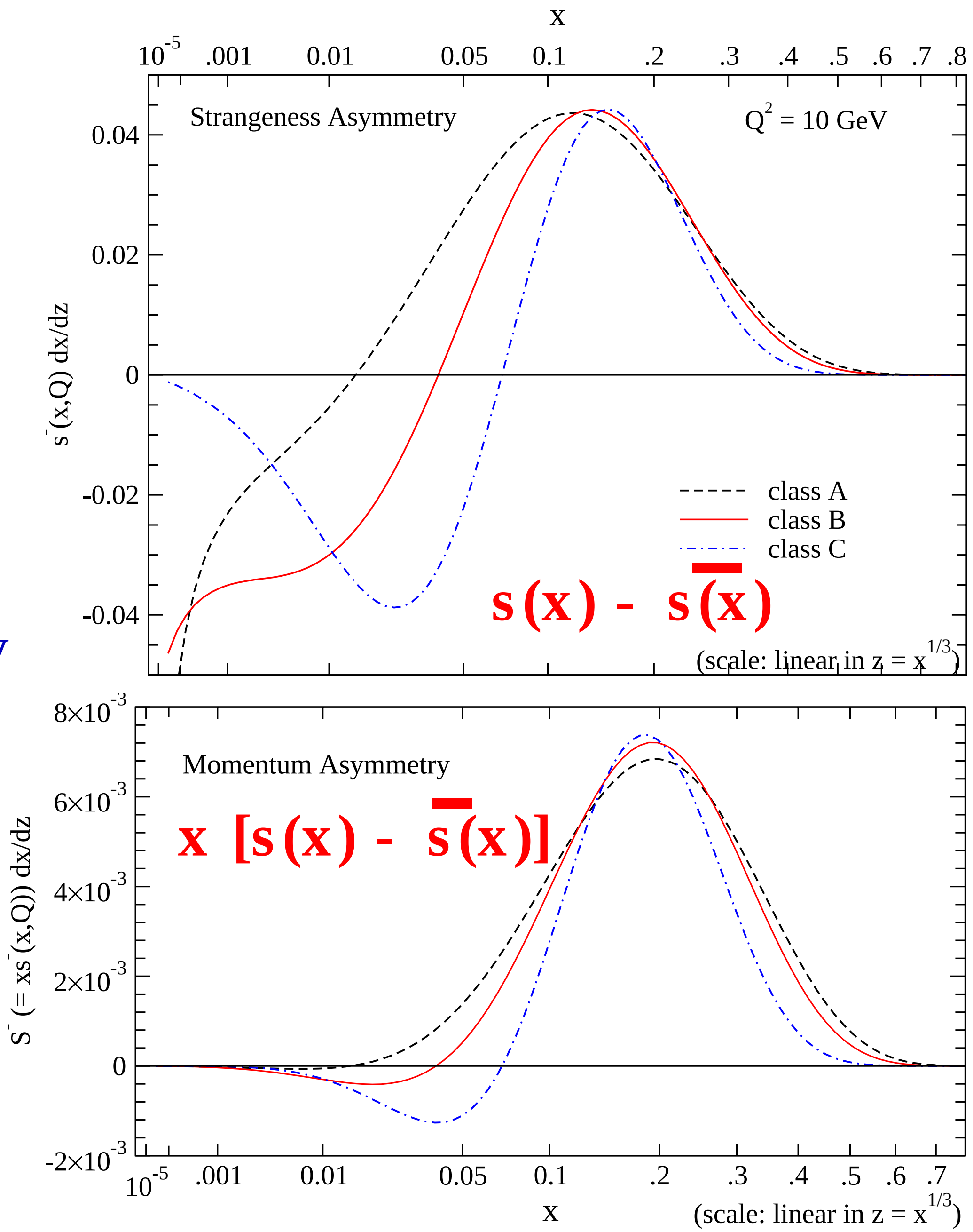




Higher statistics for ν- data ⇒ stronger pull for fit

What does the strange PDF look like?





General range of the asymmetry

$$[S^-] \equiv \int_0^1 x\{s(x) - \bar{s}(x)\}$$

$$+0.40 \geqslant 100 \times [S^-] \geqslant -0.10$$

Olness et al.,Eur.Phys.J.C40:145-156,2005
Kretzer et al., Phys.Rev.Lett.93:041802,2004

What is the range of the $s-\bar{s}$ Asymmetry?

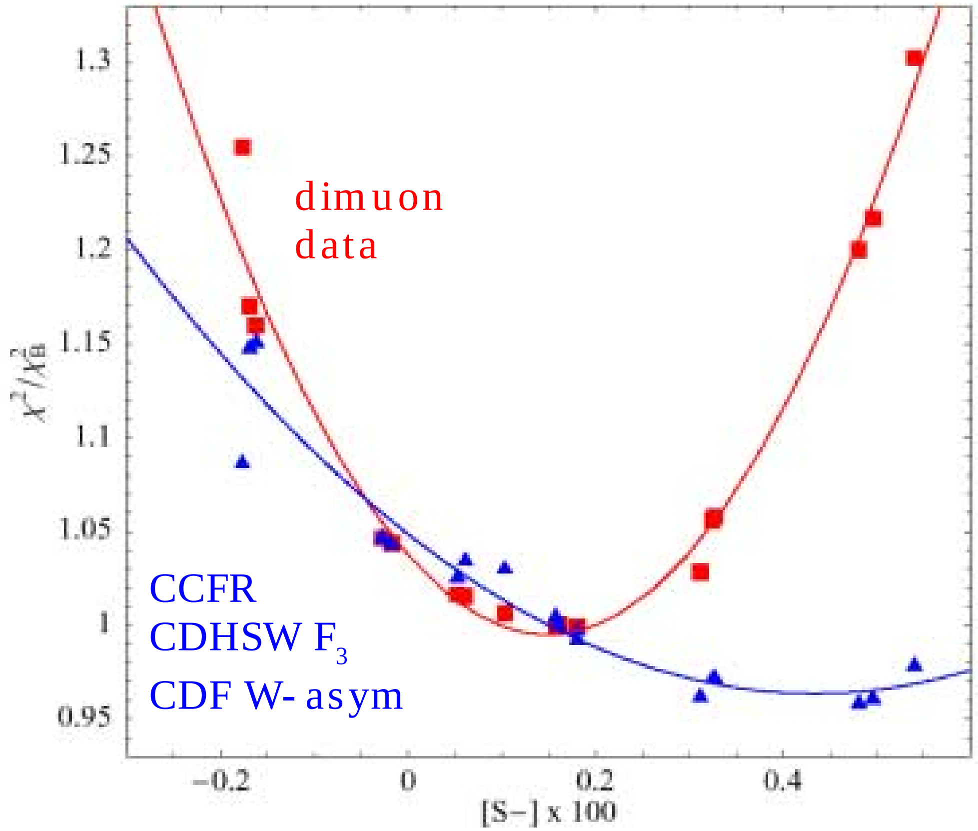
General range of the asymmetry

$$[S^-] \equiv \int_0^1 x\{s(x) - \bar{s}(x)\}$$

$$+0.40 \geqslant 100 \times [S^-] \geqslant -0.10$$

$s-\bar{s}$: large uncertainty affected by:

- charm fragmentation
- charm mass
- PDF set



	# pts	B+	A	B	C	B-
$A_1 + b$	-	-0.78	-0.99	-0.78	0	-0.78
$[S^-] \times 100$	-	0.540	0.312	0.160	0.103	-0.177
Dimuon	174	**1.30**	1.02	*1.00* (126)	1.01	**1.26**
Inclusive I	194	0.98	0.97	*1.00* (141)	1.03	**1.09**
Inclusive II	2097	1.00	1.00	*1.00* (2349)	1.00	1.00

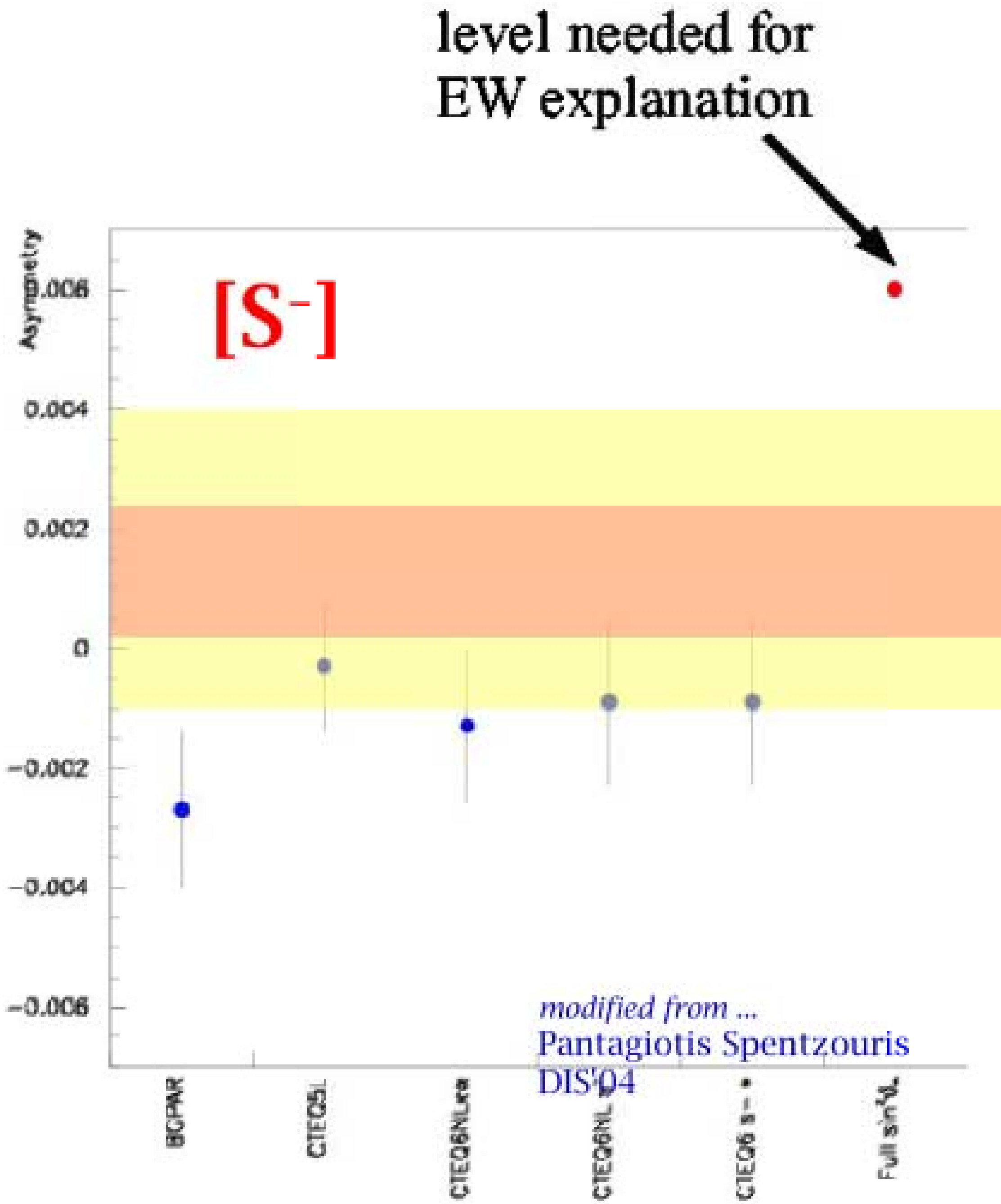
{ CCFR
CDHSW F_3
CDF W- asym

What is the status:

- Tremendous new information on $\bar{s}+s$

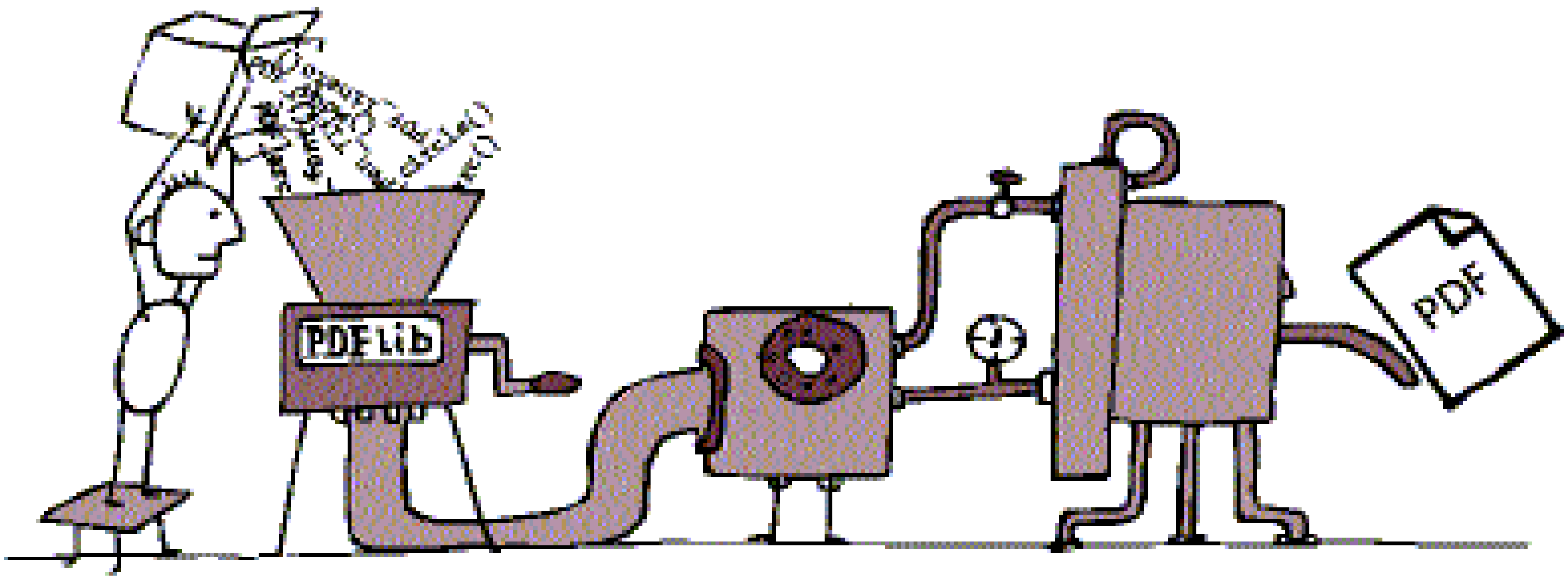
- $s-\bar{s}$: large uncertainty affected by:
  - charm fragmentation
  - charm mass
  - PDF set

- Strong interplay between the existing experimental constraints and the global theoretical constraints, particularly the # sum



That was LO

How do we make heavy quarks at NLO???



A Thought Experiment:

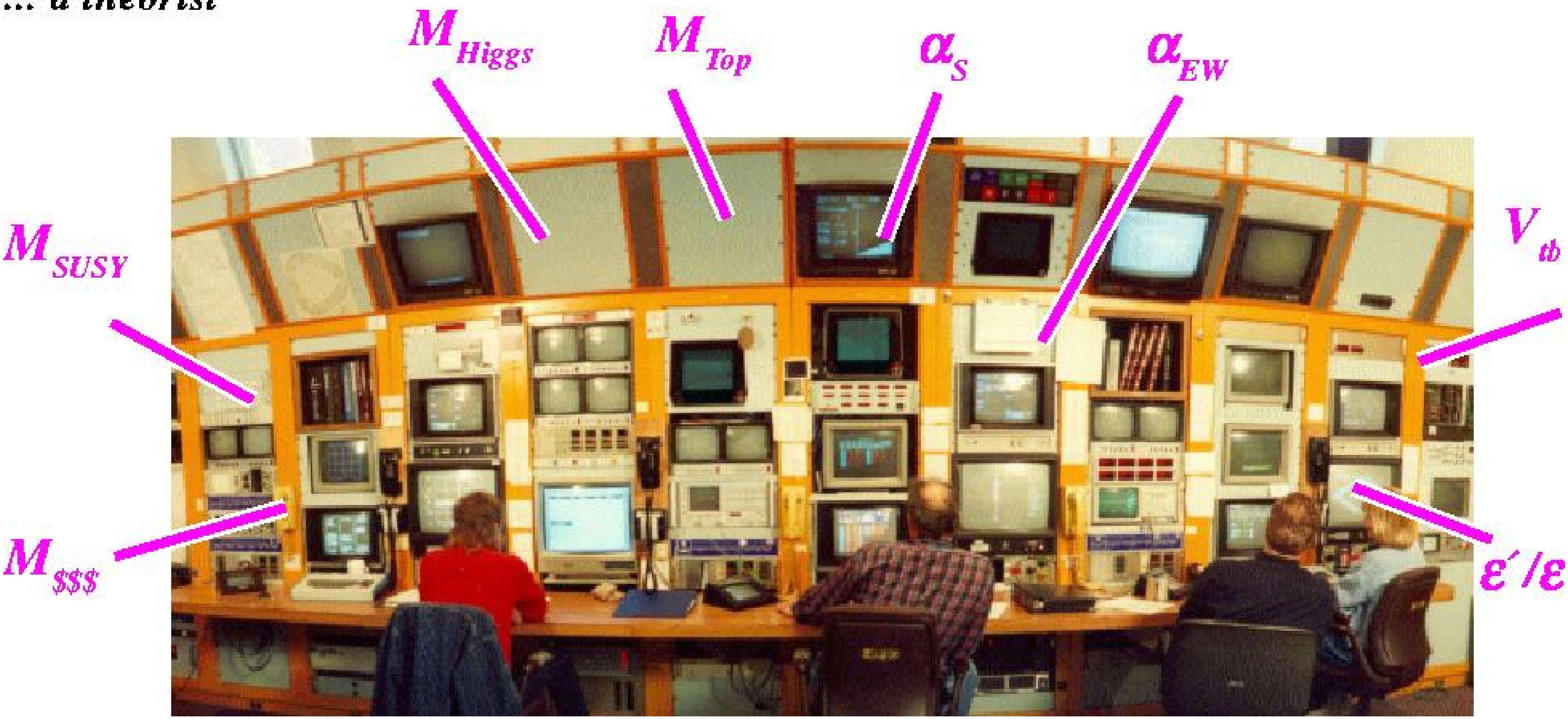
What is the ideal way to learn about quark masses and their effects on a physical process?

As a theorists, I simply run my calculation over the full range of mass values from 0 to ∞, and study the behavior.

Wouldn't it be great if the experiments could do the same???

What's really in the Experimental control room ...

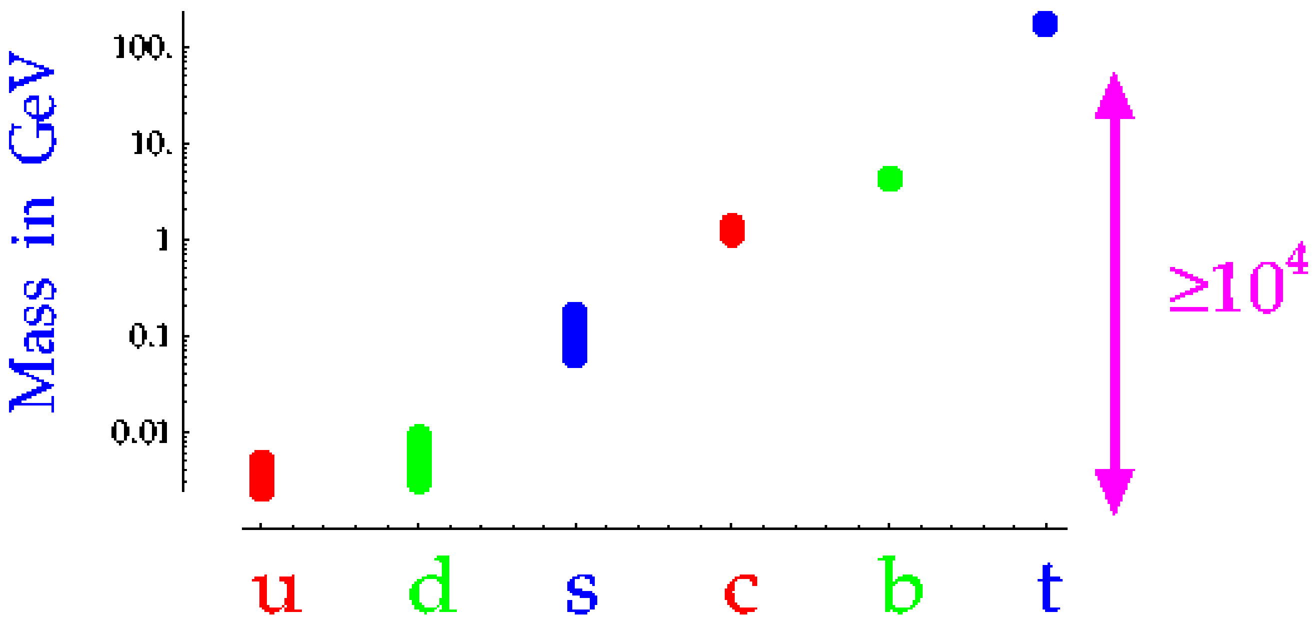
... a theorist



Unfortunately, in real life, we can't vary parameters continuously

The UP Side

Quark Masses Span Wide Dynamical Range ~ 10^4



u	0.008
d	0.015
s	0.300
c	1.500
b	5.000
t	175.000

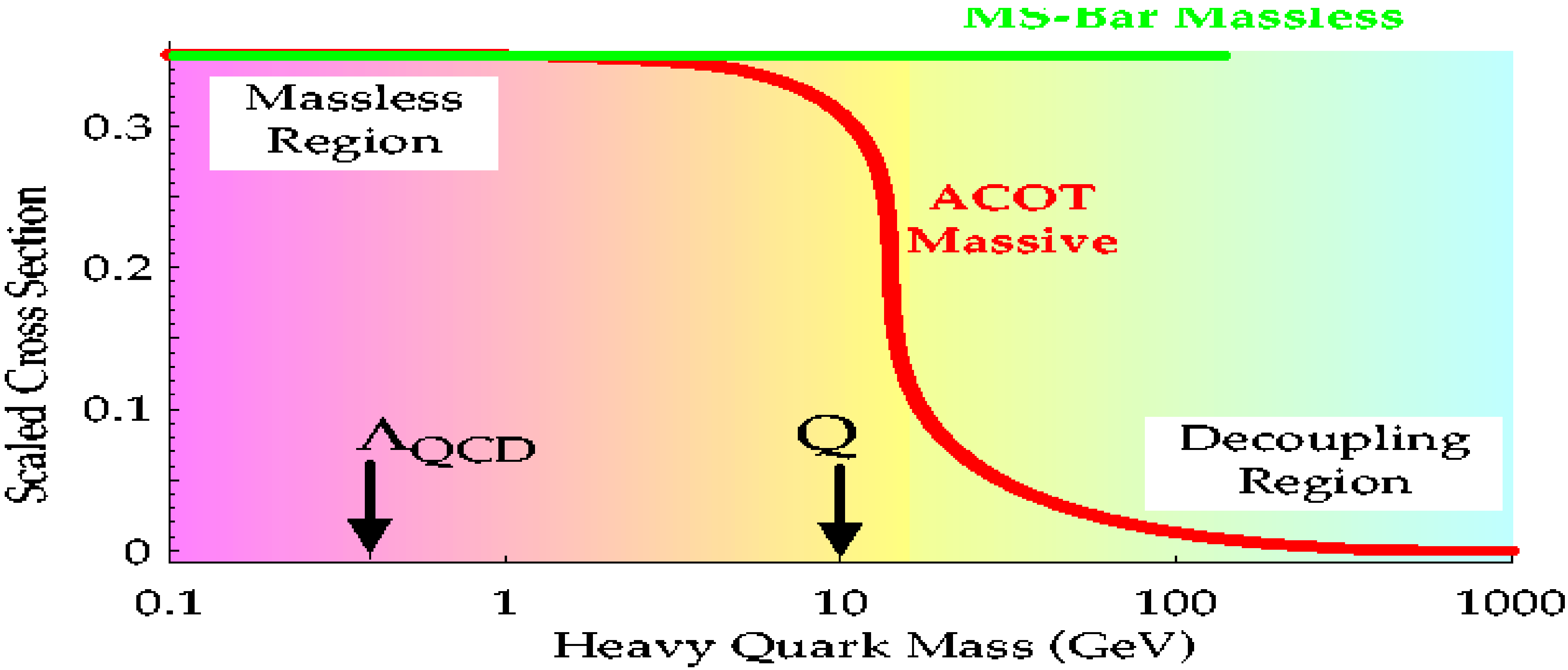
We can't vary the quark mass continuously, but these ``notches'' on our control panel give us a lot of flexibility

The DOWN Side

Theorists would much prefer that quark masses only come in 2 varieties:

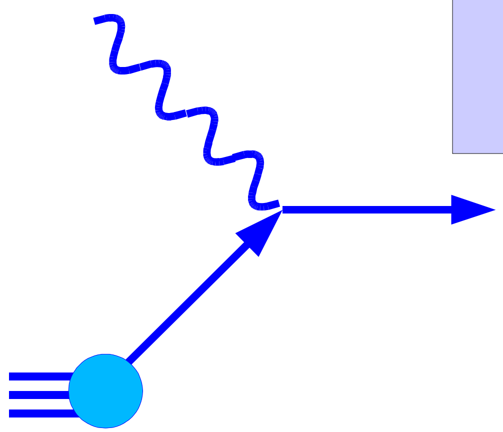
m = 0: Massless case.
Mass plays no dynamic role
Well understood.

m = ∞: Infinite case.
Mass Decouples.
We can forget about this object



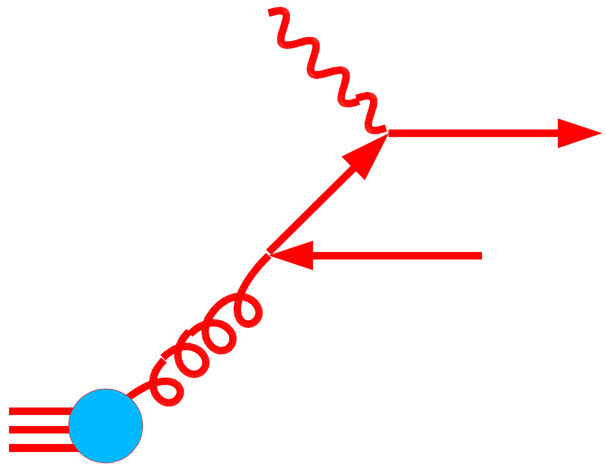
Production of Heavy Quarks: The Problem

Which is the correct production mechanism?



Heavy Excitation (HE)

Quark	Channel
s	YES
t	NO
c	???
b	???

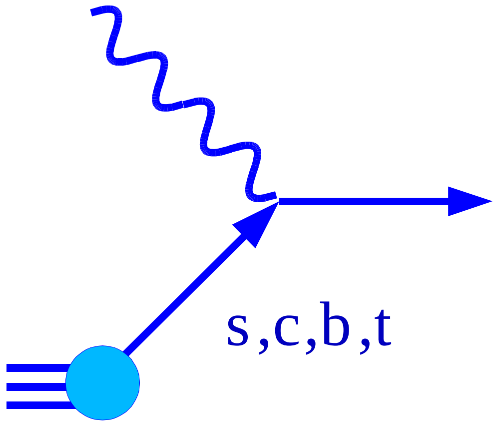


Heavy Creation (HC)

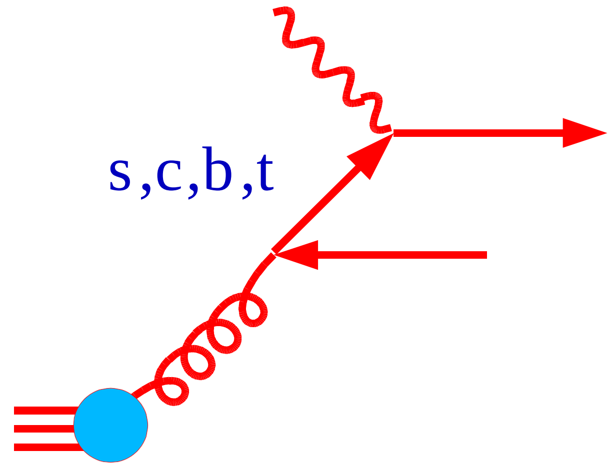
Quark	Channel
s	NO
t	YES
c	???
b	???

If you can't beat 'em, join 'em.

How to Join without ``Double Counting"???

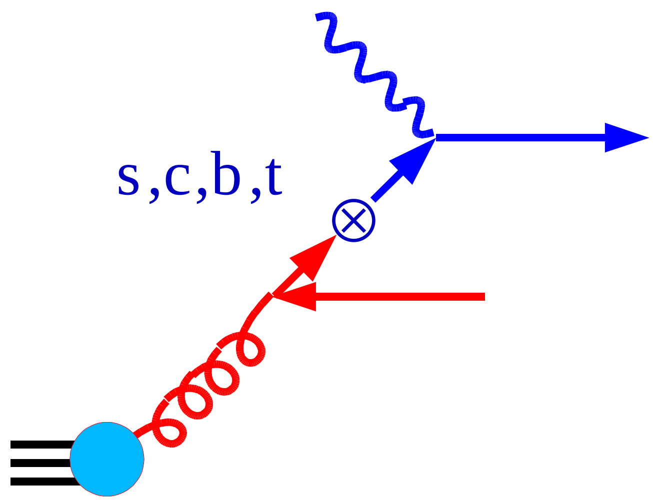


Heavy Excitation (HE)

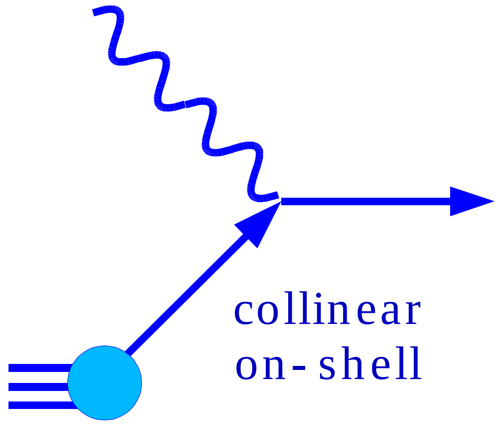


Heavy Creation (HC)

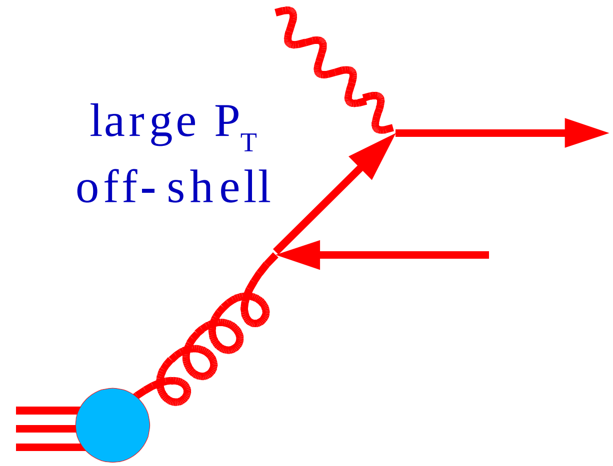
Wait a minute!
Since the heavy quark originally came from a gluon splitting, these diagrams are ***Double Counting***



How to Join without ``Double Counting"???

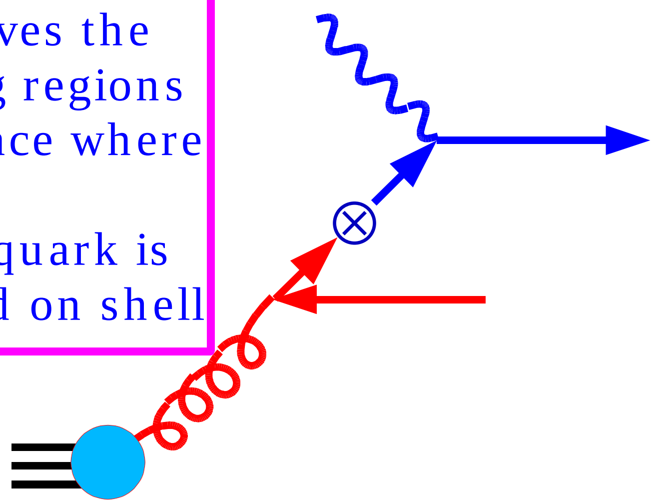


Heavy Excitation (HE)



Heavy Creation (HC)

SUB removes the overlapping regions of phase space where the t-channel quark is collinear and on shell



Subtraction (SUB)

TOT = HE + (HC – SUB)

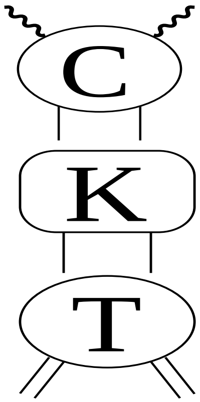
Formally, NLO

There is a rigorous factorization proof ...

Ingredients of Factorization

Decompose into (t-channel) 2PI amplitudes:

$$\sigma = \Sigma_{N=1}^{\infty} \; C \; (K)^N \; T \; + \textit{Non-leading}$$



Collins, Soper, Sterman. Perturbative QCD, World Scientific (1989). Collins, in preparation

After reorganization of the infinite sum:

$$\sigma \approx \underbrace{\overbrace{C\,[1-(1-Z)\,K\,]^{-1}}^{\text{Wilson Coefficient (Hard Scatt. }\hat{\sigma})}\; Z\; \underbrace{[1-K\,]^{-1}\,T}_{\text{Parton Distribution}}}_{\text{Parton Model}} + \underbrace{C\,[1-(1-Z)\,K\,]^{-1}\,(1-Z)\,T}_{\text{Remainder}}$$

Parton Model | Remainder

Wilson Coefficient (Hard Scatt. $\hat{\sigma}$) — Parton Distribution — Power Suppressed

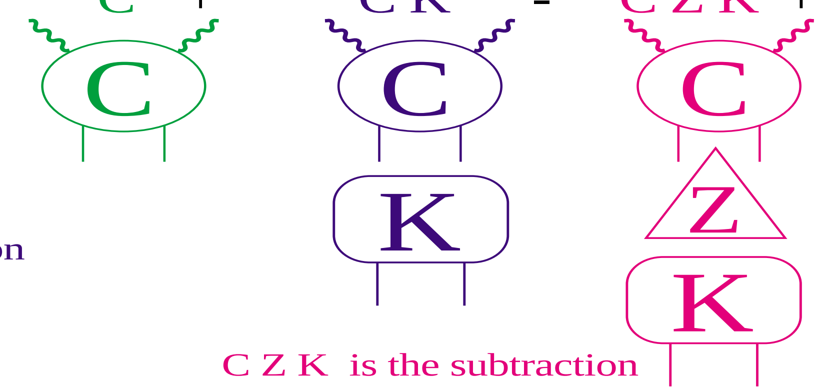
Z: collinear projection

Wilson Coefficient:

$$C\,[1-(1-Z)\,K\,]^{-1} \approx C + \overbrace{C\,K - C\,Z\,K}^{\text{Next to Leading Order}} + \ldots$$

Leading Order — Next to Leading Order

All orders result



Wilson Coefficient:
IR safe "hard"
scattering cross section

C Z K is the subtraction

A formal proof was constructed by numerous groups.

This proof was explicitly extended to the case of massive quarks

(Collins,1998)

THOUGH EXPERIMENT To keep things simple, let's consider scattering off a parton target.

An Example: How the separate pieces can conspire

Expand $f(x) = x$ in Taylor Series about x_0.

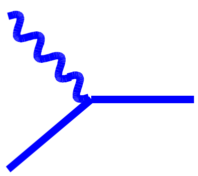
For $x_0 = 0$: $f(\varepsilon) = 0 + (\varepsilon - 0) + \ldots = \varepsilon$

For $x_0 = 1$: $f(\varepsilon) = 1 + (\varepsilon - 1) + \ldots = \varepsilon$

TOT **HE** **HC** **SUB**

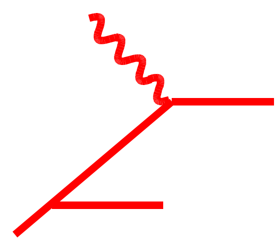
Subtraction

Heavy Excitation

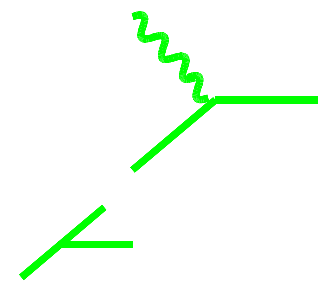


σ^0

Heavy Excitation



σ^1



$f^1 \otimes \sigma^0$

TOT = HE + HC − SUB

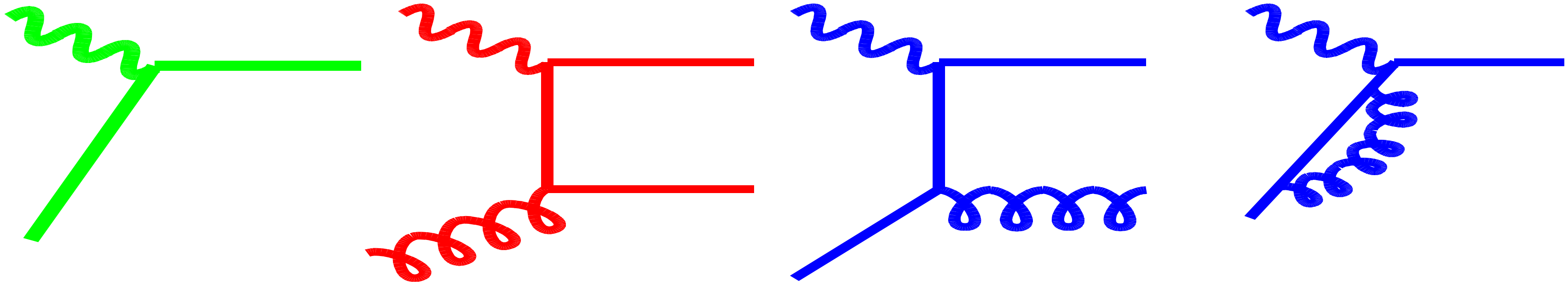
The Moral

It doesn't matter which expansion point you use;
QCD will compensate (if you go to high enough order).

In practice ...

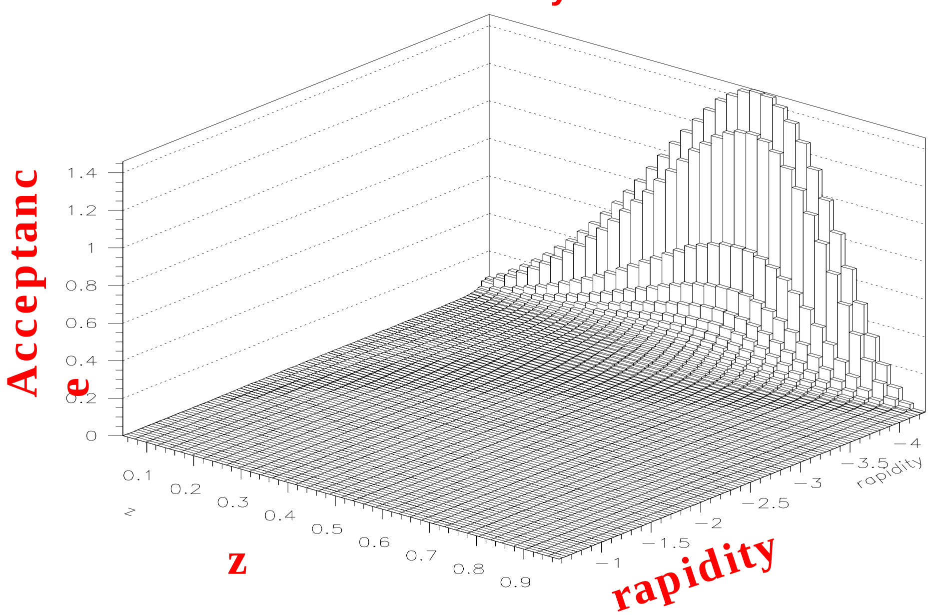
we are often limited to low-order calculations,
so it is wise to choose your expansion point carefully.

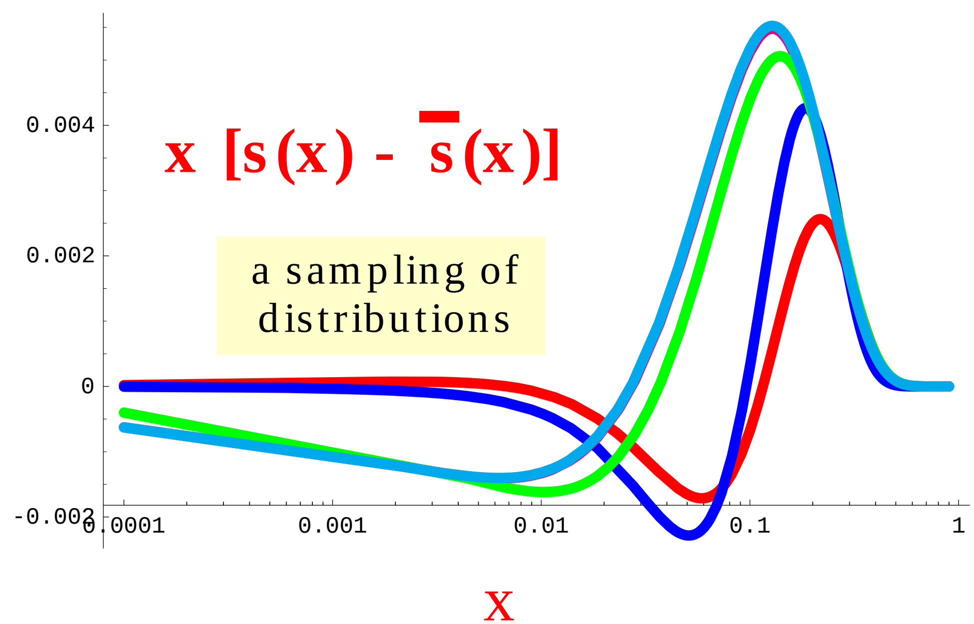
NLO Analysis: In progress ...



* Higher order diagrams
* More differential distributions
* Encounter :$\delta(p_T)$ and $1/(1-x)_+$

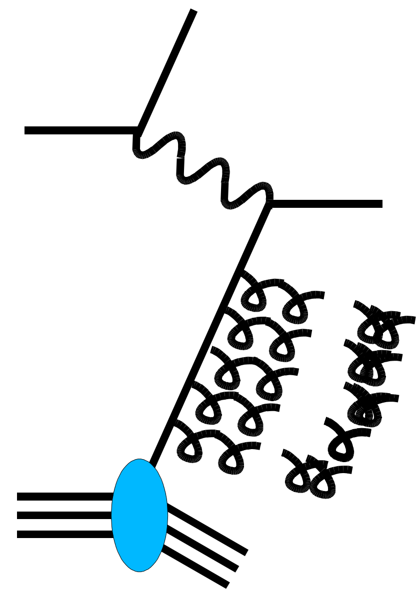
DISCO numerical Fortran program available for data analysis





Kretzer, Mason, Olness PRD 65:074010 (2002)

Future Work: Resummation of soft gluons for massive processes



* Uses CSS Formalism to resum $\mathrm{Log}(q_T/Q)$
* Uses ACOT Formalism to resum $\mathrm{Log}(M/Q)$

Satisfies appropriate limits:

$q_T \rightarrow Q$, obtain usual perturbative result

$M \rightarrow 0$, obtain usual massless result

$M, q_T \rightarrow 0$, obtain usual Sudakov form

Theoretical basis for NLO Monte Carlo program

... provides full kinematic description

Nadolsky, Kidonakis, Olness, Yuan: PRD67:074015, 2003

Summary

* Di-Muon data incorporated in Global fit:
  - Provides important information on s(x)
  - Important for search for "New Physics" signals

* NLO Experimental Dimuon analysis:
  - NLO Experimental analysis in progress (D. Mason)
  - NLO code (DISCO) is available (S. Kretzer)

* Need to consider $s \neq$ s-bar
  - This is real progress!!! We now can discriminate!
  - Large uncertanties; must fully characterize effects; include NLO
  - Analysis in progress

* Resummation of large logarithms:
  - Resummation of Log(q_T/ Q) and Log(M/ Q) (P. Nadolsky ...)

Thanks to: P. Nadolsky, S. Berge, W. Tung, S. Kretzer, J. Owens, S. Kuhlmann, J. Pumplin, J. Morfin, H. Lai, T.Bolton, P. Spentzouris, D. Mason, M. Shaevitz, K. McFarland, U.K. Yang, A. Barzarko

<u>What is the status:</u>

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- s- s: large uncertainty affected by:
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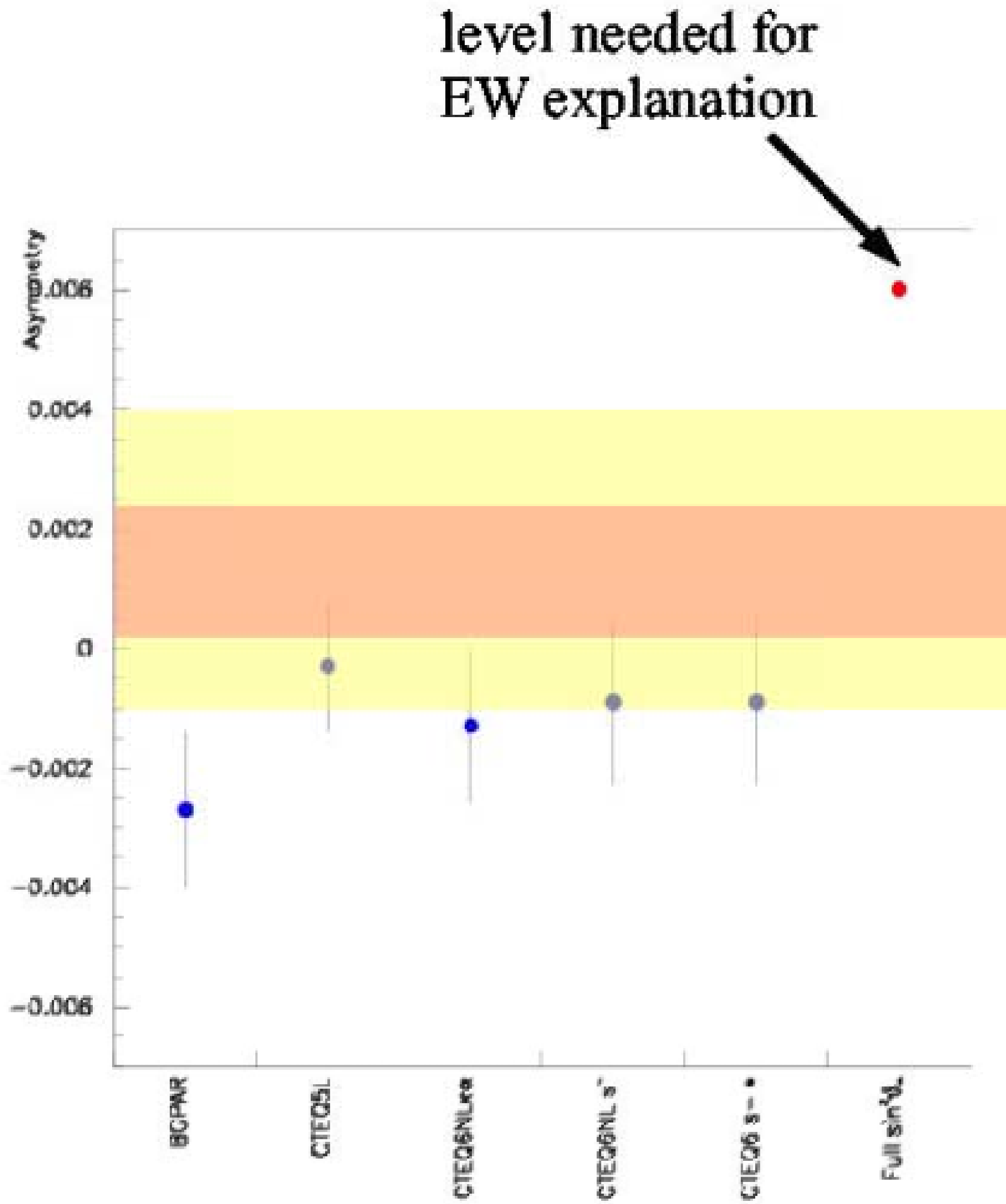
  - charm mass
  - PDF set

- Strong interplay between the existing experimental constraints and the global theoretical constraints, particularly the # sum rule



Conclusions

* Many outstanding puzzles, even with data already on tape:

    Higher Twist

    Up and Down PDF's at large x

    Nuclear corrections

    $\Delta xF_3^{\nu} \sim 4x(s-c)$

    $\sin\theta_W$

* Solving these will provide important information on proton structure

    Important for search for "New Physics" signals

This is how we will make progress