Heavy Quark Production and PDF's

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Collaborators:
P. Nadolsky, S. Berge, W. Tung, S. Kretzer, J. Owens,
S. Kuhlmann, J. Pumplin, H. Lai

DIS 2005
29 April 2004

cf., talk by Lance Dixon

m = 0: Massless case.

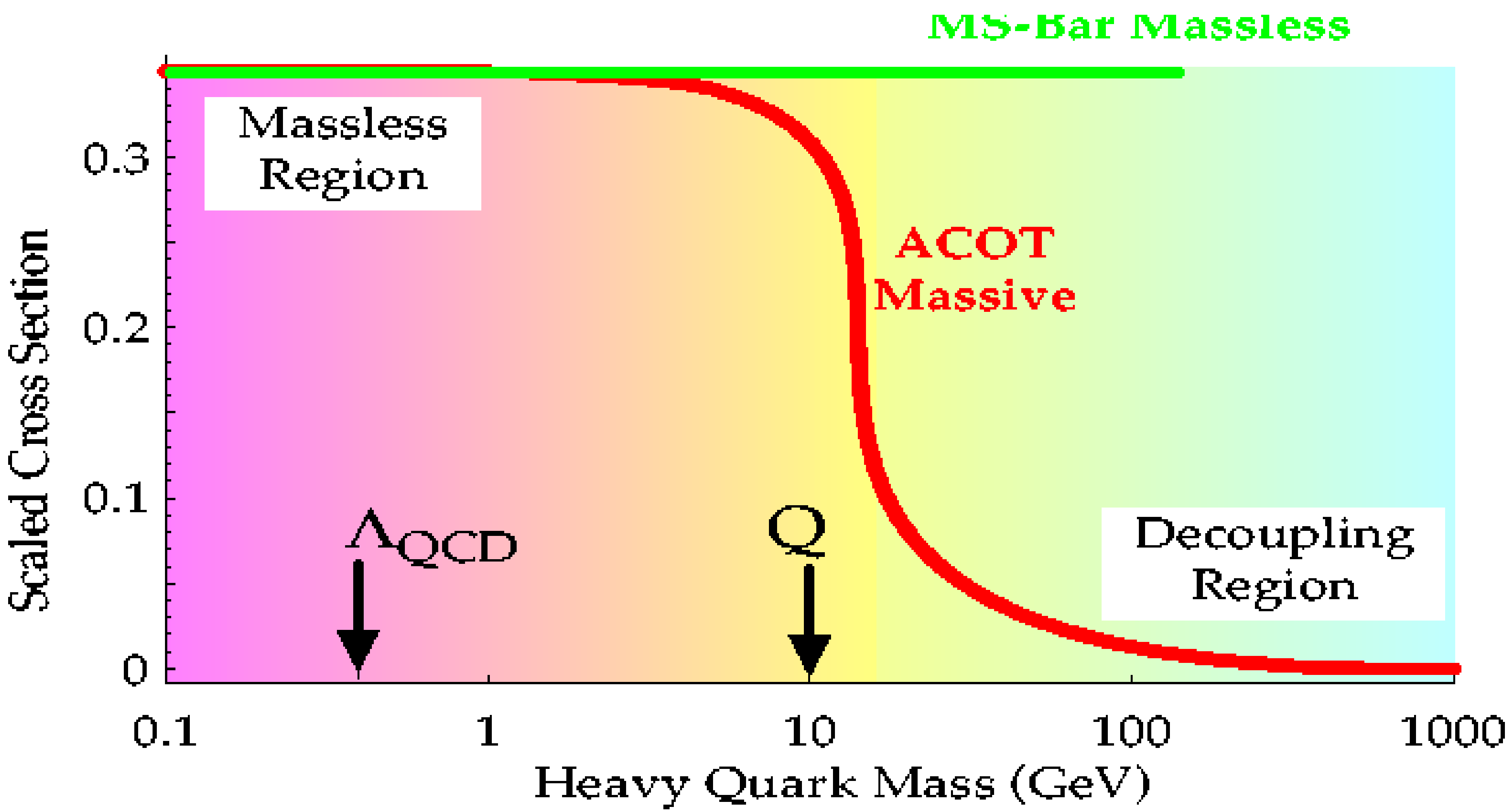
Mass plays no dynamic role

Well understood.

m = ∞: Infinite case.

Mass Decouples.

We can forget about this object



How do we deal with multiple scales???

Problem: Heavy Quark introduces new scale: $\log\left(\frac{Q^2}{\mu^2}\right)$ $\log\left(\frac{M_H^2}{\mu^2}\right)$

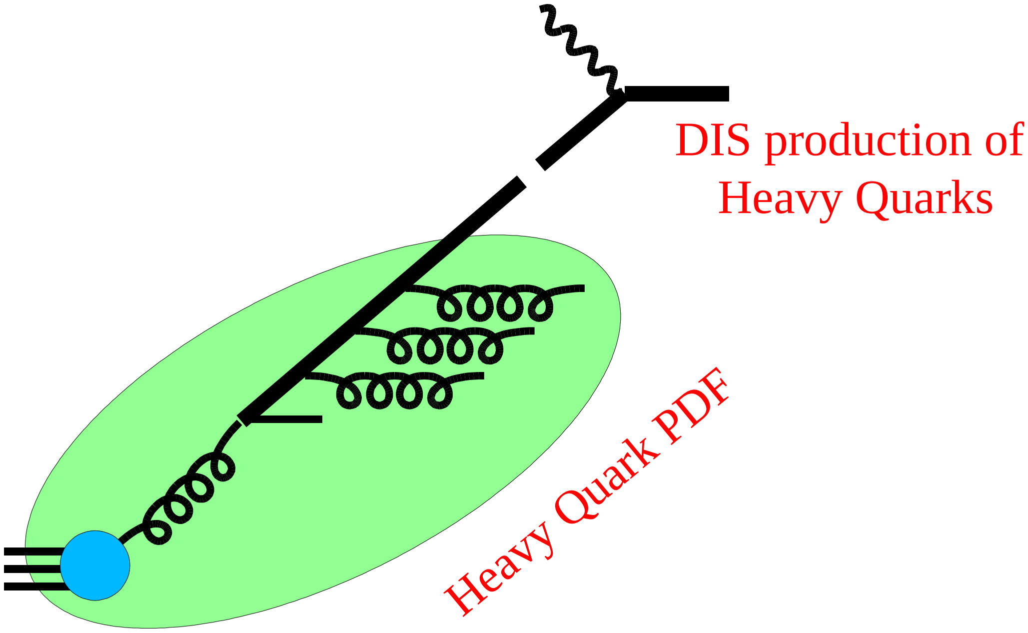
... life gets interesting.

Solution: Resum $Log(M_H)$ in the Heavy Quark PDF's:

... i.e., as in the ACOT renormalization scheme

ACOT, PRD 50, 3102

DGLAP equation
Resums iterative splittings
inside the proton



Result: We can describe the full kinematic range from low to high

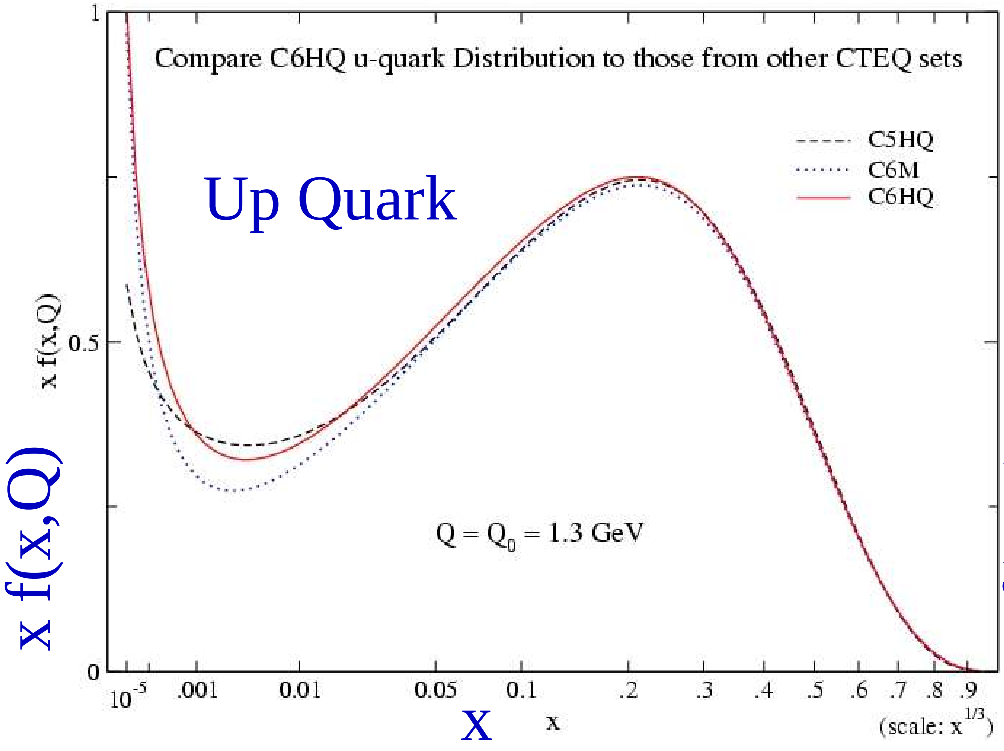
implemented in the CTEQ6HQ PDF's with finite M_Q

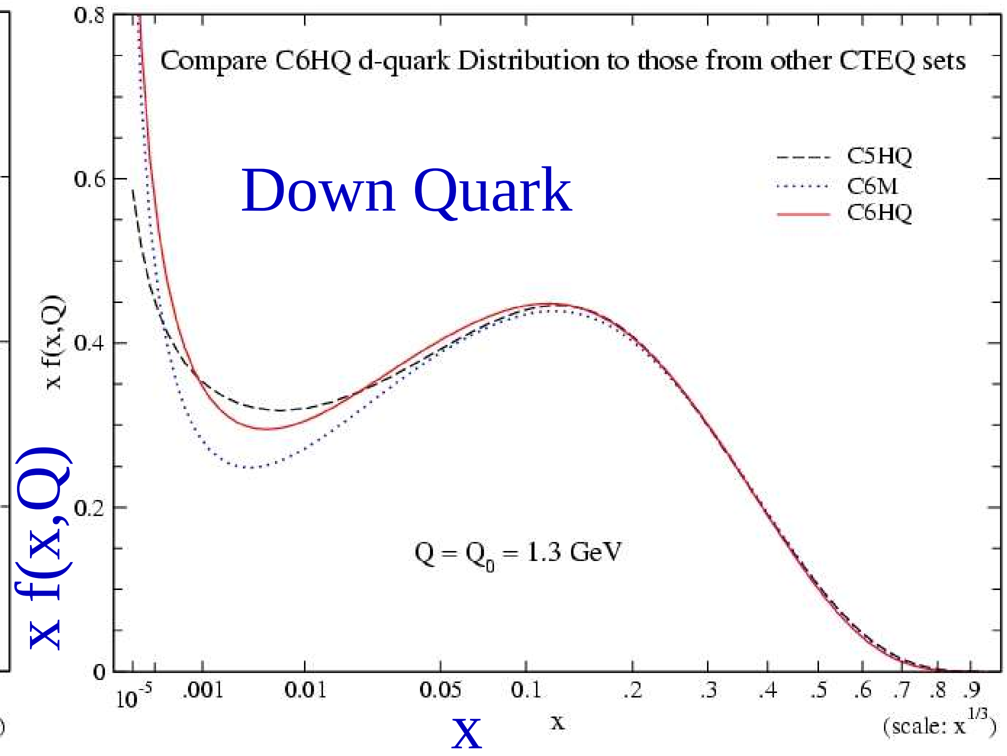
CTEQ6HQ

PDF's

CTEQ6HQ PDF's:

Compare: CTEQ6M, CTEQ6HQ, CTEQ5M





- Small difference of C5M to C6M

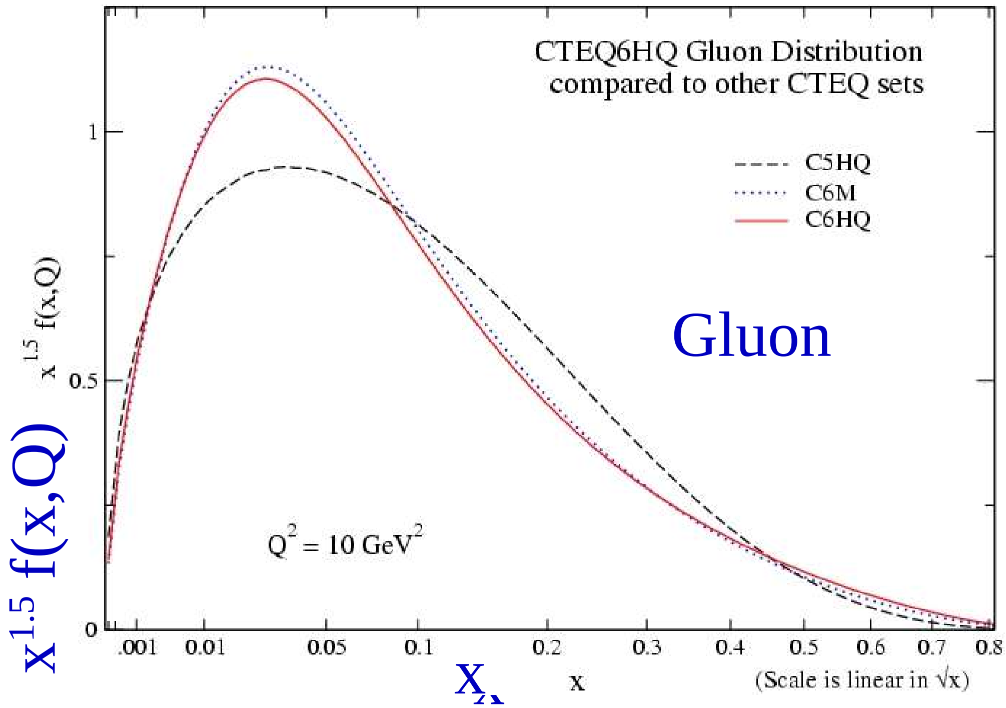
  Up and Down quarks are well determined
- Some difference between C6M and C6HQ at low x

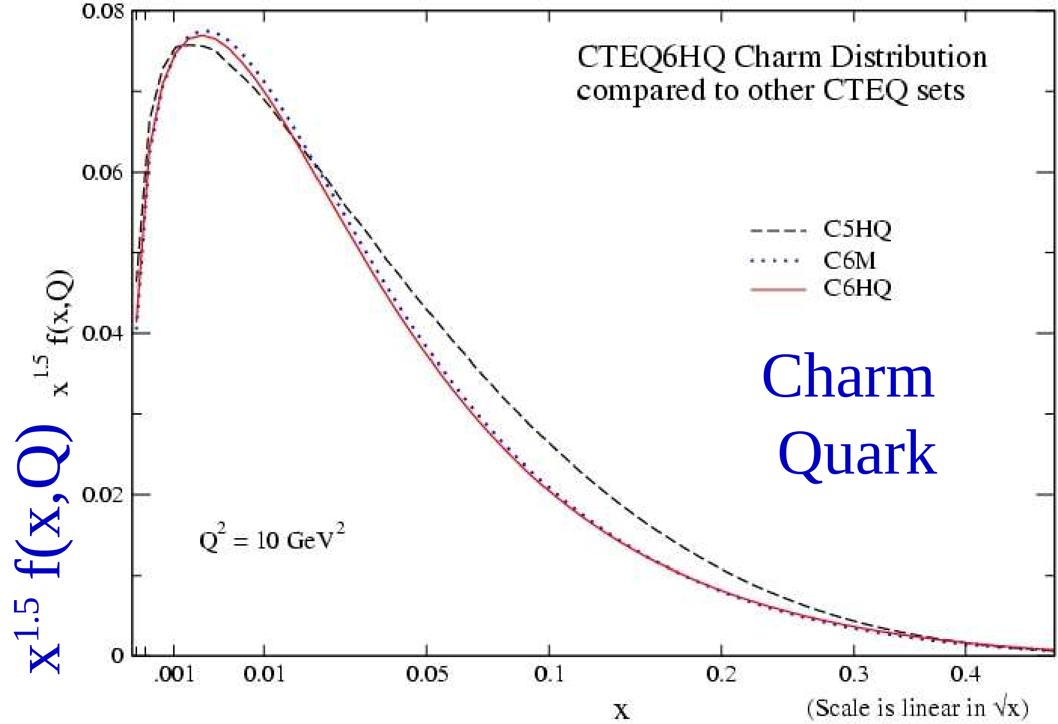
  Shift due to both scheme and uncertainty

S. Kretzer, H.L. Lai, F. I. Olness and W.K. Tung. Phys.Rev.D69:114005,2004

CTEQ6HQ PDF's:

Compare: CTEQ6M, CTEQ6HQ, CTEQ5M





- Shift of Gluon for C5M to C6M is large *(New DIS & Jet data)*
- Charm PDF tied to gluon *(g →cc)*
- Small visual difference between C6M and C6H

Shift due to both scheme and uncertainty

S. Kretzer, H.L. Lai, F. I. Olness and W.K. Tung. Phys.Rev.D69:114005,2004

Does it make a difference???

Data set	# pts	CTEQ6HQ	CTEQ6M	C6M⊗GM	C6HQ⊗ZM
Bcdms_p	339	370 (1.09)	370 (1.09)	370 (1.11)	373 (1.10)
Bcdms_d	251	269 (1.07)	279 (1.11)	274 (1.07)	281 (1.12)
Zeus	104	94 (0.91)	102 (0.98)	258 (2.84)	387 (3.72)
H1a	126	124 (0.99)	130 (1.03)	135 (1.11)	123 (0.98)
H1b	129	103 (0.80)	111 (0.86)	119 (0.84)	104 (0.80)
H1c	229	266 (1.16)	261 (1.14)	474 (2.11)	364 (1.59)
Nmc_p	201	304 (1.51)	299 (1.49)	273 (1.35)	366 (1.82)
Nmc_d/p	123	112 (0.91)	111 (0.91)	111 (0.90)	114 (0.92)
Ccfr_F2	69	90 (1.30)	120 (1.74)	116 (1.82)	107 (1.55)
Ccfr_F3	86	35 (0.41)	37 (0.43)	36 (0.40)	36 (0.42)
E605	119	102 (0.86)	103 (0.86)	101 (0.86)	102 (0.86)
Cdf_wasy	11	9 (0.78)	9 (0.83)	9 (0.83)	9 (0.78)
E866	15	5 (0.34)	6 (0.43)	6 (0.43)	5 (0.34)
D0_jet	90	71 (0.79)	49 (0.55)	49 (0.55)	71 (0.79)
Cdf_jet	33	55 (1.66)	50 (1.51)	50 (1.51)	55 (1.66)
All	1925	**2008** (1.04)	**2037** (1.06)	**2431** (1.26)	**2496** (1.30)

CTEQ6HQ CTEQ6M MIXED MIXED

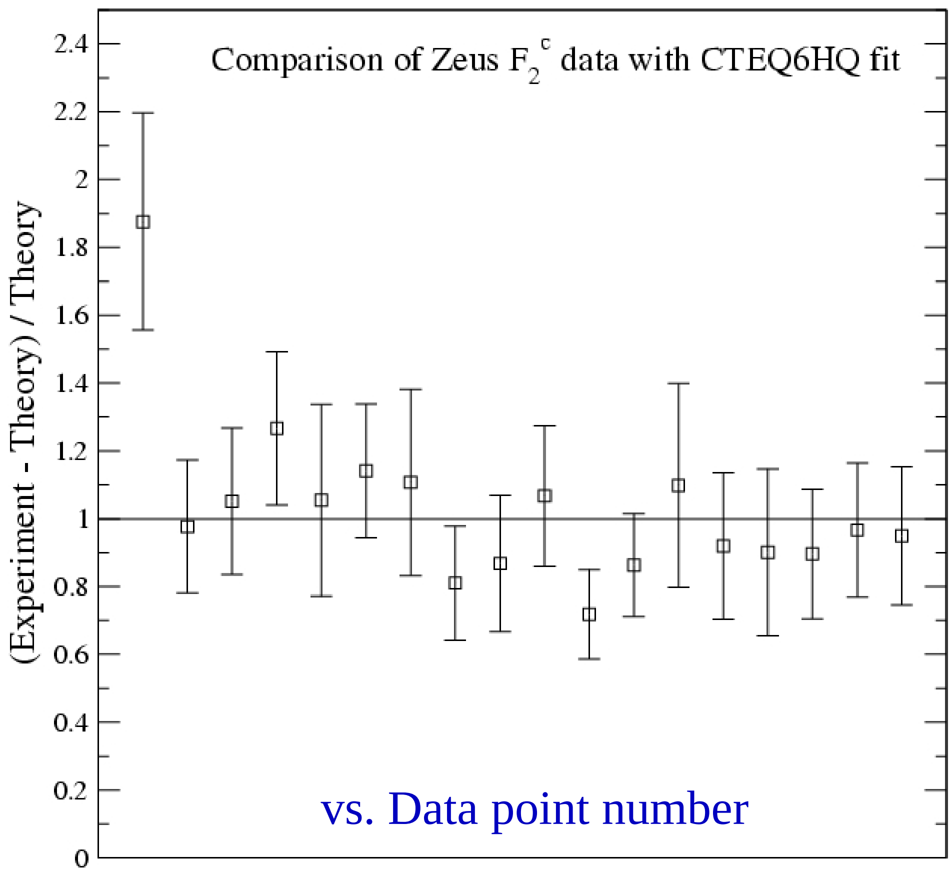
HERA experiments most sensitive to Mixed scheme

Encouraging that C6M and C6HQ are comparable

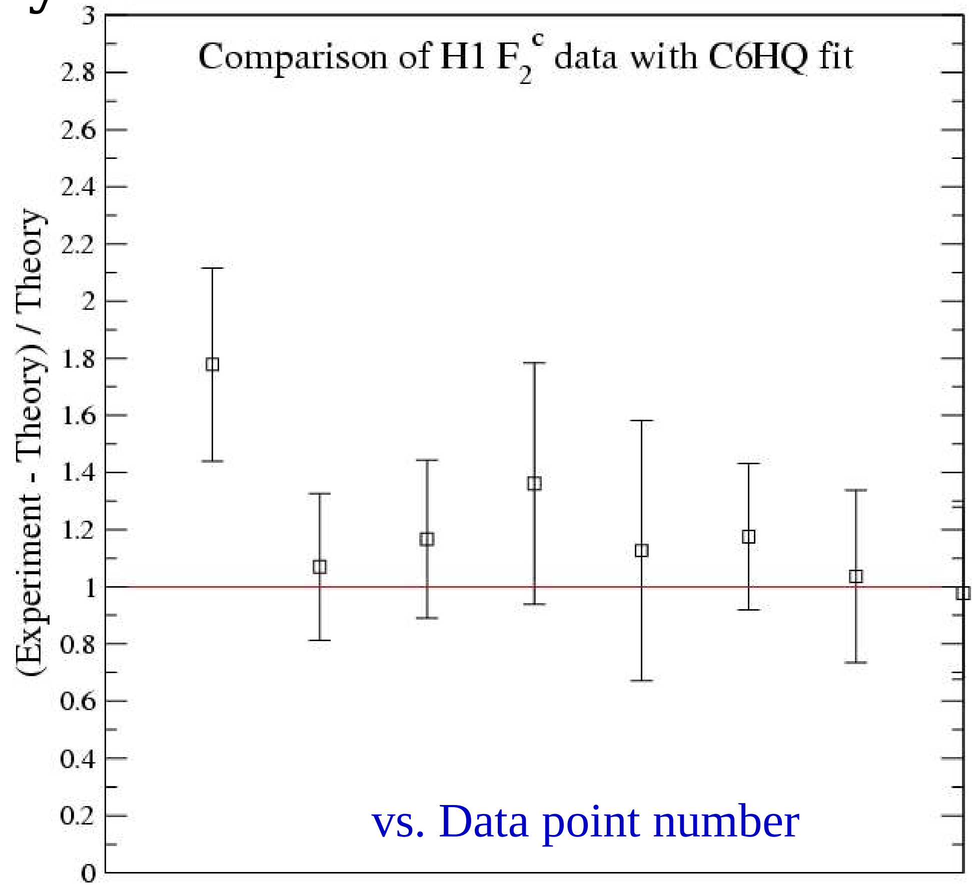
Encouraging that Mixed schemes yield large X^2

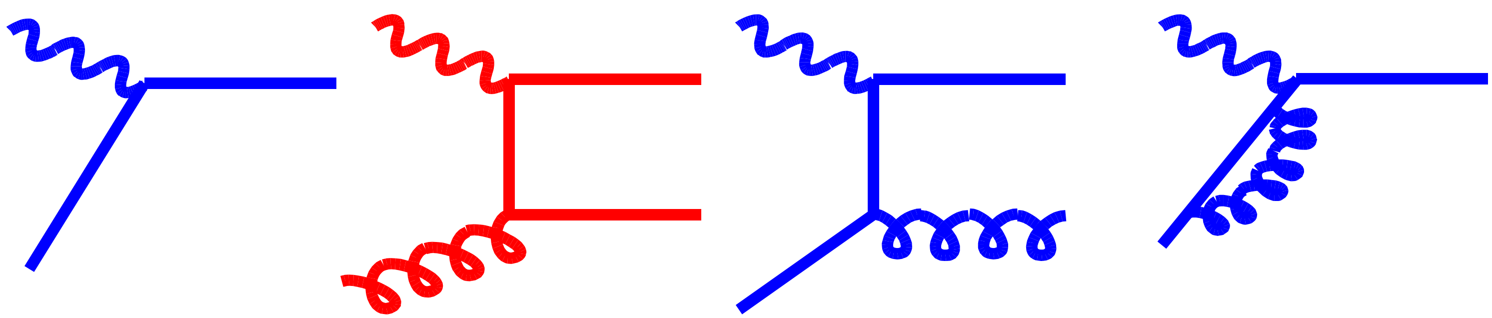
How does it do for the F_2^C data???

$$\frac{\text{Experiment} - \text{Theory}}{\text{Theory}}$$



(Exp -Theory)/Theory





Generalized heavy degrees of freedom

SUSY PDF's

Generalized heavy DOF: new thresholds for the PDFs

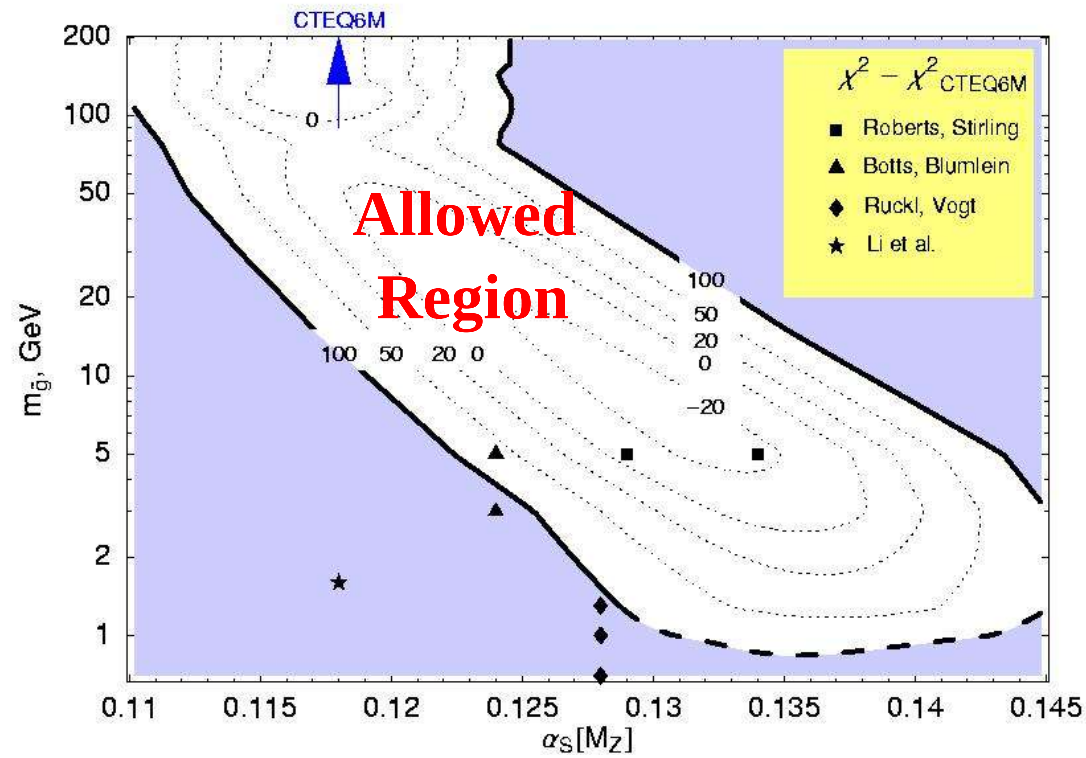
Inclusion of new strongly interacting particles *(e.g., gluino)* affect PDF's at higher scales.

Bulk of PDF constraints are at low Q scales

Strong correlation between α_s gluino (and gluon)

Will affect gluon production of Higgs

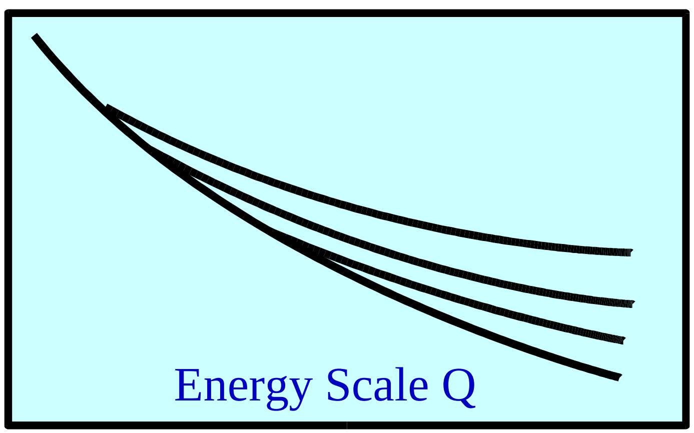
SUSY Gluino Mass Parameter



Strong Coupling Constant

Running of α_s(Q) with thresholds

Strong Coupling



New thresholds can significantly alter PDF's at large Q

E. L. Berger, P. M. Nadolsky, F. I. Olness and J. Pumplin. Phys.Rev.D71:014007,2005

Differential Distributions

or

Soft Gluon Resummation for Massive Quarks

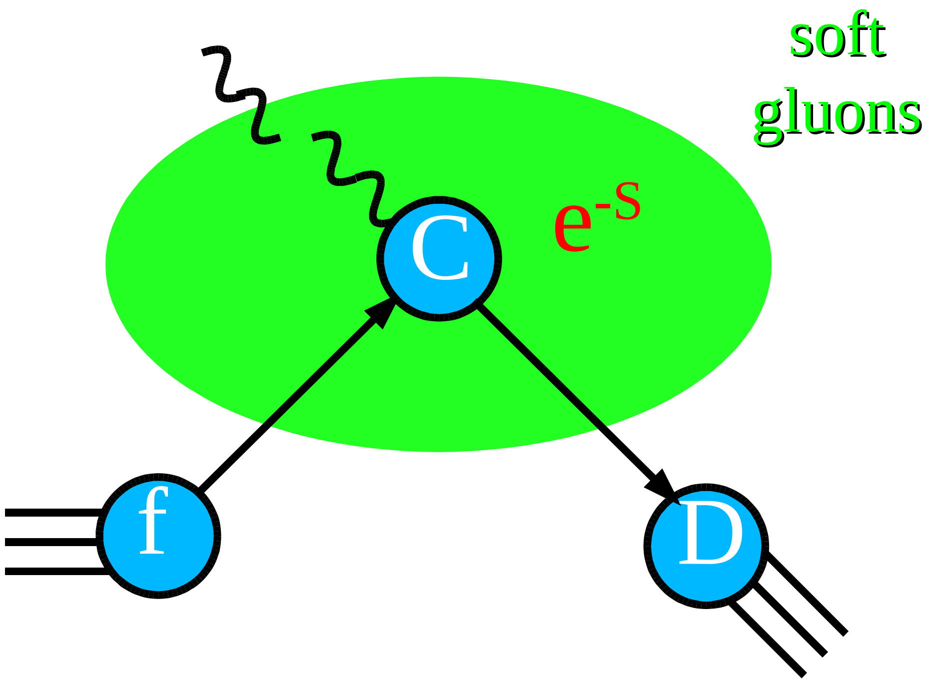
Problem: Even a new scale q_T: $\log(\frac{q_T^2}{\mu^2})$ $\log(\frac{Q^2}{\mu^2})$ $\log(\frac{M_H^2}{\mu^2})$

... life gets more interesting.

Solution: Resum *$Log(q_T)$* via the CSS Sudakov form factor

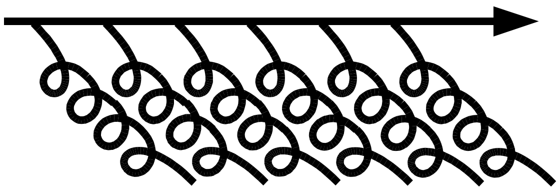
Collins, Soper, Sterman NP B250, 199 (1985)

$$d\sigma = \int f_{a/A} \otimes C_{ba} \otimes D_{H/b} \cdot e^{-S}$$

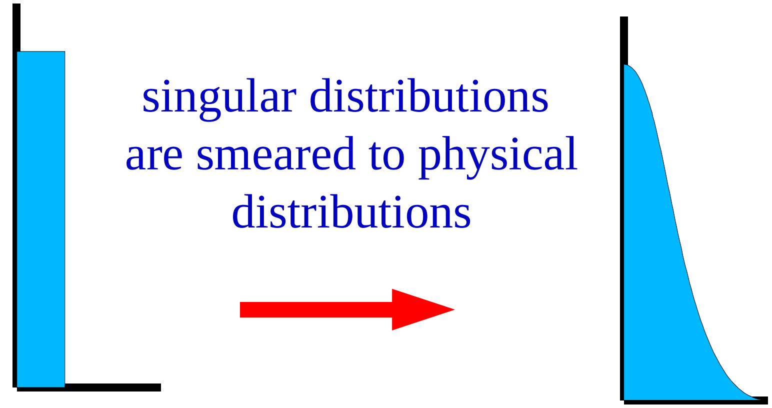


Next: Take a closer look at the Sudakov term

Sudakov Resummation of Soft Gluon Radiation



$= e^{-S}$



$$S(b,Q,M_H) = \int \frac{d\mu^2}{\mu^2} \left\{ A(\alpha_s, M_H) \ln\left(\frac{Q^2}{\mu^2}\right) + B(\alpha_s, M_H) \right\} + S_{Non-Pert}$$

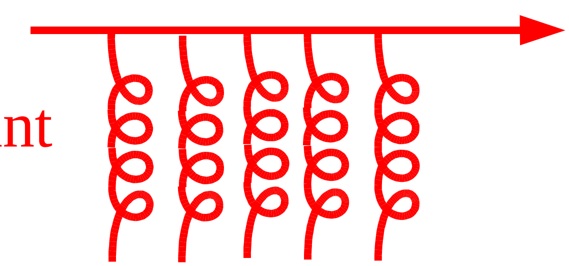
Result: In Simplified-ACOT scheme,

Set $M_H=0$ on incoming HQ lines

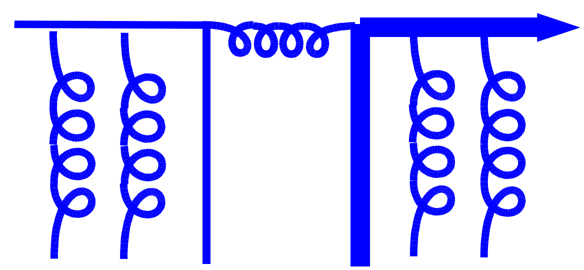
$A(\alpha_s, M_H) = A(\alpha_s, 0)$

$B(\alpha_s, M_H) = B(\alpha_s, 0)$

Why: Dominant



Suppressed



For update on VFNS developments, see Robert Thorne's talk

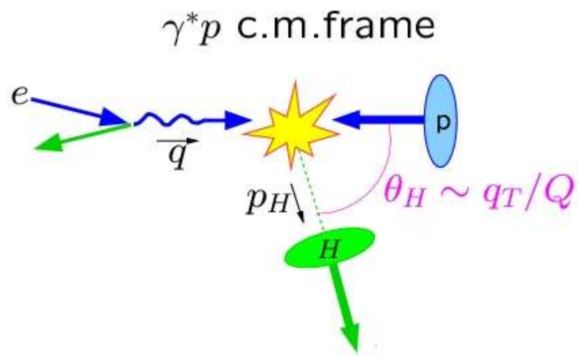
B-Production: Sudakov Resummation of Soft Gluon Radiation

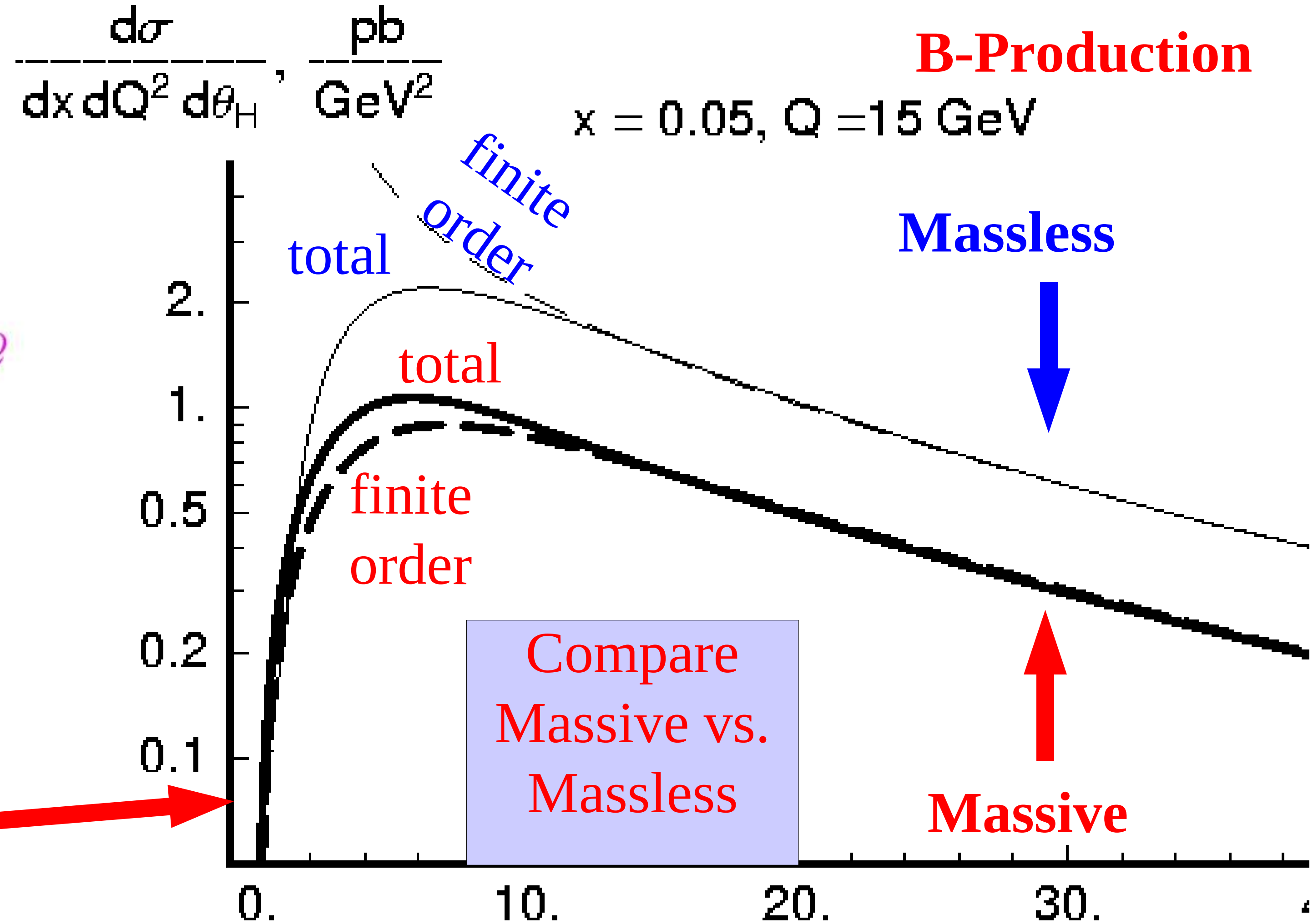
Result of S-ACOT scheme

$$S_{ba}(b,Q,M_H)=\int \frac{d\mu^2}{\mu^2}\left\{A(\alpha_s,M_H)\ln\left(\frac{Q^2}{\mu^2}\right)+B(\alpha_s,M_H)\right\}+S_{Non-Pert}$$

0 0 0

Due to finite quark mass





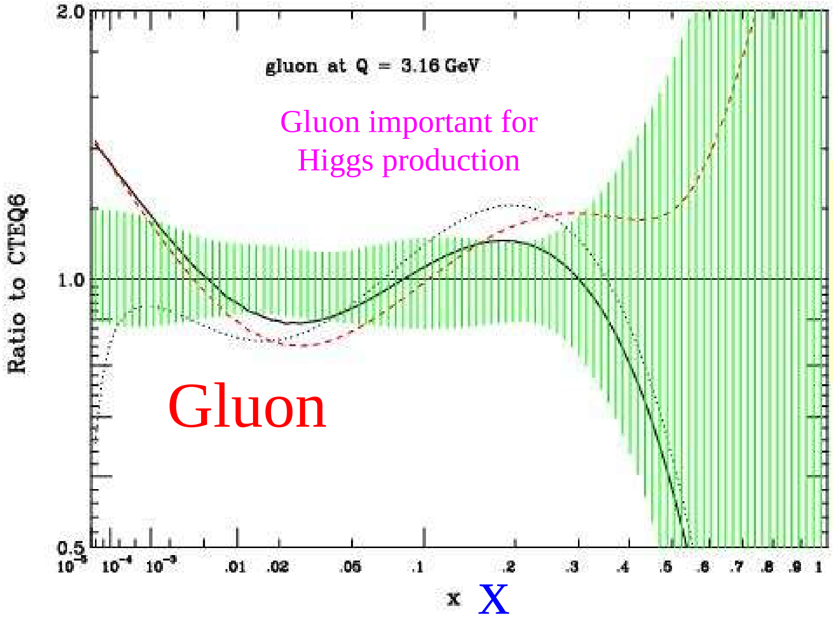
M$_H$ regulates collinear singularity

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

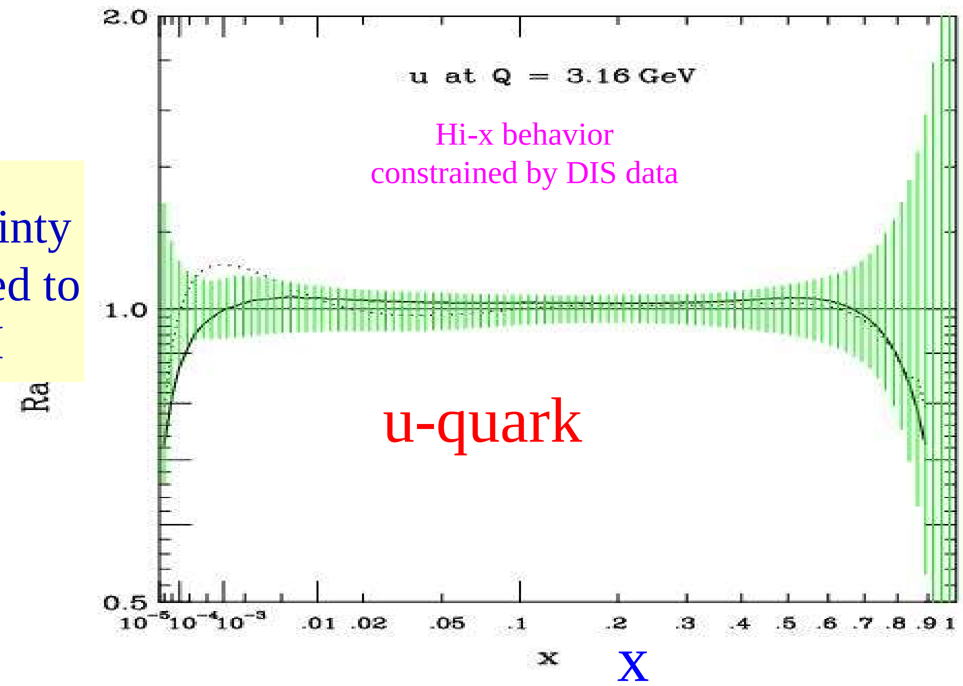
Strange

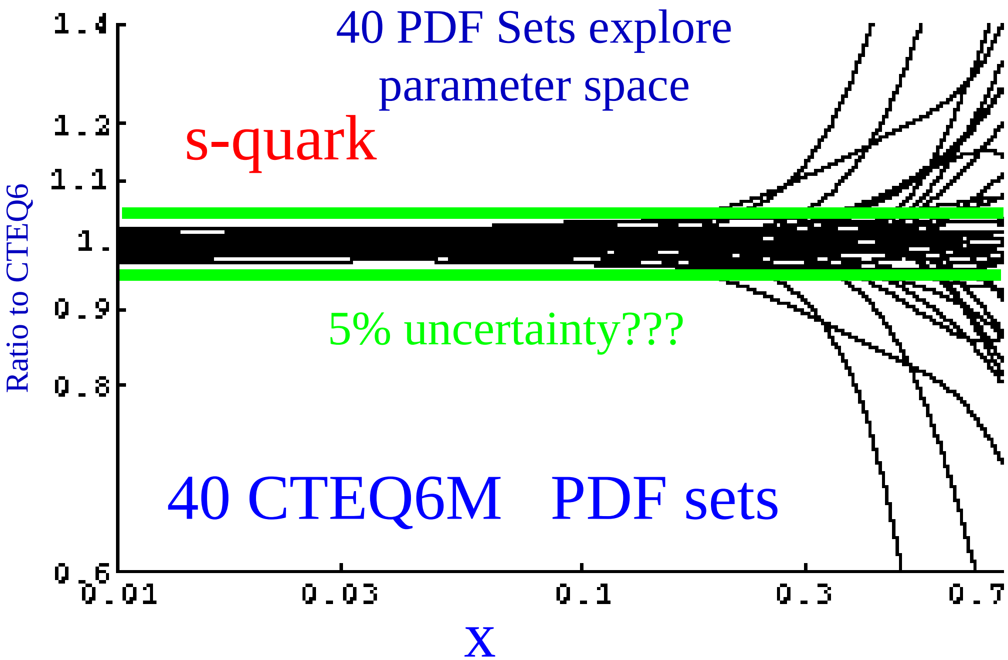
Quark PDF

What is relative uncertainty on PDFs' ???



PDF Uncertainty band compared to CTEQ6M





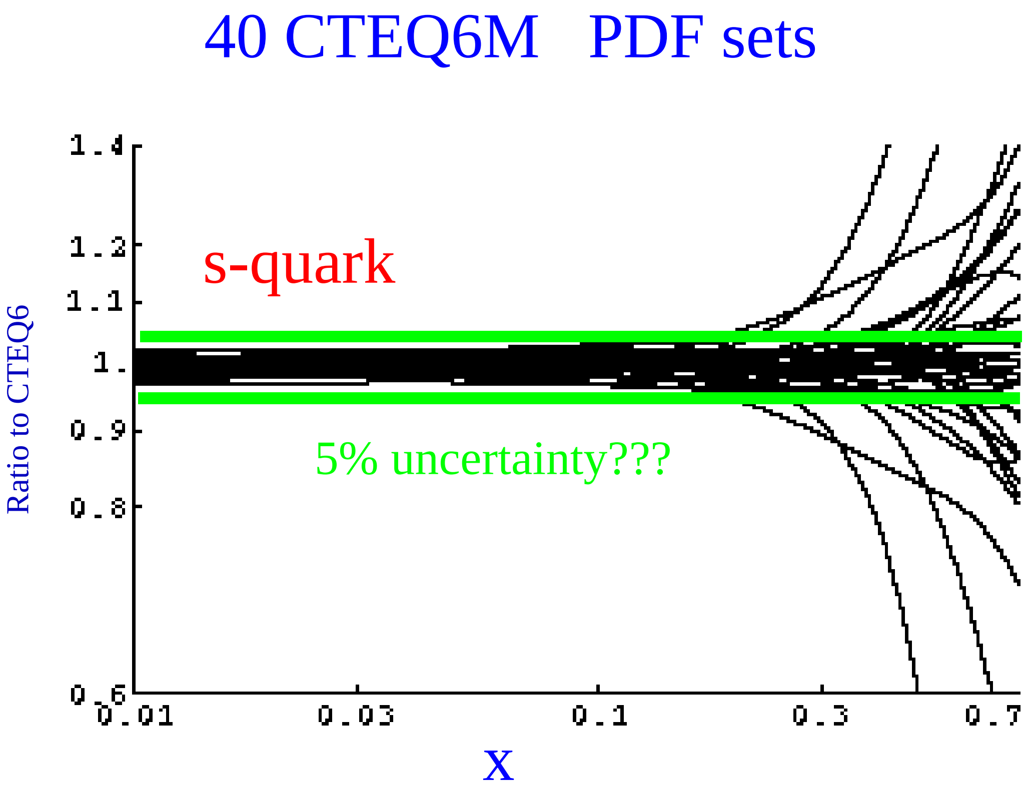
Previously, s(x) was tied to u-bar and d-bar via kappa:

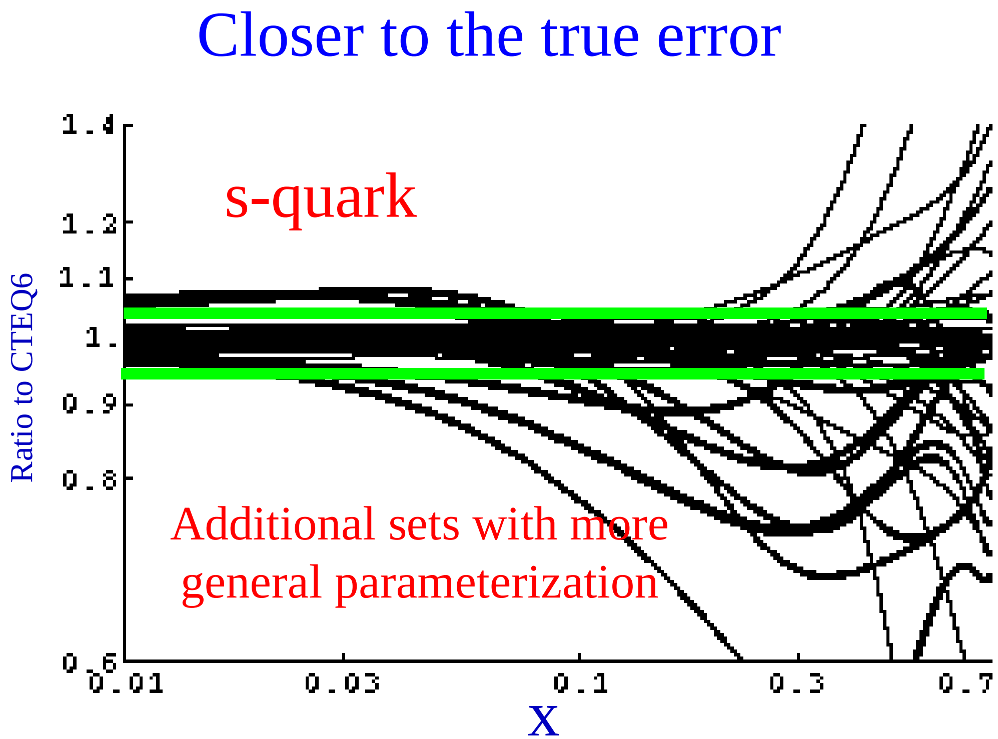
$$s(x) = \bar{s}(x) = \kappa \, \frac{\bar{u}(x) + \bar{d}(x)}{2}$$

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???

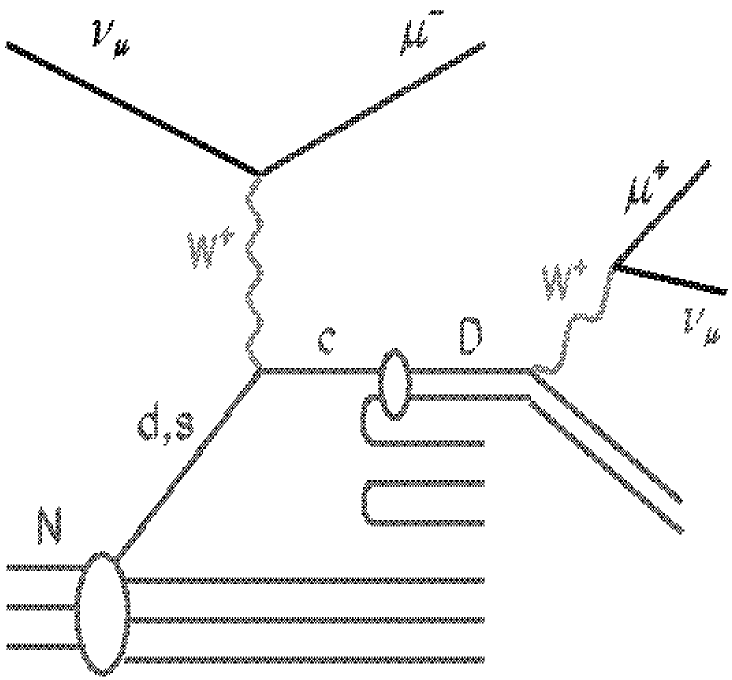




Curves shown are examples; this is not an exhaustive set

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

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

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

Di-muon cross-section

Charm Production cross-section

Fragmentation Function

Decay Distribution

M. Goncharov et al., NuTeV Collaboration PRD 64:110226 (2001)
NuTeV Collaboration (D. Mason for the collaboration). Moriond 2004, hep-ex/0405037

Global Fit: vary s(x) distribution

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
NMC F2d/F2p $\langle Q^2 \rangle$	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

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

Reasonable χ^2 values

(CTEQ6 did not fit di-muon data)

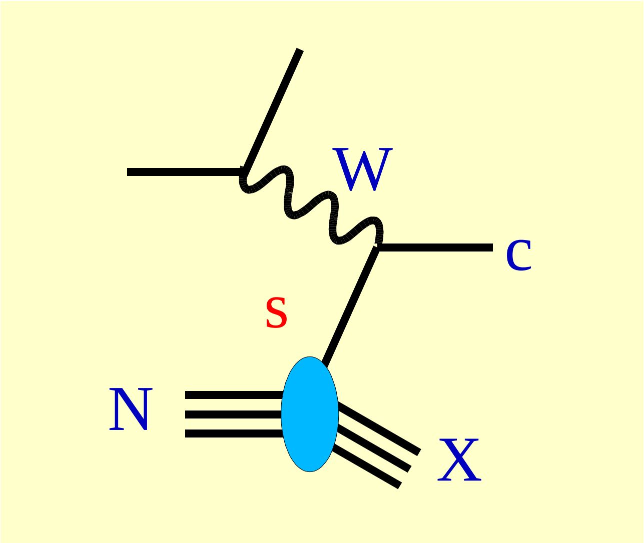
More parameters,
lower value of χ^2

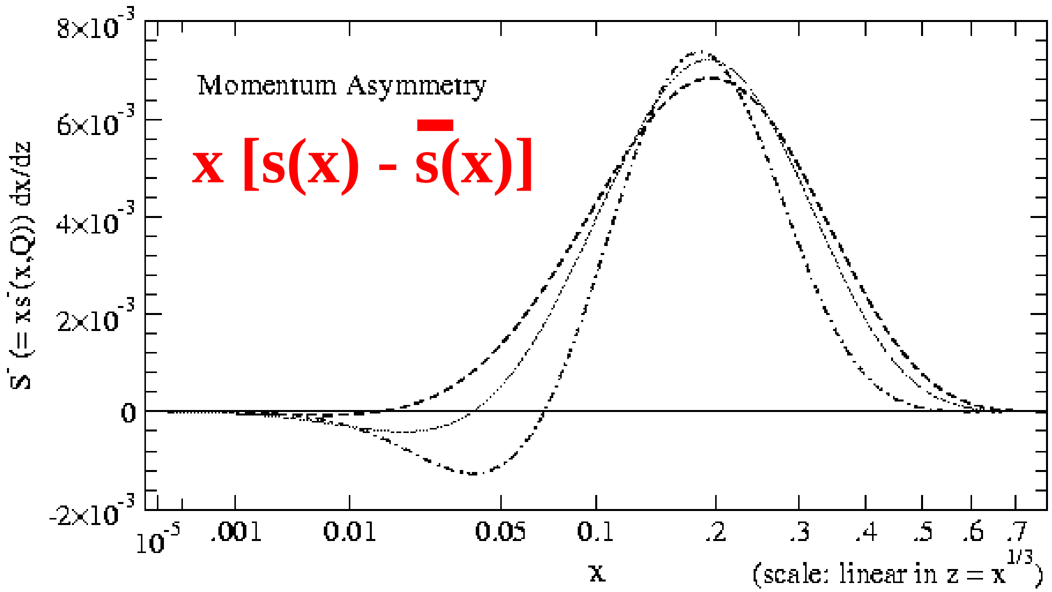
Only di-muon data is sensitive to s(x) !!!

$\therefore$

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

What does the $\Delta s(x)$ strange PDF look like?





General range of the asymmetry

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

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

$\Delta s(x)$: large uncertainty affected by:

- charm fragmentation
- charm mass
- PDF set

ongoing analysis, both LO and NLO

Olness, Pumplin, Stump, Huston, Nadolsky, Lai, Kretzer, Owens, Tung, Eur.Phys.J.C40:145-156,2005
Kretzer, Olness, Pumplin, Stump, Tung, Reno, PRL 93,041802 (2004)

See Dave Mason's talk

Conclusions

* CTEQ6HQ Distributions
  Fully massive implementation
  While "visually" small, consistent schemes are important

* SUSY PDF's:
  Generalized heavy degrees of freedom; new thresholds

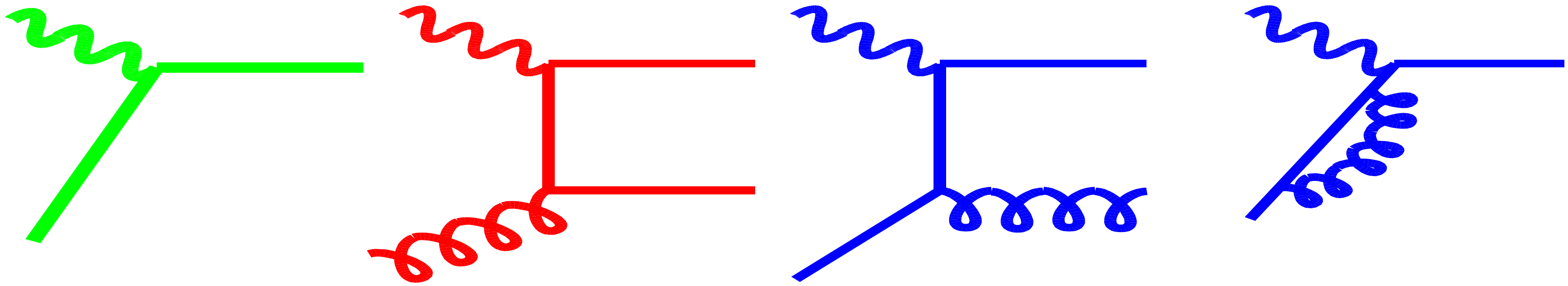
* q_T Resummation for Heavy Quarks
  Address $\text{Log}(q_T)$ and $\text{Log}(M)$
  Quark Mass M regulates singularity at $q_T \rightarrow 0$

* Strange Quark PDF
  This is real progress!!! We now can discriminate!
  Large uncertanties; must fully characterize effects; include NLO
  Analysis in progress

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

Extras

Ongoing Analysis: In progress ... both LO and NLO

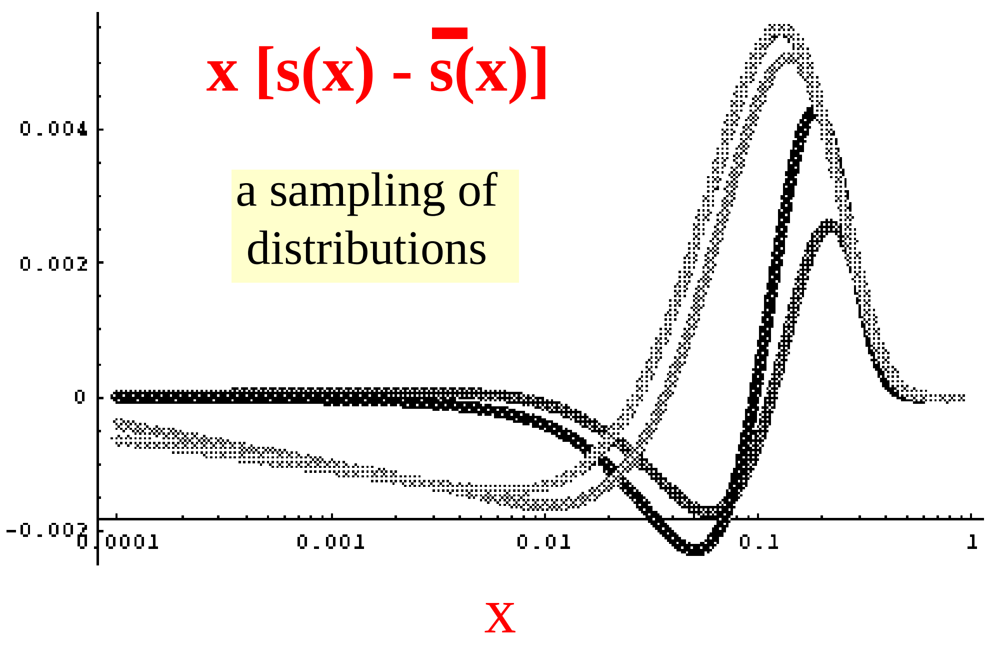


* Higher order diagrams

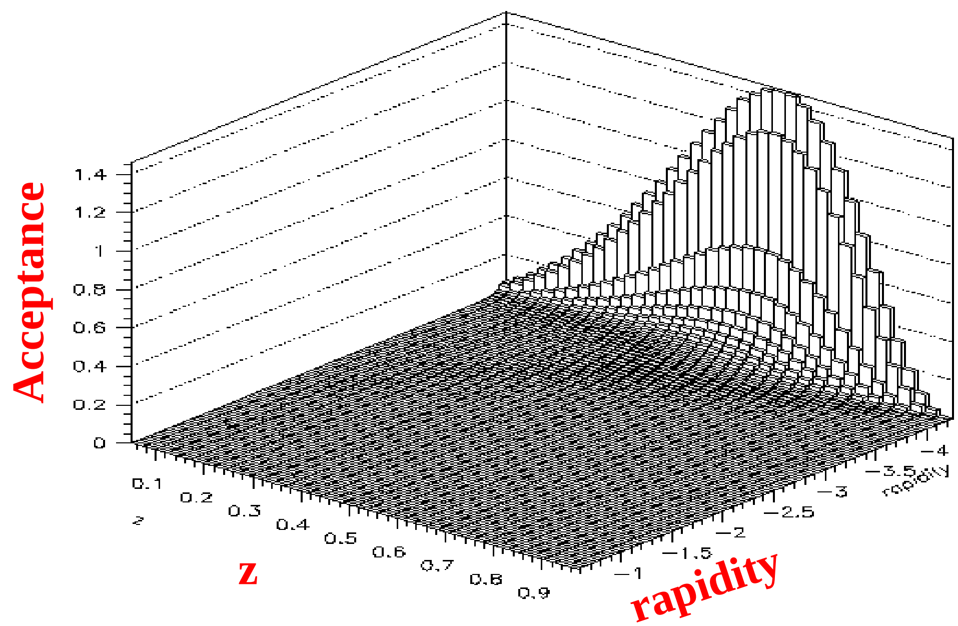
* More differential distributions

* Encounter distribution functions:

$\delta(p_T)$ and $1/(1-x)_+$



DISCO numerical Fortran program available for data analysis



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

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

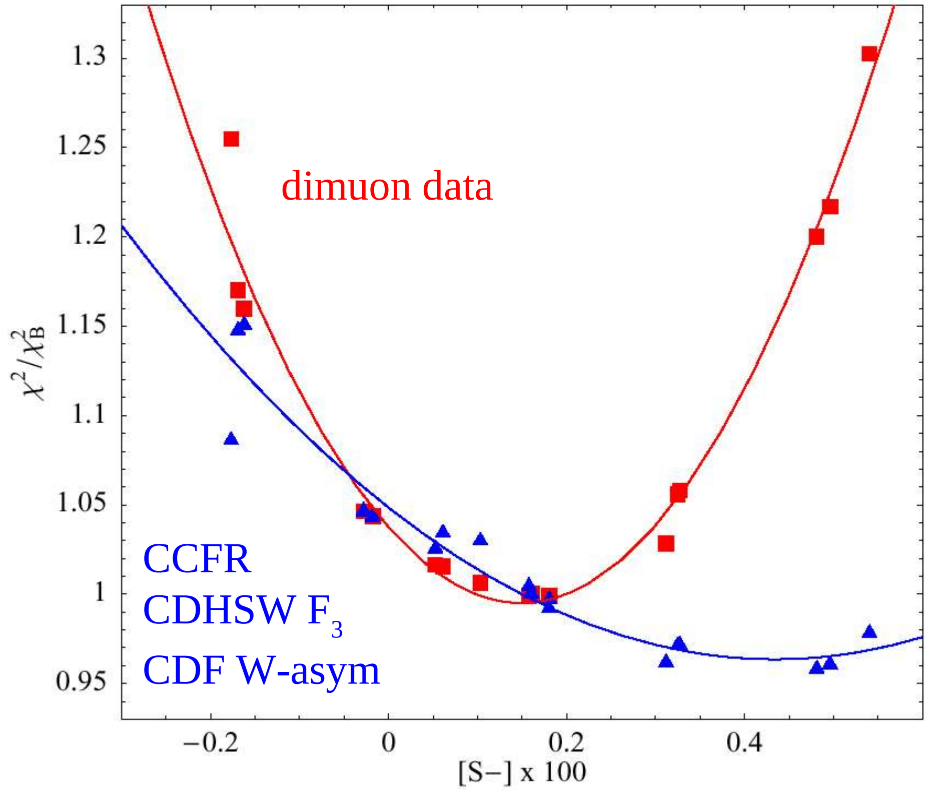
General range of the asymmetry

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

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

s-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

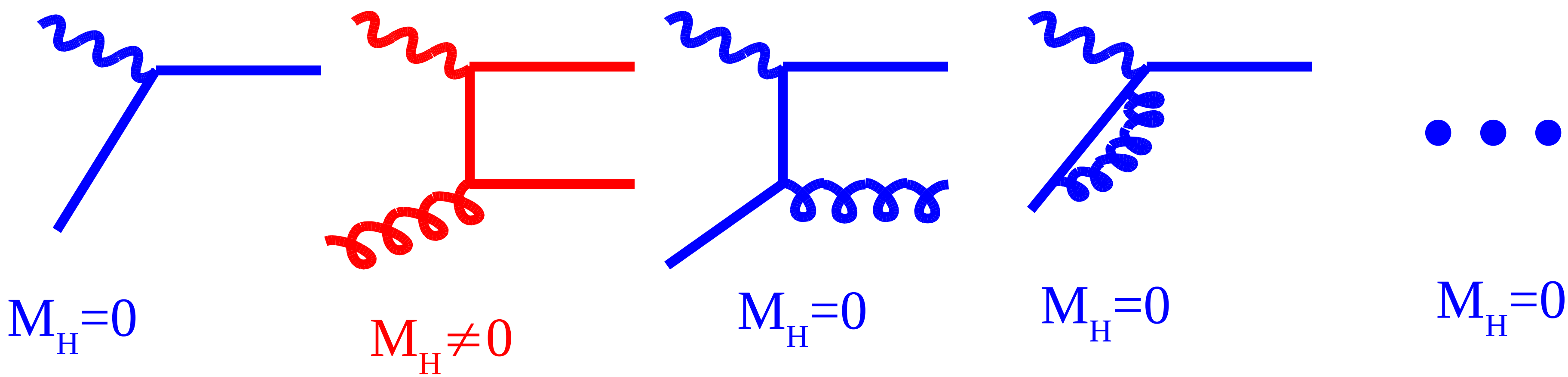
Heavy Quark Production: Formal Developments

Development: Factorization proof extended to Heavy Quark case.

Collins (1998)

Observation: Simplified-ACOT Scheme: Set $M_H=0$ on incoming HQ lines

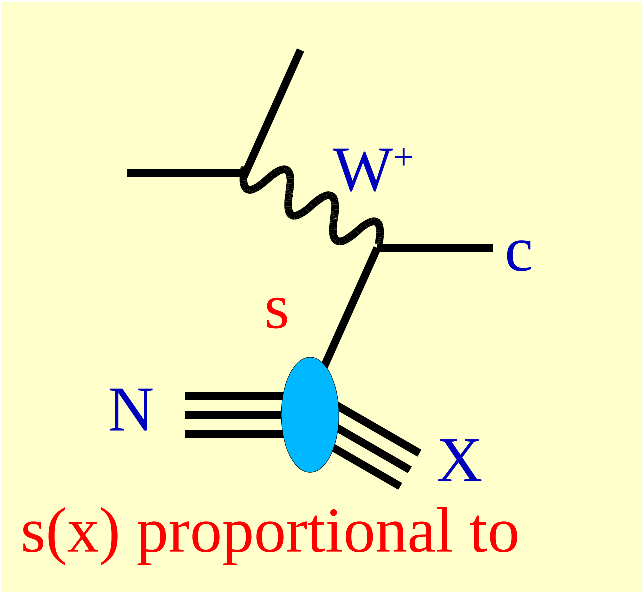
Kramer, Olness, Soper (2000)

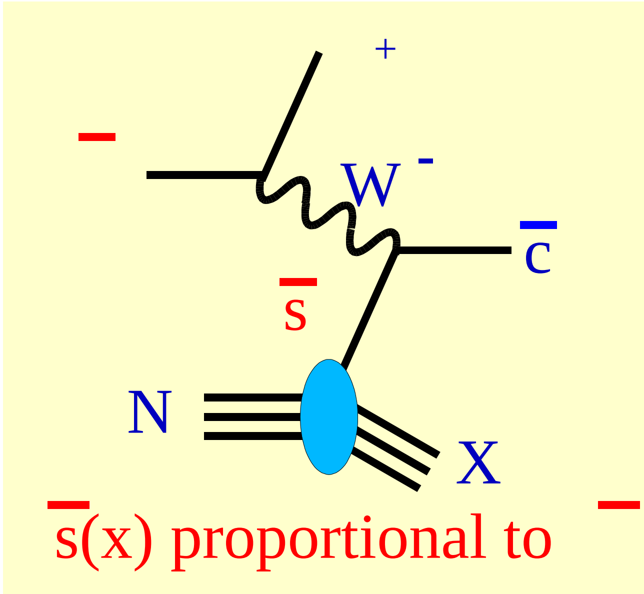


Result: 1) Comparable Numerics & 2) Simpler Calculations

See Robert Thorne's talk

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



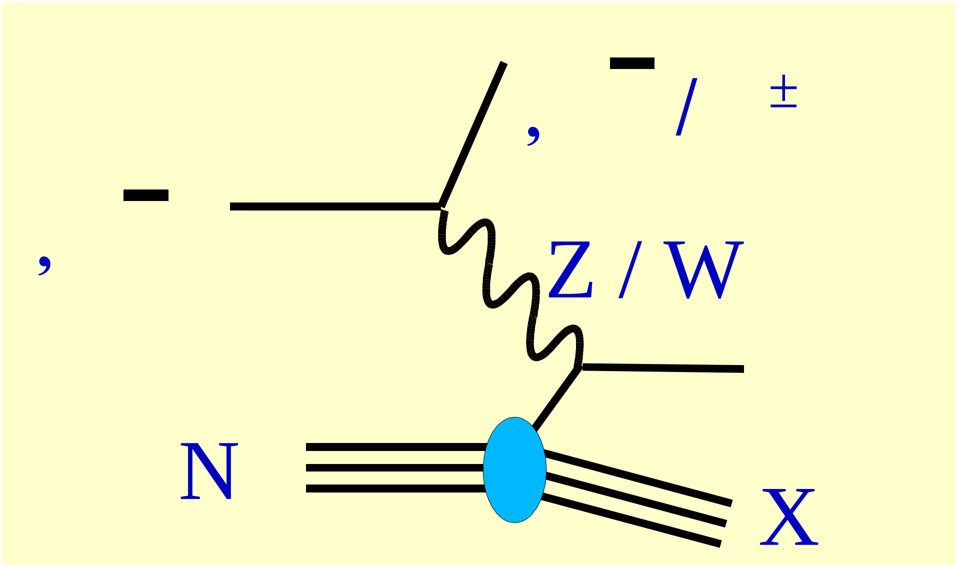


* Other data sets are insensitive to s(x)

* Caution: ensure quark number sum rule is satisfied

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

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**

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}	$\delta R^{\bar{\nu}}$
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
$\nu_e, \bar{\nu}_e$ 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
$\sigma^{\bar{\nu}}/\sigma^{\nu}$	0.00022	0.00007	0.00036
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 $R^{\bar{\nu}}$ with model predictions.

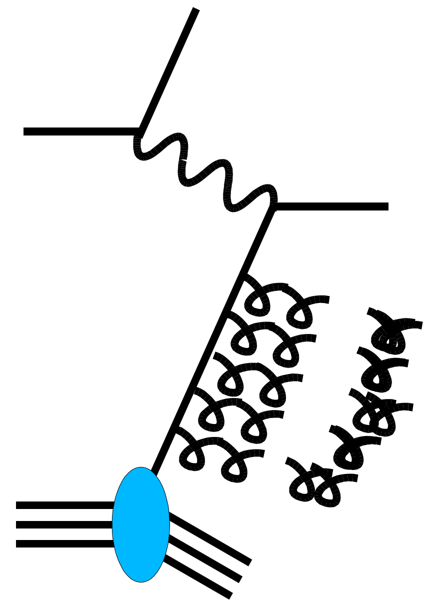
Largest model uncertainty arises from charm production and s(x)

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)

Future Work: Resummation of soft gluons for massive processes



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

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

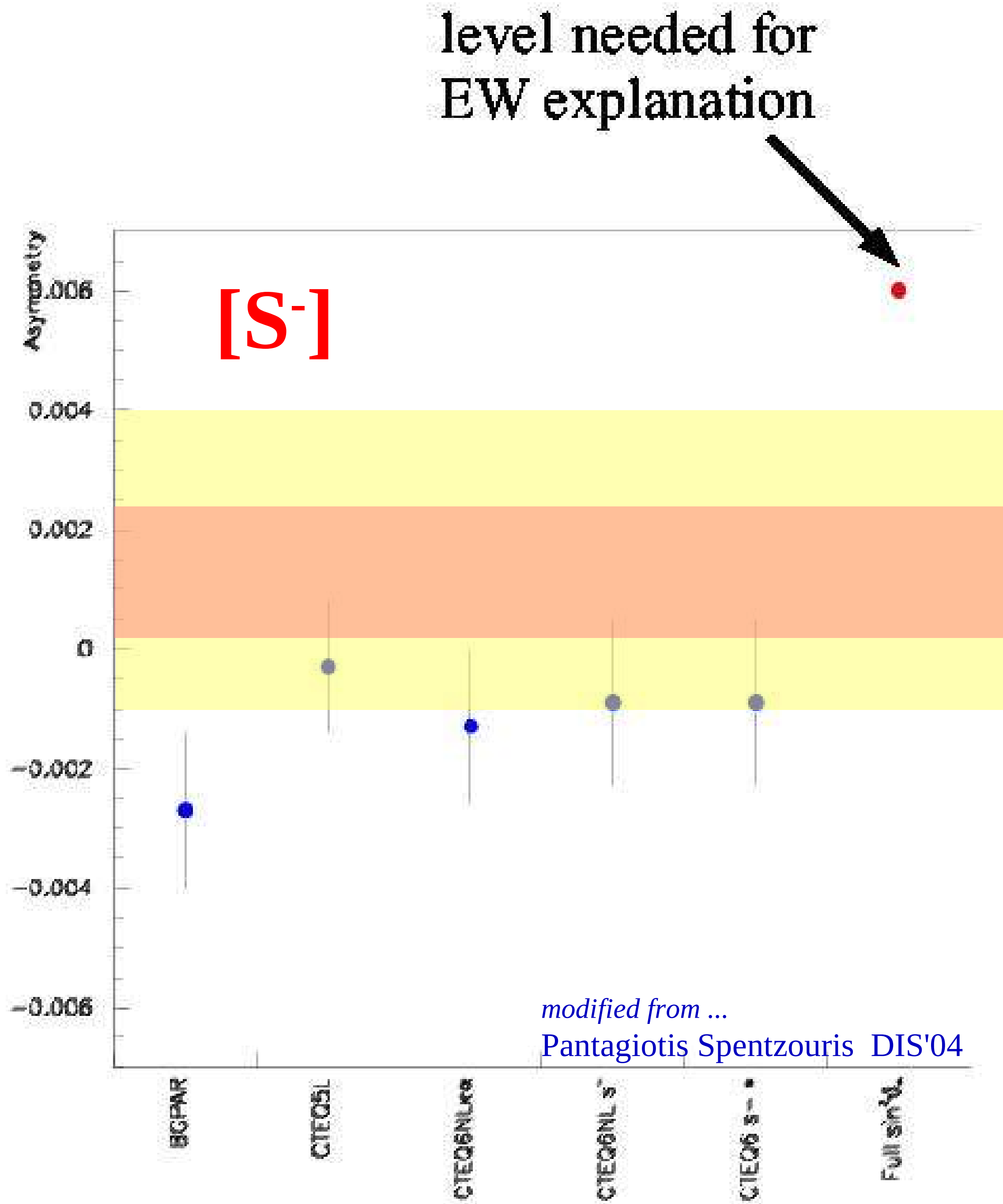
Nadolsky, Kidonakis, Olness, Yuan: PRD67:074015, 2003

What is the status:

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

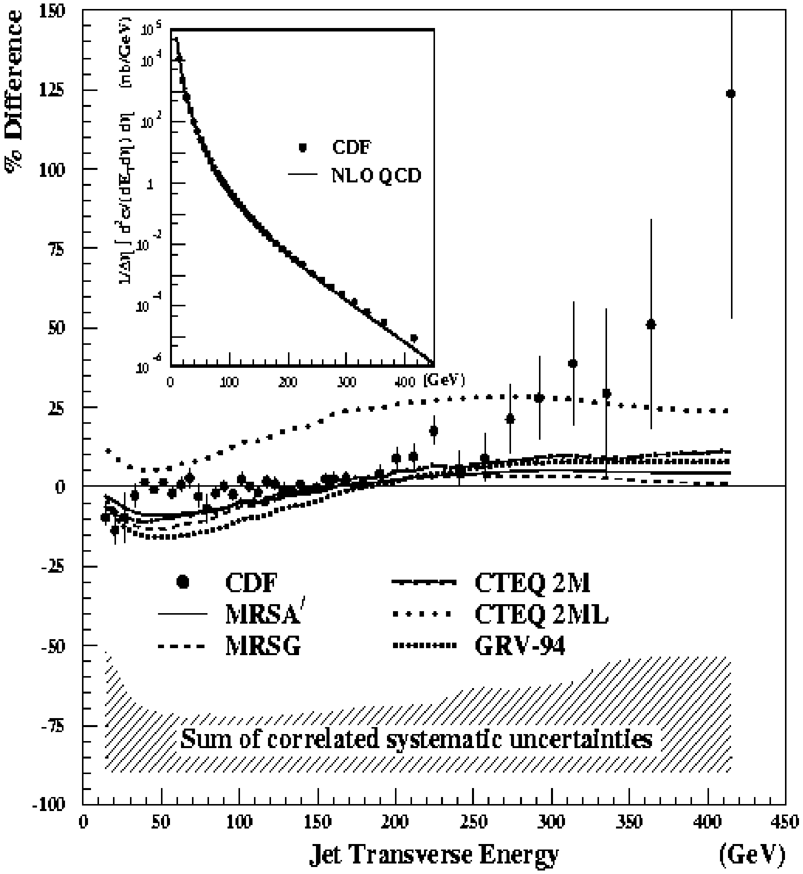
- Work is ongoing



Precision PDF's are Essential

1996: Excess High E_T

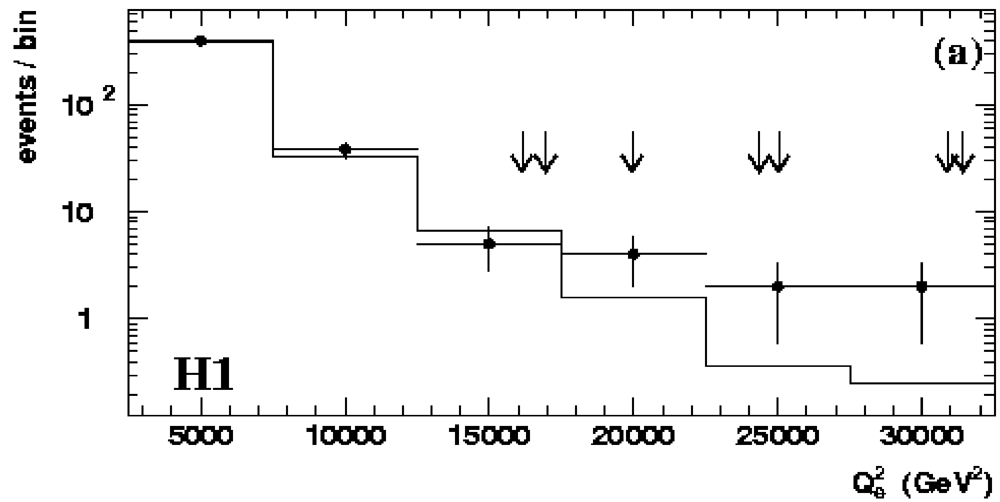
Jets at Tevatron



Is this a sign of compositeness?

1997: Excess DIS

events at large $\{x,Q^2\}$



Is this a sign of lepto-quarks?

CDF Collaboration
PRL 77, 438 (1996)

Precision PDF's are essential

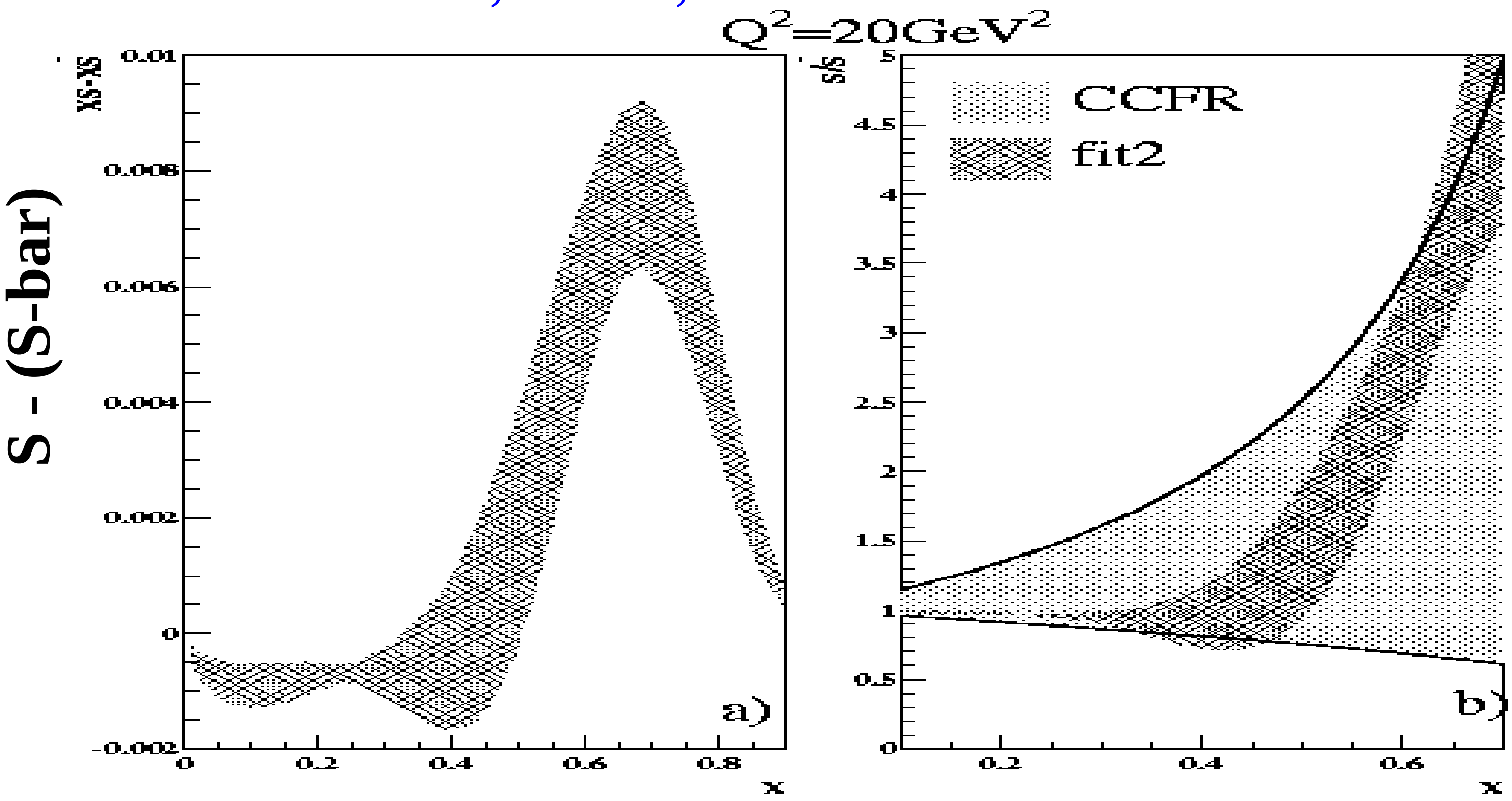
H1 Collaboration, ZPC74, 191 (1997)
ZEUS Collaboration, ZPC74, 207 (1997)

Strange Asymmetry

Global analysis: Barone, Pascaud, Zommer

DIS: BEBC, CDHS, CDHSW, BCDMS, H1, NMC

Drell-Yan: E605, NA51, E866



Barone, Pascaud, Zommer, Eur. Phys. J. C12: 243, 2000