W/Z Production at LHC
&
PDF Uncertainties

... or

are we ready to make discoveries at the LHC

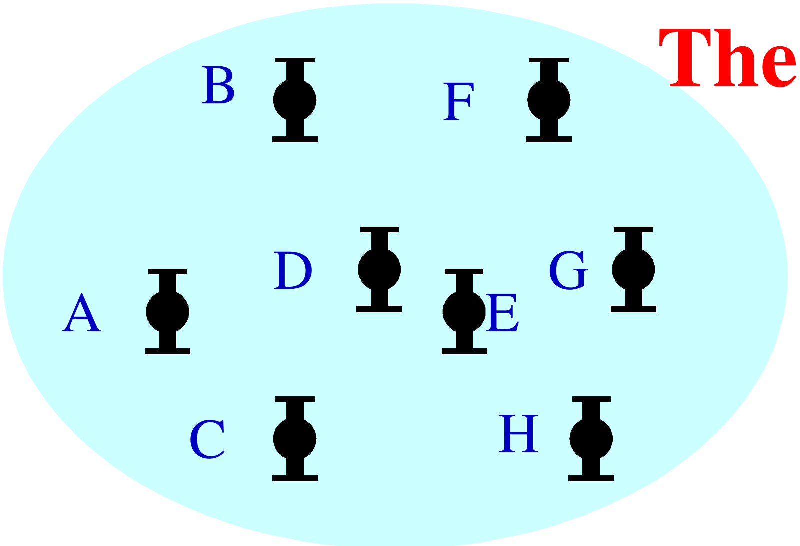
Fred Olness

SMU

Conspirators:
P. Nadolsky, S. Berge, I Schienbein,
J.-Y. Yu, W. Tung, S. Kretzer,
J. Owens, S. Kuhlmann, J. Pumplin, H. Lai

Pheno2006
16 May 2006

The LHC Coloring Book



These are experimental data points

- Theory says there is a Higgs signal at point B. Color the peak red.
- Theory says there is no Higgs signal at point B. Color the peak blue.
- This experimental data is in complete disagreement with theory. Color the error bars black and make them MUCH BIGGER.
- These points represent vertices of a Feynman diagram. Connect the points and color in a gauge invariant way.
- These points confirm the existence of SUSY. There is no time to color the points. Send your discovery to the NY Times immediately.

Adapted from "Journal of Irreproducible Results" Vol. 12, no. 3 (1964) H.J. Lipkin

It is likely that the LHC will see
many 3 σ and some 5 σ deviations

The goal is to determine if the cause is:

a) underestimating the theoretical uncertainty

b) underestimating the experimental uncertainty

c) a statistical fluctuation

d) a combination of all the above

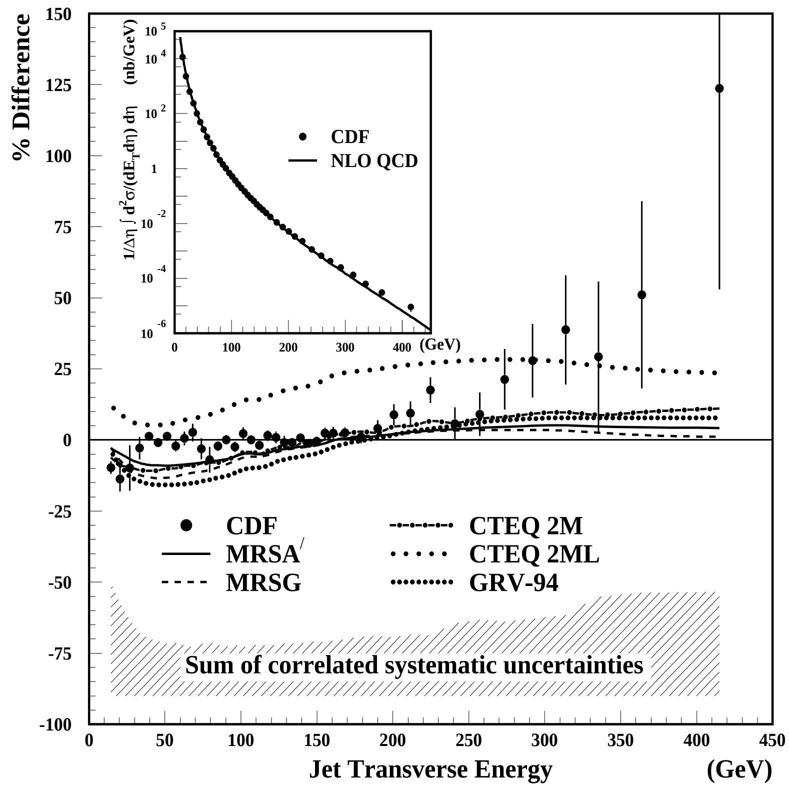
e) "New Physics"*

** If the answer is e) proceed to Stockholm to claim your Nobel Prize*

Would we know new physics if it bit us???

1996: Excess High E_T Jets at Tevatron

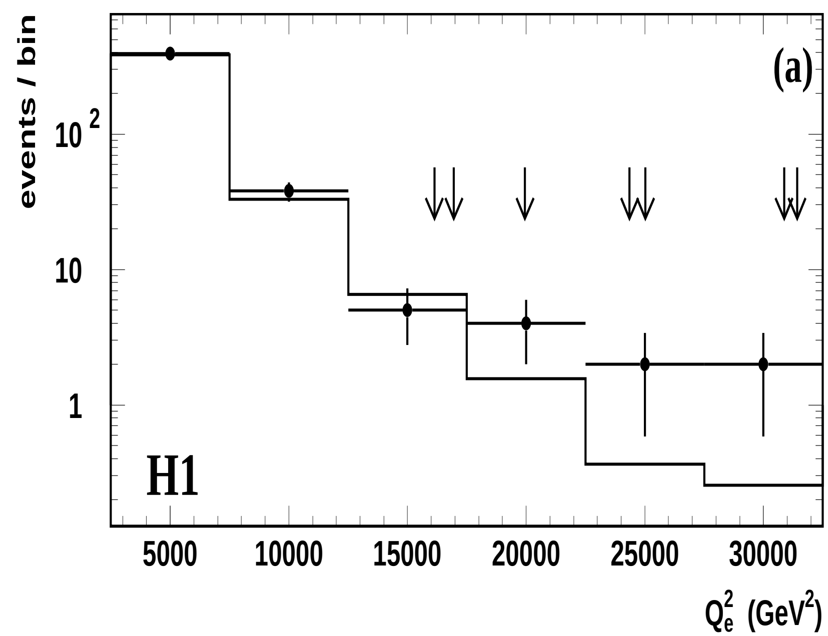
Is this a sign of compositeness?



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)

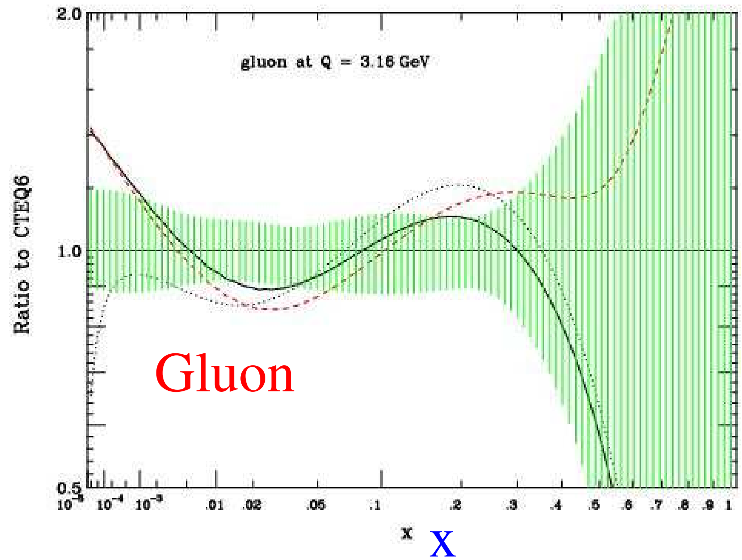
Precision PDF's are an essential ingredient for the Search For New Physics

Where are we going with this?

Where are we going with this ...

In CTEQ6:
40 PDF Sets allowed
for uncertainty analysis

Known Unknowns



A powerful tool; but, beware the **"Unknown Unknowns"**

We'll take a look at PDF Uncertainties involved in:

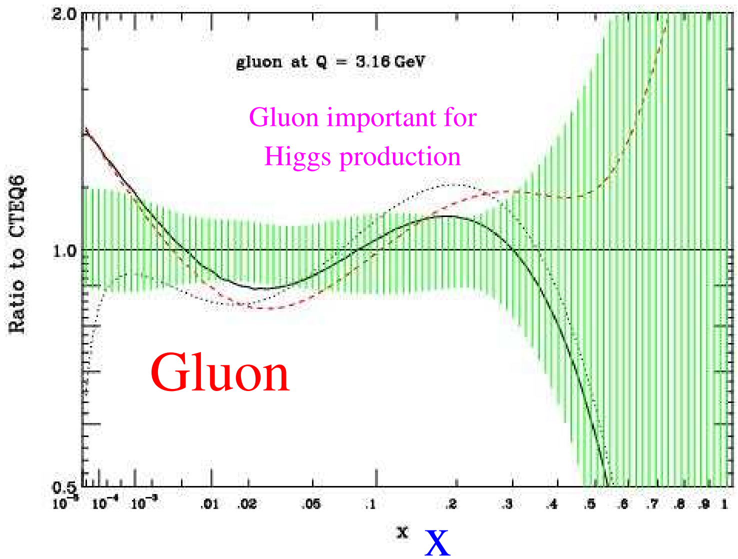
- *SUSY: Allow possibility of new light degrees of freedom*
- Strange Quark: important for $Sin\theta_W$ determination
- W/Z Production: Benchmarks for Higgs discovery

.... ingredients for next generation of PDF's

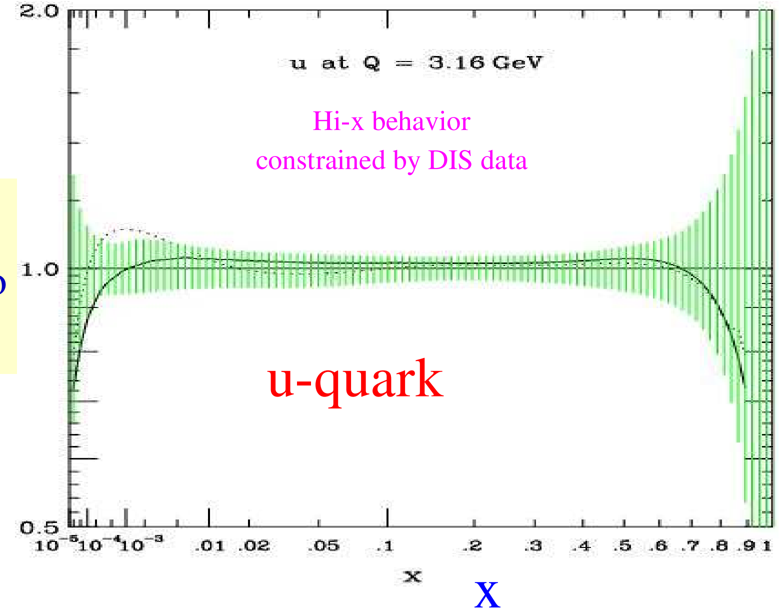
Strange

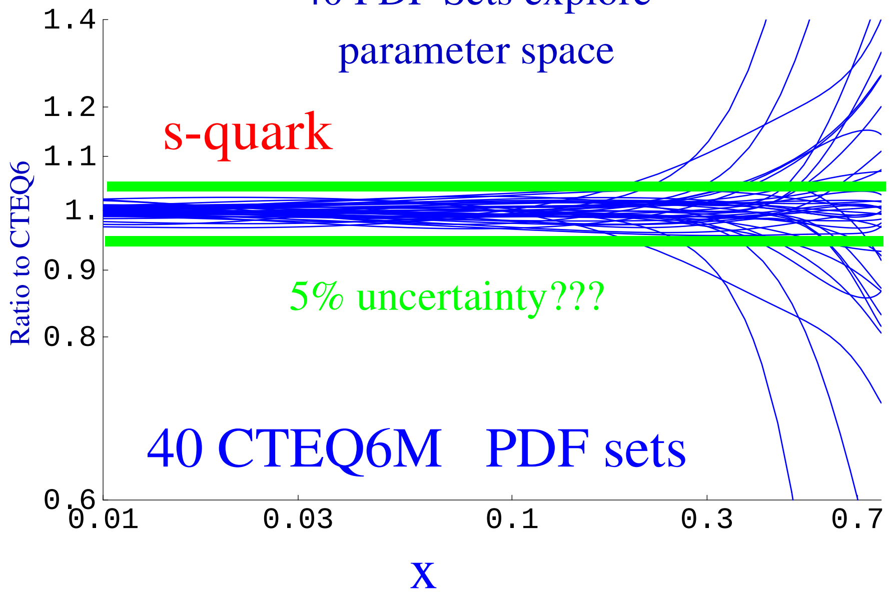
Quark PDF

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:

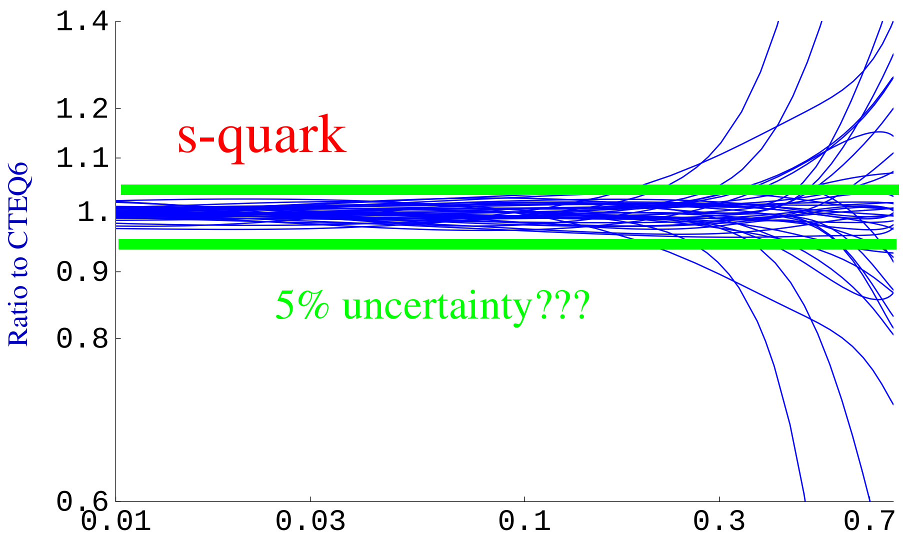
$$s(x) = \bar{s}(x) = \kappa \frac{\bar{u}(x) + \bar{d}(x)}{2}$$

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

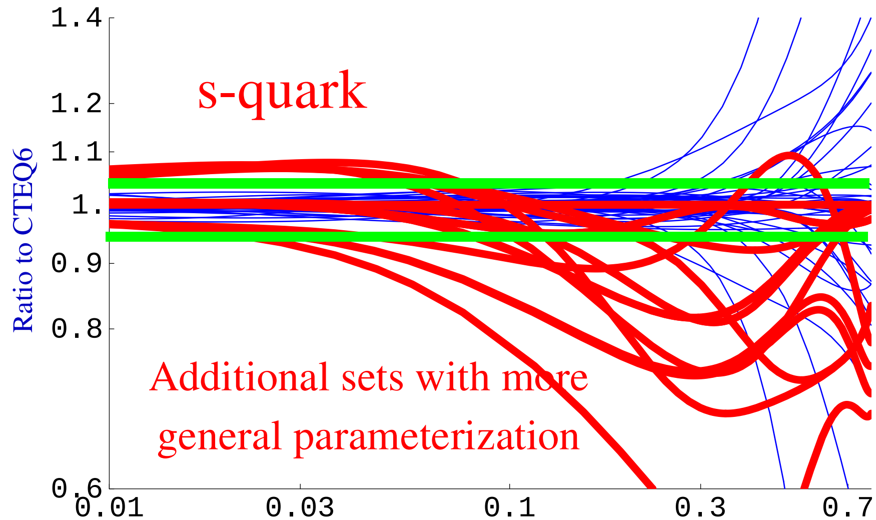
CTEQ6: Pumplin, Stump, Huston, Lai, Nadolsky, Tung, JHEP 0207, 012 (2002)

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

40 CTEQ6M PDF sets



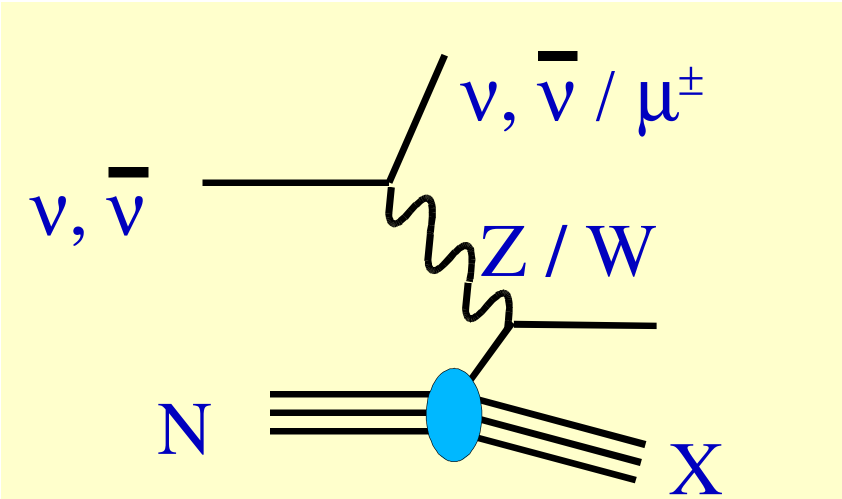
Closer to the true error



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

Electroweak Mixing Angle Measurement



Paschos-Wolfenstein Relation:

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

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

Controls the unification of
Electromagnetic & Weak Forces

NuTeV Result:

$$\sin^2\theta_W^{(on-shell)} = 0.2277 \pm 0.0013(stat) \pm 0.0009(syst)$$

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

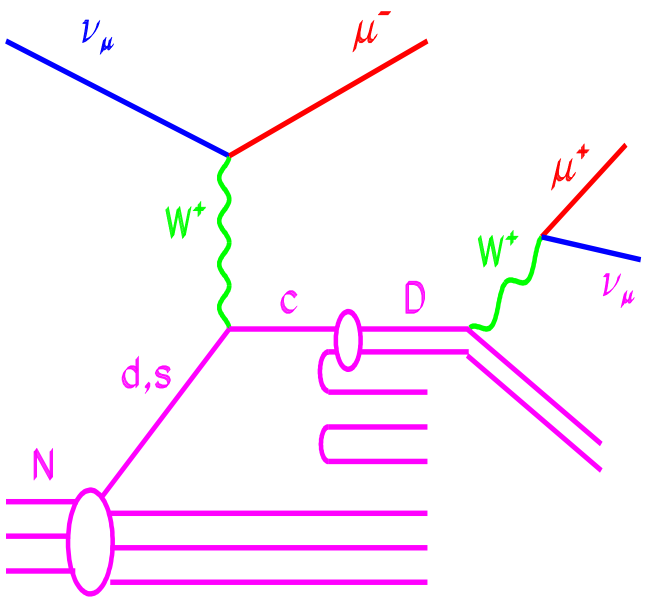
Standard Model Fit:

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

A 3 σ difference

What are the possible sources of 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

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

Di-muon cross-section

Charm Production cross-section

Fragmentation Function

Decay Distribution

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

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

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) !!!

$\therefore$

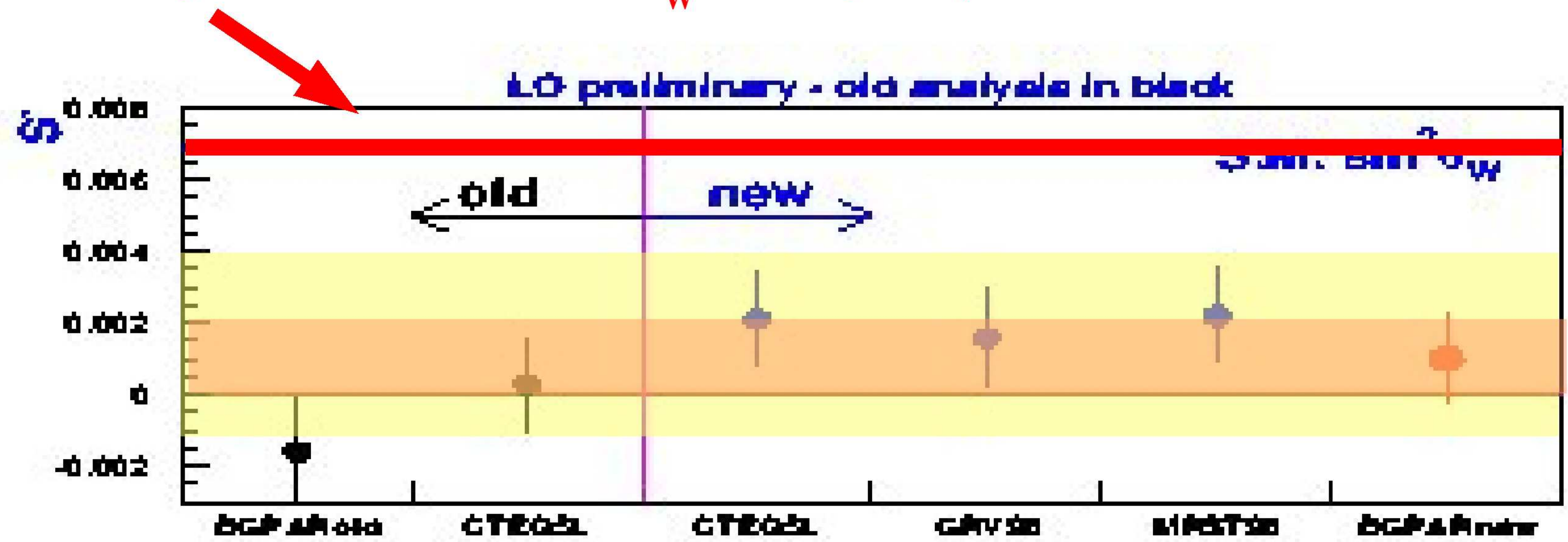
Idea: ν and ν-bar data separately determine s and s-bar distributions

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

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

Does this solve the Sinθ_W problem???

Required to resolve sinθ_W discrepancy



- Tremendous new information on BOTH $s+\bar{s}$ and $s-\bar{s}$
- Work is ongoing: extend to higher orders
- Include this information in next generation PDF sets

Three-loop kernel generates asymmetry

$$\langle x(s-\bar{s})\rangle \approx -5\times 10^{-4} \text{ @ } Q^2 \text{ 20GeV}^2$$

S. Catani, D. de Florian, G. Rodrigo, W. Vogelsang; Phys.Rev.Lett. 93 (2004) 152003

D. Mason for the NuTeV Collaboration; AIP Conf.Proc.792:851-854,2005

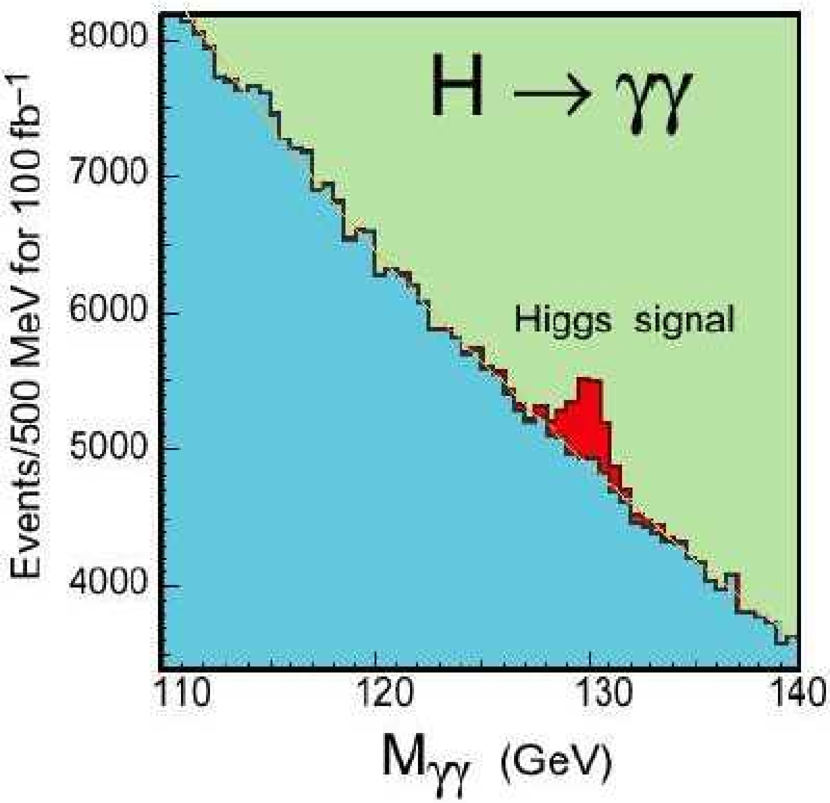
Kretzer, Mason, Olness PRD 65:074010 (2002)

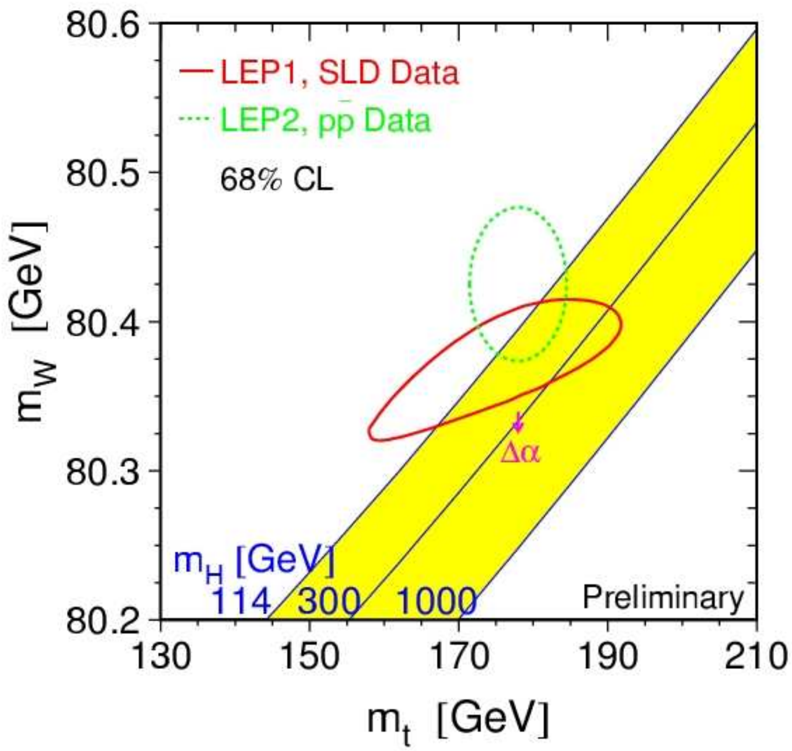
W / Z / HIGGS

Motivation: W, Z, Higgs Production

Higgs discovery relies on accurate predictions

Precision M_W provides clues of Higgs





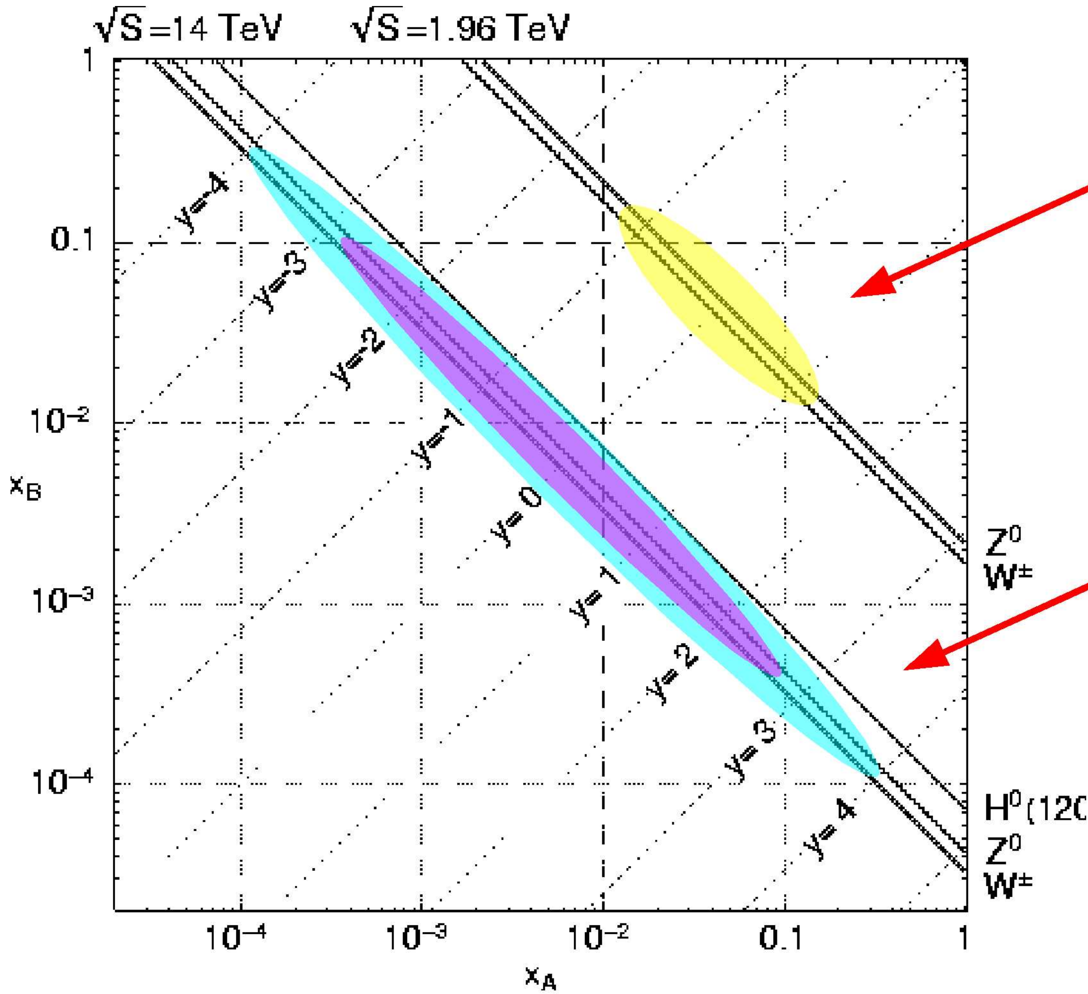
W & Z Production are "Benchmark" processes at LHC

W / Z / HIGGS

Kinematics

What is relevant x region for W / Z / Higgs Production

Kinematics of boson production $\sigma = f(x_A) f(x_B) \hat{\sigma}$



This is the region of present measurement

This is the region we need at LHC

LHC probes new {x,Q} range.

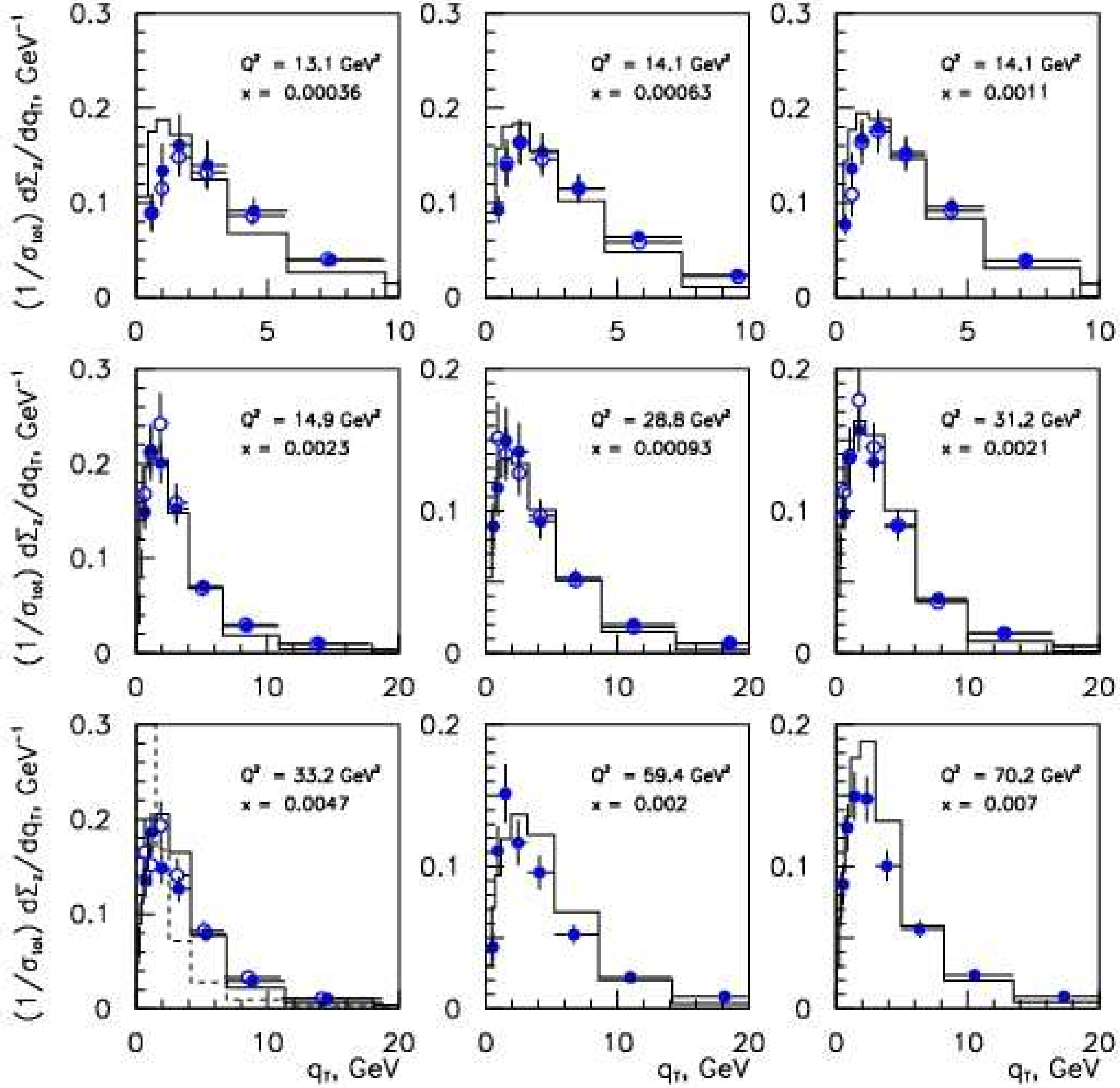
Requires extrapolation

x range for Tevatron

x range for LHC

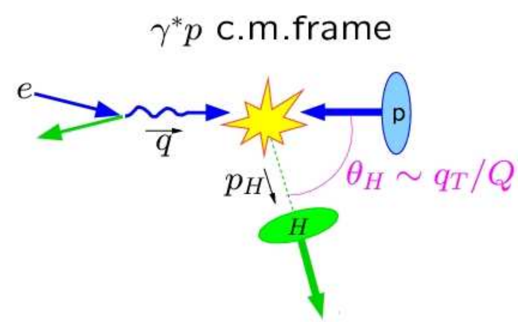
HERA has measured the crossed process (DIS) for this region and found ...

Differential energy flow at small-x???



$$\frac{d\Sigma_z}{dx\, dQ^2\, dq_T}$$

$$d\Sigma_z = \int z \frac{d\sigma}{dz}$$



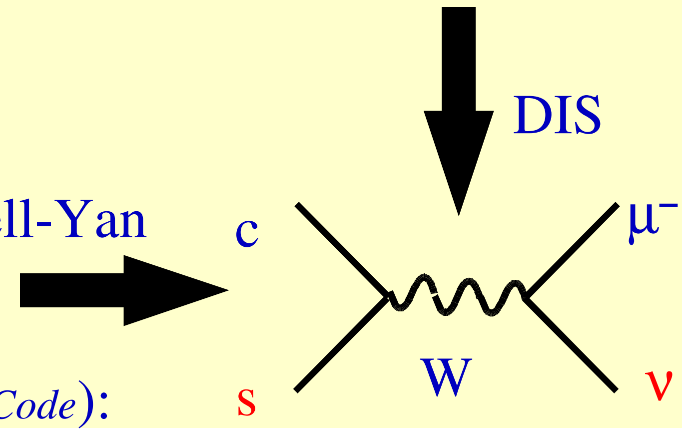
Extra q_T broadening for $x<10^{-2}$

H1 Collaboration,
PL B356, 118 (1995)
EPJ C12,595 (2000)

What are the implications for LHC???

Drell-Yan ($q\bar{q} \rightarrow W/Z/\gamma/H \rightarrow ee$) at

LHC is simply crossed DIS process



Apply to LHC:

Use ResBos (*Resummed Boson Production Code*):

Implements Sudakov soft gluon resummation via CSS

Collins, Soper Sterman

Include small-x broadening in Sudakov exponent

$$e^{-S(q_T,Q)} \rightarrow e^{-S(q_t,Q)-\rho(x)\,q_T^2}$$

Additional small-x broadening term
Form taken from HERA data

Crossing is valid.
See Collins & Metz

Only turns on at small-x

$$\rho(x) = c_0\left(\sqrt{\frac{1}{x^2}+\frac{1}{x_0^2}}-\frac{1}{x_0}\right)$$

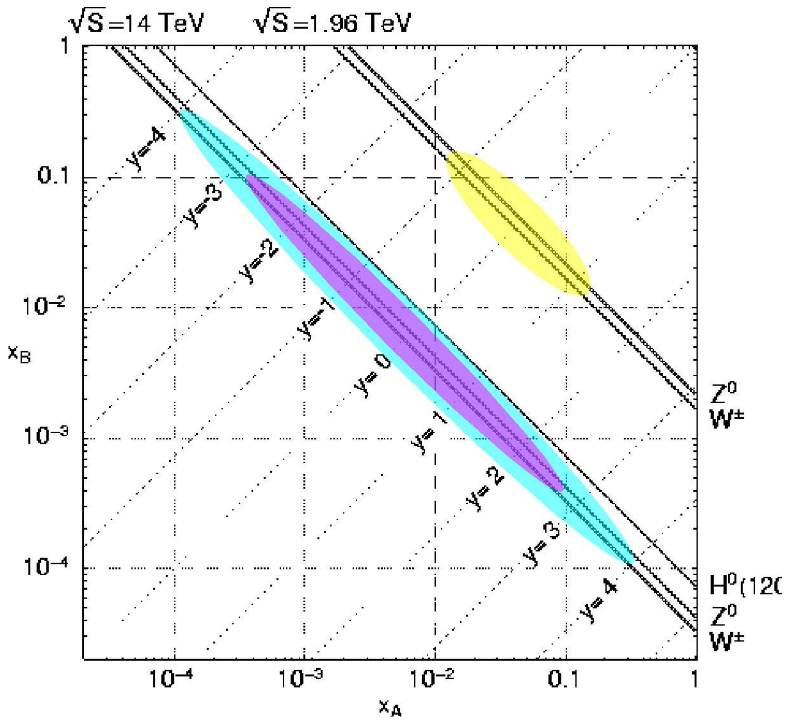
$x_0 = 0.005$

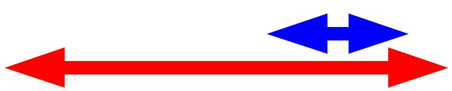
$c_0 = 0.013$

J. C. Collins and A. Metz, hep-ph/0408249.
J. C. Collins, D. E. Soper and G. Sterman, Nuc.Phys. B250, 199 (1985).

What is relevant x region for W / Z / Higgs Production

Kinematics of boson production $\sigma = f(x_A) f(x_B) \hat{\sigma}$

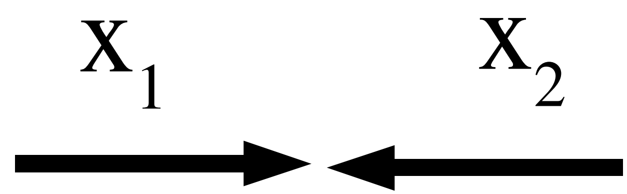




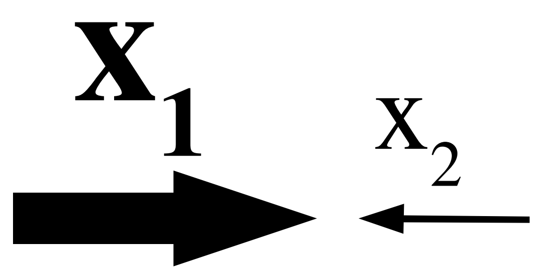
x range for LHC

x range for Tevatron

Central Rapidity



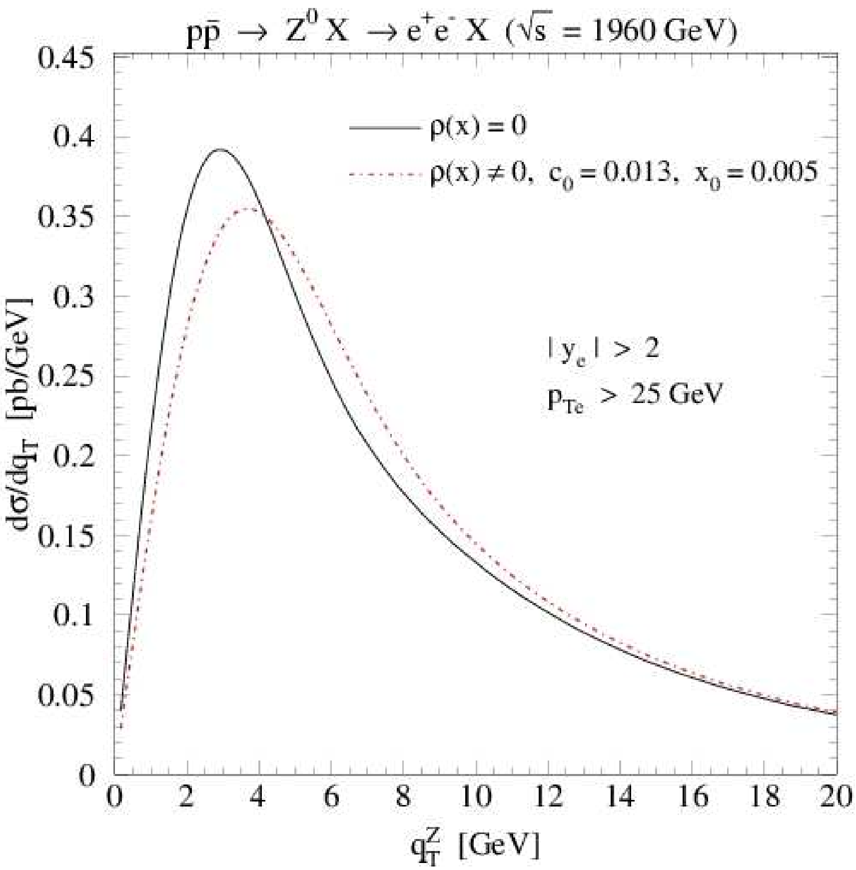
Forward Rapidity



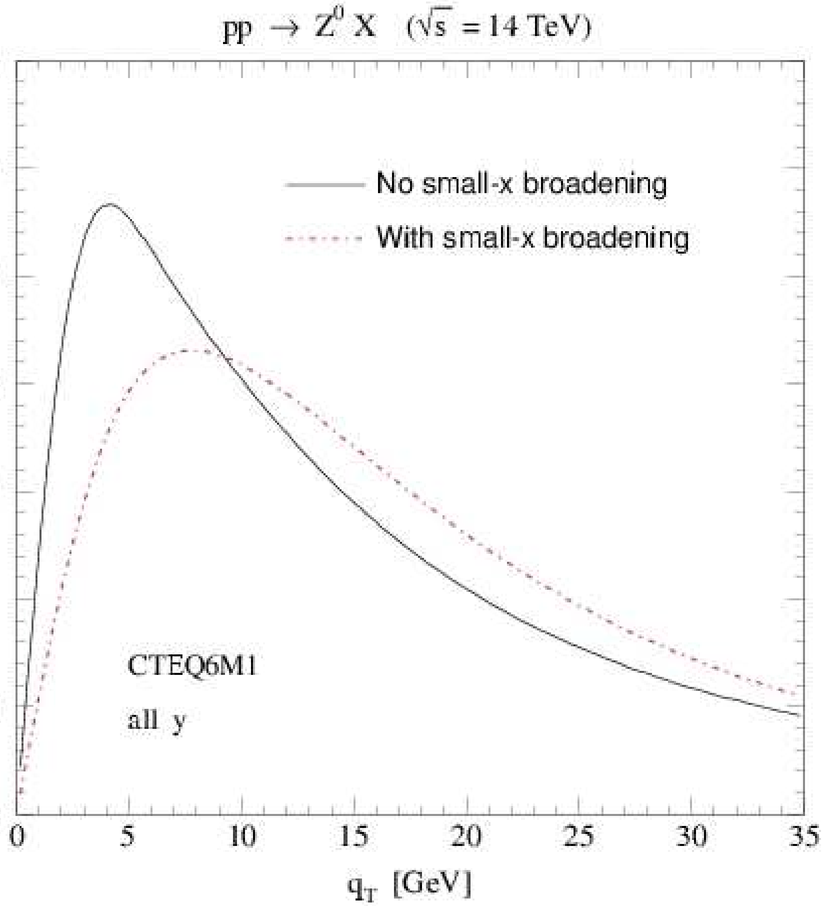
Z

Z Production: Tevatron & LHC

Tevatron



LHC

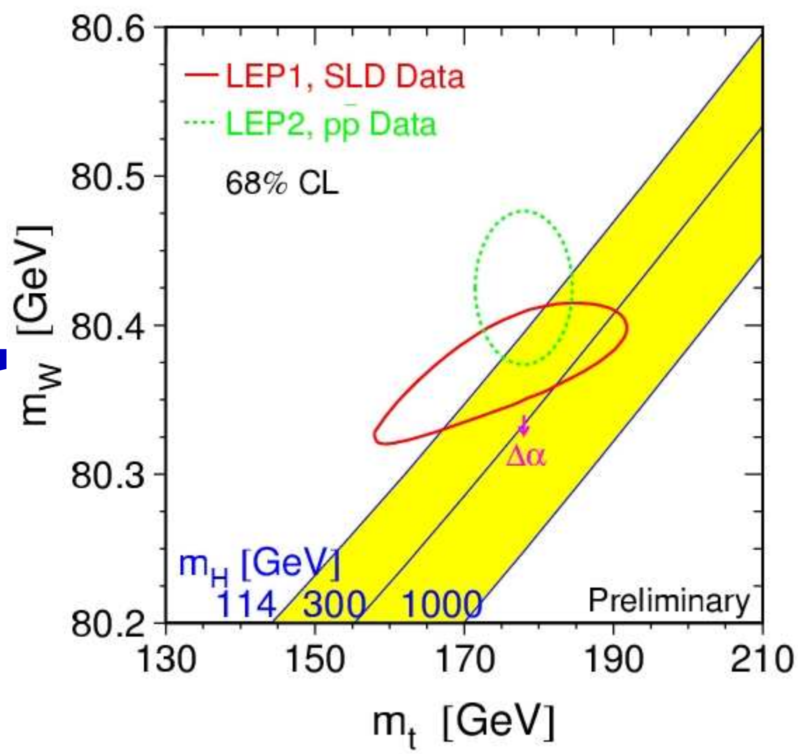


With cuts on y_e and p_{Te}

No y cut necessary !!!

These uncertainties are not acceptable for "benchmark" processes

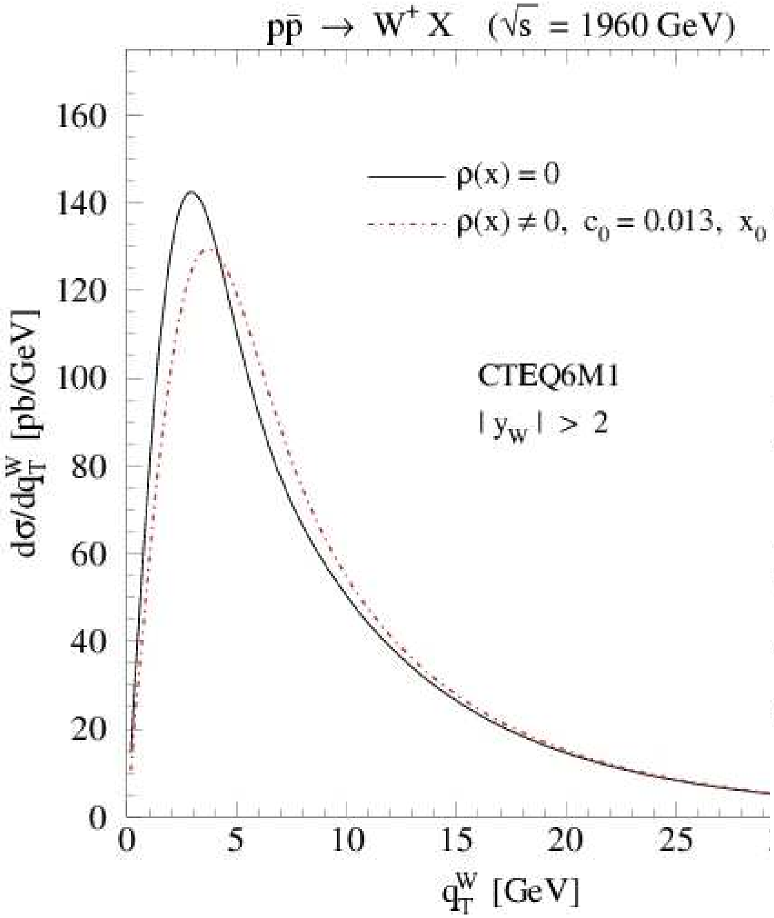
W



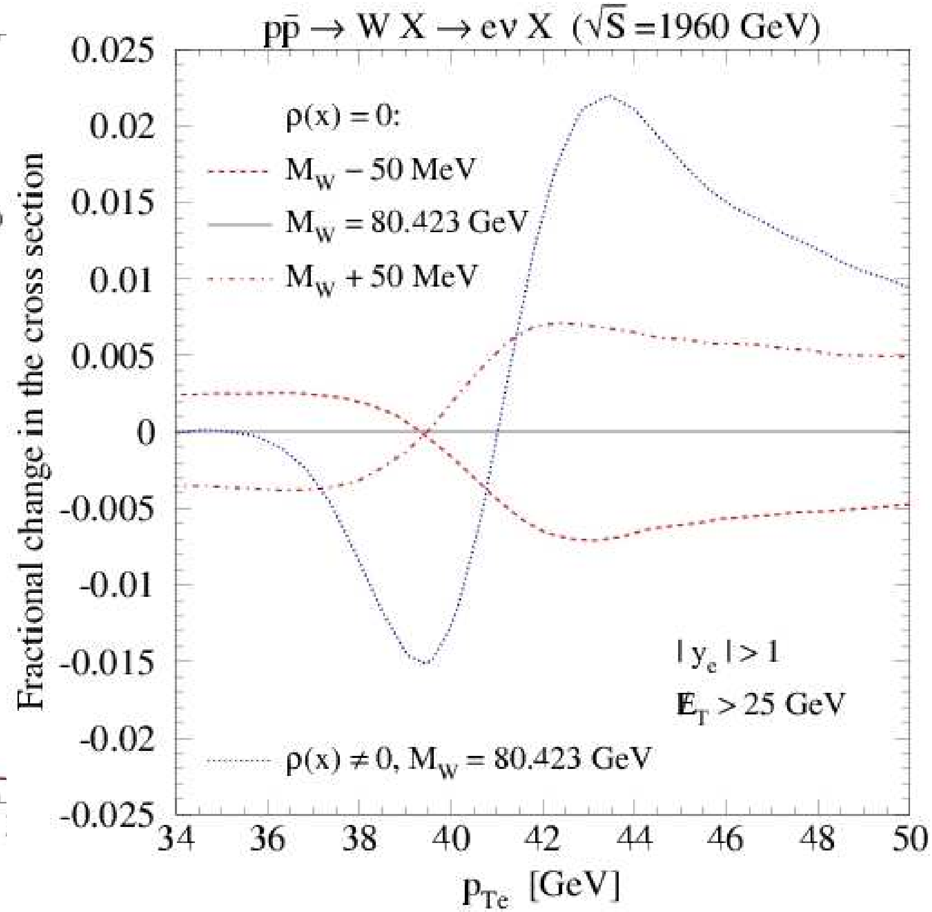
Precision M_W provides clues of Higgs

W Production at the Tevatron

Shift of W q_T distribution



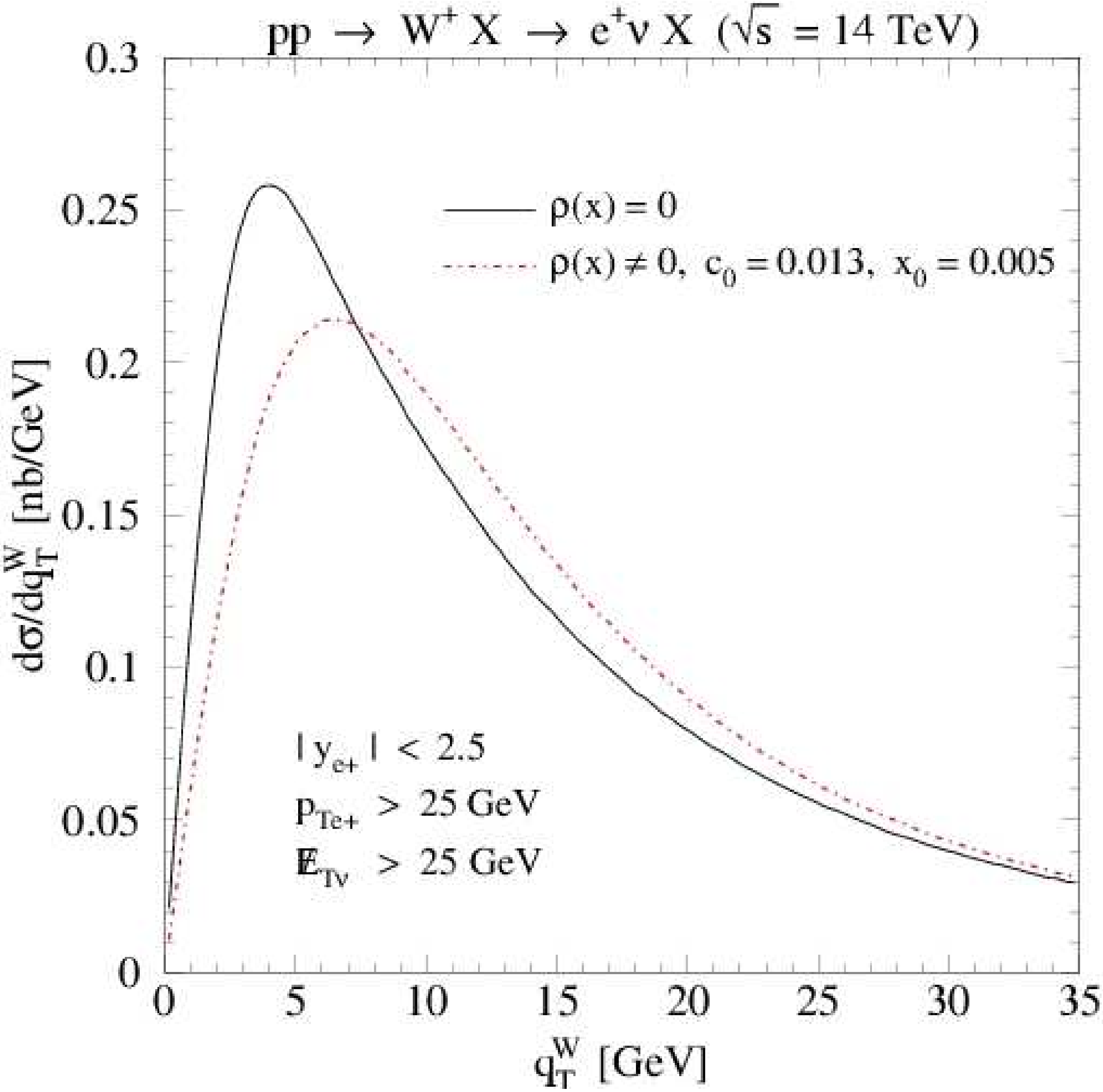
Effect on Jacobian Peak



Potentially, this effect can limit precision of M_W determination

At Tevatron δM_W can be ~10-20 MeV in the central region, and ≥50 Mev in the forward region

W Production at the LHC



effect present in
central rapidity
region

Presence/Absence
of this effect will tell
us about PDF's in
new kinematic
regime
&
soft-gluon
resummation
effects

Conclusions

* Strange Quark PDF

This is real progress!!! We now can discriminate!

Large uncertainties: Higher-Order Analysis in progress

* W/Z Production: Provides important constraints on the PDF's

Essential for exploration of Higgs, SUSY, and "New Physics"

LHC probes smaller x values where PDF’s are undetermined

Tevatron can observe such effects in forward (y~2) region

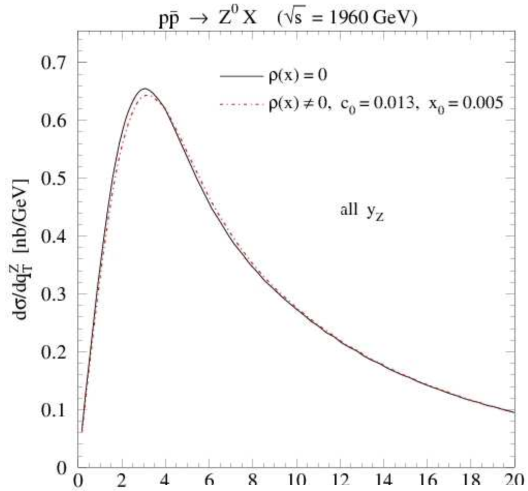
Need to accommodate these effects and uncertainties
to make best use of HERA & Tevatron data.
Also, be prepared to cross-check using early LHC data

Thanks to: P. Nadolsky, S. Berge, I. Schienbein, J.-Y. Yu, 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

BACKUP

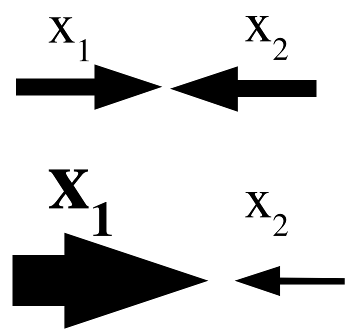
SLIDES

Z Production at the Tevatron

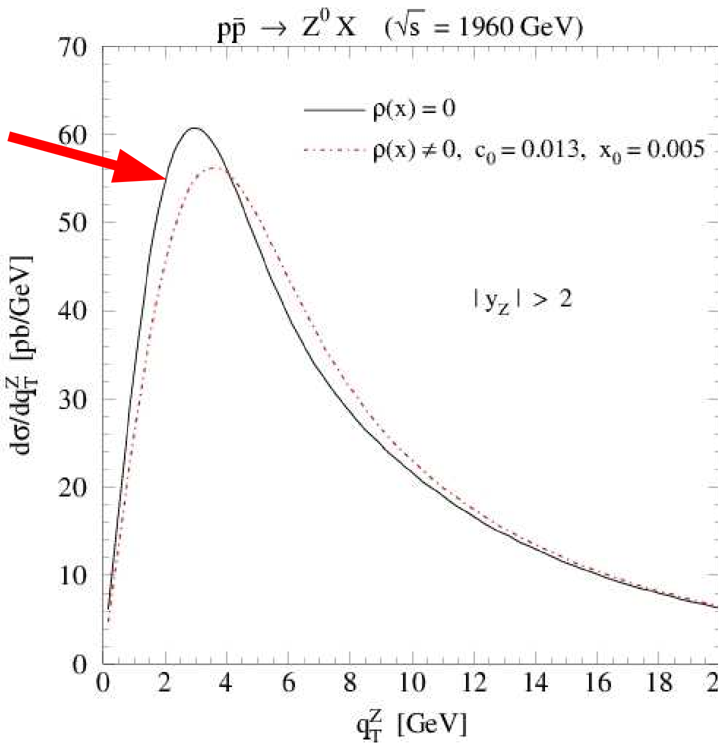


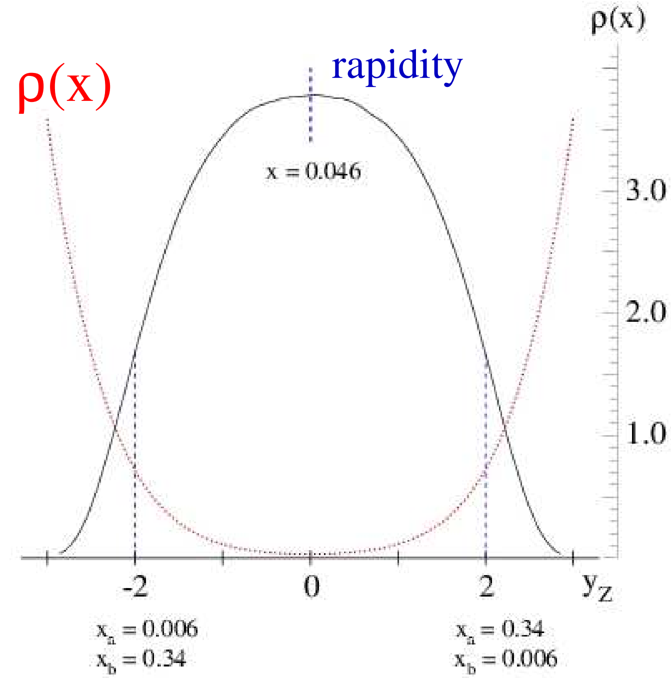
Central Rapidity

Forward Rapidity



Position of q_T peak shifts by 25%





Generalized heavy degrees of freedom

SUSY PDF's

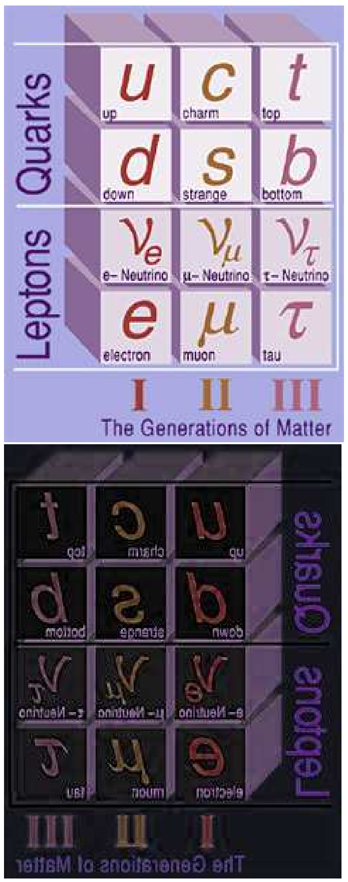
Use of PDF errors: an example

Consequences of SUSY

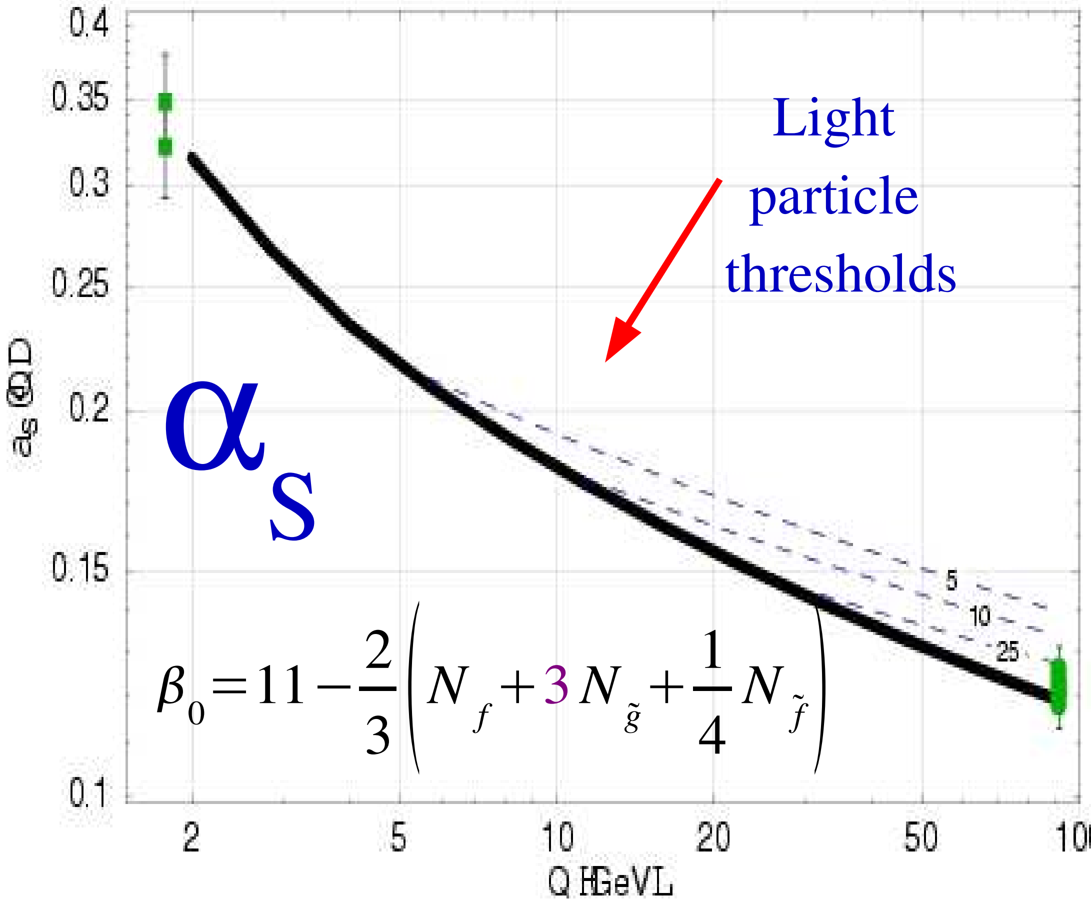
We've only discovered half the particles

Particles

Sparticles



New particles effects evolution of $\alpha_s(\mu)$



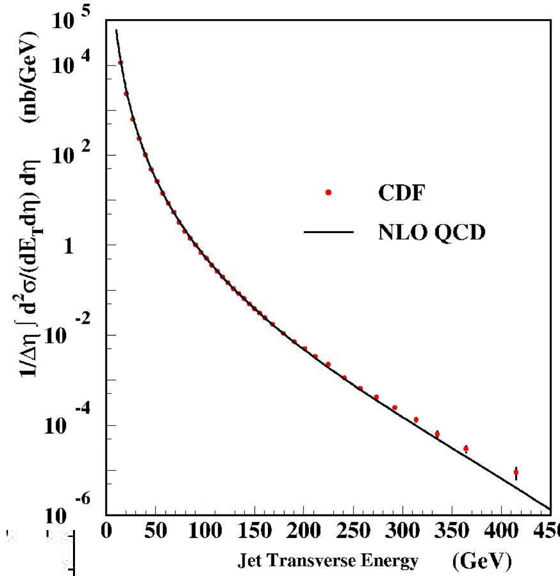
$$\beta_0 = 11 - \frac{2}{3}\left(N_f + 3N_{\tilde{g}} + \frac{1}{4}N_{\tilde{f}}\right)$$

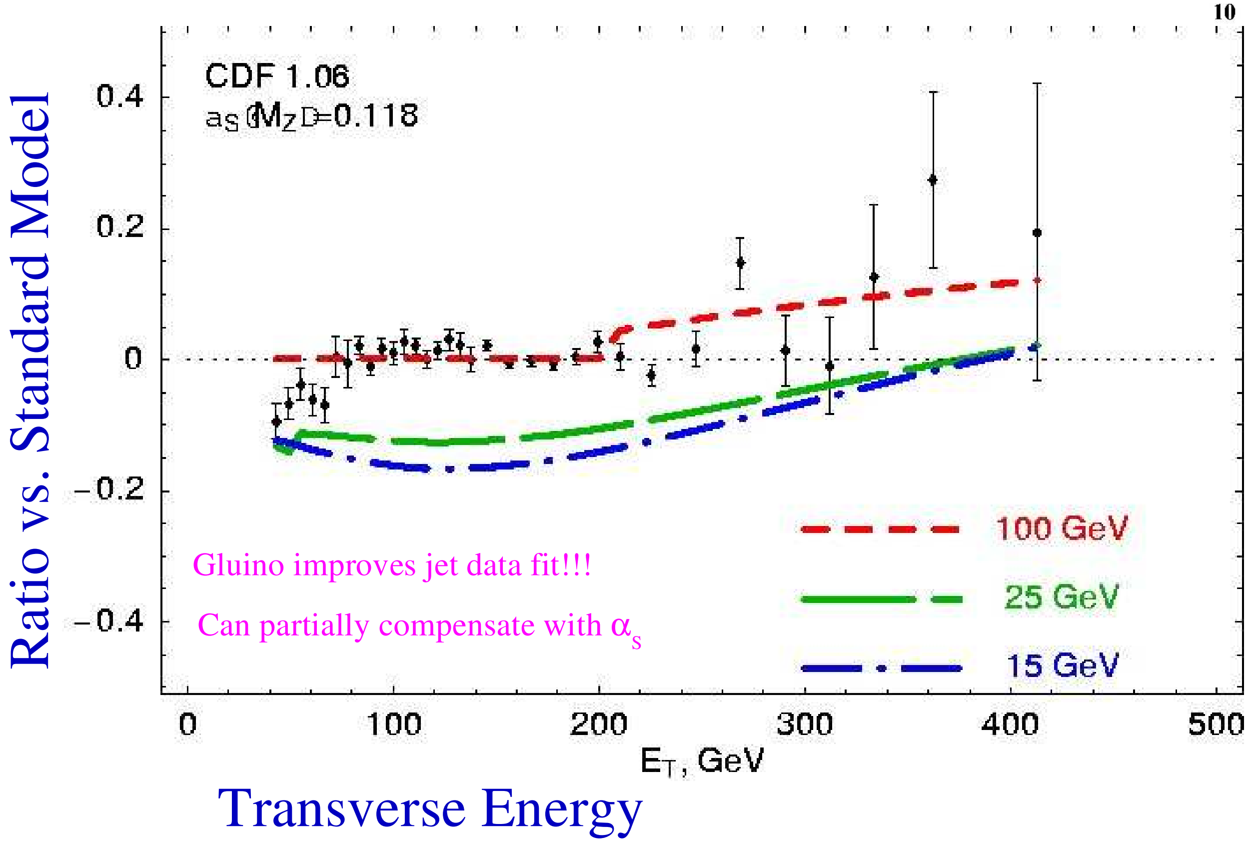
Energy Scale

Include SUSY in PDF Evolution

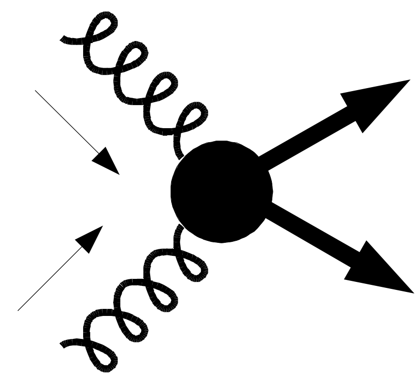
Strong constraints require large Q range:

Tevatron Jet Data has largest Q





Need to recompute dσ including SUSY



$$g\,g \rightarrow \tilde{q}\,\tilde{q}$$

$$g\,g \rightarrow \tilde{g}\,\tilde{g}$$

Generalized heavy DOF: new thresholds for the PDFs

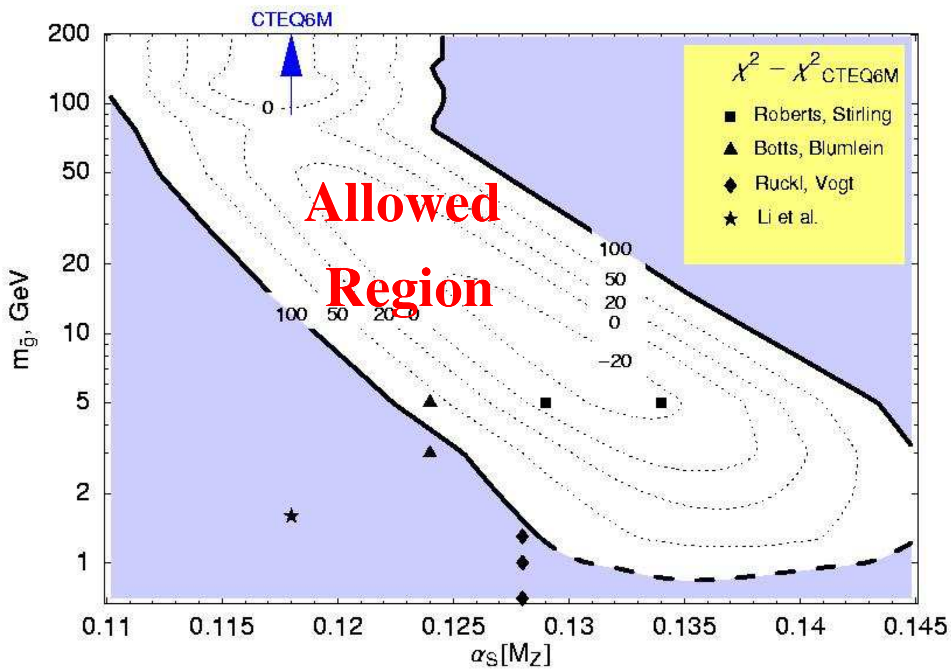
Inclusion of new strongly interacting particles *(e.g., gluino)* affect PDF's at higher scales.

Bulk of PDF constraints are at low Q scales

Strong correlation between α_s gluino (and gluon)

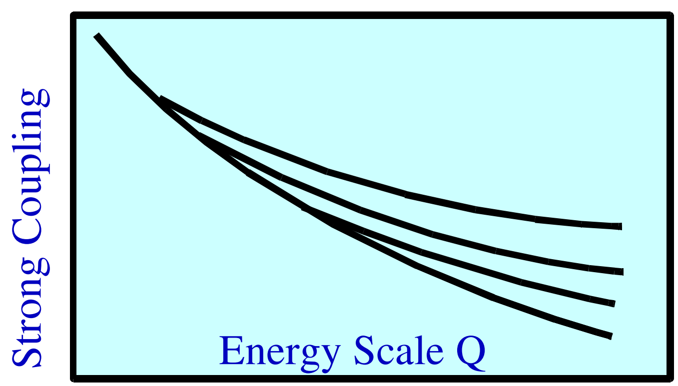
Will affect gluon production of Higgs

SUSY Gluino Mass Parameter



Strong Coupling Constant

Running of α_s(Q) with thresholds

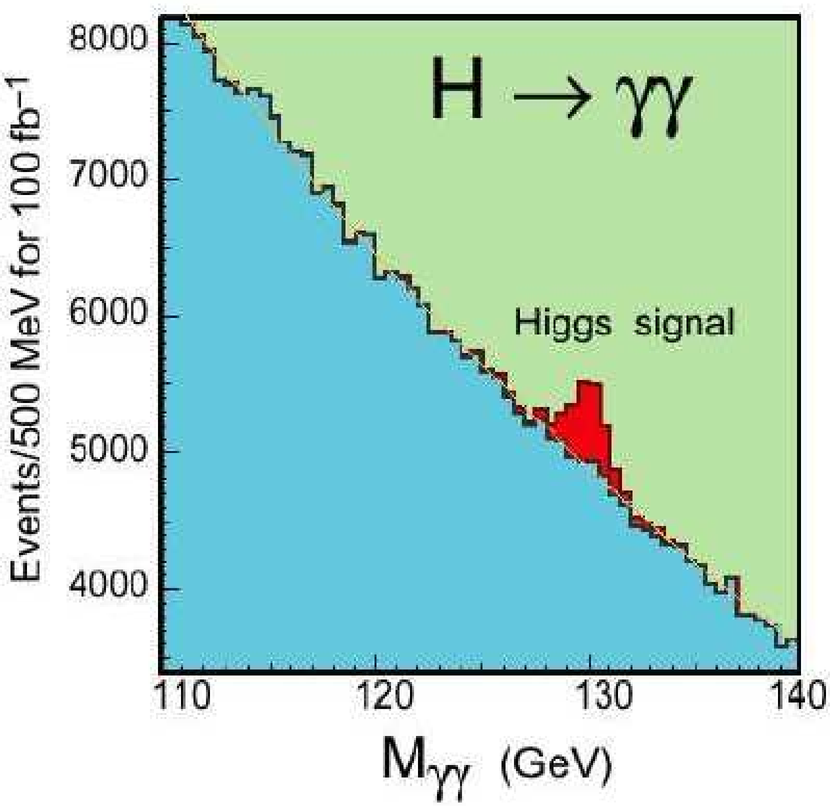


New thresholds can significantly alter PDF's at large Q

Model Independent Constraints

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

HIGGS



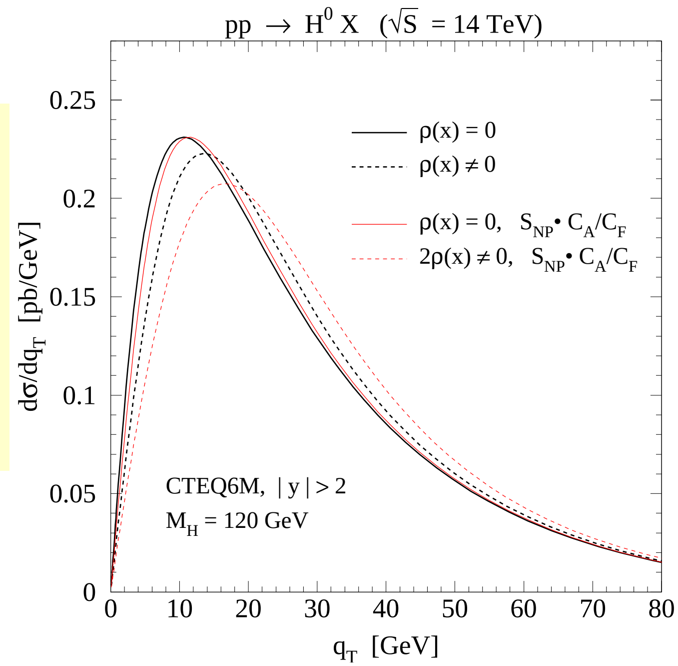
Higgs discovery relies
on accurate predictions

Effect on Higgs

Broadening not important for discovery

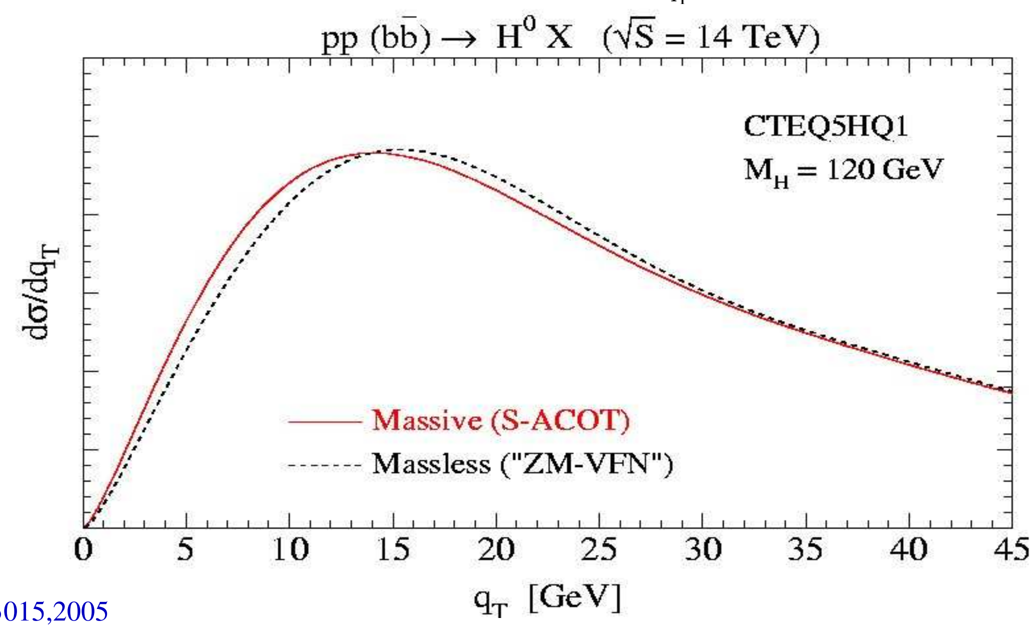
Important for precise M_H measurement

i.e., to characterize SUSY model



Separately:
Heavy quark effects

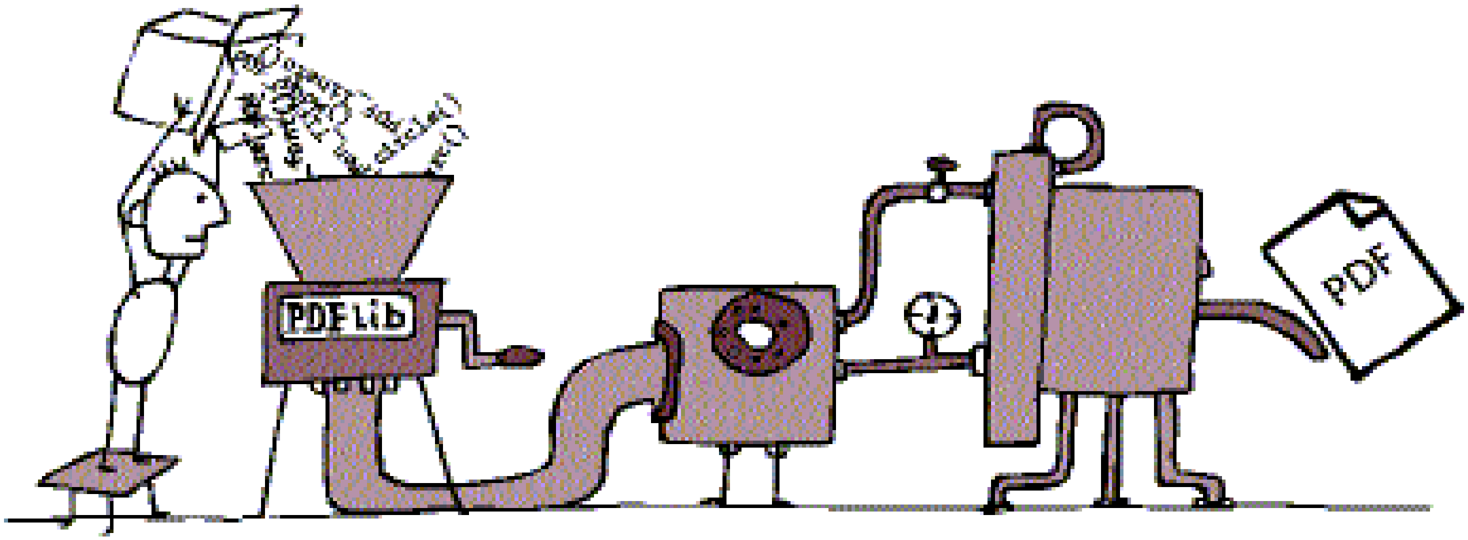
Important for
bb→H channels
E.g., MSSM models



S. Berge, P. Nadolsky, F. Olness, Phys. Rev. D73: 013002,2006

S. Berge, P. Nadolsky, F. Olness, C.-P. Yuan. Phys.Rev.D72:033015,2005

Where do PDF's come from??? *... like making sausage???*



New elements for next generation of PDF's:

SUSY: *Allows possibility of new light degrees of freedom*

ν-DIS di-muon data: *Important for strange quark PDF*

W/Z Production: *Calibrate at TeVatron or LHC*

DIS Cross Section Data: *In contrast to* F_{123} *data*

NNLO Kernels

Strange

Quark PDF

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.

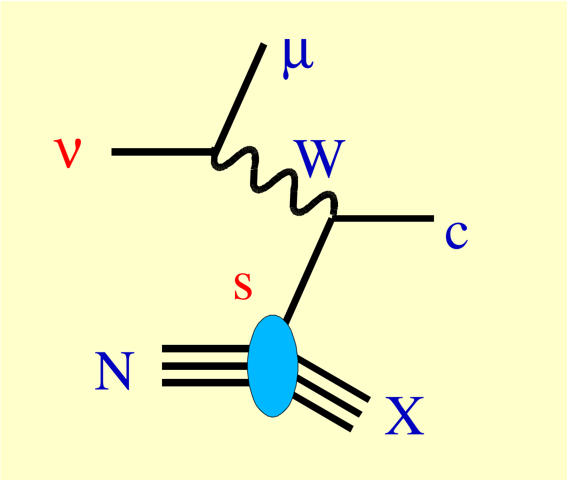
Largest model uncertainty arises from charm production and s(x)

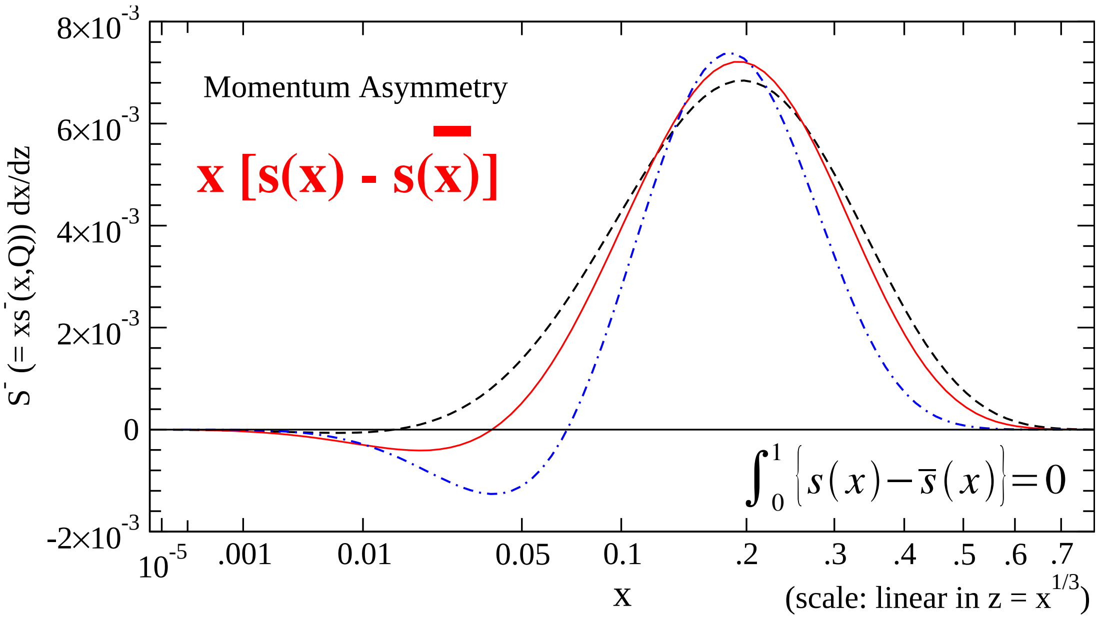
s and s-bar difference can have large effect

… relative uncertainty is reduced for combination

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

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





General range of the asymmetry

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

$$+0.0040 \geqslant [S^-] \geqslant -0.0010$$

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

- charm fragmentation
- charm mass
- PDF set

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)