Collider Physics
Lecture 1

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Past Colliders

Name	Type	Ecm (GeV)	Lint (pb-1)	Years of Operatio n	Detectors	Location
LEP-1	e+e-	91.2 (Mz)	~200	1989-95	ALEPH, L3,DELPHI, OPAL	CERN
LEP-2	e+e-	161-209	~600	1996-2000	ALEPH, L3,DELPHI, OPAL	CERN
SLC	e+e- (polarized)	91.2	20	1992-98	SLD	SLAC
HERA	e-p, e+p	320	500	1992-2007	ZEUS, H1	DESY (Germany)

Past and Present

Name	Type	Ecm (TeV)	Lint (fb-1)	Years of Operation	Detectors	Location
TeVatron Run 1	p pbar	1.8	0.16	1987-96	CDF, D0	FNAL
TeVatron Run 2	p pbar	1.96	10	2001-11	CDF, D0	FNAL
LHC Run 1.1	p p	7	5	2010-11	ATLAS, CMS, LHC-b	CERN
LHC Run 1.2	p p	8	20	2012-13	ATLAS, CMS, LHC-b	CERN
LHC Run 2	p p	13	150 (planned)	2015-18	ATLAS, CMS, LHC-b	CERN

Future Colliders

Name	Type	Ecm (TeV)	Lint (fb-1)	Years of Operation	Detectors	Location
LHC Run 3	p p	14	300?	2020-22	ATLAS, CMS	CERN
HL-LHC	p p	14	3,000?	2025-35	ATLAS, CMS	CERN
ILC	e+ e-	0.25-0.5	6,000?	20X - 20X+20	???	Japan?
Circular Higgs Factory	e+ e-	0.25	10,000?	20X- 20X+Y	???	CERN? China?
100 TeV Monster tron	p p	100	???	2100?	???	CERN? China?

Parton Distribution Functions

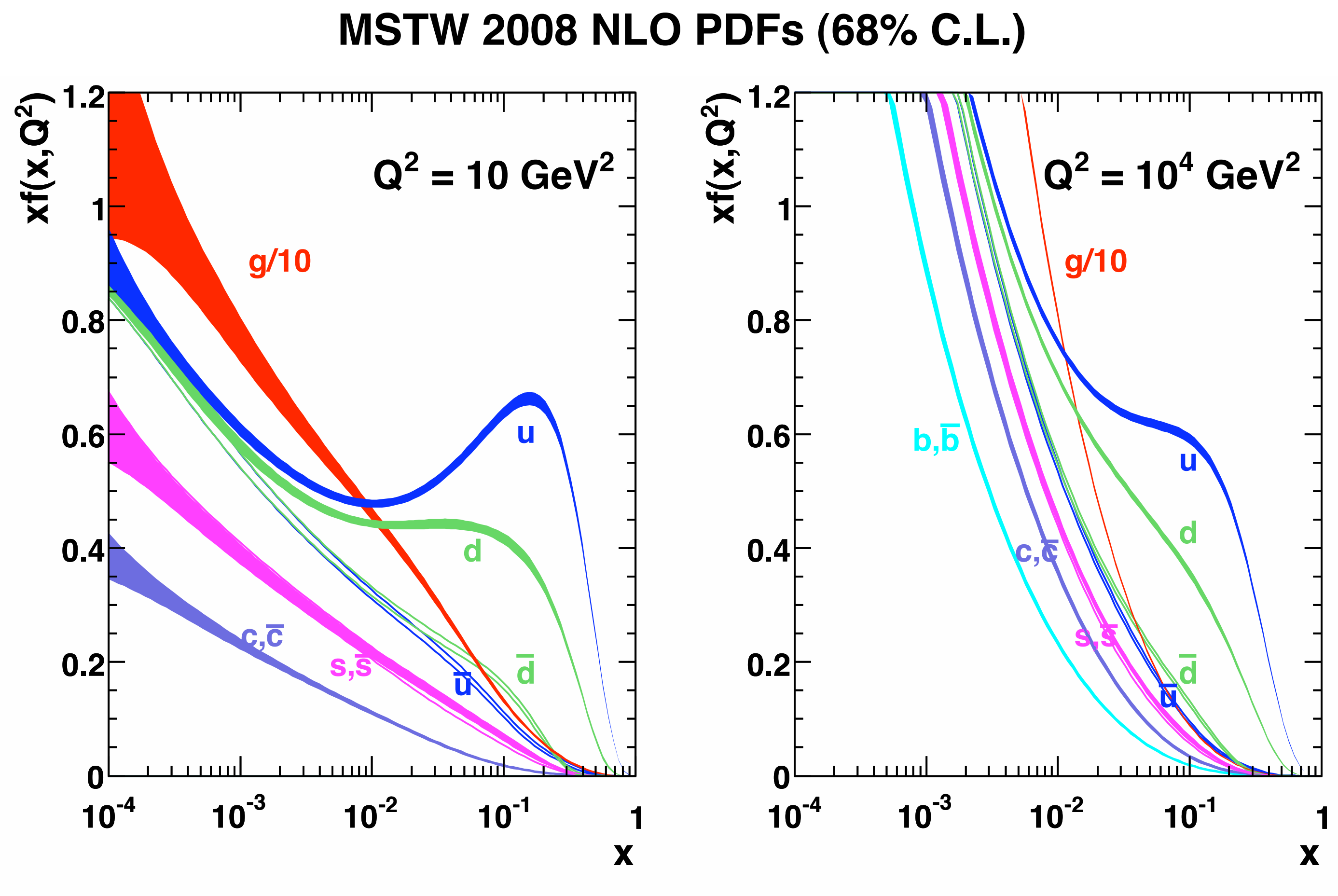


Figure 1: MSTW 2008 NLO PDFs at $Q^2 = 10$ GeV^2 and $Q^2 = 10^4$ GeV^2.

Martin, Stirling, Thorne, Watt, 0901.0002

Lesson: All PDFs (including valence) drop fast with x

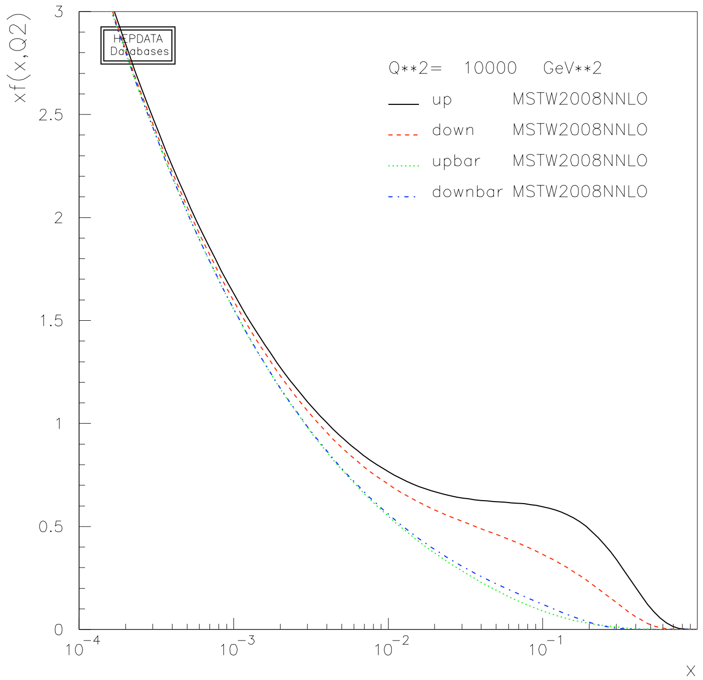
$$
\begin{aligned}
xu_v(x,Q_0^2) &= A_u\, x^{\eta_1}(1-x)^{\eta_2}(1+\epsilon_u\sqrt{x}+\gamma_u\, x),\\
xd_v(x,Q_0^2) &= A_d\, x^{\eta_3}(1-x)^{\eta_4}(1+\epsilon_d\sqrt{x}+\gamma_d\, x),\\
xS(x,Q_0^2) &= A_S\, x^{\delta_S}(1-x)^{\eta_S}(1+\epsilon_S\sqrt{x}+\gamma_S\, x),\\
x\Delta(x,Q_0^2) &= A_\Delta\, x^{\eta_\Delta}(1-x)^{\eta_S+2}(1+\gamma_\Delta\, x+\delta_\Delta\, x^2),\\
xg(x,Q_0^2) &= A_g\, x^{\delta_g}(1-x)^{\eta_g}(1+\epsilon_g\sqrt{x}+\gamma_g\, x)+A_{g'}\, x^{\delta_{g'}}(1-x)^{\eta_{g'}},\\
x(s+\bar{s})(x,Q_0^2) &= A_+\, x^{\delta_S}\,(1-x)^{\eta_+}(1+\epsilon_S\sqrt{x}+\gamma_S\, x),\\
x(s-\bar{s})(x,Q_0^2) &= A_-\, x^{\delta_-}(1-x)^{\eta_-}(1-x/x_0),
\end{aligned}
$$

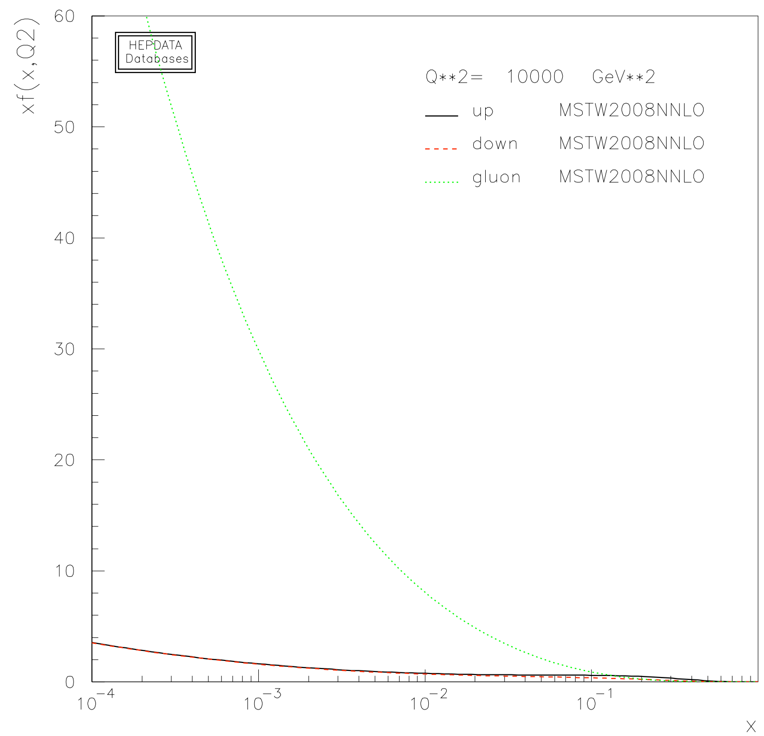
Process	Subprocess	Partons	x range
$\ell^\pm\,\{p,n\}\to\ell^\pm\,X$	$\gamma^* q\to q$	$q,\bar{q},g$	$x\gtrsim 0.01$
$\ell^\pm\,n/p\to\ell^\pm\,X$	$\gamma^*\,d/u\to d/u$	d/u	$x\gtrsim 0.01$
$pp\to\mu^+\mu^-\,X$	$u\bar{u},d\bar{d}\to\gamma^*$	$\bar{q}$	$0.015\lesssim x\lesssim 0.35$
$pn/pp\to\mu^+\mu^-\,X$	$(u\bar{d})/(u\bar{u})\to\gamma^*$	$\bar{d}/\bar{u}$	$0.015\lesssim x\lesssim 0.35$
$\nu(\bar{\nu})\,N\to\mu^-(\mu^+)\,X$	$W^*q\to q'$	$q,\bar{q}$	$0.01\lesssim x\lesssim 0.5$
$\nu\,N\to\mu^-\mu^+\,X$	$W^*s\to c$	s	$0.01\lesssim x\lesssim 0.2$
$\bar{\nu}\,N\to\mu^+\mu^-\,X$	$W^*\bar{s}\to\bar{c}$	$\bar{s}$	$0.01\lesssim x\lesssim 0.2$
$e^\pm\,p\to e^\pm\,X$	$\gamma^* q\to q$	$g,q,\bar{q}$	$0.0001\lesssim x\lesssim 0.1$
$e^+\,p\to\bar{\nu}\,X$	$W^+\,\{d,s\}\to\{u,c\}$	d,s	$x\gtrsim 0.01$
$e^\pm p\to e^\pm\,c\bar{c}\,X$	$\gamma^* c\to c,\ \gamma^* g\to c\bar{c}$	$c,\ g$	$0.0001\lesssim x\lesssim 0.01$
$e^\pm p\to \mathrm{jet}+X$	$\gamma^* g\to q\bar{q}$	g	$0.01\lesssim x\lesssim 0.1$
$p\bar{p}\to\mathrm{jet}+X$	$gg,qg,qq\to 2j$	g,q	$0.01\lesssim x\lesssim 0.5$
$p\bar{p}\to(W^\pm\to\ell^\pm\nu)\,X$	$ud\to W,\bar{u}\bar{d}\to W$	$u,d,\bar{u},\bar{d}$	$x\gtrsim 0.05$
$p\bar{p}\to(Z\to\ell^+\ell^-)\,X$	$uu,dd\to Z$	d	$x\gtrsim 0.05$

Parameter	LO	NLO	NNLO
$\alpha_S(Q_0^2)$	0.68183	0.49128	0.45077
$\alpha_S(M_Z^2)$	0.13939	0.12018	0.11707
A_u	1.4335	0.25871	0.22250
η_1	$0.45232^{+0.022}_{-0.018}$	$0.29065^{+0.019}_{-0.013}$	$0.27871^{+0.018}_{-0.014}$
η_2	$3.0409^{+0.079}_{-0.067}$	$3.2432^{+0.062}_{-0.039}$	$3.3627^{+0.061}_{-0.044}$
ϵ_u	$-2.3737^{+0.54}_{-0.48}$	$4.0603^{+1.6}_{-2.3}$	$4.4343^{+2.4}_{-2.7}$
γ_u	8.9924	30.687	38.599
A_d	5.0903	12.288	17.938
η_3	$0.71978^{+0.057}_{-0.082}$	$0.96809^{+0.11}_{-0.11}$	$1.0839^{+0.12}_{-0.11}$
$\eta_4-\eta_2$	$2.0835^{+0.32}_{-0.45}$	$2.7003^{+0.50}_{-0.52}$	$2.7865^{+0.50}_{-0.44}$
ϵ_d	$-4.3654^{+0.28}_{-0.22}$	$-3.8911^{+0.31}_{-0.29}$	$-3.6387^{+0.27}_{-0.28}$
γ_d	7.4730	6.0542	5.2577
A_S	$0.59964^{+0.036}_{-0.030}$	$0.31620^{+0.030}_{-0.021}$	$0.64942^{+0.047}_{-0.041}$
δ_S	-0.16276	-0.21515	-0.11912
η_S	$8.8801^{+0.33}_{-0.33}$	$9.2726^{+0.23}_{-0.33}$	$9.4189^{+0.25}_{-0.33}$
ϵ_S	$-2.9012^{+0.33}_{-0.37}$	$-2.6022^{+0.71}_{-0.96}$	$-2.6287^{+0.49}_{-0.51}$
γ_S	16.865	30.785	18.065
$\int_0^1 \mathrm{d}x\ \Delta(x,Q_0^2)$	$0.091031^{+0.012}_{-0.009}$	$0.087673^{+0.013}_{-0.011}$	$0.078167^{+0.012}_{-0.0091}$
A_Δ	8.9413	8.1084	16.244
η_Δ	$1.8760^{+0.24}_{-0.30}$	$1.8691^{+0.23}_{-0.32}$	$2.0741^{+0.18}_{-0.35}$
γ_Δ	$8.4703^{+2.0}_{-0.3}$	$13.609^{+1.1}_{-0.6}$	$6.7640^{+0.77}_{-0.41}$
δ_Δ	-36.507	-59.289	-36.090
A_g	0.0012216	1.0805	3.4055
δ_g	$-0.83657^{+0.15}_{-0.14}$	$-0.42848^{+0.066}_{-0.057}$	$-0.12178^{+0.23}_{-0.16}$
η_g	$2.3882^{+0.51}_{-0.50}$	$3.0225^{+0.43}_{-0.36}$	$2.9278^{+0.68}_{-0.41}$
ϵ_g	-38.997^{+36}_{-35}	-2.2922	-2.3210
γ_g	1445.5^{+880}_{-750}	3.4894	1.9233
$A_{g'}$	—	-1.1168	-1.6189
$\delta_{g'}$	—	$-0.42776^{+0.053}_{-0.047}$	$-0.23999^{+0.14}_{-0.10}$
$\eta_{g'}$	—	$32.869^{+6.5}_{-5.9}$	$24.792^{+6.5}_{-5.2}$
A_+	$0.10302^{+0.029}_{-0.017}$	$0.047915^{+0.0095}_{-0.0076}$	$0.10455^{+0.019}_{-0.016}$
η_+	$13.242^{+2.9}_{-1.4}$	$9.7466^{+1.0}_{-0.8}$	$9.8689^{+1.0}_{-0.6}$
A_-	$-0.011523^{+0.009}_{-0.018}$	$-0.011629^{+0.009}_{-0.023}$	$-0.0093692^{+0.006}_{-0.024}$
η_-	10.285^{+16}_{-6}	11.261^{+22}_{-6}	9.5783^{+26}_{-5}
x_0	0.017414	0.016050	0.018556
r_1	-0.39484	-0.57631	-0.80834
r_2	-1.0719	0.81878	1.2669
r_3	-0.28973	-0.083208	0.15098

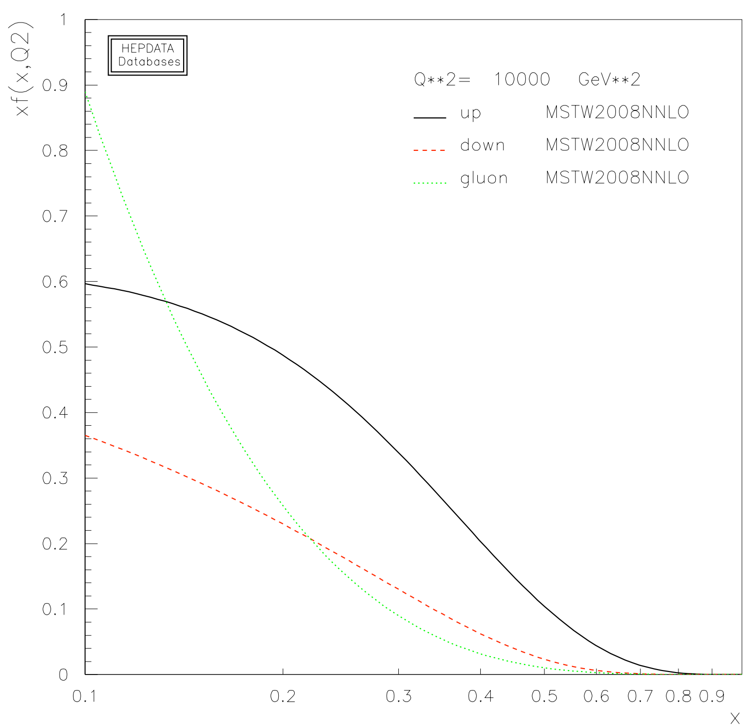
MSTW, 0901.0002

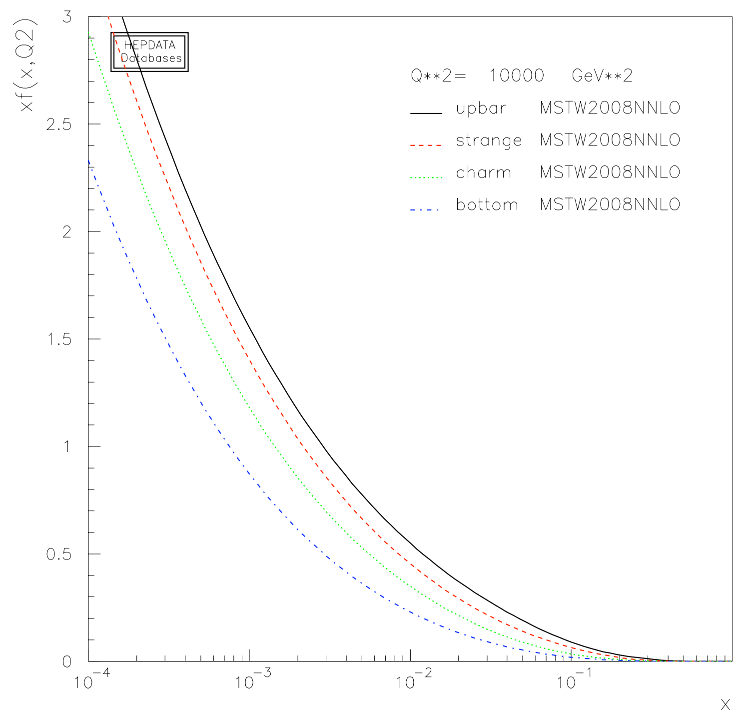
Lessons: PDFs are obtained by fitting to data
The have error bars; the x-range is limited
“Test SM”=test overall consistency





http://durpdg.dur.ac.uk/cgi-bin/hepdata/pdfplot2

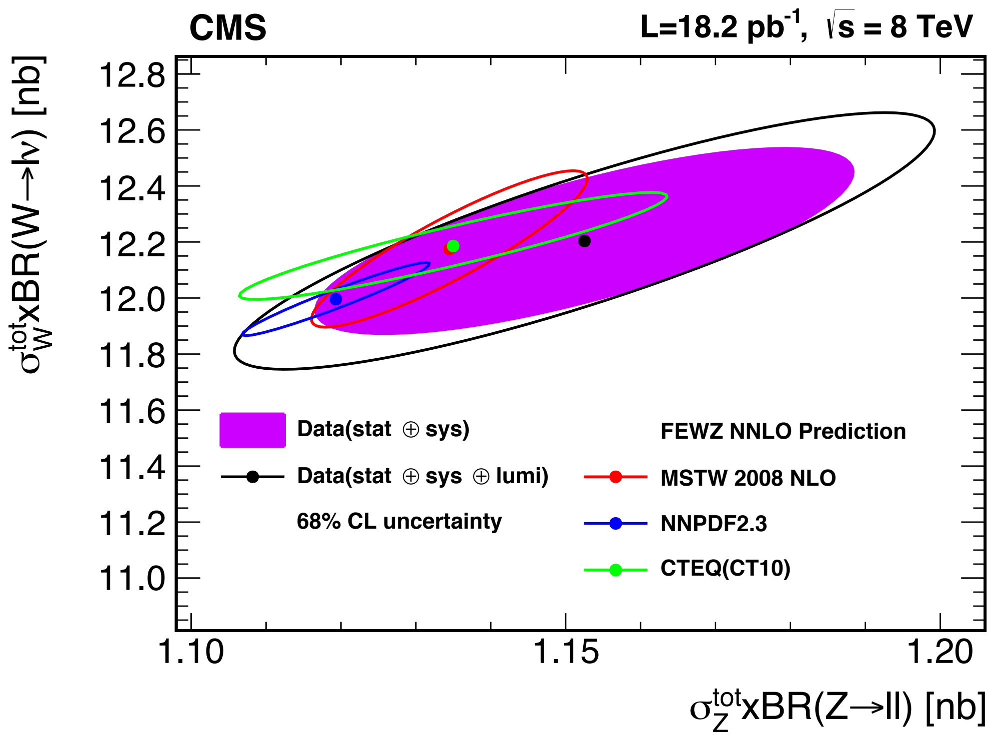




Lessons: Below x~0.01, u=ubar=d=dbar

Below x~0.1,g >> quarks

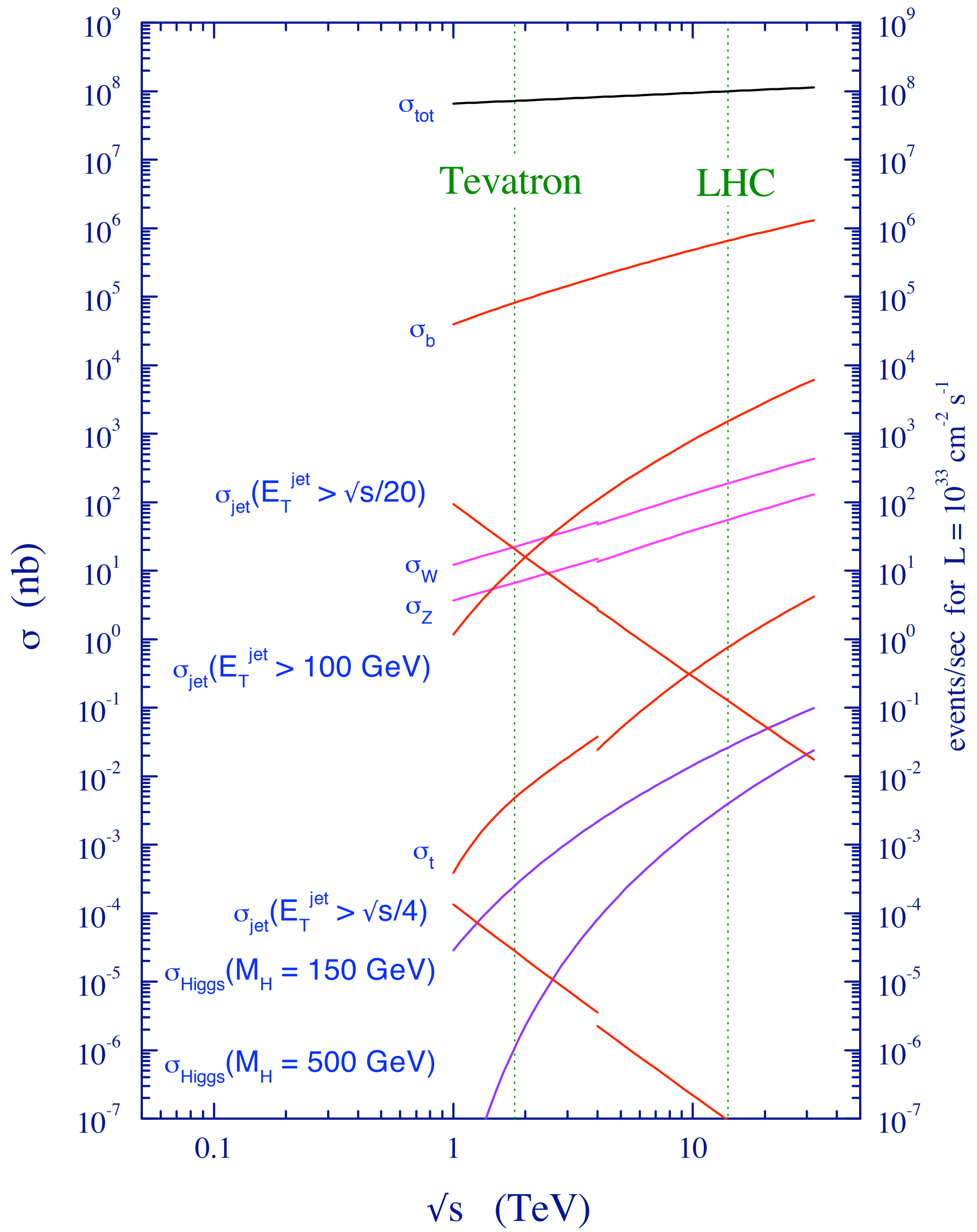
$$pp \to Z + X, \quad Z \to \ell^+\ell^-$$

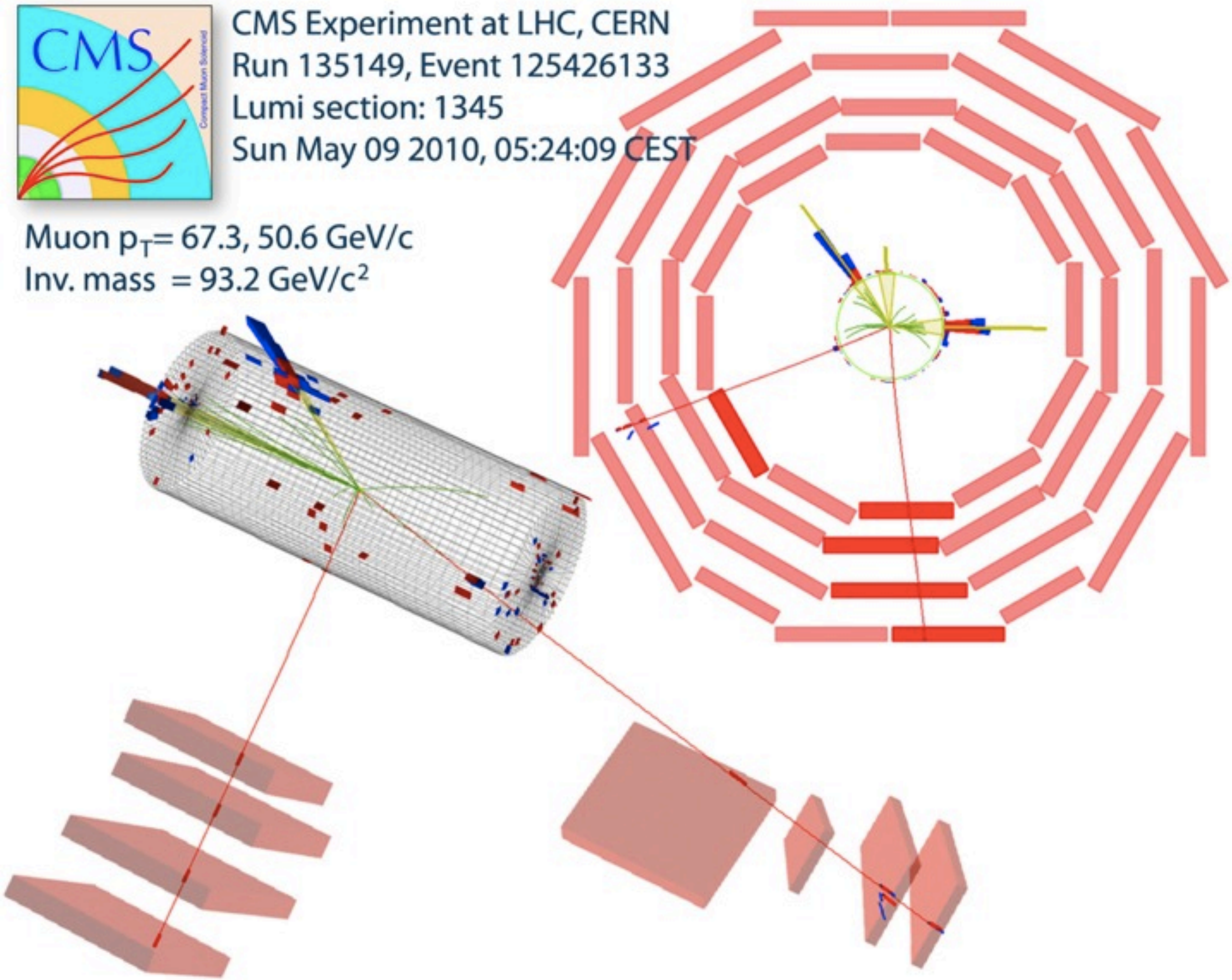


$$\sigma(\mathrm{pp} \to \mathrm{Z}X) \times \mathcal{B}(\mathrm{Z} \to \ell^+\ell^-) = 1.15 \pm 0.01\,(\mathrm{stat.}) \pm 0.02\,(\mathrm{syst.}) \pm 0.03\,(\mathrm{lum.})\,\mathrm{nb}.$$

CMS, 1402.0923

proton - (anti)proton cross sections




CMS Experiment at LHC, CERN
Run 135149, Event 125426133
Lumi section: 1345
Sun May 09 2010, 05:24:09 CEST
Muon p_T= 67.3, 50.6 GeV/c
Inv. mass = 93.2 GeV/c^2

$$pp \to Z + X, \quad Z \to \ell^+\ell^-$$

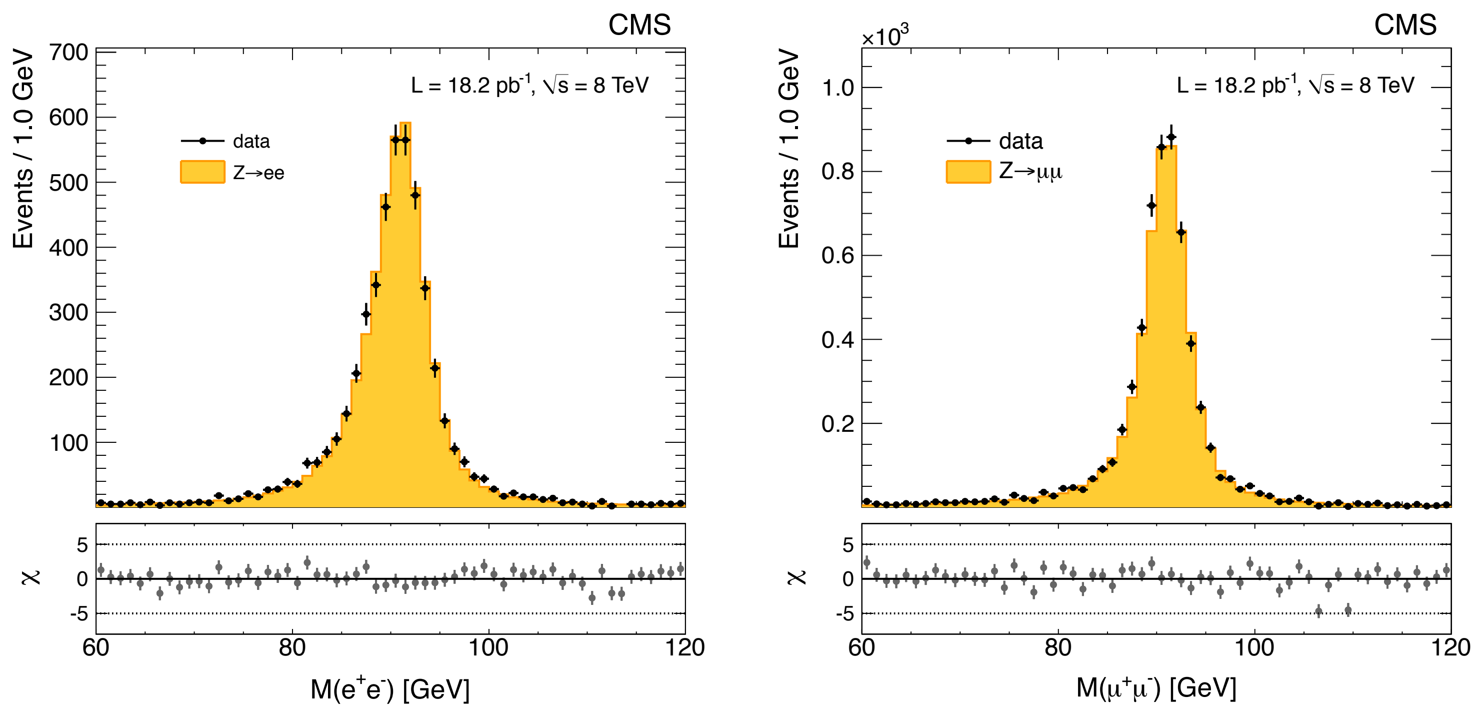
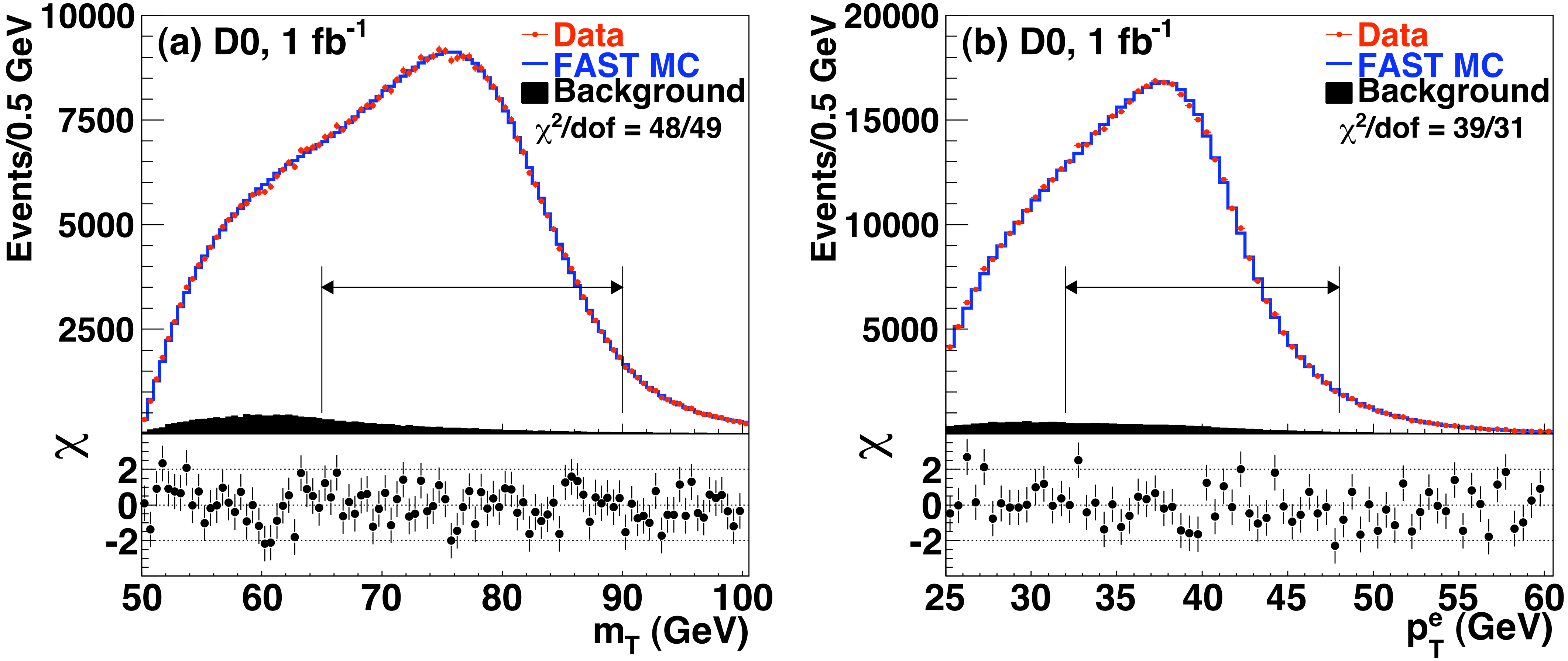


Figure 2: The dilepton mass distributions for Z boson candidate events in the electron (left) and muon (right) final states. The variable χ shown in the lower plot is defined as $(N_{\text{obs}} - N_{\text{exp}})/\sqrt{N_{\text{obs}}}$, where N_{obs} is the number of observed events and N_{exp} is the total of the signal and background yields.

CMS, 1402.0923



W mass measurement at the Tevatron

D0, PRL 103, 141801 (2009), arXiv:0908.0766

$$M_W = 80.385 \pm 0.015 \text{ GeV}$$