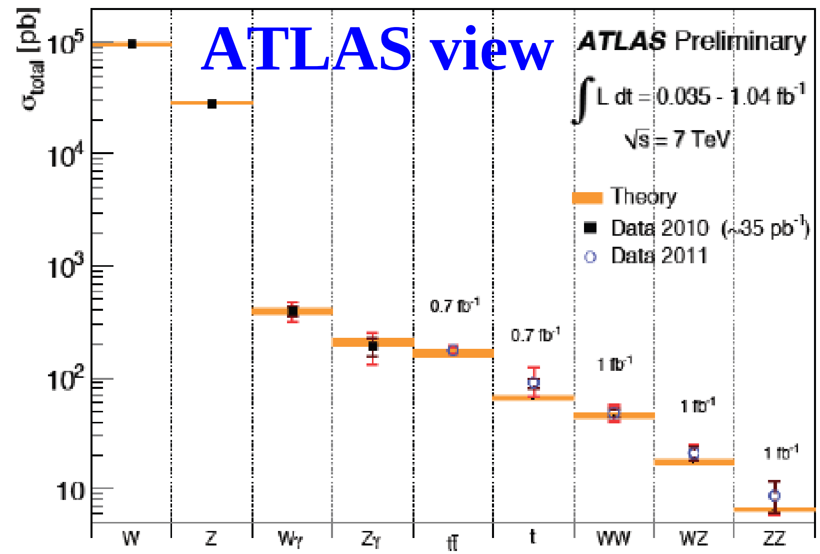
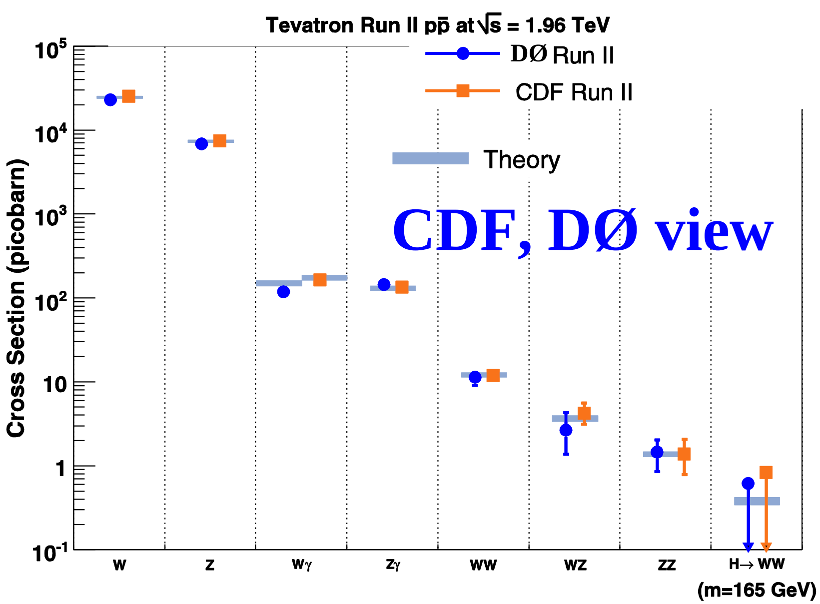
W/Z and Diboson Properties

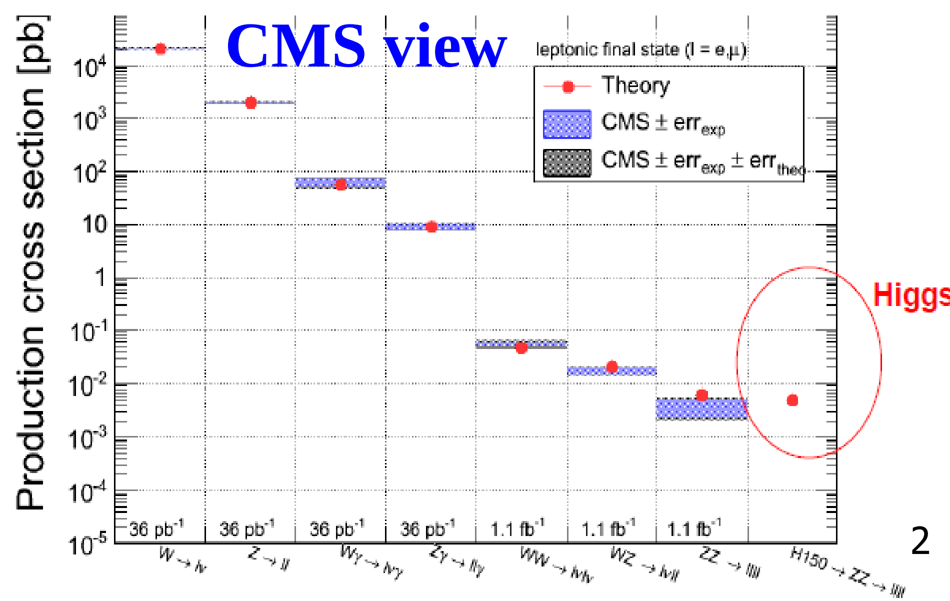
Alex Melnitchouk
University of Mississippi
on behalf of ATLAS, CDF, CMS, DØ, LHCb collaborations

Introduction

- Previous speaker covered production of W,Z and dibosons
- Lets take another look at the overall picture as a way of introducing discussion of properties

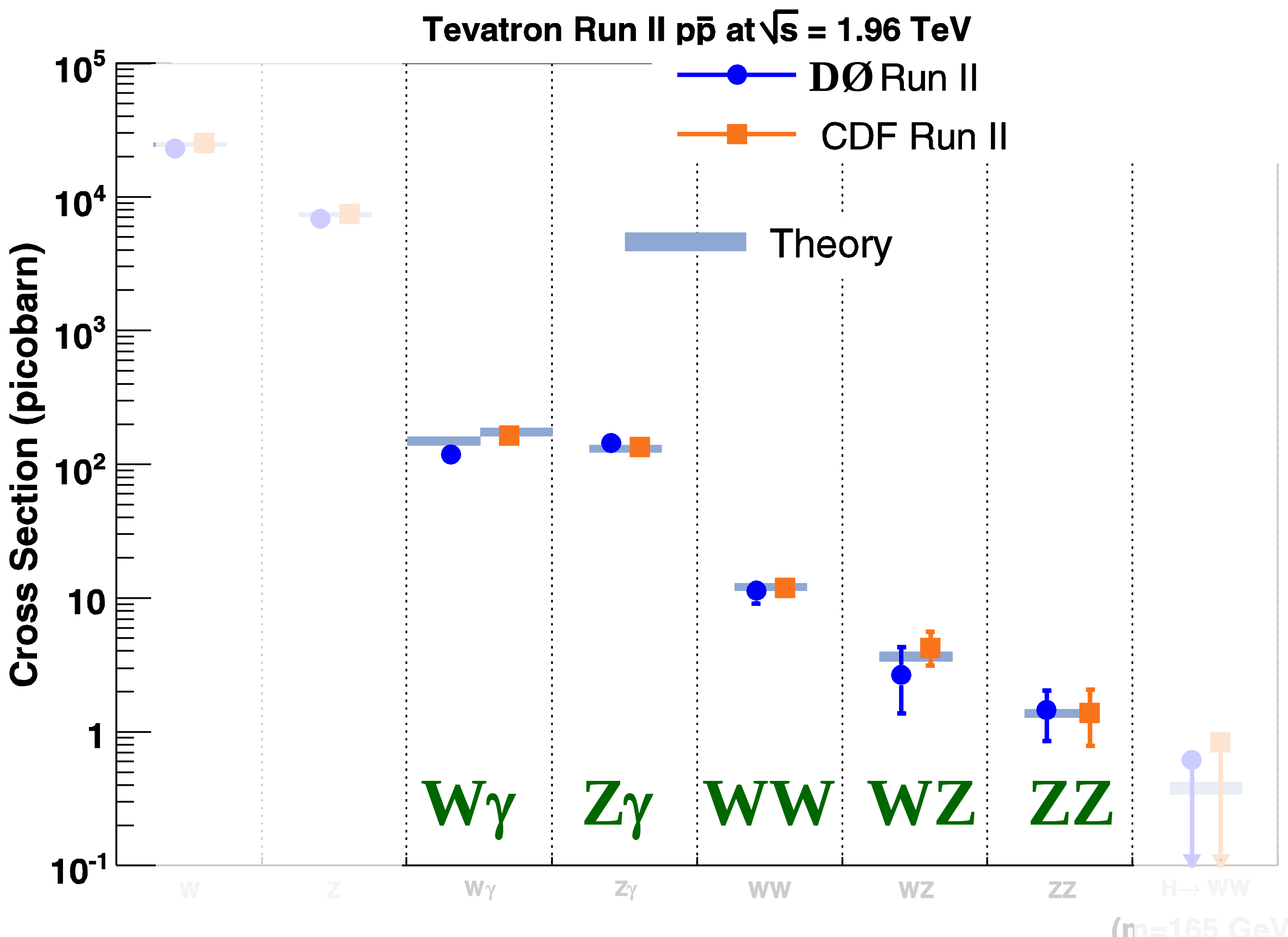




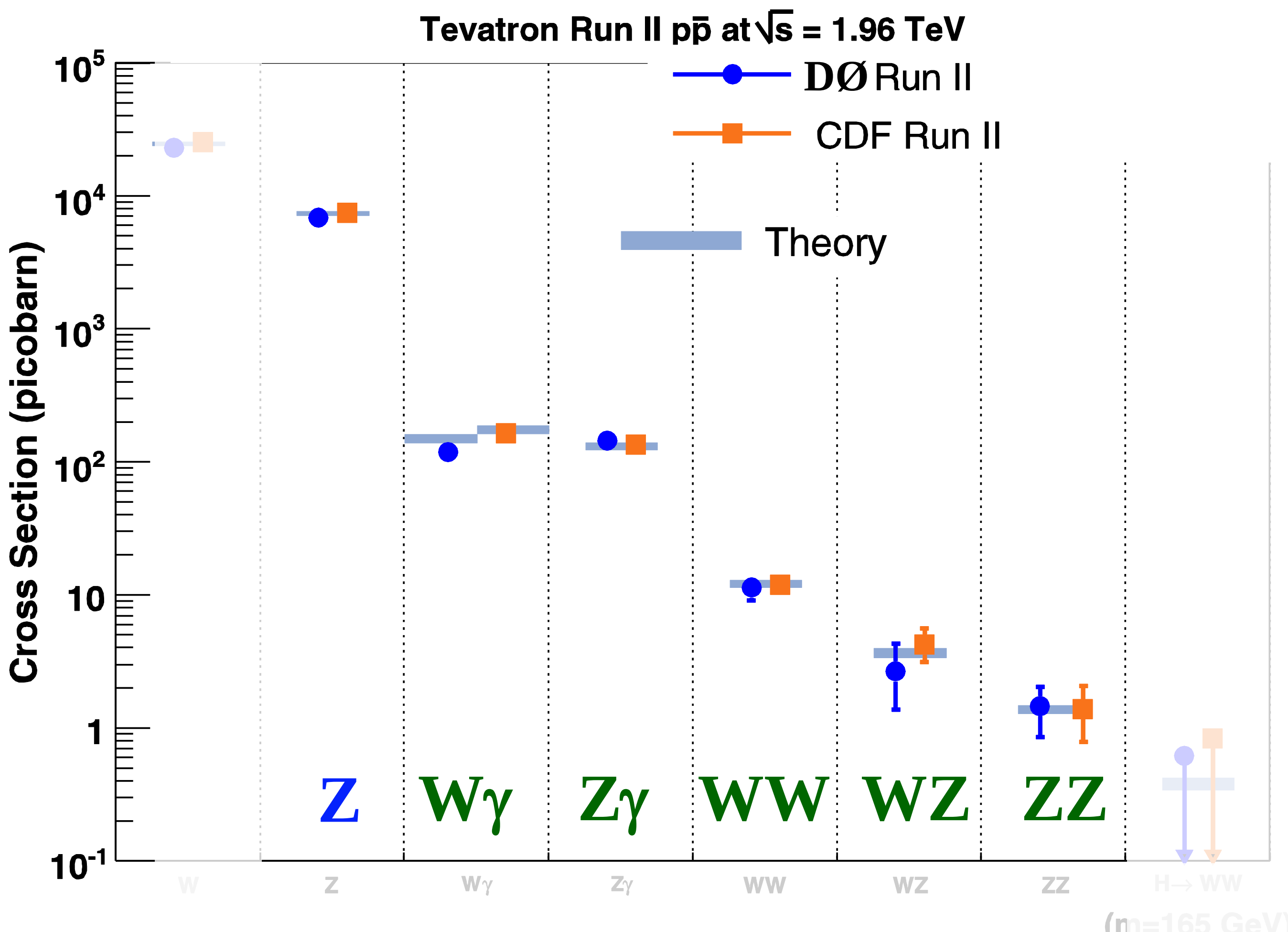


Introduction

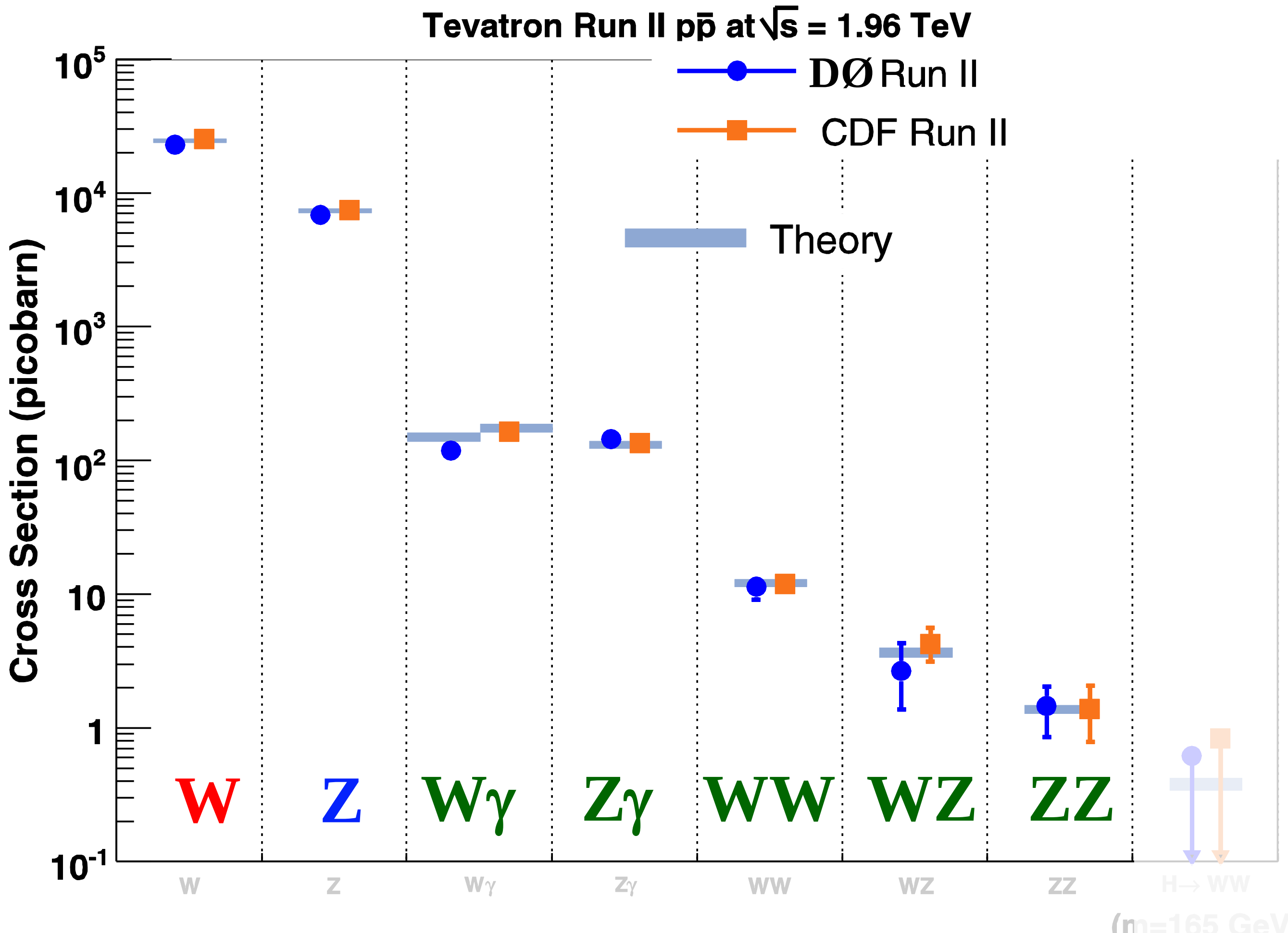
Introduction



Introduction



Introduction



W and Z Boson Properties

- Couplings between electroweak gauge bosons

$W\gamma$ $Z\gamma$ WW WZ ZZ

W and Z Boson Properties

- Couplings between electroweak gauge bosons

Wγ   Zγ   WW   WZ   ZZ

- Couplings between Z boson and fermions
- Asymmetries induced by couplings
- Angular coefficients
- Weak mixing angle

Z

W and Z Boson Properties

- Couplings between electroweak gauge bosons

Wγ Zγ WW WZ ZZ

- Couplings between Z boson and fermions
- Asymmetries induced by couplings
- Angular coefficients
- Weak mixing angle

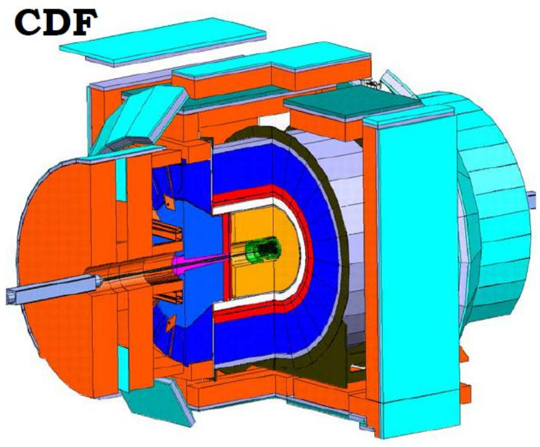
Z

- Charge asymmetries
- W polarization
- W mass
- W width

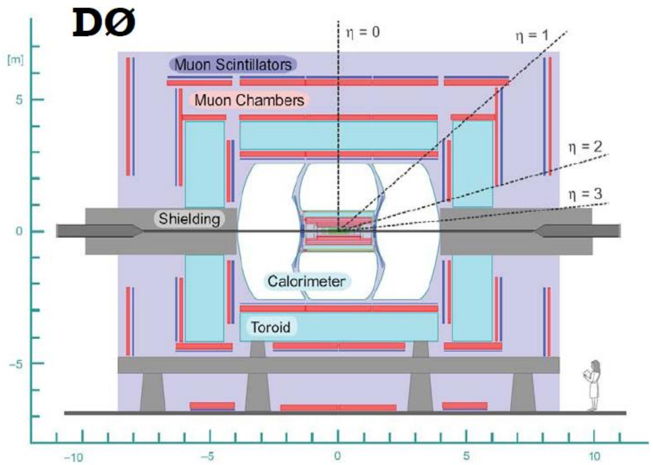
W

CDF and DØ Detectors

- CDF and DØ are multi-purpose detectors that include
  - tracking detectors in high magnetic field
  - electromagnetic and hadronic calorimeters
  - muon systems



- Comparative advantages and implications
  - CDF has larger tracking volume
    ⇒ better muon resolution
    ⇒ muons used for W mass measurement,
  - DØ muon system has wider rapidity coverage
    ⇒ muon charge asymmetry measured over a larger rapidity range
    ⇒ constraining PDFs at smaller x



Typical Selections and Backgrounds

- Typical event selections include
  - one or more high p_T isolated leptons*
  - large missing transverse energy in case of W

*electrons or muons

- Main backgrounds
  - electroweak processes other than the process of interest
    - ✓ e.g. $Z \to ee$ can be background to $W \to e\nu$
  - QCD processes in which a quark or a gluon jet is mis-identified for an isolated lepton
  - Combination of the two
    - ✓ e.g. Z+jets can be background to WZ

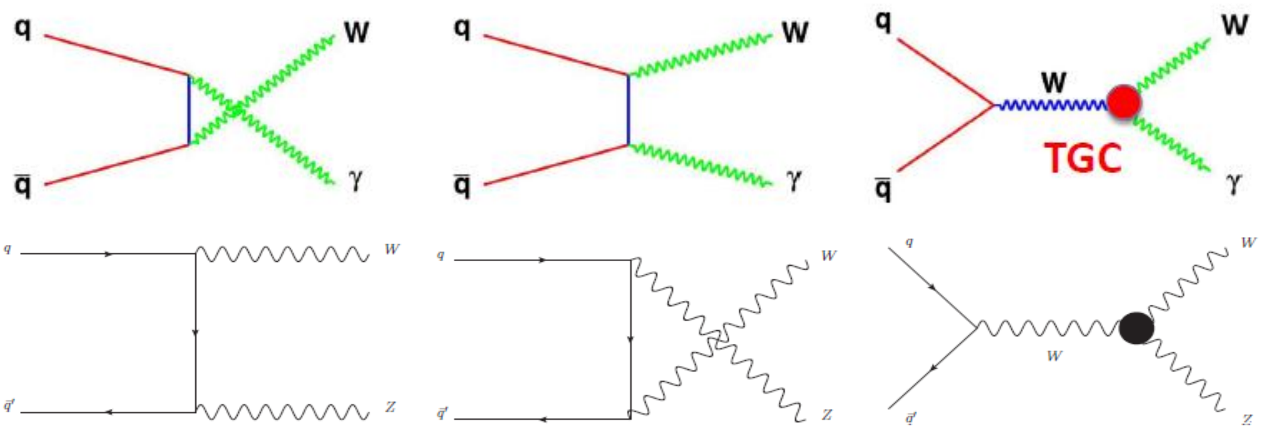
<u>Charged</u> Triple Gauge Couplings (TGCs)

$$\frac{\mathcal{L}_{WWV}}{g_{WWV}} = ig_1^V(W^\dagger_{\mu\nu}W^\mu V^\nu - W^\dagger_\mu V_\nu W^{\mu\nu}) + i\kappa_V W^\dagger_\mu W_\nu V^{\mu\nu} + \frac{i\lambda_V}{M_W^2}W^\dagger_{\lambda\mu}W^\mu{}_\nu V^{\nu\lambda}$$

V:Z/γ

general effective Lagrangian
+ C and P conservation
$\Rightarrow$ 5 parameters

$g_1^Z,\ \kappa_\gamma,\ \kappa_Z,\ \lambda_\gamma,\ \lambda_Z$



(a) *t*-channel (b) *u*-channel (c) *s*-channel

$$Q_W = -\frac{e}{M_W^2}(1+\Delta\kappa_\gamma - \lambda_\gamma)$$

$$\mu_W = \frac{e}{2M_W}(2+\Delta\kappa_\gamma + \lambda_\gamma)$$

to preserve unitarity:

$$\alpha(\hat{s}) = \frac{\alpha_0}{(1+\hat{s}/\Lambda^2)^2}$$

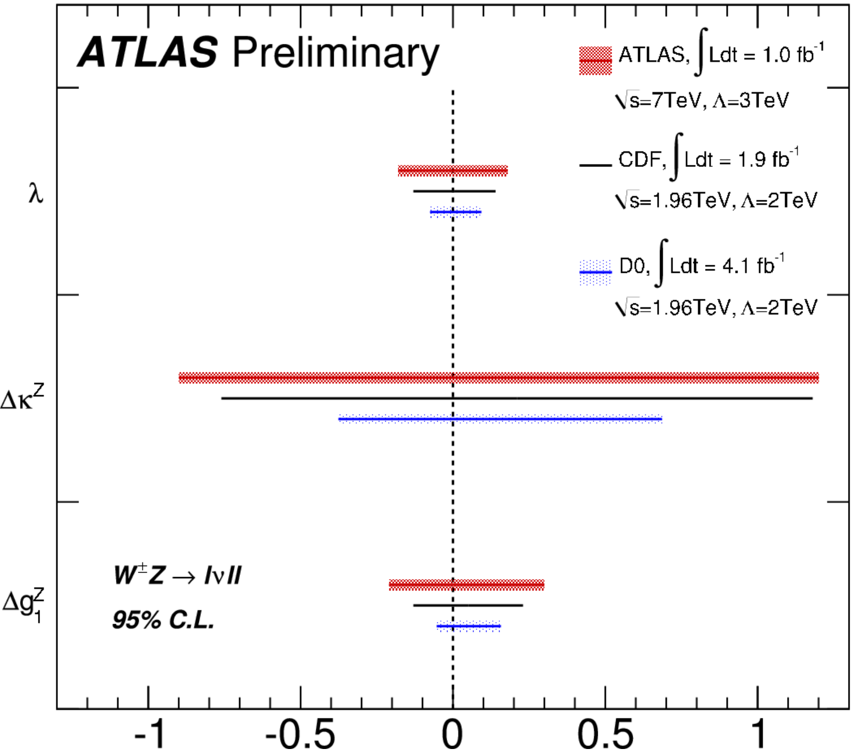
SM constraints : $\kappa_\gamma = g_1^Z = \kappa_Z = 1$ and $\lambda_\gamma = \lambda_Z = 0$

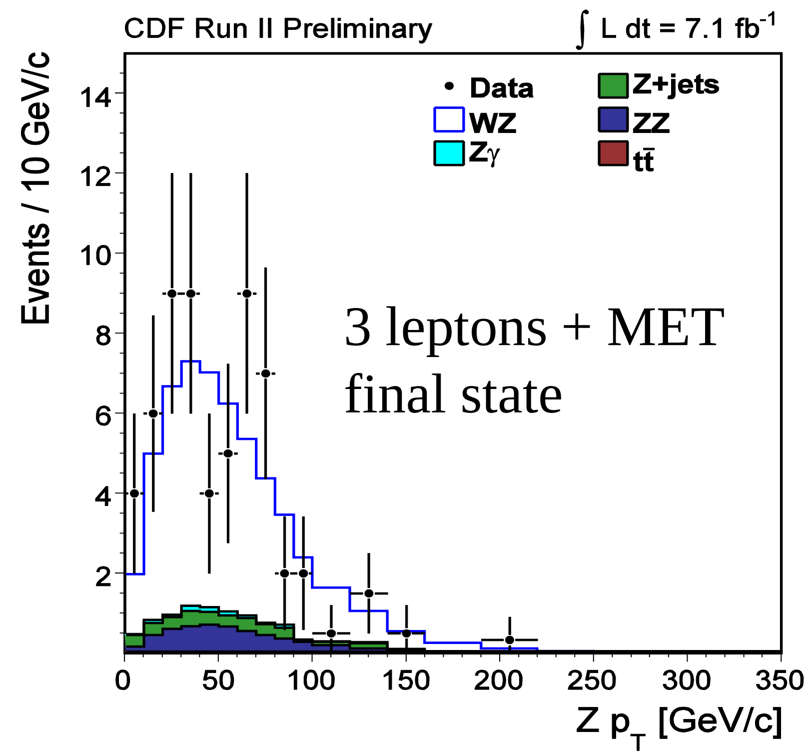
BSM searches use two reduced parameter sets :

$SU(2)\times U(1): \Delta\kappa_z = \Delta g_1^Z - \Delta\kappa_\gamma \tan^2\theta_W$ and $\lambda_\gamma = \lambda_Z$ → Related to tree-level unitarity constraints: 3 parameters

$HISZ: \Delta\kappa_z = \Delta g_1^Z(\cos^2\theta_W - \sin^2\theta_W)$ → Equal coupling between SU(2)xU(1) and Higgs fields : 2 parameters

WZ





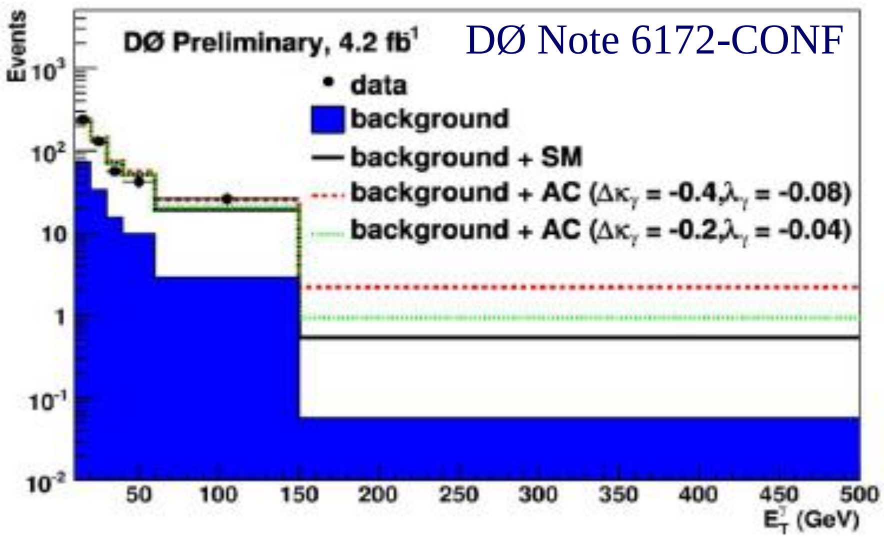
3 leptons + MET final state

most stringent limits

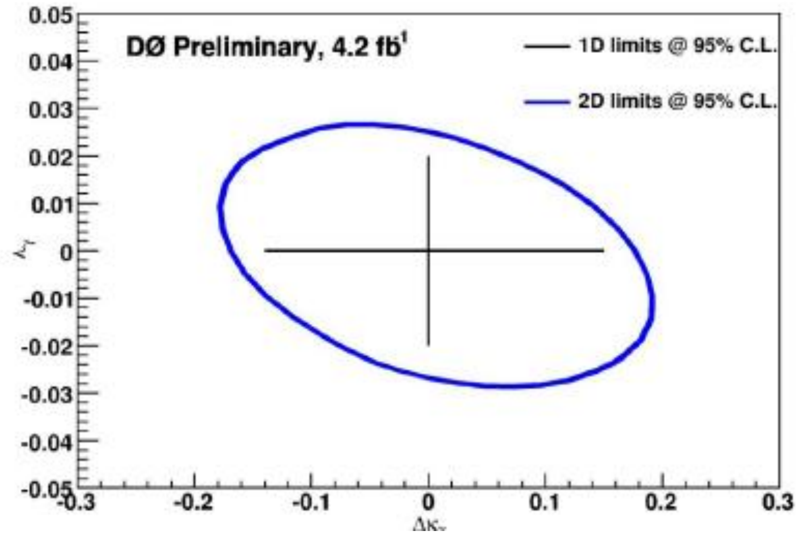
CDF Results at $7.1\mathrm{fb}^{-1}$

	λ^Z	Δg_1^Z	$\Delta\kappa^Z$
1.5TeV	-0.08 - 0.10	-0.09 - 0.22	-0.42 - 0.99
2.0TeV	-0.09 - 0.11	-0.08 - 0.20	-0.39 - 0.90

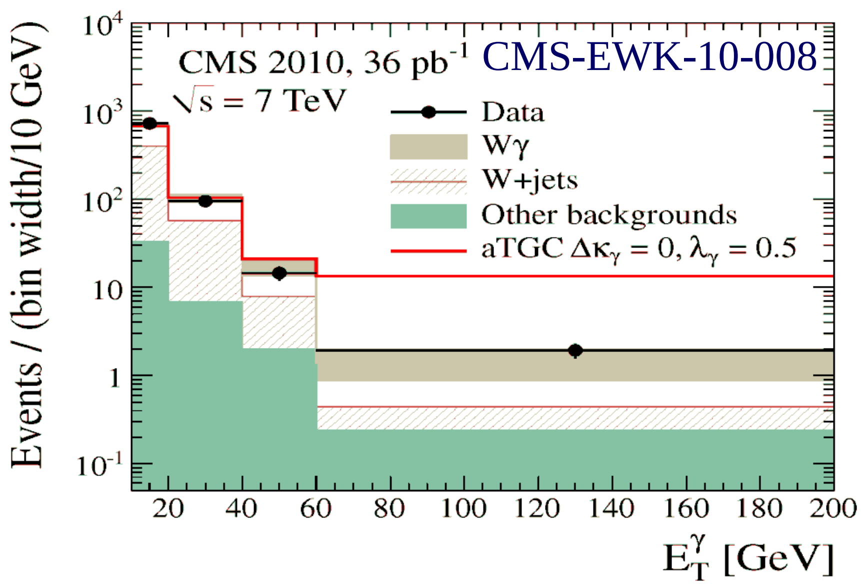
Wγ



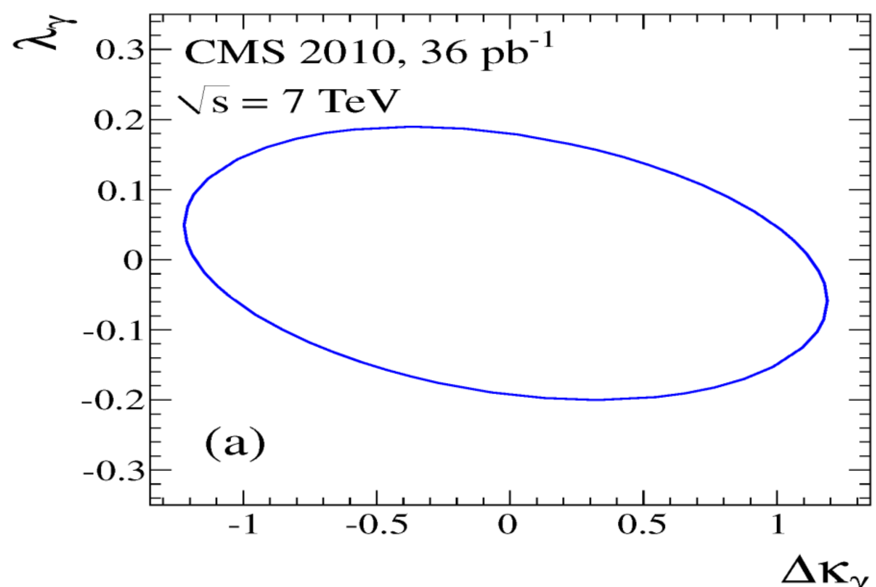
DØ Preliminary, 4.2 fb^{-1}
DØ Note 6172-CONF
data
background
background + SM
background + AC ($\Delta\kappa_\gamma$ = -0.4,λ_γ = -0.08)
background + AC ($\Delta\kappa_\gamma$ = -0.2,λ_γ = -0.04)
Events
E_T^γ (GeV)



DØ Preliminary, 4.2 fb^{-1}
1D limits @ 95% C.L.
2D limits @ 95% C.L.



CMS 2010, 36 pb^{-1}
CMS-EWK-10-008
$\sqrt{s}$ = 7 TeV
Data
Wγ
W+jets
Other backgrounds
aTGC $\Delta\kappa_\gamma = 0$, $\lambda_\gamma = 0.5$
Events / (bin width/10 GeV)
E_T^γ [GeV]



CMS 2010, 36 pb^{-1}
$\sqrt{s}$ = 7 TeV
(a)
λ_γ
$\Delta\kappa_\gamma$

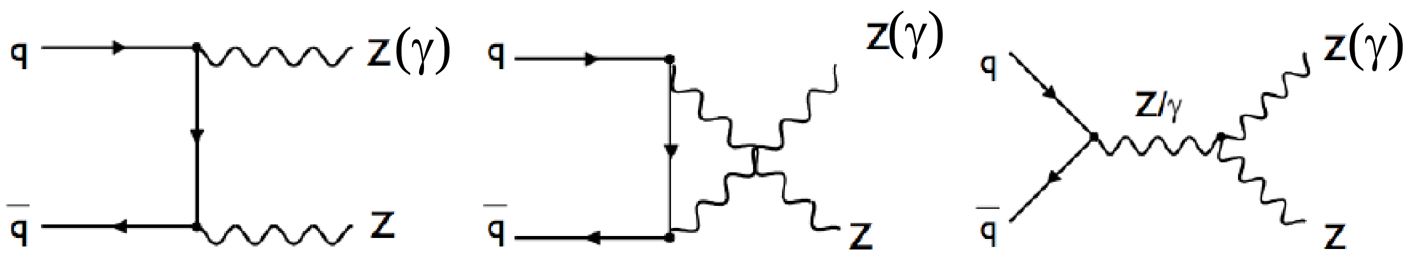
Neutral TGCs

$$\mathcal{L}_{Z\gamma V} = -ie\left[\left(h_1^V F^{\mu\nu} + h_3^V \widetilde{F}^{\mu\nu}\right) Z_\mu \frac{\left(\Box + m_V^2\right)}{m_Z^2} V_\nu \right.$$

$$\left. + \left(h_2^V F^{\mu\nu} + h_4^V \widetilde{F}^{\mu\nu}\right) Z^\alpha \frac{\left(\Box + m_V^2\right)}{m_Z^4} \partial_\alpha \partial_\mu V_\nu \right]$$

CP conserving $h_{3,4}^V$

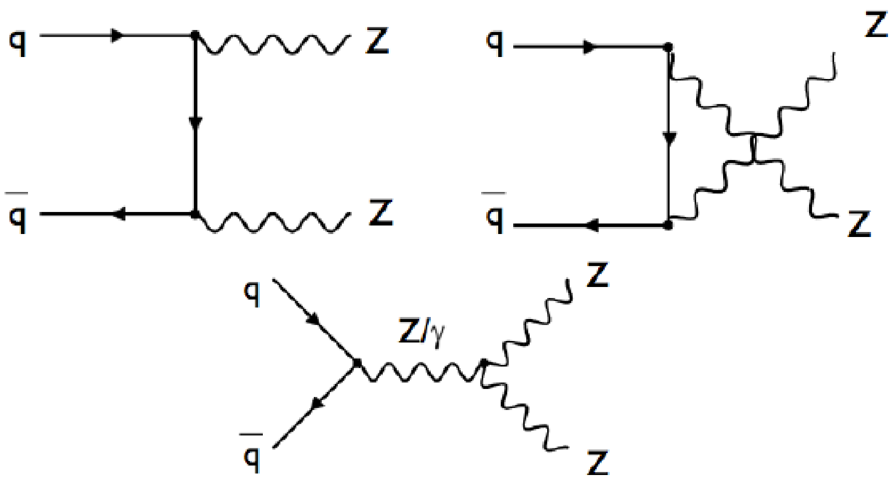
$V = Z$ or γ

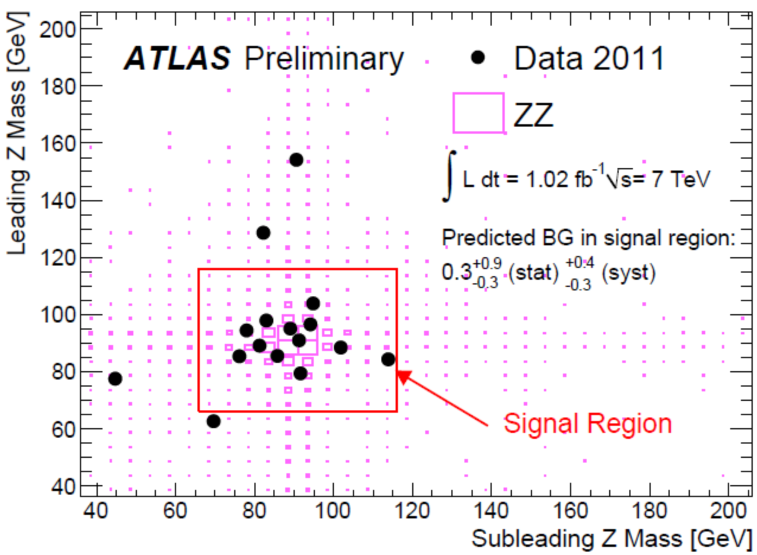


$$\mathcal{L}_{ZZV} = -\frac{e}{M_Z^2}\left[f_4^V(\partial_\mu V^{\mu\beta})Z_\alpha(\partial^\alpha Z_\beta) + f_5^V(\partial^\sigma V_{\sigma\mu})\tilde{Z}^{\mu\beta}Z_\beta\right]$$

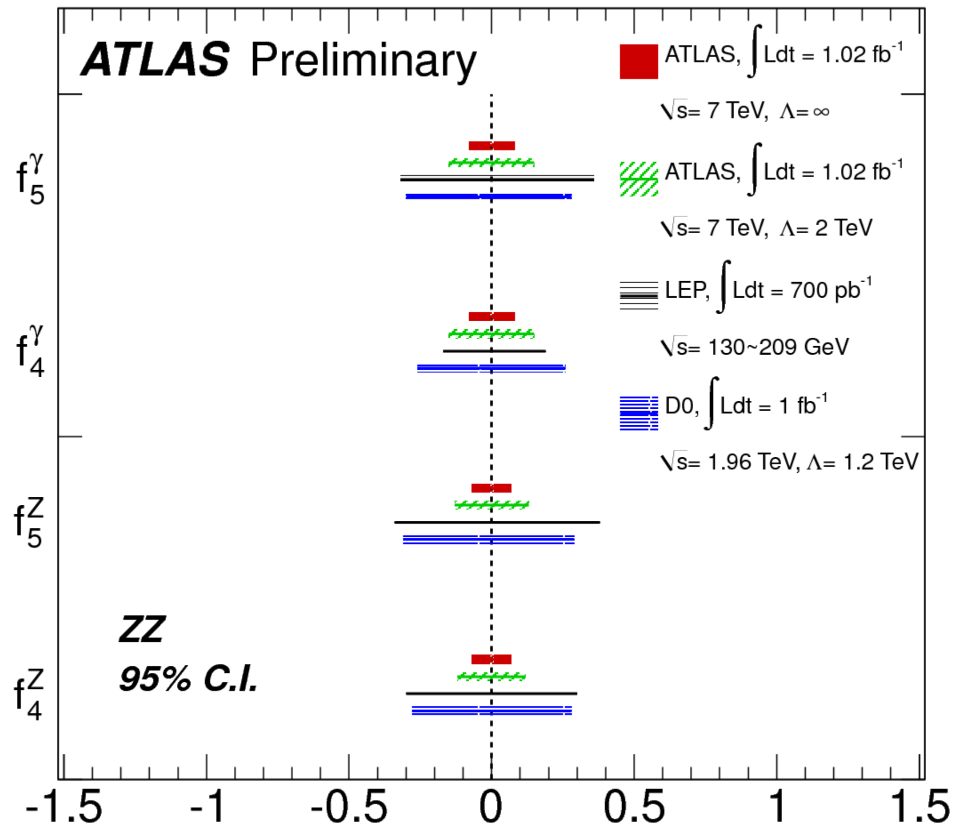
CP violating	f_4^V
CP conserving	f_5^V

ZZ





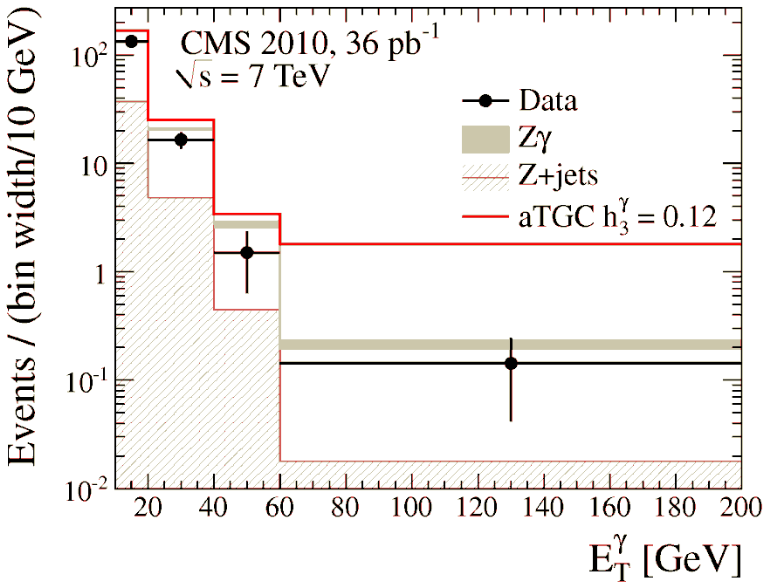
ATLAS-CONF-2011-107

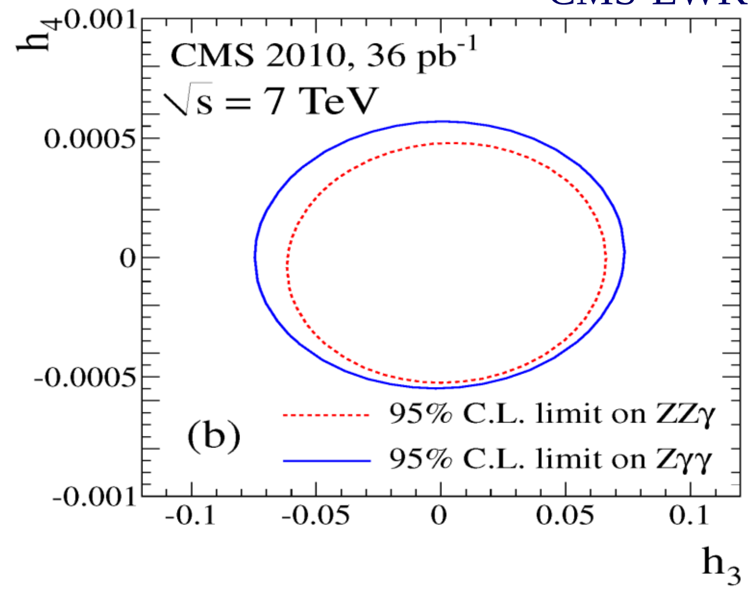


Lowest diboson cross-section; 12 candidate events

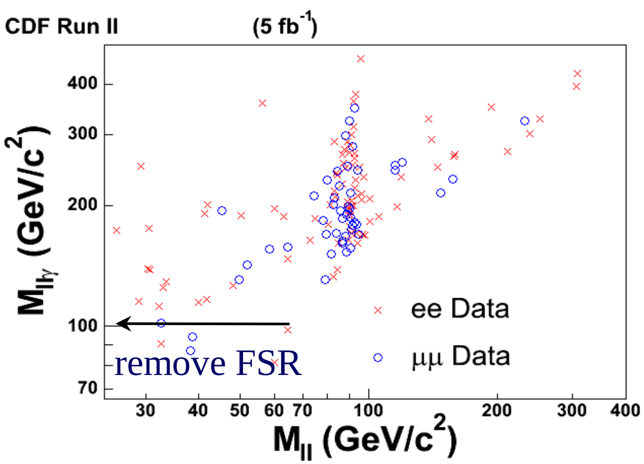
Zγ

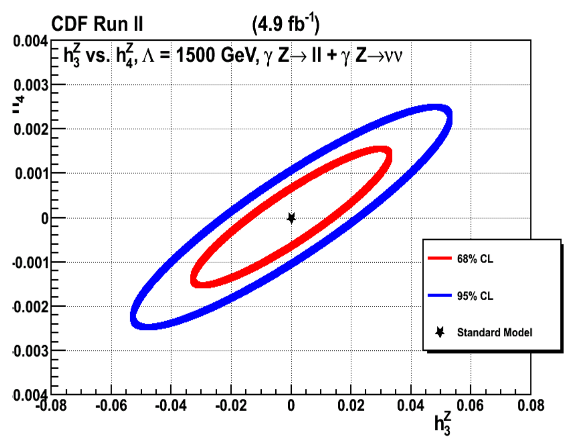
CMS-EWK-10-008

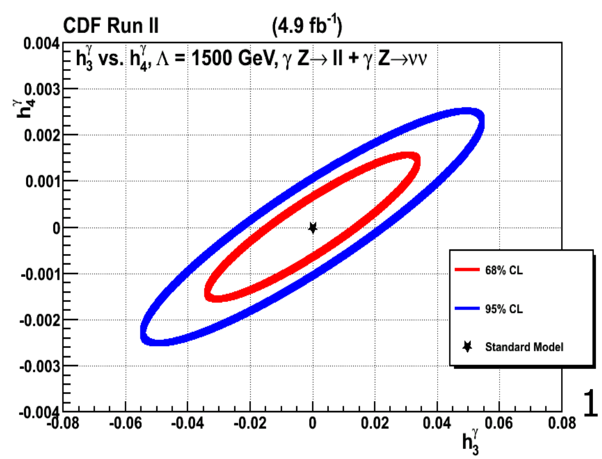




PRL 107, 051802 (2011)







W and Z Boson Properties

- Couplings between electroweak gauge bosons

Wγ Zγ WW WZ ZZ

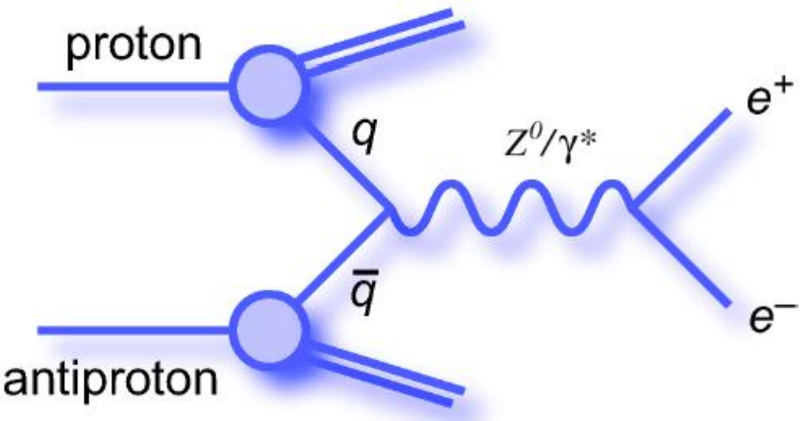
- Couplings between Z boson and fermions
- Asymmetries induced by couplings
- Angular coefficients
- Weak mixing angle

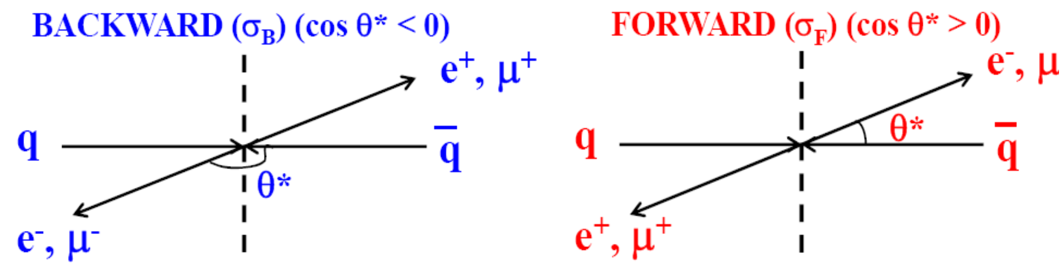
Z

- Charge asymmetries
- W polarization
- W mass
- W width

W

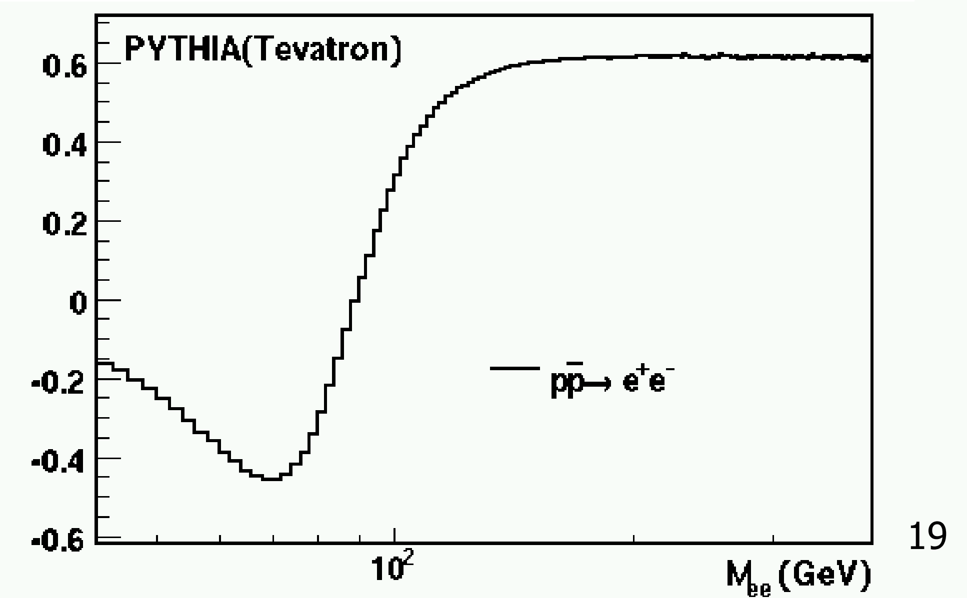
Forward-Backward Asymmetry





θ* defined in Collins-Soper frame (Z/γ* rest frame)

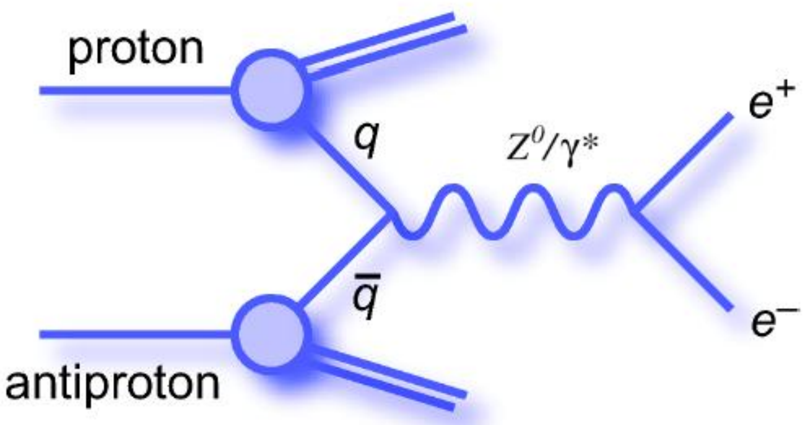
$$A_{FB} = (\sigma_F - \sigma_B) / (\sigma_F + \sigma_B) = (N_F - N_B) / (N_F + N_B)$$

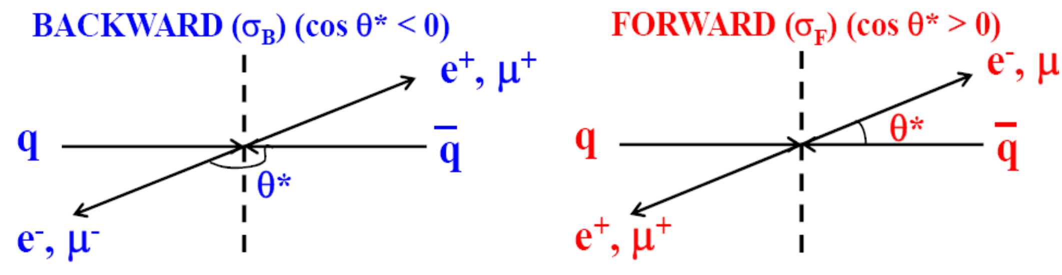


$$g_V^f = I_3^f - 2q_f \cdot \sin^2\theta_W$$
$$g_A^f = I_3^f\,,$$

Measure
effective weak mixing angle

Forward-Backward Asymmetry

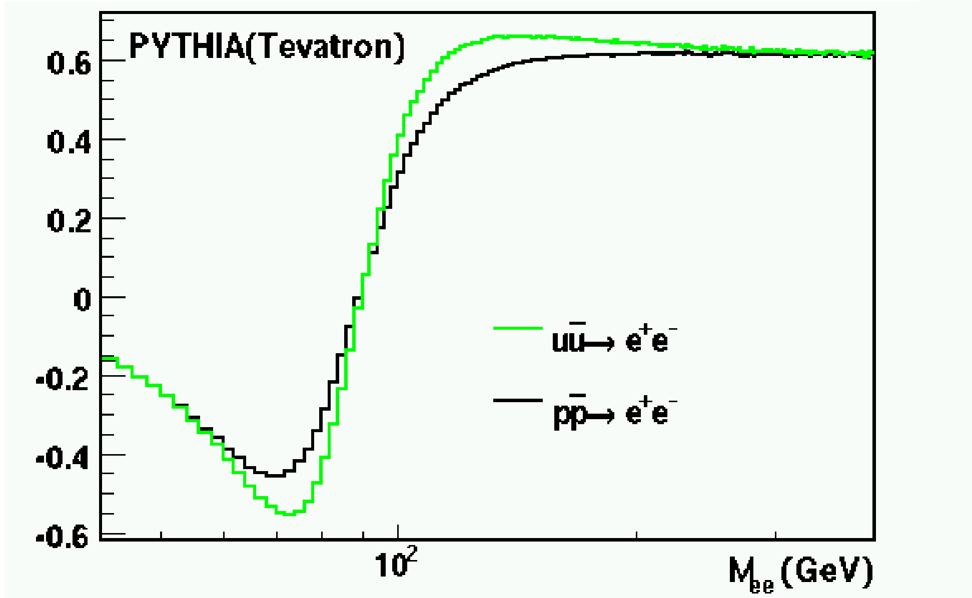




θ^* defined in Collins-Soper frame (Z/γ^* rest frame)

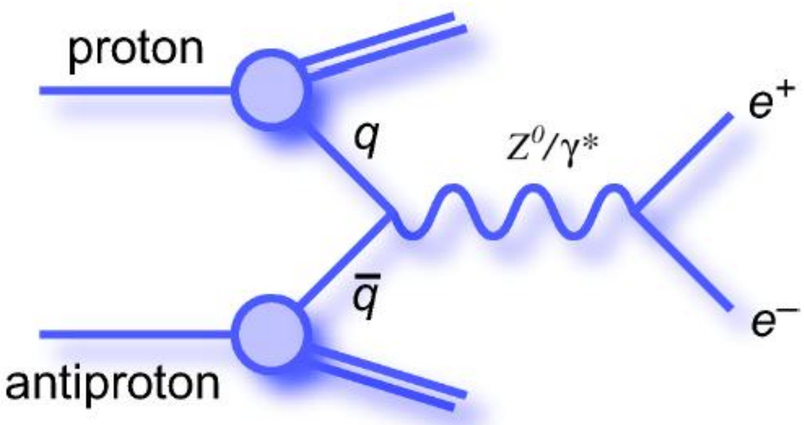
$$A_{FB} = (\sigma_F - \sigma_B) / (\sigma_F + \sigma_B) = (N_F - N_B) / (N_F + N_B)$$

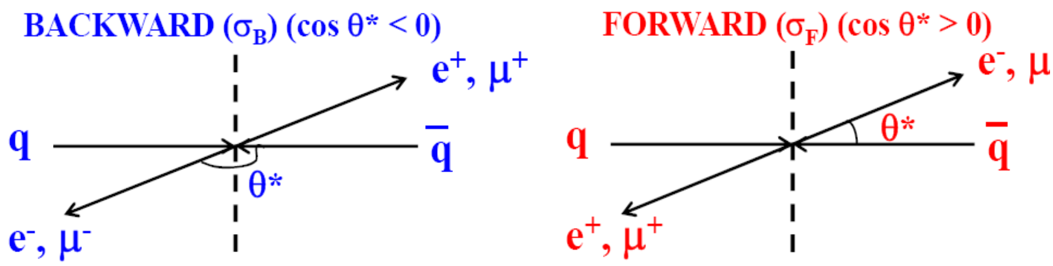
$$g_V^f = I_3^f - 2q_f \cdot \sin^2\theta_W$$
$$g_A^f = I_3^f \,,$$



Measure
effective weak mixing angle

Forward-Backward Asymmetry

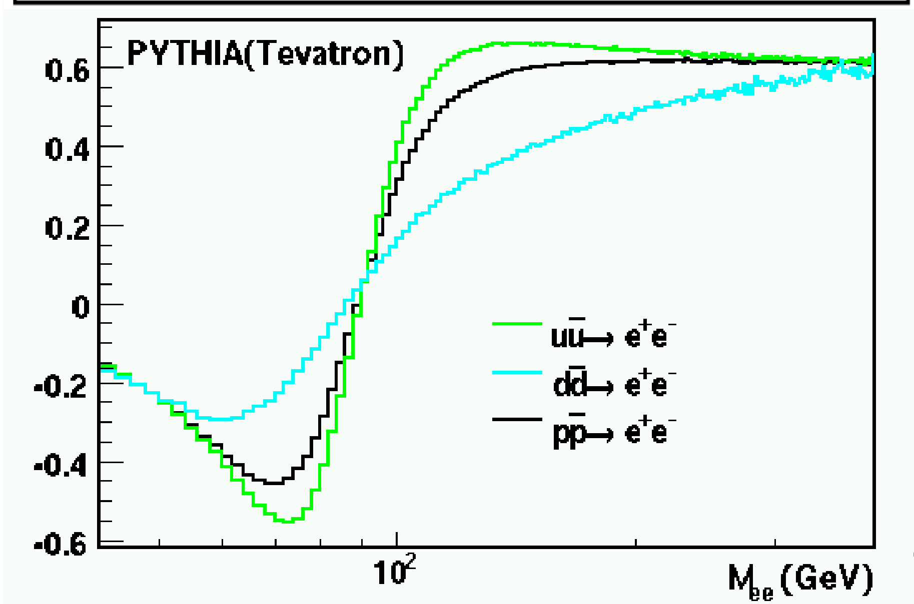




θ^* defined in Collins-Soper frame (Z/γ^* rest frame)

$$A_{FB} = (\sigma_F - \sigma_B) / (\sigma_F + \sigma_B) = (N_F - N_B) / (N_F + N_B)$$

$$g_V^f = I_3^f - 2q_f \cdot \sin^2\theta_W$$
$$g_A^f = I_3^f$$

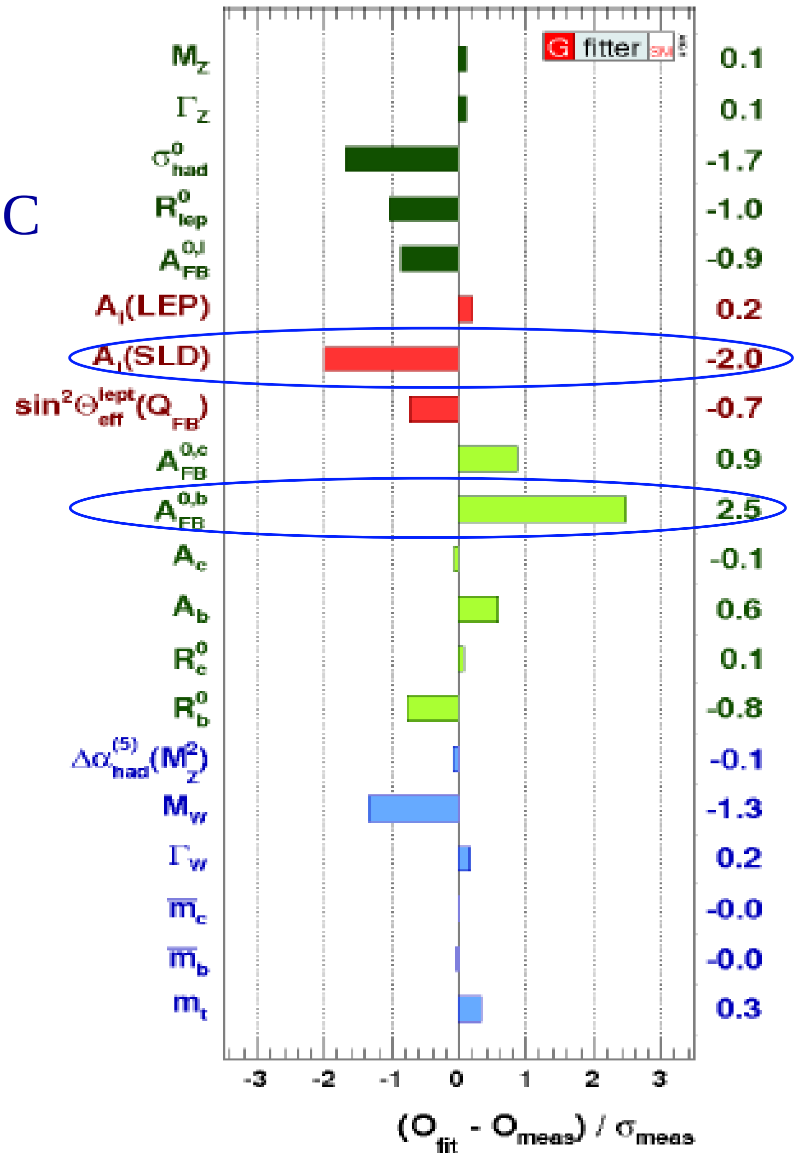


Measure
effective weak mixing angle
and couplings to u and d quarks

Forward-Backward Asymmetry

- To leading order LHC and Tevatron measure asymmetry in the same (but reversed) process as LEP and SLC

- Investigation of the two largest deviations in the SM fit

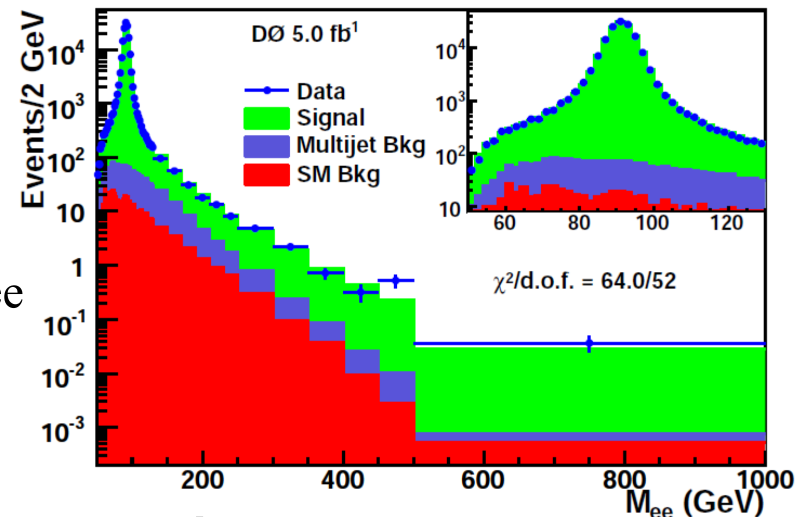


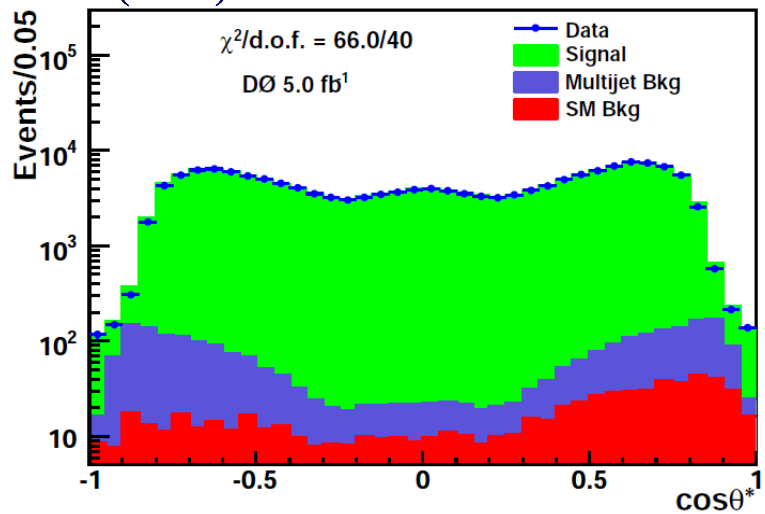
Forward-Backward Asymmetry

PRD 84, 012007 (2011)

DØ

~160k Z→ee



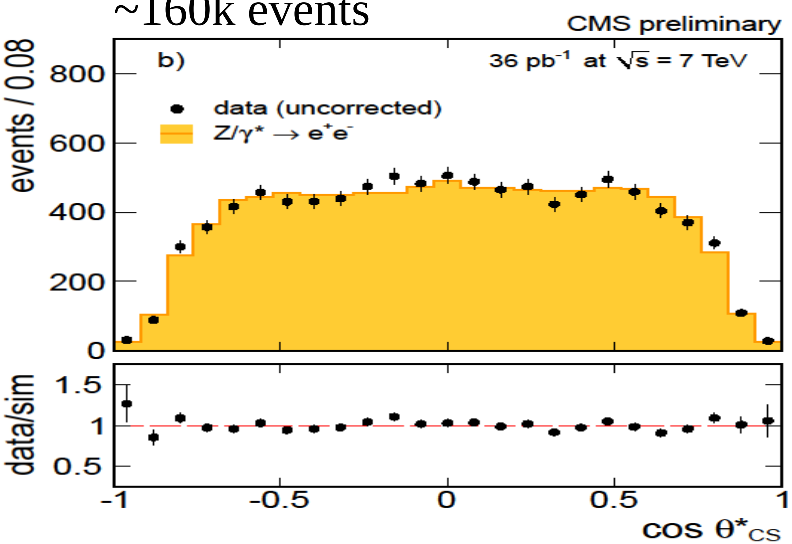


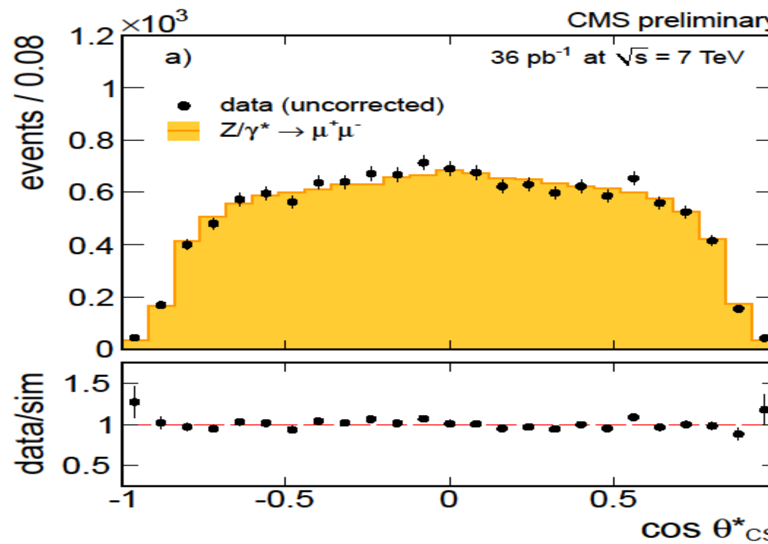
~160k events

CMS

~12k

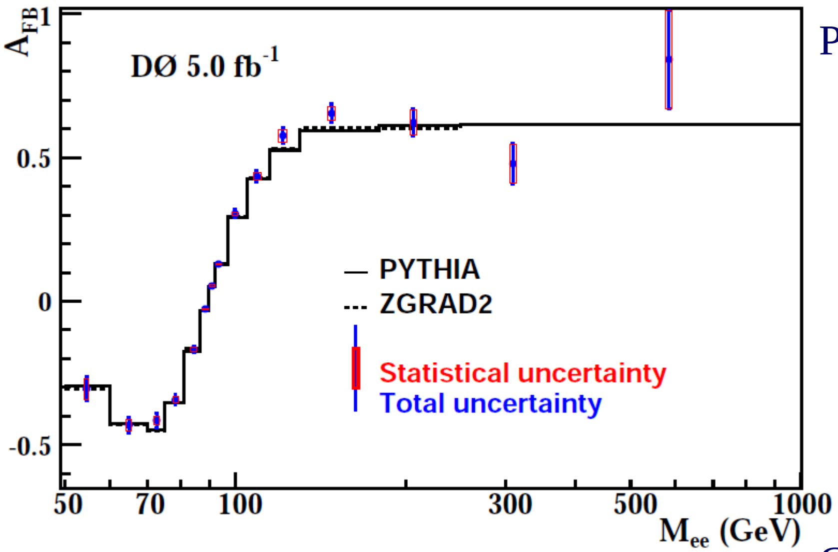
Z→ee, μμ





CMS-EWK-10-011

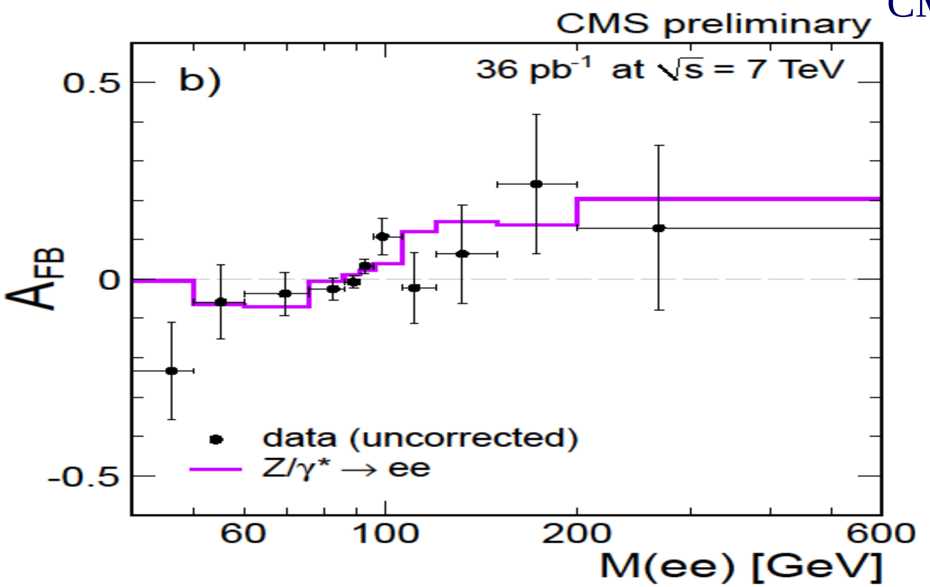
A_{FB} Distributions from DØ and CMS

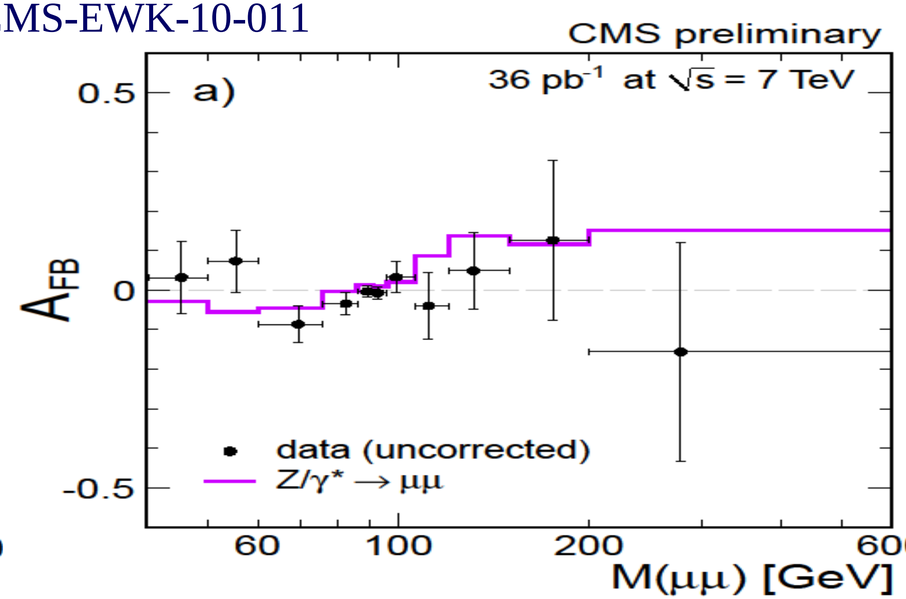


PRD 84, 012007 (2011)

Hard to classify events
into forward and backward
in pp collisions
⇒ smaller asymmetries at LHC

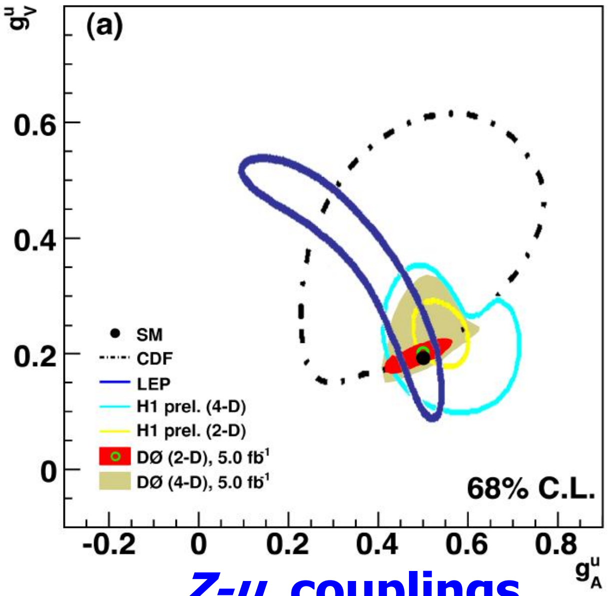
CMS-EWK-10-011



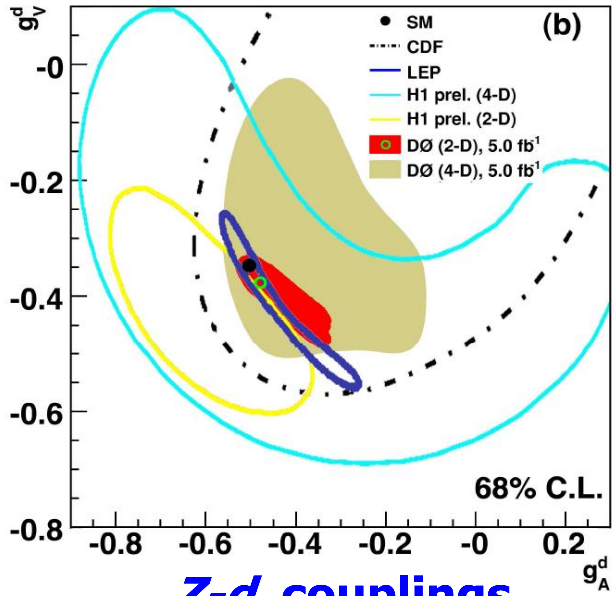


Couplings between Z and u,d quarks (DØ)

- Fit A_{FB} templates of the Z-to-light quark (u,d) couplings



Z-u couplings



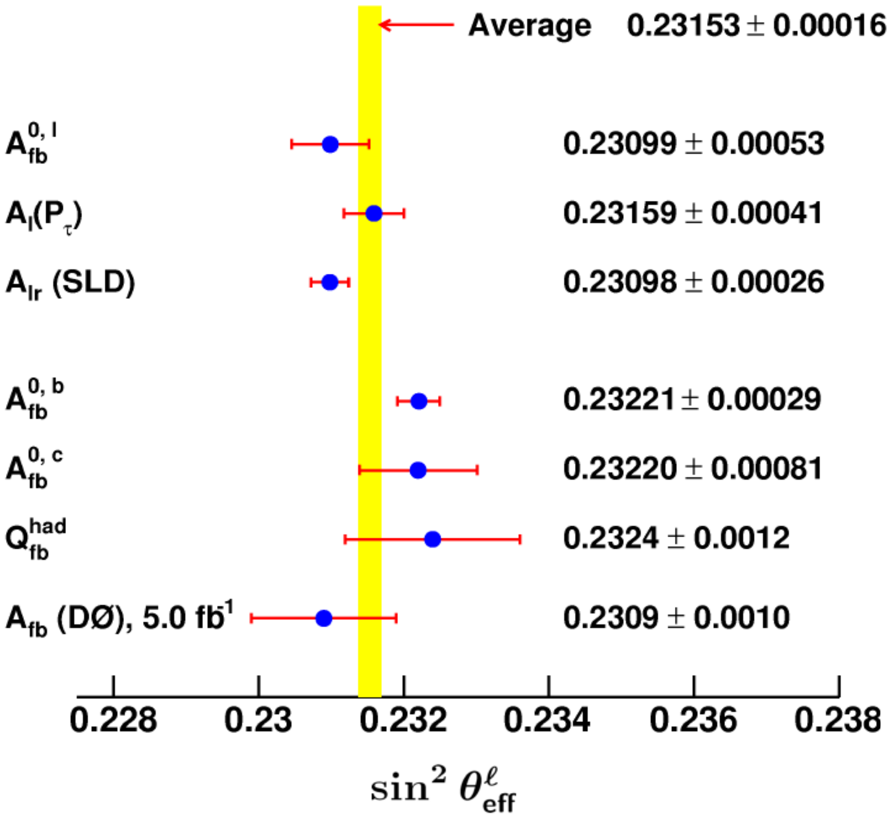
Z-d couplings

	g^u_A	g^u_V	g^d_A	g^d_V
D0 (5.0 fb^{-1})	0.502 ± 0.040	0.208 ± 0.014	-0.495 ± 0.037	-0.379 ± 0.027
SM	0.501	0.192	-0.502	-0.347

PRD 84, 012007 (2011)

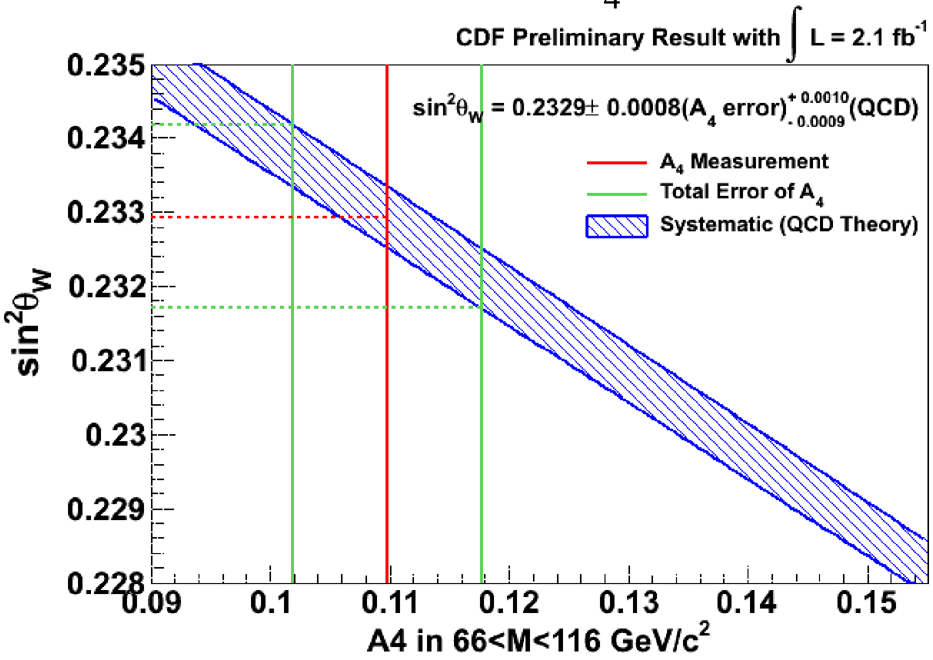
- Most precise measurement to date!

Effective Weak Mixing Angle



CDF result

extracted from A_4 measurement



CMS 234pb^{-1} result $\sin^2\theta_{\rm eff} = 0.2287 \pm 0.0020(\rm stat.) \pm 0.0025(\rm syst.)$

multivariate analysis of dilepton mass, rapidity, and decay angle effectively increases data sample ×2

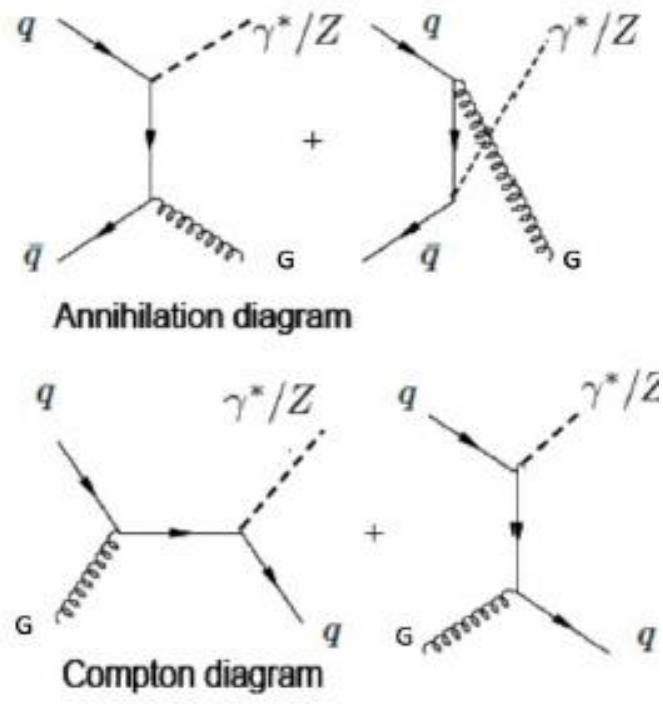
CMS-EWK-11-005

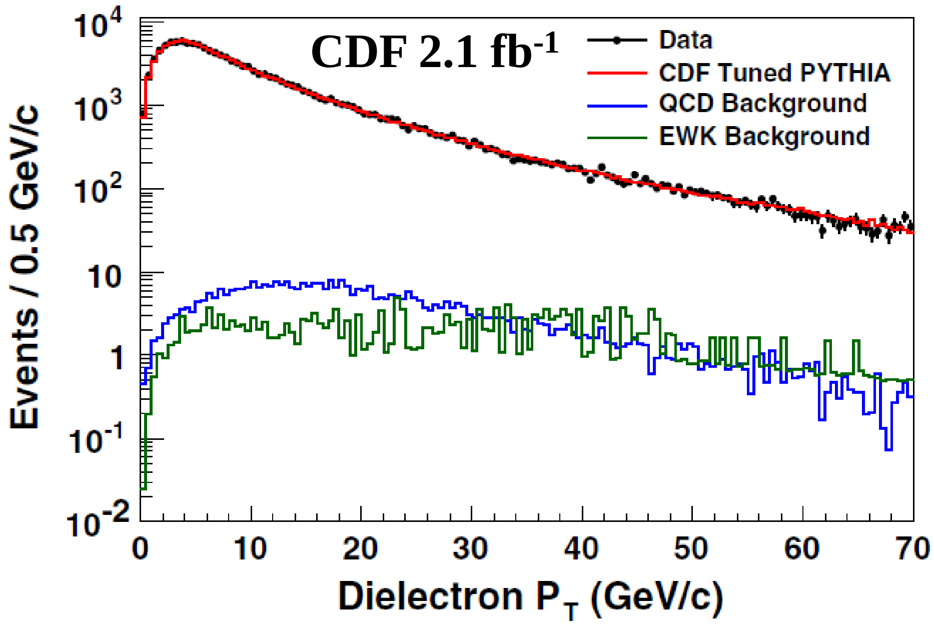
Angular Coefficients (CDF)

- Study angular coefficients as a function of P_T(Z)

$$\frac{d\sigma}{d\cos\theta} \propto \left(1+\cos^2\theta\right)+\frac{1}{2}A_0\left(1-3\cos^2\theta\right)+A_4\cos\theta$$

$$\frac{d\sigma}{d\varphi} \propto 1+\frac{3\pi A_3}{16}\cos\varphi+\frac{A_2}{4}\cos 2\varphi$$

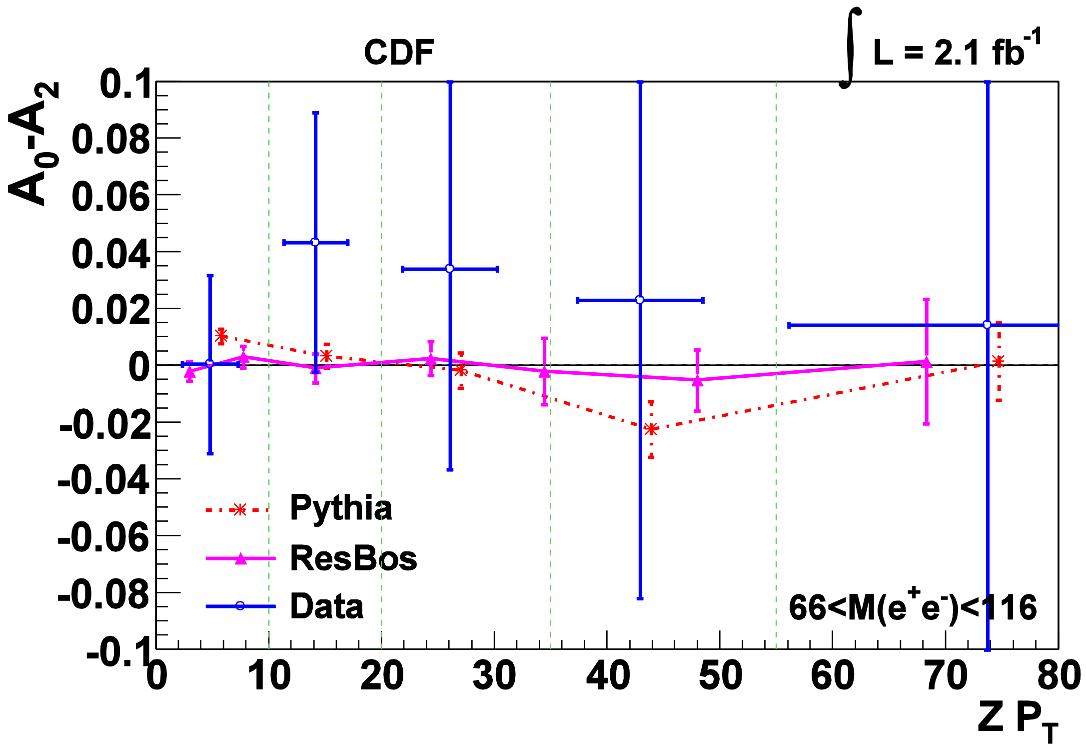




- probe production mechanisms
- establish contributions from two processes
- verify vector-like nature of gluon
- extract effective weak mixing angle(A_4)

Angular Coefficients (CDF)

- QCD predicts $A_0=A_2$ at α_s for both production processes for <u>gluon spin 1</u>

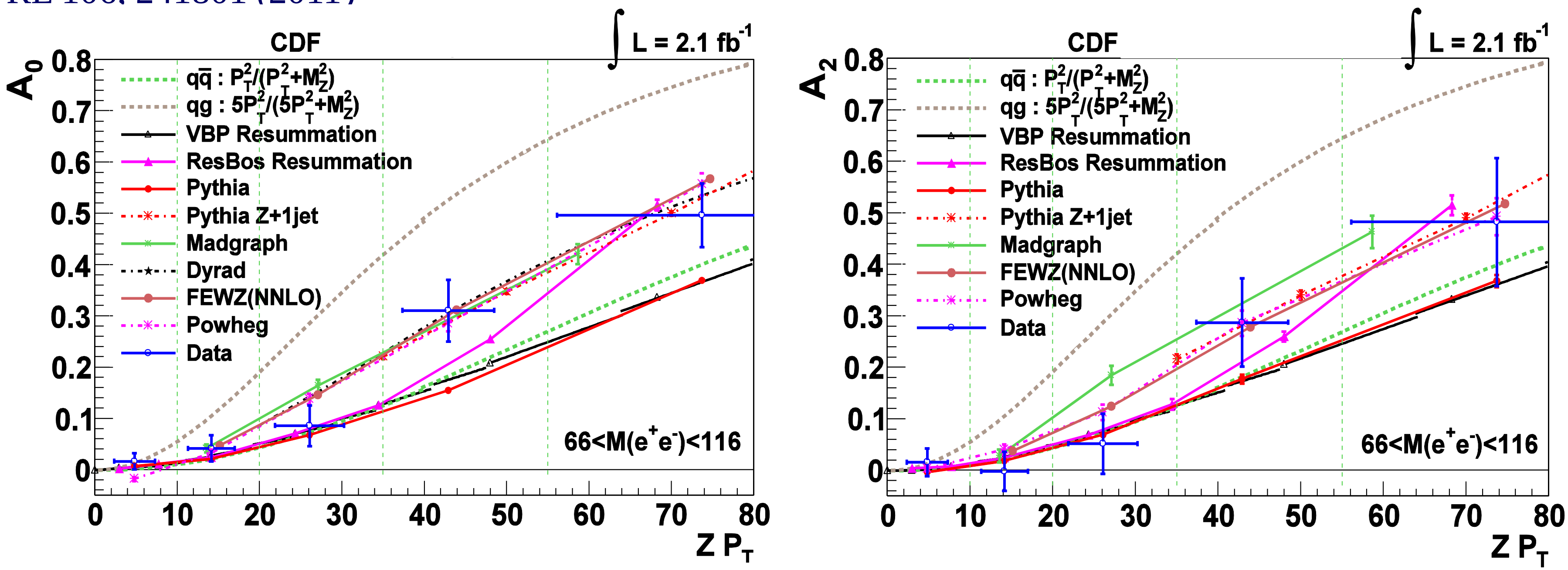


PRL 106, 241801 (2011)

- Measured $A_0 – A_2$ is consistent with zero in each PT(Z) bin
- this is indirect measurement of gluon spin ($A_0=A_2$ is badly broken for spin 0)

Angular Coefficients (CDF)

PRL 106, 241801 (2011)



- Dependence of A_0 and A_2 on $P_T(Z)$ is different for the two processes
  - dotted green and gray lines above

- Relative contribution of two production processes is established

W and Z Boson Properties

- Couplings between electroweak gauge bosons

Wγ Zγ WW WZ ZZ

- Couplings between Z boson and fermions
- Asymmetries induced by couplings
- Angular coefficients
- Weak mixing angle

Z

- W polarization
- Charge asymmetries
- W mass
- W width

W

W Polarization (CMS)

- Determine W bosons polarization fractions (f_L, f_R, f_0)
- Decays to electrons (~5k events) and muon (~8k events)

$$\frac{dN}{d\Omega} \propto (1+\cos^2\theta^*) + \frac{1}{2}A_0(1-3\cos^2\theta^*) + A_1 \sin 2\theta^* \cos\phi^* + \frac{1}{2}A_2 \sin^2\theta^* \cos 2\phi^* + A_3 \sin\theta^* \cos\phi^* + A_4 \cos\theta^*,$$

$A_0 \propto f_0$ and $A_4 \propto \pm(f_L - f_R)$

- Ambiguity in cosθ* determination due to missing neutrino p_Z
- Construct variable correlated with cosθ*

$$L_P = \frac{\vec{p}_T(\ell) \cdot \vec{p}_T(\mathrm{W})}{|\vec{p}_T(\mathrm{W})|^2}.$$

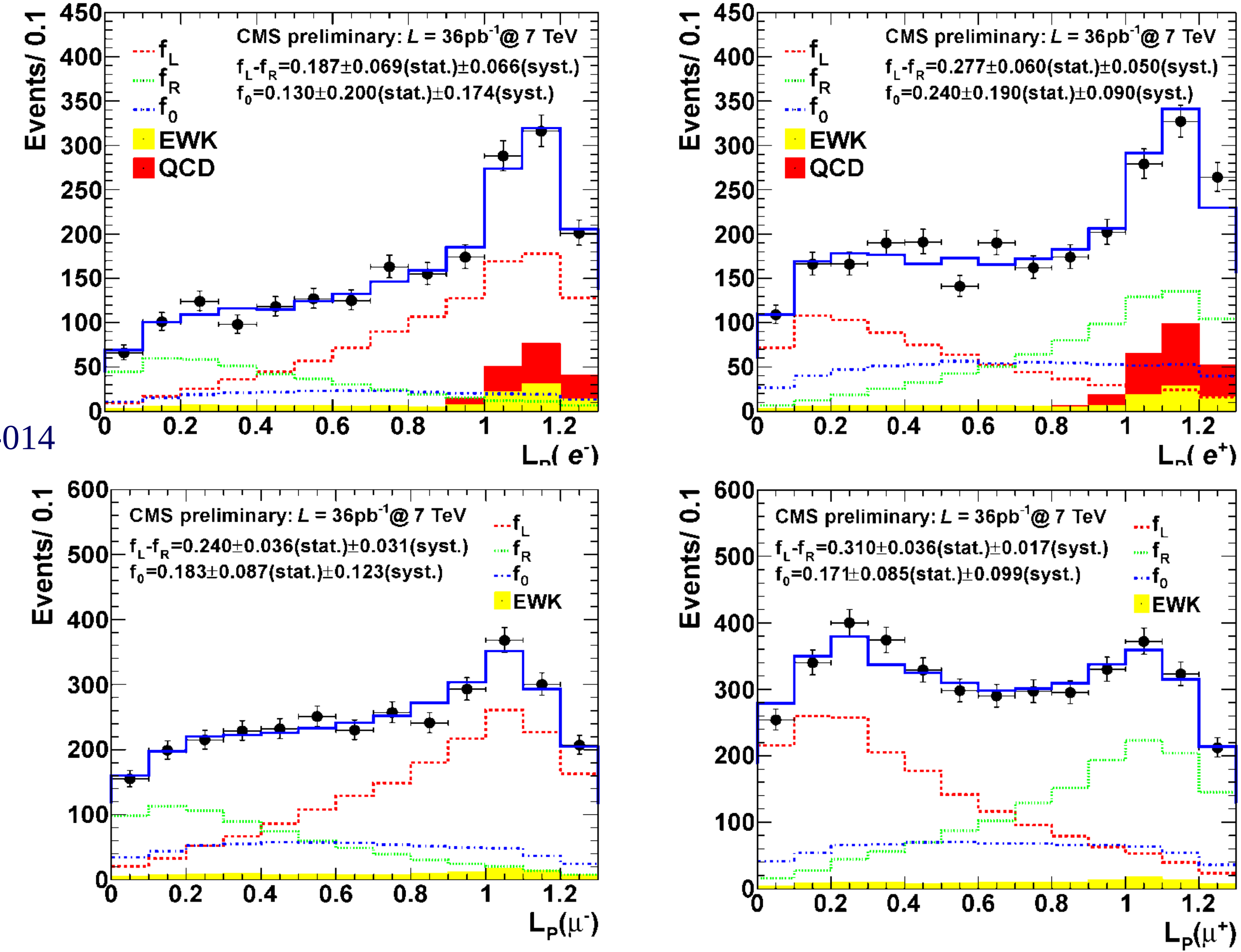
- Measure f_0 and $(f_L - f_R)$ using binned maximum likelihood fit

W Polarization (CMS)

e-, e+

CMS-EWK-10-014

μ-, μ+

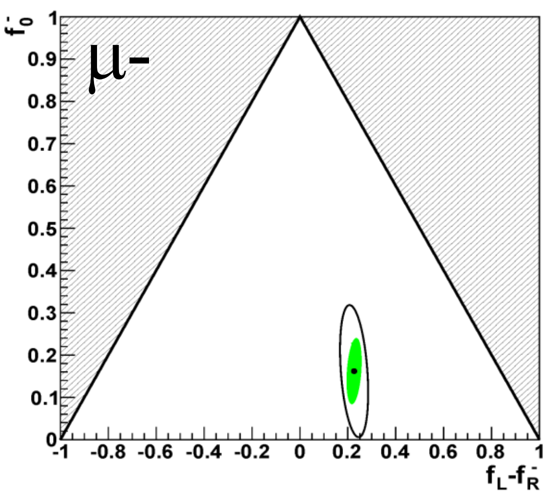


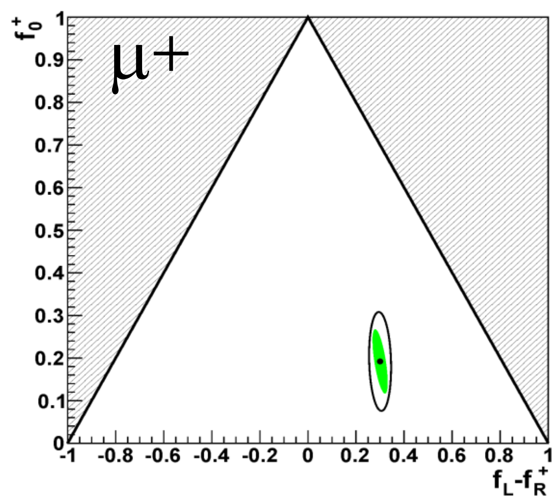
W Polarization (CMS)

- First observation that high P_T W bosons in pp collisions are predominantly left-handed, as predicted in the Standard Model

CMS-EWK-10-014

Combined: $(f_L - f_R)^-$	0.226 ± 0.031 (stat.) ± 0.050 (syst.)
Combined: f_0^-	0.162 ± 0.078 (stat.) ± 0.136 (syst.)
Correlation	0.304 (stat.), -0.326 (stat. + syst.)
Combined: $(f_L - f_R)^+$	0.300 ± 0.031 (stat.) ± 0.034 (syst.)
Combined: f_0^+	0.192 ± 0.075 (stat.) ± 0.089 (syst.)
Correlation	-0.660 (stat.), -0.121 (stat. + syst.)



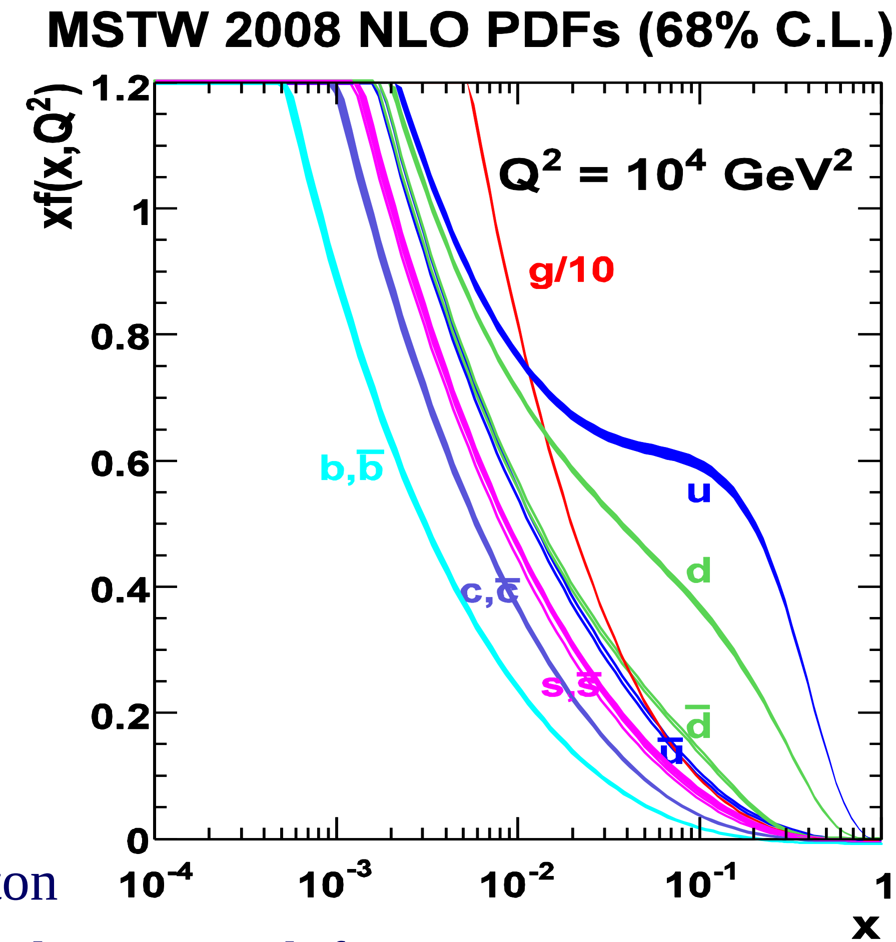


W Production Asymmetry

- Both at the Tevatron and the LHC W bosons are produced via

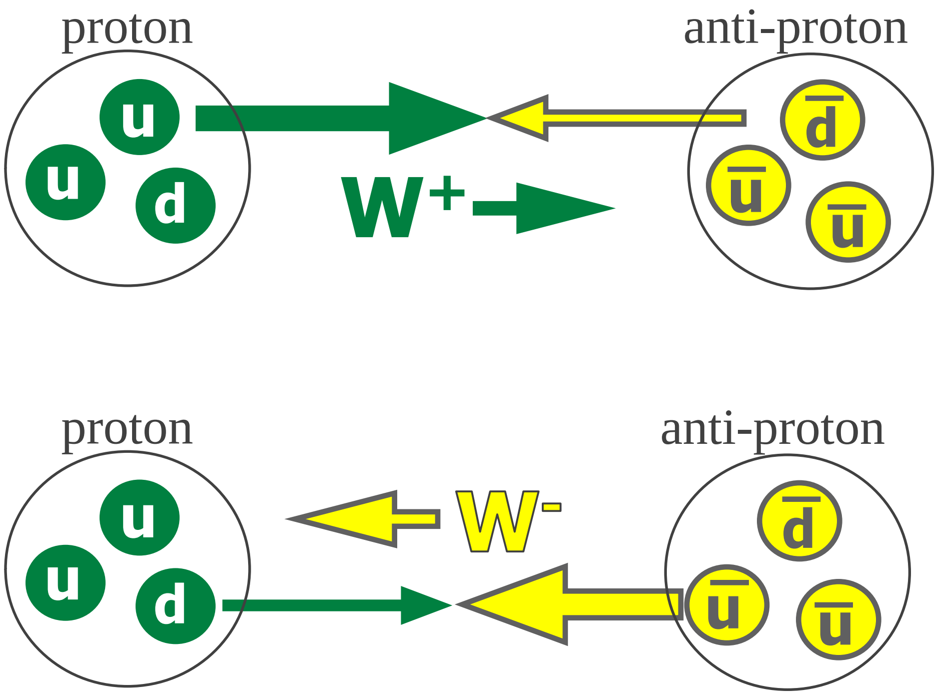
$$u\bar{d} \rightarrow W^{+}$$

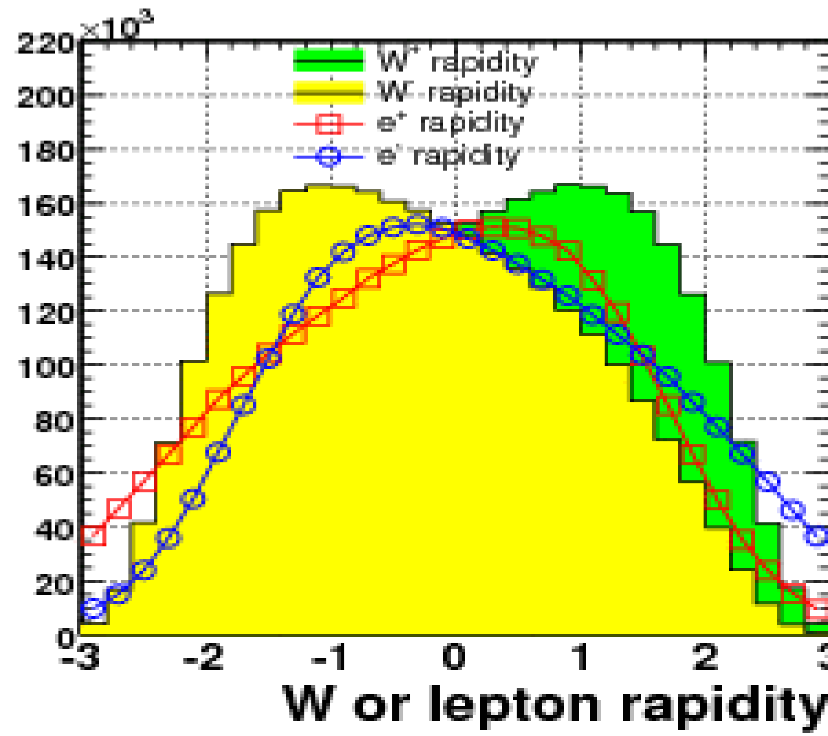
$$d\bar{u} \rightarrow W^{-}$$



- Tevatron:
  valence quark from proton
  and valence anti-quark from anti-proton
- LHC: a valence quark from proton and a sea quark from proton
- W production asymmetry is governed by the PDFs
  ⇒ constrain the PDFs with asymmetry measurements

W Production Asymmetry at Tevatron

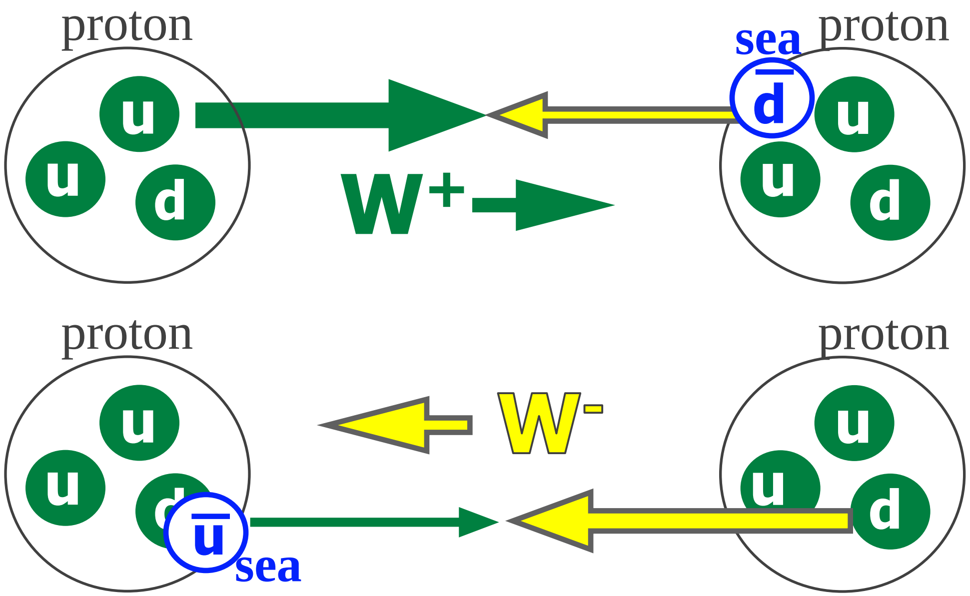




- Produced with valence quarks
- Total N(W+) = N(W-)
- Asymmetry
  as a function of W boson rapidity

$$A(y_W) = \frac{\frac{d\sigma(W^+)}{dy_W} - \frac{d\sigma(W^-)}{dy_W}}{\frac{d\sigma(W^+)}{dy_W} + \frac{d\sigma(W^-)}{dy_W}} \simeq \frac{u(x_1)/d(x_1) - u(x_2)/d(x_2)}{u(x_1)/d(x_1) + u(x_2)/d(x_2)}$$

W Production Asymmetry at LHC



- W bosons are produced with valence quarks and see quarks
- $N(u_v) > N(d_v)$
  $\Rightarrow$ Total N(W+) > N(W-)

The inclusive ratio of cross sections for W+ and W- bosons production was measured by CMS to be 1.43 ± 0.05 CMS-EWK-10-006

NEXT: W decay asymmetry

Lepton Charge Asymmetry

W rapidity cannot be reconstructed on event-by-event basis
due to non-measurable longitudinal neutrino momentum

W charge asymmetry

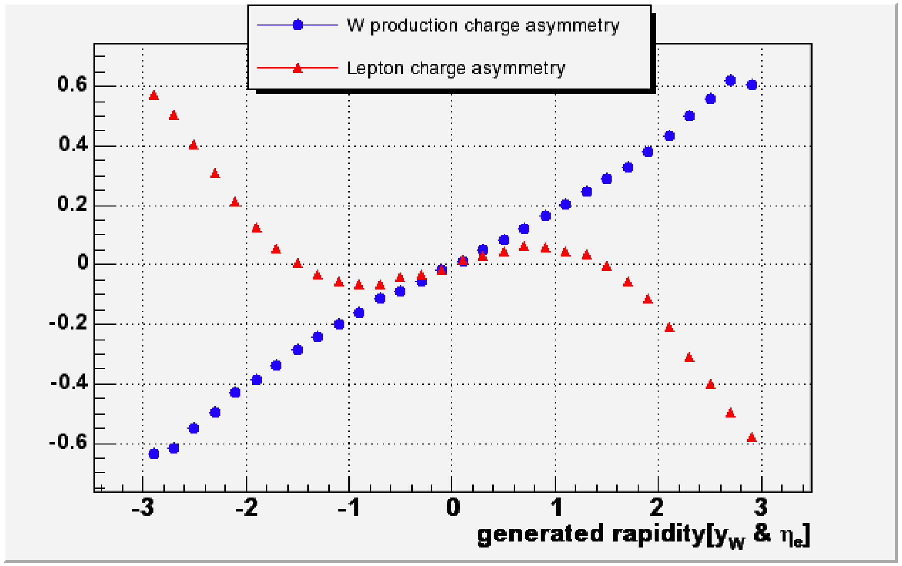
$$A(y_W) = \frac{d\sigma(W^+)/dy_W - d\sigma(W^-)/dy_W}{d\sigma(W^+)/dy_W + d\sigma(W^-)/dy_W}$$

$$y_W = \frac{1}{2}\ln\left(\frac{E+p_z}{E-p_z}\right)$$

lepton charge asymmetry

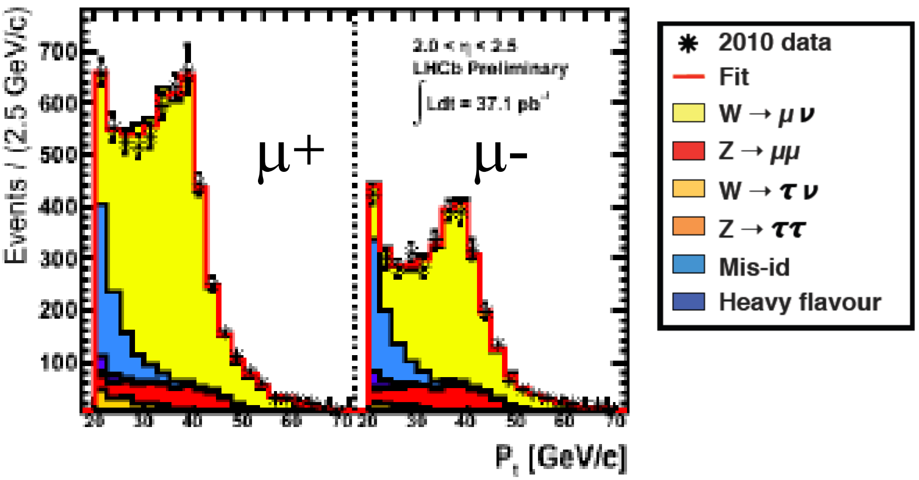
$$A(\eta_l) = \frac{d\sigma_+/d\eta_l - d\sigma_-/d\eta_l}{d\sigma_+/d\eta_l + d\sigma_-/d\eta_l} \sim \frac{d(x)}{u(x)} = A(y_W) \otimes (V\text{-}A)$$

$$x_{u,d} = \frac{M_W}{\sqrt{s}} e^{\pm y_W}$$

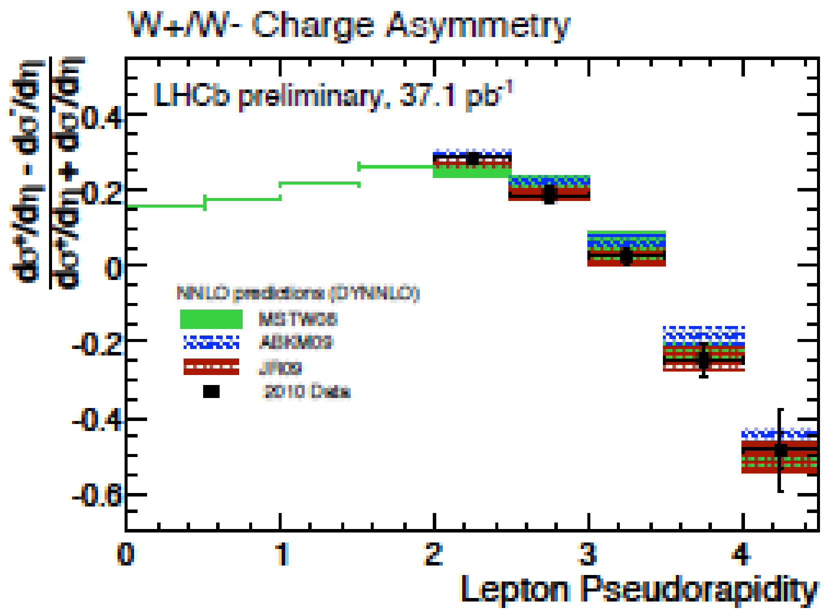


E.L. Berger, F. Halzen, C.S. Kim and S. Willenbrock; Phys. Rev. D40 (1989) 83

Lepton Asymmetry from LHCb



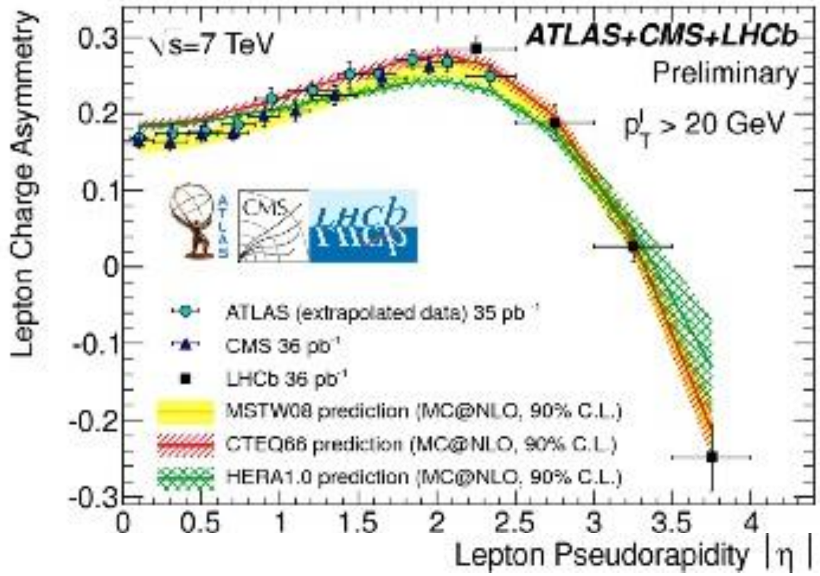
LHCb-CONF-2011-039v2



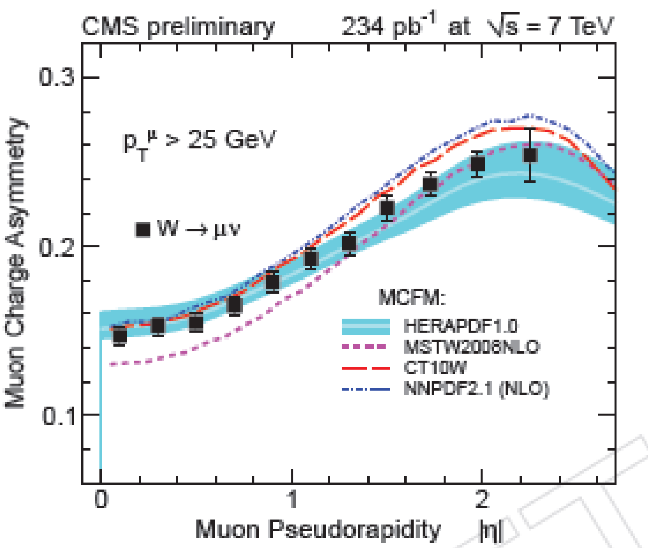
$$x_1 = M_W e^y / \sqrt{s}, x_2 = M_W e^{-y} / \sqrt{s}.$$

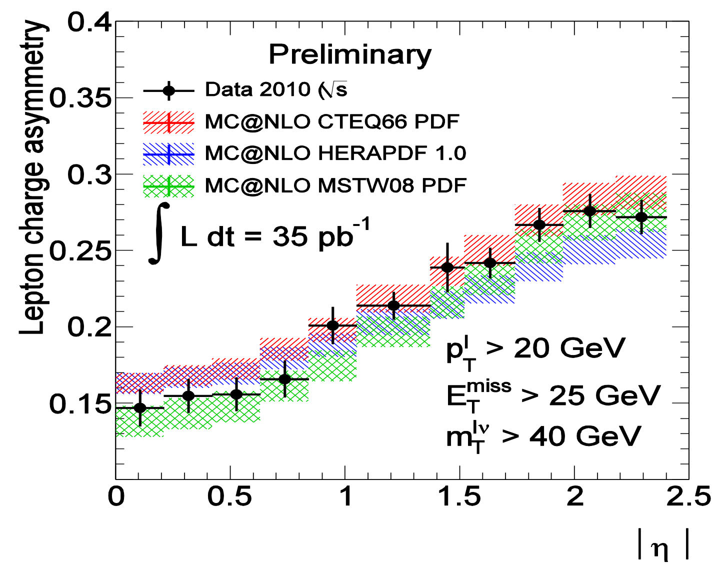
probing smaller x region than other experiments

Lepton Charge Asymmetry at LHC



ATLAS-CONF-2011-129
LHCb-CONF-2011-039
CMS-EWK-10-006 (arXiv:1103.3407)

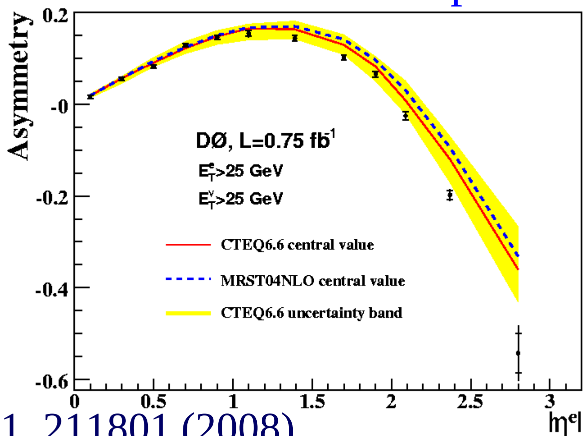




W Charge Asymmetry at Tevatron

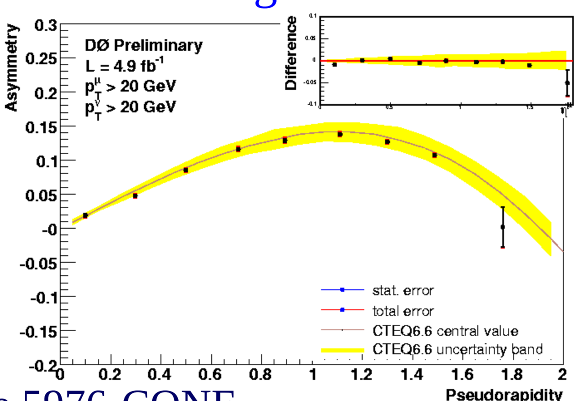
DØ:
lepton charge asymmetry

Electrons: wider acceptance



PRL 101, 211801 (2008)

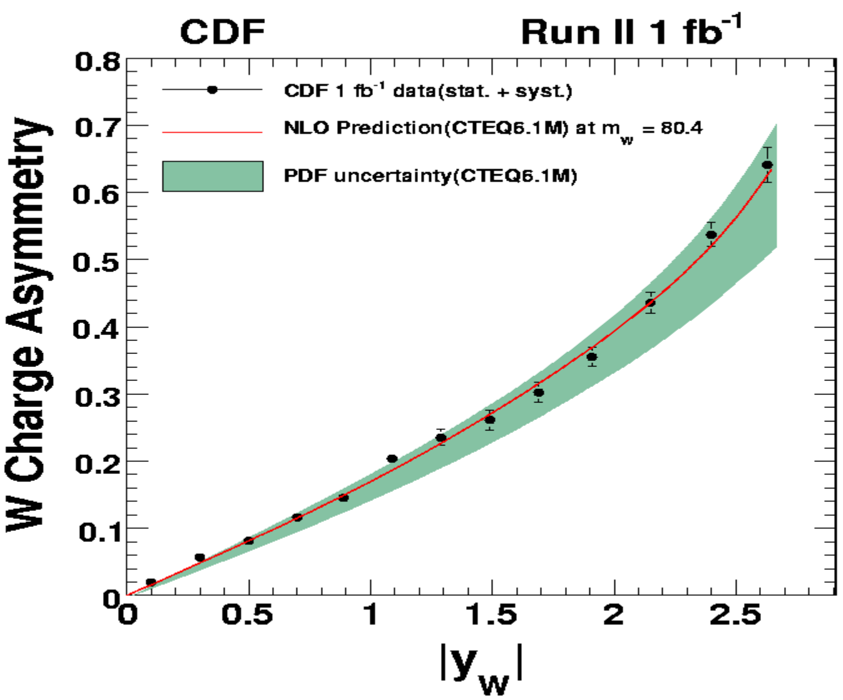
Muons: higher statistics



DØ Note 5976-CONF

CDF: direct determination of y_W

W mass constraint → neutrino momentum with weight probability assigned (decay structure; $d\sigma_W/dy$)



Uncertainties smaller than PDF one.

<u>Still statistics driven</u> PRL 102, 181801 (2009)

M(W) Motivation

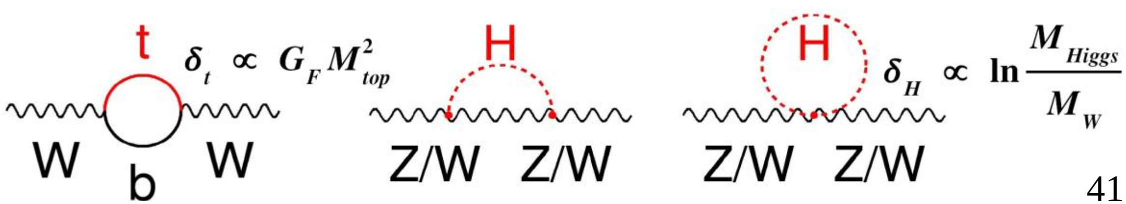
- W boson mass is an important Standard Model parameter related to **G_F** , **α_{EM}**, and **M_z** via

tree level

$$M_W^2 = \frac{\pi\alpha_{EM}(0)}{\sqrt{2}G_F\,(1 - M_W^2/M_Z^2)(1-\Delta r)}$$

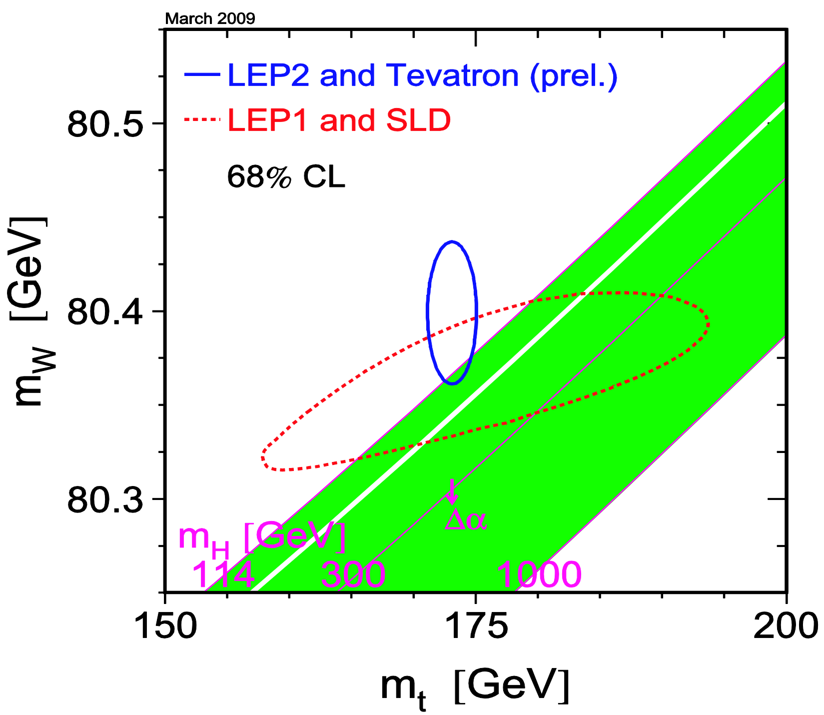
- Δr term represents (large!) higher-order corrections to M_W

Δr = $\alpha_{EM}(0 \rightarrow M_Z)$ Running of α_{EM} + Radiative Corrections



Constraining Standard Model

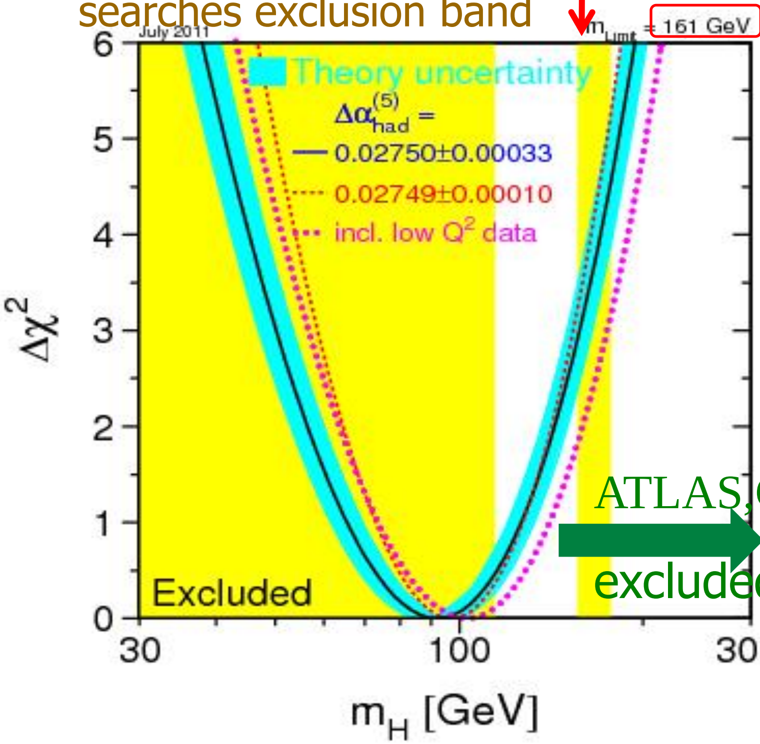
- Since M_W , M_{top} , and M_{Higgs} are all related via radiative corrections, we can constrain M_{Higgs} with precision measurements of M_W and M_{top}
- Measurements of M_W and M_{top} overlaid with theory predictions for the Higgs boson



Higgs limit from EW fits

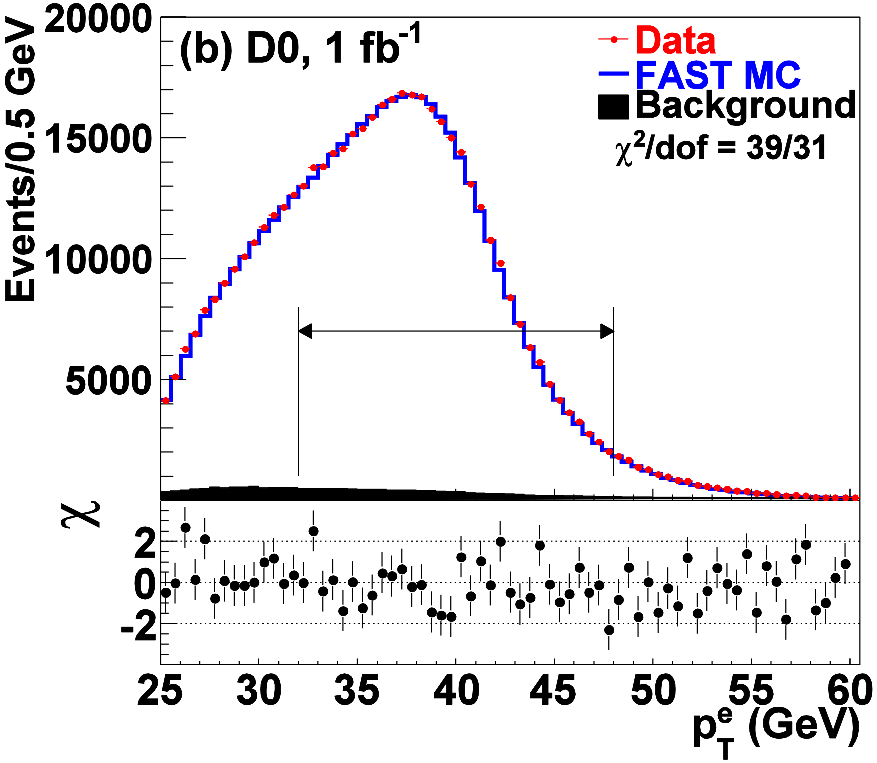
161GeV @95%CL

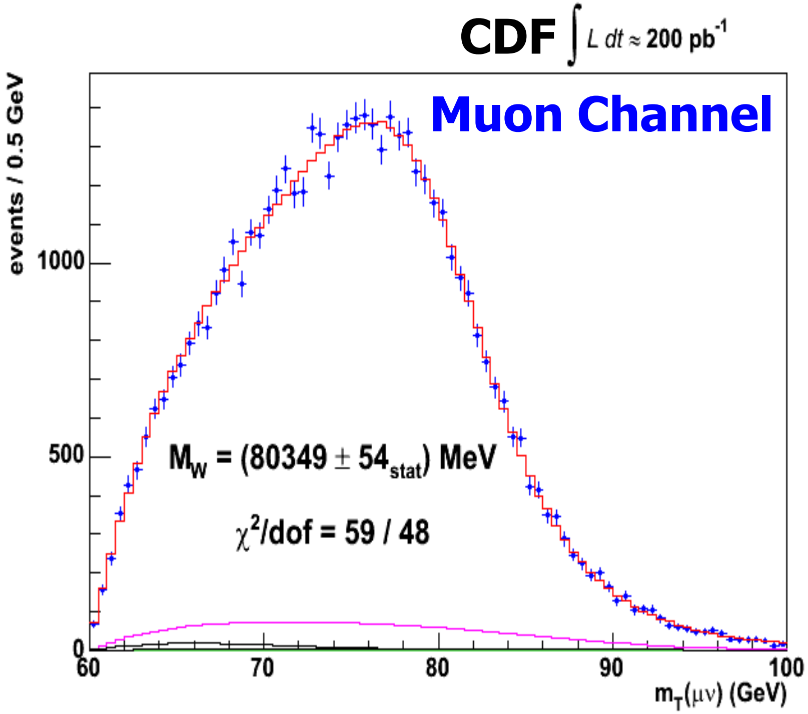
within direct searches exclusion band



ATLAS,CMS excluded

W Mass Fits: $P_T(e)$, $M_T(W)$

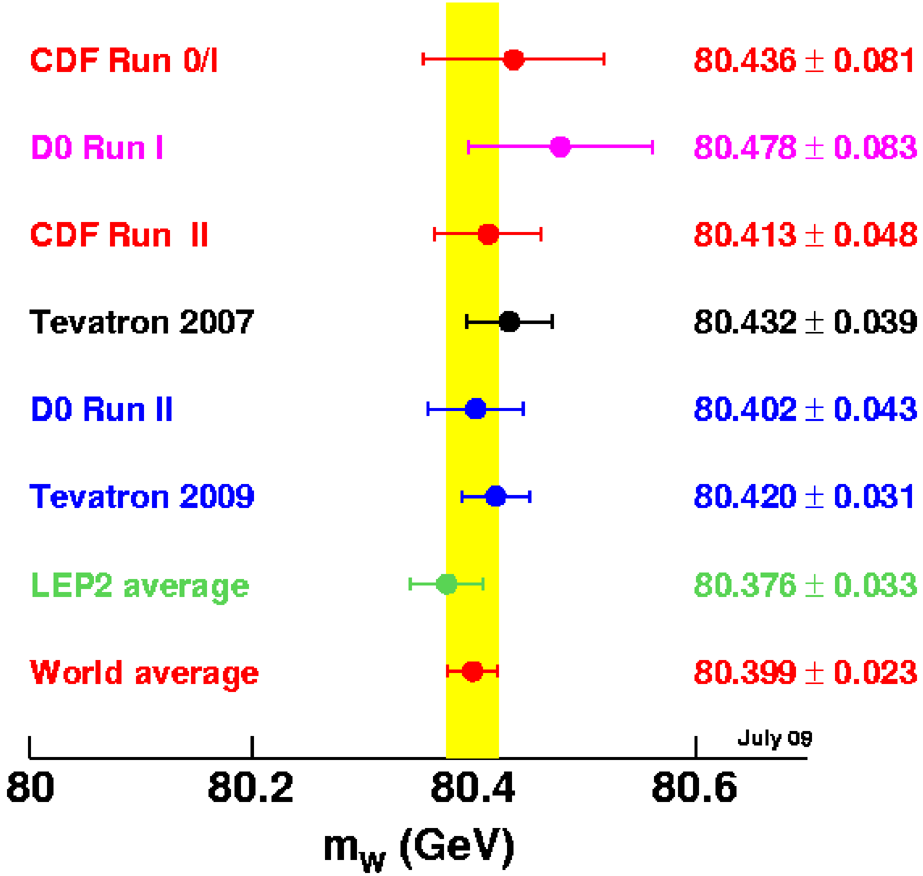




Selected distributions of W Mass observables

Largest systematic uncertainties are from lepton energy scale

DØ 1fb^{-1} W Mass Result



DØ RunII 1fb^{-1} PRL 103, 141801 (2009)

single most precise measurement of the W boson mass to date

80.401 ± 0.021(stat.) ± 0.038(syst.) GeV
80.401 ± 0.043 GeV

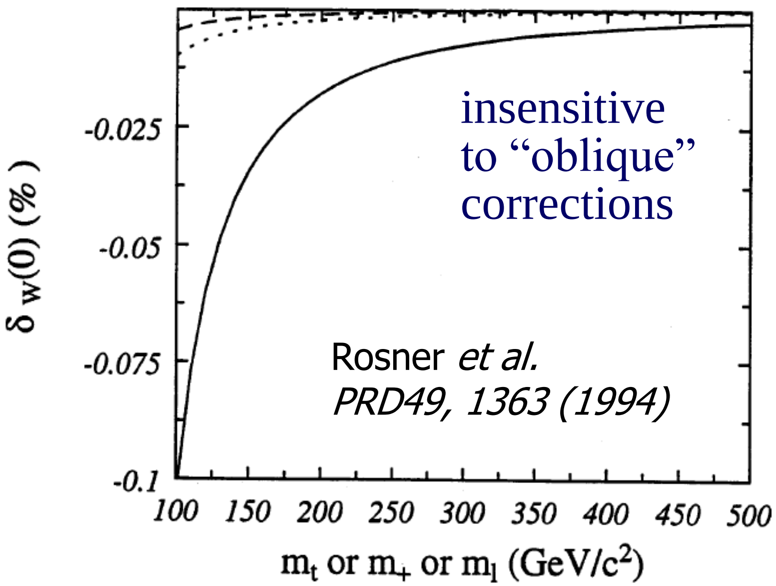
total uncertainty of 31 MeV from Tevatron is smaller than that of 33 MeV from LEPII

World average is now:
80.399 ± 0.023 GeV

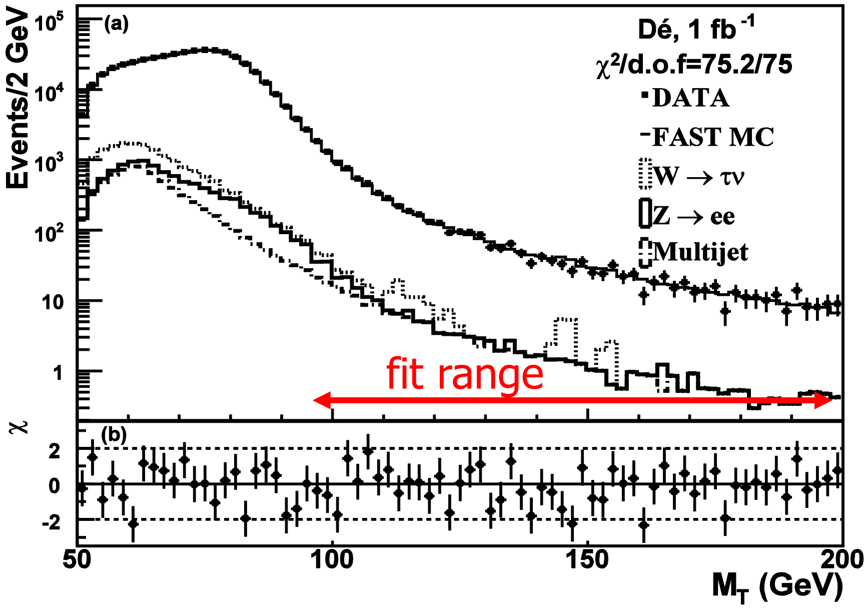
TEVEWWG/WZ 2009/01
FERMILAB-TM-2439-E

CDF RunII 0.2 fb^{-1} PRL 99, 151801 (2007) PRD 77, 112001 (2008)
80.413 ± 0.034 (stat.) ± 0.034 (syst.) GeV
80.413 ± 0.048 GeV

W Boson Width at Tevatron



PRL 103 231802(2009)



DØ Γ_W = 2.028 ± 0.072 GeV

CDF Γ_W = 2.032 ± 0.073 GeV (350 pb^{-1})

PRL 100 071801 (2008)

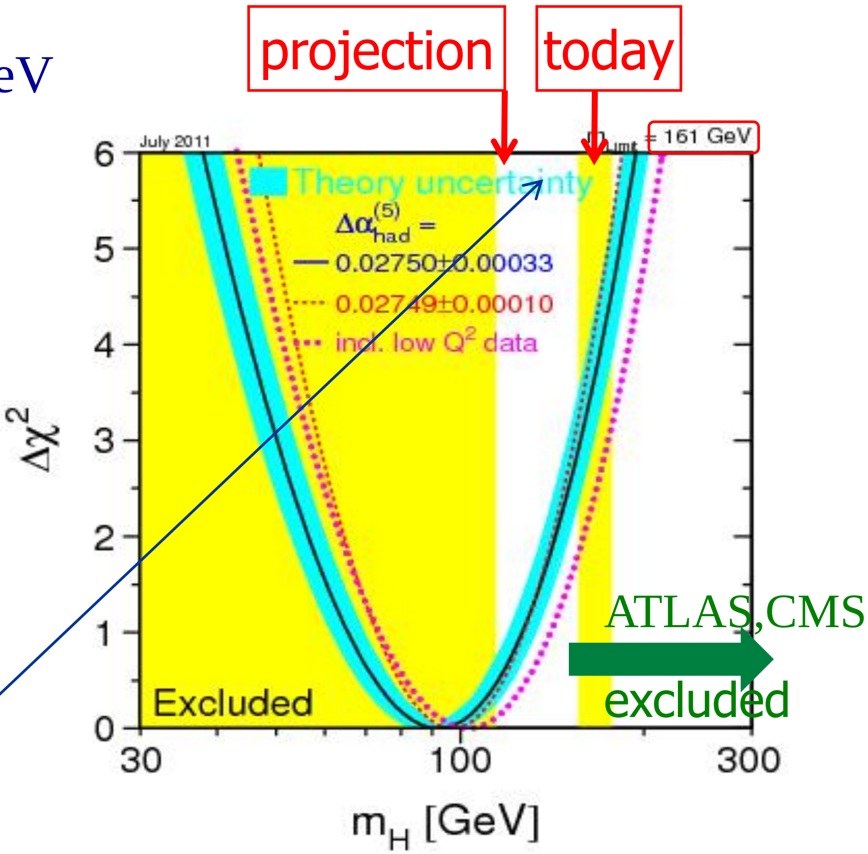
Standard Model	Γ_W = 2.093 ± 0.002 GeV
Tevatron	Γ_W = 2.046 ± 0.049 GeV
LEP	Γ_W = 2.196 ± 0.083 GeV

M(W) Prospects with all Tevatron Data

- Electroweak fits favor light Higgs
- Currently
  - most probable Higgs mass value = 92 GeV
  - excluded above 161GeV @95% CL
- Under the following example scenario*

  ΔM_W : 23 MeV $\rightarrow$ 15 MeV
  central values (M_W, M_{top}) do not move
  ΔM_{top} : 1 GeV
- Higgs:
  - most probable value = 71 GeV
  - excluded above 117GeV @95% CL
    (114.4 from current direct searches)

Higgs limit from EW fits



Pete Renton, ICHEP2008

can be achieved at the Tevatron with the full dataset !!!

Summary

- Lots of interesting measurements of W/Z and diboson properties
  - couplings between electroweak gauge bosons
  - couplings between Z and fermions
  - forward backward asymmetry in Z decays
  - weak mixing angle
  - W boson and lepton charge asymmetries
  - W boson mass, width, and polarization
  - probes of production mechanisms and constraints on the PDFs
- Two-fold goal
  - precise knowledge of Standard Model parameters
  - indirect search for new physics
- More data are being analyzed
- Expecting significant improvements in precision soon
- Thank you for your attention