

W and Z Bosons at Tevatron and LHC

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Physics with W and Z bosons

- W and Z bosons
 - discovered by UA1/UA2 at the $S\bar{p}\bar{p}S$ collider in the early 80's
 - many measurements at LEP and Tevatron since then

Physics with W and Z bosons

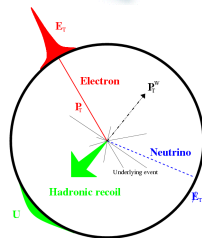
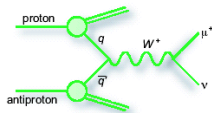
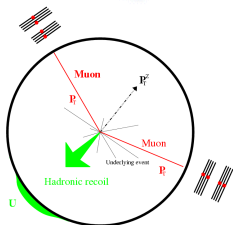
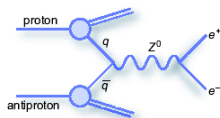
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- So, why still bother?

Physics with W and Z bosons

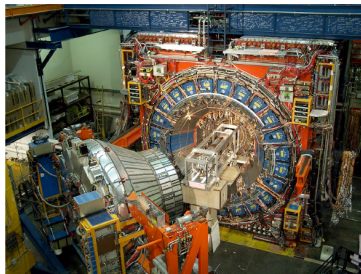
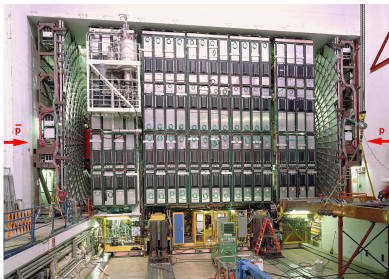
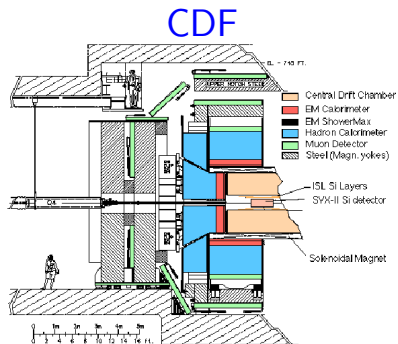
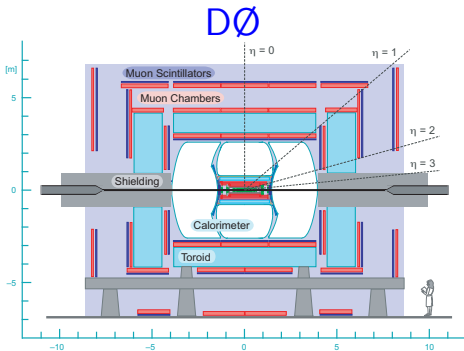
- W and Z bosons
 - discovered by UA1/UA2 at the $Sp\bar{p}S$ collider in the early 80's
 - many measurements at LEP and Tevatron since then
- So, why still bother?
 - electroweak interaction, precision tests of the standard model (SM)
 - left/right handed couplings of quarks and leptons
 - (anomalous?) triple gauge couplings
 - precision measurement of W mass
 - indirect constraint on Higgs mass due to radiative corrections to M_W
 - interplay with strong interaction (QCD)
 - sensitive to parton distribution functions (PDFs)
 - associated production with jets (constraining QCD models)
 - standard candles for calibration due to leptonic final states
 - important (or even main) backgrounds for top, Higgs, Supersymmetry, LED, new strong interactions, new gauge bosons, etc.
 - essential to measure precisely standard model processes before claiming discoveries

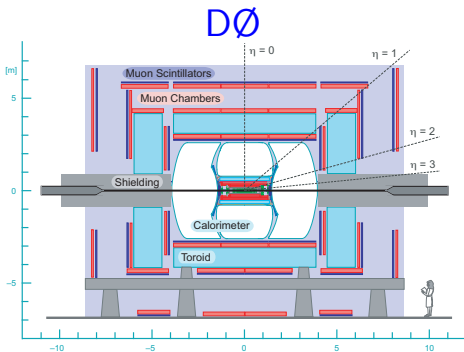
W/Z production and detection at hadron colliders

- production of weak bosons via $q\bar{q}'$ annihilation
- detection via leptonic decays $Z \rightarrow \ell^+\ell^-$, $W^\pm \rightarrow \ell^\pm\nu_\ell$
 - hadronic decays cannot be separated from QCD multi jet background



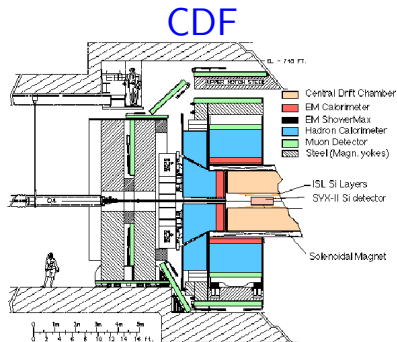
- Z signature:
2 isolated, opposite sign leptons with high transverse momentum p_T
- W signature:
isolated lepton and missing transverse energy $\cancel{E}_t$





detector highlights

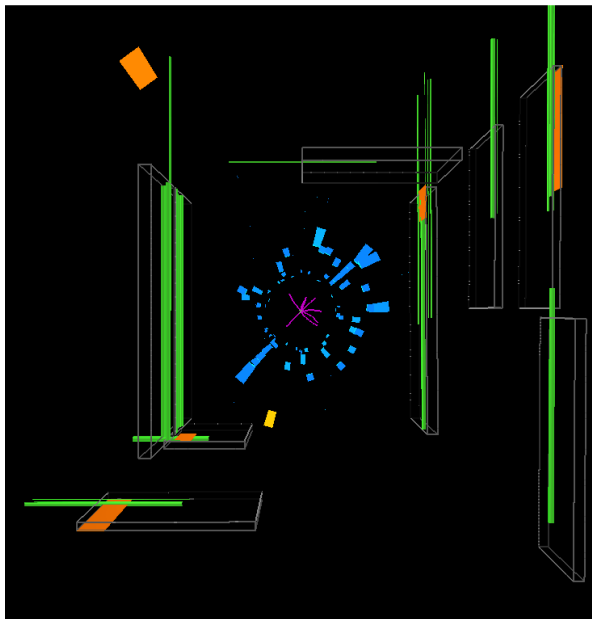
- high acceptance, low background, muon system
- finely segmented LAr calorimeter
- 16-layer fiber tracker: only 0.5 m outer radius
- 5-layer silicon tracker



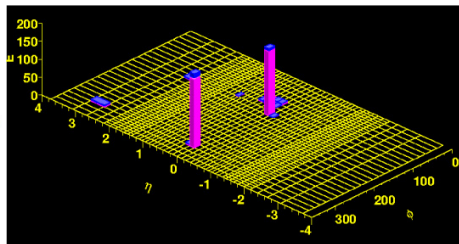
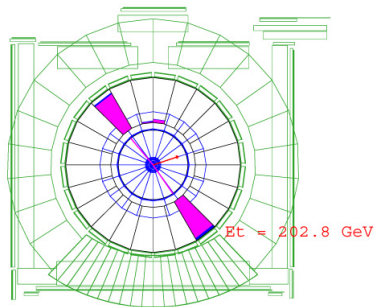
detector highlights

- large volume, high precision, charged particle tracker
- 96-layer drift chamber: 1.4 m outer radius
- 9-layer silicon tracker

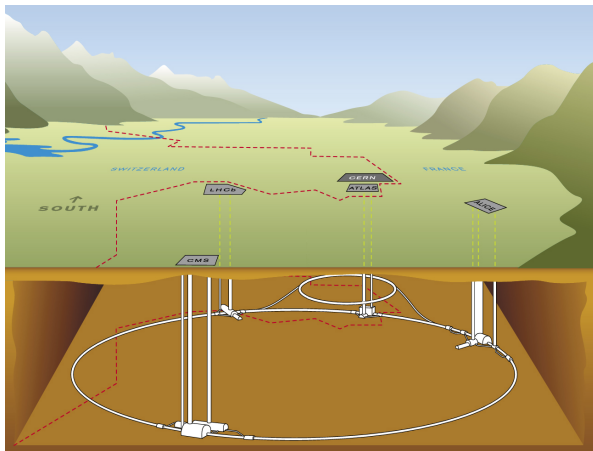
$Z \rightarrow \mu\mu$ in DØ



$Z/\gamma^* \rightarrow ee$ in CDF, $M_{ee} = 371 \text{ GeV}$



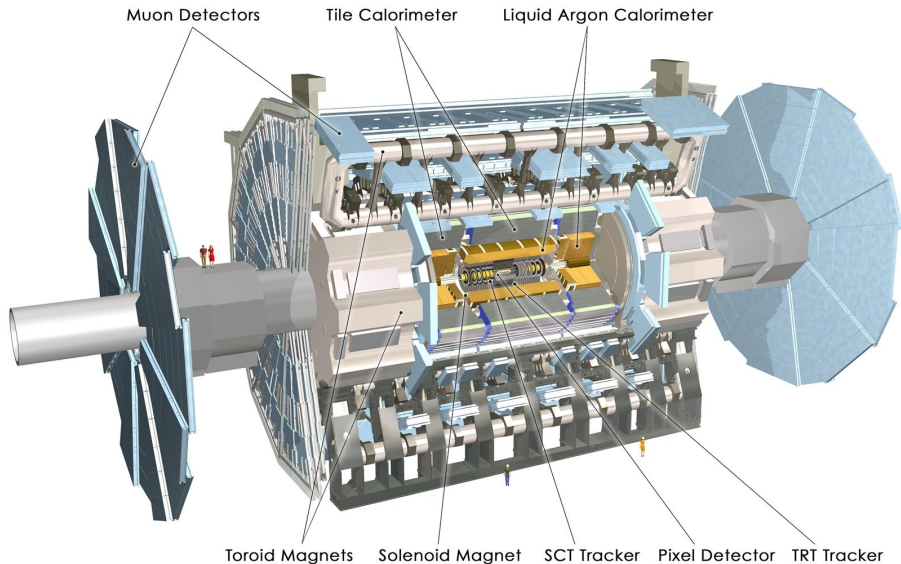
CERN's LHC Collider



pp collider

- 2010/11: $\sqrt{s} = 7$ TeV
- delivered $\sim 0.35 \text{ pb}^{-1}$
- plan: 1 fb^{-1} until end of 2011
- design: $\sqrt{s} = 14$ TeV
- colliding bunches every 25 ns with ~ 25 incl. collisions at $\mathcal{L} = 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$
- $L \sim 100 \text{ fb}^{-1}$ per year

The ATLAS detector



The CMS detector

Pixels
Tracker
ECAL
HCAL
Solenoid
Steel Yoke
Muons

STEEL RETURN YOKE
~13000 tonnes

SUPERCONDUCTING SOLENOID
Niobium-titanium coil
carrying ~18000 A

HADRON CALORIMETER (HCAL)
Brass + plastic scintillator

SILICON TRACKER
Pixels ($100 \times 150 \mu\text{m}^2$)
~1m² 66M channels
Microstrips (50-100 μm)
~210m² 9.6M channels

CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
76k scintillating PbWO₄ crystals

PRESHOWER
Silicon strips
~16m² 137k channels

FORWARD CALORIMETER
Steel + quartz fibres

MUON CHAMBERS

Barrel: 250 Drift Tube & 500 Resistive Plate Chambers
Endcaps: 450 Cathode Strip & 400 Resistive Plate Chambers

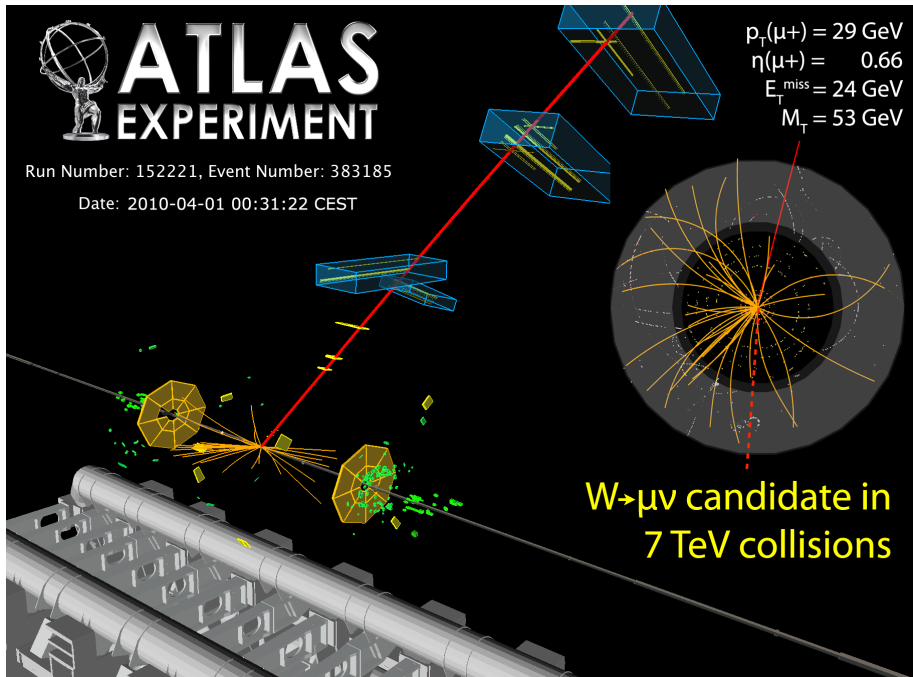
Total weight : 14000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T

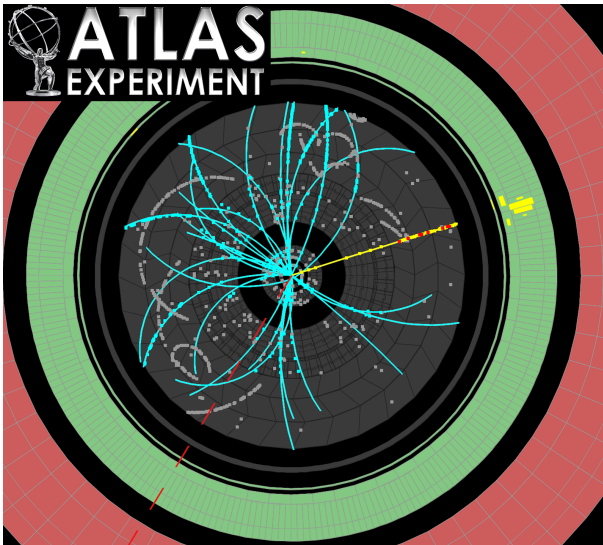


ATLAS EXPERIMENT

Run Number: 152221, Event Number: 383185

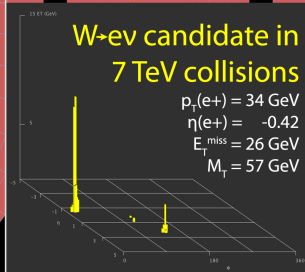
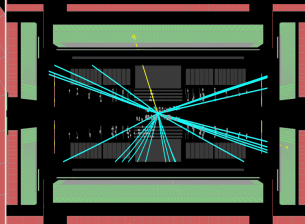
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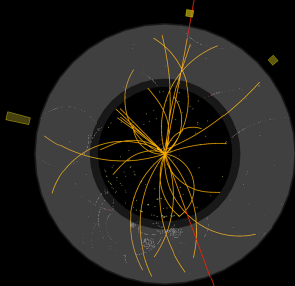
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Date: 2010-04-05 06:54:50 CEST



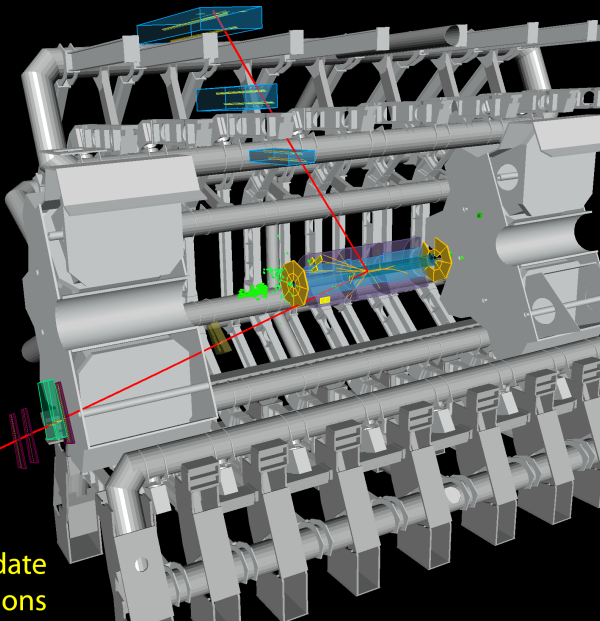
ATLAS EXPERIMENT

Run: 154822, Event: 14321500
Date: 2010-05-10 02:07:22 CEST



$p_T(\mu^-) = 27 \text{ GeV}$ $\eta(\mu^-) = 0.7$
 $p_T(\mu^+) = 45 \text{ GeV}$ $\eta(\mu^+) = 2.2$
 $M_{\mu\mu} = 87 \text{ GeV}$

**Z $\rightarrow\mu\mu$ candidate
in 7 TeV collisions**



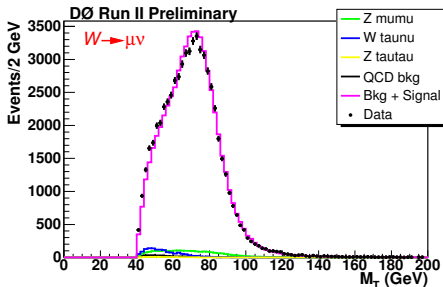
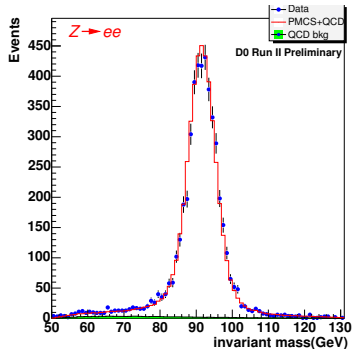
W/Z signatures

- Z/W detected as resonances in M_{ll} or M_T

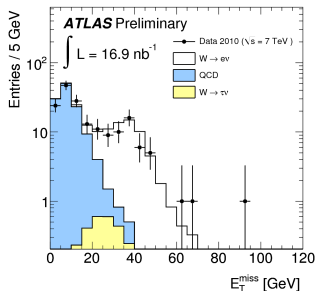
$$M_{ll} = \sqrt{(p_{l+} + p_{l-})^2} \\ = \sqrt{(E_{l+} + E_{l-})^2 - (\vec{p}_{l+} + \vec{p}_{l-})^2}$$

- longitudinal momentum of ν unknown $\rightarrow$ transverse mass M_T

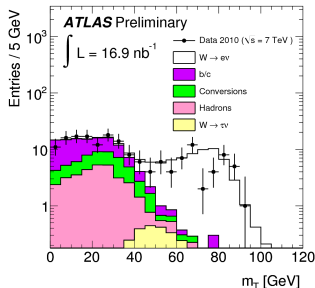
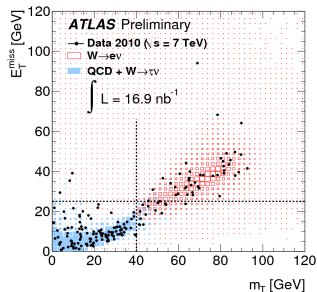
$$M_T \\ = \sqrt{(E_{T,l} + E_{T,\nu})^2 - (\vec{p}_{T,l} + \vec{p}_{T,\nu})^2} \\ = \sqrt{2E_{T,l}E_{T,\nu} (1 - \cos \Delta\phi_{l\nu})}$$



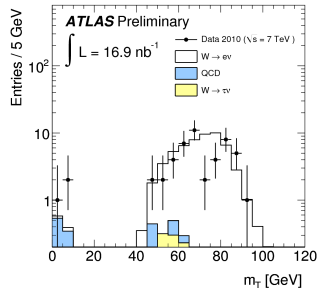
$W^\pm \rightarrow e^\pm \nu$: backgrounds and selection at LHC



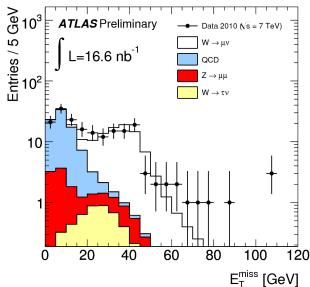
2-dim. kinem.
 selection:
 $E_t > 25 \text{ GeV}$
 $M_T > 40 \text{ GeV}$
 46 cand.



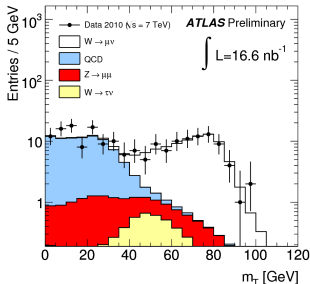
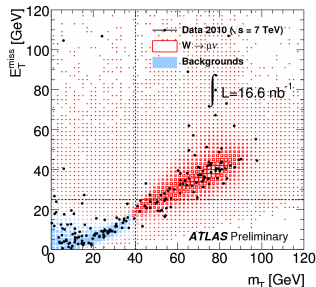
→ after
 $E_t > 25 \text{ GeV}$
 cut



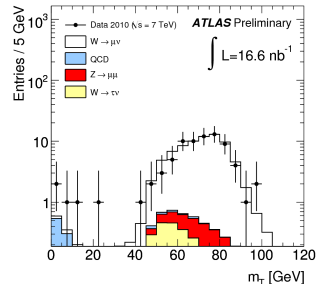
$W^\pm \rightarrow \mu^\pm \nu$: backgrounds and selection at LHC



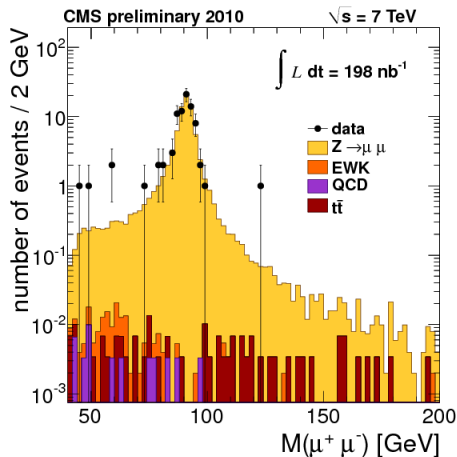
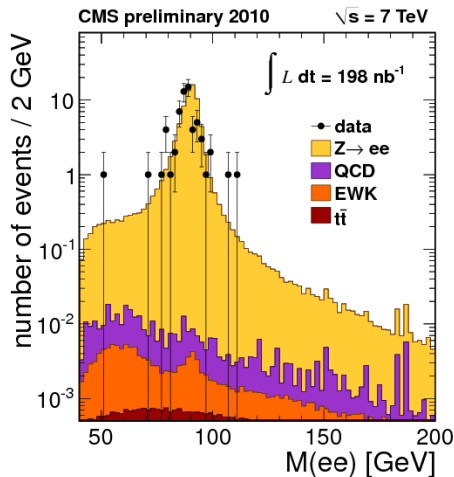
2-dim. kinem.
 selection:
 $E_t > 25 \text{ GeV}$
 $M_T > 40 \text{ GeV}$
 72 cand.



→ after
 $E_t > 25 \text{ GeV}$
 cut



$Z \rightarrow \ell^+ \ell^-$: backgrounds and signal



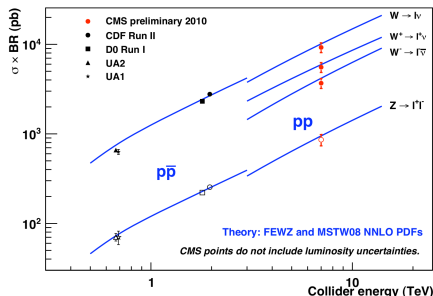
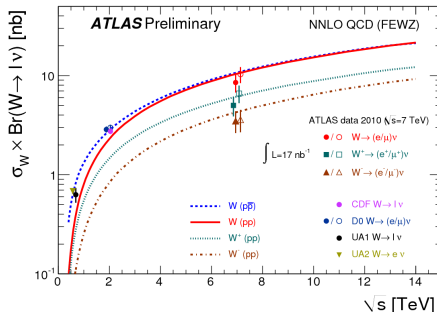
→ very clear, almost background free signature, especially for $Z \rightarrow \mu^+ \mu^-$
due to the smaller jet → lepton fake rate

W/Z production cross sections

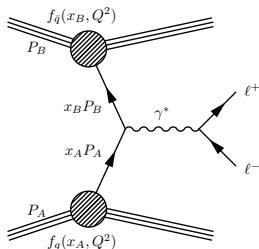
$$\sigma_{\text{tot}} = \sigma_{W/Z} \times \mathcal{B}(W \rightarrow \ell\nu / Z \rightarrow \ell\ell)$$

$$= \frac{N_{W/Z}^{\text{obs}} - N^{\text{bkgd}}}{A_{W/Z} C_{W/Z} L}$$

- $N_{W/Z}^{\text{obs}}$: # of observed cand. events
 - N^{bkgd} : # of background events
 - $A_{W/Z}$: geometrical acceptance
 - $C_{W/Z}$: reconstruction/selection efficiency
 - L : integrated luminosity
 - LHC meas. still limited by statistics
 - Tevatron meas. limited by systematic uncert. (luminosity, efficiencies)
 - well described by $\mathcal{O}(\alpha_s^2)$ QCD
 - uncert. of prediction $\sim 4\%$ (PDFs and QCD scale)
- ⇒ could provide alternative luminosity determination



Phenomenology of W/Z production



- lepton pair production in the Drell-Yan model
- invariant mass of lepton pair $M = M_{\ell^+\ell^-}$
- parton momentum fraction x
- parton distribution functions $f_{q,\bar{q}}(x_i, Q^2)$
- factorization:

PDFs $\otimes$ fundamental $2 \rightarrow 2$ process ($q\bar{q} \rightarrow \ell^+\ell^-$)

$$\Rightarrow \sigma_{AB \rightarrow \ell^+\ell^-} = \sum_q \int dx_A dx_B f_{A,q}(x_A) f_{B,\bar{q}}(x_B) \hat{\sigma}_{q\bar{q} \rightarrow \ell^+\ell^-} [+(q \leftrightarrow \bar{q})]$$

- if $M \ll M_Z \rightarrow$ only γ^* contribution, in analogy to $e^+e^- \rightarrow \mu^+\mu^-$:

$$\hat{\sigma}_{q\bar{q} \rightarrow \ell^+\ell^-} = \frac{1}{N} Q_q^2 \frac{4\pi\alpha^2}{3\hat{s}}$$

- $\hat{s} = M^2$: cm energy² of $q\bar{q}$ annihilation
- $1/N = 1/3$: probability that $q\bar{q}$ is colorless

- for larger M^2 also Z exchange and $\gamma^* Z$ interference contribute:

$$\hat{\sigma}_{q\bar{q} \rightarrow \ell^+ \ell^-} = \frac{1}{N} \frac{4\pi\alpha^2}{3\hat{s}} \left[\underbrace{Q_q^2}_{\gamma^*} - \underbrace{Q_q \frac{\sqrt{2}G_F M_Z^2}{4\pi\alpha} g_V^\ell g_V^q \Re(\chi(\hat{s}))}_{\gamma^* Z} + \underbrace{\frac{G_F^2 M_Z^4}{8\pi^2\alpha^2} (g_V^{\ell^2} + g_A^{\ell^2})(g_V^{q^2} + g_A^{q^2}) |\chi(\hat{s})|^2}_{Z} \right]$$

g_V, g_A vector and axial-vector couplings of the Z to q and ℓ

Z -propagator (Breit-Wigner) $\chi(\hat{s}) = \frac{\hat{s}}{\hat{s} - M_Z^2 + iM_Z\Gamma_Z}$

- with $|\chi(\hat{s})|^2 \stackrel{\Gamma_Z \ll 1}{\approx} \frac{\pi\hat{s}}{M_Z\Gamma_Z} \delta(\hat{s} - M_Z^2)$ follows for $M \approx M_Z$

$$\hat{\sigma}_{q\bar{q} \rightarrow Z \rightarrow \ell^+ \ell^-} = \underbrace{\frac{\sqrt{2}\pi}{N} G_F M_Z^2 (g_V^{q^2} + g_A^{q^2}) \delta(\hat{s} - M_Z^2)}_{\hat{\sigma}_{q\bar{q} \rightarrow Z}} \times \underbrace{\frac{\Gamma(Z \rightarrow \ell^+ \ell^-)}{\Gamma_Z}}_{\mathcal{B}(Z \rightarrow \ell^+ \ell^-)}$$

- partial width $\Gamma(Z \rightarrow f\bar{f}) = N_C \frac{G_F M_Z^3}{6\sqrt{2}\pi} (g_V^{f^2} + g_A^{f^2})$
 $N_C = 1 (3)$ for leptons (quarks)
- full width Γ_Z
- branching fraction $\mathcal{B}(Z \rightarrow \ell^+ \ell^-) = \frac{\Gamma(Z \rightarrow \ell^+ \ell^-)}{\Gamma_Z}$

in analogy: W boson production

$$\hat{\sigma}_{q\bar{q}' \rightarrow W} = \frac{\sqrt{2}\pi}{3} G_F M_W^2 |V_{qq'}|^2 \delta(\hat{s} - M_W^2)$$

- $V_{qq'}$: corresponding element of the Cabbibo-Kobayashi-Maskawa (CKM) matrix
transition probability for $q_i \rightarrow q_j$ proportional to $|V_{qq'}|^2$

- partial width: $\Gamma(W^- \rightarrow f\bar{f}') = N_C \frac{G_F M_W^3}{6\sqrt{2}\pi}$

W couples equally to all left handed fermions, thus:

$$\mathcal{B}(W^- \rightarrow \ell^- \nu) = 1/9, (\ell = e, \mu, \tau)$$

$$\mathcal{B}(W^- \rightarrow \text{hadrons}) = 2/3, (\bar{u}d', \bar{c}s' \text{ contribution})$$

Γ_W : indirect measurement

- can be derived from the W/Z cross-section ratio

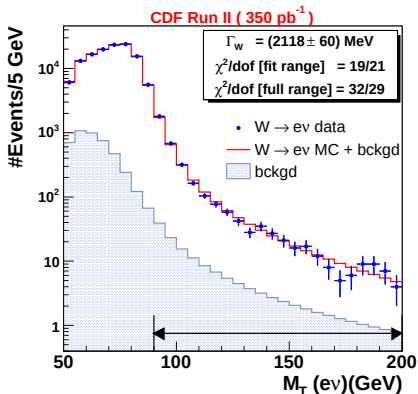
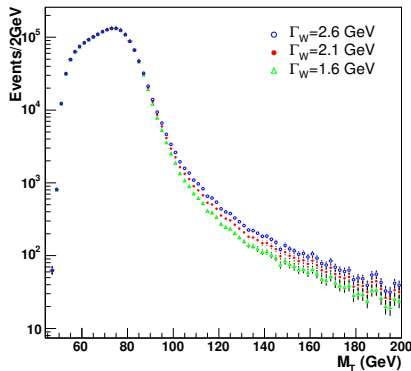
$$R = \frac{\sigma(W) \times \mathcal{B}(W \rightarrow l\nu)}{\sigma(Z) \times \mathcal{B}(Z \rightarrow ll)}$$
$$= \frac{\sigma_t(W)}{\sigma_t(Z)} \times \frac{\Gamma(W \rightarrow l\nu)}{\Gamma(W)} \times \frac{\Gamma(Z)}{\Gamma(Z \rightarrow ll)}$$

- perturbative QCD
- electroweak theory
- LEP measurement

$\Rightarrow \Gamma(W)$

CDF Run II: $\Gamma(W) = 2092 \pm 42 \text{ MeV}$

Γ_W : direct measurement



- from the tails in the $M_T(e\nu)$ distribution
 - larger tails for Breit-Wigner (Γ_W) compared to Gaussian (resolution)
- larger systematic uncertainty compared to indirect measurement (energy resolution for leptons and hadronic remnant)
- CDF+DØ combination: $\Gamma(W) = 2046 \pm 49 \text{ MeV}$

Boson rapidity and parton momentum fraction

- rapidity of particle with E , p_z : $y \equiv \frac{1}{2} \ln \left(\frac{E+p_z}{E-p_z} \right)$

note: if $p \gg m$ (i.e. **not** for W/Z):

$$y \approx \frac{1}{2} \ln \left(\frac{|\vec{p}|+p_z}{|\vec{p}|-p_z} \right) = -\ln \left(\tan \frac{\theta}{2} \right) \equiv \eta$$

η : pseudo-rapidity

- boson y is related (at leading order) to Bjorken $x_{1,2}$ of incoming partons with 4-momenta

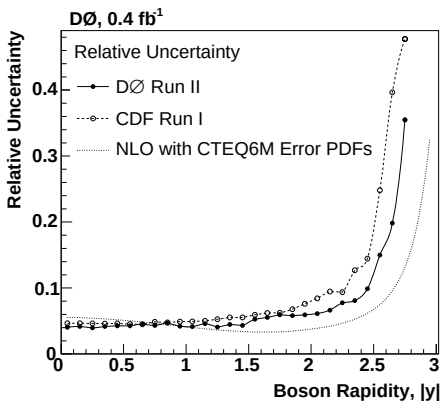
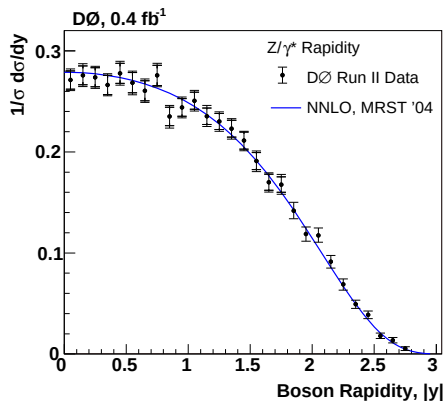
$$p_1 = \frac{\sqrt{s}}{2}(x_1, 0, 0, x_1), \quad p_2 = \frac{\sqrt{s}}{2}(x_2, 0, 0, -x_2)$$

$$\Rightarrow 1. \hat{s} = (p_1 + p_2)^2 = x_1 x_2 s = M_{Z/W}^2$$

$$\Rightarrow 2. y = \frac{1}{2} \ln \frac{(x_1+x_2)+(x_1-x_2)}{(x_1+x_2)-(x_1-x_2)} = \ln \left(\frac{x_1}{x_2} \right)^{1/2}$$

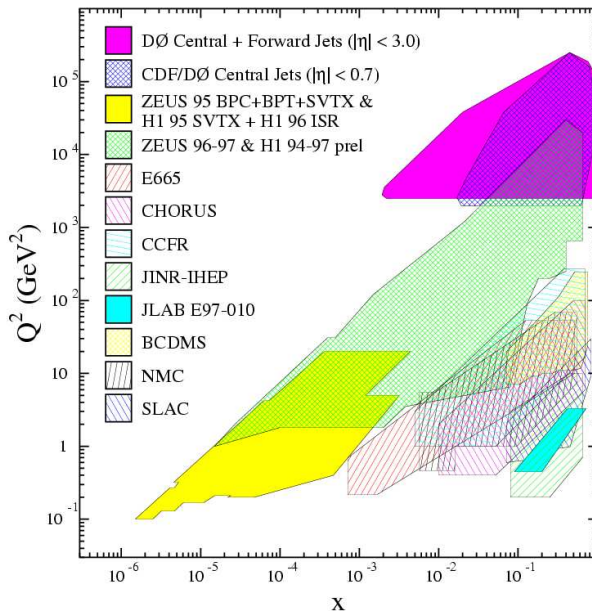
$$\stackrel{1.+2.}{\Rightarrow} x_{1,2} = M_{Z/W} / \sqrt{s} \cdot e^{\pm y}$$

Z rapidity



- at large $|y|$ (forward production): sensitivity to PDFs at large and small x and $Q^2 \approx M_Z^2$

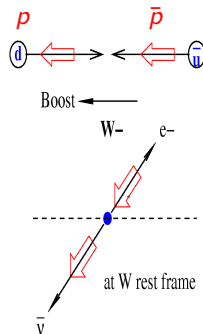
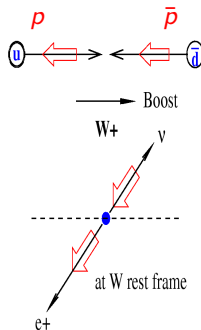
Measurements on proton structure



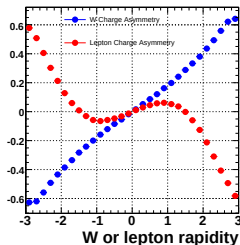
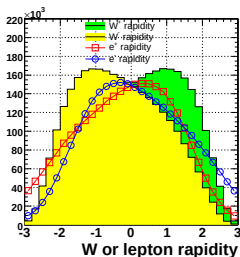
W charge asymmetry

- sensitive to PDFs
- u quarks carry larger average x than d quarks ($\leftarrow F_2^p/F_2^n$)
- $u\bar{d} \rightarrow W^+$ preferentially boosted along p direction
- W charge asymmetry:

$$A(y) = \frac{d\sigma^+/dy - d\sigma^-/dy}{d\sigma^+/dy + d\sigma^-/dy}$$
- $A(\eta)$ is standard observable

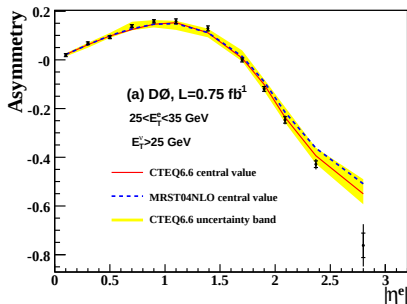
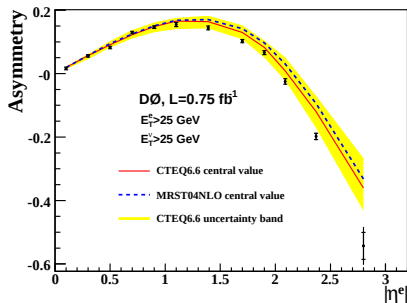


- convolution of W prod. asymmetry and (V-A) decay
- assumption: SM $W \rightarrow l\nu$ coupling
- cancellation of syst. uncert. related to lepton reconstruction



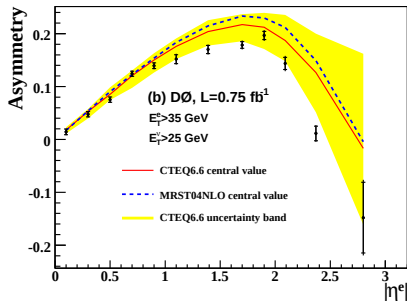
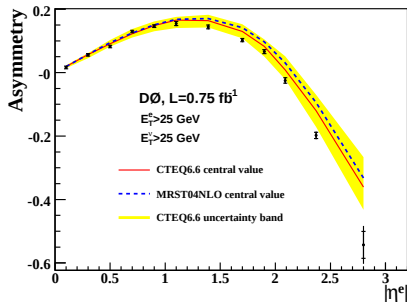
$A(|\eta_e|)$ in $W \rightarrow e\nu$ events

- exp. challenge: lepton charge determ.
- momentum resolution degrades with p_T :
 $dp_T/p_T \propto p_T$
- *bremsstrahlung* for electrons
- charge mis-ID rate:
0.2% ($|\eta_e| \approx 0$) to 9% ($|\eta_e| \approx 3$)
- dominant syst. uncert. from charge mis-ID and multi-jet bgd.
- $A(|\eta_e|)$ in different $E_T(e)$ bins: probe different $y_W (\rightarrow x)$ for fixed $|\eta_e|$
- yellow band: PDF uncertainty obtained from global fit to previous data (CTEQ6.6)
- for nearly all $|\eta_e|$ bins: experimental uncertainties much smaller than CTEQ6.6 band
 $\Rightarrow$ expect impact on new PDF fits with improved precision



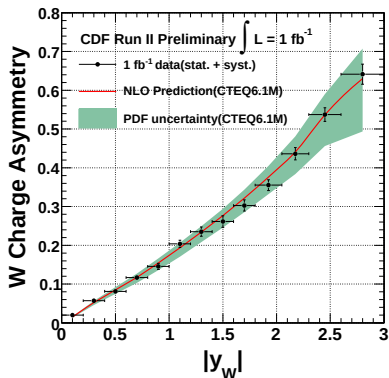
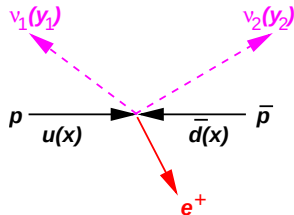
$A(|\eta_e|)$ in $W \rightarrow e\nu$ events

- exp. challenge: lepton charge determ.
- momentum resolution degrades with p_T :
 $d p_T / p_T \propto p_T$
- *bremsstrahlung* for electrons
- charge mis-ID rate:
0.2% ($|\eta_e| \approx 0$) to 9% ($|\eta_e| \approx 3$)
- dominant syst. uncert. from charge mis-ID and multi-jet bgd.
- $A(|\eta_e|)$ in different $E_T(e)$ bins: probe different $y_W (\rightarrow x)$ for fixed $|\eta_e|$
- yellow band: PDF uncertainty obtained from global fit to previous data (CTEQ6.6)
- for nearly all $|\eta_e|$ bins: experimental uncertainties much smaller than CTEQ6.6 band
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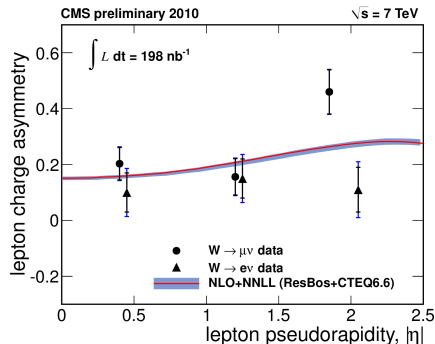
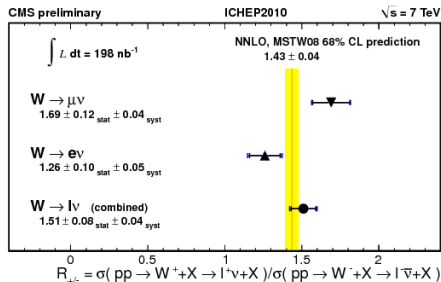
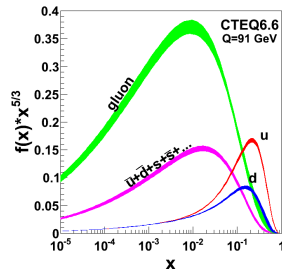
Direct measurement of $A(|y_W|)$

- reconstruct y_W distribution with M_W constraint
 - weight both ν solutions with probability given by production and decay
 - iterate as weight depends on y_W
- $\Rightarrow$ improved statistical precision w.r.t. $A(\eta_l)$
 - for fixed $y_{W^\pm}$: $\eta_{e^+} \neq \eta_{e^-}$
- $\Rightarrow$ different acceptance for W^+/W^-
- $W \rightarrow e\nu$, 1 fb^{-1}
 - largest syst. uncert.: e-ID efficiency, modeling of hadronic recoil
 - provides new constraints on PDF fits



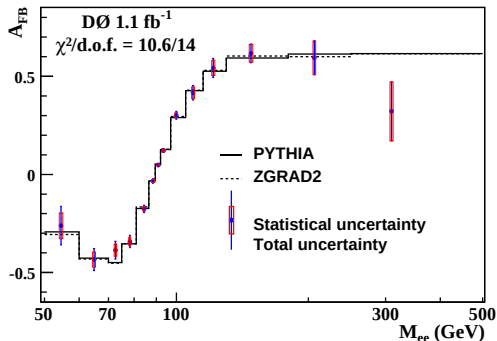
$A(|\eta_\ell|)$ in $W \rightarrow \ell\nu$ events at LHC

- $A(\eta_\ell) = \frac{d\sigma^+/d\eta_\ell - d\sigma^-/d\eta_\ell}{d\sigma^+/d\eta_\ell + d\sigma^-/d\eta_\ell}$
- pp collisions: no valence anti-quarks as in $p\bar{p}$ collisions
- $u + \bar{d} \rightarrow W^+$, $d + \bar{u} \rightarrow W^-$
 $\Rightarrow \sigma(W^+) > \sigma(W^-)$
 - $\bar{x}(u) > \bar{x}(d)$, $\bar{x}(\bar{u}) \approx \bar{x}(\bar{d})$
 $\Rightarrow |\overline{y}|(W^+) > |\overline{y}|(W^-)$



Forward-backward asymmetry in $Z \rightarrow \ell^+ \ell^-$

$$A_{FB} = \frac{N_F - N_B}{N_F + N_B}$$



- first: a reminder of electroweak gauge theory

Electroweak coupling

gauge theory, unifies weak and electromagnetic coupling:

$$SU(2)_L \otimes U(1)_Y$$

$\vec{W}_\mu = (W_\mu^1, W_\mu^2, W_\mu^3)$ gauge field of $SU(2)_L$ with coupling constant g_w
couples only to left-(right-)handed (anti-)fermions

B_μ gauge field of $U(1)_Y$ with coupling constant g'
couples to hyper charge $Y \equiv 2(Q_{em} - I_3)$

Electroweak gauge bosons

rotation in $SU(2)_L \otimes U(1)_Y$ with angle θ_w ($\sin^2 \theta_w \approx 0.23$)

$$W_\mu^\pm = \frac{1}{\sqrt{2}}(W_\mu^1 \pm iW_\mu^2) \quad W^\pm$$

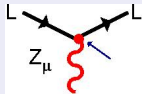
$$A_\mu = B_\mu \cos \theta_w + W_\mu^3 \sin \theta_w \quad \gamma$$

$$Z_\mu = -B_\mu \sin \theta_w + W_\mu^3 \cos \theta_w \quad Z$$

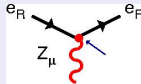
using γ couplings: $e = g_e = g' \cos \theta_w = g_w \sin \theta_w$

- ⇒ $W^\pm$ bosons (charged current) couple only to left handed fermions (parity is maximally violated)
- ⇒ Z bosons (neutral current) couple to both left and right handed fermions, but with different strength

Z boson couplings



$$\tilde{g}_L = \frac{e}{\sin \theta_w \cos \theta_w} g_L$$



$$\tilde{g}_R = \frac{e}{\sin \theta_w \cos \theta_w} g_R$$

$$g_L = I_3 - Q \sin^2 \theta_w$$

$$g_R = -Q \sin^2 \theta_w$$

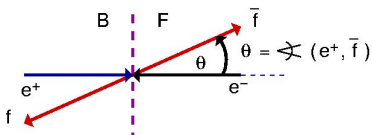
right and left handed couplings

$$g_V \equiv g_L + g_R = I_3 - 2Q \sin^2 \theta_w$$

$$g_A \equiv g_L - g_R = I_3$$

vector and axial vector couplings

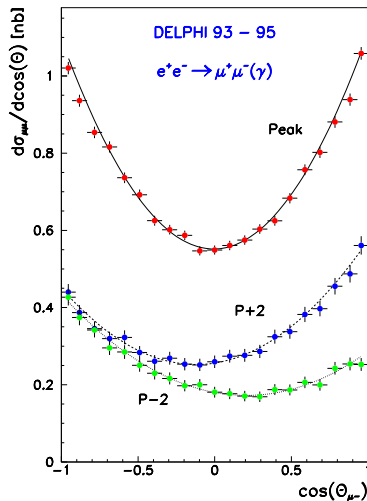
⇒ forward-backward asymmetry in $e^+e^- \rightarrow f\bar{f}$



$$A_{FB} = \frac{N_F - N_B}{N_F + N_B}$$

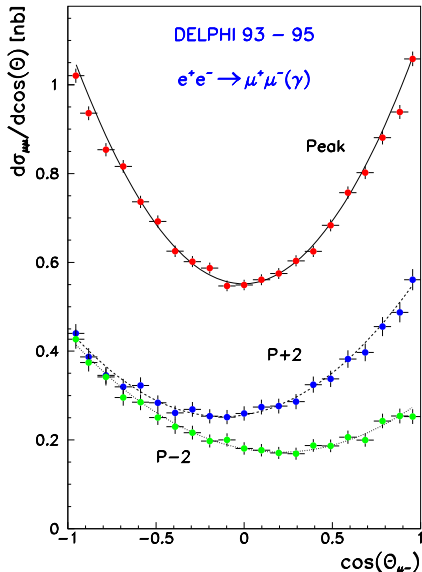
- at $\sqrt{s} = M_Z$: due to different g_L/g_R , g_V/g_A couplings
 $A_{FB} \propto g_V^e \cdot g_V^f$, small as
 $g_V = I_3 - 2Q \sin^2 \theta_w$ and $\sin^2 \theta_w \approx 0.23$
- around Z resonance: due to $\gamma^* Z$ interference

Peak: $\sqrt{s} \approx M_Z = 91.2 \text{ GeV}$
 P-2: $\sqrt{s} \approx 89.5 \text{ GeV}$
 P+2: $\sqrt{s} \approx 93.0 \text{ GeV}$

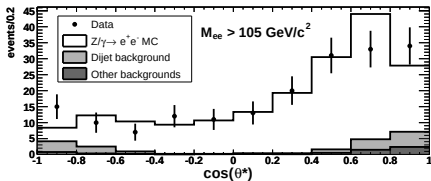
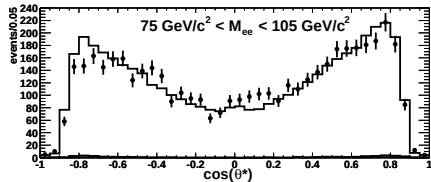
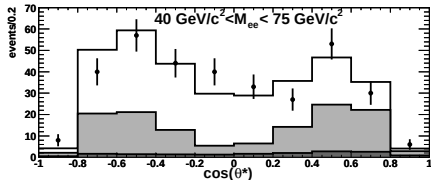


Forward-backward asymmetry in $Z/\gamma^* \rightarrow \ell^+ \ell^-$

LEP



CDF RunII Preliminary



- $A_{FB} = \frac{\sigma(\cos\theta^- > 0) - \sigma(\cos\theta^- < 0)}{\sigma(\cos\theta^- > 0) + \sigma(\cos\theta^- < 0)}$

$\theta^- = \angle(\ell^-, p)$ in dilepton rest frame

- (V-A) coupling: $\gamma_\mu(v_q - a_q\gamma^5)$
standard model:

$$a_q = I_q^3$$

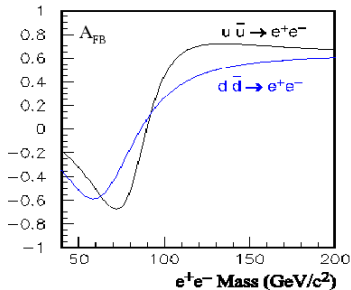
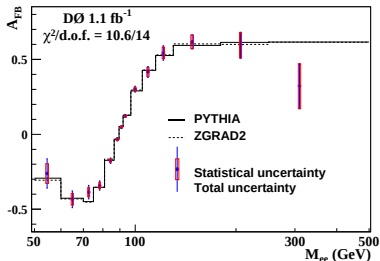
$$v_q = I_q^3 - 2e_q \sin^2 \theta_w$$

different notation: $g_{V/A}$

$$A_{FB}(s = M_Z^2) \approx \frac{3}{4} \mathcal{A}_q \mathcal{A}_\ell \otimes PDFs$$

with $\mathcal{A}_f = 2 \frac{g_{A,f} g_{V,f}}{g_{A,f}^2 + g_{V,f}^2}$

- sensitive to $\sin^2 \theta_W^{\text{eff}}$ (but less sensitive than LEP)
- exchange of additional gauge boson Z' would change A_{FB} around $m_{Z'}$



- $A_{FB} = \frac{\sigma(\cos\theta^- > 0) - \sigma(\cos\theta^- < 0)}{\sigma(\cos\theta^- > 0) + \sigma(\cos\theta^- < 0)}$

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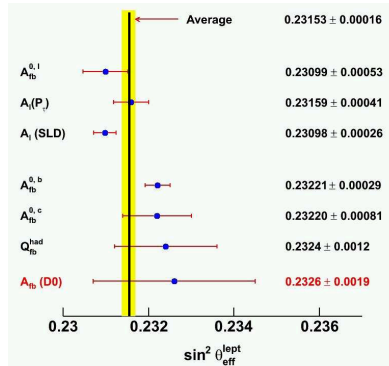
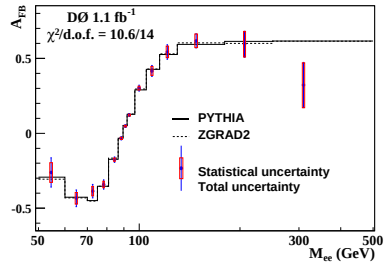
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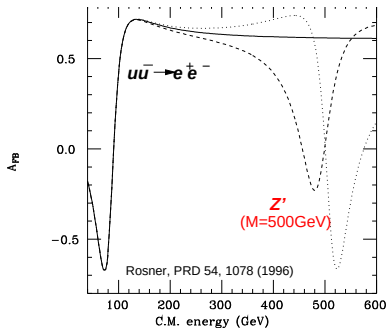
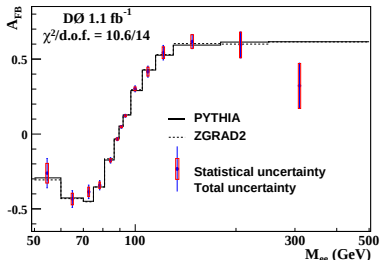
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different notation: $g_{V/A}$

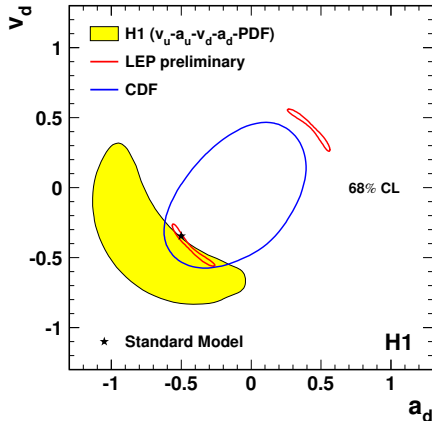
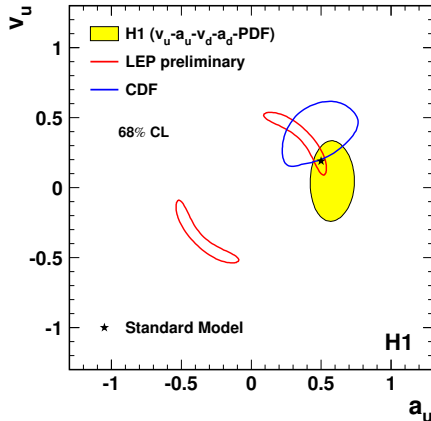
$$A_{FB}(s = M_Z^2) \approx \frac{3}{4} \mathcal{A}_q \mathcal{A}_\ell \otimes PDFs$$

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- sensitive to $\sin^2 \theta_W^{\text{eff}}$ (but less sensitive than LEP)
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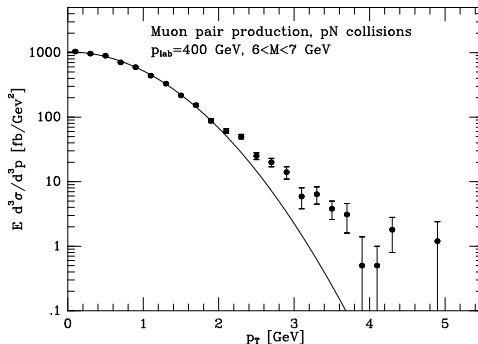
u/d quark couplings to Z



- CDF (72 pb^{-1}): A_{FB} in Drell-Yan lepton pair production
- H1: EW+QCD fit (HERA, deep inelastic ep scattering)
- LEP: sign and $v_q \leftrightarrow a_q$ ambiguities

QCD corrections

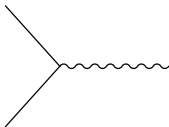
p_T of lepton pair in Drell-Yan production, $p_\mu(\gamma^*) = p_\mu(\ell^+) + p_\mu(\ell^-)$



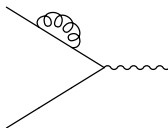
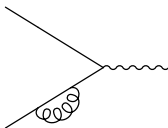
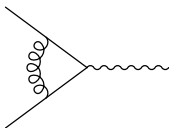
- graph: expectation from intrinsic k_T of quarks inside proton
 assumption: Gaussian $\rho(k_T) = b/\pi \exp(-bk_T^2)$ with $\langle k_T \rangle = \sqrt{\pi/(4b)} = 760$ MeV
 compare: Fermi momenta of neutrons and protons in nucleus:
 $p_F \approx \frac{\hbar}{R_0} \left(\frac{9\pi}{8} \right)^{1/3} \approx 250$ MeV
- excess at large p_T due to QCD corrections, expectation from $q\bar{q} \rightarrow \gamma^* g$ scattering:
 $\frac{d^2\sigma}{d^2p_T} \sim \frac{\alpha_s(p_T^2)}{p_T^4}$

Drell-Yan process: Feynman diagrams at LO and NLO

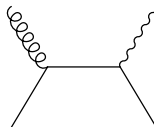
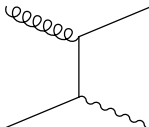
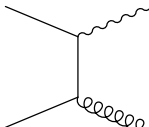
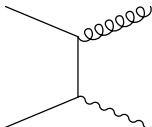
- Born level (lowest order): $\propto \alpha_s^0$



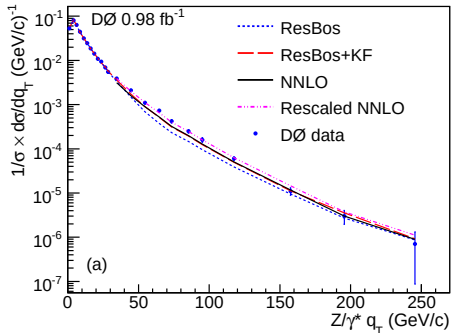
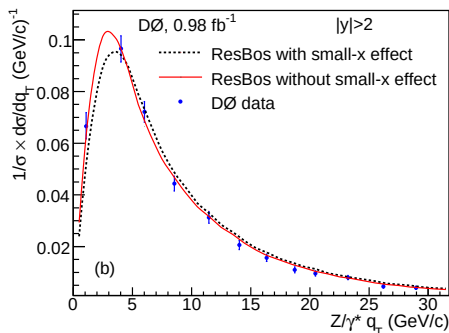
- virtual corrections: $\propto \alpha_s$



- real corrections: $\propto \alpha_s$



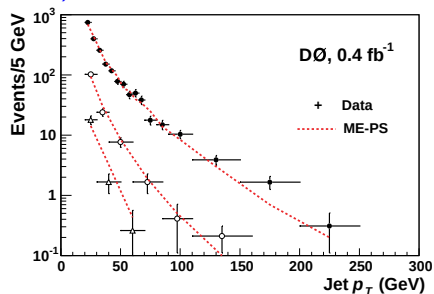
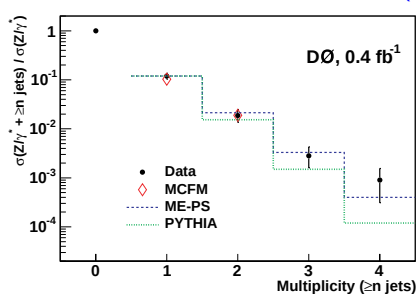
Z transverse momentum



- QCD corrections result in $p_T(Z)$
 - **small $p_T(Z)$** : multiple soft gluon radiation (resummation of leading terms $\propto \alpha_s^n \ln^{2n-1} \frac{M_Z^2}{p_T^2}$), in addition non-perturbative form factor (incl. parton intrinsic k_T)
 - RESBOS event generator
 - **large $p_T(Z)$** : fixed-order perturbative QCD, *next-to-next-to-leading-order* (NNLO), $\mathcal{O}(\alpha_s^2)$

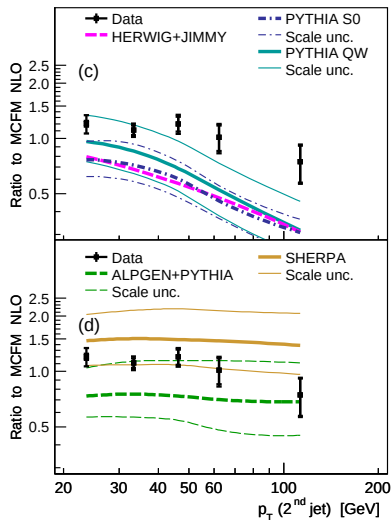
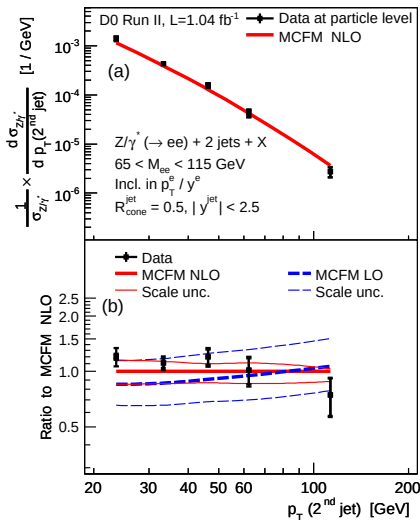
Associated production of jets with W/Z

- production of associated jets via QCD corrections
cross section for $Z + n$ jet prod. (LO): $\sigma_{Z+n\text{jets, LO}} \propto \alpha_s^n$
- jet multiplicity and p_T in $Z(\rightarrow e^+e^-)$ events:



- MCFM: NLO pQCD, matrix elements
- Pythia: numerical simulation of successive gluon and quark radiation (*parton shower*)
- ME-PS: matching of matrix element calculations (LO) with parton shower

in detail: $N^{\text{Jets}} \geq 2$, p_T of 2. Jet, $p_T^{\text{jet}_1} \geq p_T^{\text{jet}_2}$



- p_T shape well described by NLO QCD (MCFM) and ME-PS generators but large scale uncertainty for LO and ME-PS
- parton-shower generators: spectrum too soft

W mass: techniques

based on different observables:

- lepton transv. momentum $p_T(\ell)$
 - *Jacobian* edge at $M_W/2$
 - knowledge of $p_T(W)$ is essential
 - independent of moderate $\cancel{E}_t$ resolution

- transversal mass

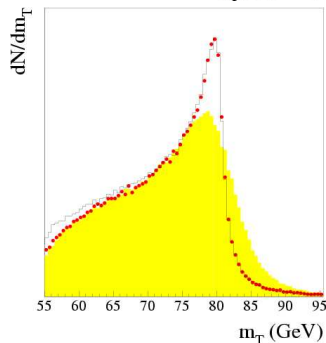
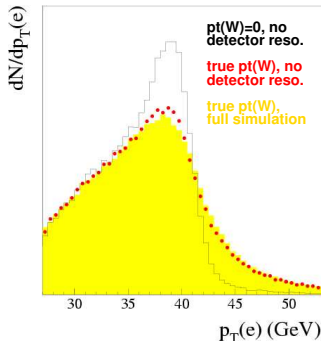
$$M_T = \sqrt{2p_T(e)\cancel{E}_t [1 - \cos \Delta\phi]}$$

- marginally affected by $p_T(W)$
 - largely affected by detector resolution
 - in total: highest precision
- (also: $\cancel{E}_t \rightarrow p_T(\nu)$)

⇒ W production mechanism and detector (energy scale and resolution) needs to be very well known!

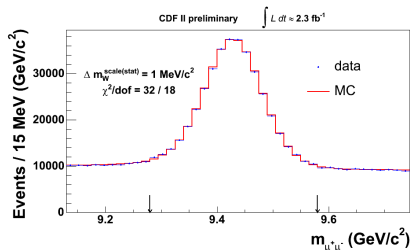
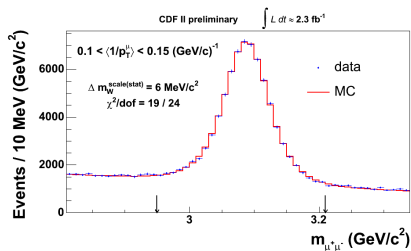
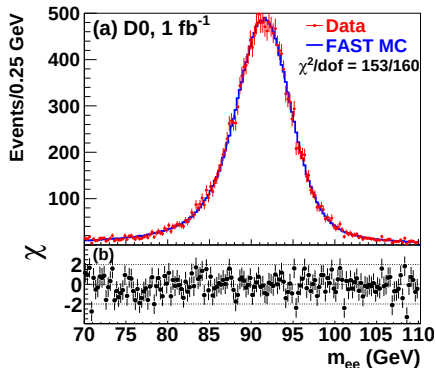
- Z events as calibration tool

$$p_T(Z) \rightarrow p_T(W)$$



Calibration of energy scale and resolution

- using M_Z
LEP: $\Delta M_Z = 2.1 \text{ MeV}$
problem: $\sigma_Z \cdot \mathcal{B}(Z \rightarrow \ell\ell) \approx 0.1 \cdot \sigma_W \cdot \mathcal{B}(W \rightarrow \ell\nu)$
- using quarkonia resonances (J/ψ , $\Upsilon(1)$)
challenge: extrapolation to $p_T(\ell) \approx M_W/2$



W mass measurement

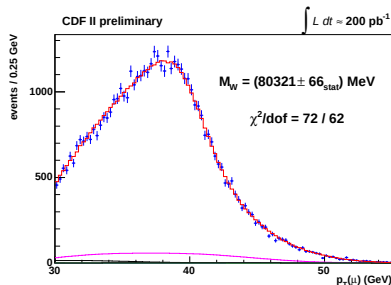
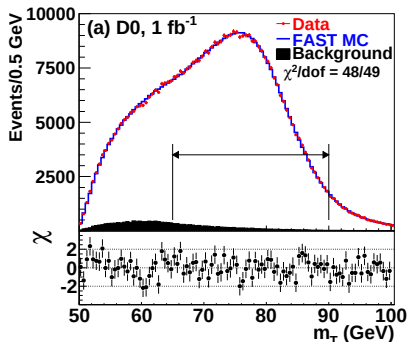
- CDF (200 pb⁻¹): $W \rightarrow e\nu, \mu\nu$
- DØ (1 fb⁻¹): $W \rightarrow e\nu$
- measurements using
 $m_T, p_T(\ell), \cancel{E}_t \quad (\rightarrow p_T(\nu))$
- systematic uncert. (DØ):

Source	ΔM_W (MeV)		
	m_T	p_T^e	$\cancel{E}_T$
Electron energy calibration	34	34	34
Electron resolution model	2	2	3
Electron shower modeling	4	6	7
Electron energy loss model	4	4	4
Hadronic recoil model	6	12	20
Electron efficiencies	5	6	5
Backgrounds	2	5	4
Experimental Subtotal	35	37	41
PDF	10	11	11
QED	7	7	9
Boson p_T	2	5	2
Production Subtotal	12	14	14
Total	37	40	43

DØ: $M_W = 80401 \pm 43 \text{ MeV}$

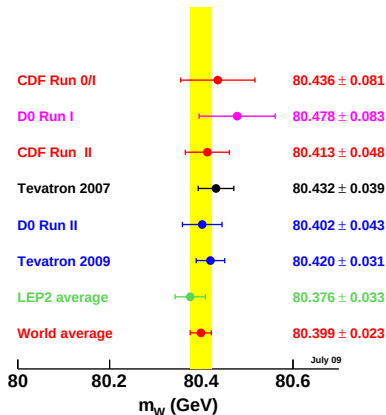
(stat: 21 MeV, syst: 38 MeV)

⇒ most precise single measurement



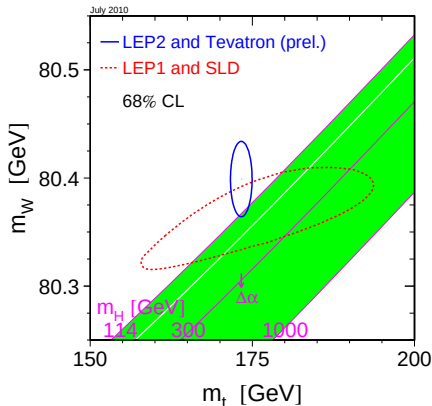
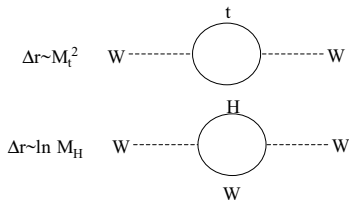
M_W mass combination

- Tevatron: CDF/DØ combination: $\Delta M_W = 33 \text{ MeV}$
- LEP: M_W measured by all 4 exp. $\rightarrow$ ADLO combination: $\Delta M_W = 33 \text{ MeV}$
- Tevatron/LEP combination: $M_W = 80399 \pm 23 \text{ MeV}$



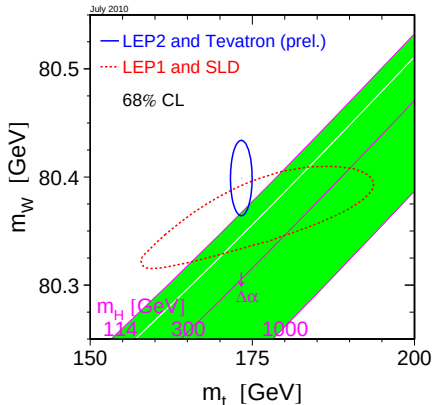
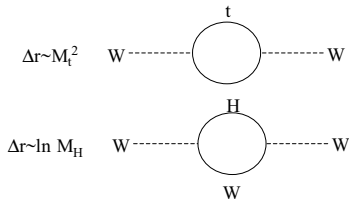
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- **Tevatron/LEP combination:** $M_W = 80399 \pm 23 \text{ MeV}$
- for Higgs mass constraint, current $\Delta M_{\text{top}} = 1.1 \text{ GeV} \rightarrow \Delta M_W \approx 6 \text{ MeV}$



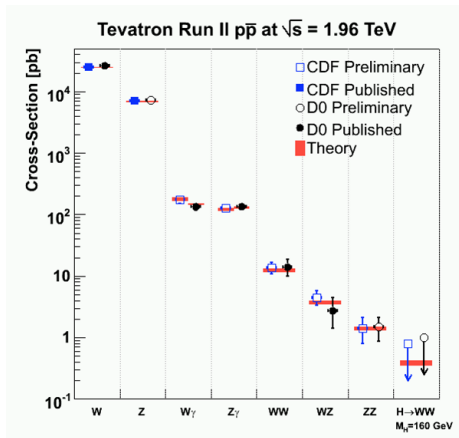
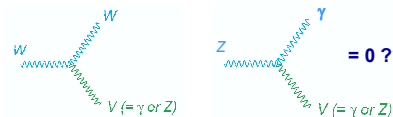
M_W mass combination

- **Tevatron:** CDF/DØ combination: $\Delta M_W = 33 \text{ MeV}$
- **LEP:** M_W measured by all 4 exp. $\rightarrow$ ADLO combination: $\Delta M_W = 33 \text{ MeV}$
- **Tevatron/LEP combination:** $M_W = 80399 \pm 23 \text{ MeV}$
- for Higgs mass constraint, current $\Delta M_{\text{top}} = 1.1 \text{ GeV} \rightarrow \Delta M_W \approx 6 \text{ MeV}$
- **ATLAS (10 fb^{-1}):** (over?-)optimistic study: $\Delta M_W \approx 7 \text{ MeV}$ for e and μ channel separately

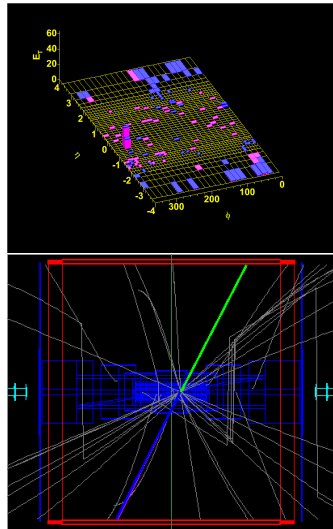
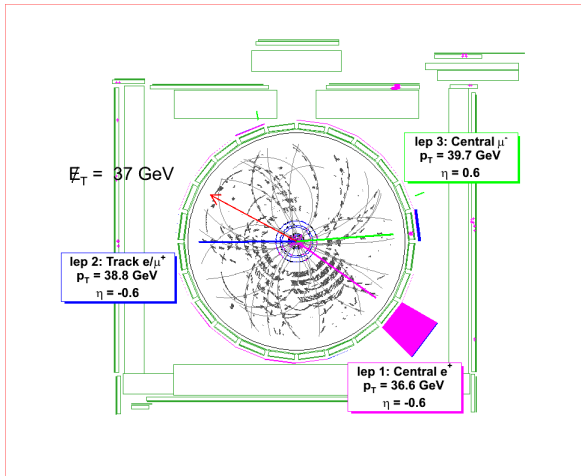


Boson pair production

- non-Abelian structure of SM: probe trilinear gauge boson coupling
SM: coupling of only neutral bosons (Z, γ) is forbidden
- sensitive to new physics via anomalous couplings
- TeV/LHC and LEP complementary
 - at TeV/LHC higher $\sqrt{s}$ and p_T
 - sensitivity to different combinations of couplings
- background to and reference signal for numerous searches ($H \rightarrow WW/ZZ$, SUSY (trilepton))
- small cross sections
→ both CDF/DØ have $\sim 8 \text{ fb}^{-1}$ recorded

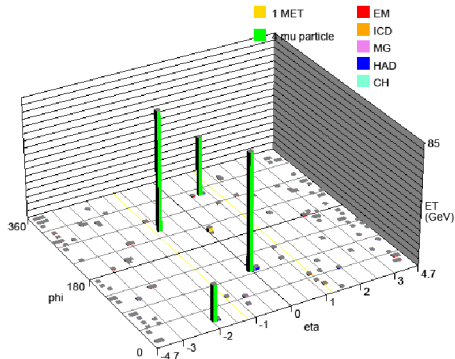


WZ candidate (CDF)



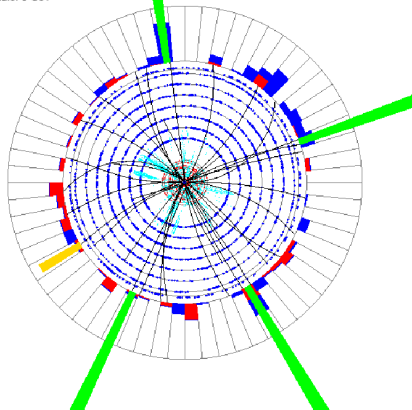
$ZZ \rightarrow 4\mu$ candidate (DØ)

Run 232216 Evt 15136574 Mon Apr 16 12:01:04 2007

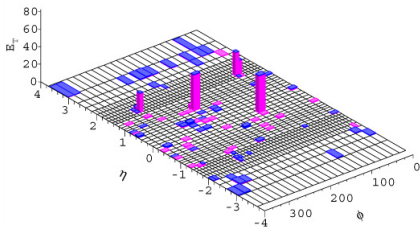
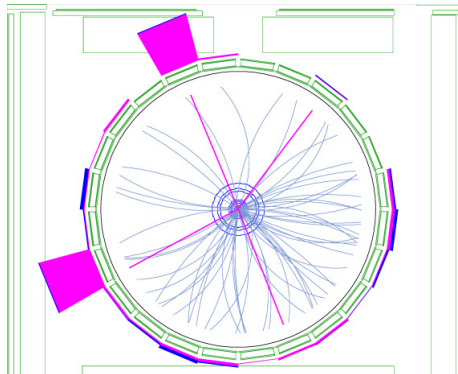


Run 232216 Evt 15136574 Mon Apr 16 12:01:04 2007

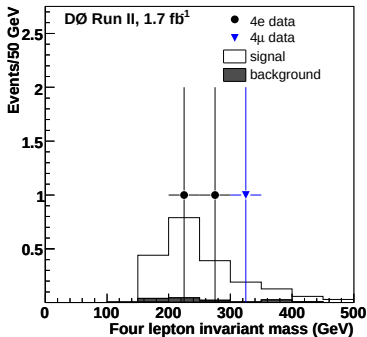
ET scale: 3 GeV



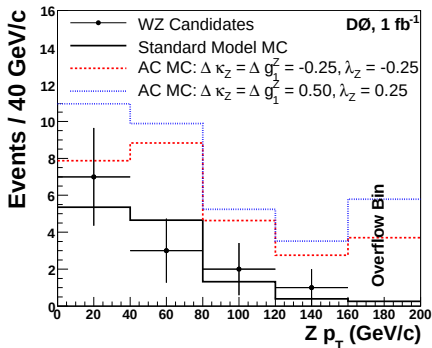
$ZZ \rightarrow 4e$ candidate (CDF)



ZZ



WZ



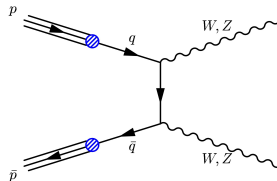
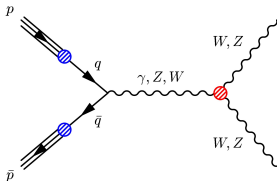
ZZ:

- DØ: 5.7σ discovery $ZZ \rightarrow \ell\ell\ell'\ell'$ and $ZZ \rightarrow \ell\ell E_T$
- $\sigma = 1.60 \pm 0.63(\text{stat})^{+0.16}_{-0.17}(\text{syst}) \text{ pb}$, NLO-QCD: $\sigma = 1.4 \pm 0.1 \text{ pb}$

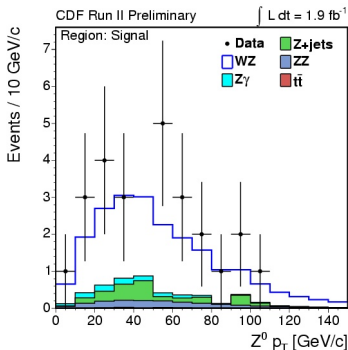
WZ:

- DØ: $\sigma = 2.7^{+1.7}_{-1.3} \text{ pb}$, CDF: $\sigma = 4.1 \pm 0.7 \text{ pb}$, NLO-QCD: $\sigma = 3.7 \pm 0.3 \text{ pb}$
- sensitive to WWZ vertex: anomalous couplings alter p_T^Z spectrum

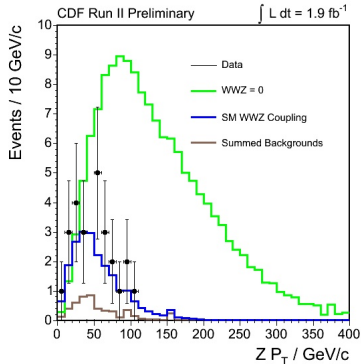
Trilinear gauge couplings



SM (both diagrams)



without trilinear coupling



Conclusions

- Physics with W and Z bosons at the Tevatron and LHC:
 - electroweak interaction, precision tests of the standard model (SM)
 - left/right handed couplings of quarks and leptons
 - (anomalous?) triple gauge couplings
 - precision measurement of W mass
 - indirect constraint on Higgs mass due to radiative corrections to M_W
 - interplay with strong interaction (QCD)
 - sensitive to parton distribution functions (PDFs)
 - associated production with jets (constraining QCD models)
 - standard candles for calibration due to leptonic final states
 - important (or even main) backgrounds for top, Higgs, Supersymmetry, LED, new strong interactions, new gauge bosons, etc.
 - essential to measure precisely standard model processes before claiming discoveries