Electroweak Physics

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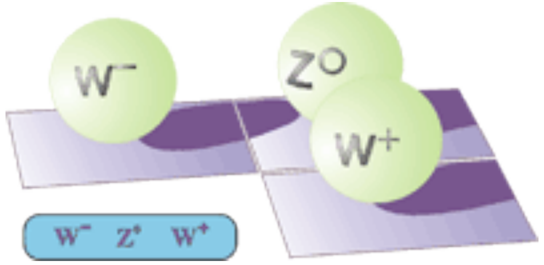
Contents



- The electroweak model and parameters
- Precision measurements of the W-boson and top-quark
- Boson pair production
- W and Z boson physics in Deep Inelastic Scattering

Electroweak Model

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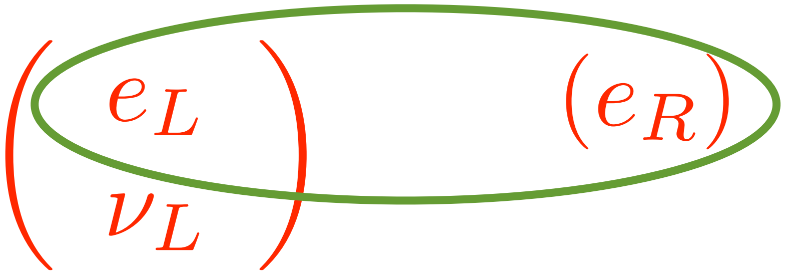

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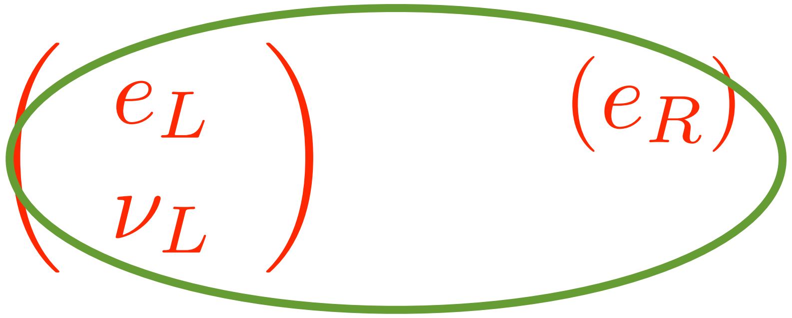

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- Three parameters, v, g_W and g'_W describe all couplings and boson masses.

Electroweak Parameters

- Electroweak model parameters ***v***, ***g*** $_W$ and ***g'*** $_W$ can be combined at tree level to obtain measurable quantities *e.g.*:

Mass of the ***W***-boson

$$M_W = \frac{v\, g_W}{2}$$

Weak mixing angle

$$\sin^2\theta_W = \frac{g_W'^2}{g_W^2 + g_W'^2}$$

W and ***Z*** masses

$$M_W = M_Z \cos\theta_W$$

Alpha-weak

$$\alpha_W = \frac{g_W^2}{4\pi}$$

Fermi-coupling constant

$$\frac{G_F}{\sqrt{2}} = \frac{g_W^2}{8M_W^2} = \frac{1}{2v^2}$$

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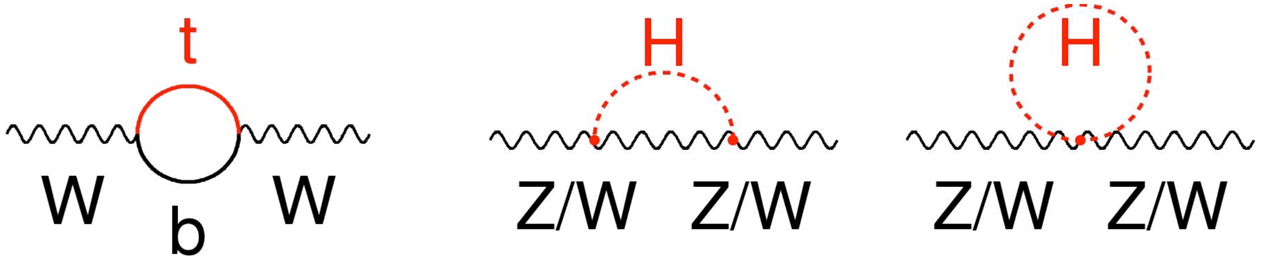


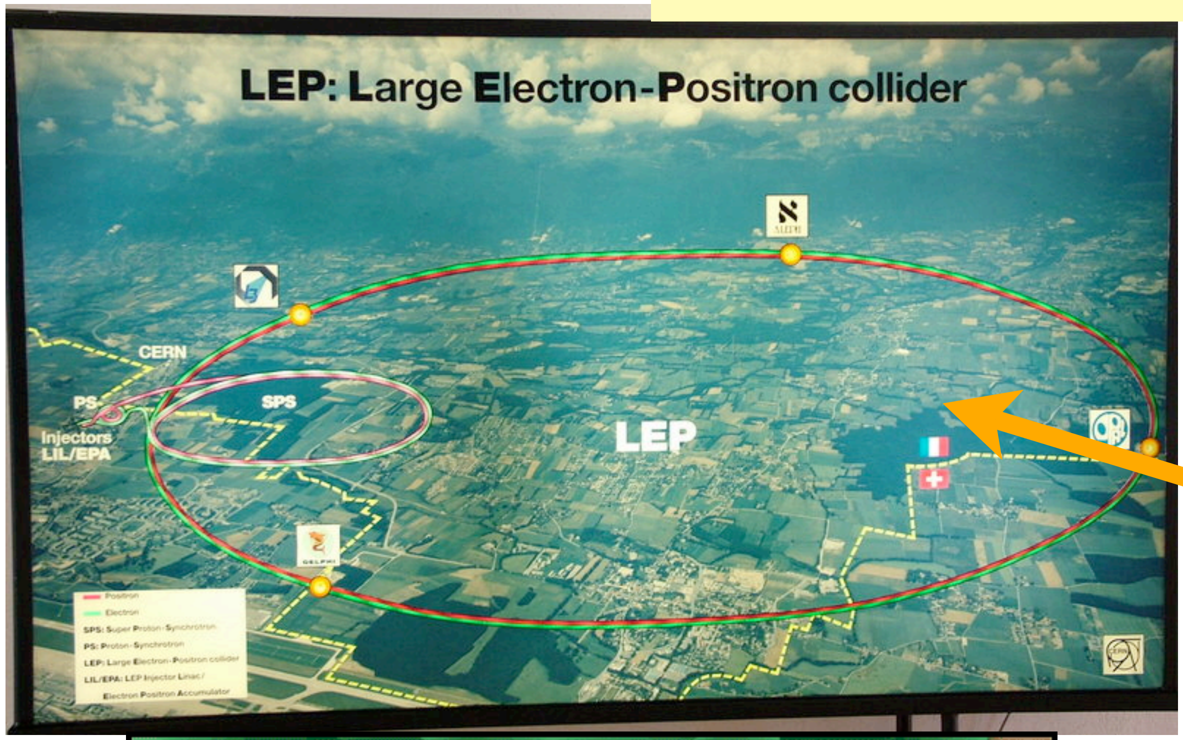
Including loop effects, measurements and predictions also depend on:

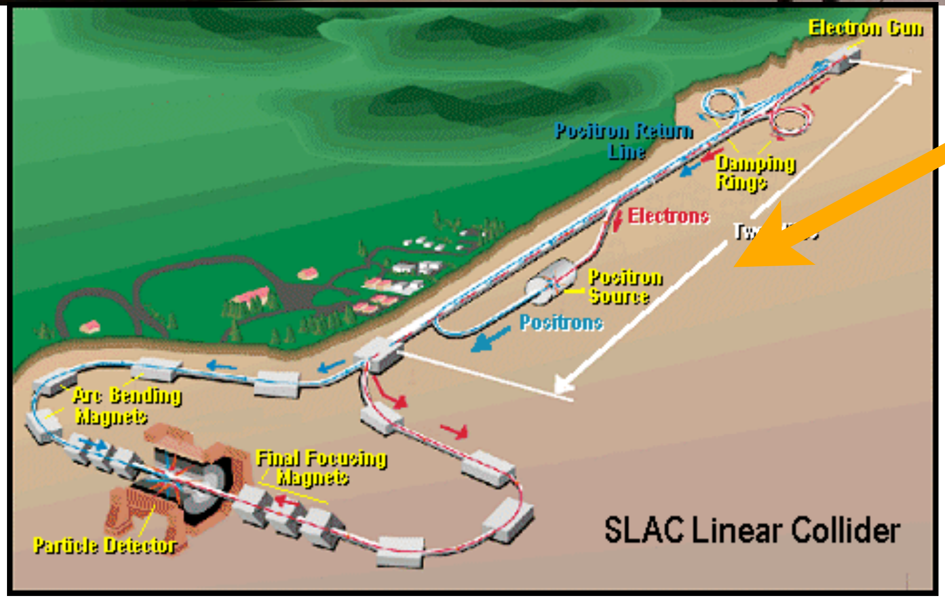
- masses of the fermions
  - ➡ m_{top} most influential as much more massive than other fermions
- mass of the Higgs boson $m_H = \sqrt{2\lambda}\, v$

Electroweak theory tells us nothing about fermion and Higgs masses.

Electroweak Precision Measurements

Very high Q^2 physics at LEP, SLC, and the Tevatron:
More than 1000 measurements with (correlated) uncertainties
Combined to 17 precision electroweak observables





	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02758 ± 0.00035	0.02767
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959
σ_{had}^0 [nb]	41.540 ± 0.037	41.478
R_l	20.767 ± 0.025	20.743
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01643
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1480
R_b	0.21629 ± 0.00066	0.21581
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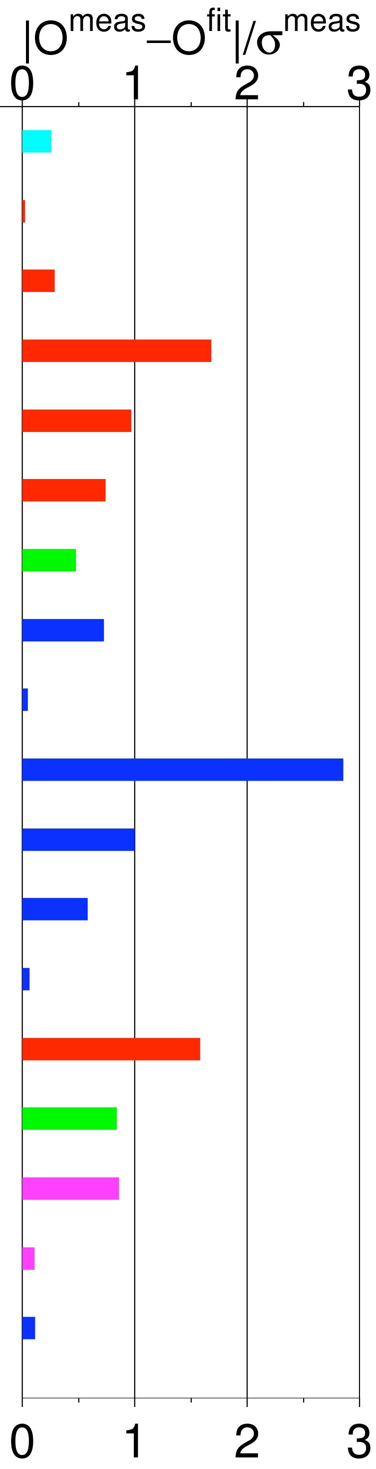
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1038
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1480
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.398 ± 0.025	80.377
Γ_W [GeV]	2.097 ± 0.048	2.092
m_t [GeV]	172.6 ± 1.4	172.8



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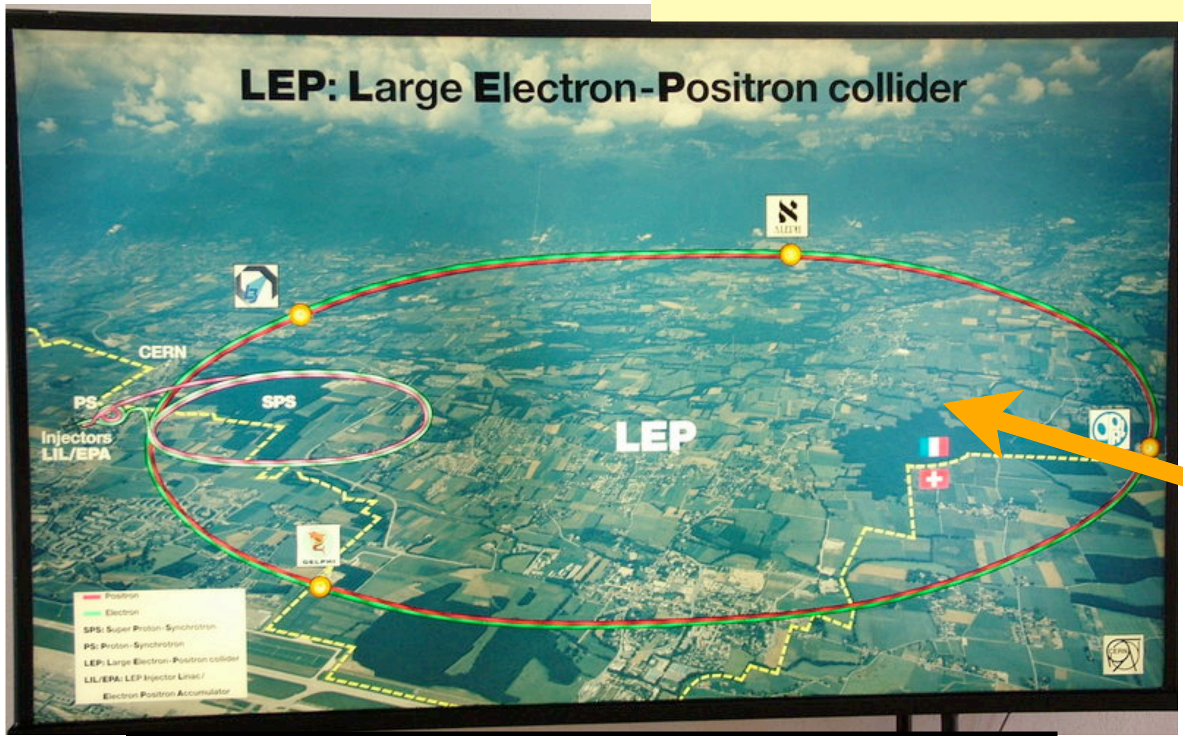

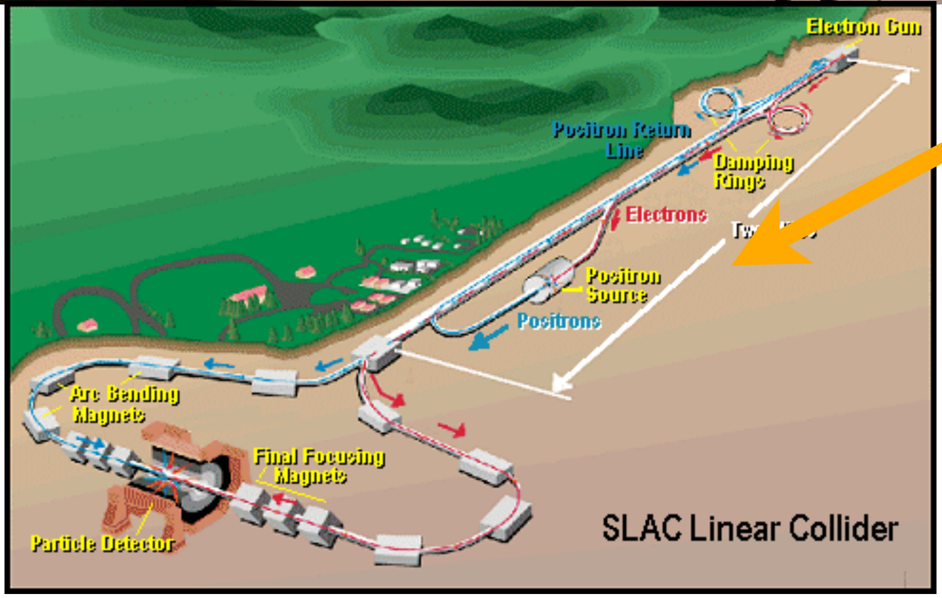

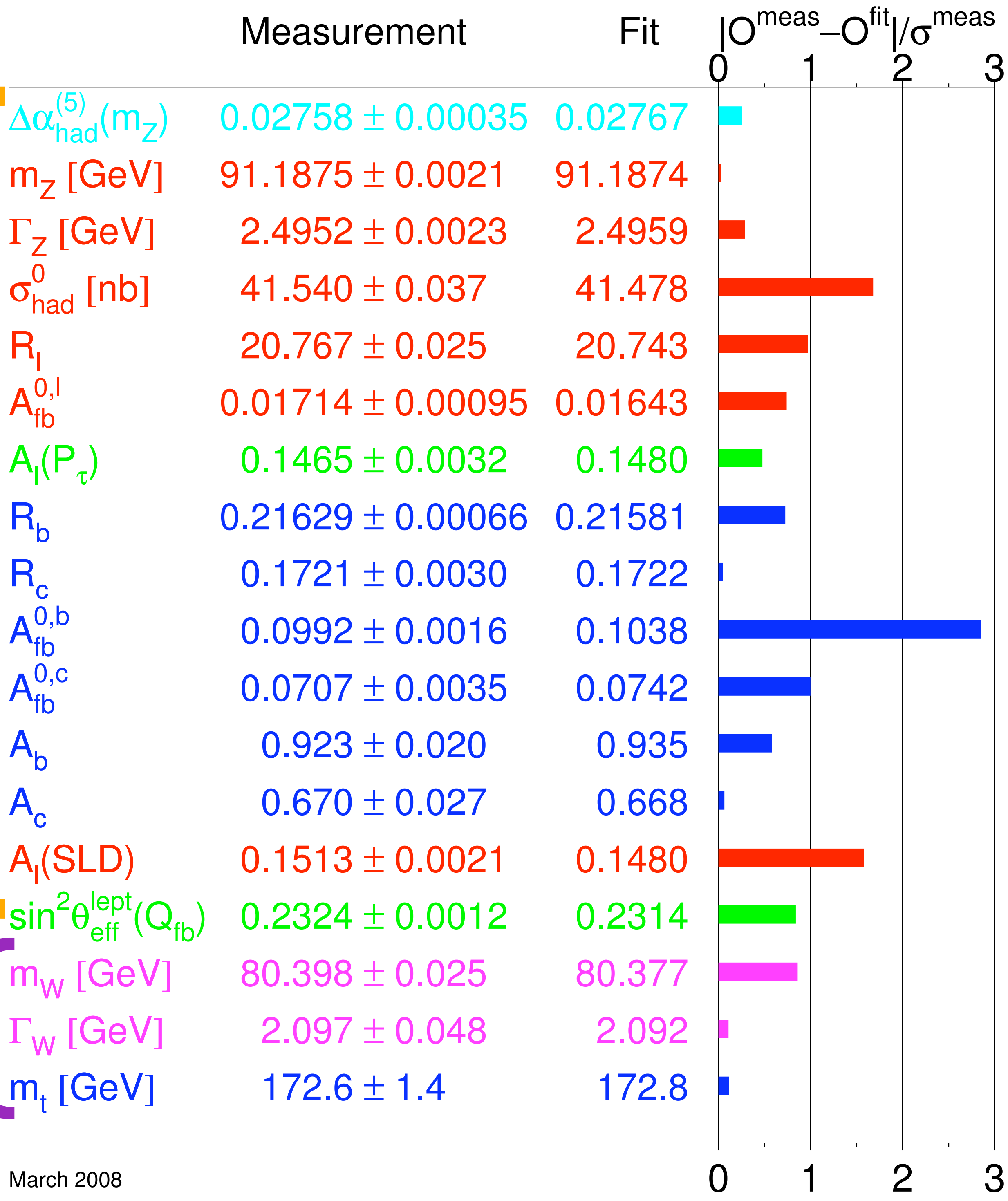

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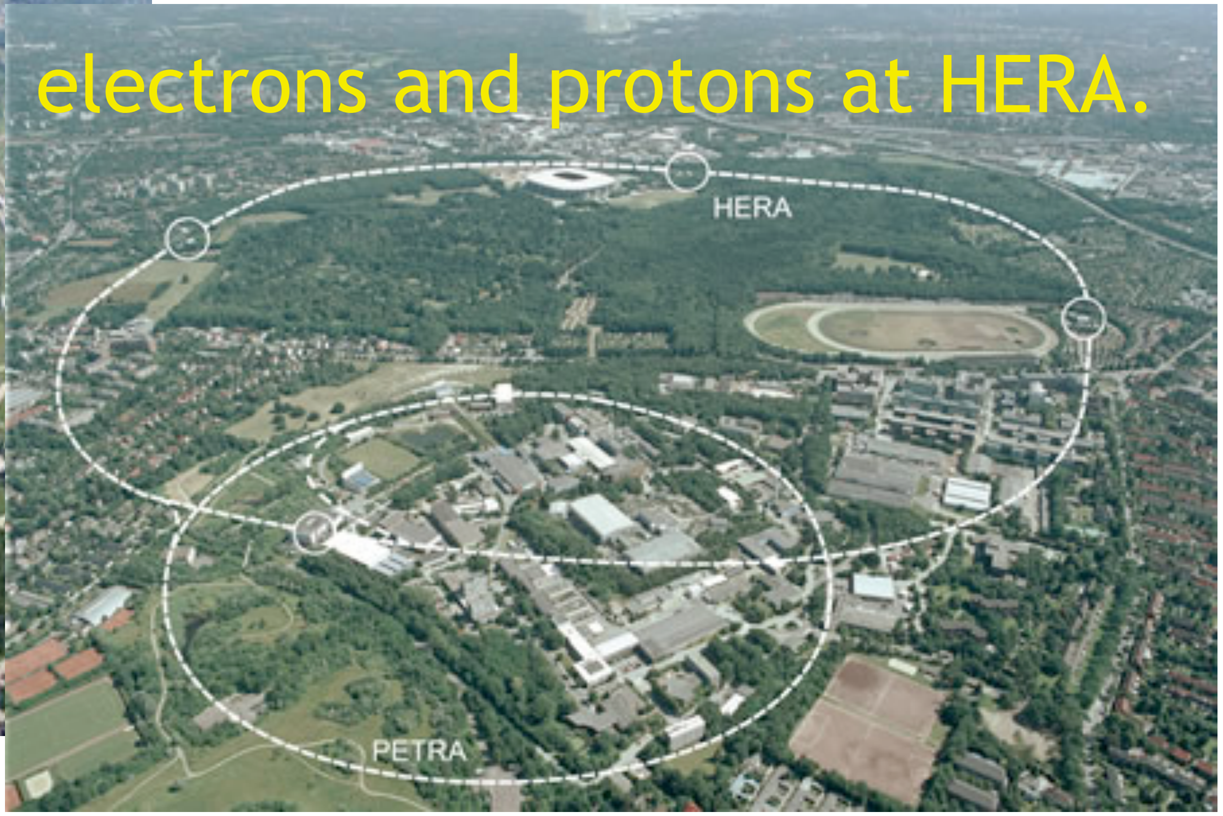
Main focus recently

Recent Electroweak Results

Since LEP and SLC we have been exploring on-shell W and Z bosons with ...

protons and anti-protons at the Tevatron &



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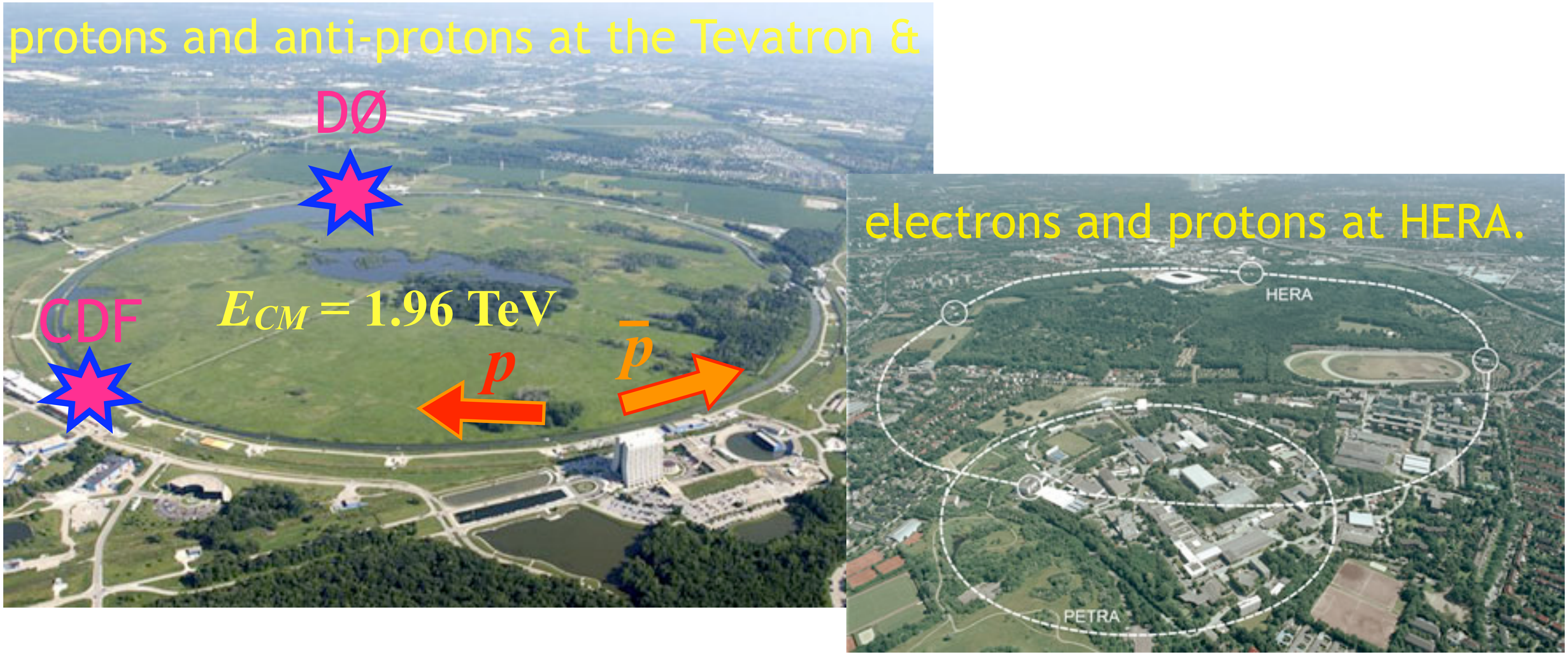

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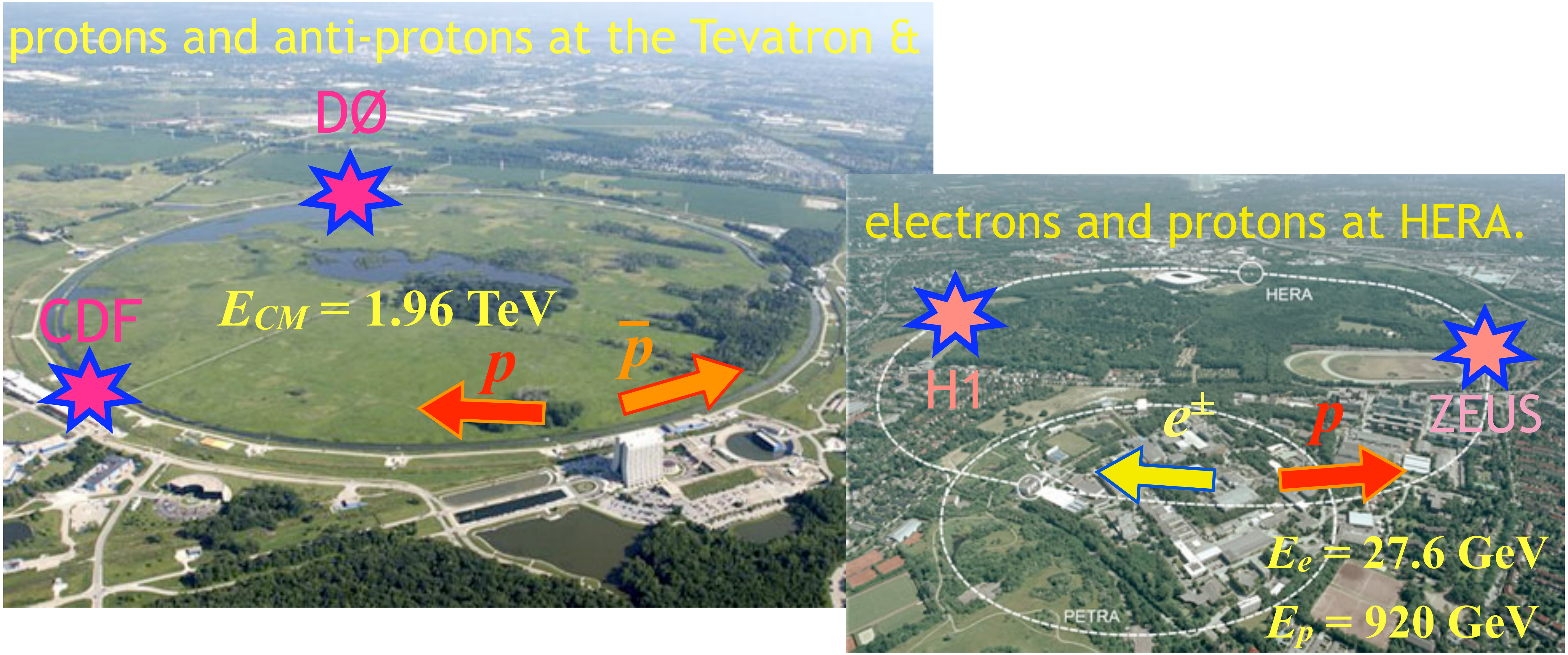

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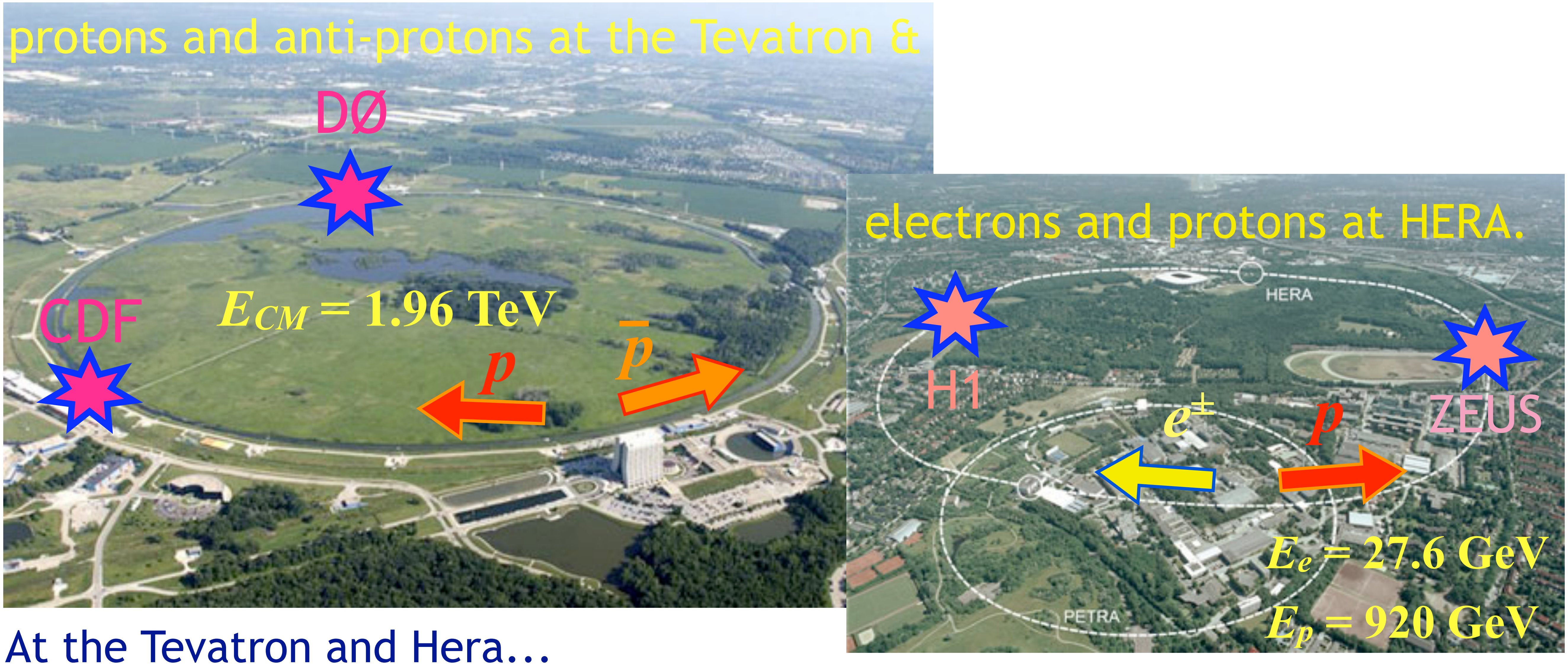

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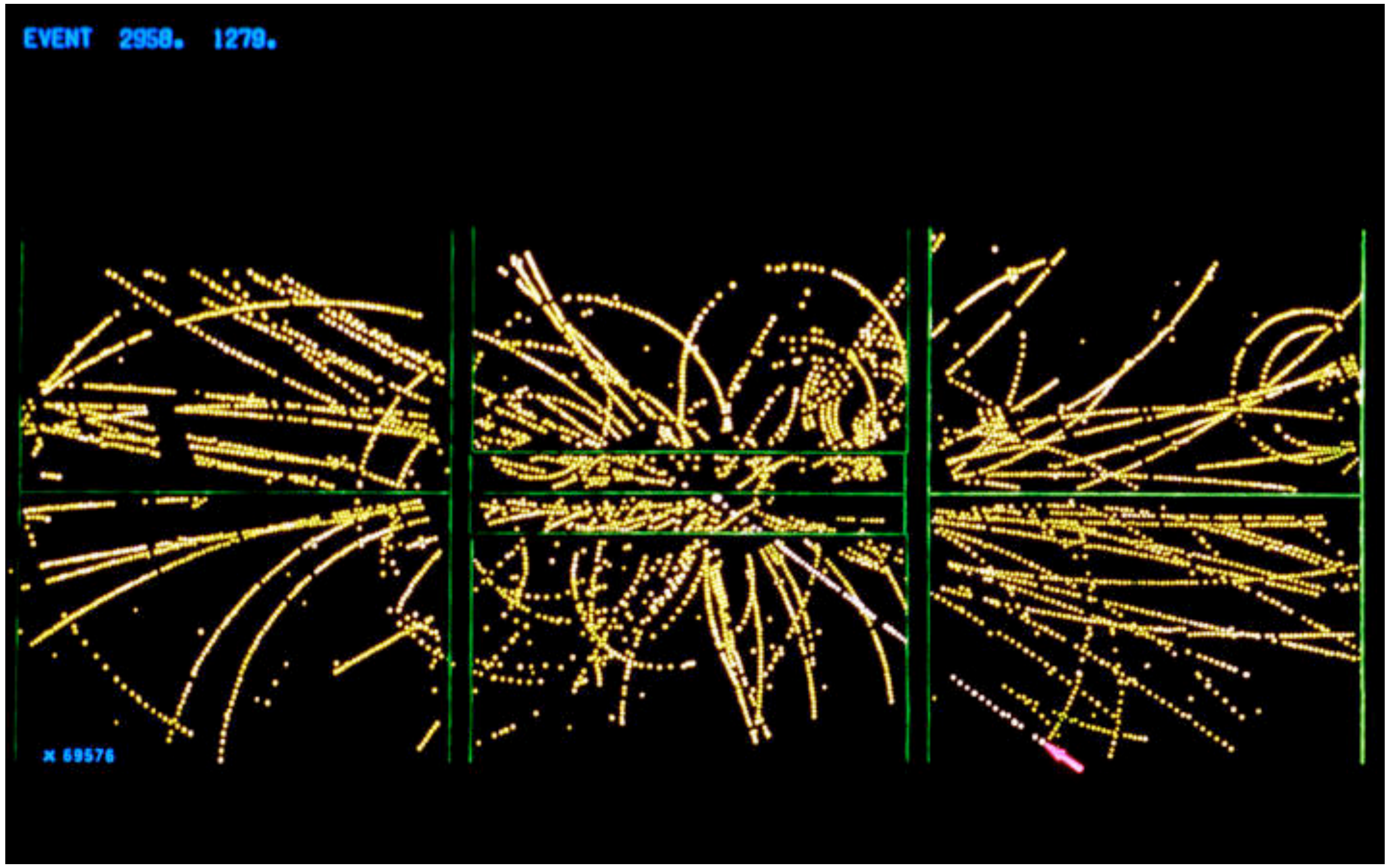
At the Tevatron and Hera...

- we can measure the W-boson properties (more accurately) and top-quark properties (directly)
- we have enough energy to produce di-boson pairs
- study couplings between bosons and up & down quarks and polarised electrons & positrons

W-boson properties



W-boson mass and width

- Use $W\to\mu\nu$ and $W\to e\nu$ events
- Use the **transverse mass**, m_T, defined using the components of momentum transverse to beam:

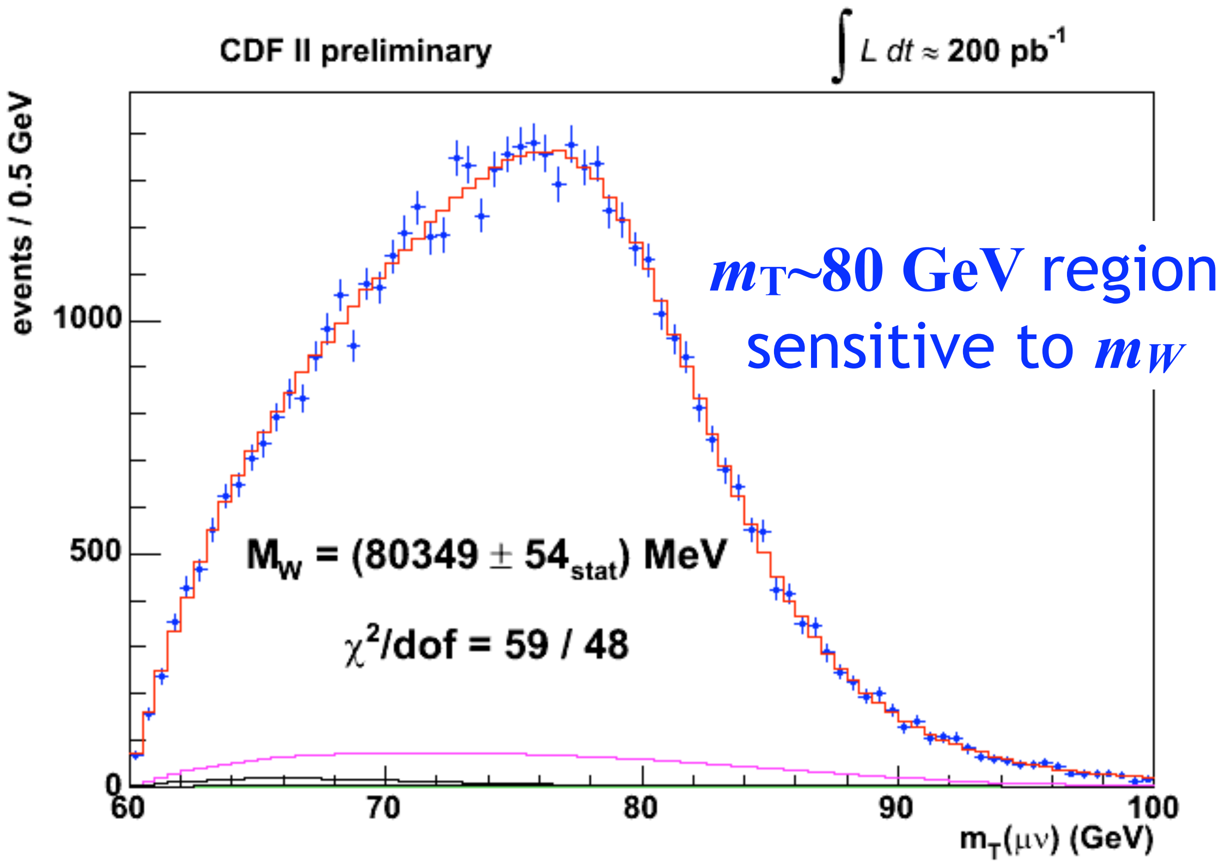
$$m_T = \sqrt{E_T(\ell)E_T(\nu)(1-\cos(\phi_\ell-\phi_\nu))}$$

- Fit to template with different input values of m_W, Γ_W
- CDF Run II

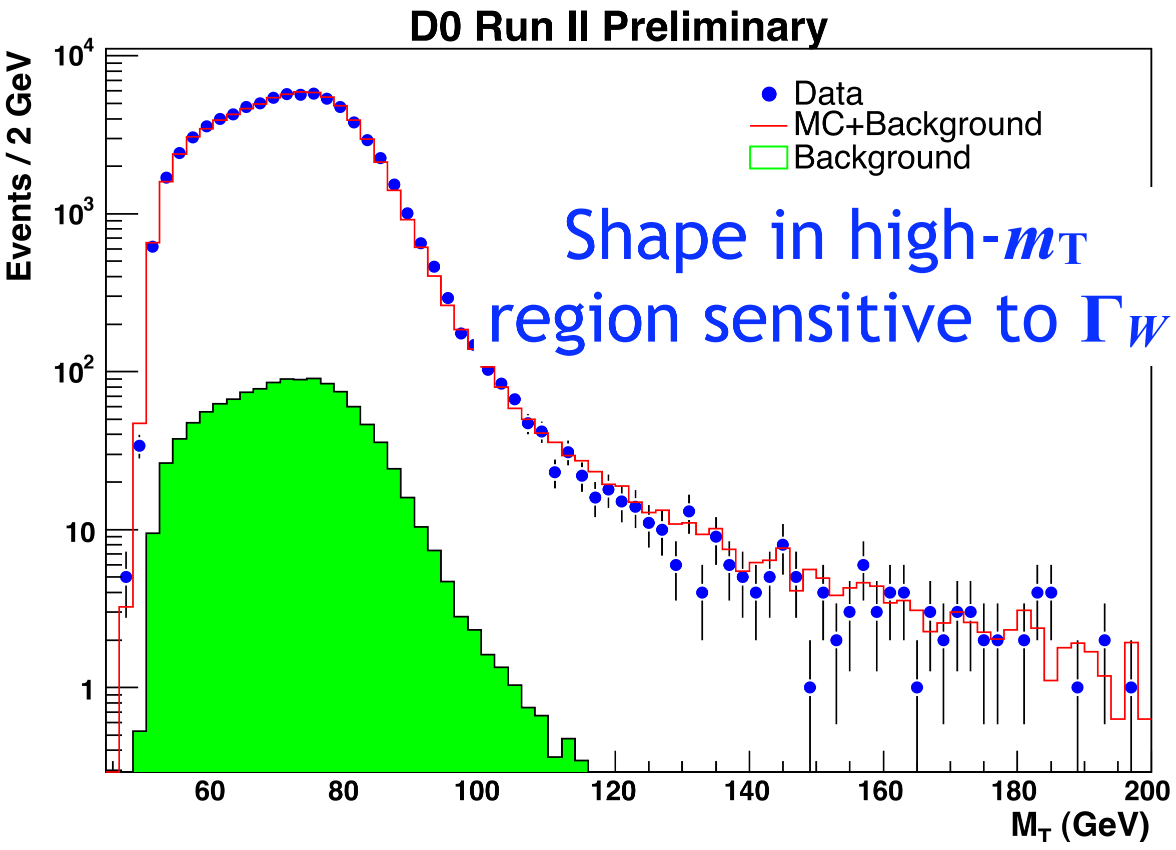
$$m_W = 80413 \pm 34(\text{stat}) \pm 34(\text{syst})\ \text{MeV}/c^2$$
$$\Gamma_W = 2032 \pm 45(\text{stat}) \pm 57(\text{syst})\ \text{MeV}$$

- DØ Run II

$$\Gamma_W = 2011 \pm 93(\text{stat}) \pm 107(\text{syst})\ \text{MeV}$$

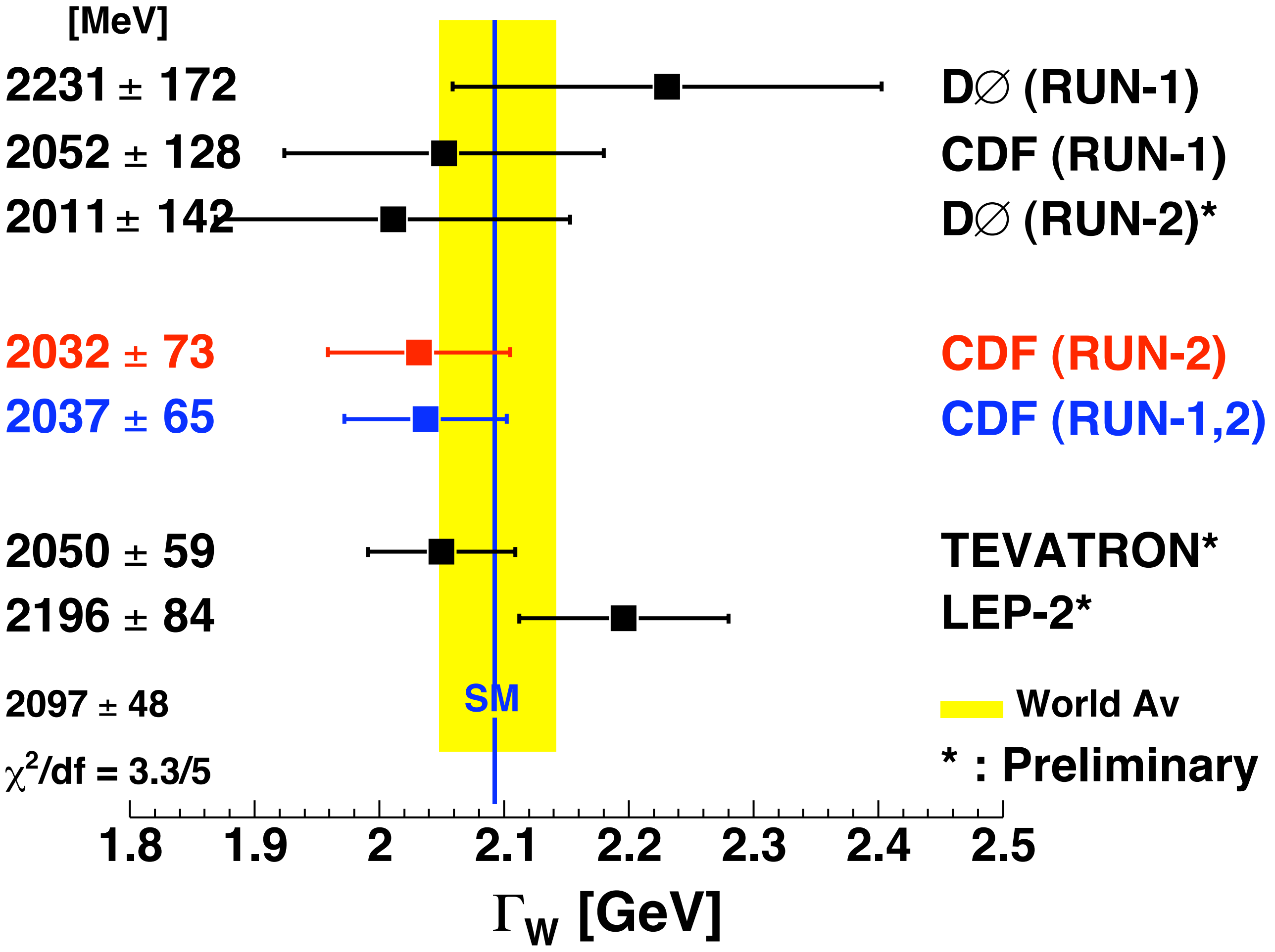


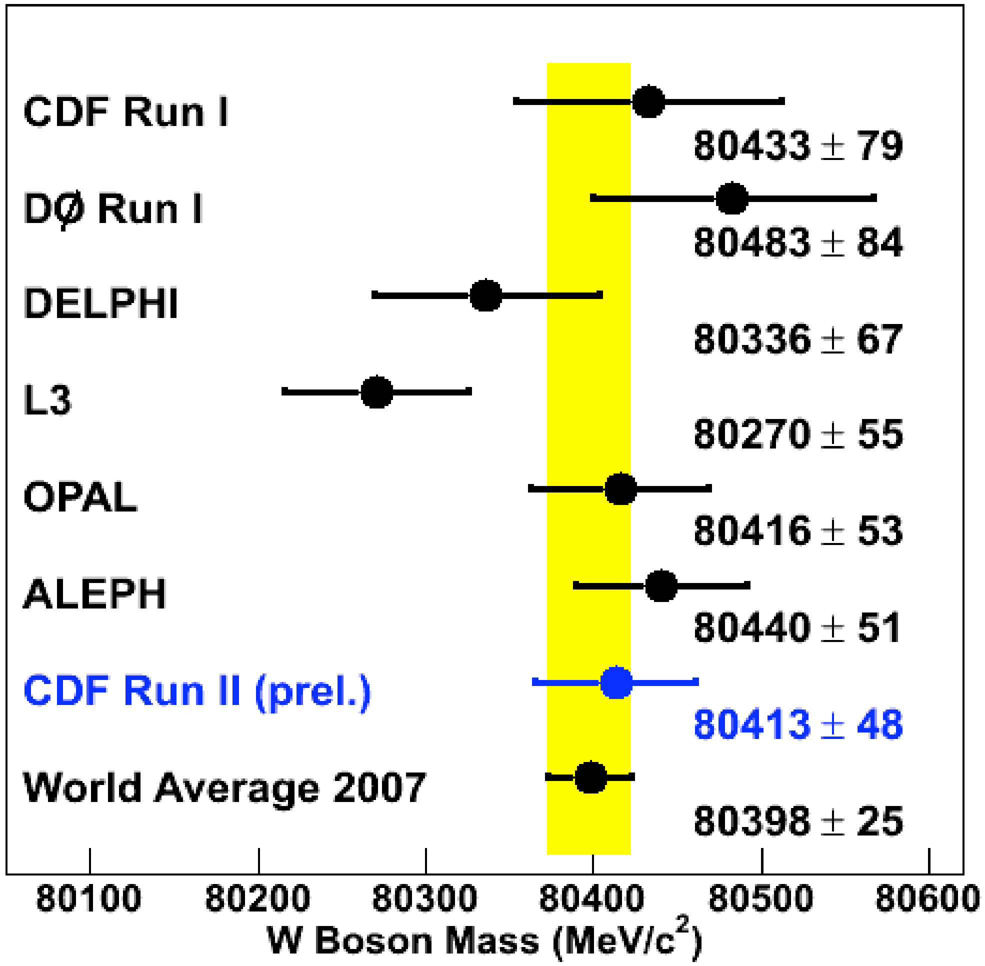
m_T~80 GeV region sensitive to m_W



Shape in high-m_T region sensitive to Γ_W

World average W-boson mass and width

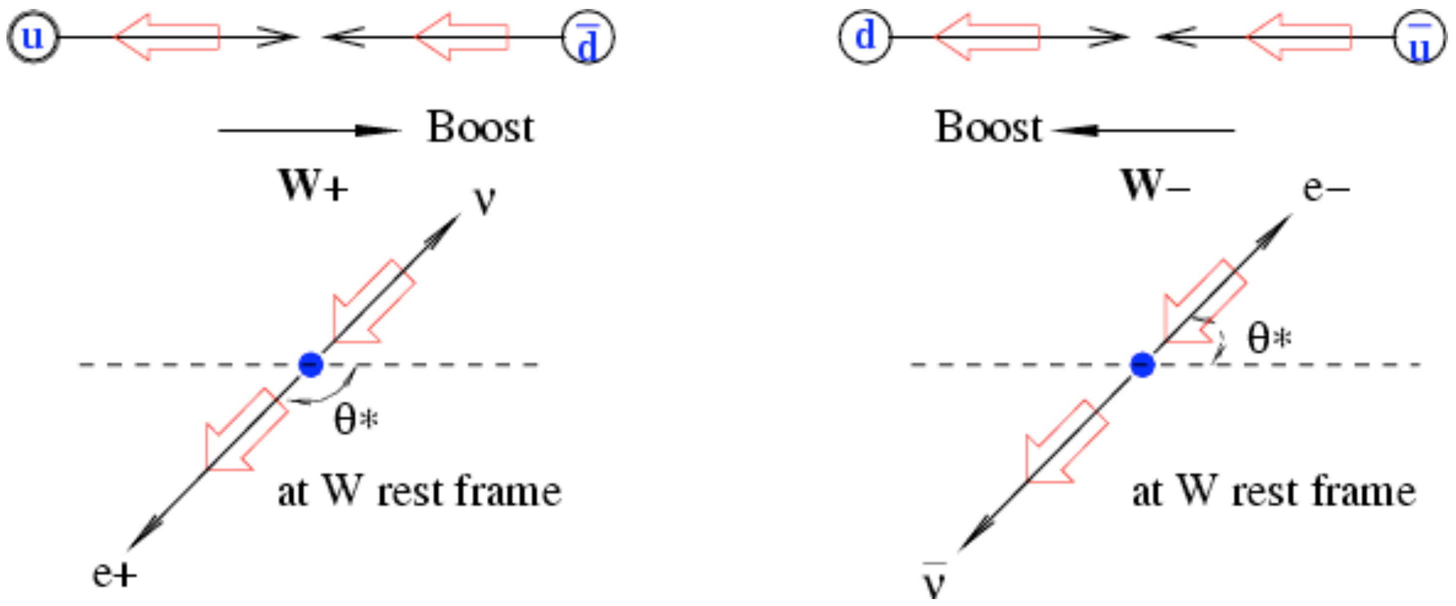


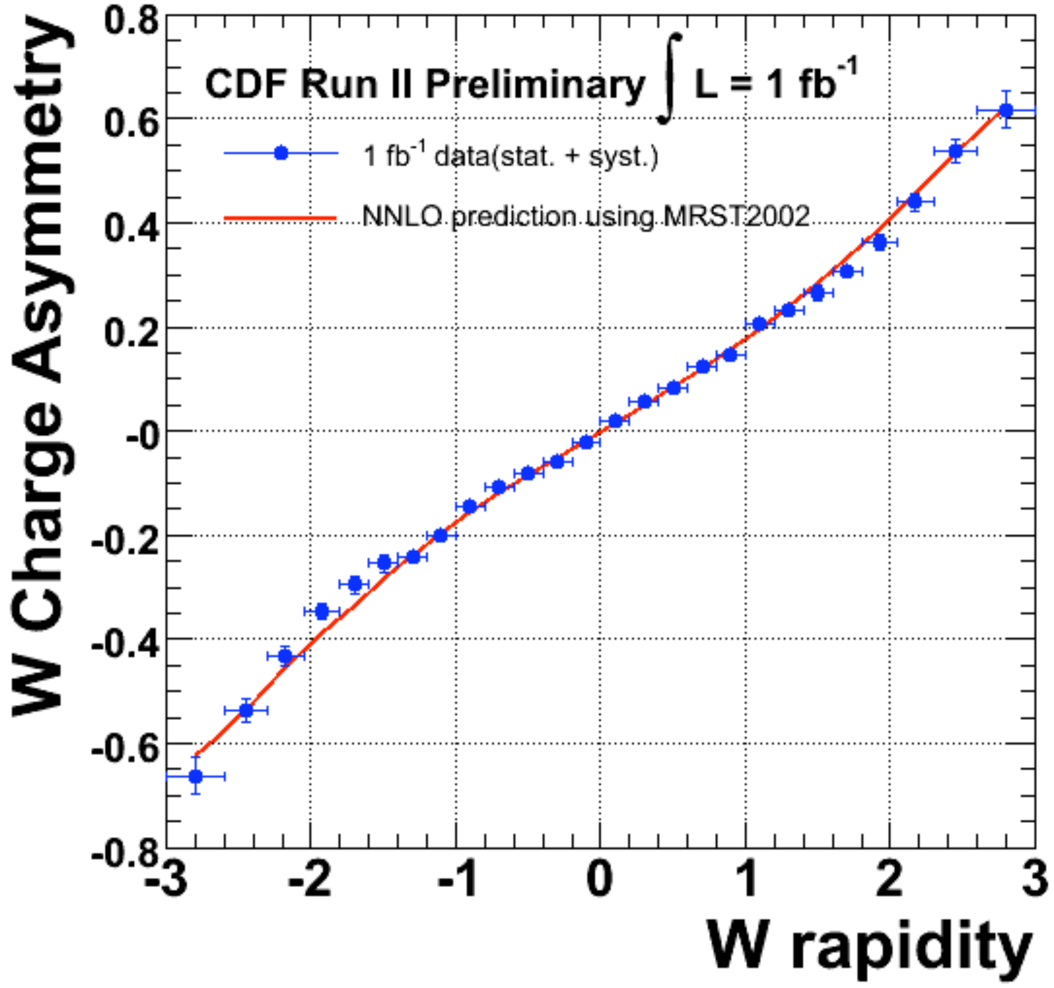


- Accuracy requires detailed understanding of how electrons and muons interact in the detector
- Work currently underway on combined m_W and Γ_W fit

W-boson charge asymmetry

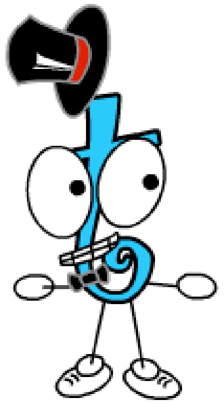
- Asymmetry in direction of charged leptons from *W*-boson decays





- Rapidity of the *W*-boson not directly reconstructed due to two fold-ambiguity in the longitudinal momentum of neutrino.
- Two solutions are weighted using V-A hypothesis.
- Results used to constrain proton PDFs.

Top Quark Physics

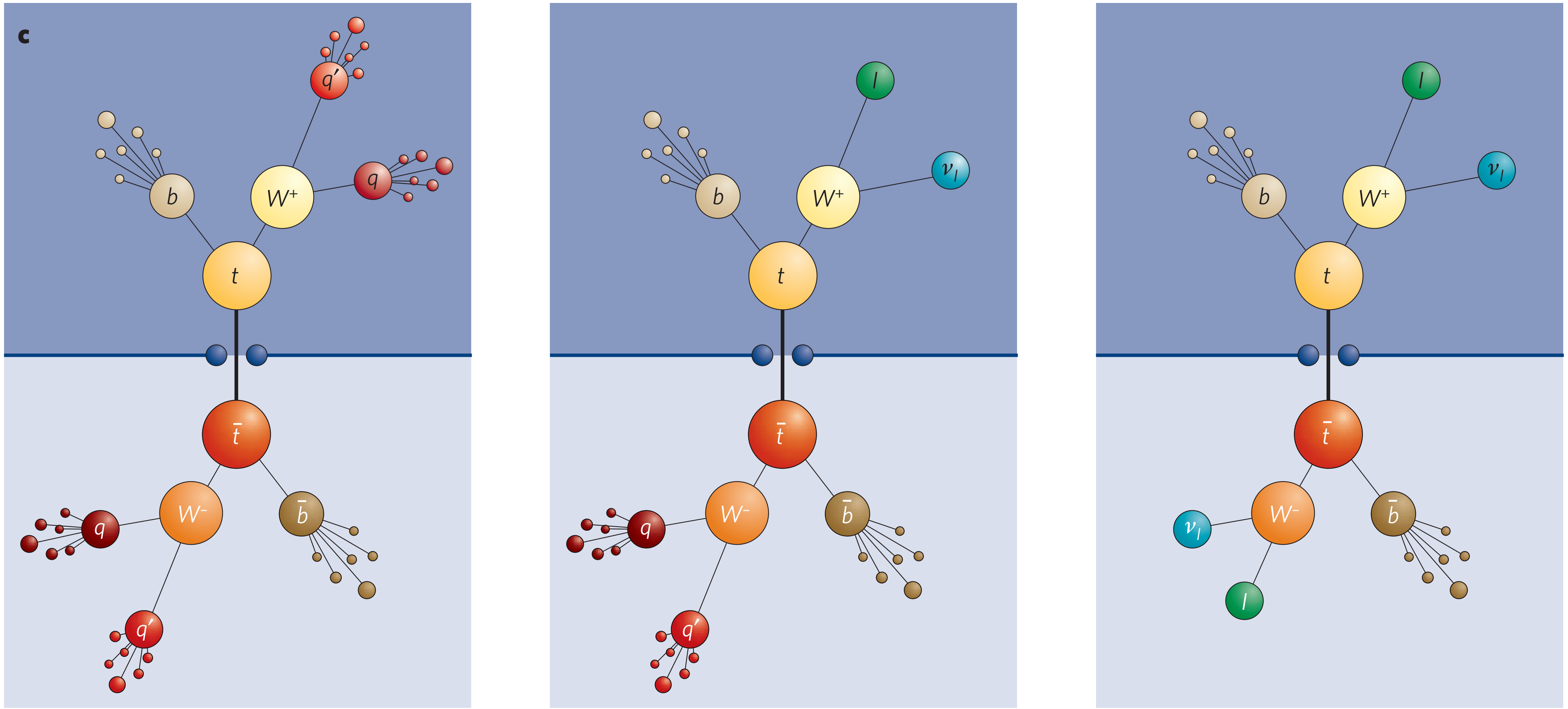


top

Top-quark Events

- Top mass and single top-quark production

Three top-quark pair production signatures $p\bar{p} \to t\,\bar{t} \to W^+ b\, W^- \bar{b}$



“All jets” 6 jets (2 b-jets)

“Lepton+Jets” $\ell\nu$ + 4 jets (2 b-jets)

“Di-lepton” $\ell^+\ell^-$ 2ν + 2 b-jets

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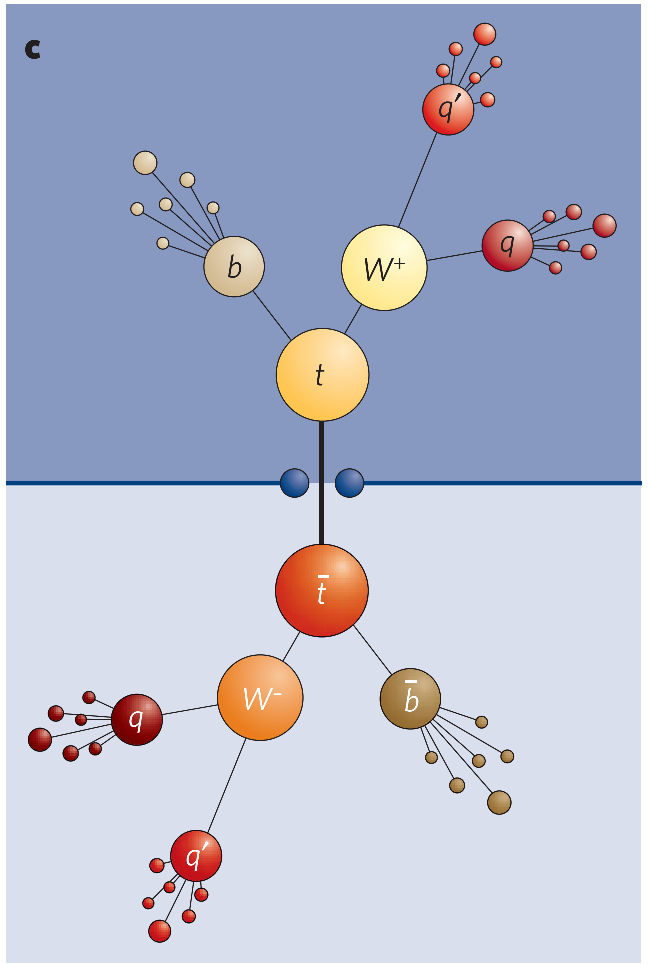
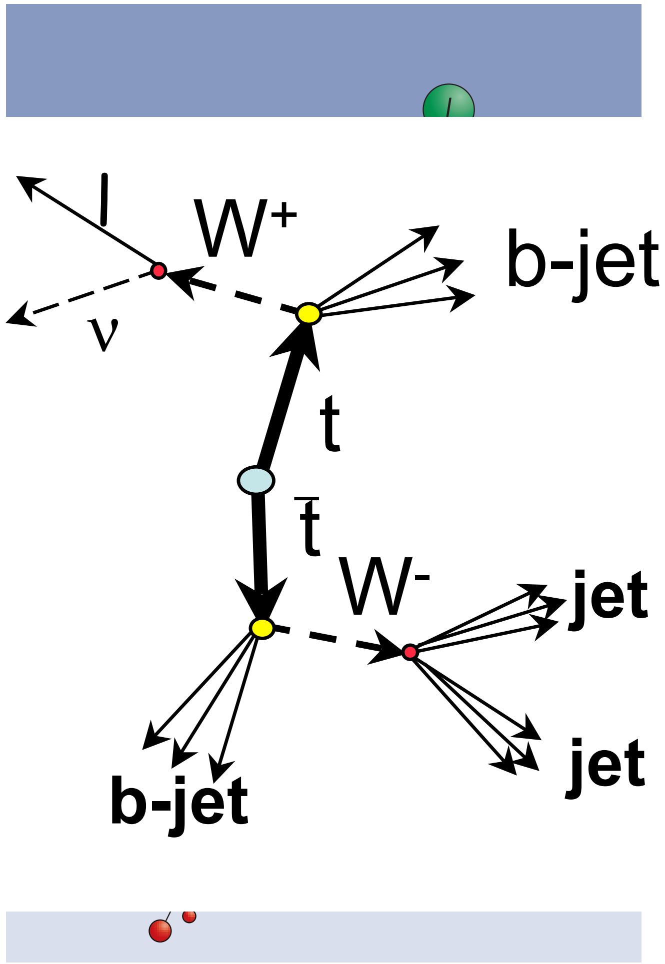
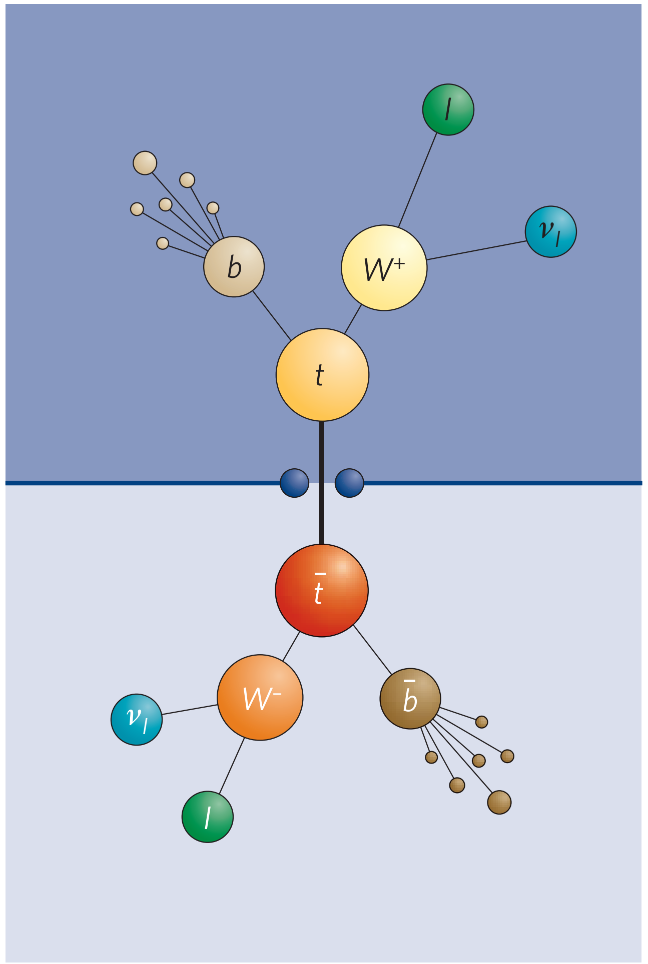


“All jets” **6 jets (2 b-jets)**



“Lepton+Jets” $\ell\nu$ + **4 jets (2 b-jets)**



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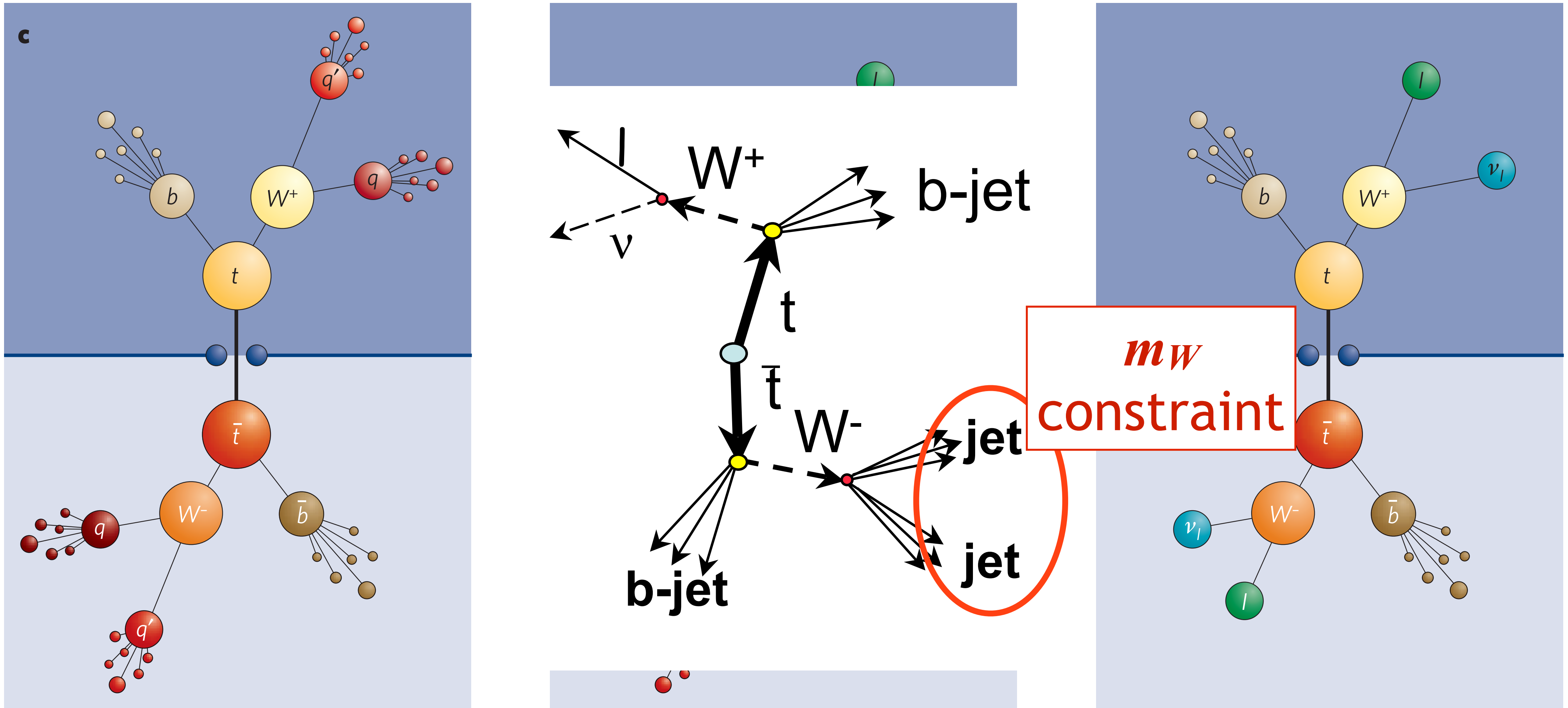

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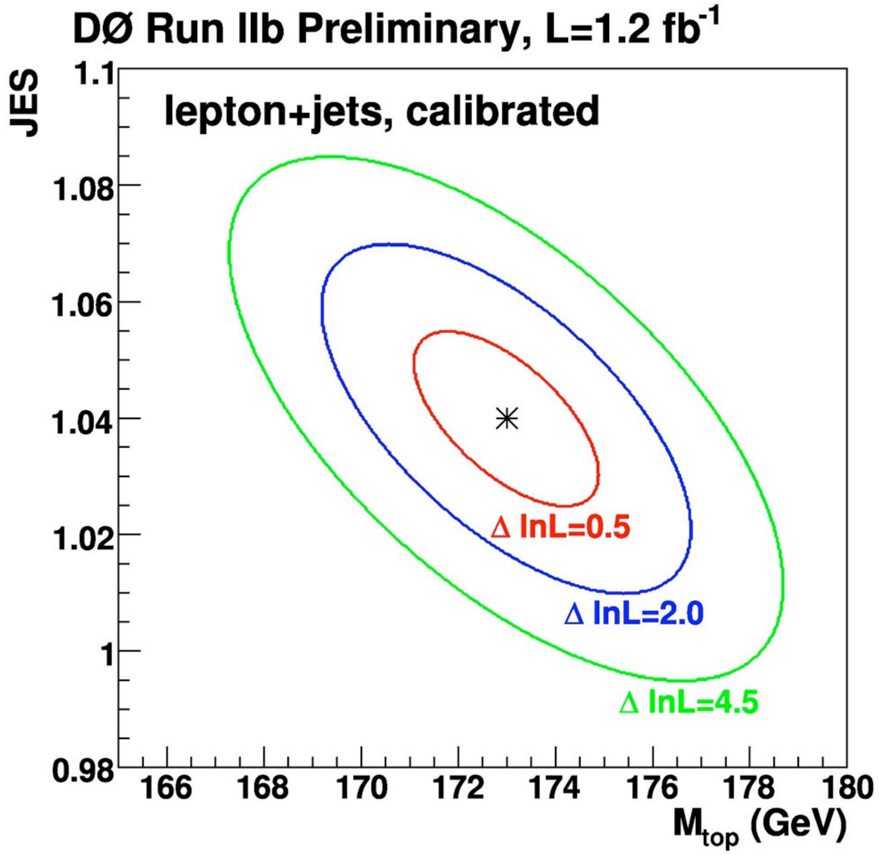
Finding 1 or 2 b-tagged jets significantly reduces backgrounds

Top Quark Mass

- Many methods used to measure top quark mass - *e.g.* matrix element method
- Largest systematic effect from uncertainty on Jet Energy Scale of calorimeters (**JES**)
- Calibrate **JES** in-situ to with known-value of m_W.
- Find best values of m_t, **JES** consistent with observed kinematics, $\vec{y}$

$$L(\vec{y} \mid m_t, \mathrm{JES}) = \frac{1}{N(m_t)} \frac{1}{A(m_t, \mathrm{JES})} \sum_{i=1}^{24} w_i \int \frac{f(z_1) f(z_2)}{FF} \; \mathrm{TF}(\vec{y} \cdot \mathrm{JES} \mid \vec{x}) \; |M_{\text{eff}}(m_t, \vec{x})|^2 \; d\Phi(\vec{x})$$



One or two *b*-tags required

“World's single most precise measurement”

m_t = **172.2 ± 1.1 (stat) ± 1.6 (syst) GeV/c^2**

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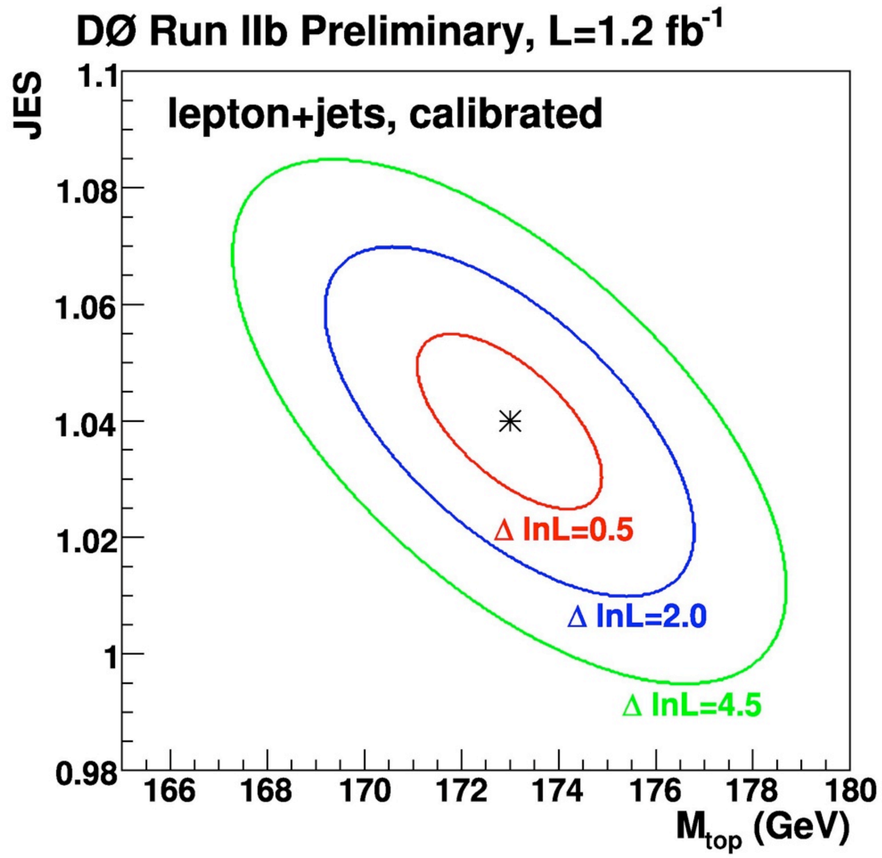
CDF: Lepton+Jets and Di-lepton, template fit



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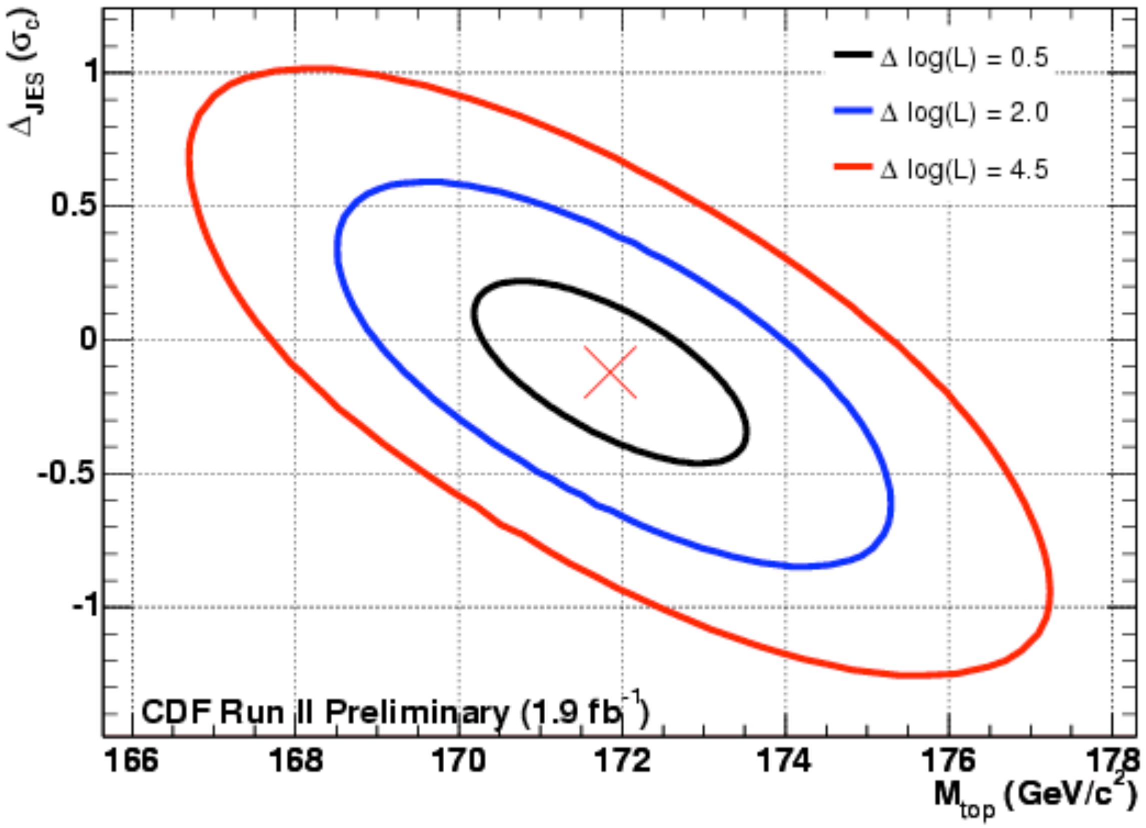
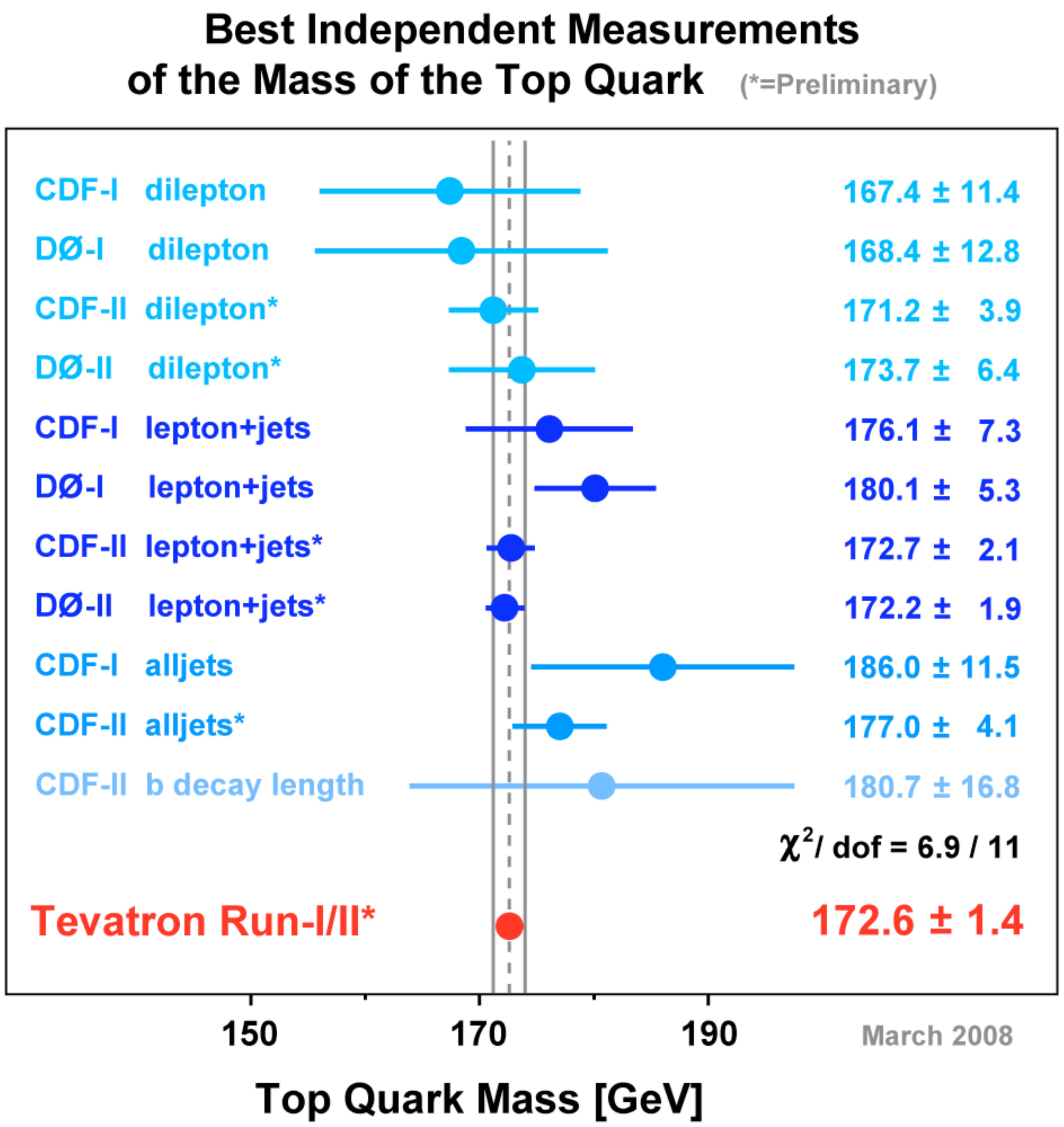


"World's single most precise measurement"
$m_t = 172.2 \pm 1.1$ (stat) ± 1.6 (syst) GeV/c^2

"World's single most precise measurement"
$m_t = 171.9 \pm 1.7$ (stat +JES) ± 1.0 (syst) GeV/c^2

World Average Top Quark Mass



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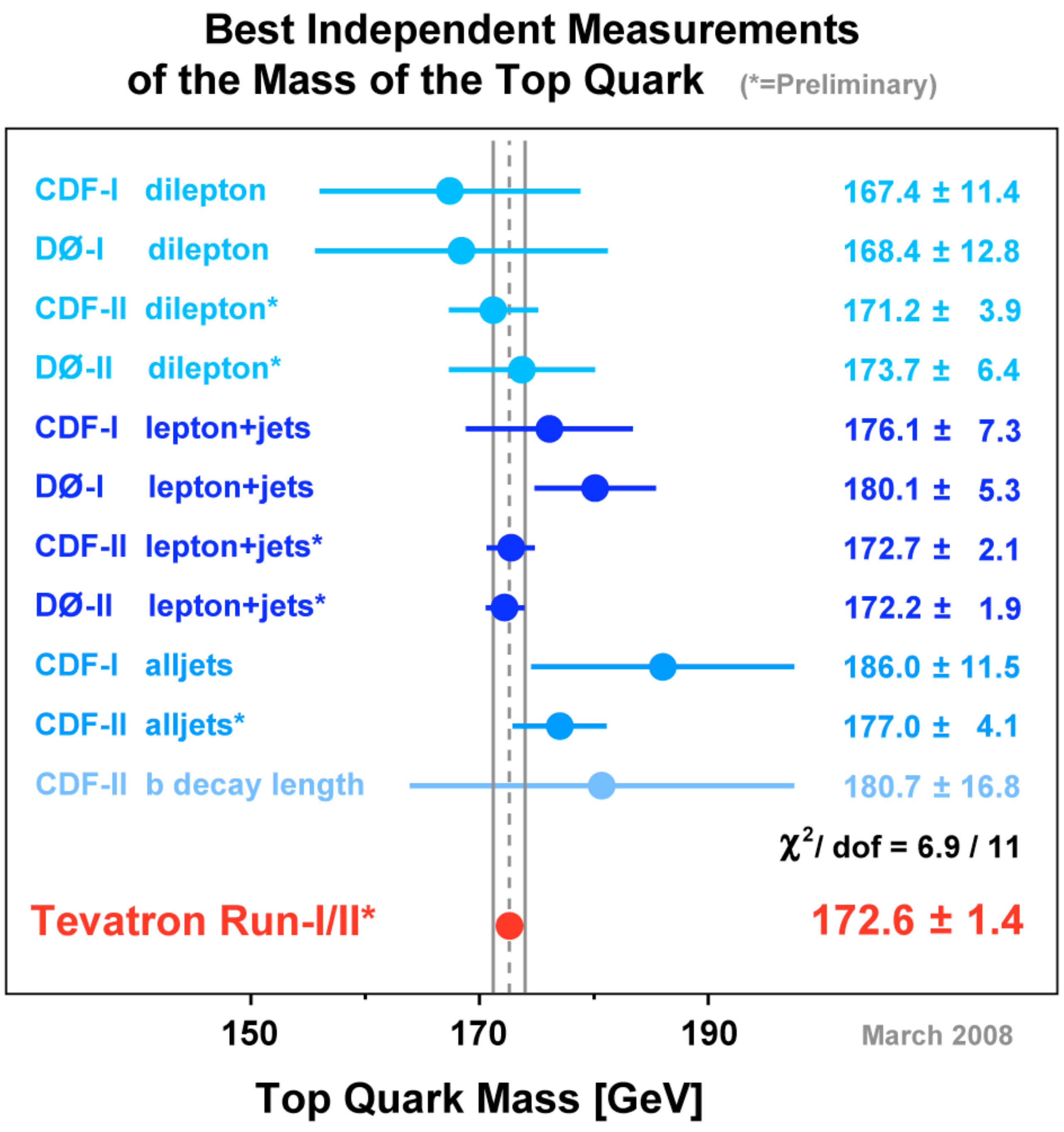

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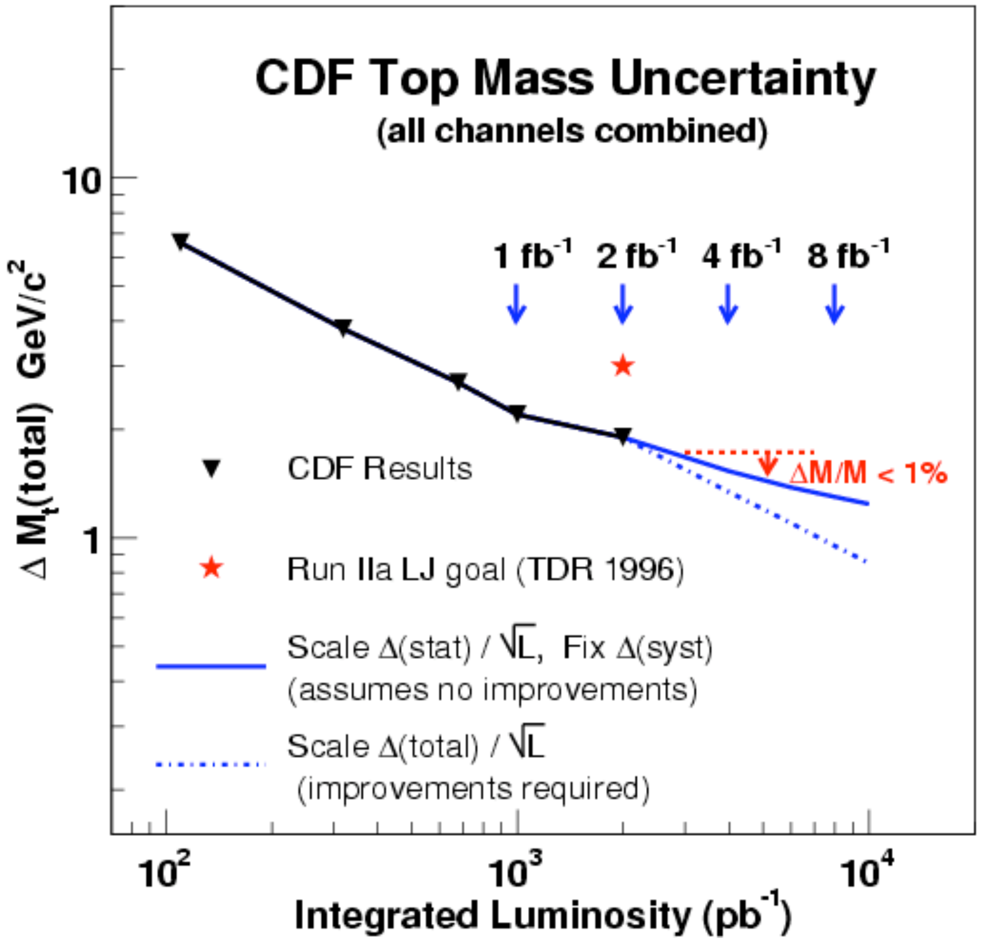
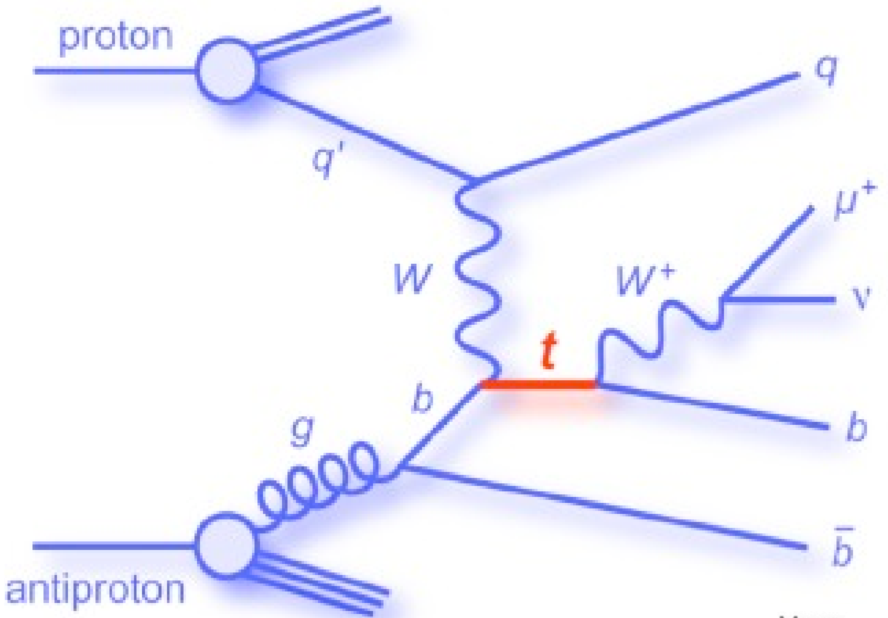
What improvements can be expected?

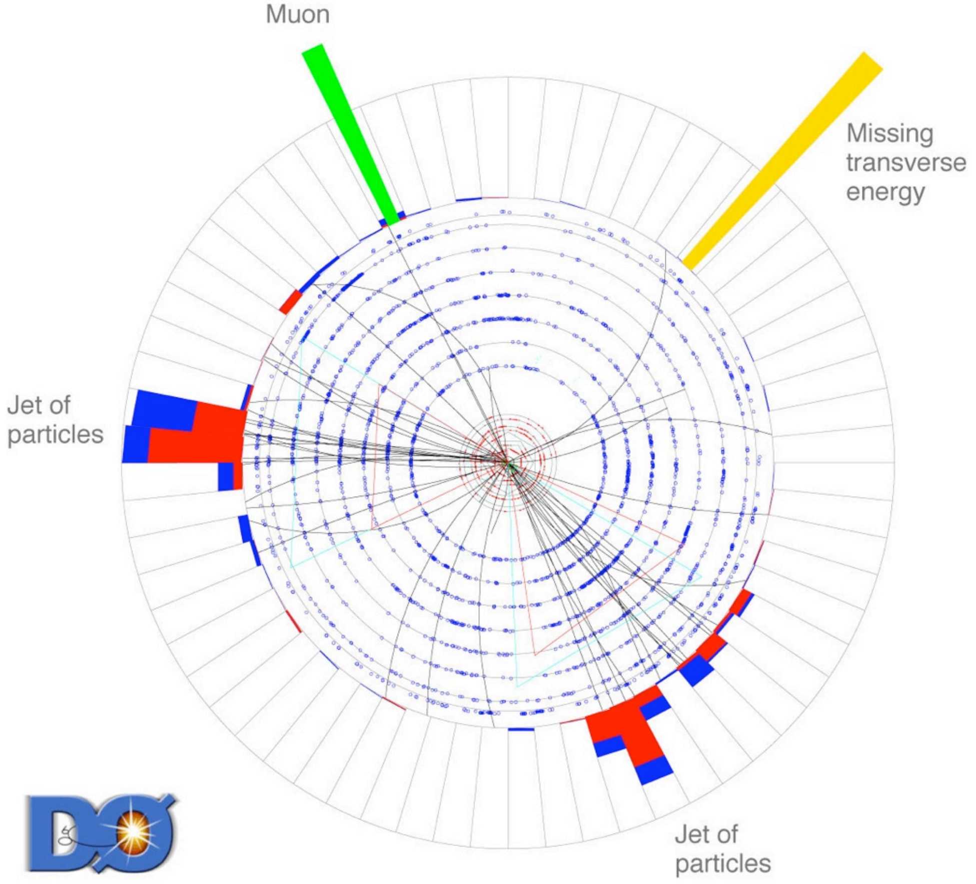


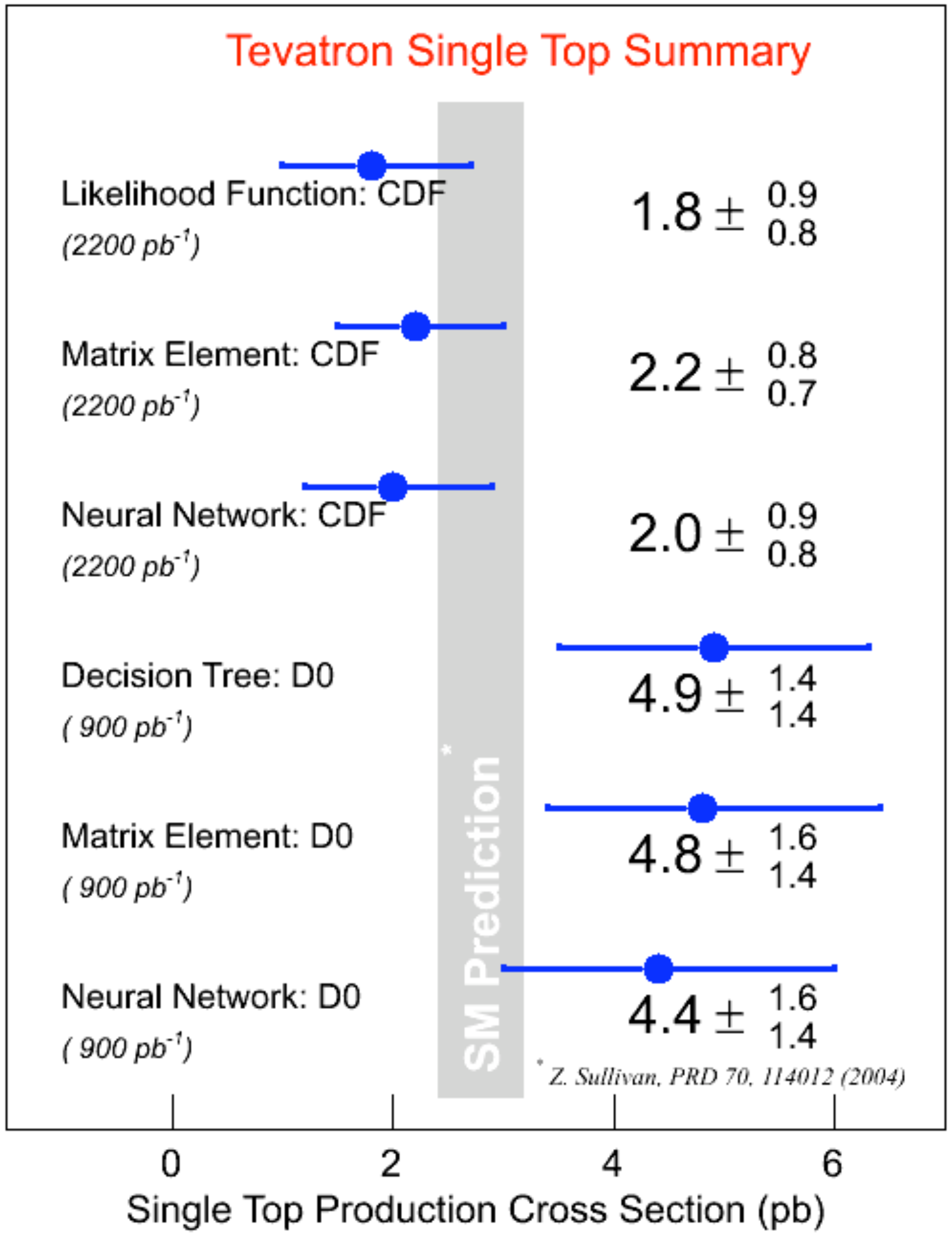
Not far from 1% accuracy per experiment!

Single Top Production



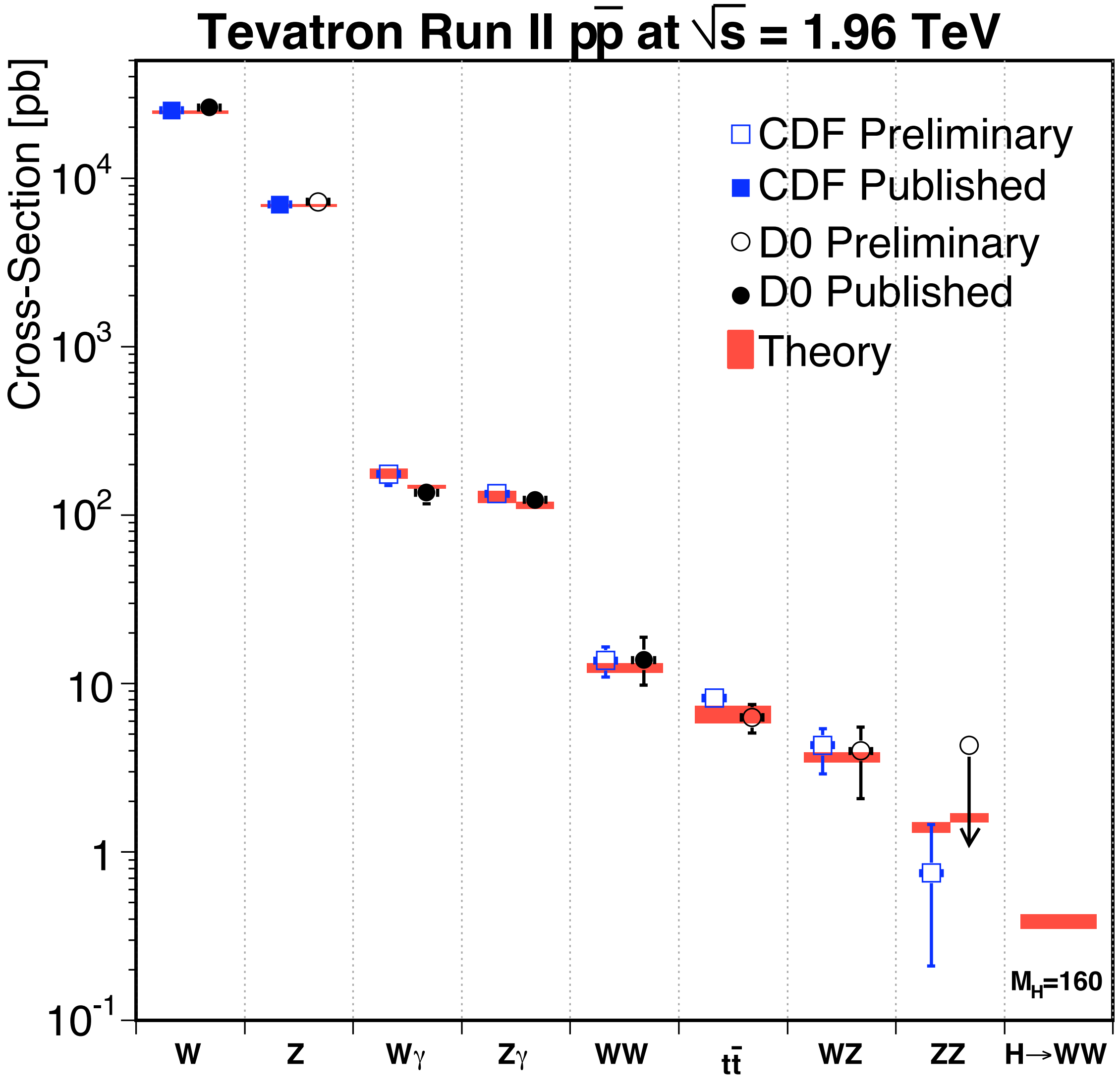
- Cross section is test of QCD and Electroweak
- SM prediction: **$\sigma = 2.9 \pm 0.4$ pb**
- Can be used to extract a result for **V*tb***





CDF: $|V_{tb}| = 0.88 \pm 0.14(\text{exp}) \pm 0.07(\text{theory})$

Boson Pair Production



$p\bar{p}\to Z\gamma$ production at the Tevatron

DØ 1fb^{-1}

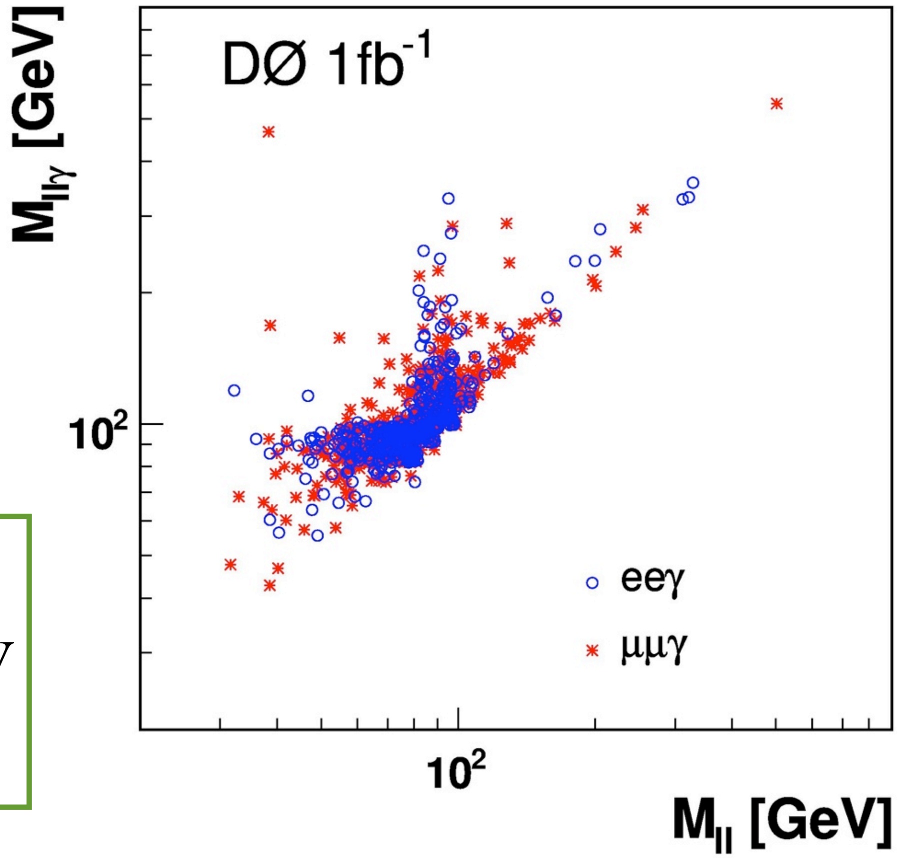
- $M_{\ell\ell} > 30$ GeV/c^2
- NLO prediction $\sigma = 4.7 \pm 0.2$ pb

$\sigma = 5.0 \pm 0.3$ (stat+syst) $\pm$ 0.3 (lum)

both expts:

$E_T(\gamma) > 7$ GeV

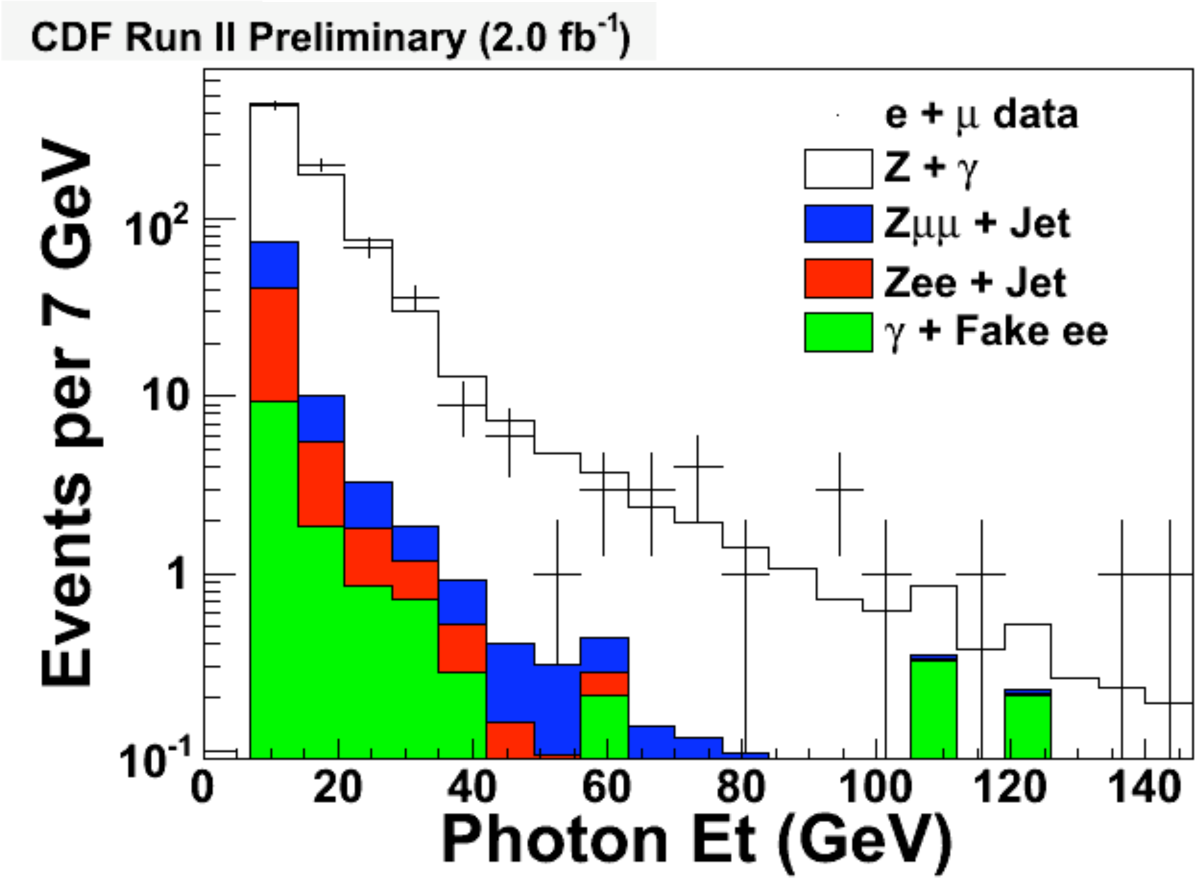
$\Delta R(\ell,\gamma) > 0.7$



CDF 2fb^{-1}

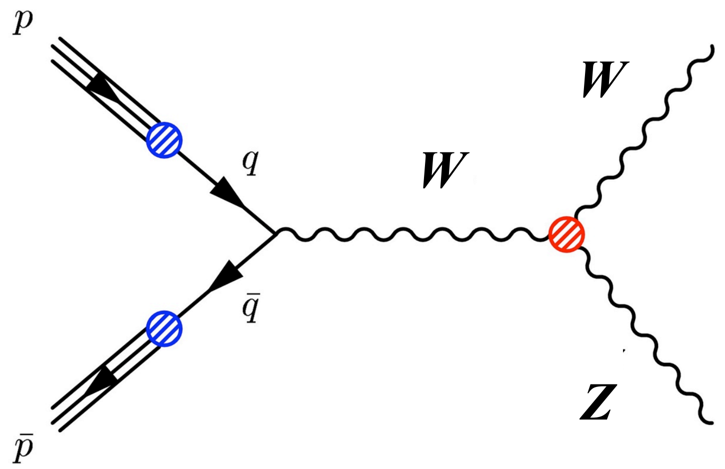
- $M_{\ell\ell} > 40$ GeV/c^2
- NLO prediction $\sigma = 4.5 \pm 0.3$ pb
- ISR 1.2 pb FSR 3.4 pb

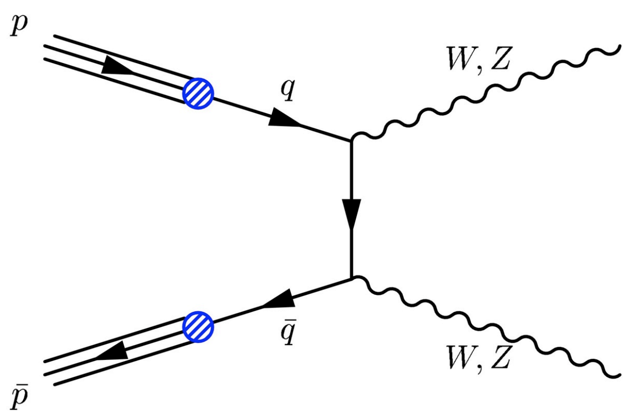
$\sigma = 4.6 \pm 0.2$ (stat) $\pm$ 0.3 (syst) $\pm$ 0.3 (lum)



Measurements consistent with SM predictions

$p\bar{p}\to WZ$ production at the Tevatron

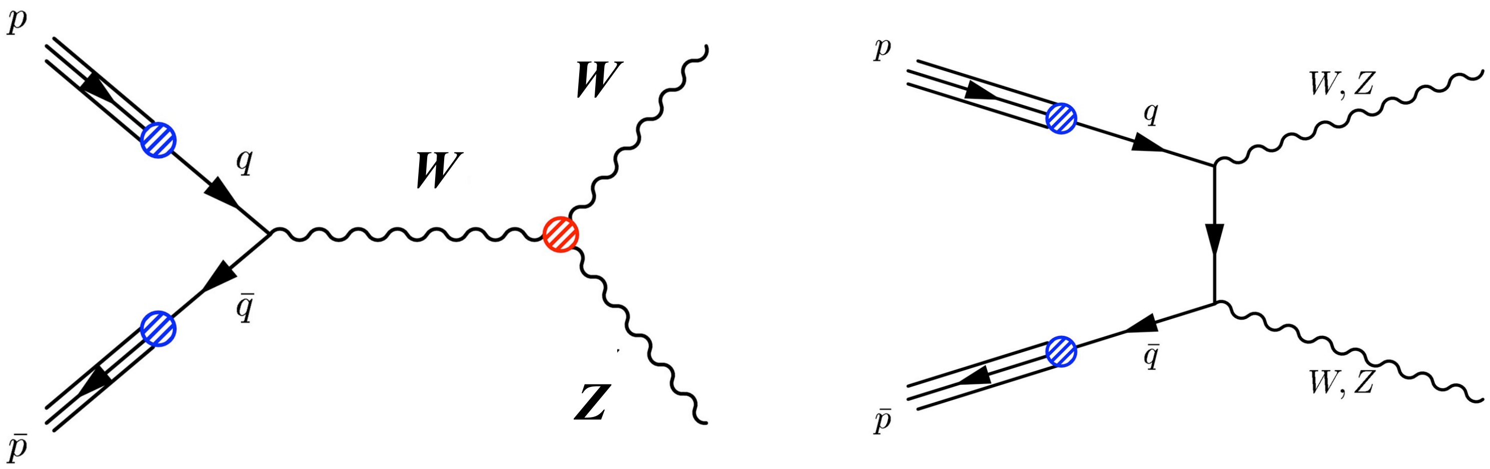




	CDF 1.9 fb^{-1}	DØ 1fb^{-1}
candidates	25	13
background	5.2±0.8	4.5±0.6

Both *s*-channel and *t*-channel: $\sigma_{\rm NLO}(WZ) = 3.7 \pm 0.3\ {\rm pb}$

$p\bar{p} \to WZ$ production at the Tevatron



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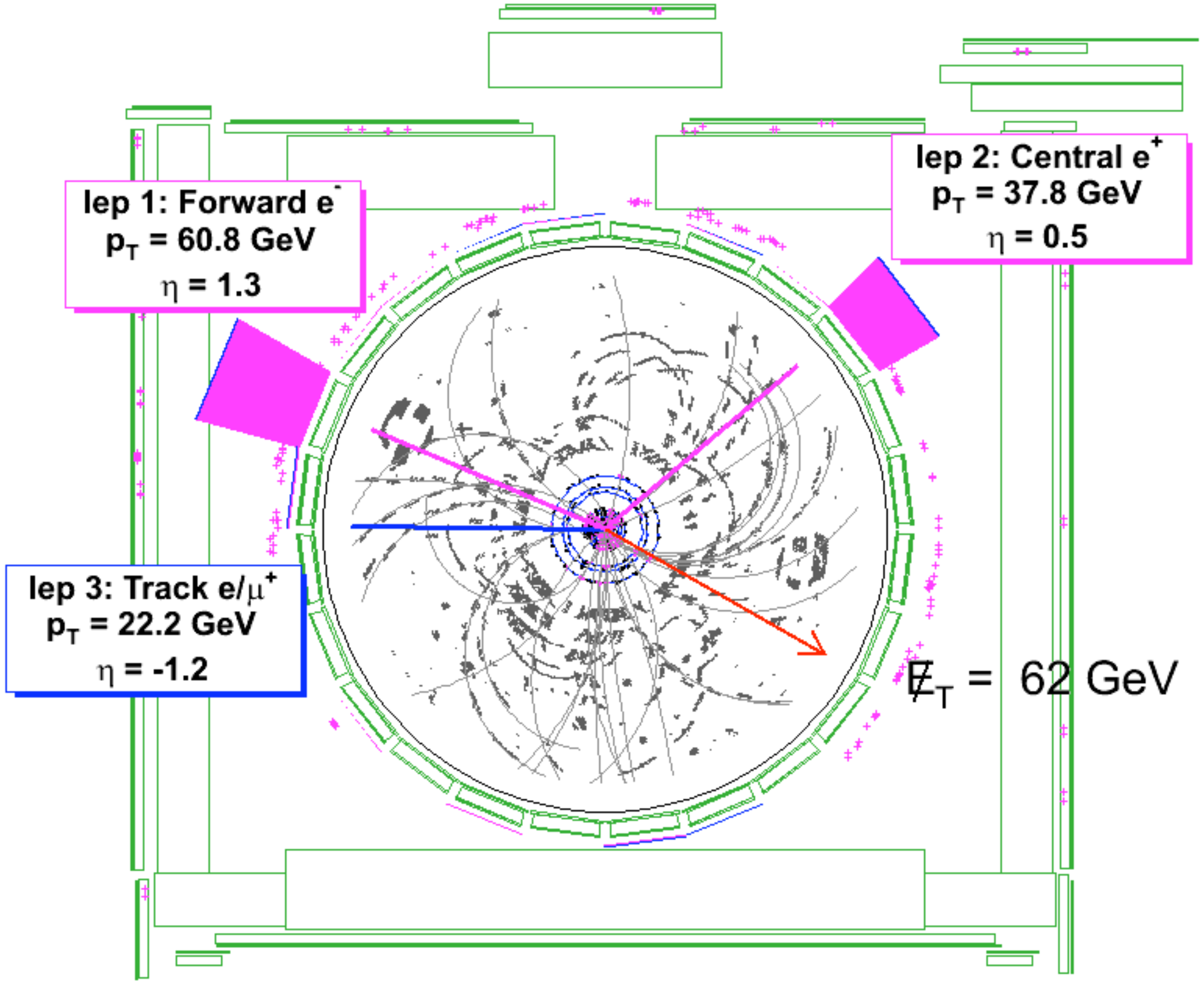
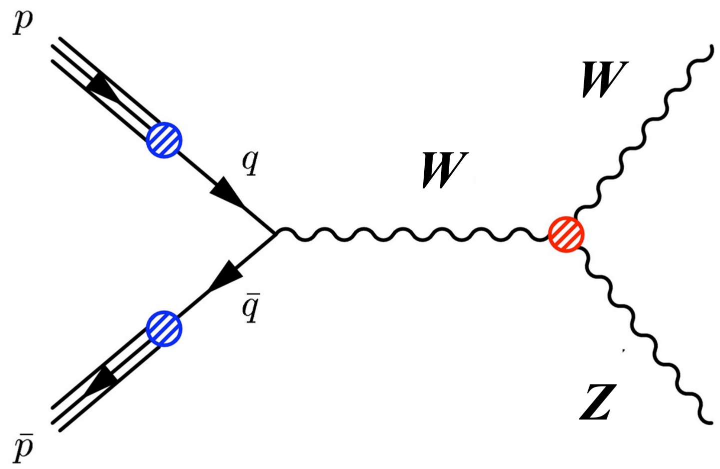

lep 1: Forward e$^-$
p_T = 60.8 GeV
η = 1.3

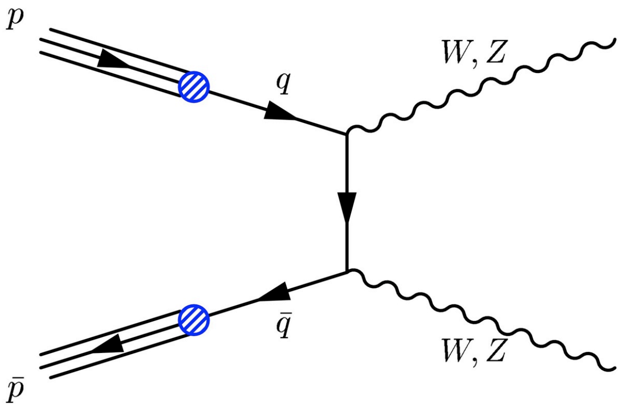
lep 2: Central e$^+$
p_T = 37.8 GeV
η = 0.5

lep 3: Track e/μ^+
p_T = 22.2 GeV
η = -1.2

$\not{E}_T$ = 62 GeV

$p\bar{p}\to WZ$ production at the Tevatron



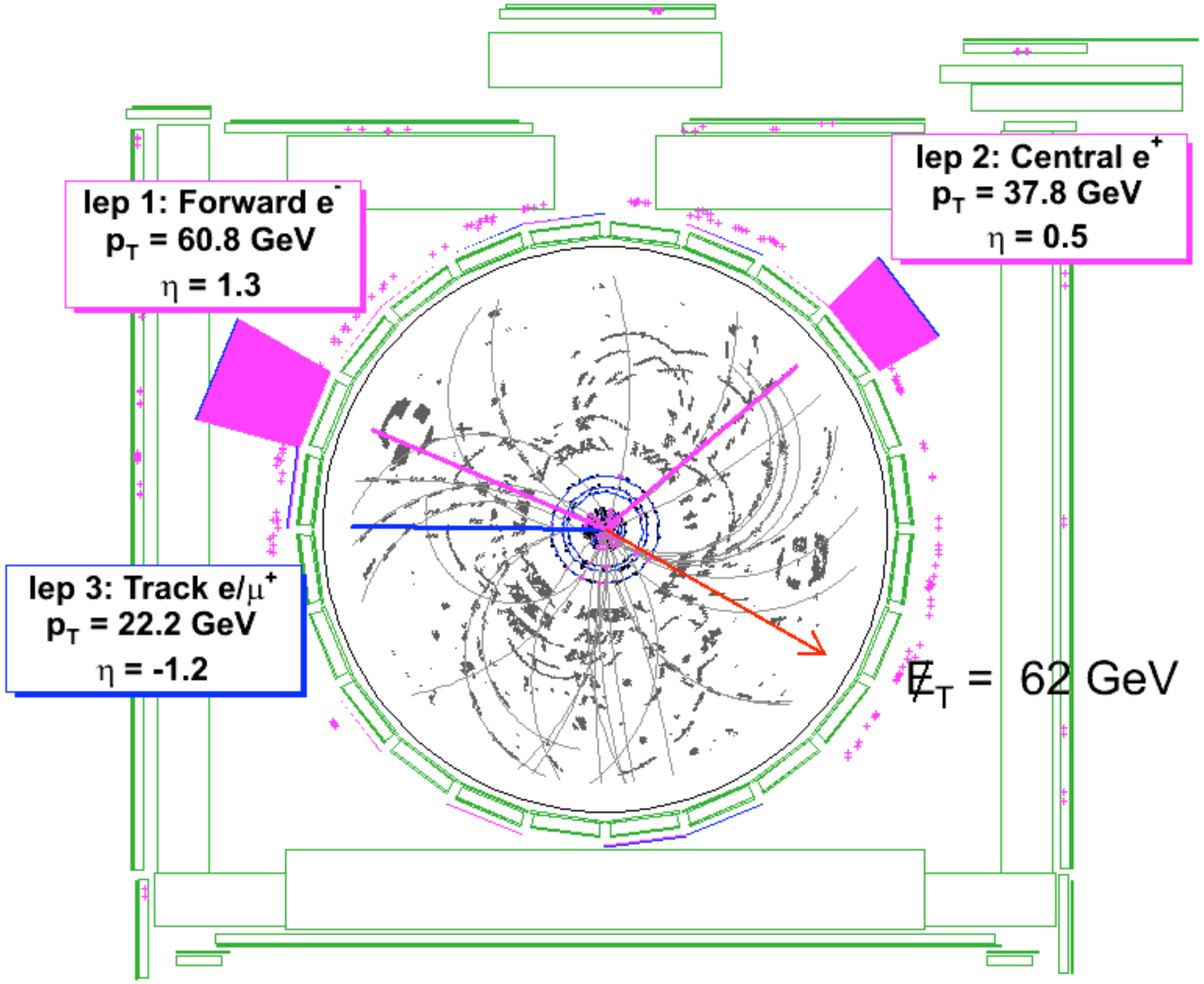


	CDF $1.9\ \mathrm{fb}^{-1}$	DØ $1\mathrm{fb}^{-1}$
candidates	25	13
background	5.2±0.8	4.5±0.6

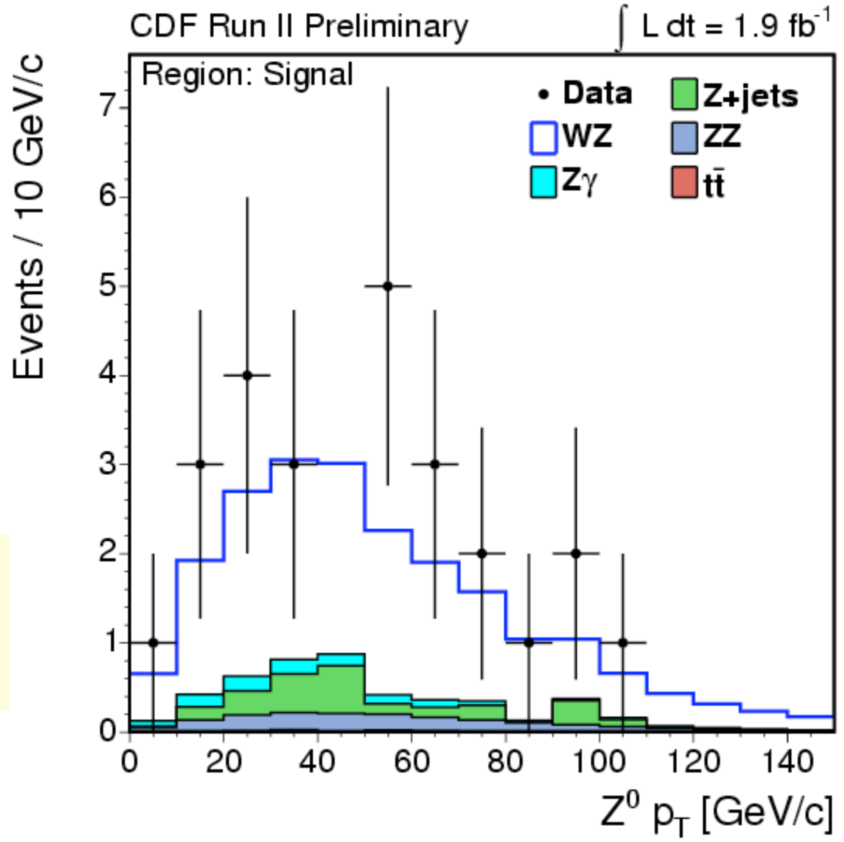
Both *s*-channel and *t*-channel: $\sigma_{\rm NLO}(WZ) = 3.7 \pm 0.3\ \mathrm{pb}$

CDF: $\sigma(WZ) = 4.3^{+1.4}_{-1.1}\ \mathrm{pb}$

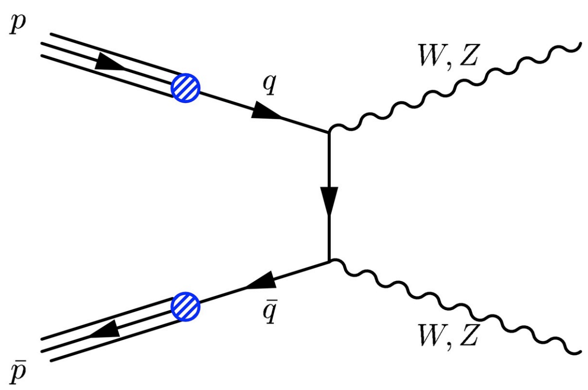
DØ: $\sigma(WZ) = 2.7^{+1.7}_{-1.3}\ \mathrm{pb}$

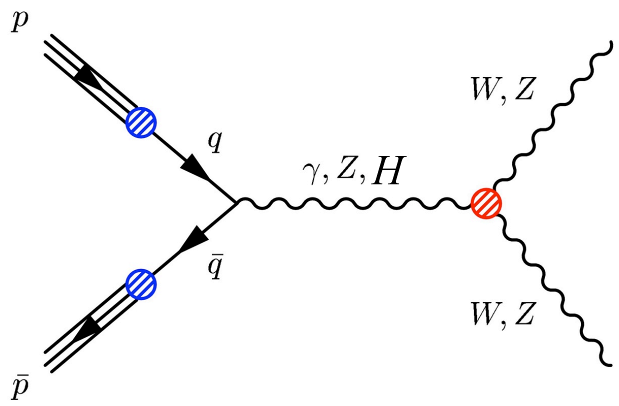


Consistent with SM predictions



$p\bar{p}\to ZZ$ production at the Tevatron





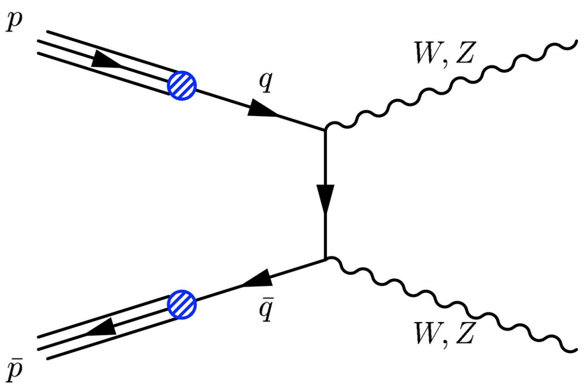
t-channel: SM production $q\bar{q}\to ZZ$

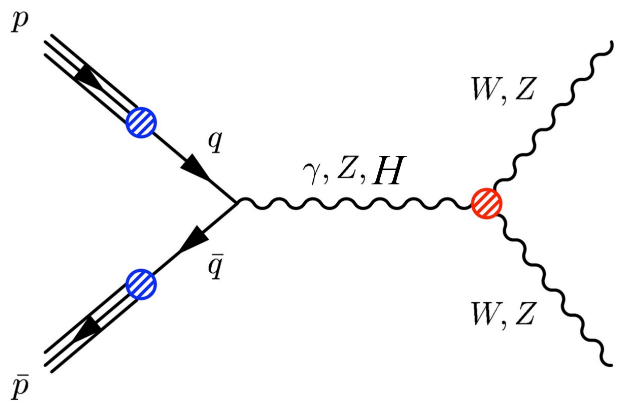
s-channel:

- SM Higgs: $q\bar{q}\to H\to ZZ$
- non-SM: γZZ and ZZZ verticies

NLO prediction $\sigma(p\bar{p}\to ZZ) = 1.4\pm0.1$ pb

$p\bar{p}\rightarrow ZZ$ production at the Tevatron





t-channel: SM production $q\bar{q}\rightarrow ZZ$

s-channel:

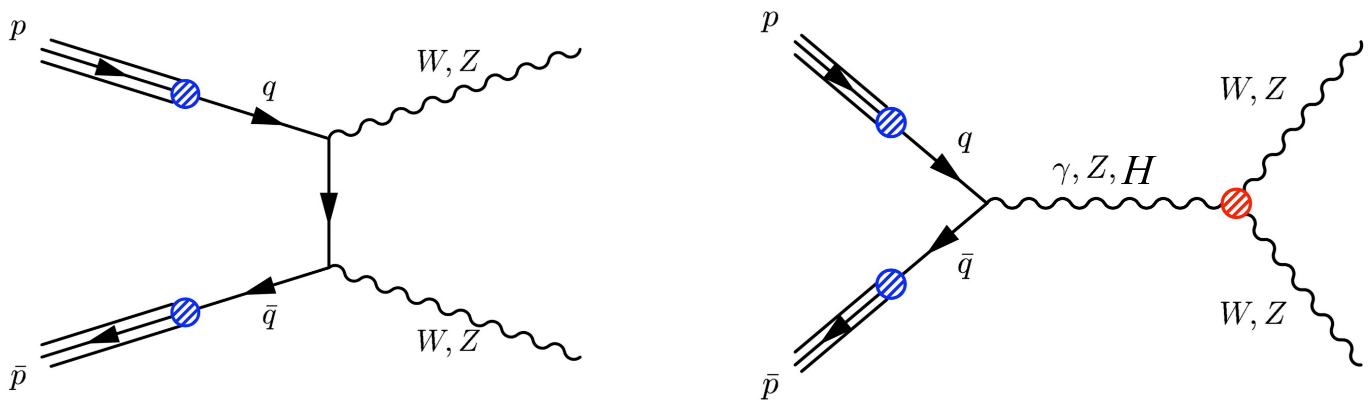
- SM Higgs: $q\bar{q}\rightarrow H\rightarrow ZZ$
- non-SM: γZZ and ZZZ verticies

NLO prediction $\sigma(p\bar{p}\rightarrow ZZ) = 1.4\pm0.1$ pb

Two search channels:

- $ZZ\rightarrow \nu\bar{\nu}\ell^+\ell^-$: large background from $WW\rightarrow \ell^+ \nu\, \ell^- \bar{\nu}$
- $ZZ\rightarrow \ell^+\ell^-\ell'^+\ell'^-$: very clean

$p\bar{p}\to ZZ$ production at the Tevatron



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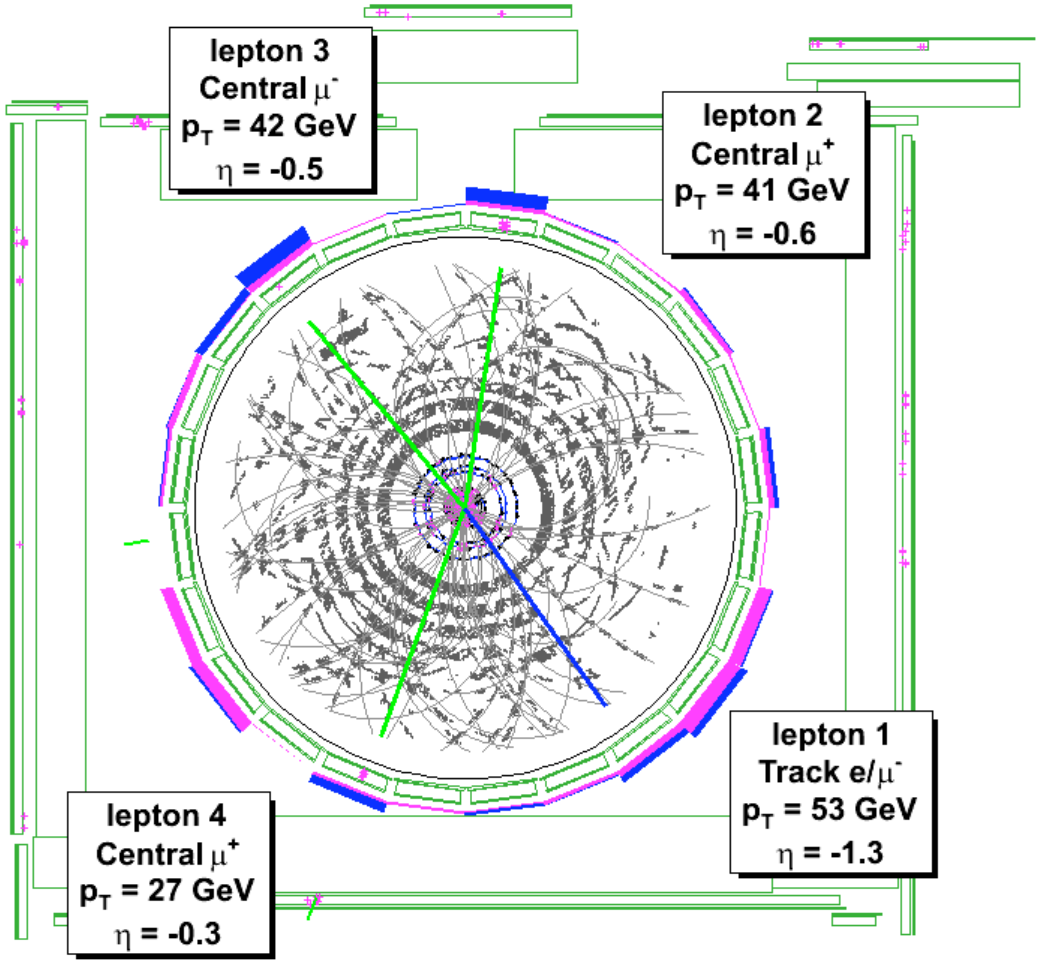
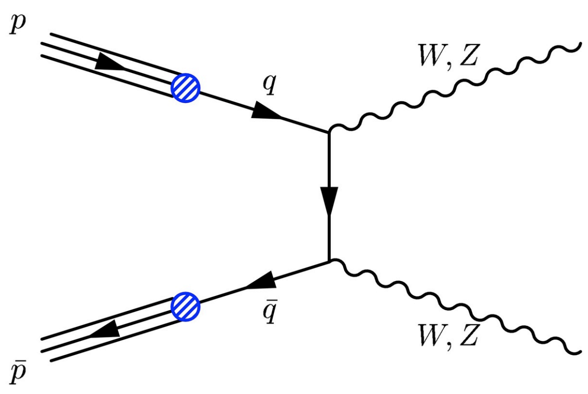
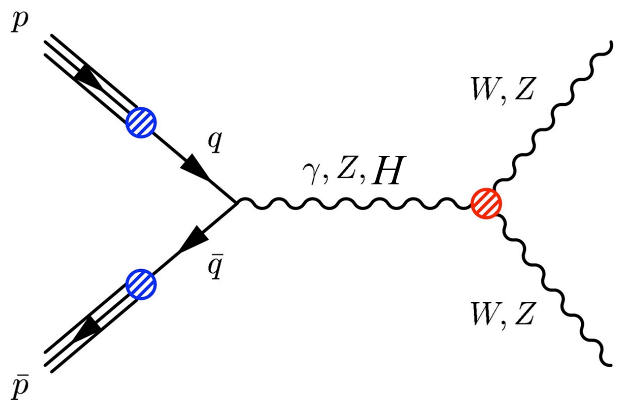
- $ZZ\to\ell^+\ell^-\ell'^+\ell'^-$: very clean

CDF 4 charged leptons	
ZZ pred.	2.27 ± 0.24
Z+jets pred.	$0.10^{+0.12}_{-0.09}$
total	$2.36^{+0.58}_{-0.39}$
observed	3



$p\bar{p}\to ZZ$ production at the Tevatron





t-channel: SM production $q\bar{q}\to ZZ$

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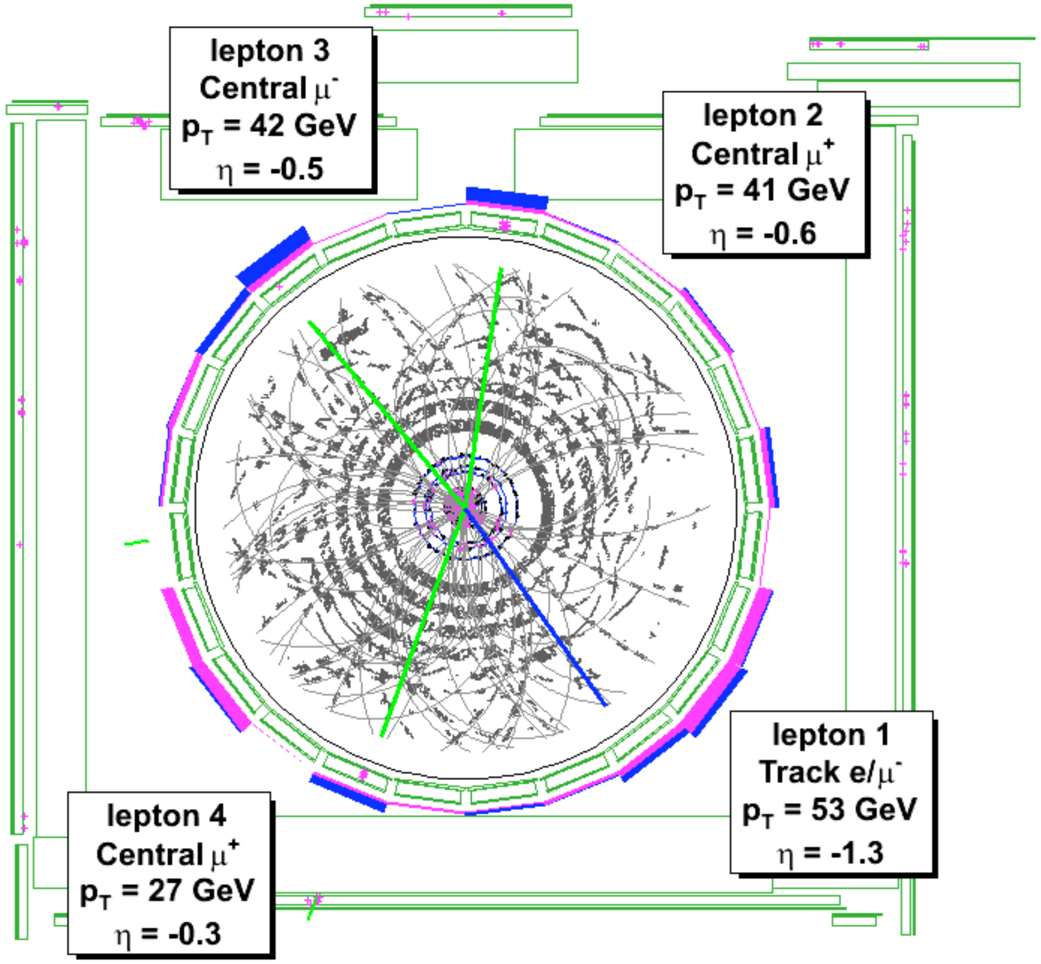


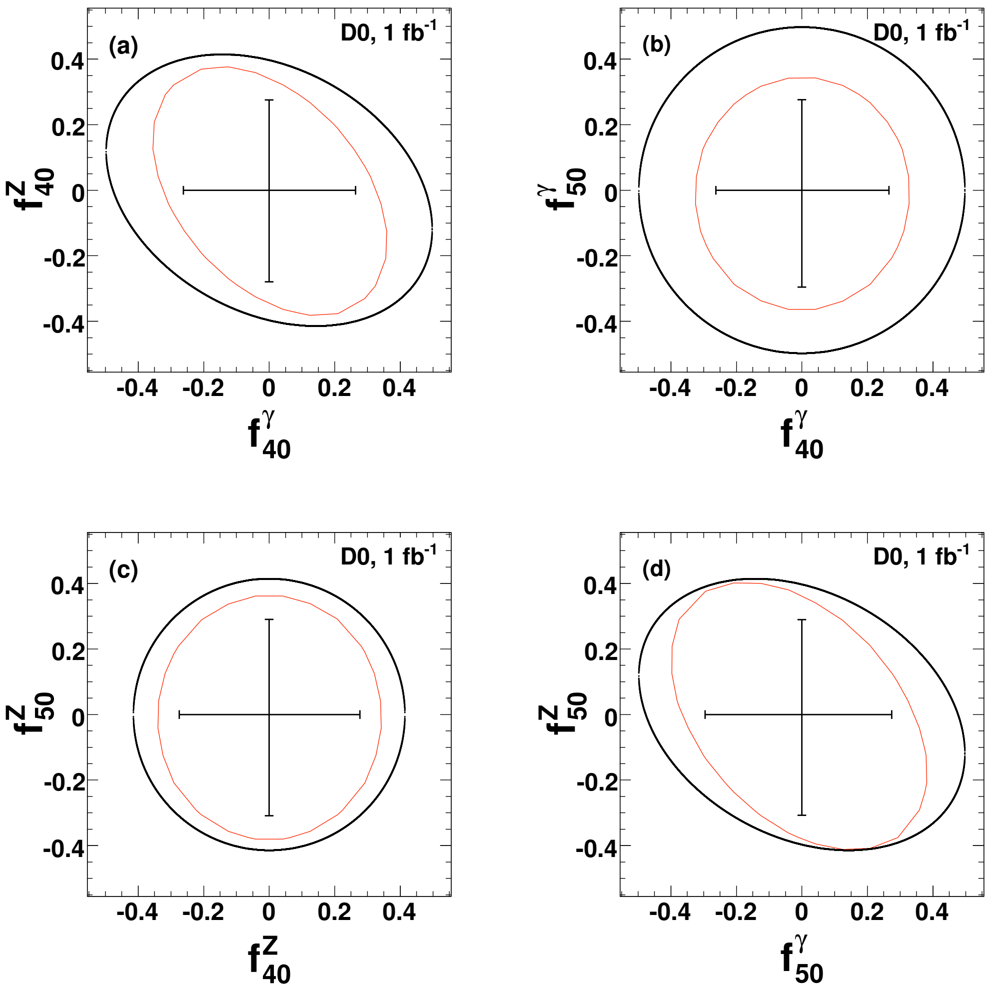
- DØ limit: $\sigma(p\bar{p}\to ZZ) < 4.4$ pb at 95%CL
- CDF measurement $\sigma(p\bar{p}\to ZZ) = 1.4^{+0.7}_{-0.6}$ pb (4.4σ significance)

Limits on anomalous tri-boson couplings

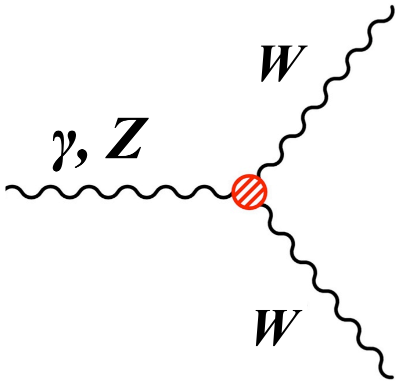
- Measured di-boson cross sections agree with SM
- Contributions from ***ZZZ***, ***γZZ*** and ***γγZ*** vertices enhance cross sections
- Non-SM ***ZWW*** coupling changes shape of Z-boson p_T distribution

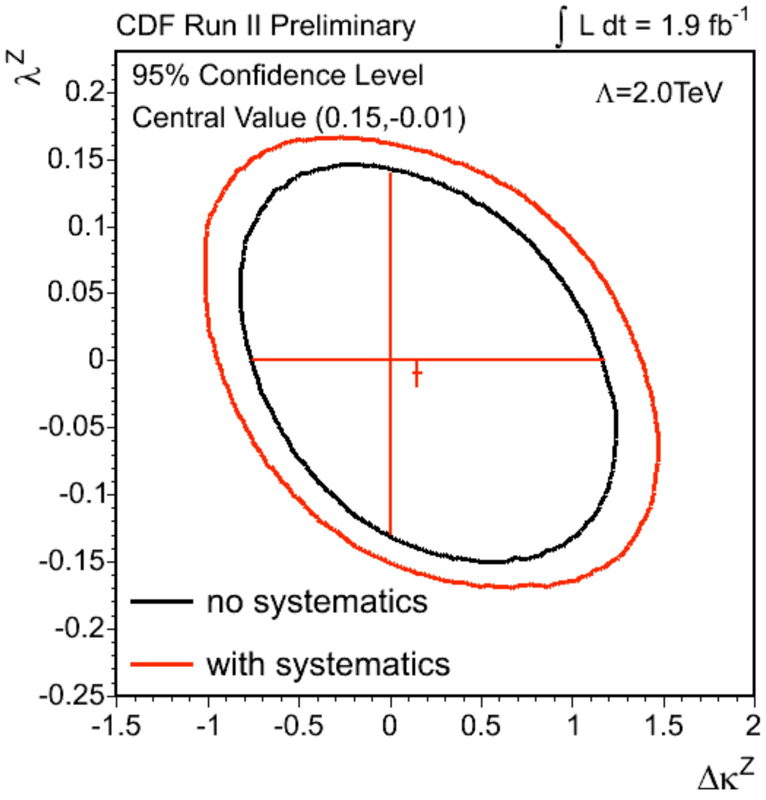
Limits on *γγZ*, *γZZ*, *ZZZ* couplings

CDF		Observed Limits	Expected Limits
ZZγ vertex	$\lvert h_3^Z \rvert$	0.083	0.085 ± 0.018
	$\lvert h_4^Z \rvert$	0.0047	0.0052 ± 0.0009
Zγγ vertex	$\lvert h_3^\gamma \rvert$	0.084	0.086 ± 0.017
	$\lvert h_4^\gamma \rvert$	0.0047	0.0051 ± 0.0009



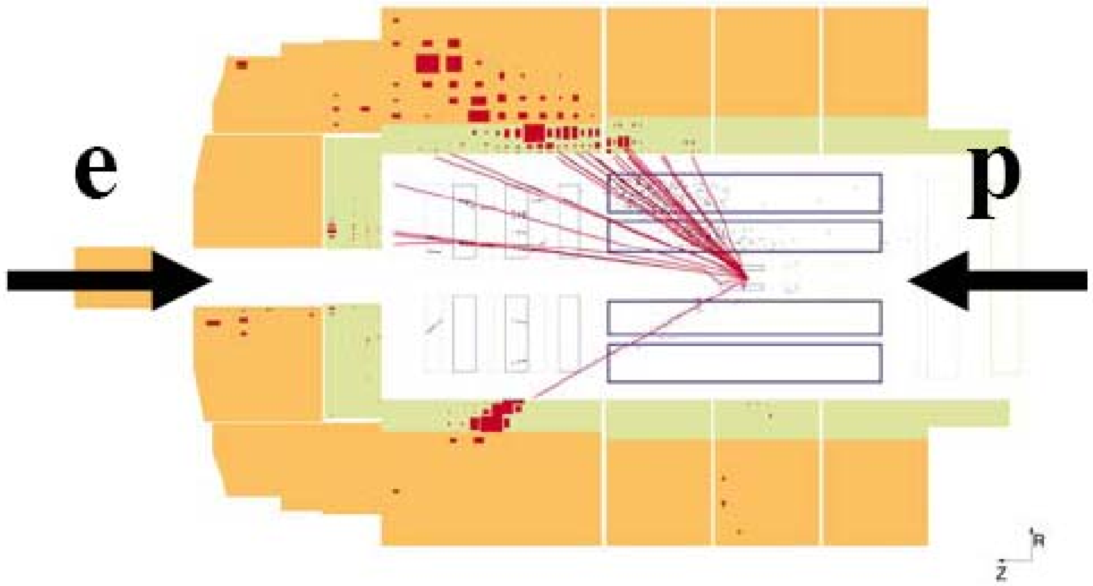
Limits on non-electroweak model *ZWW* coupling



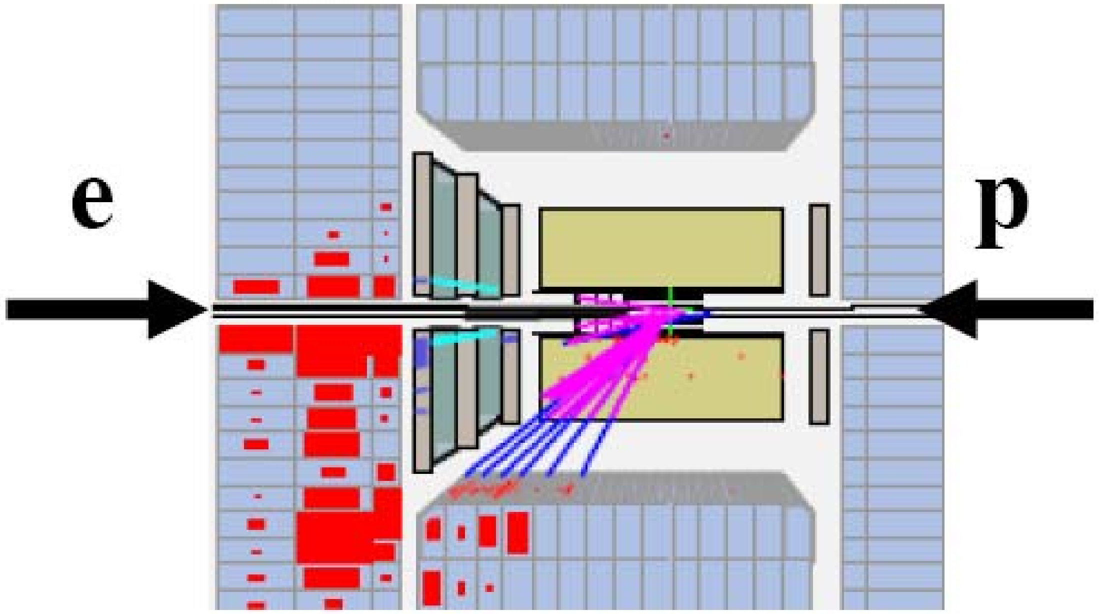


All constrained parameters are =**0** in SM

W and *Z* boson couplings at HERA



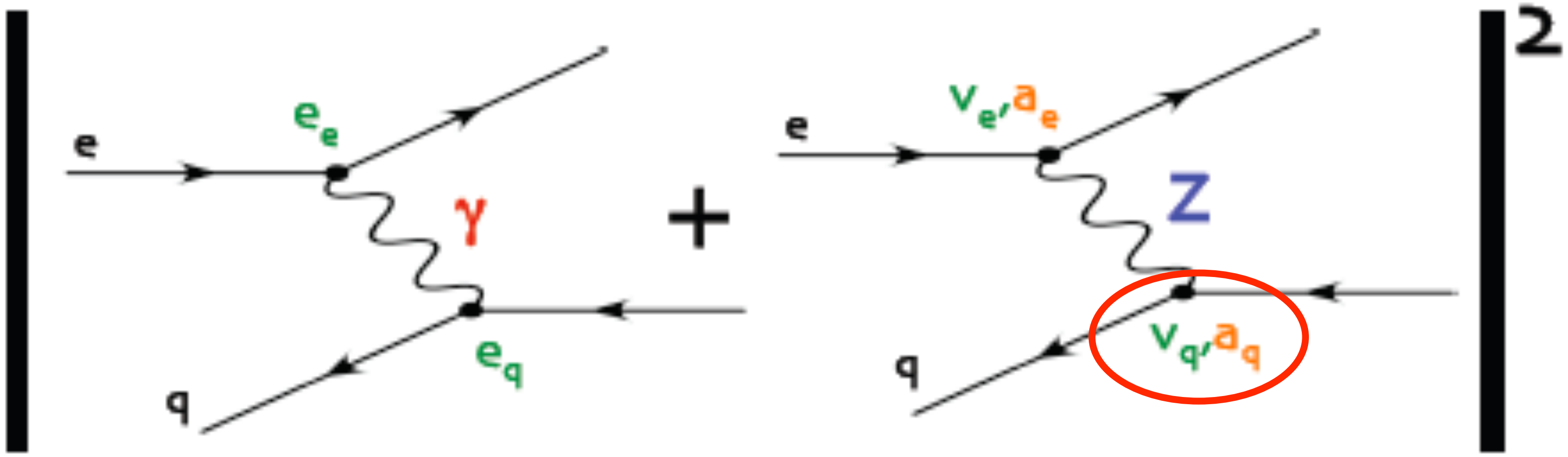
$ep \to eX$



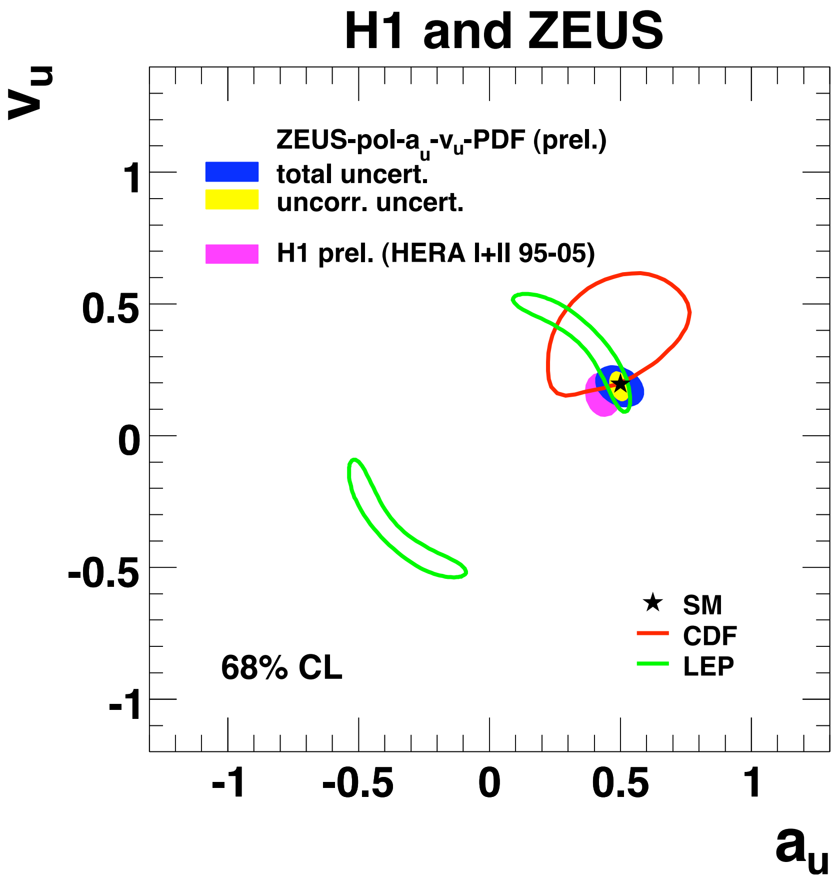
$ep \to \nu X$

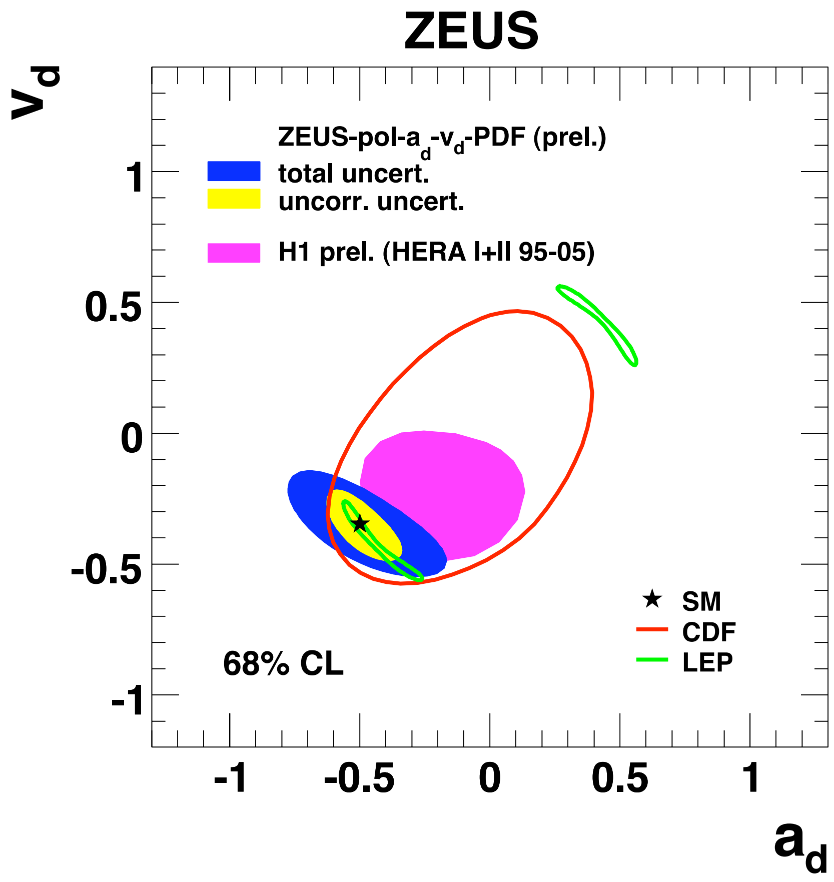
Z coupling to light quarks at HERA

- Deep inelastic scattering events: interference between Z and γ exchange probes vector and axial couplings separately.
- PDF constraints also used to obtain better bounds.



Fermion	v_f	a_f
up-type quarks	$+\frac{1}{2} - 2Q_u \sin^2\theta_W$ $= 0.193$	$+1/2$
down-type quarks	$-\frac{1}{2} - 2Q_d \sin^2\theta_W$ $= -0.347$	$-1/2$



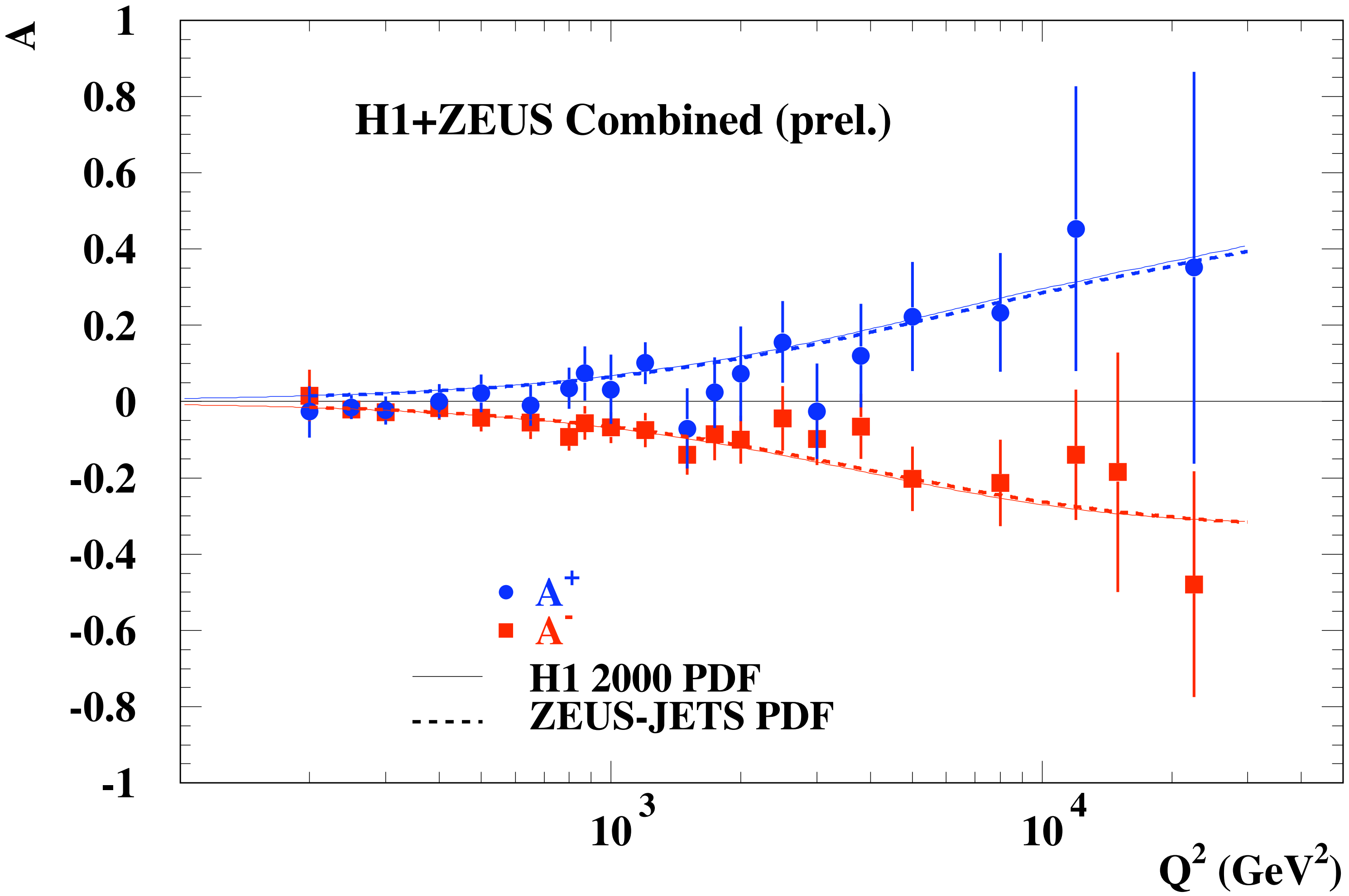


NC Parity Violation at high-Q^2

- Asymmetry in neutral current between right-handed and left-handed electrons/positrons.

$$\sigma^{\pm} = \sigma(e^{\pm}p \rightarrow e^{\pm}X)$$

$$\mathcal{A}^{\pm} = \frac{2}{\mathcal{P}_R - \mathcal{P}_L}\frac{\sigma^{\pm}(\mathcal{P}_R) - \sigma^{\pm}(\mathcal{P}_L)}{\sigma^{\pm}(\mathcal{P}_R) + \sigma^{\pm}(\mathcal{P}_L)}$$



- Difference between electrons and positrons due to parity violation in *Z*-exchange.

- First observation of parity violation in weak NC at high-Q^2

HERA Charged Current Cross Sections

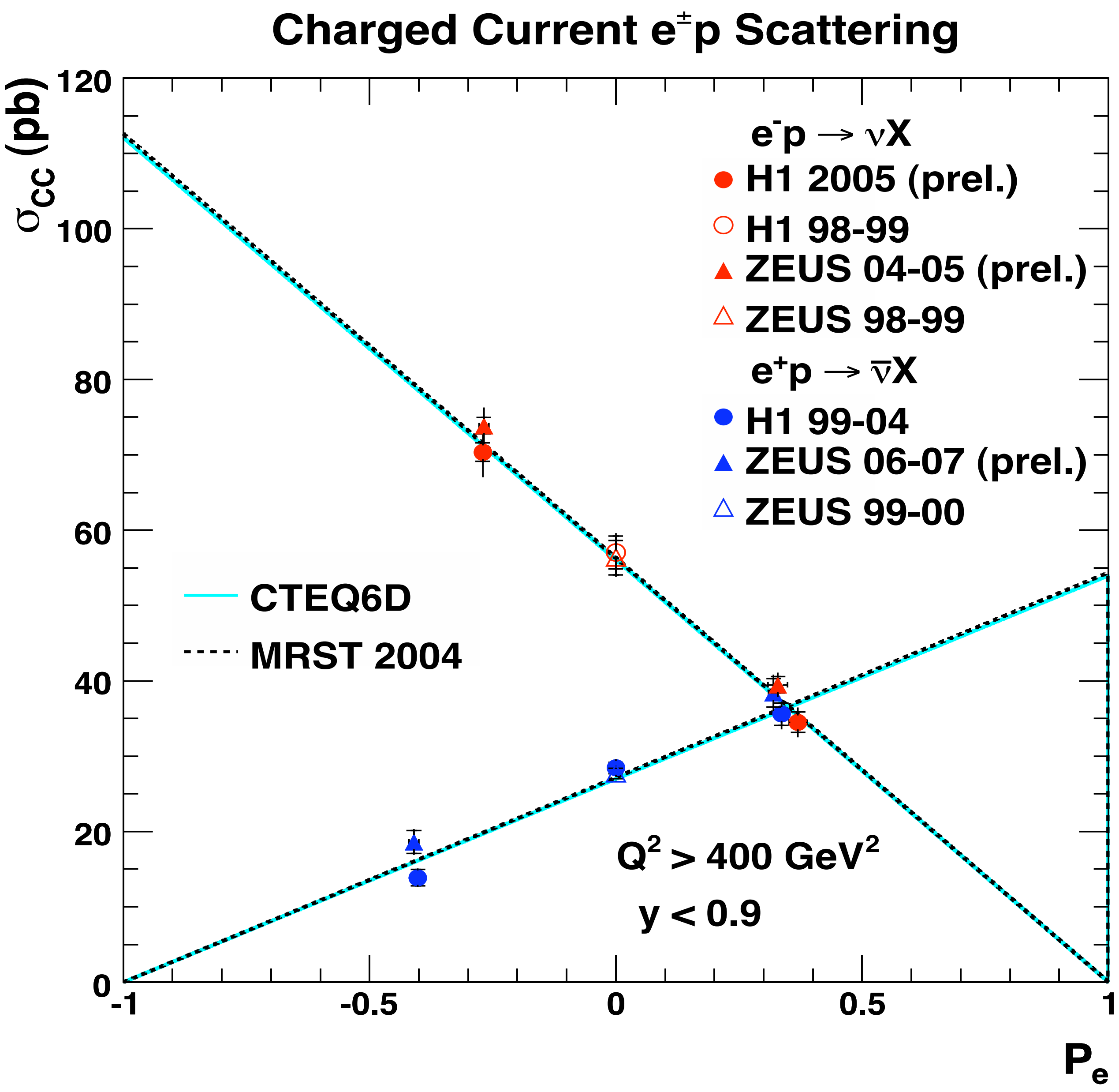
- Interaction between W-boson and *polarised* electron and positrons
- Electroweak model has maximal parity violation.

➡ W interacts **only** with left-handed electrons and right-handed positrons

- $\mathcal{P}_e$: degree of polarisation

$$\sigma^{\pm}_{\mathrm{CC}}(\mathcal{P}_e) = (1 \pm \mathcal{P}_e)\,\sigma^{\pm}_{\mathrm{CC}}(0)$$

- Consistent with Standard Model prediction



- Can set limits massive charged boson coupling to RH fermions.
- For $g_L = g_R$, and ν_R light; $M_{W_R} > 208$ GeV

Summary and Outlook

- Experiments at the Tevatron have made precise measurements of m_W, Γ_W and m_t. Errors on this will reduce with more statistics and improved analysis techniques.

- First evidence for single-top production.

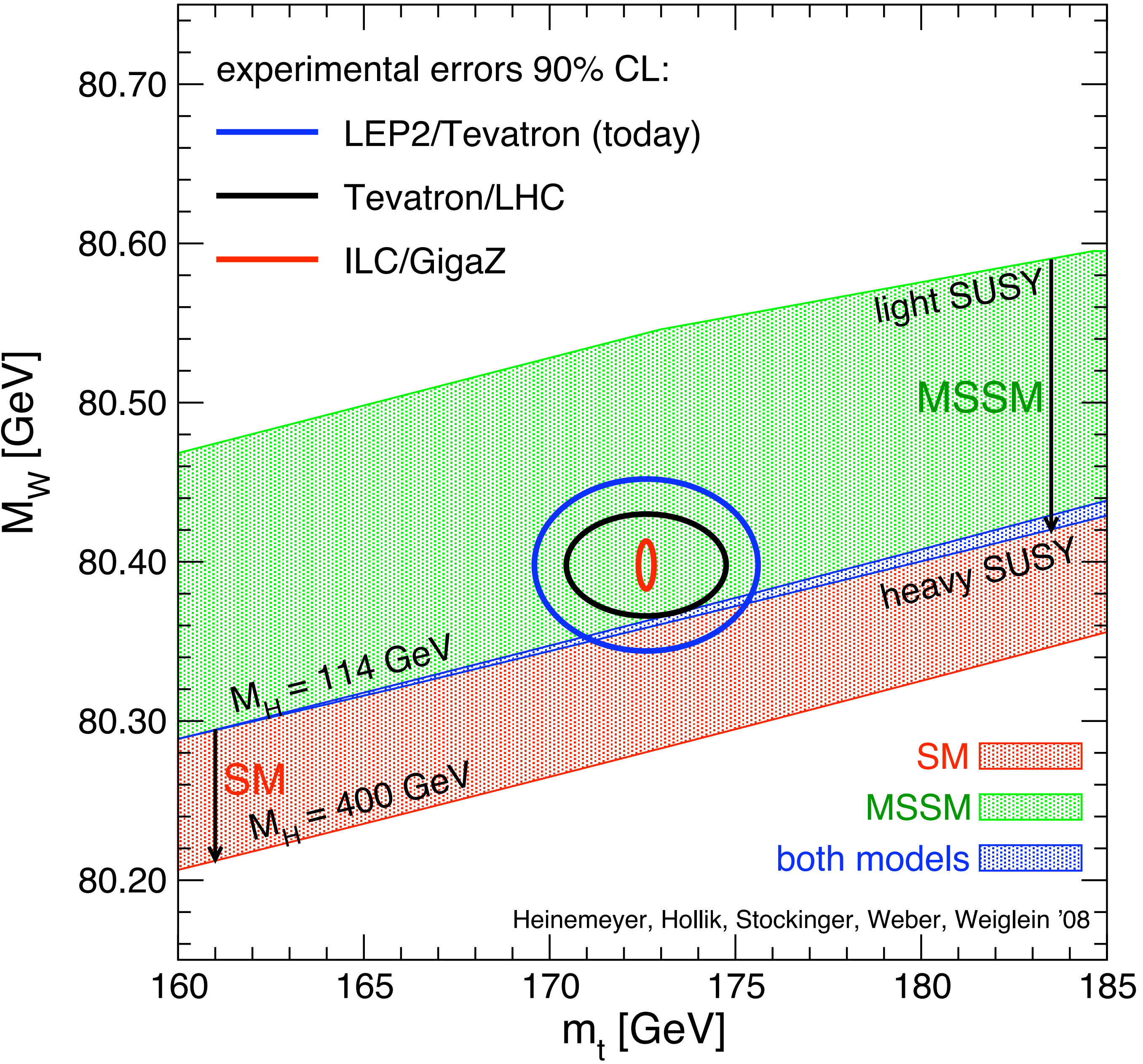
- First observations and measurements of di-boson production: WZ, ZZ.
  - With $Z\gamma$ used to probe tri-boson couplings.

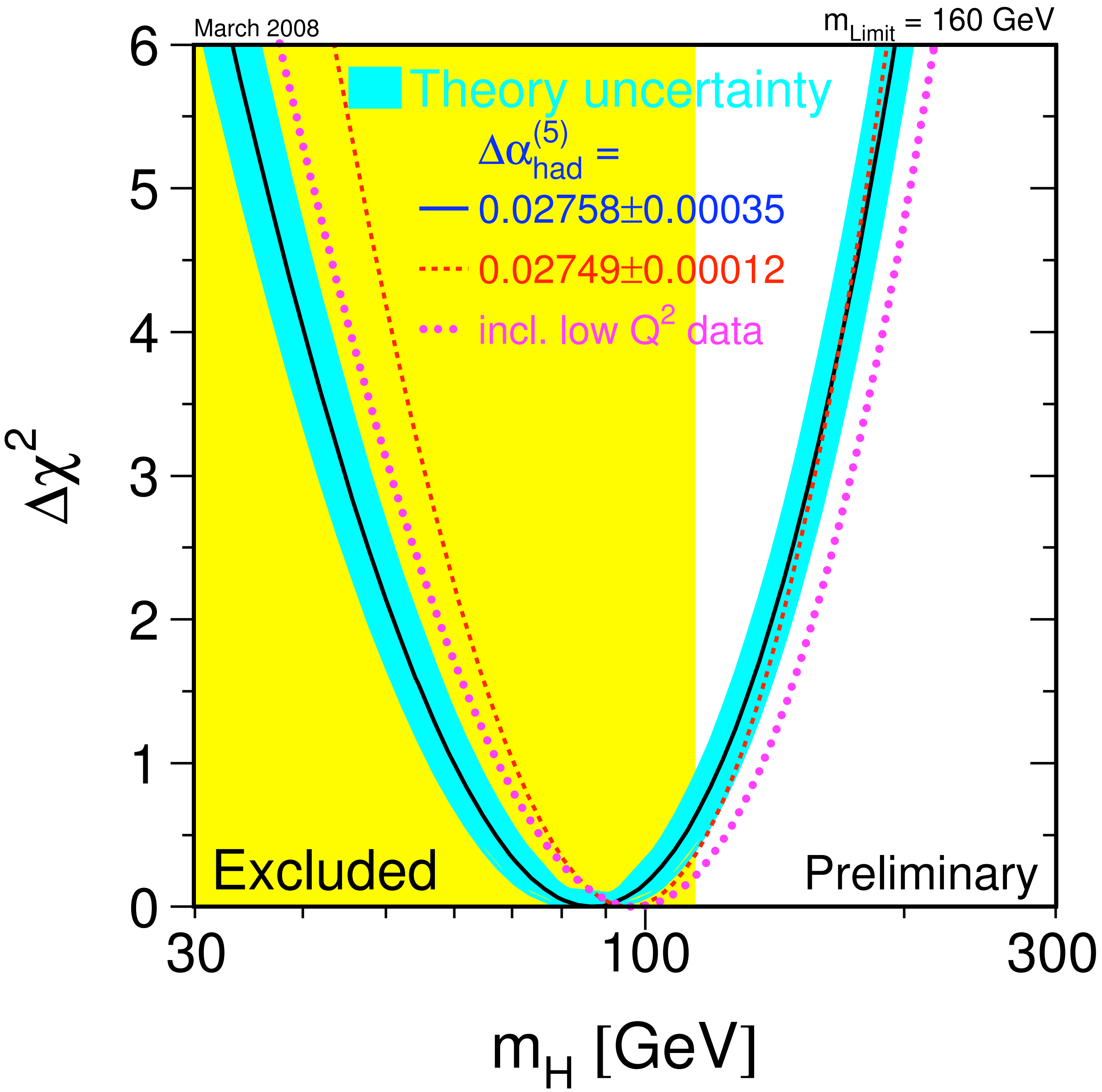
- Measurements at HERA test electroweak couplings at high-Q^2.

- Once again, the electroweak model (with some help from QCD) triumphs!

- The LHC will be able to make huge improvements to the measurements of electroweak parameters ... perhaps it will see the first signs that the electroweak model is not the whole truth.

Conclusions - the Big Pictures

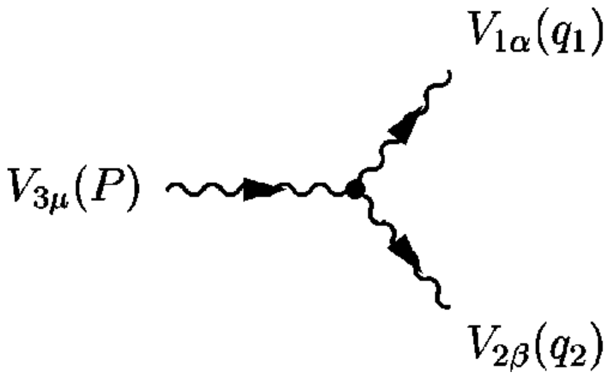




Backup

Anomalous Couplings: γZ, ZZ

- All gauge invariant terms:



$$= ie\,\Gamma^{\alpha,\beta,\mu}_{V_1V_2V_3}(q_1,q_2,P)$$

$$\Gamma^{\alpha\beta\mu}_{Z\gamma V}(q_1,q_2,P) = \frac{i(s-m_V^2)}{m_Z^2}\{h_1^V(q_2^\mu g^{\alpha\beta} - q_2^\alpha g^{\mu\beta}) + \frac{h_2^V}{m_Z^2}P^\alpha[(Pq_2)g^{\mu\beta} - q_2^\mu P^\beta]$$

$$-h_3^V\epsilon^{\mu\alpha\beta\rho}q_{2\rho} - \frac{h_4^V}{m_Z^2}P^\alpha\epsilon^{\mu\beta\rho\sigma}P_\rho q_{2\sigma}\},$$

$$\Gamma^{\alpha\beta\mu}_{ZZV}(q_1,q_2,P) = \frac{i(s-m_V^2)}{m_Z^2}[f_4^V(P^\alpha g^{\mu\beta} + P^\beta g^{\mu\alpha}) - f_5^V\epsilon^{\mu\alpha\beta\rho}(q_1-q_2)_\rho],$$

- For all neutral gauge boson in SM all terms h_1, h_2 , h_3, h_4, f_4, f_5 are zero.
  - h_1, h_2, f_4 describe CP-violating couplings
  - h_3, h_4, f_5 describe CP-conserving couplings

Anomalous Couplings: *WZ*

Hagiwara, Ishihara,
Szalapski, Zeppenfeld
Phys Rev **D48**, 5, p48

$$\begin{aligned}\mathcal{L}_{\text{eff}}^{WWV} = i\, g_{WWV} \Big(& g_1^V (W_{\mu\nu}^+ W^{-\mu} - W^{+\mu} W_{\mu\nu}^-) V^\nu \\ & + \kappa_V\, W_\mu^+ W_\nu^- V^{\mu\nu} \\ & + \frac{\lambda_V}{m_W^2} W_\mu^{+\nu} W_\nu^{-\rho} V_\rho{}^\mu \Big) , \qquad (2.8)\end{aligned}$$

- In SM:
  - $g_{WW\gamma} = -e, \quad g_{WWZ} = -e \cot\theta_W,$
  - $g_1{}^Z = g_1{}^\gamma = \kappa_Z = \kappa_\gamma = 1, \;\; \lambda_Z = \lambda_\gamma = 0$

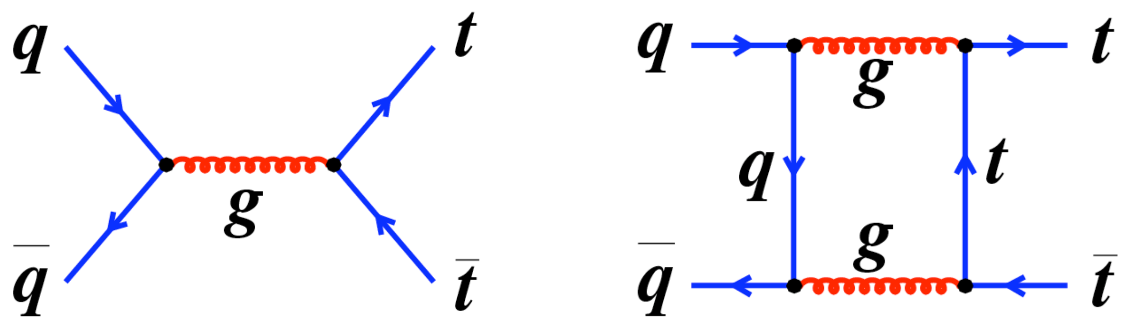
- Non-SM D≤6 terms, consistent with gauge invariance:

$$\begin{aligned} g_1^Z &= \kappa_Z + \frac{s^2}{c^2}(\kappa_\gamma - 1) \; , \\ \lambda_\gamma &= \lambda_Z = \lambda \; . \end{aligned}$$

- Λ is scale to used to control new operators.

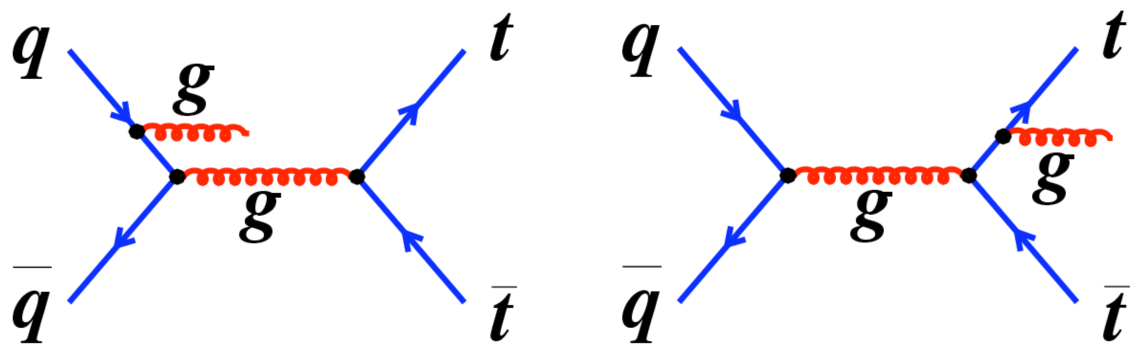
Forward-Backward Asymmetry $p\bar{p}\to t\bar{t}$

- jet asymmetry arises from interference between symmetric and antisymmetric contributions under the exchange $t \leftrightarrow \bar{t}$



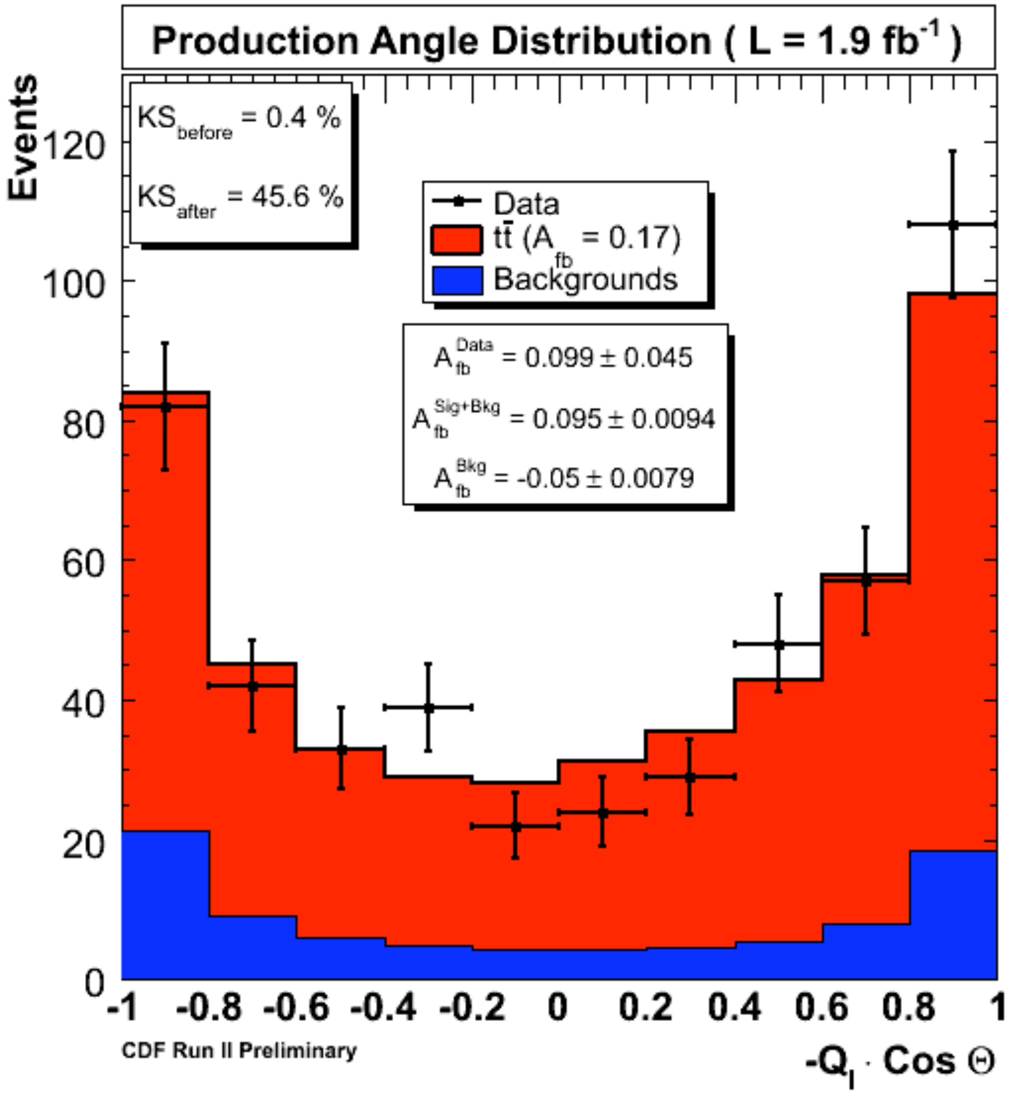
Interference between LO
and box gives positive *Afb*

- NLO asym ~ **5-10%**



Interference between ISR
and FSR gives negative *Afb*

- asym depends on the phase space region probed (due to additional jets)
- overall FSR+ISR corrections asym = **(4 ± 1)%**

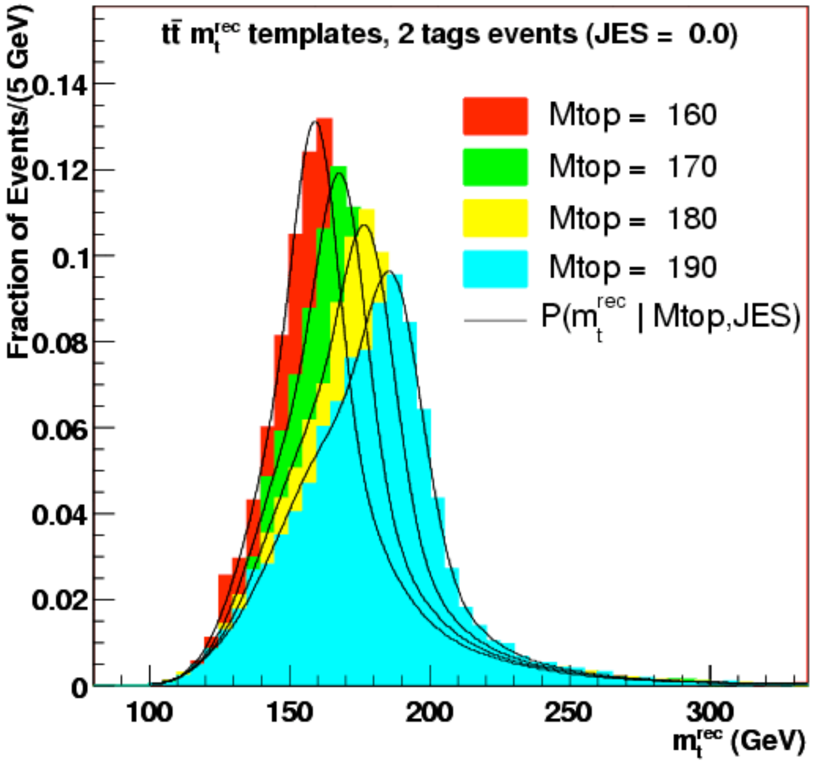


CDF: A_{fb} = 0.17 ± 0.07 (stat) ± 0.04 (syst)

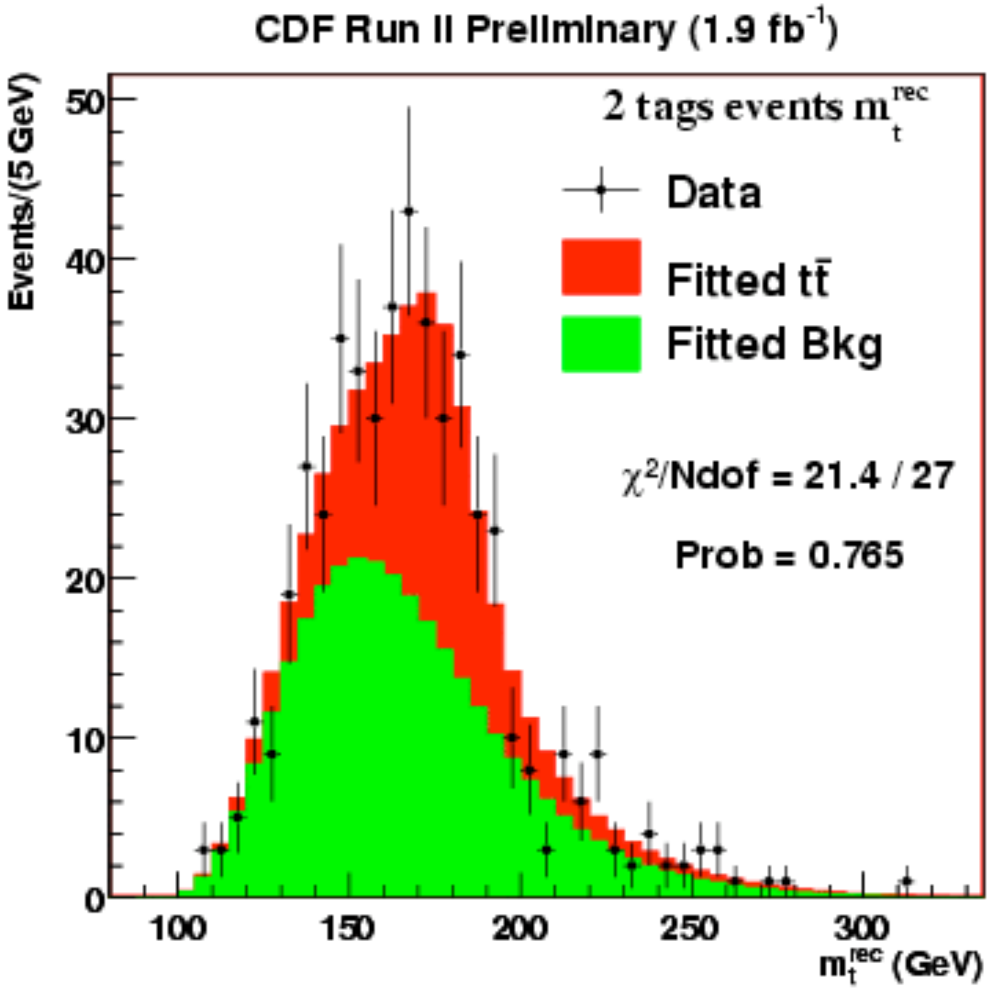
DØ: A_{fb} = 12±8(stat)±1(syst) % (for n jets < 4)
A_{fb} = 19±9(stat)±2(syst) % (for n jets = 4)
$A_{fb} = -16^{+17}_{-15}$ (stat)±3(syst) % (for n jets ≥ 5)

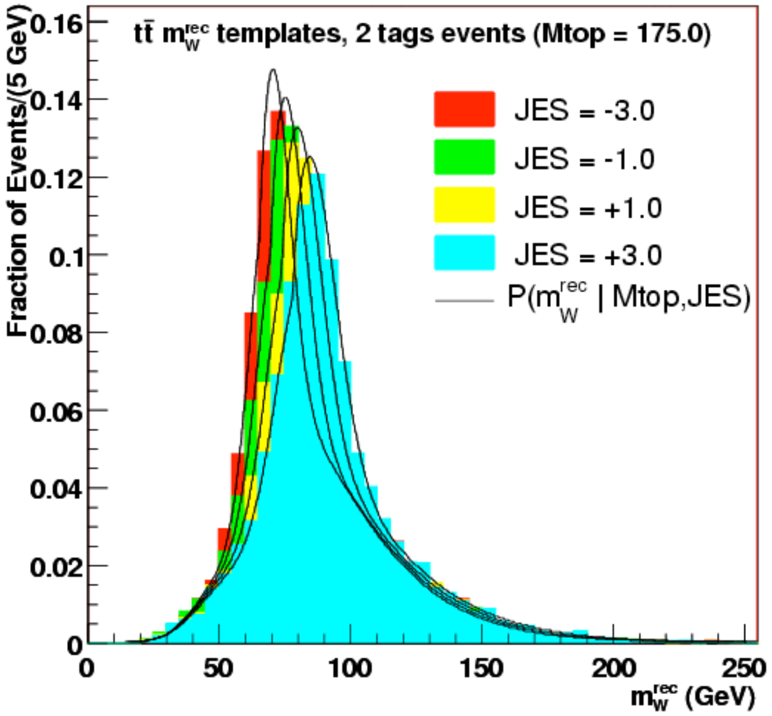
Top Quark Mass - Template Method

- Create MC templates with different input values of m_t to fit to observed data.



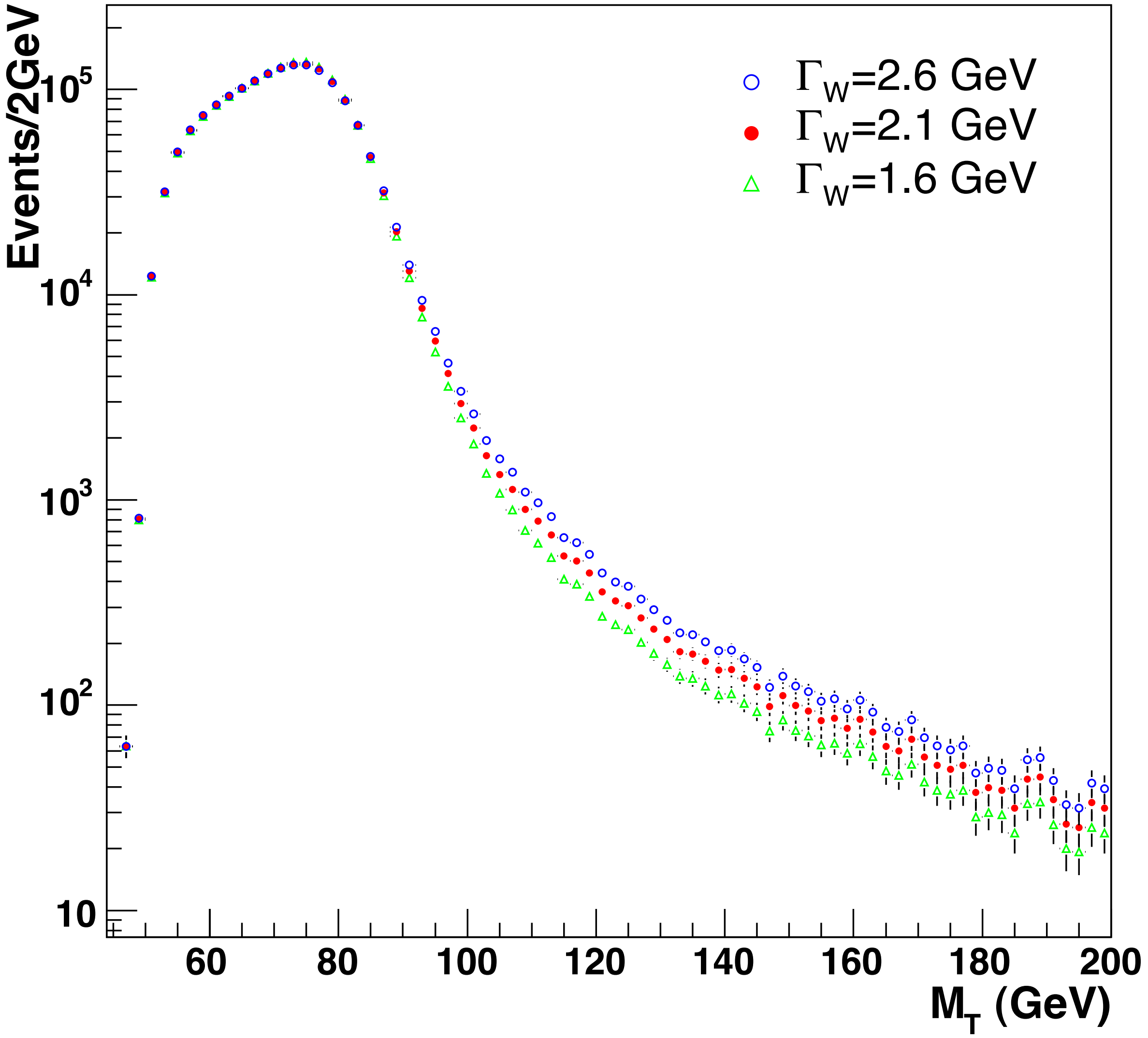
CDF All hadronic
2 *b*-tags



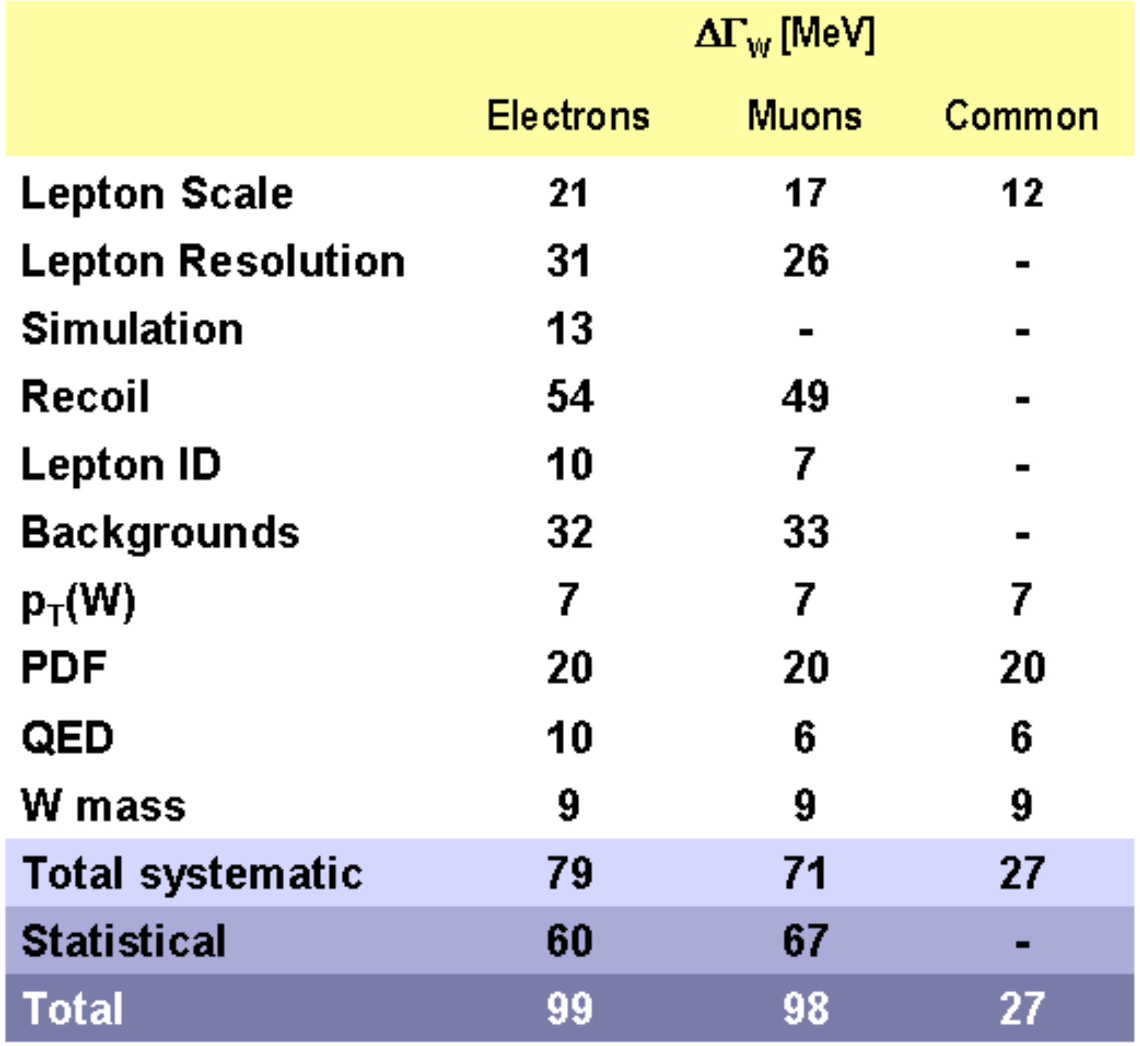


W-boson width

DØ templates



CDF systematics



	$\Delta\Gamma_W$ [MeV]		
	Electrons	Muons	Common
Lepton Scale	21	17	12
Lepton Resolution	31	26	-
Simulation	13	-	-
Recoil	54	49	-
Lepton ID	10	7	-
Backgrounds	32	33	-
p_T(W)	7	7	7
PDF	20	20	20
QED	10	6	6
W mass	9	9	9
Total systematic	79	71	27
Statistical	60	67	-
Total	99	98	27