Physics With Vector Bosons @ The Tevatron

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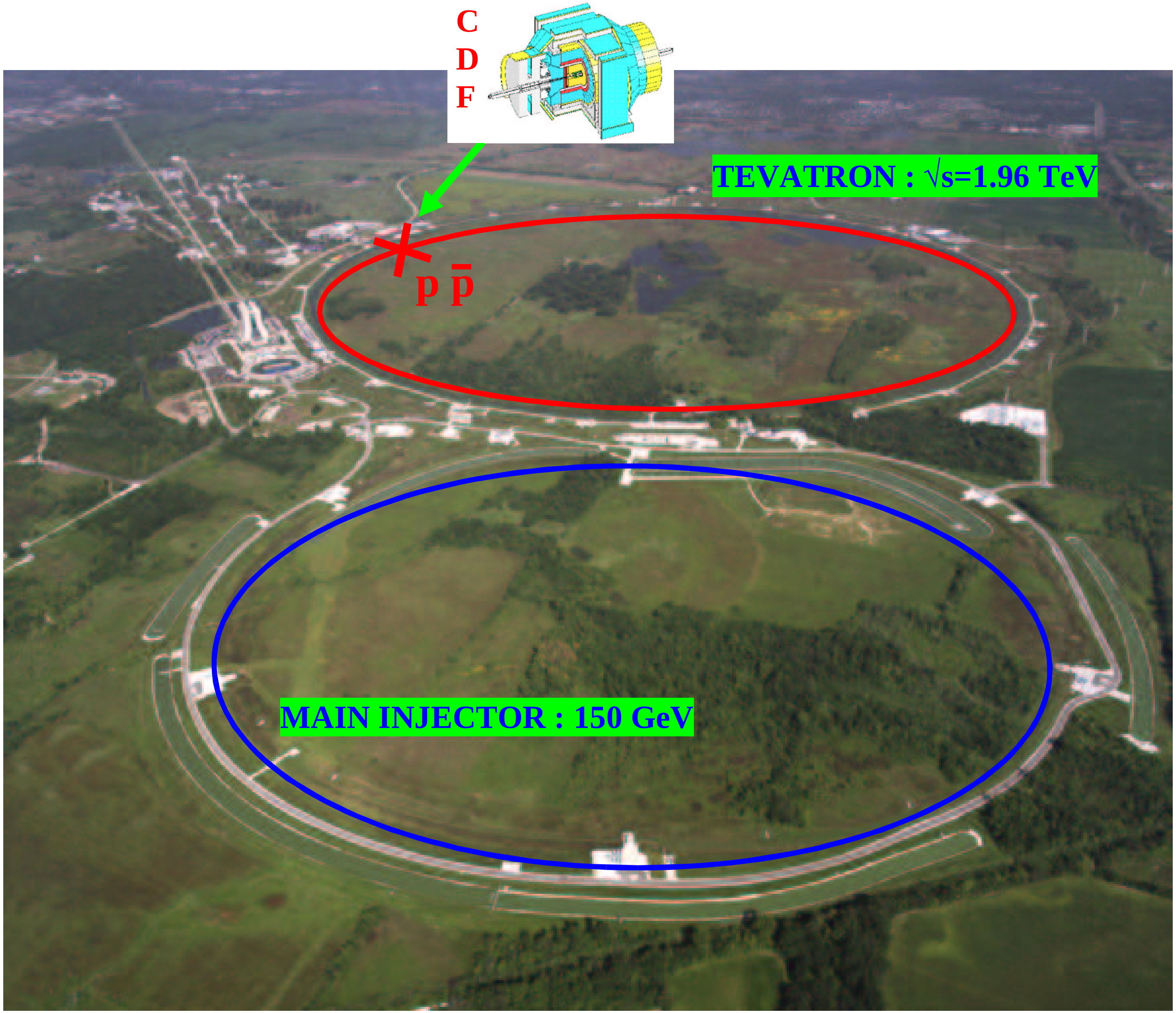
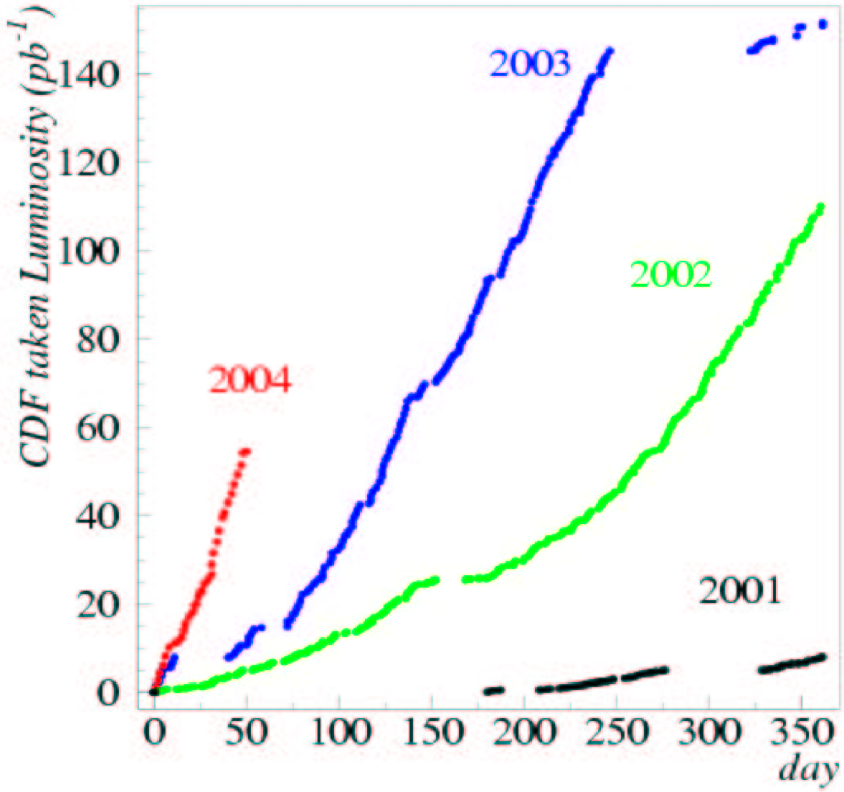
- Tevatron & CDF
- W & Z Cross Section Measurements
- Di−Boson Production
- Higgs Searches
- Precision Measurements
- Outlook

HEP Seminar, Oxford, 18th May



C
D
F
TEVATRON : √s=1.96 TeV
p $\bar{p}$
MAIN INJECTOR : 150 GeV

Tevatron Performance

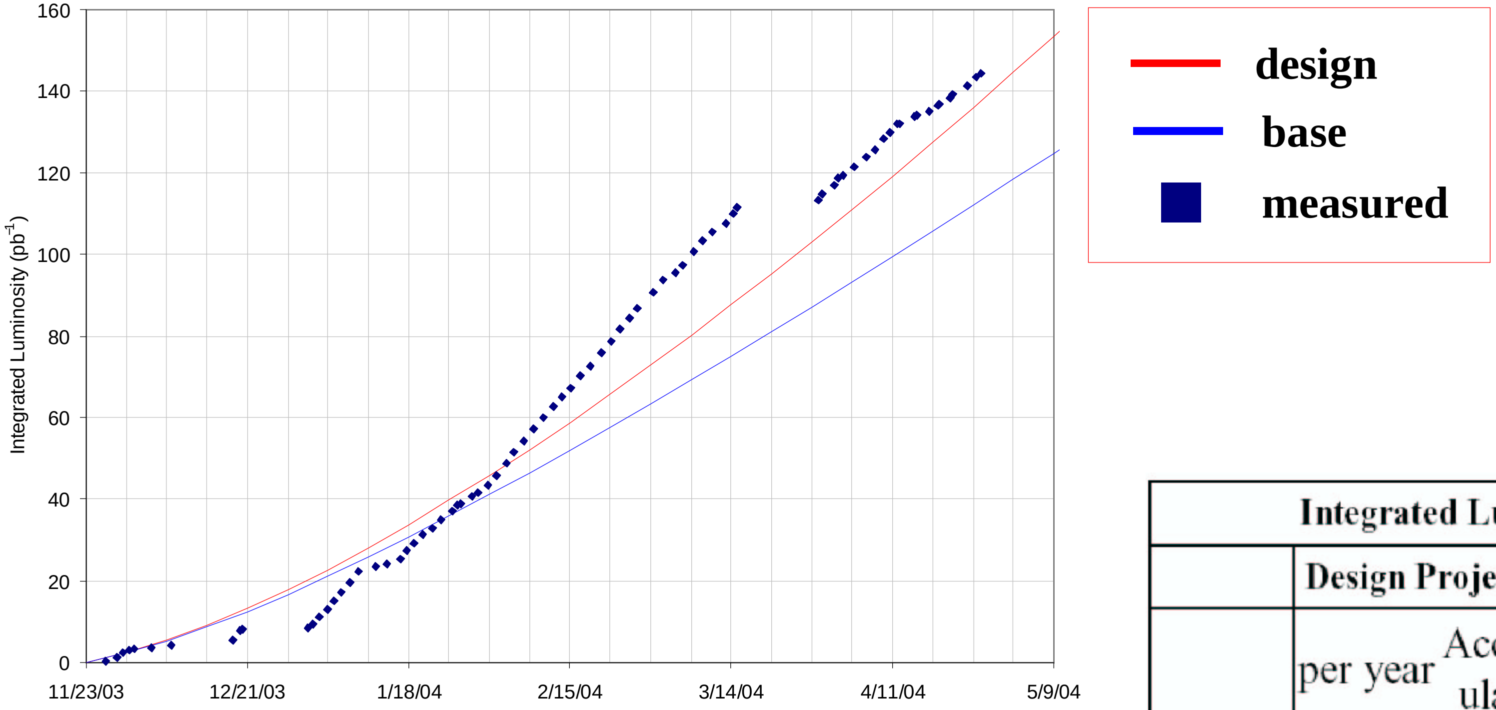


- Accelerator performance in 2004 is excellent. "Design goals" surpassed.
- Peak luminosity $7\times10^{31} cm^{-2}s^{-1}$ (Spring 04)
- CDF takes data with efficiency > 85%.
- Beam conditions good : silicon is typically integrated for the entire store.
- >400 pb^{-1} delivered so far in Run 2.

CDF now collects $\geqslant$ 1pb^{-1}/day :

Process	Events/Week
$t\bar{t}$	50
$W \to e\nu_e$	18,000
$Z \to e^+e^-$	1700
WW	90
$W\gamma \to e\nu\gamma$ (high-$p_T\gamma$)	130
$gg \to H$ (M_H=115 GeV)	6

Tevatron Performance



projections based on above curves

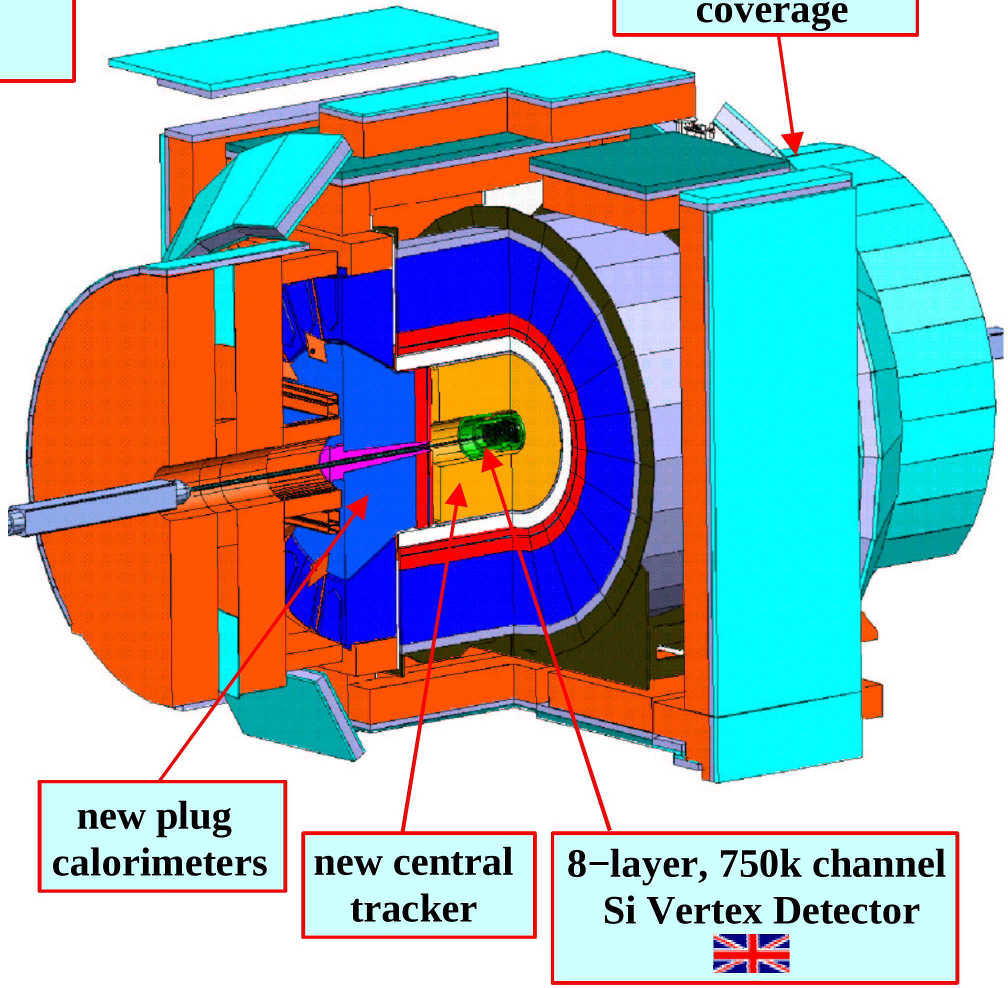
Integrated Luminosity (fb^{-1})				
	Design Projection		Base Projection	
	per year	Accum-ulated	per year	Accum-ulated
FY03	0.22	0.30	0.20	0.28
FY04	0.38	0.68	0.31	0.59
FY05	0.67	1.36	0.39	0.98
FY06	0.89	2.24	0.50	1.48
FY07	1.53	3.78	0.63	2.11
FY08	2.37	6.15	1.14	3.25
FY09	2.42	8.57	1.16	4.41

CDF Run 2 Detector

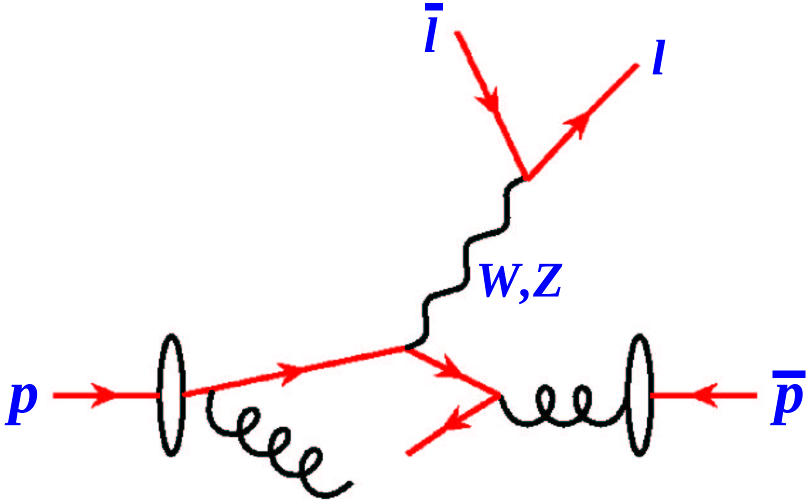
<u>CDF Run 2 Detector :</u>

- Largely new detector.
- New trigger system : displaced tracks, taus, etc.
- Data handling : ≈ 0.5 PetaBytes/year processed and analysed.

Glasgow, Liverpool, Oxford, UCL

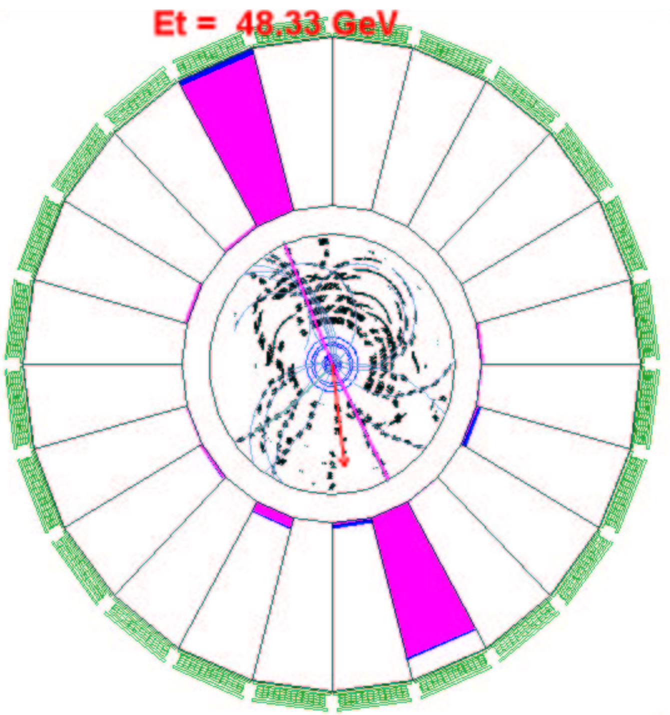


W and Z Production



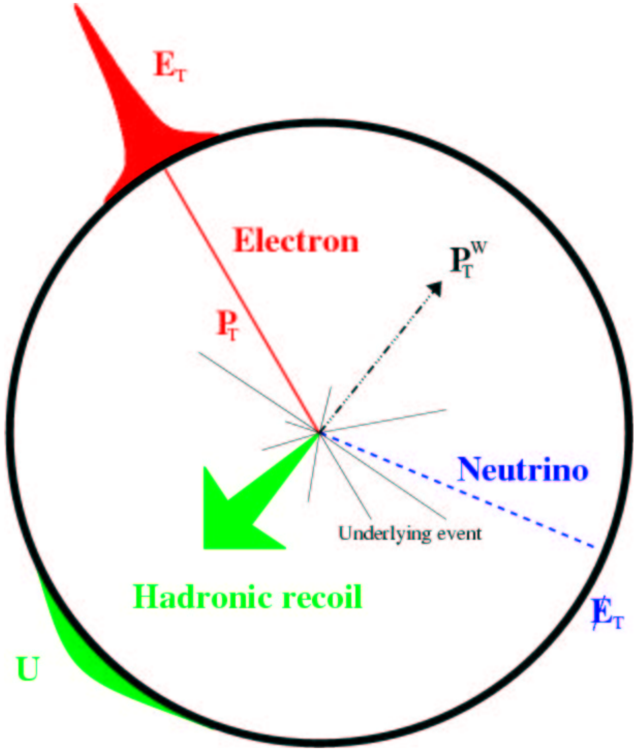
Physics :

- PDF's
- Production and decay −soft and hard QCD & EWK.
- Detector response to high−p_T leptons and low−p_T hadrons.

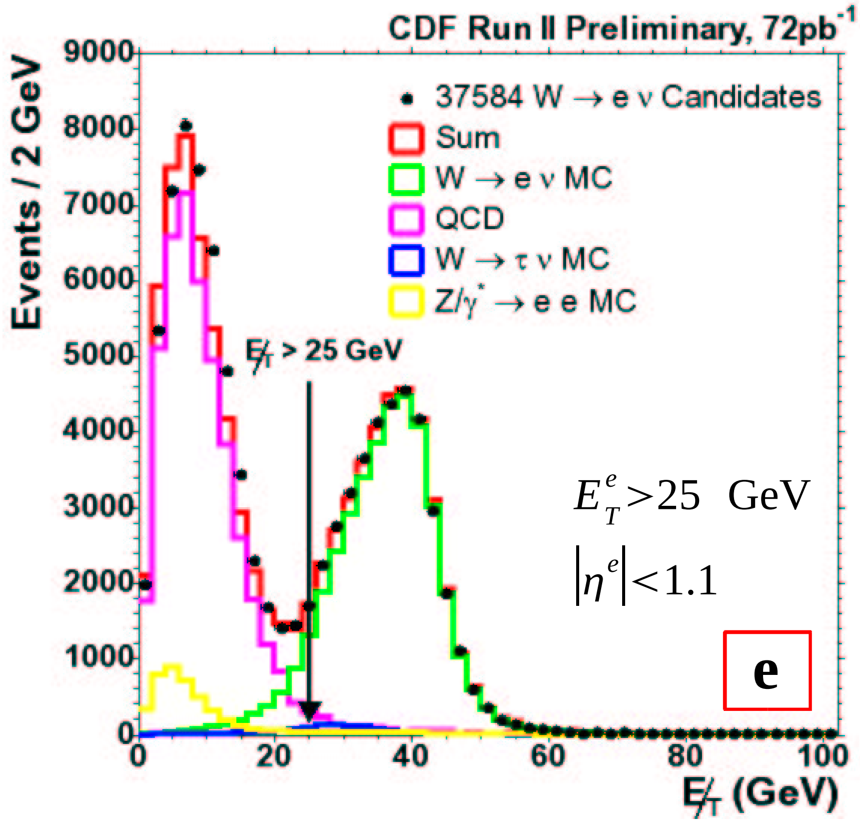


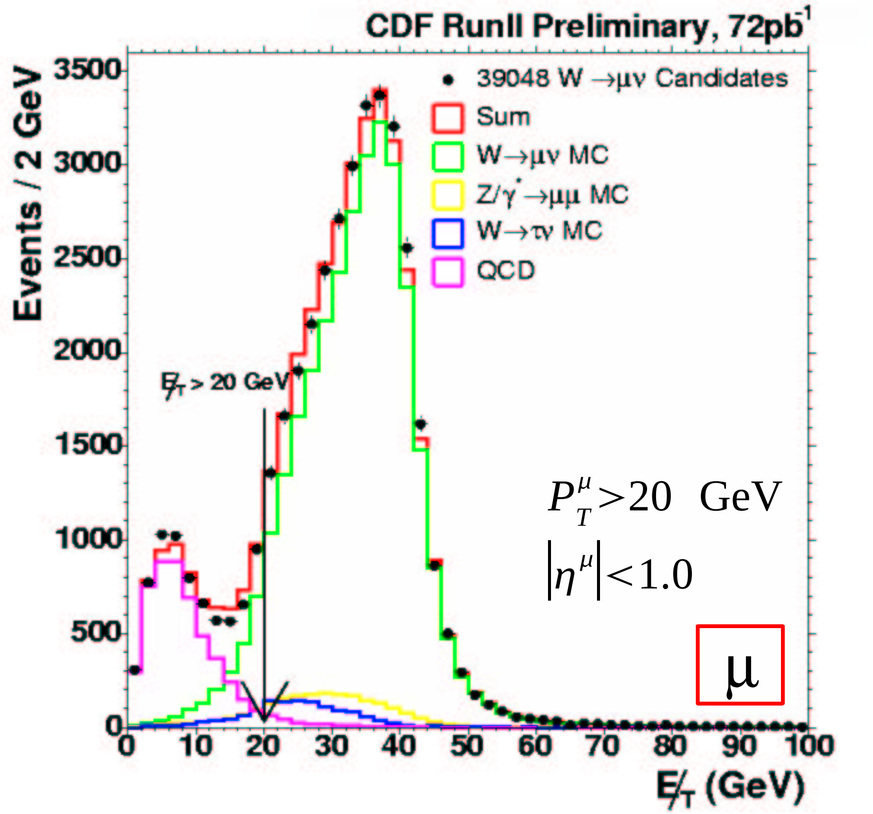
$Z^0 \to e^+ e^-$

$W \to e\,\nu$



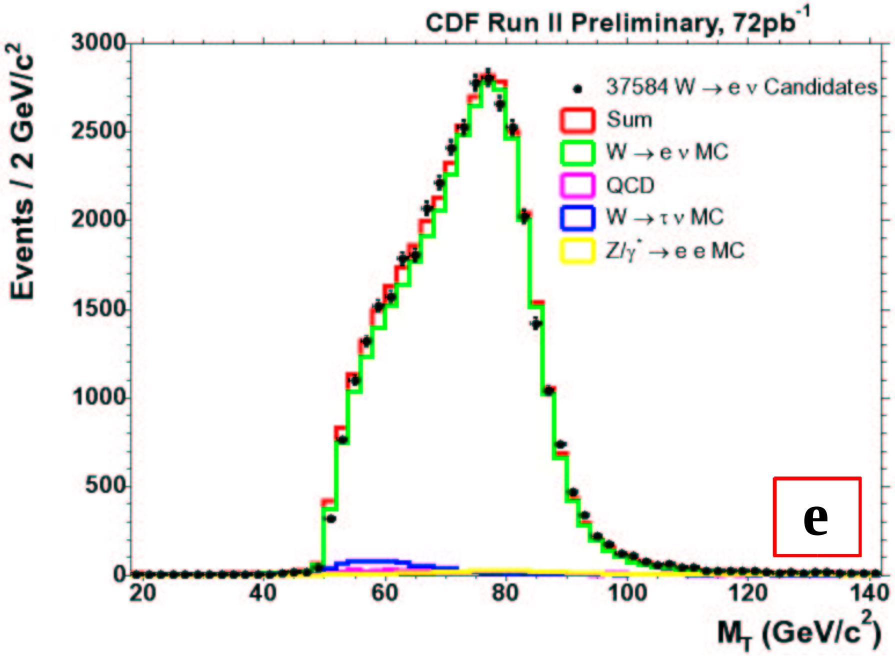
W Cross Section

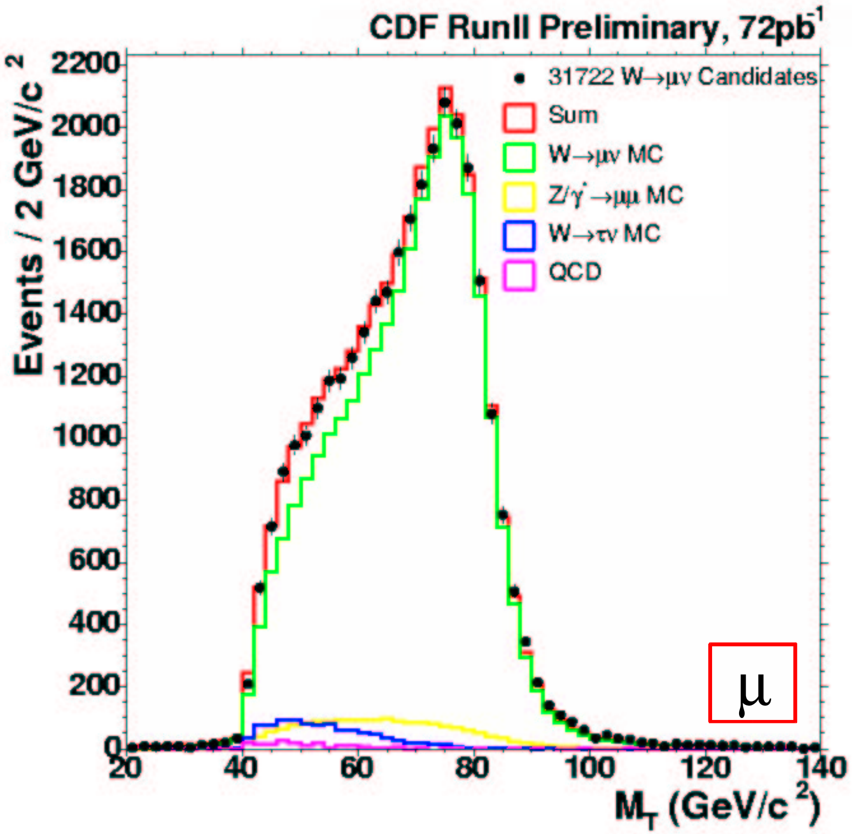




- Background shapes well described well below the final cut value.
- Backgrounds (QCD, W→τν, Z, cosmics) : 4.4 ± 0.8% (e), 9.4 ± 0.4% (μ).
- Trigger & lepton identification efficiencies all have to be understood at the 1% level.

Oxford : Manca, Renton, Robson



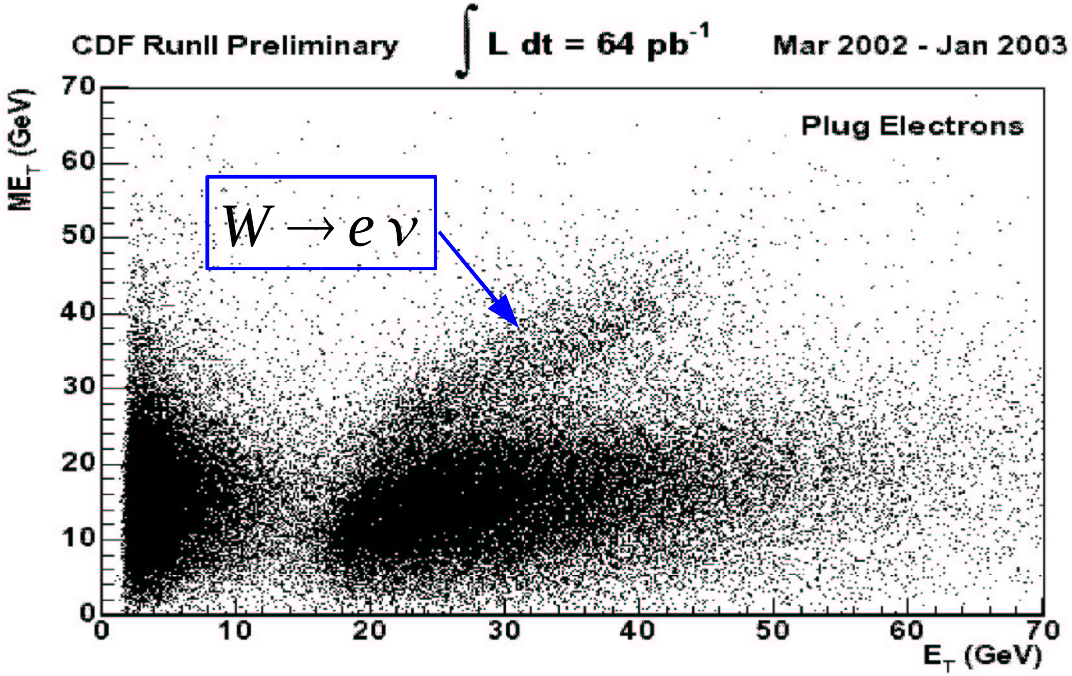


- PDF's
- Energy scales
- Detector description (material)
- Recoil model
- Lepton ID
- Backgrounds

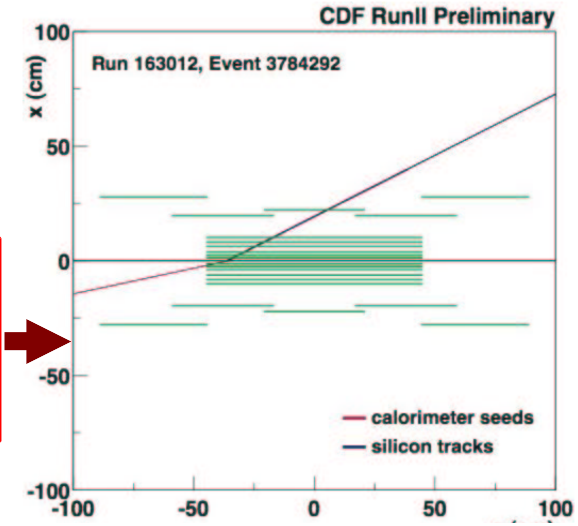
$$\sigma \times BR(W \rightarrow e\nu) = 2782 \pm 14_{STAT} \pm 59_{SYST} \pm 167_{LUM}\ \mathrm{pb}$$

$$\sigma \times BR(W \rightarrow \mu\nu) = 2772 \pm 16_{STAT} \pm 62_{SYST} \pm 166_{LUM}\ \mathrm{pb}$$

Forward W's : $1.1 < |\eta^e| < 2.8$

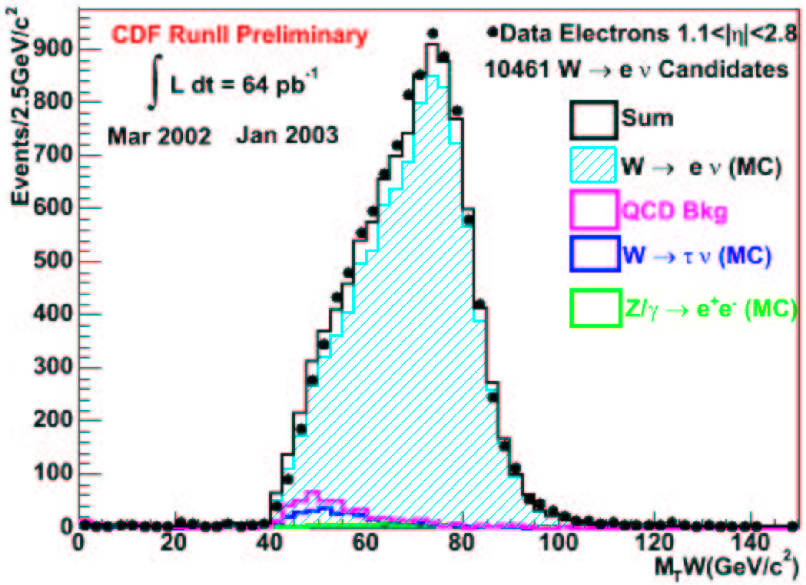


Silicon tracking algorithms

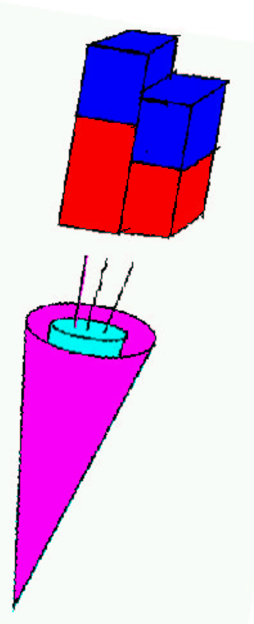


$$\sigma \times BR(W \to e\nu) = 2874 \pm 34_{STAT} \pm 167_{SYST} \pm 172_{LUM}\ \text{pb}$$

- Confirming "central" result in difficult kinematic region.



$W \rightarrow \tau\nu$



Triggers :

(1) $\tau \rightarrow$hadrons + missing−E_T (2) di−τ (3) lepton + track

Reconstruction :

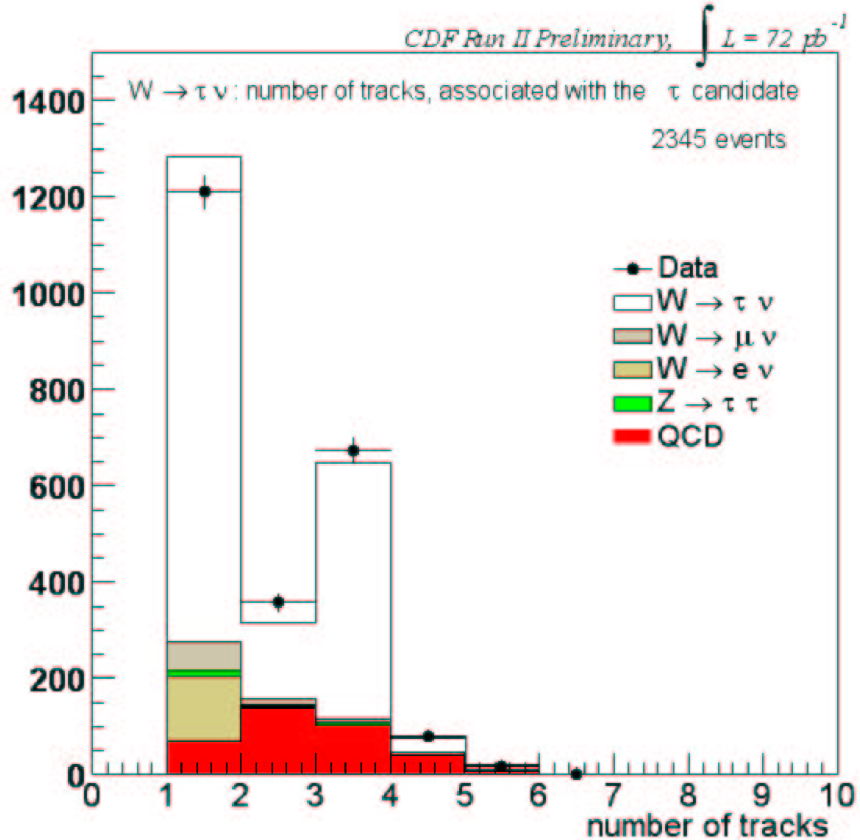
- Count tracks in τ−cone (10^o) and require no tracks in isolation cone (30^o)
- Reconstruct π^0 candidates in shower max detector
- Require combined mass to be < 1.8 GeV

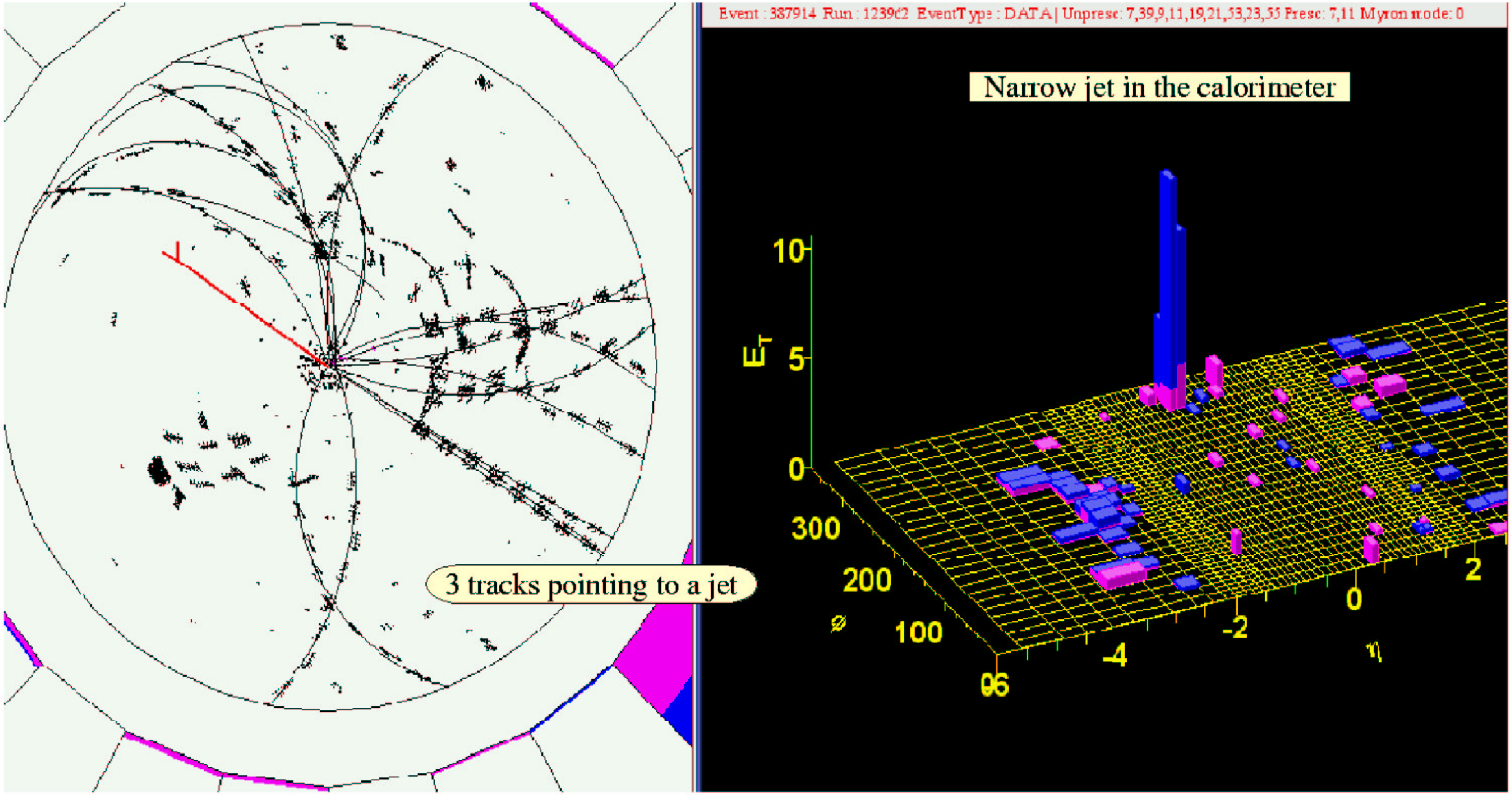
- $\tau \rightarrow$hadrons
  - $|\eta|<1.0$
  - $E_T>25$ GeV
- missing−$E_T>25$ GeV

$\sigma \times BR(W \rightarrow \tau\nu) =$ **2.62 $\pm$ 0.07$_{STAT}$ $\pm$ 0.21$_{SYST}$ $\pm$ 0.16$_{LUM}$ pb**

Backgrounds : ~ 25%

Systematics : τ ID, bkgnd, PDF's & e−scales





3 tracks pointing to a jet
Event : 387914 Run : 123962 EventType : DATA | Unpresc: 7,39,9,11,19,21,33,23,33 Presc: 7,11 Myron mode: 0
Narrow jet in the calorimeter
E_T
10
5
0
300
200
100
ϕ
-4
-2
0
2
η

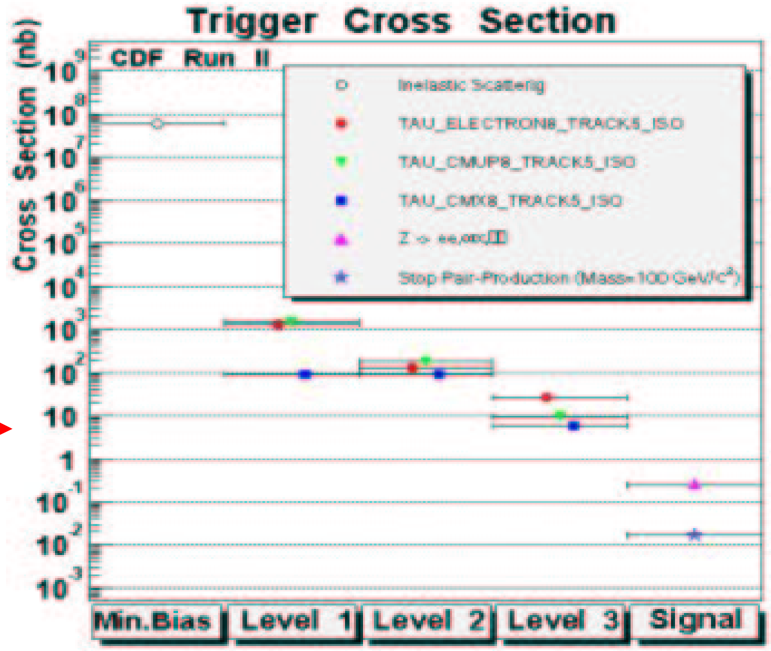
$Z \to \tau^+\tau^-$

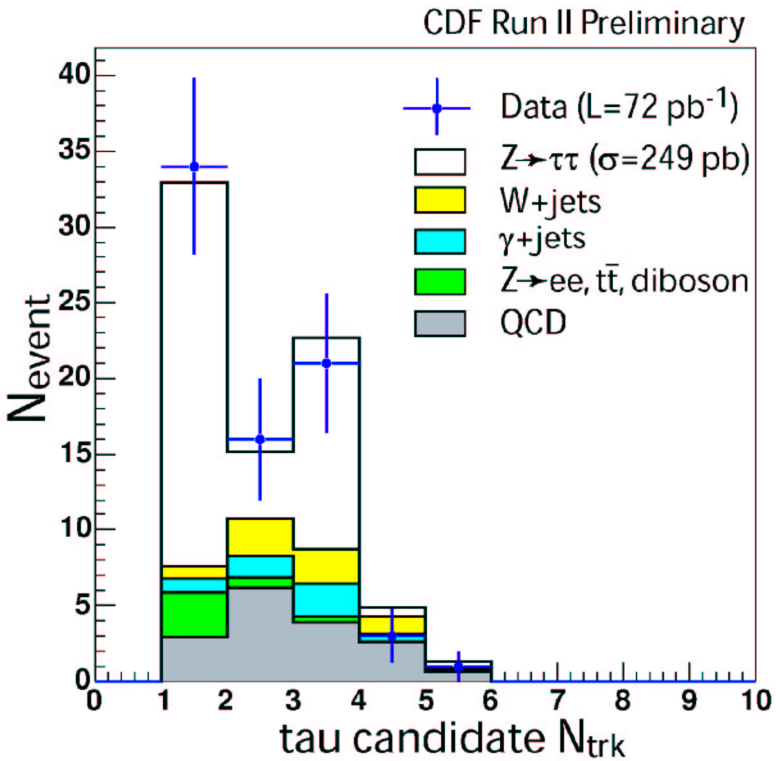
e

$Z^0 \to \tau\ \tau$

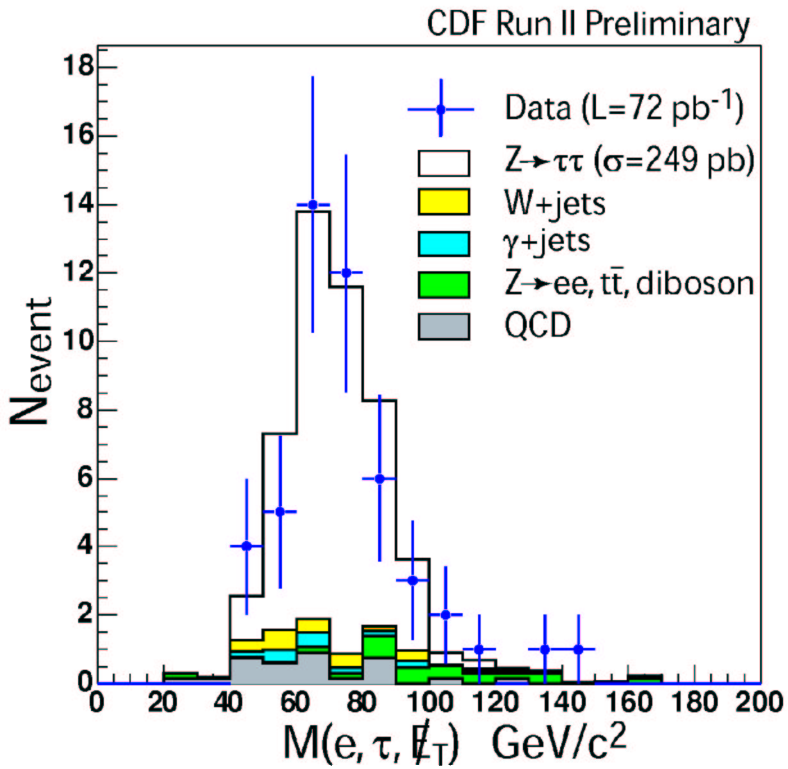
hadrons

Collected in a lepton+track trigger.

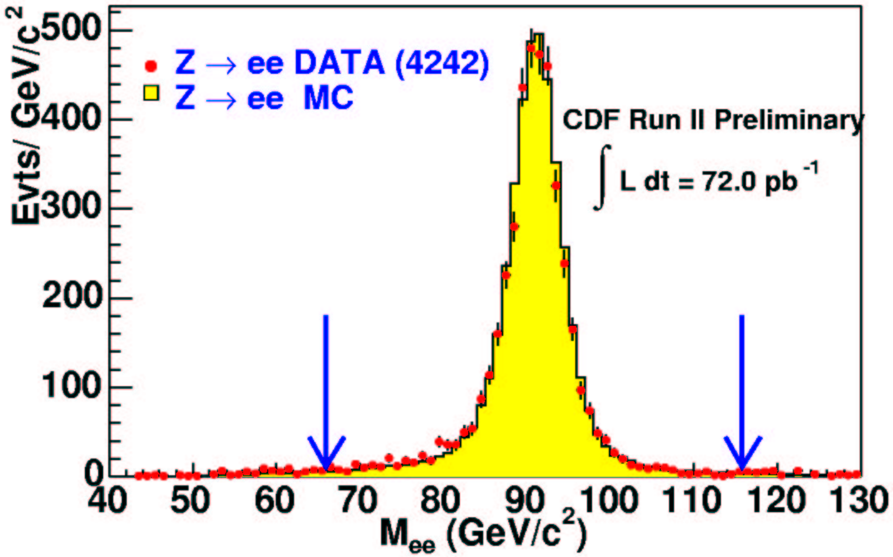


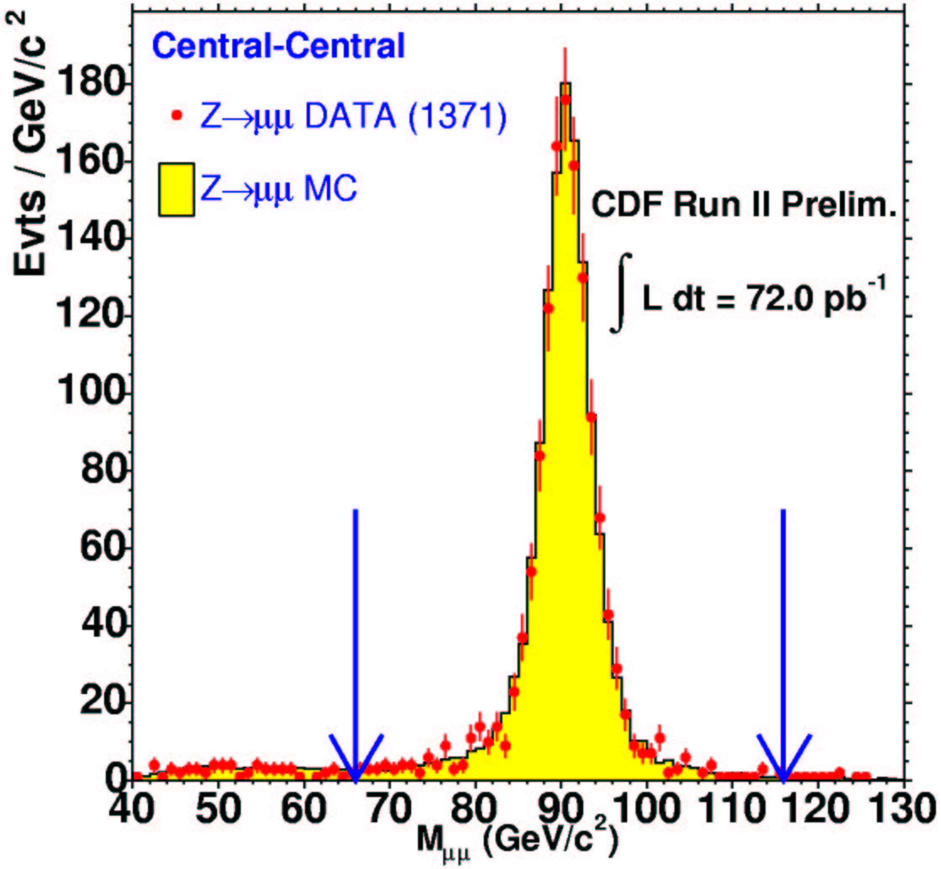


$$Q_\tau \cdot Q_e = -1$$



Z Cross Section



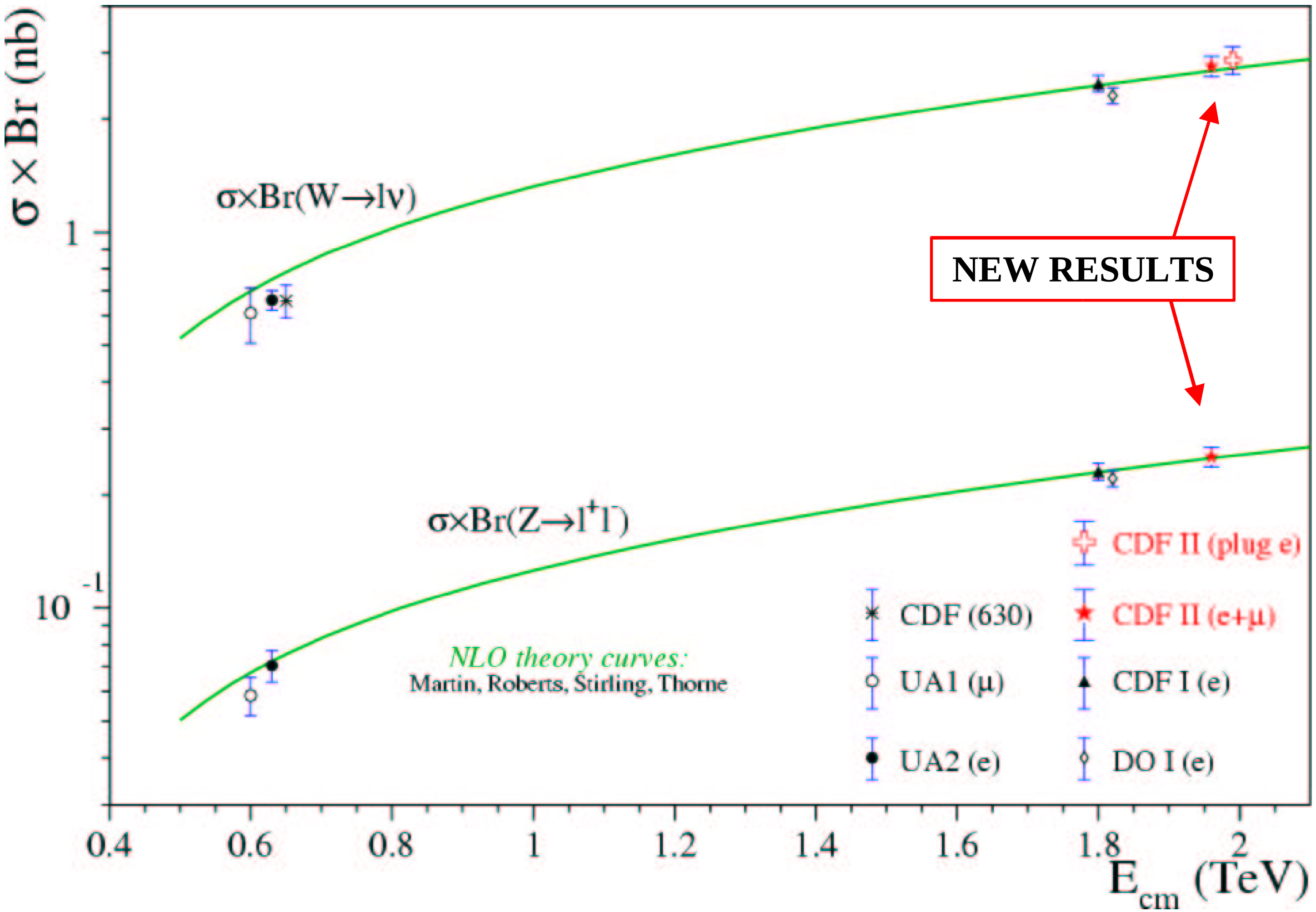


- Very low backgrounds (QCD, $Z\rightarrow\tau\tau$, cosmics) : < 1−2 %
- Important systematics : PDF's, Material Descriptions, Lepton ID

$$\sigma(p\bar{p}\rightarrow Z/\gamma^*\rightarrow ee) = 255.2 \pm 3.9_{STAT} \pm 6.0_{SYST} \pm 15.3_{LUM}\ \mathrm{pb}$$

$$\sigma(p\bar{p}\rightarrow Z/\gamma^*\rightarrow \mu\mu) = 248.9 \pm 5.9_{STAT} \pm 7.2_{SYST} \pm 14.9_{LUM}\ \mathrm{pb}$$

Cross−Section Summary



$$R = \frac{\sigma_W \times BR(W \rightarrow l\nu)}{\sigma_Z \times BR(Z \rightarrow l^+ l^-)} = 10.93 \pm 0.15(\text{stat.}) \pm 0.14(\text{syst.})$$

- e, μ combined
- correlated systematics fully taken into account

$$R = \frac{\sigma_W \times BR(W \rightarrow l\nu)}{\sigma_Z \times BR(Z \rightarrow l^+ l^-)}$$

$$= \frac{\sigma_W}{\sigma_Z} \frac{\Gamma_Z}{\Gamma(Z \rightarrow l^+ l^-)} \frac{\Gamma(W \rightarrow l\nu)}{\Gamma_W}$$

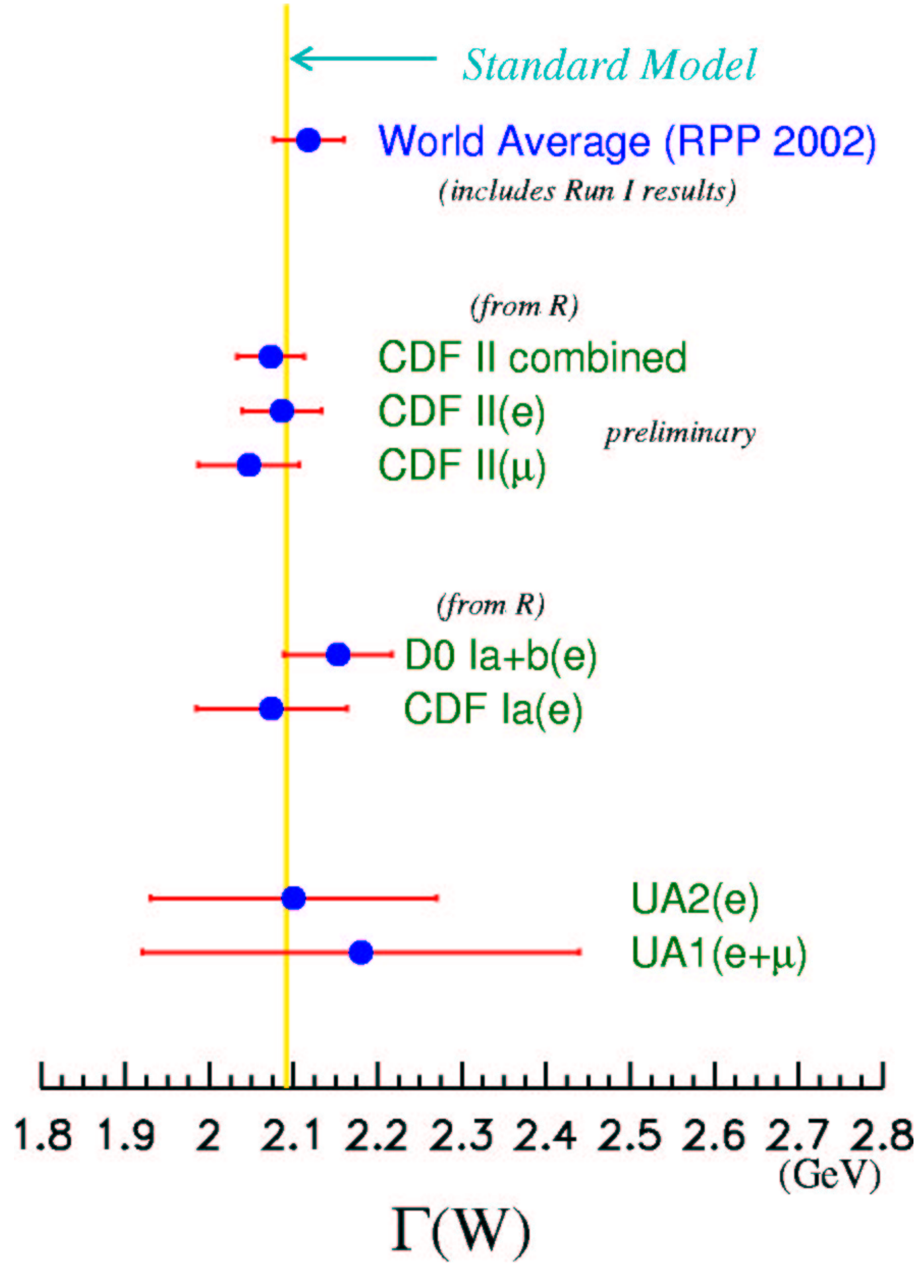
SM : 3.361 ± 0.024

LEP

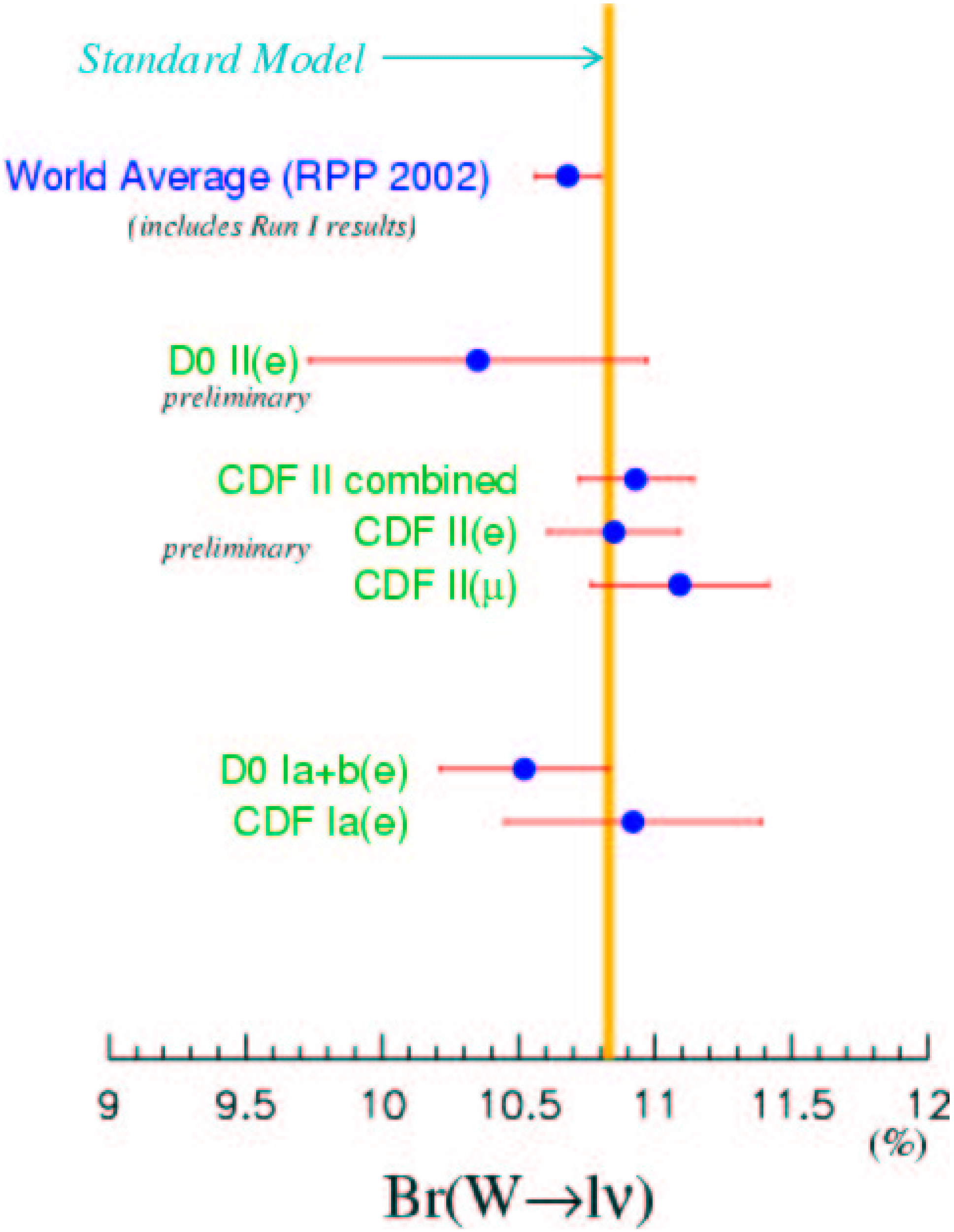
SM : 226.4 ± 0.3 MeV

$$\Gamma_W(\text{indirect}) = 2.072 \pm 0.040 \text{ GeV}$$

$$\Gamma_W(\text{WA}) = 2.118 \pm 0.042 \text{ GeV}$$



Caveat : Branching Ratios



BUT :

$$BR(W \to l\nu)_{CDF} = 10.93 \pm 0.21\ \%$$

$$BR(W \to l\nu)_{WA} = 10.68 \pm 0.12\ \%$$

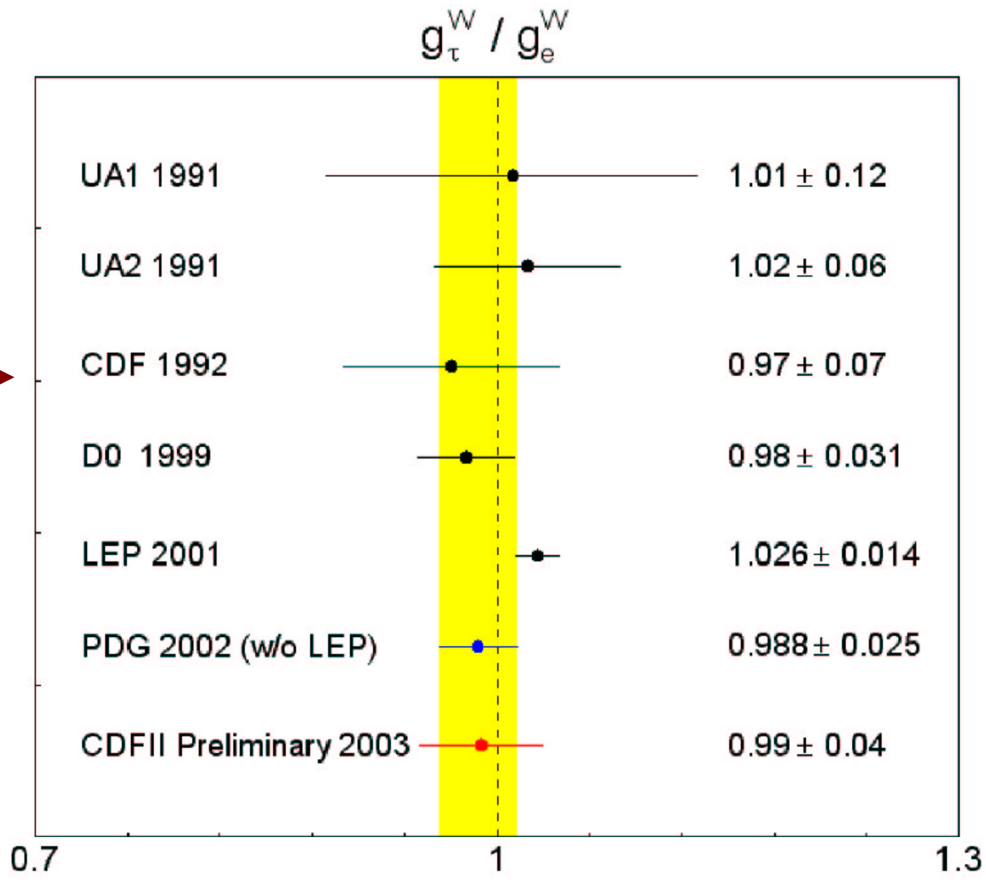
Universality Tests

$$\sqrt{\frac{R_\mu}{R_e}} = \frac{g_\mu^W}{g_e^W}(\text{CDF}) = 1.011 \pm 0.018$$

[similar to LEP]

$$\sqrt{\frac{\text{BR}(W \to \tau\nu)}{\text{BR}(W \to e\nu)}} = \frac{g_\tau^W}{g_e^W}(\text{CDF})$$

$$= 0.99 \pm 0.04$$



W & Z Cross−Sections : Overview

- Competitive precision EWK results with 72 pb^{-1}. We already have 250 pb^{-1} on tape. Many errors are still scaling with luminosity, either directly or indirectly (Z statistics).

- Luminosity monitor. Current error is 6% :

$$\boxed{\frac{\sigma(L)}{L} = 2.5\% \oplus 5.5\%}$$

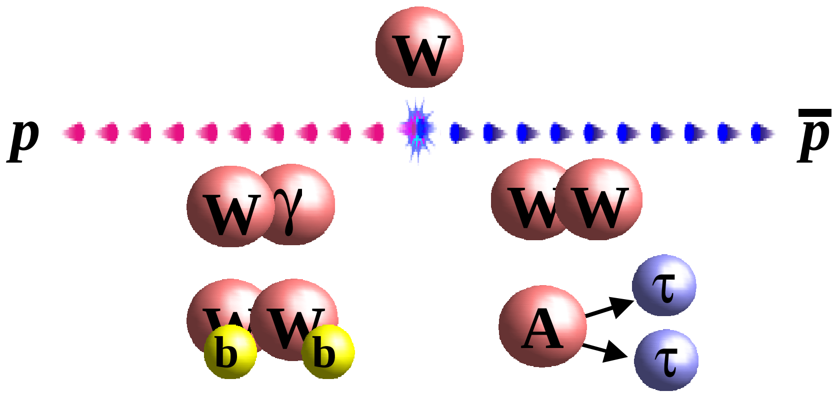
$$\sigma_{TOT}(p\bar{p}) \qquad \epsilon(\text{lumi detector})$$

By comparison :

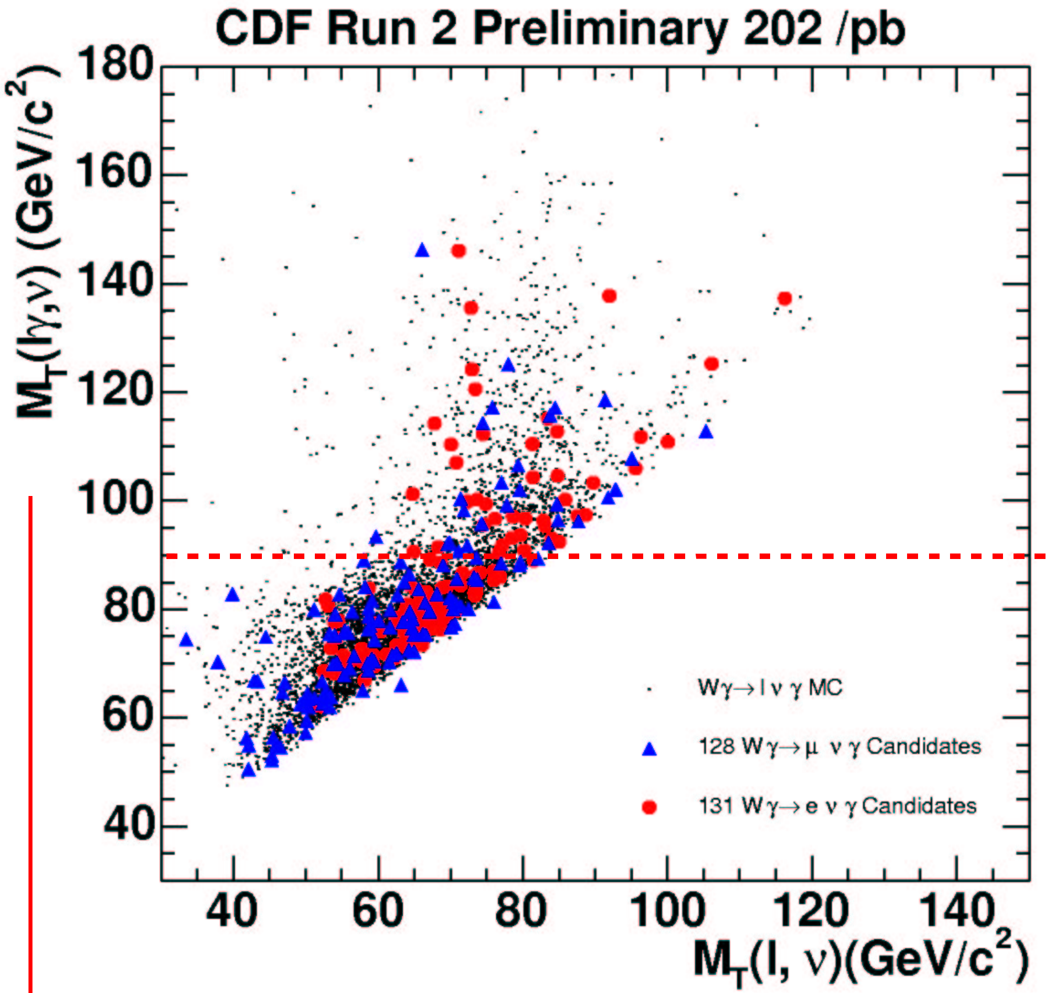
- Systematic error on W cross−section measurement : 2%
- NNLO theory uncertainty : 2−3%.

viable lumi monitor

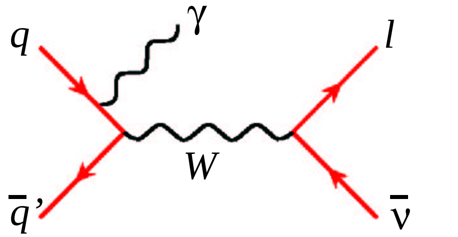
- These analyses have been the benchmark for many other CDF analyses :



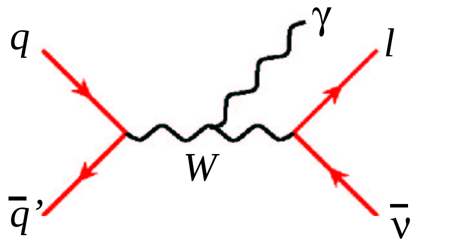
W+γ



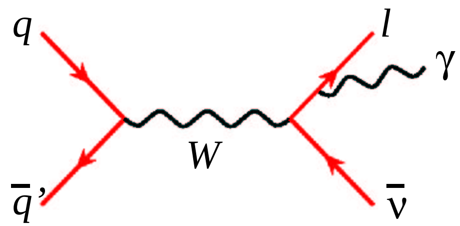
"cluster transverse mass"



ISR



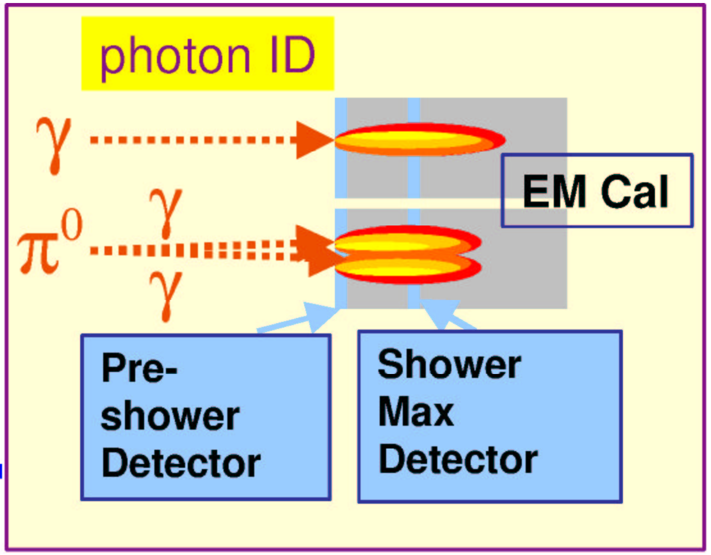
WWγ



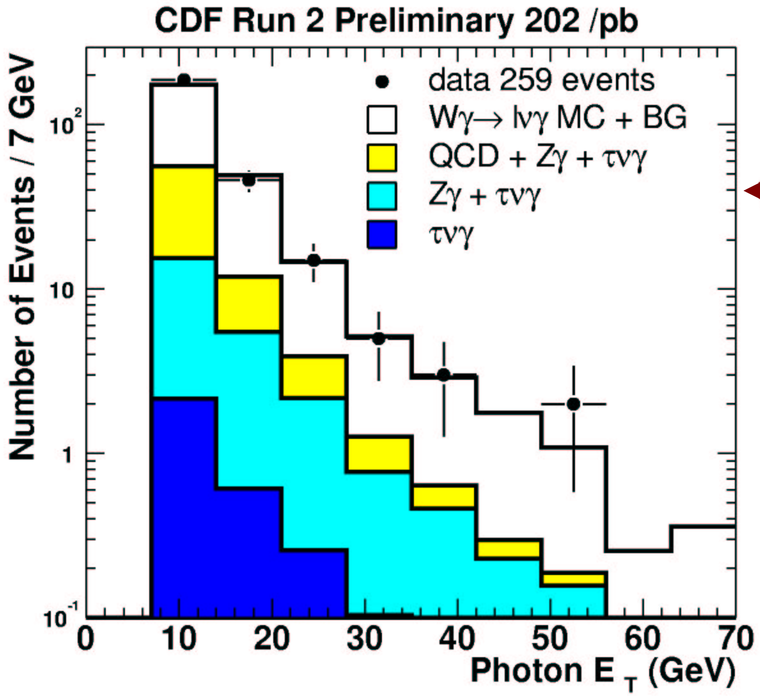
FSR

W+γ

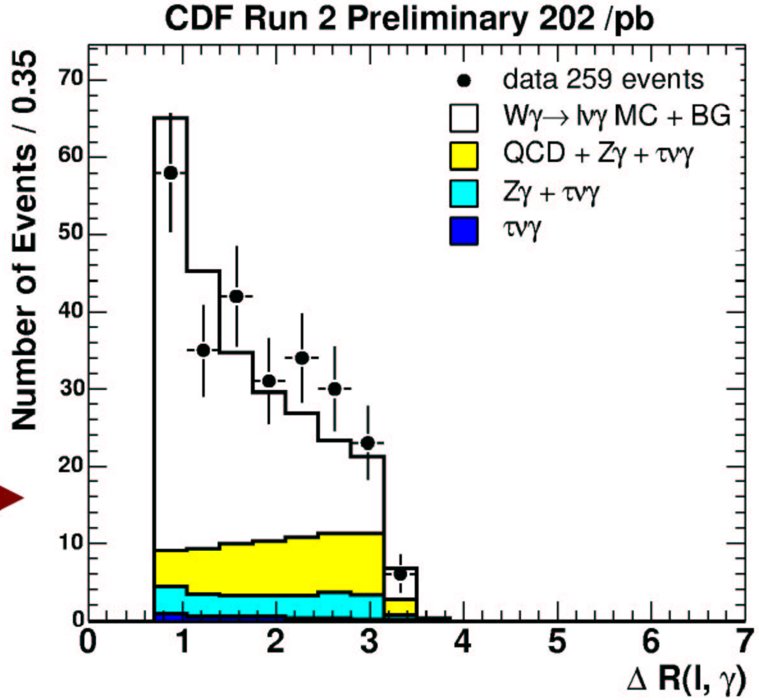
- First select $W \to l\nu$ events :
  - Electrons : $E_T > 25$ GeV; missing- $E_T > 25$ GeV
  - Muons : $E_T > 20$ GeV; missing- $E_T > 20$ GeV
- Then look for additional photons :
  - E_T(photon) > 7 GeV
  - $|\eta^\gamma| < 1.1$
  - $\Delta R(l,\gamma) > 0.7$



- Evaluate jet→photon fake rate :
  - 0.2% @ 10 GeV
  - 0.06% @ 25 GeV



data well described over all photon E_T's and separations

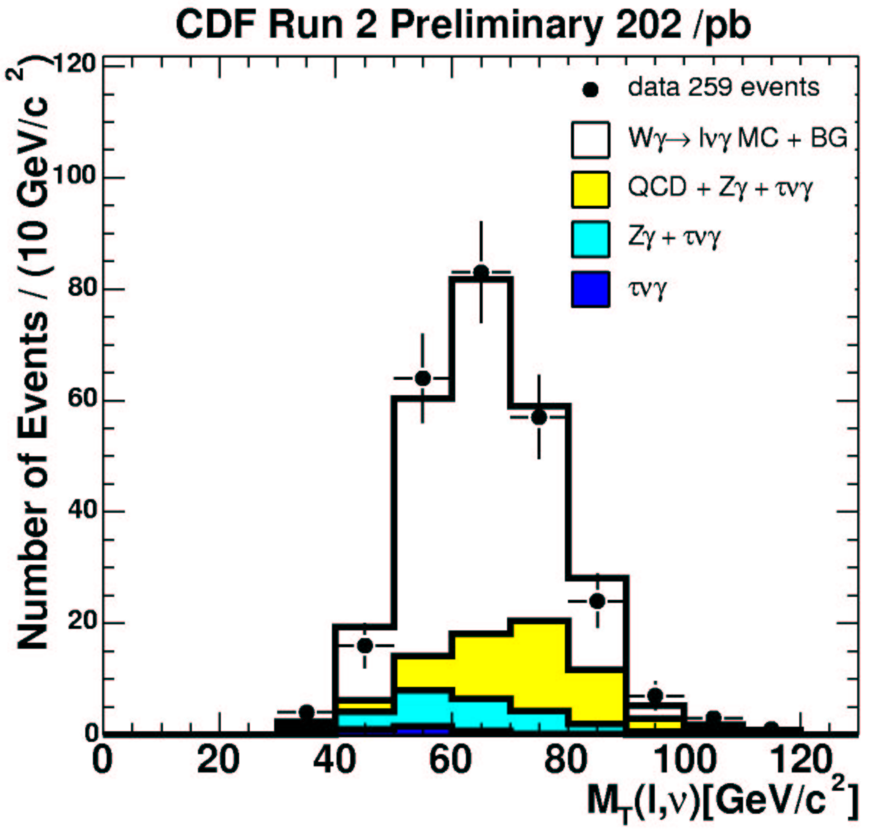


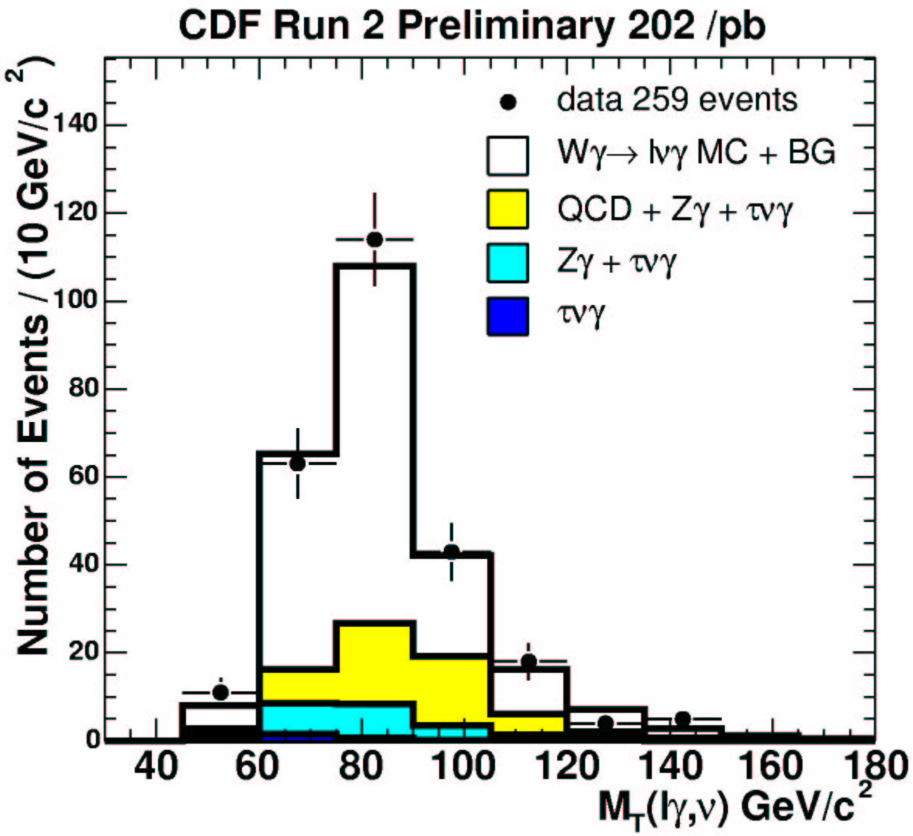
W+γ

$\sigma(W\gamma) \times BR(W \to l\nu) = 19.7 \pm 1.7_{STAT} \pm 2.0_{SYST} \pm 1.1_{LUM}$ pb

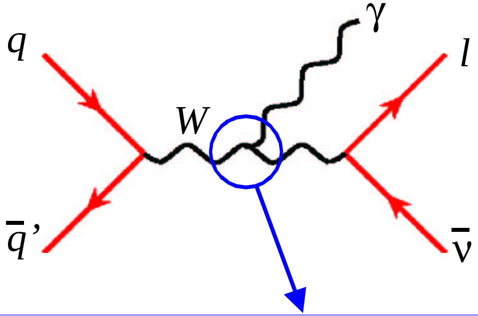
★ For E_T(photon) > 7 GeV and $\Delta R(l,\gamma) > 0.7$:

$\sigma(W\gamma) \times BR(W \to l\nu)$ (Theory) = 19.3 ± 1.4 pb





W+γ : Anomalous Coupling Prospects

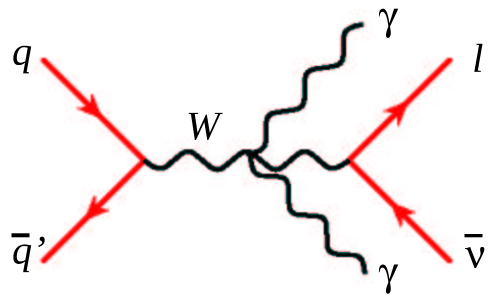


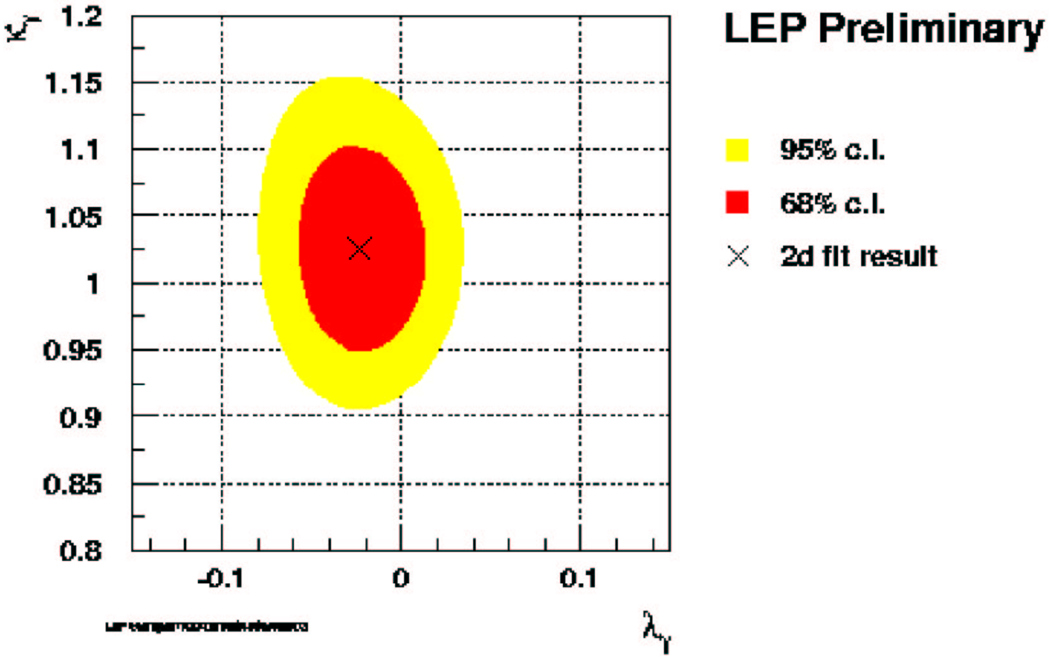
Anomalous couplings : Δκ, λ

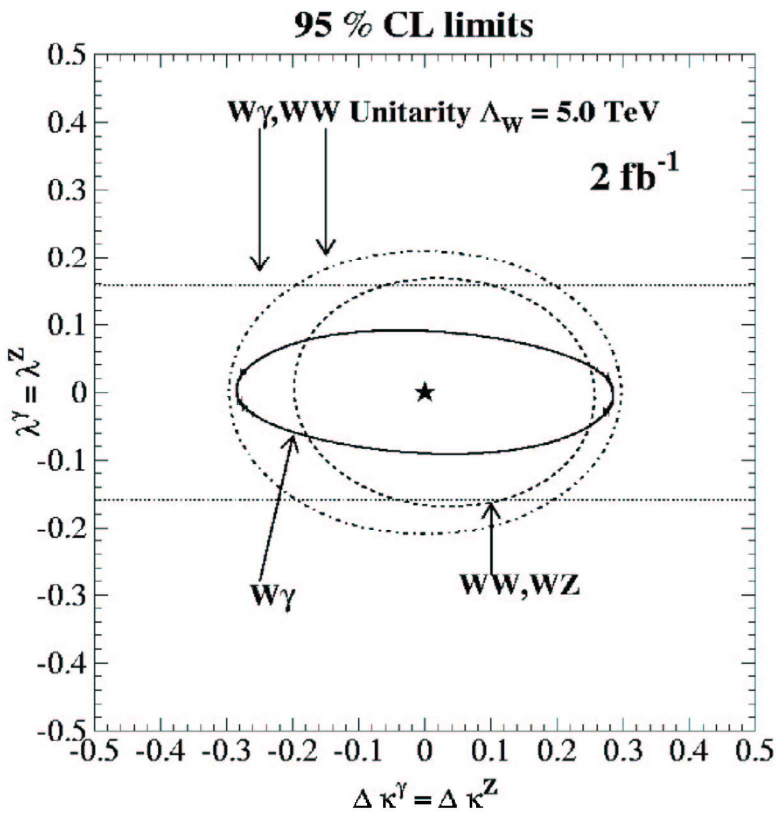
$$\mu_W = e(1+\kappa_\gamma+\lambda_\gamma)/2m_W$$

$$q_W = -e(\kappa_\gamma-\lambda_\gamma)/m_W^2$$

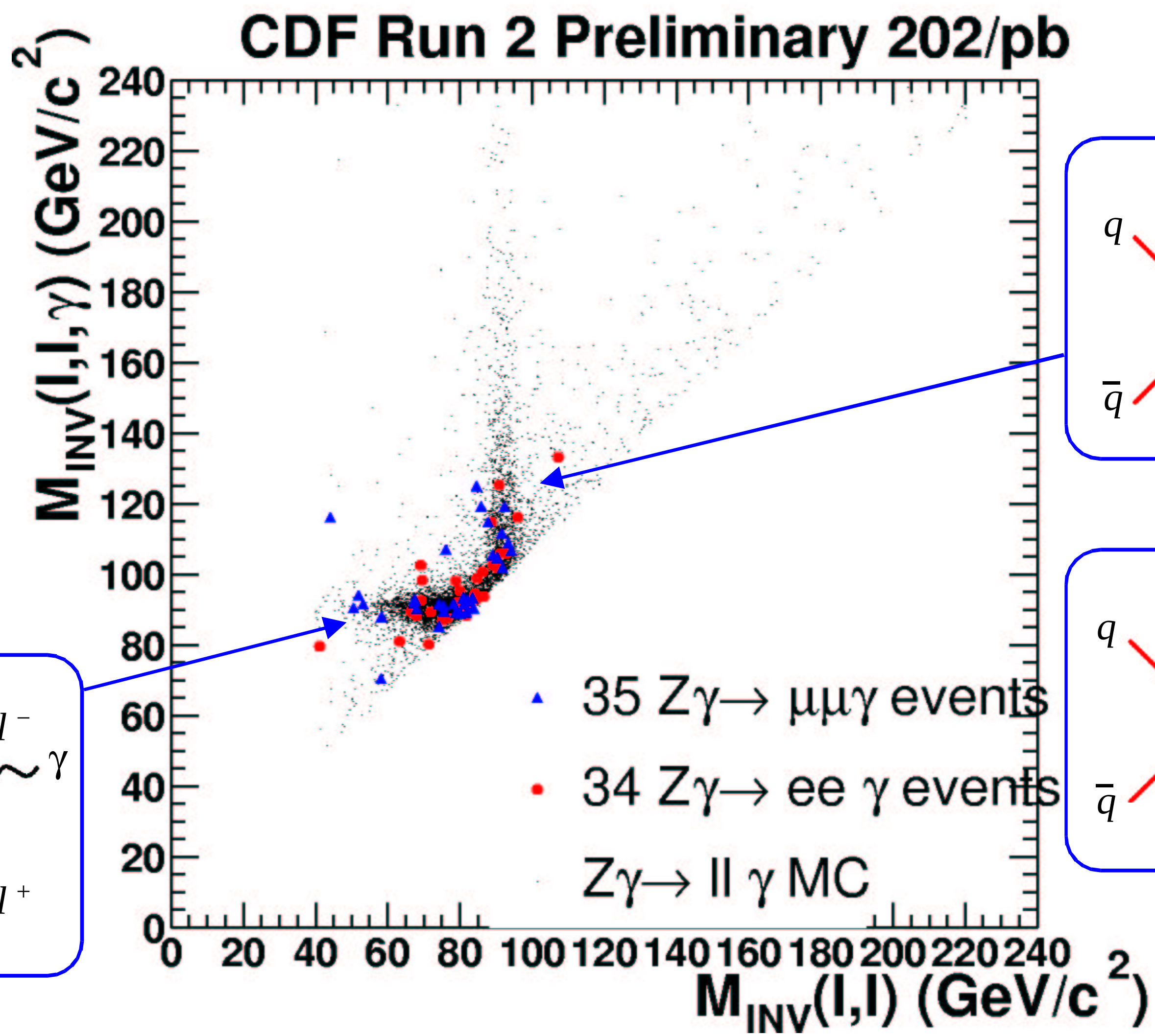
& quartic couplings ...

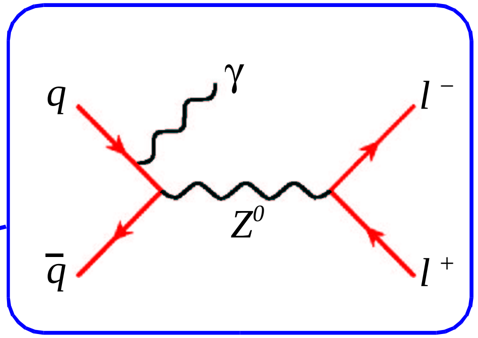


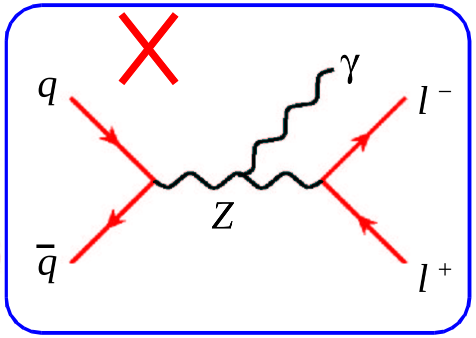


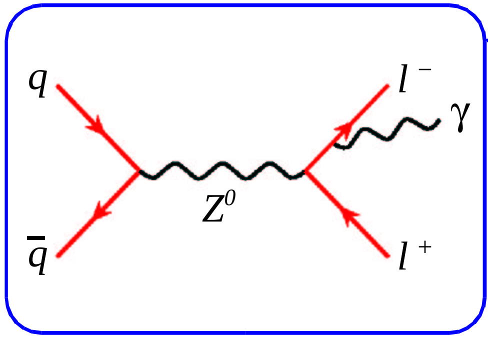


Z+γ


CDF Run 2 Preliminary 202/pb
$M_{INV}(l,l,\gamma)$ (GeV/c^2)
$M_{INV}(l,l)$ (GeV/c^2)
35 Zγ→ μμγ events
34 Zγ→ ee γ events
Zγ→ ll γ MC


q
γ
l^-
Z^0
$\bar{q}$
l^+


q
γ
l^-
Z
$\bar{q}$
l^+

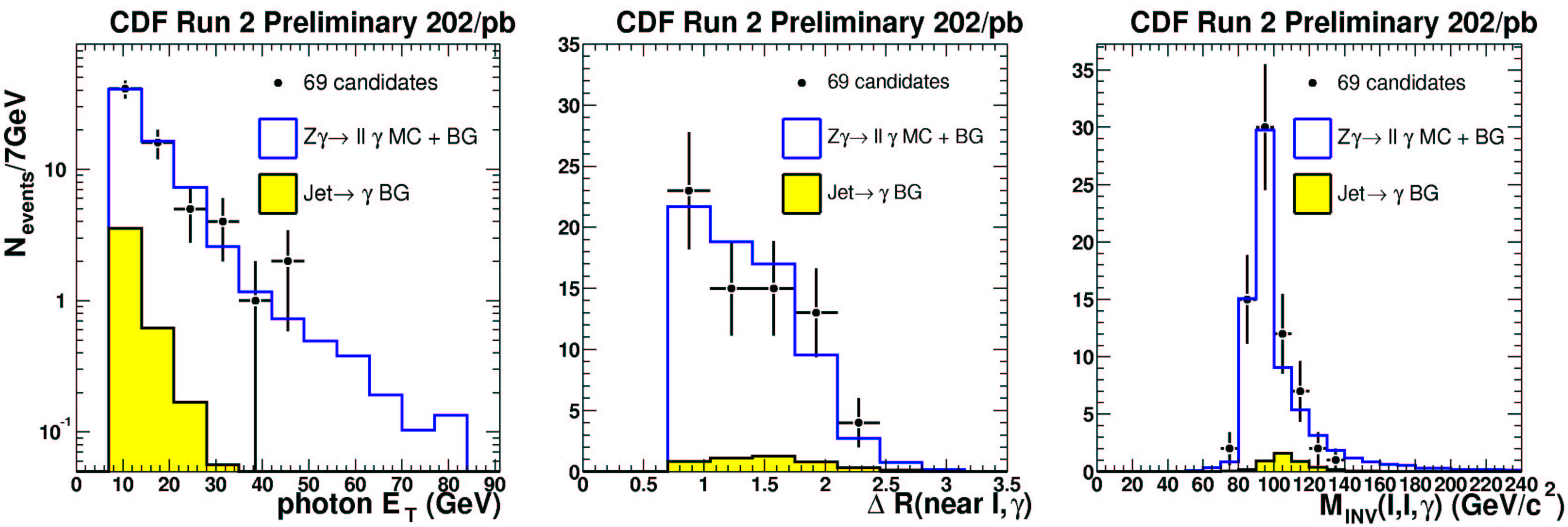

q
l^-
γ
Z^0
$\bar{q}$
l^+

Z+γ

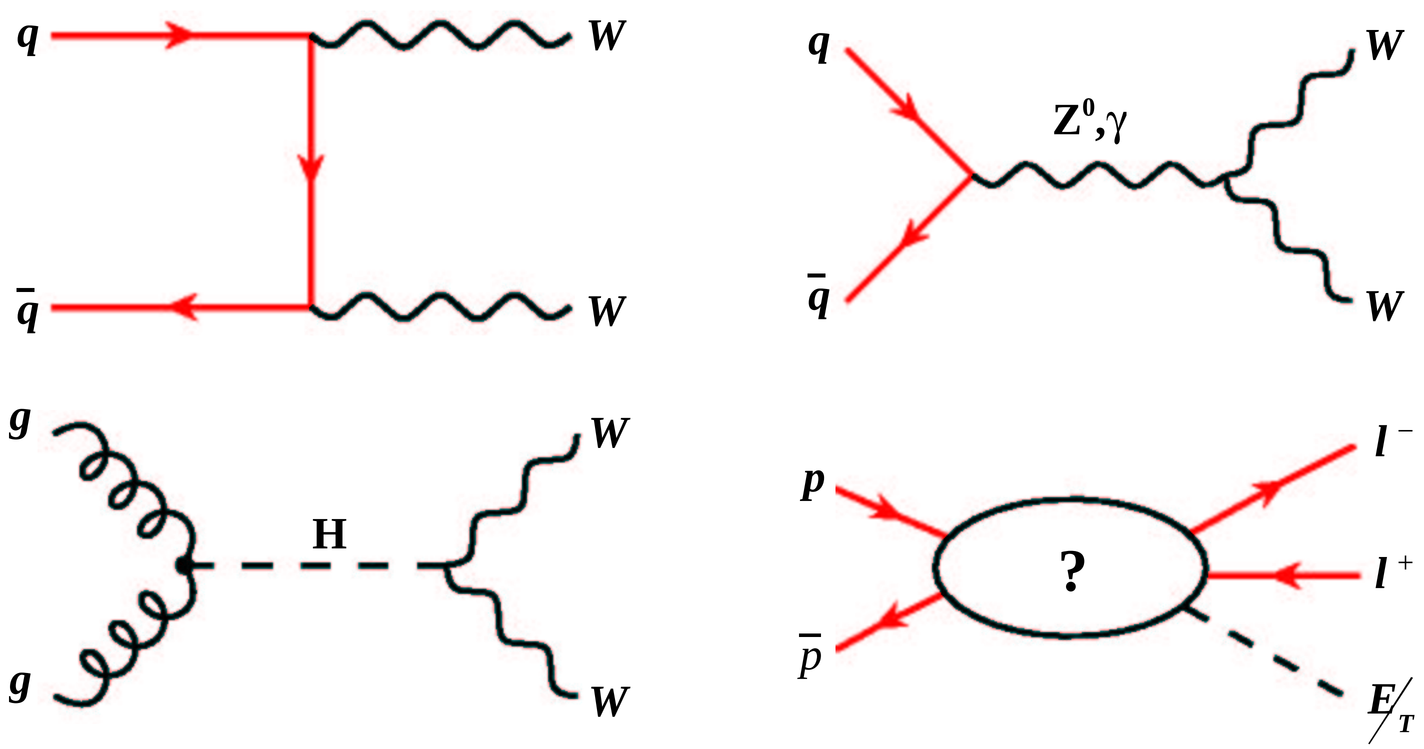
$\sigma(Z\gamma) \times BR(Z \to l^+l^-) = 5.3 \pm 0.6_{STAT} \pm 0.3_{SYST} \pm 0.3_{LUM}$ pb

- For E_T(photon) > 7 GeV and $\Delta R(l,\gamma) > 0.7$:
  $\sigma(Z\gamma) \times BR(Z \to l^+l^-)$ (Theory) = 5.4 ± 0.3 pb

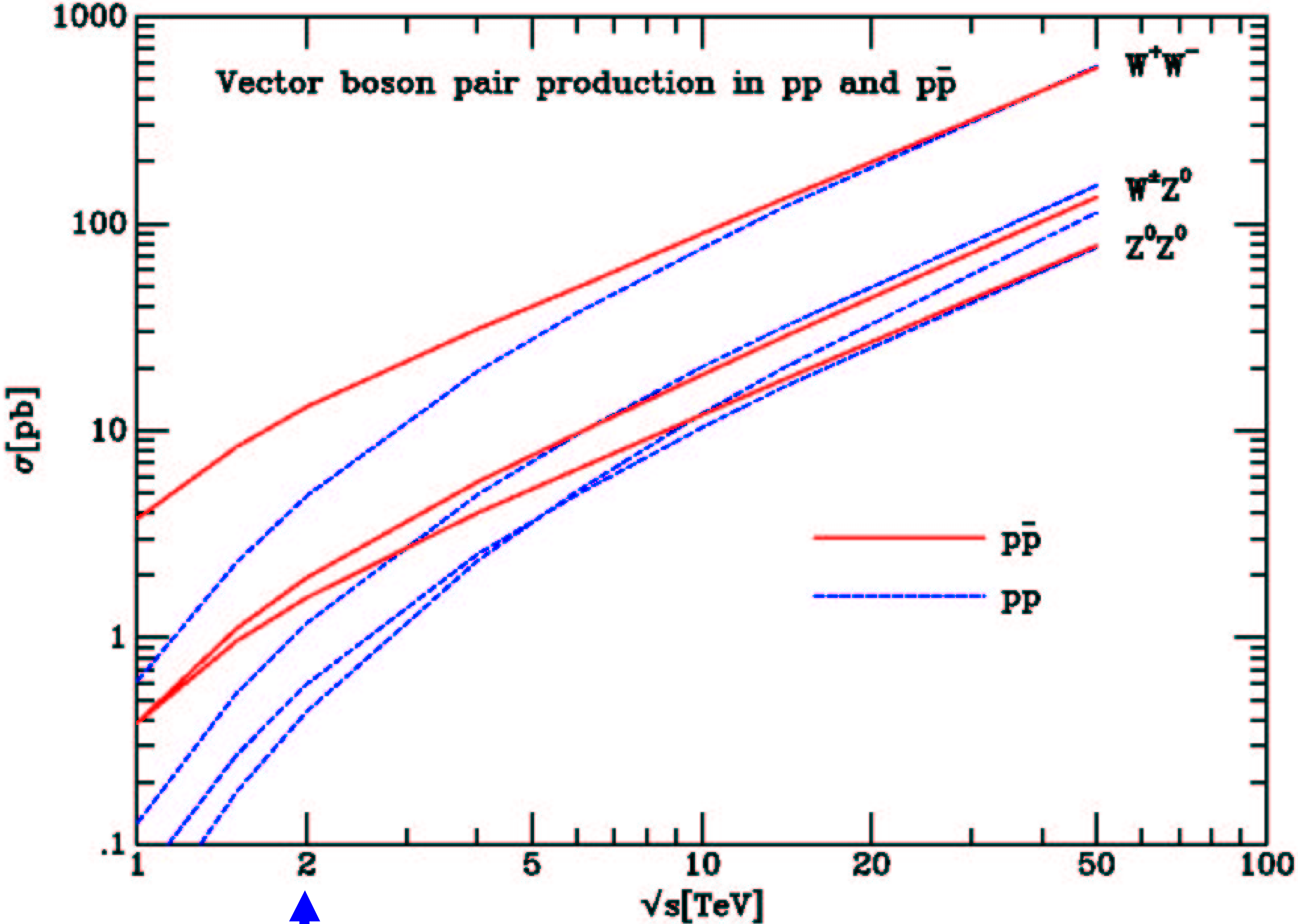
- Now V+γ cross−sections well established :
  - extending acceptance
  - optimising sensitivity to anomalous couplings and new physics
  - testing the Standard Model in ways unique to the Tevatron (e.g. observing the radiation amplitude zero in W+γ production).



WW : Why ?



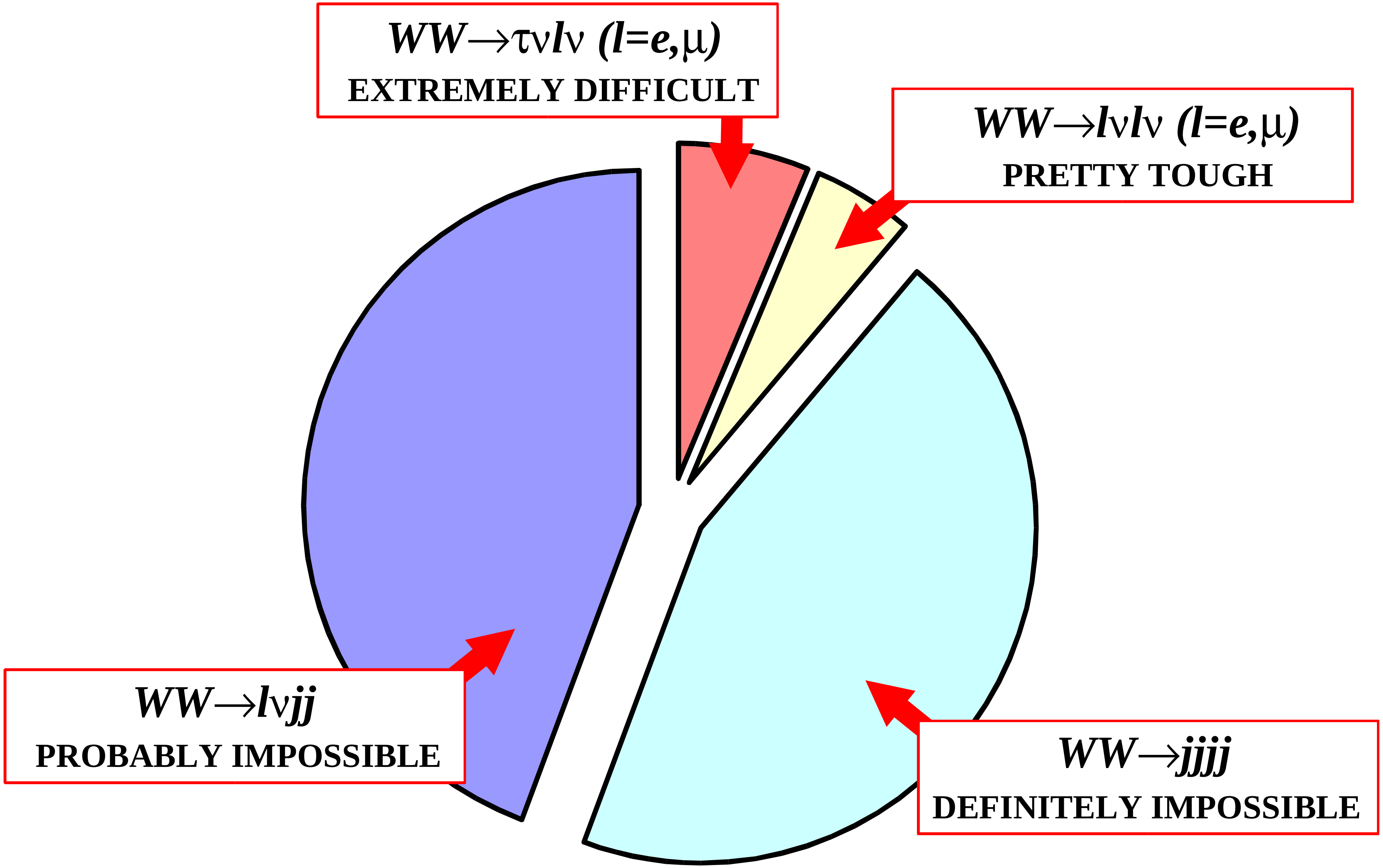
- Never observed in hadron collisions with any significance (Run I @ CDF : 5 events observed with 1.2±0.3 background).
- Many interesting tests of the Standard Model are possible.
- Critical channel @ LHC (background & signal).

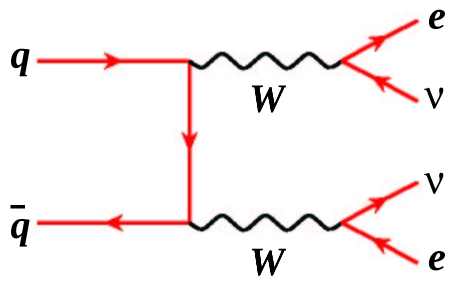


Campbell & Ellis 1999

Tevatron (NLO) : 12.5 ± 0.8 pb

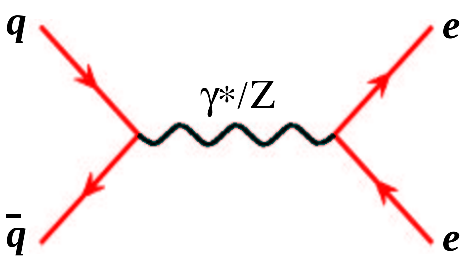
WW : Decay Channels





Signal:

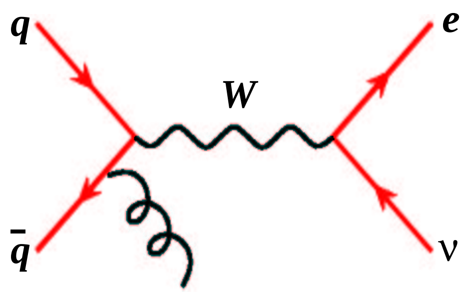
$\sigma(p\bar{p}\to WW\to e\nu e\nu)$ ~ 0.15 pb



Drell−Yan :

$\sigma(p\bar{p}\to\gamma^*/Z\to ee)$ ~ 250 pb

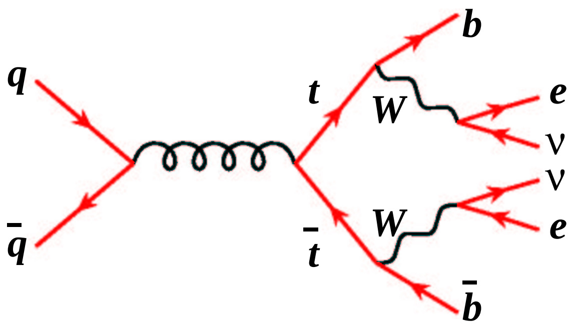
Must have "fake" missing−E_T.



W+jets :

$\sigma(p\bar{p}\to W(\to e\nu)+\geq 1\text{−jet})$ ~ 500 pb

Jet must fake a lepton.



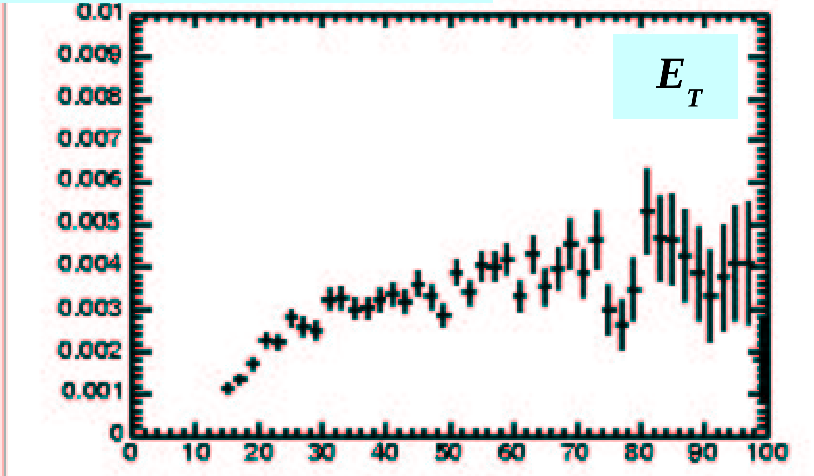
$t\bar{t}$:

$\sigma(p\bar{p}\to t\bar{t}\to e\nu e\nu b\bar{b})$ ~ 0.1 pb

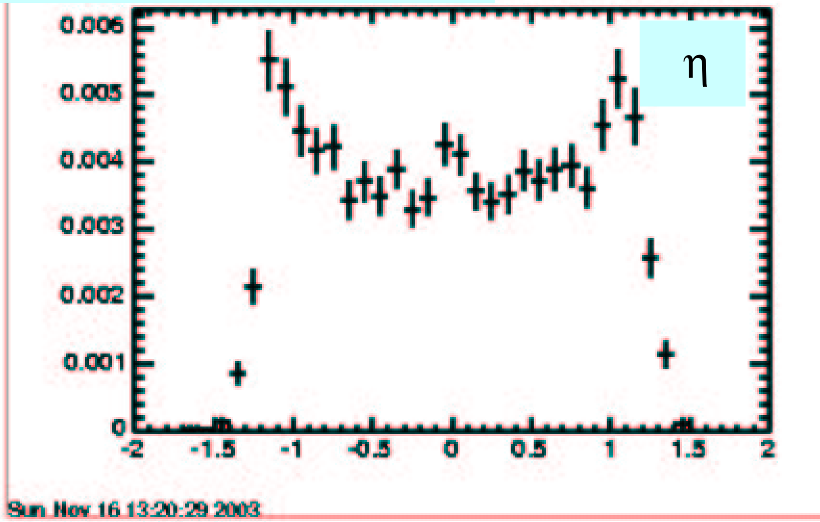
Contains additional jets.

WW : Fake Background

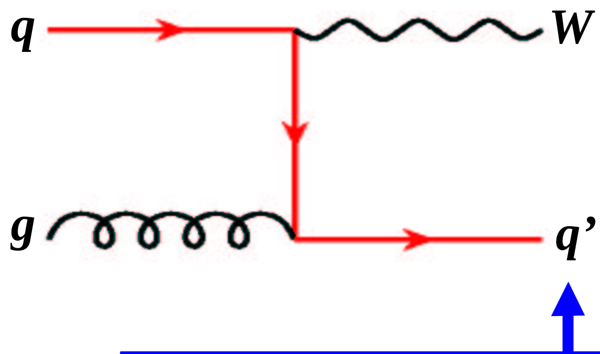
P(jet→ track lepton)



P(jet→ track lepton)

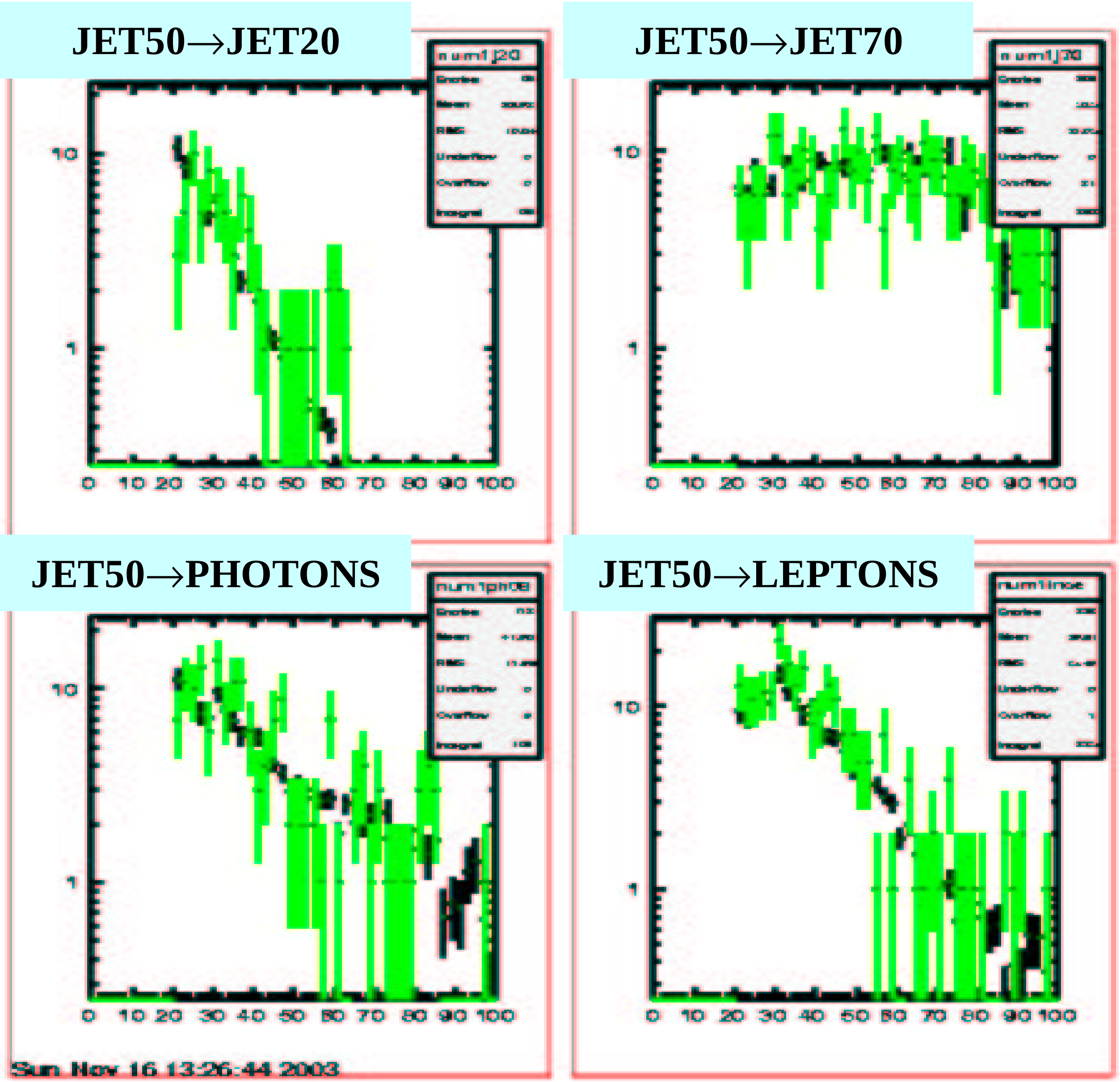


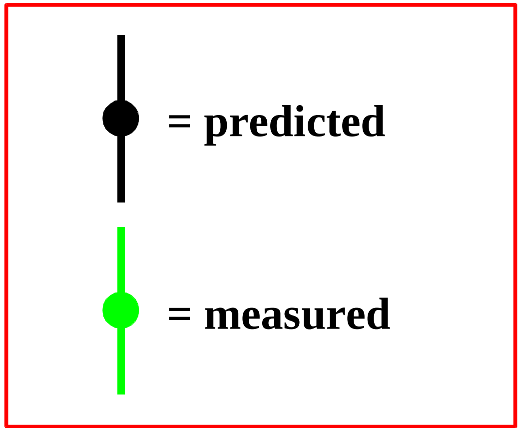
- Jets can "fake" leptons due to jet fragmentation fluctuations, punch−through, heavy quark decays, etc.
- Measure "fake rates" in jet samples.
- Apply them to events that contain 1 lepton and 1 jet but which are identical in all other respects to signal events.
- Many thorny issues. For example, charge correlations :



fake lepton charge correlated with charge of quark, anti−correlated with W charge

WW : Fake Predictions



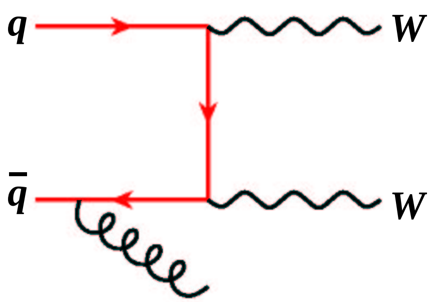


- Apply fake rates measured in one sample to jets in other samples : "predicted"
- Find leptons in other samples: "measured"
- Compare.
- Not easy to get right.

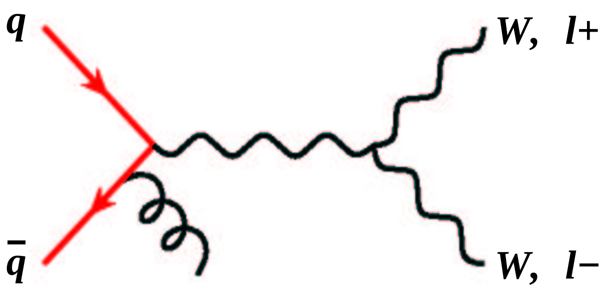
WW : Jet Rates

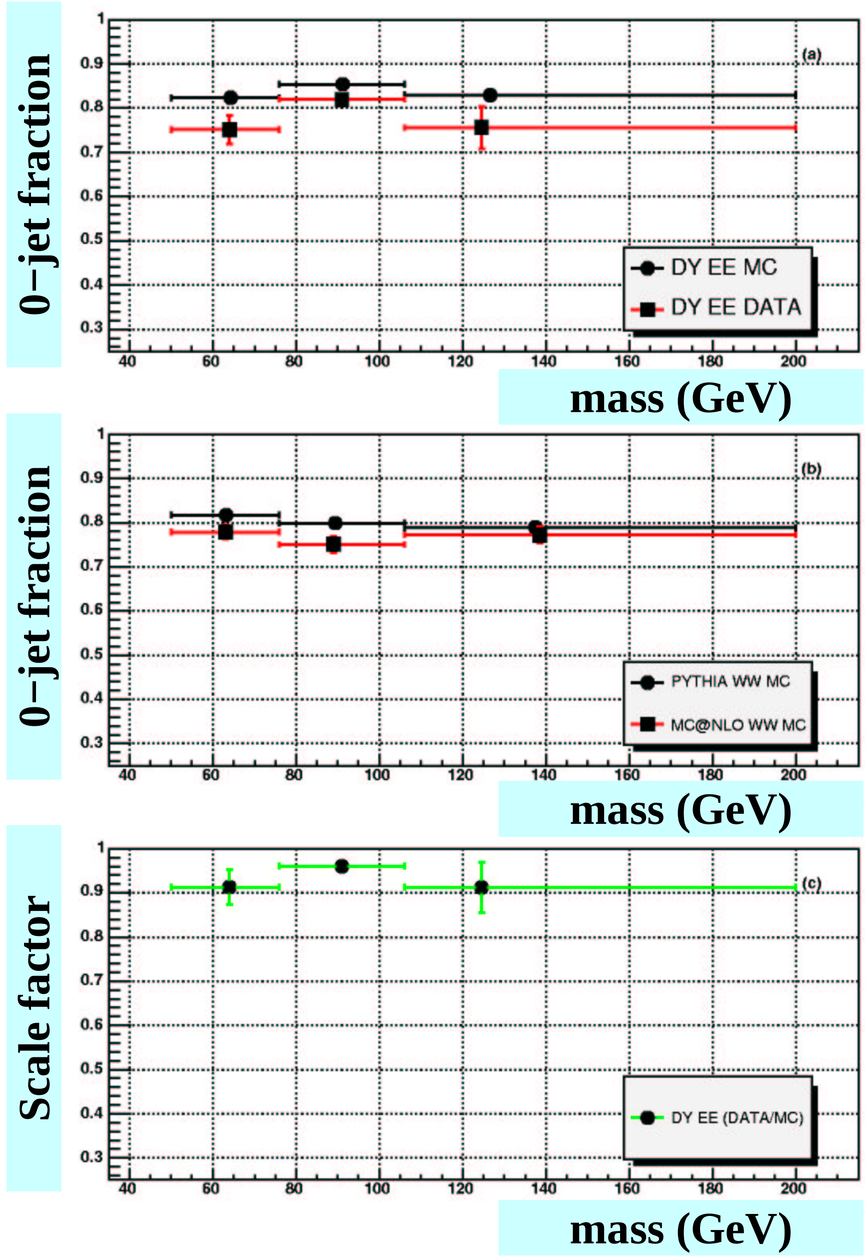
- Jet multiplicity is a crucial discriminant between WW and top production.
- We don't expect this to be well described by leading−order Monte Carlo programs.
- Derive correction factors from Drell−Yan data.

WW



WW & Drell−Yan





WW : Analysis Strategies

- Two isolated E_T>20 GeV leptons (e or μ) with full identification criteria applied.
- Missing−E_T > 25 GeV.
- Topological cuts to remove Drell−Yan events.
- Remove top background by requiring no additional jets.

→ "**DILEPTON**" **high purity**

- One isolated E_T>20 GeV lepton (e or μ) with full identification criteria applied.
- One isolated track with P_T>20 GeV/c.
- Missing−E_T > 25 GeV.
- Topological cuts to remove Drell−Yan events.
- Allow 0−jet and 1−jet events.

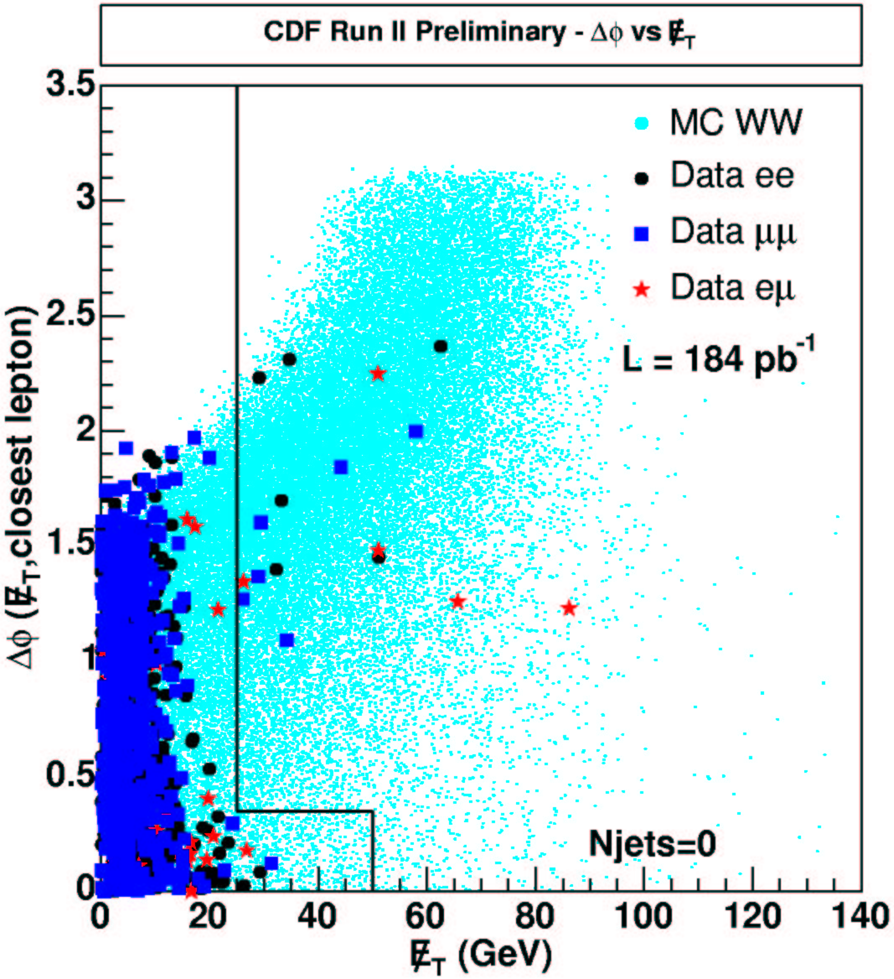
→ "**LEPTON + TRACK**" **high acceptance**

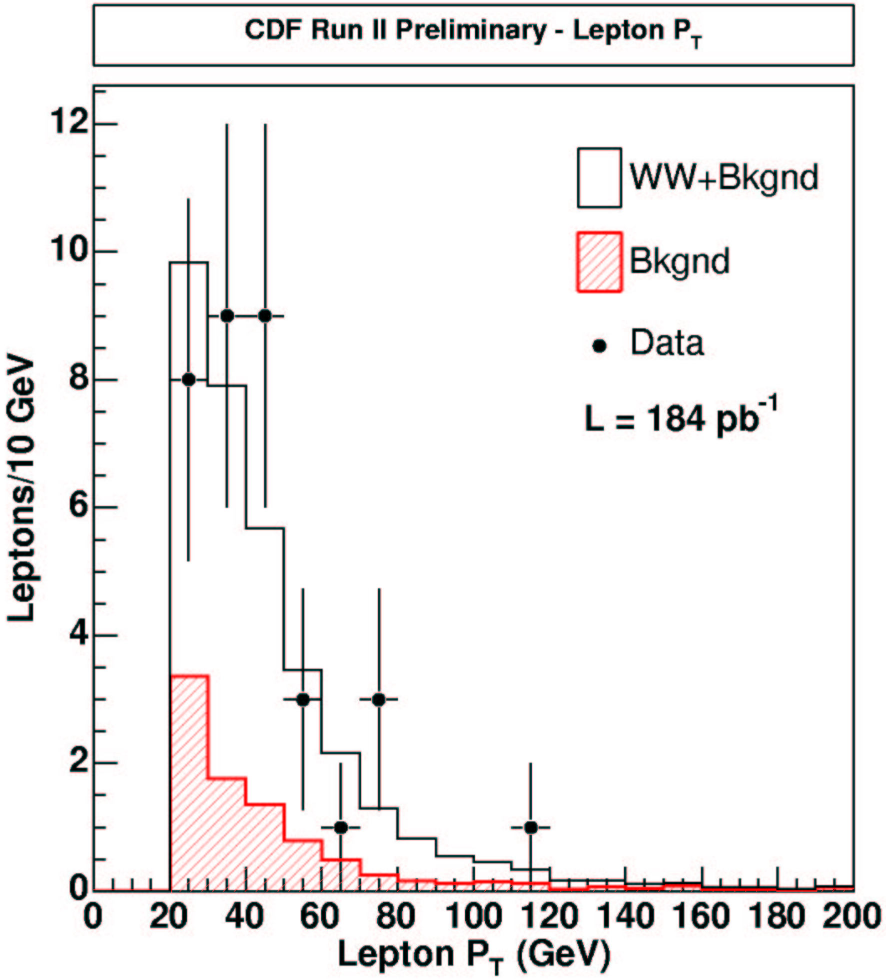
	DILEPTON	LEPTON+TRACK
WW Signal	11.3 ± 1.3	16.3 ± 0.4
Drell–Yan Background	1.8 ± 0.4	1.8 ± 0.3
Fake Background	1.1 ± 0.5	9.1 ± 0.8
Other Background	1.9 ± 0.2	4.2 ± 0.1
Total Background	4.8 ± 0.7	15.1 ± 0.9
Total Expected	16.1 ± 1.6	31.5 ± 1.0
Data Observed	17	39
σ(WW) [pb]	$14.3^{+5.6}_{-4.9}\,(\mathrm{stat}) \pm 1.6\,(\mathrm{syst}) \pm 0.9\,(\mathrm{lum})$	$19.4 \pm 5.1\,(\mathrm{stat}) \pm 3.5\,(\mathrm{syst}) \pm 1.2\,(\mathrm{lum})$

- Two measurements statistically consistent given estimated acceptance overlap.
- ~ 3σ significance : <u>first observation of WW production in hadron collisions.</u>

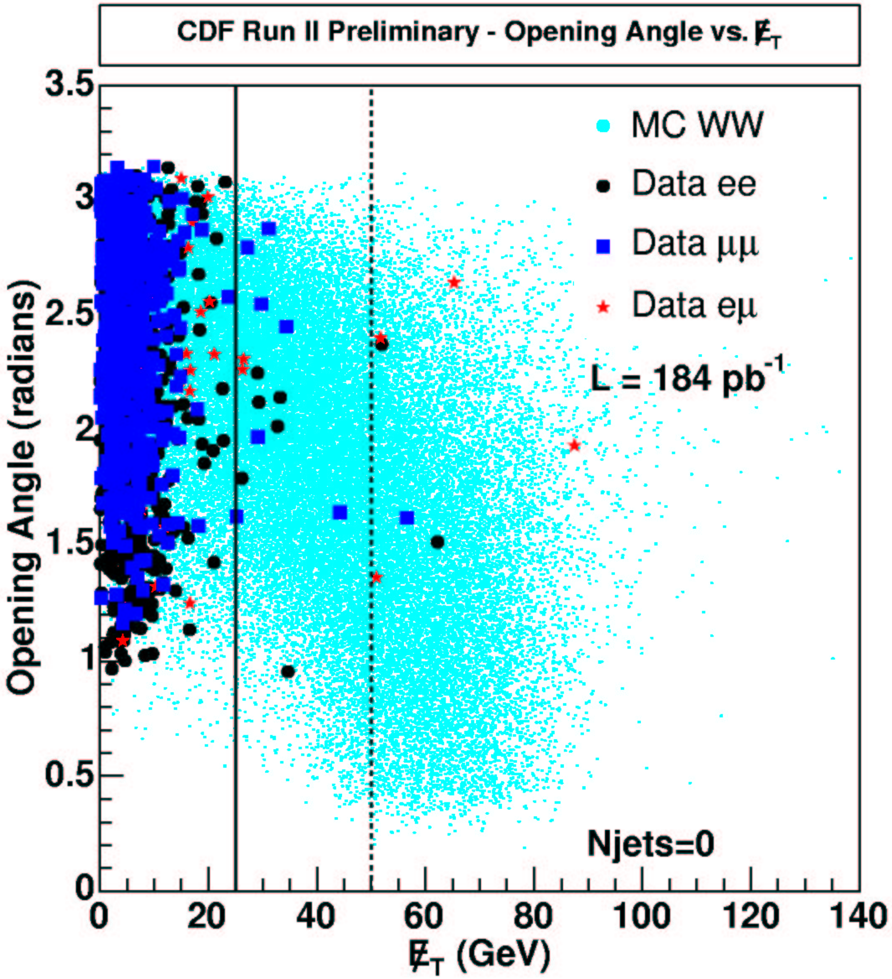
$$\boxed{\sigma(WW)^{\mathrm{THEORY}}_{\mathrm{NLO}} = 12.5 \pm 0.8 \ \ \mathrm{pb}}$$

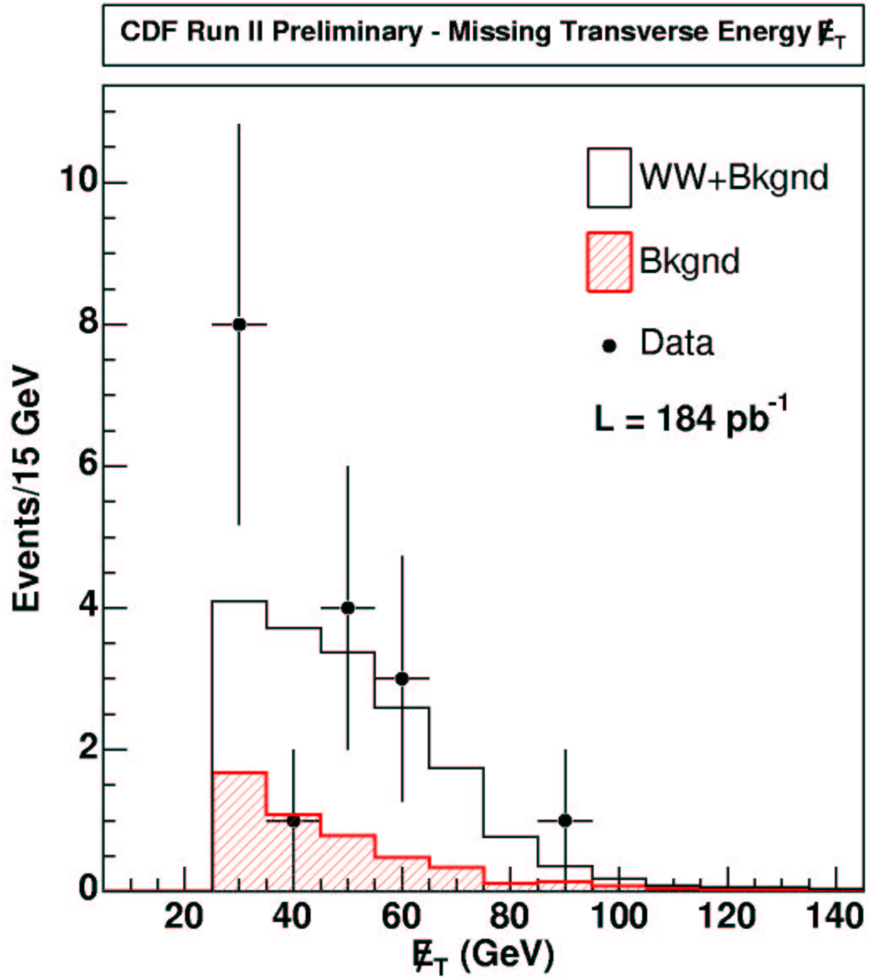
WW : "DILEPTON" Kinematics





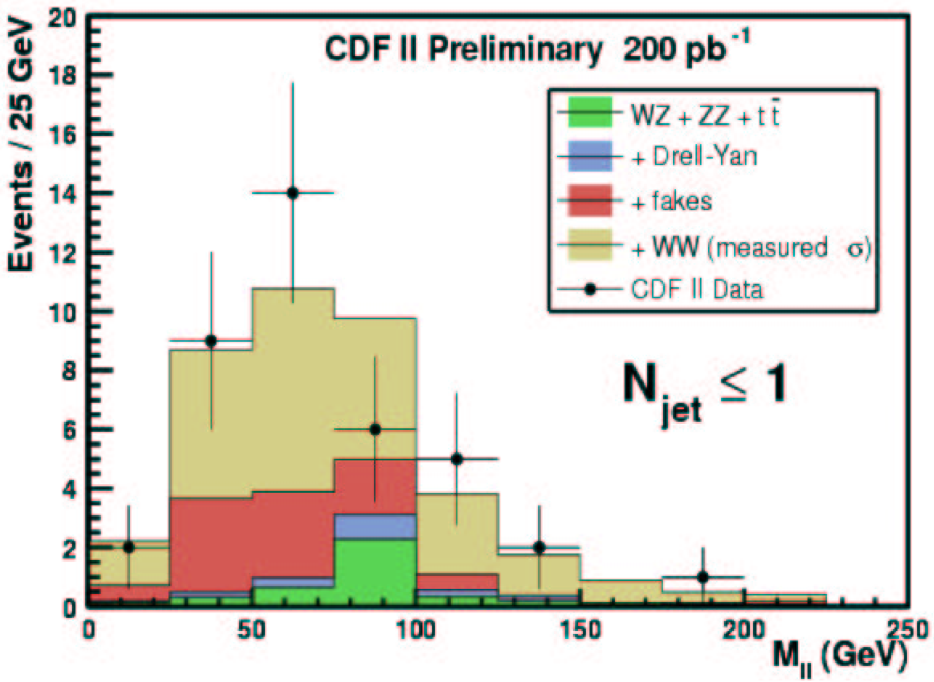
WW : "DILEPTON" Kinematics



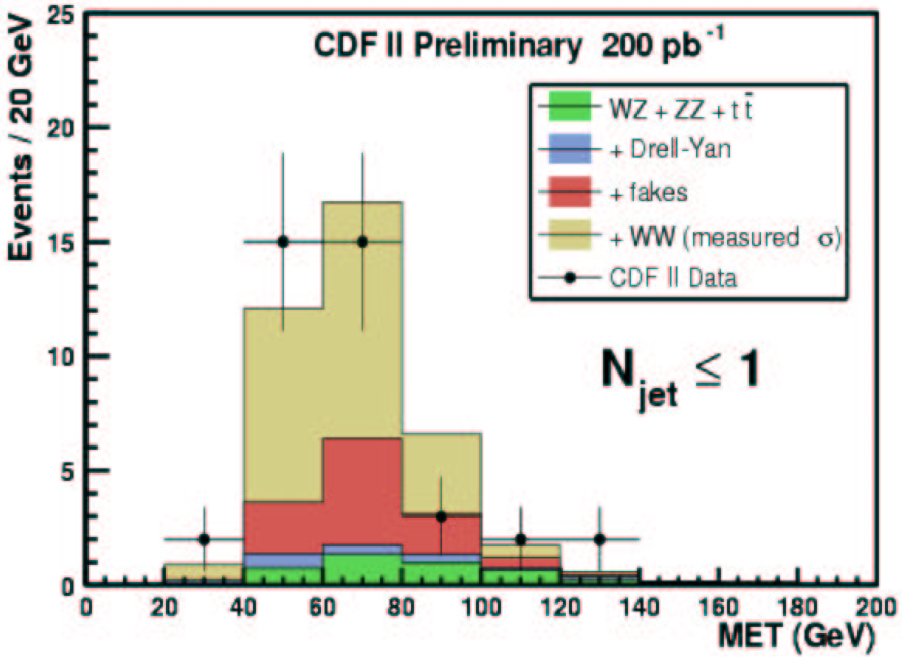


WW : "LEPTON+TRACK"
Kinematics

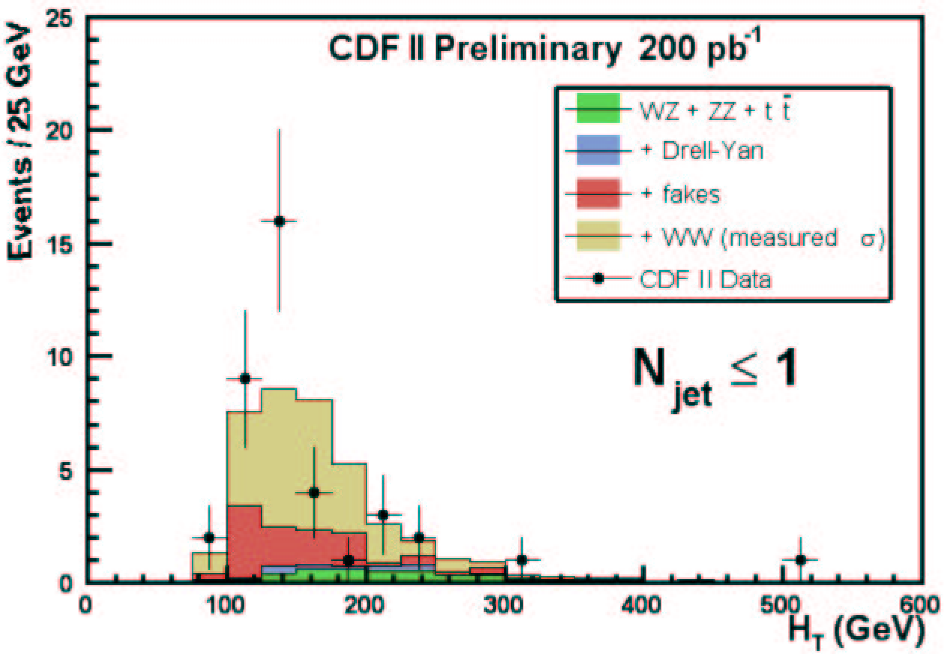
Dilepton Invariant Mass

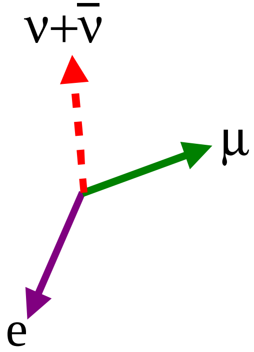


Missing Transverse Energy

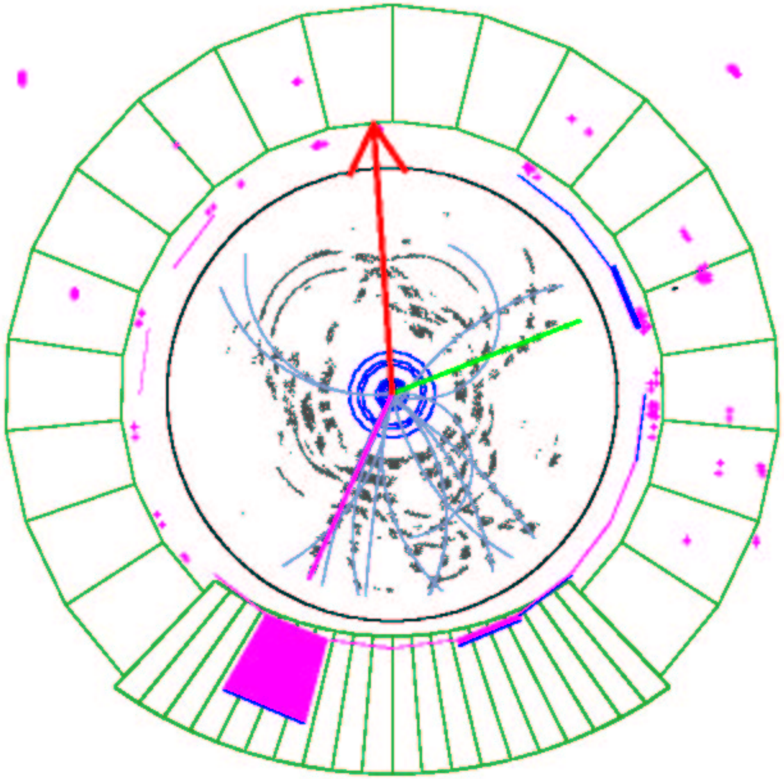


Total Transverse Energy (scalar sum)





- eμ channel has little Standard Model background
- Signal/Background ≈ 4

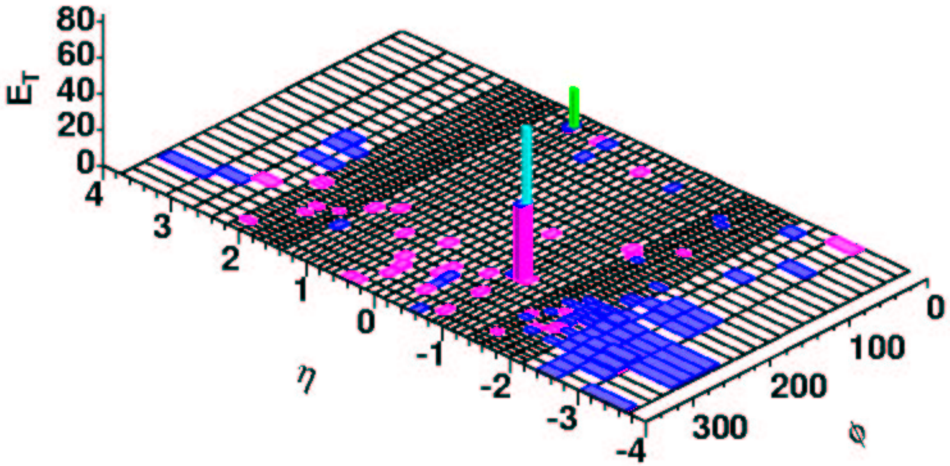


Run 155364 Event 3494901 : $WW \to e^+\nu_e\mu^-\bar{\nu}_\mu$ Candidate

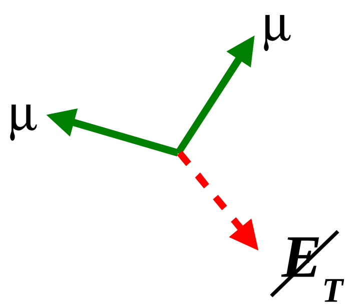
$p_T(e) = 42.0$ GeV/c; $p_T(\mu) = 20.0$ GeV/c; $M_{e\mu} = 81.5$ GeV

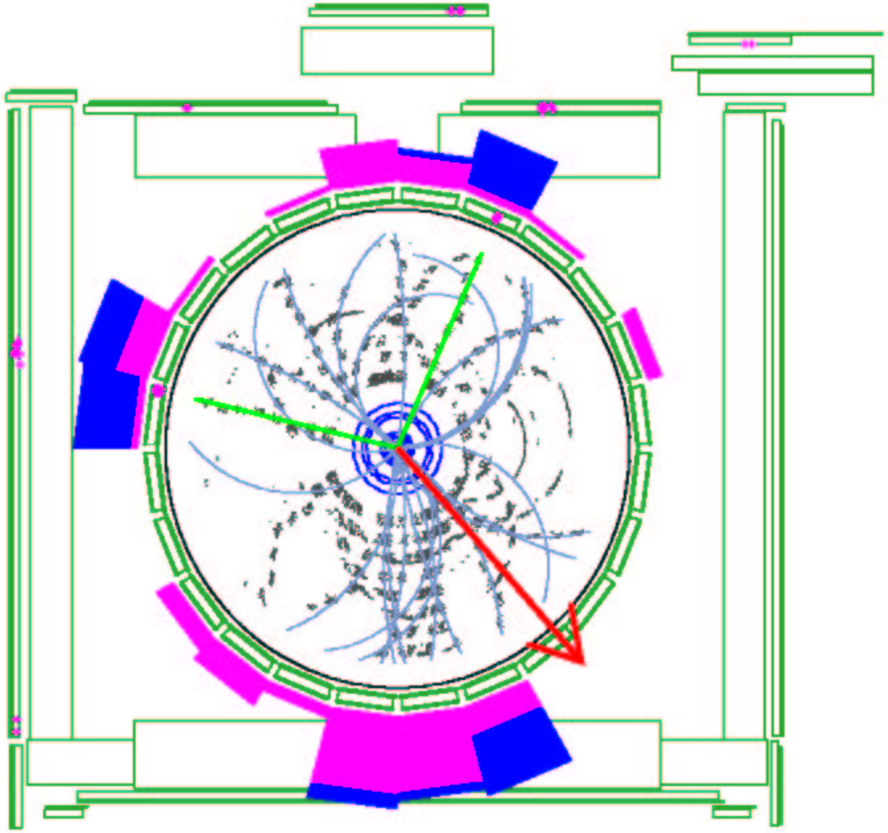
$\not{E}_T = 64.8$ GeV; $\Phi(\not{E}_T) = 1.6$

$\Delta\Phi(\not{E}_T$, lepton$) = 1.3$; $\Delta\Phi(e,\mu) = 2.4$; Opening-Angle(e,μ)=2.6



WW : Events



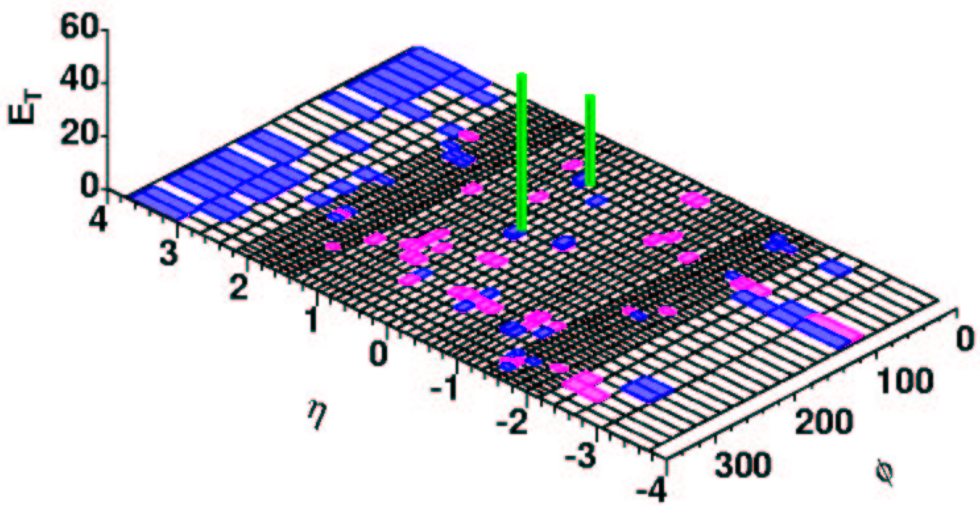


Run 160151 Event 842563 : $WW \rightarrow \mu^+\nu_\mu\mu^-\bar{\nu}_\mu$ Candidate

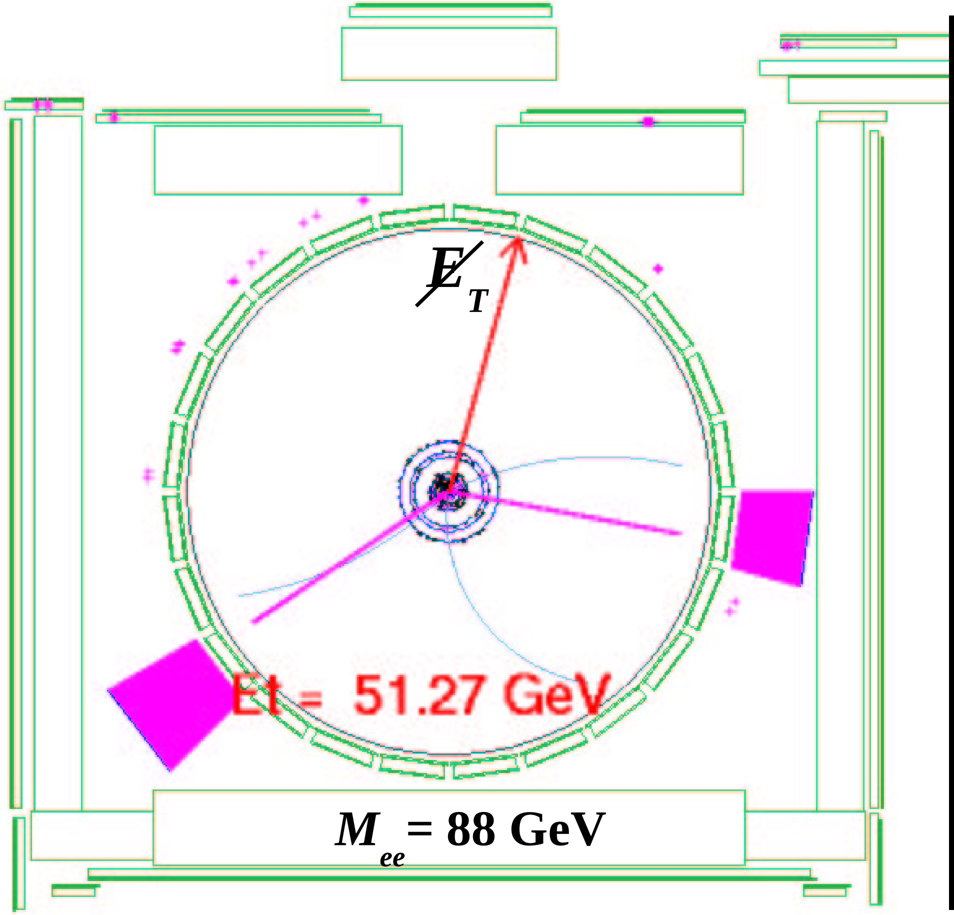
$p_T(\mu^-) = 56.6$ GeV/c; $p_T(\mu^+) = 35.5$ GeV/c; $M_{\mu^+\mu^-} = 70.1$ GeV

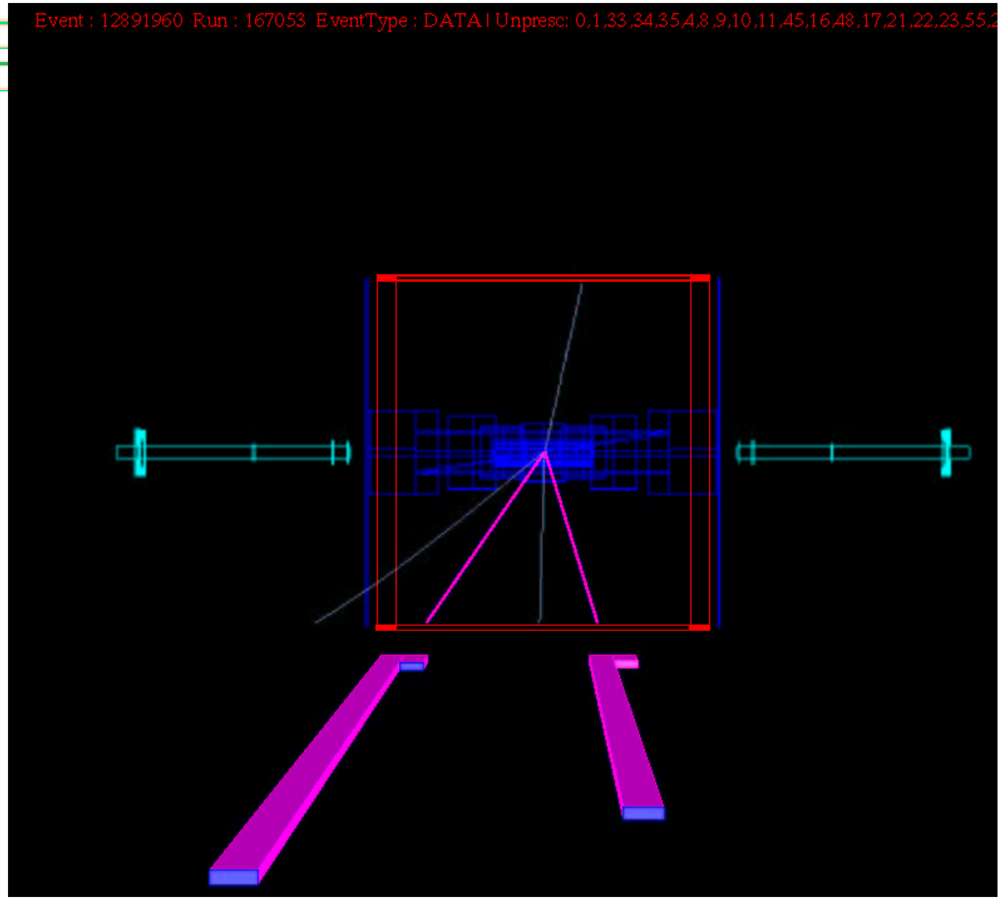
$\not{E}_T = 56.0$ GeV; $\Phi(\not{E}_T) = 5.4$

$\Delta\Phi(\not{E}_T$, lepton$) = 2.0$; $\Delta\Phi(\mu^+, \mu^-) = 1.8$; Opening-Angle$(e, \mu)$=1.6

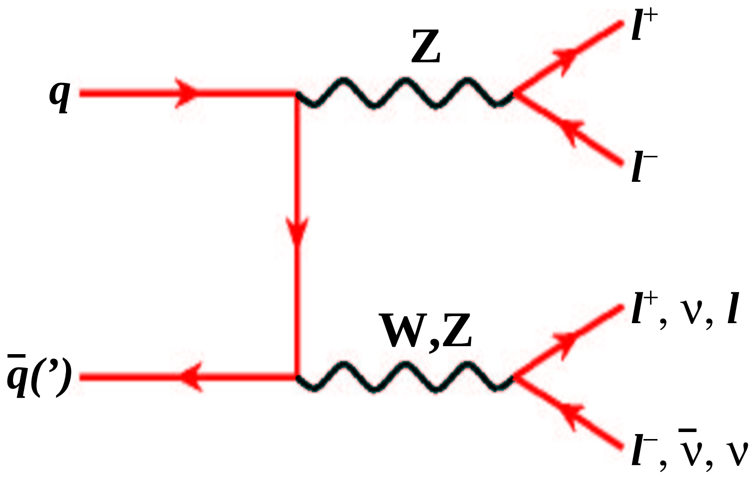


$$\boxed{Z^0Z^0 \rightarrow e^+e^-\nu\bar{\nu} \quad ?}$$





ZZ+ZW



- Search for $ZZ/ZW \to l^+ l^-$ + leptons :

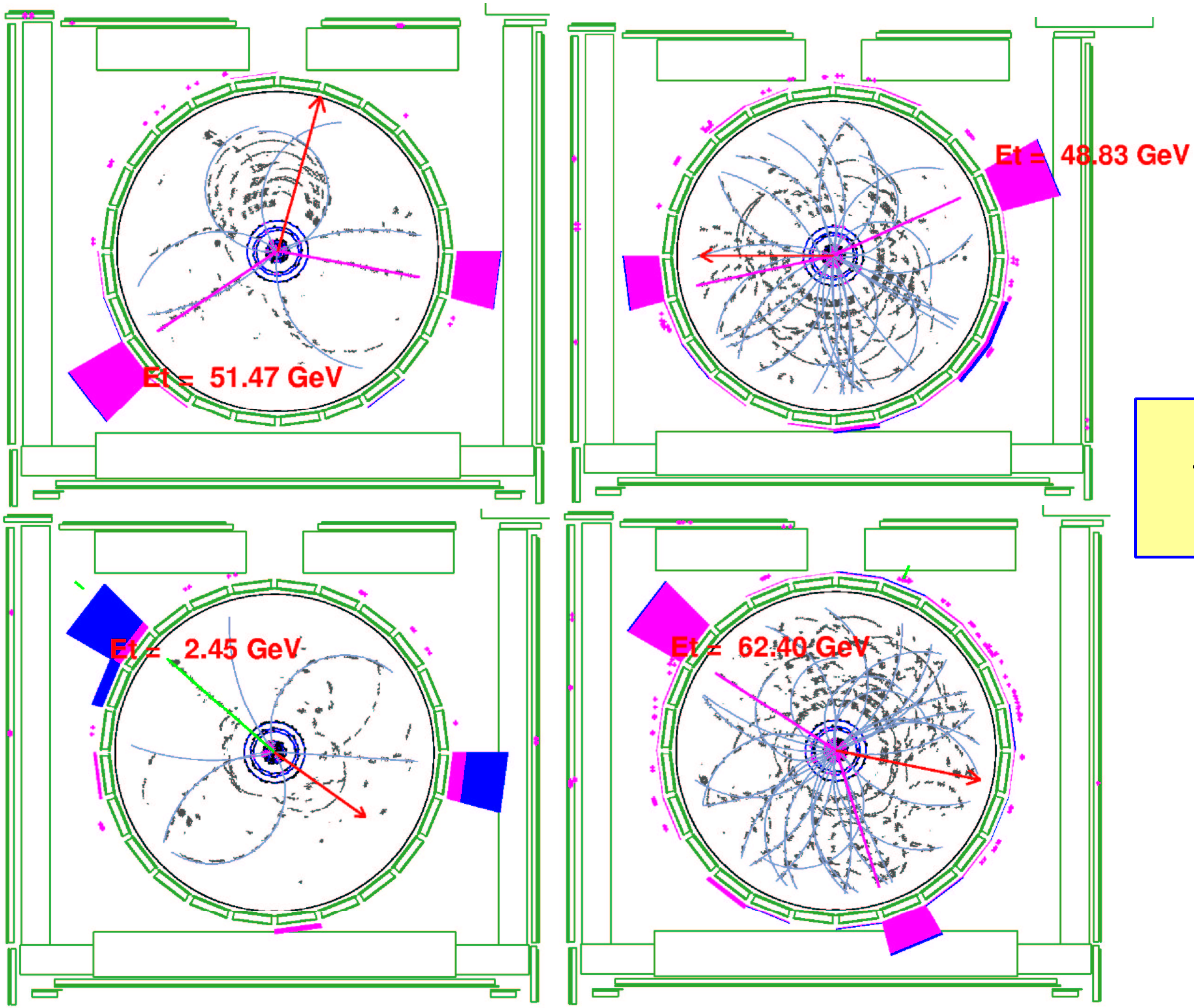
$$\sigma\left(p\bar{p} \to ZZ/ZW + X\right) = 3.3^{+5.3}_{-2.7}\ \text{pb}$$

$$\boxed{\sigma\left(p\bar{p} \to ZZ/ZW + X\right) < 13.9\ \text{pb}}$$

$$\sigma\left(p\bar{p} \to ZZ/ZW + X\right)_{\text{NLO}} = 5.2 \pm 0.4\ \text{pb}$$

CDF Run II Winter 2004 Preliminary, $\mathcal{L}$=194 pb^{-1}

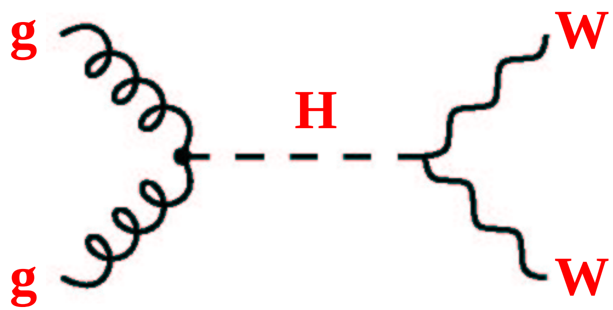
Process	$l_1 l_2 l_3 l_4$	$l_1 l_2 l_3 \not\!\!E_T$	$l_1 l_2 \not\!\!E_T$	Combined
ZZ	0.07 ± 0.01	0.13 ± 0.01	0.87 ± 0.14	1.07 ± 0.15
ZW	-	0.81 ± 0.07	0.86 ± 0.14	1.67 ± 0.19
ZZ+ZW	0.07 ± 0.01	0.94 ± 0.08	1.73 ± 0.27	2.72 ± 0.33
WW	-	-	1.26 ± 0.20	1.26 ± 0.20
Fake	0.01 ± 0.02	0.07 ± 0.06	0.56 ± 0.30	0.64 ± 0.34
Drell-Yan	-	-	0.31 ± 0.13	0.31 ± 0.13
$t\bar{t}$	-	-	0.08 ± 0.02	0.08 ± 0.02
Total Background	0.01 ± 0.02	0.07 ± 0.06	2.21 ± 0.38	2.29 ± 0.42
Expected S. + B.	0.08 ± 0.02	1.01 ± 0.10	3.94 ± 0.57	5.01 ± 0.64
Data	0	0	4	4

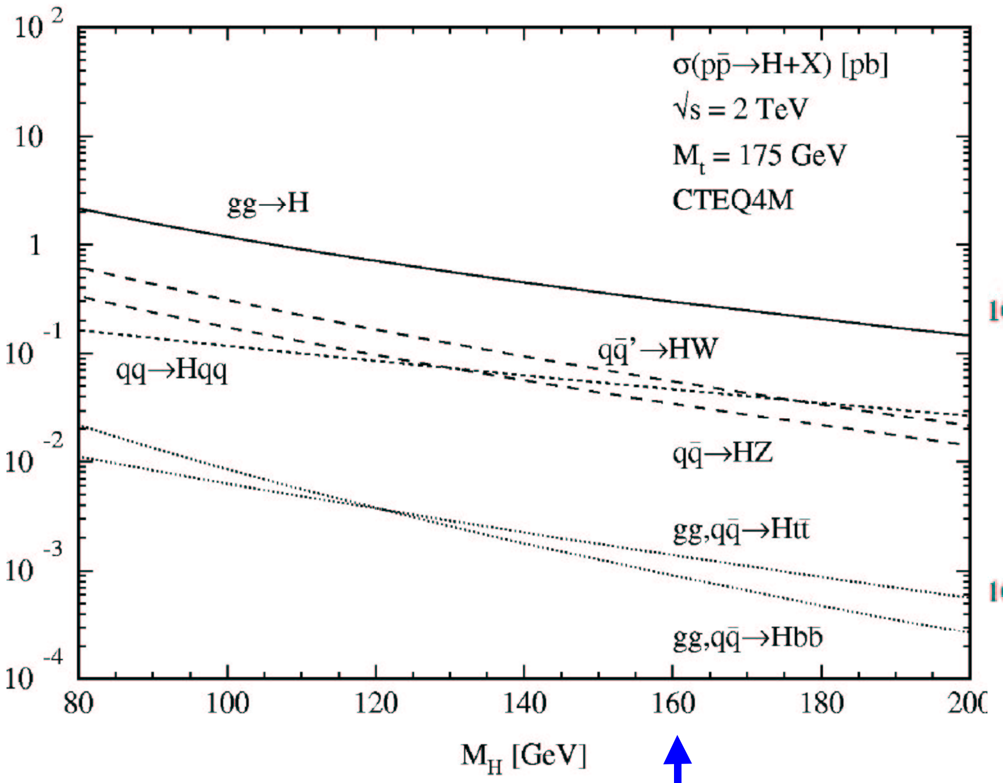


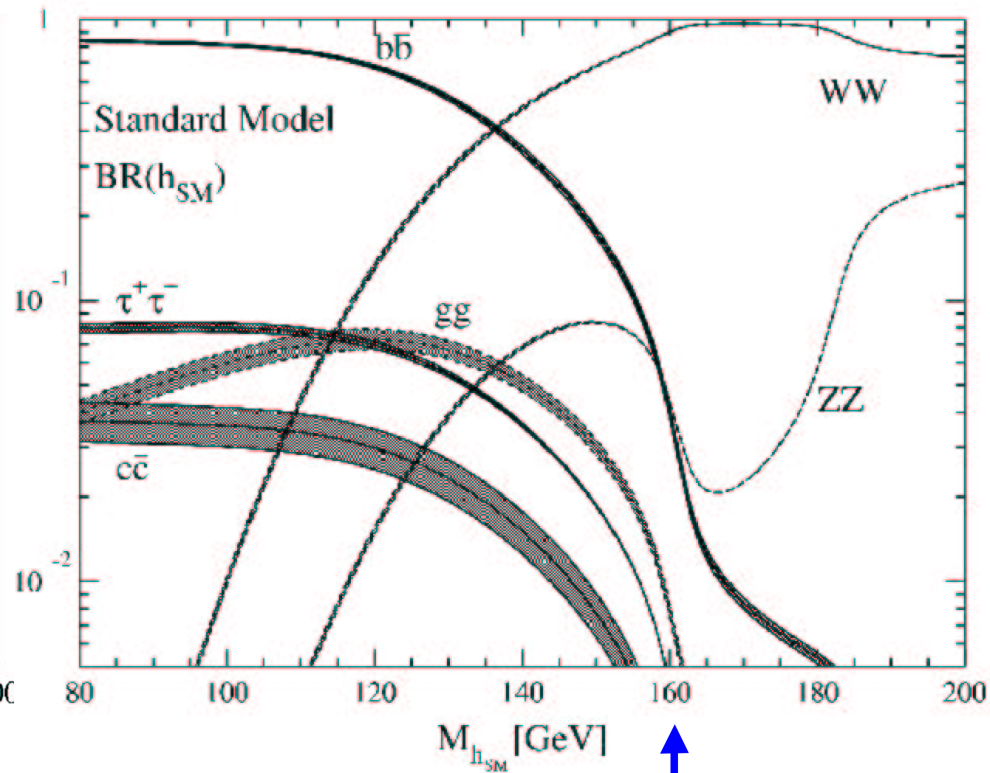
ZZ+ZW
Events

$H \to WW$

- Take advantage of largest (gluon−gluon) production cross−section.
- Large branching ratio to $WW^{(*)}$ above 140 GeV.
- Relatively low backgrounds.

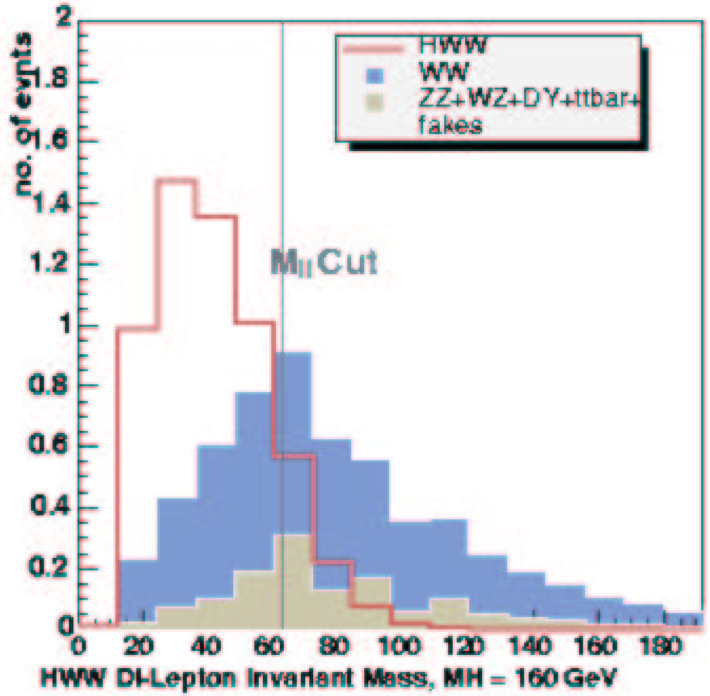


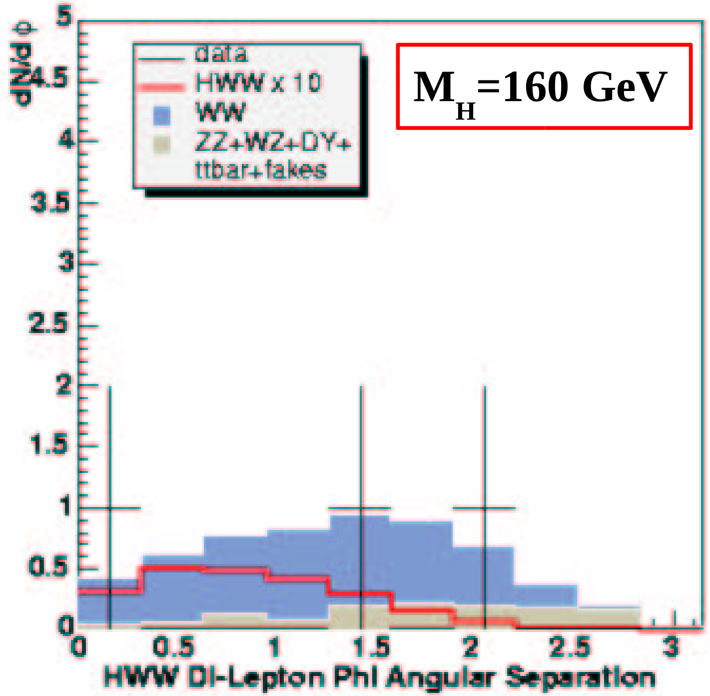




$\sigma(gg \to H) \sim 0.3$ pb @ 160 GeV

$BR(H \to WW) \sim 90\%$ @ 160 GeV

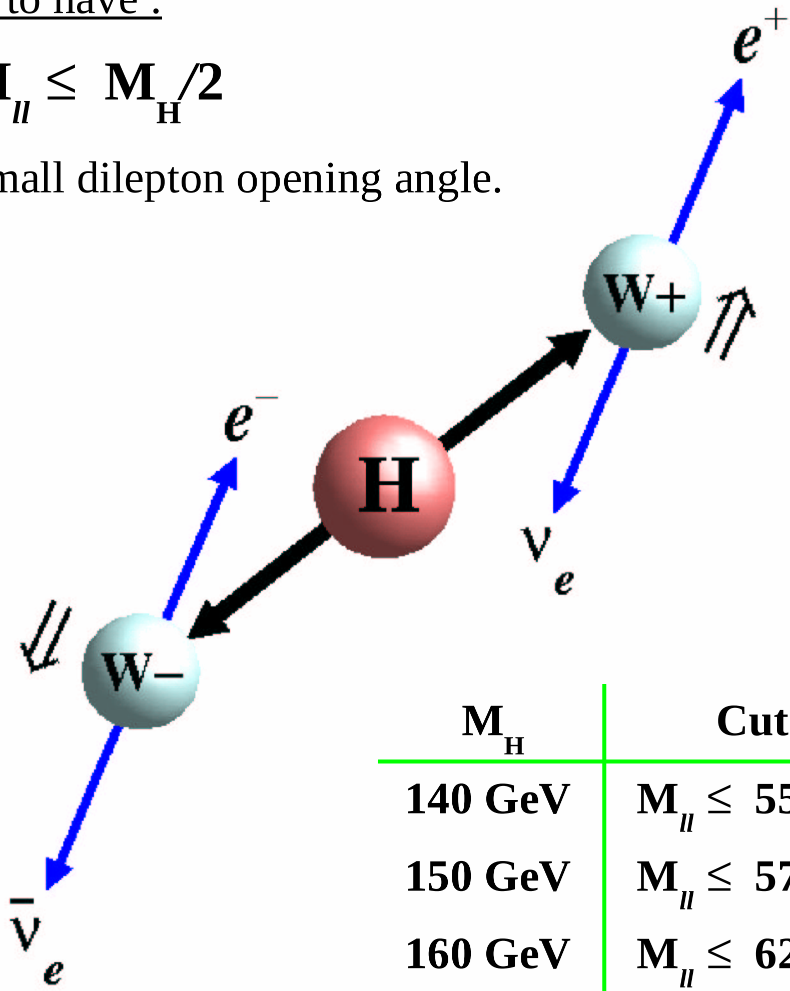




H→WW Kinematics

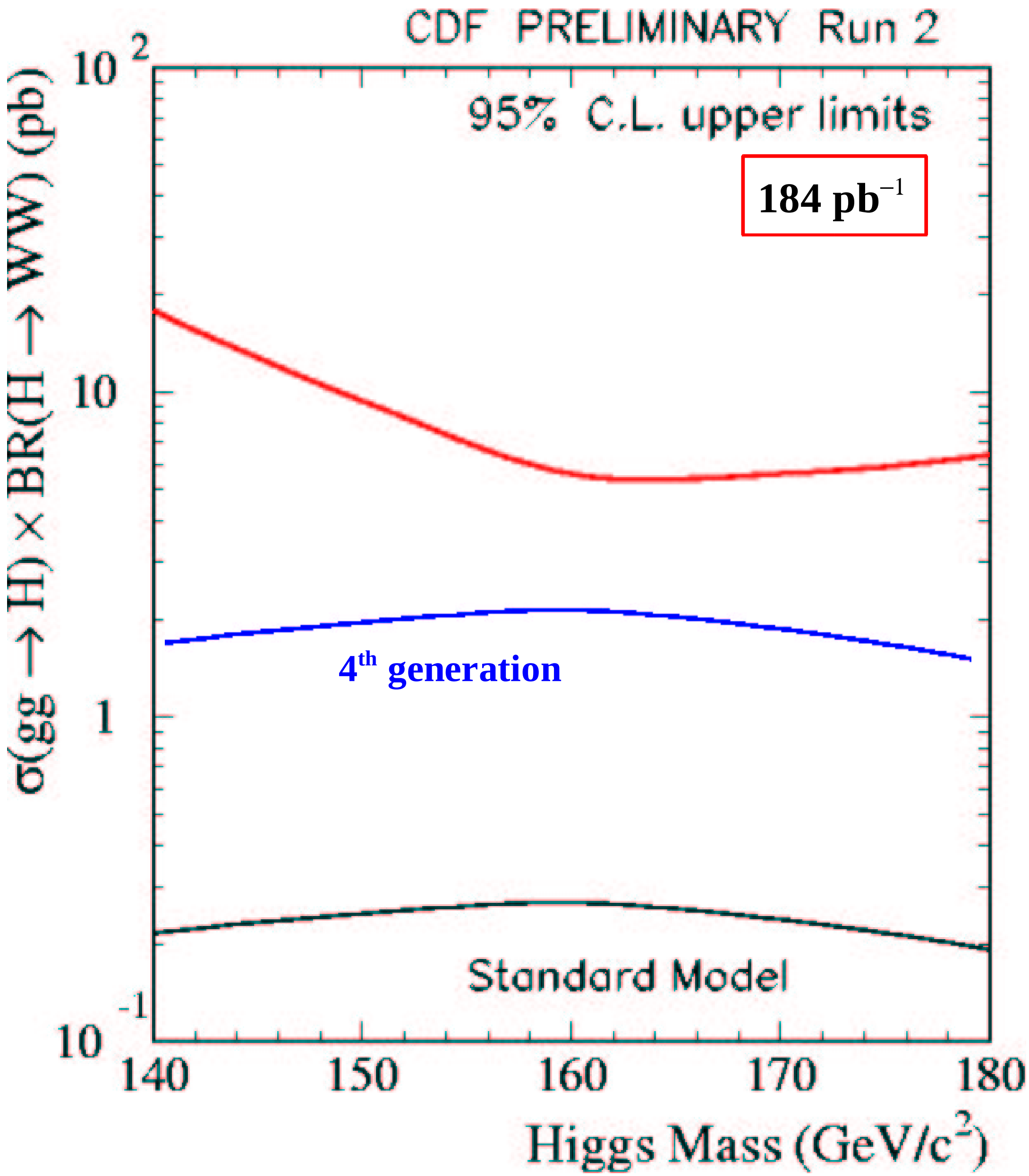
<u>Tend to have :</u>

- $M_{ll} \leq M_H/2$
- Small dilepton opening angle.



M_H	Cut
140 GeV	$M_{ll} \leq$ 55.0 GeV
150 GeV	$M_{ll} \leq$ 57.5 GeV
160 GeV	$M_{ll} \leq$ 62.5 GeV
170 GeV	$M_{ll} \leq$ 70.0 GeV
180 GeV	$M_{ll} \leq$ 80.0 GeV

H→WW

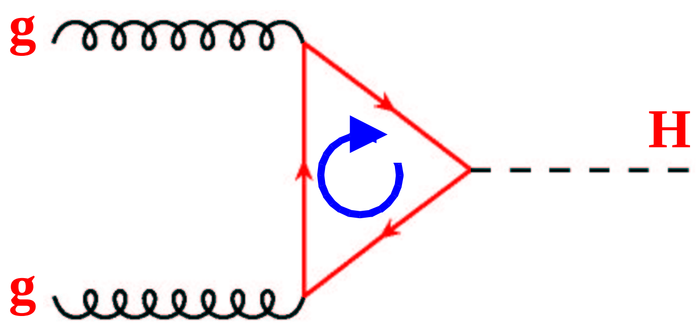


(1) Start with WW analysis.

(2) Apply dilepton mass cut.

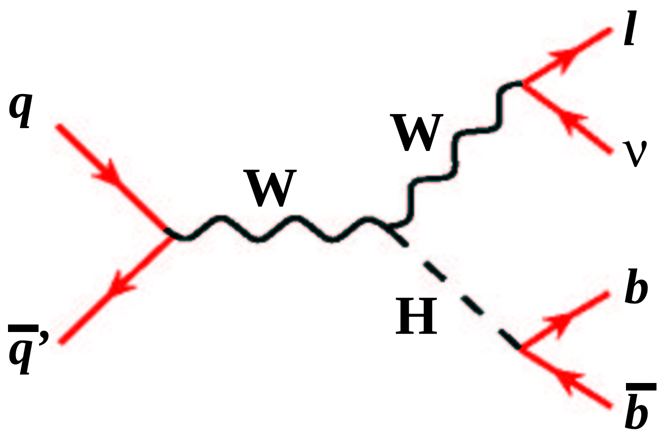
(3) Fit dilepton $\Delta\varphi$ distribution. Find maximum allowed Higgs contribution.

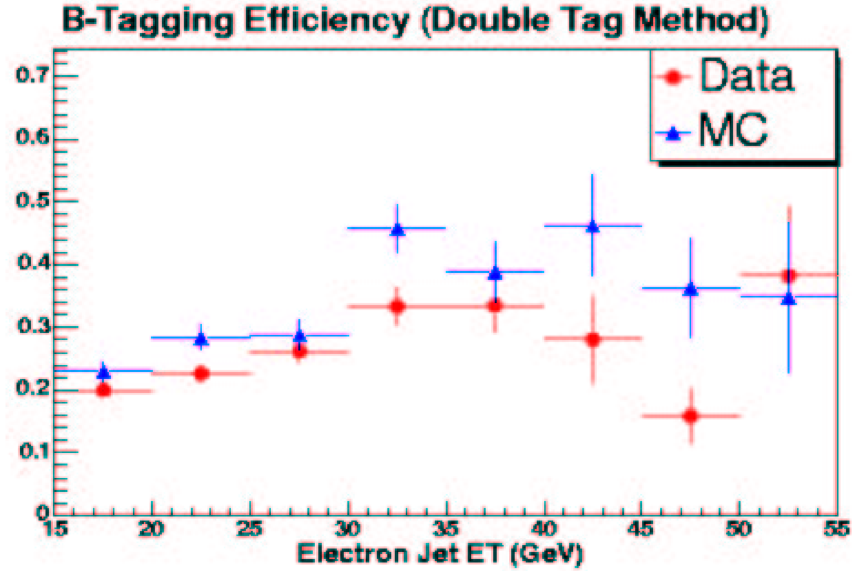
- Analysis can be further optimised.
- Will soon set model limits − for example on 4th quark generation :

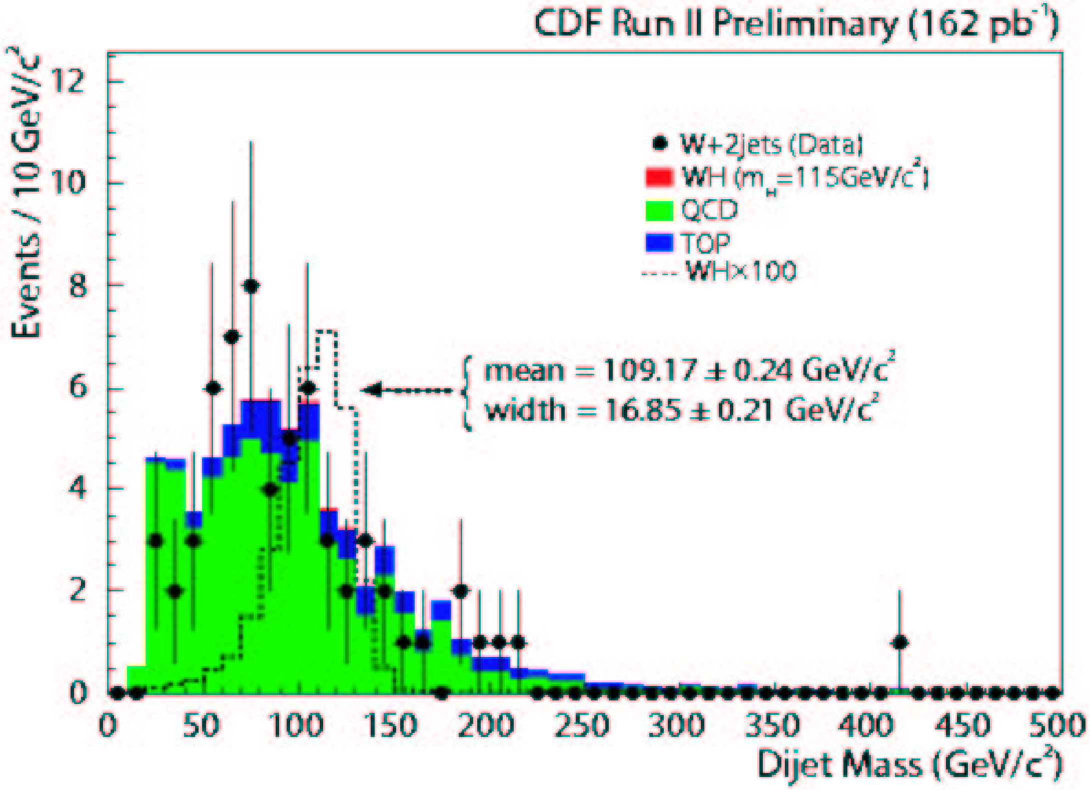


$\sigma(gg \to H; 4G) \sim 9 \times \sigma(gg \to H; 3G)$

Lower Mass Higgs Limits

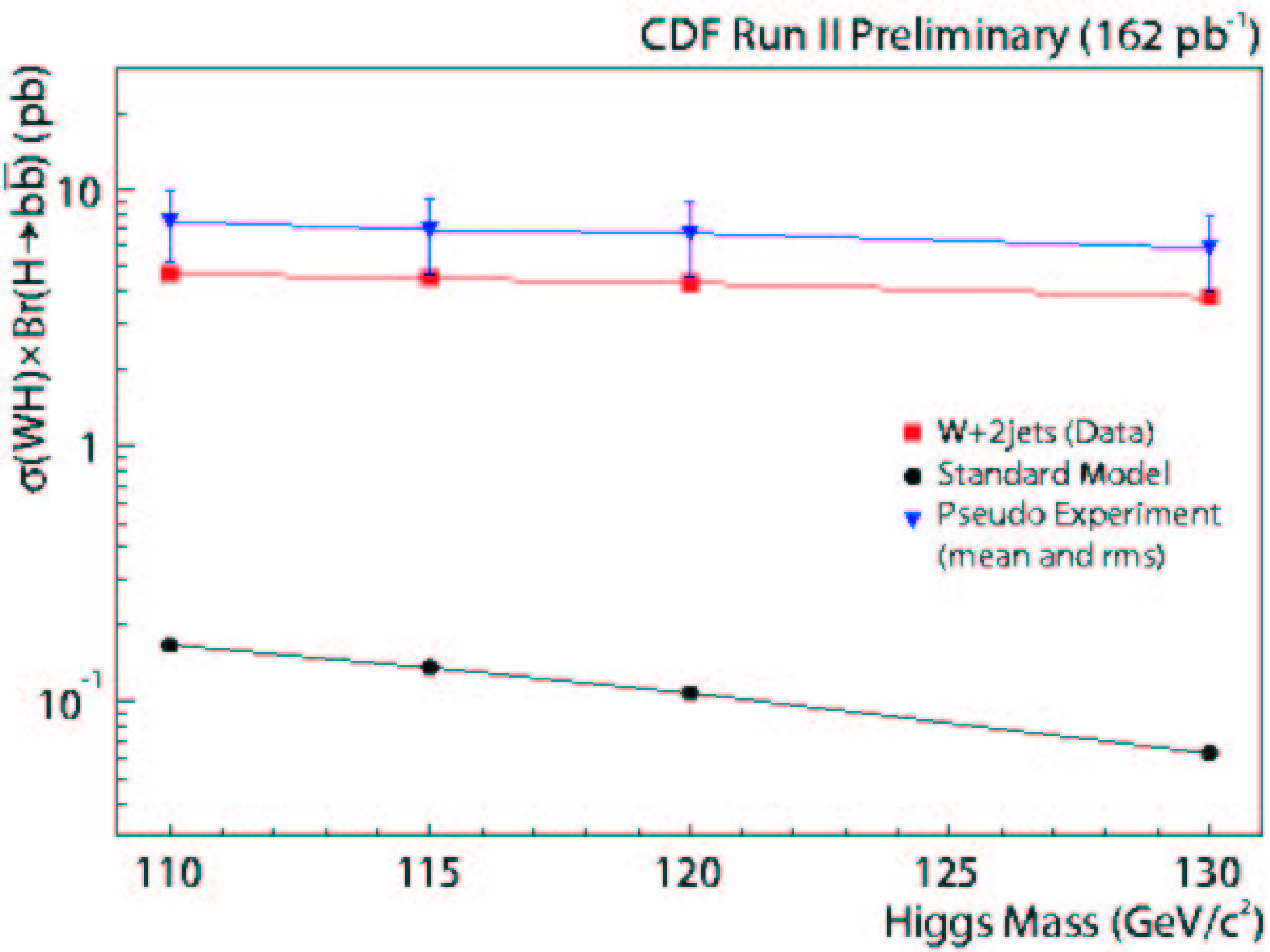


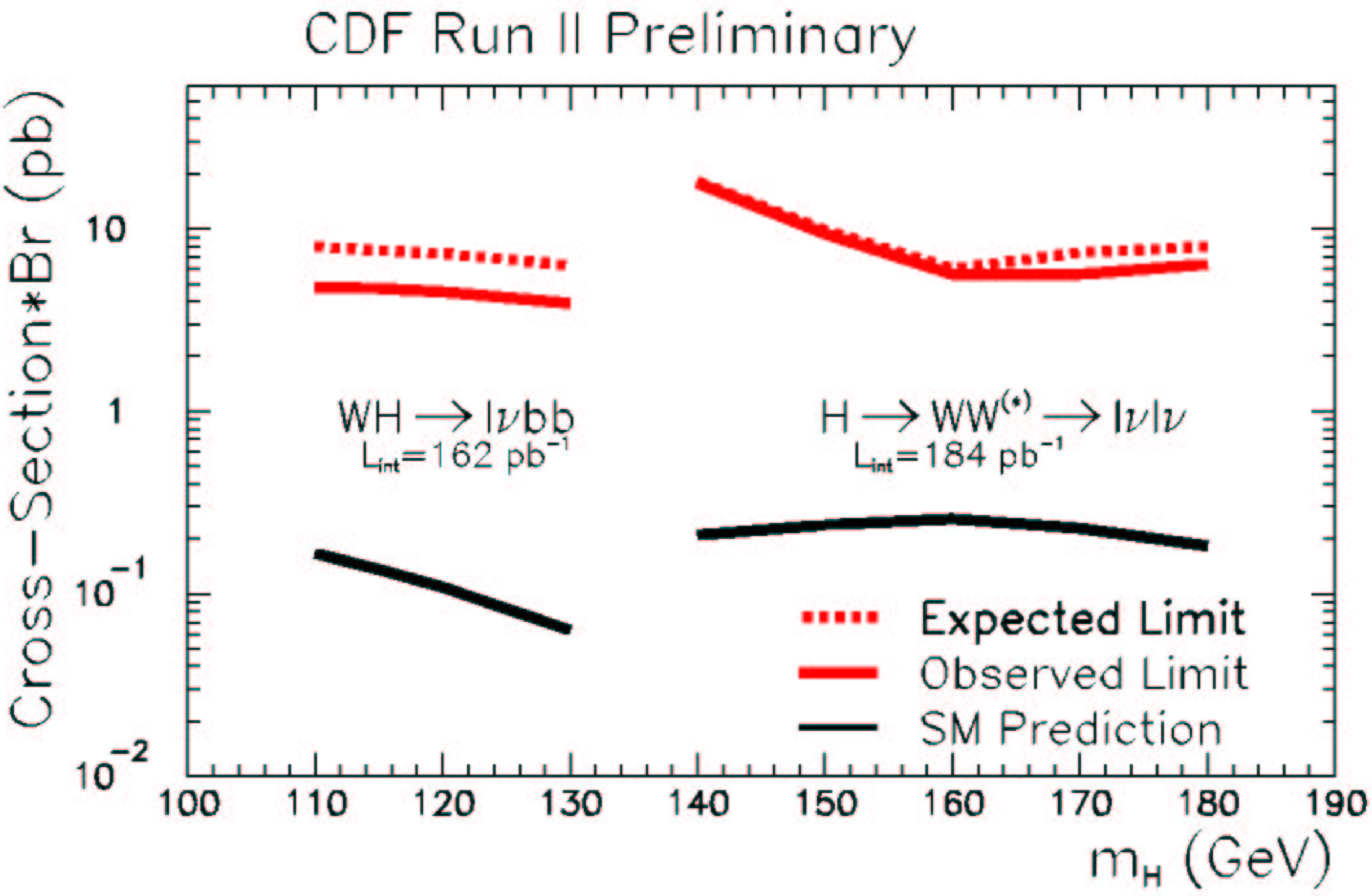




- Exactly 2 b−tagged jets required.
- "QCD" : mainly W+jets.
- Di−jet mass resolution ≈ 16%.
- Fit for maximum allowed Higgs signal as a function of mass.

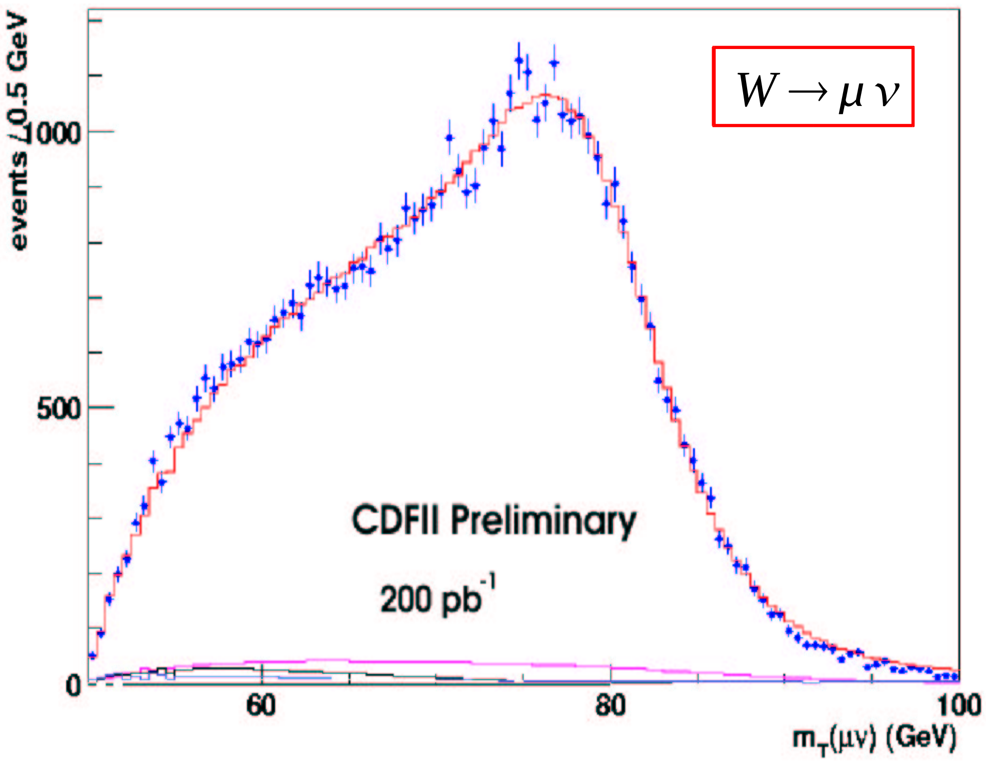
Lower Mass Higgs Limits

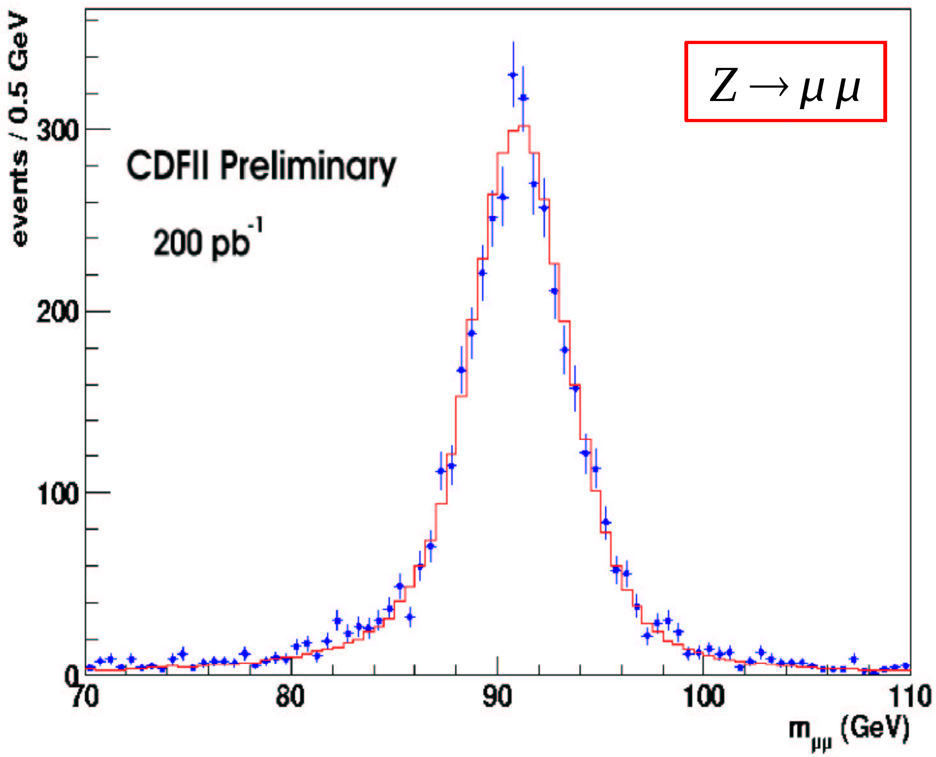



CDF Run II Preliminary
Cross−Section*Br (pb)
10
1
10−1
10−2
100
110
120
130
140
150
160
170
180
190
m_H (GeV)
WH → lνbb
L_int=162 pb−1
H → WW(*) → lνlν
L_int=184 pb−1
Expected Limit
Observed Limit
SM Prediction

W Mass :

- Fit transverse mass distribution.
- Calibrate to Z signal.





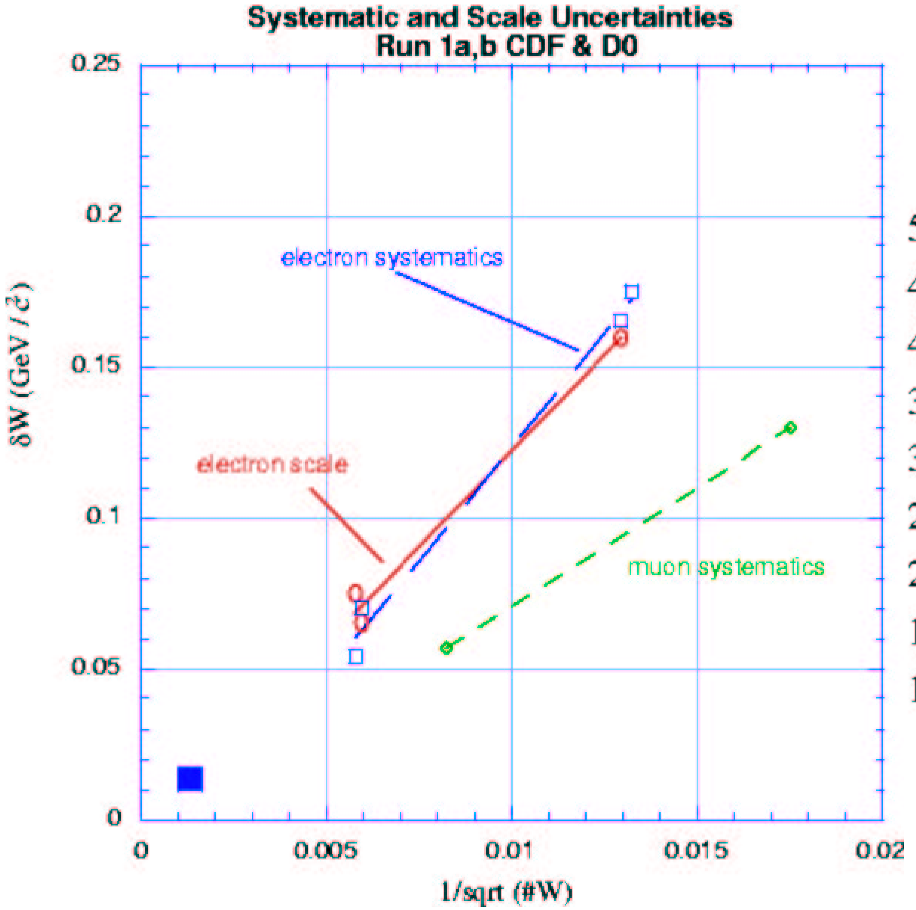
First Run 2 CDF W mass measurement to be "unblinded" this summer

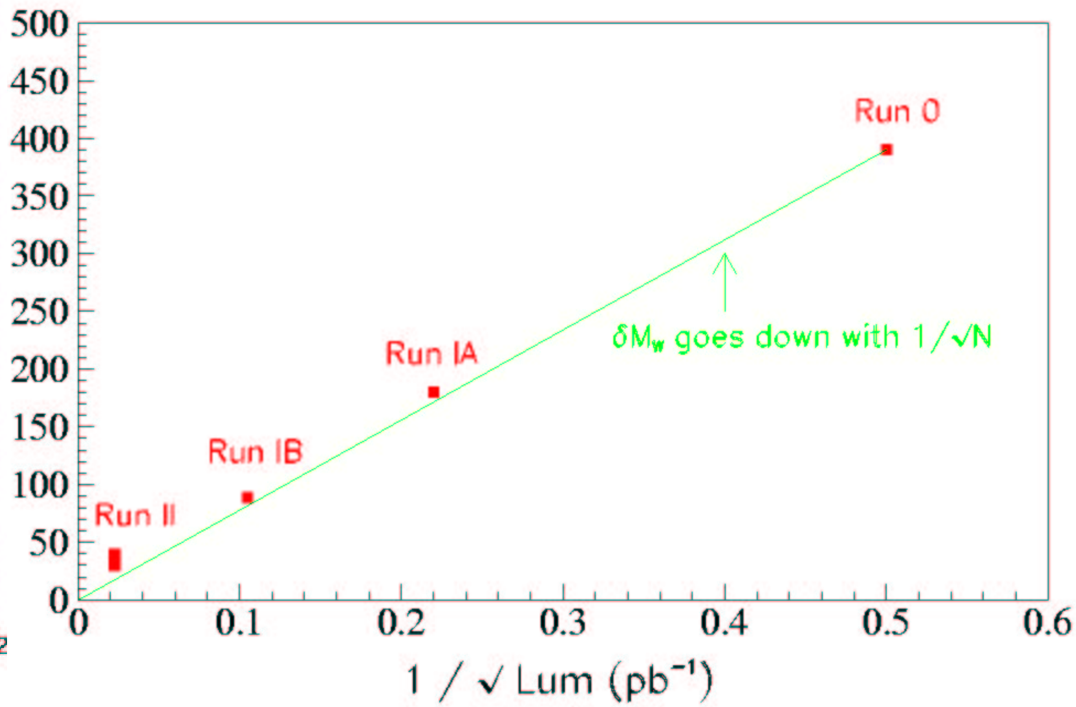
$$\delta(M_W) \approx \pm\, 55\ (\text{stat}) \pm 80\ (\text{syst})\ \text{MeV}\ \ \mu$$
$$\delta(M_W) \approx \pm\, 40\ (\text{stat}) \pm 60\ (\text{syst})\ \text{MeV}\ \ \mathbf{e}$$

250 pb^{-1} estimate

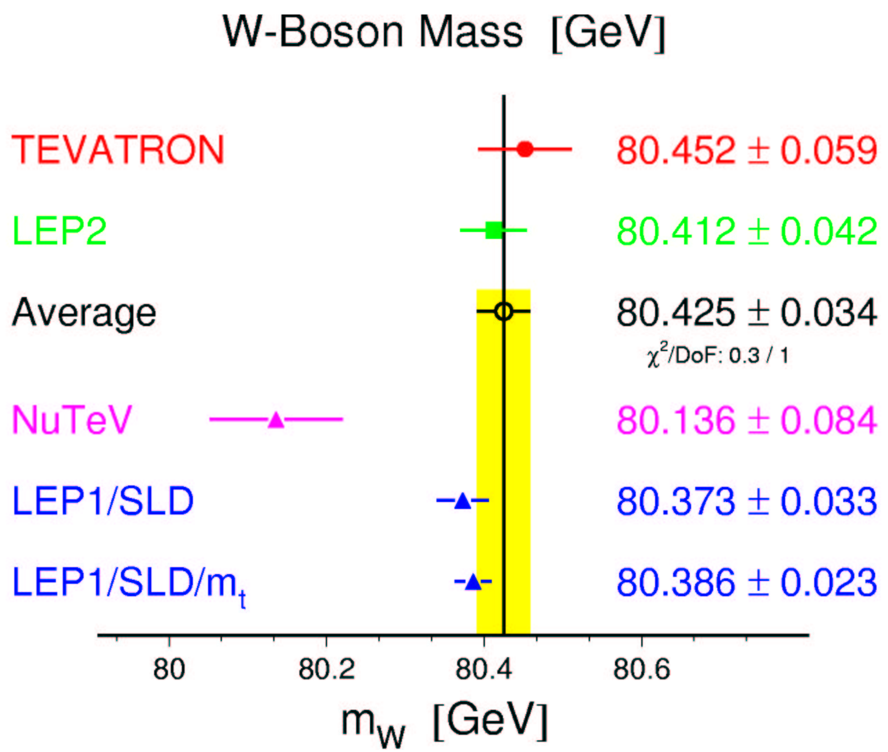
What can we expect with 2 fb^{-1} ?

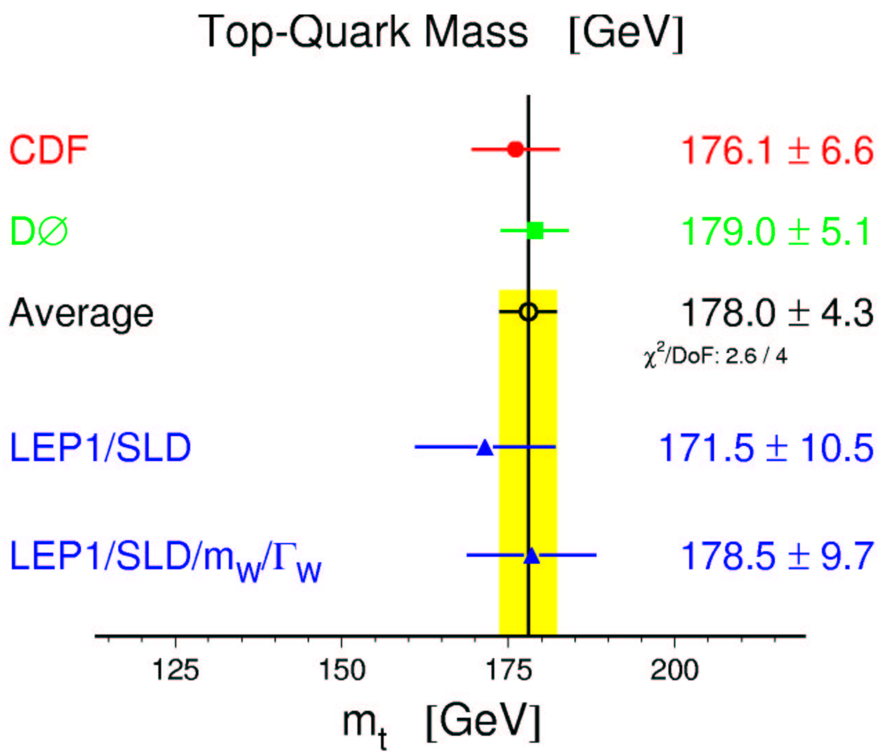
- Statistical errors at the 15 MeV level per. channel.
- So far systematics have mainly scaled statistically, but we know we will hit "hard" limits at the 10−20 MeV level :
  - Higher order QED & QCD
  - PDF’s etc.





Final Run 1 Combinations





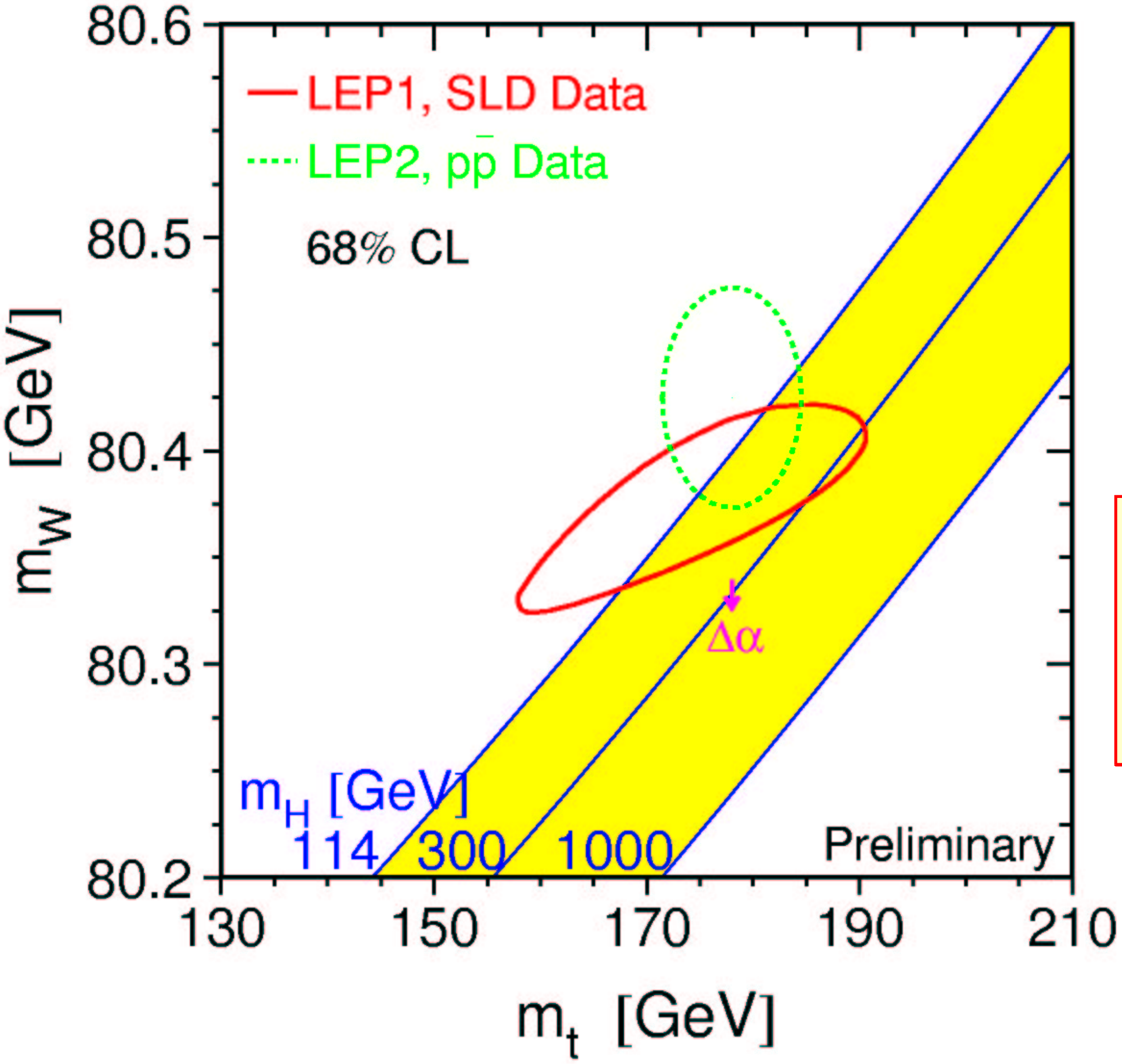
Final Run 1 W Properties from combined fit :

$$m_W^{\text{Tevatron}} = 80.452 \pm 0.059 \text{ GeV}$$

$$\Gamma_W^{\text{Tevatron}} = 2.102 \pm 0.106 \text{ GeV}$$

Including D0 "Dynamical Likelihood Method"

Final Run 1 Combinations



Indirect Higgs mass constraints :

$$M_H = 117^{+67}_{-45} \text{ GeV}$$

$$< 251 \text{ GeV} \quad @95\% \text{CL}$$

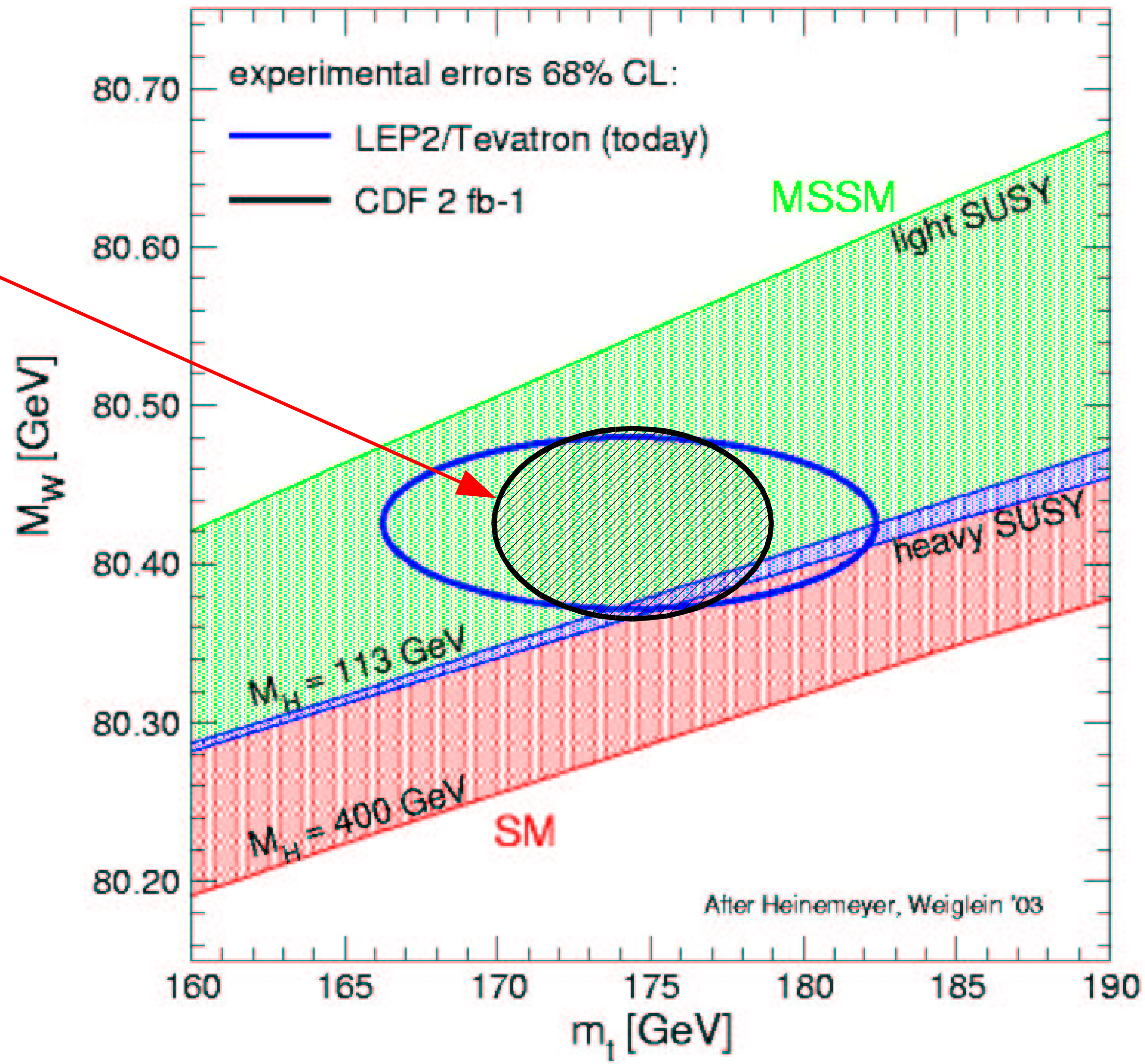
Precision Electroweak Prospects

<u>CDF *alone* with 2 fb^{-1}</u>

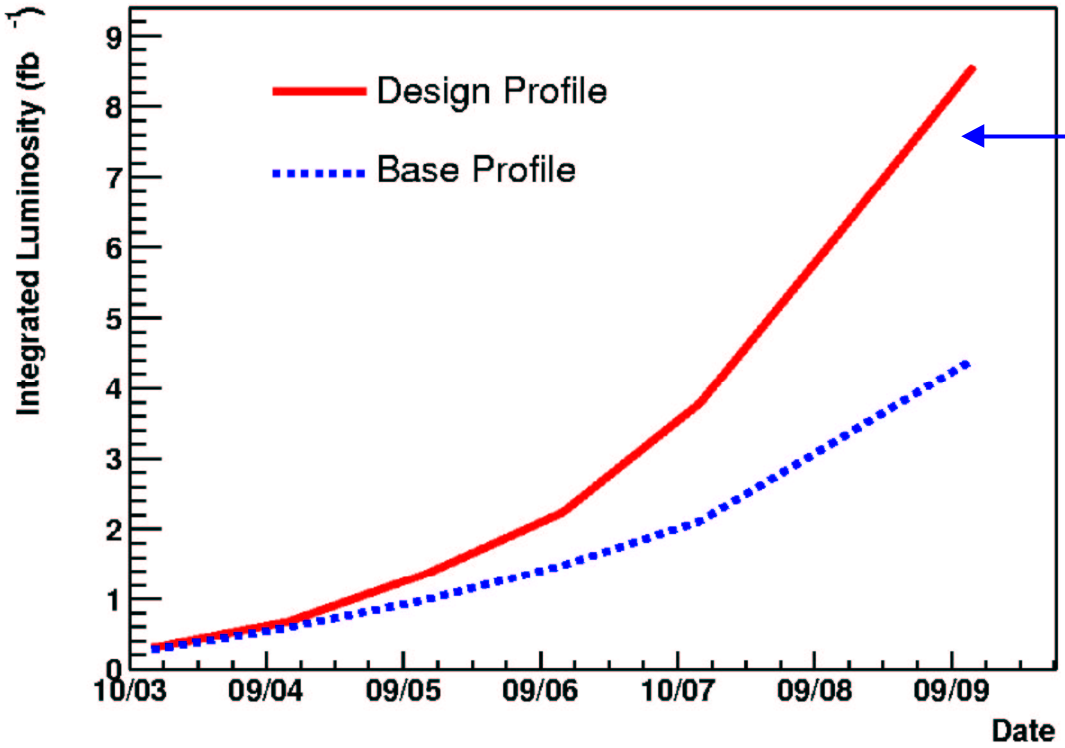
- **$\Delta M_W \approx$ 40 MeV**
- **$\Delta M_{top} \approx$ 3 GeV**

➨ Similar to all current direct measurement data combined.

- With a Higgs discovery at Tevatron or LHC, these measurements will provide a powerful consistency test of the Standard Model.
- Could provide first evidence of what lies beyond the SM.
- Will be improved at LHC, but not quickly or easily.



Tevatron Prospects

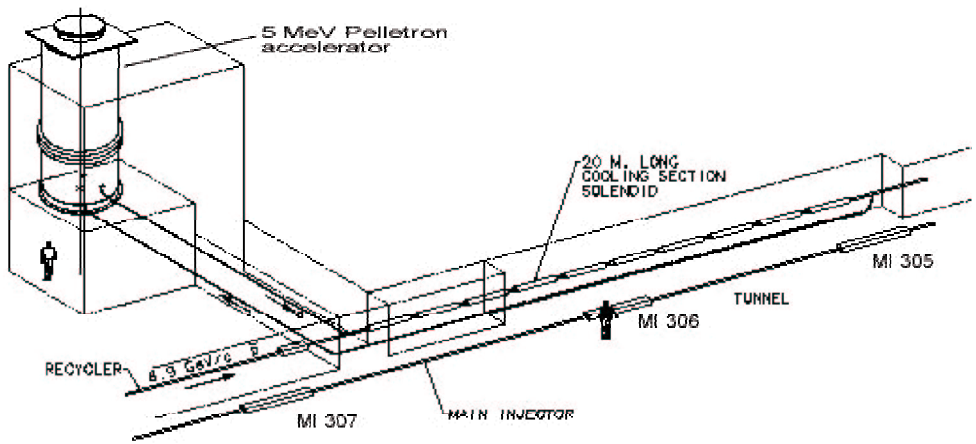


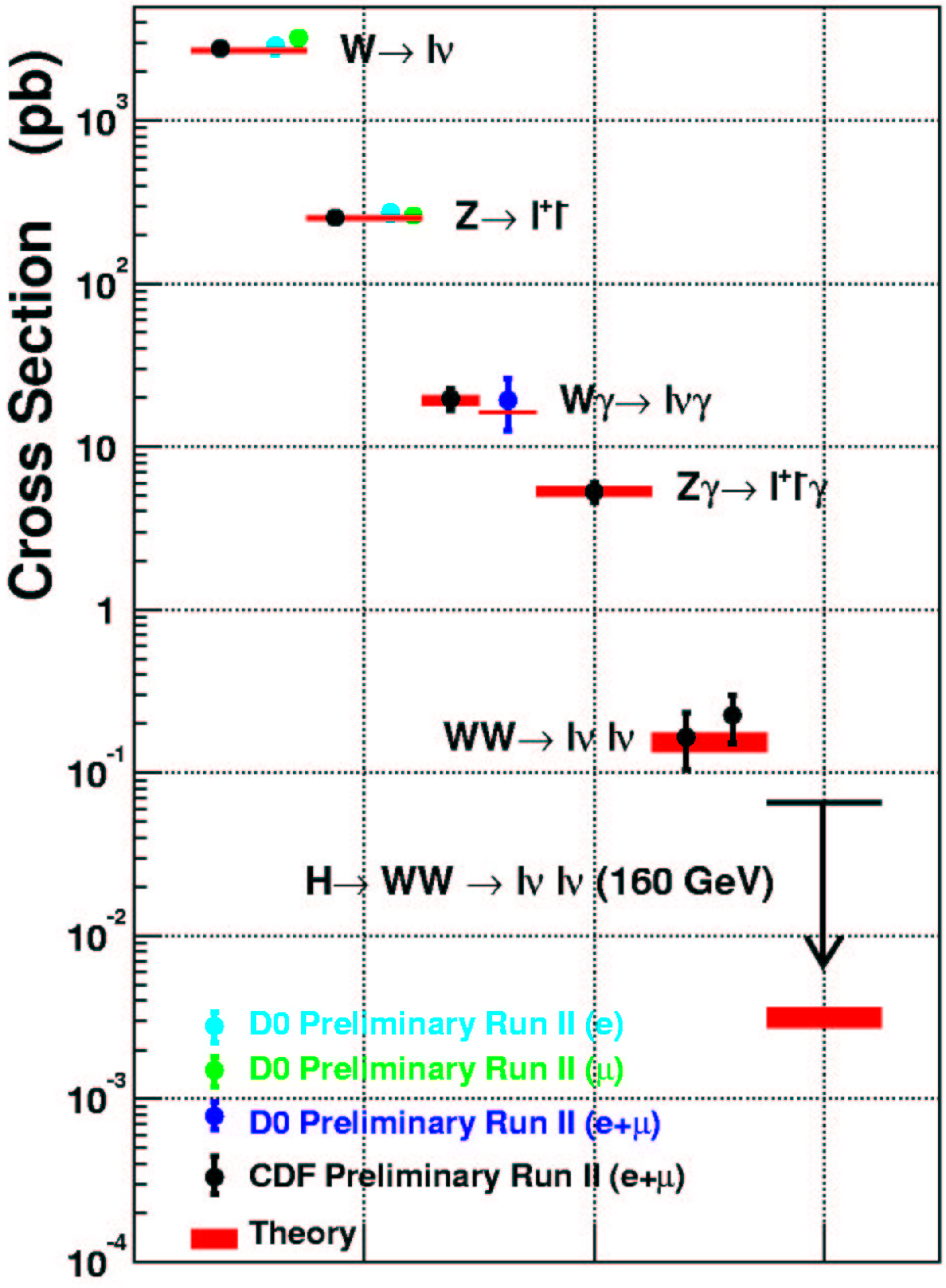
Requires electron cooling to work.

World record :

Highest power DC electron beam :

~4 MeV ⊗ 0.5A = 2 MW





Summary

- Precision measurements have been made of single boson production cross−sections & properties.
- Diboson signals established in Run 2.
- First observation of WW production in hadron collisions.
- Analyses being optimised for Standard Model tests − in particular anomalous coupling limits.
- Higgs limits around a mass of 160 GeV are currently around 20 times the Standard Model expectation.
- M_W & other EWK measurements soon.
- Tevatron luminosity looks good − interesting few years ahead.