Pushing the Mass Limit: Recent Searches for High Mass Resonances at CDF

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Introduction

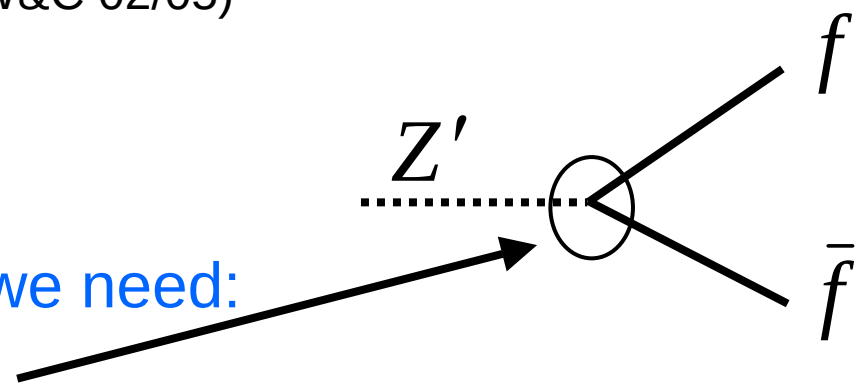
- Massive gauge bosons predicted in many extensions to the standard model
- Highest energies are accessible by the Tevatron
- Looking for resonances decaying to leptons and photons provides very clean signature even in a hadron collider

Extensions to Standard Model

- Most extensions to SM predict new gauge interactions
  - ➔ **Most give neutral or singly charged bosons**
  - ➔ **Tight constraints on Z^0-Z' mixing from LEP**
- Examples with popular models:
- Heavy *neutral* gauge boson: Z'
  - ➔ **Spin 0: sneutrino (SUSY)**
  - ➔ **Spin 1: E6 GUT theories (Z_η, Z_ψ, Z_χ), Z'_{SM}**
    - Sequential Z'_{SM} is a toy Z' model
    - same couplings as Standard Model Z boson
    - Pretty difficult to get from theory, but easy to generate in Pythia
    - Useful as a benchmark
  - ➔ **Spin 2: gravitons (ED)**
- Heavy *charged* gauge boson: W'
  - ➔ **Left-Right symmetric theories**
  - ➔ **Tevatron has unique sensitivity compared to LEPII**

A Generic Z′

- Previous analyses have focused on specific Z′ models
- Generic Z' extension:
  - **Carena, Daleo, Dobrescu, and Tait (FNAL)**
    - **Phys.Rev.D70:093009,2004** (W&C 02/05)
  - **$SU(3)_C \times SU(2)_W \times U(1)_Y \times U(1)_Z$**
  - **Z'-Z mixing small**
    - tightly constrained by LEP
- To fully specify the Z′ model, we need:
  - **$M_{Z'}$, $\Gamma_{Z'}$, 15 couplings**



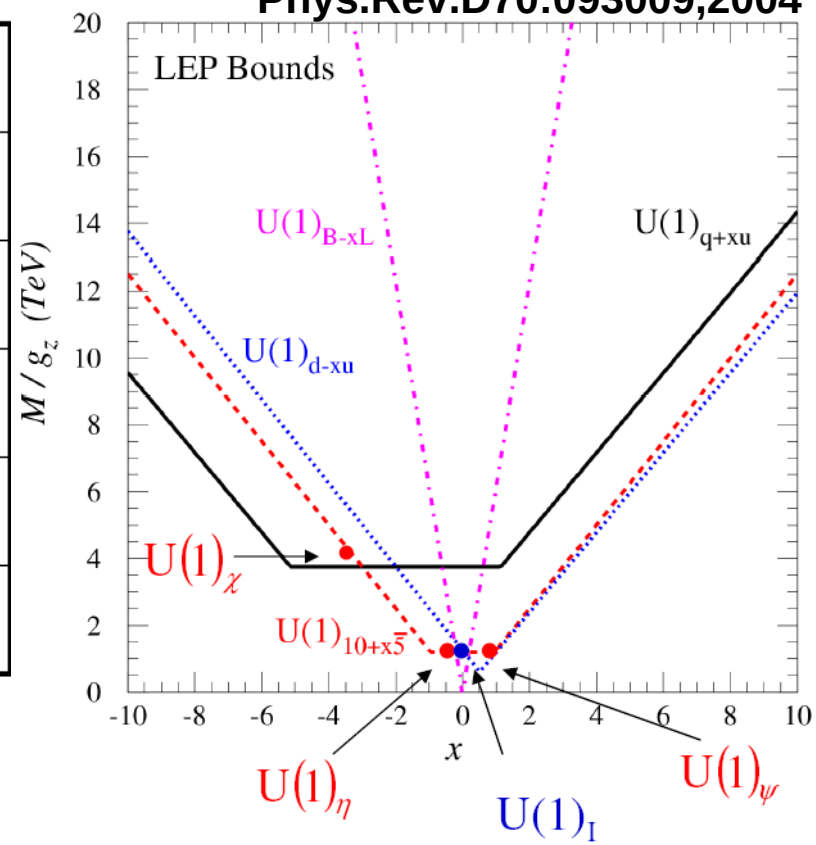
- Theory constraints 17 parameters to 3
  - **Flavor-changing Neutral Currents Constraints**
  - **No new particles that the Z′ can decay into**
  - **Anomaly cancellations**
- Four classes of solutions are found

4 models lines for Generic Z′

- Within a class, a Z′ model is specified by:
  - ➔ **Mass $M_{Z'}$, strength $g_{Z'}$, parameter x**

	B-xL	q+xu	10+$x\bar{5}$	d-xu
$q_L=(u_L,d_L)$	+1/3	+1/3	+1/3	0
u_R	+1/3	+x/3	-1/3	-x/3
d_R	+1/3	(2-x)/3	-x/3	+1/3
$l_L=(e_L,\nu_L)$	-x	-1	+x/3	(x-1)/3
e_R	-x	-(2+x)/3	-1/3	+x/3

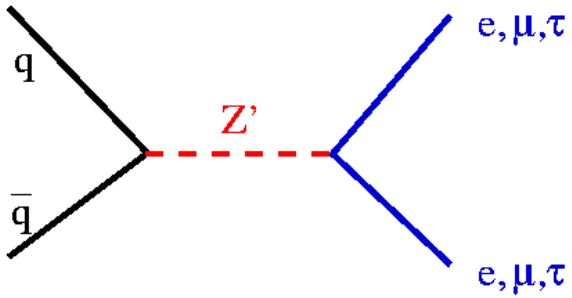
Phys.Rev.D70:093009,2004



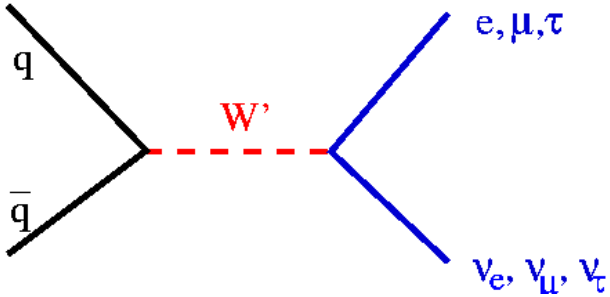
- E6 motivated models:
  - ➔ **D-xu models: Z_I (x=0)**
  - ➔ **10+x5 models: Z_η(x=-0.5), Z_ψ(x=1),Z_χ(x=-3)**

Signatures of New Gauge Bosons

- Heavy neutral gauge boson: Z′
  - ➔ **Cleanest signature at hadron collider: Dilepton final states**
    - ↓ **ee and μμ have very low backgrounds (mainly Drell-Yan)**
    - ➢ ττ also sensitive to SUSY models with high tanβ
    - ➢ Resolution for ττ not as good as other dileptons

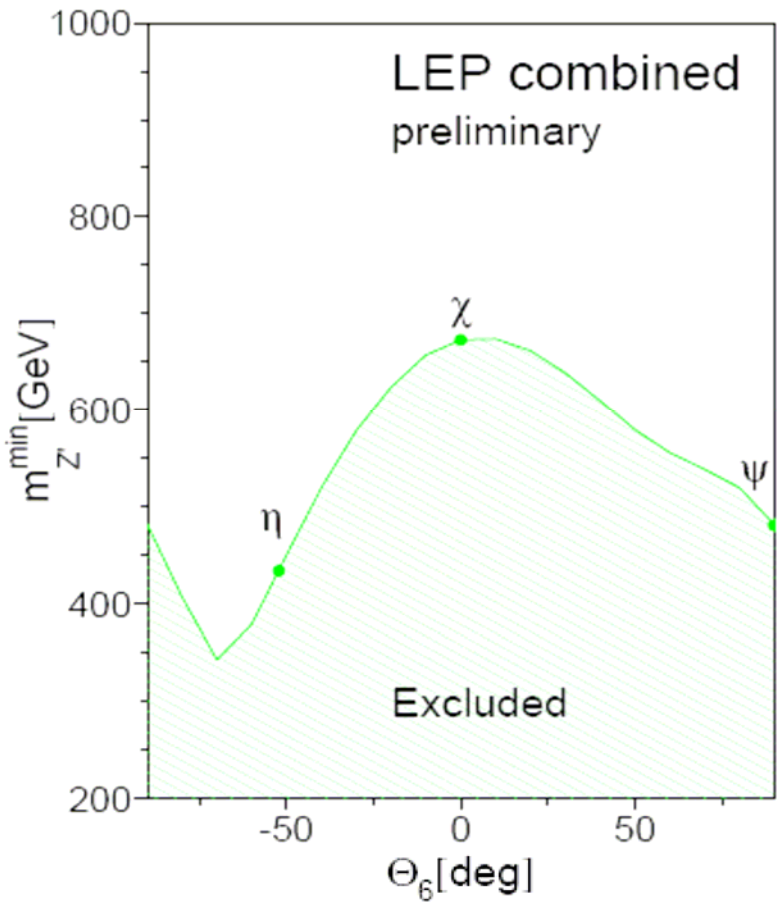


- Heavy charged gauge boson: W′
  - ➔ **Neutrino assumed to be light and long-lived**
    - ➢ Kinematics similar to SM W



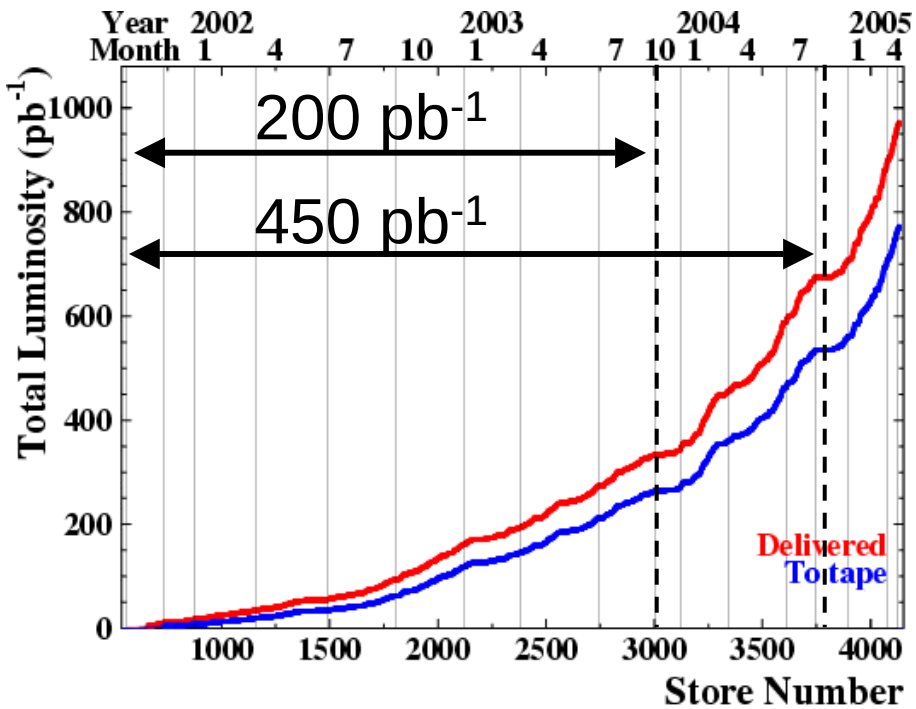
Previous Searches

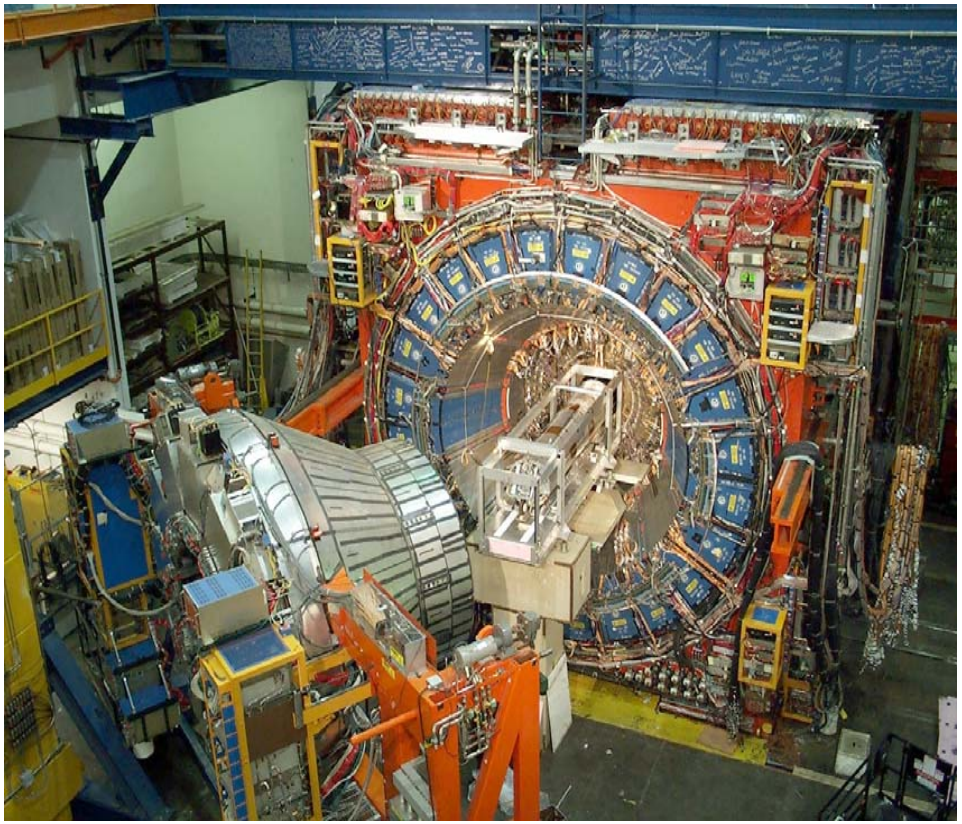
- LEPII
  - ➔ **Uses mass and cosθ**
    - ➢ Limited to low energies
  - ➔ **Contact interactions**
    - ➢ In all conceivable channels
  - ➔ **Only sensitive to physics that couples to electrons**
- Low-energy experiments
  - ➔ **Not very strong limits**
    - ➢ Atomic parity violation
    - ➢ Polarized electron-nucleon scattering
- Tevatron
  - ➔ **Non-electron final states new territory**
  - ➔ **Much higher energies accessible**
  - ➔ **Direct bump searches!**



CDF detector

- 800 pb^{-1} has been written to tape
- Analyses shown here use first 200-450pb^{-1}

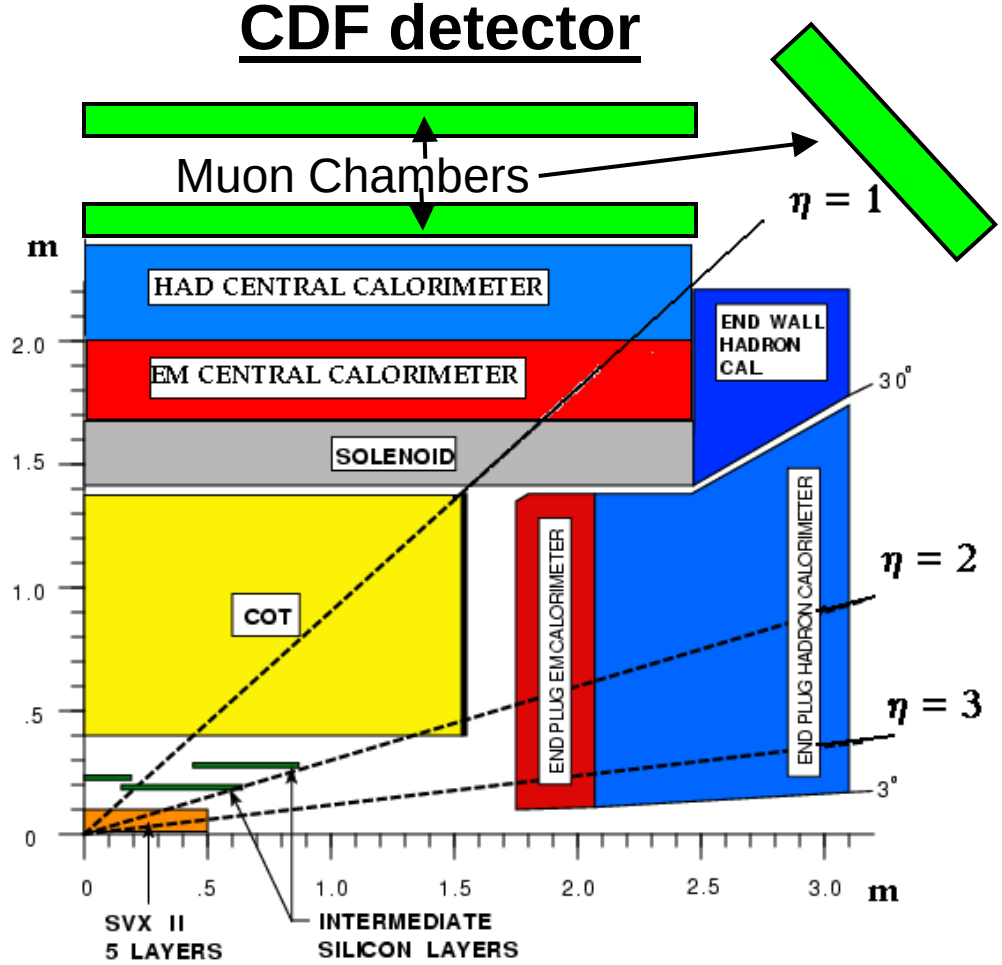




Muons and Electrons at CDF

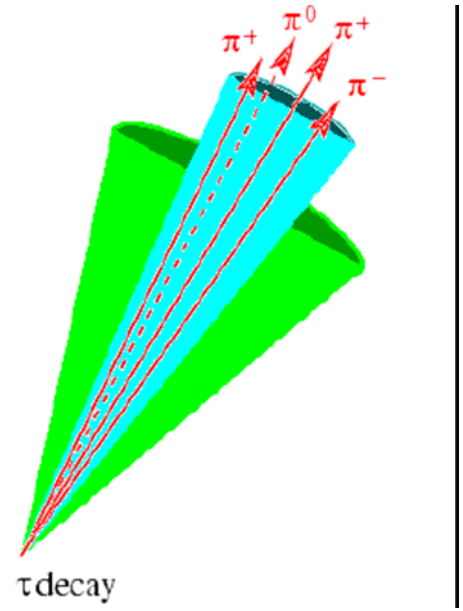
- Electrons
  - ➔ **Good energy resolution at high E**
- Central Electrons
  - ➔ **ID consists of track and EM cluster**
- Plug Electrons
  - ➔ **Consists of EM cluster**
  - ➔ **Forward-Forward combinations require at least one track E_T > 25 GeV**
- Muons
  - ➔ **Consistent tracks in central and muon drift chambers**
  - ➔ **Momentum (mass) resolution decreases with p**

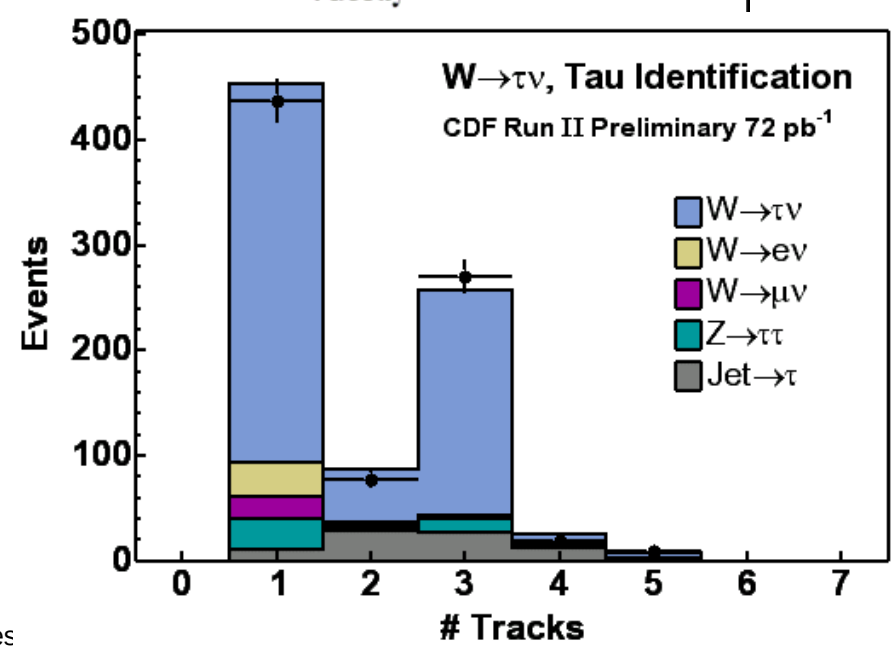
CDF detector



Tau's at CDF

- τ's identified in central region
  - ➔ **Always have missing energy**
- Need to separate from jets
  - ➔ **One track with pt>5 GeV/c**
  - ➔ **π^0 identification**
  - ➔ **Narrow calorimeter clusters**
- Triggers
  - ➔ **e/μ + track**
  - ➔ **τ_h + met**
    - ➢ $\not{E}_T$ >20 GeV
    - ➢ Jet E_T>20 GeV
    - ➢ 2-d track isolation



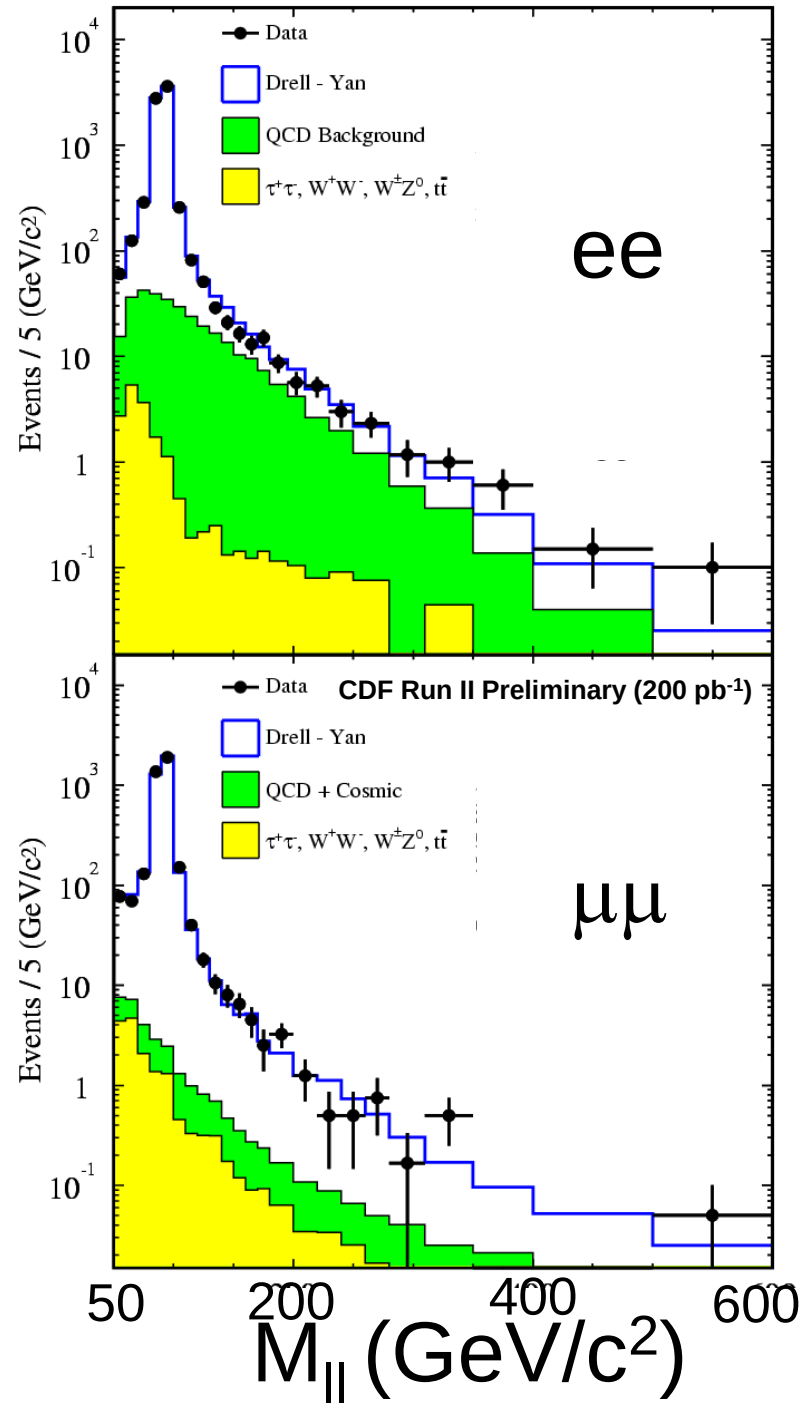


Outline of Results

- Searches for Z′
  - ➔ **Results from ’04 (~200 pb^{-1})**
    - ➢ ee & μμ final states
    - ➢ ττ final state
  - ➔ **Recent Results (450 pb^{-1})**
    - ➢ ee final state
      - ↓ **New Method**
- Searches for W′
  - ➔ **eν final state**

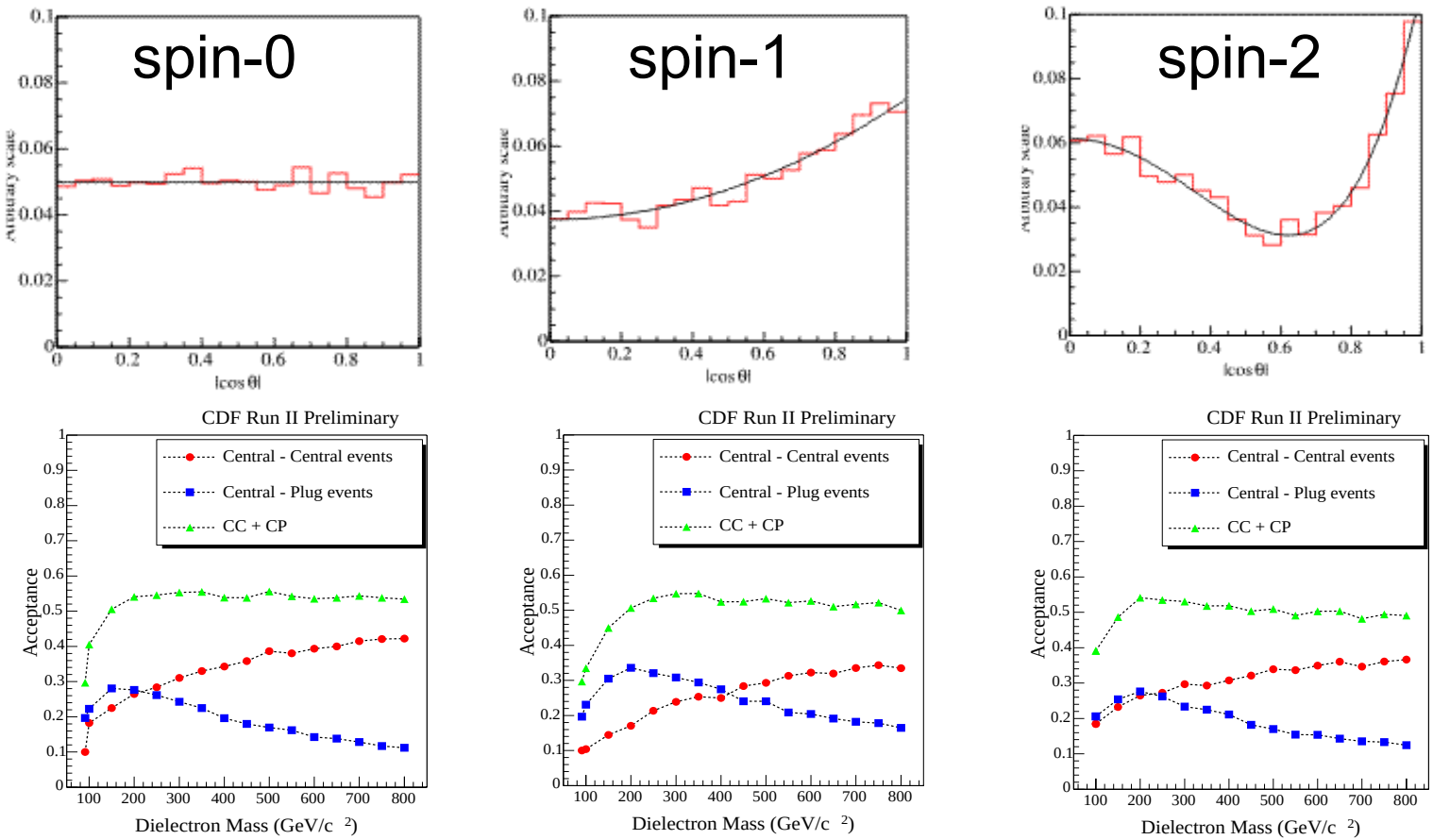
Z′ →ll: Selection

- Strategy
  - ➔ **Perform general searches**
  - ➔ **Find acceptance for general spin-0,1,2 particles**
  - ➔ **Get limits of cross section**
- Dilepton final states
  - ➔ **Dielectron use Central and forward electrons**
    - ➢ Forward-Forward events add 10% acceptance
  - ➔ **Dimuons use central muons**
- Backgrounds
  - ➔ **Dijet dominates for electrons**
  - ➔ **Cosmic and QCD dominate for muons**



Z′ →ll (~200 pb^{-1}): Acceptance

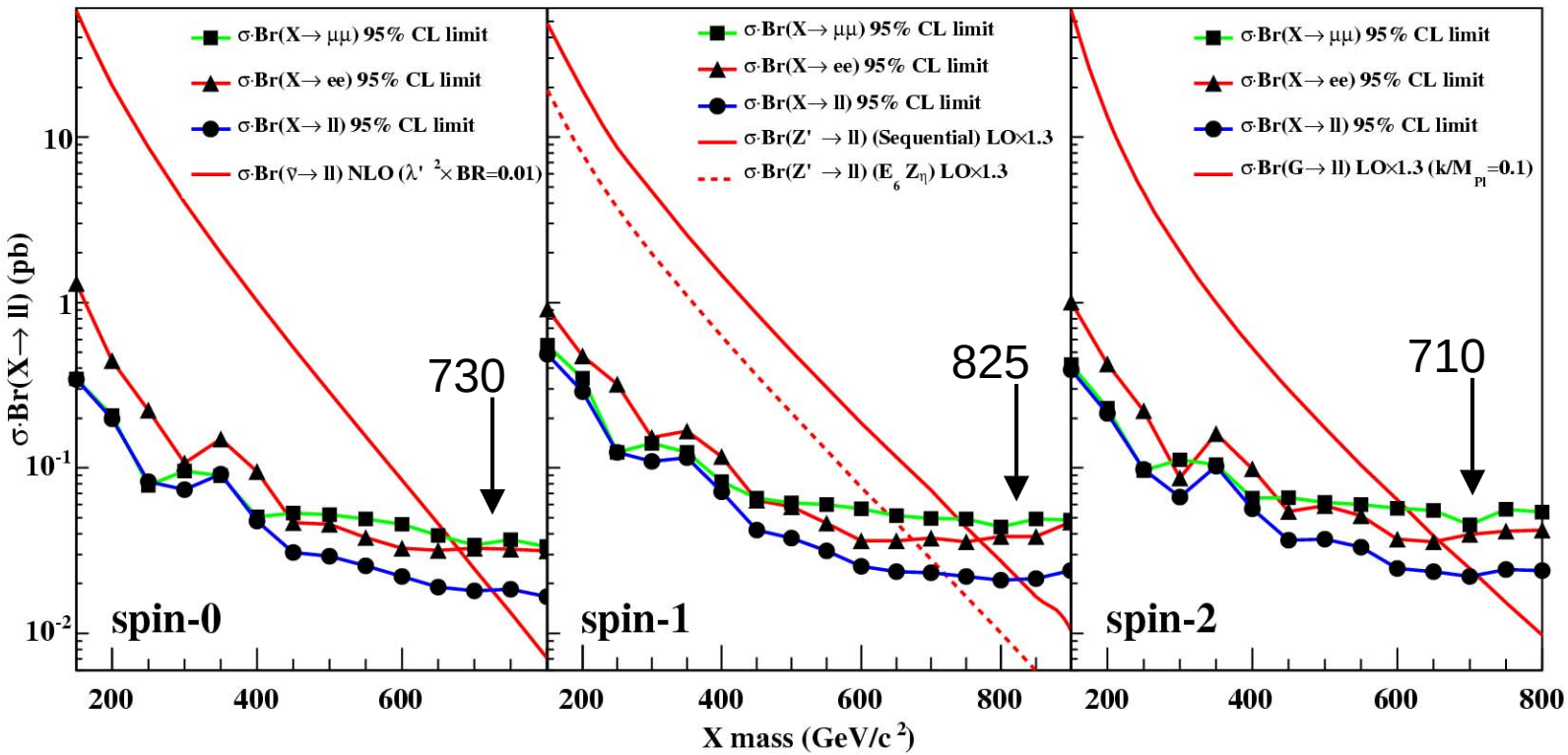
Angular distribution and therefore acceptance of decay product depends on the spin of the decaying particle.



central-central electrons
central-forward electrons
above combined

central: $|\eta| < 1.1$
forward: $1.1 < |\eta| < 3.6$

Z′ →ll (~200 pb^{-1}): Limits



σ*Br(X → μμ) 95% CL limit

σ*Br(X → ee) 95% CL limit

ee, μμ combined limit

σ*Br limit ~ 17-25 fb independent of spin for M>600 GeV

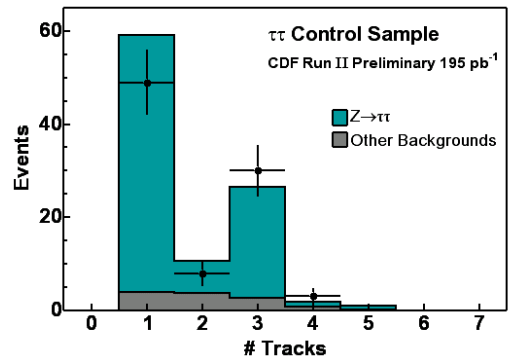
These limit curves can be compared with many models

Individual channel limits are still important: lepton universality?

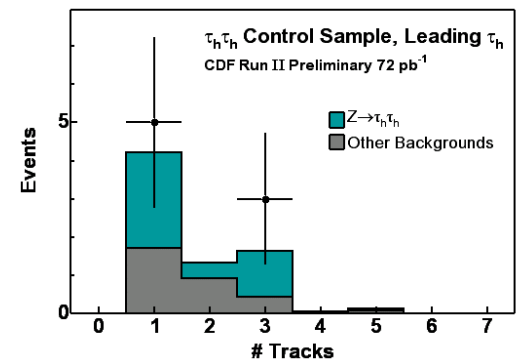
$Z' \rightarrow \tau\tau$ (195 pb^{-1}): Selection

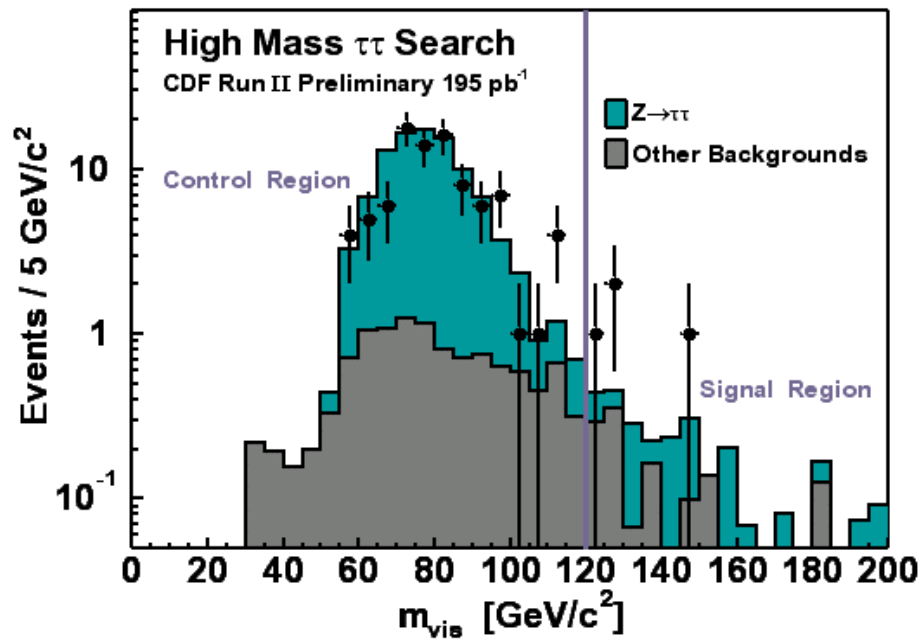
- Selection
  - 2 central τ pairs
  - At least one hadronic and leptonic decays
    - 3 final states
    - First $\tau_h \tau_h$ SM Z signal
      - consistent with predictions
  - E_T cut
    - $\tau_l \tau_x$: $\not{E}_T$ > 15 GeV
    - $\tau_h \tau_h$: $\not{E}_T$ > 25 GeV
  - M_{vis}>120 GeV/c^2
    - Control: M_{vis}<120 GeV/c^2
- Backgrounds
  - $Z/\gamma^* \rightarrow \tau\tau$
  - Jets faking τ
    - W+jet, multi-jet events

All τ's



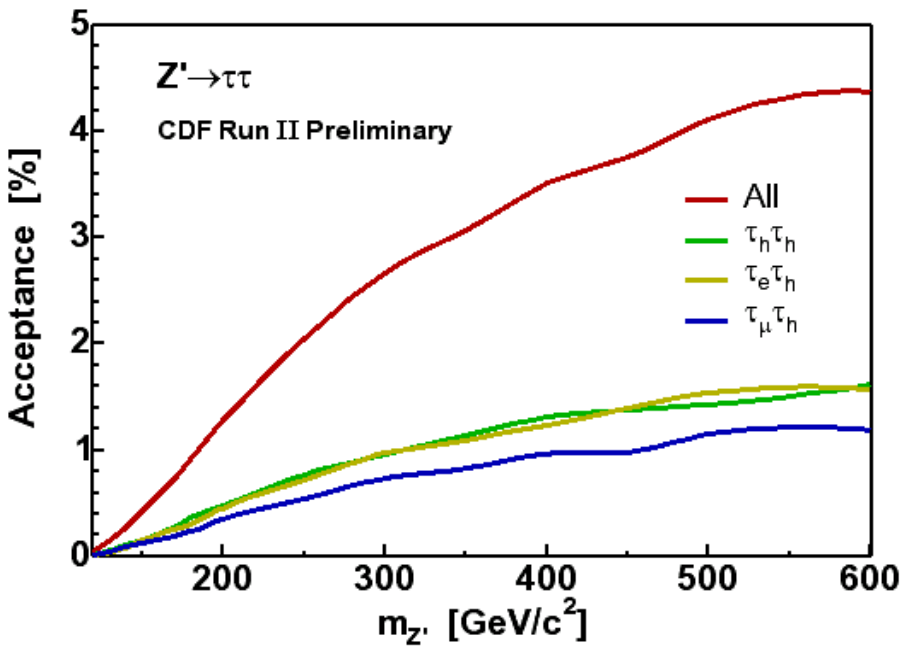
$\tau_h \tau_h$



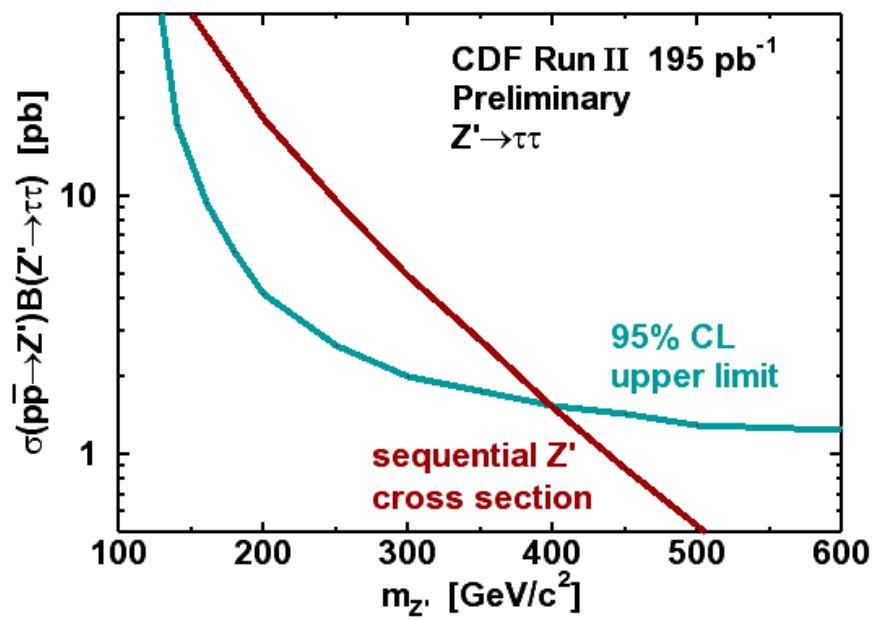


Z′ →ττ (195 pb^{-1}): limits

- Three channels have equivalent acceptance
- Set limits on Z′ : $M_{Z'}$ >394

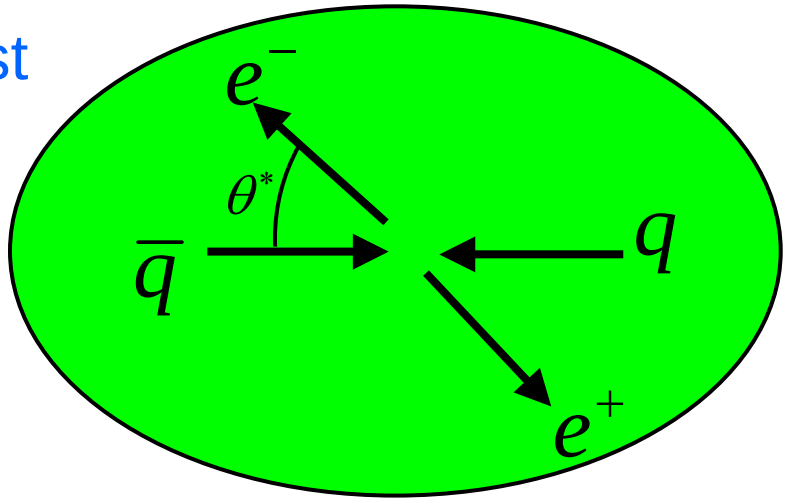


Limit



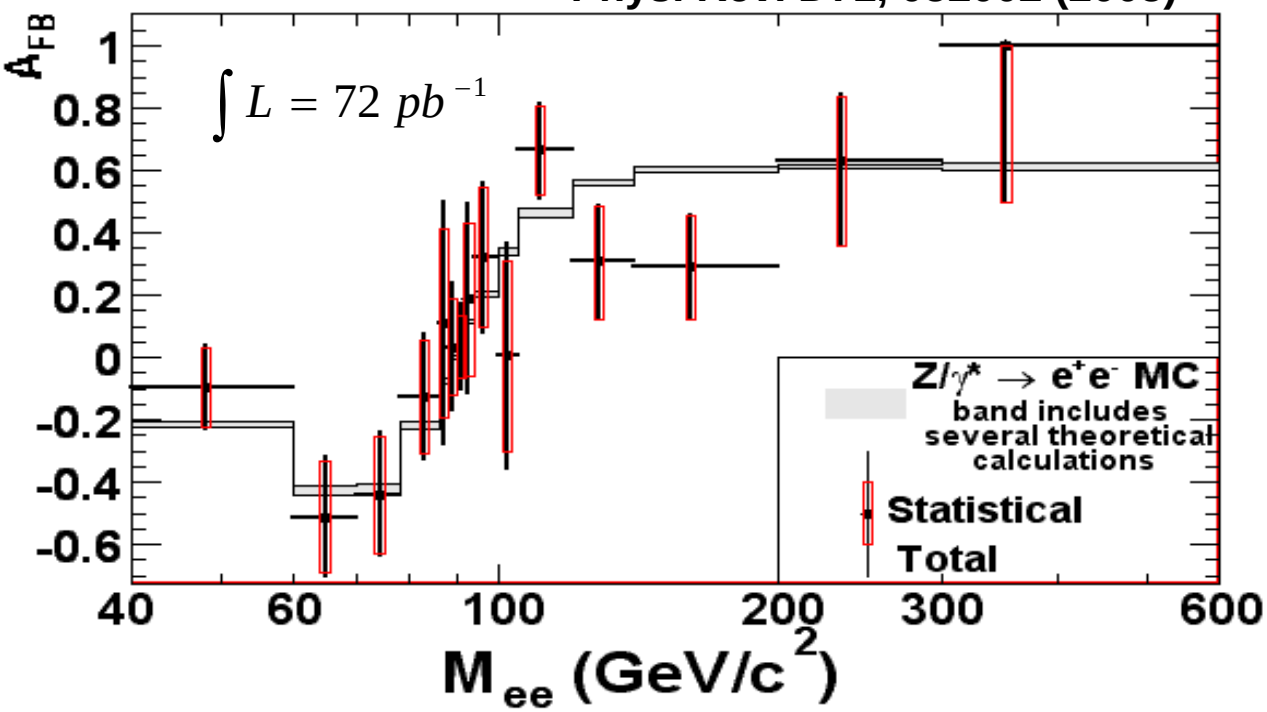
Z′→ee (448 pb^{-1}): Z′ at Hadron Colliders

- Previous analyses have used just M_{ee} distribution to set limits, and A_{FB} has been measured

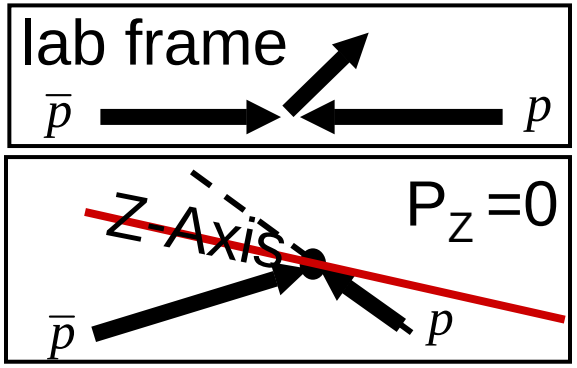


$$A_{FB} = \frac{d\sigma(\cos\theta^* > 0) - d\sigma(\cos\theta^* < 0)}{d\sigma(\cos\theta^* > 0) + d\sigma(\cos\theta^* < 0)}$$

Phys. Rev. D71, 052002 (2005)



- $\cos\theta^*$ in Collins-Soper frame
  - ➔ Minimize incoming quark Pt ambiguity

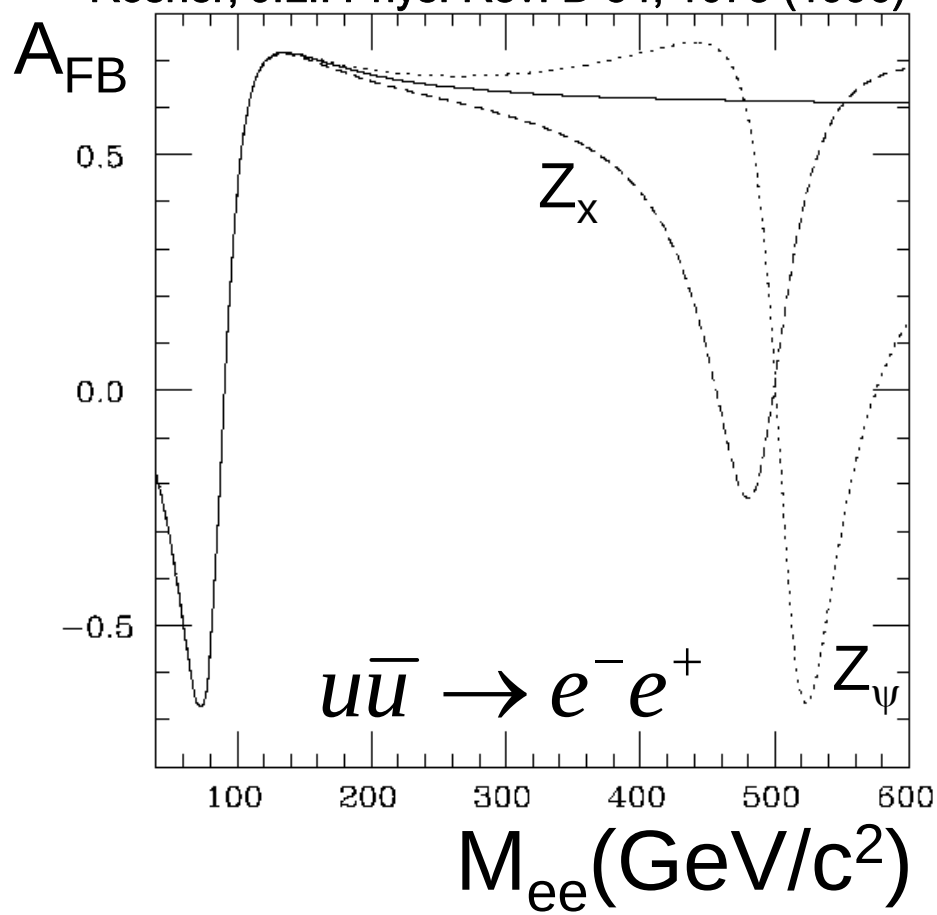


Z′ →ee (448 pb^{-1}): A_{FB} and Z′

- Looking for symmetries beyond the SM
  - ➔ Various models predict new neutral, heavy bosons: Z′ s
- New resonance could interfere with γ and Z.
- Information about the angular distribution will strengthen the search
- Can be used to distinguish between different models
- Can see evidence below Z′ pole

500 GeV/c^2 Z′:

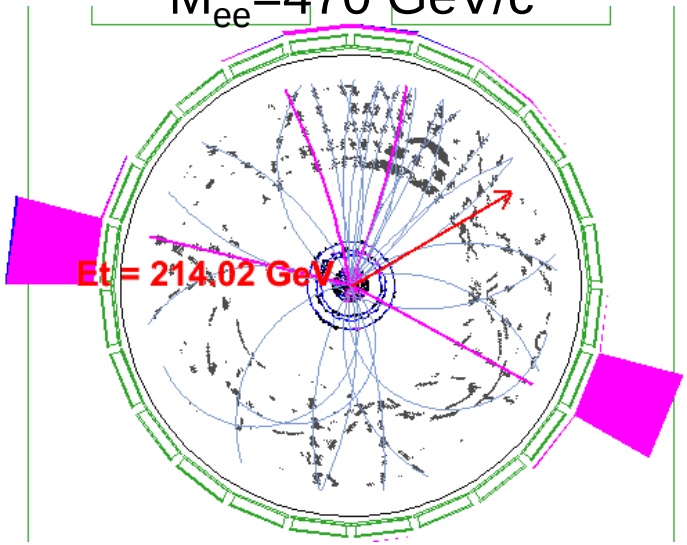
Rosner, J.L.: Phys. Rev. D 54, 1078 (1996)



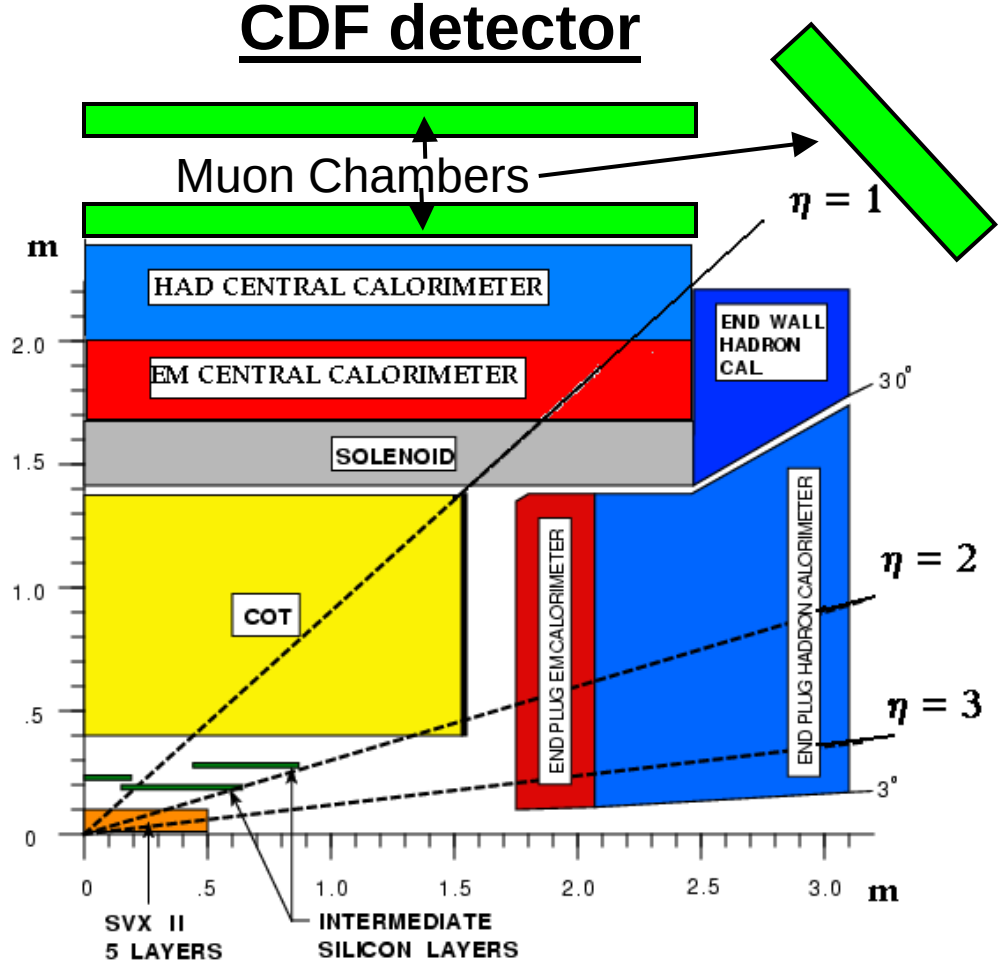
Z/γ^* Candidates and CDF

- Selection
  - ➔ 2 high P_T isolated electrons
  - ➔ Central-Central, or Central-Plug pairs
  - ➔ Require opposite sign for Central-Central
- Sample: 448 pb^{-1}

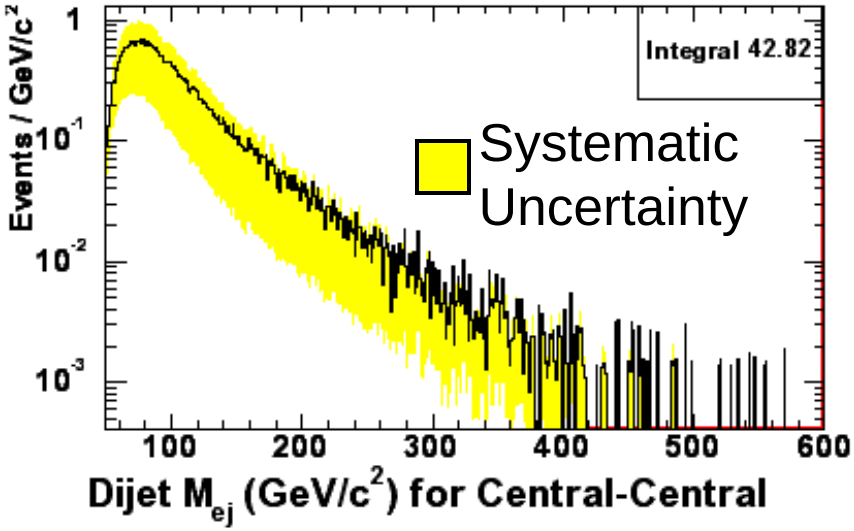
M_{ee}=470 GeV/c^2

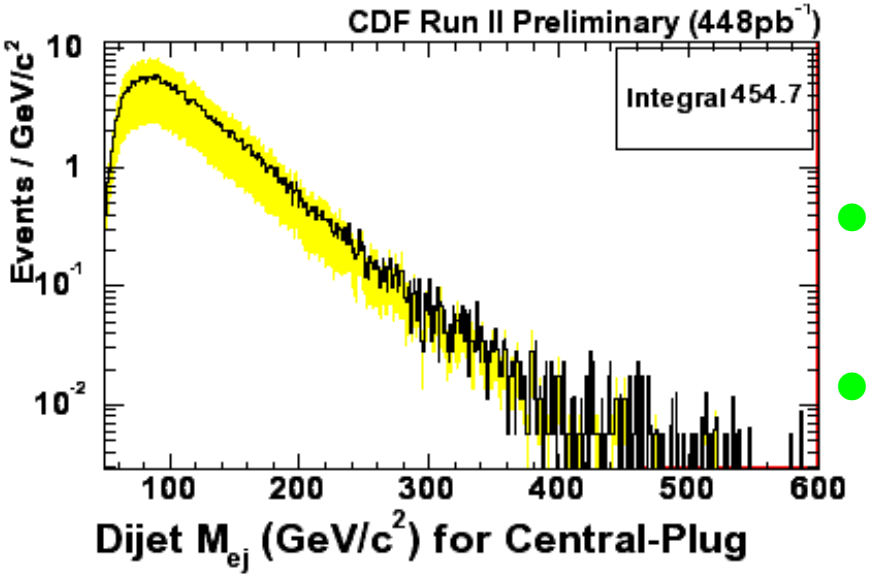


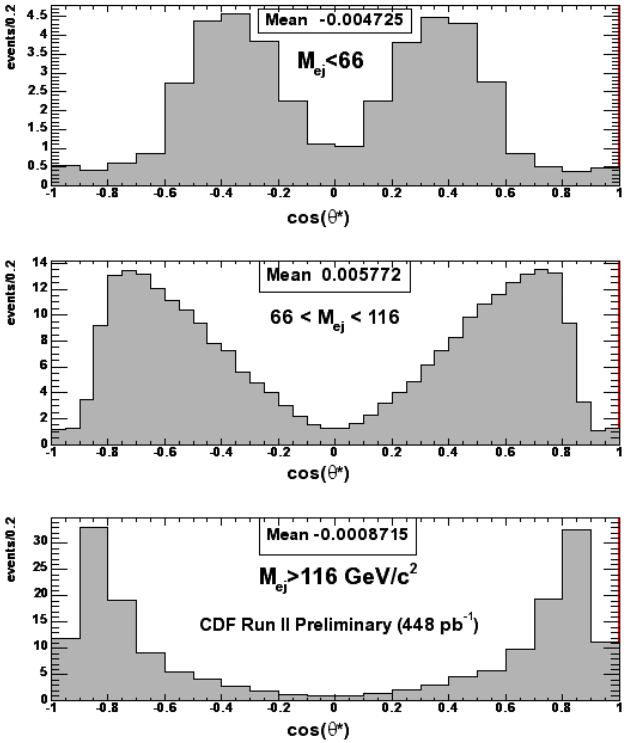
CDF detector



Z′ →ee (448 pb^{-1}): Dijet Backgrounds







- Dijet background estimated using the rate for jet to fake a lepton
- Systematic uncertainty dominated by comparisons of fake rates in different kinematic samples

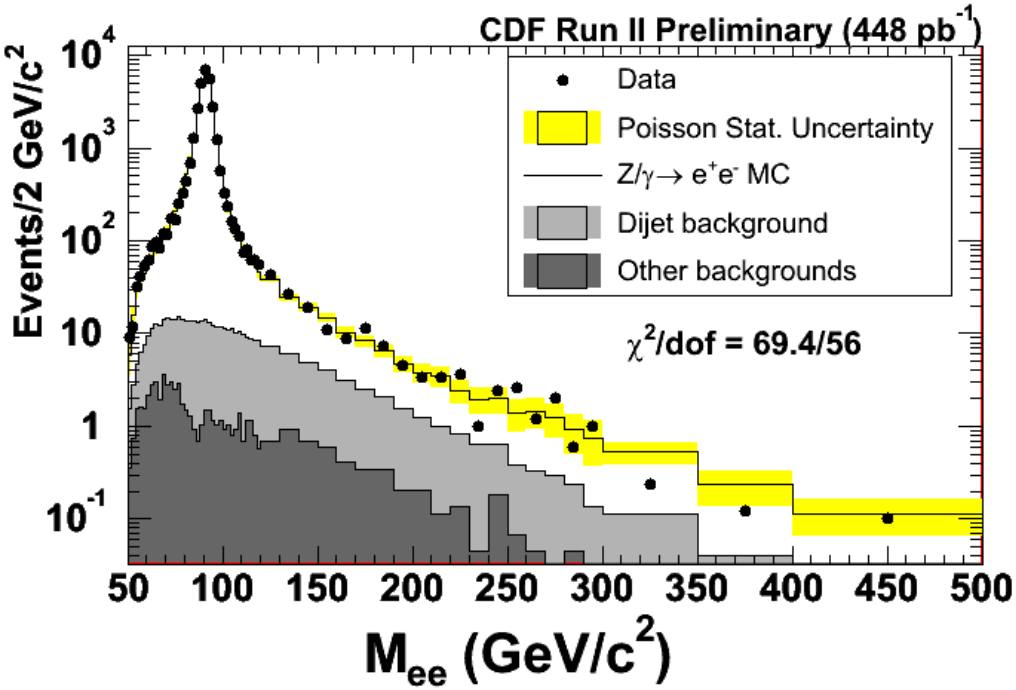
$Z' \rightarrow ee$ (448 pb^{-1}): Backgrounds

- Backgrounds are fit to exponential to estimate cross section at high masses M>200
- Angular distribution taken from Monte Carlo samples
- Compare to Z/γ^*, expect 89.6 events

CDF Run II Preliminary (448 pb^{-1})

Back-ground	Source	# of events		M_{ee}>200 GeV
		C-C	C-P	
Dijet	Data	42.5	453	28.5
$W \rightarrow e\nu+\gamma$	MC	1.9	48.3	4.9
$Z \rightarrow \tau\tau$	MC	11.6	17.6	0.13
WW	MC	7.7	9.3	1.2
Top	MC	5.1	3.3	0.65
WZ	MC	6.3	7.9	0.19
Total		75	540	35.6

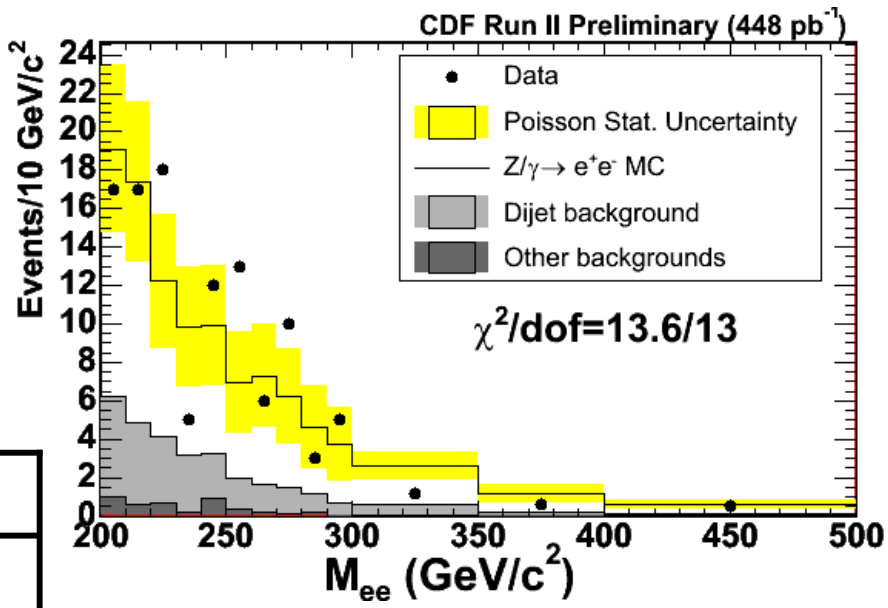
Z′ →ee (448 pb^{-1}): Mass Distribution



- **Statistical uncertainty shown for the prediction rather than on the data**
  - ➔ More statistically correct
  - ➔ Systematic uncertainties not shown

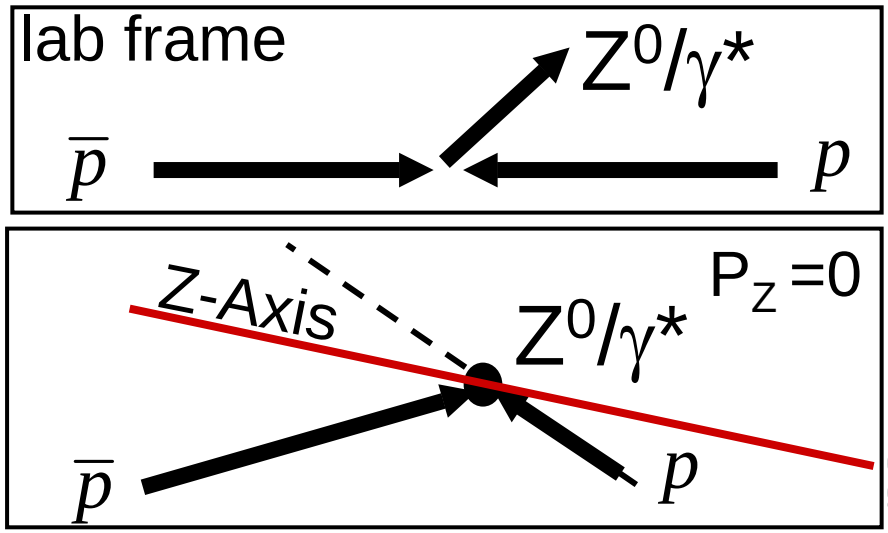
- **Very good agreement between data and prediction for full mass region and high mass signal region.**
  - ➔ Number of events in Signal Region

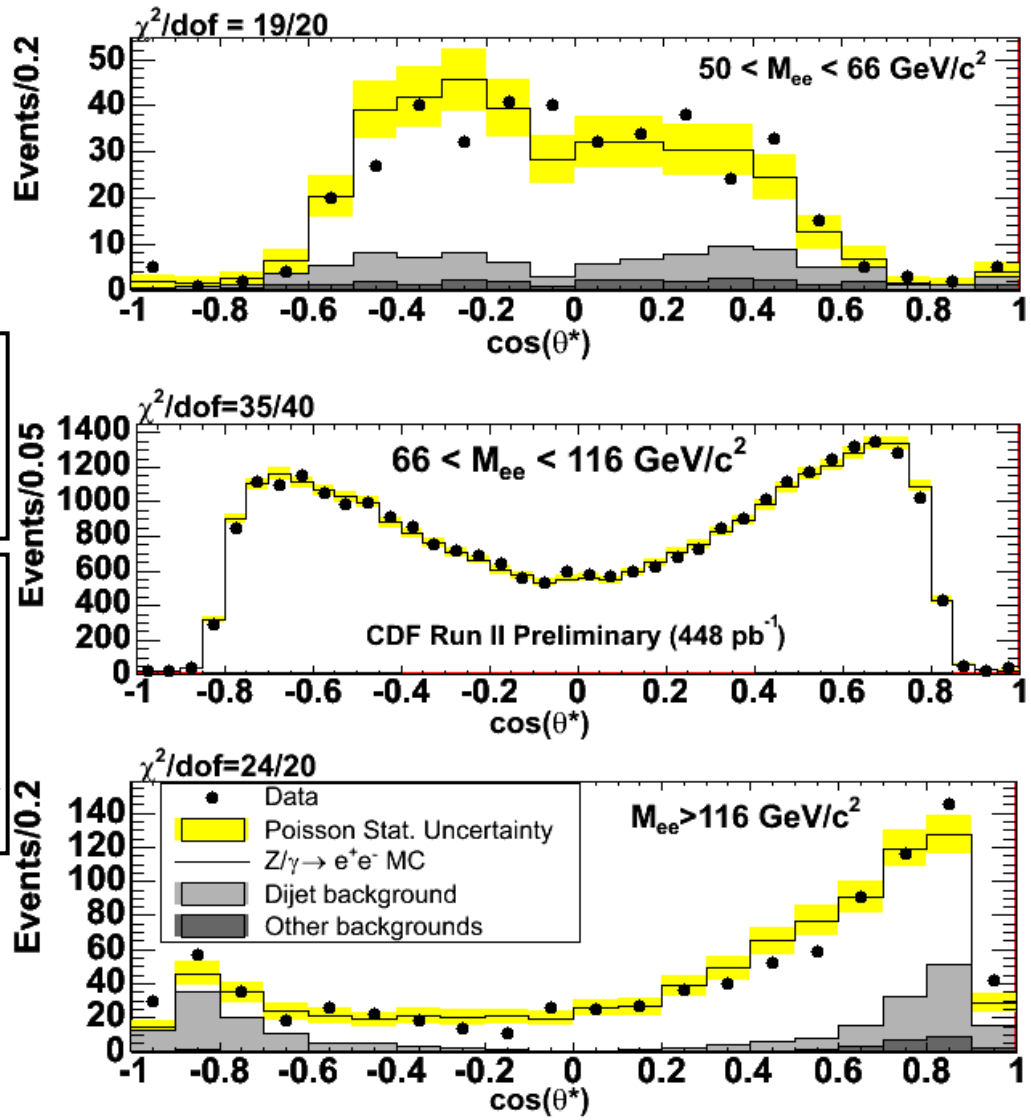
	Data	Predicted
M_{ee}>200 GeV/c^2	120	$125 \pm 11_{stat}$



Z′ →ee (448 pb^{-1}): cosθ* Distribution

- cosθ* in Collins-Soper frame
  - ➔ Minimize ambiguity in the incoming quark Pt



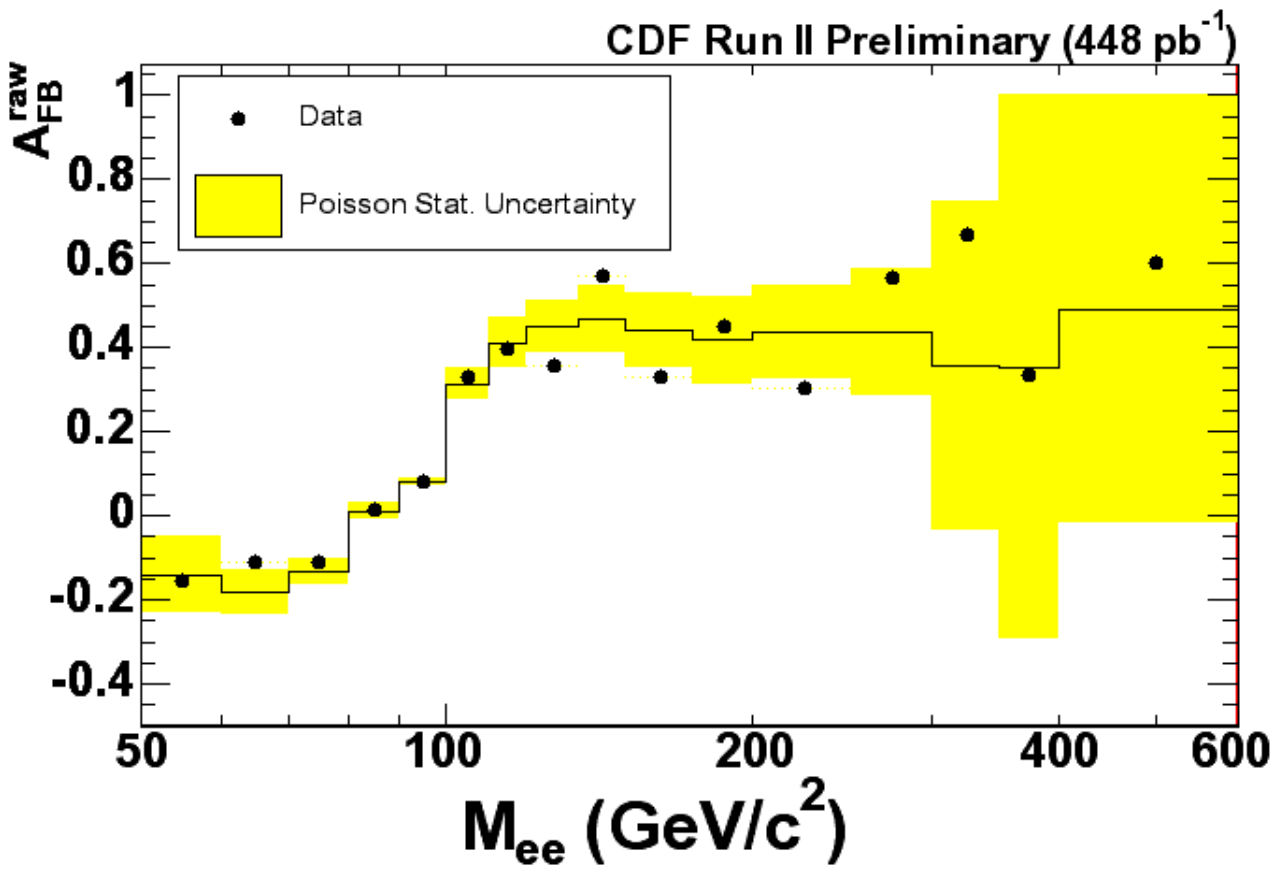


Z′ →ee (448 pb^{-1}): A_{FB} Measurement

- Calculating uncorrected A_{FB}:

$$A_{FB}^{raw} = \frac{(N^{+} - N^{+}_{Bkgrnd}) - (N^{-} - N^{-}_{Bkgrnd})}{(N^{+} - N^{+}_{Bkgrnd}) + (N^{-} - N^{-}_{Bkgrnd})}$$

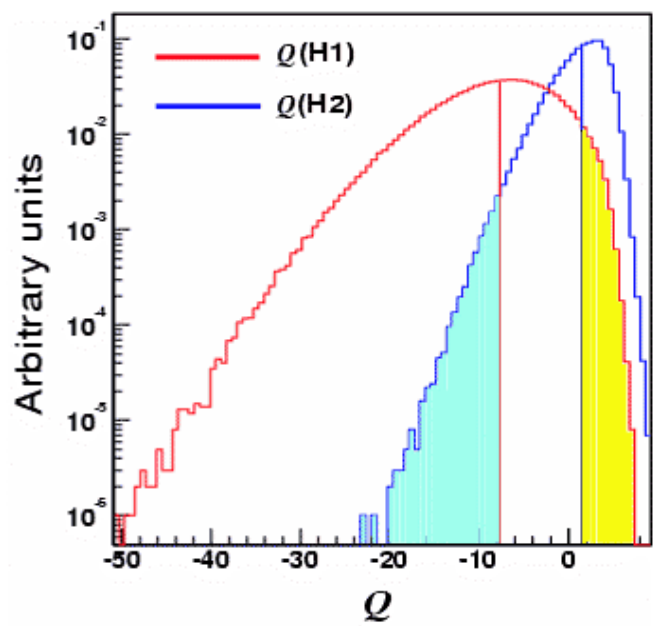
$N^{\pm}$: Forward/Backward Candidates



Z′ →ee (448pb^{-1}):CL$_s$

- Use CL$_s$ method for setting limits
  - ➔ **Used for LEPII Higgs mass limits**
- Test between two hypotheses:
  - ➔ **H1: Data is described by Z′/Z/γ and backgrounds**
  - ➔ **H2: Data is described by SM Z/γ and backgrounds**
- Use Poisson probabilities and get a test statistic
  - ➔ $Q = -2\ln[P(data|H1)/P(data|H2)]$
- Pseudo experiments of SM and new physics
  - ➔ **Separation determines limit or discovery**

B-xL model.
$M_{Z'}$=440 GeV
g_z=0.03
x=10



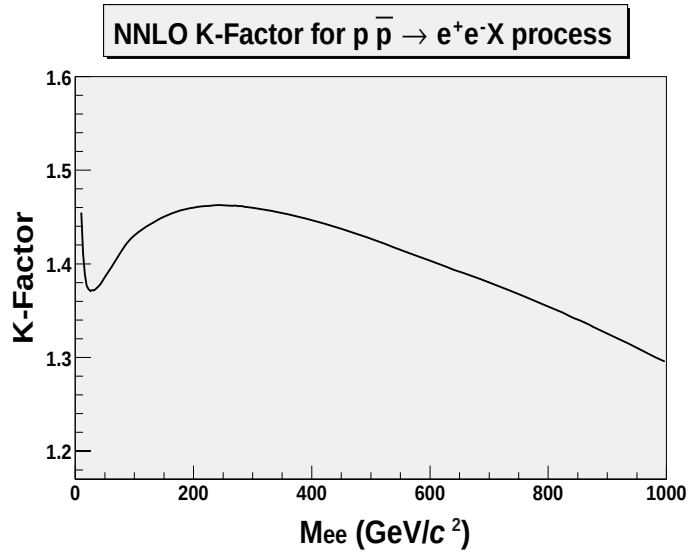
Z′ →ee (448pb^{-1}): Systematic Uncertainties

- Uncertainties on Shape
- Energy Scale
  - → **3% on energy**
- Energy Resolution
  - → **3% gaussian added**

- Uncertainties on Yield
- Rate uncertainties
  - → **~20%**
    - Luminosity
    - ID efficiency
    - Acceptance
    - Physics cross section
- PDF uncertainty
  - → **MRST uncertainty PDFs**
- Background
  - → **QCD: ~50-60%**
  - → **Montecarlo: ~20%**

$Z' \rightarrow ee$ (448 pb^{-1}): Testing many models

- Consider 40,000 models in 4 model lines
  - ➔ **3 parameters: $M_{Z'}$, g_z, and x.**
- Use a LO calculation with NNLO k(M) factor
- Parameterize γ^* Monte Carlo in bins of M_Z and $\cos\theta$ to get detector acceptance and resolutions
  - ➔ **Use 10 GeV Mass bins and 8 $\cos\theta$ bins**



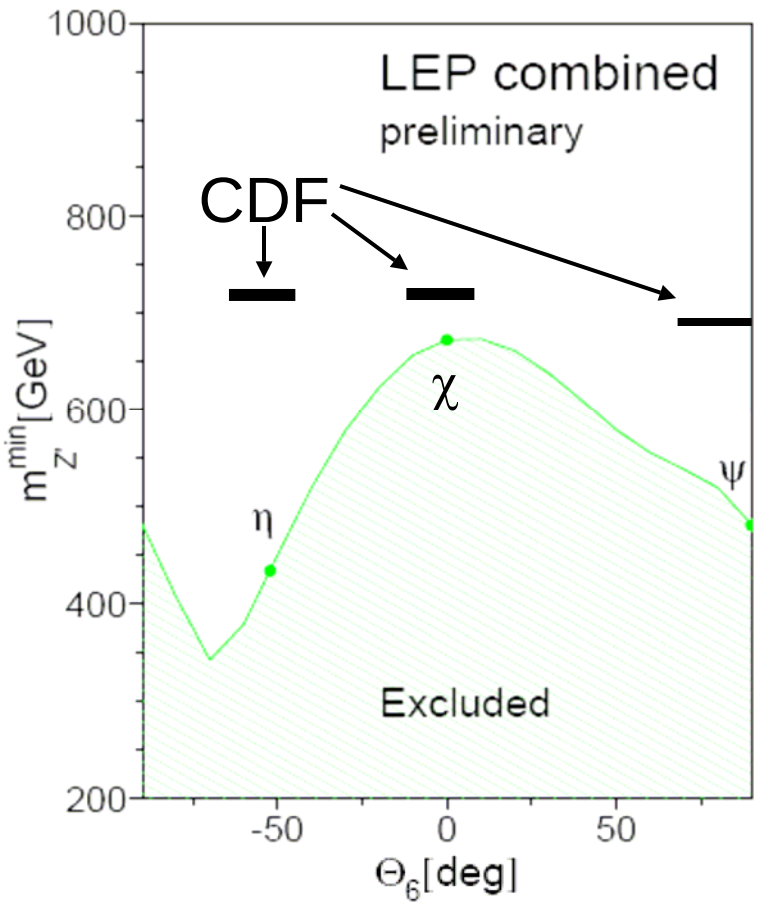
$Z' \rightarrow ee$ ($448 pb^{-1}$): Z'_{SM} limits

- New limit on Z'_{SM} (expected: 850 GeV)
  - ➔ **Adding cosθ is equivalent to adding 25% more data!**

	CDF e^+e^- **448 pb^{-1}**	**CDF** **ee + μμ** **~200 pb^{-1}**	D0 ee 200 pb^{-1}	CDF ee 200 pb^{-1}	LEPII
Limits on Z'_{SM}	**845 GeV**	825 GeV	780 GeV	750 GeV	1.8 TeV

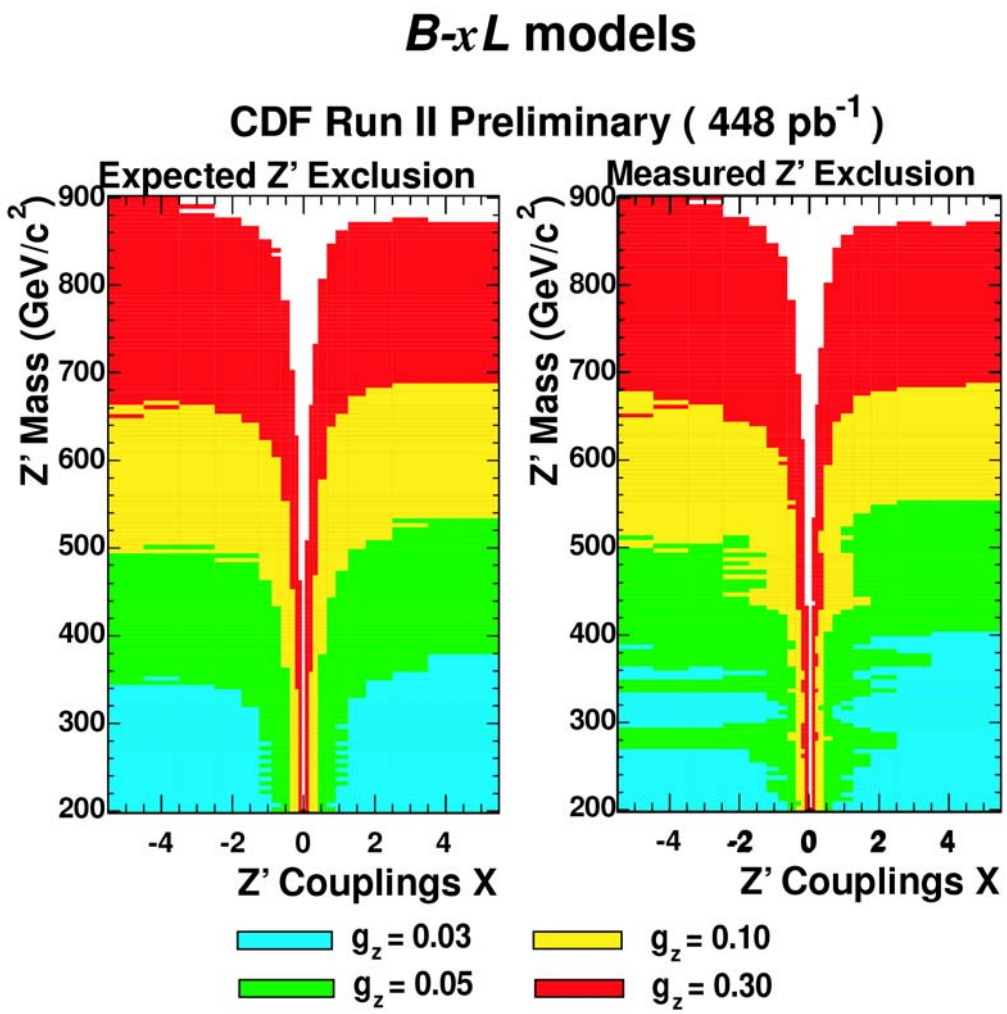
Z′ →ee (448pb^{-1}): E6 Z′ limits

	CDF e^+e^- 448 pb^{-1}	CDF ee + μμ ~200 pb^{-1}	D0 ee 200 pb^{-1}	CDF ee 200 pb^{-1}	LEP
Z_I	625 GeV	615 GeV	575 GeV	570 GeV	
Z_χ	720 GeV	690 GeV	640 GeV	610 GeV	673 GeV
Z_ψ	690 GeV	675 GeV	650 GeV	625 GeV	481 GeV
Z_n	715 GeV	720 GeV	680 GeV	650 GeV	434 GeV



Z′ →ee (448pb^{-1}): *B-xL*

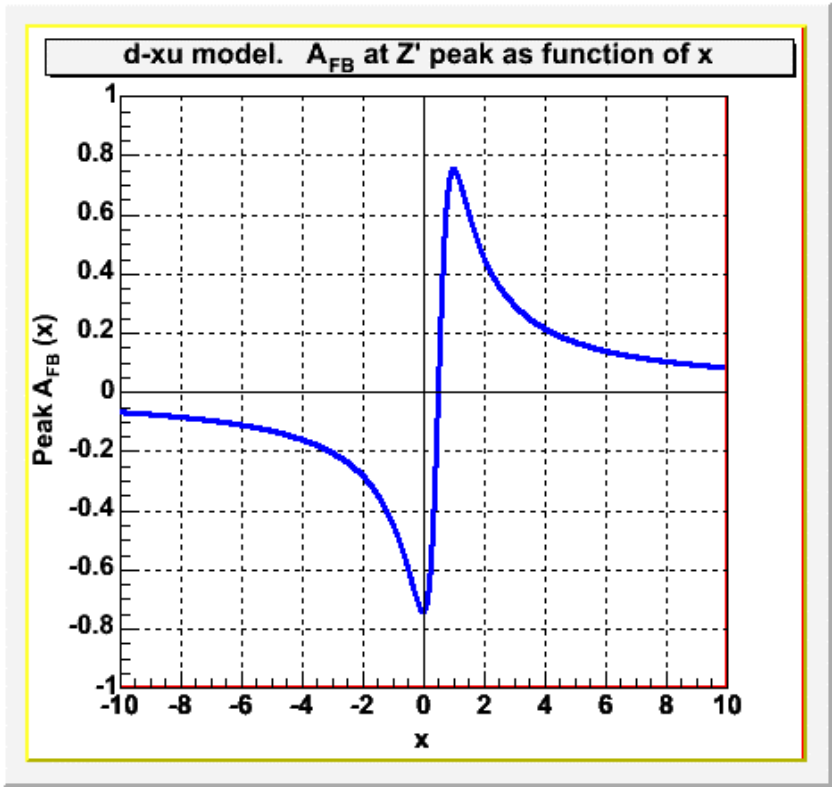
- Finding a limit for a Z′ model
  - ➔ **Expected is drawn from pseudo-experiments**
- Values for g_z, x chosen with guidance from theorists
- A_{FB} ($M_{Z'}$) = 0 for all x
- Color-filled regions show models that are excluded

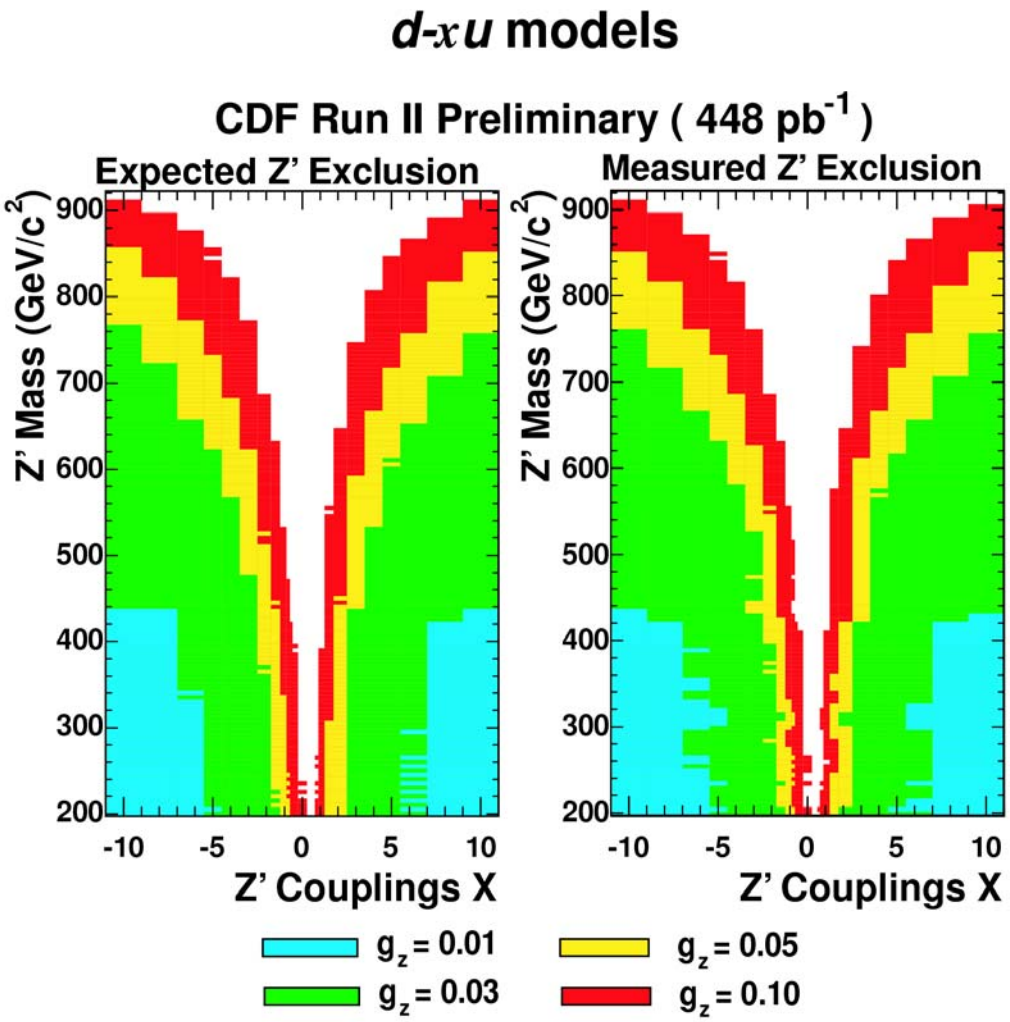


Carena, Daleo, Dobrescu, Tait, PRD 70, 093009 (2004)

Z′ →ee (448pb^{-1}): *d-xu*

- E6 Models:
  - → Z_I x=0, g_z = 0.667
- $A_{FB}(M_{Z'})$:

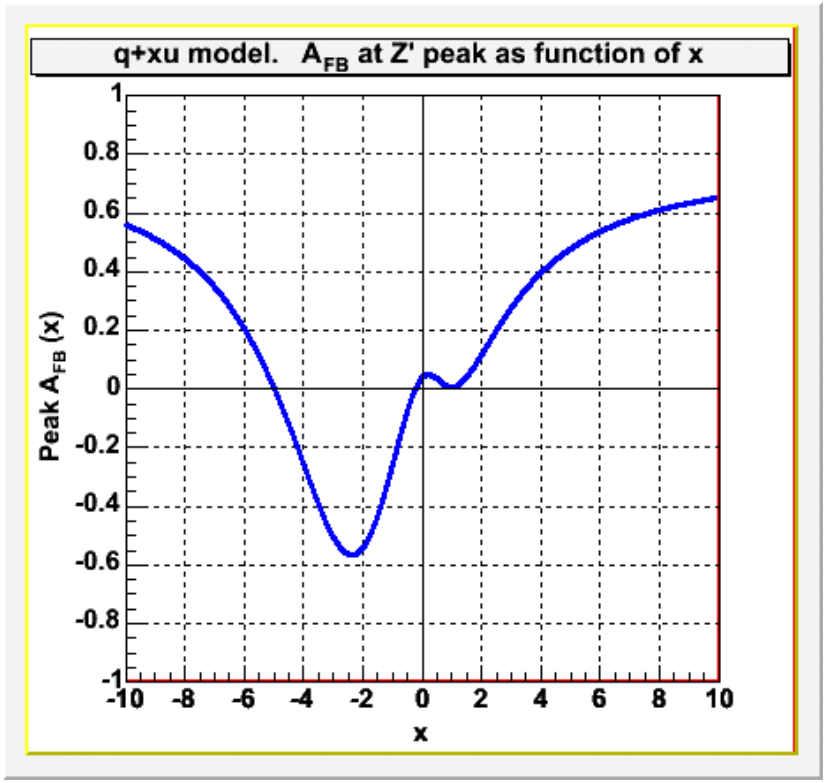


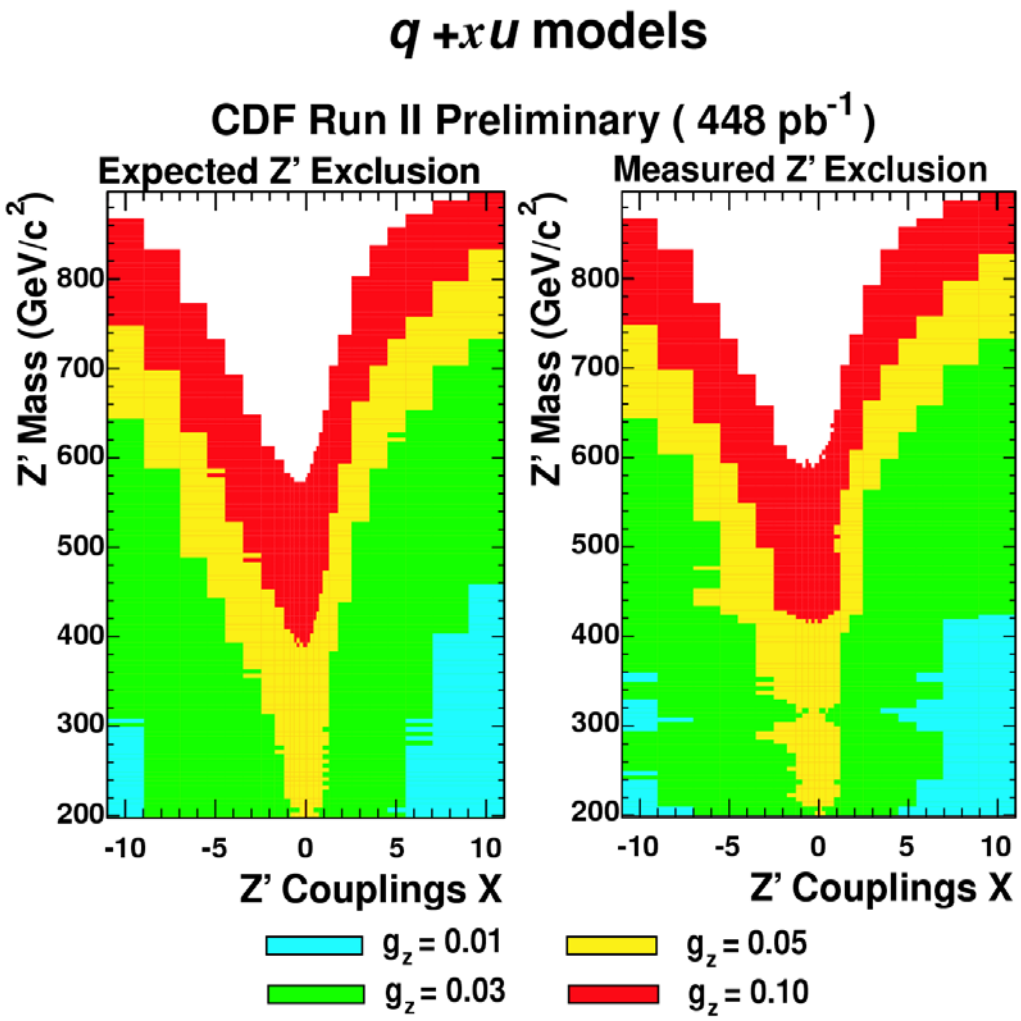


Carena, Daleo, Dobrescu, Tait, PRD 70, 093009 (2004)

Z′ →ee (448pb^{-1}): Q+*xu*

- $A_{FB}(M_{Z'})$:

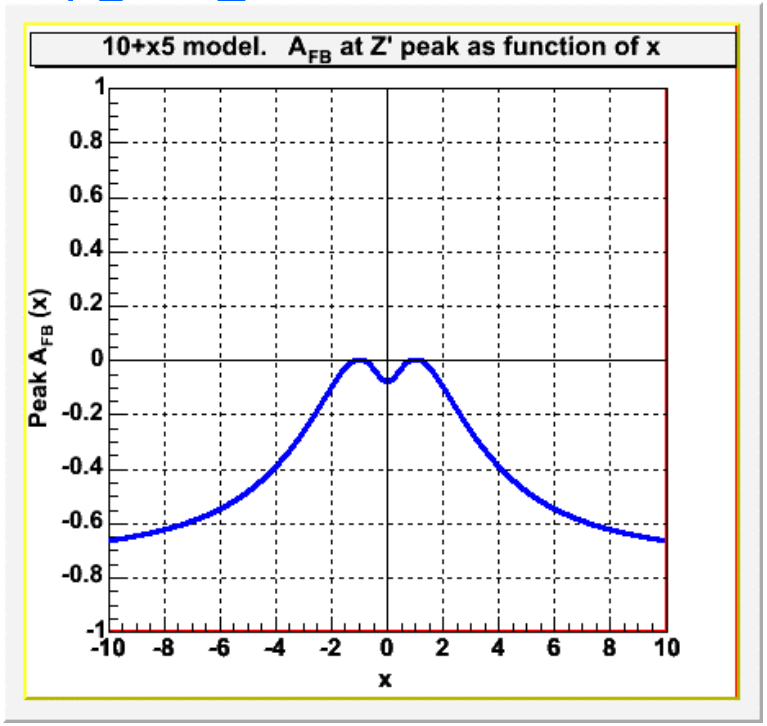


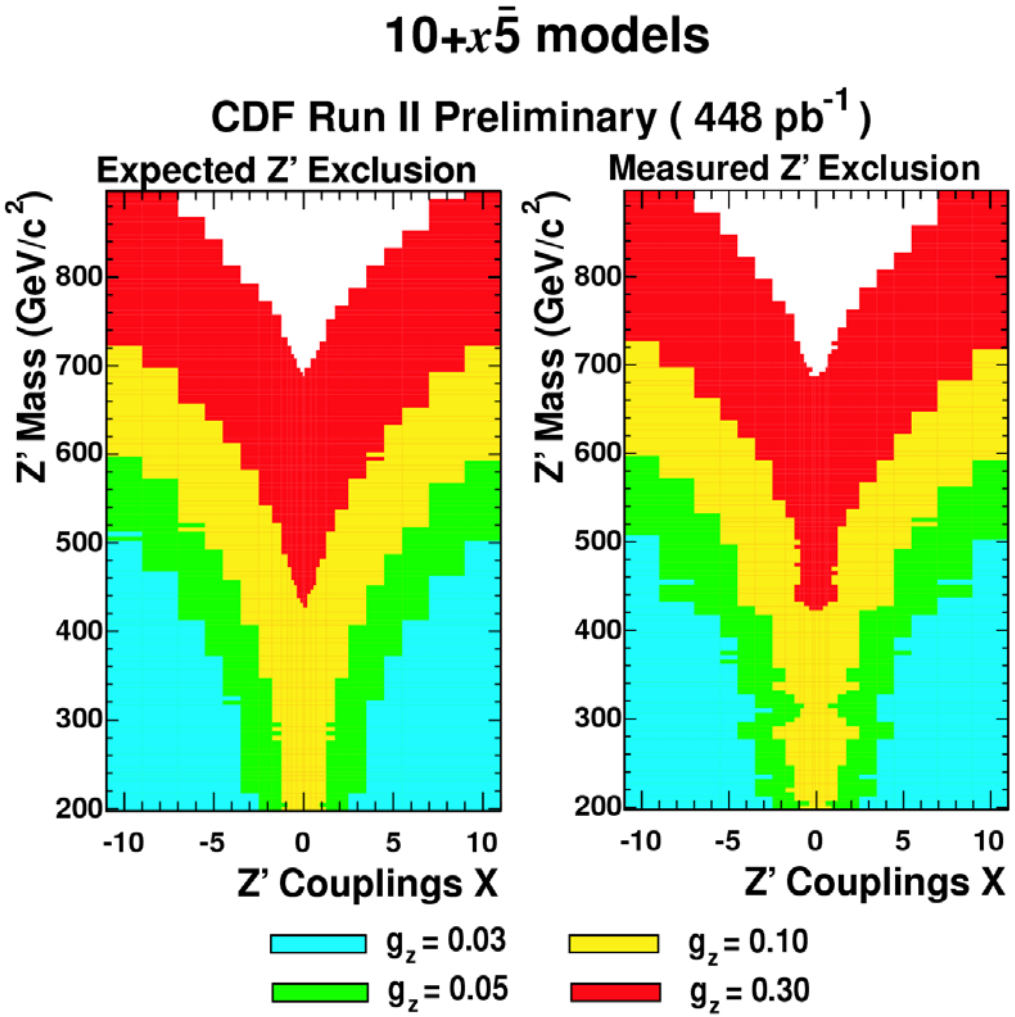


Carena, Daleo, Dobrescu, Tait, PRD 70, 093009 (2004)

Z′ →ee (448pb^{-1}): *10+x5*

- E6 Models:
  - → Z_η: x=-0.5, g_z = 0.344
  - → Z_ψ: x= 1, g_z = 0.272
  - → Z_χ: x=-3, g_z = 0.211
- $A_{FB}(M_{Z'})$:

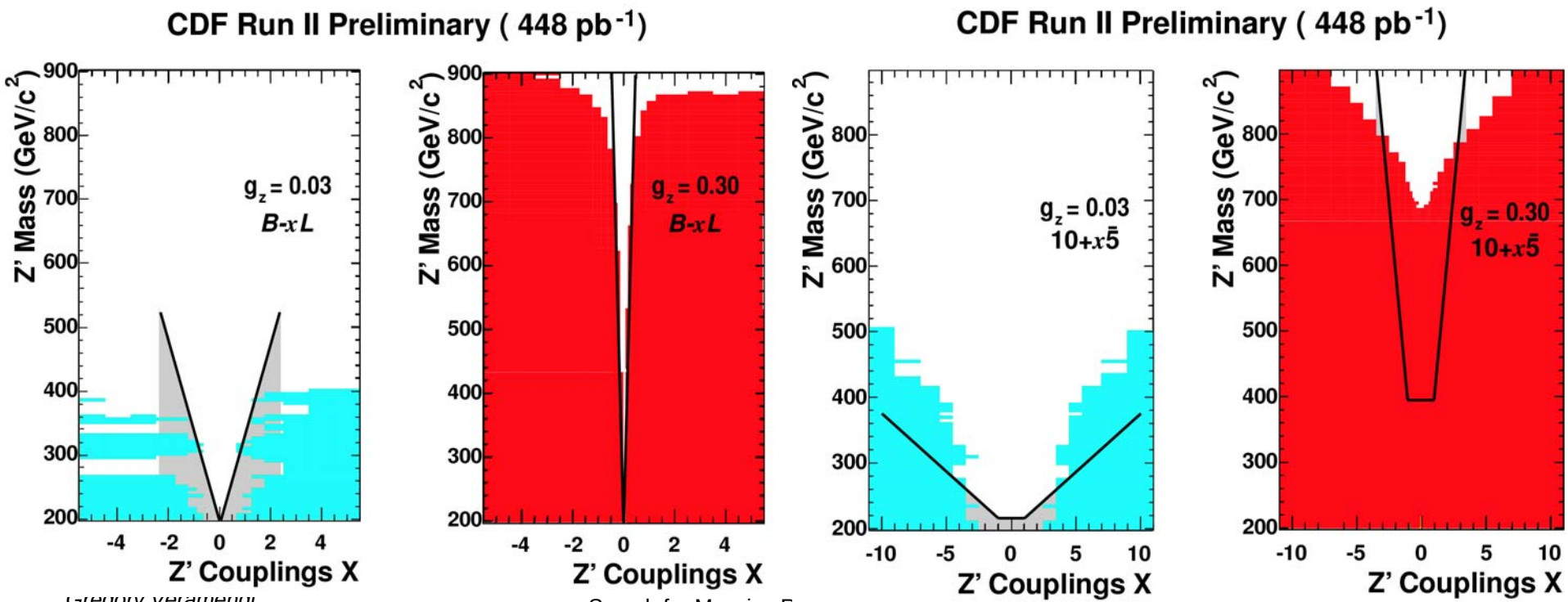




Carena, Daleo, Dobrescu, Tait, PRD 70, 093009 (2004)

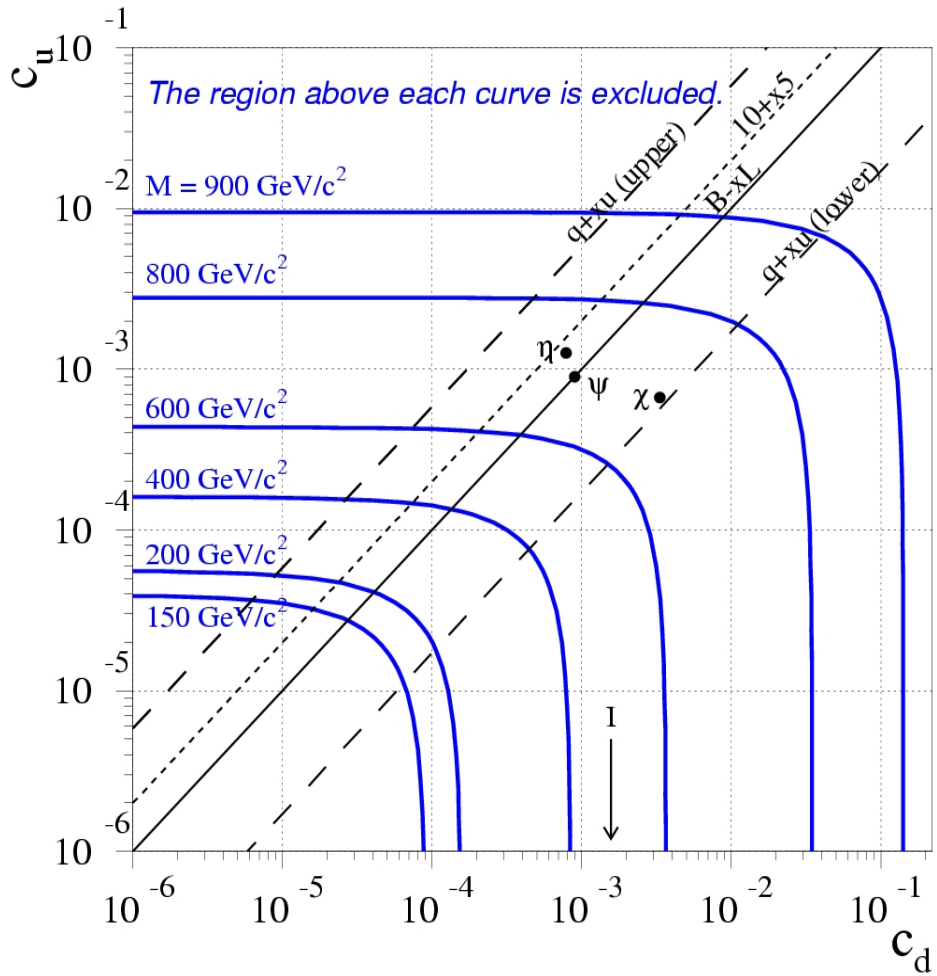
Z′→ee (448pb^{-1}): Comparing w/ LEPII

- CDF's sensitivity relative to LEPII depends on model and X
  - ➔**Lines and gray areas are LEPII exclusions**
  - ➔**B-xL: sensitivity similar to LEPII**
  - ➔**10+x5: more sensitive than LEPII**



Z′ →ll (~200 pb^{-1}): Couplings limits

- Present results with easy connection to models
  - ➔ **Don't have to calculate cross sections with PDFs**
- Show limits in terms of c_u and c_d:
- z is gauge charge for each fermion
  - ➔ **q→left-handed quarks**

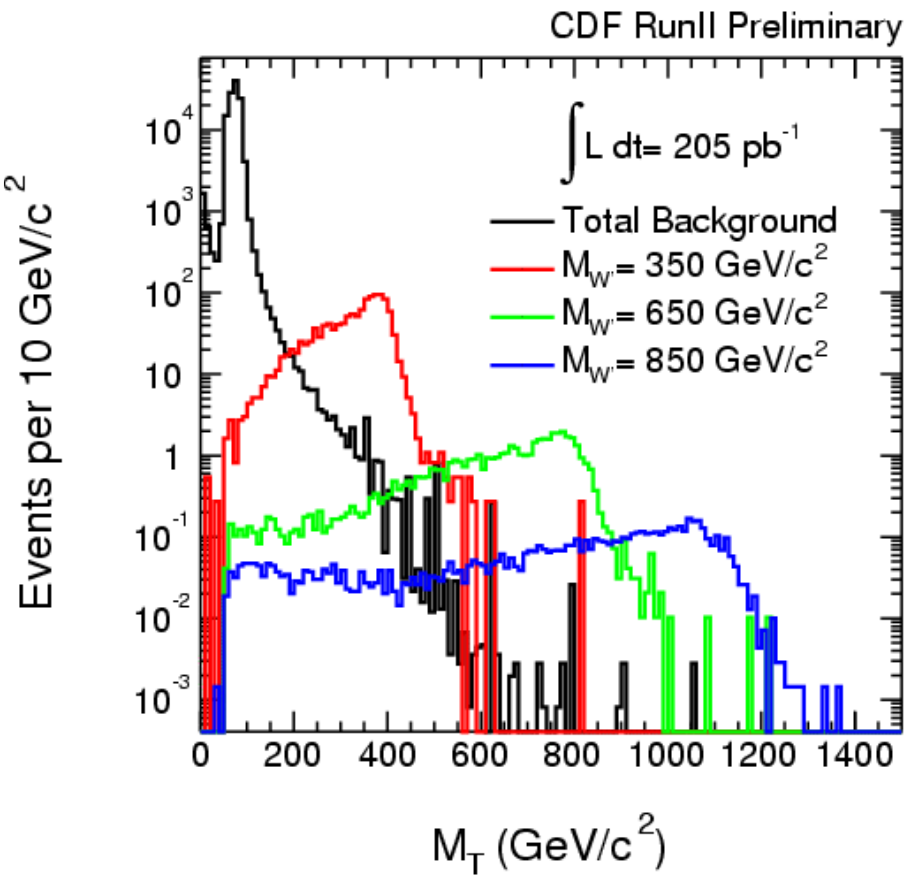


$$c_{u,d} = g_{Z'}^2 (z_q^2 + z_{u,d}^2) Br(Z' \to \ell^+ \ell^-)$$

Search for W′

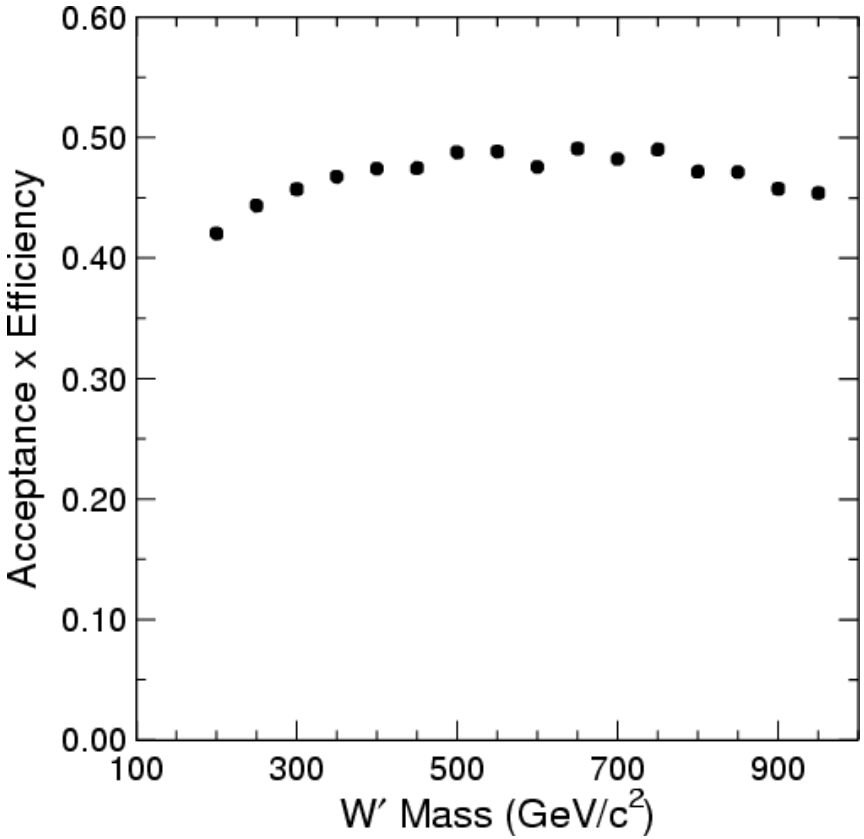
Searching for W′

- W′: additional charged heavy vector boson
- Appears in theories based on the extension of the gauge group
- e.g. Left-right symmetric models: $SU(2)_R \rightarrow W_R$



Selection and Backgrounds

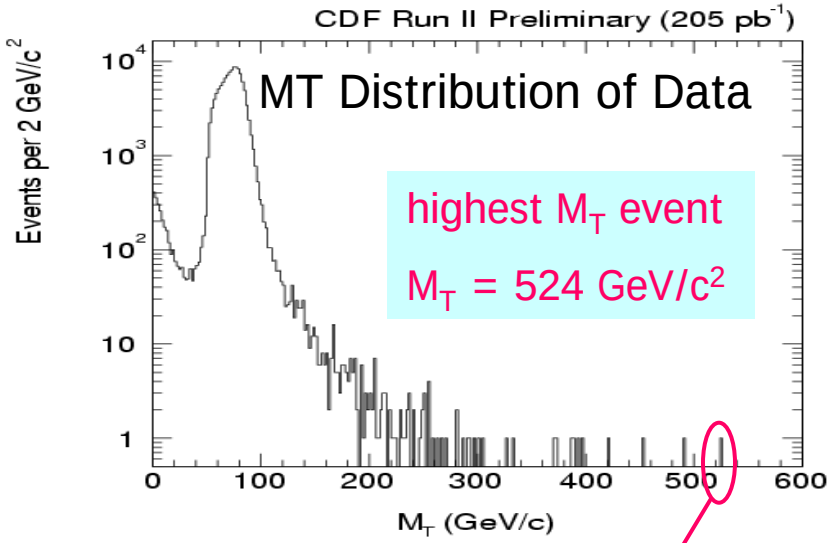
- Data taken 2/02-9/03
  - ➔ **205 pb^{-1}**
- High P_T central electron
  - ➔ **E_T>25 GeV**
- Met > 25 GeV
- Dilepton removal
- Multi-jet mismeasurement removal
  - ➔ **0.4 < E_T/Met < 2.5**

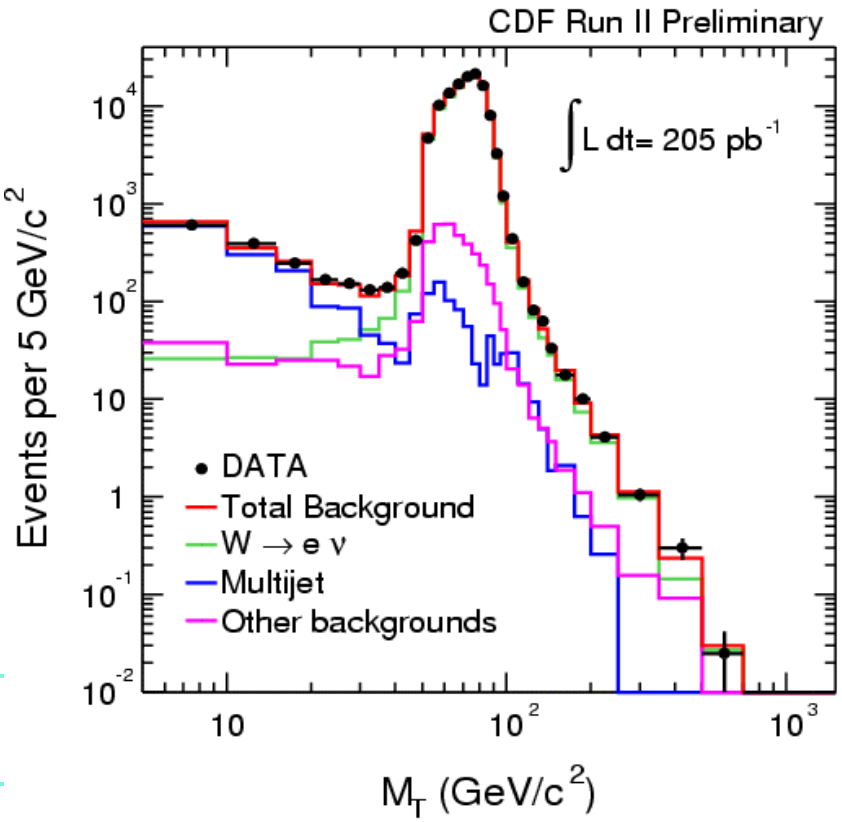


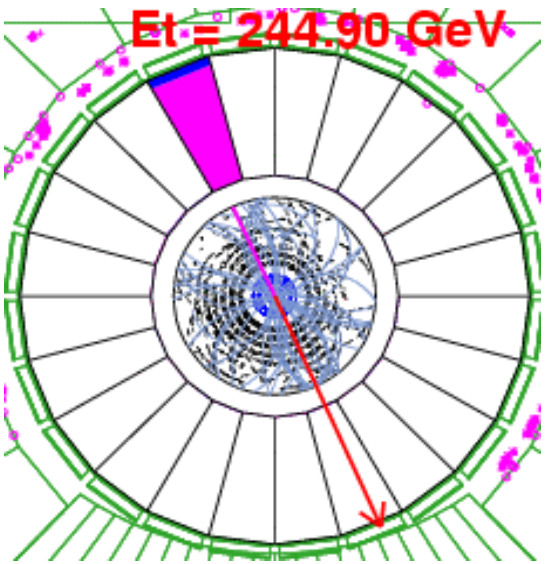
- Backgrounds
  - ➔ **W→τν**
  - ➔ **Multi-jet backgrounds**
  - ➔ **Ttbar, diboson, Z/γ***

Data comparisons

- Very good agreement over many orders of magnitude in M_T

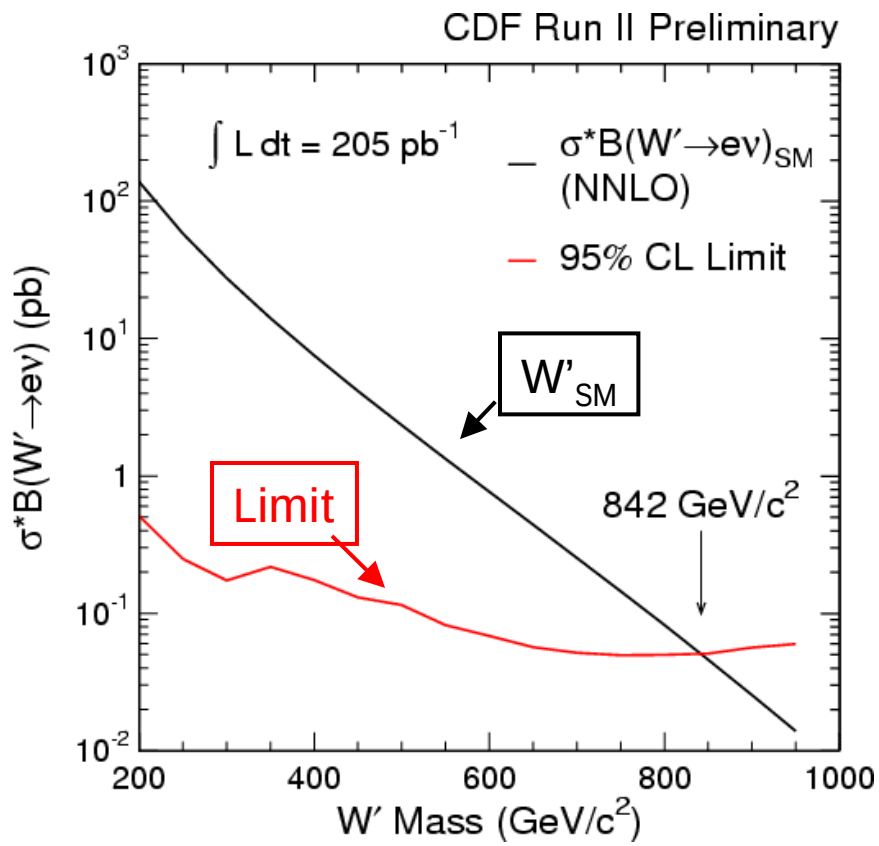






Setting limits on W′

- →No evidence for W’
- Set limits on W production
  - → **Assume ν daughter is light, and escapes detector**
- Use binned likelihood fitting method
- Two types of systematics are examined as a function of M_T:
  - → **Event rate (mostly PDF)**
  - → **Signal shape (mostly E scale)**
- $\sigma * B(W' \rightarrow e\nu)$ > 50-100 fb at 95% CL
  - → **M(W’)> 500 GeV/c² at 95% Confidence Level**

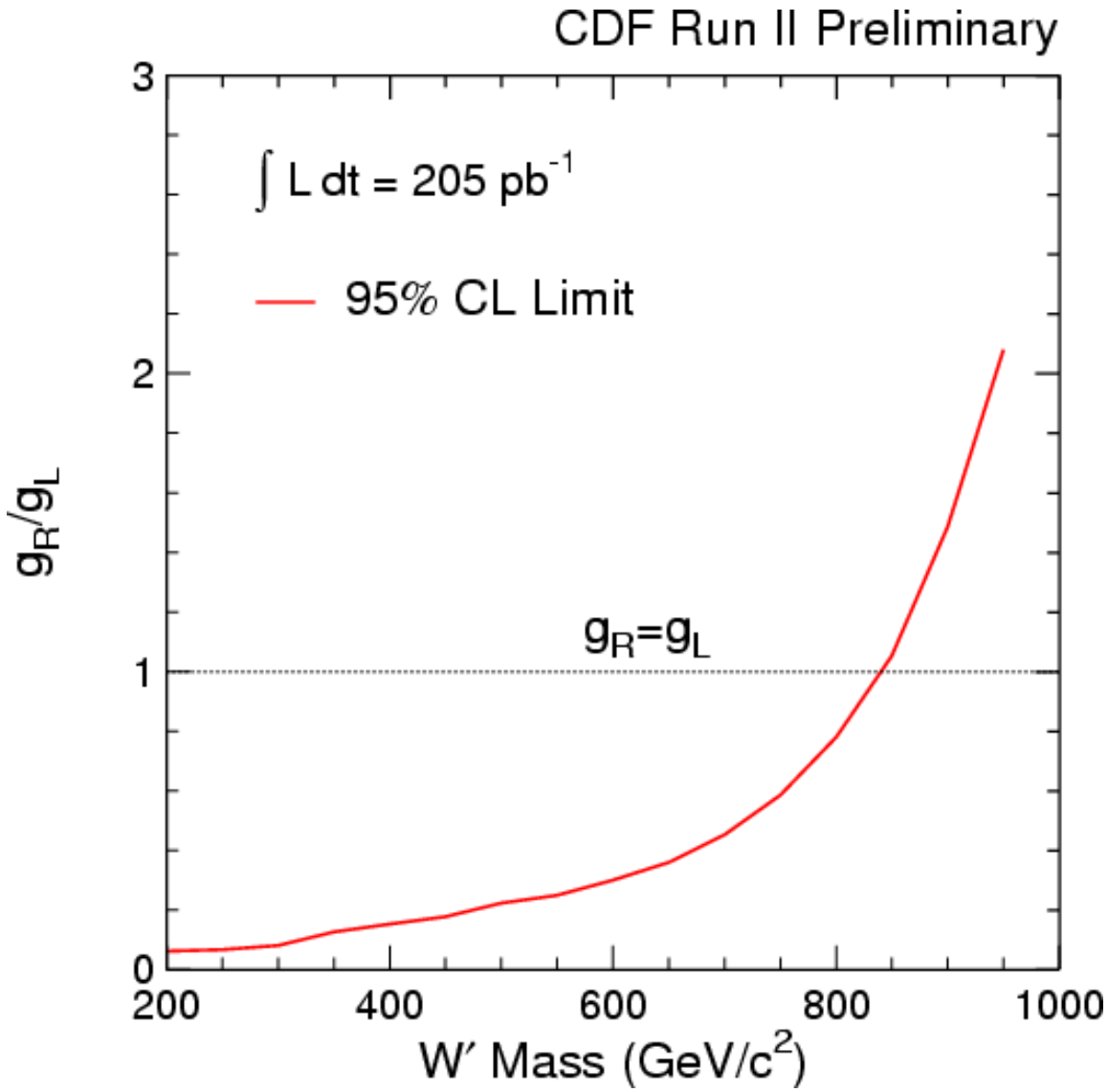


Limit: $M(W'_{SM}) > 842$ GeV/c²

Run I results (with the same assumptions):
$M(W'_{SM}) > 754$ GeV/c²

Limit vs. Couplings

- Releasing assumption of SM couplings
- Plot limit vs g_R/g_L couplings ratio



Summary

- Summary of limits (new world best direct)

	CDF e^+e^- 448 pb^{-1}
Z_I	625 GeV
Z_χ	720 GeV
Z_ψ	690 GeV
Z_n	715 GeV

	CDF e^+e^- 448 pb^{-1}
Z'_{SM}	845 GeV

	CDF $e\nu$ 205 pb^{-1}
W'_{SM}	842 GeV

Conclusions

- Many searches underway at CDF
  - ➔ **Sharpening analysis tools**
- New W′ result
- New Z′ result
  - ➔ **Twice the luminosity of previous results**
  - ➔ **Increased sensitivity by using angular distribution**
- Data consistent with Standard Model
- Lots more data to analyze and lots more to come!

✓ **Limits shown either exceed any published results of direct searches or are the first limits ever!**

Is there new physics waiting to be found??