Search for High-Mass Resonances in CDF Dimuon Data

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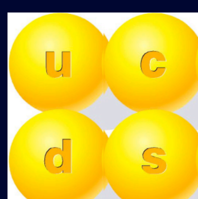
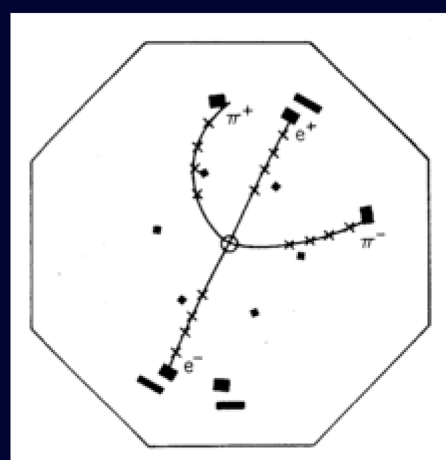
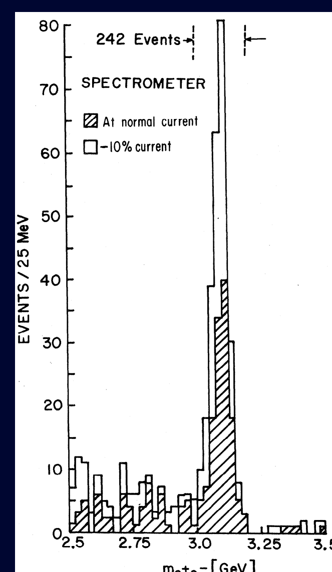
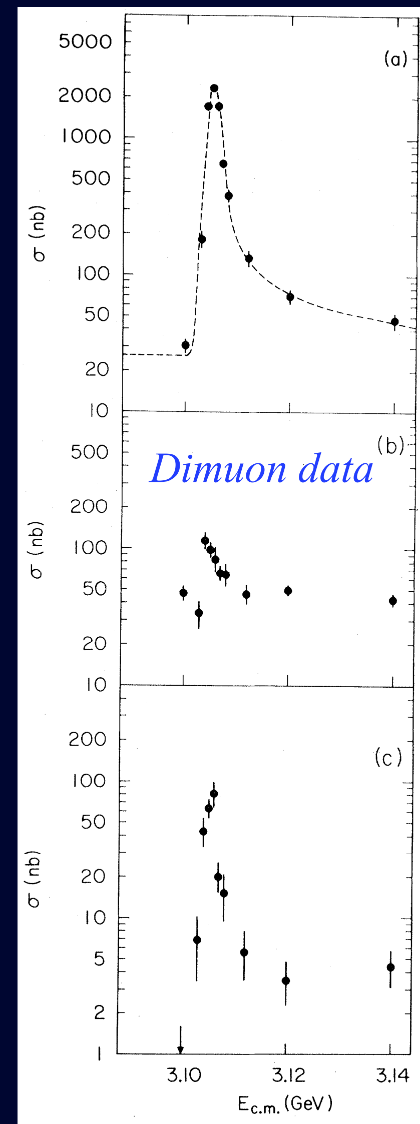
A Brief History of Neutral Resonances

- **J/ψ discovery**
  - 1970: Fourth quark would prevent flavor changing neutral currents (s → d)
    - *GIM mechanism (Glashow, Iliopoulos, and Maiani)*
  - 1974: "November revolution"
    - *Resonance discovered in e^+e^- collisions at SLAC (ψ)*
    - *Resonance discovered in pp collisions at Brookhaven (J)*
  - Verified existence of charm quark



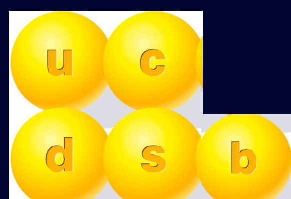




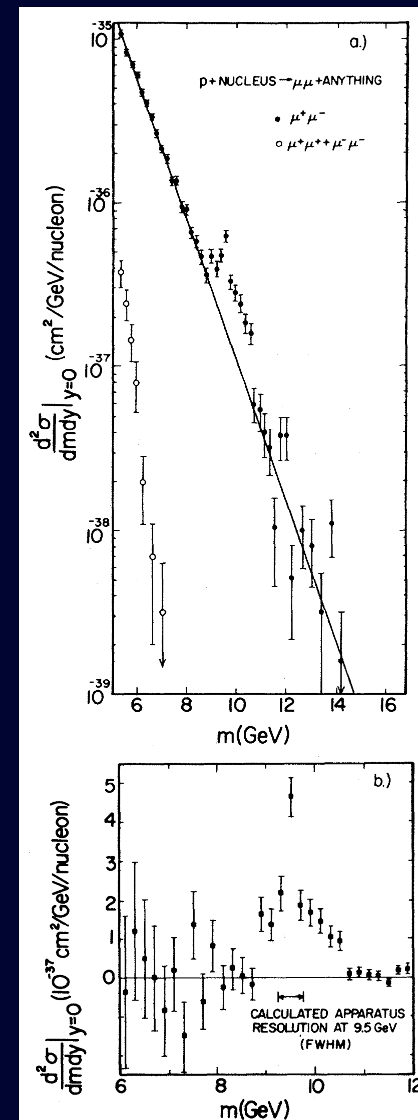


A Brief History of Neutral Resonances

- **Upsilon discovery**
  - Discovered at Fermilab in 1977 in the dimuon final state
  - Demonstrated existence of third generation of quarks



- **Z^0 discovery**
  - Discovered 1983 with 8 events from UA1 and UA2
  - Confirmed central prediction of electroweak theory



The Next Discovery

- **Good chance a neutral resonance will be the next discovery**
  - Standard model Higgs?

- **Many weaknesses of the standard model 'fixed' with resonances**

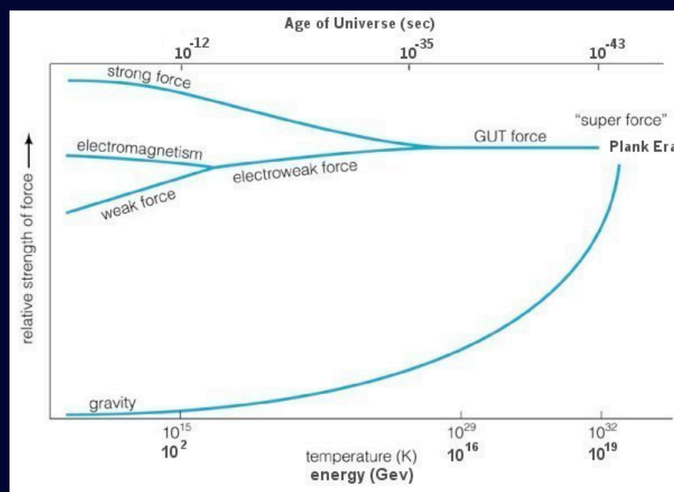
Hierarchy between weak and Planck scales (Higgs mass fine-tuning)

Extra dimensions

Supersymmetry (SUSY)

Lack of force unification

U(1) symmetries in grand unified theories



Light neutrino masses

U(1) or $SU(2)_R$ symmetries

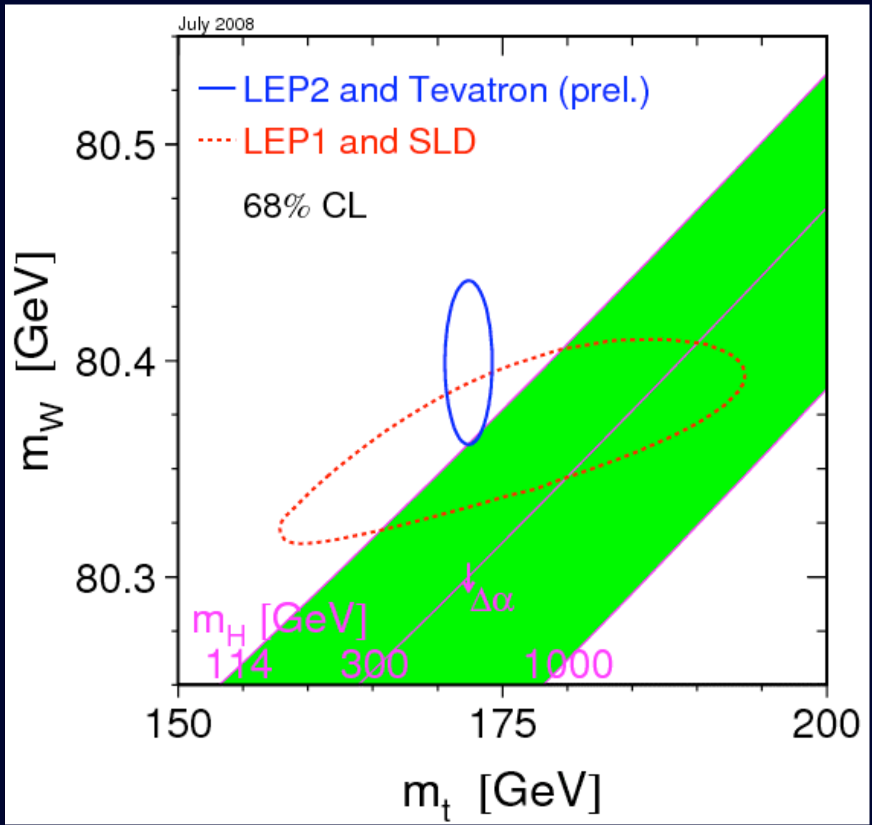
Parity violation in the weak force

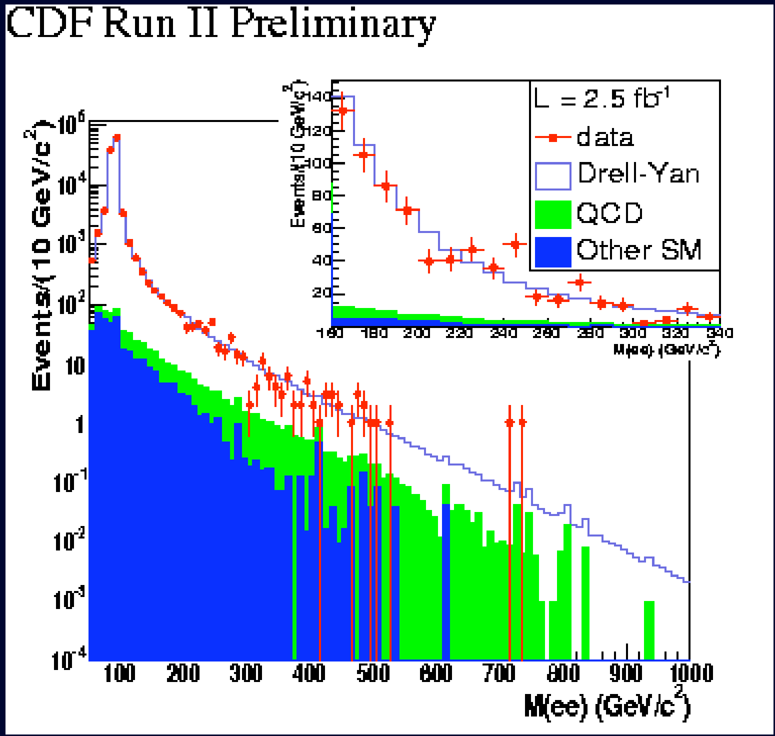
Left-right symmetric model ($SU(2)_L$ x $SU(2)_R$)

Hints?

Electroweak data more compatible with new physics than SM

Z-Z' mixing one possible explanation





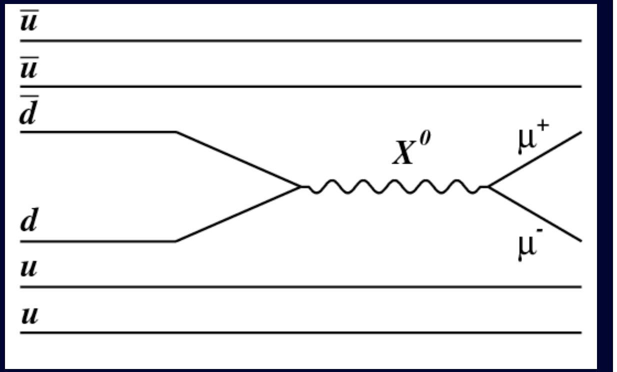
CDF search in dielectron data found excess at m ≈ 240 GeV

0.6% of pseudoexperiments find more significant excess in search region

Search for Neutral Resonances

- **A resonance decaying to dimuons can have spin 0, 1, or 2**

- **Spin 0**
  - No fundamental scalar particle yet observed
  - Higgs branching ratio to dimuons $O(10^{-4})$
  - MSSM Higgs can have enhanced production rate
  - Sneutrino resonance possible if *R*-parity violated



- **Spin 1**
  - Many models predict new U(1) or SU(2) with neutral gauge boson *Z′*

- **Spin 2**
  - Excited graviton resonances *G** predicted by Randall-Sundrum model of warped extra dimensions

Sneutrino Production

- **To solve hierarchy problem, sparticles should have electroweak-scale masses**

- **Resonant sparticle production requires 'R-parity' violation**
  - SM particles: R = 1; sparticles: R = -1
  - Implication: lightest sparticle decays
    - *Can still be dark matter candidate if coupling is weak*

- **Two terms in Lagrangian relevant for production and decay**

$$\mathcal{W}_{\not{R}p} = \lambda_{ijk} L_i L_j e^c_k + \lambda'_{ijk} L_i Q_j d^c_k$$

Decay
$\tilde{\nu}_i \rightarrow \mu\mu^c \,(\lambda_{i22})$

L_i, Q_i: SU(2) doublet superfields
e^c_k, d^c_k: SU(2) singlet superfields

Production
$dd^c \rightarrow \tilde{\nu}_i \,(\lambda'_{i11})$

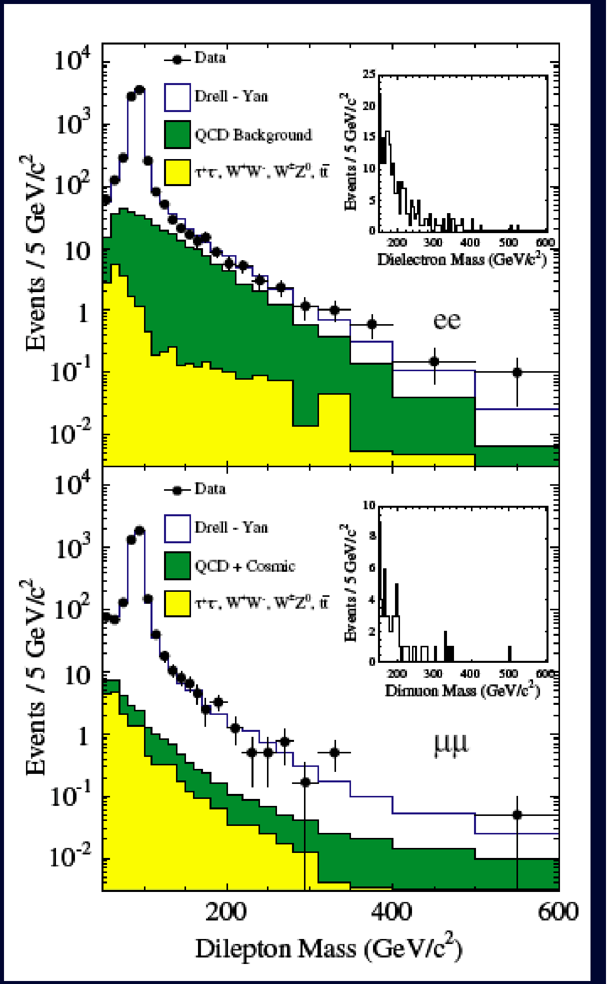
Sneutrino Width and Limits

- **Sneutrino width**
  - Partial width:

$$\Gamma(\tilde{\nu}_i \rightarrow f_j f_k) = c_{jk}/(16\pi)\, \lambda^{(')}{}_{ijk}{}^2\, m_{\tilde{\nu i}}$$

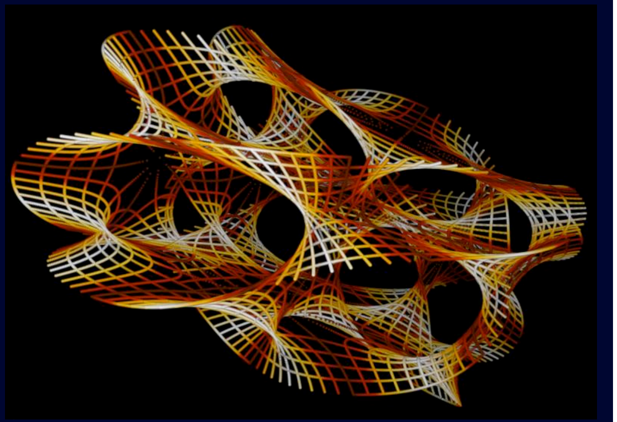
For $\lambda'_{211} = 0.5$, $\lambda_{222} = 1$, and $m_{\tilde{\nu}i} = 100$ GeV: $\Gamma = 3.5$ GeV

- **Mass and coupling limits**
  - Indirect:
    - *Ratio of $\pi \rightarrow e\nu$ to $\pi \rightarrow \mu\nu$ partial widths*
      - $\lambda'_{111} < 0.26\, m_{\tilde{d}}$/ TeV and $\lambda'_{211} < 0.59\, m_{\tilde{d}}$/ TeV
    - *Ratio of $\tau \rightarrow \pi\nu$ to $\pi \rightarrow \mu\nu$ partial widths*
      - $\lambda'_{311} < 1.2\, m_{\tilde{d}}$/ TeV
  - Direct:
    - *CDF searches in ee and $\mu\mu$ decays (200 pb^{-1})*
      - $m_{\tilde{\nu}} > 680$ (ee), 665 GeV ($\mu\mu$) for $\lambda'_{i11}{}^2 \times BR = 0.01$
      - $m_{\tilde{\nu}} > 460$ (ee), 450 GeV ($\mu\mu$) for $\lambda'_{i11}{}^2 \times BR = 0.001$



Z' Production

- **Z' observable if new gauge symmetry broken at TeV scale**
  - Many models predict electroweak-scale U(1) symmetry
  - Useful test model: Superstring-inspired grand unified theory ($E_8 \times E_8'$)
    - *Compactification of extra dimensions breaks E_8 to $E_6 \times SU(3)$*
    - *E_8' is a hidden sector that breaks supersymmetry*

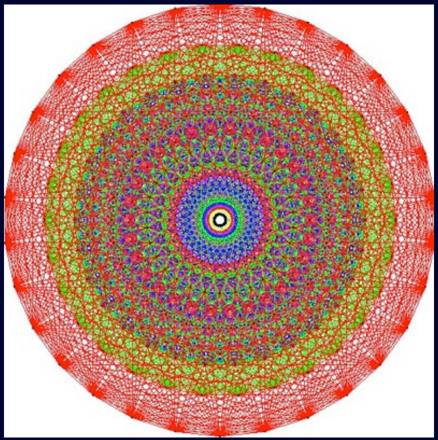


An example of breaking E_6 to the Standard Model:

$$
\begin{aligned}
E_6 &\rightarrow SO(10) \times U(1) \\
&\rightarrow SU(4)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L} \\
&\rightarrow SU(3)_c \times SU(2)_L \times U(1)_Y
\end{aligned}
$$

All matter particles in fundamental 27 representation of E_6

Contains 16 (SM fermions), 10 (Higgs doublets) and 1 of SO(10)



$$
(\mathbf{16})_1 = \begin{pmatrix} \bar{u} & \bar{u} & \bar{u} & \bar{\nu}_e & | & u & u & u & \nu_e \\ \bar{d}' & \bar{d}' & \bar{d}' & e^+ & | & d' & d' & d' & e^- \end{pmatrix}_L
$$

Restores parity conservation, allows for seesaw mechanism for small neutrino masses, and requires quantized EM charge

Z' Production

- **E_6 breaking can result in multiple U(1) symmetries**

$$
\begin{aligned}
E_6 &\rightarrow SO(10) \times U(1)_\psi \\
&\rightarrow SU(5) \times U(1)_\chi \times U(1)_\psi \\
&\rightarrow SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)_\chi \times U(1)_\psi \\
&\rightarrow SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)' \\
&\rightarrow SU(3)_c \times SU(2)_L \times U(1)_Y
\end{aligned}
$$

Assume electroweak-scale U(1)' is a linear combination of $U(1)_\chi \times U(1)_\psi$

$$U(1)' = U(1)_\psi \cos\theta + U(1)_\chi \sin\theta$$

Generic U(1)' can be expressed in terms of θ:

$E_6 \rightarrow SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)_\eta$ $(\theta = \tan^{-1}(3/5)^{1/2})$

$SU(2)_I$ (instead of $SU(2)_R$) with W' and Z' with zero EM charge $(\theta = \pi - \tan^{-1}(5/3)^{1/2})$

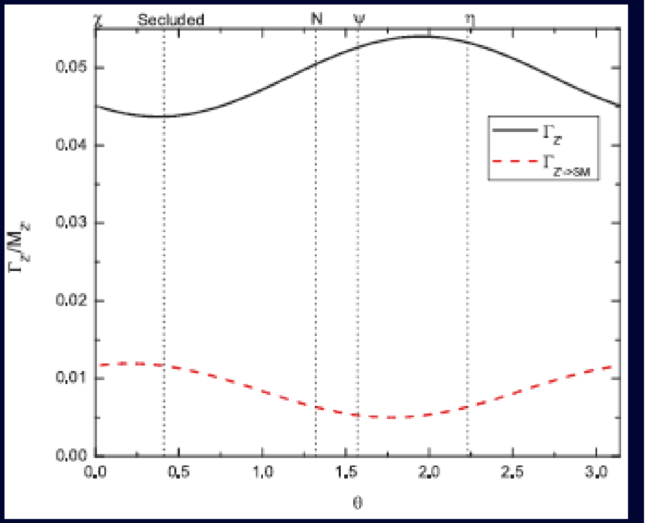
$U(1)_N$ where right-handed neutrino has no charge $(\theta = -\tan^{-1}(1/15)^{1/2})$

Secluded U(1)' with Z'_{sec} mass resulting from VEV of scalar with no SM charge $(\theta = \pi - \tan^{-1}(27/5)^{1/2})$

Couplings of Z_ψ', Z_χ' Z_η', Z_I', Z_N', Z_{sec}' determined by group theory and weak charge

Z' Width and Limits

- **E_6 Z' couplings smaller than SM Z**
  - $\Gamma_{Z'} < \Gamma_Z$ if Z' only decays to SM particles
  - If Z' decays to 27 of E_6, width can increase by factor of 5-10



- **Z' mass limits dominated by CDF**
  - LEP uses angular distributions of fermion pairs to set 1787 GeV mass limit for Z' with SM couplings

Analysis	Z'_{sec}	Z'_I	Z'_N	Z'_ψ	Z'_χ	Z'_η
CDF *ee* + μμ (0.20 fb^{-1})	-	615	-	675	690	720
CDF *ee* (0.45 fb^{-1})	680	650	710	725	740	745
CDF *ee* (1.3 fb^{-1})	-	729	-	822	822	891
CDF *ee* (2.5 fb^{-1})	794	735	837	851	862	930

Graviton Production

- **Apparent hierarchy between weak and gravitational scales could be due to metric (Randall-Sundrum model)**
  - Add exponential factor as function of extra dimension:

$$\mathbf{ds^2 = e^{-2kr\phi}\,\eta_{\mu\nu}dx^\mu dx^\nu - r^2 d\phi^2}$$

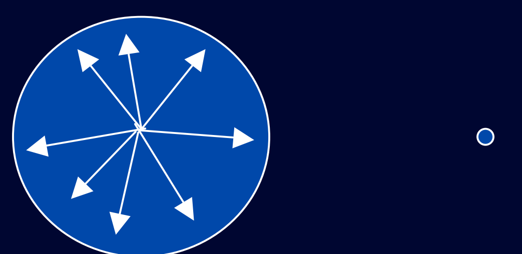
r: compactification radius

Standard model fields confined to 'brane' at $\phi = \pi$

Gravitational field determined by graviton flux through a surface

Exponentially larger surface area at $\phi = 0$

Most gravitons propagate in extra dimension, tiny fraction 'leaks' to SM brane



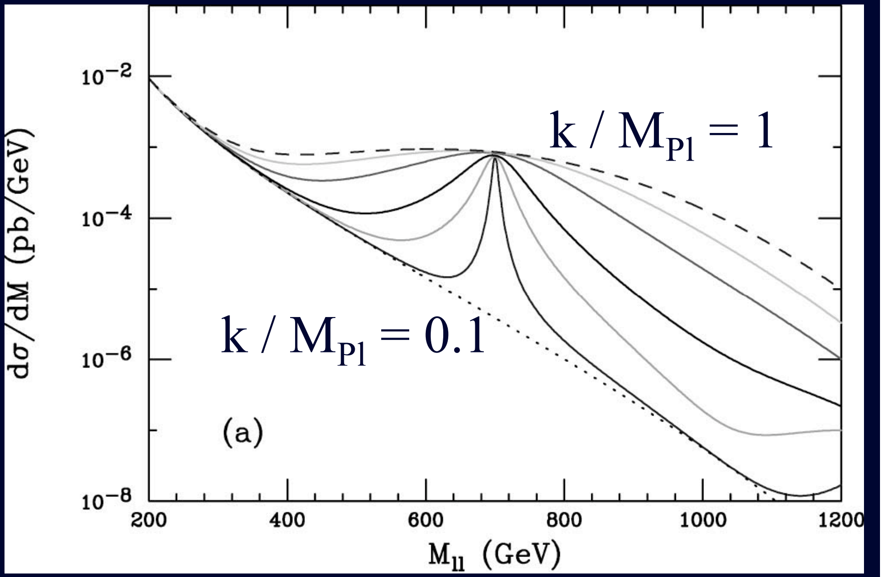
'Gravity brane' 'SM brane'

$$\mathbf{F = m_1 m_2 / (M_{Pl}{}^2\, R^2) \rightarrow}$$
$$\mathbf{F = m_1 m_2 / (M_{EW}{}^2\, e^{2kr\pi}\, R^2)}$$

Requires kr ~ 12

Graviton Width and Limits

- **Graviton excitations occur at the gravity mass scale**
  – Expect first excitation to be ~1 TeV in R-S model

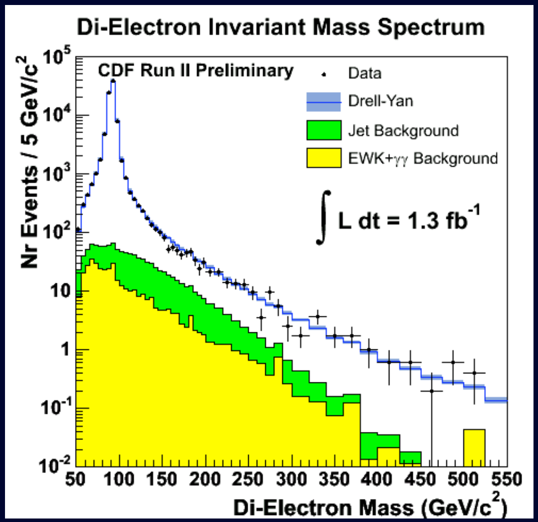


- **Width proportional to $(k / M_{Pl})^2$**
  – Narrow resonance for $k / M_{Pl} \lesssim 0.1$
  – String theory with O(1) couplings:
    $k / M_{Pl} \sim 0.01$

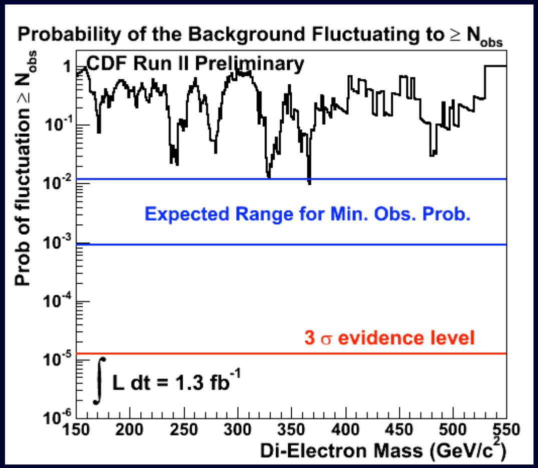
- **Tevatron sensitive to O(1 TeV) graviton resonances**
  – DØ ee + γγ search: $M_{G*} > 900$ GeV for $k / M_{Pl} = 0.1$
  – CDF combination of ee, γγ searches: $M_{G*} > 889$ GeV for $k / M_{Pl} = 0.1$

Resonance Searches

- **General strategy**
  - Scan invariant mass spectrum for narrow peak
    - *Width dominated by detector resolution*
  - Quantify significance of all excesses
    - *Understand background shape and uncertainty*
  - Determine probability of observing most significant excess



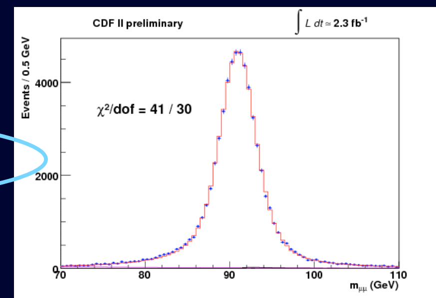
- **Common issues**
  - Search window varies with mass due to resolution
    - *Window causes a loss in acceptance*
  - Coarse scan can miss a significant fraction of the resonance



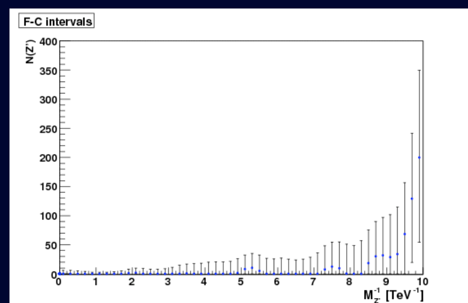
CDF Dimuon Resonance Search

- **Procedure**

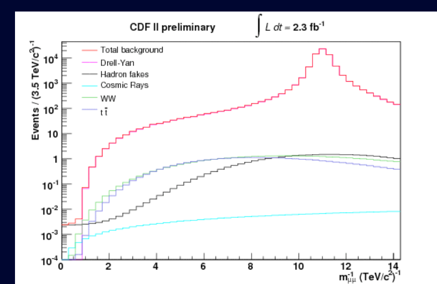
Calibrate detector resolution and scale



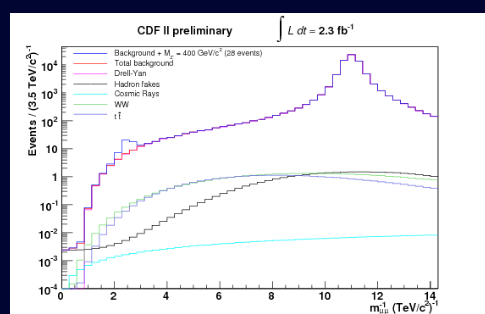
Determine scanning procedure



Understand background and uncertainty

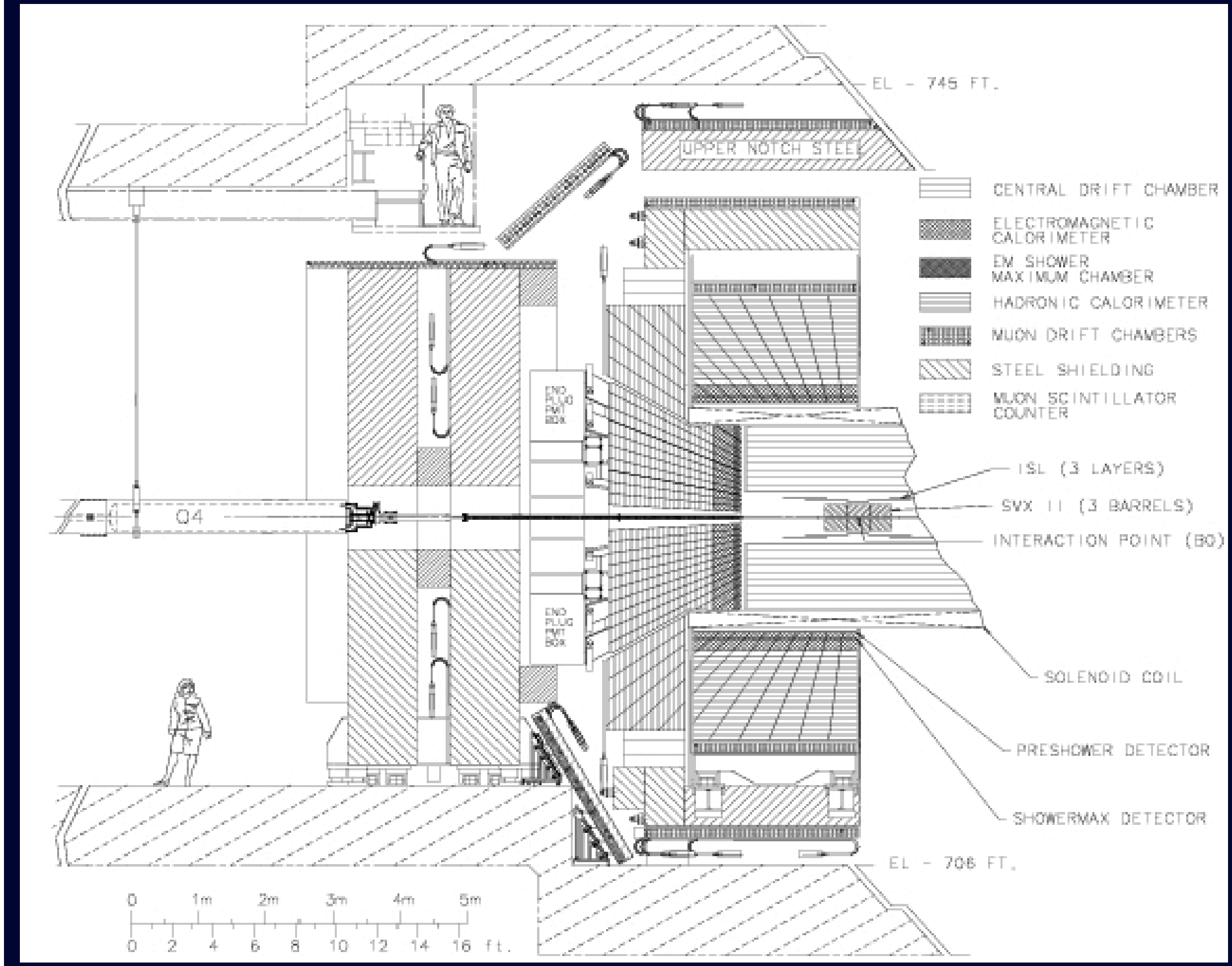


Predict signal and uncertainty



Interpret results from data

CDF Detector



Muon detectors for triggering in $|\eta| < 1$

Tracking drift chamber in 1.4 T magnetic field for momentum measurement in $|\eta| < 1$

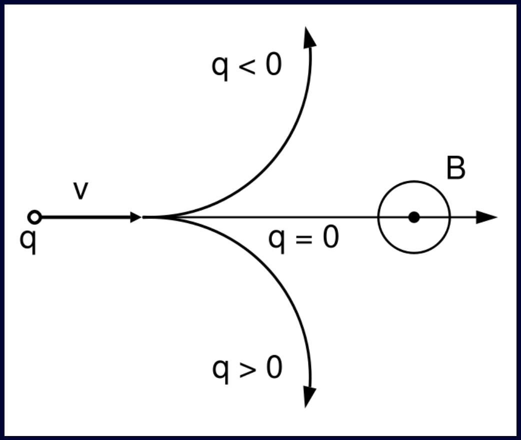
Drift Chamber Momentum Measurement

- **Lorentz force:**

  $\vec{F} = q\vec{v} \times \vec{B}$ $(\vec{B} = B\hat{z},\ \vec{v} = v_r\hat{r} + v_z\hat{z},\ \vec{F} = (mv_r^2/R)\hat{\phi})$

  $mv_r^2/R = evB$

  $p_T = eBR$



- **CDF tracker measures 96 hits in $r\hat{\phi}$**

  Hit resolution $r\delta\phi \rightarrow$ curvature resolution δc

  - *$c \equiv 1/(2R)$ $(c \propto 1/p_T)$*

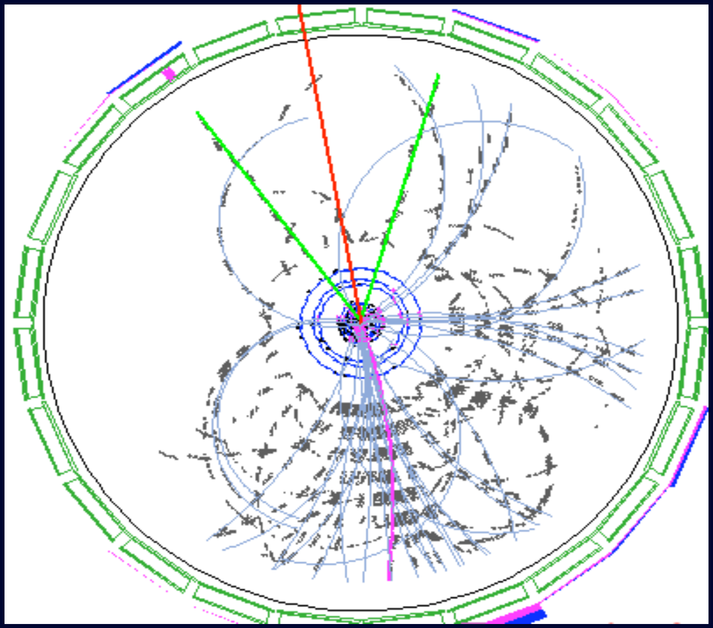
  Parameters:

  150 μm intrinsic hit resolution

  Inner hit $r \approx 40$ cm, outer hit $r \approx 130$ cm

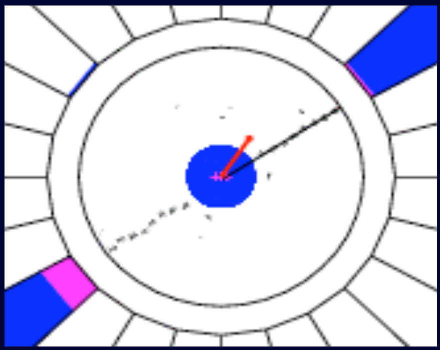
  Relative curvature resolution 0.15%

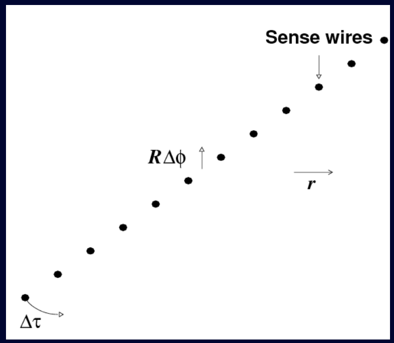
  With beam constraint $\delta c/c \approx 0.05\%$

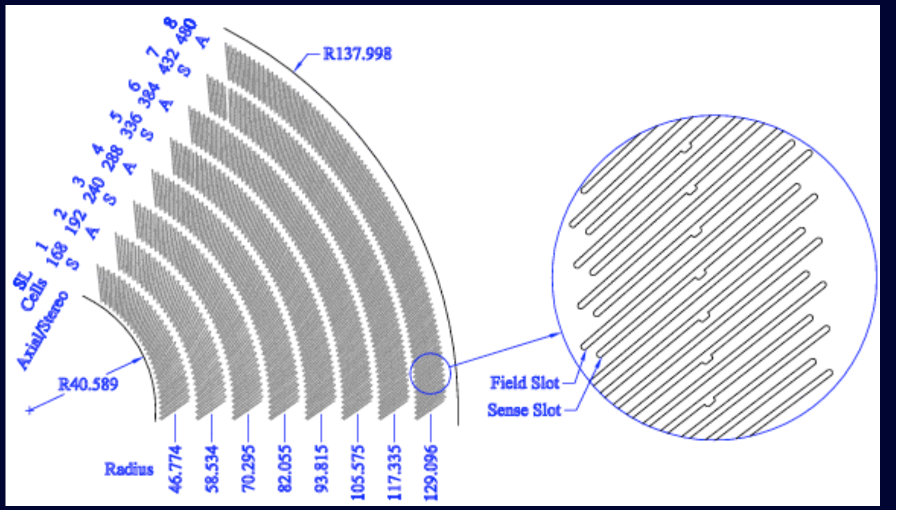


Drift Chamber Alignment

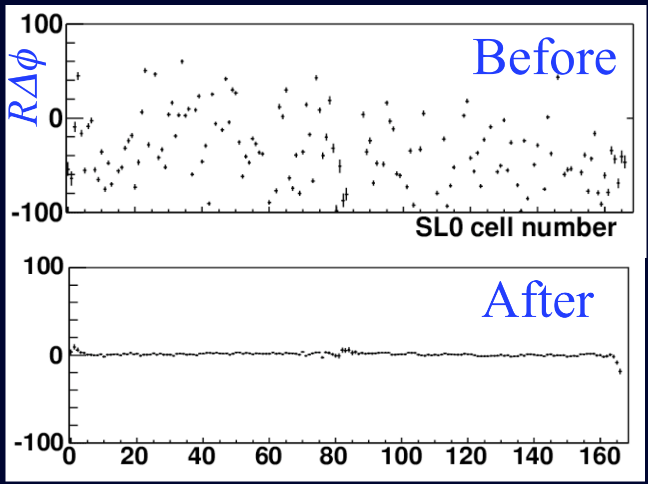
- **Alignment optimizes resolution and reduces biases**
- **Two-step procedure:**
  - Fix wire positions at endplates
  - Adjust wire shapes between endplates







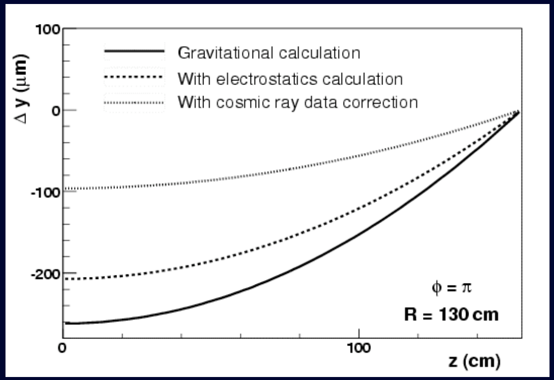
Endplate positions fit using hit residuals from cosmic-ray tracks

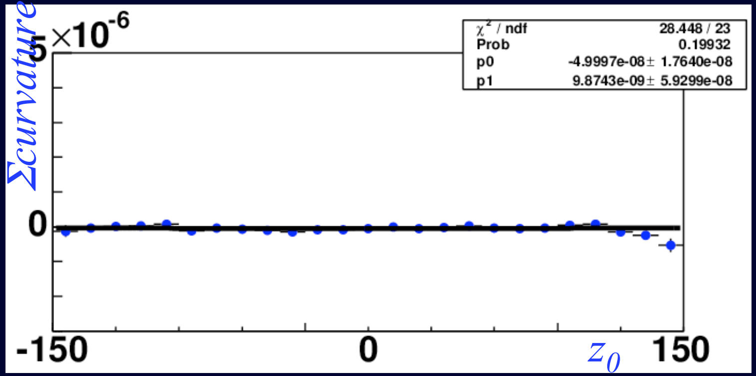


Single track fit through both sides of detector

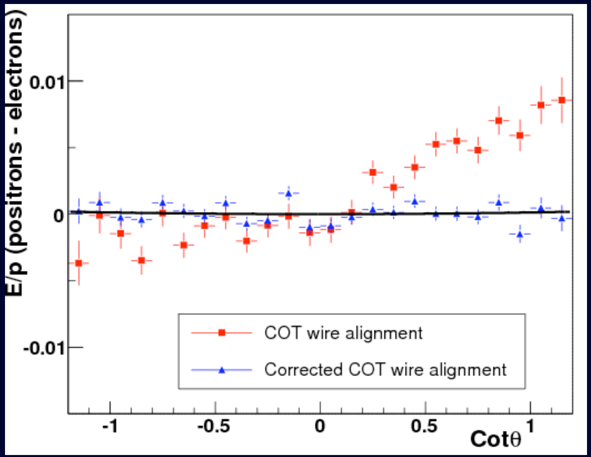
Drift Chamber Alignment

- **Adjust wire positions using cosmic-ray track parameters**
  - Correct shape determined from gravitational and electrostatic calculations
  - Derive corrections from incoming-outgoing track parameter differences



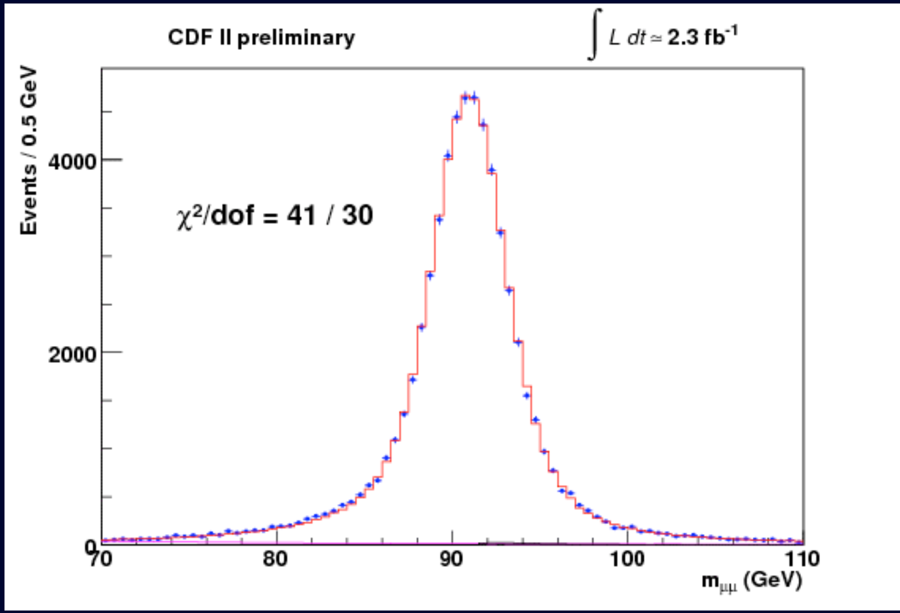


- **Apply track-level curvature corrections**
  - Use difference between e^+ and e^- ratio of calorimeter energy (E) to track momentum (p)
    - *E charge-independent*
    - *p can have charge-dependent misalignment bias*



Resolution and Scale Calibration

- **Simulate muons in tracker using fast tunable simulation**
  - Developed for W mass measurement
- **Tune hit resolution using width of upsilon → μμ resonance**
- **Tune beam spot size using width of Z resonance**
- **Calibrate momentum scale using J/ψ, upsilon, Z resonances**

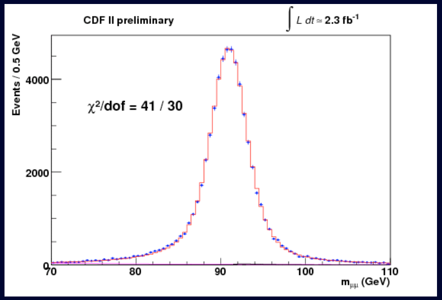


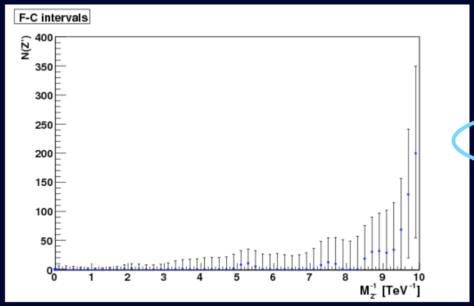
Residual scale and resolution uncertainties have negligible effect on search

CDF Dimuon Resonance Search

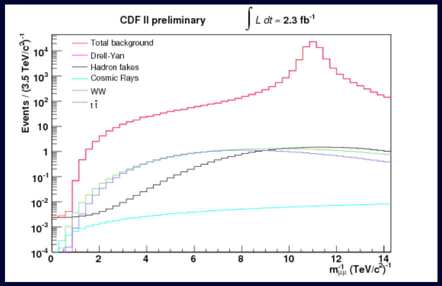
- **Procedure**

Calibrate detector resolution and scale

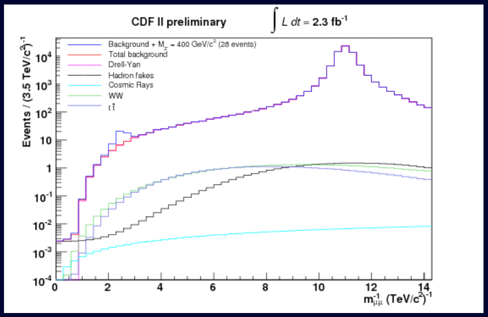




Determine scanning procedure



Understand background and uncertainty

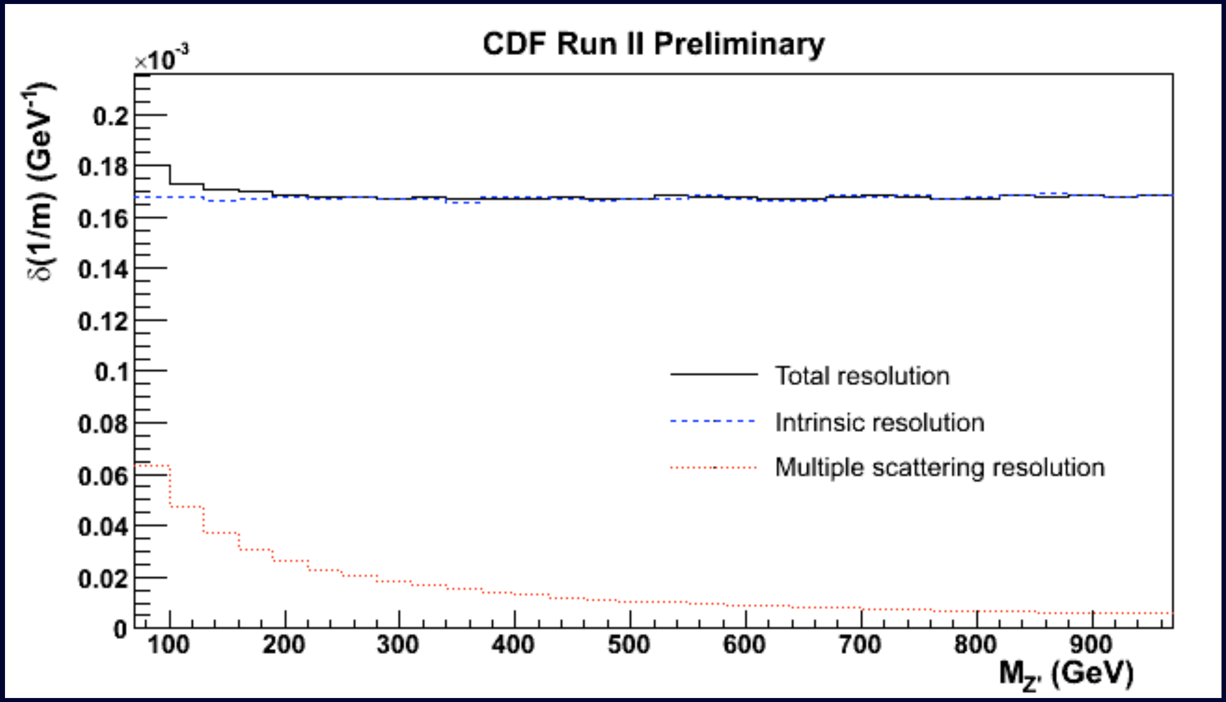


Predict signal and uncertainty

Interpret results from data

Scanning Distribution

- **Mass scan: significant variation of resolution with mass**
- **Intrinsic curvature resolution independent of curvature**
  - Low momentum: multiple scattering causes curvature dependence
  - High-mass resonance search: constant resolution in $1/p_T \rightarrow 1/m$



17% inverse mass resolution at 1 TeV

Scan inverse mass distribution for resonance

Scanning Procedure

- **Search $m^{-1} < 10\ TeV^{-1}$ ($m > 100$ GeV) using 35 bins**
  - Peak width due to resolution ≈3 bins (i.e., step size ≈1/3 of resolution)
- **Use 70 GeV < m < 100 GeV for normalization**
  - Removes luminosity and other systematic uncertainties at 100 GeV
- **Fit for number of signal events in search region at each mass**
  - Compare signal-plus-background templates to data
  - Determine Feldman-Cousins 95% confidence limits
- **Calculate probability of observing most significant excess**
  - Obtain from background-only pseudoexperiments

CDF Dimuon Resonance Search

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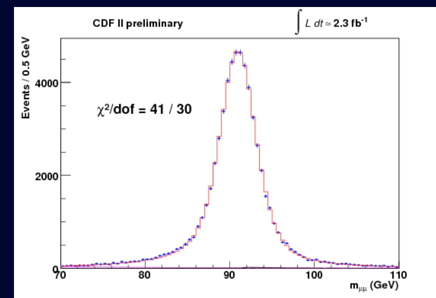

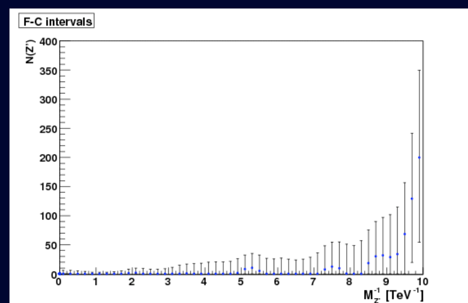

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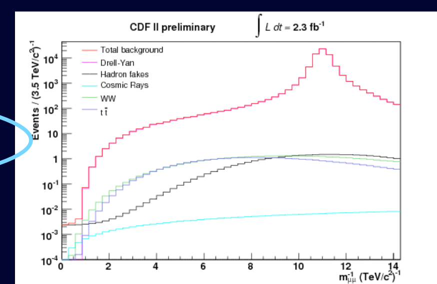
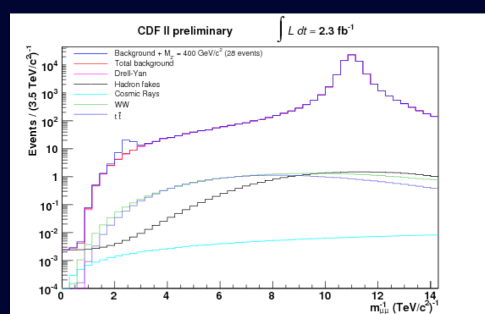


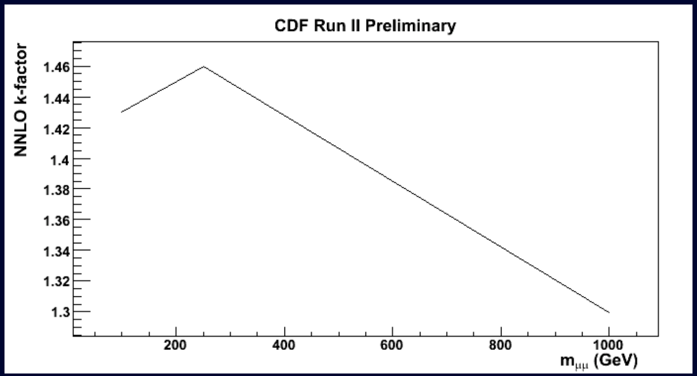


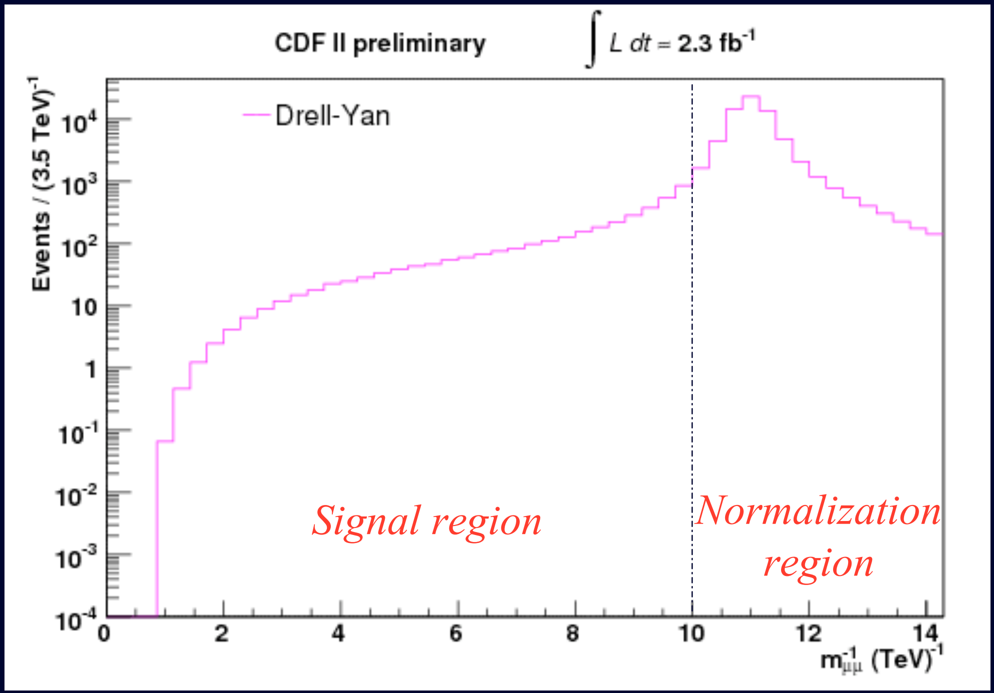
Predict signal and uncertainty

Interpret results from data

Drell-Yan Background

- **Z/γ* dominates SM expectation in almost entire search region**
  - Predict using PYTHIA with a NNLO multiplicative k-factor correction
    - *≈10% variation in search region*





Smooth background shape

Resonance peak clearly observable above Drell-Yan background

Dominant uncertainties due to PDFs (16% at 1 TeV) and higher-order corrections (9% at 1 TeV)

Misreconstructed Muon Background

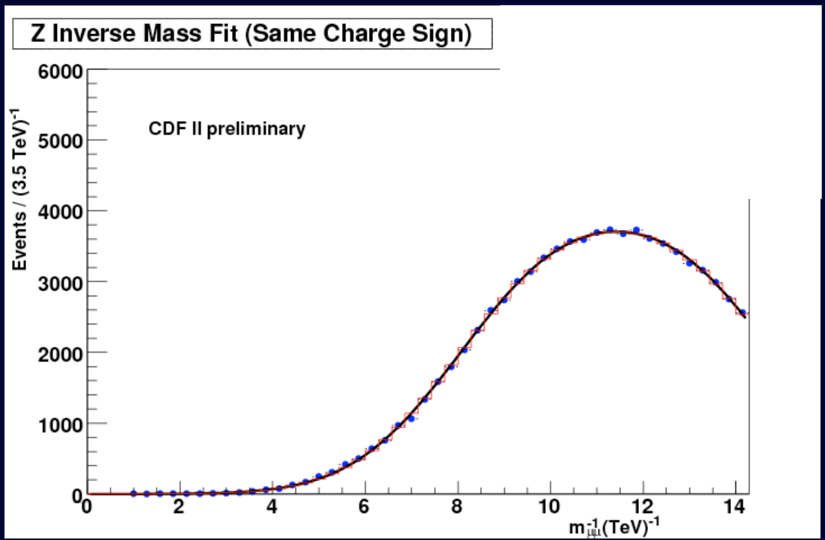
- **W + jet and multijet events can produce dimuons**
  - Hadron decays to muons or pions escaping calorimeter (no hard collision)
  - Dominate like-charge dimuon sample
    - *Use to obtain background normalization*

- **Inverse invariant mass shape has two components**
  - 1: Decays before tracker / pions escaping calorimeter
  - 2: Decays inside tracker

1: *Use minimum-ionizing same-sign (SS) tracks in multijet events to obtain mass shape*

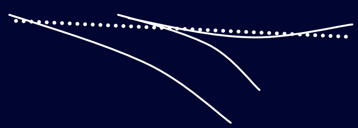
Consistent with opposite-sign (OS) m^{-1} shape

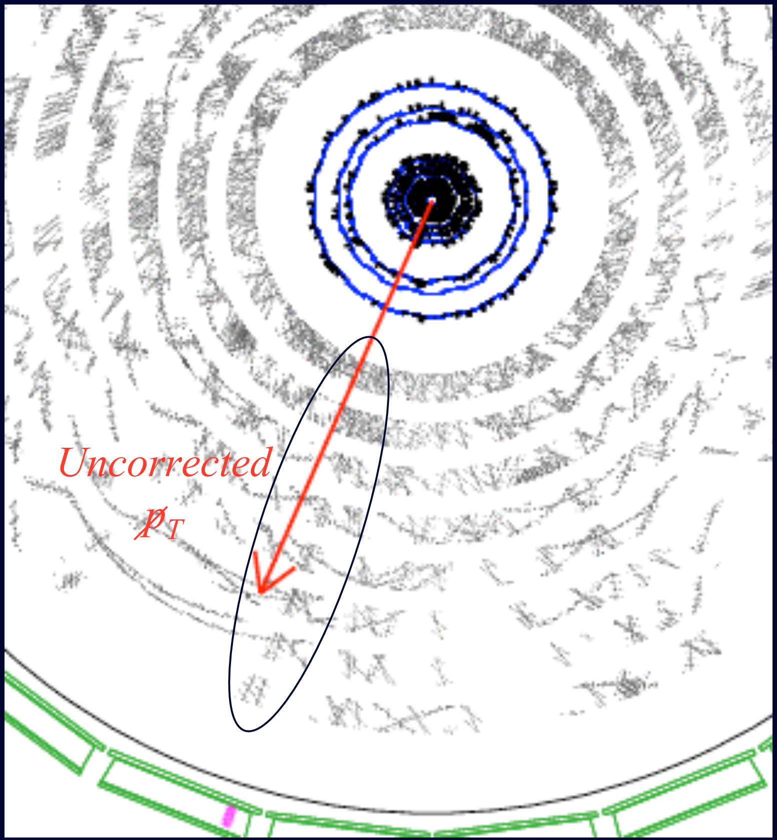
Obtain OS/SS ratio from multijet events



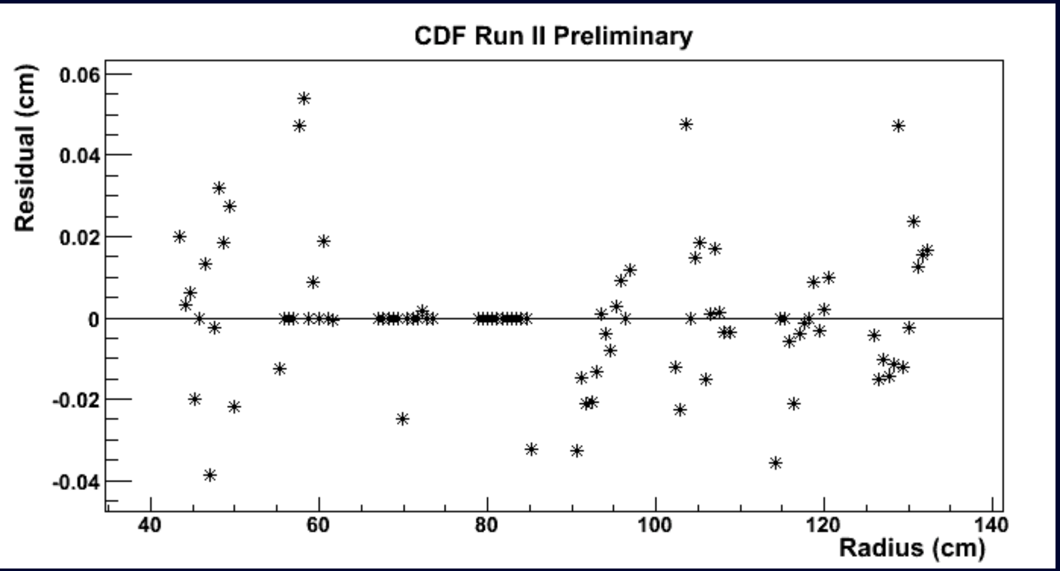
Misreconstructed Muon Background

- **Decays inside tracker the dominant background at highest mass**
  - Outer hits are attached to another track's inner hits
    - *Can result in a straight track (i.e., infinite momentum)*





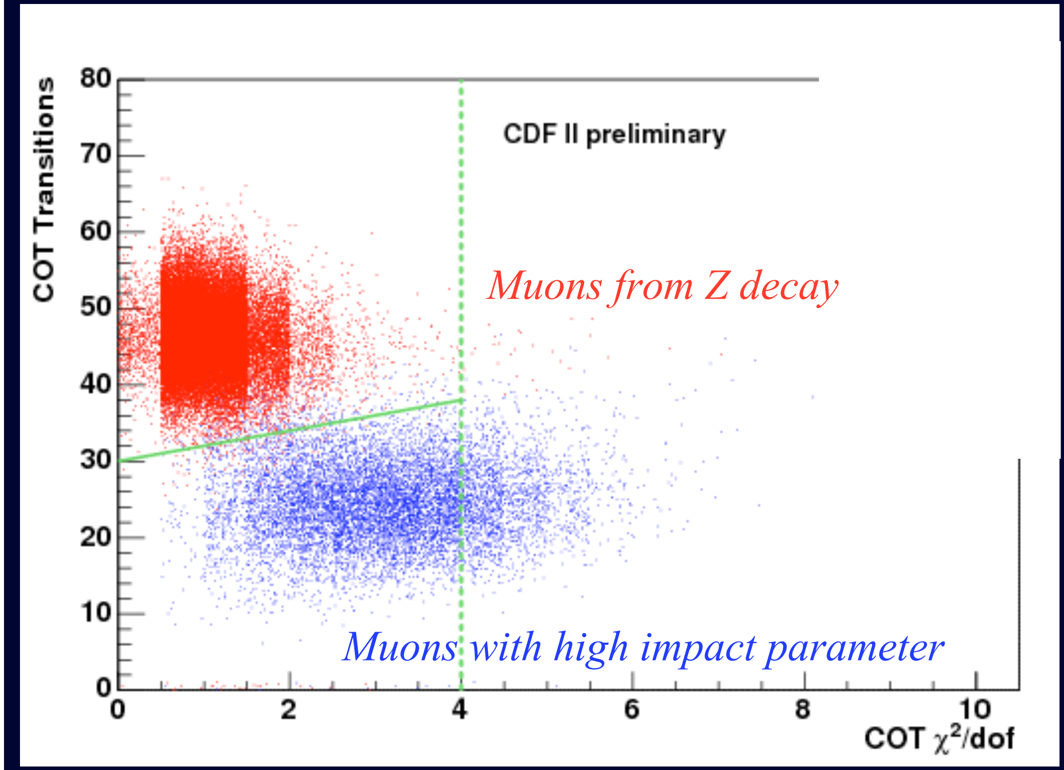
Example: **Reconstructed p_T = 443 GeV**



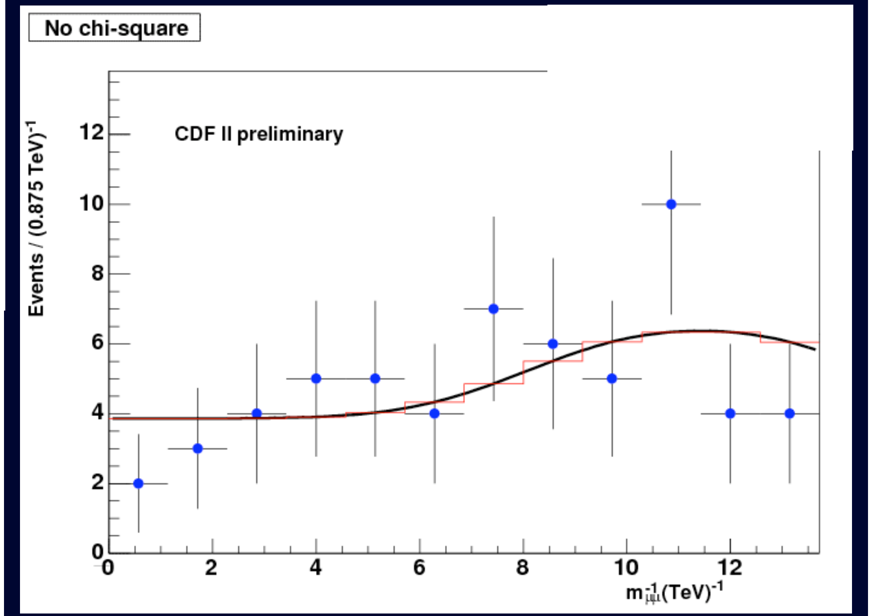
Decays-in-flight have poor χ^2/dof and many consecutive hits on same side of wires

Misreconstructed Muon Background

- **Reduce decay-in-flight background using hit residual pattern**
  - χ^2/dof and number of transitions to opposite side of wire

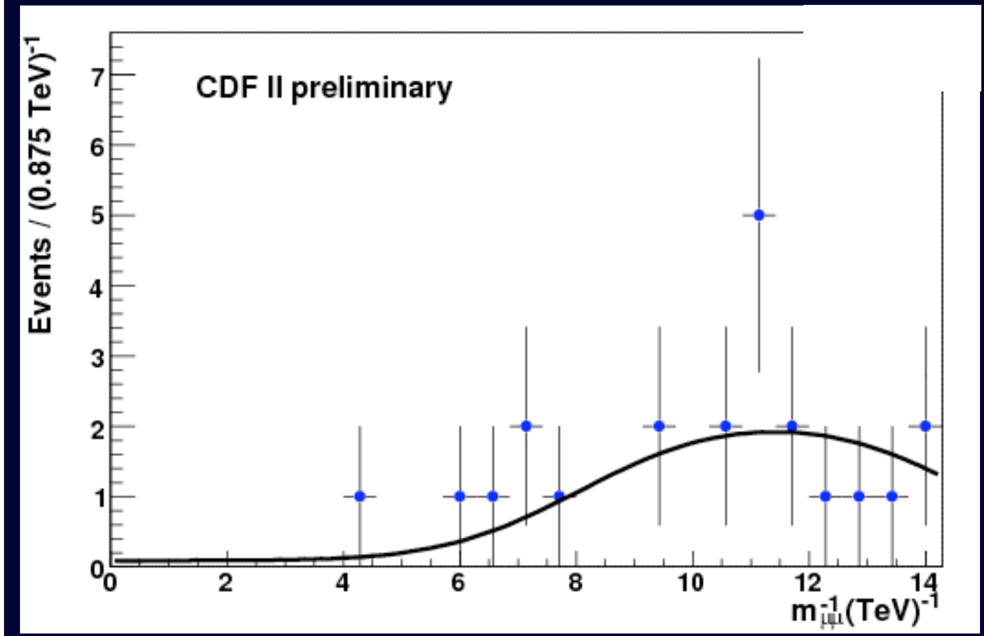


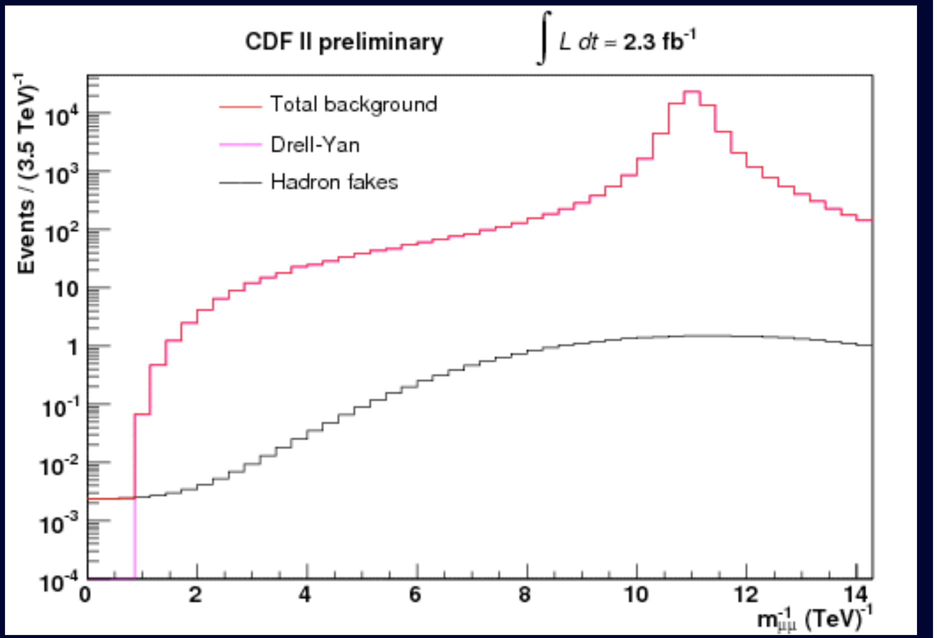
Without cuts, same-sign distribution has long tail to high invariant mass



Misreconstructed Muon Background

- **Fit same-sign distribution to two shape components**
  - Flat component from decays-in-flight, peaking shape from multijet data



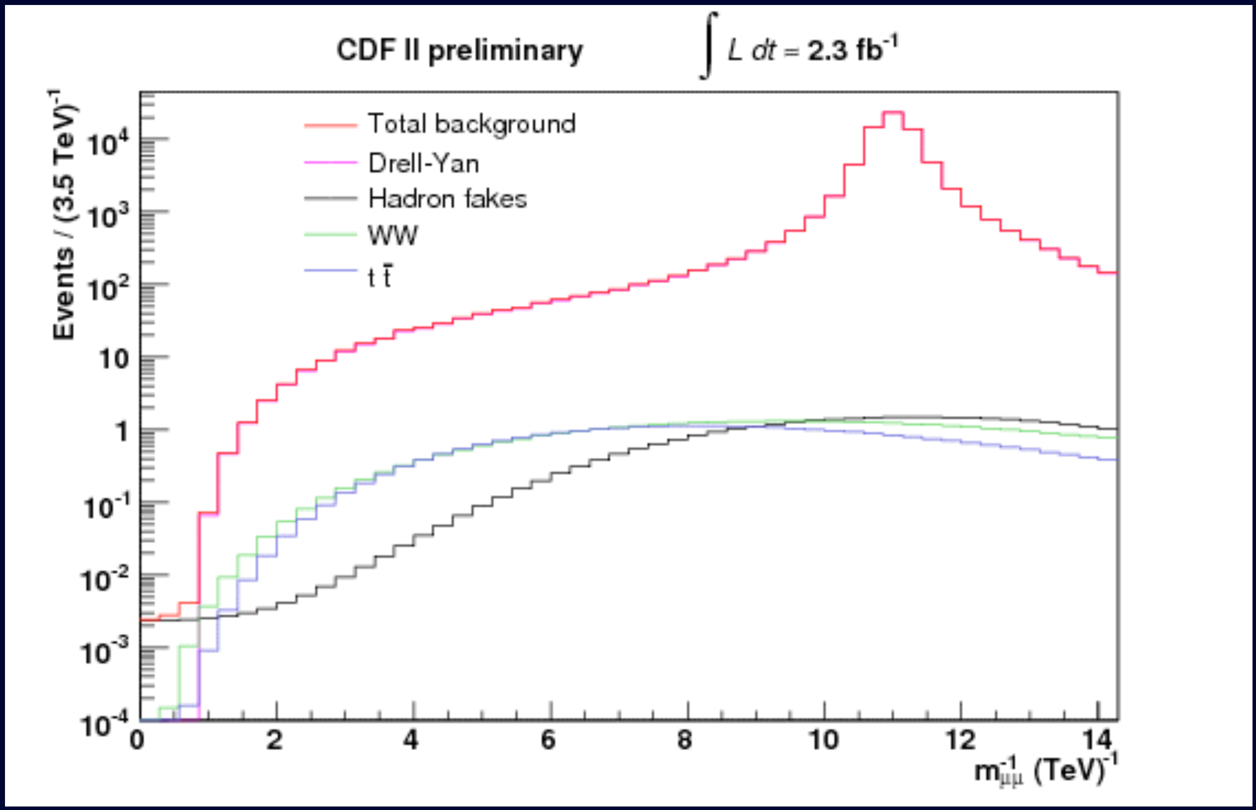


Expect few 10^{-3} events from misreconstructed muons at highest masses

100% normalization uncertainty for m > 1 TeV

WW and $t\bar{t}$ Background

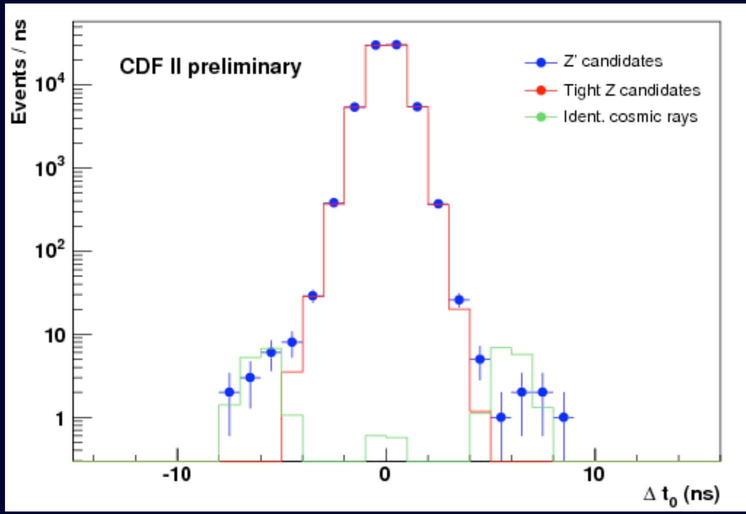
- **W-boson decays to muons result in muon pairs**
  - Use NLO cross section prediction
  - Obtain inverse mass shape from PYTHIA and full detector simulation

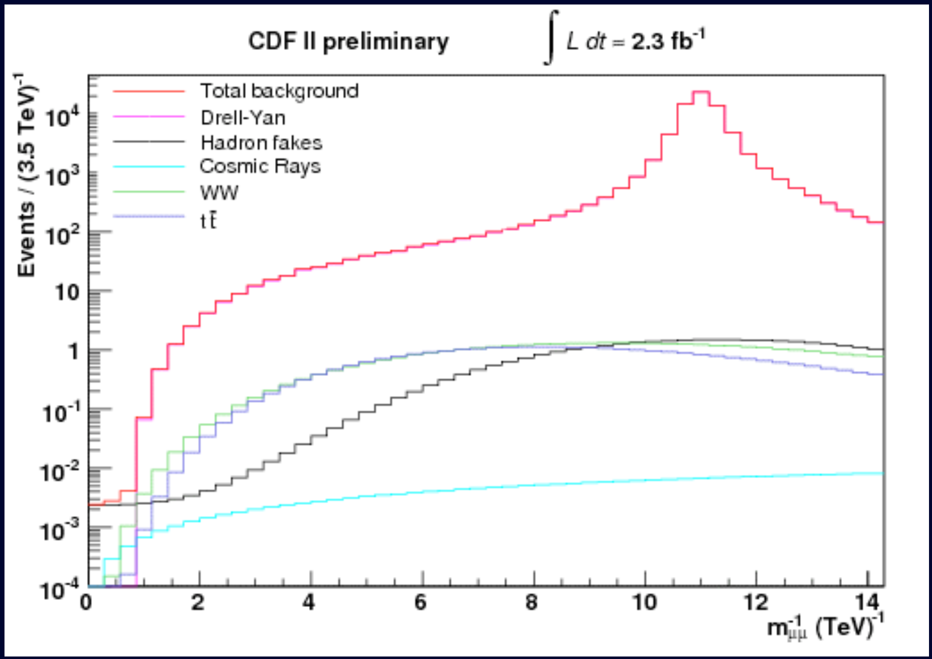


Cosmic-Ray Background

- **Cosmic-ray muons are reconstructed as muon pairs**
  - Can have very large momentum and reconstructed mass
  - Reduced to small level by cosmic-ray track-fit algorithm and χ^2 cut
  - Further reduction: require consistent origination times between muons
    - *~3 ns time difference between cosmic ray on opposite sides of tracker*
    - *~3 ns bias in fit for origination time of incoming muon*

Fit for background fraction using difference between muon origination times

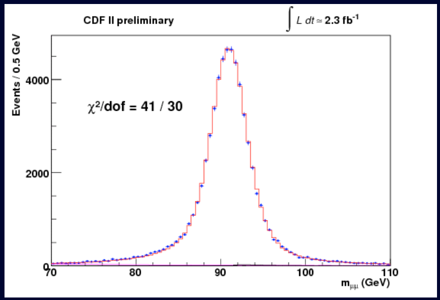


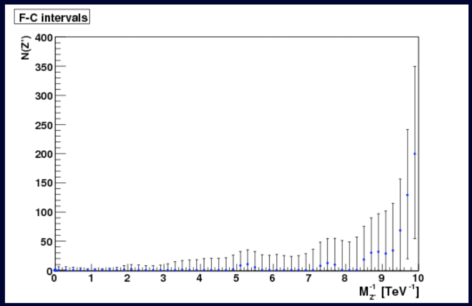


CDF Dimuon Resonance Search

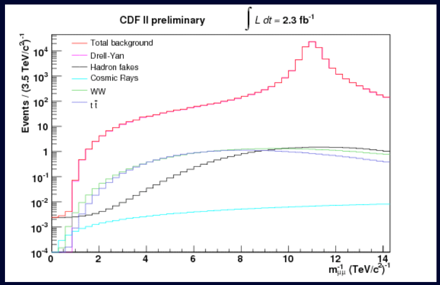
- **Procedure**

Calibrate detector resolution and scale

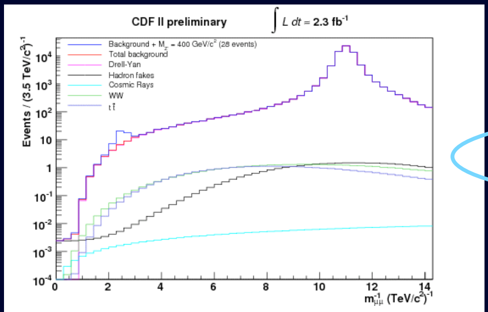




Determine scanning procedure



Understand background and uncertainty

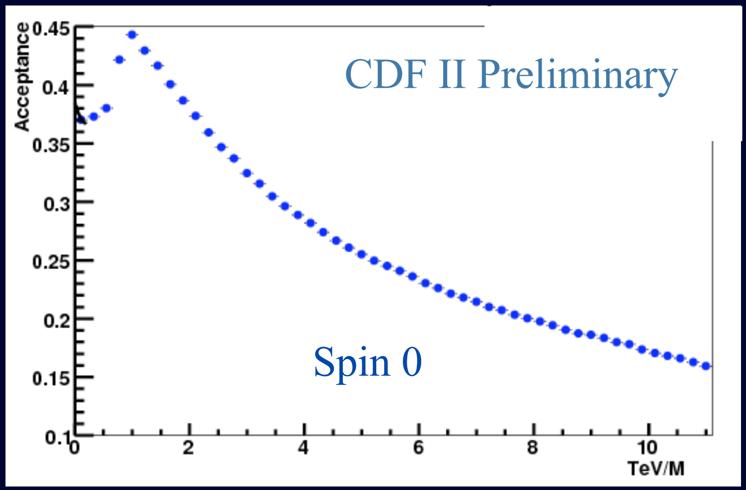


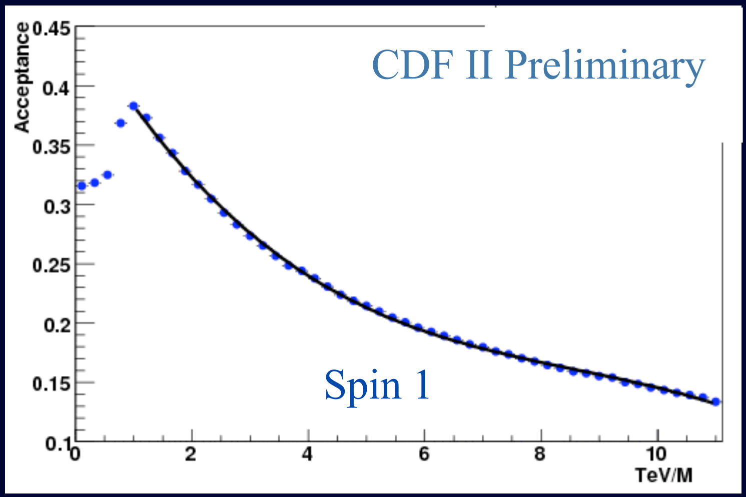
Predict signal and uncertainty

Interpret results from data

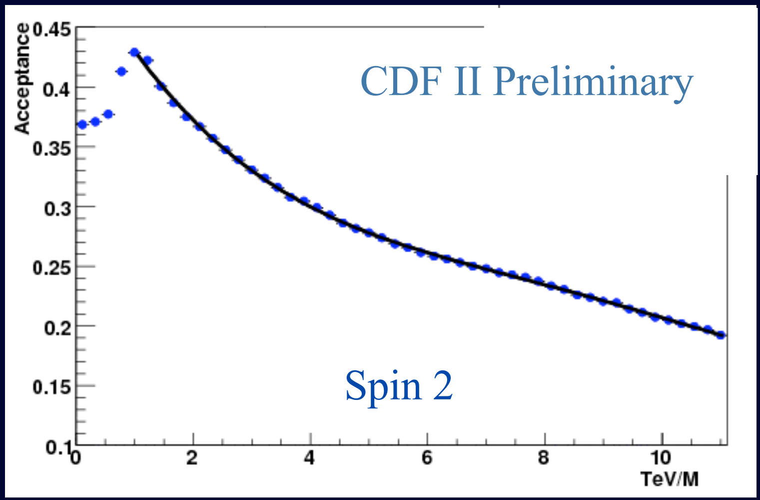
Signal Acceptance

- **Determine acceptance as functions of spin and inverse mass**





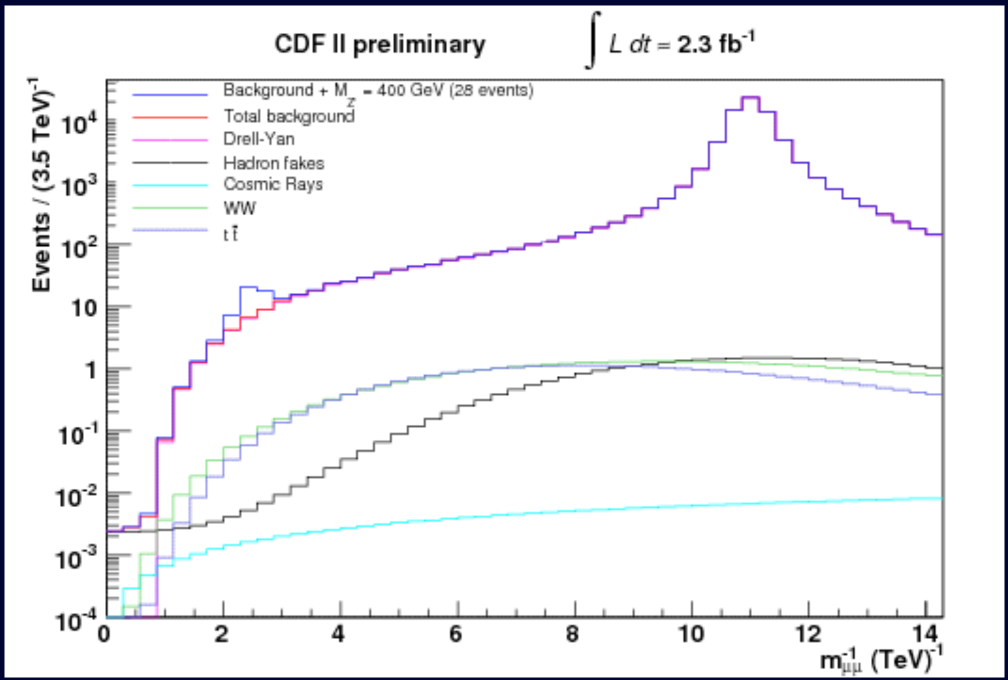
Acceptance increases with increasing mass: lower p_z, more central mouns



Acceptance decreases for masses above 1 TeV: parton luminosity suppresses resonance peak

Acceptance Uncertainty

- **Compare acceptance from fast simulation to full simulation**
  - 3% uncertainty on slope
- **Compare calorimeter selection efficiency to Z data**
  - Few percent inconsistency in low-p_T region
    - *Negligible (~0.1%) effect on integrated signal*

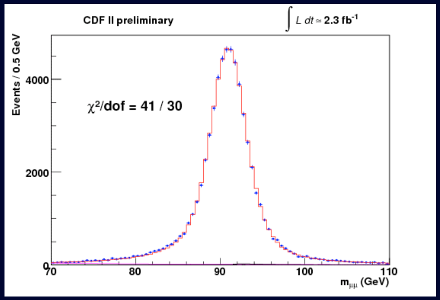


Effect of 28 events of $m_{Z'}$ = 400 GeV after selection

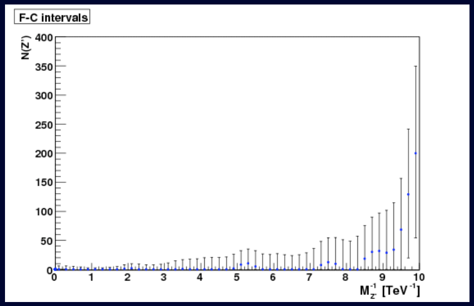
CDF Dimuon Resonance Search

- **Procedure**

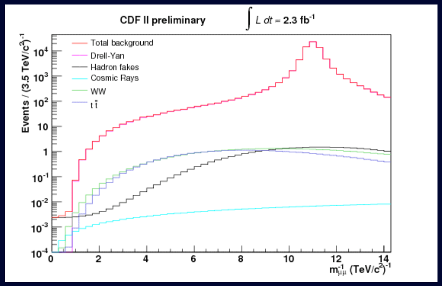
Calibrate detector resolution and scale



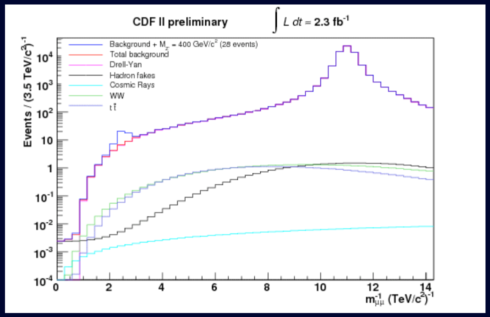
Determine scanning procedure



Understand background and uncertainty



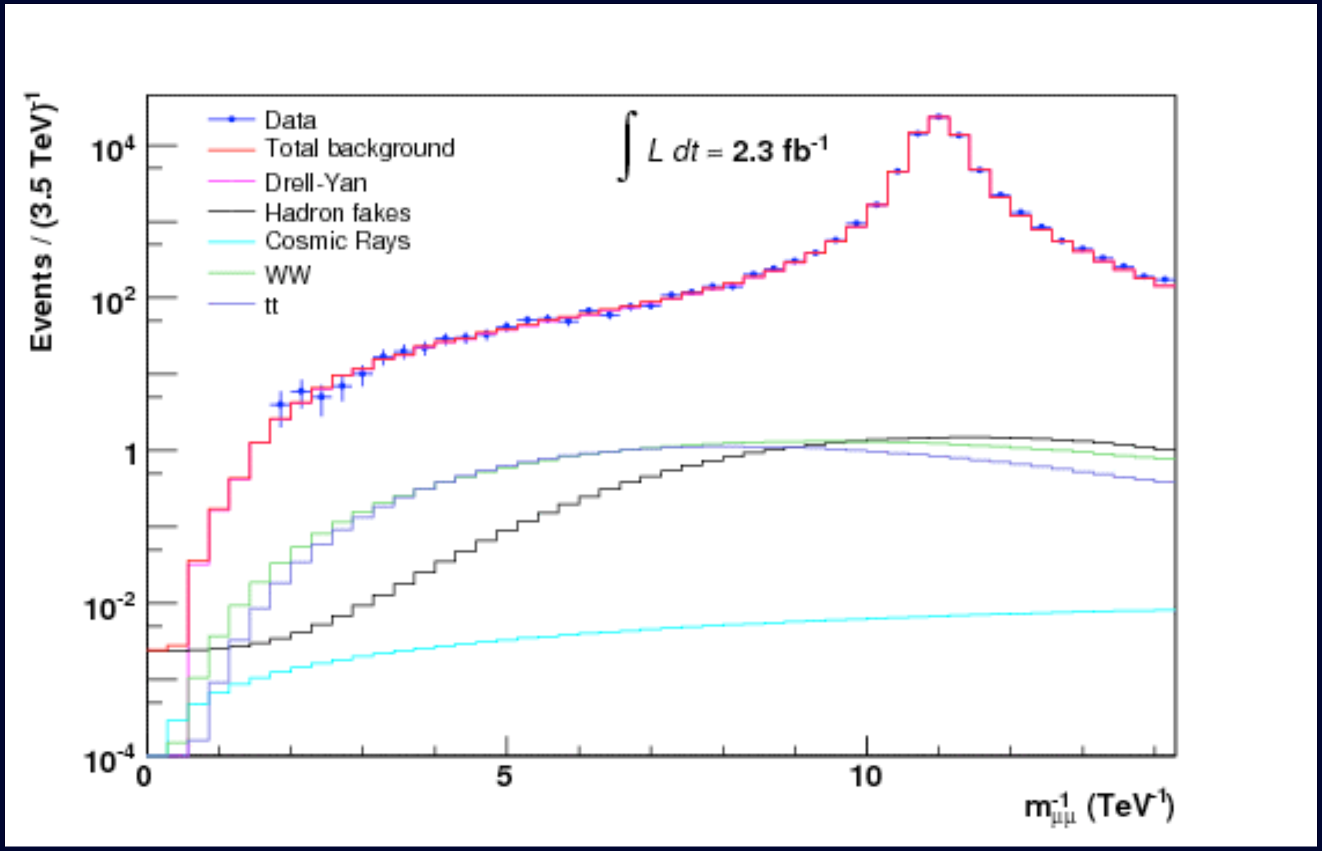
Predict signal and uncertainty



Interpret results from data

Data

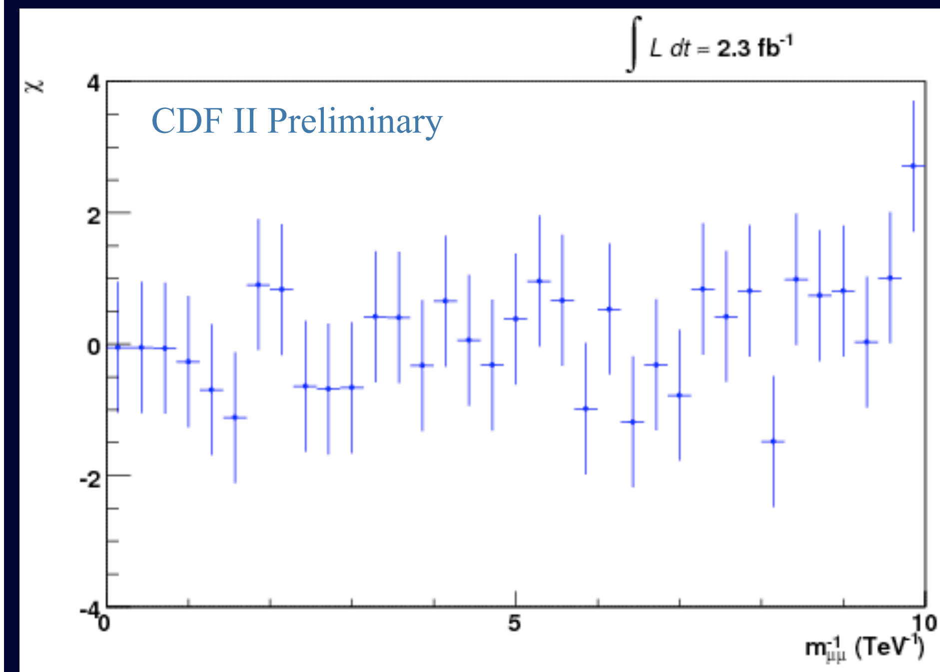
- **Good agreement in the normalization region...**

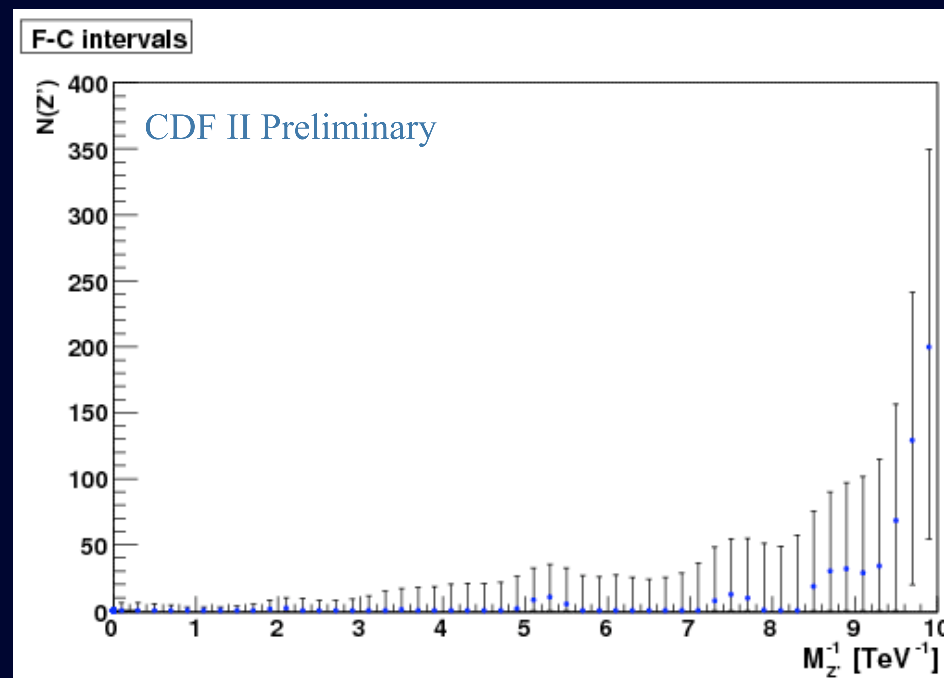


...and in the signal region

Data Results

- **Most significant excess at 103 GeV**

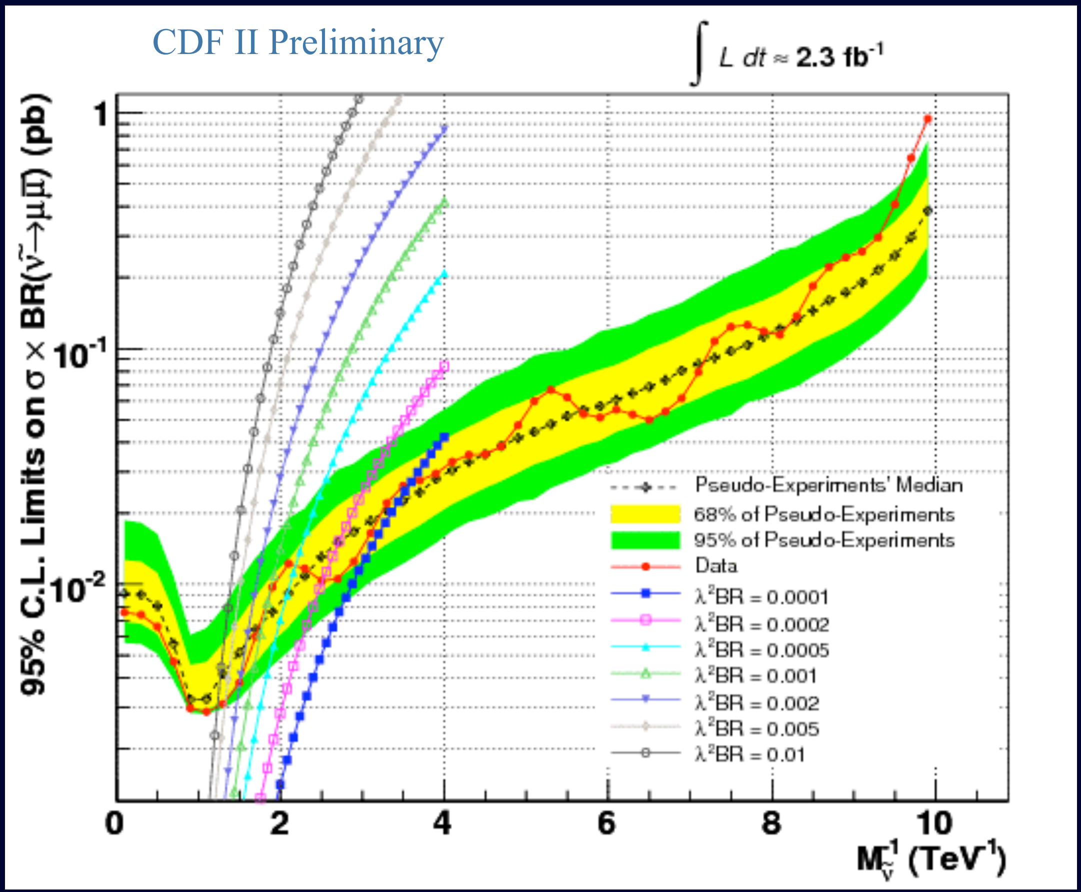




6.6% of pseudoexperiments observe a more significant excess

Spin-0 Limits

- **Limits on cross section and sneutrino mass**
  - Choose a variety of $\lambda^2 \times$ BR values (λ: $dd\tilde{\nu}$ coupling at production)

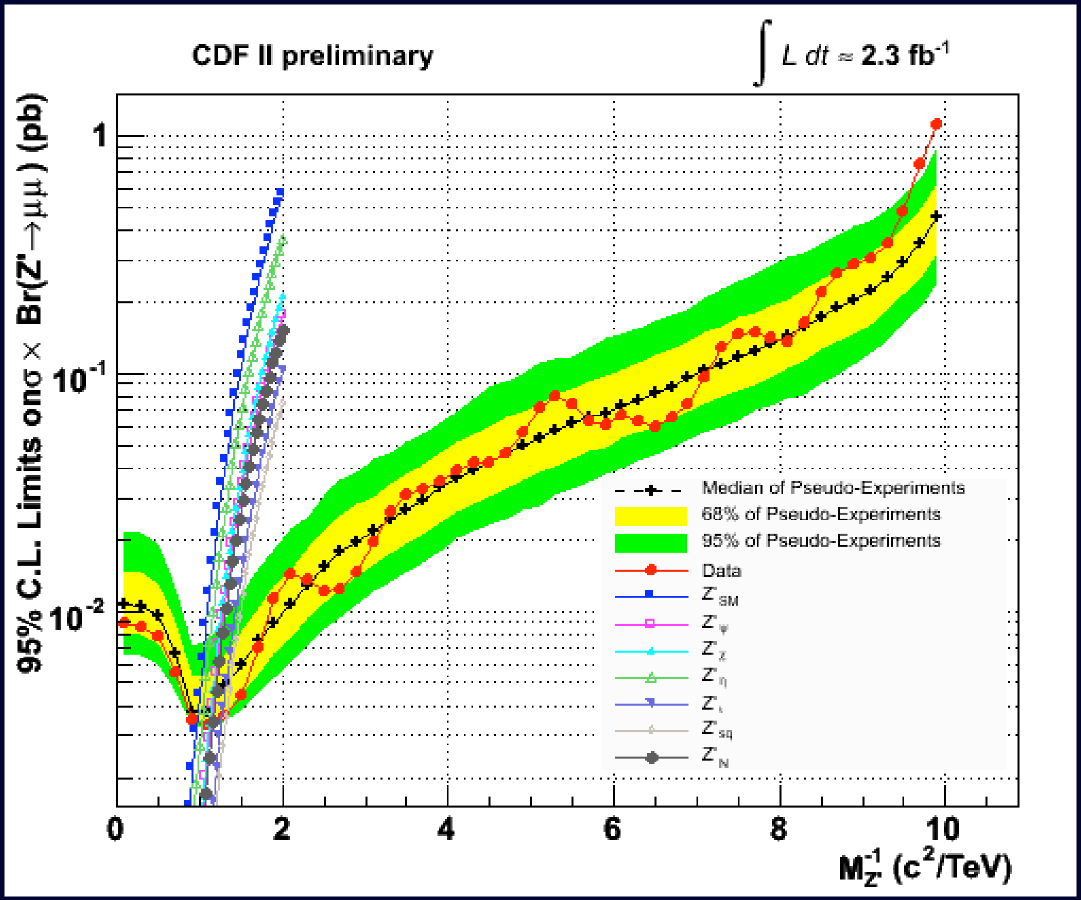


CDF II Preliminary

$\tilde{\nu}$ $\lambda^2_{\tilde{\nu}}$BR	$\tilde{\nu}$ mass limit
0.0001	278
0.0002	397
0.0005	457
0.001	541
0.002	662
0.005	751
0.01	810

Spin-1 Limits

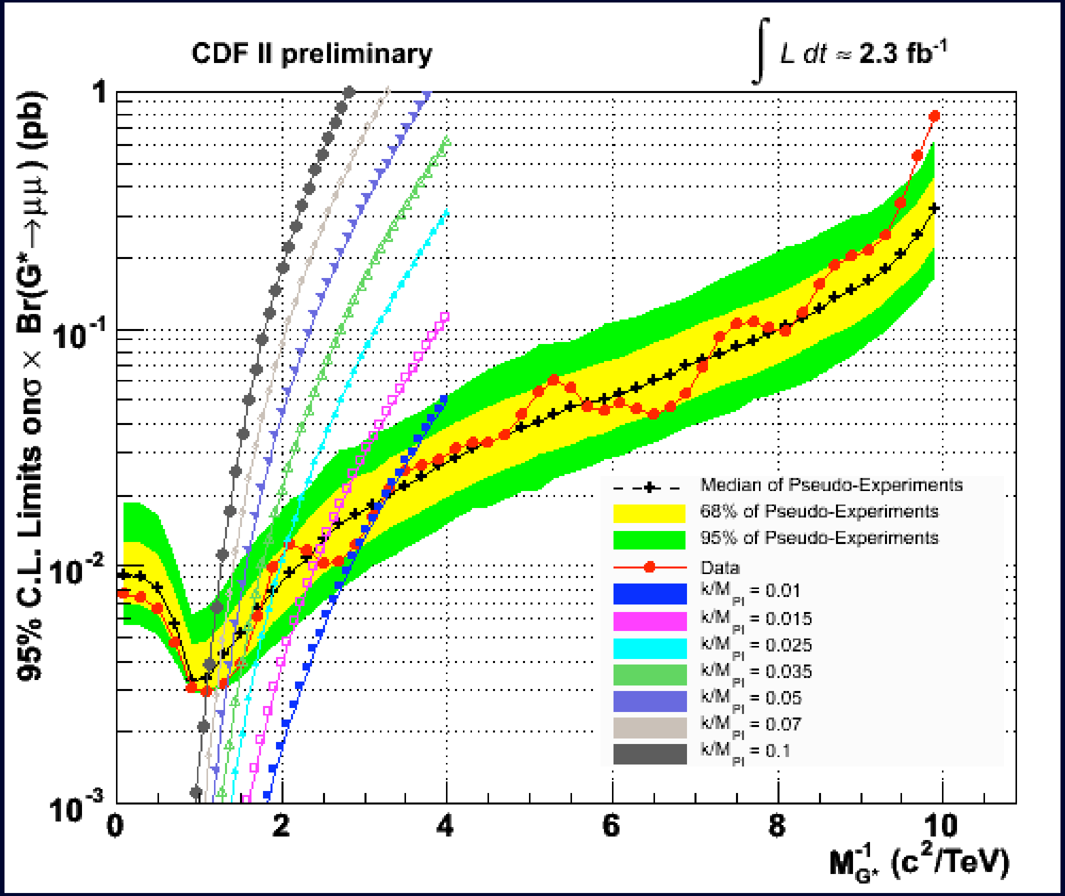
- **Limits on cross section and Z' mass for various models**



Model	Mass Limits, 95% CL (GeV/c^2)
Z' (SM)	1030
Z' (η)	975
Z' (χ)	892
Z' (ψ)	878
Z' (N)	861
Z' (ι)	789
Z' (sq)	754

Spin-2 Limits

- **Limits on cross section and mass of first excited R-S graviton**
  - Choose several couplings (k / M_{Pl})



Graviton k/M_{Pl}	Mass Limit, 95% CL (GeV/c^2)
0.1	921
0.07	824
0.05	746
0.035	651
0.025	493
0.015	409
0.01	293

Neutral Resonances: Present Limits

- **New results are world's highest direct mass limits for almost every model**

Analysis	Spin 0: $\tilde{\nu}$ (λ^2BR = 0.01)	Spin 1: Z'_η	Spin 2: G^* (k/M_{Pl} = 0.1)
CDF $ee + \mu\mu$ (0.20 pb^{-1})	665 ($\mu\mu$)	720	710
CDF ee (0.45 pb^{-1})	-	745	-
DØ $ee + \gamma\gamma$ (1.0 fb^{-1})	-	-	900
CDF $ee + \gamma\gamma$ (1.3 fb^{-1})	-	891	889
CDF ee (2.5 fb^{-1})	-	933	850
CDF $\mu\mu$ (2.3 fb^{-1})	**810**	**975**	**921**

Summary

- **New technique applied to search for high-mass resonances decaying to dimuons**
  - Simplifies search and interpretation
- **Set world's highest mass limits for almost every model, mass and coupling**
  - Key: excellent CDF tracker resolution
- **Neutral resonance discovery could be just around the corner**
  - Will soon have increases in luminosity and energy