Search for Narrow Dimuon Resonances at CDF

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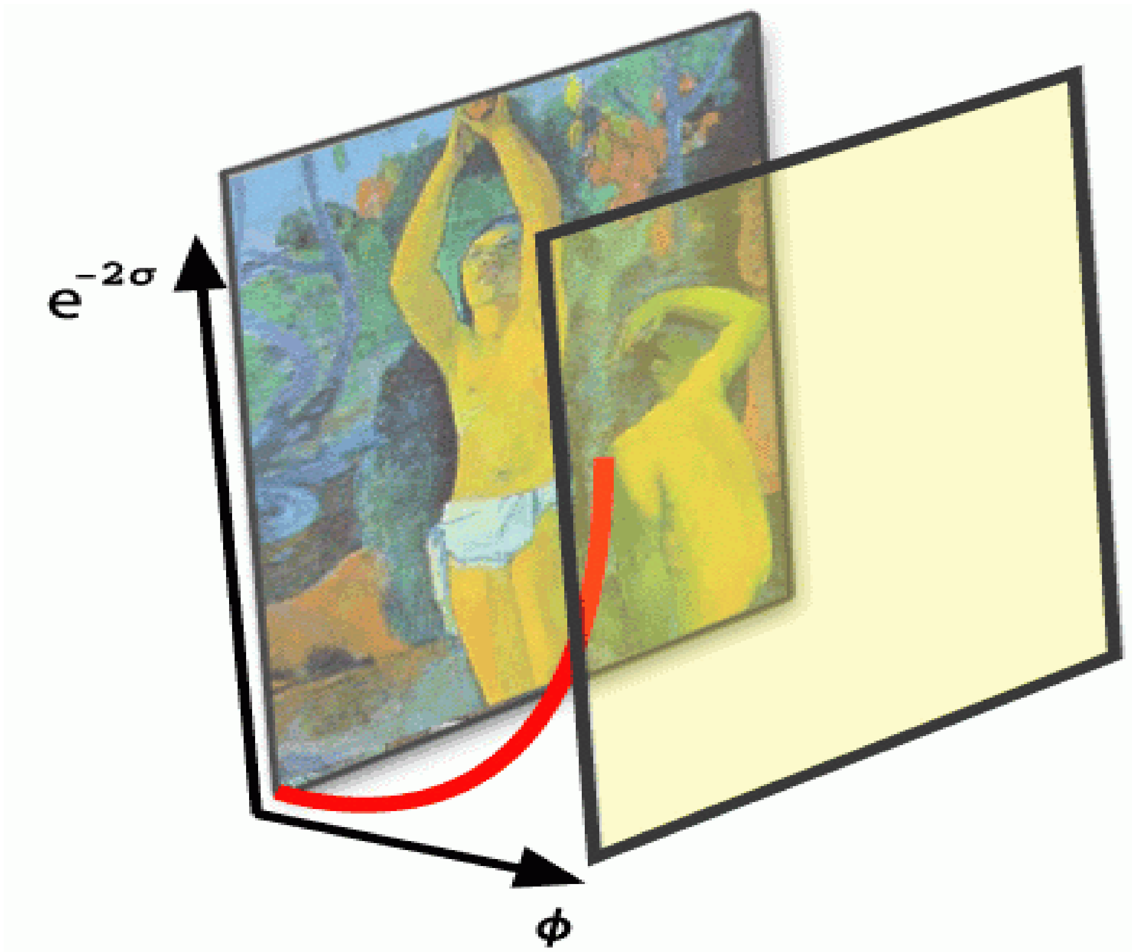


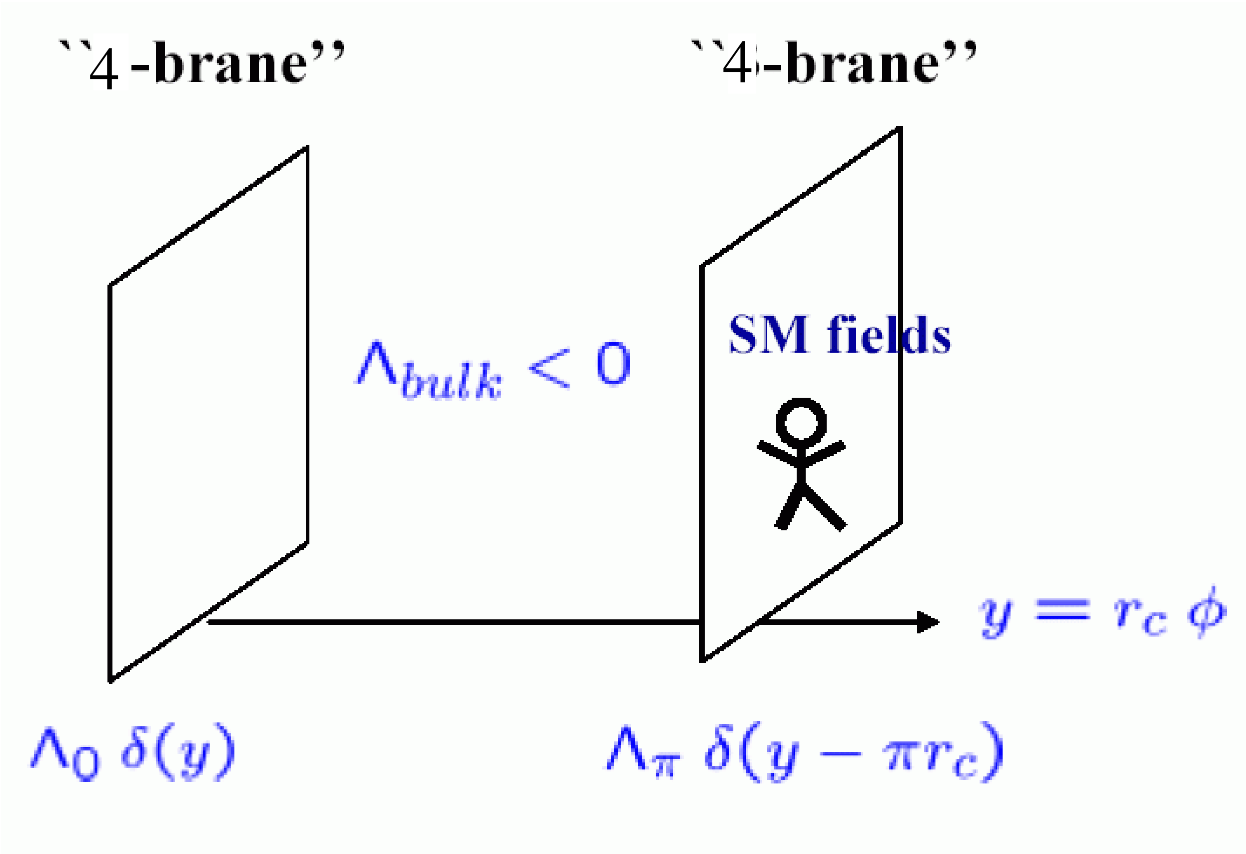
High Energy Physics Seminar
Tata Institute of Fundamental Research
19 December 2008

Motivation

- Dilepton resonances have a strong track record for discovery
  - J/ψ, Υ, *Z*
- Motivation continues at higher energy:
  - Unification of fermions/forces in the context of grand unified theories / String Theory typically based on extended gauge group, eg. SO(10), E_6
  - Symmetry-breaking of larger gauge group to SM groups generates additional U(1) gauge groups in intermediate stages, eg.
    - $E_6 \rightarrow SO(10) + U(1)_\psi \rightarrow SU(5) + U(1)_\psi + U(1)_\chi$
  - The breaking of these intermediate U(1) gauge symmetries produces heavy Z' bosons
  - Coupling of $\mathcal{O}(\alpha_{EW})$ implies small width/mass ratio

Motivation

- Gravity also enters the game
- Randall-Sundrum model of "gravity unification"
  - i.e. Ameliorating the problem of large hierarchy between electroweak symmetry breaking energy scale and Planck mass scale
  - a.k.a. "why is gravity so much weaker than electroweak force?"
- Suggested solution: its not really, but just appears to be so weak...

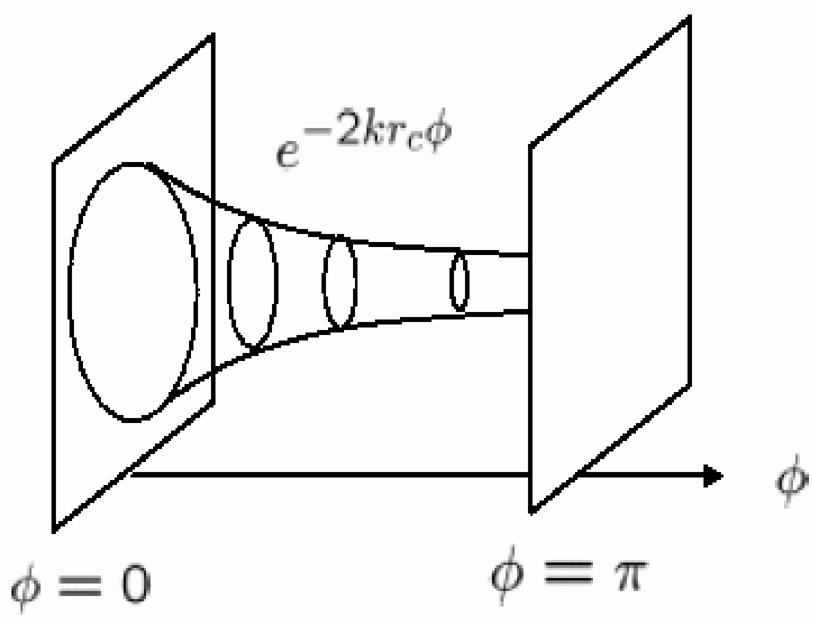


Randall and Sundrum, PRL 83 (1999) 3370

Motivation

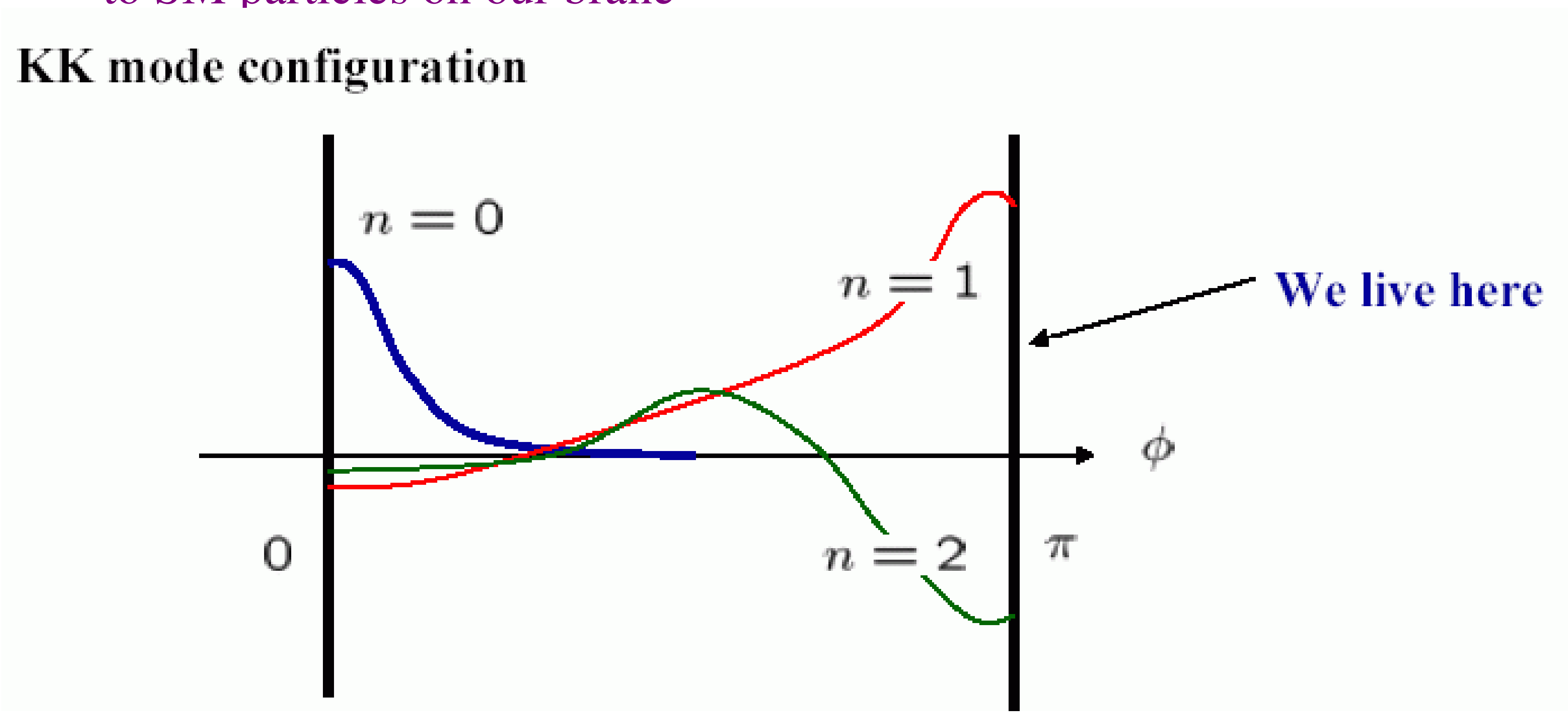
- Randall-Sundrum prescription
  - Construct Gravitational Lagrangian in bulk and on branes
  - Derive equation of motion for the metric, from principle of stationary action
  - Solve for metric $g_{\mu\nu}$:

Solution: $$ds^2 = e^{-2kr_c|\phi|}\eta_{\mu\nu}dx^\mu dx^\nu + r_c^2 d\phi^2$$



Motivation

- Randall-Sundrum prediction:
  - Ground-state wave function of graviton small on our brane, ie gravity appears weak
  - But excited states of graviton wave function has big overlaps, ie. Massive Kaluza-Klein gravitons with electroweak-strength couplings to SM particles on our brane



Motivation

- Models of new physics also contains scalar particles
  - Higgs bosons with enhanced couplings to muons
  - Supersymmetric partner of neutrino in R-parity violating SUSY models: s-channel resonant production of sneutrino, decaying to dimuons
- We use sneutrinos, Z', and Gravitons as examples of new particles with spin 0, 1 and 2 respectively
- Particle spin affects the angular distribution of decay muons and the detector acceptance

Methodology

- Using the Z' resonance as an example, we scan the dimuon mass spectrum using simulated templates generated as a function of Z' mass

- For each Z' mass, we scale the expected dimuon mass distribution so as to vary its integrated number of Z' events, N(Z').

- The total expected distribution in dimuon mass is obtained by adding the (scaled) Z' template distribution and the standard model and misidentification background distributions

- The total expected distribution is normalized to the data in the Z mass peak region.

- The binned poisson likelihood is computed between the total expected distribution and the data distribution in dimuon mass.

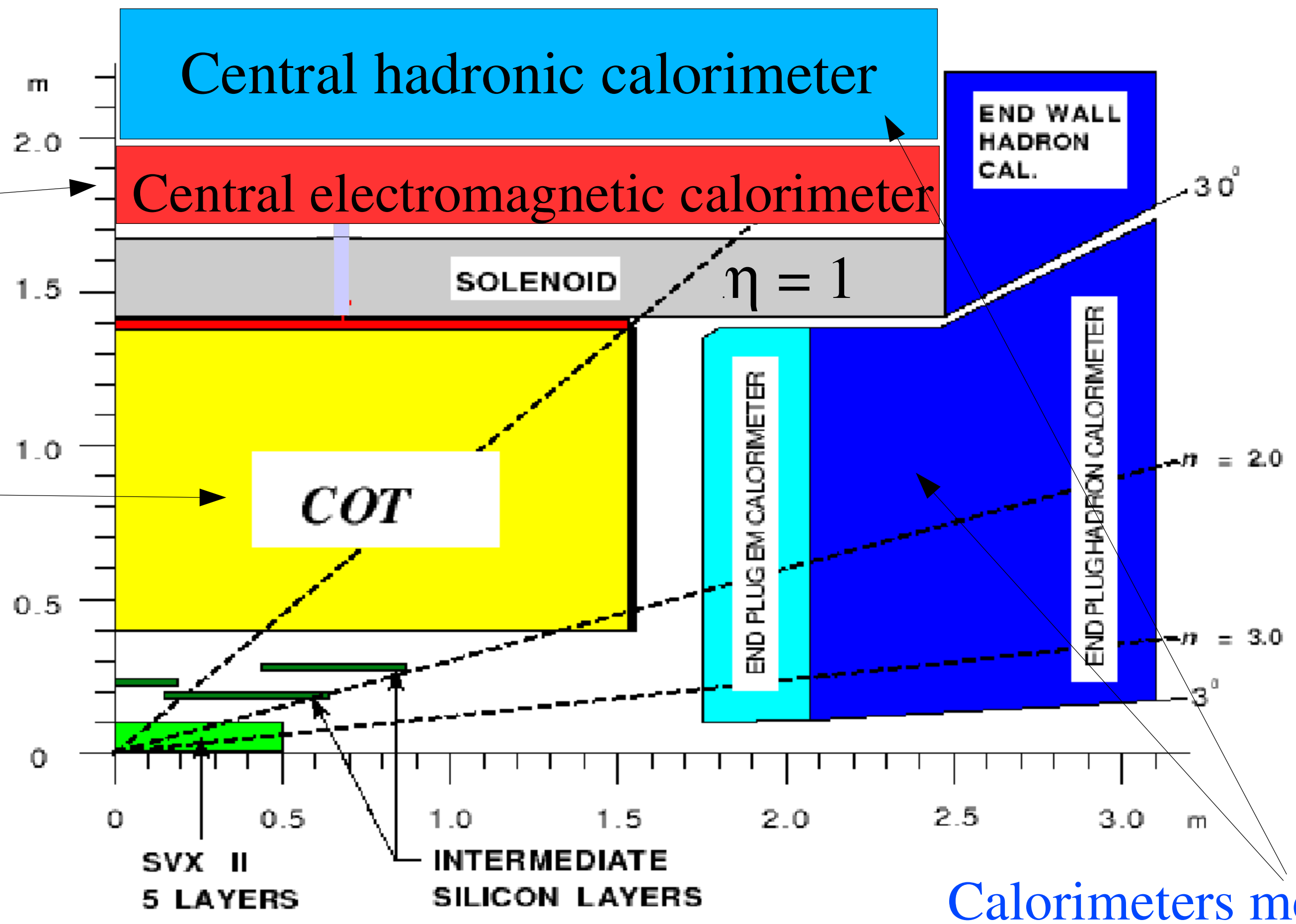
Methodology

- At each Z' pole mass, we compute the total poisson likelihood over all data bins, as a function of N(Z')
  - Systematic uncertainties are correlated across the bins and are incorporated as nuisance parameters
  - Nuisance parameters are varied by expected uncertainty and averaged over
- We use the total poisson likelihood to compute the interval for N(Z') at any specified confidence level
  - Feldman-Cousins prescription is used to construct the interval
  - The prescription automatically chooses 1-sided or 2-sided interval depending on whether N(Z')=0 is excluded
- We obtain the “maximum-likelihood” estimate of N(Z') and its confidence interval at each value of the Z' pole mass

Quadrant of Collider Detector at Fermilab (CDF)

EM calorimeter provides precise electron energy measurement

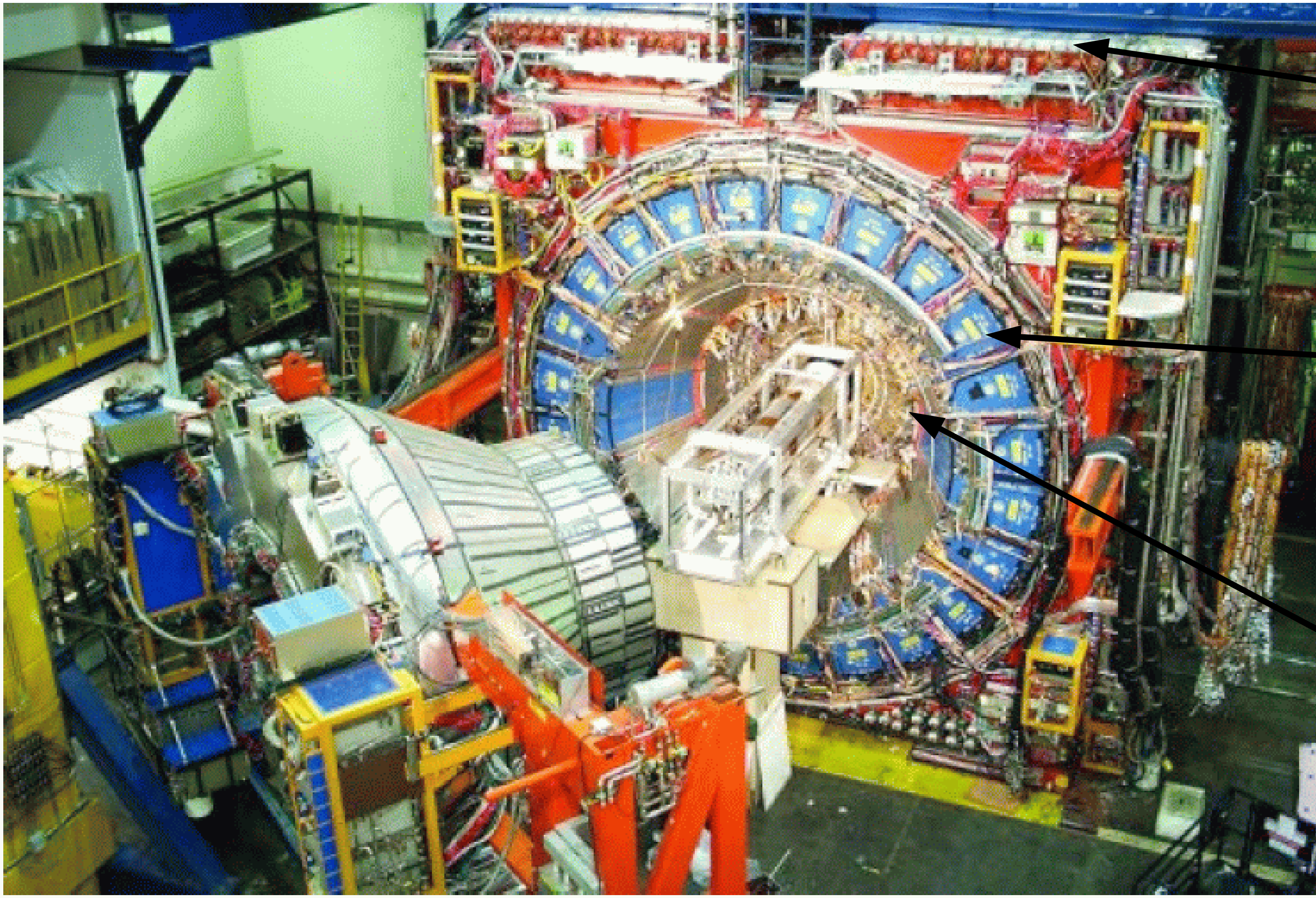
COT provides precise lepton track momentum measurement



Calorimeters measure hadronic recoil particles

Select events with two central (| η | < 1) muons

Collider Detector at Fermilab (CDF)

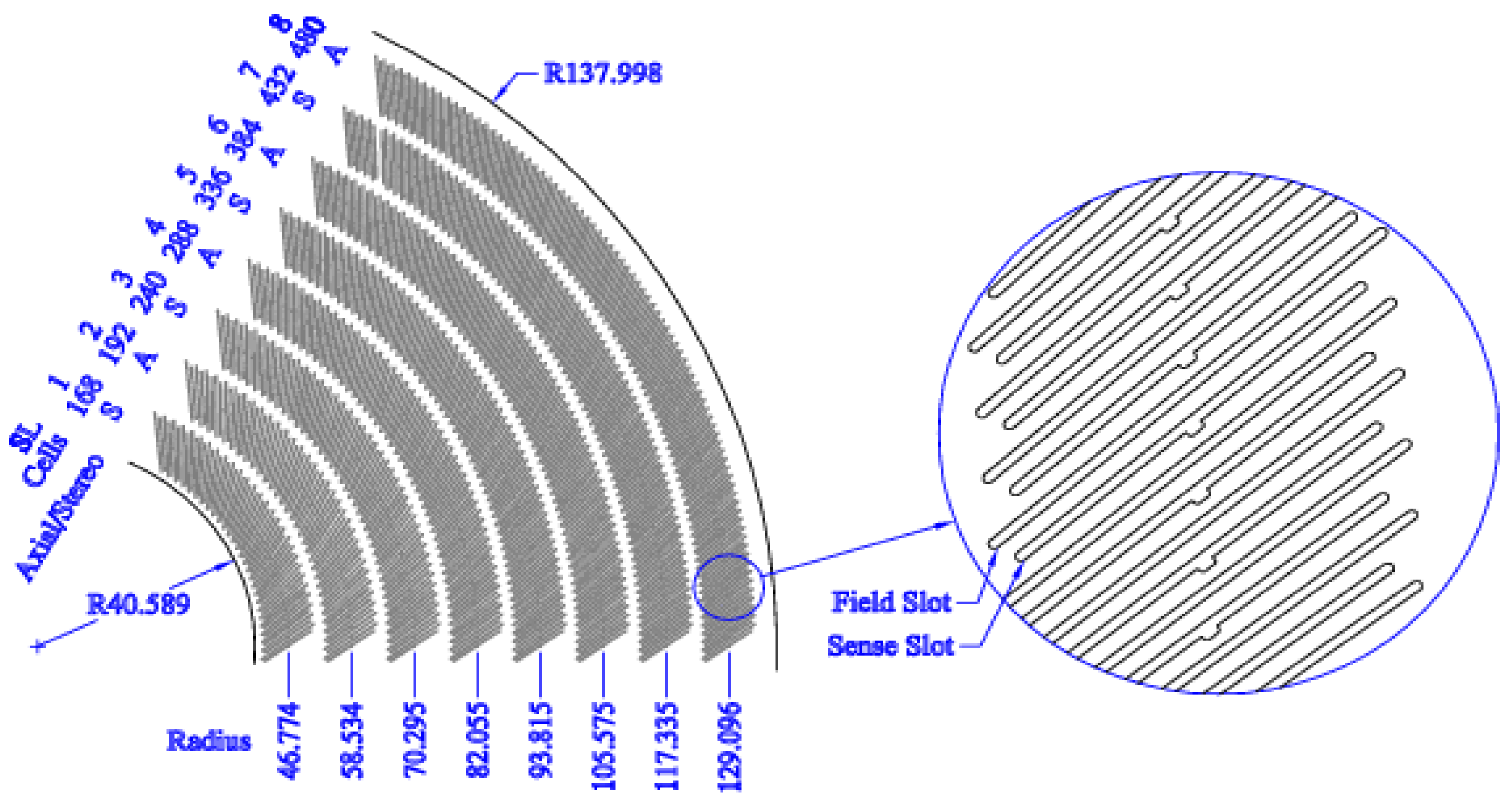


Muon detector

Central hadronic calorimeter

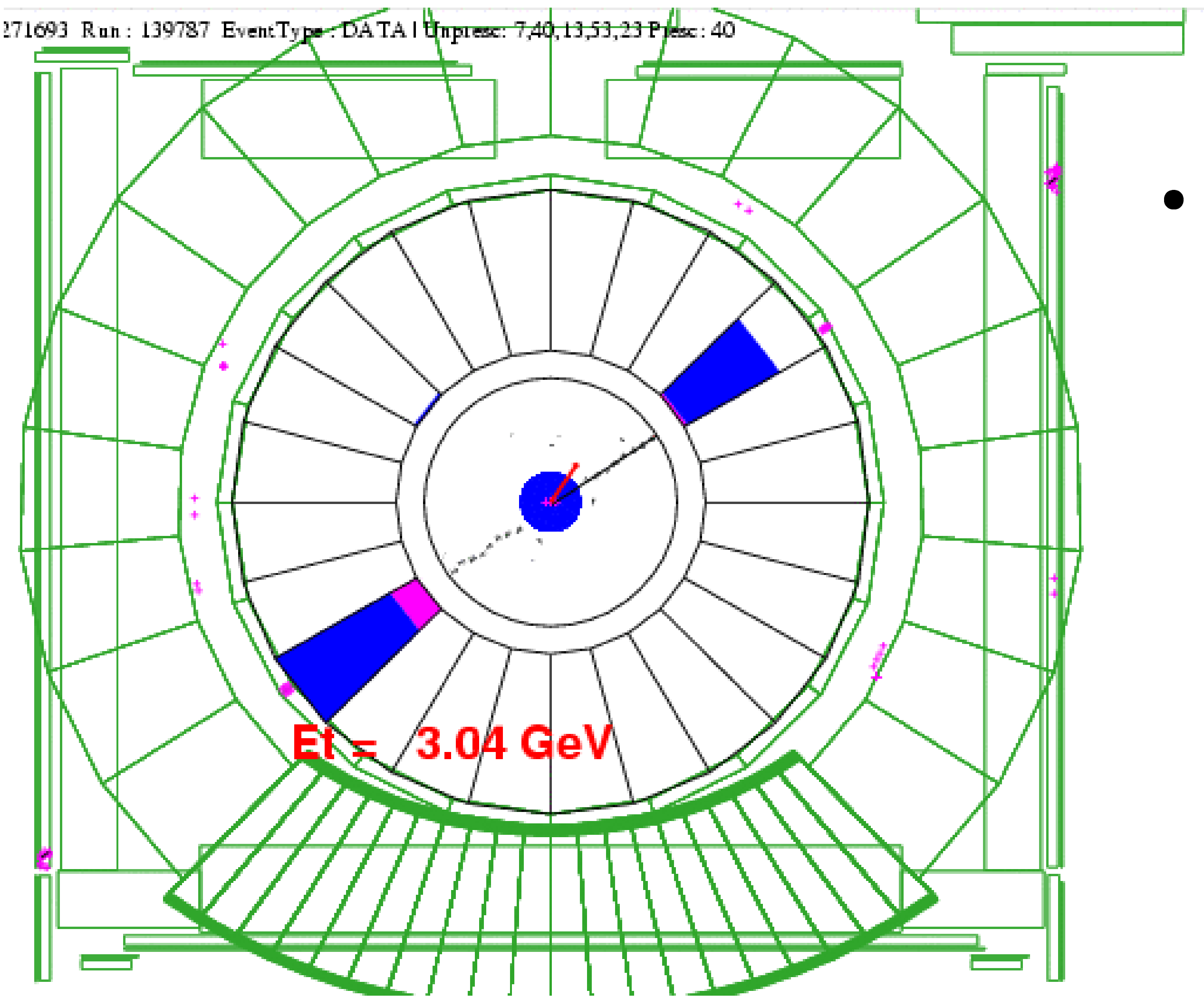
Central outer tracker (COT)

Drift Chamber (COT) Alignment



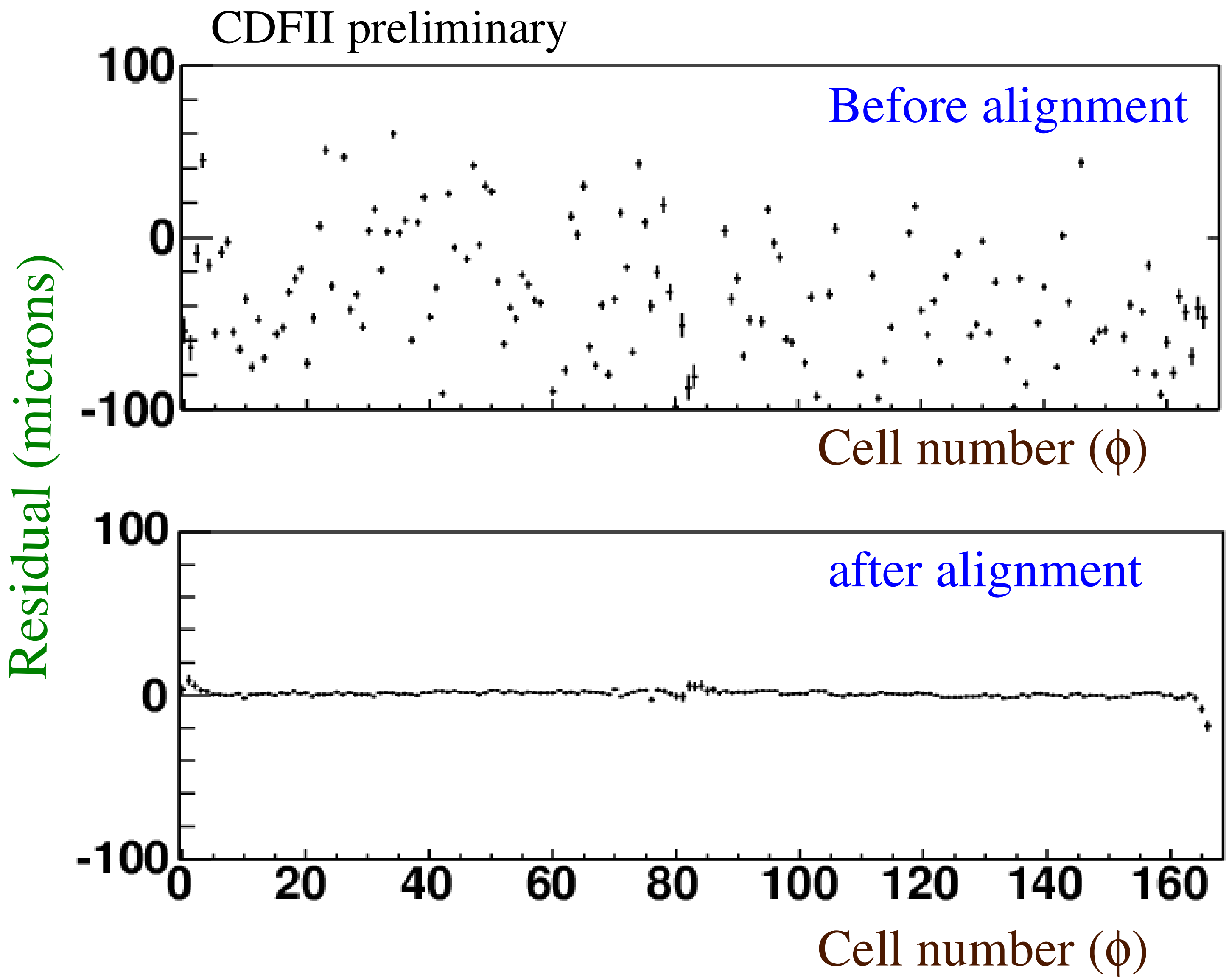
Internal Alignment of COT

- Use a clean sample of ~200*k* cosmic rays for cell-by-cell internal alignment



- Fit COT hits on both sides simultaneously to a single helix (AK, H. Gerberich and C. Hays, NIMA 506, 110 (2003))
  - Time of incidence is a floated parameter in this 'dicosmic fit'

Residuals of COT cells after alignment

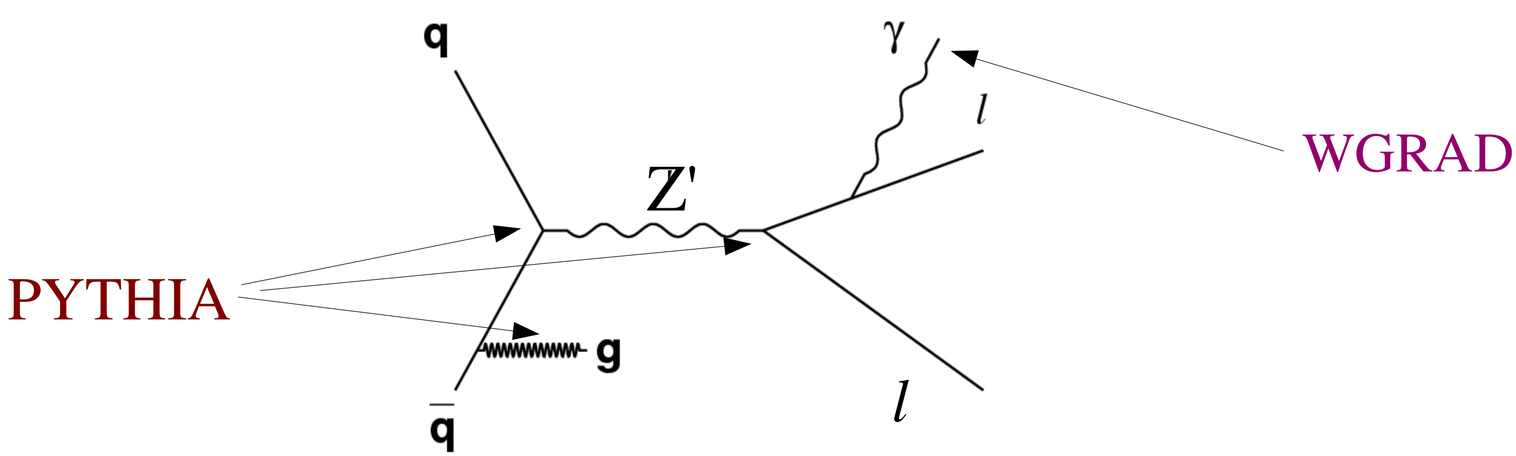


Final relative alignment of cells ~5 μm (initial alignment ~50 μm)

Signal Simulation and Fitting

Signal Simulation and Template Fitting

- All signals simulated using a fast Monte Carlo
  - Generate finely-spaced templates as a function of the resonance pole mass
  - perform binned maximum-likelihood fits to the data
- Custom fast Monte Carlo makes smooth, high statistics templates
  - And provides analysis control over key components of the simulation



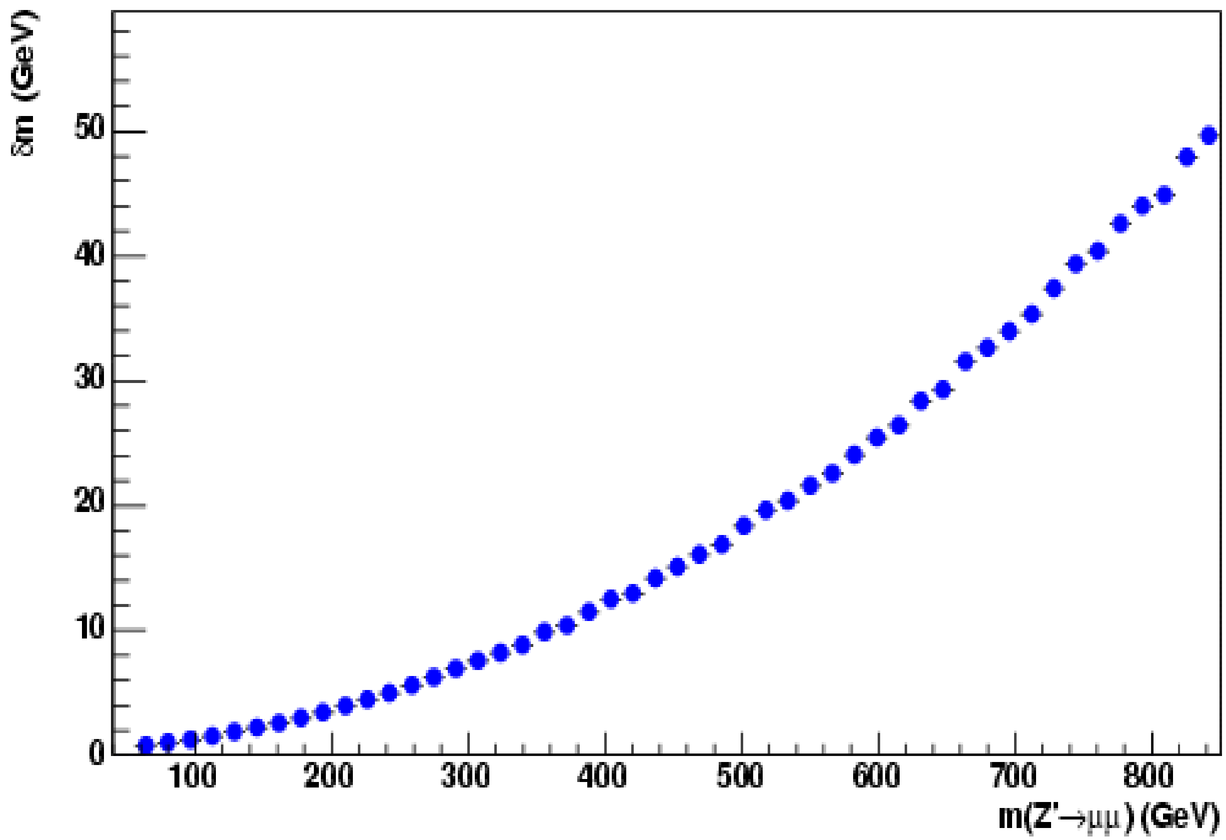
- Generator-level input for W & Z simulation provided by PYTHIA
- Radiative photons generated according to energy *vs* angle lookup table from WGRAD (U. Baur, S. Keller & D. Wackeroth, PRD59, 013002 (1998))

Fast Monte Carlo Detector Simulation

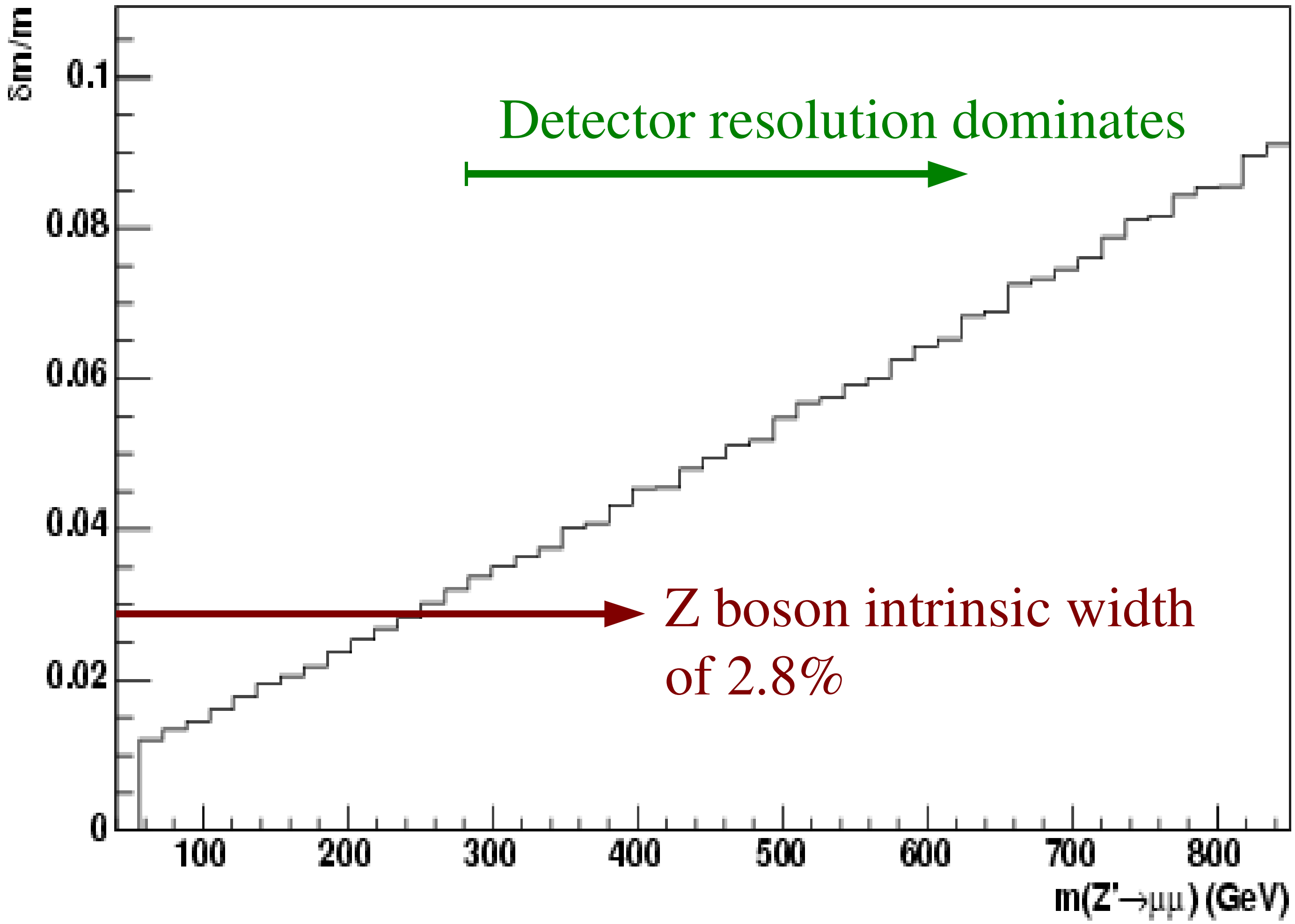
- A complete detector simulation of all quantities measured in the data
- First-principles simulation of tracking
  - Tracks and photons propagated through a high-resolution 3-D lookup table of material properties for silicon detector and COT
  - At each material interaction, calculate
    - Ionization energy loss according to complete Bethe-Bloch formula
    - Simulate multiple Coulomb scattering, including non-Gaussian tail
  - Deposit and smear hits on simulated COT wires, perform full helix fit including beam-constraint

Mass resolution vs mass

- Tracking resolution of muon momentum degrades rapidly as mass and p_T increase, as $\Delta p_T \sim p_T^2$
- Rapidly varying resolution makes fixed binning sub-optimal at either low mass or high mass – ideally want variable mass binning such that Z' propulates a fixed number of bins at any mass

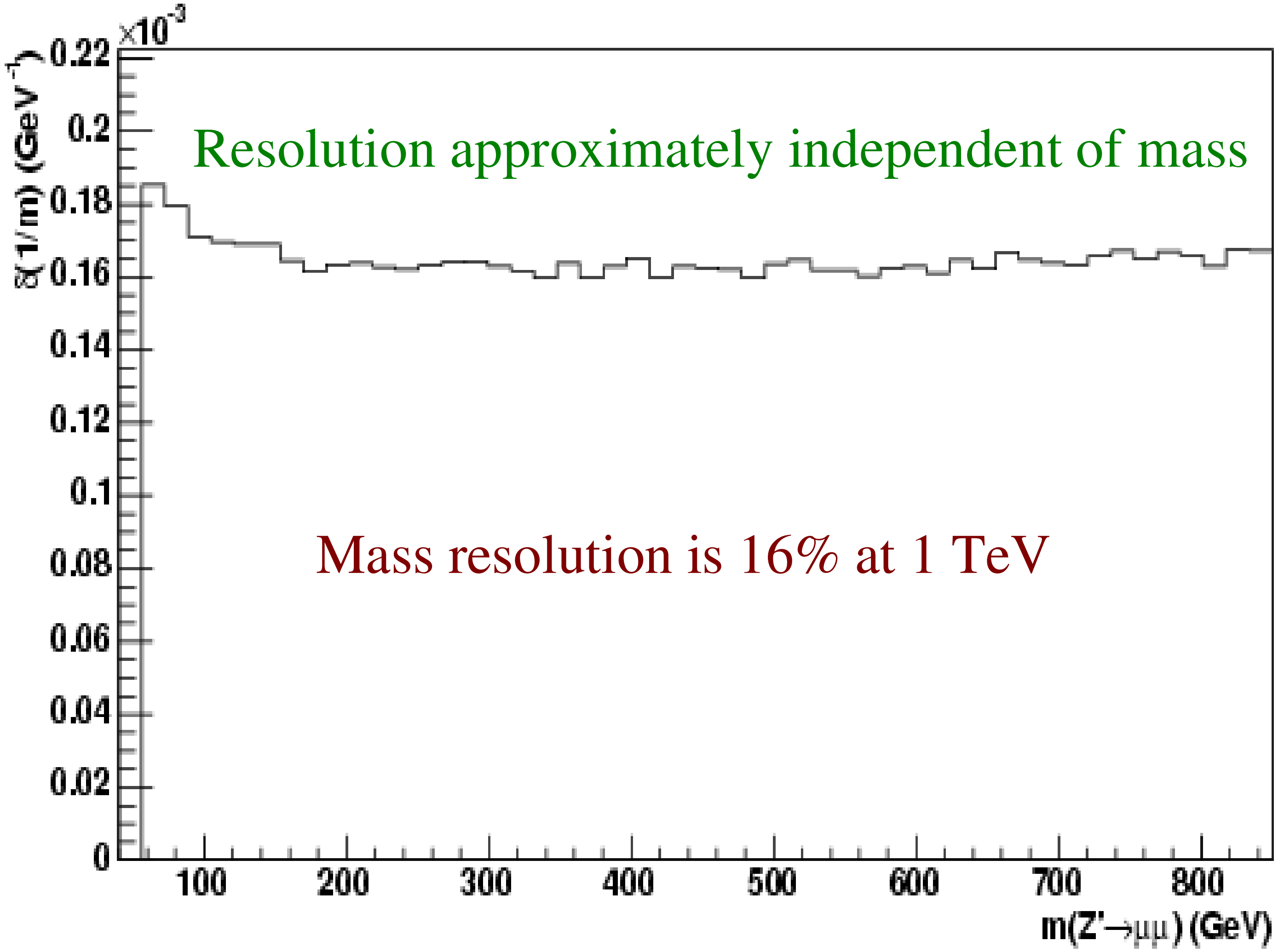


Fractional mass resolution vs mass

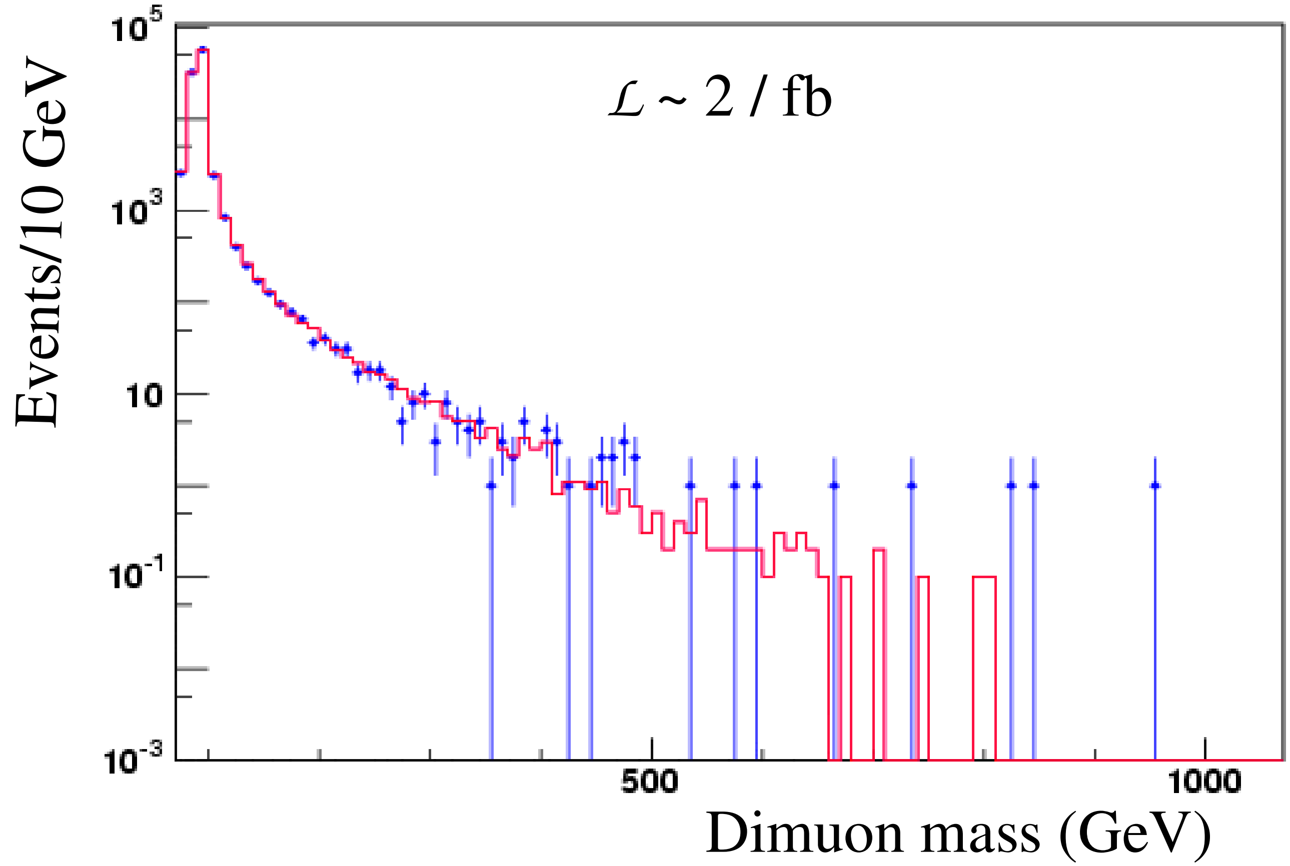


Mass^{-1} resolution vs mass

- Tracking resolution of muon momentum $\Delta(1/p_T)$ ~ constant
- Instead of the dimuon mass distribution, we choose to work with the dimuon (1/mass) distribution, where resolution ~ constant

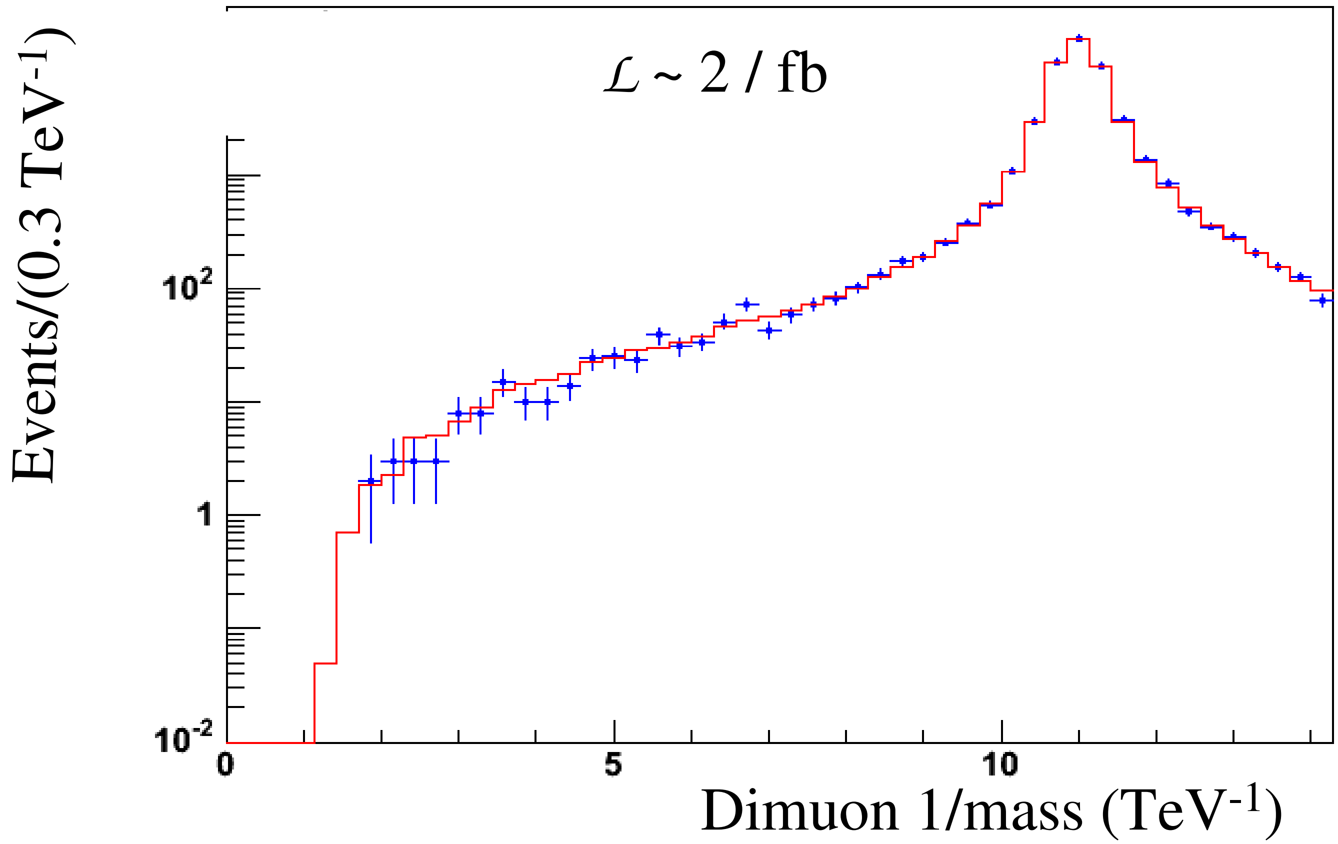


Monte Carlo Pseudo-Experiment



- simulated Standard Model (Drell-Yan) background (RED) and Monte Carlo pseudo-experiment (BLUE) with SM + Z' (900 GeV)
- PYTHIA used as generator

Monte Carlo Pseudo-Experiment

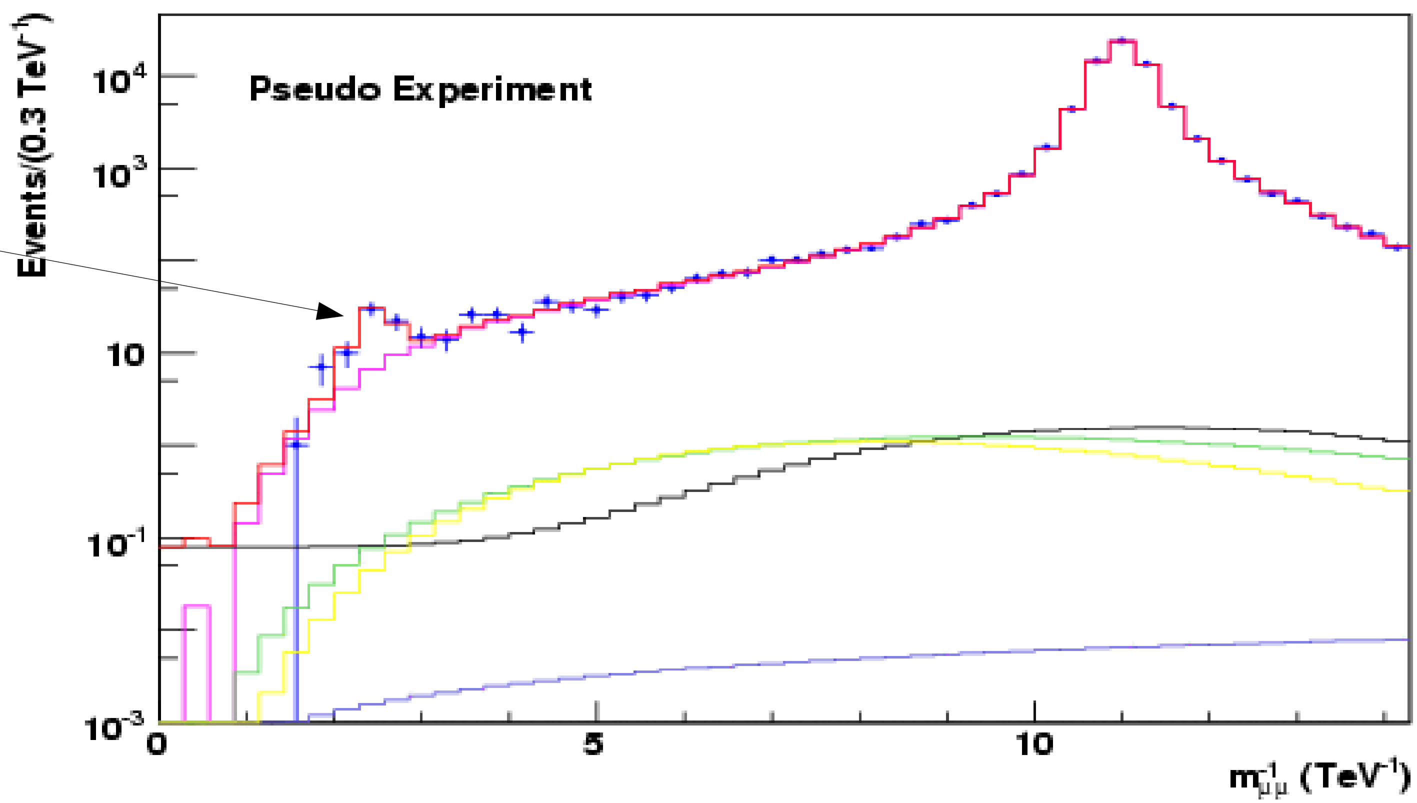


- Simulated SM (Drell-Yan) background (RED) and SM pseudo-experiment (BLUE)

Mass Peak Fitting

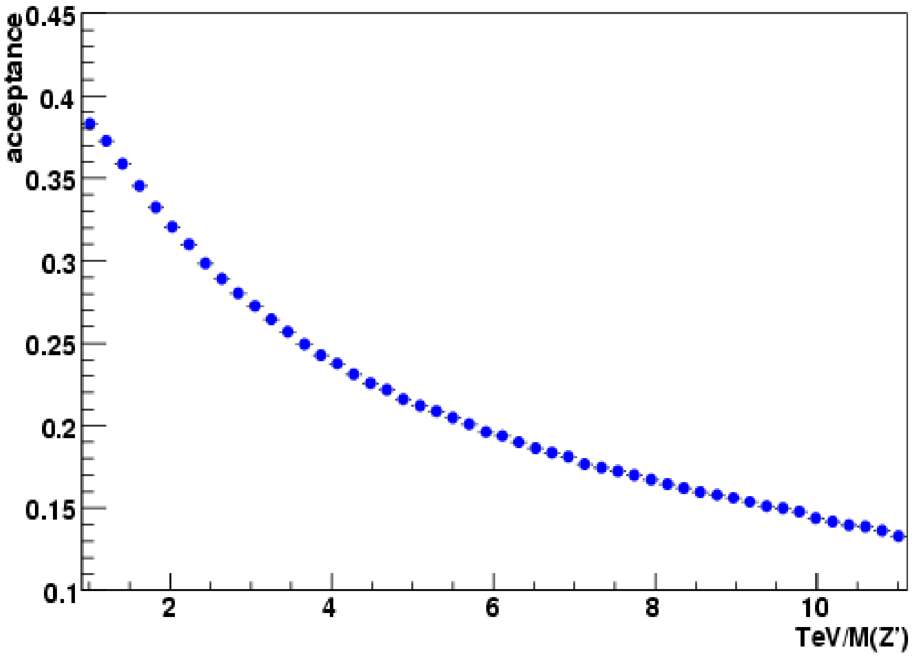
- Integral of Z' template = number of Z' events N(Z')
- Perform maximum likelihood fit to data for N(Z'), using sum of background and Z' template shapes
  - Poisson probability per bin, product over bins

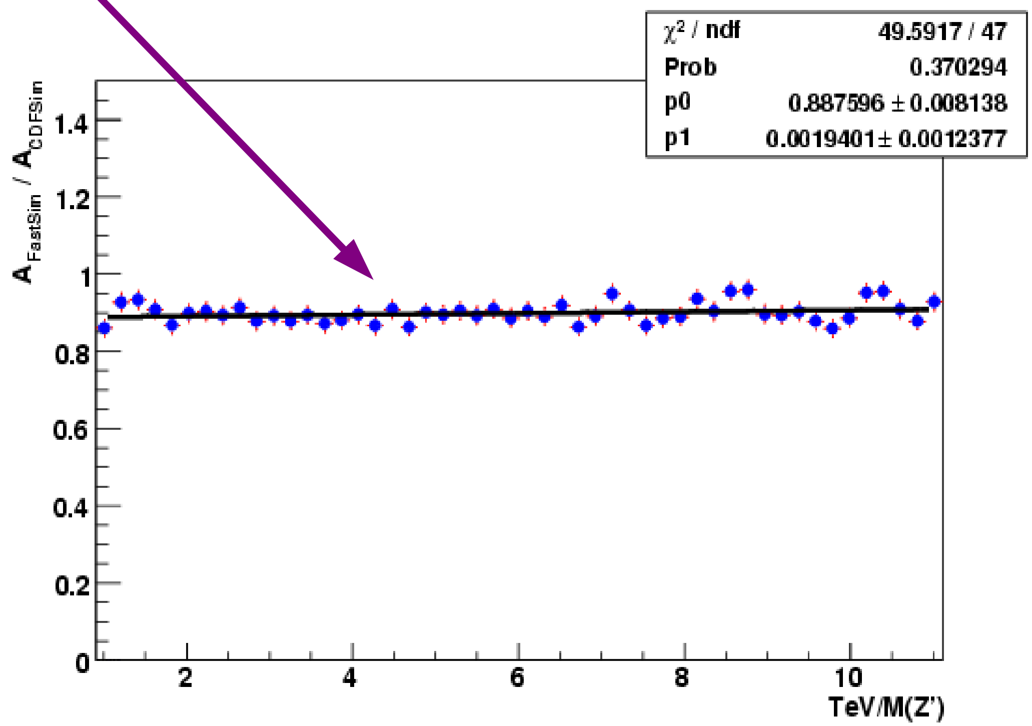
Z' MC



Technique

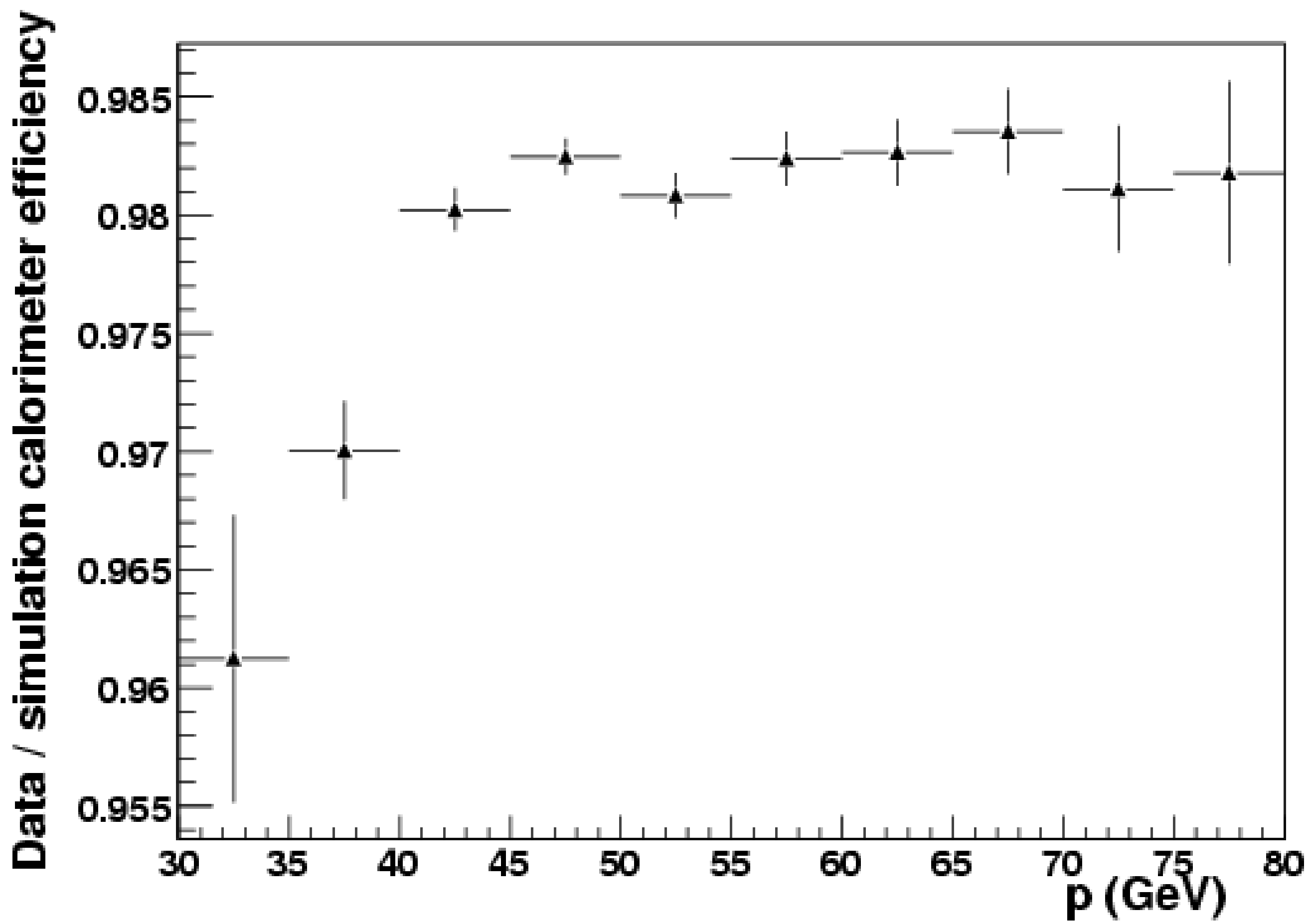
- We normalize all backgrounds to the data in the control region of the Z boson mass peak: $70 < m_{\mu\mu} < 100$ GeV
- We use the fast simulation to generate resonance templates
- Validate the acceptance and efficiency calculation of the fast simulation as a function of track momentum or dimuon mass, by comparing to data or detailed GEANT-based simulation





Muon Identification Efficiency

- Measure and correct the fast simulation for momentum-dependent identification efficiency measured from data
  - Use Z boson data, tagged with one well-identified muon and one loosely-identified track, use the latter for measuring efficiency

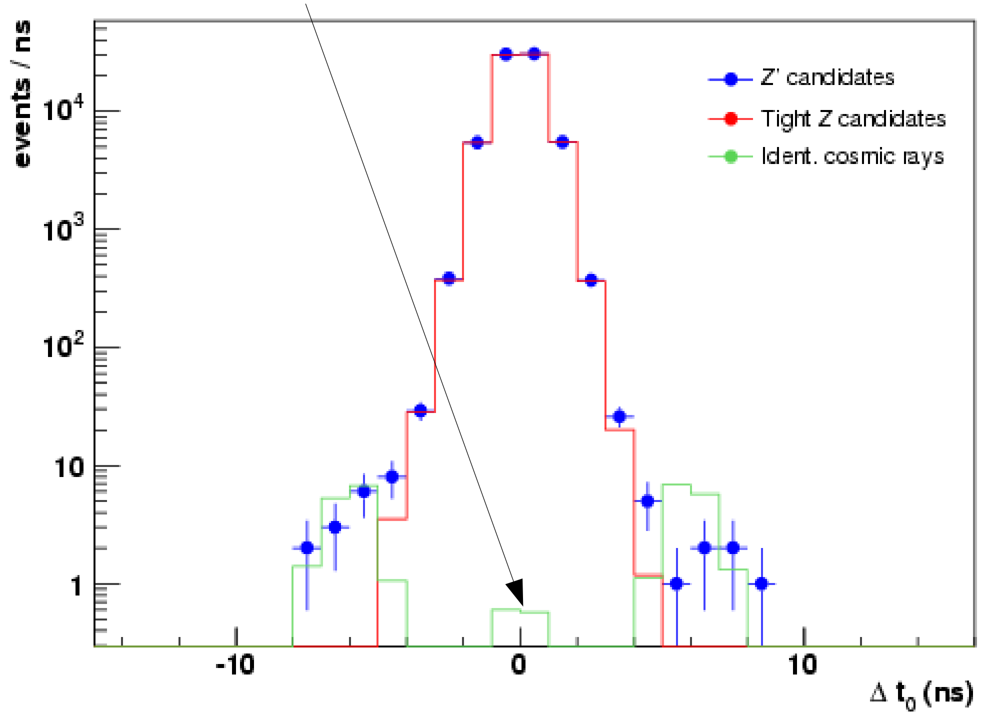


Backgrounds

- SM Drell-Yan dominant by far: generated from PYTHIA and simulated with fast simulation
- WW and ttbar from PYTHIA using GEANT simulation of detector
- Cosmic rays
- Jet fakes
- Decays-in-flight

fitted time of drift chamber track at beamline is called t_0 assuming outgoing direction

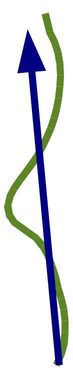
Normalization of cosmic ray bkg



Difference of t_0 between two candidate tracks

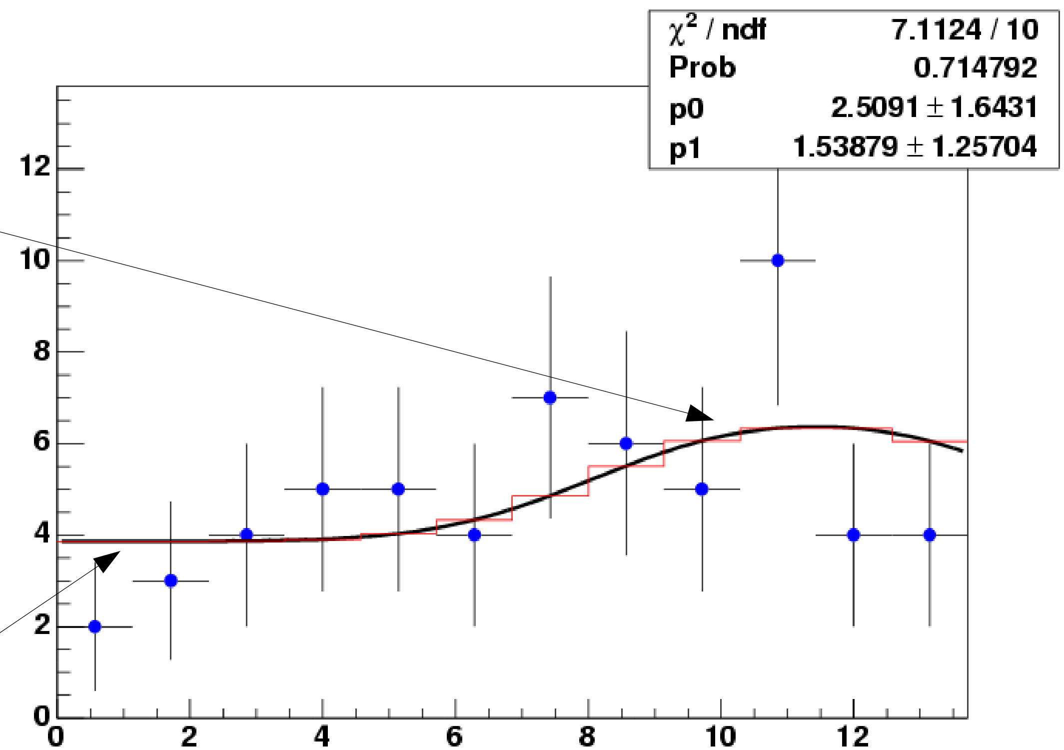
Jet Fakes and Decays-in-Flight Backgrounds

- Jet fakes = punch-throughs + combinatoric + heavy-flavor decays
  - "Muon" track momentum is correctly measured
  - Shape obtained from jet triggers
- Decay-in-flight component from "kinked" tracks when decay occurs in COT active volume



  - Kink causes large mismeasurement of track momentum

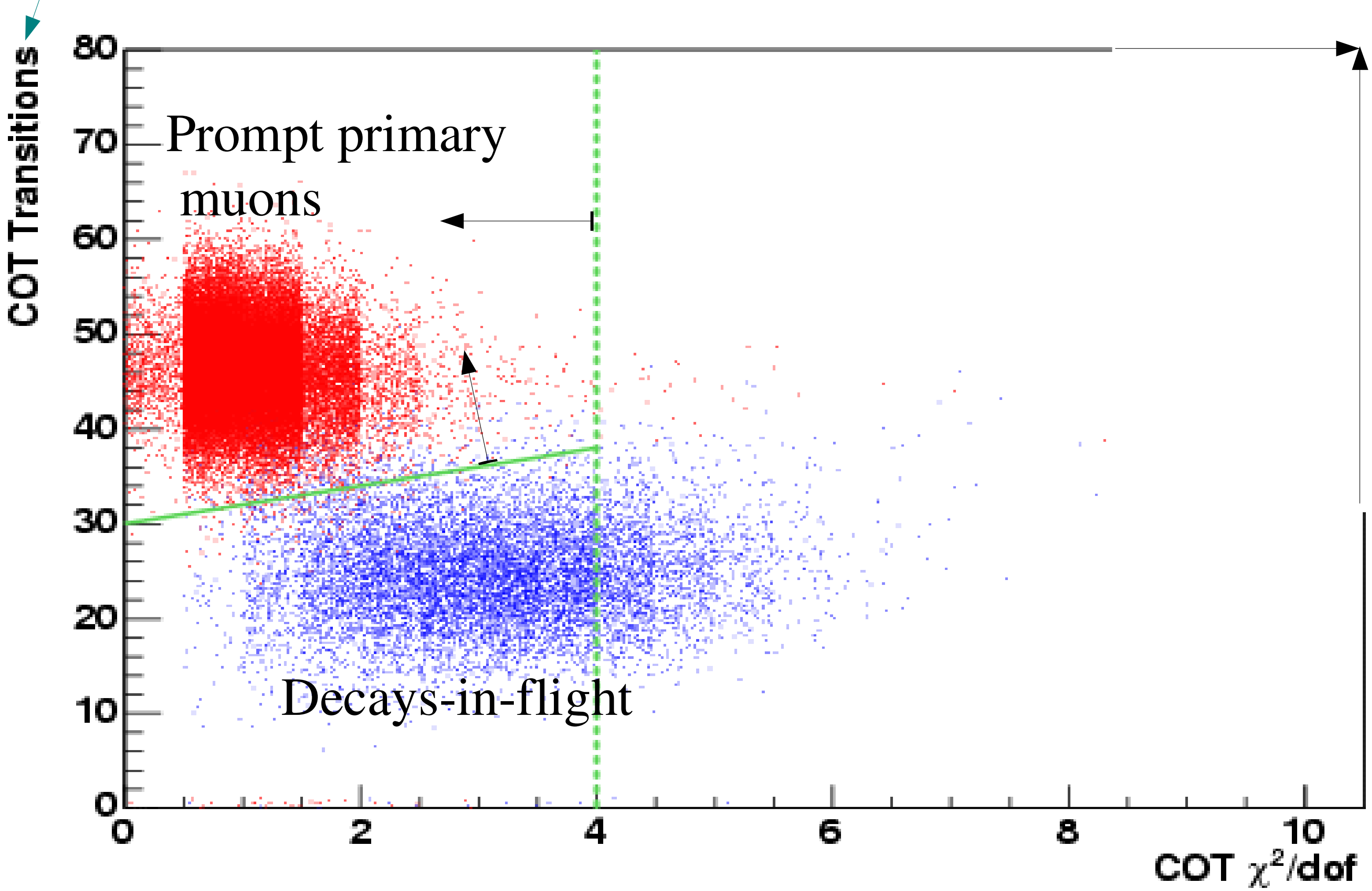
Same-sign data with loose cuts

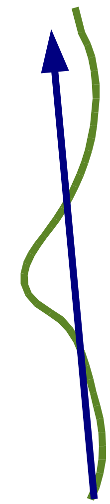


(dimuon mass (TeV))$^{-1}$

COT Hit Pattern Cut for Decays-in-flight

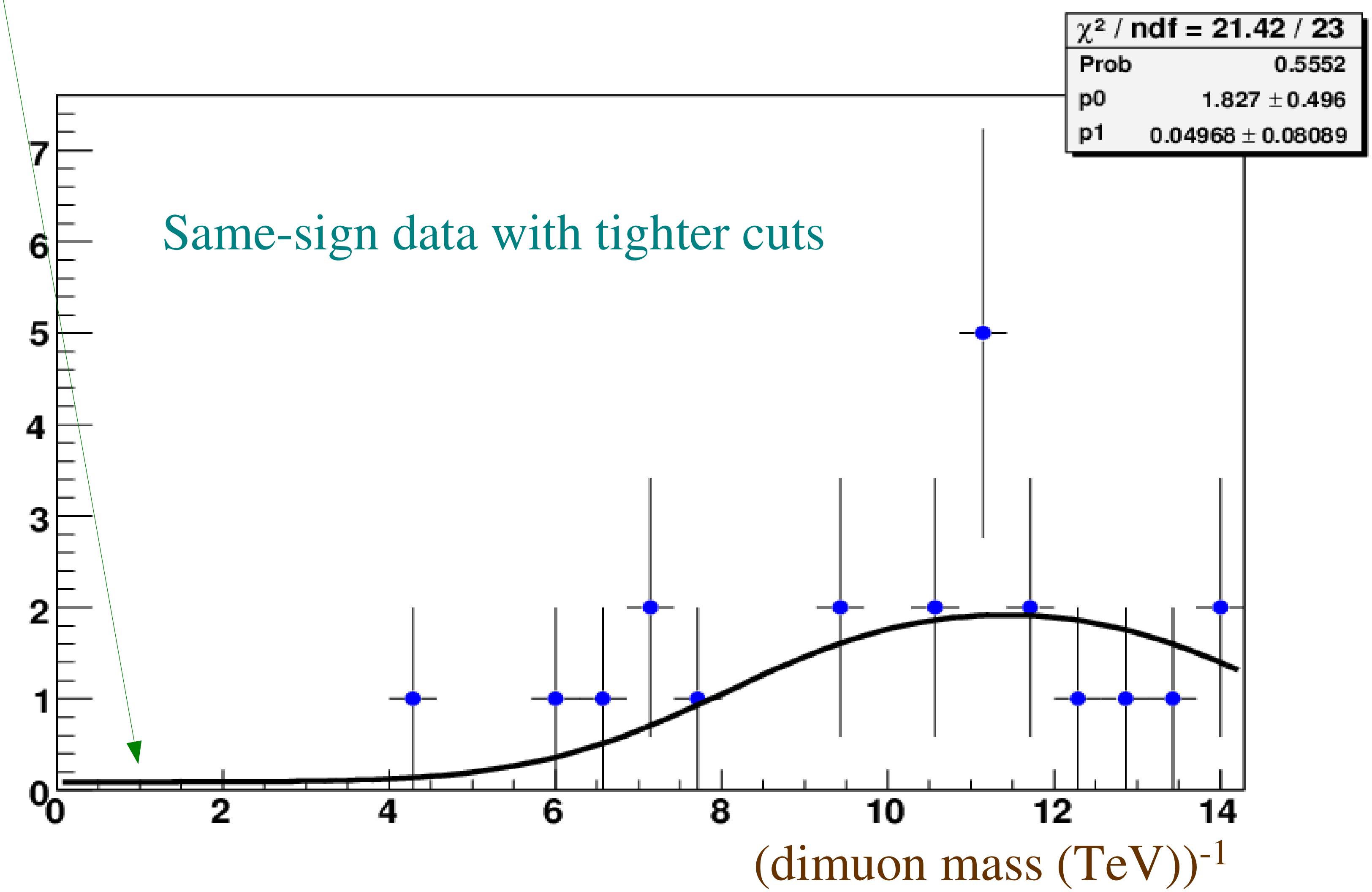
A “transition” implies consecutive hits on opposite sides of the fitted track





Jet Fakes and Decays-in-Flight Backgrounds

- Decay-in-flight component suppressed by COT-based cuts: track χ^2, Δz_0, pattern of hit residuals



Systematic Uncertainties

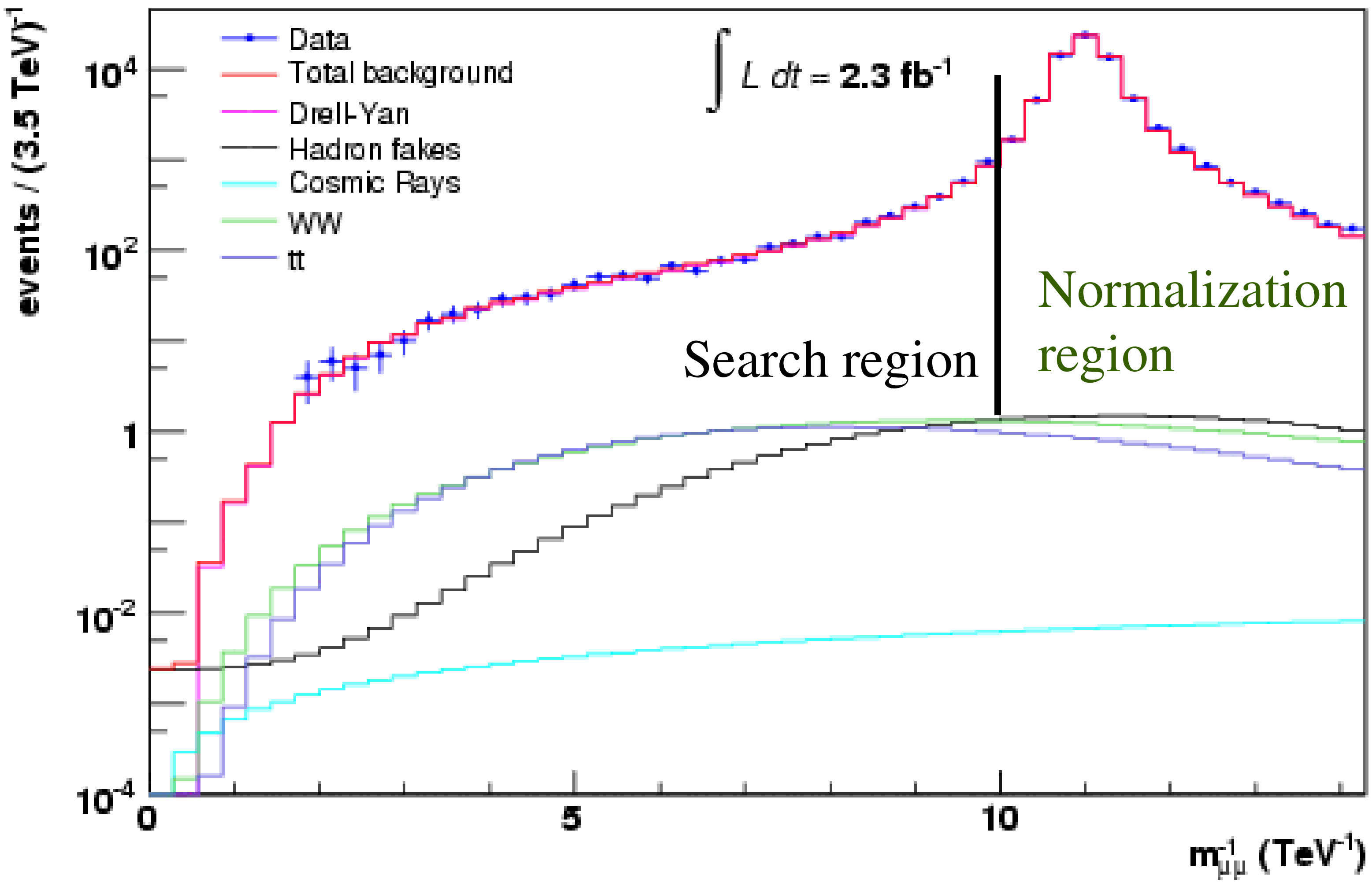
- Uncertainties on luminosity and absolute acceptance and efficiency cancel, due to normalization of backgrounds to the Z boson control region
- Mass-dependent uncertainties only..
  - PDFs: increase linearly to 16% at 1 TeV
  - QCD k-factor: increase linearly to 9% at 1 TeV
  - Electroweak radiative corrections: increase linearly to 3% at 1 TeV
  - Total acceptance: increase linearly to 3% at 1 TeV
  - Momentum scale and resolution: tuned on Z boson peak, negligible uncertainty
- Systematic uncertainties incorporated as nuisance parameters and integrated out in likelihood calculation

Blind Analysis

Followed “Blind Analysis” procedure:

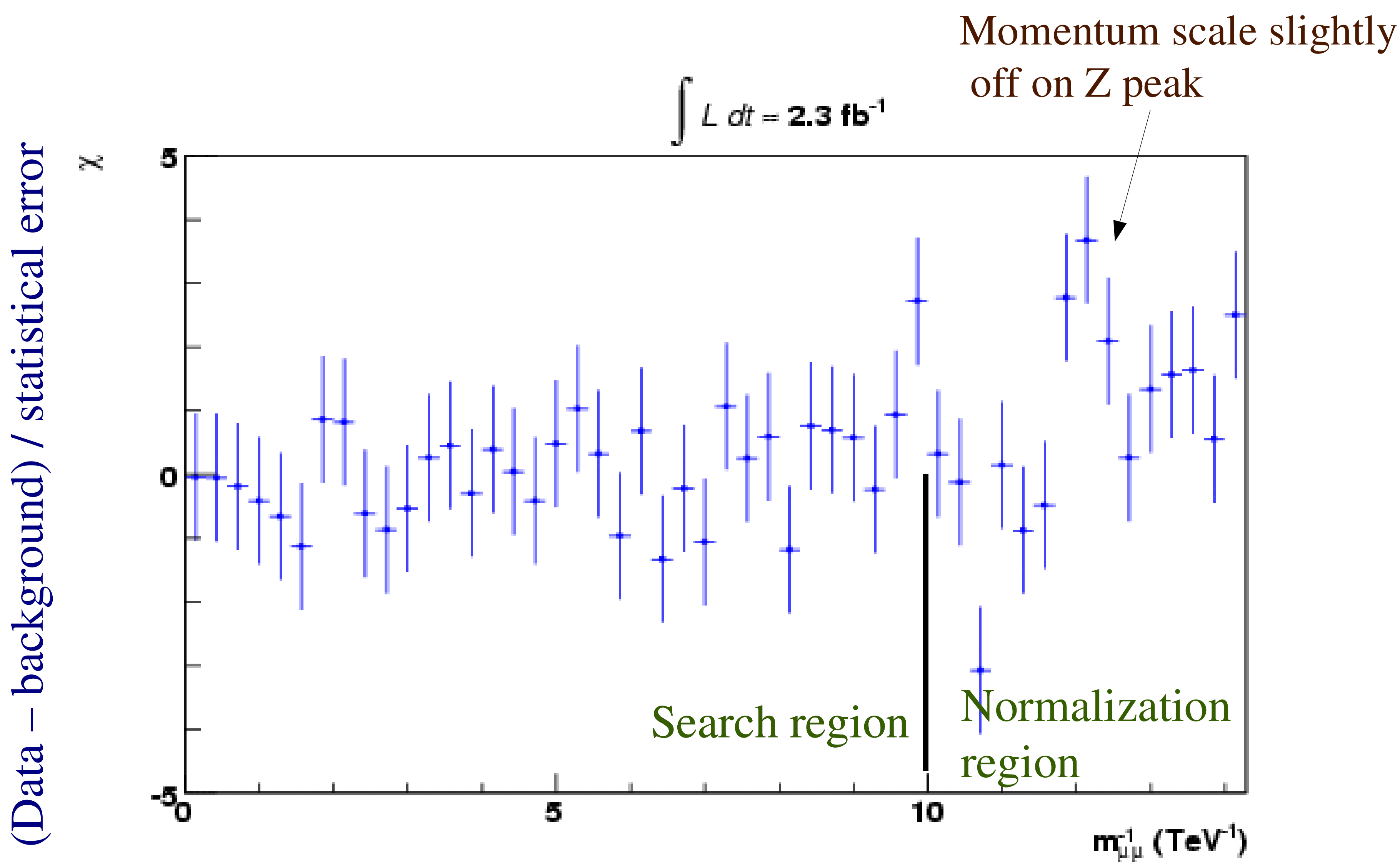
analysis method approved in CDF and frozen, prior to unblinding the data

ArXiv:0811.0053



Data-Background Agreement

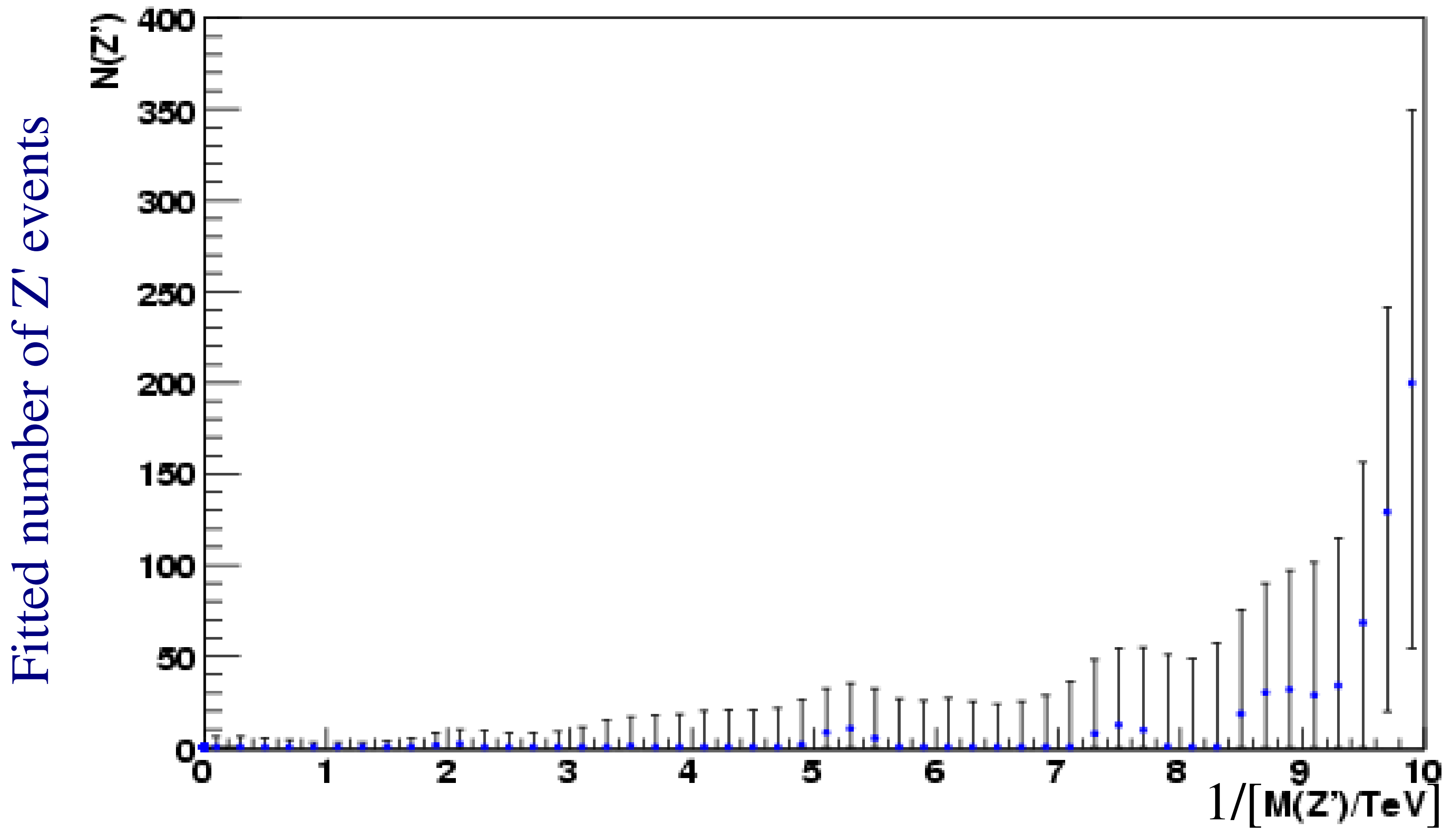
Generally good agreement between data and backgrounds in the search region



Best-Fit and Confidence Intervals on Potential Signal

At each value of Z' pole mass, the point shows the best fit value of Z' signal events

Error bar shows the 95% C.L. Interval on N(Z'), built using Feldman-Cousins prescription

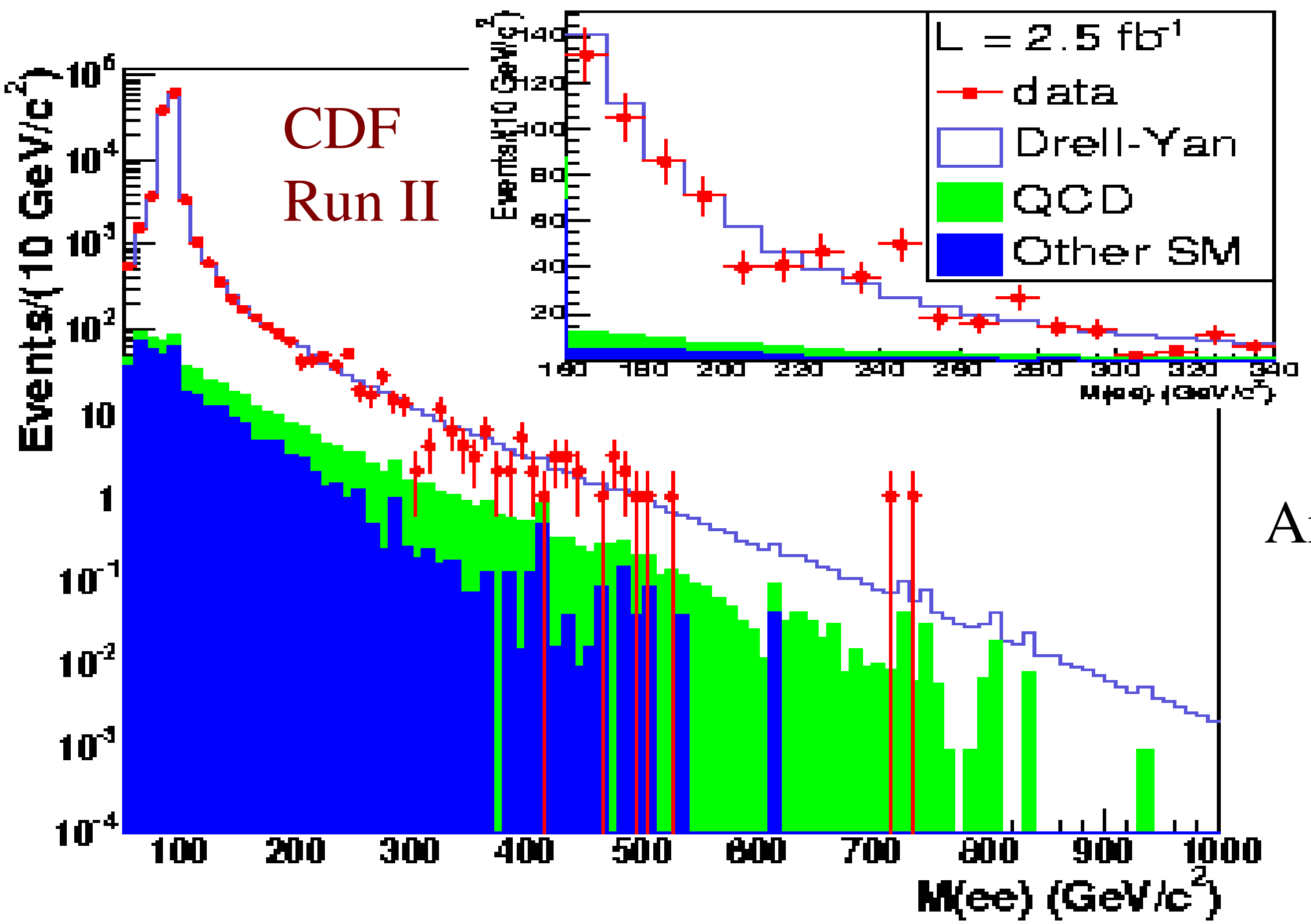


Dielectron Search

An independent analysis at CDF of the dielectron mass spectrum

3.8σ excess at 240 GeV

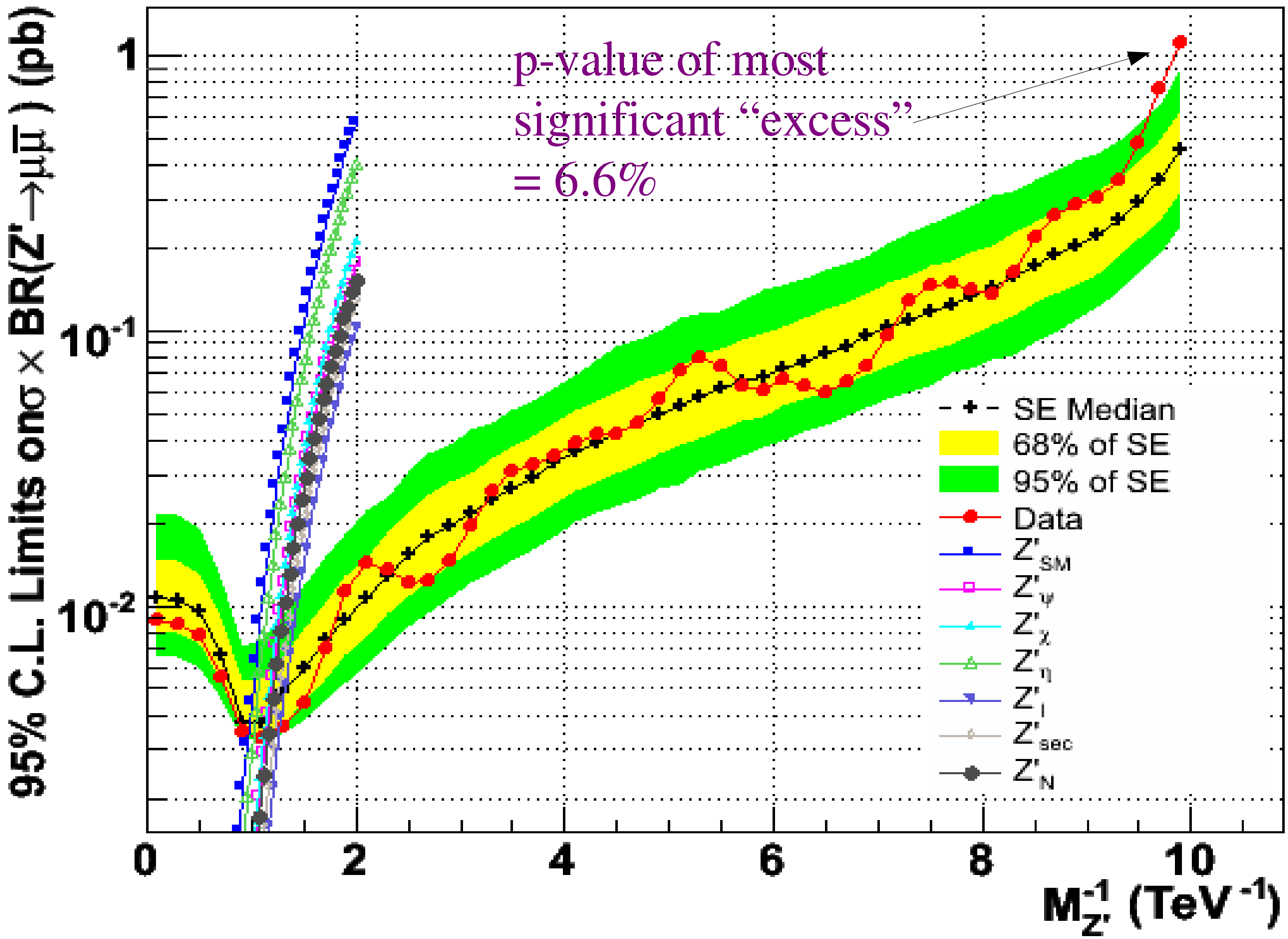
2.5σ significance including “trials factor”



ArXiv:0810.2059

Z' Cross Section and Mass Limits

Convert N(Z') limit to Z' cross section limit, by incorporating mass-dependent acceptance and number of Z boson events observed



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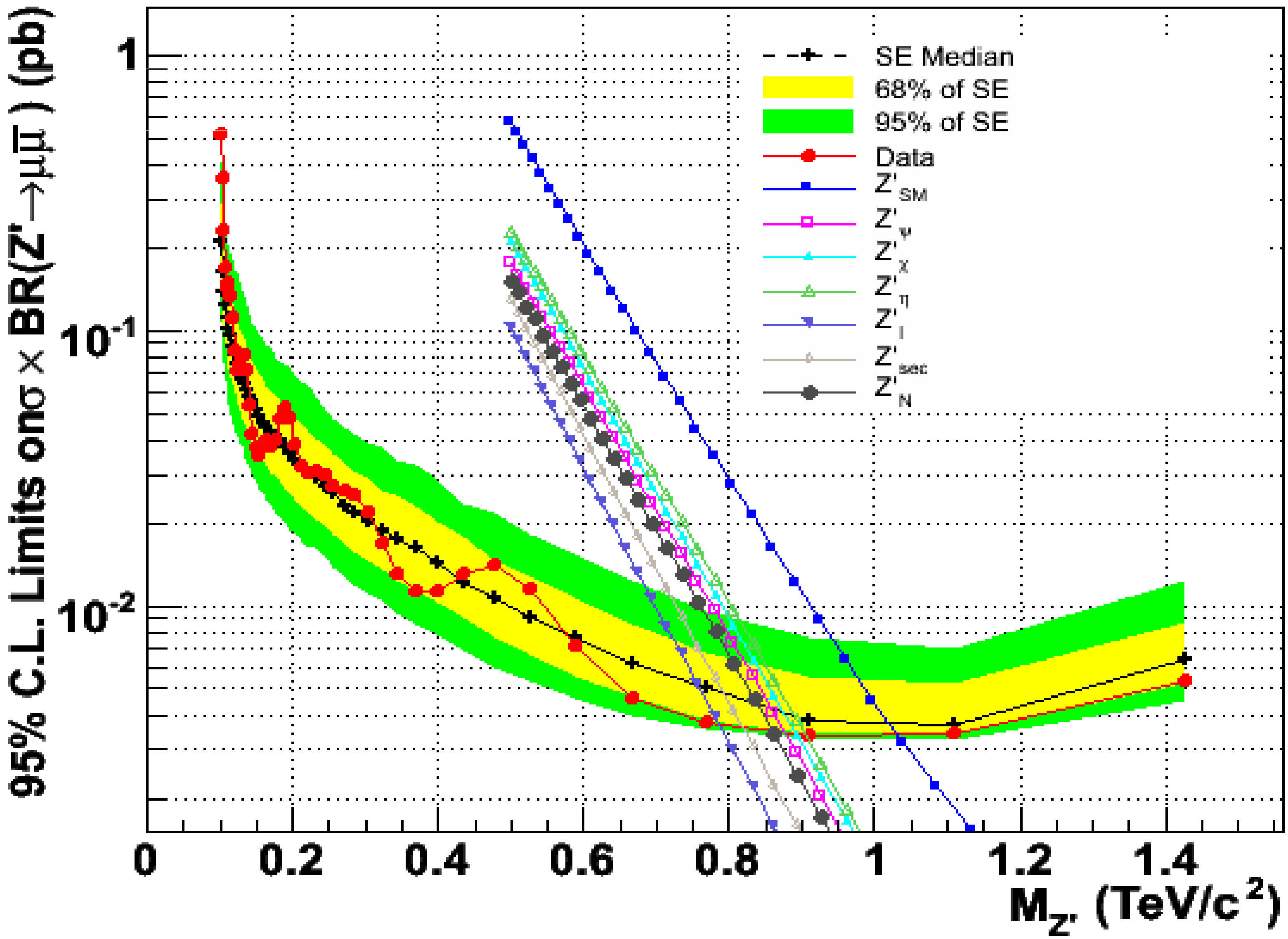


Z' Mass Limits

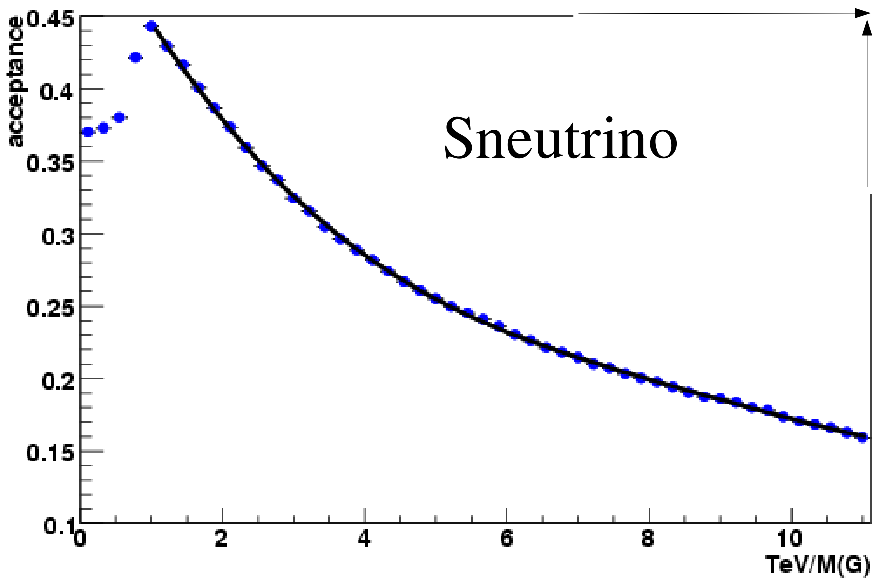
Z' mass lower limits at 95% CL in specific models (eg. E_6-inspired models specifying left- and right-handed couplings to *u* and *d* quarks and leptons):

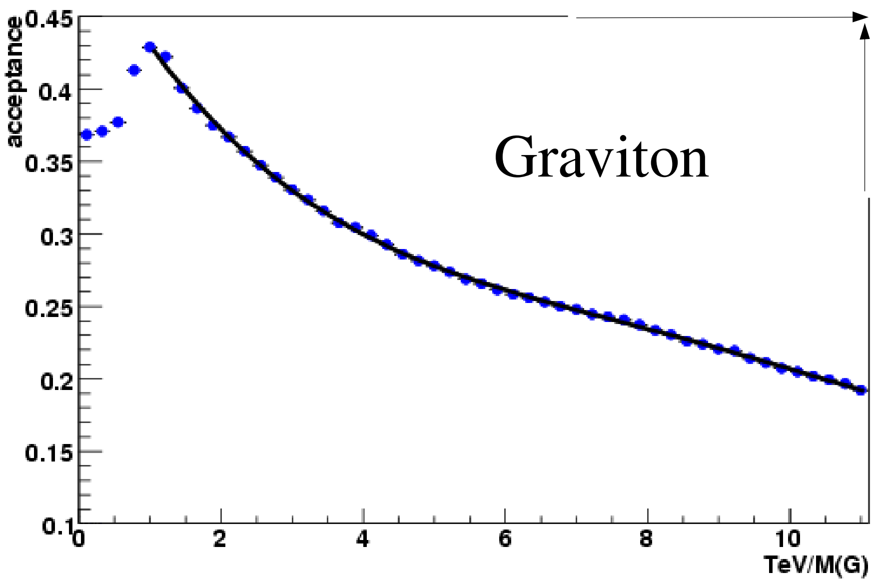
Z'_{SM}	1030 GeV
Z'_{ψ}	878 GeV
Z'_{χ}	892 GeV
Z'_{η}	904 GeV
Z'_{I}	789 GeV
Z'_{sec}	821 GeV
Z'_{N}	861 GeV

Sneutrino & Graviton Acceptance

Incorporate spin-dependence of acceptance

include different graviton polarizations for qq→G and gg→G





Sneutrino & Graviton Mass Limits

Lower mass limits at 95% CL

RS graviton k/M_{Planck}	graviton mass limit	$\tilde{\nu}$ $\lambda^2 \cdot BR$	$\tilde{\nu}$ mass limit
0.01	293	0.0001	278
0.015	409	0.0002	397
0.025	493	0.0005	457
0.035	651	0.001	541
0.05	746	0.002	662
0.07	824	0.005	751
0.1	921	0.01	810

Spacetime curvature in the extra spatial dimension in the Randall-Sundrum model is given by k^2

BR denotes the sneutrino branching ratio to muons, λ is the qq-sneutrino coupling

Summary

- search for narrow dimuon resonance in 2.3 fb^{-1} at CDF

- Data consistent with Drell-Yan expectation and other (small) backgrounds

  - Most significant “excess” occurs with p-value of 6.6%

- Most stringent limits on spin 0, 1 and 2 resonances at high mass