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SEARCHES FOR NEW PARTICLES AT THE ENERGY FRONTIER AT THE TEVATRON

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ABSTRACT

Run 2 at the Tevatron started in spring 2001. CDF and DØ are taking data at a center-of-mass energy of 1.96 TeV. First results on searches for phenomena beyond the Standard Model are presented. In January 2003, the integrated luminosity recorded per experiment was lower than the luminosity collected at Run 1. Nevertheless, these results are already competitive due to improved detector capabilities and to the increase in the center-of-mass energy.

1 Introduction

The CDF and DØ experiments are taking data at a center-of-mass energy of 1.96 TeV since the beginning of Run 2 at the Tevatron in March 2001. 130 pb^{-1} were delivered between January 2002 and January 2003. The integrated luminosity used for these first results is between 30 and 80 pb^{-1} depending on the data sample. Both experiments are searching for new phenomena in a large variety of channels. With a lower luminosity, Run 2 results starts to be competitive with those of Run 1 thanks to higher center-of-mass energy and upgraded detector capabilities.

2 Supersymmetry

2.1 SUGRA jets and missing E_T search

In SUGRA models with R-parity conservation, the Lightest Supersymmetric Particle (LSP) is heavy, neutral, stable and weakly interacting. The cascade decays of the squarks and gluinos into quarks, gluons and the LSP lead therefore to the signature of jets and missing transverse energy (missing E_T). At the Tevatron, this signal has the highest cross section. However, the main background is instrumental and comes from the tail of the Standard Model jet production (QCD), which largely dominates. A preliminary analysis using 4 pb^{-1} of DØ data shows that the backgrounds can be controlled and understood. A high p_T jet above 65 GeV/c is required at the trigger level. This cut is reinforced offline to 100 GeV/c where the trigger efficiency reaches 100%. The QCD background is fitted at low missing E_T and extrapolated to higher values. Figure 1 shows the missing E_T distribution and the agreement with the QCD fit. For a missing E_T cut at 100 GeV, the number of selected events is 3 while the Standard Model expectation is 2.7±1.8.

2.2 SUGRA di- and trilepton search

Gauginos are predicted to be light in SUGRA models and they have a clear multiple leptons signature at the Tevatron. However, this so-called golden channel suffers from a much lower cross section than squarks and gluinos ones.
On 30 pb^{-1} of data, DØ is performing a model independent analysis in the channel with one electron and one muon. This signal has a very low background coming from WW and $t\bar{t}$ at high missing E_T and $Z^0/\gamma^* \rightarrow \tau^+\tau^-$ at low missing E_T. One electron and one muon both with $p_T > 15\ GeV/c$ are required. The fake electron and muon fake rate is estimated from the data and physical backgrounds are estimated with simulation. The missing E_T distribution in Figure 2 shows a good agreement

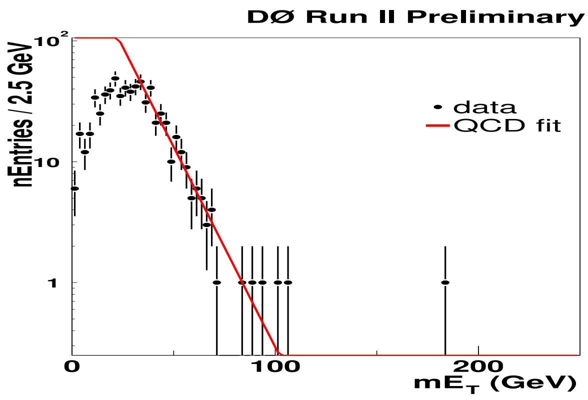


Figure 1: *Search for jets and missing E_T at DØ : missing E_T distribution for data (dot) and the QCD fit (line).*

between data and Standard Model expectation. A model independent upper limit on acceptance times cross section is set for new signal leading to $e\mu$ fnal states a function of the missing E_T cut.

In the channel with two electrons and a third lepton, 40 pb^{-1} of DØ data are analyzed. Selected events must contain at least two electrons with p_T greater than 15 GeV/c for the first one and greater than 10 GeV/c for the second one. Figure 3 shows the di-electron invariant mass at this level of the analysis. The search is restricted to di-electron invariant mass between 10 and 70 GeV/c^2 and to events with transverse mass greater than 15 GeV/c^2 . Finally, a third isolated track is

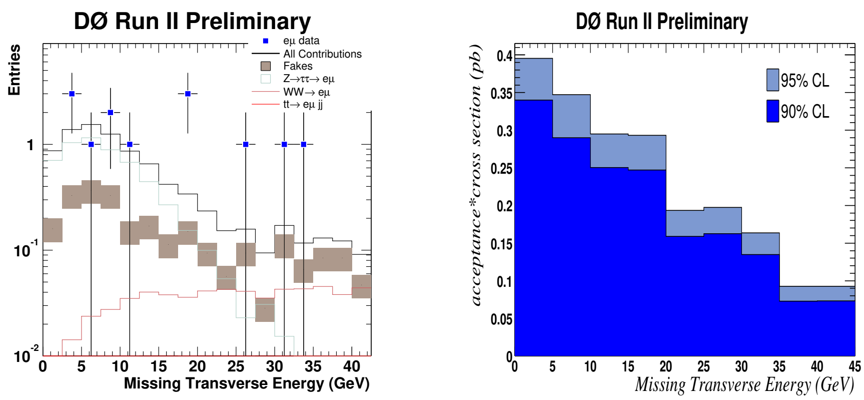


Figure 2: *Search for $e\mu$ at DØ : Missing E_T distribution (left) and cross section limit as a function of the missing E_T cut (right).*

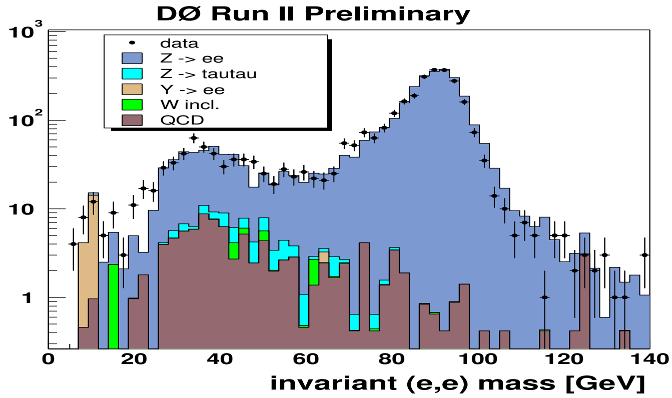


Figure 3: *Search for eel at DØ : dielectron invariant mass distribution.*

required in the pseudo-rapidity range $|\eta| < 3$ before requiring the missing E_T to be greater than 15 GeV. No events are selected while the background is estimated to be 0.0±1.4. The selection efficiency for a typical SUGRA signal at the edge of the current exclusion limit is 2-4%. It is not sufficient to extend the excluded region in the SUGRA parameter space. Higher luminosity is needed for this channel while the analysis is being improved.

2.3 GMSB photon search

In Gauge Mediated Supersymmetry Breaking (GMSB), the LSP is a light gravitino with a mass which could be much lower than the eV. If the next-to-lightest supersymmetric particle is a bino-like neutralino, it would decay into a gravitino and a photon. GMSB signature at the Tevatron is therefore two photons and missing E_T. Requiring two central photons with $E_T > 13GeV$, CDF selects 1365 events from 81 pb^{-1} of data. DØ is using a data sample of 50 pb^{-1} . Events must have two photons with $E_T > 20GeV$. The main background comes from QCD fake events and is determined from data. Figure 4 shows the missing E_T distribution of these events and the good agreement with the background expectation. The limits at 95% confidence level on the GMSB scale Λ using the Snowmass slope [1] ($M = 2\Lambda, N_5 = 1, tan\beta = 15$ and $\mu > 0$) are 51 TeV for DØ and 50 TeV for CDF. These results are very close to Run 1 results.

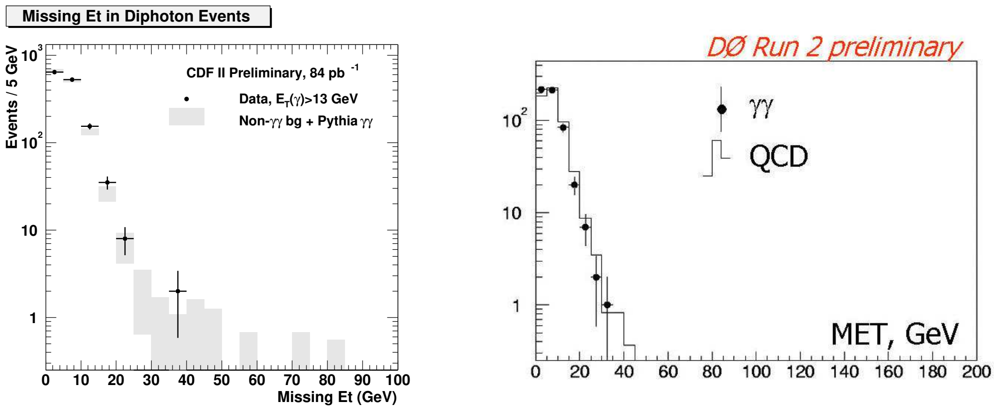


Figure 4: *Search for photon events in GMSB at CDF and DØ : Missing E_T distribution for data (points) and backgrounds (histogram) in the CDF (left) and DØ (right) analyses.*

3 Leptoquarks

At the Tevatron, leptoquarks would be pair produced through gluon fusion or quark anti-quark annihilation. Due to experimental constraints, they are expected to couple only to fermions of the same generation.

3.1 First generation leptoquarks

CDF investigated the following decay of leptoquarks : $LQ_1 LQ_1 \rightarrow eeqq$. Events are selected if they contains two electrons with $E_T > 25$ GeV, and two jets with $E_T > 30$ GeV for the first one, and $E_T > 15$ GeV for the second one. Then topological cuts are applied and no events from 72 pb^{-1} of data survive the analysis cuts. The Standard Model background is expected to be 3.4±3.0.
DØ also searched for leptoquarks in this decay channel. The data sample corresponds to 43 pb^{-1} . The analysis is very similar to the one of CDF. No events are selected for an expected background of 0.08±0.02.
95% confidence level (CL) limits on the first generation leptoquark cross section are derived (Figure 5). These can be translated into a lower limit on the leptoquark mass : $M(LQ_1) > 230$ GeV/c^2 for CDF, and $M(LQ_1) > 179$ GeV/c^2 for DØ . These results already improved those of Run 1.

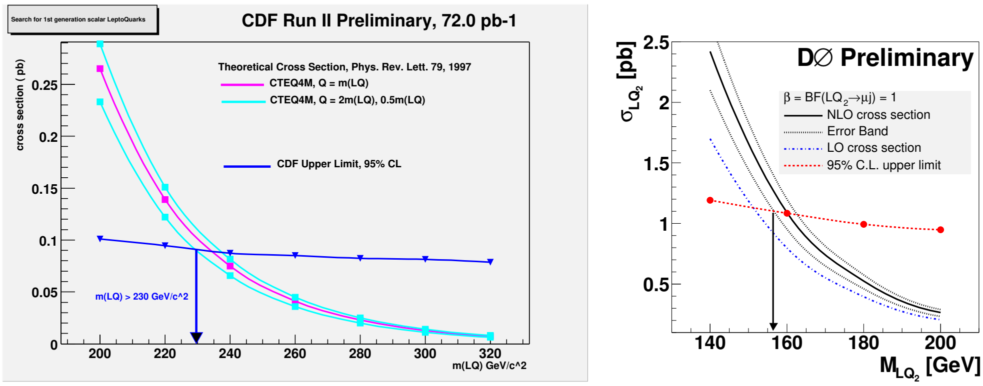


Figure 5: *Search for leptoquarks : 95% cross section limit as a function of the leptoquark mass for the CDF analysis* $LQ_1 LQ_1 \rightarrow eeqq$ *(left) and for the DØ analysis* $LQ_2 LQ_2 \rightarrow \mu\mu qq$ *(right).*

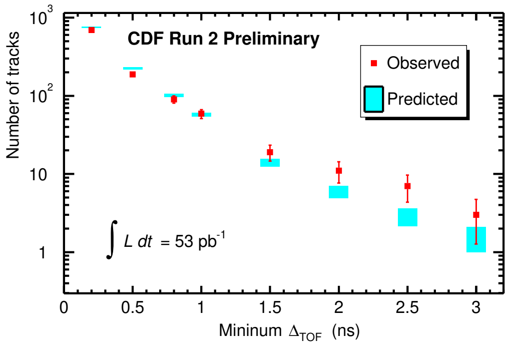
3.2 Second generation leptoquarks

Another topology comes from second generation leptoquark decay : $LQ_2 LQ_2 \rightarrow \mu\mu qq$. In 30 pb^{-1} of DØ data, events must contain two opposite sign muons with $p_T > 15$ GeV/c , two jets with $p_T > 20$ GeV/c , and the invariant dimuon mass is required to be greater than 110 GeV/c^2 . The dominant background comes from $Z^0/\gamma^* \rightarrow \mu\mu$ accompanied by jets due to radiation. No events are found, and a cross section limit is derived (Figure 5). The lower limit on the leptoquark mass is 157 GeV/c^2 . It is still far from the Run 1 limit of 200 GeV/c^2 .

4 Exotics

4.1 Charged massive stable particles

The new Time of flight system of CDF provides a better sensitivity to $\beta\gamma$ than a dE/dx measurement. It is therefore used to search for charged massive particles long lived enough to escape the detector. A data sample of 52 pb^{-1} coming from high p_T muon trigger is used, and an offline P_T cut at 40 GeV/c is applied in order to have full tracking efficiency. The time t_0 at which the interaction occurred is obtained from tracks with $P_T < 20$ GeV/c . Tracks with high $\Delta_t = t_{tracks} - t_0$ are searched for. Figure 6 shows the distribution of Δ_t. Optimized to maximize the discovery probability, the final cut at 2.5 ns keeps 7 events. The background is estimated using tracks with $20 < P_T < 40$ GeV/c : $2.9 \pm 0.7(stat.) \pm 3.1(syst.)$.
In the stable stop scenario, cross section upper limits are derived (Figure 6). The resulting mass limit is $M(stop) >$ 108 GeV/c^2 .



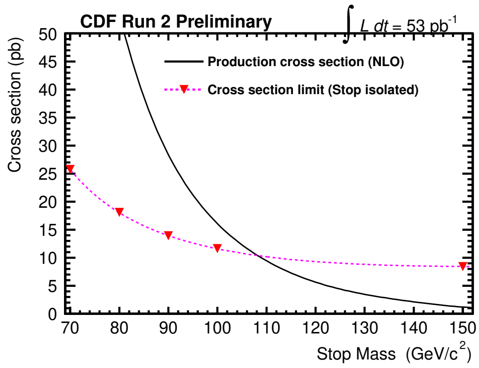


Figure 6: *Search for charged massive stable particles at CDF : Δ_t distribution measured with the time of flight detector (left), cross section upper limit as a function of the stop mass (right).*

4.2 Search for resonances in dijets

A search for new particles decaying to dijets is performed with 75 pb^{-1} of CDF data. The dijet invariant mass spectrum is obtained with the two highest E_T jets of each event. It is fitted with a simple background parametrization and no significant evidence for a signal is observed. 95% CL upper limits on the cross section times branching ratio are set and compared with the prediction for axigluons, flavor universal colorons, excited quarks, Color Octet Technirhos, E6 diquarks, W' and Z' (Figure 7). CDF first Run 2 results improved Run 1 limits and allow to exclude :

- axigluons or flavor universal colorons for masses between 200 and 1130 GeV.
- excited quarks with mass between 200 and 760 GeV.
- color octet technirhos between 260 and 640 GeV.
- E6 diquarks with mass between 280 and 420 GeV.
- W' with mass between 300 and 410 GeV.

4.3 Extra Gauge Bosons

CDF and DØ are searching for a new neutral gauge boson Z' using the Drell-Yan dilepton mass spectrum. Such high mass particles would be produced by quark-antiquark annihilation and would decay into a pair of opposite sign leptons.
For the decay channel $Z' \to e^+e^-$, CDF analysis requires two good electrons with P_T greater than 25 GeV/c either in the central or in the plug calorimeter and additional

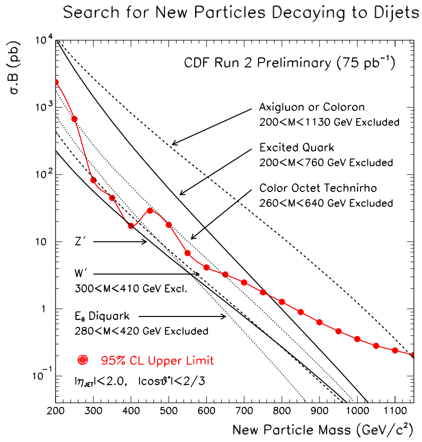


Figure 7: *Search for resonances in dijets at CDF : 95% CL upper limits on the cross section times branching ratio for new particles decaying into dijets.*

cuts are imposed to remove the remaining $W + jets$ background. DØ selects events with two good electrons with P_T greater than 25 GeV/c but restricts the selection to the pseudo-rapidity range $|\eta| < 1.1$. Figure 8 shows the obtained dielectron mass distribution and the good agreement between data and Standard Model expectation. CDF also performed the search for Z' boson in the muon channel $Z' \to \mu^+\mu^-$. It is based on the selection of two good muons with $P_T > 20$ GeV/c . Cosmic and QCD background are removed with cuts on the track impact parameter and on the muon isolation. The dimuon mass spectrum is shown in Figure 8.
Assuming Standard Model couplings, 95% CL lower limits are set on the Z' boson mass : 650 GeV/c^2 by CDF and 620 GeV/c^2 by DØ in the electron channel, 455 GeV/c^2 by CDF in the muon channel.

5 Extra Dimensions

5.1 *Search for small extra dimensions*

Extra dimensions have been recently introduced to solve the hierarchy problem[2]. In the Randall-Sundrum graviton model[3], the Kaluza Klein excitations of the graviton can be separately produced as resonances, enhancing the Drell-Yan cross section at large mass. CDF interprets the high dilepton mass analysis 4.3 in this model. The results are lower mass limits on the graviton mass as a function of the graviton mass coupling k/M_{PL} (Figure 9).

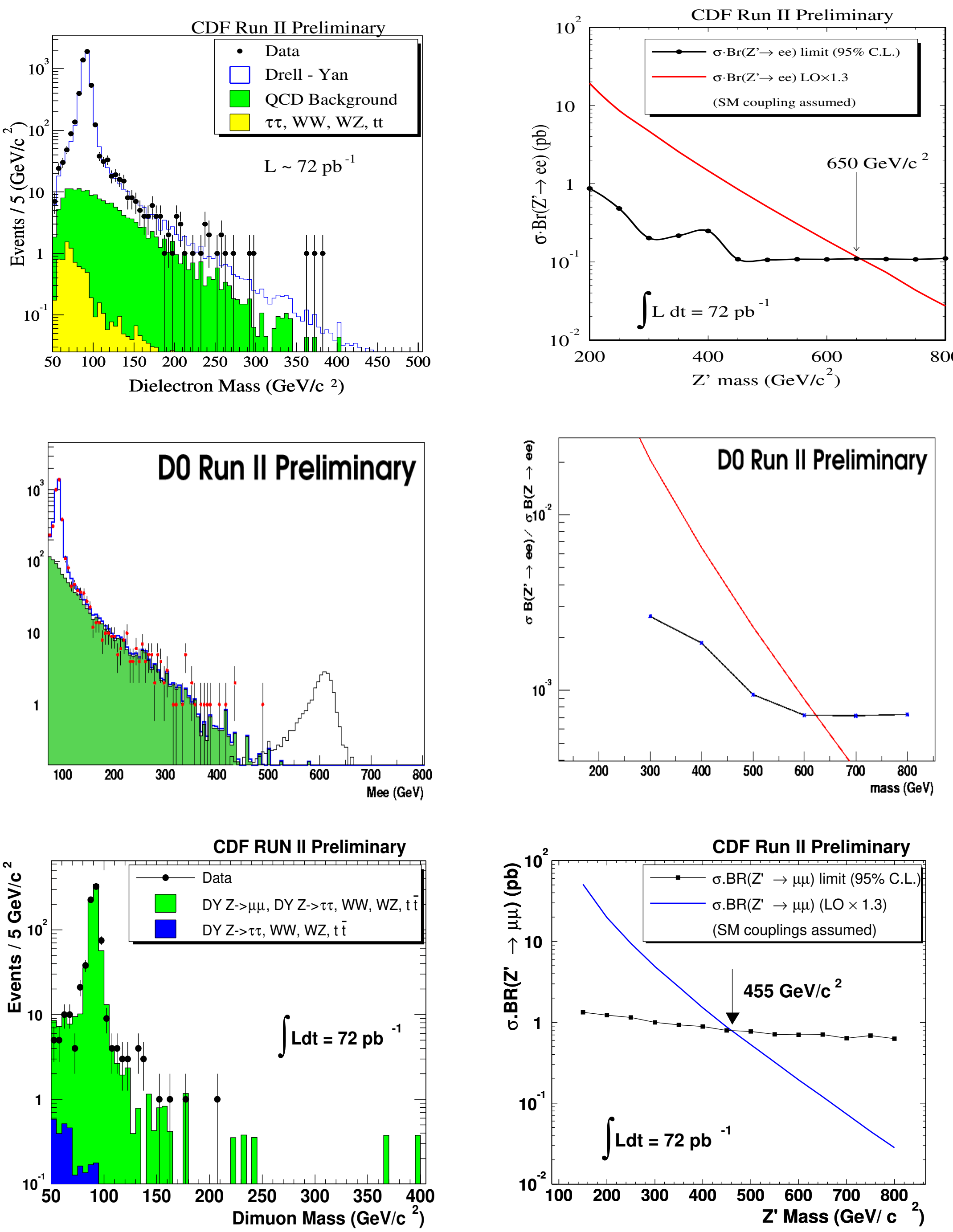


Figure 8: *Search for extra gauge bosons Z' : Drell-Yan dilepton invariant mass spectra (left) and the corresponding cross section limit (right) of CDF dielectron analysis (upper), of DØ dielectron analysis (middle) and of CDF dimuon analysis (lower).*

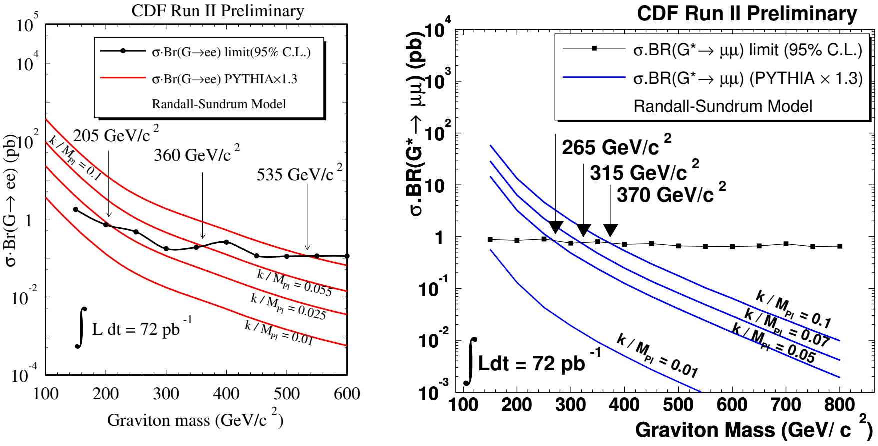


Figure 9: *Search for small extra dimensions at CDF : Cross section limits as a function of the Randall Sundrum graviton mass in the dielectron (left) and dimuon (right) channels.*

5.2 *Large Extra Dimensions*

The ADD model [2] predicts an excess of high-mass dielectron, diphoton or dimuon events due to the coupling to Kaluza-Klein gravitons. Feynman diagrams of the Standard Model and graviton contributions to dilepton final states are shown in Figure 10. The differential cross section can be parametrized as:

$$\frac{d^2\sigma}{dM d\cos\theta^*} = f_{SM} + f_{interf}\eta_G + f_{KK}\eta_G^2. \tag{1}$$

where $\cos\theta^*$ is the scattering angle in the di-em or dimuon rest frame, and η_G measures the contribution from gravitons.

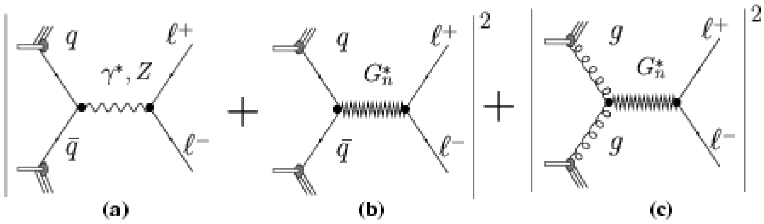


Figure 10: *Feynman diagrams showing contributions of virtual graviton exchange to Drell-Yan processes.*

DØ is searching for LED. In the diEM analysis, no track requirement is imposed, and the dielectron and diphoton channels are treated simultaneously. Events with 2

Table 1: Large Extra Dimension search at DØ : Lower limits in TeV on M_S, the fundamental Planck scale, for various LED formalisms.

Formalism	GRW	HLZ, n=2	HLZ, n=7	Hewett, $\lambda = +1$
Di-Em ($\approx 50pb^{-1}$)	1.12	1.16	0.89	1
Dimuon ($\approx 30pb^{-1}$)	0.79	0.68	0.63	0.71

electromagnetic objects with E_T >25 GeV are selected. The missing E_T is required to be smaller than 25 GeV. In the dimuon channel, events must have two isolated muons with p_T >15 GeV/c matched with a central track. The dimuon mass must be greater than 40 GeV/c^2 . In both analyses, physics backgrounds are derived from simulation and instrumental backgrounds from data. The data distribution (Figures 11 and 12) are fitted in the invariant mass-cos θ^* plane to the signal plus background distribution. This procedure allows to set a lower limit on η_G which is translated into a lower limit on M_S, the fundamental Planck scale. Results are shown in Table 1 for different LED formalisms.

The diEM limits are very close to the Run 1 results and the dimuon analysis is new at the Tevatron.

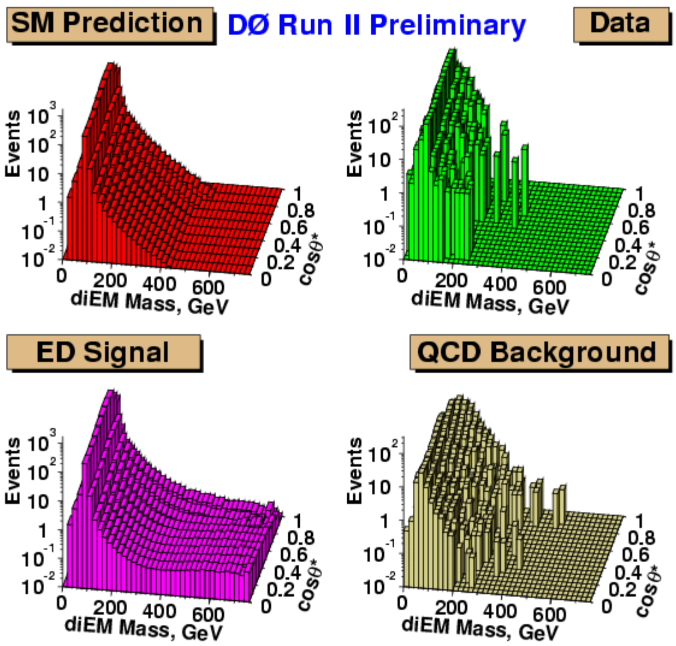


Figure 11: *Large Extra Dimension search at DØ in the diEM channel : invariant mass distribution as a function of* $\cos\theta^*$ *for Standard Model expectation, data, LED signal and QCD background.*

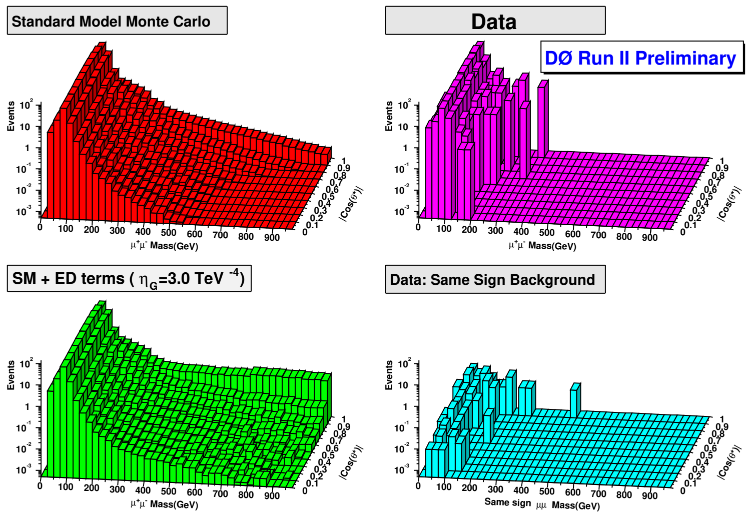


Figure 12: *Large Extra Dimension search at DØ in the dimuon channel : invariant mass distribution as a function of* $\cos\theta^*$ *for Standard Model expectation, data, LED signal and same-sign dimuon background.*

6 Conclusion

CDF and DØ are searching for many signatures of physics beyond the Standard Model in Run 2 data. These first results show the effects of improved detector capabilities and higher center-of-mass energy. Discovery potential at the Tevatron will increase with higher luminosity, improved analyses, better understanding of the detector and extended trigger capabilities.

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