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Search for high mass resonances decaying to muon pairs

The CDF Collaboration
URL http://www-cdf.fnal.gov
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We present a search for a new high-mass resonance decaying to $\mu^+\mu^- + X$, using a matrix-element-based likelihood and a simultaneous measurement of the mass and rate. We see no significant excess; the best fit point is $M_{Z'} = 199$ GeV, with 1.3% signal fraction, consistent with the standard model at 16% confidence level. We place limits on a set of Z' models, including $M > 1071$ GeV for a standard-model-like Z'.

I. INTRODUCTION

We search for a high mass spin-1 resonance decaying to muon pairs, see Fig 1. Such a resonance appears in many models of new physics [1], and is a natural extension of the standard model.

Previous limits from CDF in used 2.3 fb^{-1}[2]. This analysis uses the same event selection as the previous but makes several significant enhancements:

- Twice the dataset, 4.6^{-1} of data.
- A matrix-element-based likelihood which gives 20% enhancement in sensitivity for cross-section limits
- A new statistical approach which is designed to maximize discovery potential as well as mass exclusion limits.

II. SELECTION

The event selection is unchanged from the previous search; see Ref. [2] for details. We summarize it here.

The event selection is

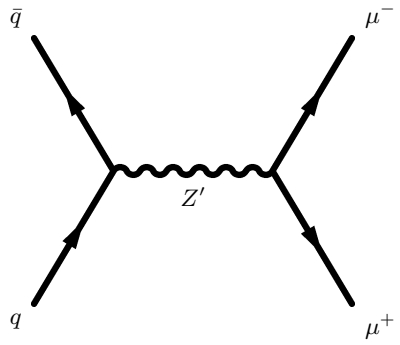

FIG. 1: Feynman diagram for Z' production

- at least two opposite sign muons
- $M_{\mu\mu} > 130$ GeV
- No identified cosmic rays

The muon selection is standard, requiring $p_T > 30$ GeV, calorimeter isolation and a good track matched to the muon hits.

A. Signal kinematics and efficiency

Distributions of event kinematics for simulated Z' events which survive the selection requirements are given in Figure 2. The acceptance for Z' events varies with mass, and is given in Figure 3. The dip above 1 TeV is due to the decreased mean invariant mass, as the peak position is highly suppressed by the parton distribution functions.

B. Backgrounds

The dominant background is γ^*/Z production; we also describe the contributions from WW, $t\bar{t}$, cosmic rays and mis-identified muons.

III. DATA

We use a datasample of 4.6 fb^{-1} of integrated luminosity. The muon-pair invariant mass spectrum is shown in Figure 4.

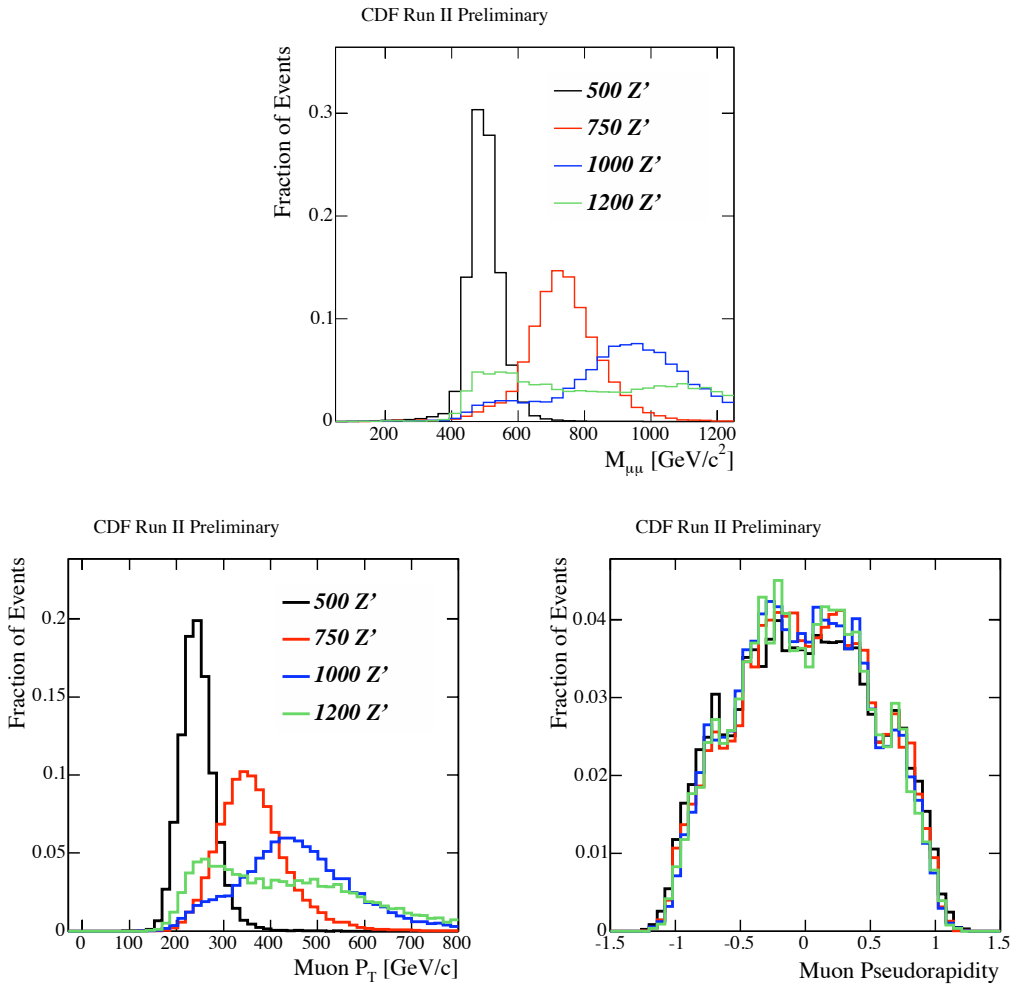

FIG. 2: Distributions of selected signal events.

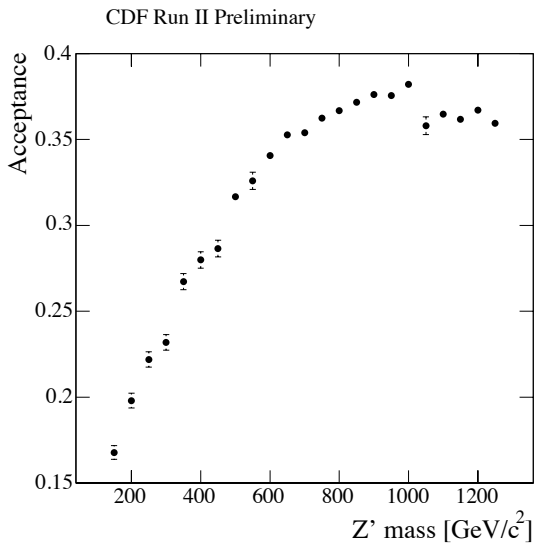

FIG. 3: Acceptance for Z' events as a function of $M_{Z'}$

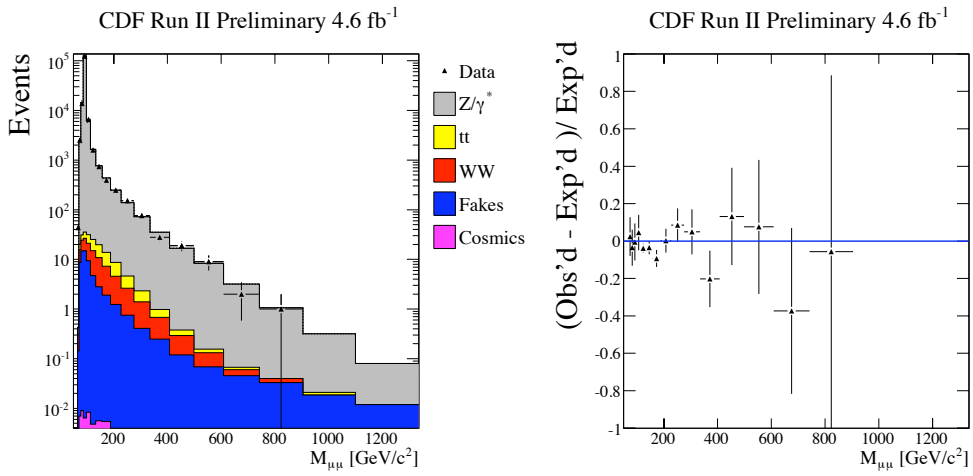

FIG. 4: Distribution of $M_{\mu\mu}$ for 4.6 fb^{-1} of data and expected backgrounds.

IV. ANALYSIS TECHNIQUE

We extract the best-fit mass $\hat{M}_{Z'}$ and signal fraction $\hat{s_{Z'}}$ using the extended maximal-likelihood technique, maximizing

$$L(M_{Z'}, s_{Z'}|x_{i\ldots N_{data}}) = \text{Poisson}(N_{bg} + N_{Z'}, N_{data}) \prod_{i}^{N_{data}} P(x_i|M_{Z'})$$

where x_i is the i-th event,

$$s_{Z'} = \frac{N_{Z'}}{N_{bg} + N_{Z'}}$$

the per-event probability is written:

$$P(x_i|M_{Z'}) = s_{Z'} P_{Z'}(x_i|M_{Z'}) + (1 - s_{Z'}) P_Z(x_i)$$

and the individual probabilities are calculated as

$$P_{Z'}(x_i|M_{Z'}) = \int dq_1 dq_2 |\mathcal{M}_{Z'}(M_{Z'})|^2$$

$$\times f_{PDF}(x_p) f_{PDF}(x_{\bar{p}}) T(p_1, q_1) T(p_2, q_2) P_{PT}(q_1 + q_2, N_{jets})$$

for signal, and similarly for the dominant background, where $p_{1,2}$ represents the four-vectors of the two measured muons , $q_{1,2}$ represents the unknown four-vectors of the two true muons, $T(p, q)$ is the transfer function that parametrized the detector resolution, $\mathcal{M}$ is the matrix-element, f_{PDF} is the parton density function, and P_{PT} is the probability density function for p_T of the $\mu\mu$ system.

V. RESULT

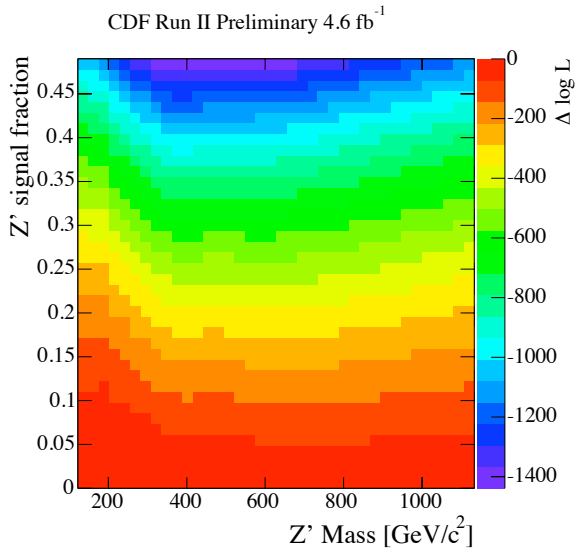

FIG. 5: Log likelihood of the data in 4.6/fb.

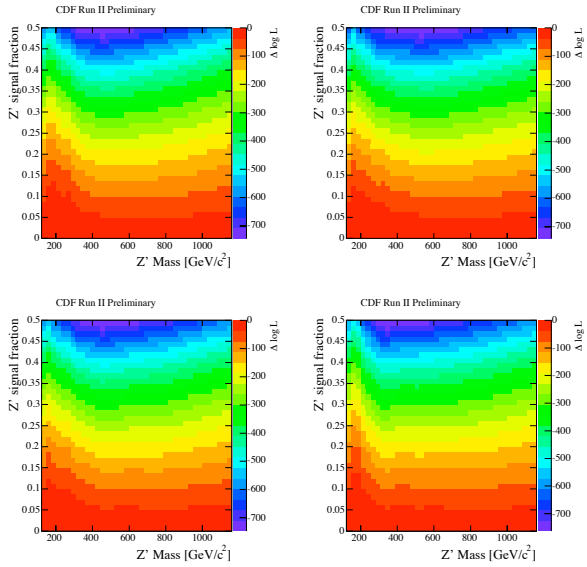

FIG. 6: Logarithm of likelihood as a function of $M_{Z'}$ and signal fraction, for four background-only pseudo-experiments

VI. STATISTICAL ANALYSIS

The search for a Z' has two goals:

- Discover values of $(M_{Z'}, s_{Z'})$ consistent with the data and inconsistent with the SM. For this purpose, we perform a *2D interval* analysis to determine which values of $(M_{Z'}, s_{Z'})$ are consistent with the data, making no assumptions about the relationship between $M_{Z'}$ and $s_{Z'}$.
- Set limits on Z' masses. We perform a *raster scan* in mass, using 1D rate limits to deduce mass limits.

The 1D raster scan is the traditional approach, used in many analyses including the previous Z' search [2]. It is well designed for mass limits, but not for discovery, as it does not account for the look-elsewhere effect.

The 2D interval is constructed via the Feldman-Cousins approach in two dimensions. At each point in the $(M_{Z'}, s_{Z'})$ space, we perform pseudo-experiments and ask how often we should expect the maximum of the likelihood to be as far away as it appears in the data. This is well designed for discovery, as it automatically calculates the significance of the best-fit point and includes the look-elsewhere effect.

We quote both types of analysis, as they answer different questions, see Figure 7.

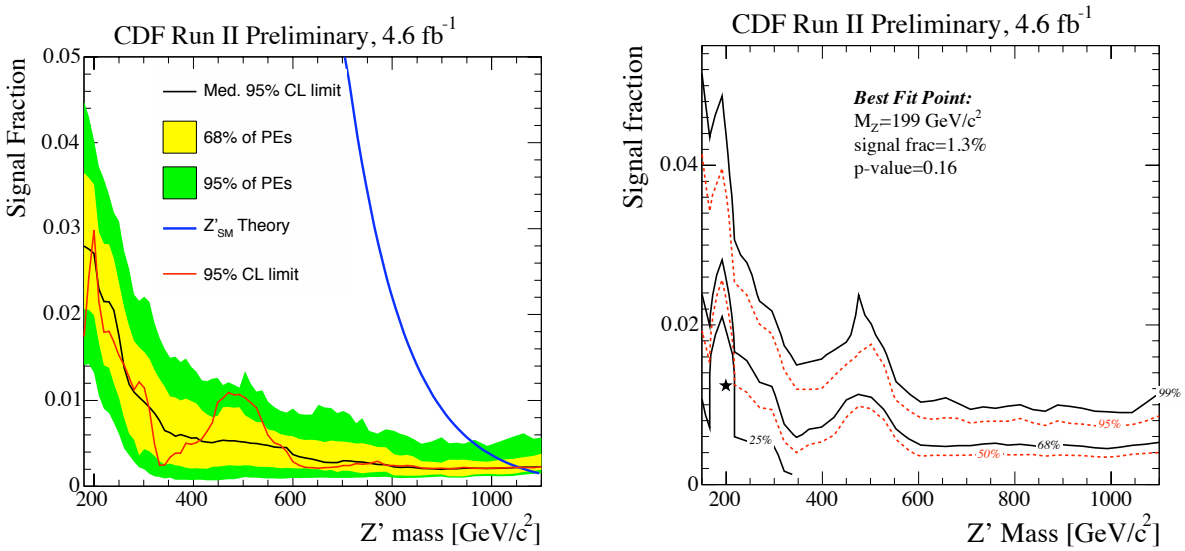

FIG. 7: Observed 95% CL limits in 1D raster scan and 2D intervals for 4.6 fb^{-1} of data.

A. Mass Limits

The raster scan in mass allows us to set strong limits on specific models of Z' production, see Figure 8 and Table I. We set limits on a new model, Z'_F [3], see Figure 9.

B. Highest Mass Event

The highest mass observed events, with $M_{\mu\mu} = 882$ GeV/c^2 is shown in Figure 10.

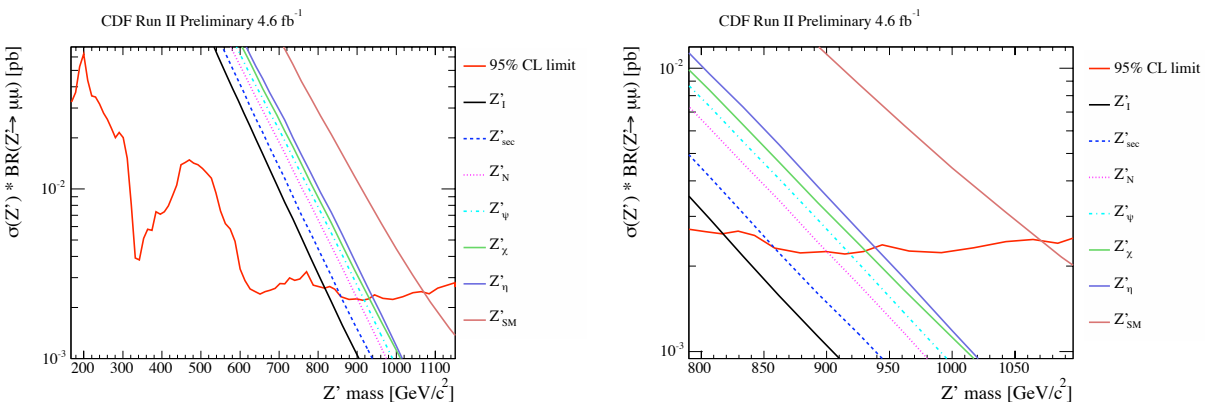

FIG. 8: Observed 95% CL limits for 4.6 fb^{-1} of data.

Model	Mass Limit (GeV/c^2)
Z'_l	817
Z'_{sec}	858
Z'_N	900
Z'_ψ	917
Z'_χ	930
Z'_η	938
Z'_{SM}	1071

TABLE I: Limits in 4.6/fb of data.

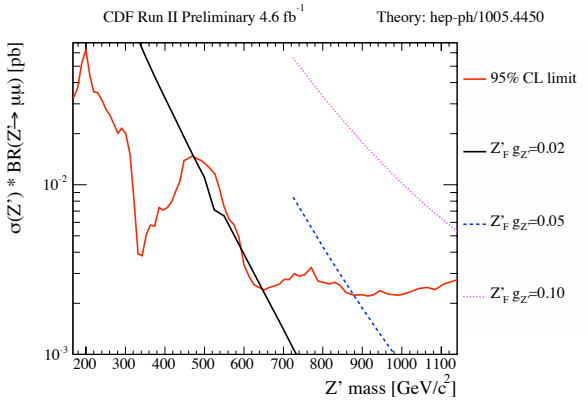

FIG. 9: Observed 95% CL limits in 1D for several choices of $g_{Z'}$ in the Z'_F model [3]

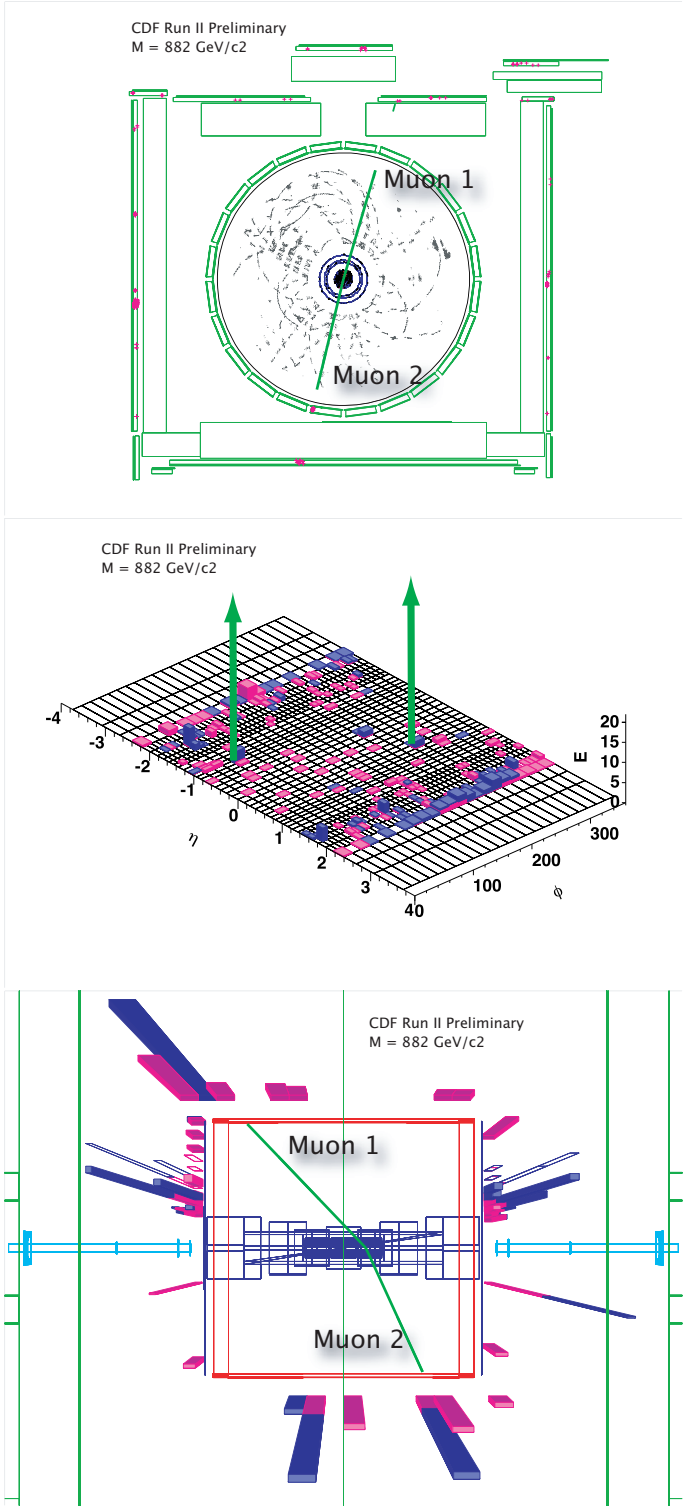

FIG. 10: Display of highest mass event

VII. APPENDIX: EXAMPLE LIKELIHOODS WITH SIGNAL

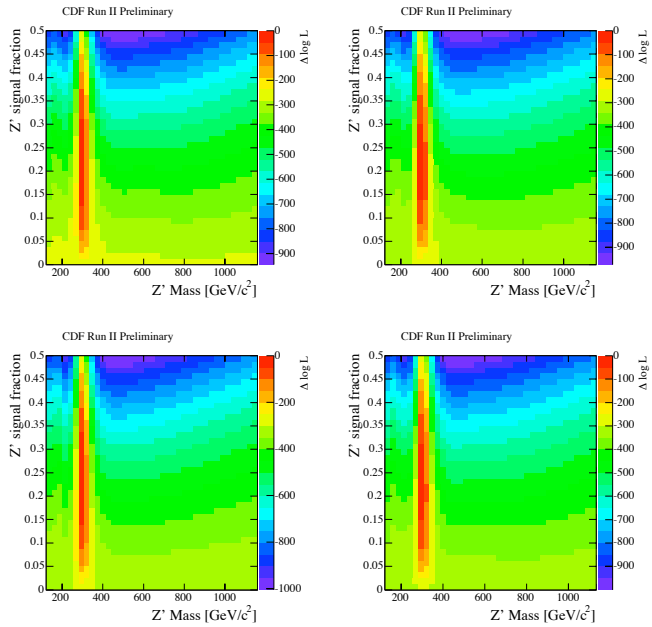

FIG. 11: Logarithm of likelihood as a function of $M_{Z'}$ and signal fraction $s_{Z'}$ for four pseudo-experiments at $M_{Z'} = 300$ GeV and $s_{Z'} = 0.25$

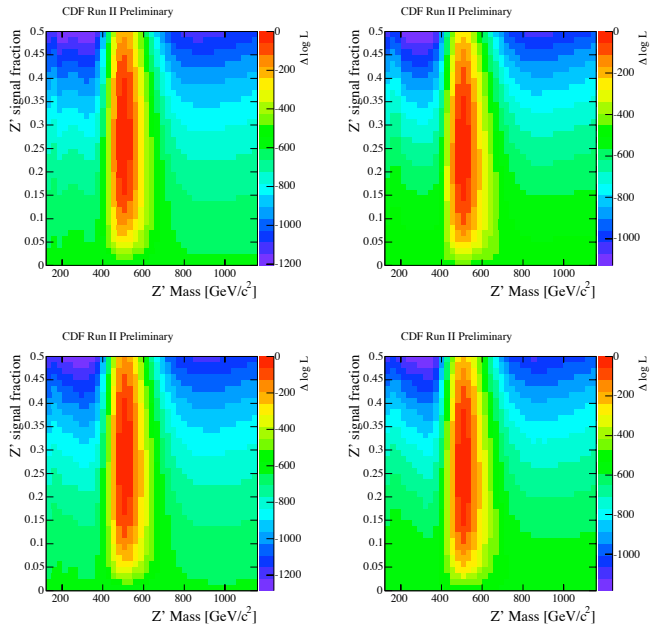

FIG. 12: Logarithm of likelihood as a function of $M_{Z'}$ and signal fraction $s_{Z'}$ for four pseudo-experiments at $M_{Z'} = 500$ GeV and $s_{Z'} = 0.25$

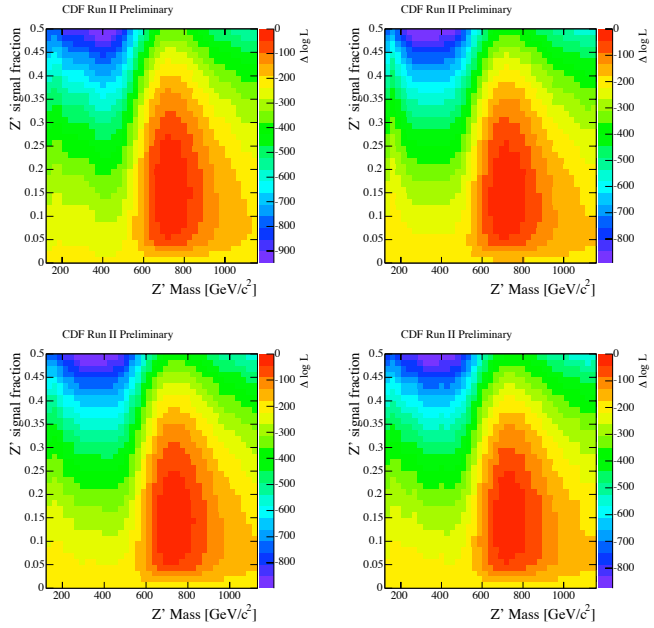

FIG. 13: Logarithm of likelihood as a function of $M_{Z'}$ and signal fraction $s_{Z'}$ for four pseudo-experiments at $M_{Z'} = 700$ GeV and $s_{Z'} = 0.15$

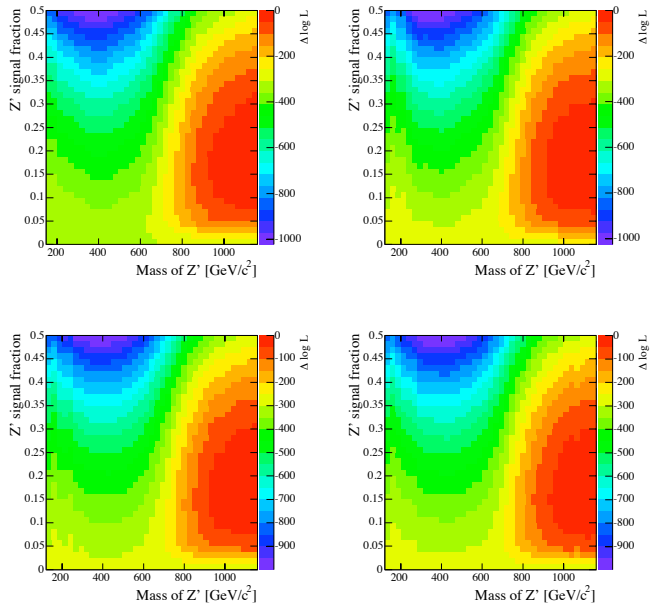

FIG. 14: Logarithm of likelihood as a function of $M_{Z'}$ and signal fraction $s_{Z'}$ for four pseudo-experiments at $M_{Z'} = 1100$ GeV and $s_{Z'} = 0.15$

Acknowledgments

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[1] Carena et al, Phys. Rev. D 70, 093009 (2004)
[2] Phys. Rev. Lett. 102, 091805 (2009). arXiv:0811.0053.
[3] M-C Chen and J. Huang, hep-ph/1005.4450