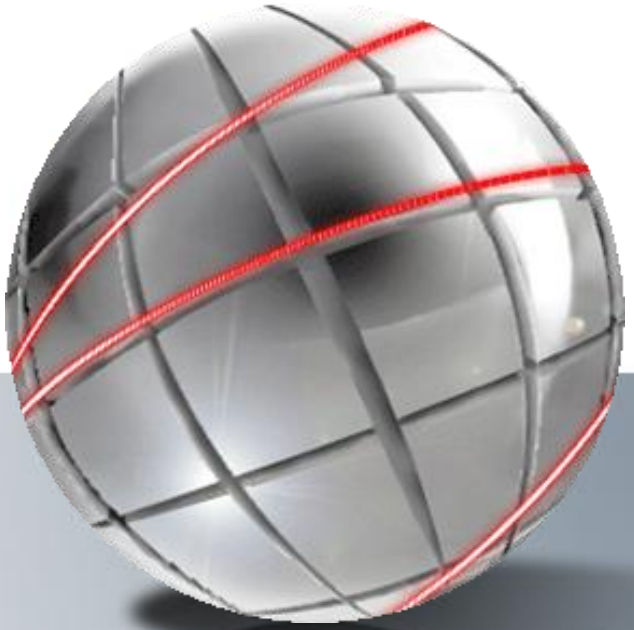
# *Search for Universal Extra Dimensions in $p\bar{p}$ Collisions*



Angelo Santos

SPRACE-IFT/Unesp

*On Behalf of DØ Collaboration*

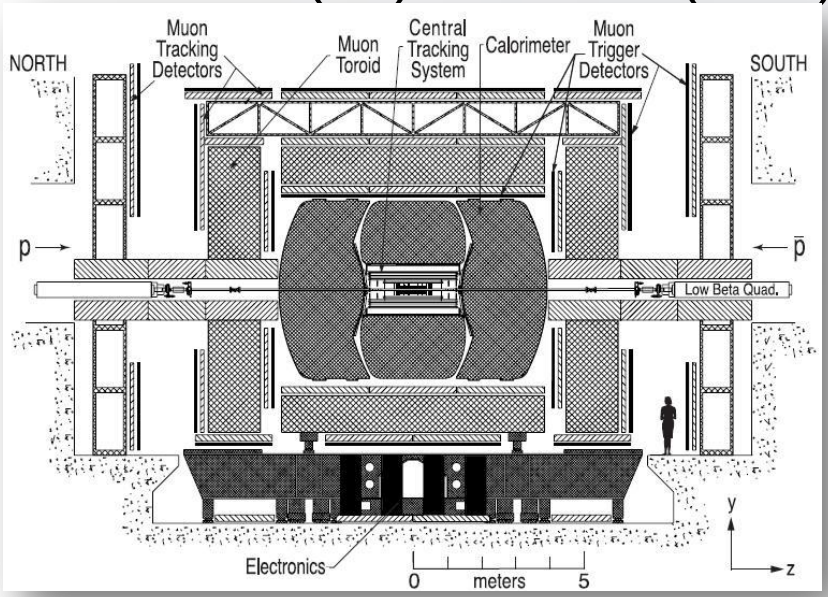
# Outline

- Tevatron and DØ
- Universal Extra Dimensions
- Channel of $\mu^{\pm}\mu^{\pm}$ + *Jets* + $\not{E}_T$
- Background Estimation
- Statistical Test
- Conclusion

# Tevatron and DØ

- Tevatron
  - $p\bar{p}$ collider
  - $\sqrt{s}$ = 1.96 TeV
  - Detectors: CDF and DØ
  - Run II int. Lumi: 10 fb$^{-1}$


- DØ Detector
  - Silicon Microstrip and Central Fiber Trackers
  - Liquid-Ar/Uranium calorimeter
  - Muon chambers
  - Solenoid (2T) + Toroid (1.8T)



# Universal Extra Dimensions

- Universal ED → all fields in the extra dimensions
- Periodic boundary conditions
  - Discrete KK modes

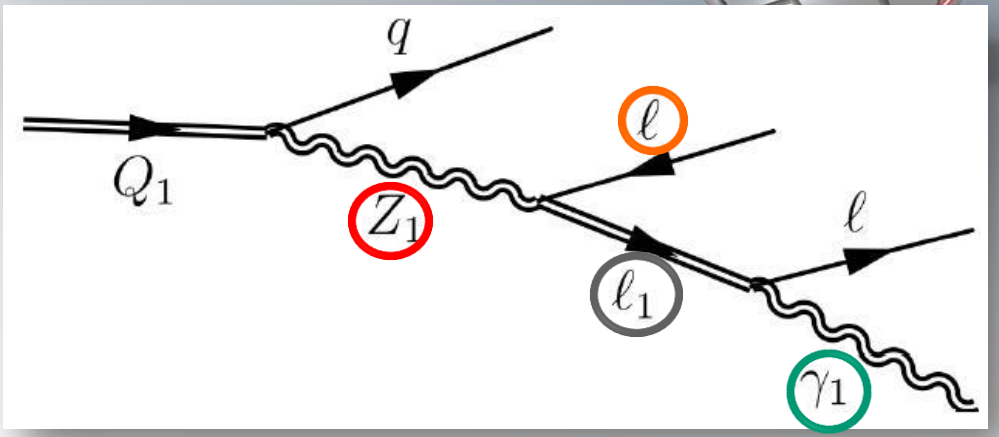
$$M_n^2 = M_0^2 + \frac{n^2}{R^2}, \qquad n = 0, 1, 2...$$

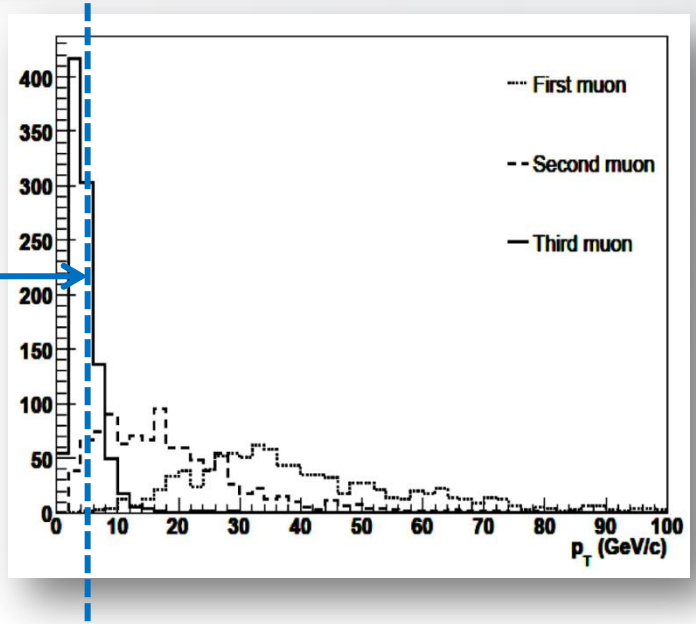
- Minimal UED (MUED)
  - 1 extra dimension
  - First KK level → $n = 1$
- Parameters:
  - Size of extra dimension $R$
  - Cutoff scale $\Lambda$

# MUED: Production

- Lightest KK particle
  - Stable → $\not{E}_T$
  - Dark matter candidate
- Promising channel
  - 2-4 leptons + Jets + $\not{E}_T$
- KK modes nearly degenerate
  - If $M_{V_1} \approx M_{\ell_1}$ → very low $p_T(\ell)$
    - → Bellow detection threshold
- Final state

$$\mu^{\pm}\mu^{\pm} + Jets + \not{E}_T$$



# Data and MC Events

- 7.3 $fb^{-1}$ of Data
  - April/2002 → July/2010
- Backgrounds
  - $W+Jets$, $Z+Jets$,
  - $WW$ / $WZ$ / $ZZ$
  - $t\bar{t}$ .
- MUED signal: 9 selected points
  - $R^{-1}$ = 200, …, 320 GeV (steps of 15 GeV)
  - $\Lambda$ = 10 TeV

# Selection of Events

- At least
  - 1 single muon trigger
- At least
  - 2 muons of the same charge
- Muon track in the muon system matched to the muon track in the central tracking system

- $15 < p_{T1} < 200$ GeV
- $p_{T2} > 10$ GeV
- $\not\!\!E_T > 25$ GeV
- $M(\mu^{\pm}, \mu^{\pm}) < 250$ GeV
- $0.25 < \Delta\phi(\mu^{\pm}, \mu^{\pm}) < 2.9$ rad
- $dca(\mu_{1,2}, PV) < 0.05$ cm
- $\Delta z < 1$ cm
- $|\eta| < 1.5$

# Multijet Background

- $b\bar{b}$ and $c\bar{c}$ → Multijet background
  - Multijet background estimated from data
- UED signal
  - $W_1W_1 / W_1Z_1 / Z_1Z_1 \rightarrow \mu^{\pm}\mu^{\pm} + X$

    No correlation between $\mu_1$ and $\mu_2$ directions

    No correlation between $\mu$ and jet directions

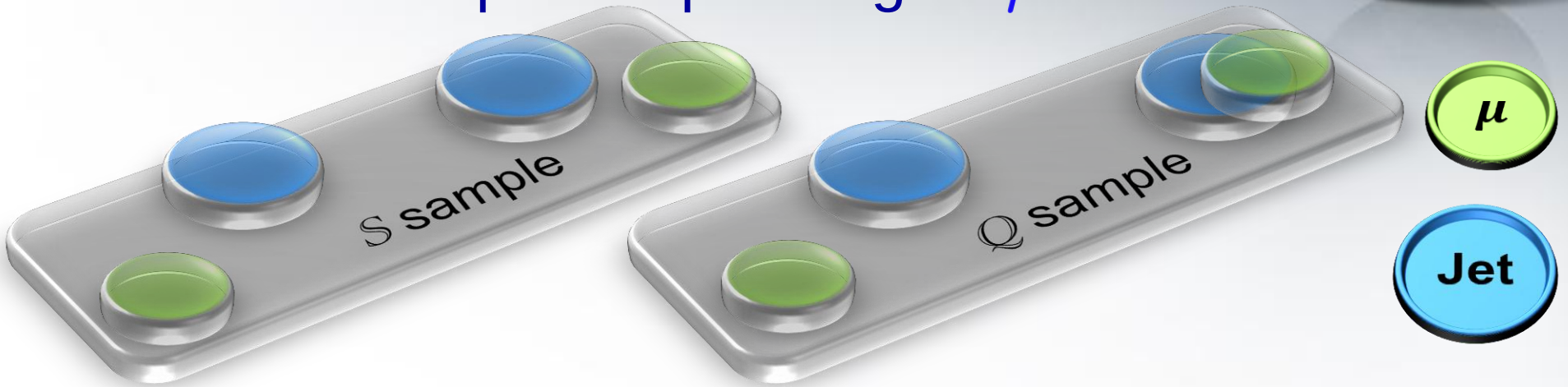
    **Isolated muons**
- Multijet background
  - Semileptonic meson decays

    Correlations between $\mu$ and jet directions

    **Non-isolated muons**

# Estimation of Multijet Background

- Define 2 samples depending on $\mu$ isolation




- Normalization factors from integrals $I_i$ ($i = N_{Jets}$)

$$N_i = \frac{I_i(\mathcal{S})}{I_i(\mathcal{Q})}$$

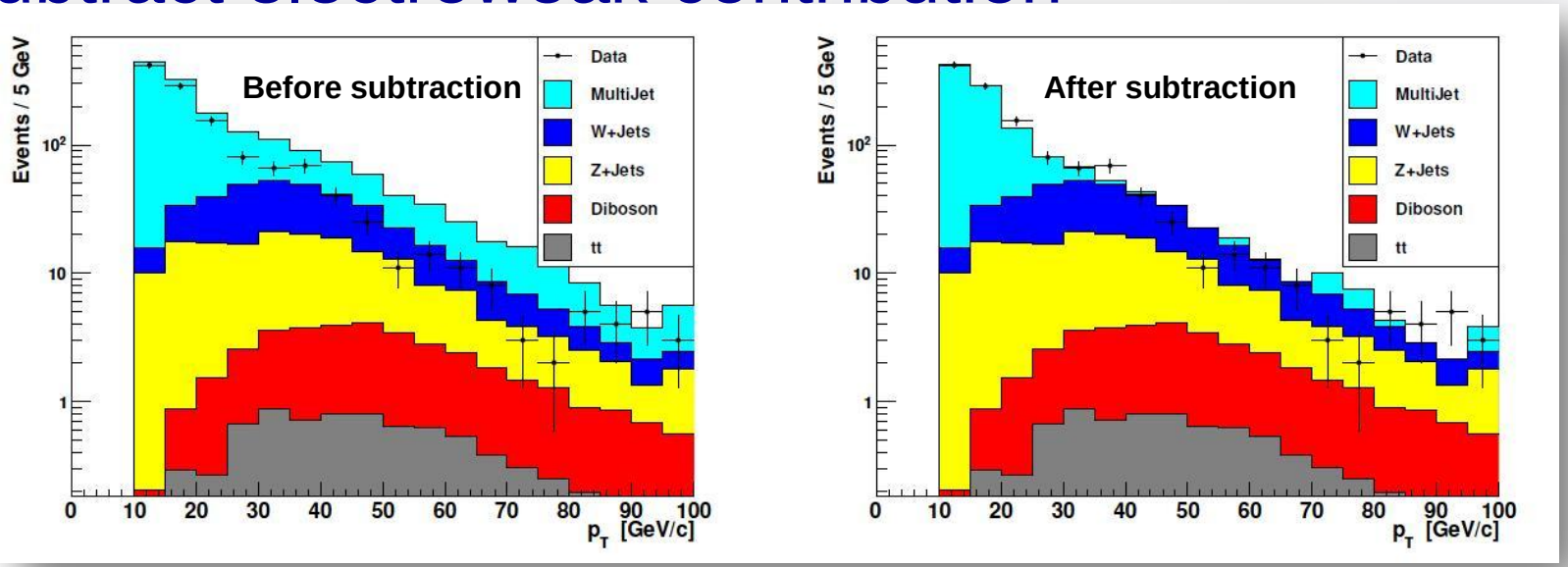
$N_i \times \mathcal{Q}$ → Multijet background

5 10

$p_T$ of the most isolated muon (GeV)

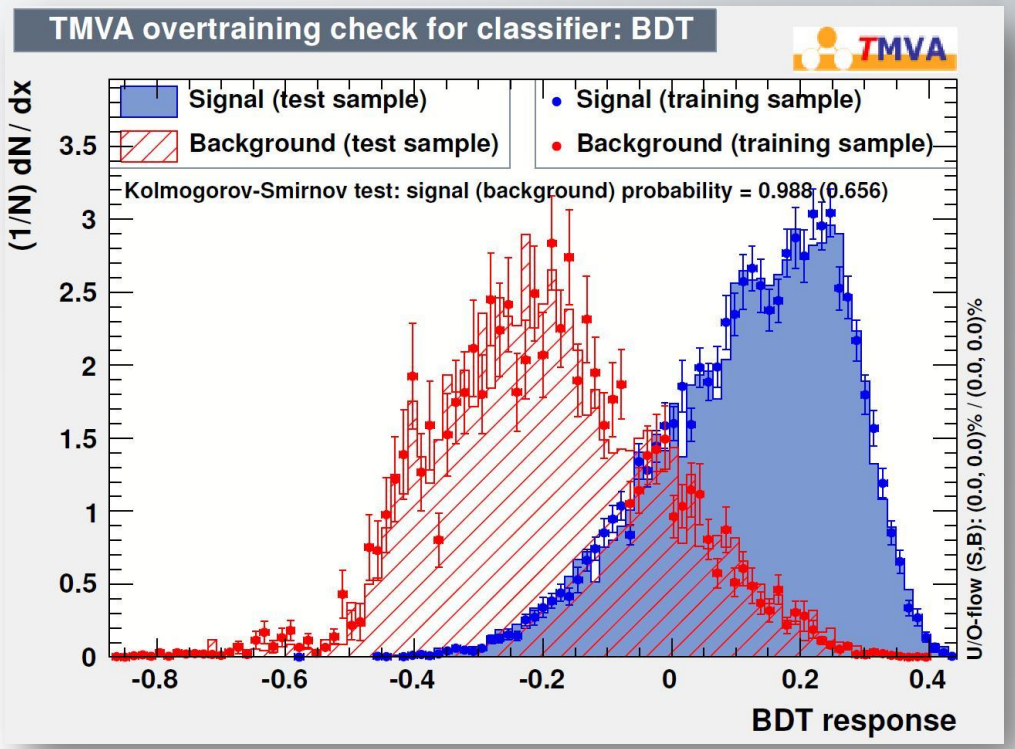
# Electroweak Contamination

- High $p_T$ region
  - Significant contribution from other SM processes
  - Mainly $W + Jets$
    - $W$ → isolated muon
    - $Jets$ → non-isolated muon
- Subtract electroweak contribution

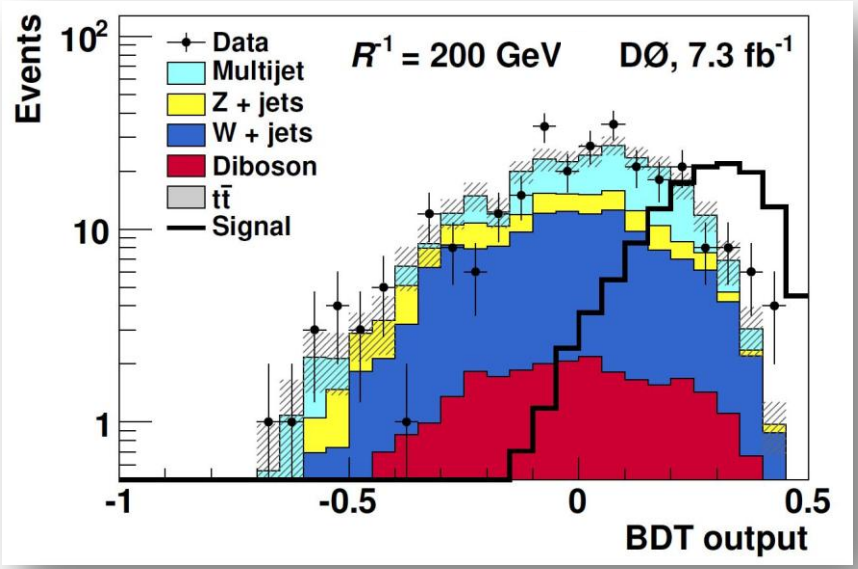


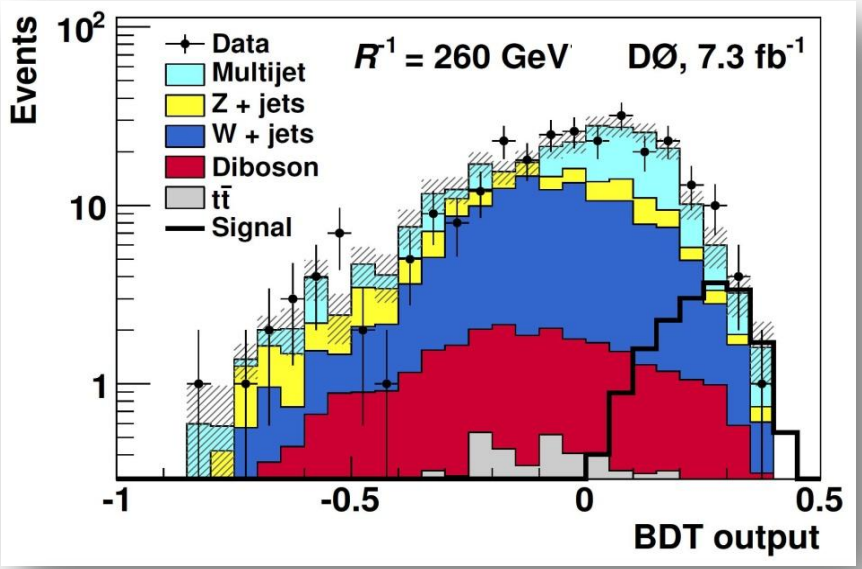
# BDT: Multivariate Analysis

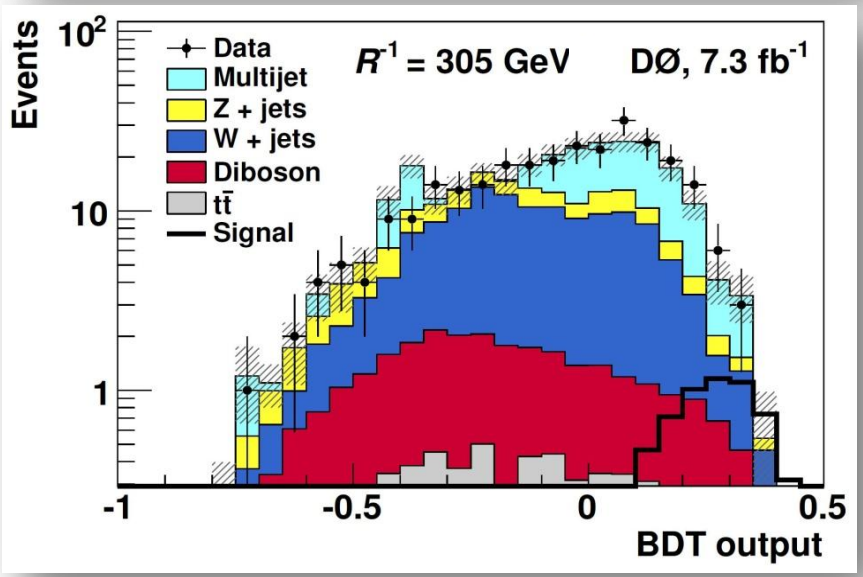
- Increase sensitivity to the UED signal
  - Discriminate between signal and background
- Several input variables:
  - $\not{E}_T$
  - $p_{T1}, p_{T2}$
  - $\not{E}_T \times p_{T2}$
  - $M(\mu^{\pm}, \mu^{\pm})$
  - $\Delta\phi(\mu^{\pm}, \mu^{\pm})$
  - $Sig(\not{E}_T) = \dfrac{\not{E}_T}{\sum_{objects} \sigma^2_{proj}}$
  - $MT_{1,2} = \sqrt{2\,\not{E}_T . p_{T1,2}(1 - \cos[\Delta\phi(\vec{\not{E}}_T, \mu_{1,2})])}$

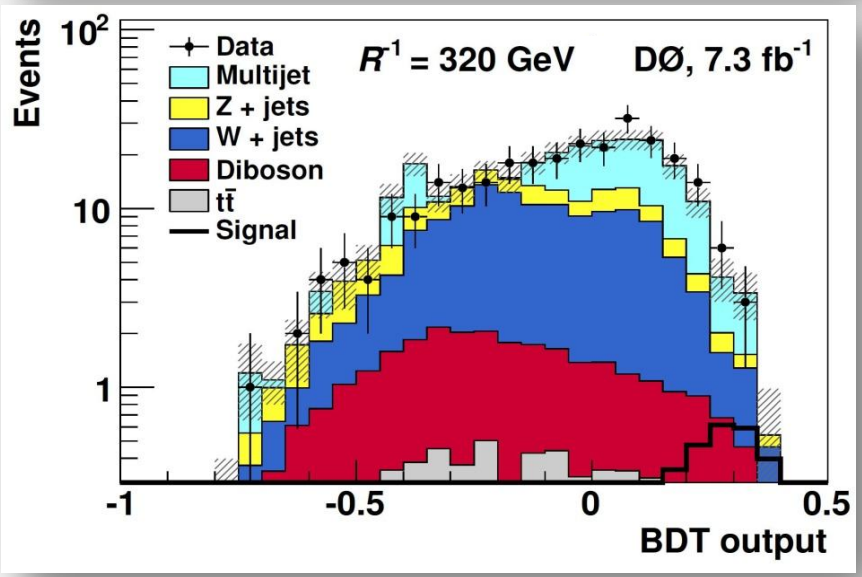


# BDT Output


Events
$10^2$
10
1
Data
Multijet
Z + jets
W + jets
Diboson
$t\bar{t}$
Signal
$R^{-1}$ = 200 GeV
DØ, 7.3 fb$^{-1}$
-1
-0.5
0
0.5
BDT output

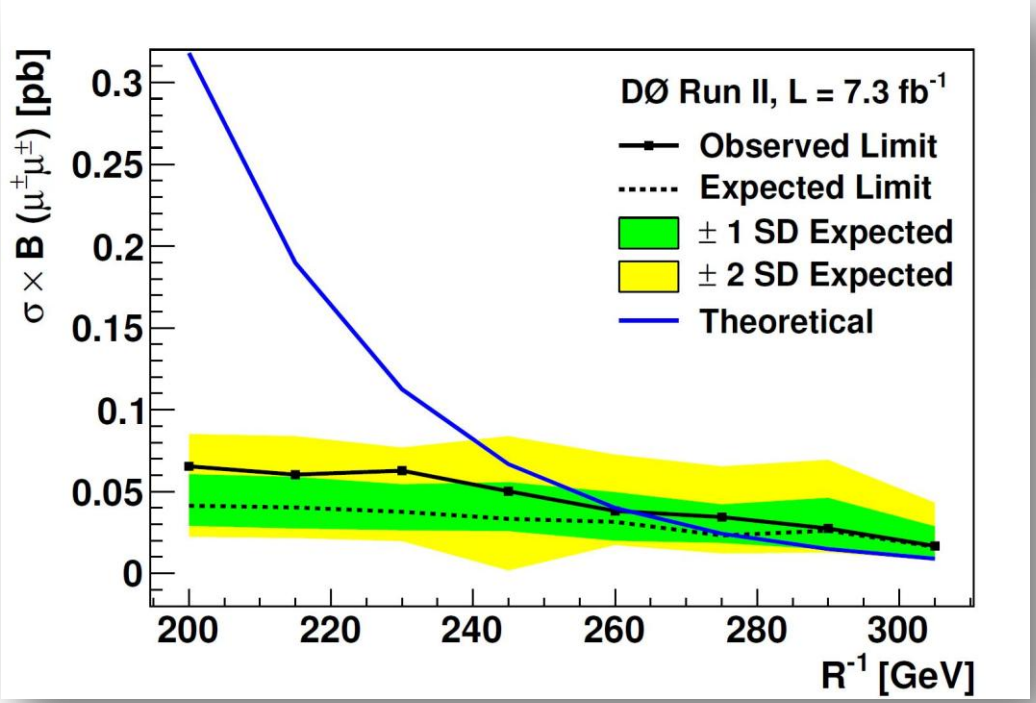

Events
$10^2$
10
1
Data
Multijet
Z + jets
W + jets
Diboson
$t\bar{t}$
Signal
$R^{-1}$ = 260 GeV
DØ, 7.3 fb$^{-1}$
-1
-0.5
0
0.5
BDT output


Events
$10^2$
10
1
Data
Multijet
Z + jets
W + jets
Diboson
$t\bar{t}$
Signal
$R^{-1}$ = 305 GeV
DØ, 7.3 fb$^{-1}$
-1
-0.5
0
0.5
BDT output


Events
$10^2$
10
1
Data
Multijet
Z + jets
W + jets
Diboson
$t\bar{t}$
Signal
$R^{-1}$ = 320 GeV
DØ, 7.3 fb$^{-1}$
-1
-0.5
0
0.5
BDT output

# Extraction of Limits

- Statistical studies → CLs
  - $R^{-1} \leq$ 260 GeV @ 95% C.L.
  - The first direct limit on UED.




*Phys. Rev. Lett., 108, 131802 (2012)*

# Conclusions

- Search for signal of extra dimensions
  - All fields in the extra dimensions

    Compactified extra dimensions
  - Minimal UED model → 1 extra dimension
- DØ @ Tevatron:
  - 1.96 TeV and $\int \mathcal{L} = 7.3\ fb^{-1}$
- No excess → The first direct limit on UED
  - Phys. Rev. Lett., 108, 131802 (2012)

$$R^{-1} \leq 260\ GeV \quad @\ 95\%\ C.L.$$

# Backup

# Definition of samples

- Muon isolation variables

$$\mathcal{I}_{cal} = \sum \frac{E_T^{0.1<\Delta R<0.4}}{p_T^{\mu}} \qquad \mathcal{I}_{trk} = \sum \frac{p_T^{\Delta R<0.5}}{p_T^{\mu}}$$

$$\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$$

- Defining samples
  - $\mathcal{S}$ sample → 2 isolated muons

$$\mathcal{I}_{cal} < 0.4 \quad + \quad \mathcal{I}_{trk} < 0.12$$

$$\text{or} \quad \mathcal{I}_{cal} < 0.4 \quad + \quad \mathcal{I}_{trk} < 0.25$$

  - $\mathcal{Q}$ sample → 1 isolated and 1 non-isolated muon

    One muon fail one of the isolation criteria.

# MUED: Mass Spectrum

TABLE I: Masses of KK particles for each $R^{-1}$ value used in the MC generation with corresponding total production cross section.

| $R^{-1}$ | Masses (GeV) | | | | | Cross Section* |
|---|---|---|---|---|---|---|
| (GeV) | $\gamma_1$ | $Z_1$ | $g_1$ | $\ell_1$ | $Q_1$ | (pb) |
| 200 | 201 | 230 | 269 | 207 | 249 | $34.9 \pm 0.2$ |
| 215 | 216 | 245 | 287 | 222 | 266 | $20.4 \pm 0.1$ |
| 230 | 231 | 260 | 305 | 238 | 283 | $12.1 \pm 0.1$ |
| 245 | 246 | 274 | 323 | 253 | 300 | $7.24 \pm 0.05$ |
| 260 | 261 | 289 | 341 | 268 | 317 | $4.39 \pm 0.03$ |
| 275 | 276 | 304 | 359 | 284 | 334 | $2.69 \pm 0.02$ |
| 290 | 291 | 319 | 377 | 299 | 351 | $1.65 \pm 0.01$ |
| 305 | 306 | 335 | 395 | 314 | 368 | $1.02 \pm 0.06$ |
| 320 | 321 | 350 | 413 | 330 | 385 | $0.63 \pm 0.01$ |

(*) All KK gluon and quark production modes included.