Large Extra Dimension Searches in Mono-Jet and Mono-photon signatures at the Tevatron

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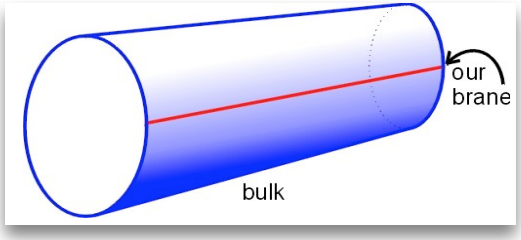
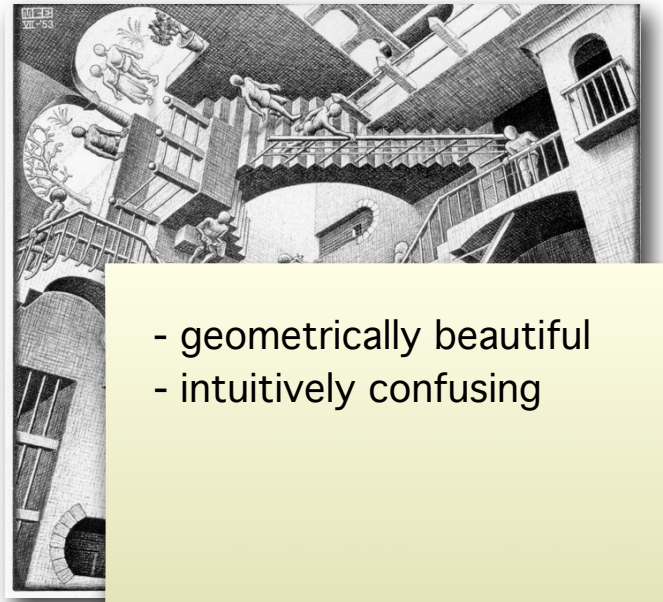
Large Extra Dimensions

Thinking outside of the Box

- Hierarchy problem: why gravity is so weak?
  - suppressed by a number of compactified ED



$$M_{Pl}^2 = 8\pi M_D^{\delta+2} R^\delta$$



- geometrically beautiful
- intuitively confusing

- Observable experimental consequences:
  - Detectable individual KK modes (RS)
  - Tower of KK modes behaves like a stable massive stable particle

Extra Dimensions

- Extra Dimensions: a geometrical approach to hierarchy problem (EW vs Plank scales)
  - SM particles exist only in 3+1 dimension
  - gravity exist in all (3+1) + n dimensions
  - EDs have to be compactified (e.g. donuts for n=2)
- Fundamental scale can be (much) lower than the Plank scale:
  - accessible Quantum Gravity (superstring theory)
  - pros: dark matter candidate, black holes at LHC etc.
  - cons: proton will have to decay, electron magnetic moment, same problems emerge etc.

Large Extra Dimensions

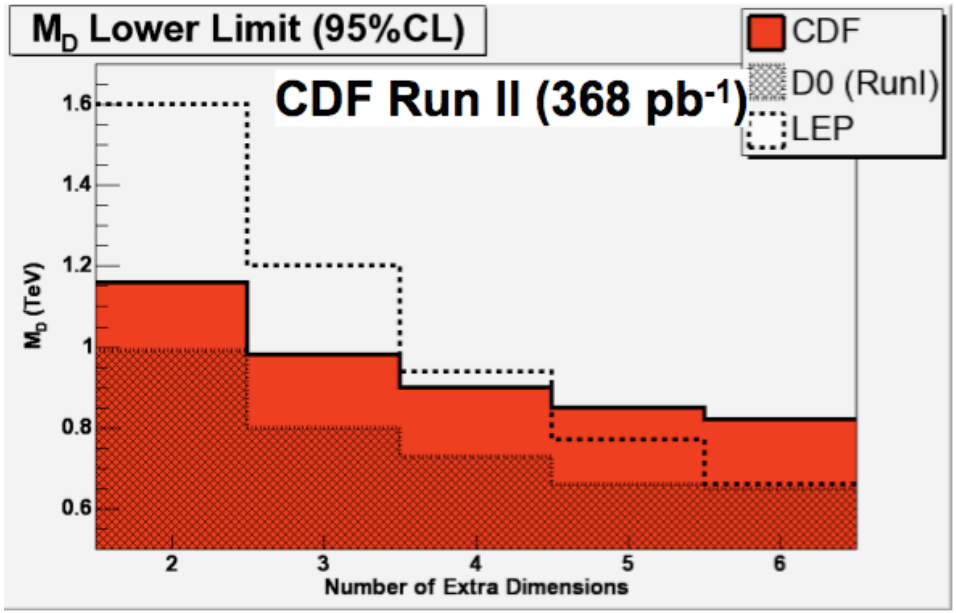
- ADD paradigm
- Large (w.r.t. Plank scale) ED → Compactified on a sub-mm scale R
  - Plank mass in (3+1)D related to the fundamental mass M_D in 4+d: $M_{pl}^2=8\pi\cdot M_D^2\cdot(M\cdot R)^d$
  - thus fundamental scale >~1 TeV, and R~0.1mm (1fm) for d = 2(6)
- KK graviton mode mass ~n/R
  - almost continuous spectrum: $\delta M_{n,n+1}$~mEv (MeV) for d = 2(6)
- In RS dM~1TeV: resonances

Existing Constraints

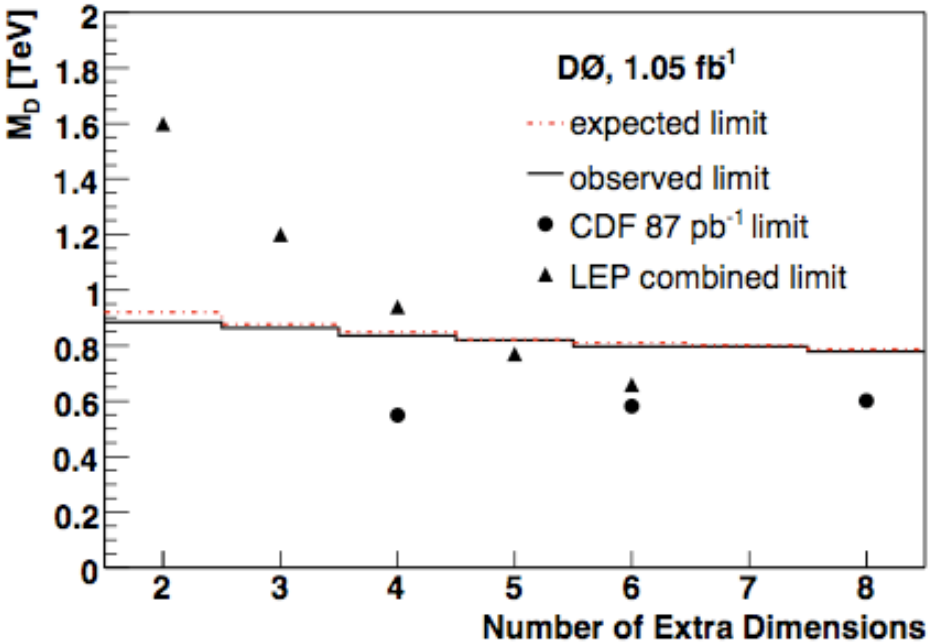
- LEP/Tevatron limits ~ 1 TeV scale [PRL 2006, 2008]:
  - R < 0.2 mm for d=2 to R < 30 fm for d=6
- Direct studies of Newton Law (Cavendish):
  - Stronger than collider limits for d =2: R < 37 μm [PDG 2007]; equivalent to M_D>3.6 TeV
- Astrophysics: faster (Hubble-wise) evaporation of BH's, neutron stars:
  - Up to R < 10^{-10} m (700 TeV) from neutron stars [PDG 2007]
  - ... black holes go here [arXiv 2008]...
  - Many assumptions about star internals, sensitive only to low n/R: limit can be relaxed

Existing Constraints

CDF: PRL **97**, 171802 (2006)



DO: accepted to PRL(2008); arXiv:0803.2137v1



n	M_D (TeV)	R(mm)
2	>1.18	<0.35
3	>0.99	$<3.6\times10^{-6}$
4	>0.91	$<1.1\times10^{-8}$
5	>0.86	$<3.5\times10^{-10}$
6	>0.83	$<3.4\times10^{-11}$

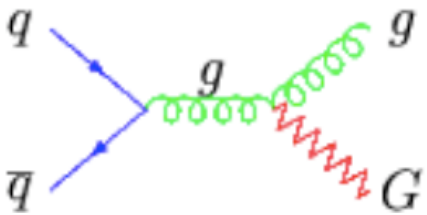
LED: Collider Signatures

- Direct production: something + nothing
  - jet + MET (Missing Et)
  - γ+MET: clean but suppressed by $\alpha_{QED}/\alpha_{QCD}$
  - Single mode: $\sigma(n) \sim 1/M_{Pl}^2$
    - M_{Pl} cancels out after sum over n
    - $\sigma \sim 1/M_D^2 \cdot (s/M_D^2)^{d/2}$
- Virtual Exchange (not covered in this talk)

Jet+MET

1.1 fb^{-1} update to PRL **97**, 171802 (2006)

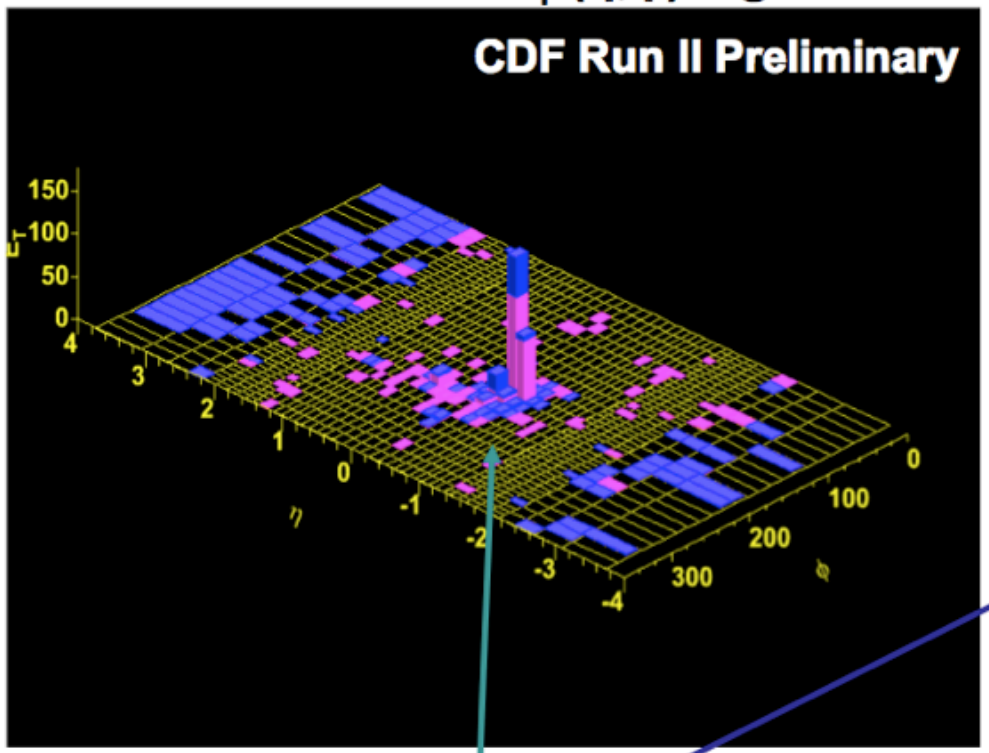
- Data sample of 1.1 fb^{-1}: **CDF**: arXiv:0807.3132v1
  - collected with a jet trigger with Et >100 GeV
- Leading jet Et > 150 GeV
- Extra acceptance (ISR/FSR)
  - Allow secondary jet Et < 60 GeV
  - No other jets with Et > 20 GeV)



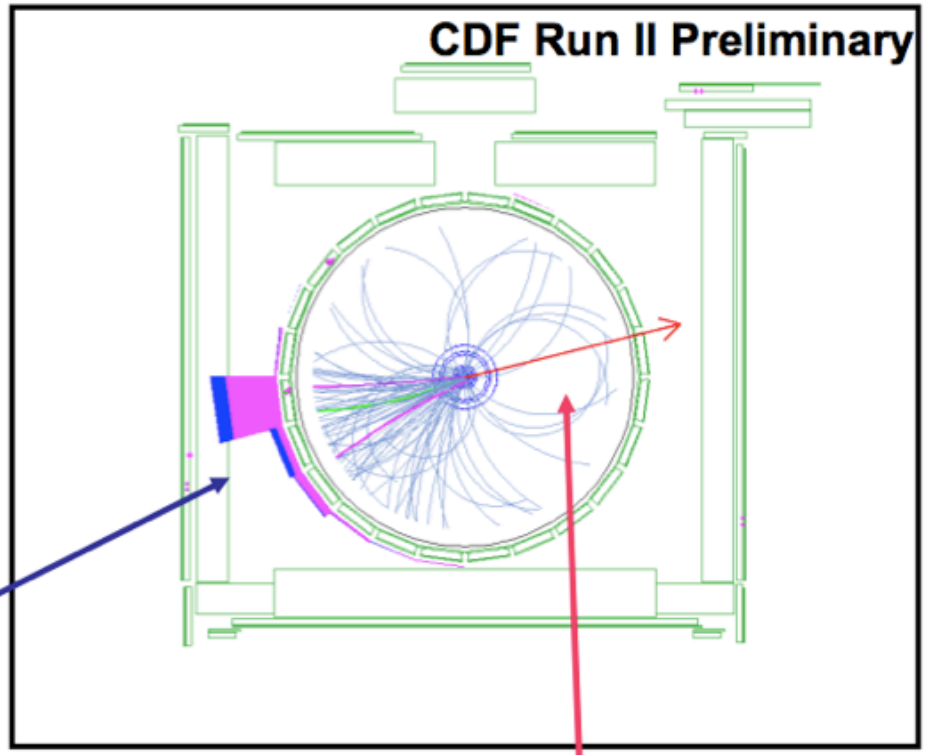
- Missing Et > 120 GeV (away from any jet)
- Major background: Z (νν), W(lν) ⇐ Estimated from data
- QCD (lost jet) ~6%: 2j/3j from MC, 2j from data
- Non-collision background: timing in HCAL

Jet+MET: example event

Calorimeter E_T (η,φ) lego view



Detector (r,φ) side view



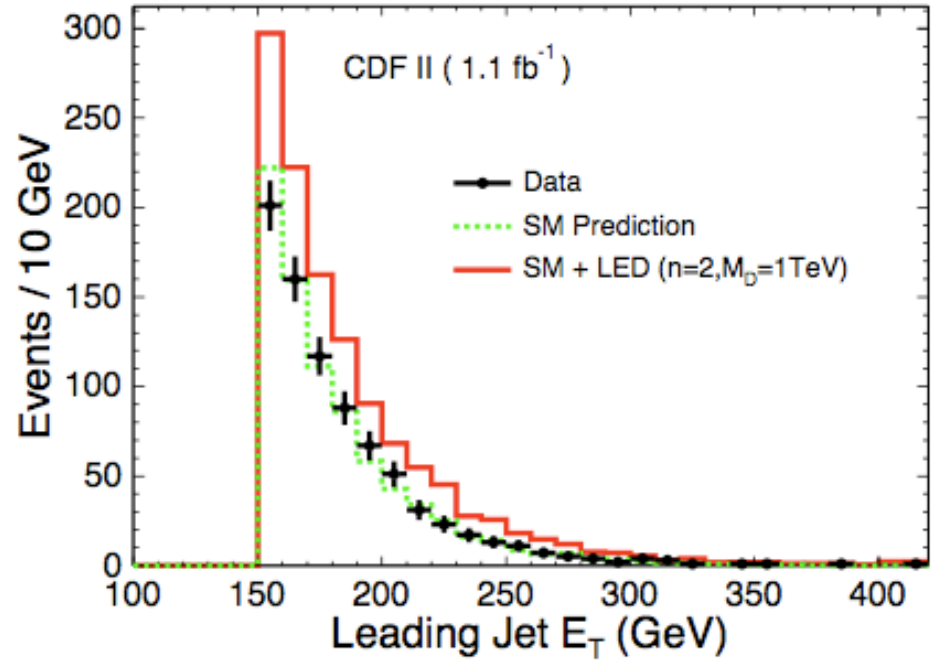
Jet E_T = 419 GeV, MET = 417 GeV

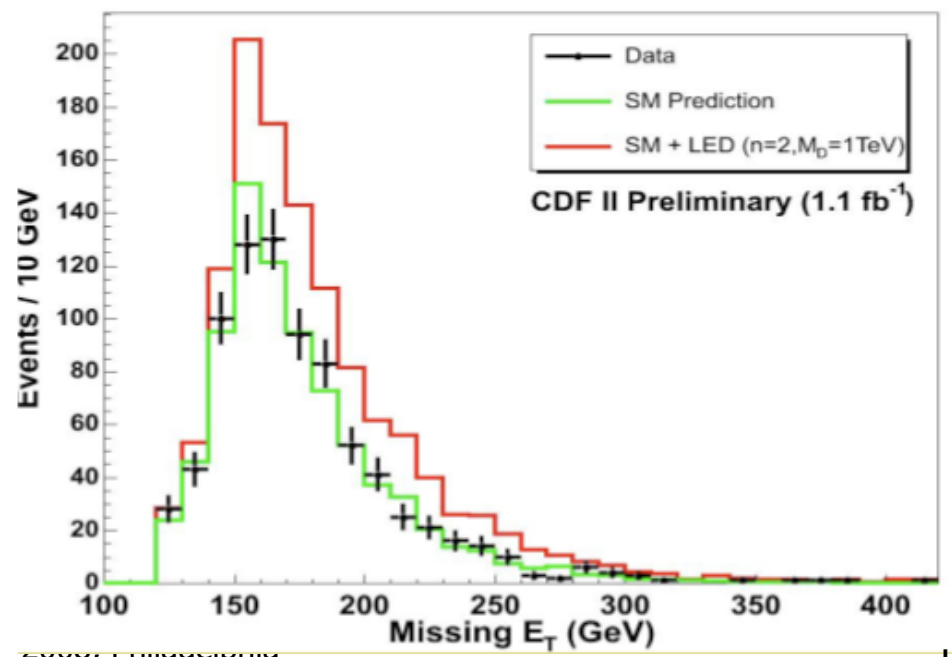
1.1 fb^{-1} update to PRL **97**, 171802 (2006)

CDF: arXiv:0807.3132v1

Jet+MET: Data

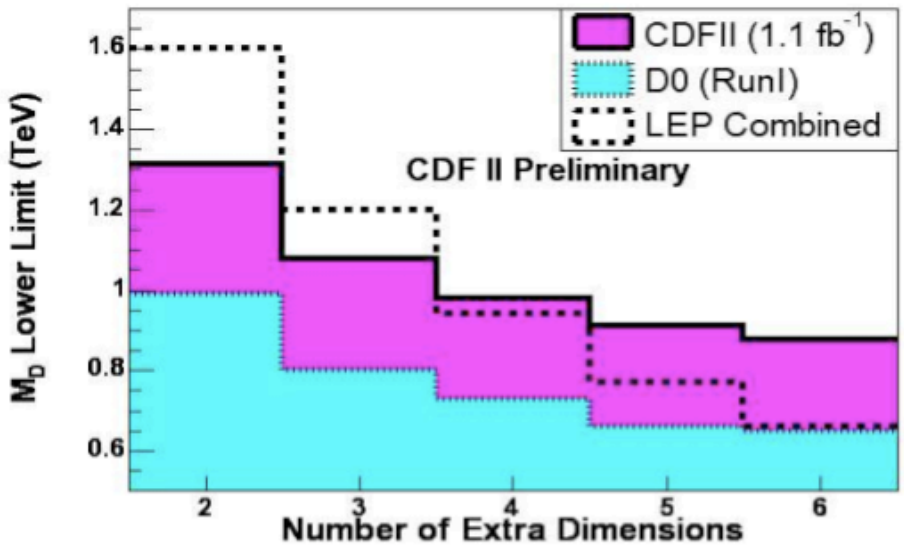
Background	Events
$Z \to \nu\bar{\nu}$	388 ± 30
$W \to \tau\nu$	187 ± 14
$W \to \mu\nu$	117 ± 9
$W \to e\nu$	58 ± 4
$Z \to \ell\ell$	8 ± 1
Multi-jet	23 ± 20
γ+jet	17 ± 5
Non-collision	10 ± 10
Total predicted	808 ± 62
Data observed	809





LED Constraints from Jet+MET

CDF: arXiv:0807.3132v1



n	M_D (TeV)	R(mm)
2	> 1.31	< 0.279
3	> 1.08	< 3.15×10^{-6}
4	> 0.98	< 1.01×10^{-8}
5	> 0.91	< 3.20×10^{-10}
6	> 0.88	< 3.16×10^{-11}

- Limits are set using only event counts (e.g. no shape information is used)

Enlightenment of the Invisible: LED γ+MET

- Energetic photon + nothing (explicit jet/track veto)
- Data-driven background estimation
  - Important to suppress non-collision backgrounds
  - Fakes ($e \rightarrow \gamma$, $jet \rightarrow \gamma$)
  - Irreducible: Z(invisible)+ γ

LED in γ+MET: fighting cosmics

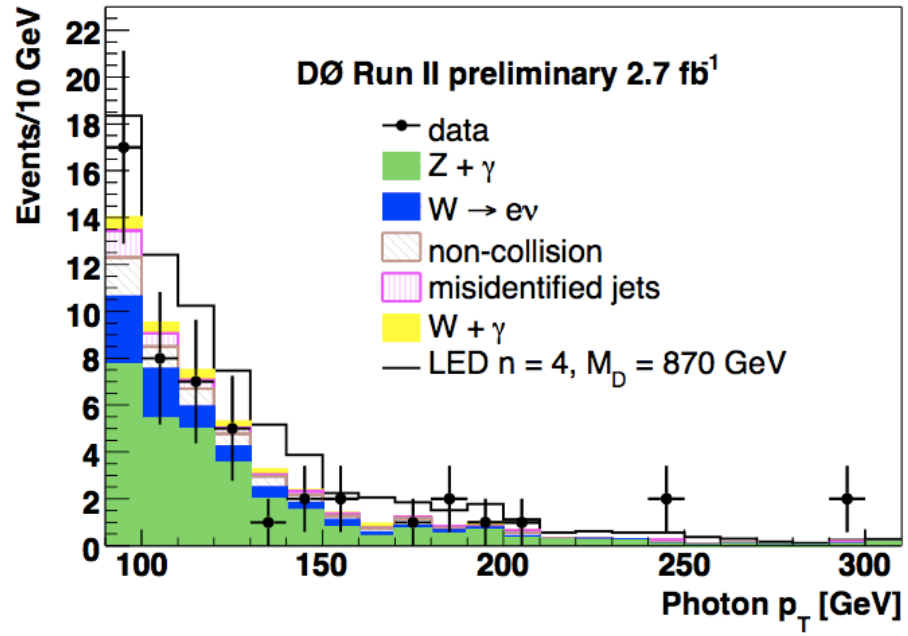
aka Star Wars

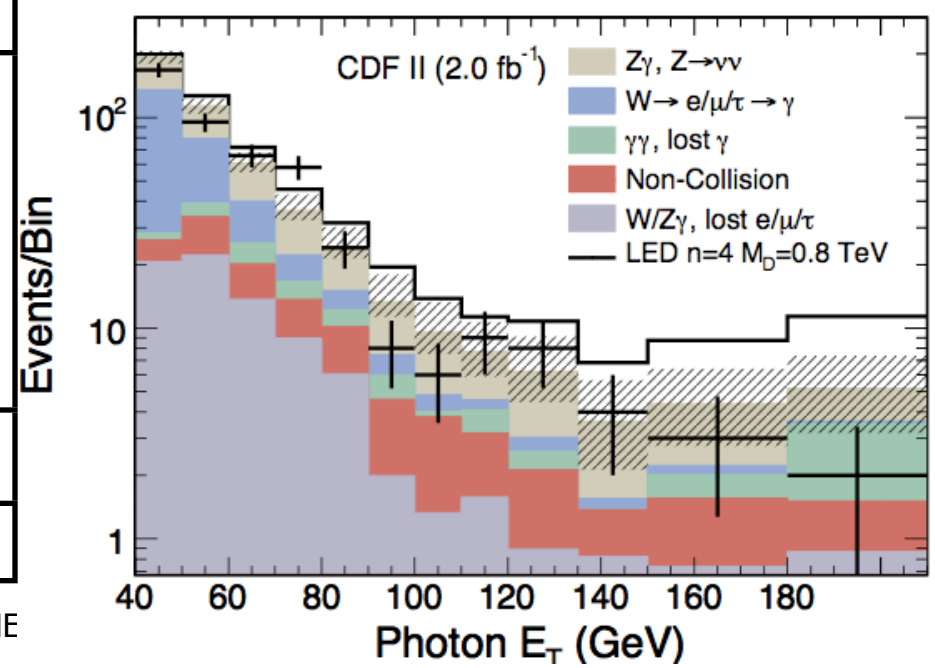
- DZero:
  - pointing: use fine segmentation of EM calorimeter to separate photons from jets and cosmics
- CDF:
  - timing: interpolate cosmics from sidebands: x20
  - topological cuts: removes most of beam halo, additional x30 for cosmics
  - **yet** 20% bkg after x600 suppression!

LED in γ+MET: Data

- Photon Et > 90 GeV
- Central: |η| <1.0
- Jet/high-pt track veto

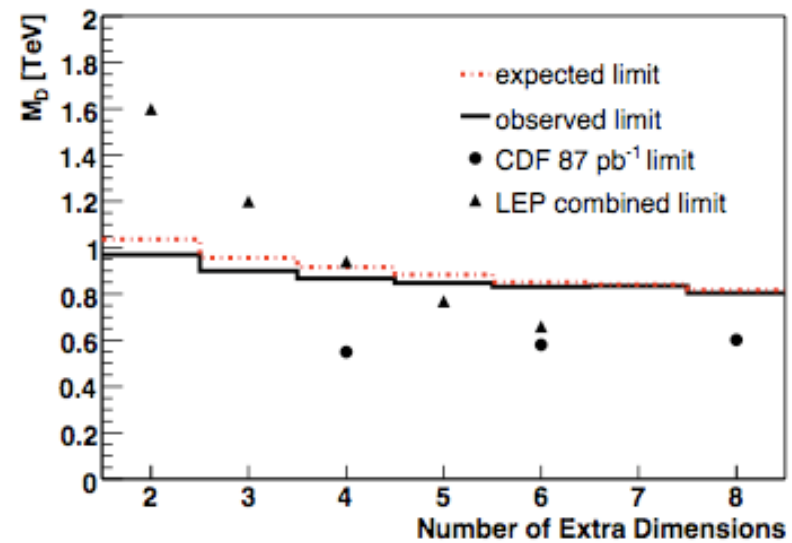
Luminosity MET cut	CDF 2.0 fb^{-1} 50 GeV	DZero 2.7 fb^{-1} 70 GeV
Cosmics + halo Fake photons W→l→γ Wγ→lost lepton γγ→γ Zγ→ννγ	9.8±1.3 - 3.6±0.4 5.0±1.4 2.3±0.6 25.2±2.8	6.6±2.3 3.1±1.5 8.5±1.7 2.22±0.3 - 29.5±2.5
Total	46.7±3.0	49.9±4.1
Data	40	51





LED Constraints from γ+MET

d	Observed (Expected) 95 % CL lower limit on M_D, GeV	
	CDF, 2 fb^{-1}	DO, 2.7 fb^{-1}
2	1080(1000)	970(1037)
3	1000(940)	899(957)
4	970(910)	867(916)
5	930(880)	848(883)
6	900(860)	831(850)
7	-	834(841)
8	-	804(816)



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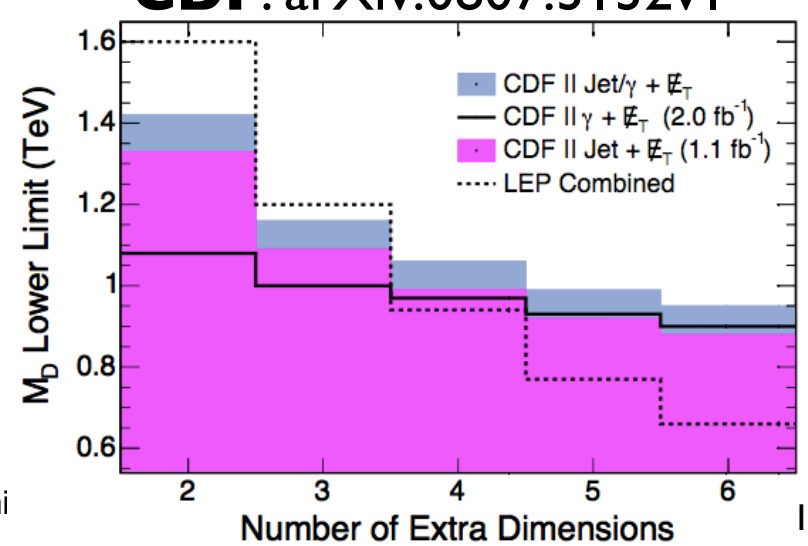
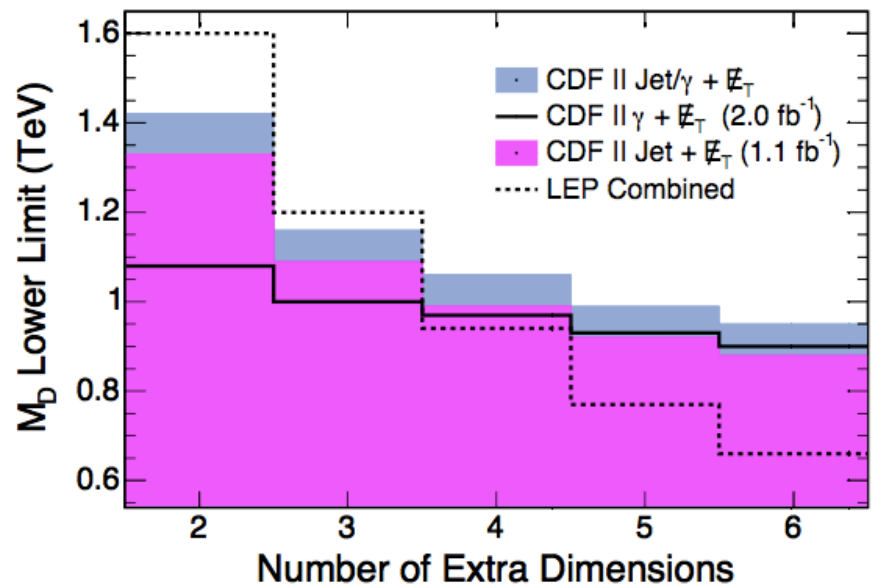


- DZero: limits are set using log-likelihood ratio test statistics (modified frequentist approach) employing photon **pT** distribution

Combination of γ+MET and Jet+MET

CDF: arXiv:0807.3132v1

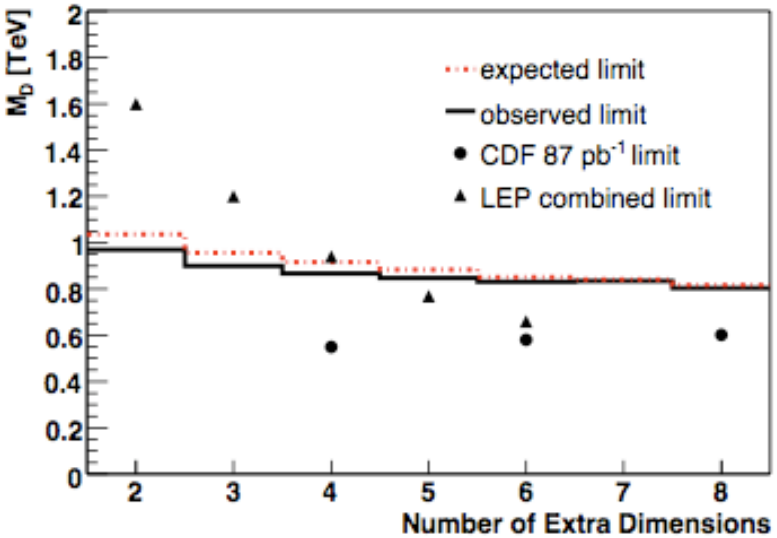
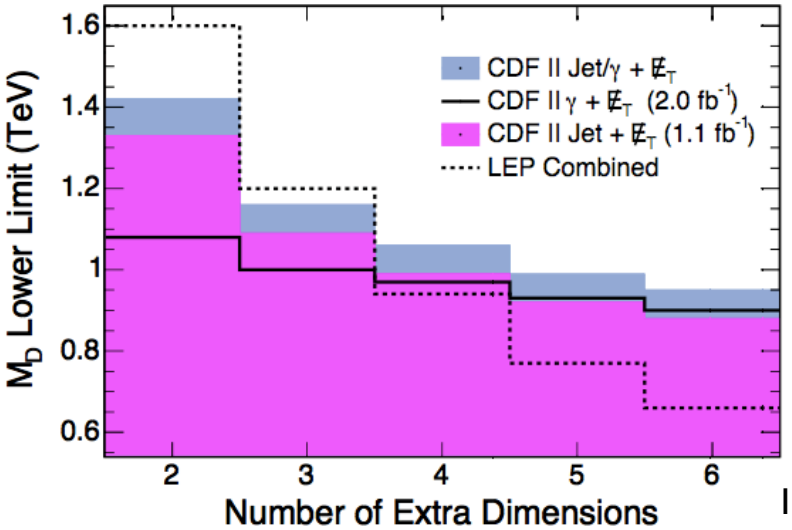
	$\gamma + \not{E}_T$		Jet + $\not{E}_T$		Combined
n	α	M_D^{obs}	α	M_D^{obs}	M_D^{obs}
2	7.2	1080	9.9	1310	1400
3	7.2	1000	11.1	1080	1150
4	7.6	970	12.6	980	1040
5	7.3	930	12.1	910	980
6	7.2	900	12.3	880	940



- Limits from Jet+MET and g+MET are combined
- Similar sensitivity in for d>3
- Tevatron combination is *en route*
- NB: for Newton Law tests: M_D>3.6 TeV for d=2

Outlook

- No evidence for LED
- Sensitivity to the fundamental mass scale is M_D>~ 1TeV
- More data is coming
- Invaluable experience for LED searches at the LHC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