Search for Large Extra Dimensions in the Jets+ Missing E_T Channel at CDF

Fermilab Wine and Cheese Seminar
January 13, 2006

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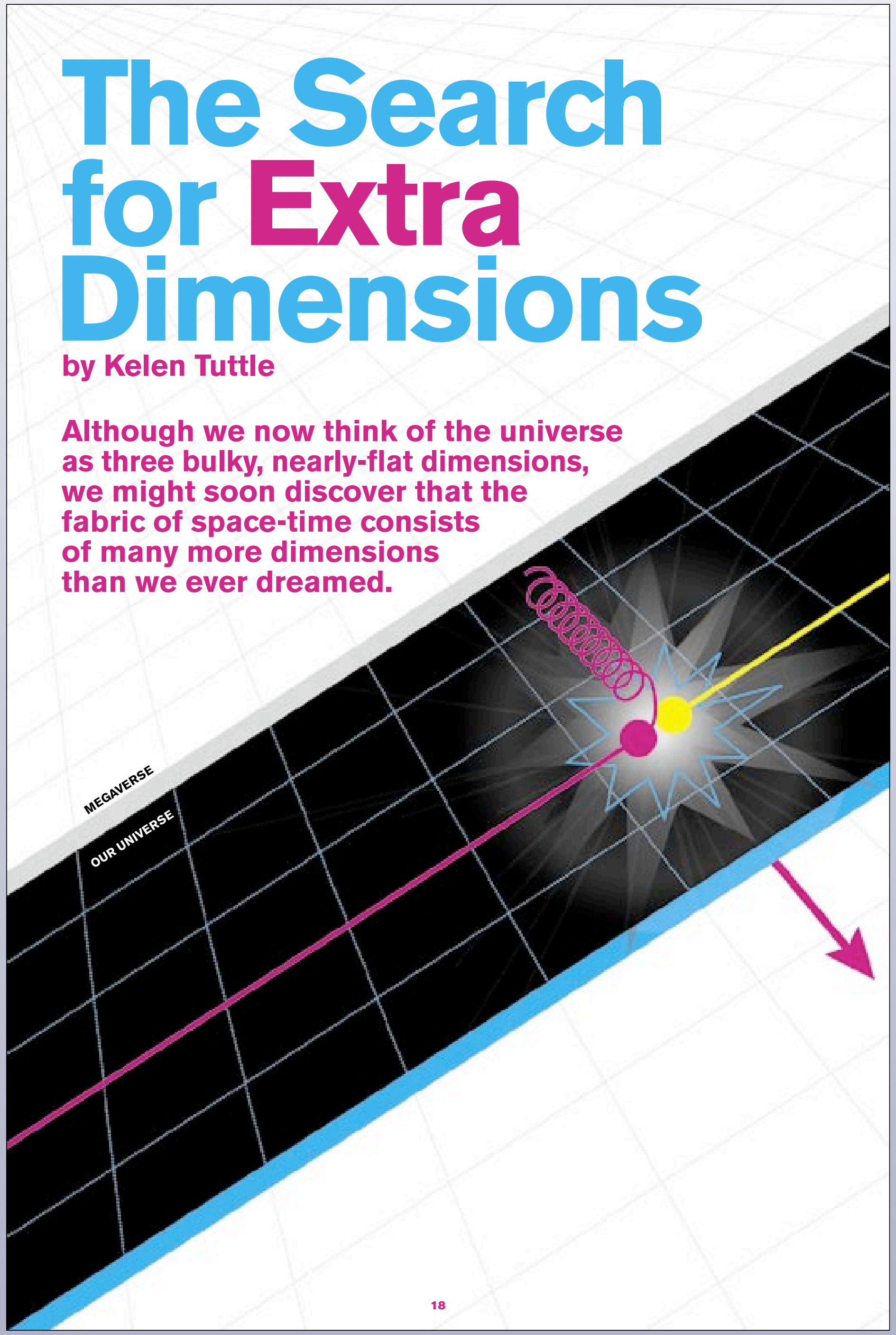
for the **CDF Collaboration**

A Timely Topic

Symmetry Magazine Dec05/Jan06



Outline

- Introduction
  - Gravity with Large Extra Dimensions
  - Collider Signatures of LED
- Monojet Data Analysis
  - Data Selection
  - Standard Model Monojet Production
  - Results
- Future Expectations
- Conclusions

Introduction

- In Nature, there are 4 forces

Force	Carrier	Range	Relative Strength
Strong	g	10^{-18}m	1
Electromagnetic	γ	Infinite	10^{-2}
Weak	$W^{\pm},Z^{0}$	10^{-15}m	10^{-13}
Gravity	G	Infinite	10^{-38}

- In particle physics, we usually focus on first three since gravity is so much weaker
  - e.g., gravitational attraction between two electrons is ~x10^{42} weaker than EM repulsion

Introduction

- While it may be safe to ignore gravity at EWK energies, there are places where all forces should be relevant (e.g. Big Bang)
- At very high energies, all 4 forces should unify
  - Gravity unites with other forces at the Planck Scale (10^{19} GeV)
- Hierarchy Problem:
  - Why is EWK scale so different from Planck scale?
  - Alternatively, why is gravity so much weaker than other forces?
- Extra Dimensions could allow the fundamental Planck scale to be as low as the EWK scale

Introduction

- Large Extra Dimensions were proposed as a new solution to the hierarchy problem in the late 1990's
- Since then, LED have been invoked to explain nearly all unsolved problems of the SM:
  - EWSB
  - Dark Matter, Dark Energy
  - SUSY breaking
  - ...
- Extra Dimensions must be somehow hidden or we would have seen them already
  - Either compactified or inaccessible to some part of SM

Models of Extra Dimensions

Only a partial list of models

- ADD Model:
  - Arkani-Hamed, Dimopoulos, and Dvali
  - Phys.Lett. B429(1998), Nuc.Phys.B544(1999)
  - *n* extra dimensions, compactified at radius *R*
  - SM is confined to brane in a higher dimensional space
  - Only gravity can access extra dimensions
  - Signatures:
    - Jets+MissingE_T, γ+MissingE_T, lepton pairs

Models of Extra Dimensions

- Randall-Sundrum Model:
  - PRL**83** 3370(1999)
  - One warped extra dimension
  - Two branes, gravity localized on one, SM localized on second
  - Signature: Narrow, high mass resonances
- Universal Extra Dimensions
  - Phys.Rev.**D64**:035002 (2001)
  - One or more extra dimensions of TeV^{-1} size
  - SM particles allowed to live in bulk
  - Signature: Excited gauge bosons

Gravity in Extra Dimensions

- Gravitational Potential in 4 Dimensions (Newton)

$$V(r) = G_N \frac{m_1 m_2}{r} = \frac{1}{(M_{Pl})^2} \frac{m_1 m_2}{r}$$

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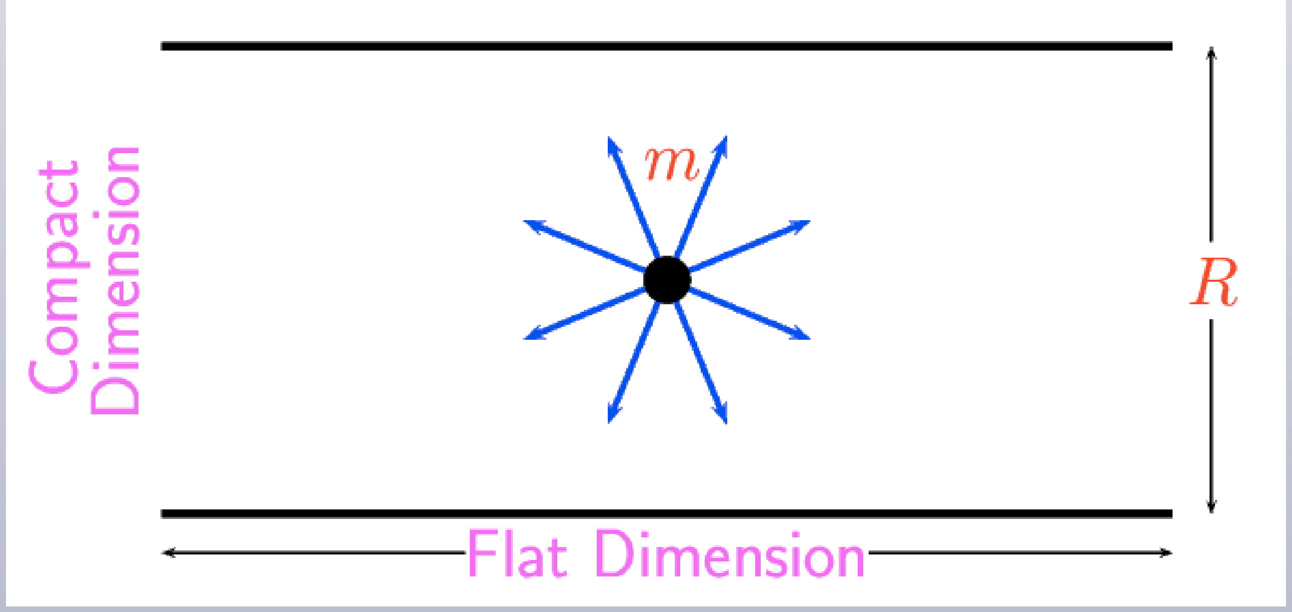
- n extra dimensions, compactified at radius R

r<<R $$V(r) \sim \frac{1}{(M_D)^{n+2}} \frac{m_1 m_2}{r^{n+1}}$$



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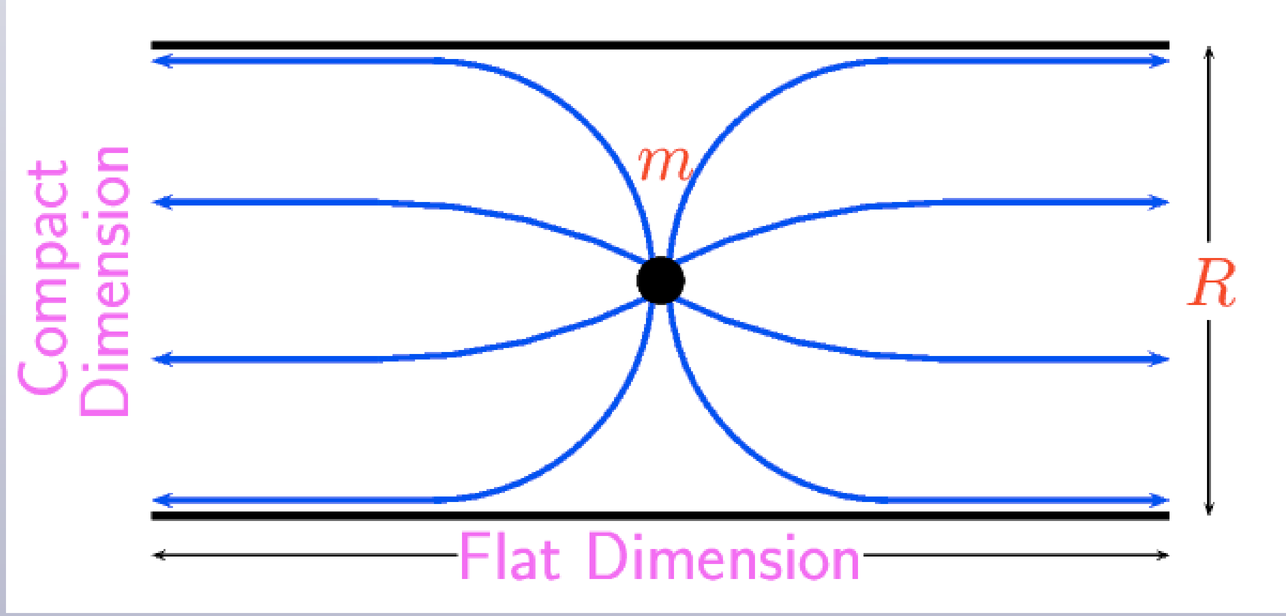
r<<R $$V(r) \sim \frac{1}{(M_D)^{n+2}} \frac{m_1 m_2}{r^{n+1}}$$ → $$V(r) \sim \frac{1}{(M_D)^{n+2}} \frac{m_1 m_2}{R^n} \frac{1}{r}$$ r>R



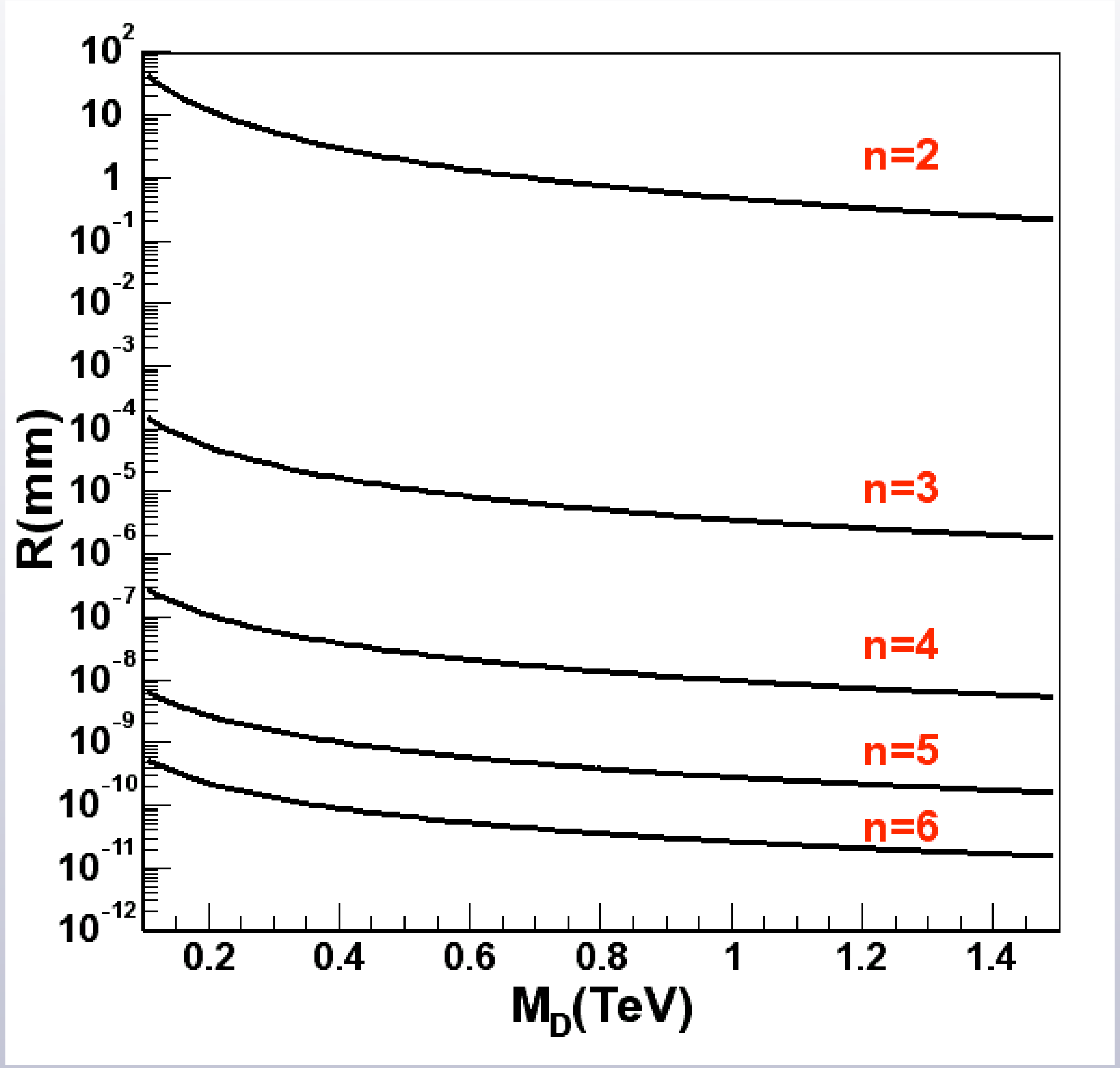
At large distances, must return to original potential

$$(M_{PL})^2 \sim R^n (M_D)^{2+n}$$

Gravity in Extra Dimensions

- 4 dimensional M_{PL} related to the (4+n)-dimensional M_D by

  $(M_{PL})^2 \sim R^n (M_D)^{2+n}$



- Setting M_D=1TeV
  - $n=1 \Rightarrow R=10^{13}$m

    excluded by astro. data
  - $n=2 \Rightarrow R \sim 400\ \mu$m

    same order as direct probes of gravity
  - $n=6 \Rightarrow R=10^{-13}$ m

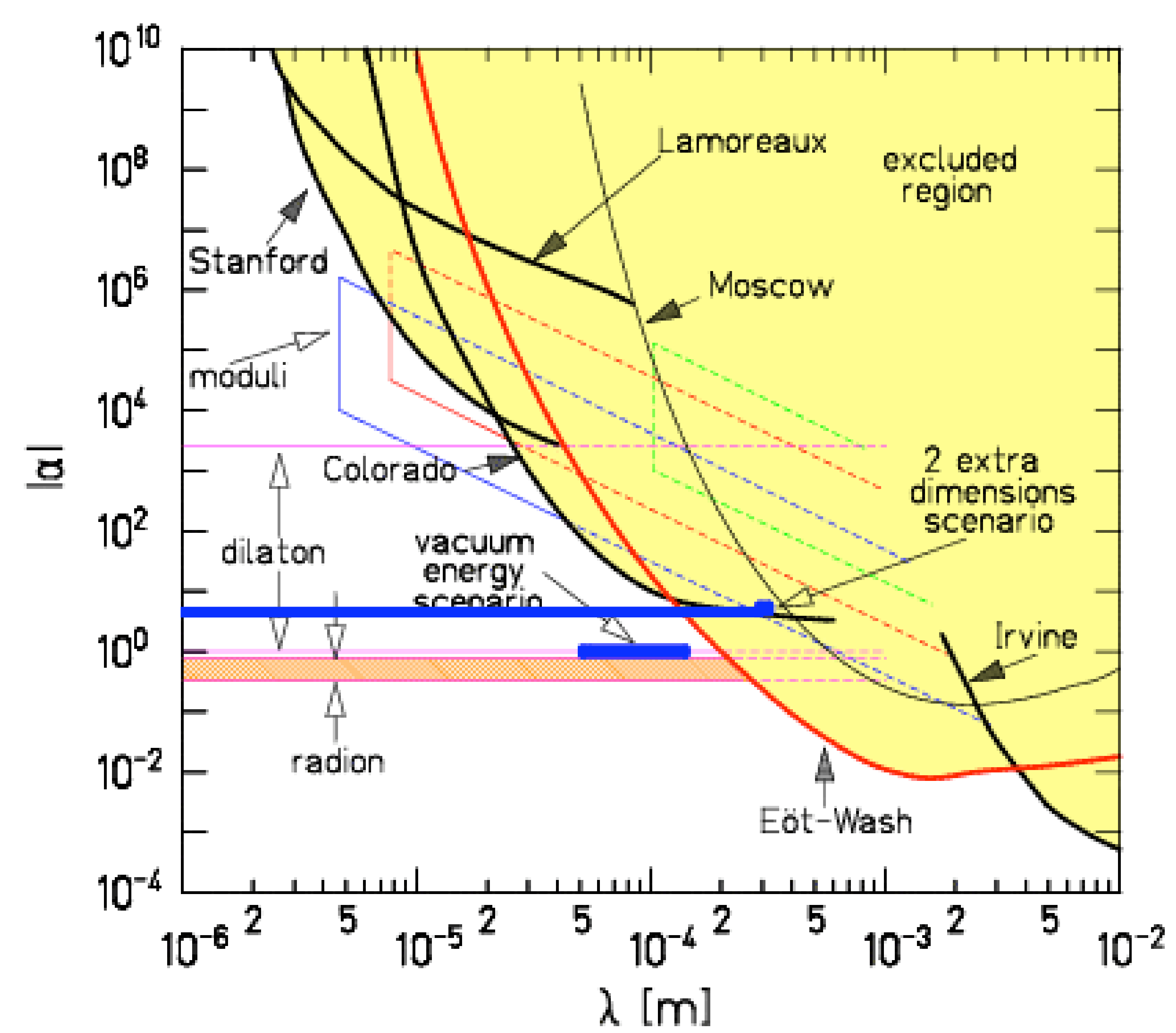
    only testable at high energy colliders

Direct Test of Short-Range Gravity

- Look for deviations in $1/r^2$ law of gravity
- Replace Newtonian potential with more general expression:

$$V(r) = -G\frac{m_1 m_2}{r}(1 + \alpha e^{-r/\lambda})$$

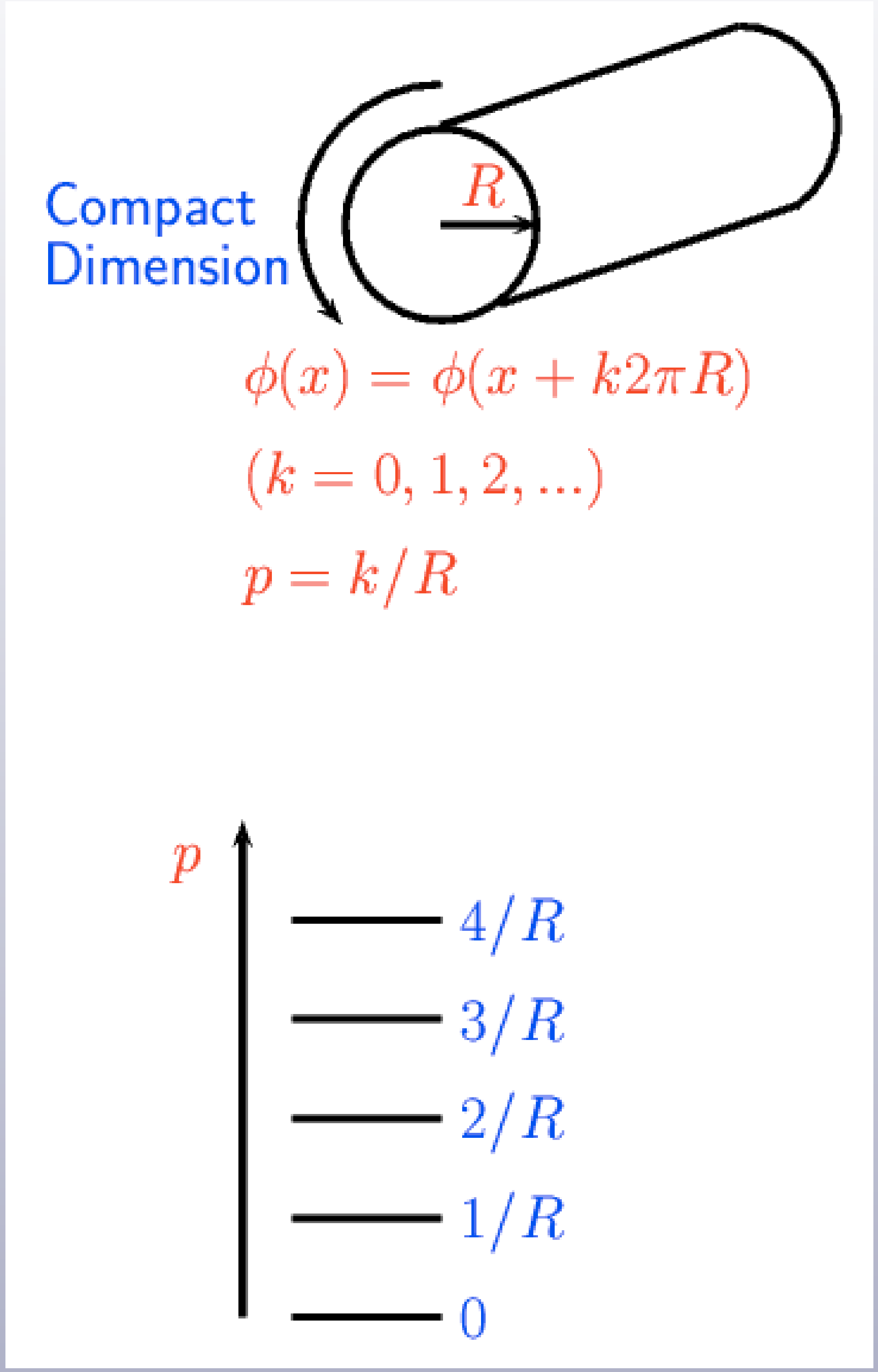
  - λ = range
  - α = strength relative to gravity
- For the case of *n* toroidal extra dimensions, α=8*n*/3



Relevant Limit from Eöt-Wash Experiment: *R*<130μm (n=2) (PR**D70**, 042004)

Gravity in Extra Dimensions

- Compactified dimension is periodic
- Momentum in extra dimensions is quantized, $p=k/R$
- Gravitons appear to have mass, $m^2 = m_0^2+p^2$
- Tower of KK modes
  - mass splittings $\Delta m \sim 1/R$
  - nearly continuous
    - n=2: $\Delta m \sim 10^{-4}$ eV
    - n=6: $\Delta m \sim 10$ MeV



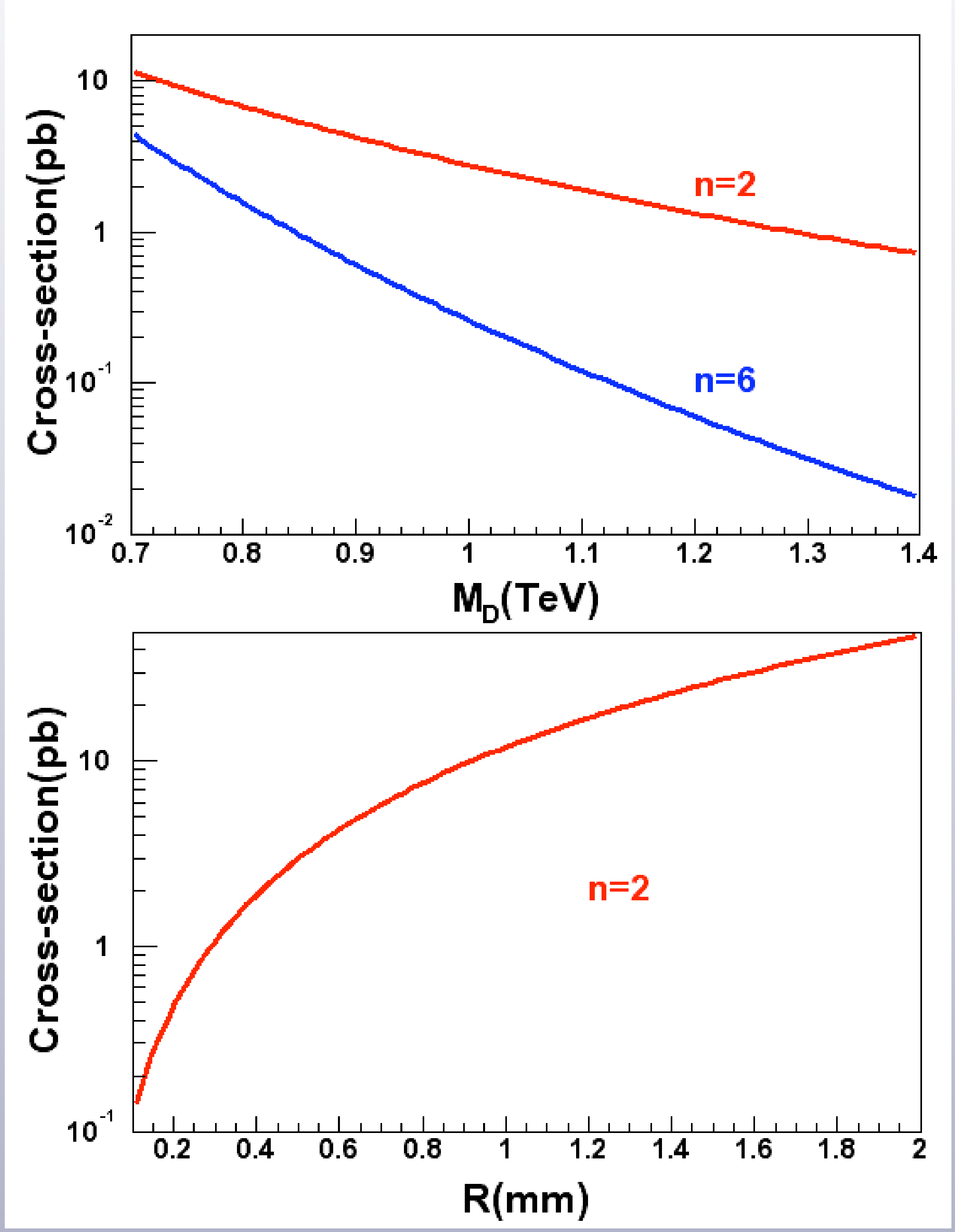
Gravity in Extra Dimensions

- Though each graviton couples with strength M_{PL}^{-1}, there are $(ER)^n$ possible modes
- Consider cross-section for a single graviton, summed over all momenta:

$$\sigma \sim \frac{1}{M_{Pl}^2}(\sqrt{s}R)^n$$

- M_{PL} suppression replaced by M_D suppression

$$\sigma \sim \frac{1}{M_D^2}\left(\frac{\sqrt{s}}{M_D}\right)^n$$

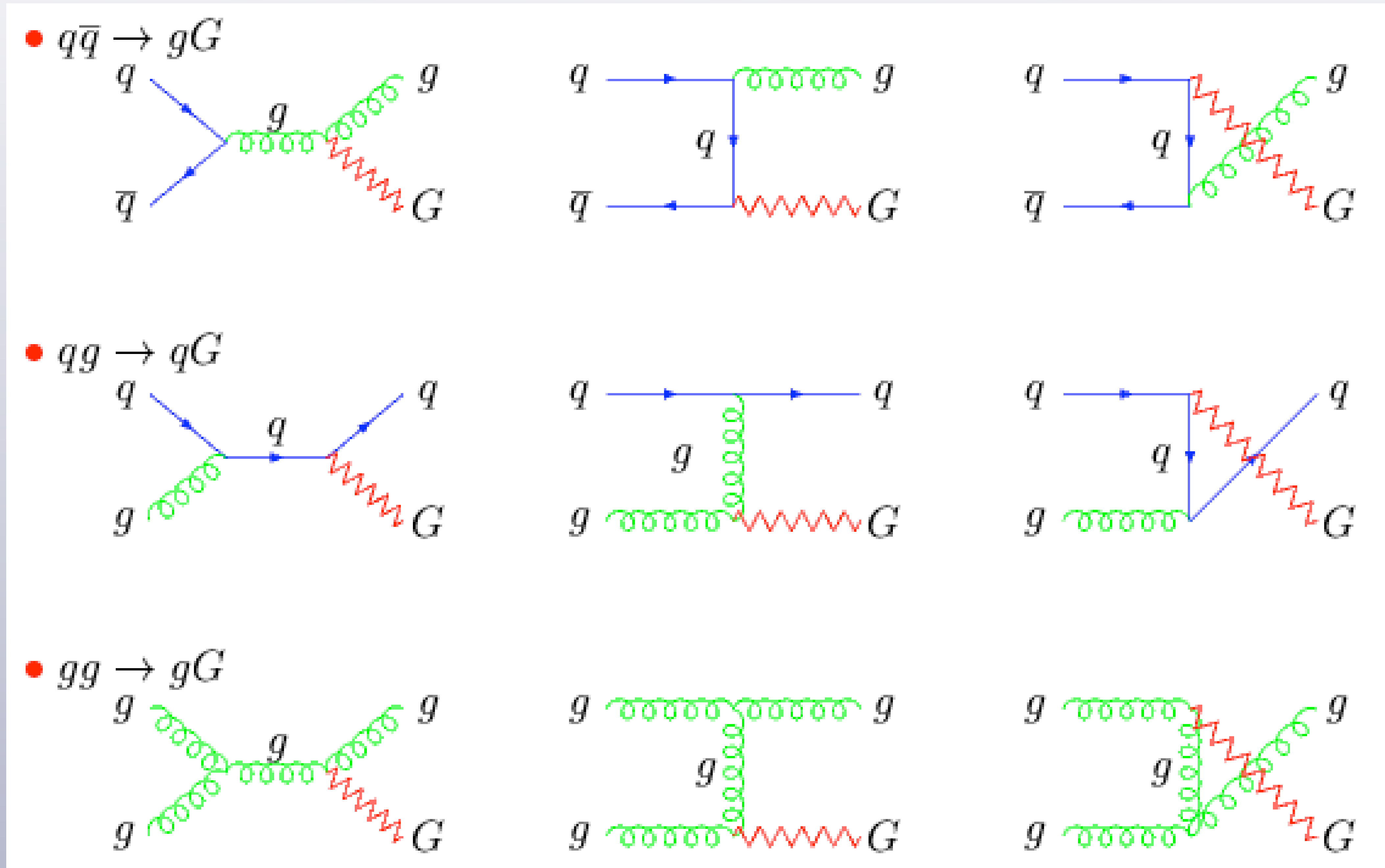


Collider Signatures of LED

- How could we see evidence of large extra dimensions at colliders?
- Two different signatures (ADD model):
  - Direct graviton production
    - Real graviton emitted in final state
    - G+jet, $G+\gamma$
  - Virtual graviton exchange
    - pair production of leptons, photons, etc.

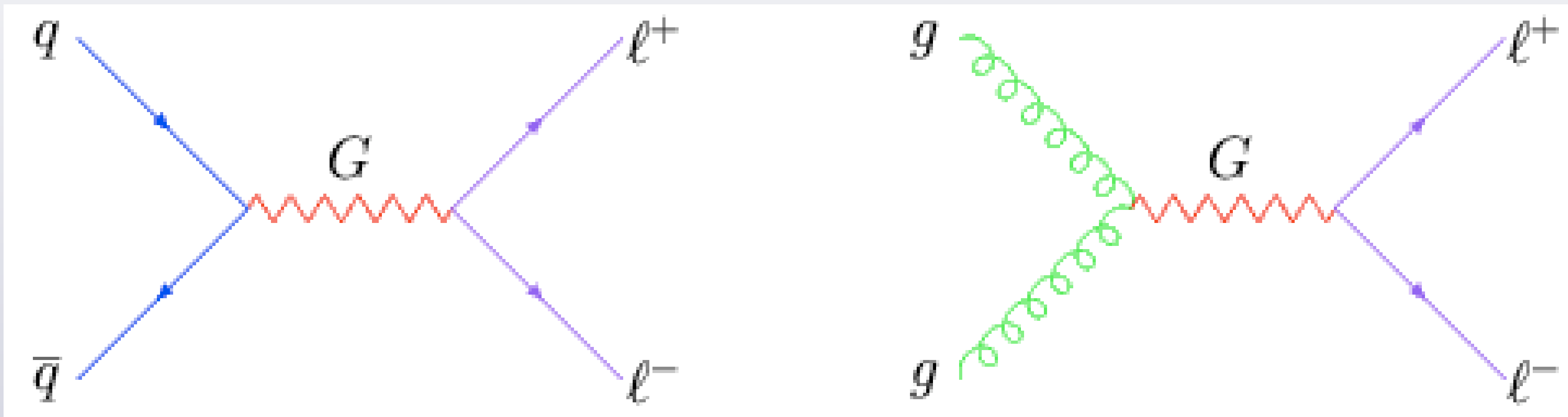
Collider Signatures of LED

Real Graviton Emission

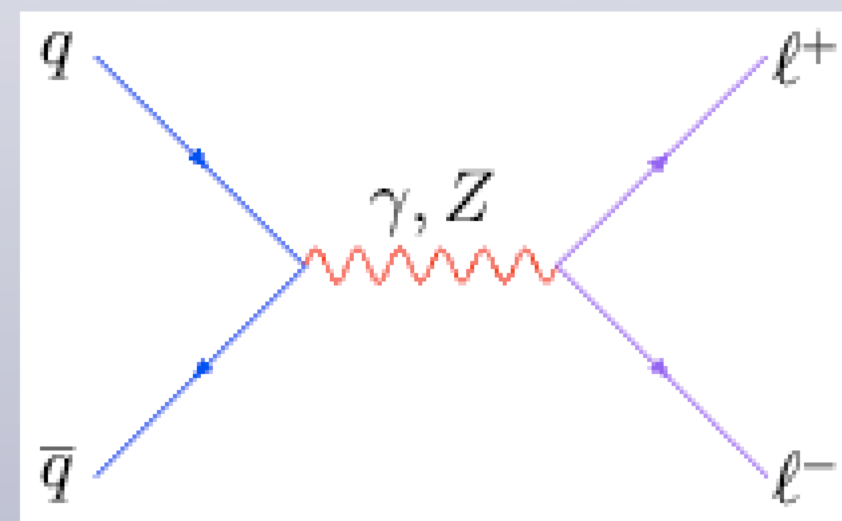


Undetected graviton leads to Missing E_T

Virtual Graviton Exchange



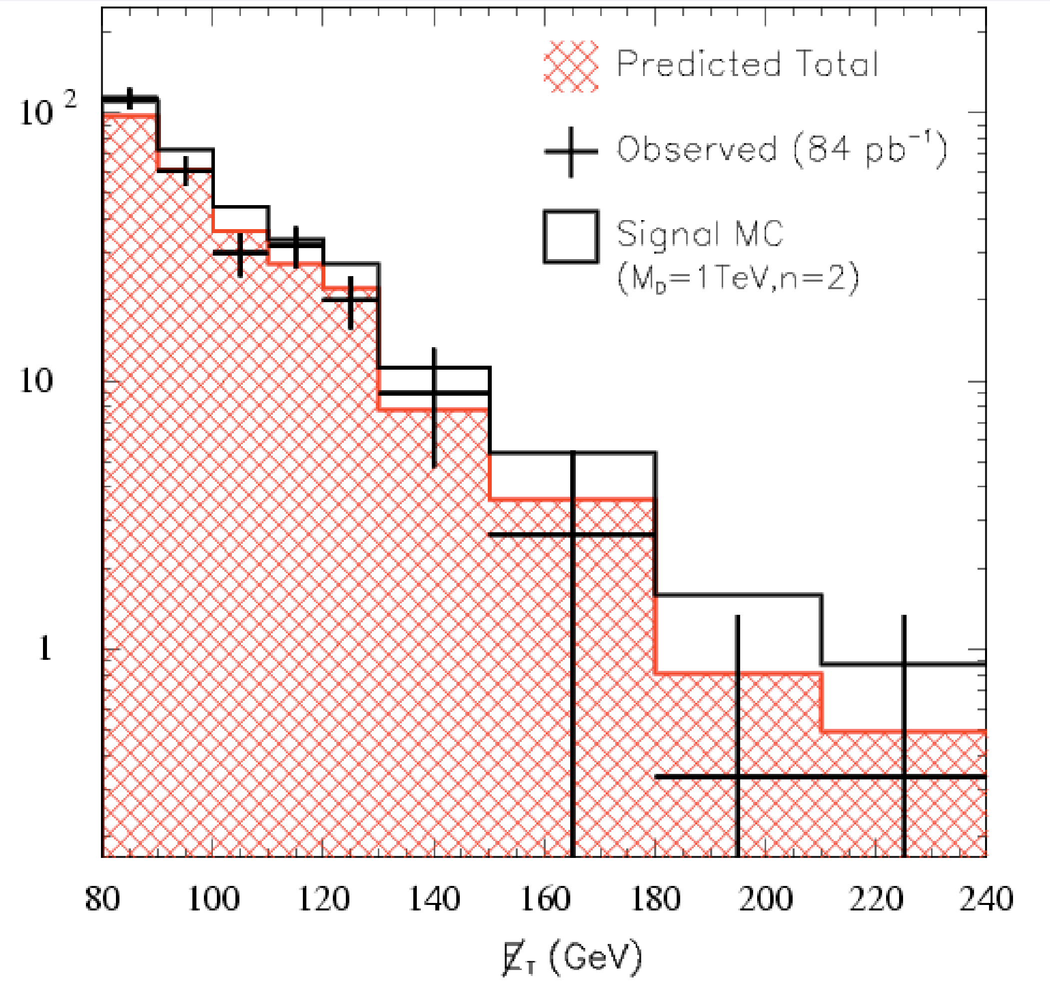
Interference from Standard Model



Graviton exchange is more model dependent than graviton emission due to cutoff scale

Summary of Existing Limits

CDF RunI



M_D Limits (TeV) From Monojet Searches in RunI:

n	CDF	D0
2	1.06	0.99
4	0.80	0.73
6	0.73	0.65

Limits on M_S(~M_D) From RunII Virtual Graviton Searches

M_S Limit(TeV)	CDF	D0 (RunII)	D0(Run1+11)	LEP
λ=+1	0.96	1.22	1.28	1.1
λ=−1	0.99	1.10	1.16	1.2

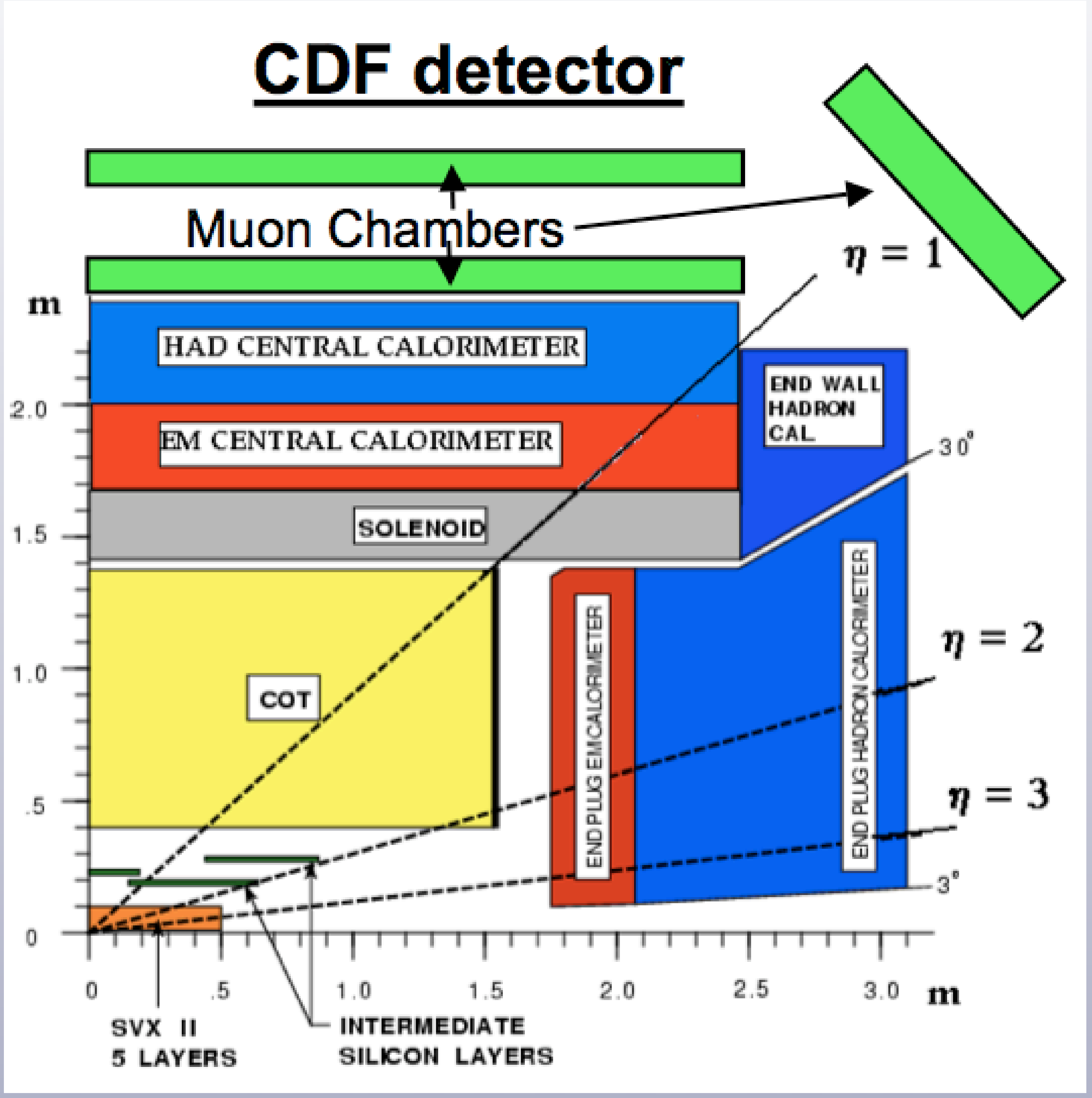
Summary of Existing Limits

Constraints from Non-Collider Experiments:

- Short Range Gravity Experiments:
  - R<130 μm(n=2) ⇔ M_D>1.7 TeV
- Many cosmological constraints:
  - M_D>20-100 TeV (n=2), M_D>2-5 TeV (n=3)
  - But these depend on a lot of assumptions

CDF Detector

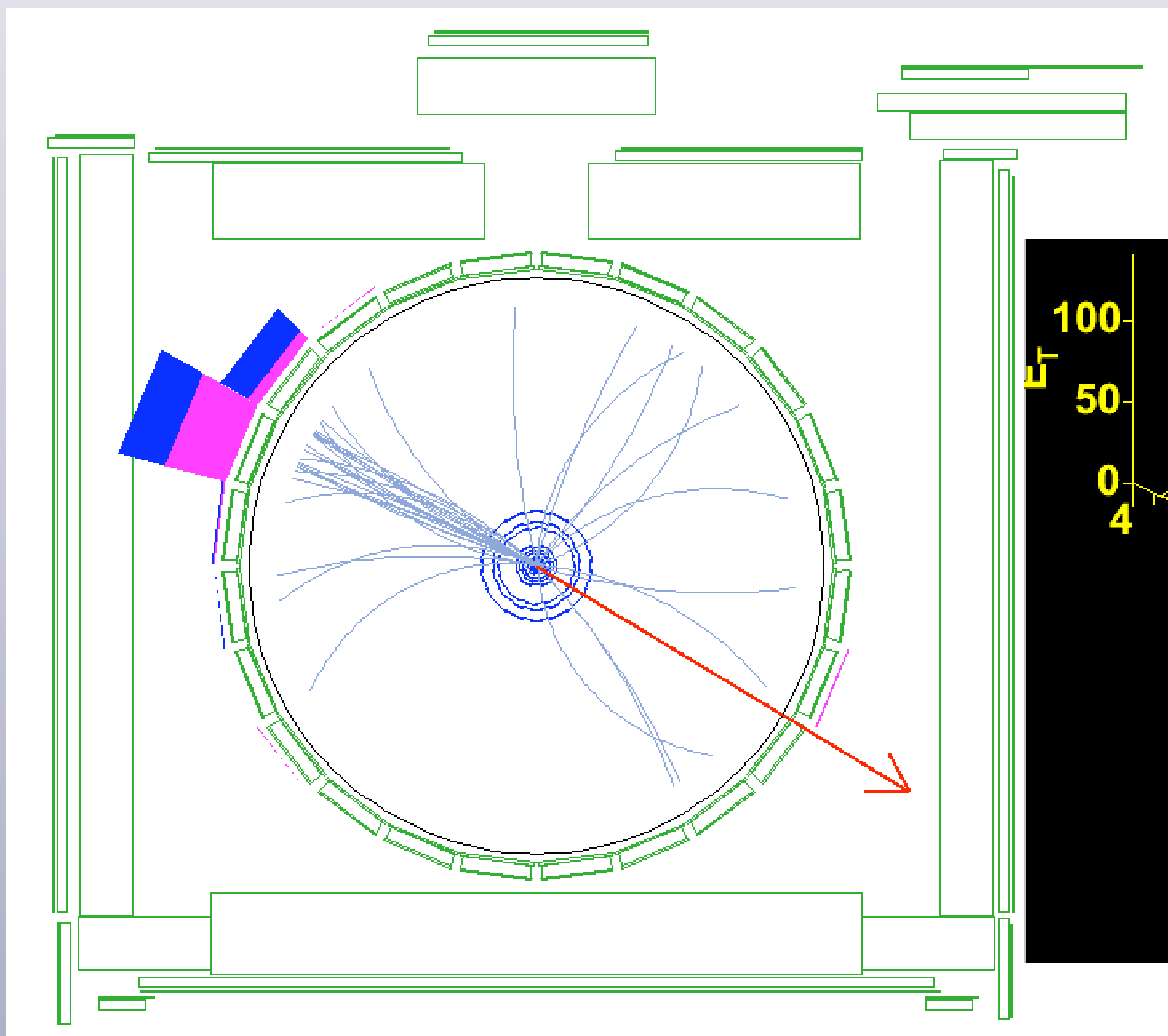
- Most important upgrade for the monojet signal is the plug calorimeter
- Old gap between plug and forward at |η|=2.4 is gone

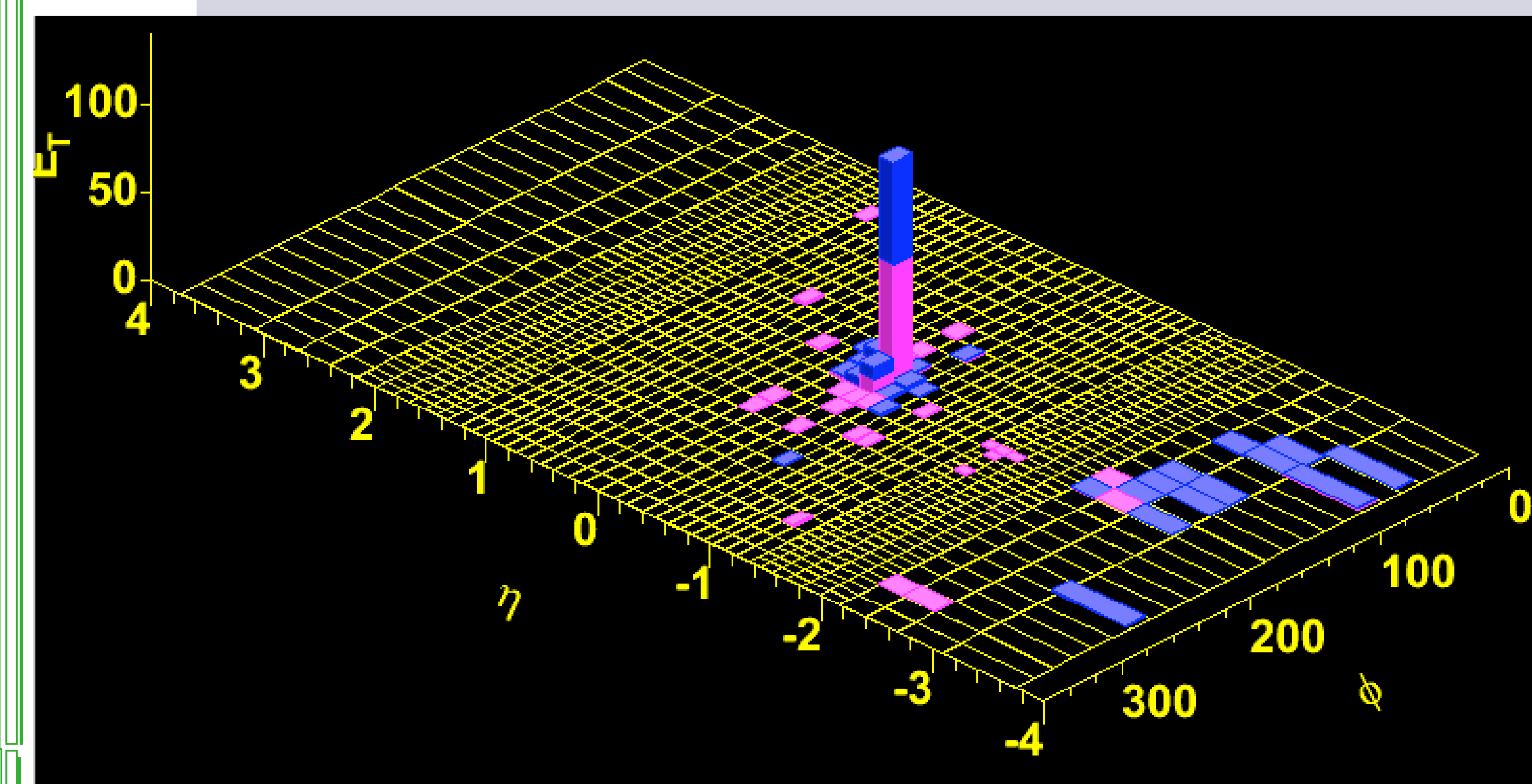


Signal Topology

- What would the signal look like in the detector?
- All 3 graviton emission processes have same signature
- Graviton produces Missing E_T, quark/gluon creates a Jet

→ Monojet





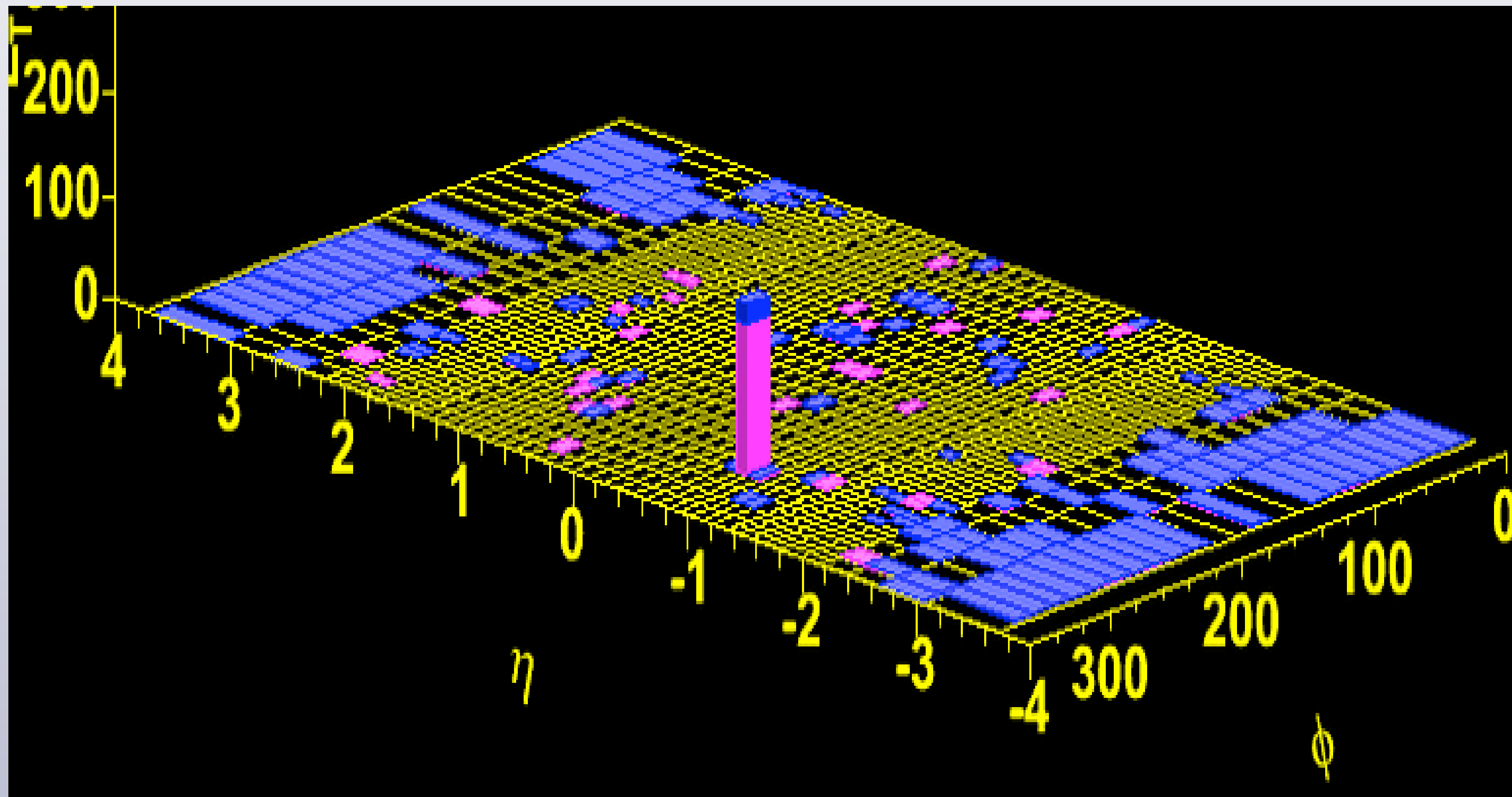
From Joe Lykken's talk
"is particle physics ready for the LHC"

- missing energy + multijets among the most challenging searches at Tevatron Runs I and II

- monojet searches are even more difficult
- at the Tevatron, the *Run I* monojet analyses were not completed until 2003/2004
- but monojet searches are essential for probing extra dimensions

Finding LED in the Monojets

High E_T Jet and Missing E_T triggered events need to be checked carefully

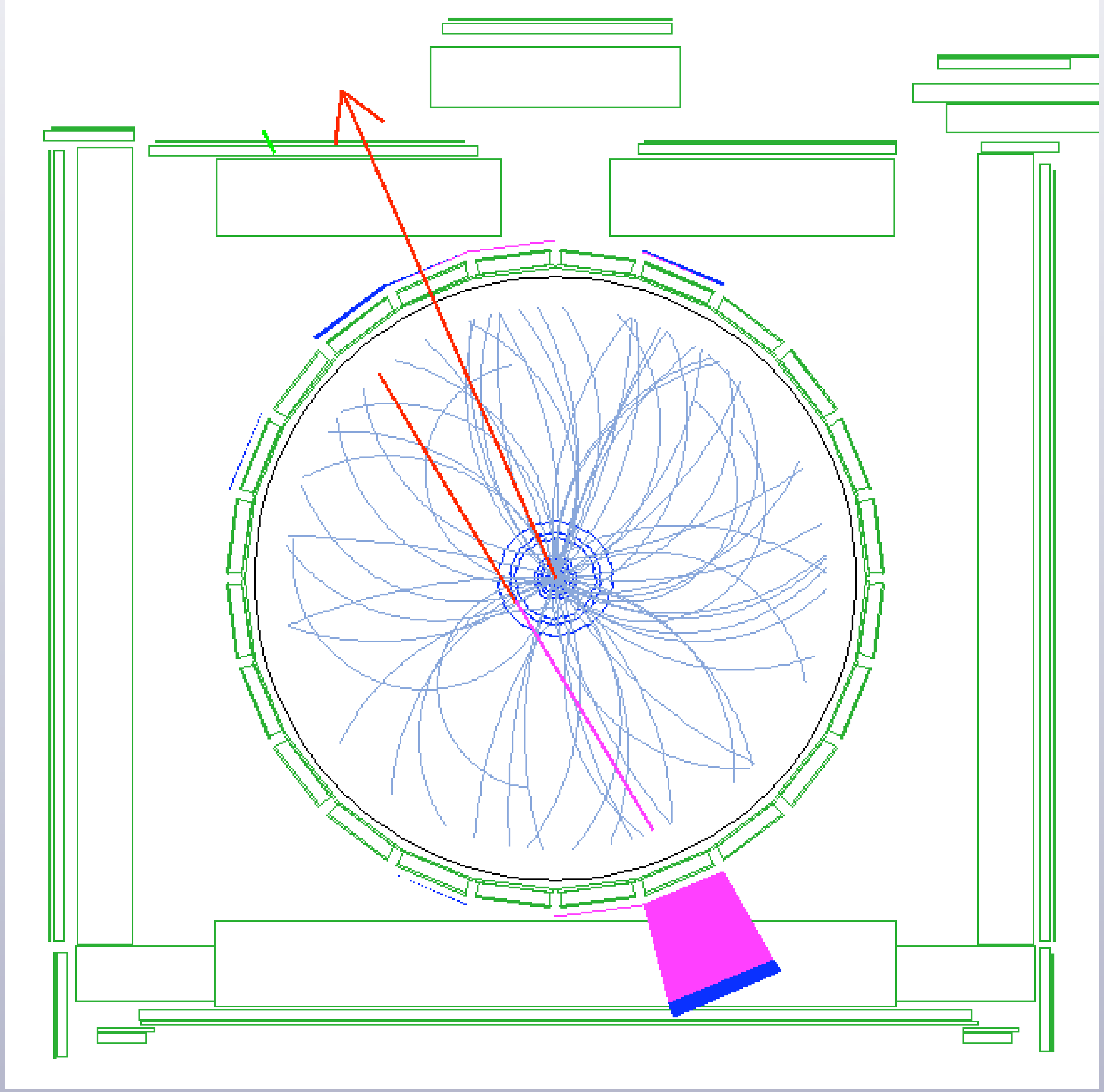


E_T(Jet) = 175 GeV

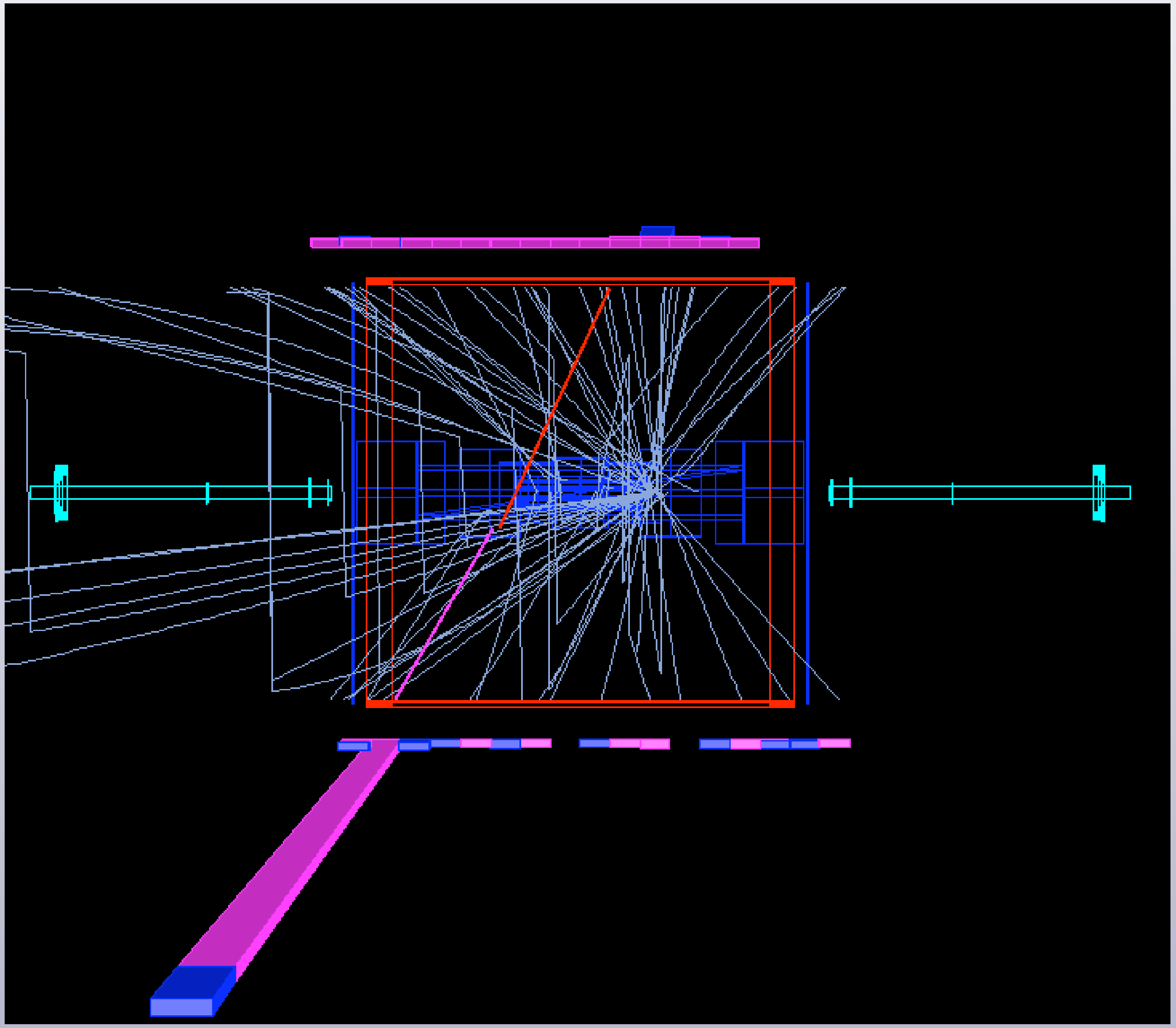
MET = 170 GeV

Finding LED in the Monojets

On closer inspection, it's a cosmic



COT View



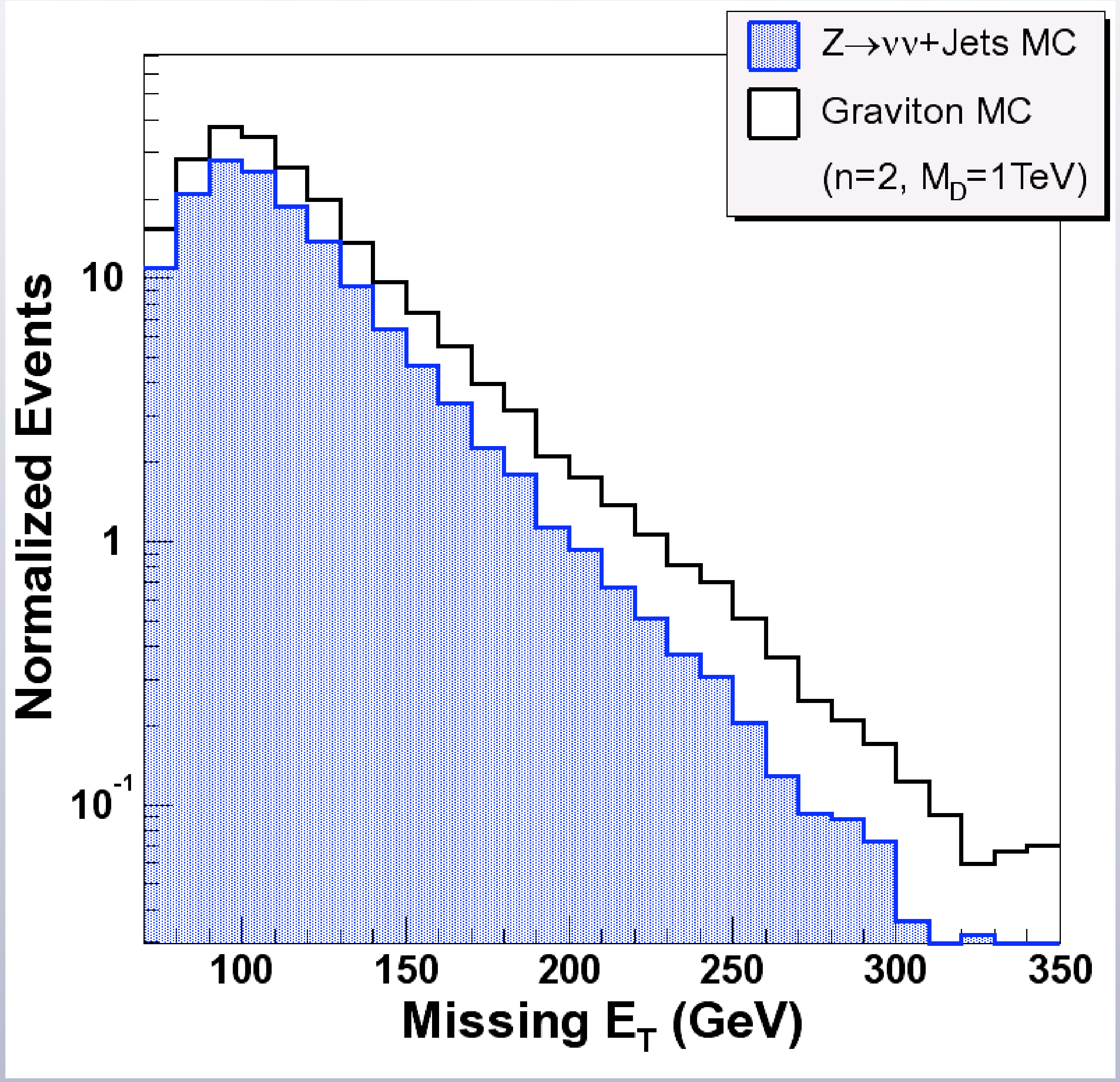
R-Z View

SM Sources of Monojets

- $Z \rightarrow \nu\nu$ + jets
  - Irreducible - looks just like signal
- $W \rightarrow l\nu$ + jets (l= τ,μ,e)
  - Real Missing E_T $\Rightarrow$ Reduce by vetoing leptons
- QCD
  - Fake Missing E_T
- Non-Collision (cosmic, beam) Backgrounds

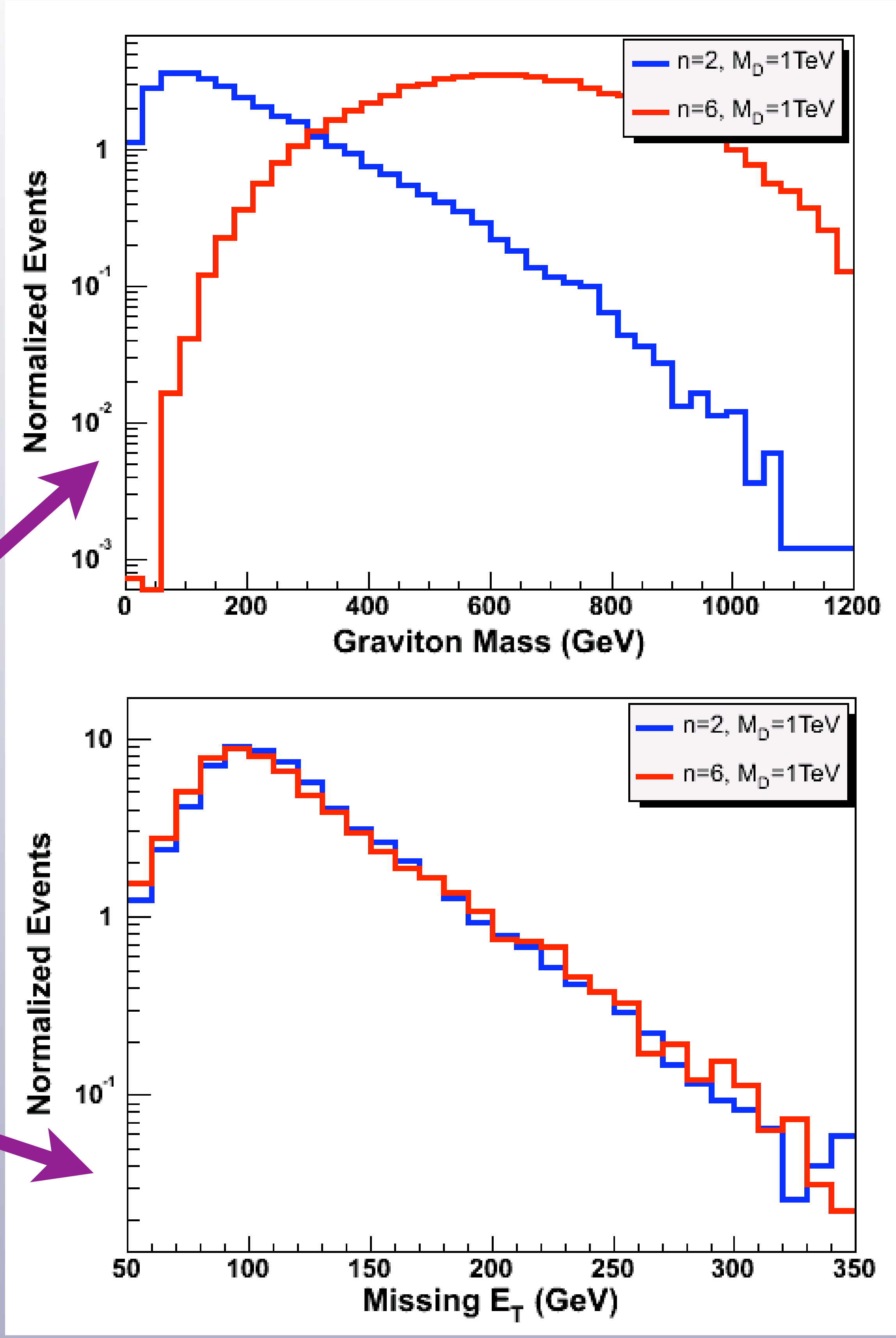
Finding LED in the Monojets

- After removing all the non-collision backgrounds, graviton production will appear as a smooth excess over the SM backgrounds



Finding LED in the Monojets

- It would be difficult to determine *n* and M_D from an observed excess
- The graviton mass spectra differ with *n*, but the P_T of the graviton (observed as Missing E_T) is almost identical

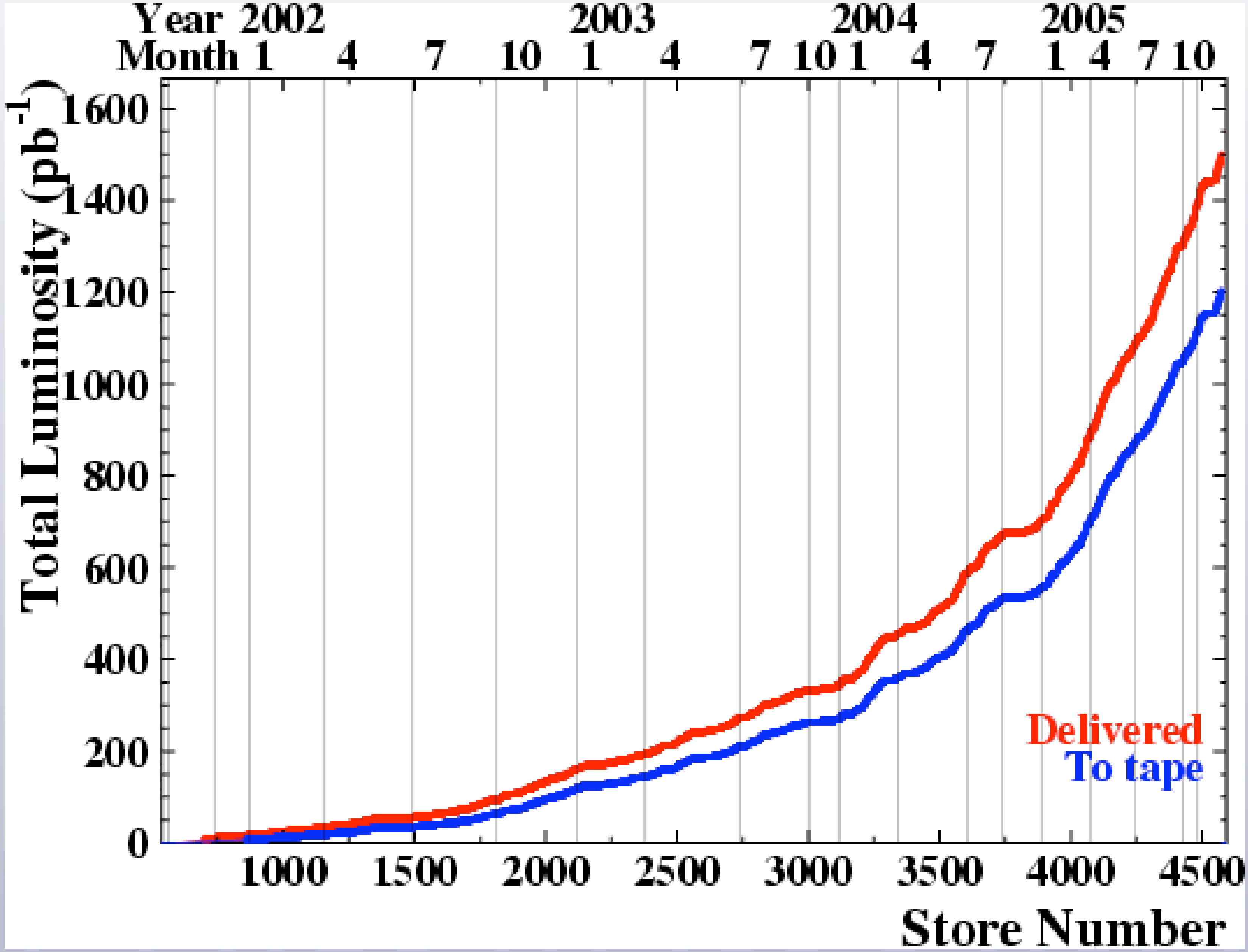


Analysis Strategy

1. Semi-model independent analysis
   - Cuts not uniquely optimized for graviton signature
   - Use data from highest E_T Jet trigger
   - general optimization of cuts to remove electroweak and fake MET backgrounds
2. As much as possible, estimate backgrounds from data
   - e.g. use $Z \rightarrow ll$+jets and $W \rightarrow l\nu$+jets to estimate electroweak backgrounds

Data Samples

- Most samples used in analyses presented today use physics data taken prior to shutdown in Aug 2004
- Luminosity analyzed is ~370 pb^{-1}

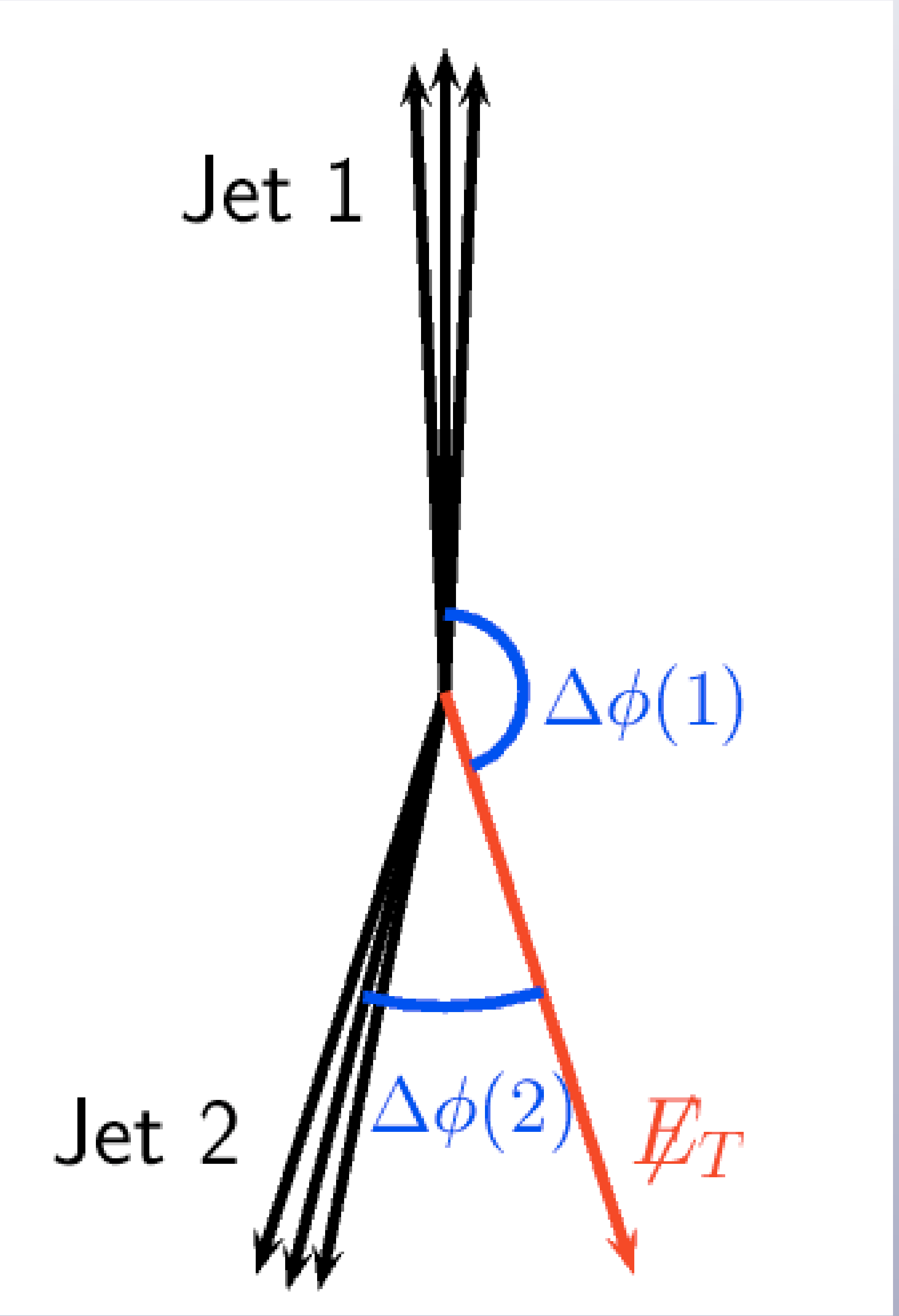


Monojet Data Selection

- Using High E_T Jet Trigger
  - Same non-collision backgrounds as Missing E_T trigger
  - Need initial event cleanup
    - Vertex reconstructed with >5 tracks, |z|<60cm
    - Event EM Fraction > 0.1
    - Leading jet central, Jet charge fraction>0.1
    - Veto events with jets pointing to cracks

Monojet Data Selection

- Require 1 High E_T jet (E_T>150 GeV)
  - Allow soft second jet (E_T<60 GeV), likely from radiation
- Missing E_T > 120 GeV



- Veto leptons to reduce EWK backgrounds
  - Isolated tracks P_T >10 GeV/c
  - Jets with EM Fraction > 0.9
- Reduce fake Missing E_T background by requiring $\Delta\Phi$(MET-Jet) > 0.3

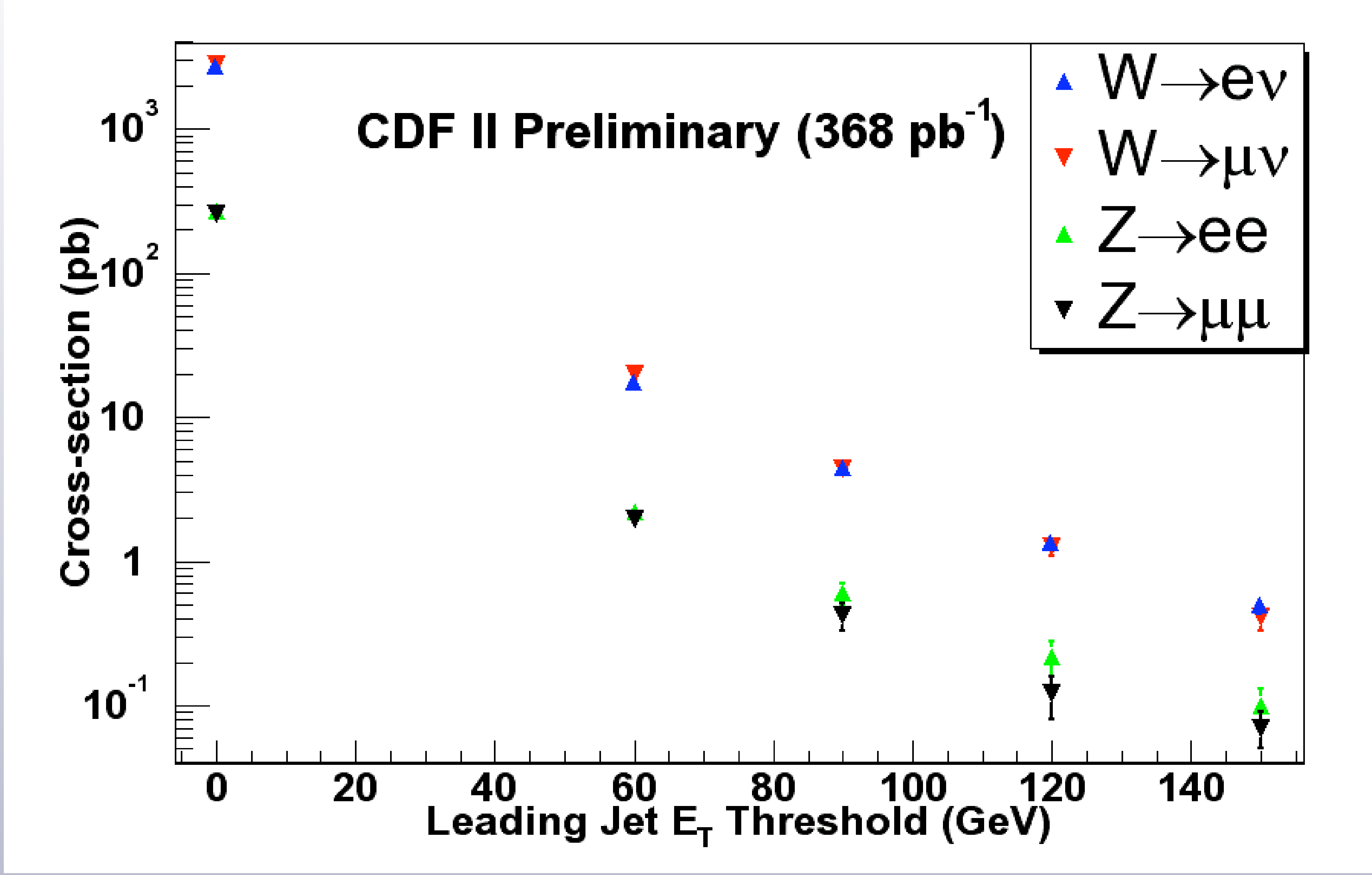
Electroweak Backgrounds

- Dominant background is $Z \to \nu\nu$ + jets
- Large integrated luminosity in RunII means backgrounds can be estimated from data rather than from MC
  - Use $Z \to ee$+jets and $Z \to \mu\mu$+jets events, with leptons removed to model $Z \to \nu\nu$+jets
  - Can also estimate $Z \to \nu\nu$+jets background from higher statistics $W \to l\nu$+jets samples, using theoretical prediction for $R_{W/Z} = \sigma(W)/\sigma(Z)$

Electroweak Backgrounds

- Measure $\sigma(W)$ and $\sigma(Z)$ for inclusive and for a range of leading jet cuts (60, 90, 120, 150 GeV)
  - Use standard W,Z selection to take advantage of known efficiencies, scale factors, etc.
  - Check inclusive cross-section against published results
  - Higher statistics at lower jet E_T cuts allow statistically significant comparisons
- Estimate $Z\rightarrow\nu\nu$+jets with:
  - $\sigma(Z\rightarrow\nu\nu+\text{jets}) = 6\times\sigma(Z\rightarrow ll+\text{jets})$
  - $\sigma(Z\rightarrow\nu\nu+\text{jets}) = 6\times\sigma(W\rightarrow l\nu+\text{jets})/R_{W/Z}$

W/Z+jet Cross-sections



σ(W→eν) = 2727 ± 46 pb

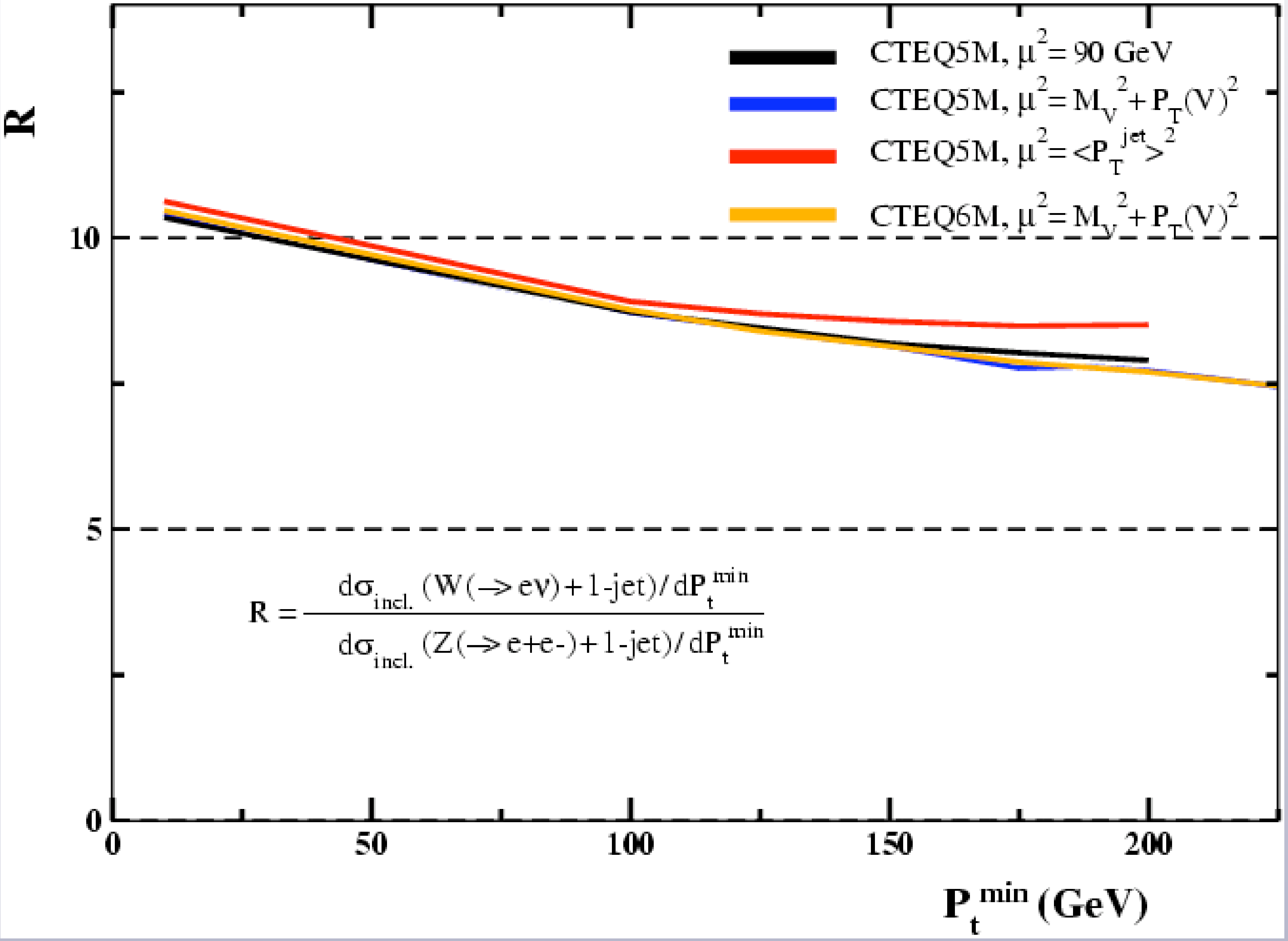
σ(W→μν) = 2778 ± 31 pb

σ(Z→ee) = 268 ± 5 pb

σ(Z→μμ) = 258 ± 3 pb

W/Z+jet Cross-sections

- Use MCFM (MonteCarlo for FeMtobarn processes) to calculate $R_{W/Z}$
- $R_{W/Z}$=8.15±0.40 (P_T^{min}=150 GeV)
- Uncertainties:
  - 4% renorm. scale
  - 1% PDF
  - 2% JES



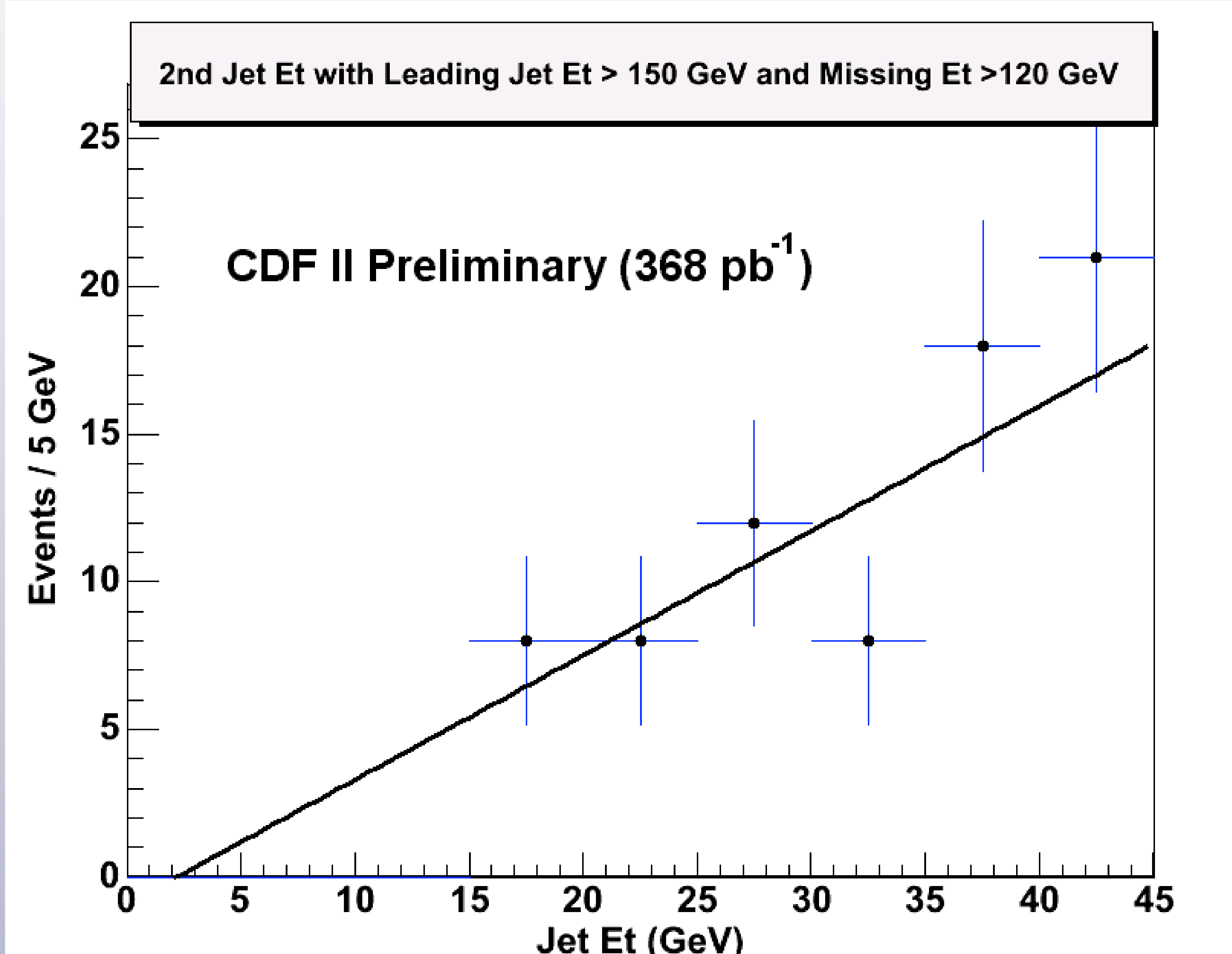
Electroweak Backgrounds

- Estimates of $Z \rightarrow \nu\nu$+jets
  - From $\sigma(Z \rightarrow ll$+jets) estimate 177±44 events
  - From $\sigma(W \rightarrow l\nu$+jets) estimate 125±15 events
  - Combined estimate: 130±14 events
- Same samples used to estimate other EWK backgrounds:
  - $W \rightarrow \tau\nu$: 60 ± 7
  - $W \rightarrow \mu\nu$: 36 ± 4
  - $W \rightarrow e\nu$: 17 ± 2
  - $Z \rightarrow ll$: 3 ± 1

QCD Backgrounds

- Dominant source of QCD background is dijet events where 2nd jet is lost
- ~15% of QCD background comes from 3-jet events (ratio determined from MC)
- Use data to estimate background
  - Select dijets where 2nd jet close in ϕ to MET
  - Extrapolate E_T(Jet2) distribution to region where jet falls below threshold and is lost

QCD Backgrounds



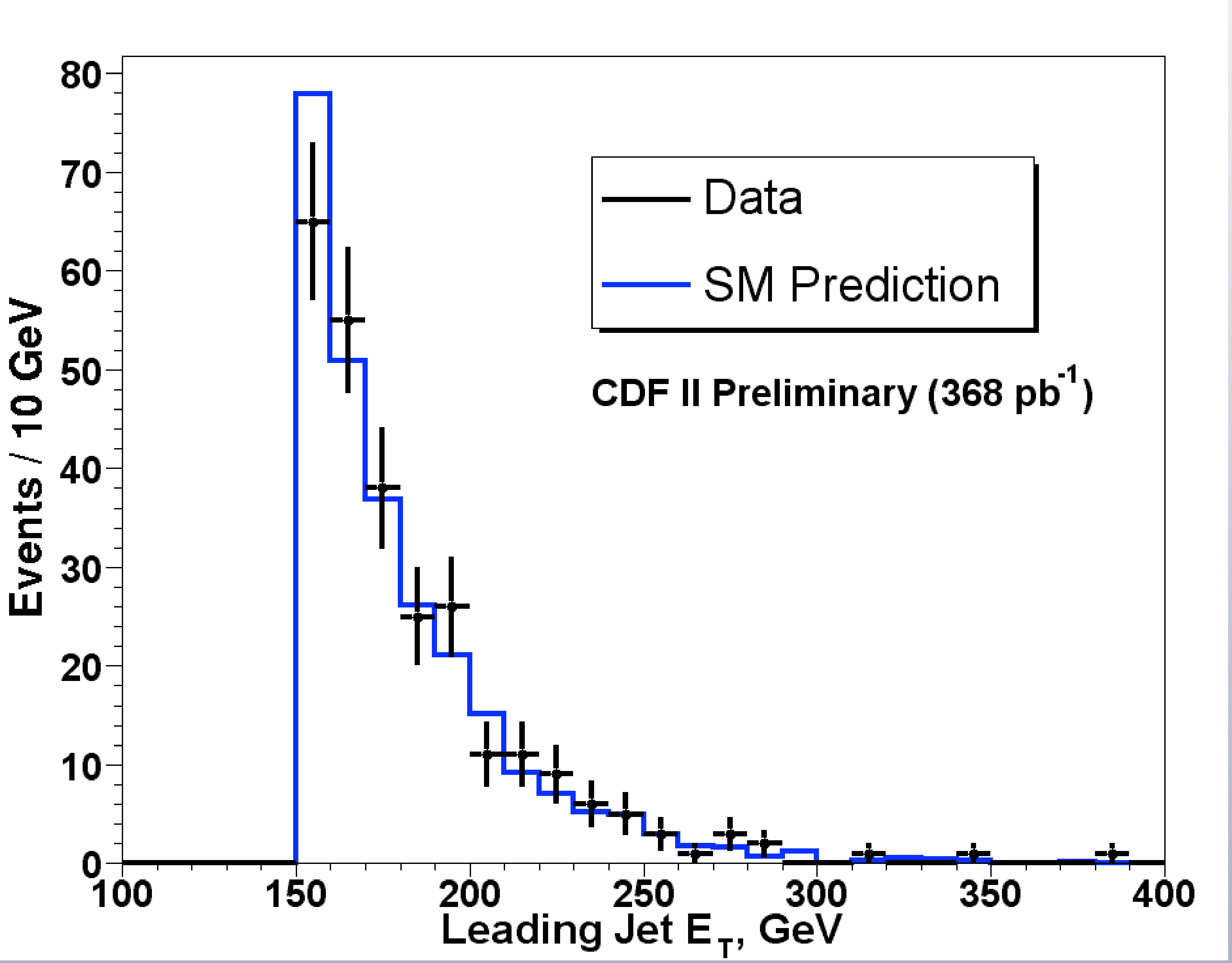
- Extrapolation yields 13 dijet events
- 2 additional events from 3-jet events
- Total QCD background: 15±10 events

Summary of Backgrounds

Background	Expected Events
$Z \rightarrow \nu\nu$	130 ± 14
$W \rightarrow \tau\nu$	60 ± 7
$W \rightarrow \mu\nu$	36 ± 4
$W \rightarrow e\nu$	17 ± 2
$Z \rightarrow ll$	3 ± 1
QCD	15 ± 10
Non-Collision	4 ± 4
Total Predicted	265 ± 30

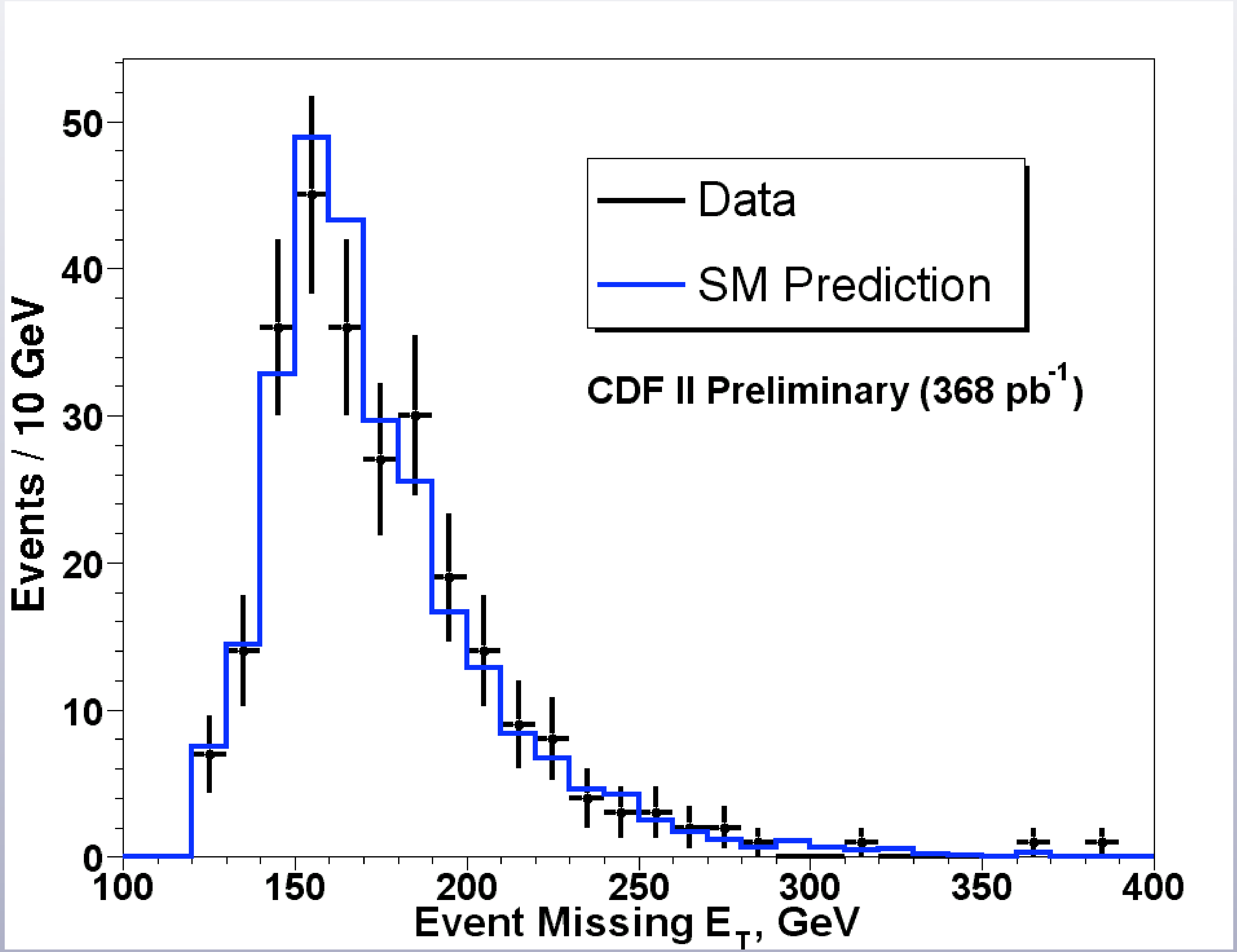
Data vs. Predicted Background

E_T of Leading Jet

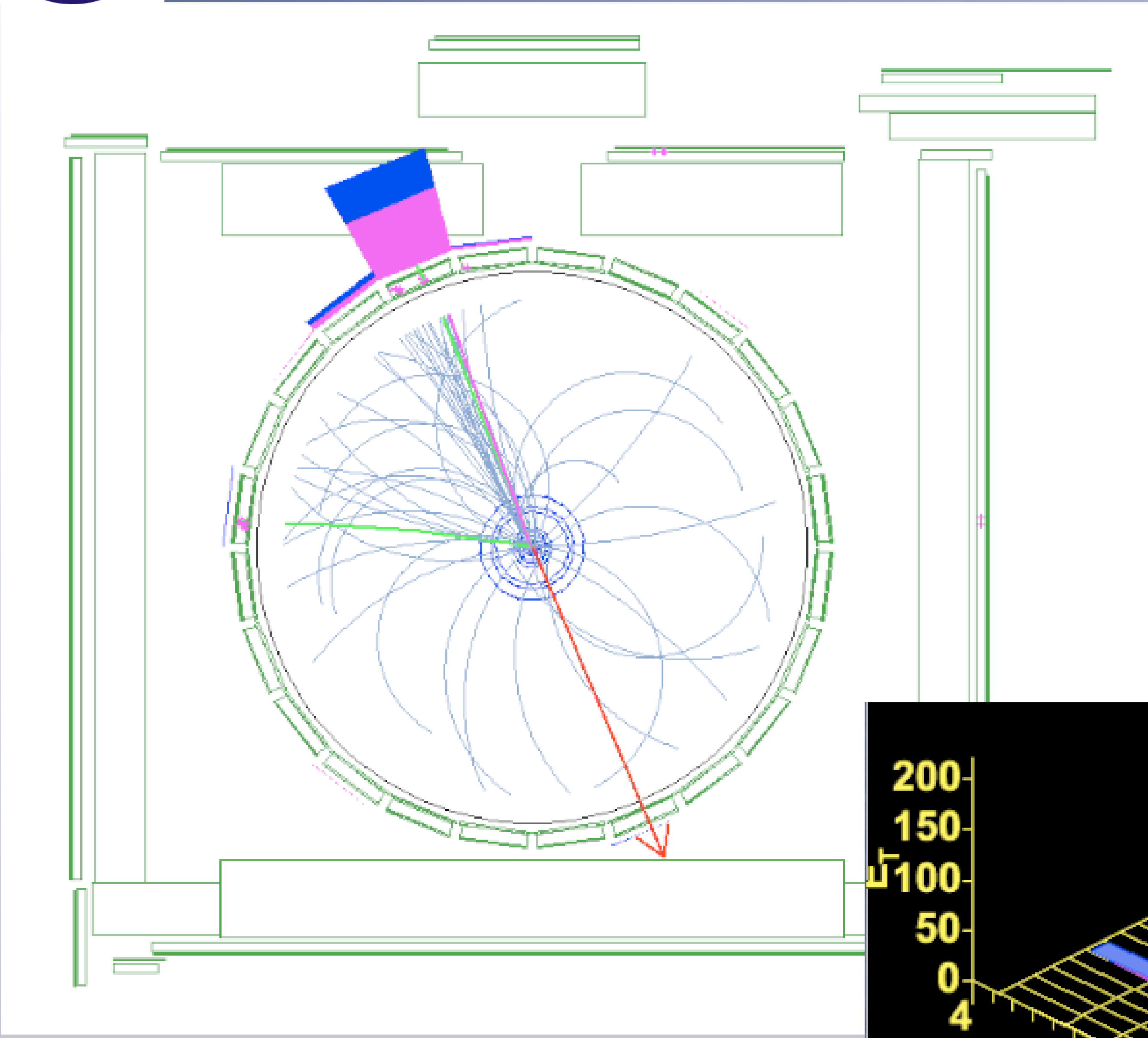


Data vs. Predicted Background

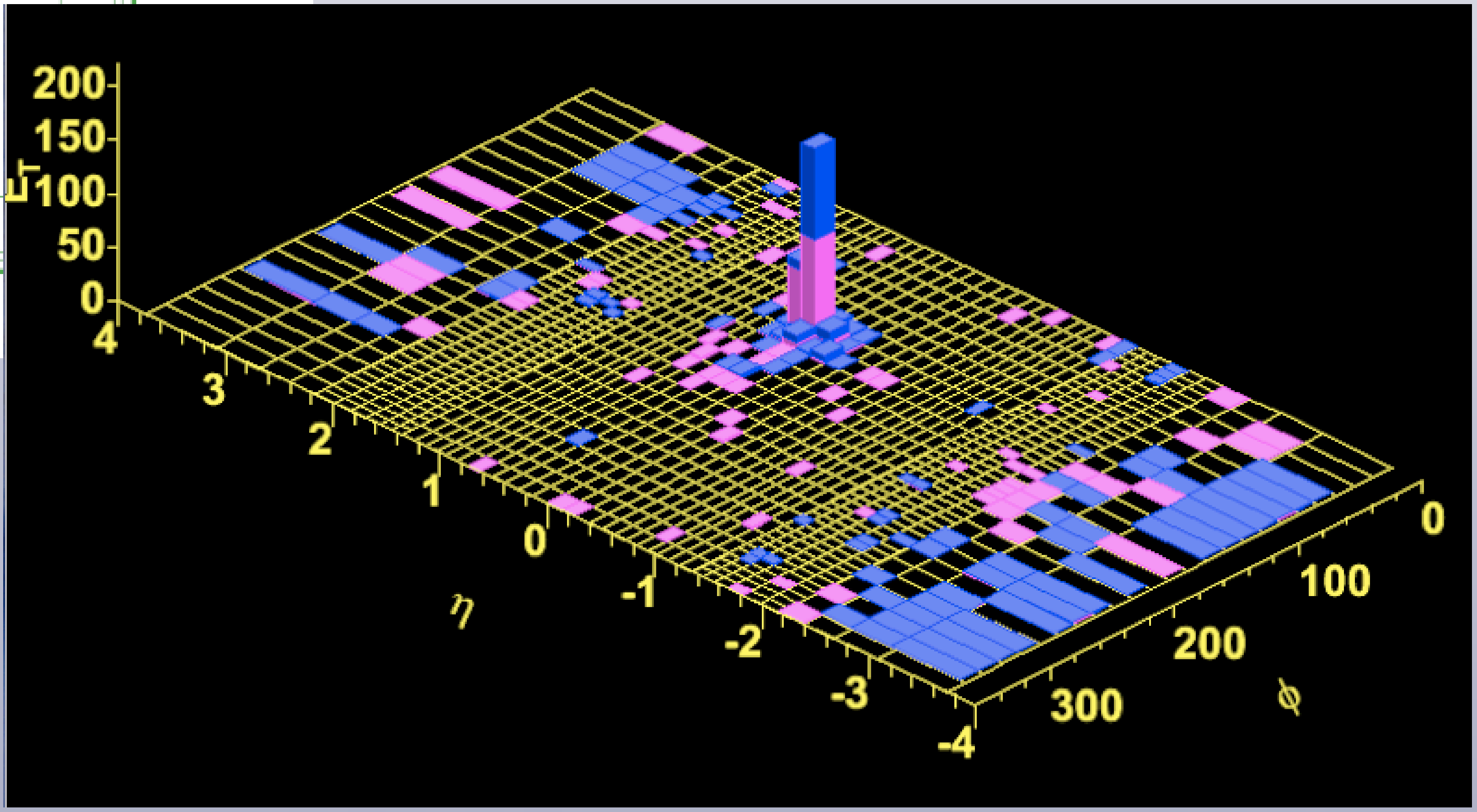
Missing E_T



Example Candidate Event



- E_T(Jet 1) = 361 GeV
- Missing E_T = 350 GeV



Data vs. Backgrounds

Background	Expected Events
$Z\rightarrow\nu\nu$	130 ± 14
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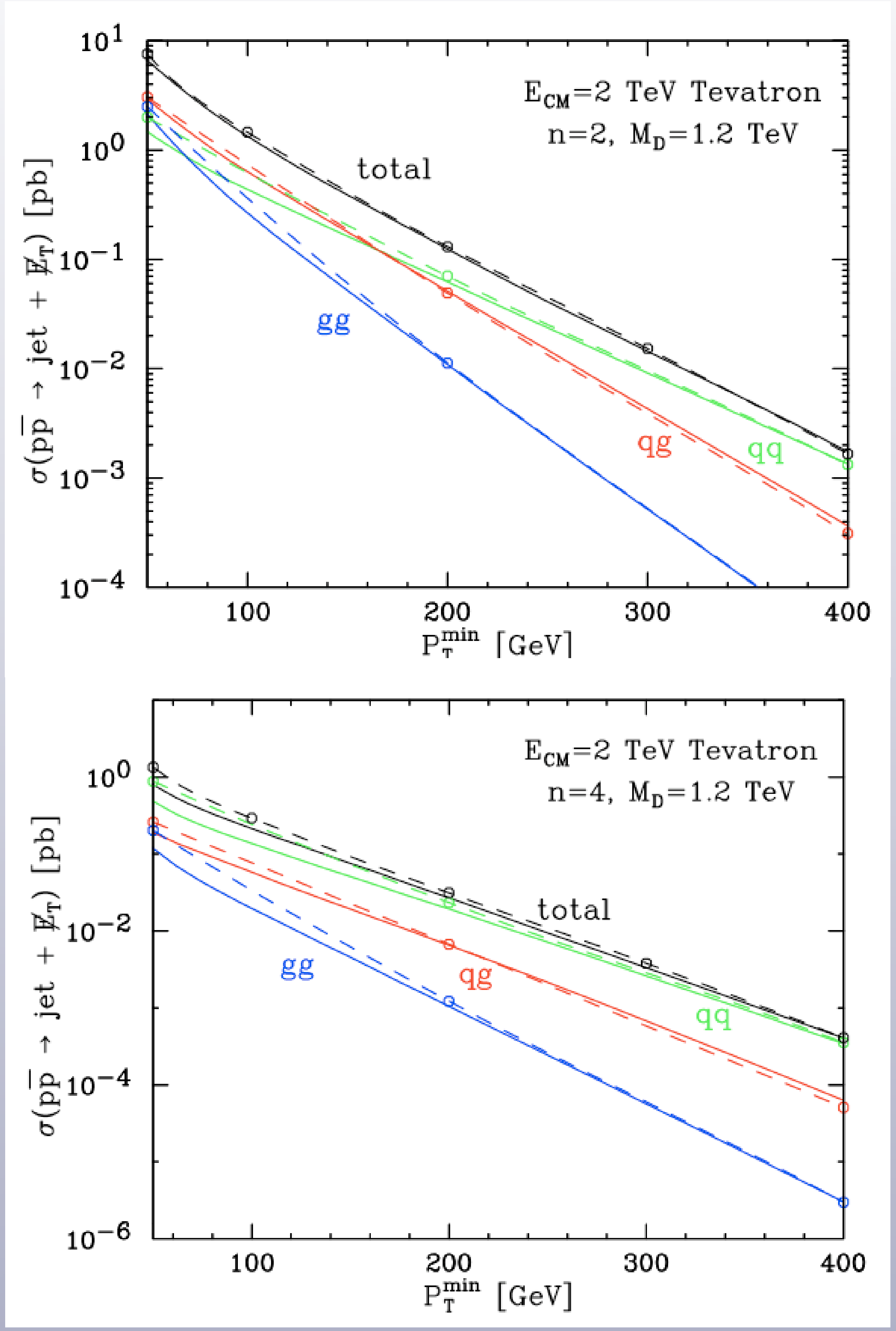
$Z\rightarrow ll$	3 ± 1
QCD	15 ± 10
Non-Collision	4 ± 4
Total Predicted	265 ± 30
Data Observed	263

Signal Monte Carlo

- Signal MC based on calculations of GRW
- Pythia "bootleg" from Matchev and Lykken (same as used in RunI)
- Generate each of 3 processes separately for specified values of *n* and M_D
- Determine expected number of events for our selection



Signal Acceptance

- Total Acceptance (P_T^{min}>90) ~10%
  - Acceptance is flat in M_D, slight variation with n
  - Uncertainty on signal acceptance:

Source	Relative Uncertainty (%)
Jet Energy Scale	8.0
PDF	5.9
FSR	4.4
ISR	2.7
Q^2 Scale	1.9
Luminosity	6.0
MC Statistics	3.0
Total Uncertainty	13.2

Setting a Limit

- Predicted Events: 265 ± 30
- Observed Events: 263
- Upper Limit (95%CL): 70.3 events
- Convert to Limits on M_D:

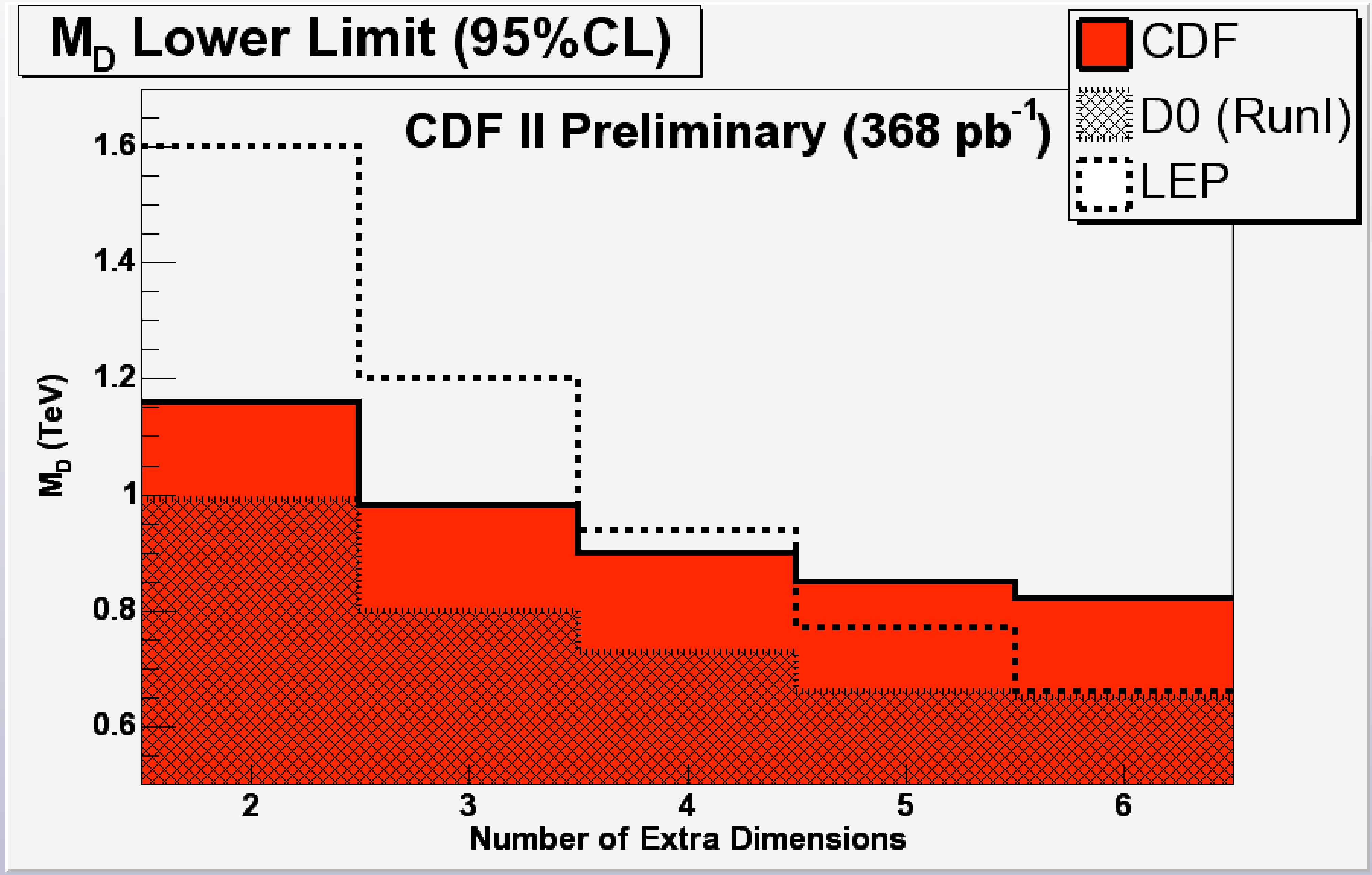
n	M_D (TeV)
2	1.16
3	0.98
4	0.90
5	0.85
6	0.83

Comparisons to Other Expt's

- Searches for Direct Graviton Production
- 95%CL Lower Limits on M_D (TeV)

n	CDF	D0(Run1)	LEP
2	1.16	0.99	1.60
3	0.98	0.80	1.20
4	0.90	0.73	0.94
5	0.85	0.66	0.77
6	0.83	0.65	0.66

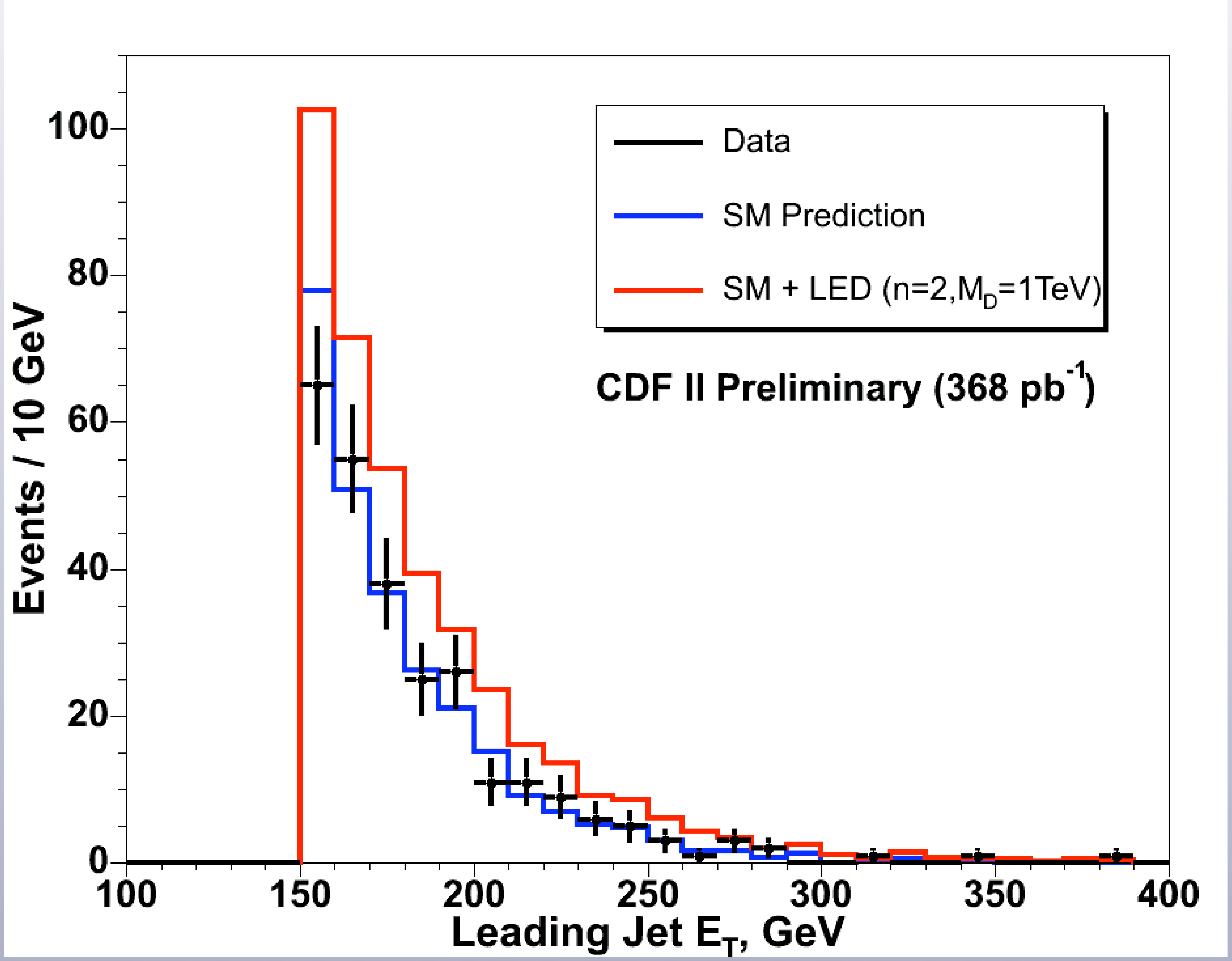
Comparison to Other Expt's



- Best limits for large values of *n* from CDF
- Best limits for *n*=2,3 from LEP

What would a signal look like?

Add contribution for LED with n=2, M_D=1TeV



What would a signal look like?

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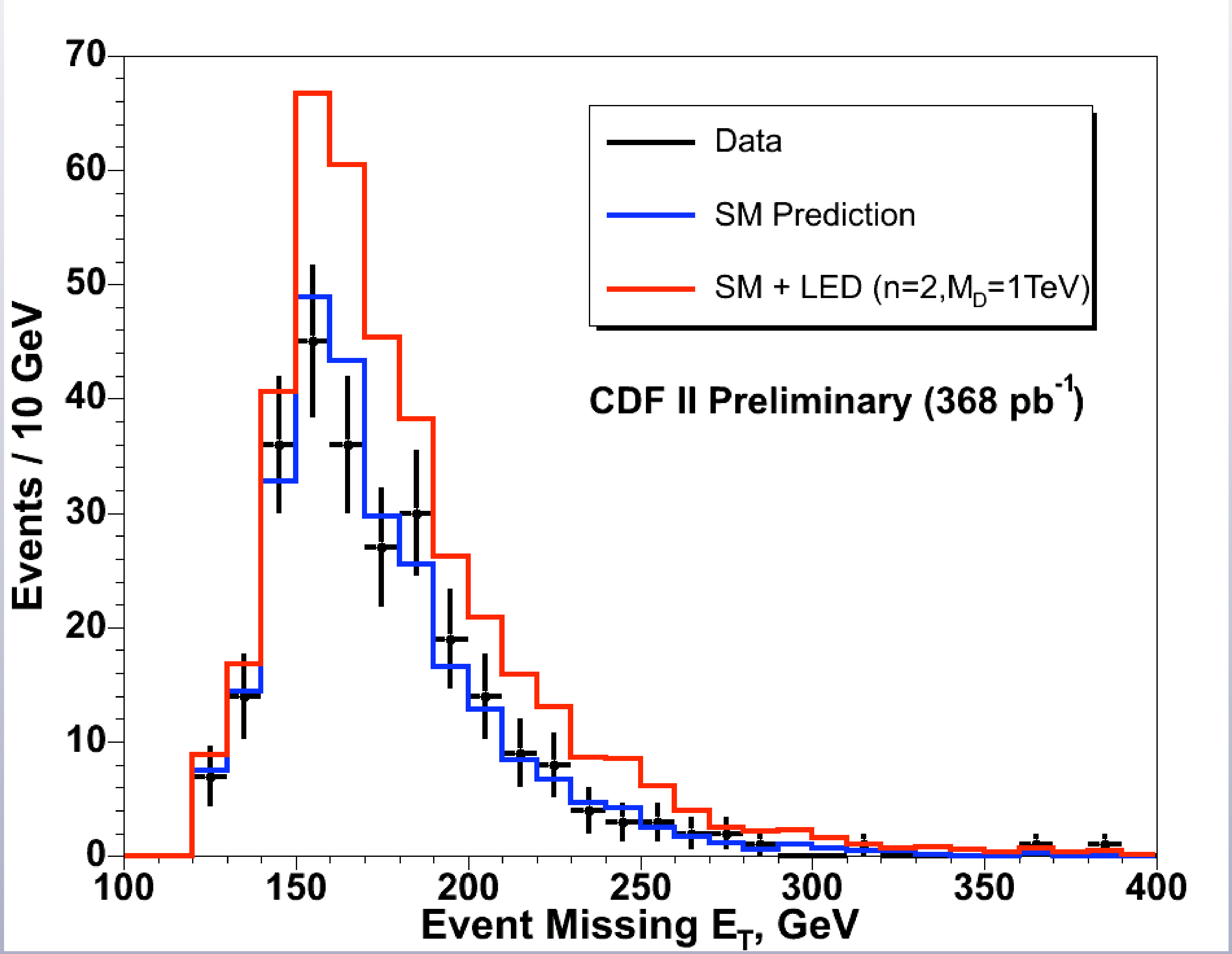


Limits on R

- Assuming compactification on a torus, M_D is related to R by:

$$R^n = \frac{1}{8\pi}\left(\frac{M_{PL}}{M_D}\right)^2 \frac{1}{M_D^n}$$

- Limits on R:

n	M_D (TeV/c^2)	R (mm)
2	> 1.16	$< 3.6 \times 10^{-1}$
3	> 0.98	$< 3.7 \times 10^{-6}$
4	> 0.90	$< 1.1 \times 10^{-7}$
5	> 0.85	$< 3.5 \times 10^{-10}$
6	> 0.83	$< 3.4 \times 10^{-11}$

- Recall: Eöt-Wash limit: $R < 1.3 \times 10^{-1}$ mm (n=2)

Looking Ahead

- Current analysis uses 368 pb^{-1} of data
- Because backgrounds are estimated from data, uncertainty will continue to improve with more data
  - Expect updated result with 1 fb^{-1} for summer
  - Additional gains using lower E_T cut and MET trigger
- Estimates of improved M_D limits with 1fb^{-1}

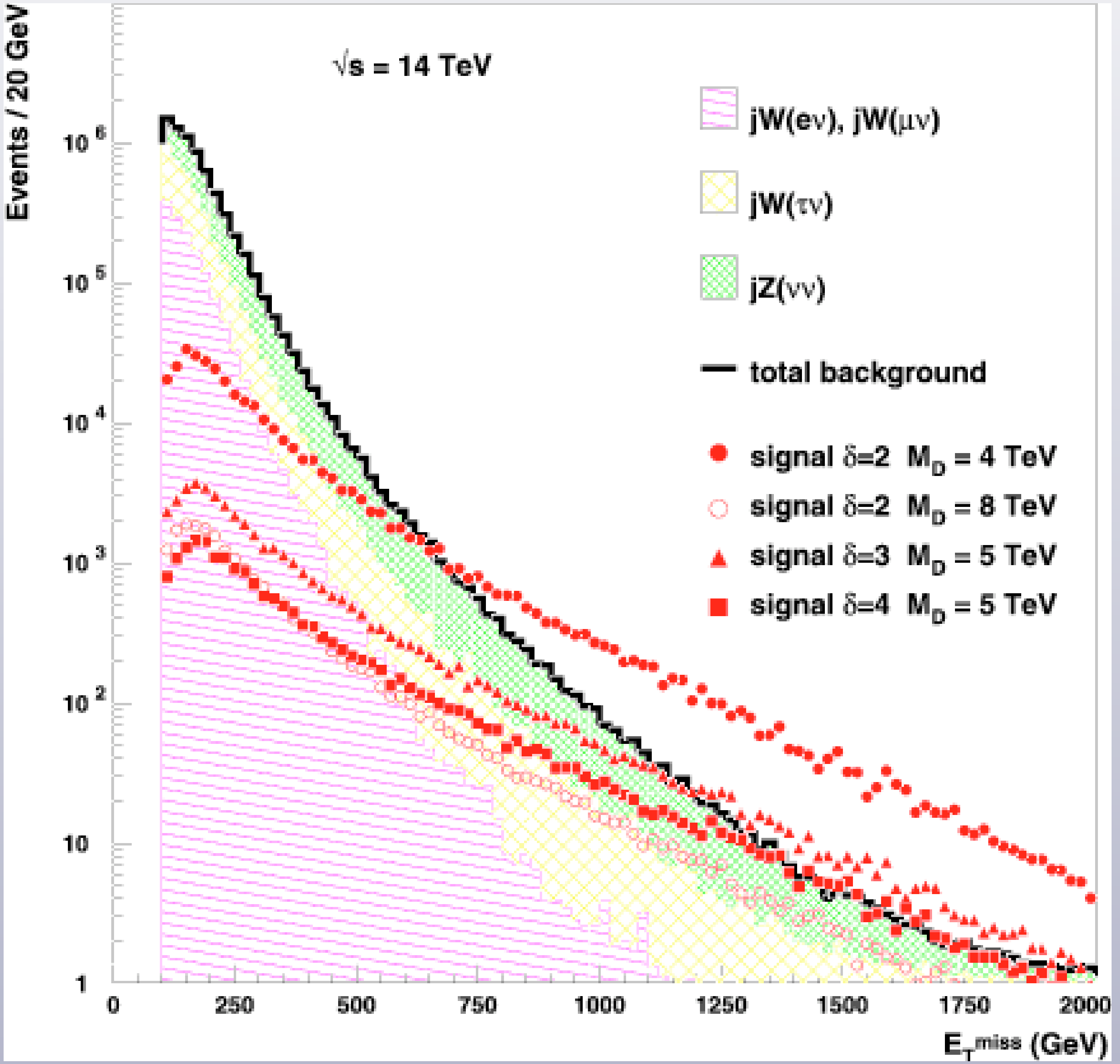
n	M_D (TeV)
2	1.40
3	1.14
4	1.03
5	0.95
6	0.91

Looking Further Ahead

LHC can extend searches to higher values of M_D

- Have to deal with same Standard Model backgrounds
- If there is a signal, could try to determine values of n and M_D by running at different energies

n	M_D(TeV) LL, 30 fb^{-1}	M_D(TeV) HL, 100 fb^{-1}
2	7.7	9.1
3	6.2	7.0
4	5.2	6.0



(Hinchliffe, Vacavant)

Conclusions

- First results from CDF monojet data in RunII show good agreement with SM expectations
- In context of ADD extra dimensions models, set limits on effective Planck scale M_D
  - M_D>1.16TeV (n=2) --- M_D>0.83TeV (n=6)
  - Most stringent limits for higher values of n
  - By the end of RunII (if no discovery) should have most stringent limits for all n>2
- For higher values of n, collider searches have best sensitivity for LED, so we must continue to look