Non-SUSY Searches for Physics Beyond the Standard Model @ the Tevatron

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for

the CDF and D0 Collaborations

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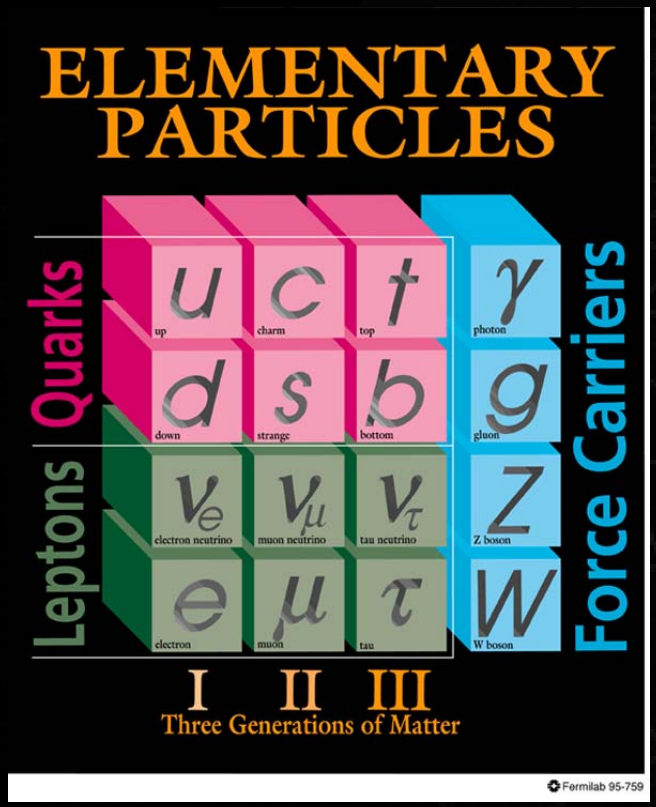
Particle Physics Today - Motivation

The Standard Model has been enormously successful, but it leaves many important questions unanswered:



The Standard Model of particle physics is a description of the known particles and their interactions

What is the origin of mass ?

Why are there three generations ?

Why the large difference between Plank and EWK scale ?

How can we incorporate gravity ?

Are fermions point-like or do they have substructure ?

What is the source of dark matter ?

Many theories/models attempt to address these issues.

SUSY is most commonly invoked to address these, but there are many other models that seek to answer some or all of these questions

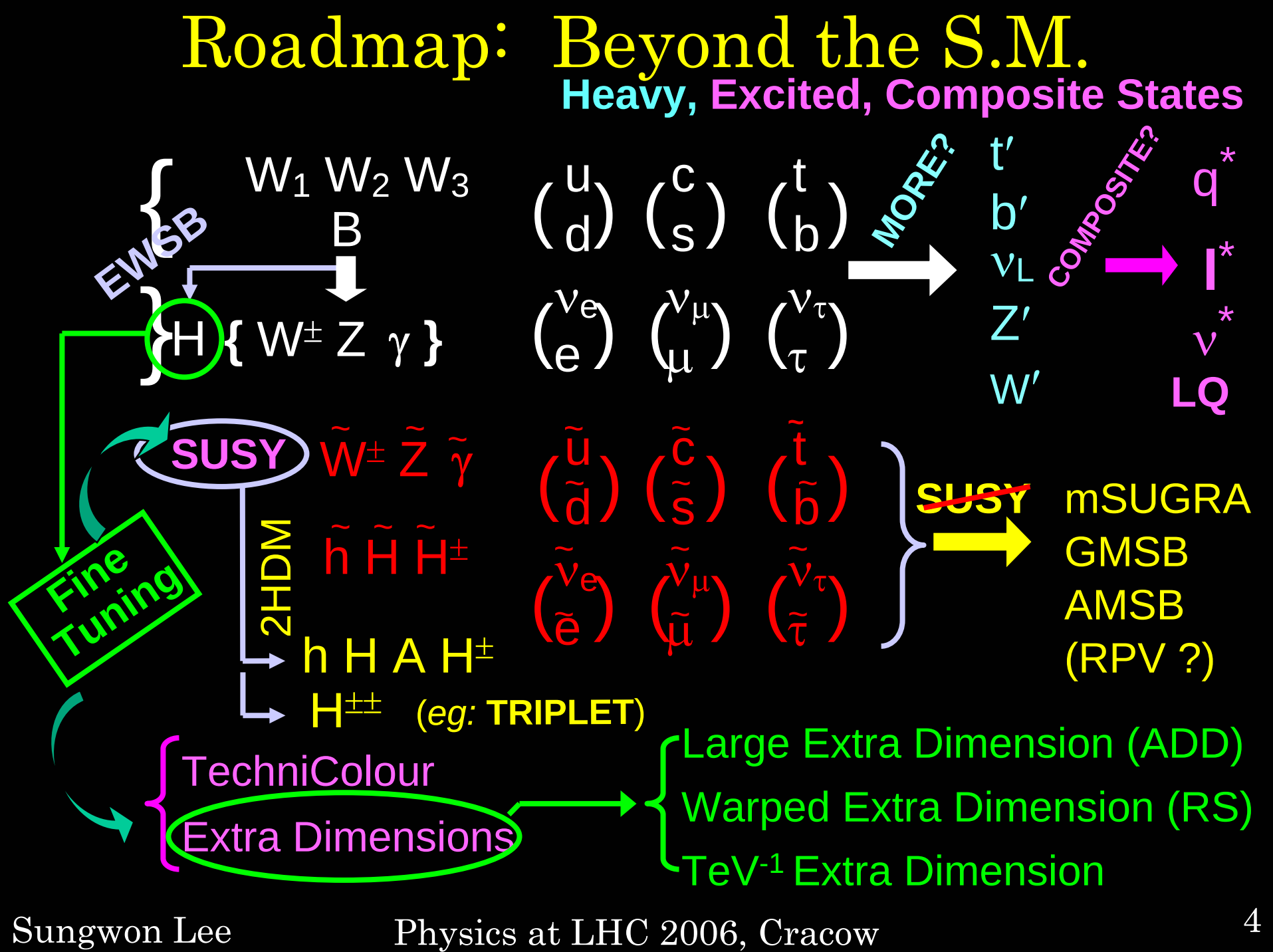
What can be (non-SUSY) BSM? Many possibilities !

Extended Gauge Symmetries, Dynamical EWSB, Extra Dimensions, Compositeness, etc… (see next slides)

One physicist's schematic view of particle physics in the 21st century

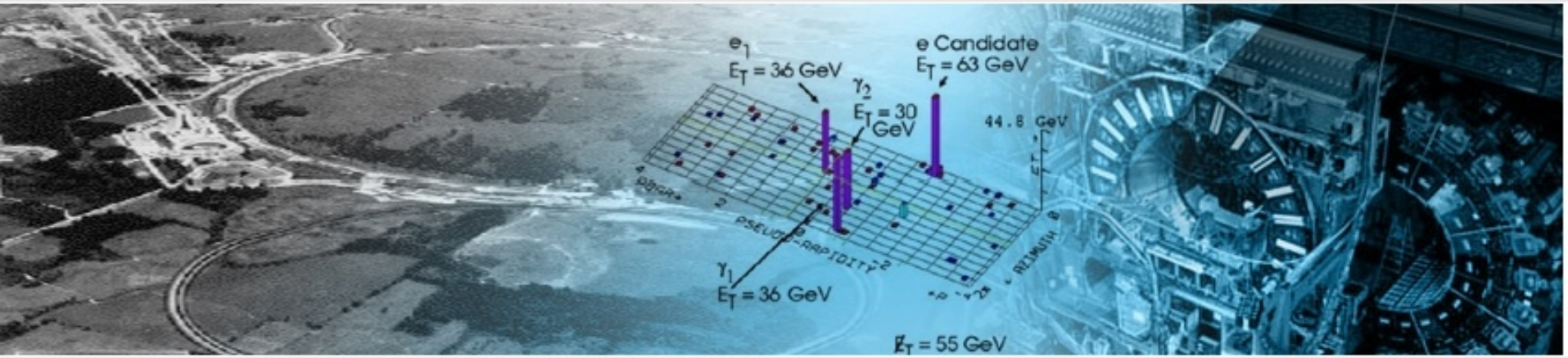
Roadmap: Beyond the S.M.

Heavy, Excited, Composite States



Introduction

- This talk (non-SUSY Searches @ Tevatron) describes
  - some of interesting hints we've found
  - some of the important theories we've tested
    - Extra Dimensions
    - New Heavy Quarks
    - New Gauge Bosons…
  - some new strategy & method we've developed
    - Signature-based searches look to compare how well the data agrees with the Standard Model, without applying any particular model



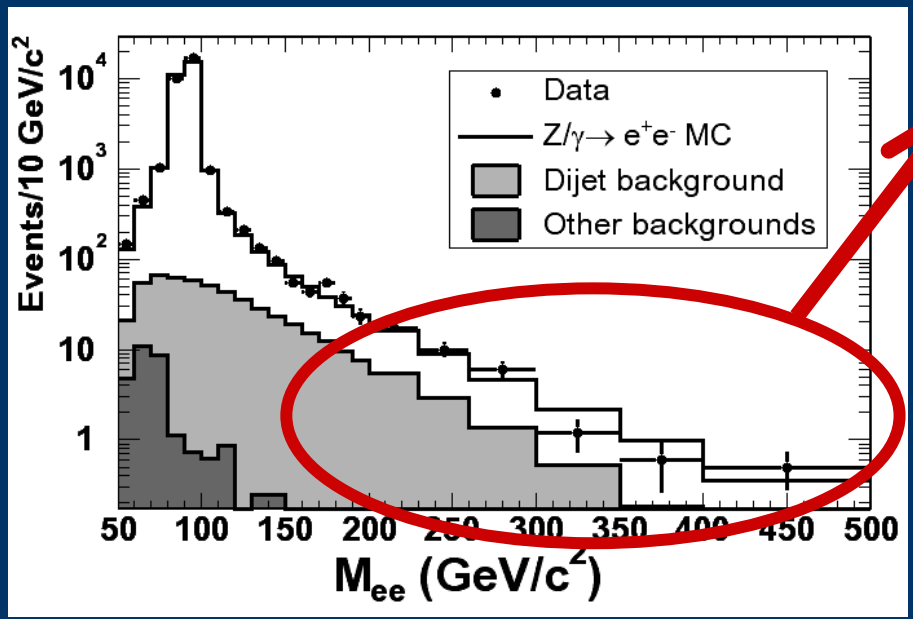
Heavy Gauge Bosons
Z´, W´

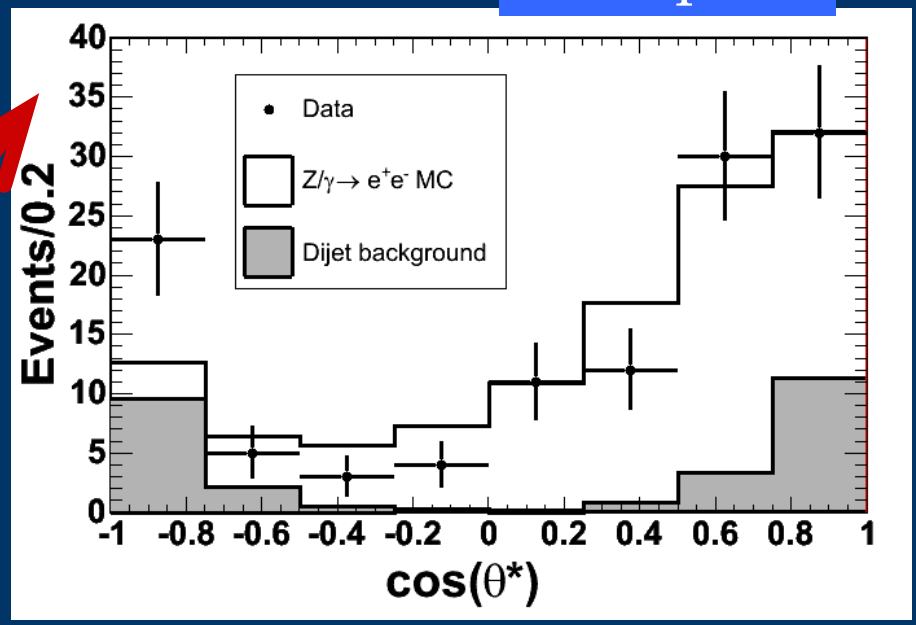
Search for $Z' \rightarrow e^+e^-$

Look for a peak in M_{ee} and look for a distortion in $\cos(\theta^*)$

- Small source of background; irreducible SM Z/γ^*
- Results applicable to many theories!

448 pb^{-1}





For M_{ee} > 200 GeV region for search

Source	$Z/\gamma^* \rightarrow e^+e^-$	Dijet	Diboson	Total SM	Observed
Events	80.0 ± 8.0	28^{+14}_{-17}	6.8 ± 1.4	115^{+16}_{-19}	120

No excess observed in dielectron final state → Set limits

Search for $Z' \rightarrow e^+e^-$

- Most extensions to SM predict new gauge interactions
- If Z' exists, it will interfere with SM Z/γ^* (well understood)
- Use the M_{ee} and $\cos\theta^*$ data distributions, adding angular information helps
- Test $Z'/Z/\gamma^*$ fit for different models and extract limits for sequential Z' and multiple E6 models

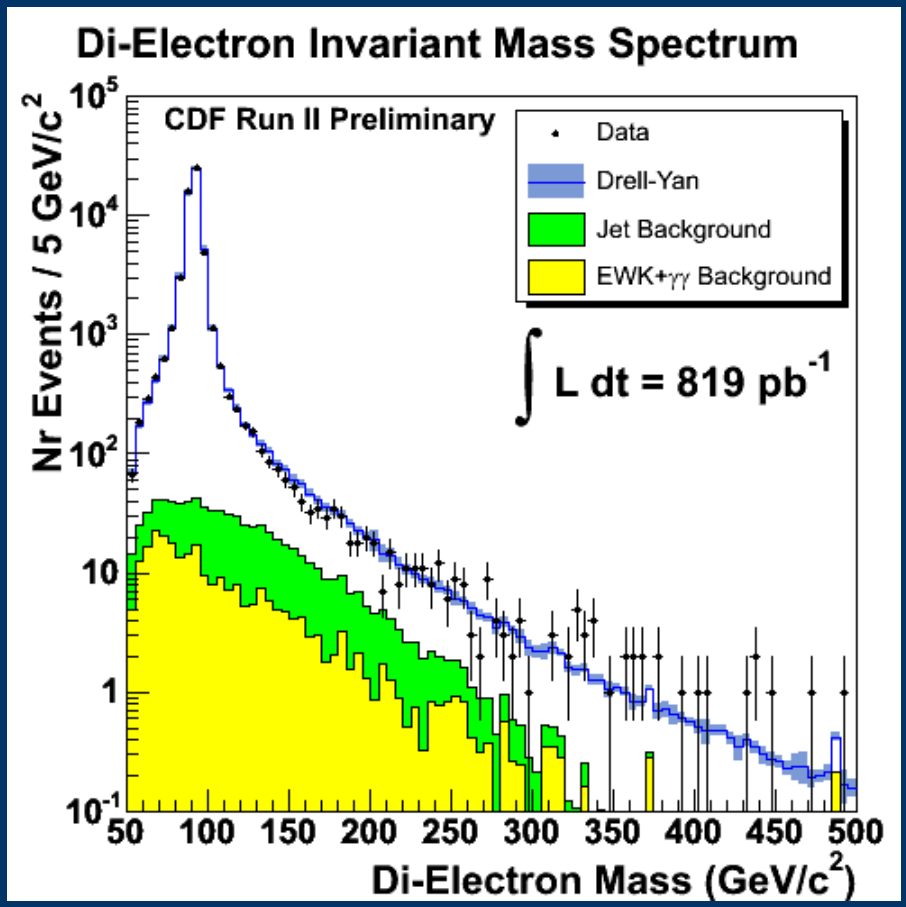
Set 95% C.L. limits

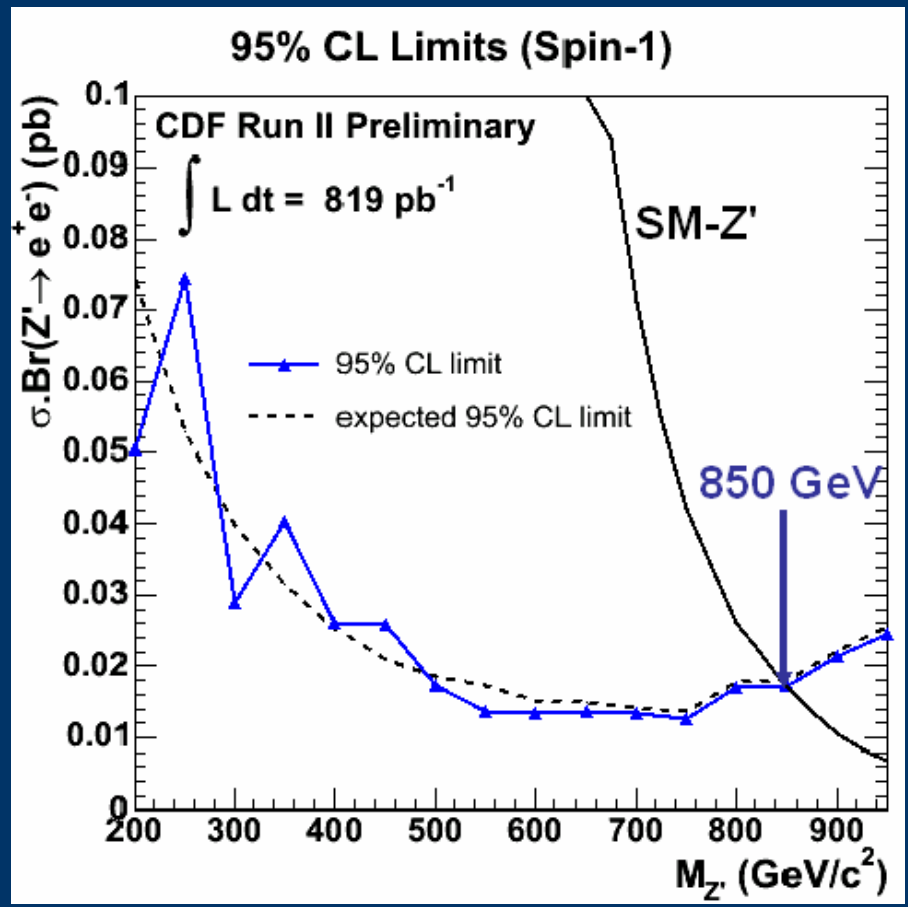
Z´ Model	Seq. Z'	E6 Z_χ	E6 Z_ψ	E6 Z_η	E6 Z_I
CDF Limit (GeV/c^2)	850	740	725	745	650
D0 Limit [200 pb^{-1}]	780	640	650	680	575

- Can also test for contact interactions
  - See hep-ex/0602045 for details

Dielectrons

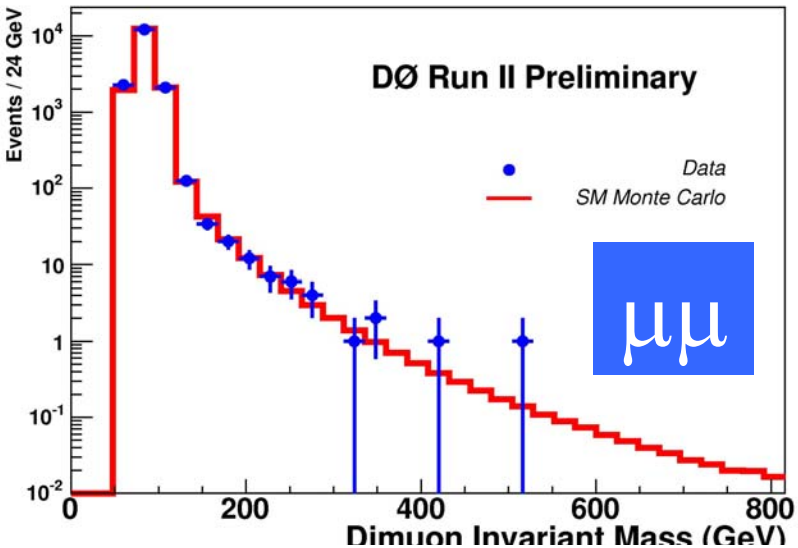
New CDF result using 819 pb^{-1}

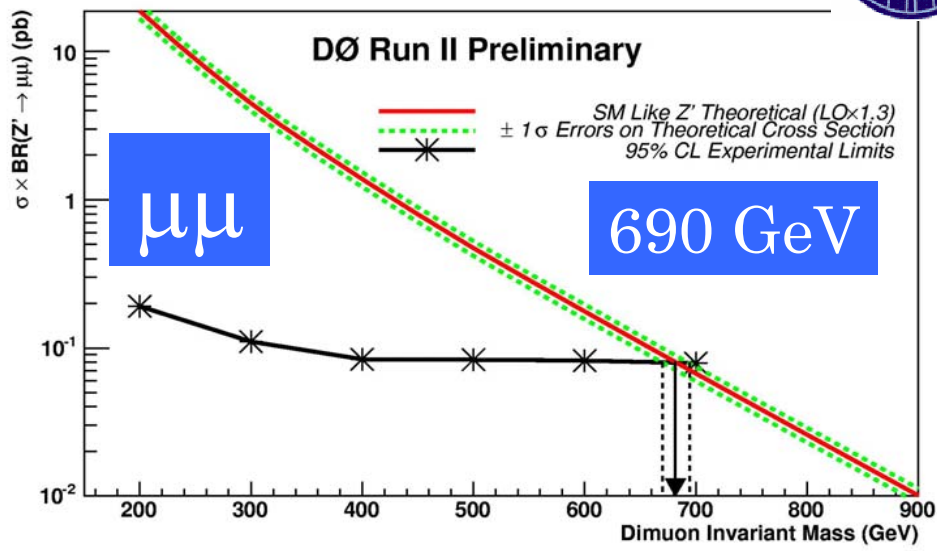


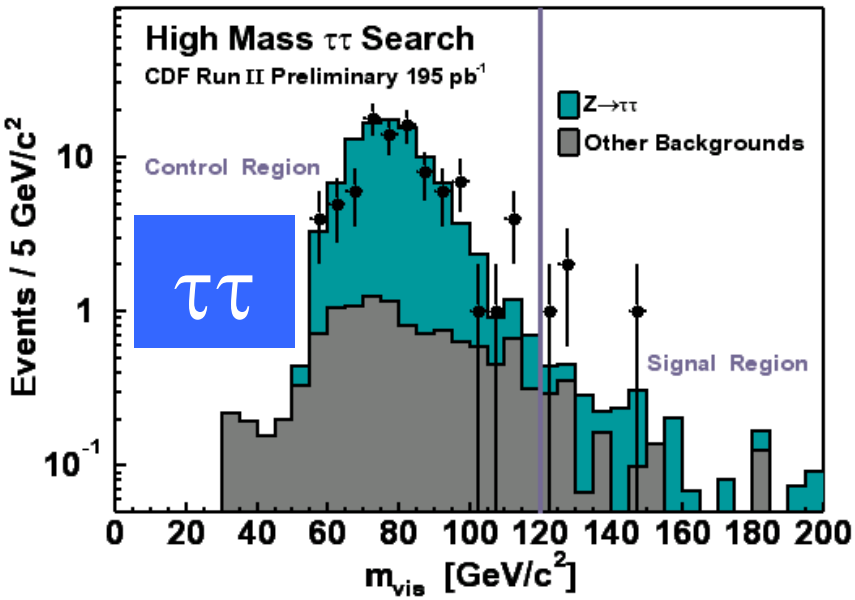


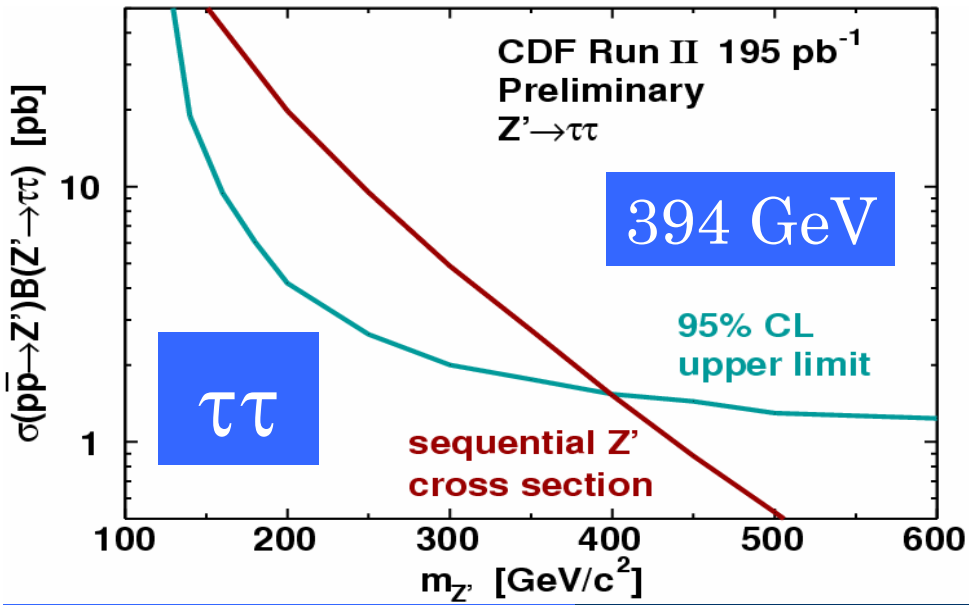
Good agreement between data and SM prediction for full mass region; both CDF and D0 have no significant excess!!

More Z' Searches: μμ & ττ







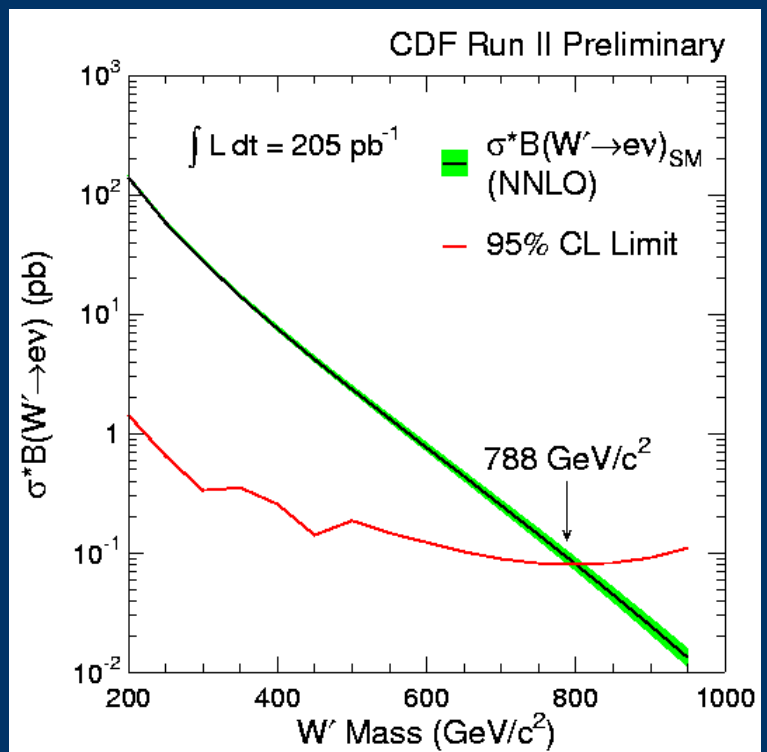


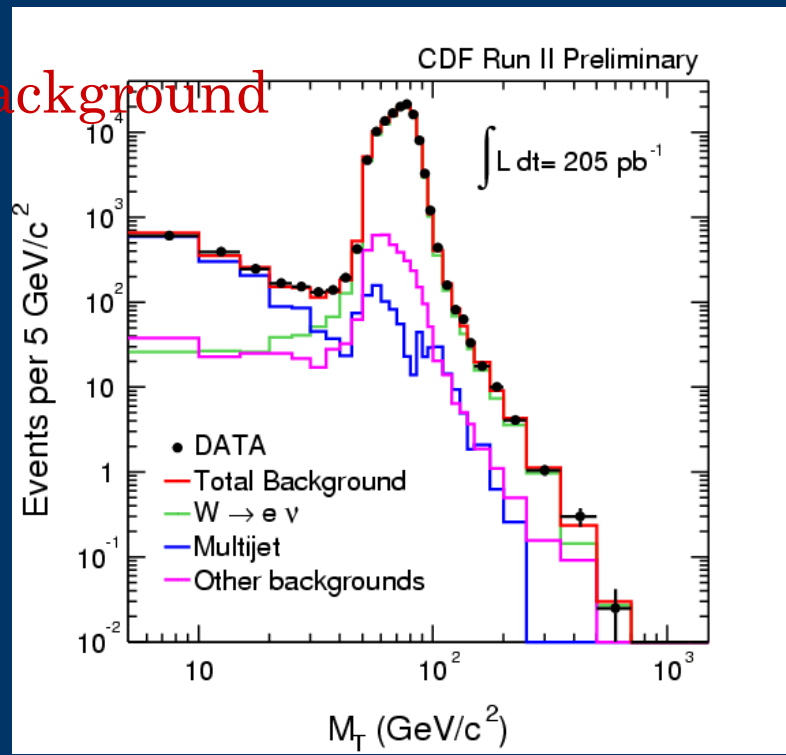
Both CDF and D0 have no significant excess!!

Charged Heavy Vector Boson, W'(→eν) search

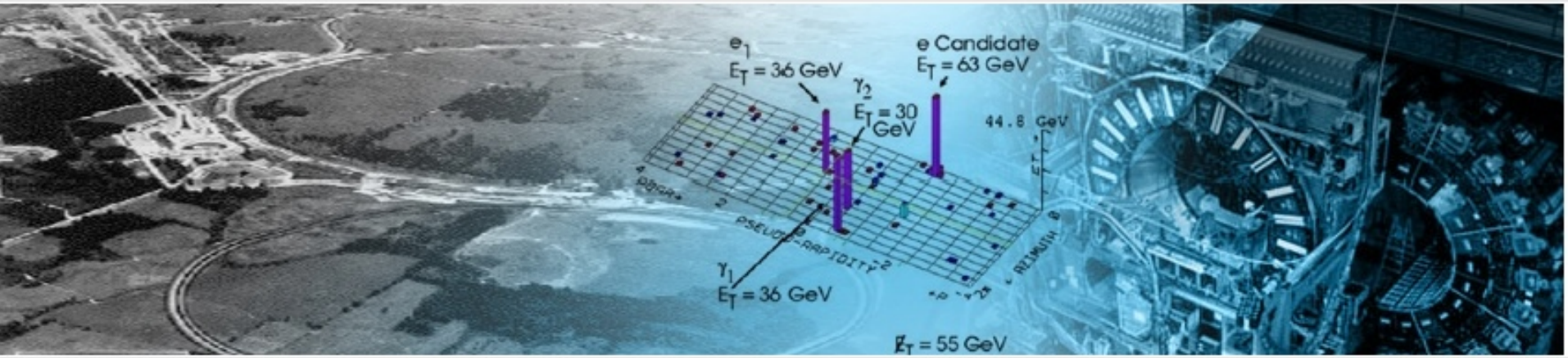
W' appear in theories based on the extension of the gauge group. Left-Right Symmetric Model: $SU(2)_R \rightarrow W'$

- Signature: High p_T electron (> 25 GeV) + MET (> 25 GeV)
  - Compare M_T distribution
  - No signal observed above SM background





M(W') > 788 GeV/c^2



Extra Dimensions
ADD, RS, TeV^{-1}

Models of Extra Dimensions (ED)

Alternatives to SUSY for resolving the hierarchy problem (M_{EW}<<M_{Plank}?)
In this model, gravition can propagate in additional spatial dimensions

Models with n extra spatial dimensions

Large ED (LED)

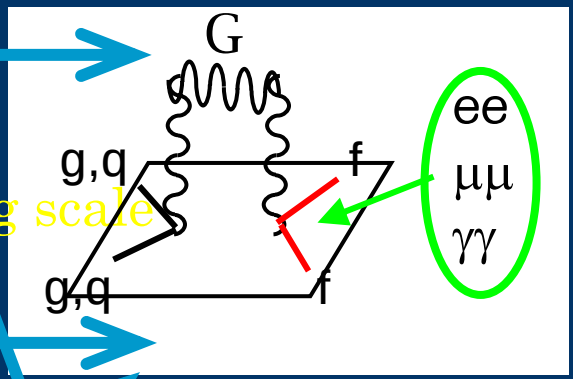
- n>0 (n>2) compactified
- $M^2_{Pl} \sim R^n M_D^{n+2}$, M_D: string scale

TeV^{-1} ED

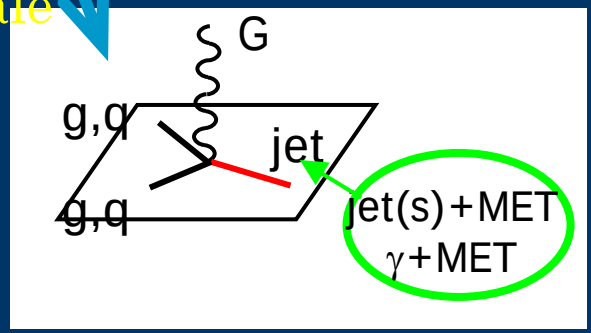
- n>=1 (n=1)
- M_c: compactification scale
- Gauge Boson Exchange

Warped ED (RS)

- n=1, highly curved
- k/M_{Pl}, k: curvature scale



Graviton Exchange



Graviton Emission

At the Tevatron, searched

LED
ee, μμ, γγ, jet+MET

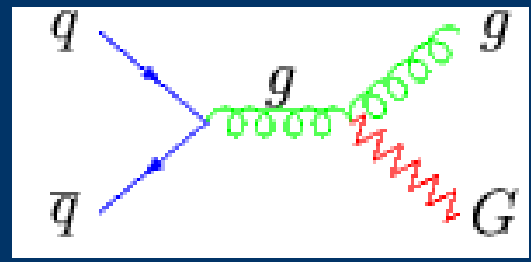
TeV^{-1}ED
ee

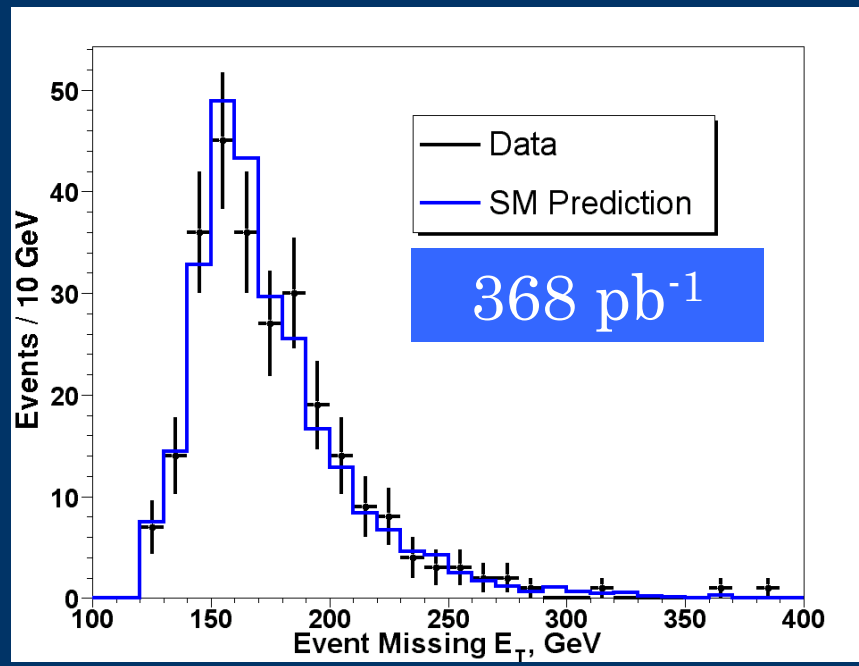
RS
ee, μμ, γγ

Monojet Search for LED (ADD)

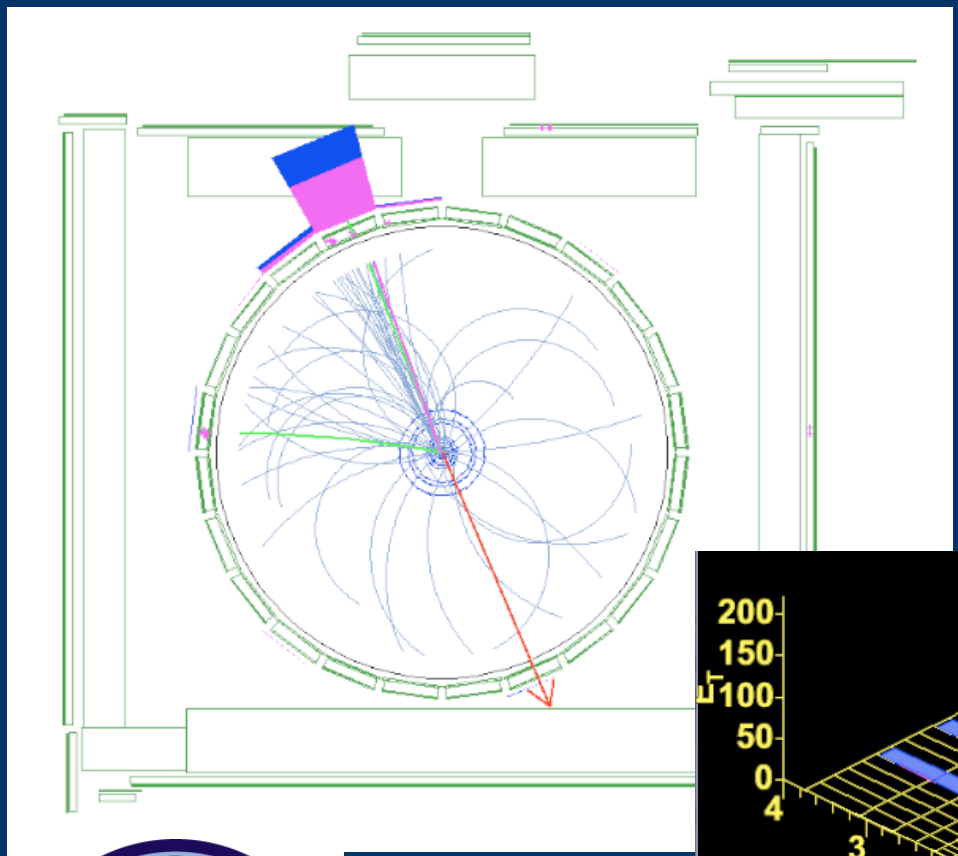
Direct Graviton Emission

- Single high E_T Jet + MET
  - E_T > 150 GeV, MET > 120 GeV
- SM Backgrounds
  - $Z \rightarrow \nu\nu$ + Jets (irreducible)
  - $W \rightarrow l\nu$ + Jets, QCD Dijets
- Results:
  - 265 ± 30 events predicted
    - 130 ± 14 [$Z \rightarrow \nu\nu$]
    - 113 ± 13 [$W \rightarrow l\nu$]
  - 263 events observed

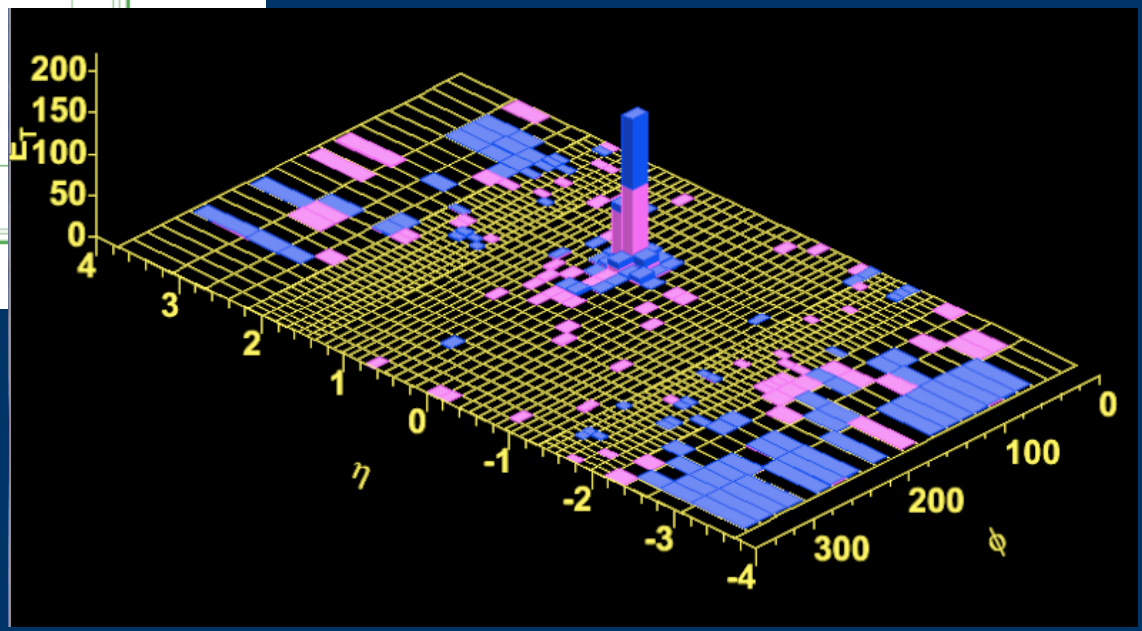




Example Candidate Event for LED



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



Monojet Search for LED (ADD)

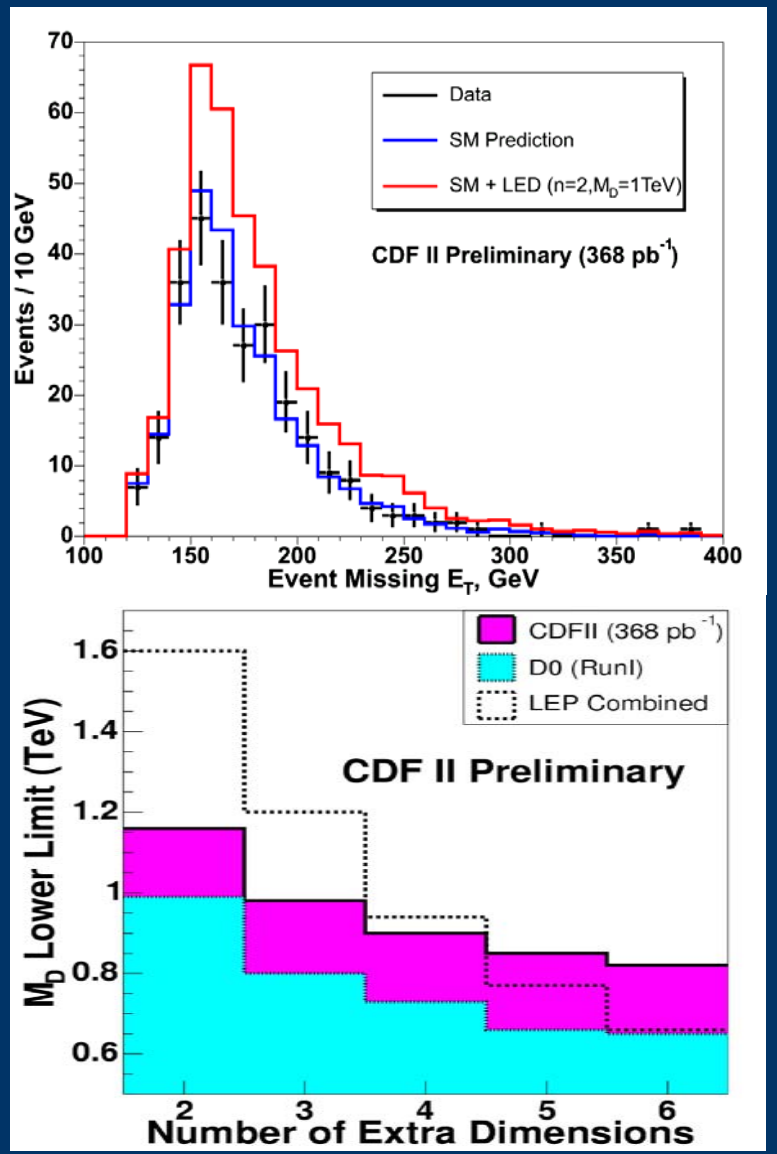
Based on ADD Model, place lower limit on Effective Planck scale (M_D) and upper limit on size (R)

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

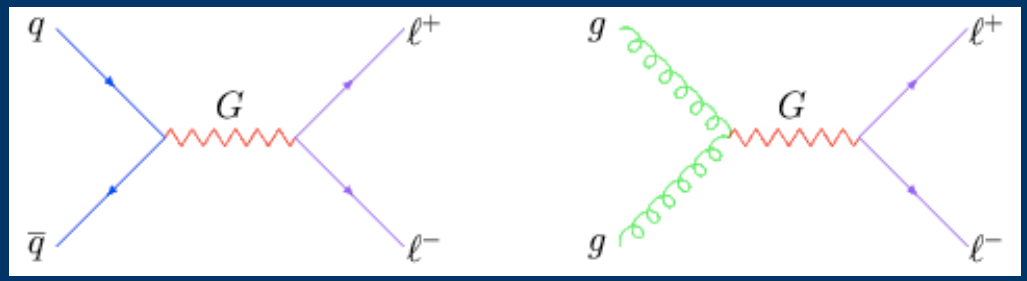
$$M_{Planck}^{\ 2} \sim R^n M_D^{\ 2+n}$$

95% C.L. limits

n	M_D(TeV/c²)	R(mm)
2	> 1.16	$< 3.6 \times 10^{-1}$
3	> 0.98	$< 3.7 \times 10^{-6}$
4	> 0.90	$< 1.1 \times 10^{-8}$
5	> 0.85	$< 3.5 \times 10^{-10}$
6	> 0.83	$< 3.4 \times 10^{-11}$



Search for LED-Graviton Exchange



Three terms in cross-section: SM, Interference, Graviton

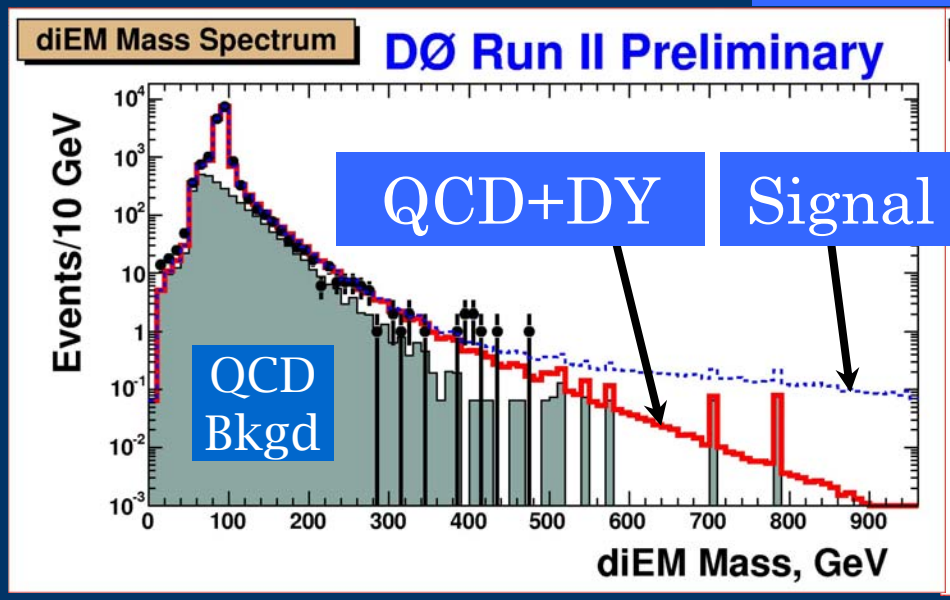
$\sigma_{TOT} = \sigma_{SM} + \eta\sigma_{INT} + \eta^2\sigma_{GRV}$ ($\sigma = F/M_s^4$)

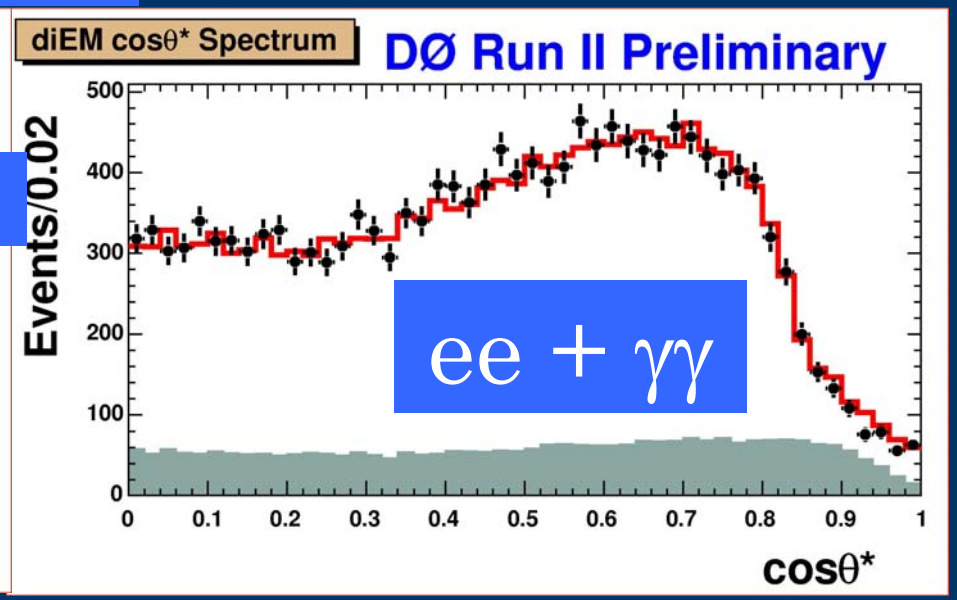
- D0 Analysis Strategy
  - Use Di-EM objects (ee + $\gamma\gamma$)
- 2D fit to M and cosθ*
- Set limits on η and convert to limit on model

Convention for F	
GRW	1
HLZ (n=2)	$\log(M_s^2/M)$
HLZ (n>2)	$2/(n-2)$
Hewett	$2\lambda/\pi$

Search for LED-Graviton Exchange

200 pb^{-1}





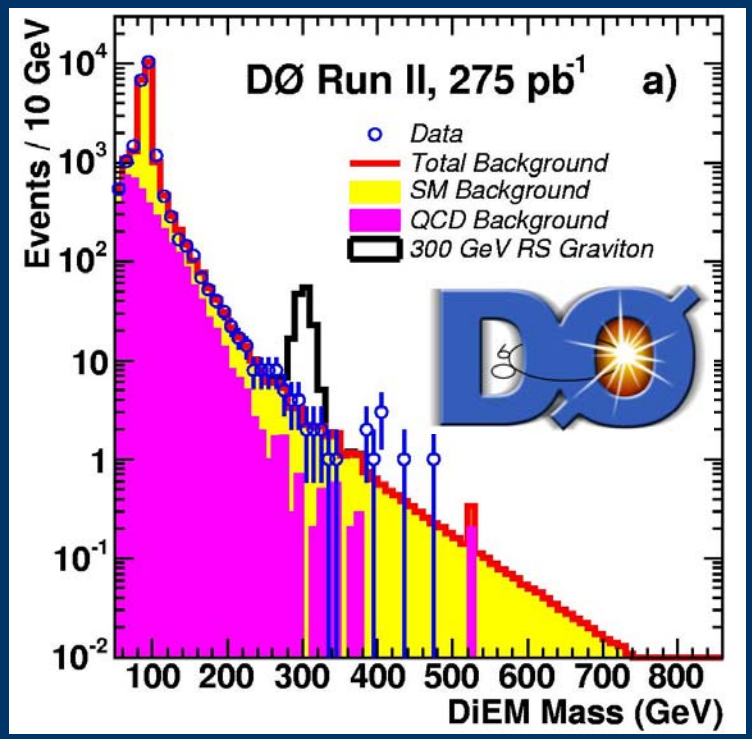
Limits on Fundamental Plank Scale, in TeV

M_S Limit(TeV)	D0 (RunII)	D0(Run1+II)	CDF	LEP
$\lambda = +1$	1.22	1.28	0.96	1.1
$\lambda = -1$	1.10	1.16	0.99	1.2

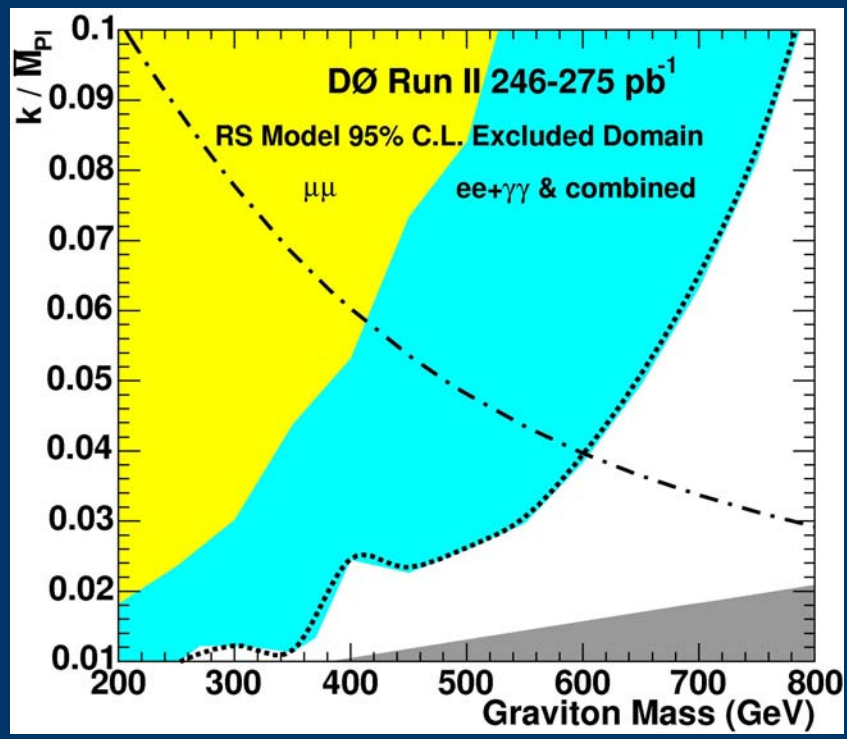
D0 limits in μμ (Run II only): 0.96, 0.93 TeV ($\lambda = +1, -1$)

Search for Warped ED-RS Gravitons

In RS Model, two branes in one curved ED, with gravity on a different brane from SM. Analysis looks for resonances in dilepton and diphoton mass distributions: ppbar → G → γγ, ee, μμ

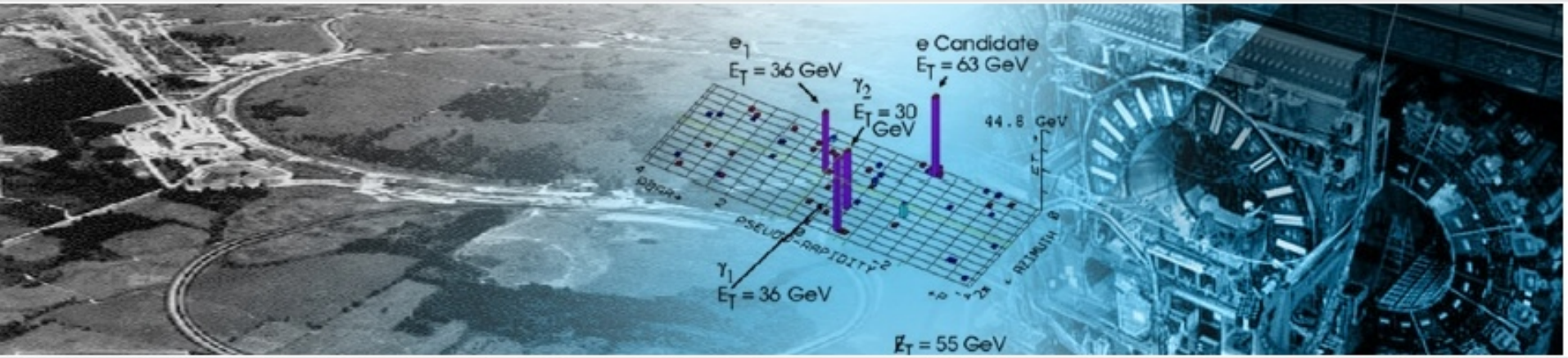


Di-EM Mass Distribution



Mass Limit vs. k/M_{PL}

RS Gravitons are excluded in the plane of coupling vs effective gaviton mass; 785 (250) GeV for $k/M_{PL} = 0.1$ (0.01)



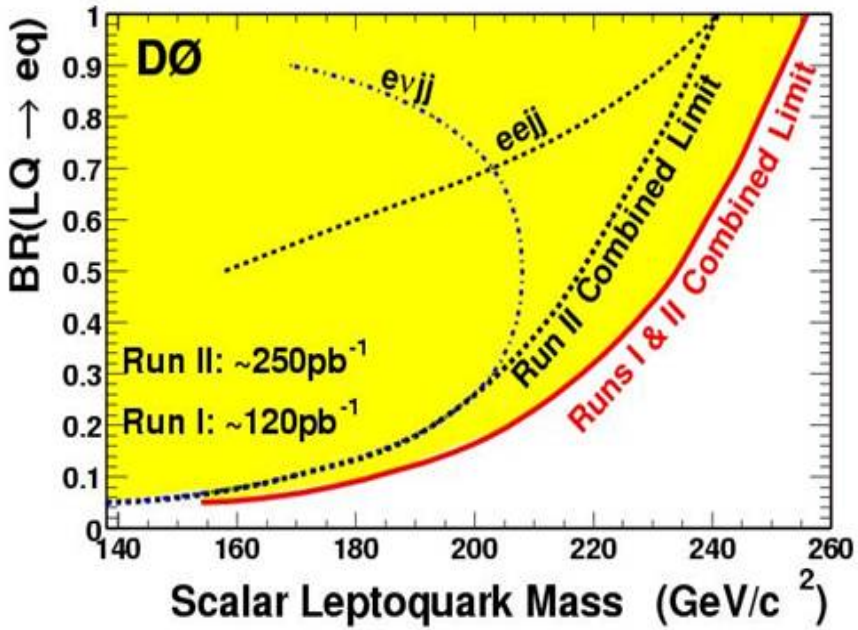
Leptoquarks
1st, 2nd, 3rd generations

Search for Leptoquarks

Natural consequence of unification of quarks and leptons into a single multiplet

- Many extensions of SM assume additional symmetry between leptons and quarks
- Leptoquarks
  - Carry both lepton and color quantum numbers
  - Couple to quark and lepton of same generation
  - Three generations
- Pair produced at the Tevatron
- Decay channel controlled by $\beta = BR(LQ \rightarrow lq)$
- Signature: lljj, lvjj, vvjj

1st Generation: eejj, evjj



For $\beta = 1$:

D0 : Run I+II, $M_{LQ} > 256$ GeV/c^2

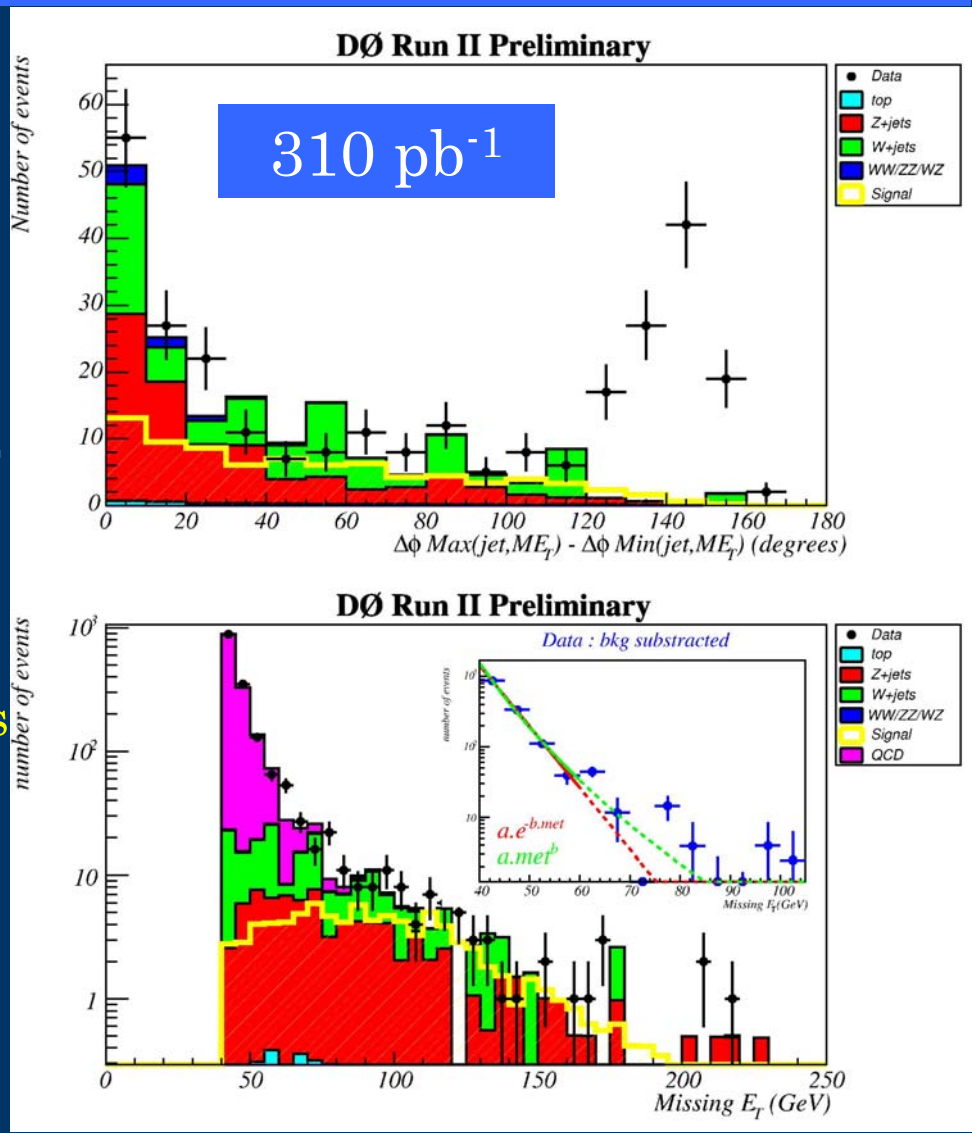
CDF: Run II, $M_{LQ} > 235$ GeV/c2

Search for Leptoquarks

LQ → qν : Acoplanar Jets [1st Generation: ννjj]

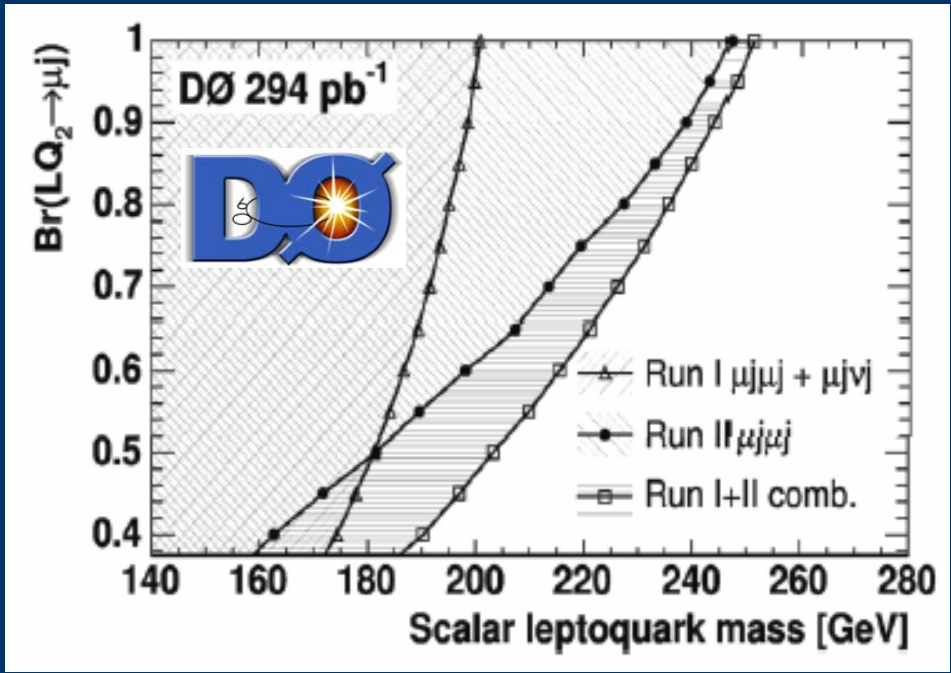
- Search for LQ decaying to quark+ neutrino suffers from substantial QCD backgrounds
  - require exactly 2 acoplanar jets
  - Non-QCD SM background dominated by $Z \rightarrow \nu\nu$ + 2 jets

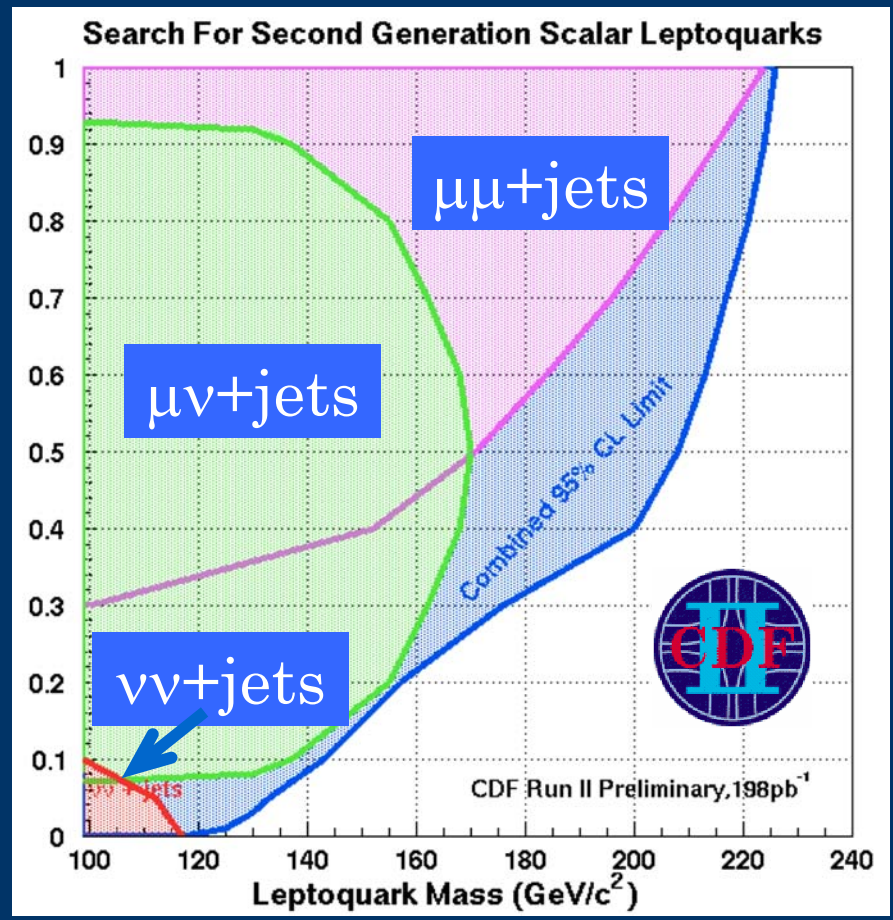
For β = 0:
D0 : Run II, $M_{LQ} > 136$ GeV/c²
CDF: Run II, $M_{LQ} > 117$ GeV/c²



Search for Leptoquarks

2nd Generation: μμjj, μνjj, ννjj





For β = 1:
D0 : Run I+II, $M_{LQ} > 251$ GeV/c^2
CDF: Run II, $M_{LQ} > 224$ GeV/c2

Search for Leptoquarks

3rd Generation: $\tau_l\tau_h jj$ (one leptonic, one hadronic dacayed τ's)

- Vector LQ: Br(VLQ3 $\rightarrow \tau b$) = 100% (β=1)

$\tau_l + \tau_h \rightarrow p_T(l) > 10$ GeV/c,
$p_T(\tau_h) > 15$ GeV/c

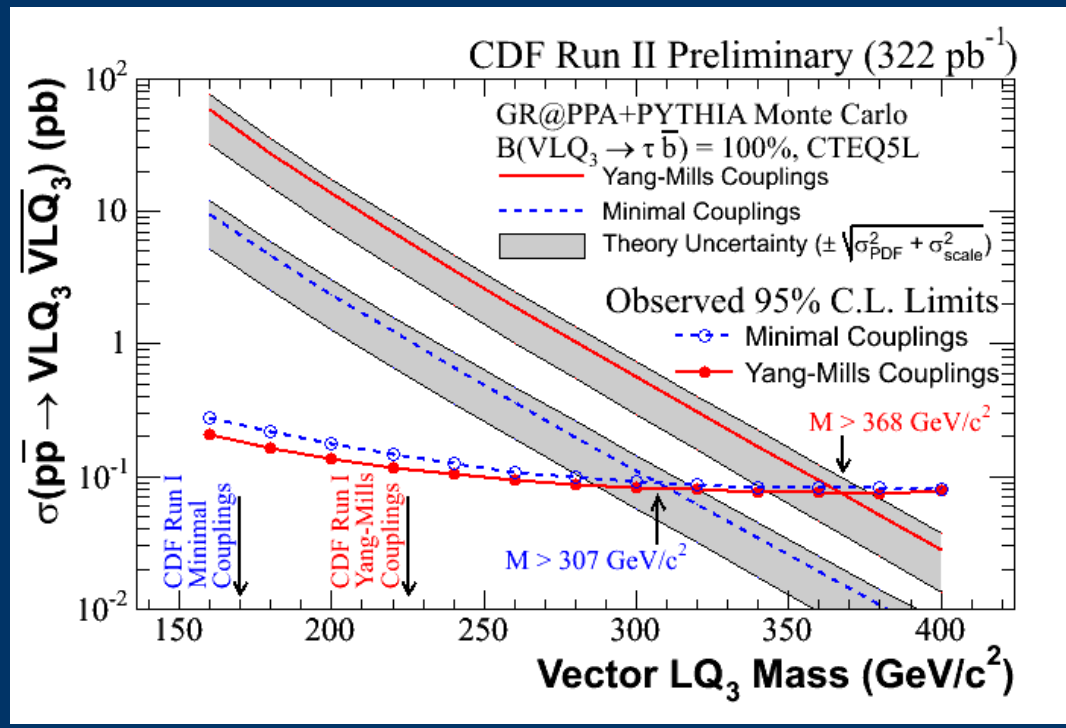
Opposite sign of lepton & tau

MET > 10 GeV

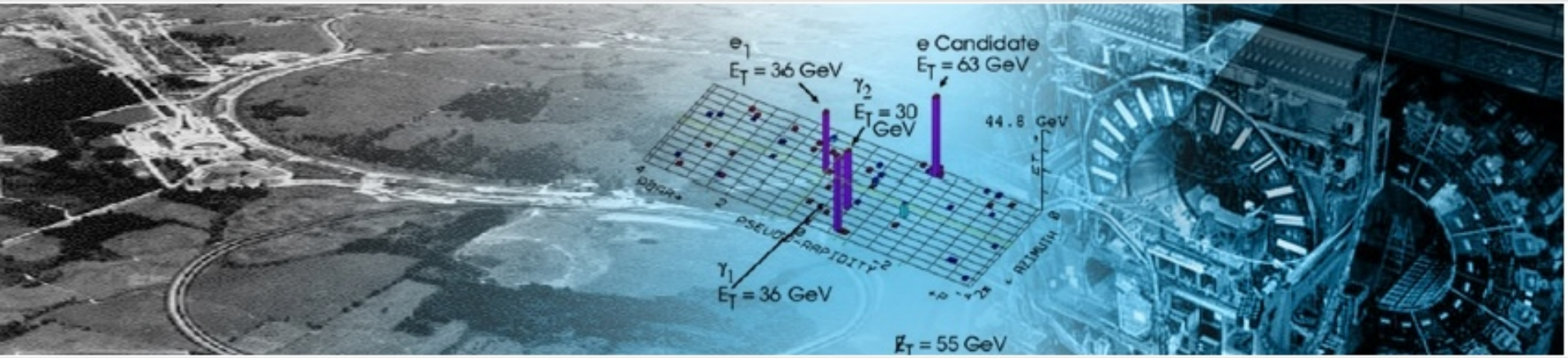
$H_T = p_T(l)+p_T(\tau_h)+p_T(jet)+MET > 400$ GeV/c

$N_{jet} >= 2$

Removal of conversions, cosmics, and DY



For β =1, $M_{VLQ3} > 368$ GeV/c^2 @ 95% C.L.
For β =1, $M_{SLQ3} > 155$ GeV/c^2 @ 95% C.L.



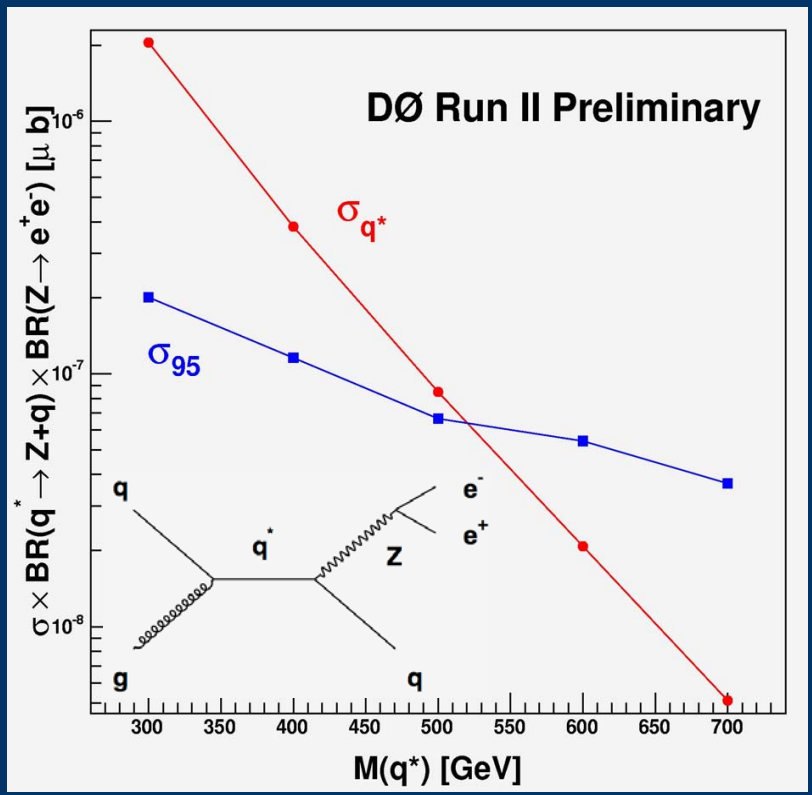
New Fermions

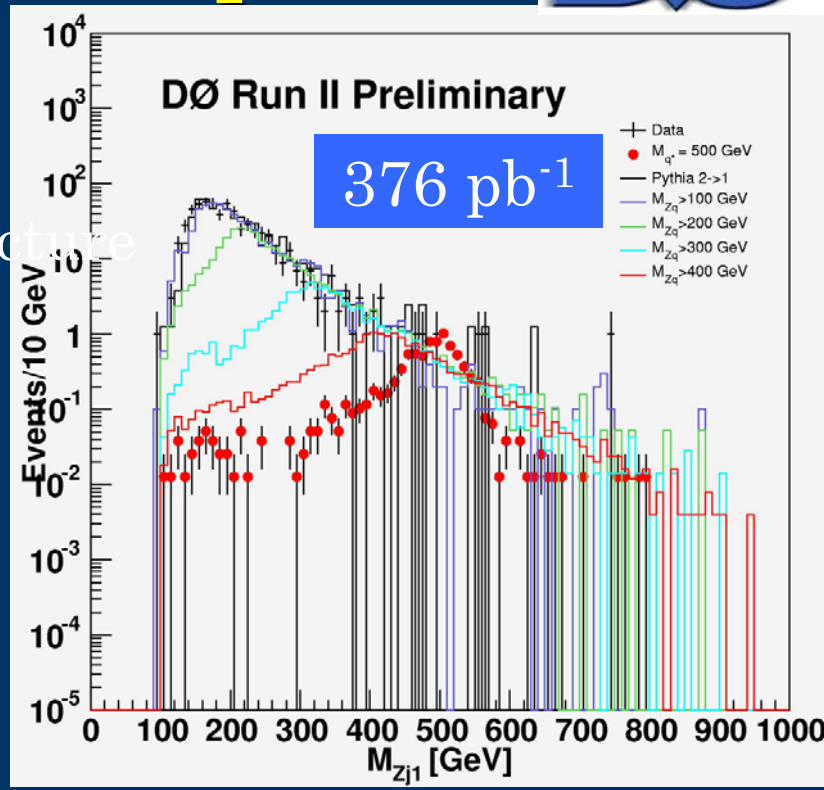
q*, e*, μ*, t'

Excited Quark (q*)

Search for Resonances in Z + jets

- Heavy resonances decaying into W/Z+Jet could signal quark substructure
- Study Z + Jets ($Z \rightarrow ee$)
  - Essentially background free





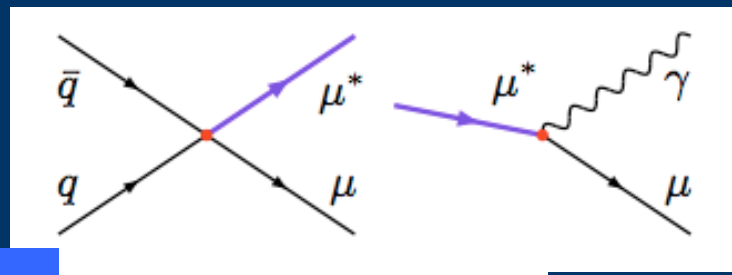
For SM expectation, generate MC w/ different thresholds for M(Z+j)

M(q*) > 520 GeV @ 95% C.L.

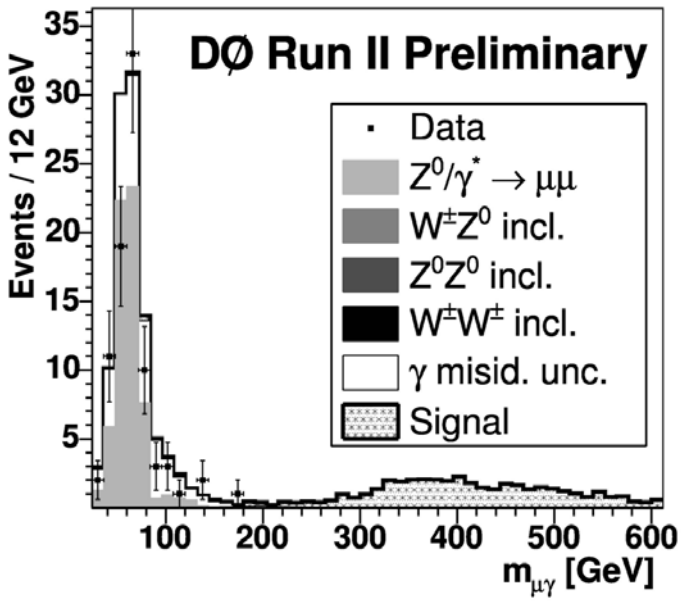
Search for Excited Muons

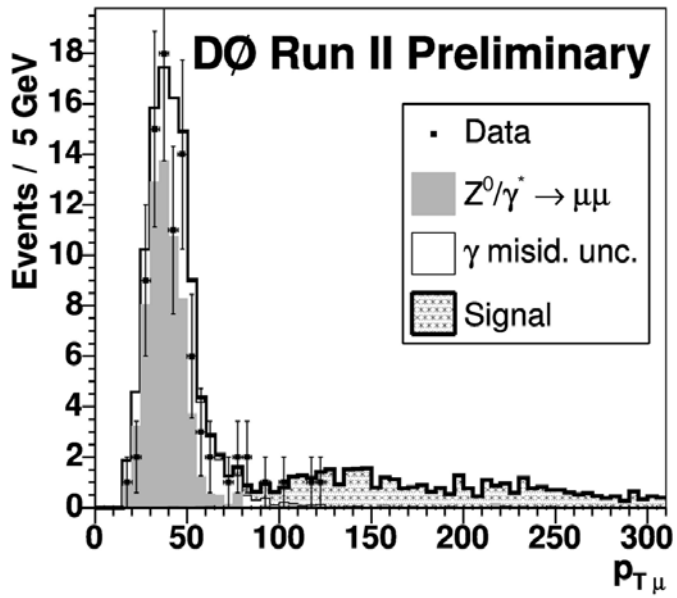
Excited leptons are a possible sign of compositeness

Search for $p\bar{p} \rightarrow \mu\mu^*$, $\mu^* \rightarrow \mu\gamma$ through Contact Interaction Model



380 pb^{-1}



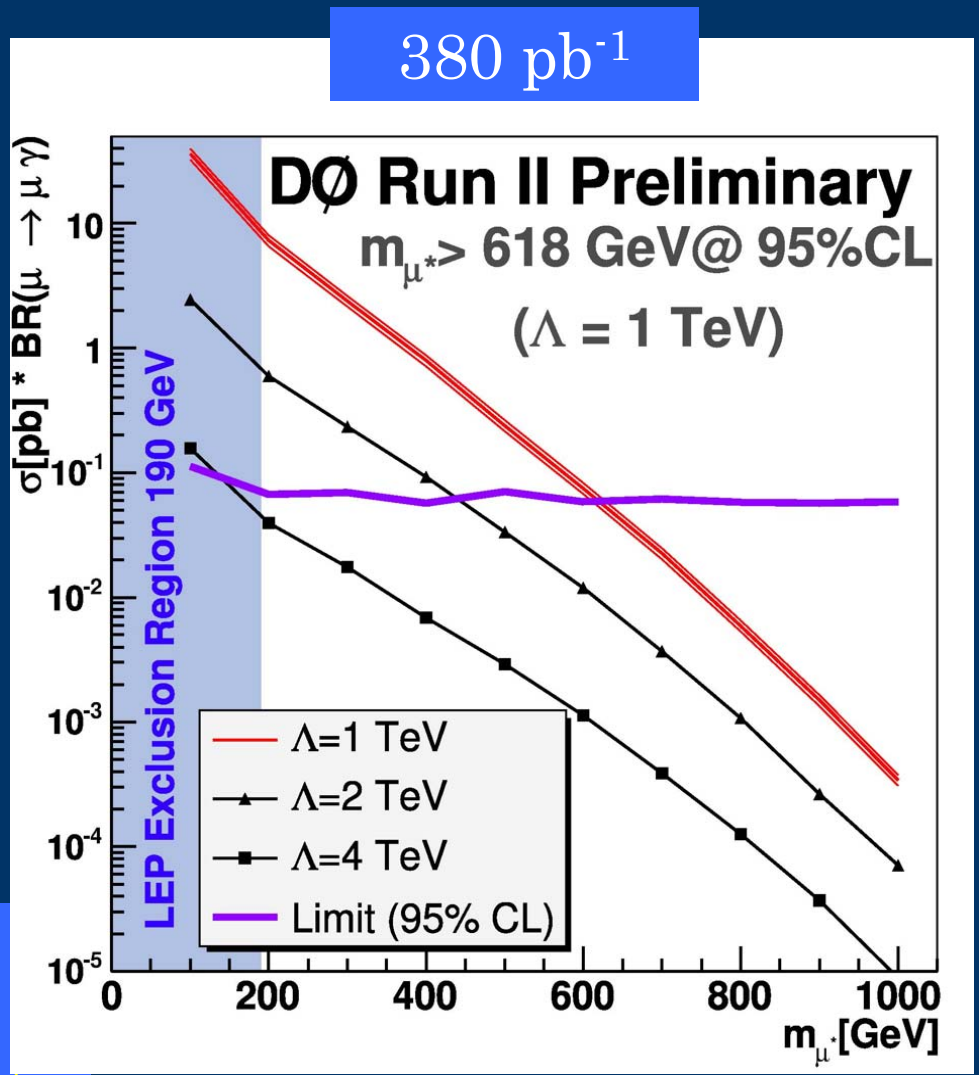


Signal should have large $m_{\mu\gamma}$

Search for Excited Muons

- No events above $m_{\mu\gamma}$ cuts
- Set limits on m_{μ^*} for different value of Λ [Compositeness Scale]
  - $m_{\mu^*} > 618$ GeV ($\Lambda = 1$ TeV)
  - $m_{\mu^*} > 688$ GeV ($\Lambda = m_{\mu^*}$)
- Limits from CDF on both m_{e^*} and m_{μ^*} with similar sensitivity in sight different models

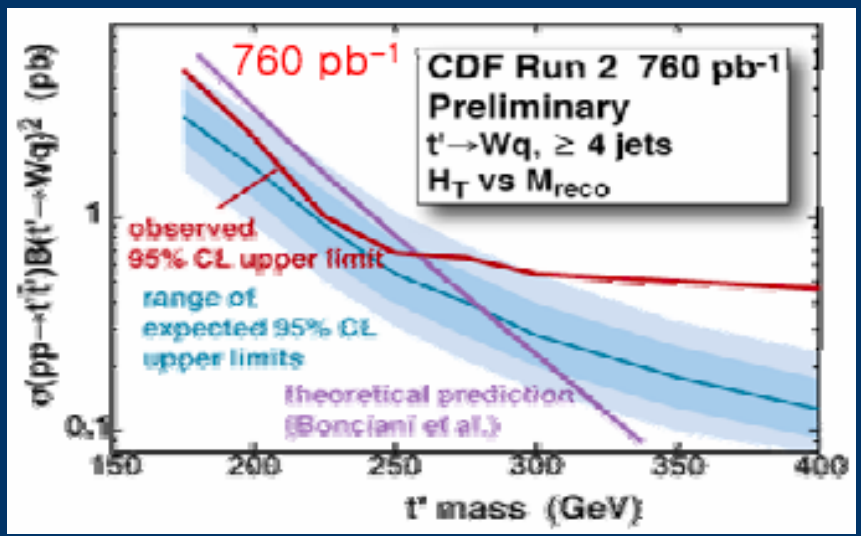
For $\Lambda = 1$:
D0 : $m_{\mu^*} > 618$ GeV/c^2 (CI decays)
CDF: $m_{\mu^*} > 800$ GeV/c^2 (GM decays)

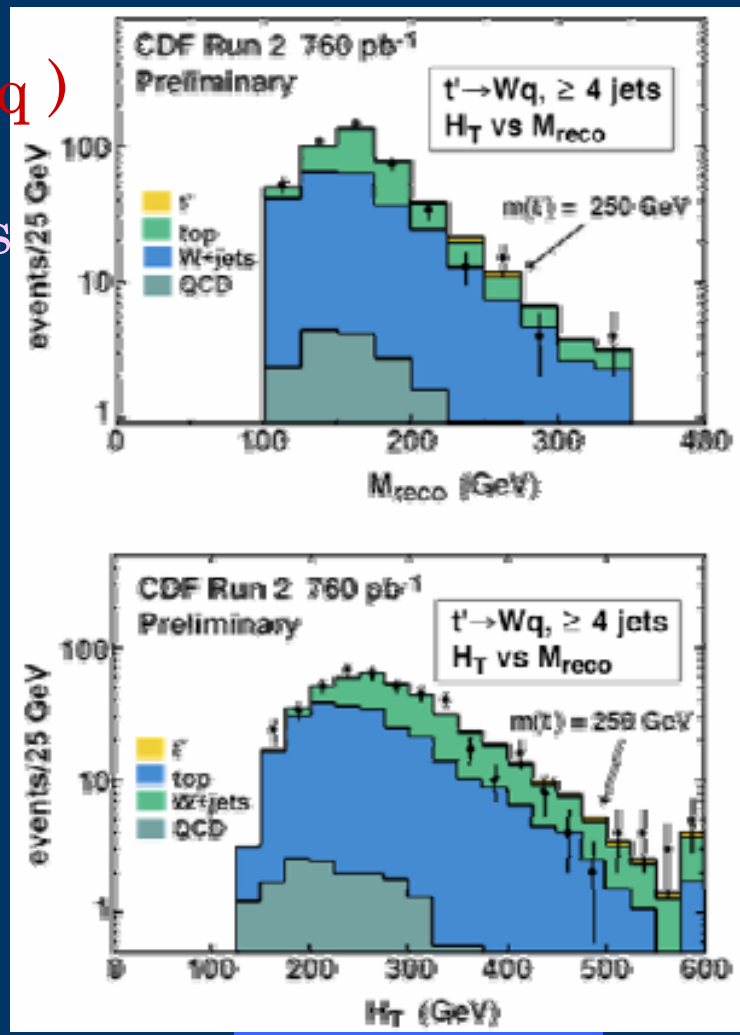


4^{th} Generation Quark [t']

Excited Signature: lν + 4 jets

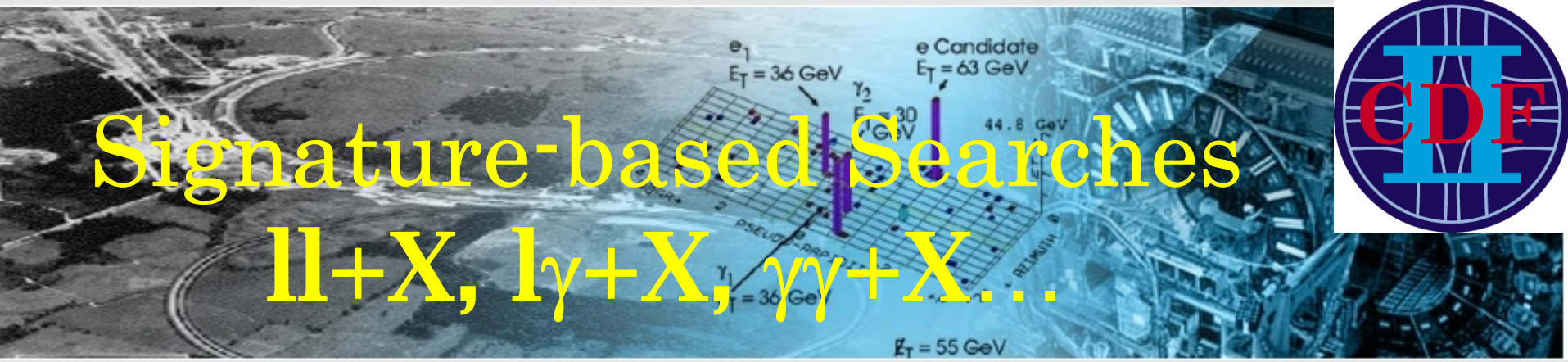
- Heavy top quark pair production decaying to Wq final states ($t' \rightarrow Wq$)
  - Reconstruct the mass of the t´ quark
- 2D fit of the observed distributions to discriminate signal from SM
- Exclude 4^{th} generation t´ quark with mass below 258 GeV @ 95% C.L.

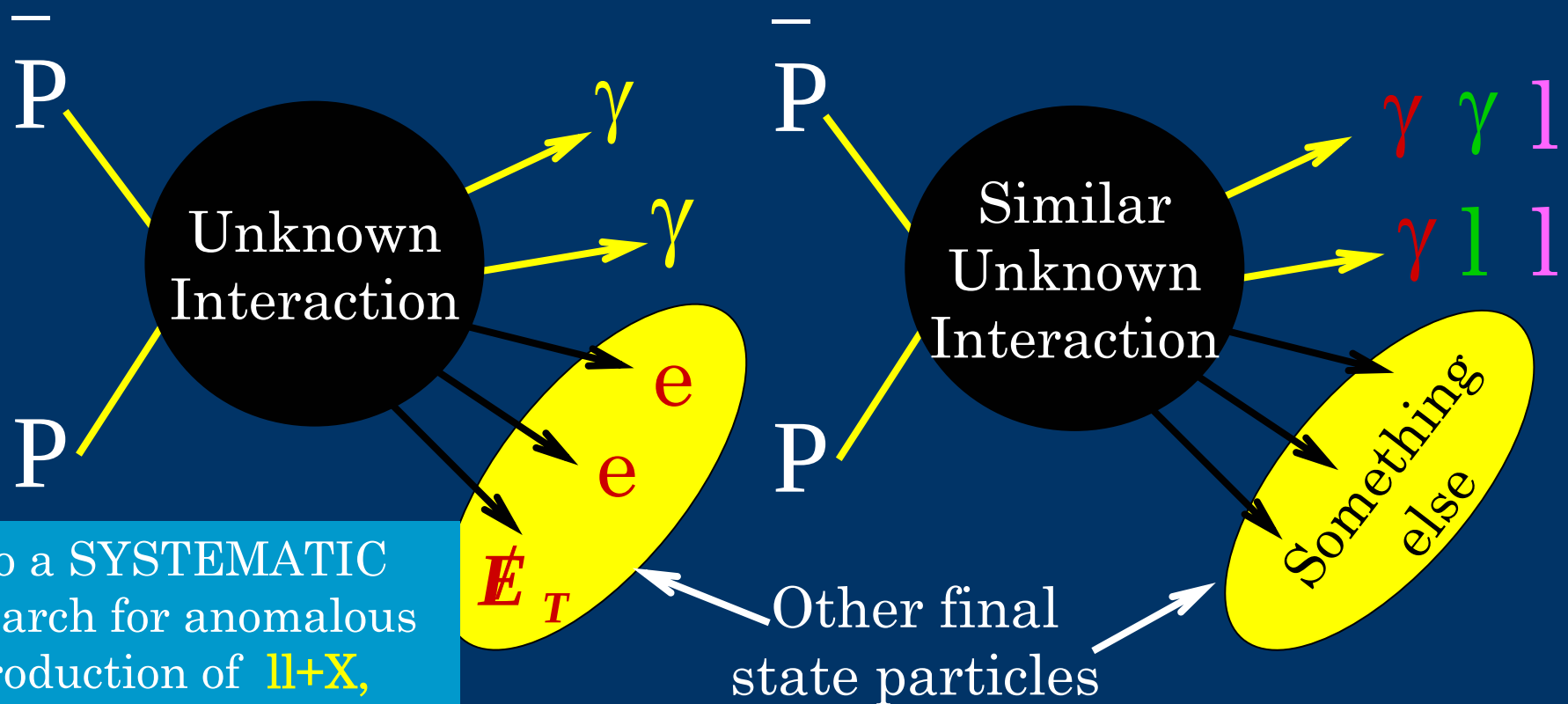




322 pb^{-1}

Signature-based Searches
ll+X, lγ+X, γγ+X…





Do a SYSTEMATIC search for anomalous production of ll+X, lγ+X, γγ+X

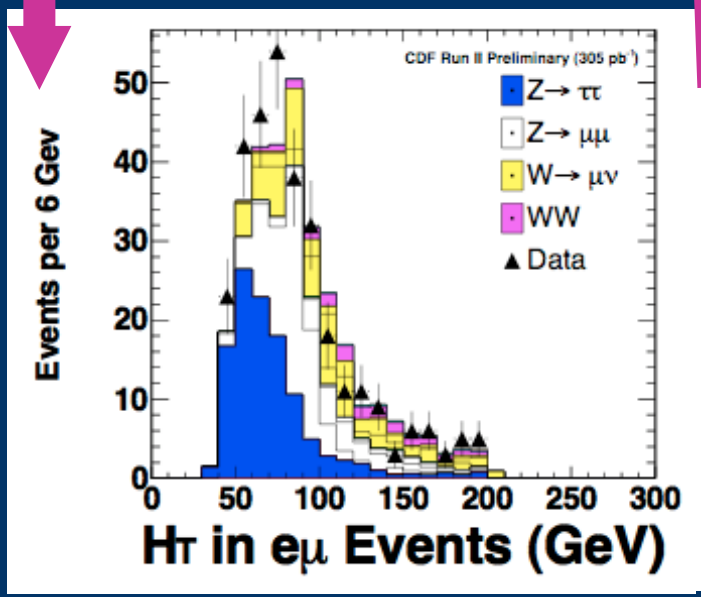
Signature-Based Search: Dilepton+X

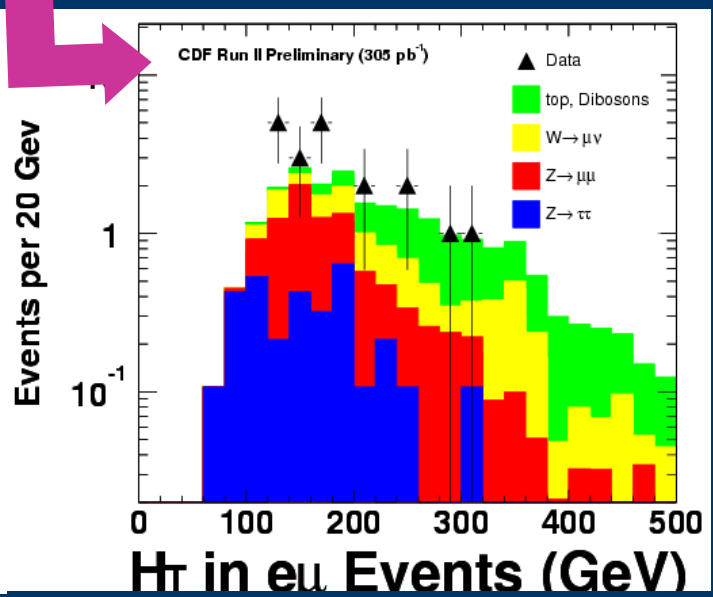
Looking for anomalous Dilepton + X events

- X = Large H_T, Large MET, b-tags, High E_T jets, 3rd leptons..
- Open to heavy quark model, b', t', extra dimensions, SUSY

$H_T = E_T(e) + E_T + p_T(\mu) + MET$
Control Region: $H_T < 200$ GeV
Signal Region: $H_T > 400$ GeV,
2 jets $E_T > 50$ GeV

No events seen in 305 pb^{-1}
Expect:
0.802 ± 0.440 SM
0.526 ± 0.058 QQ



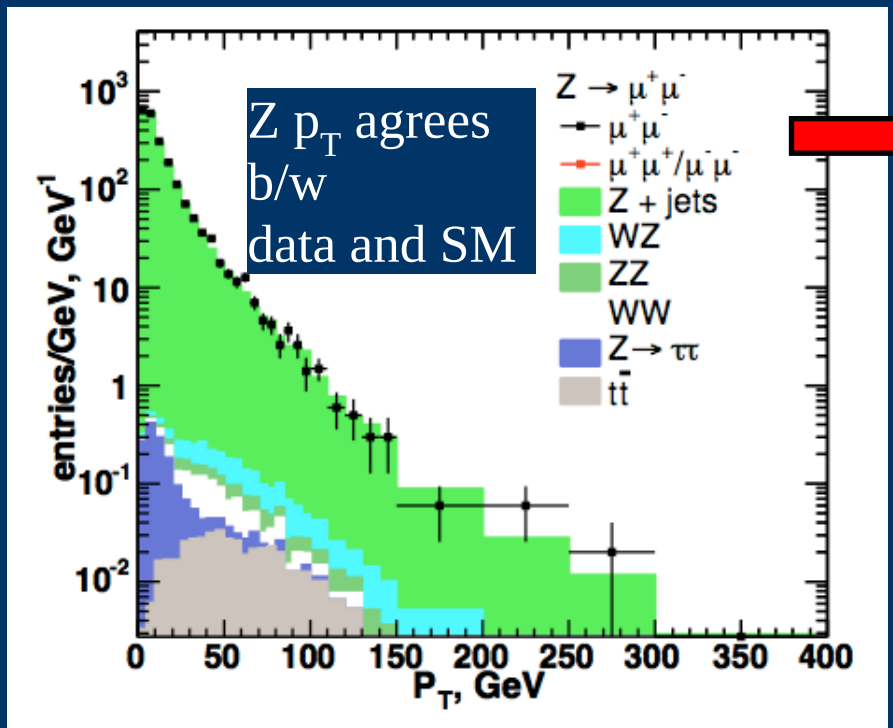


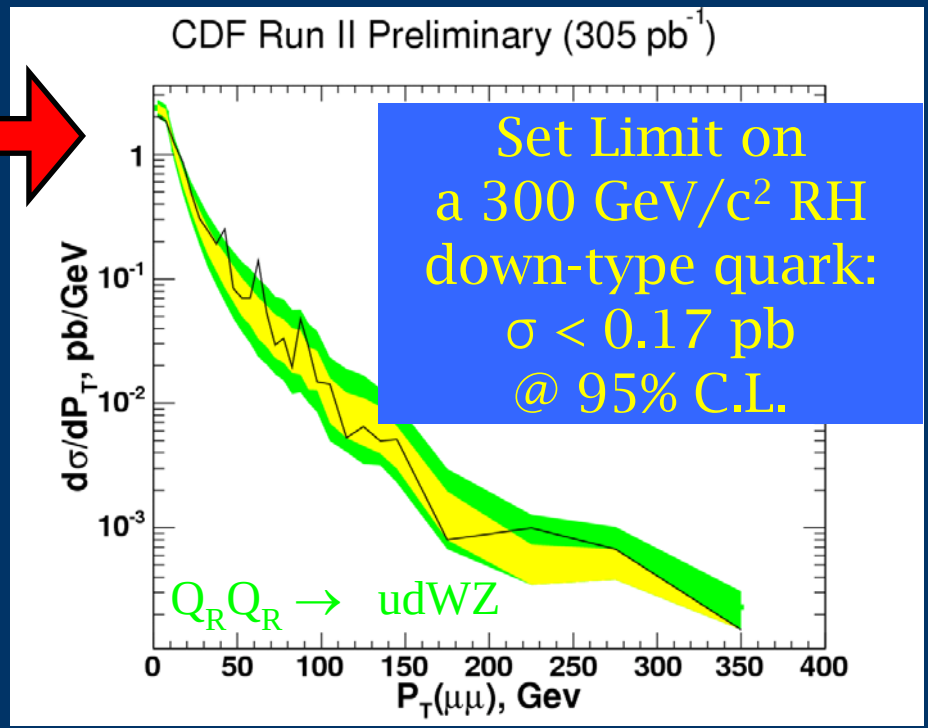
Set Limit on a 300 GeV/c^2 RH down-type quark:
$\sigma < 1.3$ pb
@ 90% C.L.

Signature-Based Search: High P_T Zs

.. or Looking for heavy objects decaying to Z bosons

- Open to many different models (SUSY, ED, etc.)
- Start with heavy quark model of Bjorken, Paksava, Tuan
  - 3 down-type iso-singlet right-handed quarks, Q_R,
  - decaying $Q_R \rightarrow Z/H+d$ or $Q_R \rightarrow W+u$; would create high p_T Z's

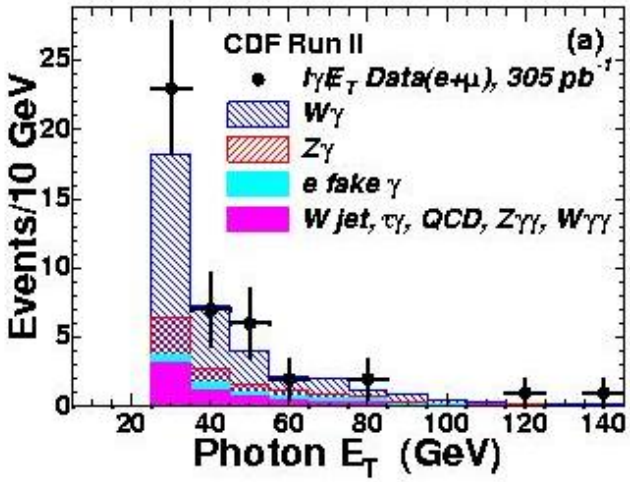


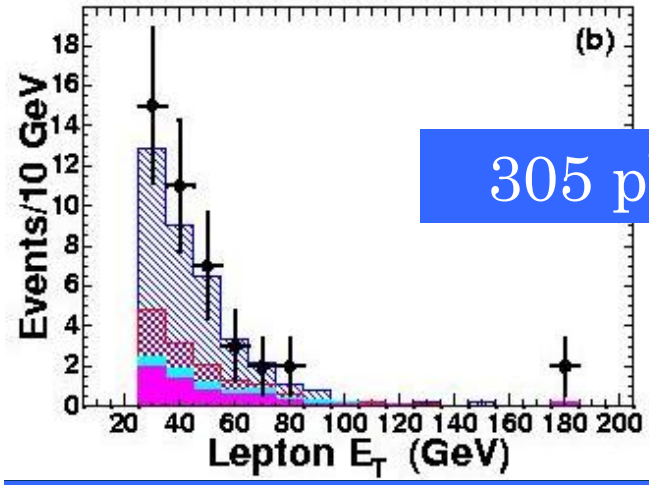


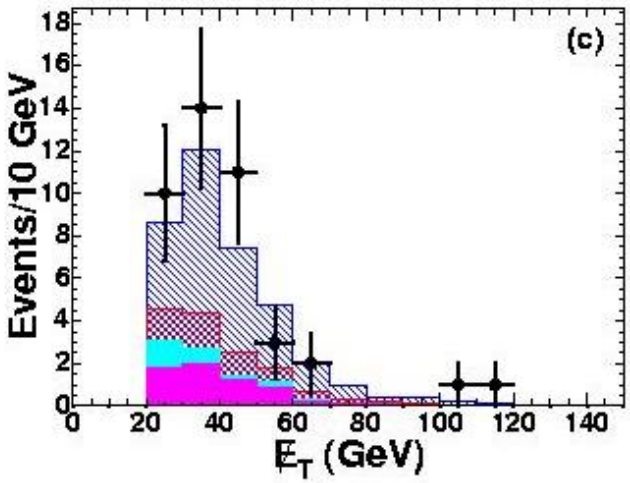
$\sigma < 0.170 \pm 0.005$ pb @ 95% C.L. limit, for 300 GeV quark

Signature-Based Search: l+γ+X

In Run I, CDF saw an excess of lγ+MET events (16 observed, 7.6±0.7 expected). New study with 305 pb^{-1} of Run II data







305 pb^{-1}

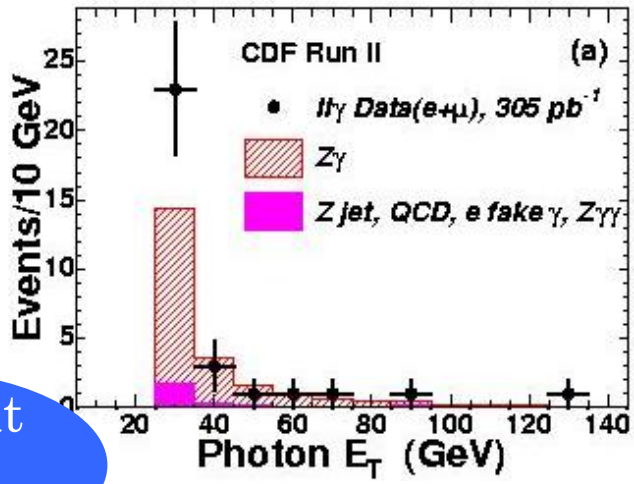
Photon E_T > 25 GeV
Lepton p_T > 20 GeV
MET > 25 GeV

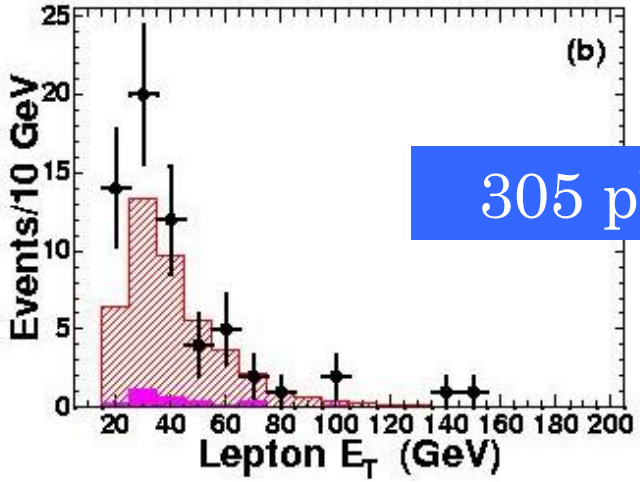
Predicted 37.3 ± 5.4

Observed 42

Signature-Based Search: l+γ+X

Looking for Multi-Lepton+Photon events

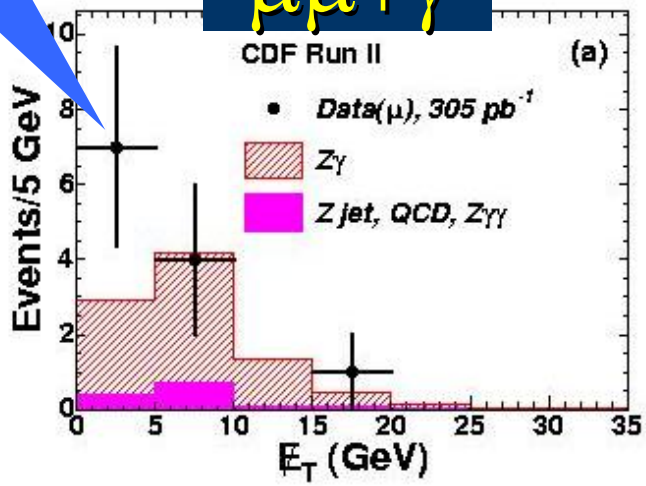




305 pb^{-1}

Excess at Low MET

μμ+γ



Photon E_T > 25 GeV
Lepton p_T > 20 GeV

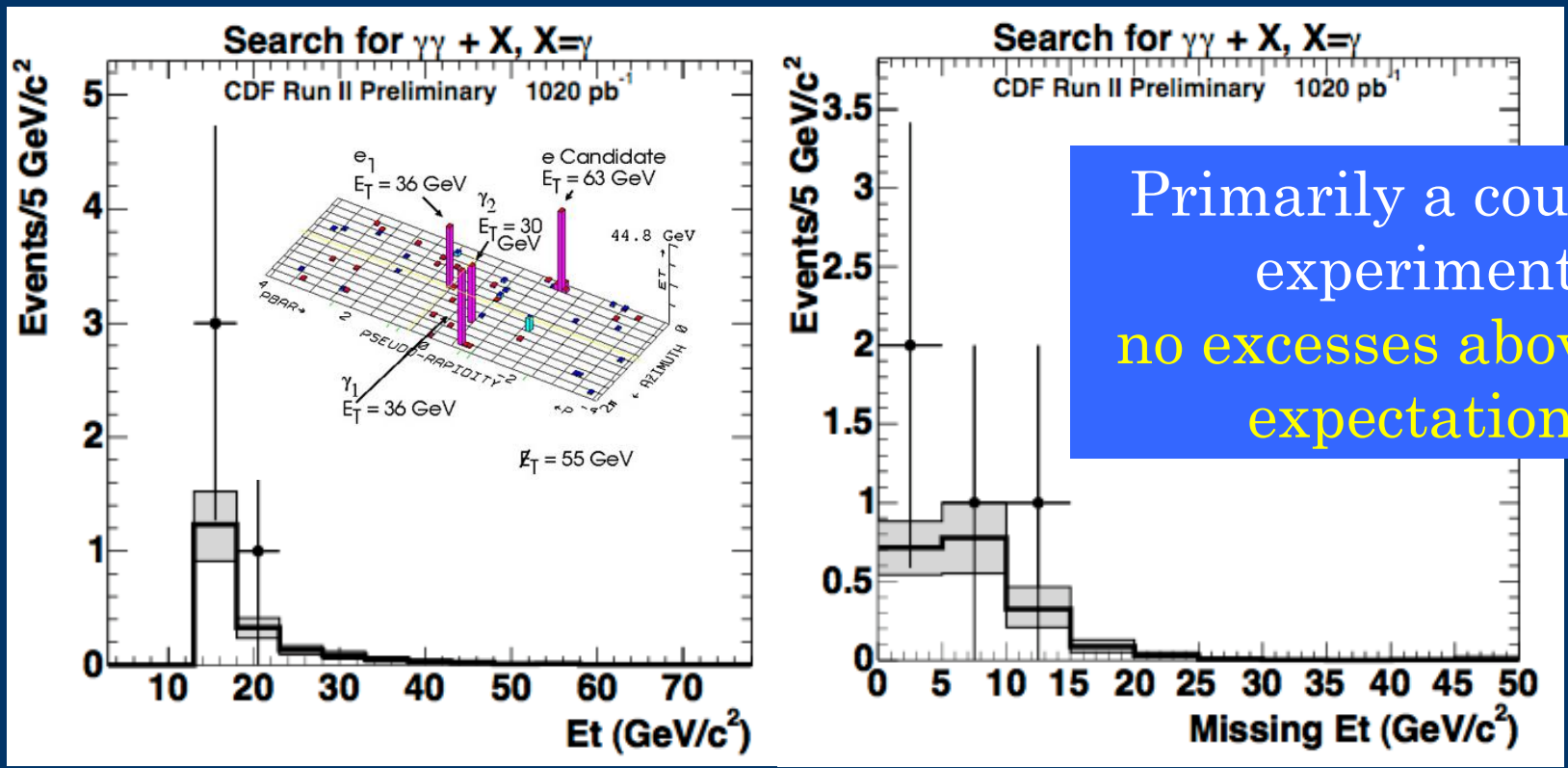
Predicted 23.0 ± 2.7

Observed 31

Signature-Based Search: γγ+γ/e/μ

Motivated by eeγγ+MET event in Run I, study events with 2 photons plus another object.

- First analysis look at γγ+γ (all E_T > 13 GeV)
  - Expect 1.9 ± 0.6 events (real tri-γ, fakes)
  - Observe 4 events



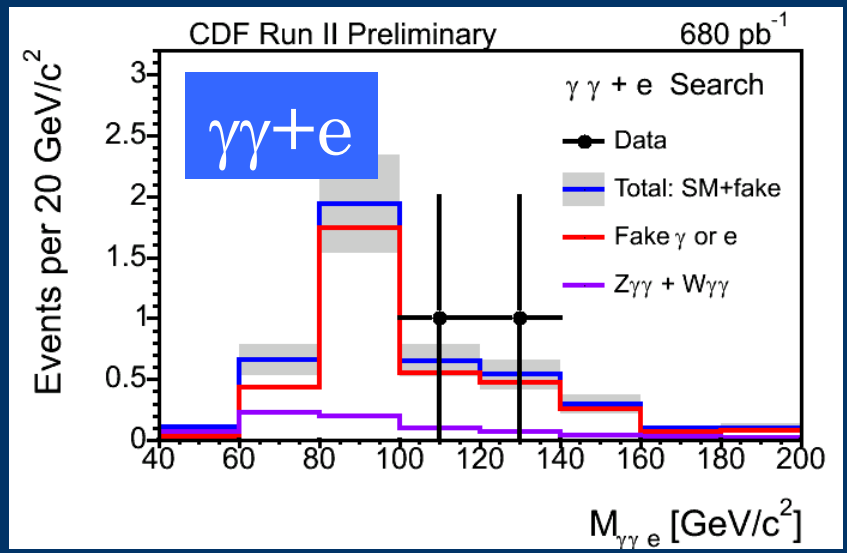
Primarily a counting experiment, no excesses above SM expectations

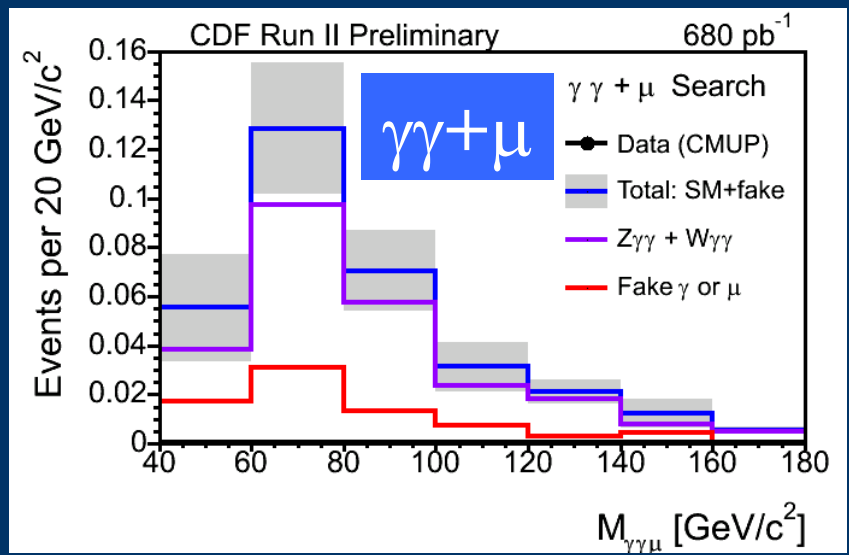
Signature-Based Search: γγ+γ/e/μ

Also look for γγ+e and γγ+μ – same photon selection

- γγ+e analysis
  - $E_T(e) > 20$ GeV
  - Expect 4.49 ± 0.84 events: [Zγγ, fakes etc.]
  - Observe 2 events
- γγ+μ analysis
  - $p_T(\mu) > 20$ GeV
  - Expect 0.47 ± 0.12 events: [Zγγ, fakes, etc.]
  - Observe 0 events

Good agreement between data and SM predictions; Continue to add objects in γγ+X search





Conclusions

- CDF and D0 are searching for evidence of many different models of new physics in many channels. Only recent results shown here. Many new physics searches are underway.

- No signals of the new physics observed in Tevatron data yet.

- More Tevatron data on the way; analyses of $1fb^{-1}$ data samples just beginning. New exciting results are in the pipeline. Stay tuned!