Extra Dimension

Searches at Accelerators

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Outline

Why search for Extra Dimensions (ED) ?

Motivation & different models: ADD, RS, TeV^{-1}

How are ED detectable at accelerators?

Signatures

Where are searches being performed?

Accelerator facilities

What searches are being performed?

Search channels

What are the results?

Analysis descriptions

What are the future prospects?

LHC MC studies

Extra dimensional Models

Alternatives to SUSY for solving the hierarchy problem:

M_{EW} (1 TeV) << M_{Planck} (10^{19} GeV)?

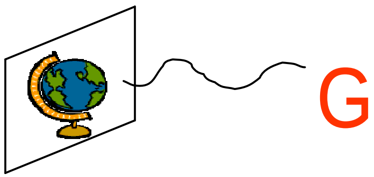
ADD

Arkani-Hamed, **D**imopoulos, **D**vali,

Phys Lett B429 (98)

Many large compactified EDs

In which G can propagate



$M_{Pl}^2 \sim R^n M_{Pl(4+n)}^{(2+n)}$

Effective M_{Pl} ~ 1TeV → if compact space (R^n) is large

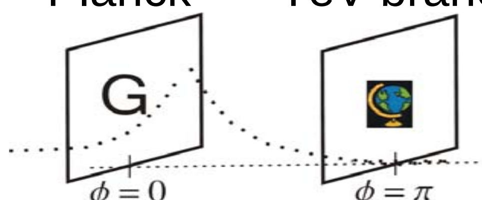
RS

Randall, **S**undrum,

Phys Rev Lett 83 (99)

1 highly curved ED

Gravity localised in the ED



$\Lambda_\pi = \overline{M}_{pl} e^{-kR_c\pi}$

$\Lambda_\pi \sim$ TeV

if warp factor kR_c ~11-12

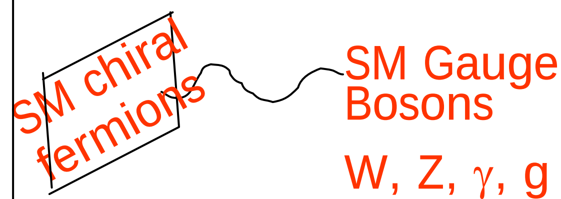
k/M_{Pl}, k: curvature scale

TeV^{-1}

Dienes, Dudas, Ghergnetta,

Nucl Phys B537 (99)

TeV^{-1} sized EDs



See Extra Dimension lectures for more details on the theory & models!

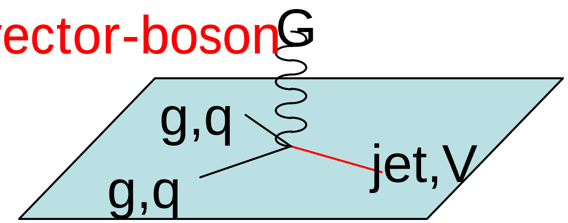
What are the experimental signatures at colliders?

Experimental Signatures for ADD

➢ **Direct Graviton emission** in association with a vector-boson

Signature: ME_T + jet(s), ME_T + V

σ depends on the number of ED



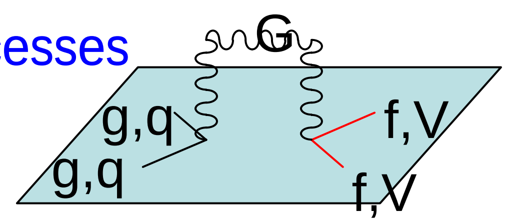
➢ **Virtual Graviton exchange**

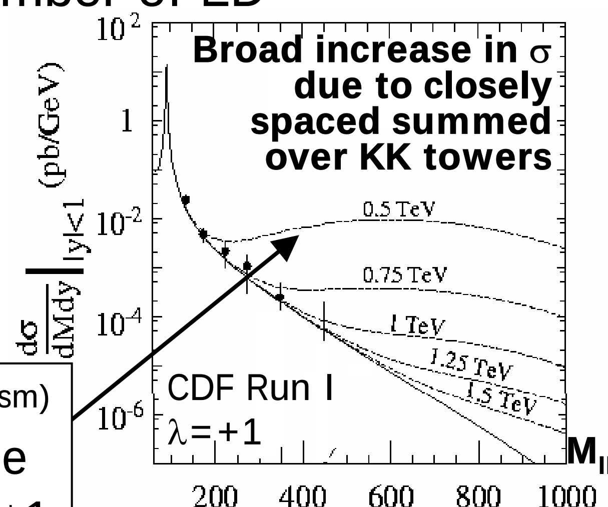
Signature: deviations in σ and asymmetries of SM processes

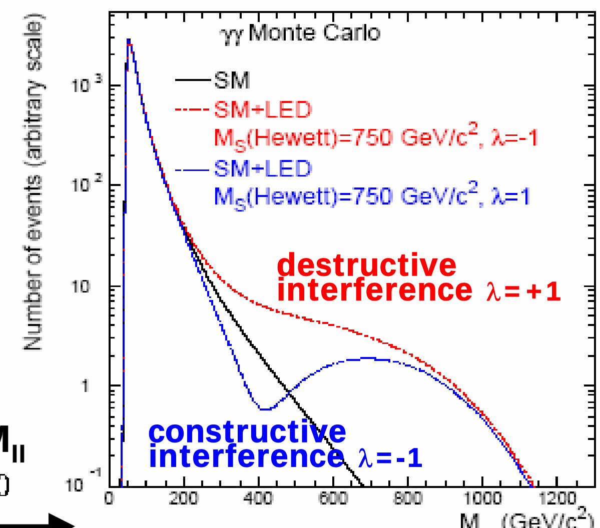
e.g. $qq \rightarrow l^+l^-$, $\gamma\gamma$

Or new processes e.g. $gg \rightarrow l^+l^-$

σ independent of the number of ED*







<u>New Parameters</u> (*Hewett formalism)

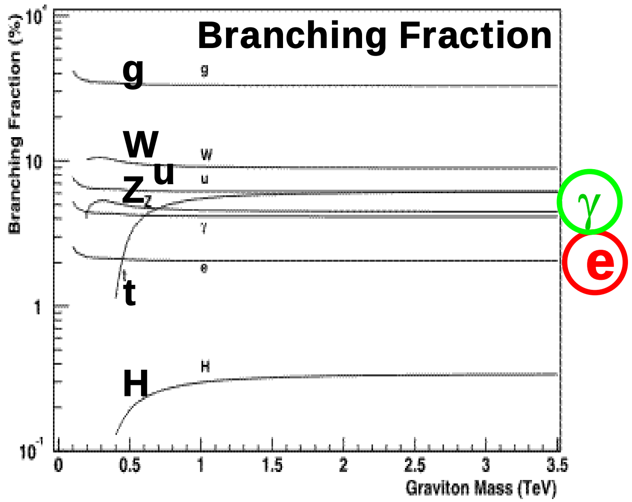
M_{S} ~ M_D ~ $M_{Pl(4+n)}$: string scale

λ: dimensionless parameter, ±1

Experimental Signature for RS Model

Virtual Graviton exchange

Signature: an excess of events in dilepton/dijet/diboson channels



New parameters:

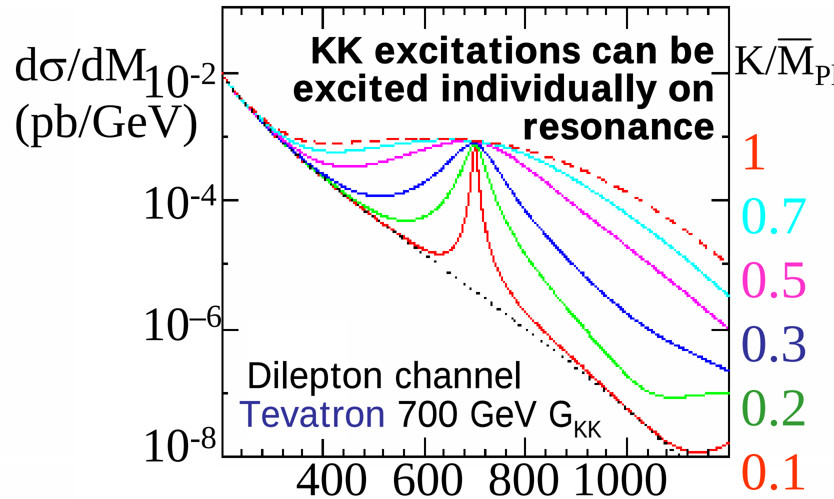
1^{st} graviton excitation mass: m_1 → position

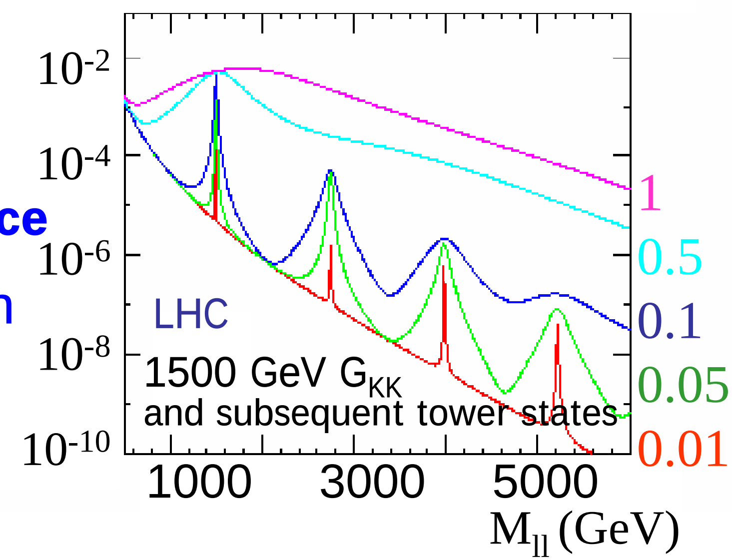
$\Lambda_\pi = m_1 \overline{M}_{pl} / kx_1, \; m_n = kx_n e^{krc\pi} (J_1(x_n)=0)$

Ratio: $k/\overline{M}_{Pl}$ → width

$\Gamma_1 = \rho m_1 x_1^2 (k/\overline{M}_{pl})^2$

Resonance





Experimental Signature for TeV-1 Size ED and KK Gauge Bosons

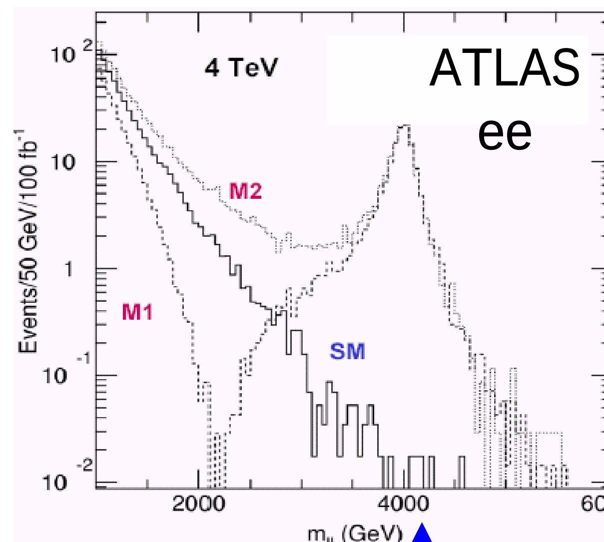
From 4-d point of view:

Mass of SM gauge bosons (M_n) that propagate in the ED are equivalent to towers of KK states with masses : $M_n = \sqrt{(M_0^2 + n^2/R^2)}$ where (n=1,2,…)

Potentially detectable consequences:

1) **Mixing** among the 0th (SM gauge boson) and the nth-modes (n=1,2,3..) of the W and Z bosons.
(Since the entire tower of KK states have the same quantum numbers as their 0th-state gauge boson)

2) **Direct production and virtual exchanges** → of the 0th-state gauge bosons, AND both direct production and virtual effects of the KK states of the W, Z, γ and g bosons at high energies



↑ $M_n = M_0$

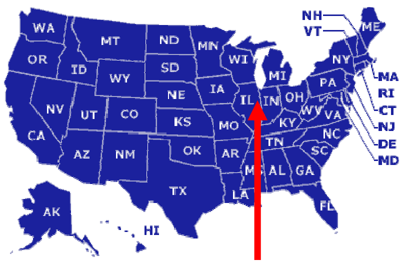
<u>New Parameters</u>

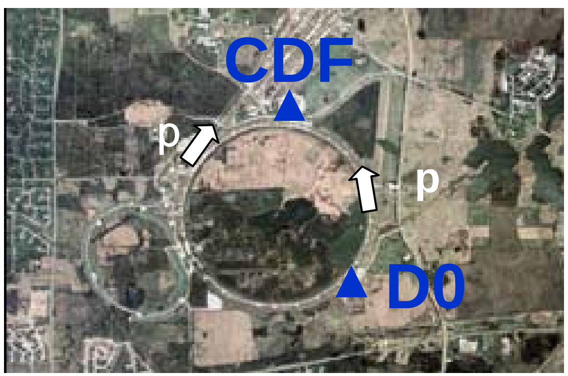
$R = M_C^{-1}$: size of the compact dimension
M_C : corresponding compactification scale
M_0 : mass of the SM gauge boson

hep-ph/9811291

ED Search Facilities

Tevatron, Fermilab, USA

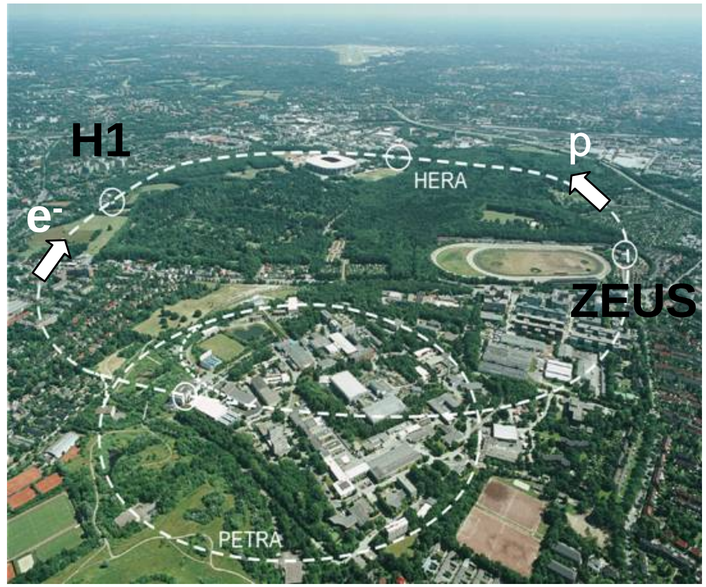


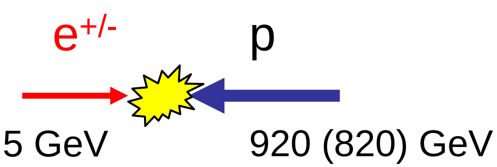


Tevatron: Highest energy collider operating in the world!

Run I $\sqrt{s}$ = 1.8 TeV
Run II $\sqrt{s}$ = 1.96 TeV

HERA, DESY, Hamburg



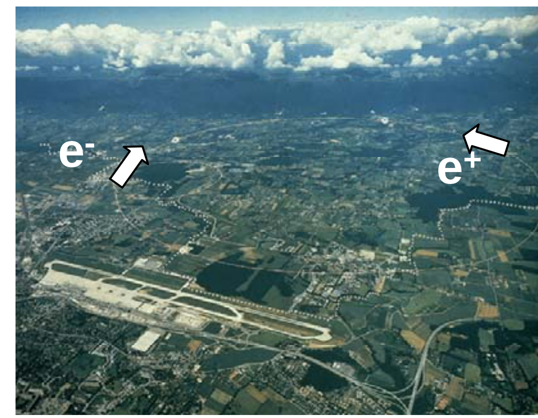


World's only ep collider

Run I $\sqrt{s}$ ~ 300 GeV
Run II $\sqrt{s}$ ~ 320 GeV

LEP, CERN, Geneva

CERN: world's largest particle physics laboratory

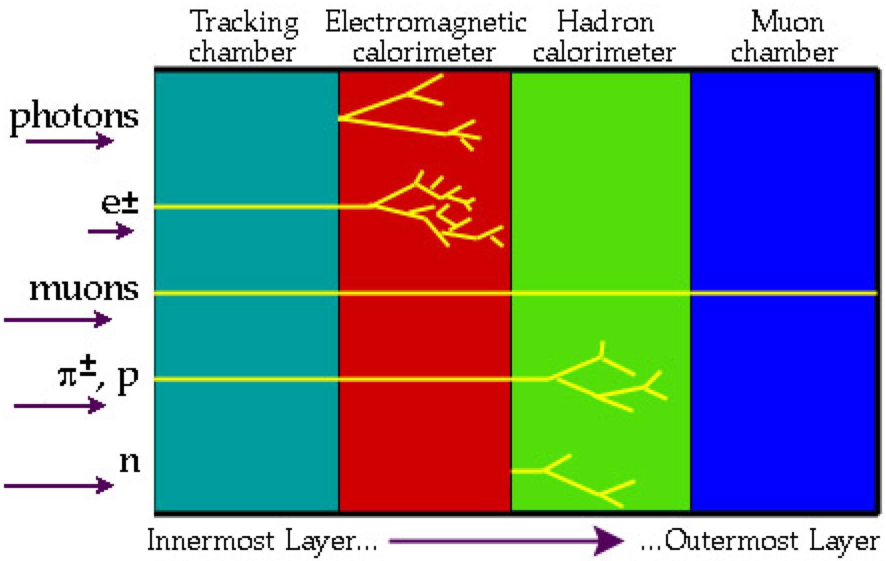


LEP I $\sqrt{s}$ = 91 GeV
LEP II $\sqrt{s}$ = 136-208 GeV

LHC ~2007
$\sqrt{s}$ = 14 TeV

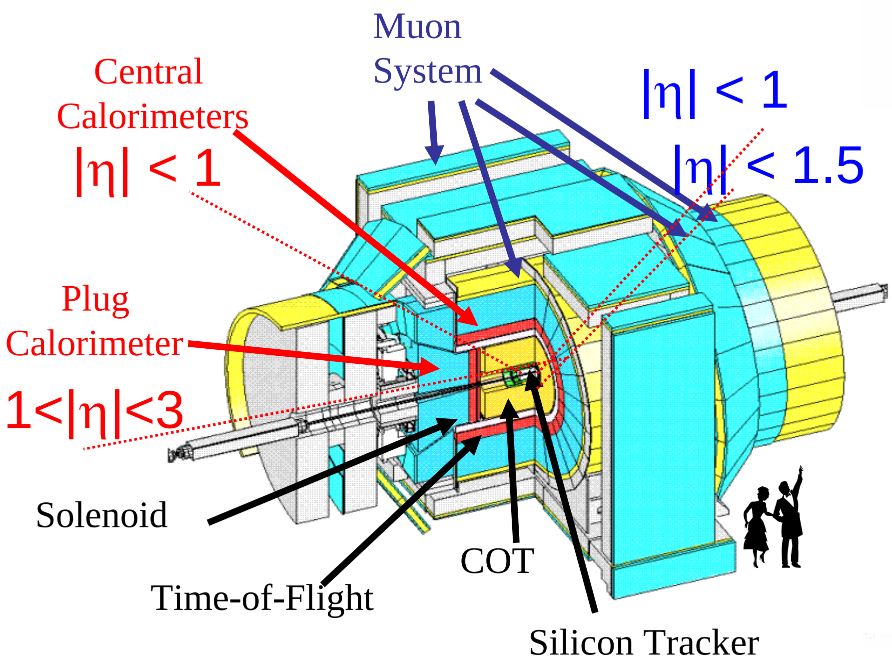
General Particle Detection

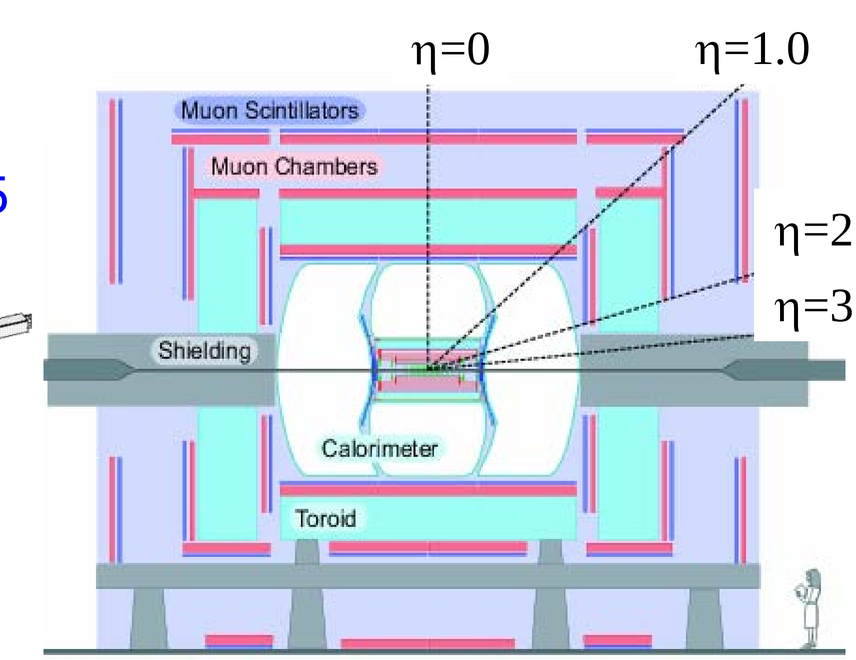
- ➢ Both e and γ: deposit energy in the EM calorimeter ($\rightarrow$EM object)
  - However, γ are uncharged, so leave no track in the tracking chamber
  - Whereas $e^{+/-}$ leave a track
- ➢ Muons: leave a track in the tracking chamber
  - deposit minimum energy in the calorimeters
  - leave tracks in the muon chambers



Tevatron Experiments: CDF & D0

Hermitic calorimeter (central & plug)/muon coverage
Precision tracking and silicon vertex detectors
$\Rightarrow$ Excellent particle ID



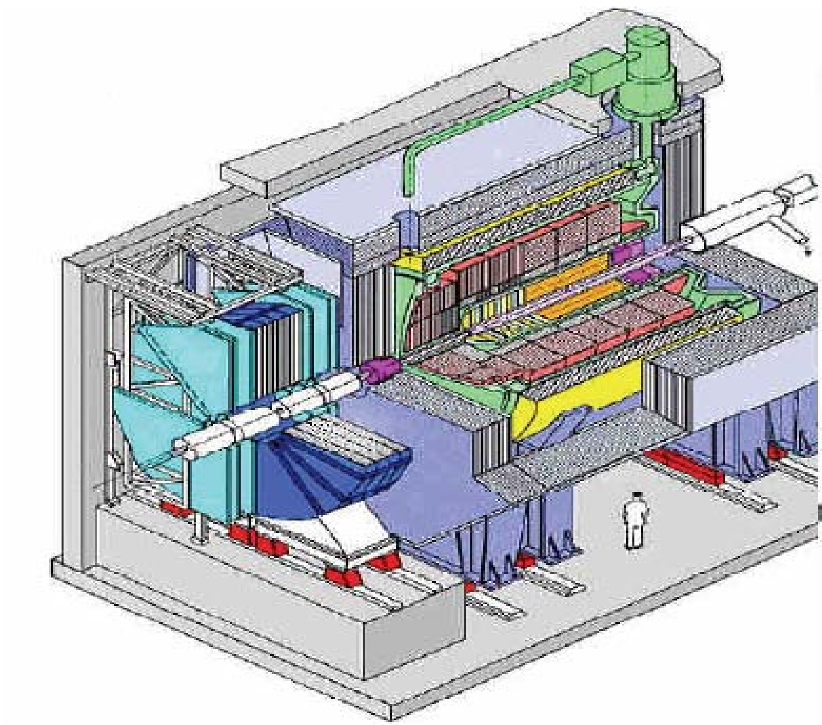


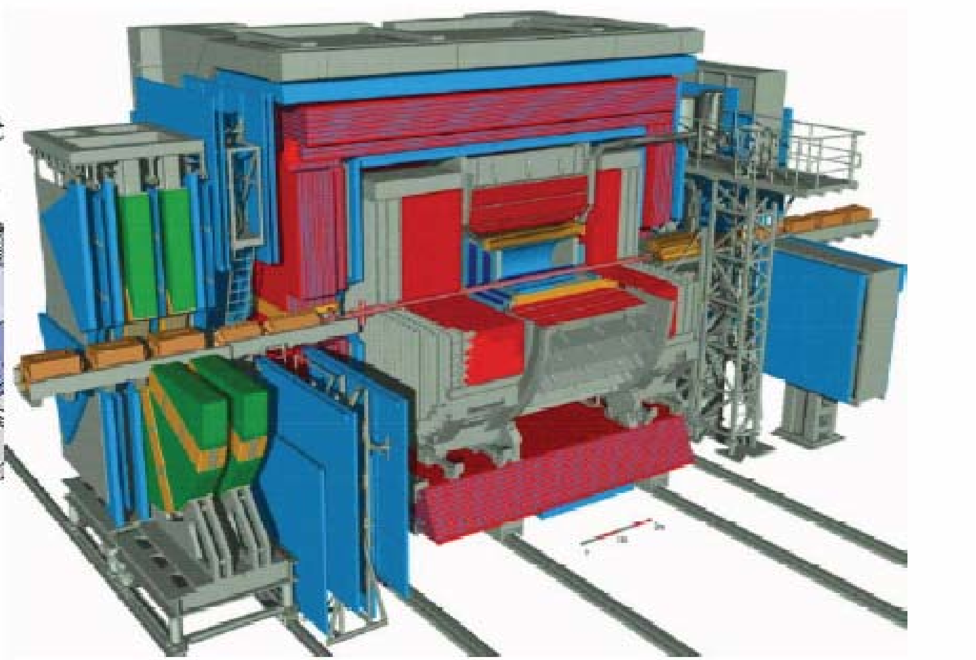
HERA: H1 & ZEUS

H1 is a finely segmented calorimeter

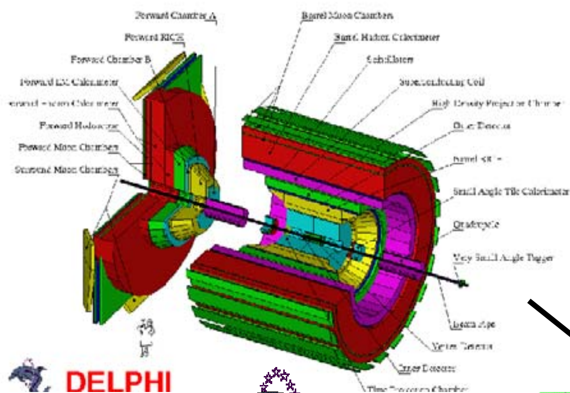
ZEUS has a compensating calorimeter

Both have good hermetic muon coverage

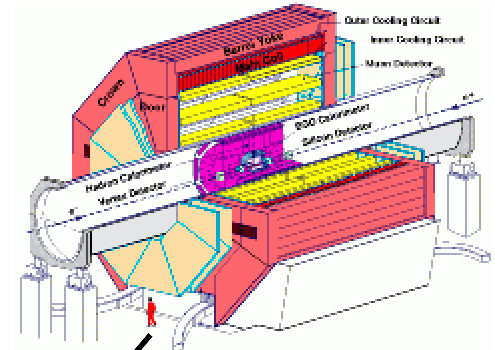




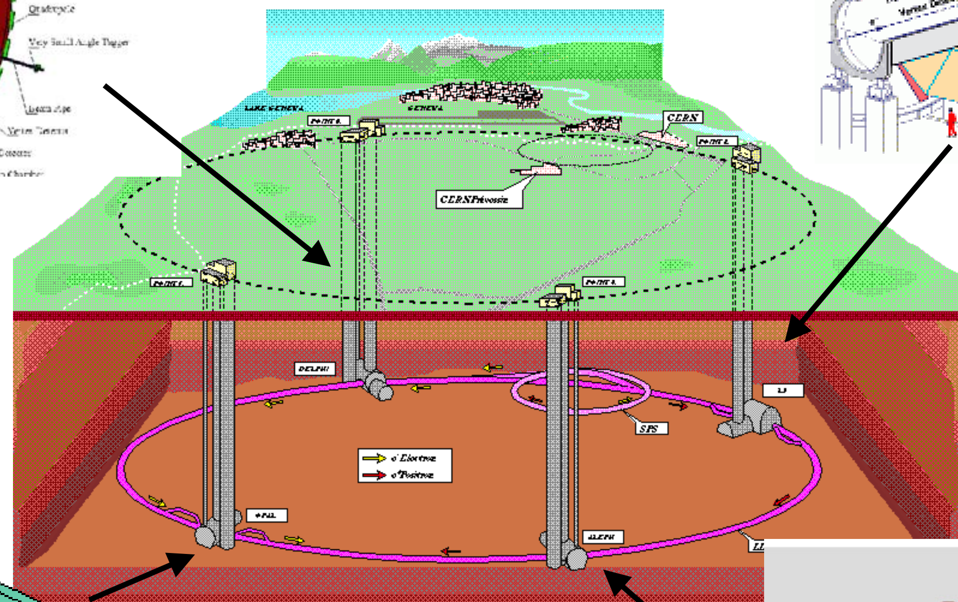
LEP Detectors

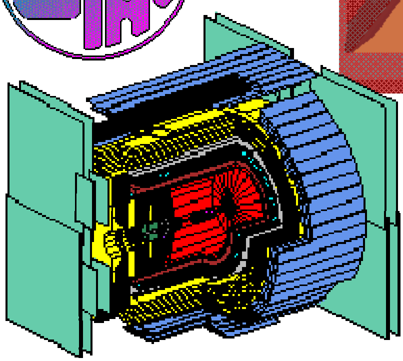


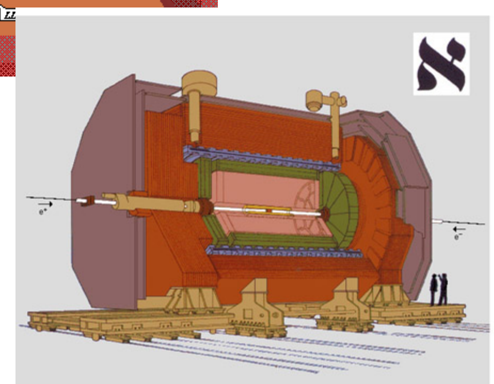
DELPHI



L3





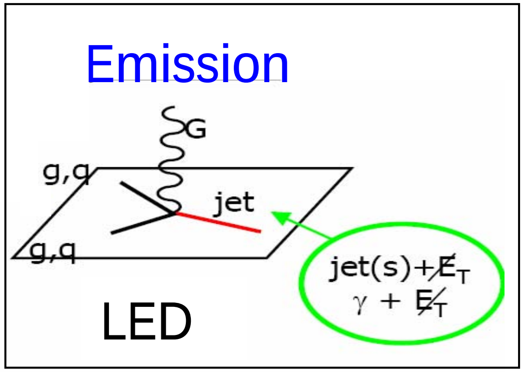


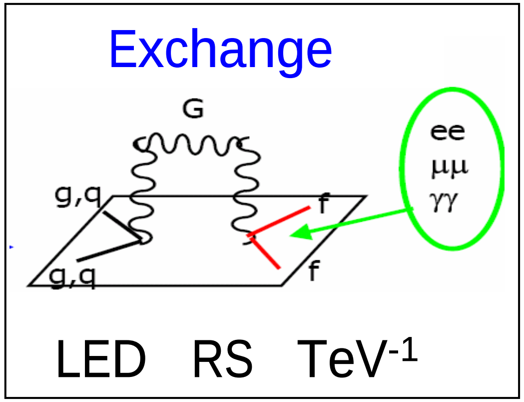
The ALEPH Detector

Tracey Berry

Summary of Searches performed

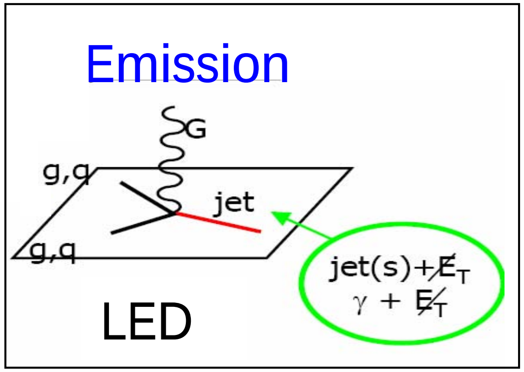
Signature		Experiment	Model
Graviton Emission	γ+ME$_T$	LEP, CDF	LED
	jets+ME$_T$	CDF, D0	
Graviton Exchange	$\mu\mu$	CDF, D0	LED, RS
	ee	CDF, D0	
	ee+$\gamma\gamma$	D0	
	$\gamma\gamma$	CDF	
	e$^{+/-}$X	H1	LED
Boson Exchange	ee		TeV^{-1}

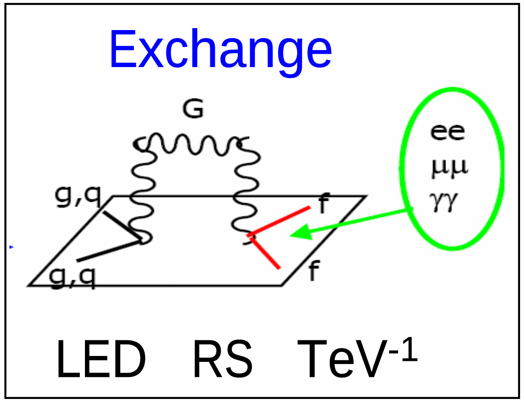




ED Searches

Signature		Experiment	Model
Graviton Emission	γ+ME_T	LEP, CDF	LED
	jets+ME_T	CDF, D0	
Graviton Exchange	$\mu\mu$	CDF, D0	LED, RS
	ee	CDF, D0	
	ee+$\gamma\gamma$	D0	
	$\gamma\gamma$	CDF	
	$e^{+/-}X$	H1	LED
Boson Exchange	ee		TeV^{-1}

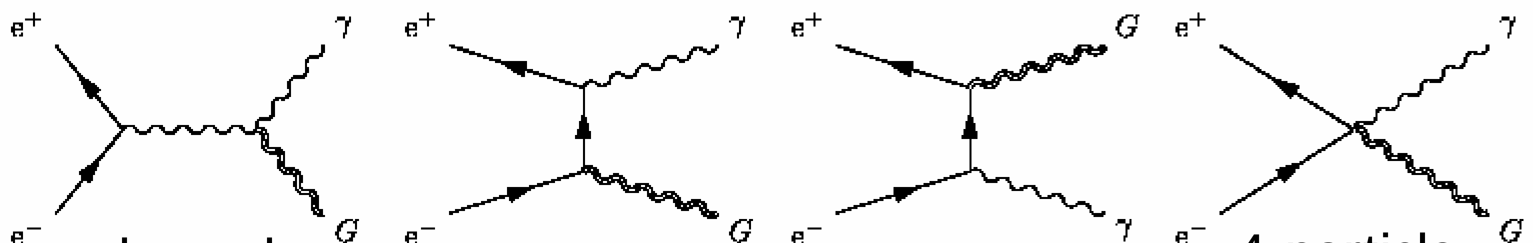




G emission: LEP γ+ME$_T$

LED Search Signature: $e^+e^- \rightarrow \gamma G$

G escapes detection: enhanced rate of γ+ME$_T$ events



s-channel γ exchange

t-channel γ exchange

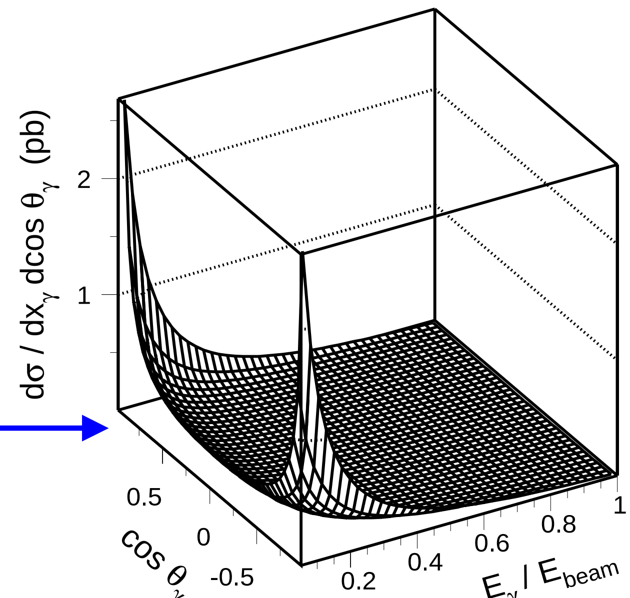
4-particle contact interaction

$$\frac{d^2\sigma}{dx_\gamma d\cos\theta_\gamma} = \frac{\alpha}{32s}\frac{\pi^{n/2}}{\Gamma(n/2)}\left(\frac{\sqrt{s}}{M_D}\right)^{n+2} f(x_\gamma, \cos\theta_\gamma)$$

x_γ: ratio of γ energy to beam energy

θ_γ: polar angle of γ relative to beam line

- $d\sigma$ depends on M_D and n
- $d\sigma$ increases rapidly at low γ energies ($E\gamma$) and angles



G emission: LEP $\gamma + ME_T$

LEP: ALEPH, DELPHI, L3

$\sqrt{s}$= 189-208 GeV 1998-2000

~0.6 fb^{-1}/experiment: 1.9 fb^{-1} Total

Search Selection

1 cluster in the EM calorimeter with

No matching charged track

$P_t^{\gamma} > 0.02\sqrt{s} - 0.04\sqrt{s}$

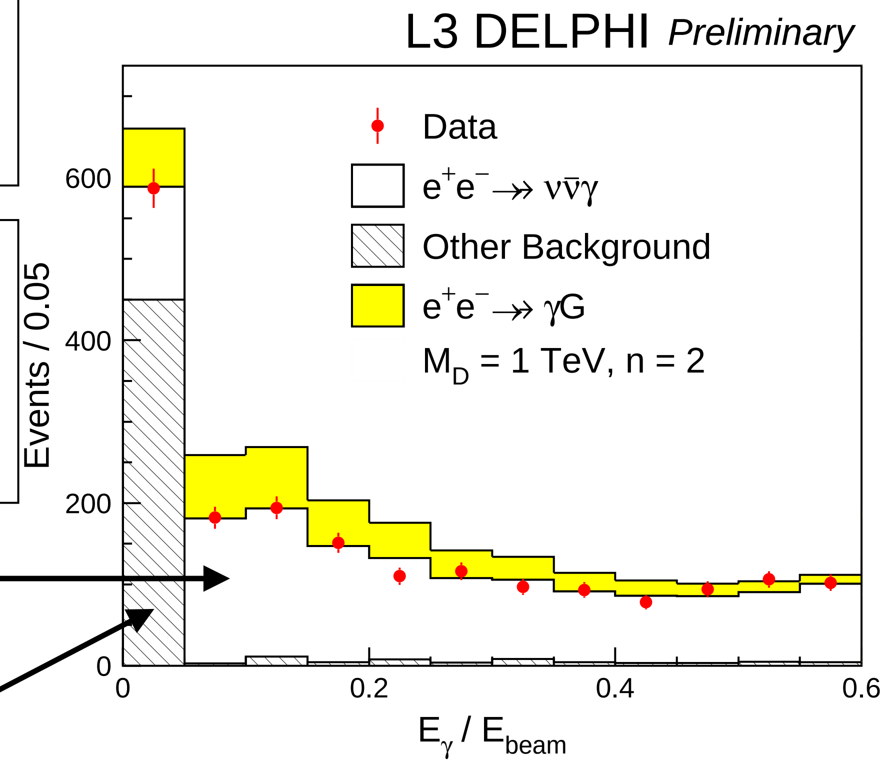
No other significant detector activity

Principal Background

$e^+e^- \to \nu\nu\gamma$

Other Background

$e^+e^- \to e^+e^-\gamma(\gamma)$



In low P_t^{γ} region: SM bkgd enhanced due to $e^+e^- \to e^+e^-\gamma(\gamma)$,where both e have low θ and cannot be detected

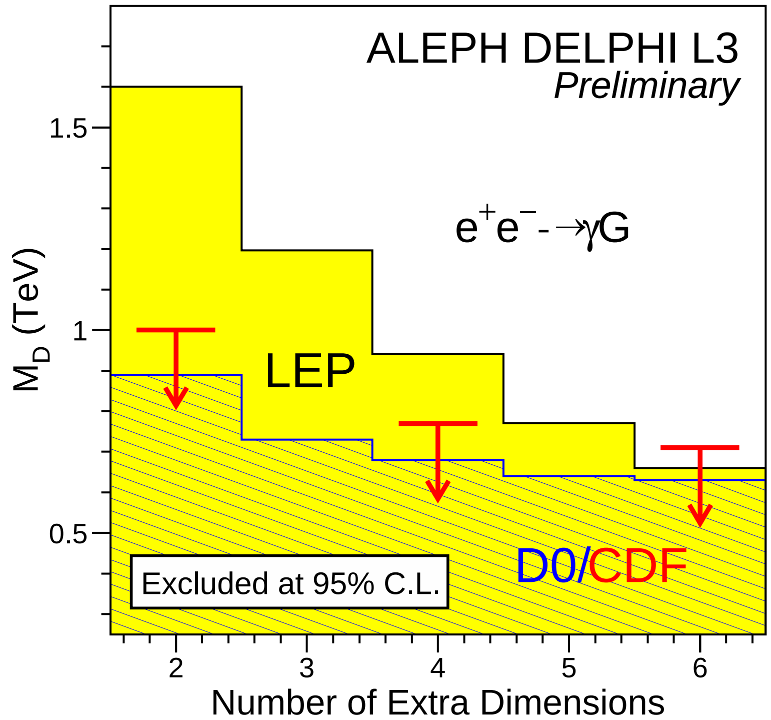
Good agreement with SM observed by all experiments

G emission: LEP γ+ME_T

Lower limits on the gravity scale (M_D) derived individually by each experiment as functions of number of ED (n)

Results are combined

$\sigma \propto (1/M_D)^{n+2}$



n	M_D (TeV)	R (mm)
2	> 1.60	< 0.19
3	> 1.20	$< 2.6 \times 10^{-6}$
4	> 0.94	$< 1.1 \times 10^{-8}$
5	> 0.77	$< 4.1 \times 10^{-10}$
6	> 0.66	$< 4.6 \times 10^{-11}$

LEP: best limits on direct G emission from collider experiments for n<6

For n>6 .....

G Emission: CDF: γ+ME$_T$

CDF also search for G emission: γ+ME$_T$

Search Selection 87 pb^{-1} Run I

- One γ with E_T > 55 GeV and $|\eta|$<1
- ME$_T$ > 45 GeV
- No jets with E_T > 15 GeV
- No tracks with p_T > 5 GeV

Main backgrounds

Cosmic ray muons	6.3 ± 2.0
$Z^0\gamma \rightarrow \nu\bar{\nu}+\gamma$	3.2 ± 1.0
W $\rightarrow e\nu$ (“γ“ν)	0.9 ± 0.1
Prompt diphotons	0.4 ± 0.1
Wγ ($\nu\gamma$)	0.3 ± 0.1

Cosmic Rays main background

Results

Expected background: 11.0 ± 2.3

Observed: 11

Data in good agreement with SM

$q\bar{q} \rightarrow \gamma G_{KK}$

Limits

n=4 M_D > 0.55 TeV

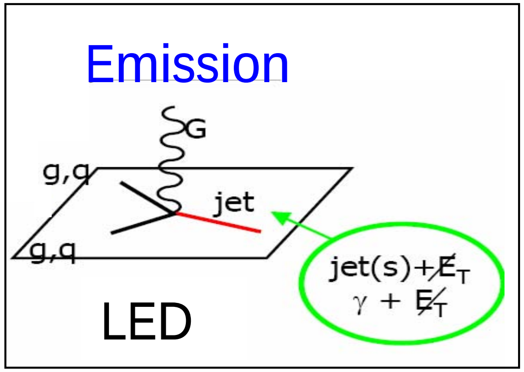
n=6 M_D > 0.58 TeV

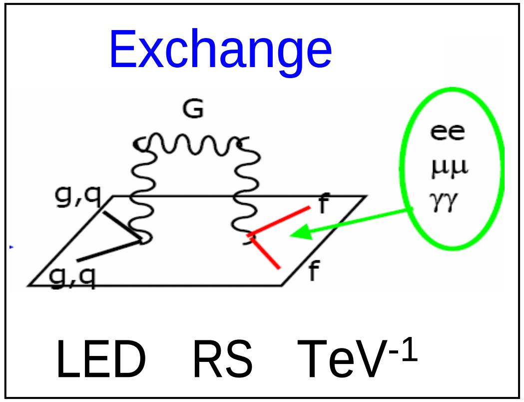
n=8 M_D > 0.60 TeV

Limits not as restrictive as LEP

ED Searches

Signature		Experiment	Model
Graviton Emission	γ+ME_T	LEP, CDF	LED
	jets+ME_T	CDF, D0	
Graviton Exchange	ee+$\gamma\gamma$	D0	LED, RS
	ee	CDF, D0	
	$\mu\mu$	CDF, D0	
	$\gamma\gamma$	CDF	
	$e^{+/-}X$	H1	LED
Boson Exchange	ee		TeV^{-1}



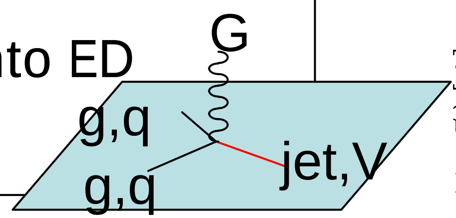


Real G Emission: jet(s)+ME_T

Better limits on G emission at the Tevatron from the jets + ME_T searches

Search Signature: $pp \rightarrow$ jet(s) + G

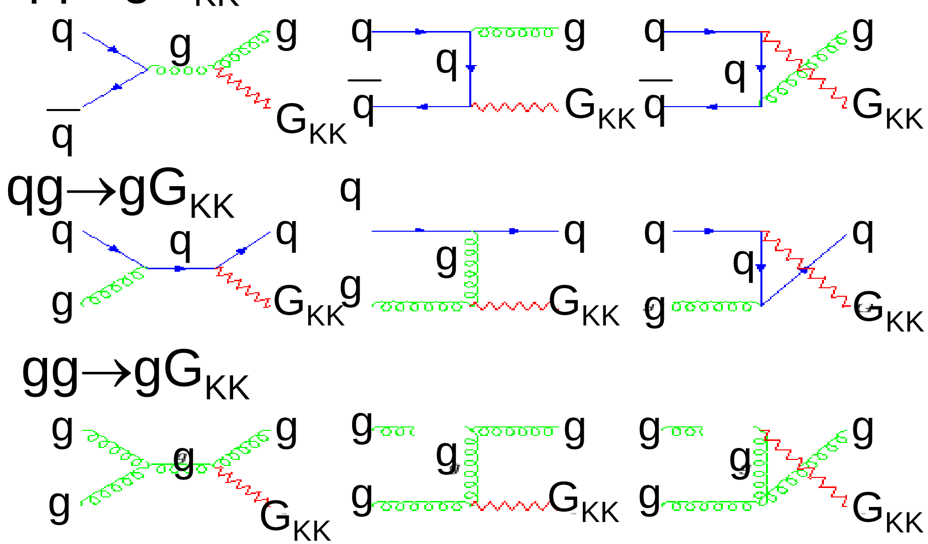
G escapes to detection into ED
$\rightarrow$Events with large ME_T
Recoil jet very energetic



$q\bar{q} \rightarrow gG_{KK}$ dominate sub-process for n>2

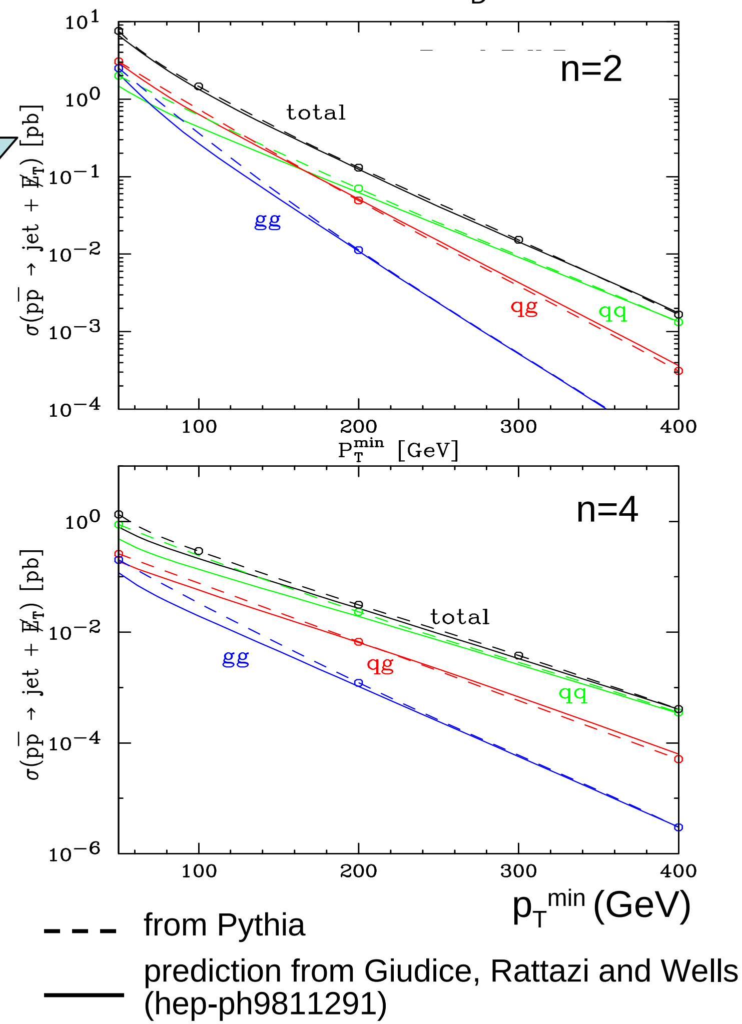
$qg \rightarrow gG_{KK}$

$gg \rightarrow gG_{KK}$



σ falls as $1/M_D^{n+2}$ for all sub-processes

Tevatron √s=2 TeV M_D = 1.2 TeV



Real G Emission: CDF: jet(s)+ME_T

Search Selection 84 pb^{-1} Run Ib

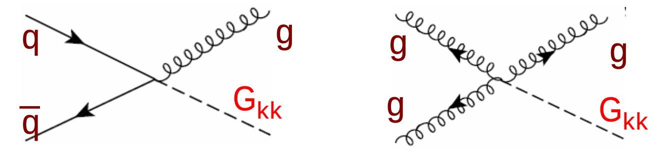
jet $E_T^{1st} \geq 80$ GeV, $|\eta| < 1.1$ and $ME_T > 80$ GeV
a second jet is allowed if $E_T^{2nd} > 30$ GeV
no isolated tracks in event ($p_T \geq 10$ GeV)

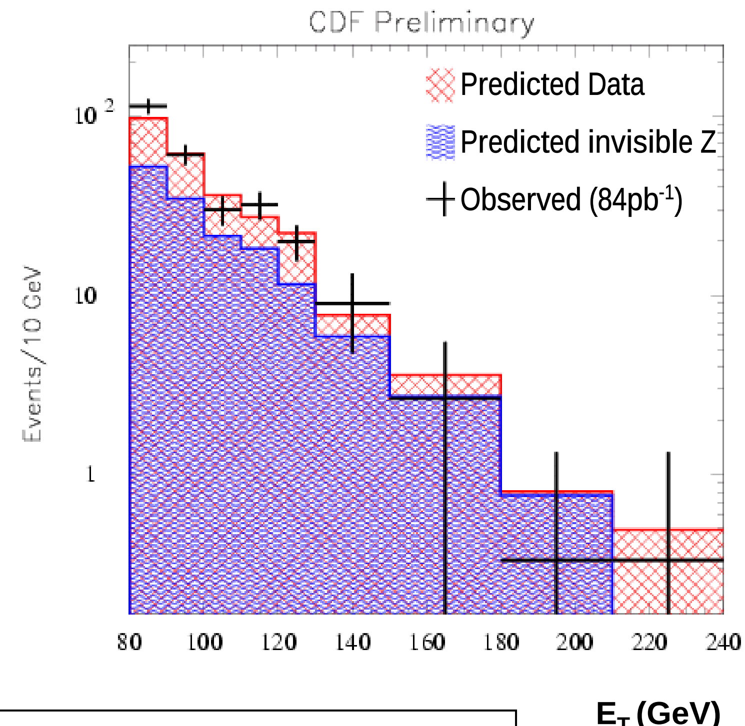
Main background

Irreducible: $Z(\rightarrow \nu\nu)$+jets,
$W(\rightarrow \tau\nu)$+jets

Results

Expected: 274 ± 16
Observed: 284 events
Relative uncertainty on the signal acceptance 25 %





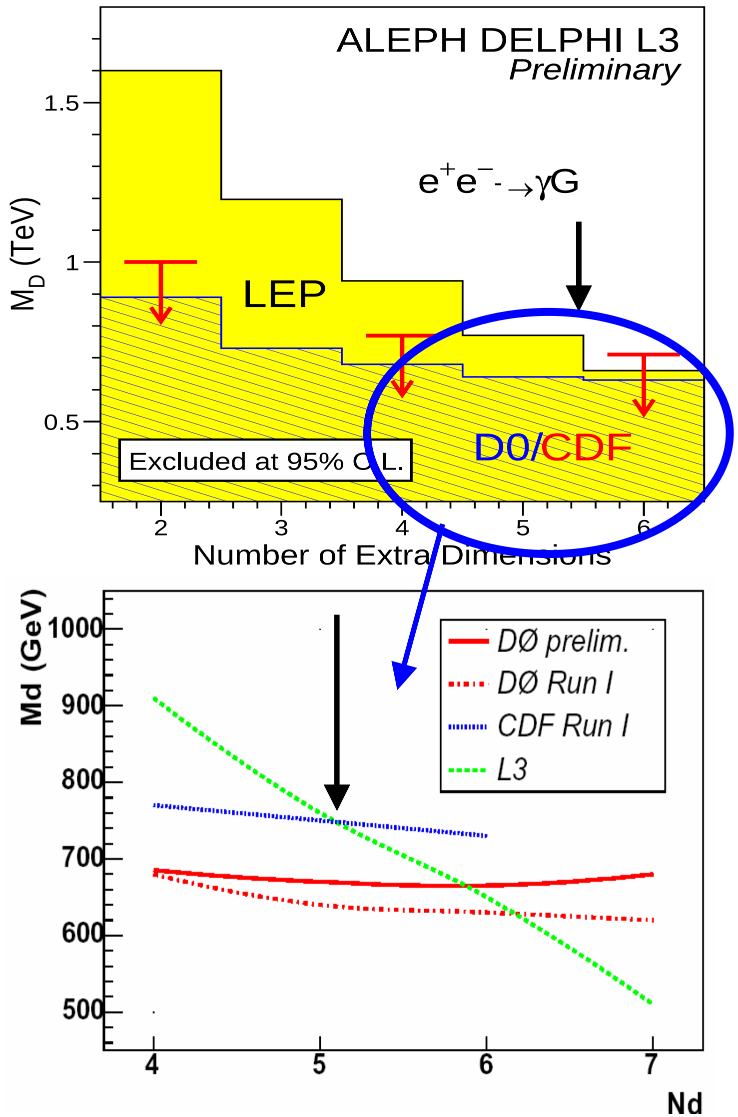
D0 have/also search for G emission (Run I & II): Monojet +ME_T presently their limits are not as restrictive as CDFs

G Emission Summary

LEP and Tevatron results are complementary

For n<6:
LEP limits best
γ+ME$_T$

LEP use γ+ME$_T$, which is cleaner & has lower backgrounds than jet+ME$_T$ (Tevatron), so the precision of their experiments wins out for lower values of n



For n>6:
Tevatron limits best
jet+ME$_T$

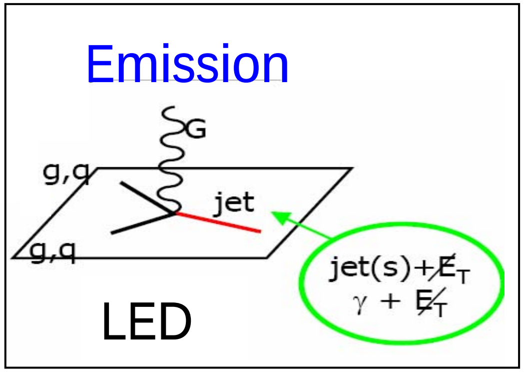
Tevatron better at large values of n,
because of the higher energy, which is a bigger effect at larger values of n.

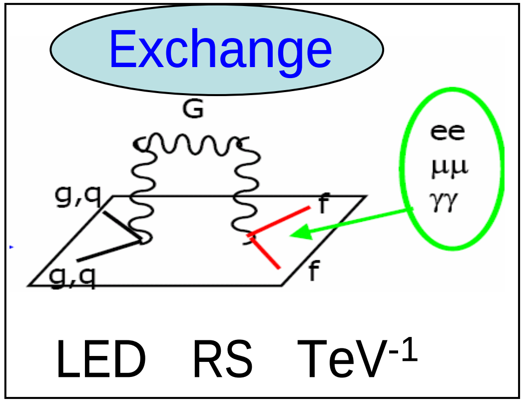
σ α total number of possible modes in the KK tower N_{KK}
σ α N_{KK} α √(s-hat)
But this is true for each ED,
so σ α $(\sqrt{(s\text{-hat})})^n$

⇒the difference in energy is a bigger effect for n=6 than n=2

ED Searches

Signature		Experiment	Model
Graviton Emission	γ+ME_T	LEP, CDF	LED
	jets+ME_T	CDF, D0	
Graviton Exchange	ee+$\gamma\gamma$	D0	LED, RS
	ee	CDF, D0	
	$\mu\mu$	CDF, D0	
	$\gamma\gamma$	CDF	
	$e^{+/-}$X	H1	LED
Boson Exchange	ee		TeV^{-1}





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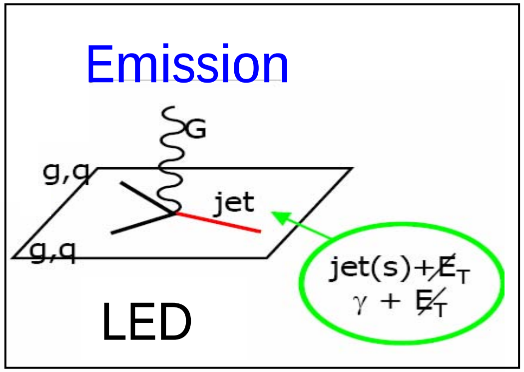
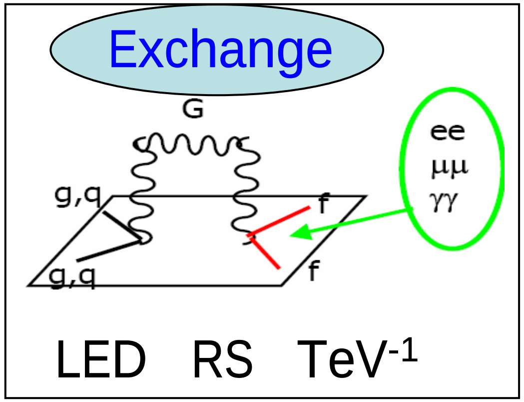
	jets+ME_T	CDF, D0	
Graviton Exchange	ee+$\gamma\gamma$	D0	LED, RS
	ee	CDF, D0	
	$\mu\mu$	CDF, D0	
	$\gamma\gamma$	CDF	
	$e^{+/-}$X	H1	LED
Boson Exchange	ee		TeV^{-1}





- ➢Many different channels in which G exchange could be detected
- ➢G exchange sensitive to several ED models
  - similarities/distinct features of their search strategies….

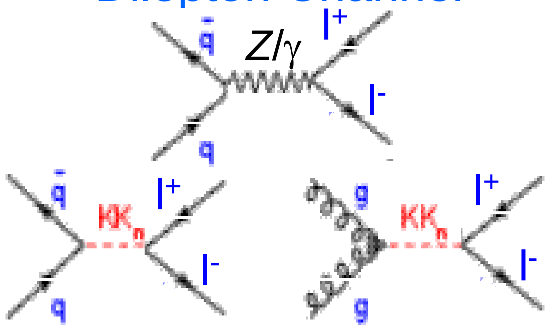
Search for G Exchange?

Similarities

Search Signature

Deviations in (ee, $\mu\mu$, $\gamma\gamma$) cross sections (σ) and angular distributions from SM processes caused by G exchange

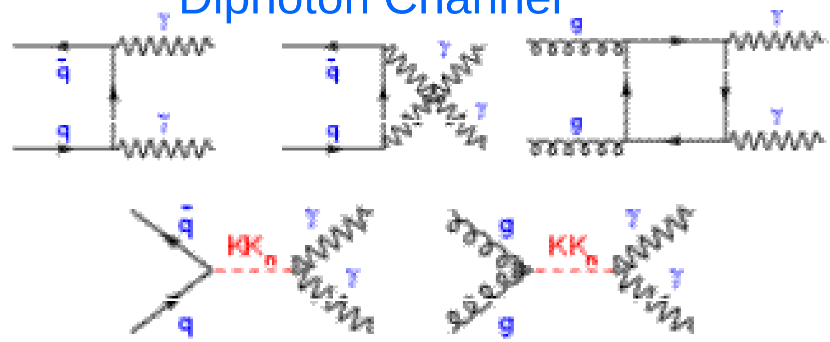
Dilepton Channel



Standard Model

Extra Dimensions

Diphoton Channel



✓Clean experimental signature (ee,$\mu\mu$) even in a hadron collider

✓Low backgrounds & Z^0 peak used as a calibration point (ee,$\mu\mu$)

Distinguish New Physics Models

Resonance in RS model and broad change in σ in ADD model

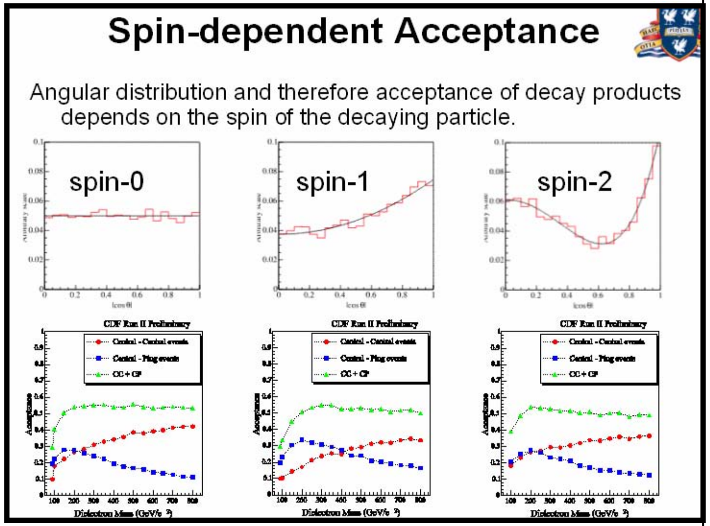
Spin 2 graviton – used to distinguish between other new physics

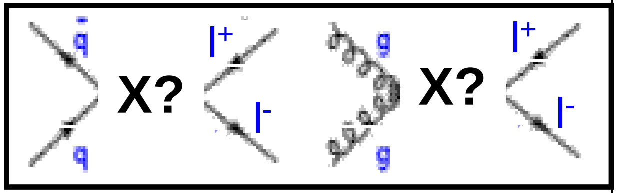
Tevatron Exchange Search Strategies

CDF Search Strategy: ee, $\mu\mu$, $\gamma\gamma$

- Perform signature based searches
  - Compare data to expectation
  - 1D fits in invariant mass performed
  - (and angular distribution studied)
- Determine spin dependent acceptance
  - and then σ.BR
- Interpret data & set limits
  - on many new models!

E.g. (ee & $\mu\mu$): Spin-0 : RPV sneutrinos
Spin-1 : Z', Technicolor ρ, ω
Spin-2 : RS G, LED, etc..



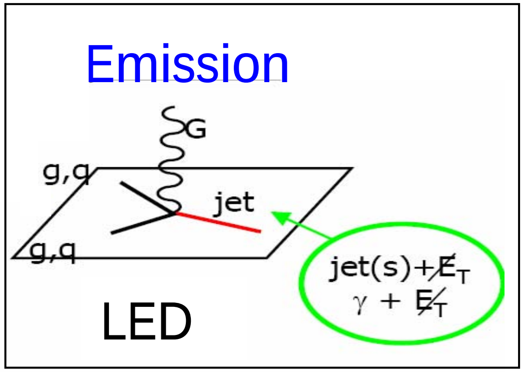


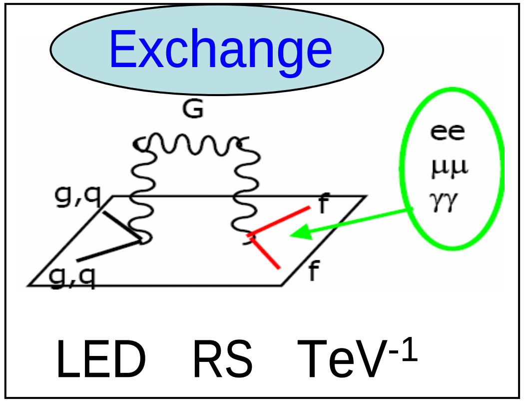
D0 Search Strategy: ee, $\mu\mu$, $\gamma\gamma$

- Perform more ED specific searches
- Optimise for specific search:
  - ADD case: combine ee+$\gamma\gamma$ to gain in efficiency
- 3D fits in angular distribution and invariant mass performed

ED Searches

Signature		Experiment	Model
Graviton Emission	γ+ME_T	LEP, CDF	LED
	jets+ME_T	CDF, D0	
Graviton Exchange	ee+$\gamma\gamma$	D0	LED, RS
	ee	CDF, D0	
	$\mu\mu$	CDF, D0	
	$\gamma\gamma$	CDF	
	$e^{+/-}X$	H1	LED
Boson Exchange	ee		TeV^{-1}



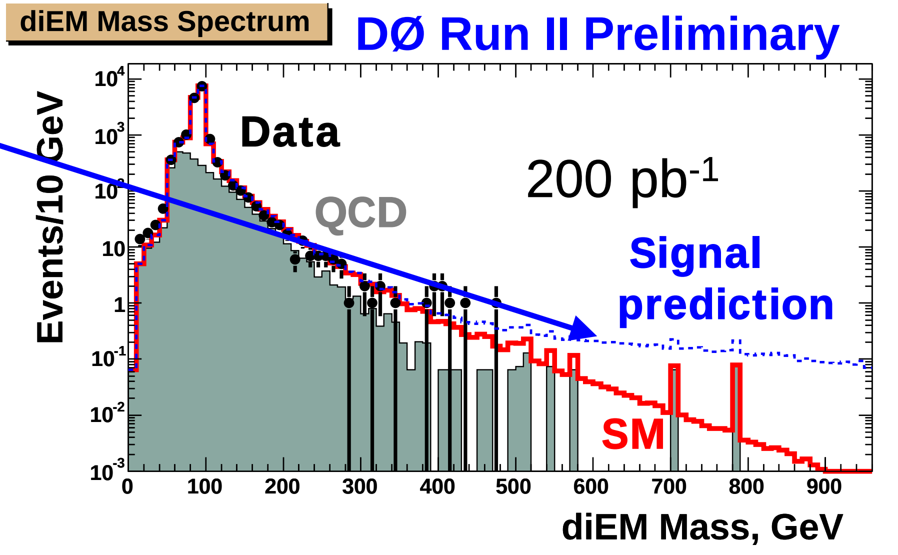


G Exchange: D0 ee+$\gamma\gamma$ ADD LED

ADD: *many Large ED in which gravitons can propagate*

Search for spin-2 broad σ change

⇒ study invariant mass
& angular distribution



Since D0 doing a ADD specific search, not searching for any new physics...

& G couples to both $\gamma\gamma$ and ee

D0 combine ee+$\gamma\gamma$ ⇒ diEM search

This maximises reconstruction efficiency....

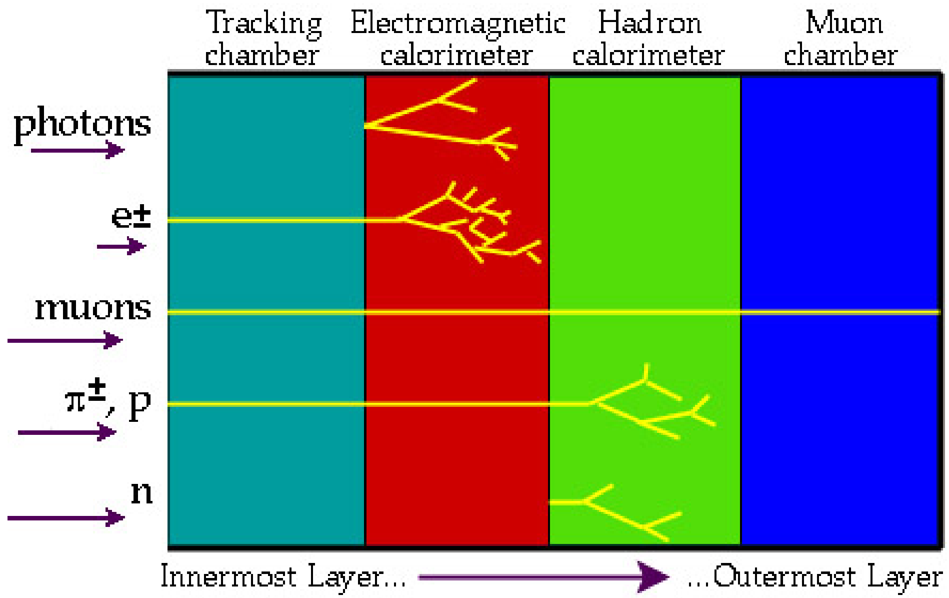
e/γ Id/Misid-entification in Detectors

Similarities

- Both e and γ deposit energy in the EM calorimeter (→EM object)

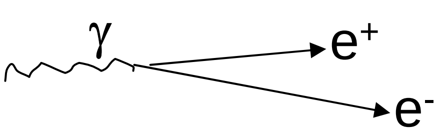
Differences

- However, γ are uncharged, so leave no track in the tracking chamber
- Whereas $e^{+/-}$ leave a track



Inefficiencies arise if:

- γ ID requires no track, but γ converts (→ee)
- e ID requires a track, but loose track due to imperfect track reconstruction/crack



To maximise reconstruction efficiency: D0 combine ee+γγ ⇒ diEM search

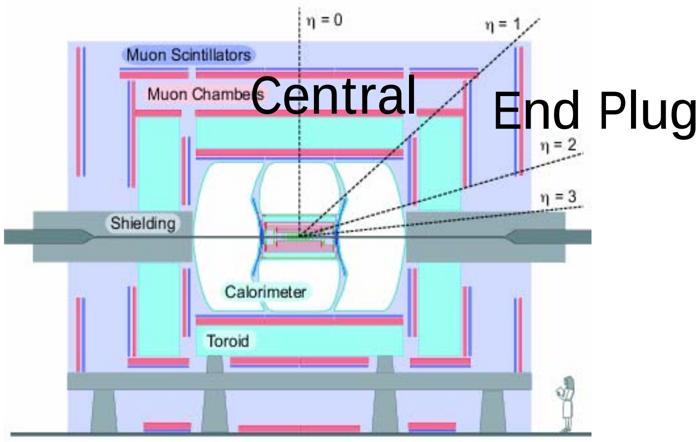
G Exchange: D0 ee+γγ ADD LED

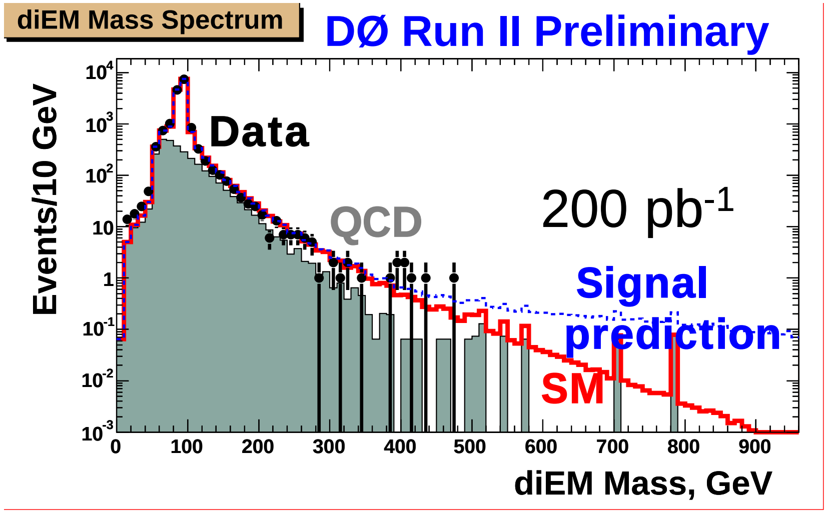
Search selection 200 pb^{-1}

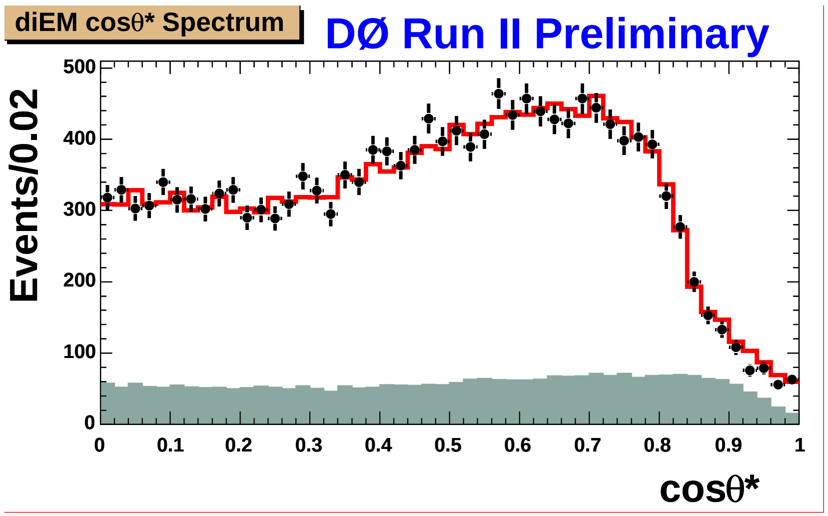
2 two isolated EM objects, E_T>25GeV

2 central (CC)

or 1 plug and 1 central (EC)







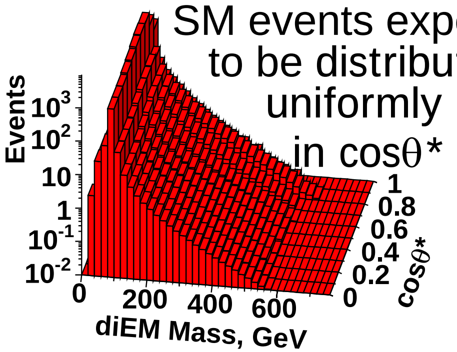
MC studies show adding EE degrades the sensitivity slightly, due to the large background in this channel

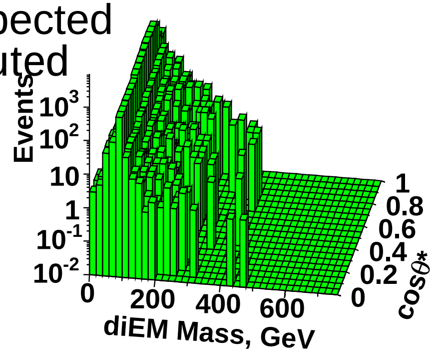
D0 ee+$\gamma\gamma$ ADD LED

D0 perform a combined fit of the invariant mass and angular information

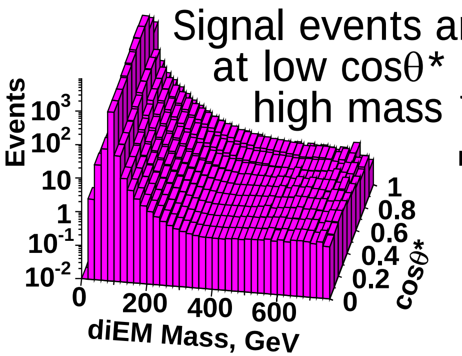
Fit combined $M_{ee,\gamma\gamma}$ and $\cos\theta^*$ spectrum to extract limits

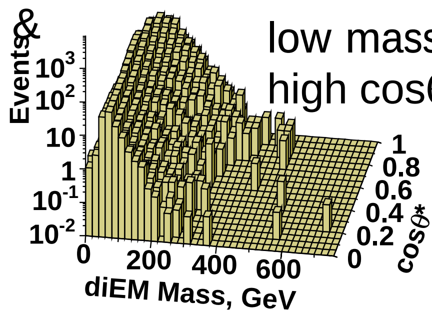
SM Prediction **DØ Run II Preliminary** **Data**





ED Signal **QCD Background**





- Parameterise σ in terms of

$$\eta = \lambda / M_s^4$$

$$\sigma = \underbrace{\sigma_{SM}}_{\text{SM}} + \underbrace{\eta\sigma_{INT}}_{\text{Interference}} + \underbrace{\eta^2 \sigma_{KK}}_{\text{ED term}} + \underbrace{\sigma_{BG}}_{\text{Background}}$$

- 3D templates used to set limits
- Bayesian likelihood fitting used to set 95%CL on η_G
- η_G translated into a 95% CL mass limit on fundamental Planck Scale (M_s)

D0's highest mass events

Hints of New Physics?

8 events with M>350 GeV

- 6 form a bump around 400 GeV

  Z'→ee resonance?

  •No: have 1 or 0 tracks AND

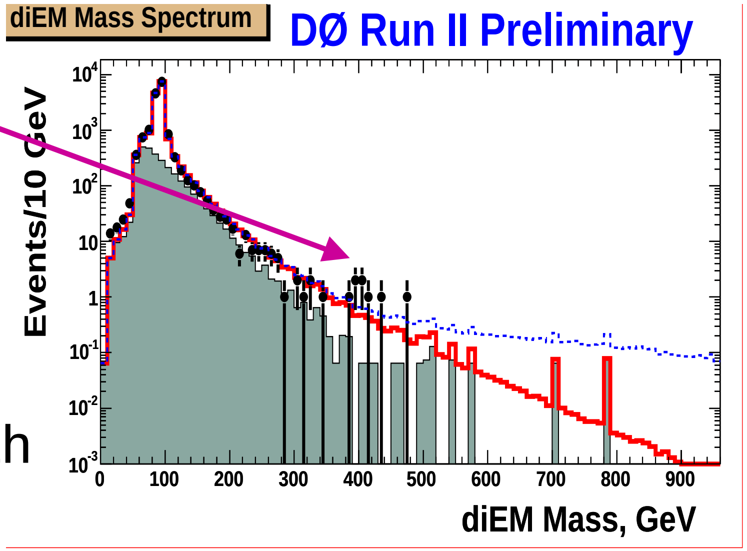
  •Bump twice as narrow as expected from a narrow resonance smeared with typical D0 EM calorimeter resolution

- 2 highest mass events:

  have very low cosθ* (0.01, 0.03)

  One is a e^+e^- pair and the other $\gamma\gamma$

  ⇨ excellent candidates for new physics beyond the SM!



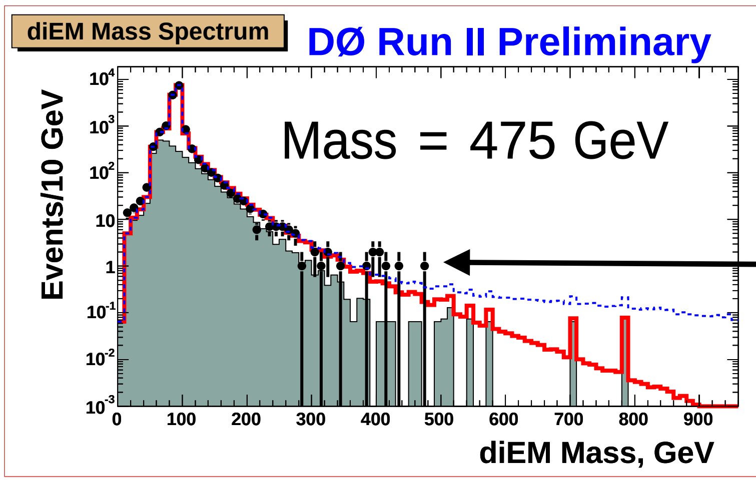
i.e. possess kinematics typical of signal from large ED. (Very high scattering angle: close to π/2.)

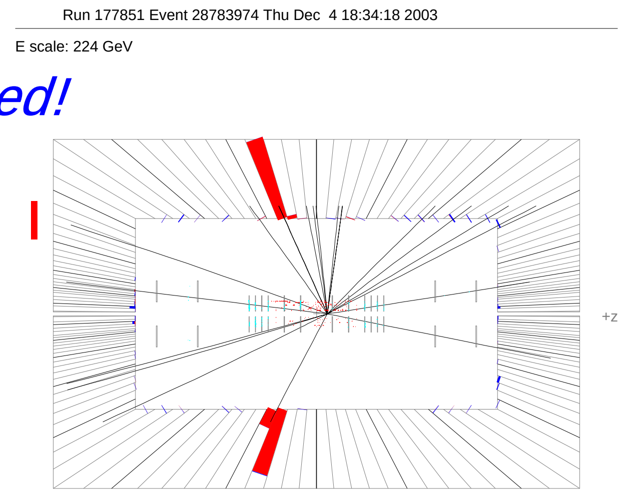
Intriguing events – but consistent with the SM

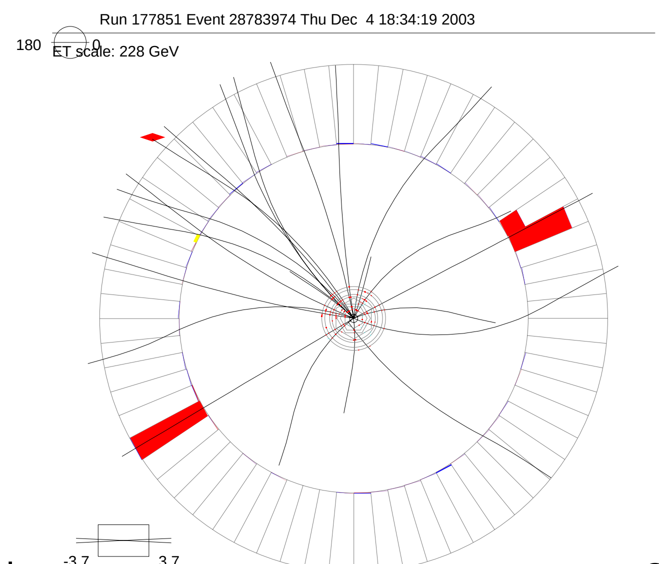
D0's highest mass event

D0's highest-mass DY candidate ever observed!

"Event Callas"







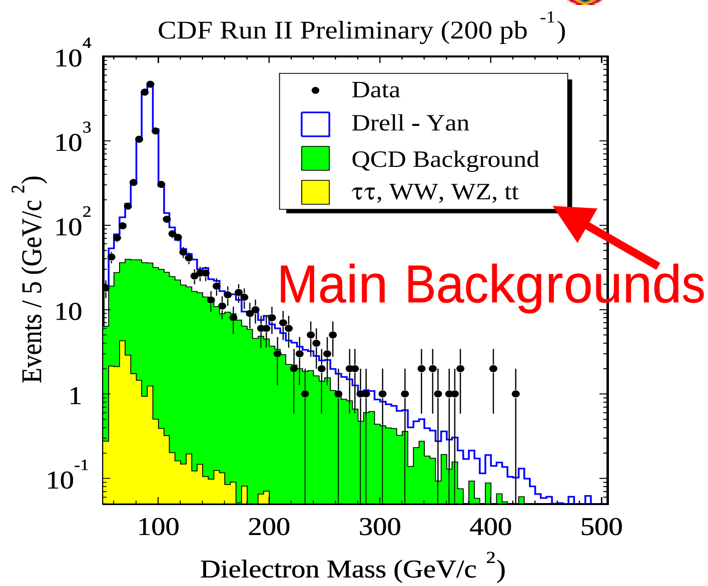
Looking forward to results with more data from Run II (higher statistics)!

G Exchange: CDF ee ADD LED

CDF perform a similar search

Differences: ee channel only

fit invariant mass only



Search selection 200 pb^{-1}

2 two isolated e, E_T > 25 GeV

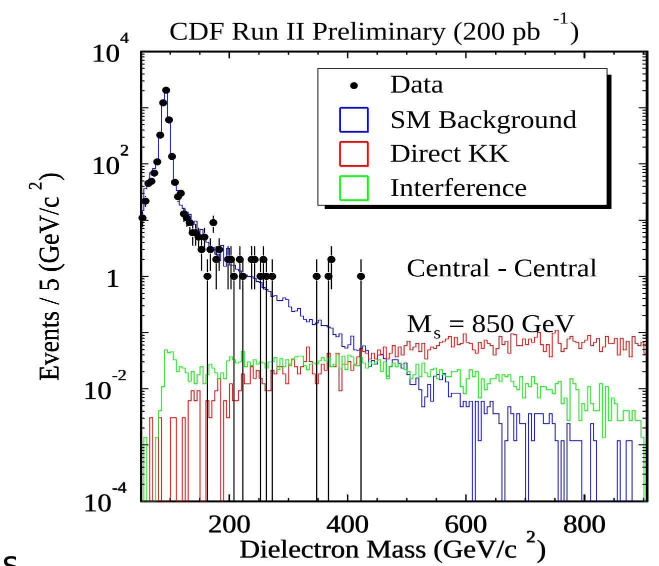
2 central e (CC)

or 1 central and 1 forward e (CP)

N_{exp}=11.1 N_{obs}=14 for M_{ee}>300 GeV/c²

N_{exp}= 4.6 N_{obs}= 9 for M_{ee}>350 GeV/c²

$$\sigma = \sigma_{SM} + \eta\, \sigma_{INT} + \eta^2\, \sigma_{KK}$$



D0 μμ ADD LED

D0 μμ search performed in a similar way to the D0 ee+γγ search

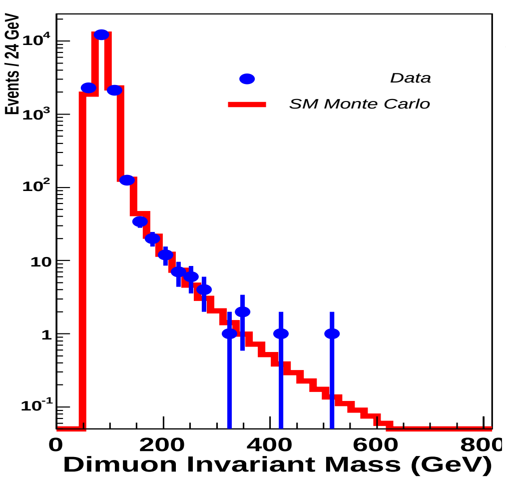
Search Selection 250 pb^{-1}

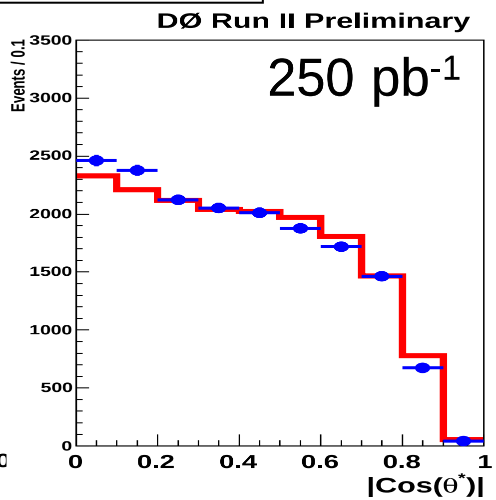
$p_T^{\mu1,\mu2}$>15 GeV

Isolated tracks

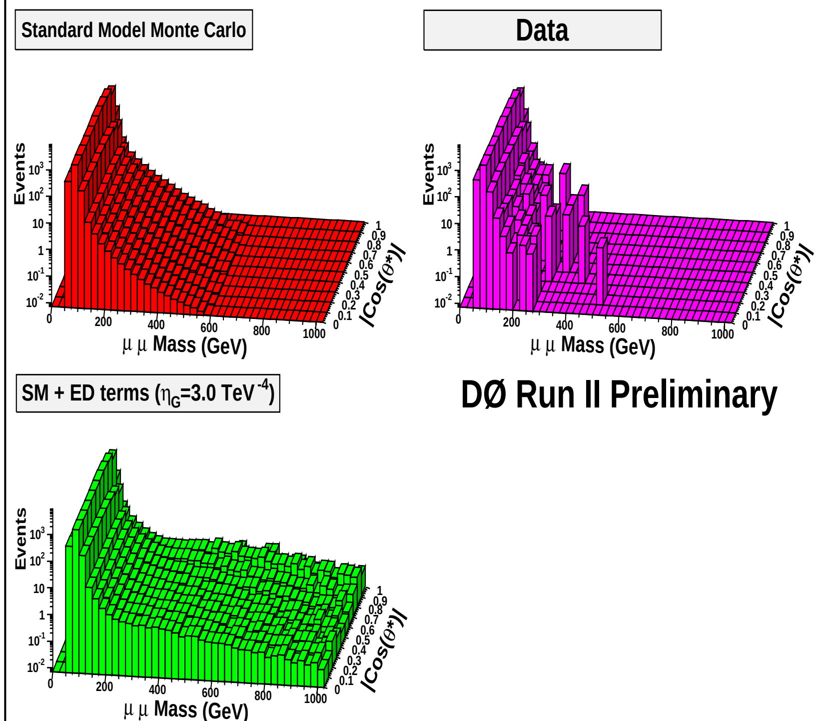
$M_{\mu\mu}$>50 GeV

Cosmics removed





3D fits to extract limits



N_{exp}=6.4 N_{obs}=5 for M_{ee}>300 GeV/c^2

N_{exp}=1.3 N_{obs}=1 for M_{ee}>450 GeV/c^2

No deviation in data from SM

Tevatron ADD LED limits

Both D0 and CDF have observed no significant excess

95% CL lower limits on fundamental Planck scale (M_s) in TeV, using different formalisms:

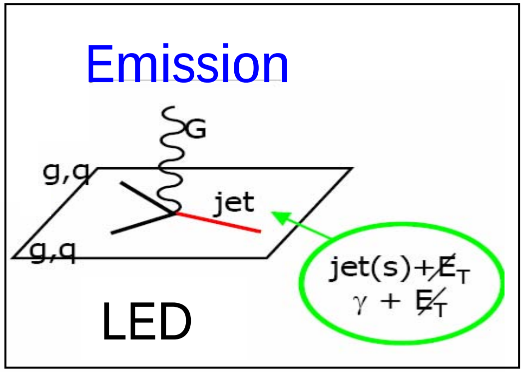
	GRW	HLZ for n=						Hewett
		2	3	4	5	6	7	λ=+1/-1
D0 Run II: $\mu\mu$	1.09	1.00	1.29	1.09	0.98	0.91	0.86	0.97/0.95
D0 Run II: ee+$\gamma\gamma$	1.36	1.56	1.61	1.36	1.23	1.14	1.08	1.22/1.10
D0 Run I+II: ee+$\gamma\gamma$	1.43	1.61	1.70	1.43	1.29	1.20	1.14	1.28/NA
CDF Run II: ee	1.11		1.32	1.11	1.00	0.93	0.88	0.96/0.99

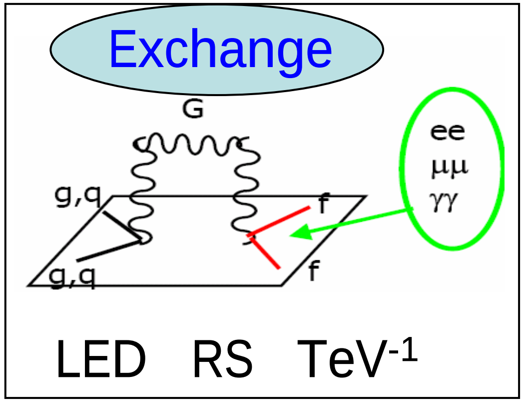
D0 Run II $\mu\mu$ result: tightest limits on LED from a single measurement in this channel!

D0 combined ee+$\gamma\gamma$ Run I & Run II result is the most stringent limit on LED to date!

ED Searches

Signature		Experiment	Model
Graviton Emission	γ+ME_T	LEP, CDF	LED
	jets+ME_T	CDF, D0	
Graviton Exchange	ee+$\gamma\gamma$	D0	LED, RS
	ee	CDF, D0	
	$\mu\mu$	CDF, D0	
	$\gamma\gamma$	CDF	
	$e^{+/-}$X	H1	LED
Boson Exchange	ee		TeV^{-1}





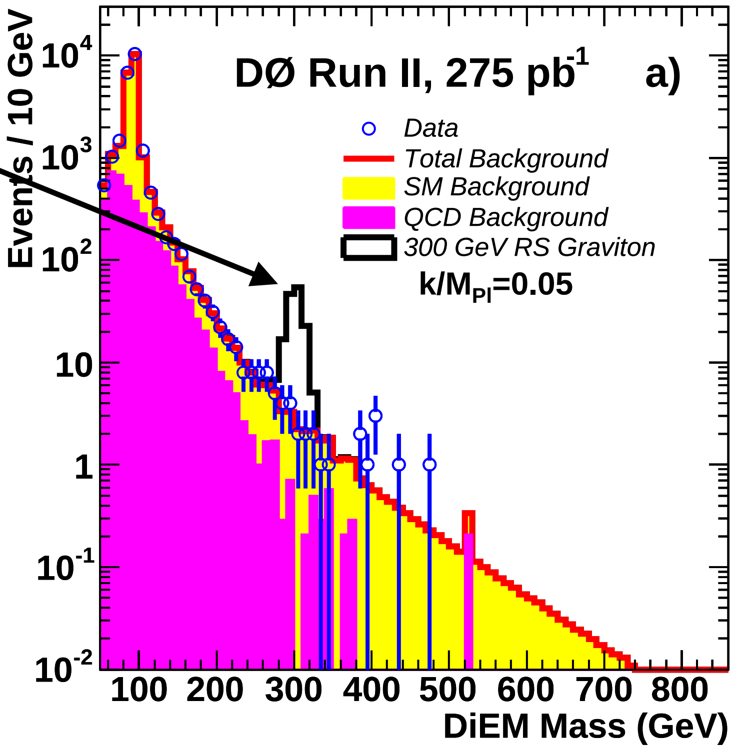
G Exchange: D0 RS ee+$\gamma\gamma$

***RS:** 1 extra compactified/warped ED in which G can propagate*

Search for spin-2 **resonance**
in invariant mass spectrum

Search Selection 275pb^{-1}
2 isolated EM objects with E_T>25 GeV
2 central e (CC)
or 1 forward and 1 central e (EC)

N_{obs}=22 786



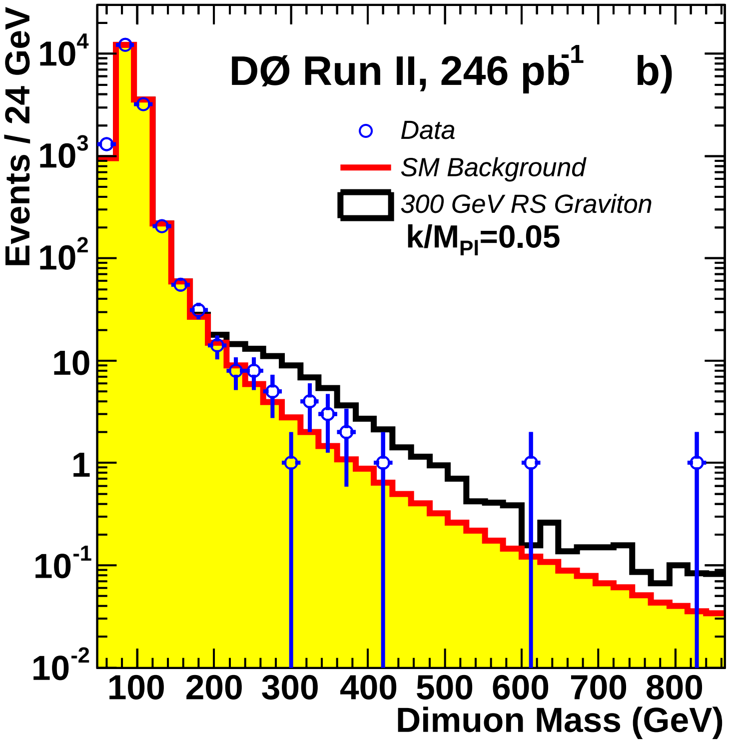
G exchange: D0 RS $\mu\mu$

Search Selection 246pb^{-1}
2 high Pt (>15 GeV) μ
Minimum ionising particles
Match a track in central tracking chamber
Signal in the μ drift chambers (if fiducial)

No opposite charge requirement, as determination of efficiency degrades fast at high p_T

Cosmic Rays reduced by requiring μ arrival times at the μ detector consistent with those from beam collisions

N_{obs}=17128

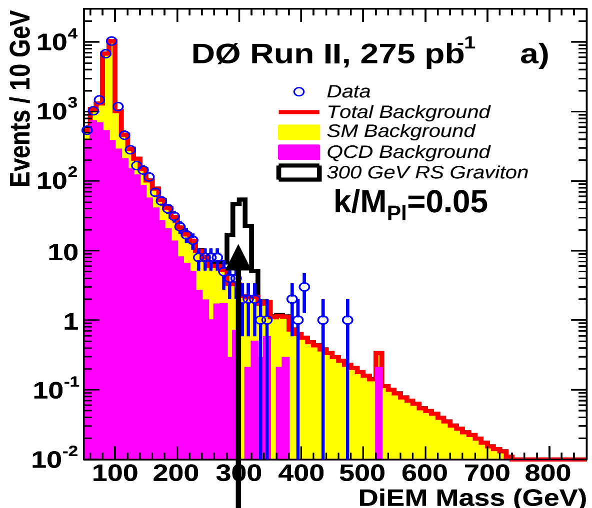


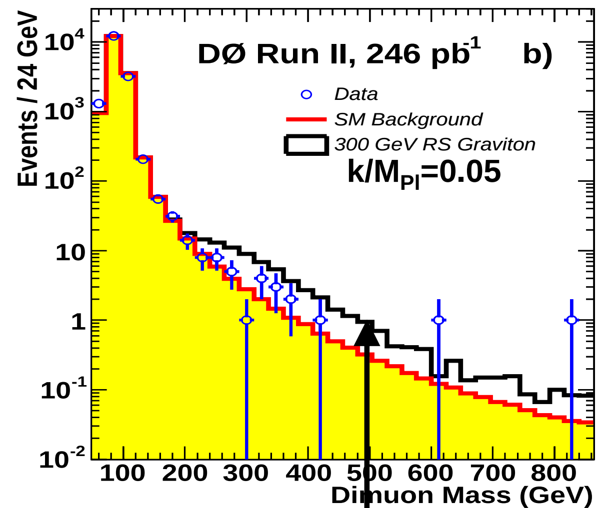
Good agreement between data and expected background

G exchange: D0 RS

1D fits used to extract limits

Different search windows are used for the ee+$\gamma\gamma$: $\mu\mu$ channels because of the different detector resolutions





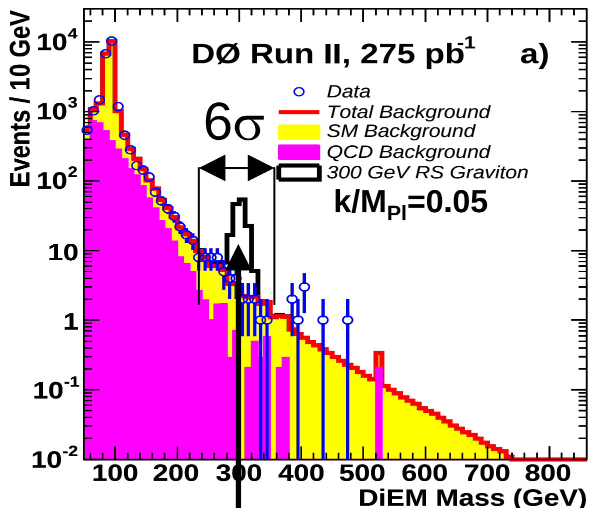
ee+$\gamma\gamma$: EM energy determined using calorimeters

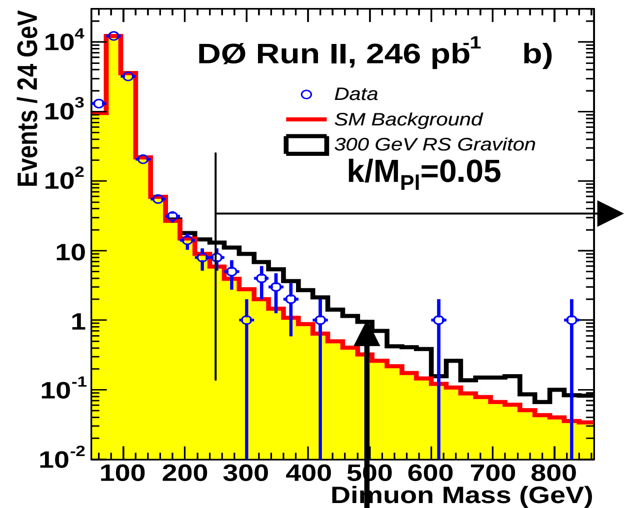
$\mu\mu$: p_T measured in tracker

G exchange: D0 RS

1D fits used to extract limits

Different search windows are used for the ee+$\gamma\gamma$: $\mu\mu$ channels because of the different detector component resolutions





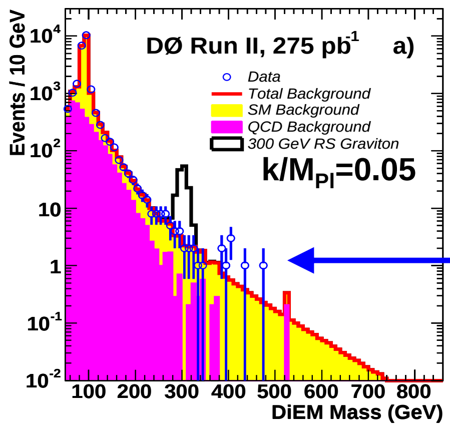
ee+$\gamma\gamma$: EM energy determined using calorimeters

$\mu\mu$: p_T measured in tracker

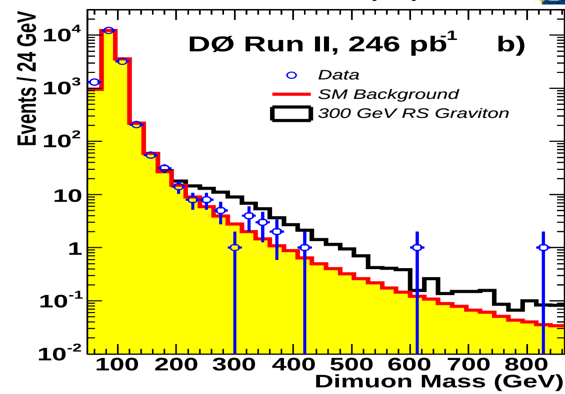
⇒ Symmetric windows
width 6 x detector resolution

⇒ Asymmetric windows
only lower mass bound used (due to long high-mass tail)

G exchange: D0 RS ee+$\gamma\gamma$



significance of upward fluctuation at 400 GeV < 2σ

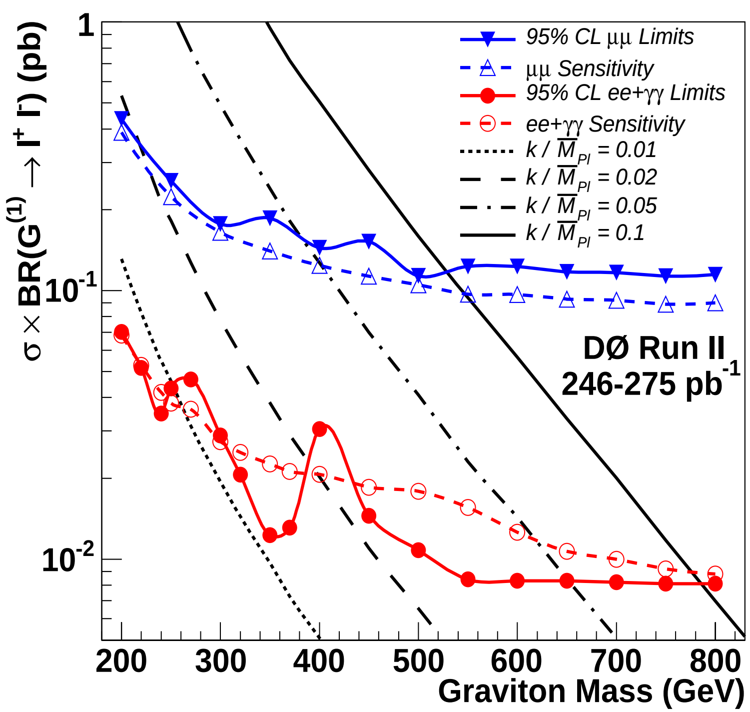


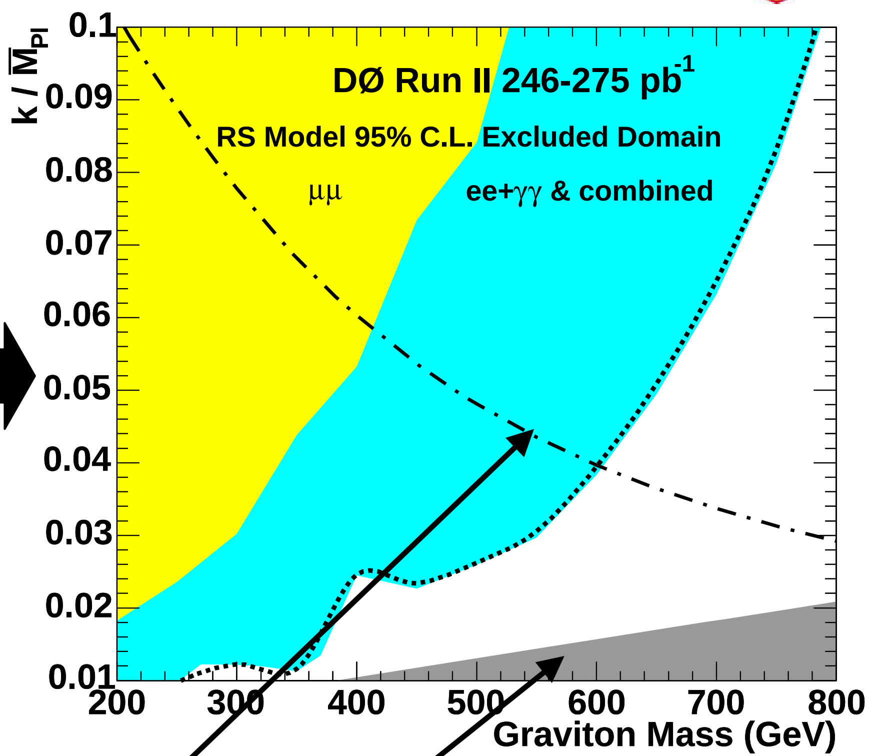
Small excess in μ channel

Graviton	DiEM Channel				Dimuon Channel				Combined
Mass	Window	Background	Data	Limit	Window	Background	Data	Limit	Limit
200	190–210	51.5 ± 5.2	53	70.2	> 160	90.1 ± 11.7	96	437	70.8
300	280–320	11.1 ± 1.1	12	28.9	> 230	26.2 ± 3.4	28	178	29.0
400	380–420	2.40 ± 0.33	6	30.5	> 270	14.7 ± 1.9	17	144	30.7
700	620–780	0.30 ± 0.25	0	8.2	> 300	10.2 ± 1.3	13	117	8.7
800	700–900	$0.13 ^{+0.25}_{-0.13}$	0	8.1	> 300	10.2 ± 1.3	13	115	8.6

Combined limits slightly less restrictive due to the overall small excess of observed events in the $\mu\mu$ channel

G exchange: D0 RS





Excluded mass limits:
785 GeV for k/M_{Pl}=0.1
250 GeV for k/M_{Pl}=0.01

Below excluded from precision electroweak data

Λ_π>10 TeV which requires a significant amount of fine-tuning

Most restrictive limits on the RS model parameters to date!

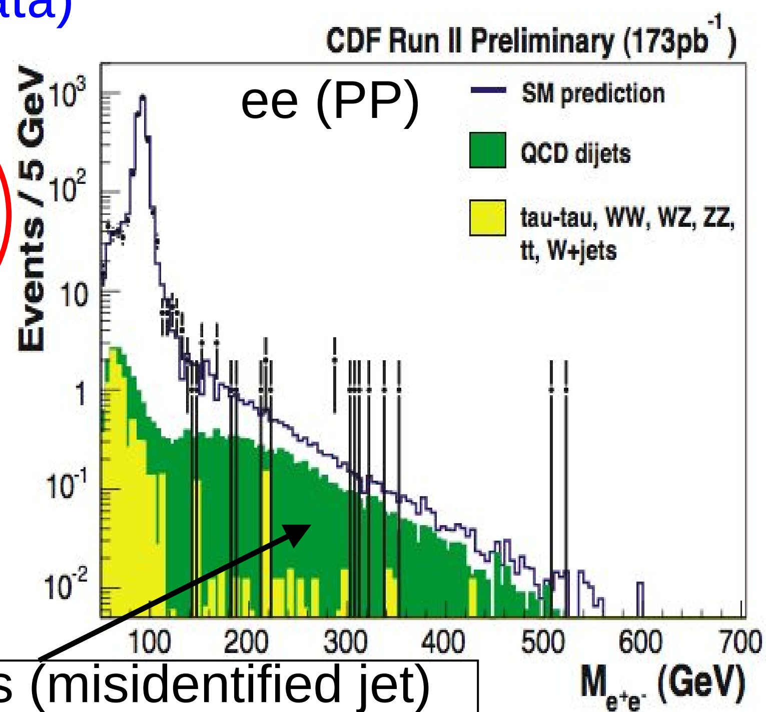
G exchange: CDF RS ee (PP)

CDF also performed a Run II RS search in the ee (& $\gamma\gamma$ separately) channel

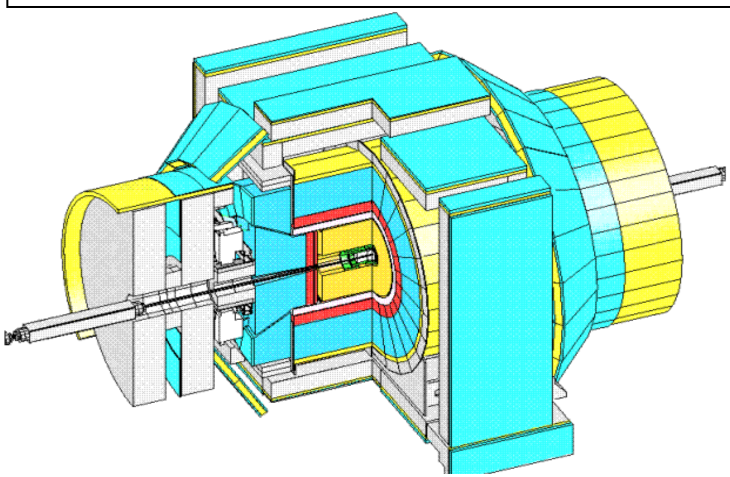
- include CC + CP (same as ADD ee data)
- add PP ee events

Search Selection
2 forward EM clusters (PP)
isolated with E_T > 25 GeV

New for Run II: increase acceptance!



New tracking algorithm developed for P photons – require a silicon track



QCD dijets (misidentified jet) background larger in the plug region than in central

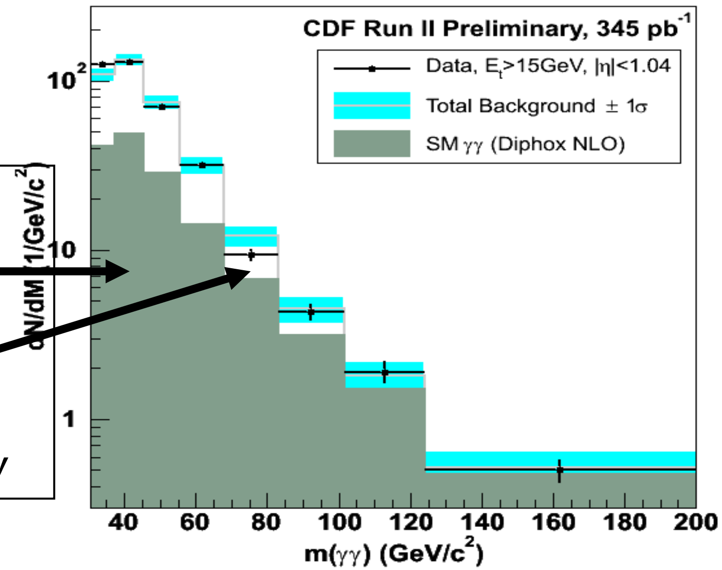
N_{exp}=2.7 ± 0.7 N_{obs}=8 for M_{ee}>300 GeV/c^2

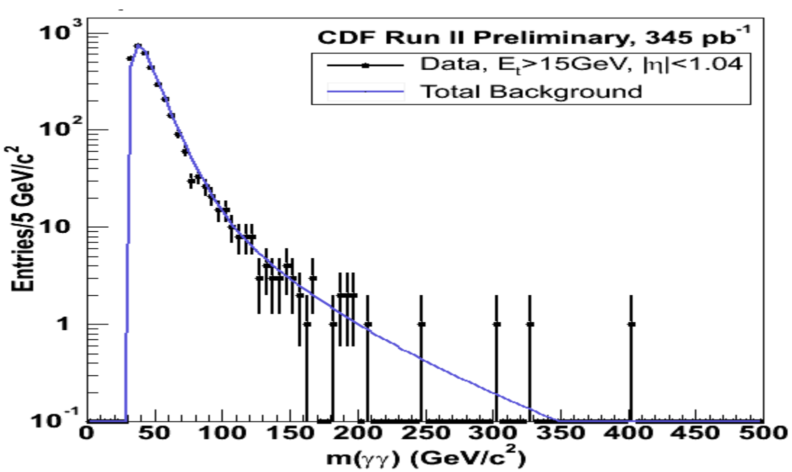
N_{exp}=1.4 ± 0.3 N_{obs}=3 for M_{ee}>350 GeV/c^2

G exchange: CDF RS $\gamma\gamma$

Search Selection
2 isolated γ E_T>15 GeV
2 central γ (CC)

Backgrounds
- Standard Model diphoton production (dominant at very high masses)
- Fakes: γ-jet and jet-jet, where jet fragments into a hard $\pi^0 \rightarrow \gamma\gamma$





N_{exp}=4.2±1.0 N_{obs}=1 for M_{ee}>300 GeV/c²
N_{exp}=1.5±0.5 N_{obs}=1 for M_{ee}>350 GeV/c²

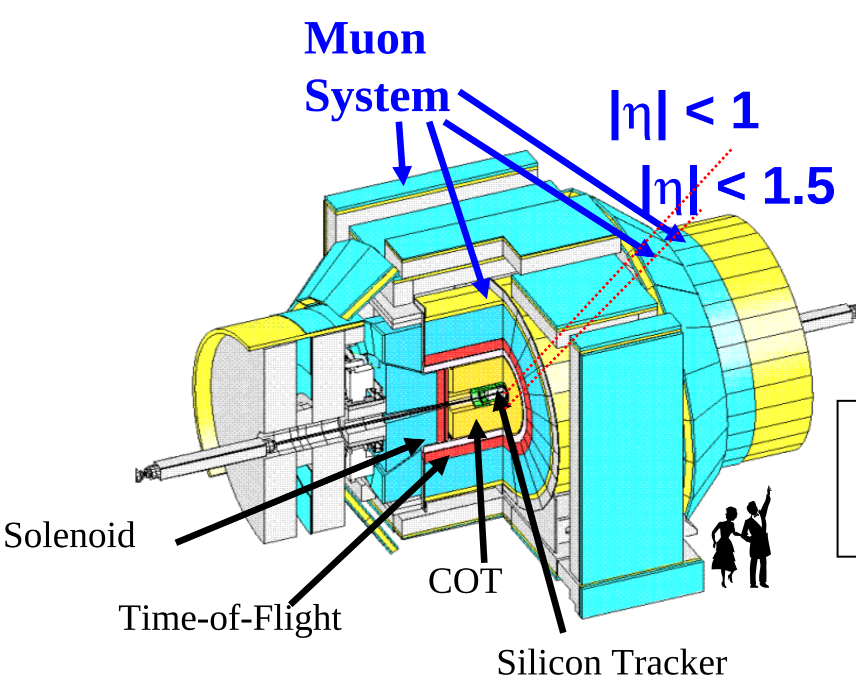
G Exchange: CDF RS $\mu\mu$

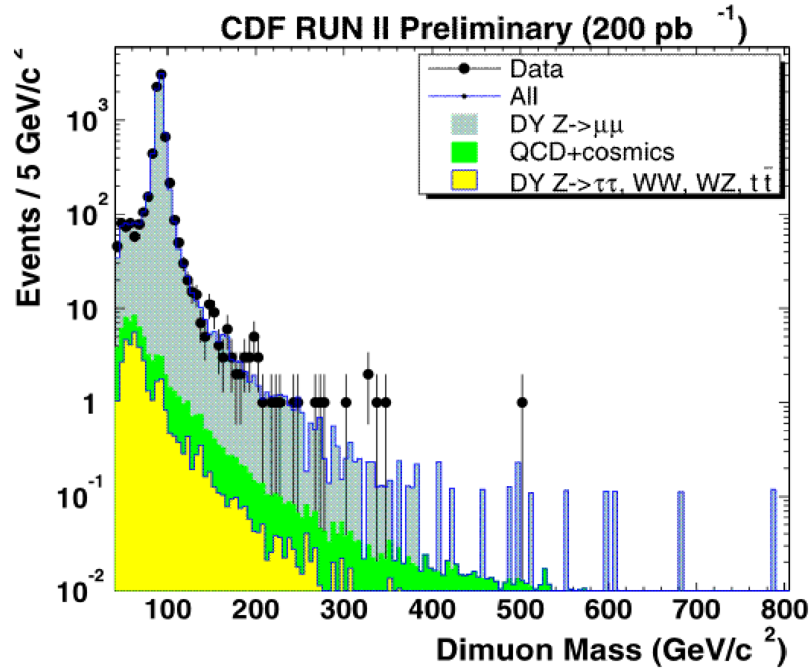
Search Selection

2 isolated μ P_T>20 GeV

$|\eta_{\mu 1}|<1$, $|\eta_{\mu 2}|<1.5$*

Veto cosmic rays using track-timing cuts





N_{exp}=5.2 ± 0.3 N_{obs}=6 for M_{ee}>300 GeV/c^2

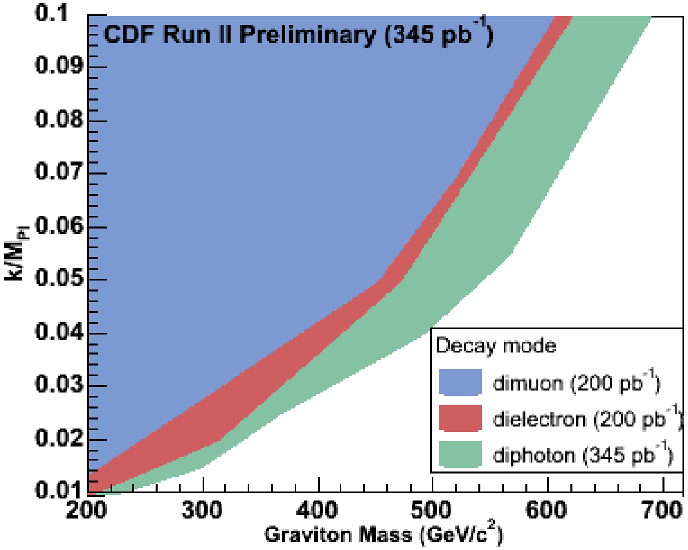
N_{exp}=3.2 ± 0.2 N_{obs}=1 for M_{ee}>350 GeV/c^2

*μ_2 may include tracks w/o μ–chamber information

CDF RS Graviton Limits

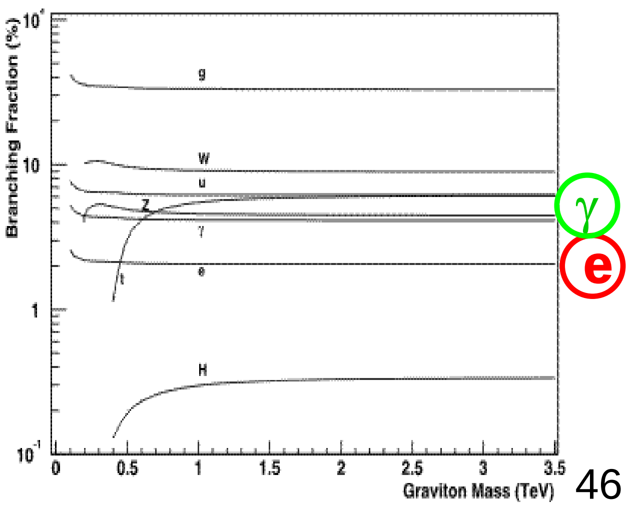
Setting 95 % C.L. upper limits on σ.BR(σ→γγ/ll):

- γγ: Like D0 ee+γγ, CDF use ±3σ windows around M_G, but in 1D only
- ee+μμ: CDF use a binned likelihood method to fit 1D M_{ll} spectra



Channel	Luminosity (pb^{-1})	M_G (GeV/c^2) K/M_{Pl}=0.01	M_G (GeV/c^2) K/M_{Pl}=0.1
ee	200	200	640
μμ	200	170	610
ee+μμ	200	200	700
γγ	345	220	690

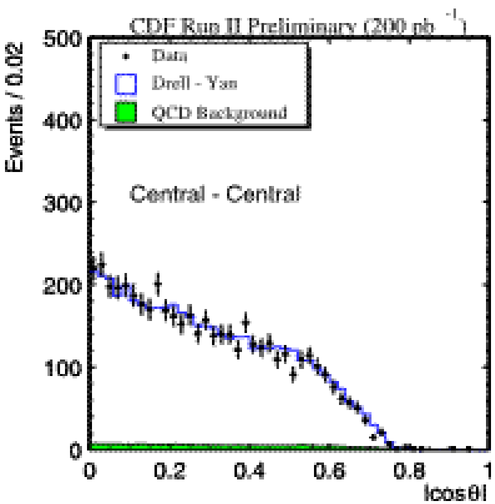
- **ee** has largest acceptance at low mass
- γγ has largest acceptance at high mass
- BR(**G→γγ**) = 2 * BR(**G→ee**)

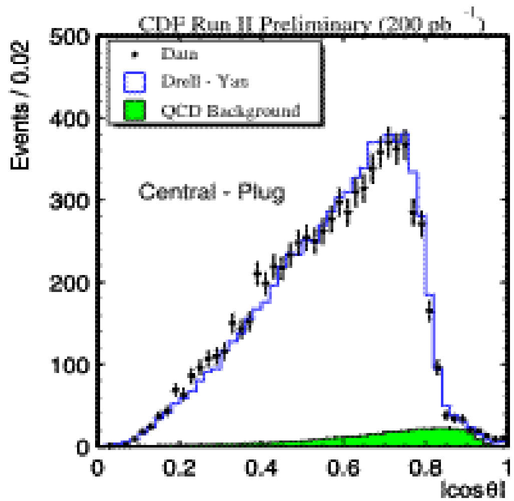


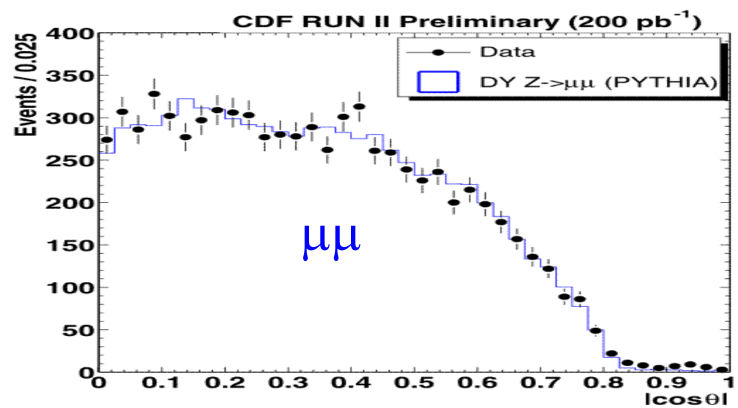
CDF limits not as exclusive as D0's

G exchange: CDF RS Searches

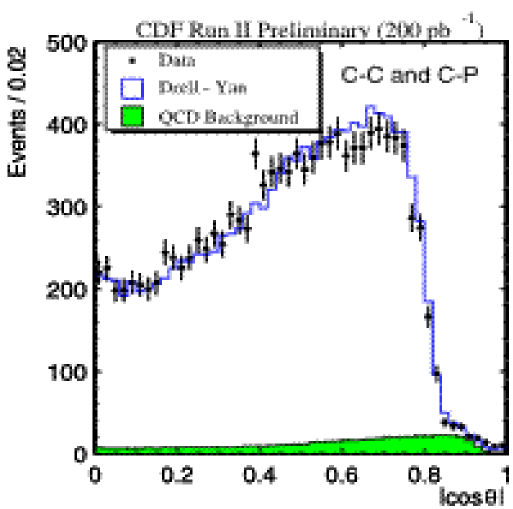
CDF perform 1-D fits, but also study (ee, $\mu\mu$, $\gamma\gamma$) angular distributions

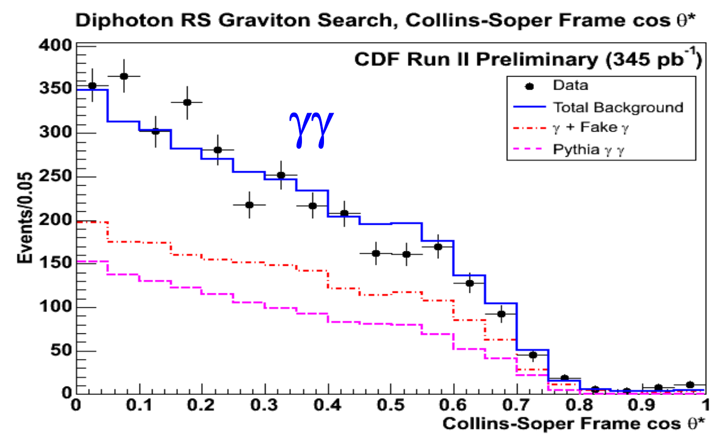






ee

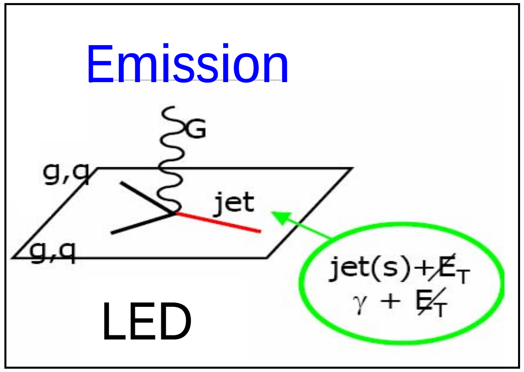


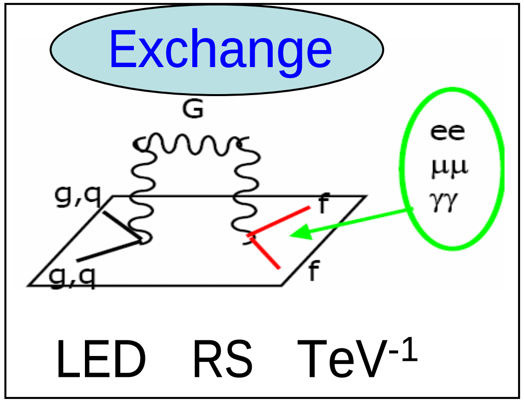


Good agreement with SM prediction

ED Searches

Signature		Experiment	Model
Graviton Emission	γ+ME_T	LEP, CDF	LED
	jets+ME_T	CDF, D0	
Graviton Exchange	ee+$\gamma\gamma$	D0	LED, RS
	ee	CDF, D0	
	$\mu\mu$	CDF, D0	
	$\gamma\gamma$	CDF	
	$e^{+/-}$X	H1	LED
Boson Exchange	ee		TeV^{-1}



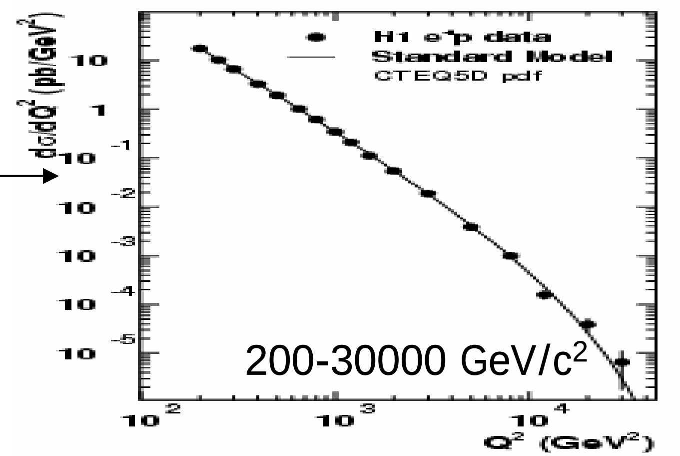


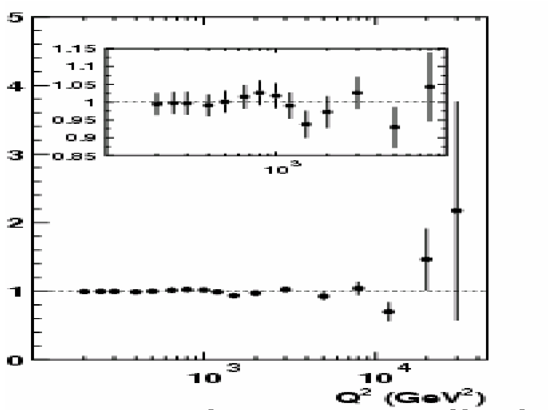
H1 LED Searches

<u>H1 Search Strategy</u>

Perform signature based searches

- Measure inclusive σ's $e^{+/-}p \rightarrow e^{+/-}X$ over a huge range in 4-momentum transfer (Q^2)
- Compare data to expectation





- Interpret data & set limits on many new models!

  E.g. Contact interactions
  Leptoquarks
  R-parity violating squarks
  Search for e or q substructure
  (Form Factor Analysis)

⇒ Fix the SM and its parameters, in particular the parton distributions, using experimental data at low Q^2, where the theory is well established.

Then extrapolate the prediction towards Q^2, (where distance scales down to 1/1000 of the proton radius are probed), where deviations due to new physics are expected to be most prominent & could indicate the presence of quark substructure or new particles

G exchange: H1 LED Search

In DIS, G-exchange may contribute to the e-q subprocess, but the new interaction also induces e-g scattering which is not present in the SM.

$$\frac{d\sigma(e^+p \to e^+X)}{dQ^2} = \int dx \left\{ q(x)\frac{d\sigma(e^+q)}{dt} + \bar{q}(x)\frac{d\sigma(e^+\bar{q})}{dt} + g(x)\frac{d\sigma(e^+g)}{dt} \right\}$$

To Set Limits

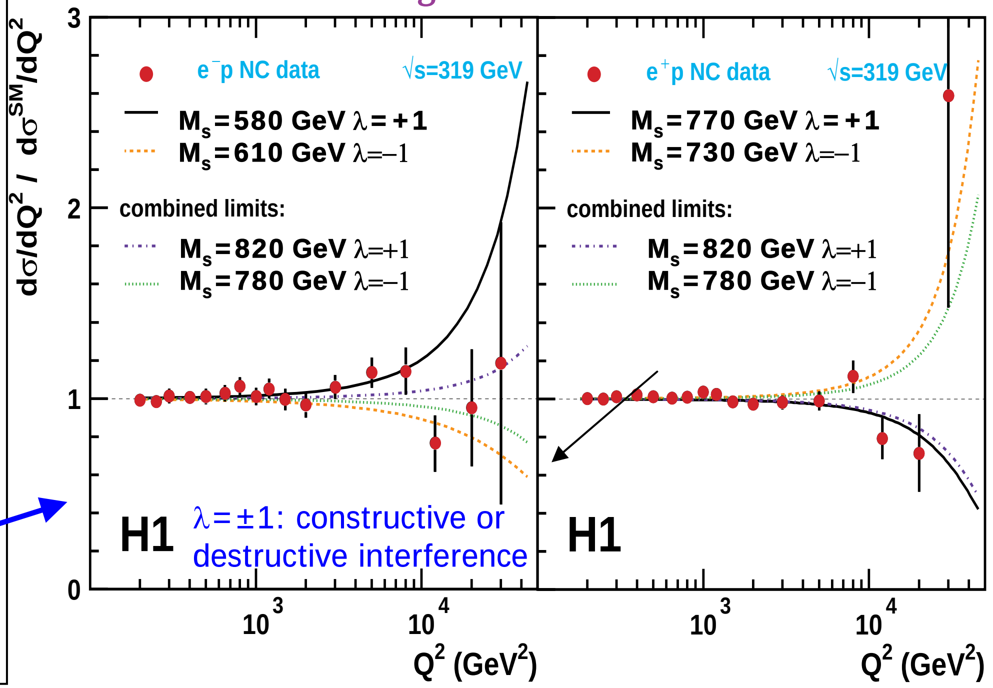
- Parameterise σ in terms of

$$\eta = \lambda / M_s^4$$

$$\frac{d\sigma(e^+q \to e^+q)}{dt} = \underbrace{\frac{d\sigma^{SM}}{dt}}_{\text{SM}} + \underbrace{\frac{d\sigma^{G}}{dt}}_{\text{ED}} + \underbrace{\frac{d\sigma^{\gamma G}}{dt} + \frac{d\sigma^{ZG}}{dt}}_{\text{Interference}}$$

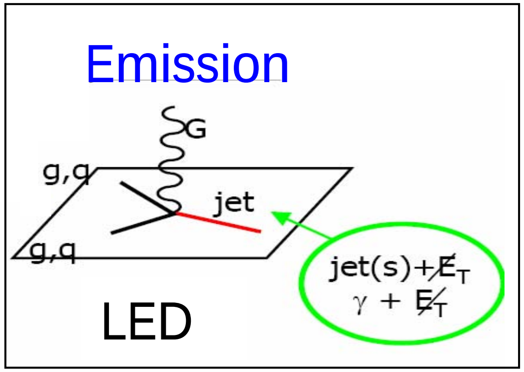
- Fit the differential σ to the formula above treating λ/M_s^4 as a free parameter
- Extract limits on M_s

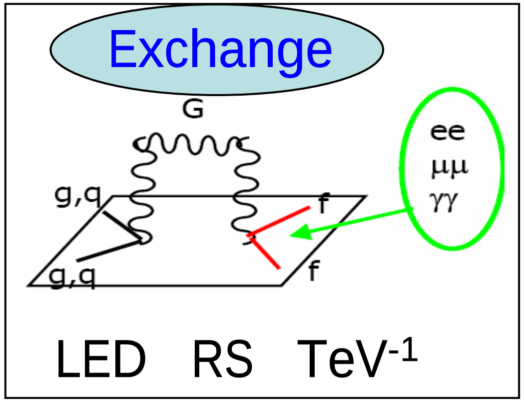
Large Extra Dimensions



ED Searches

Signature		Experiment	Model
Graviton Emission	γ+ME_T	LEP, CDF	LED
	jets+ME_T	CDF, D0	
Graviton Exchange	ee+$\gamma\gamma$	D0	LED, RS
	ee	CDF, D0	
	$\mu\mu$	CDF, D0	
	$\gamma\gamma$	CDF	
	$e^{+/-}X$	H1	LED
Boson Exchange	ee	D0	TeV^{-1}





TeV^{-1} ee Search

First dedicated experimental search for TeV^{-1} ED at a collider

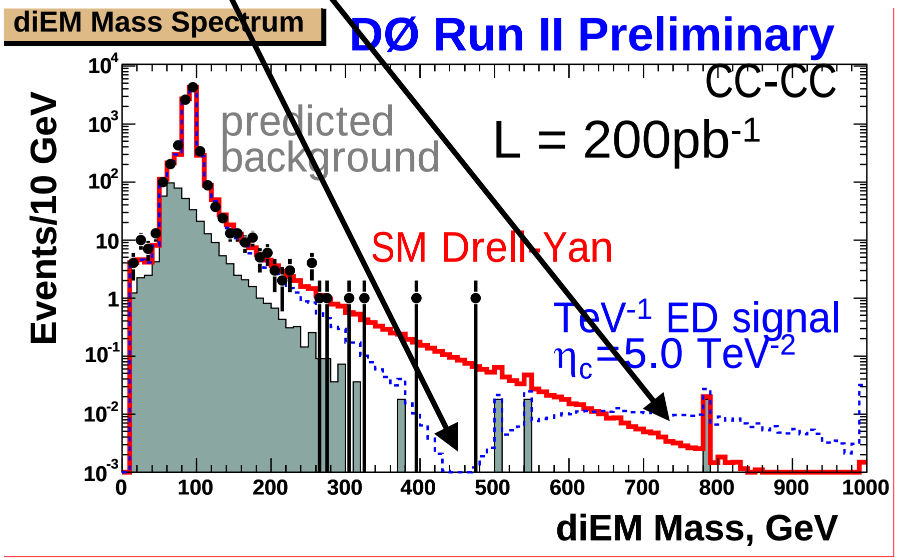
Search for effects of virtual exchanges of the KK states of the Z and γ

Search Signature: Signal has 2 distinct features:

- enhancement at large masses (like LED)
- negative interference between the 1st KK state of the Z/γ and the SM Drell-Yan in between the Z mass and M_C

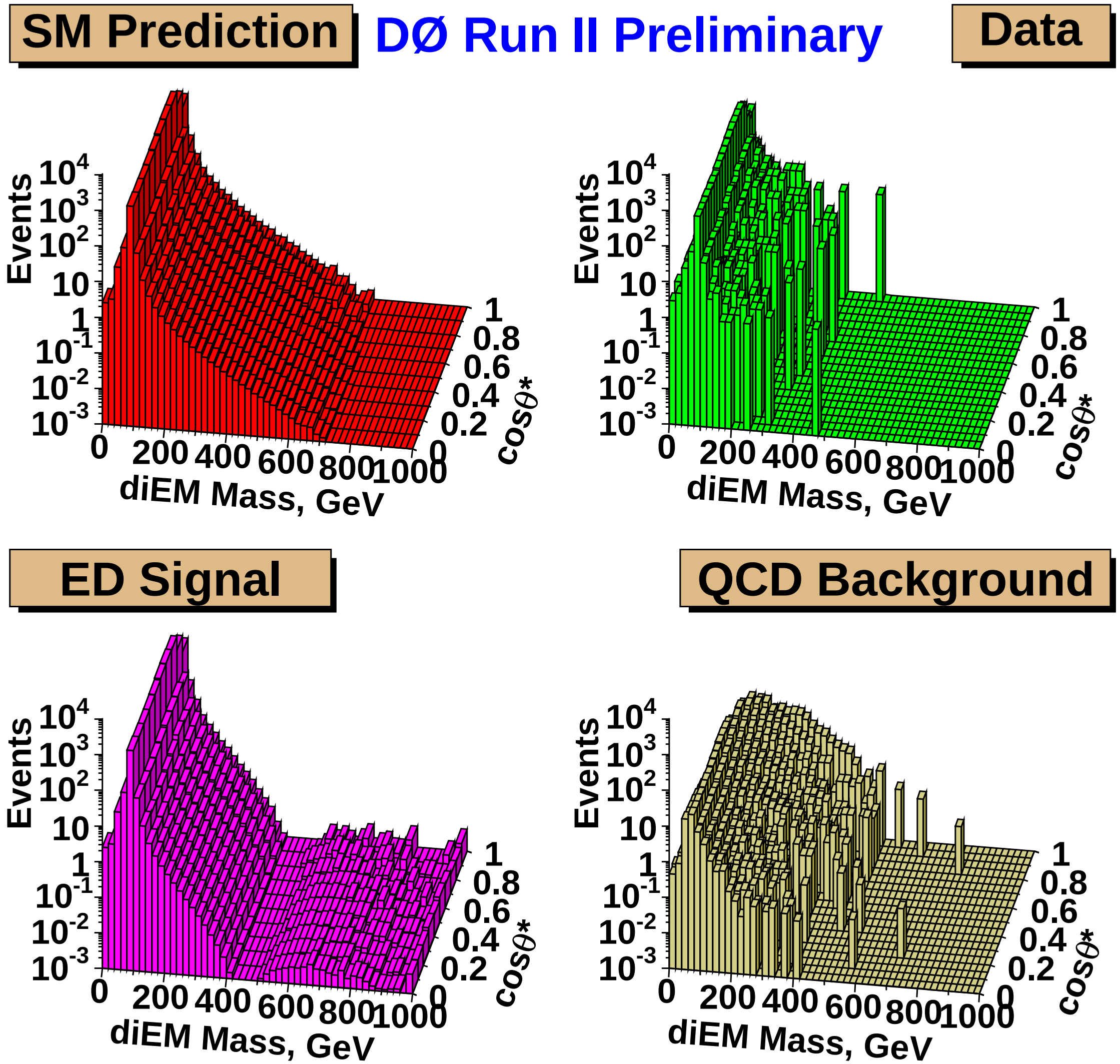
Search Selection 200pb^{-1}

Same as LED diEM search except: at least 1 EM cluster has to have a matching track & no track isolation requirement



Data are in excellent agreement with Drell-Yan production, so proceed to set limits...

TeV^{-1} ee D0



Extract limits on M_C by fitting 2D distributions to the sum of the SM, interference, and the direct gravity templates

Lower limit on the compactification scale of the longitudinal ED: M_C>1.12 TeV at 95% C.L.

World Combined Limit M_C >6.8 TeV at 95%C.L.

Better limits come from precision measurements

Summary of Present Limits
But what of the Future...?

- Present limits are up to ~ 1TeV
- Future: More data to be analysed and to come:

	HERA:	Tevatron:
Delivered	~220pb^{-1}	> 1 fb^{-1}
Analysed	~80pb^{-1}	~400 pb^{-1}
Goal	>700pb^{-1} (2007)	4.4-8.5 fb^{-1} (2009)

Promising observation potential, hope to discover ED if they exist!
Or extend limits: Tevatron Run IIa (2 fb^{-1}) extend limits:

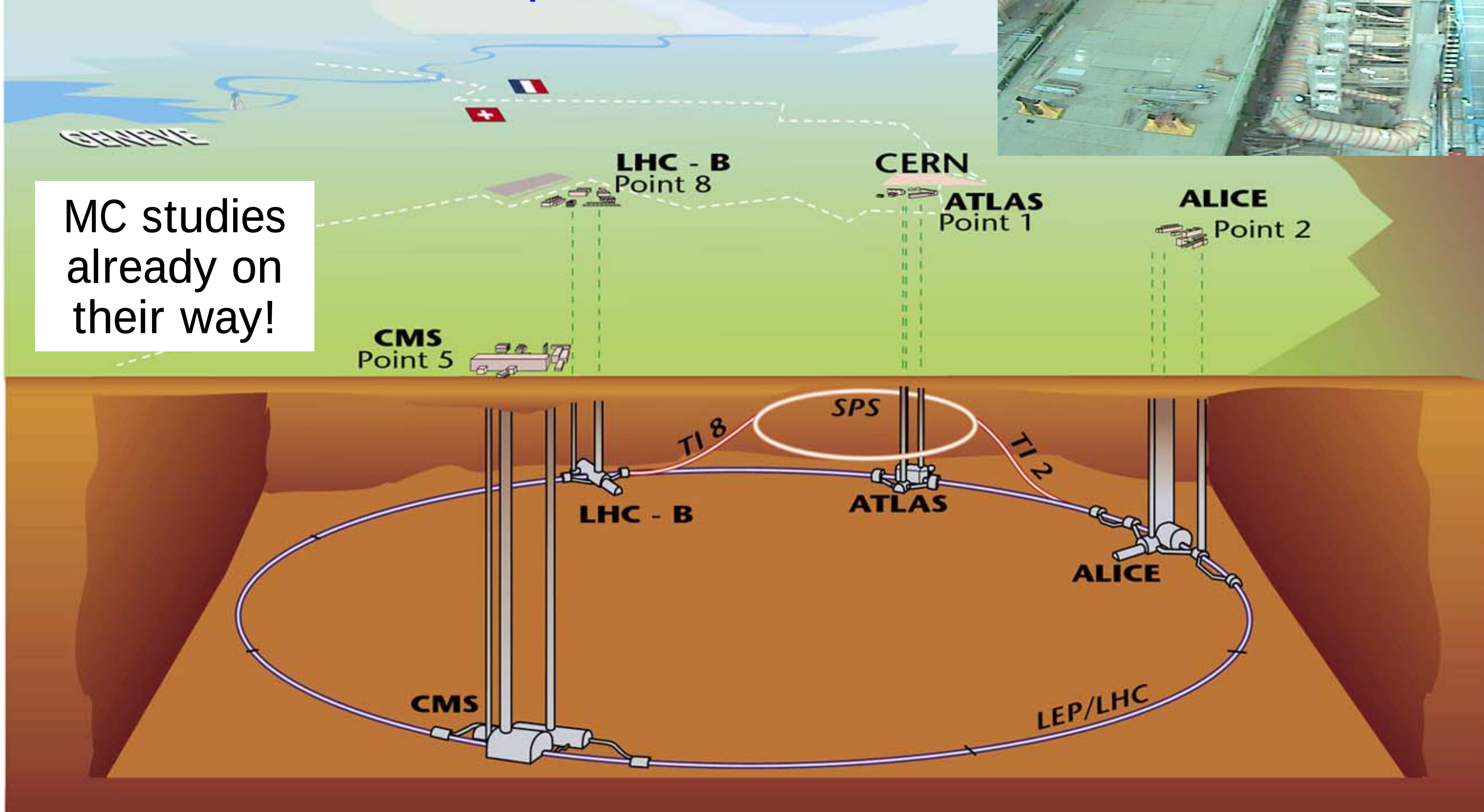
ADD: up to about M_S = 2 TeV
RS: m_1 from 0.5 to 1 TeV for k/M_{Pl} 0.01 to 0.1

And after that.....?

What limits can we reach in the future?

- Next generation of detectors being built
  LHC (2007): $\sqrt{s}$ = 14 TeV
- What limits can we expect to reach?

ATLAS pit



MC studies already on their way!

LED ADD: G Direct Emission

γ+ ME_T

M_D^{MAX} (TeV)	$\delta=2$
HL $100fb^{-1}$	4

ATLAS

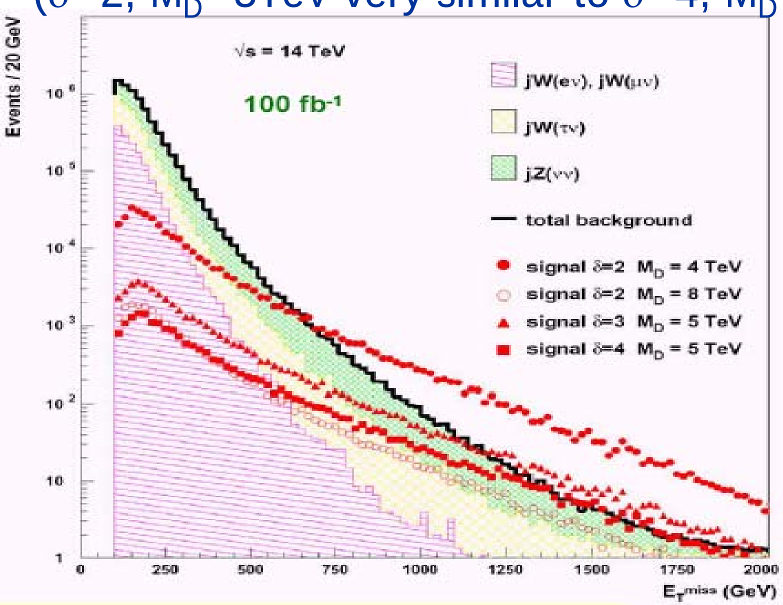
jet+ ME_T

M_D^{MAX} (TeV)	$\delta=2$	$\delta=3$	$\delta=4$
LL $30fb^{-1}$	7.7	6.2	5.2
HL $100fb^{-1}$	9.1	7.0	6.0

To characterise the model need to measure M_D and δ

Measuring σ gives ambiguous results

($\delta=2$, M_D=5TeV very similar to $\delta=4$, M_D=4TeV)

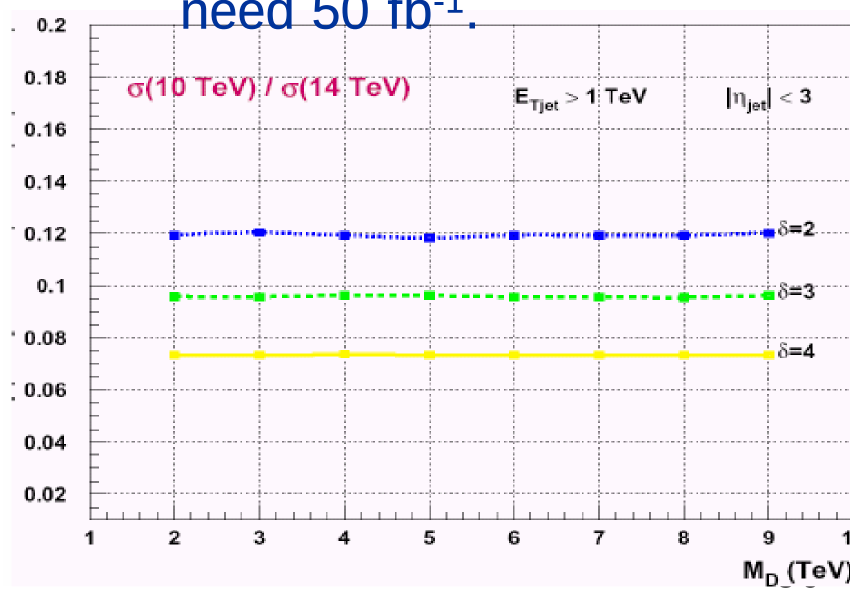


Disentangle δ and M_D:

Run at two different √s

e.g. 10 TeV and 14 TeV =>

need 50 fb^{-1}.

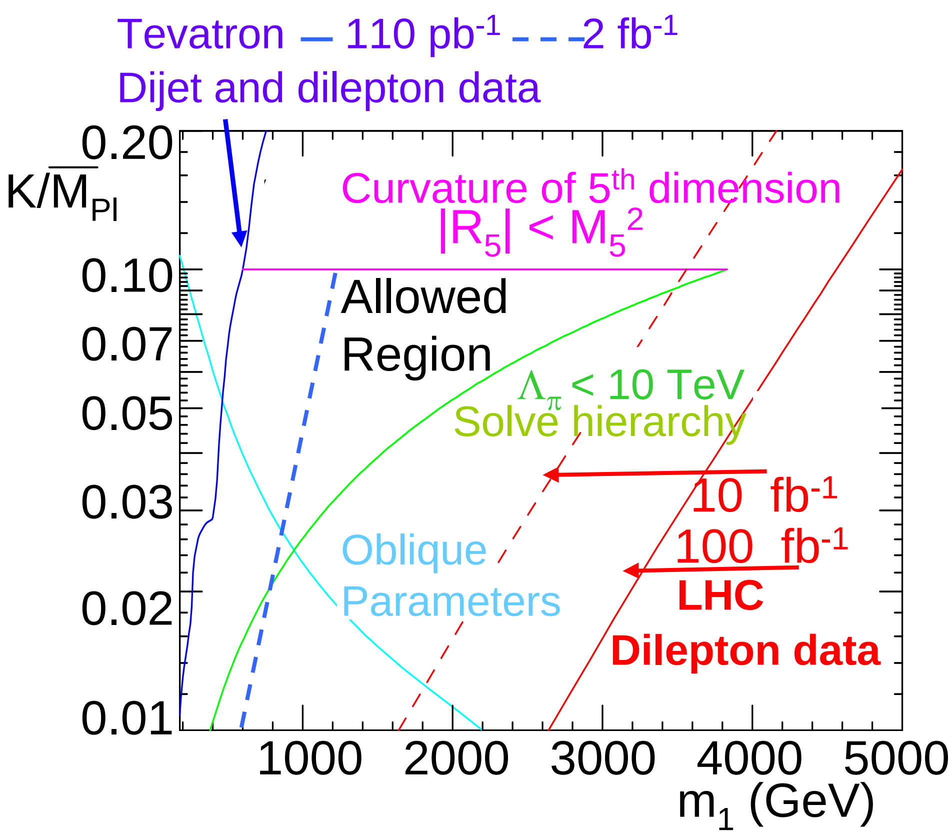


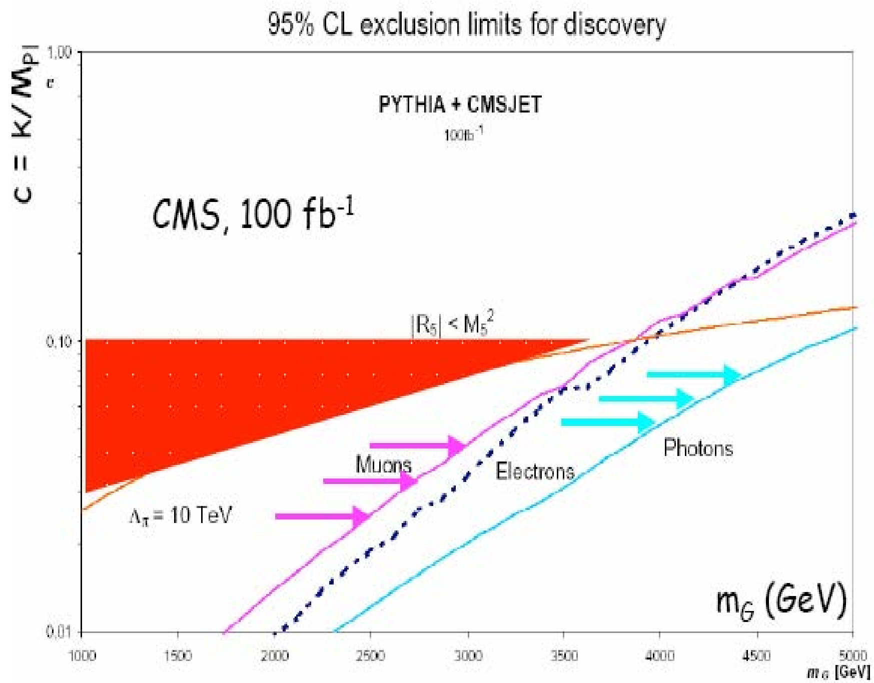
LED ADD: Virtual G Exchange

channel	Luminosity		$\delta = 2$	$\delta = 3$	$\delta = 4$	$\delta = 5$
$\gamma\gamma$	10 fb^{-1}	M_s^{max}(TeV) S/B	6.3 36/18	5.6 36/18	5.1 39/25	4.9 34/13
	100 fb^{-1}	M_s^{max}(TeV) S/B	7.9 50/53	7.3 62/96	6.7 55/72	6.3 51/53
$\ell\ell$	10 fb^{-1}	M_s^{max}(TeV) S/B	6.6 33/11	5.9 31/8	5.4 30/6	5.1 30.6
	100 fb^{-1}	M_s^{max}(TeV) S/B	7.9 45/48	7.5 38/21	7.0 36/16	6.6 29/6
$\gamma\gamma + \ell\ell$	10 fb^{-1}	M_s^{max}(TeV)	7.0	6.3	5.7	5.4
	100 fb^{-1}	M_s^{max}(TeV)	8.1	7.9	7.4	7.0

ATLAS extends reach up to ~ 6/7 TeV with 10 fb^{-1}/100 fb^{-1}
(n dependent)

RS constraints





BR(G→γγ) = 2*BR(G→ee)

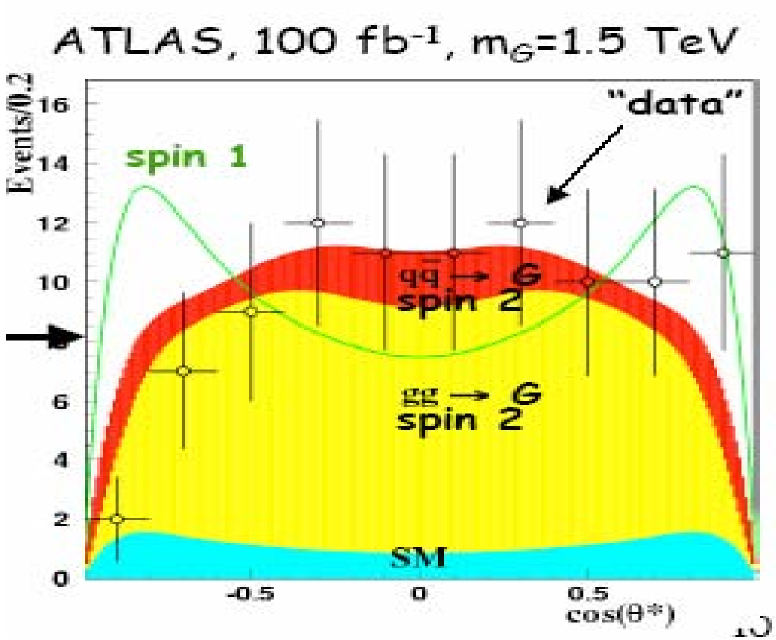
LHC completely covers the region of interest

(hep-ph 0006041)

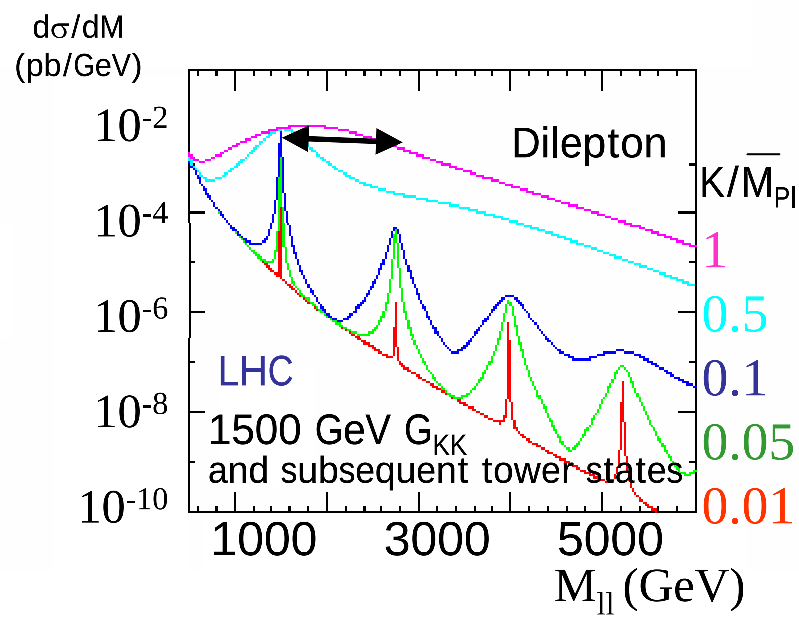
RS constraints

Distinguish RS model from other new physics

➢Distinguish Z’ (spin 1) /G (spin 2) from e^+e^- 1st resonance by studying angular distribution



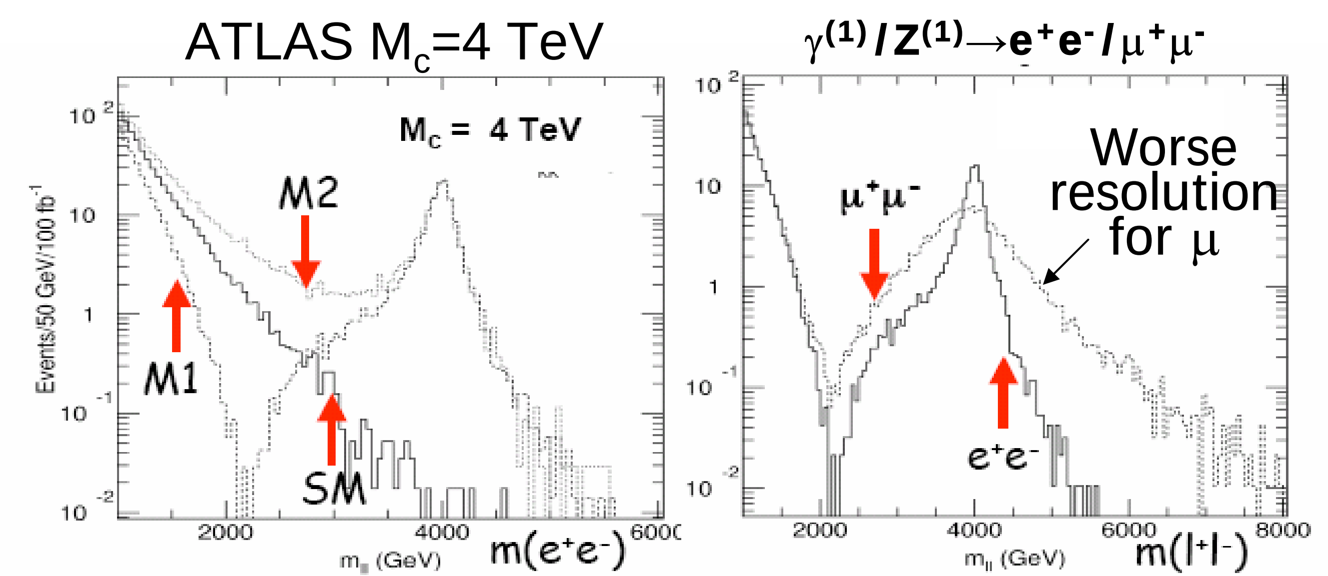
➢If many resonances observed: study separation: is it characteristic Bessel spacing?



(hep-ph 0006041)

TeV^{-1} Sized ED & KK Gauge Boson

Fermions are open strings excitations with ends stuck to our brane but gauge Bosons could also propagate in the bulk. ➡ **Search for KK excitations of Z, γ, ...**



- 2 TeV e in ATLAS: ΔE/E~0.7 ~20% for μ
- Acceptance for leptons: |η|<2.5

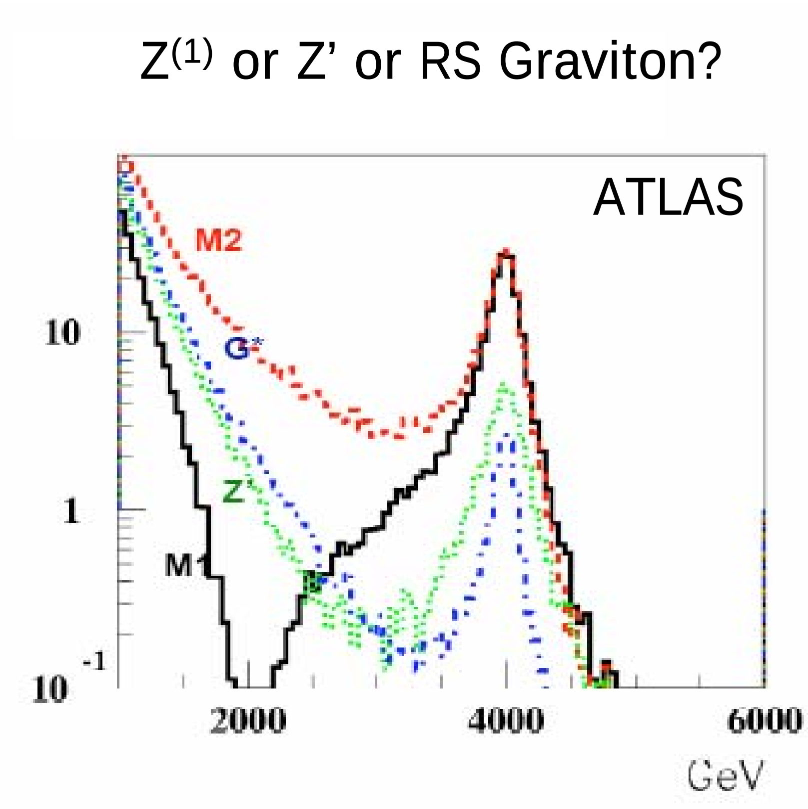
Reach: Possible to detect resonance up to 5.8 TeV

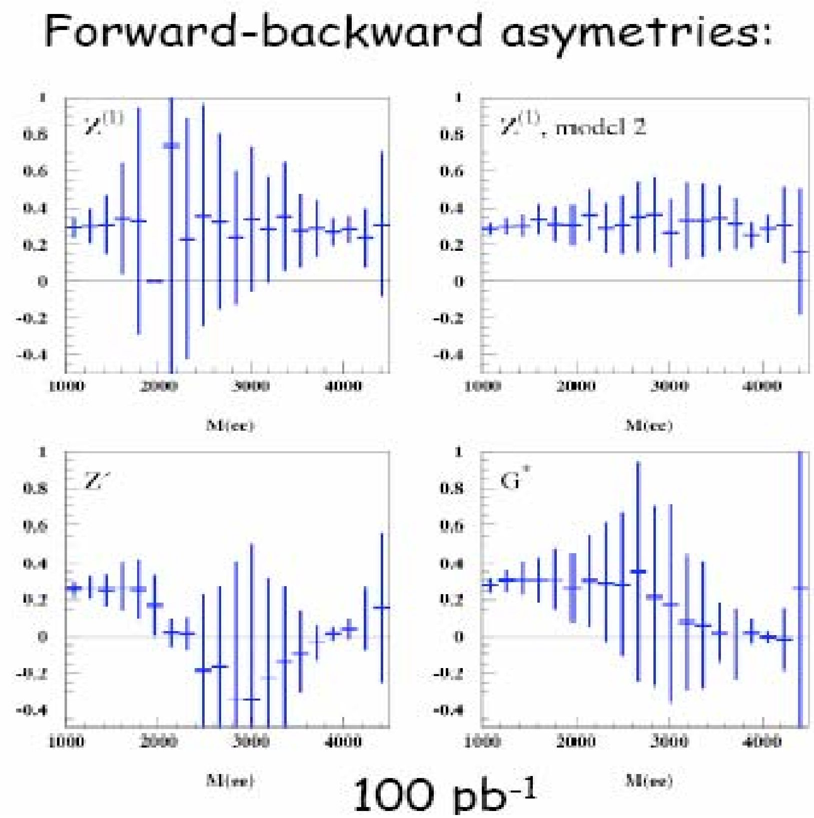
In absence of peak a 95% CL of 13.5 TeV can be achieved

G. Azuelos, G. Polesello (Les Houches 2001 Workshop Proceedings)

TeV^{-1} Sized ED & KK Gauge Boson

Distinguish RS model from other new physics





Concluding Remarks

- No significant sign of new physics!
- Increasing number of channels being used to search for EDs

  Many searches underway:

  e.g. $pp \to \tau\tau$, $pp \to$ jet jet, $pp \to G \to ZZ$
- Existing analyses being refined & improved

  Updates imminent e.g. $pp \to ee$, $pp \to$ jet+ME_T,
- Present limits are up to ~ 1TeV
- LHC will enable searches probe up to ~ 5-6 TeV

Will HERA/Tevatron discover new physics before LHC?