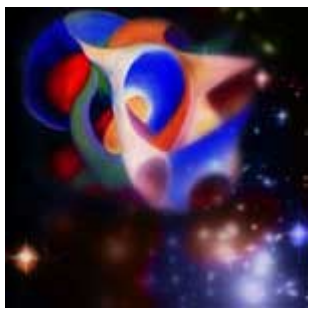
Extra Dimension

Searches at Accelerators

Tracey Berry
University of Liverpool



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

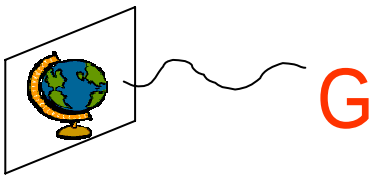
Extra dimensional Models

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



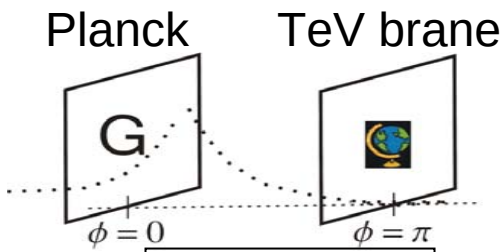
$$M_{Pl}^2 \sim R^n M_{Pl(4+n)}^{(2+n)}$$

Effective $M_{Pl} \sim$ 1TeV $\rightarrow$ 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



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

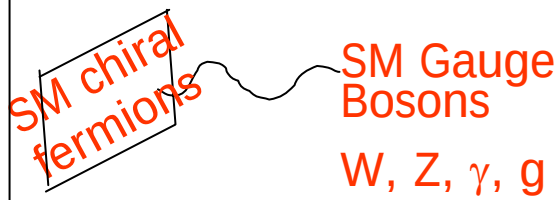
$\Lambda_\pi \sim$ TeV

if warp factor $kR_c \sim$11-12
k/M_{Pl}, k: curvature scale

TeV^{-1}

Dienes, Dudas, Gherghetta,
Nucl Phys B537 (99)

TeV^{-1} sized EDs



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

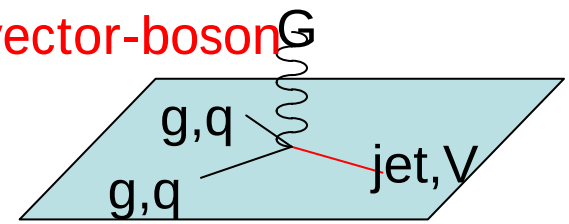
What are the experimental signatures at colliders?

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



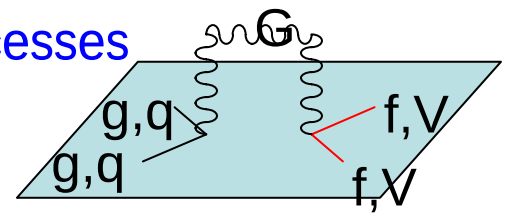
- **Virtual Graviton exchange**

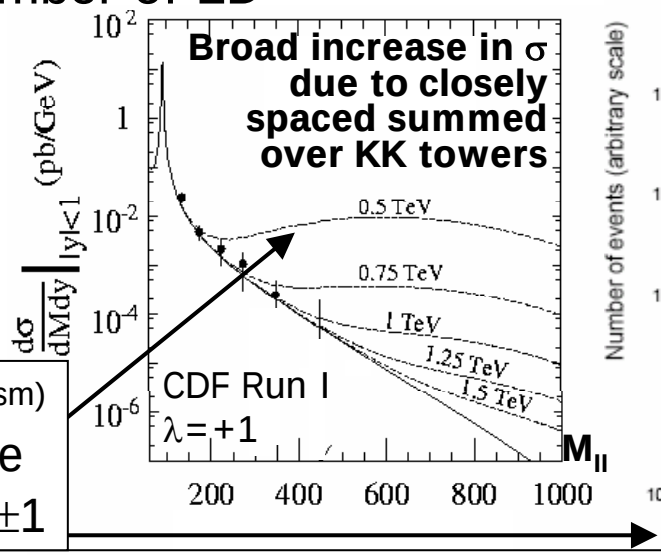
Signature: deviations in σ and asymmetries of SM processes

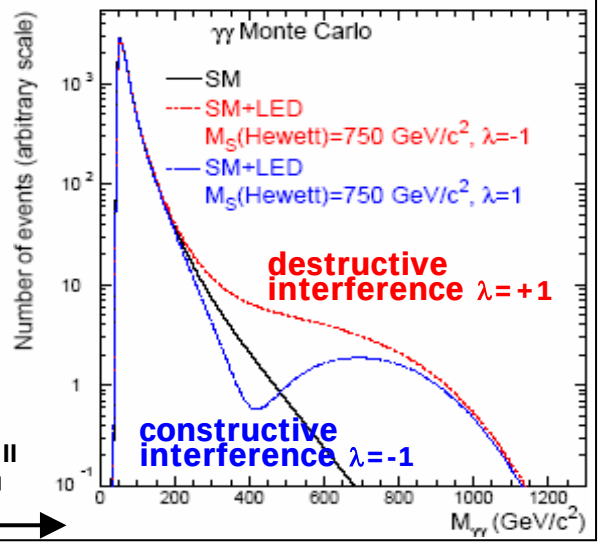
e.g. $qq \rightarrow l^+l^-$, $\gamma\gamma$

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

σ independent of the number of ED*







New Parameters (*Hewett formalism)

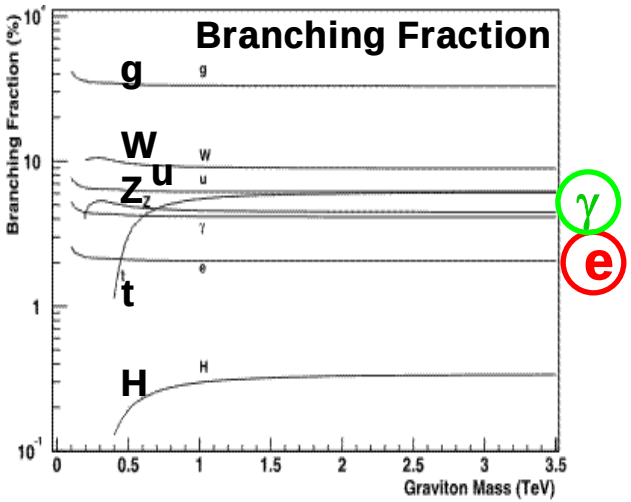
$M_s \sim M_D \sim M_{Pl(4+n)}$: string scale

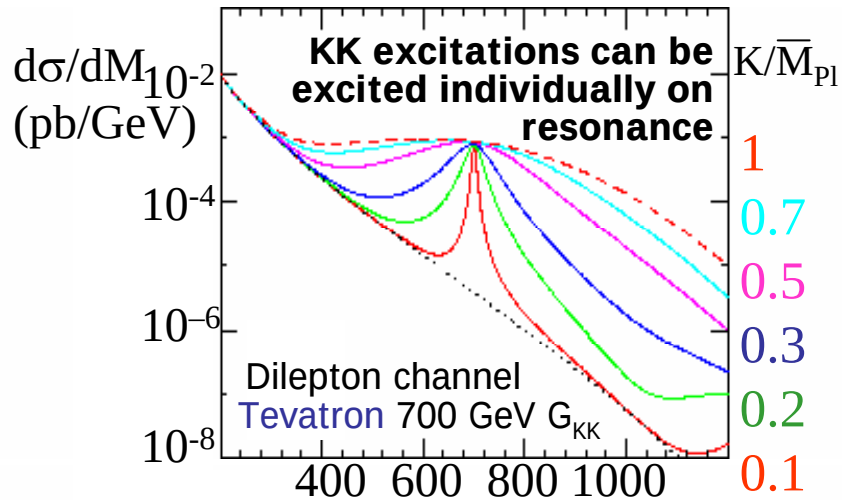
λ: dimensionless parameter, ± 1

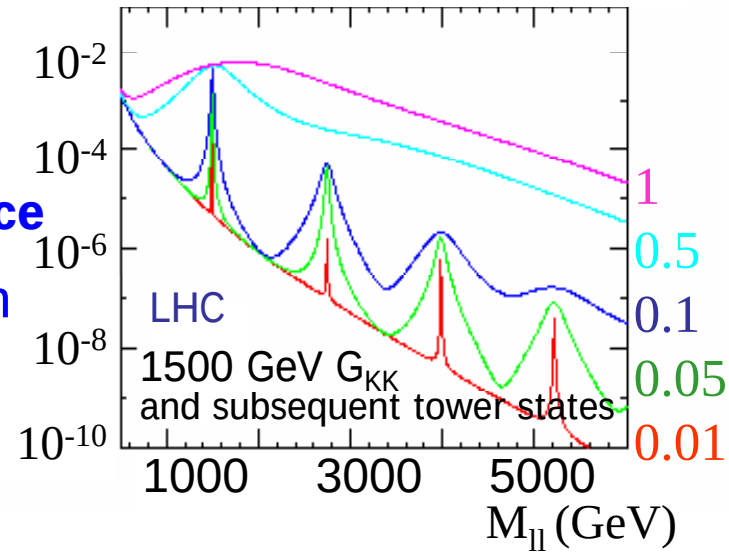
Experimental Signature for RS Model

Virtual Graviton exchange

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







New parameters:

1st graviton excitation mass: m_1 → position

$\Lambda_\pi = m_1 \overline{M}_{pl} / k x_1$, $m_n = k x_n e^{krc\pi} (J_1(x_n) = 0)$

Ratio: $k/\overline{M}_{Pl}$

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

Resonance

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

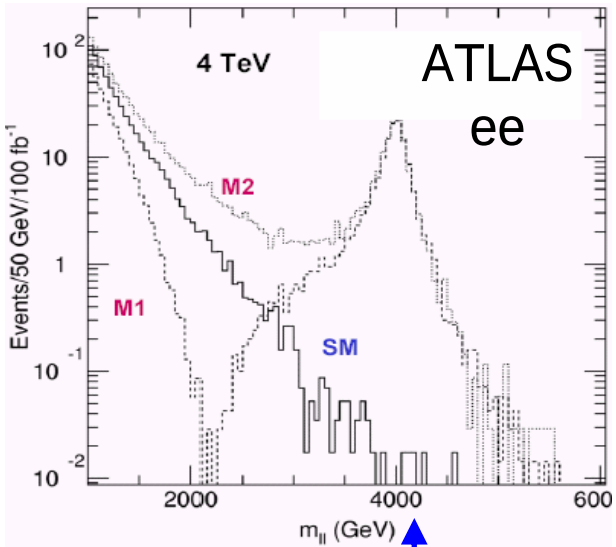
From 4-d point of view:

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



$M_n = M_0$

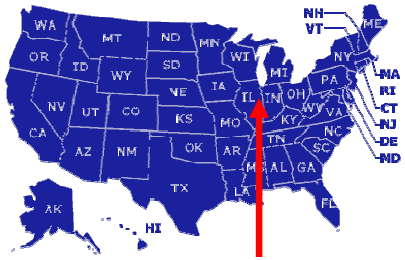
New Parameters

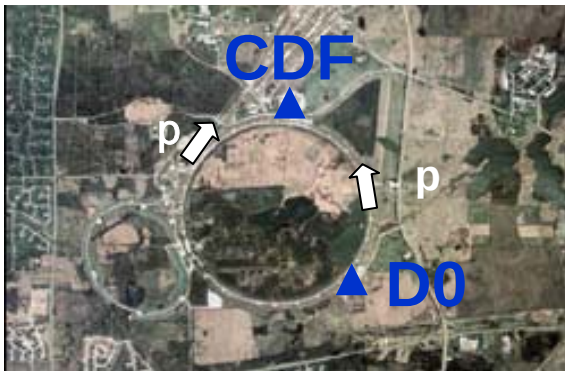
$R=M_C^{-1}$: size of the compact dimension
M_C : corresponding compactification scale
M_0 : mass of the SM gauge boson

hep-ph/9811291

ED Search Facilities

Tevatron, Fermilab, USA

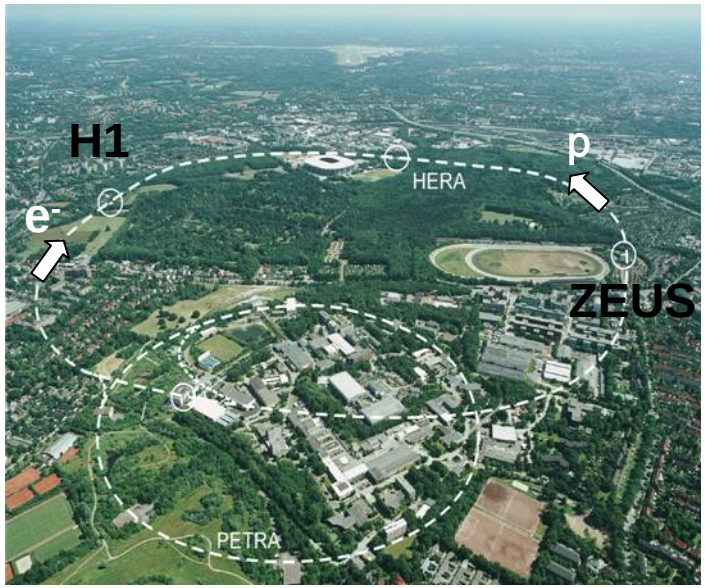


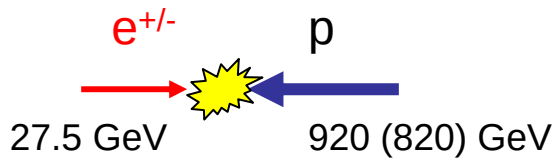


Tevatron: Highest energy collider operating in the world!

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

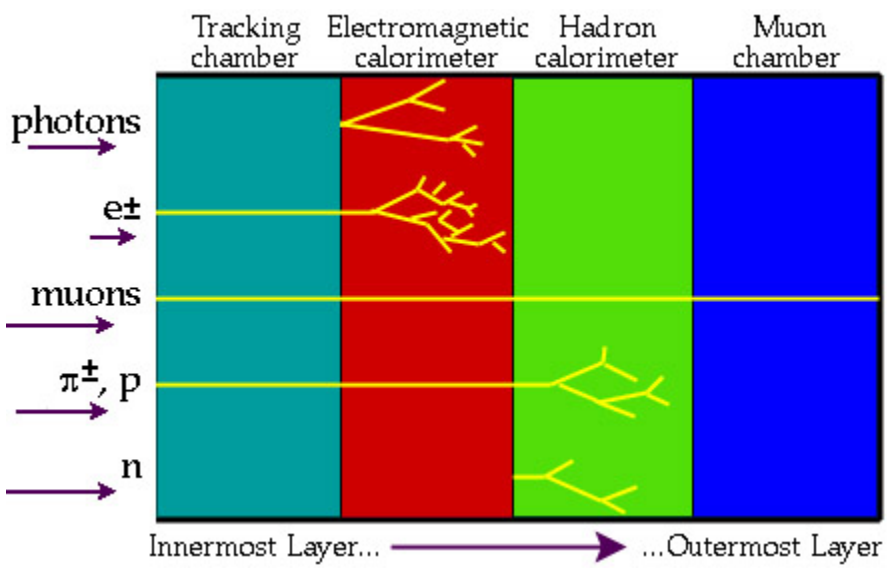
CERN: world's largest particle physics laboratory

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

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

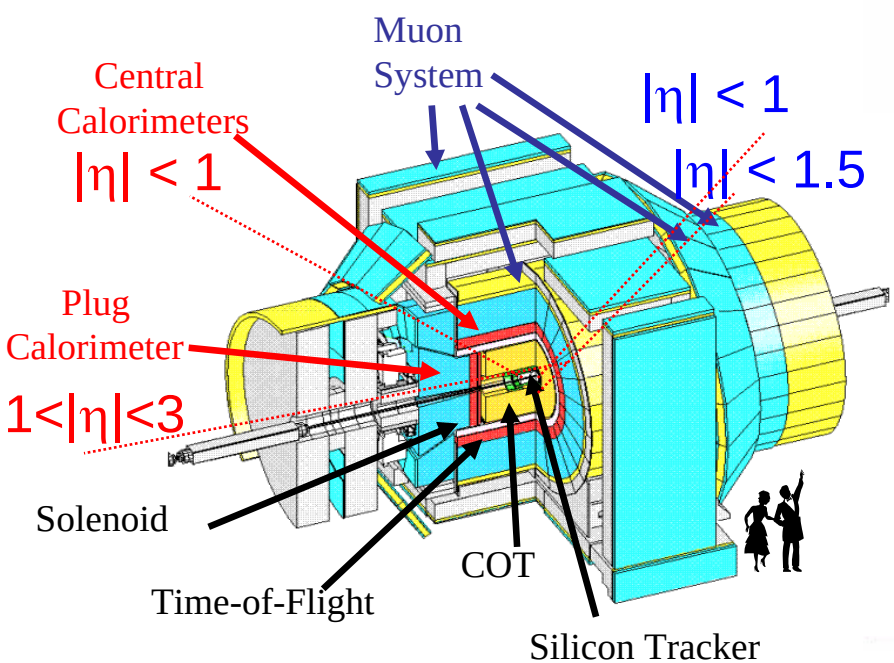
General Particle Detection

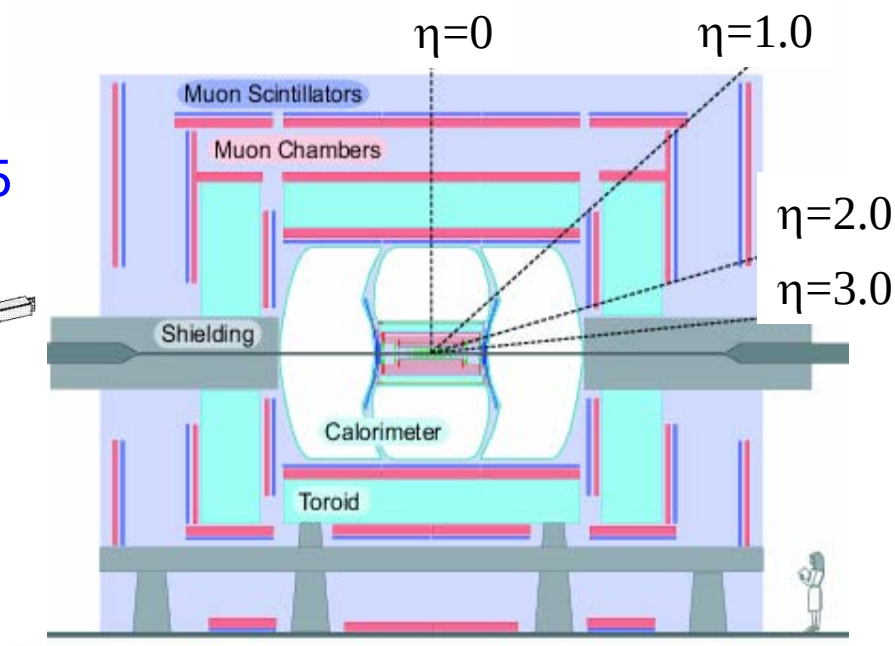
- Both e and γ: deposit energy in the EM calorimeter ($\rightarrow$EM object)
  - However, γ are uncharged, so leave no track in the tracking chamber
  - Whereas $e^{+/-}$ leave a track
- Muons: leave a track in the tracking chamber
  - deposit minimum energy in the calorimeters
  - leave tracks in the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



Tevatron Experiments: CDF & D0

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



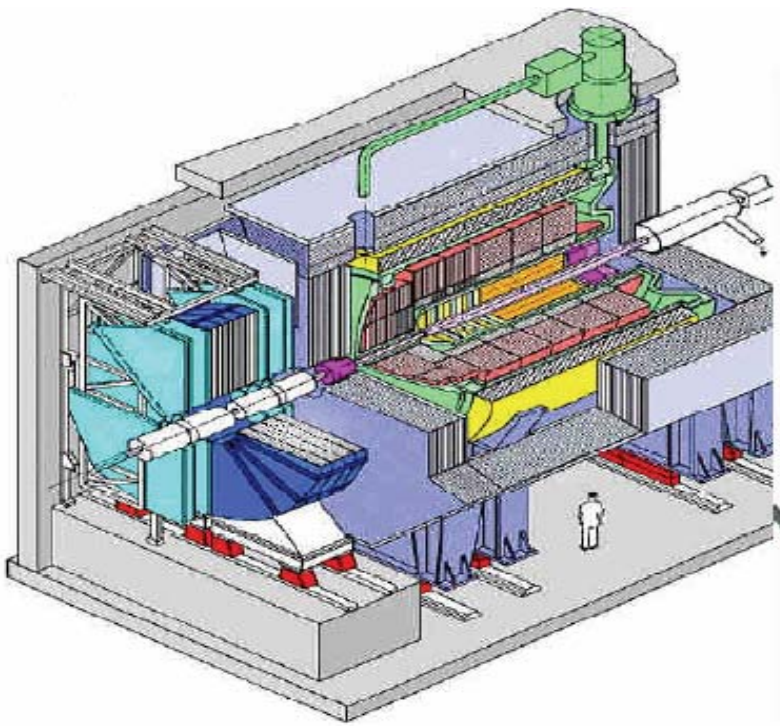


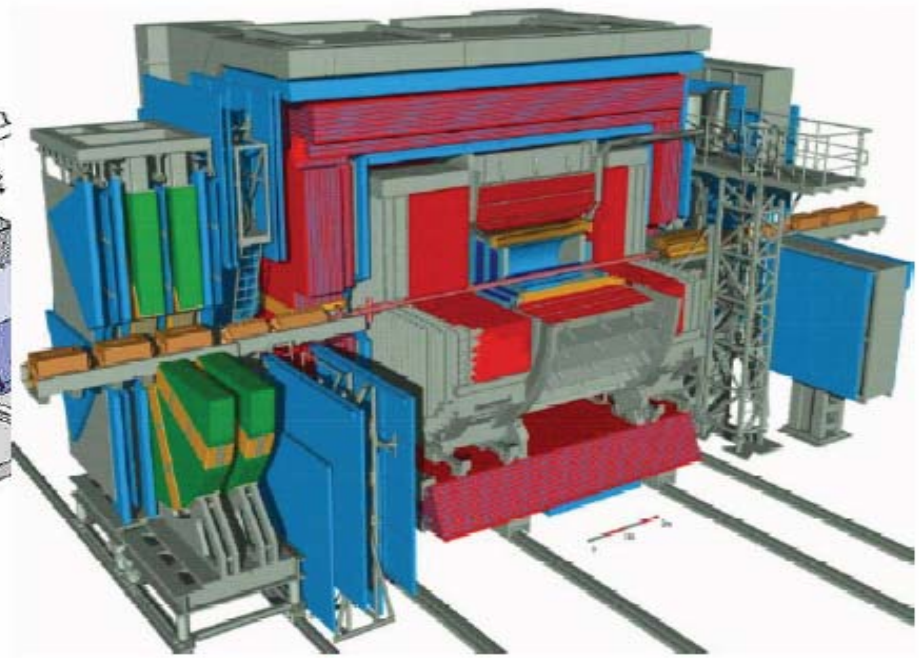
HERA: H1 & ZEUS

H1 is a finely segmented calorimeter

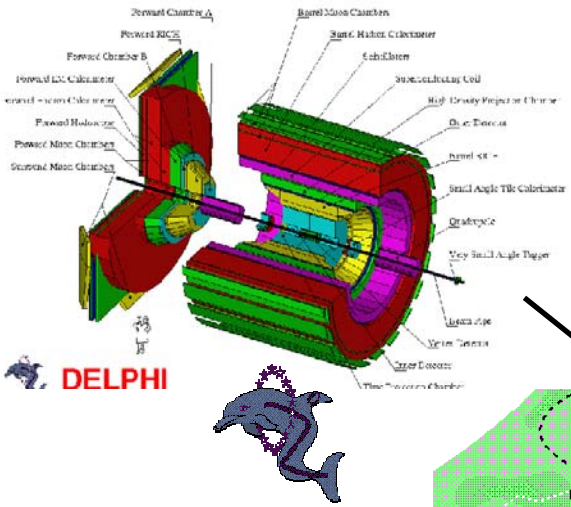
ZEUS has a compensating calorimeter

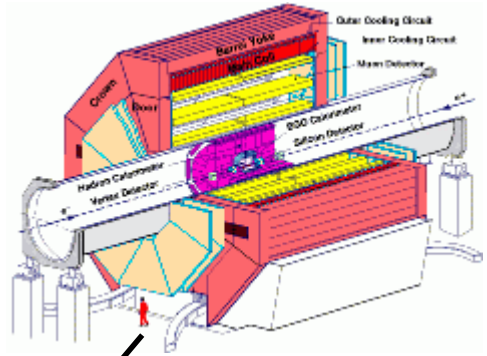
Both have good hermetic muon coverage



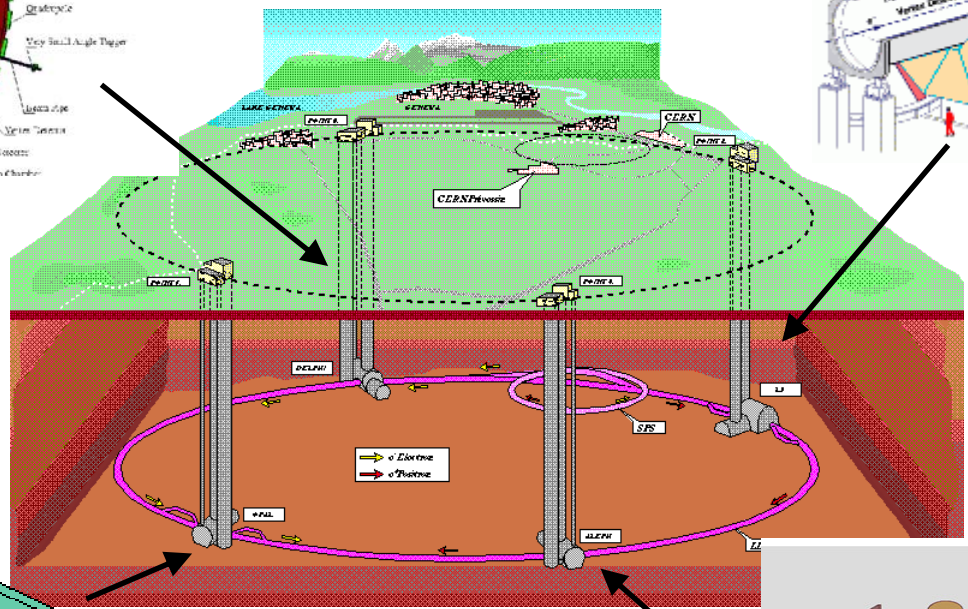


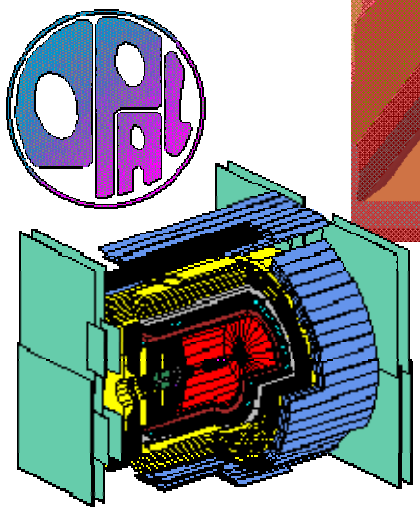
LEP Detectors

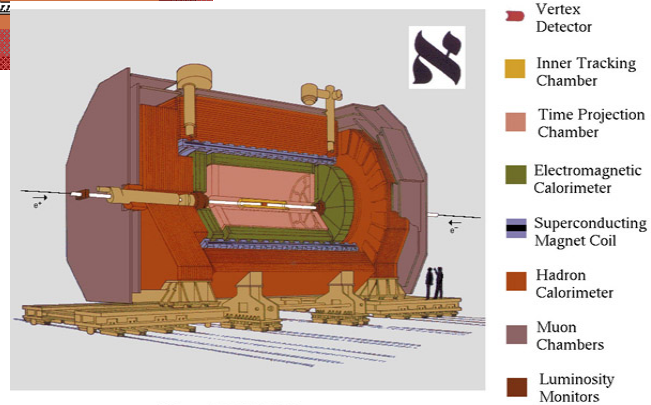




L3



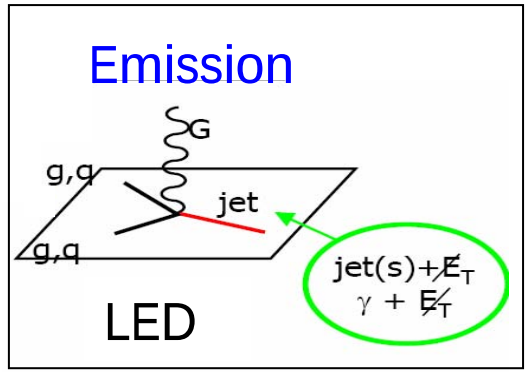


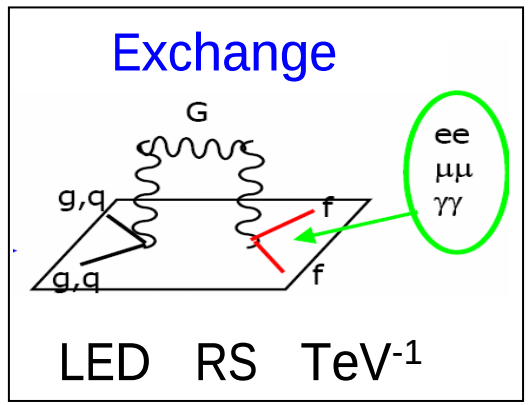


The ALEPH Detector

Summary of Searches performed

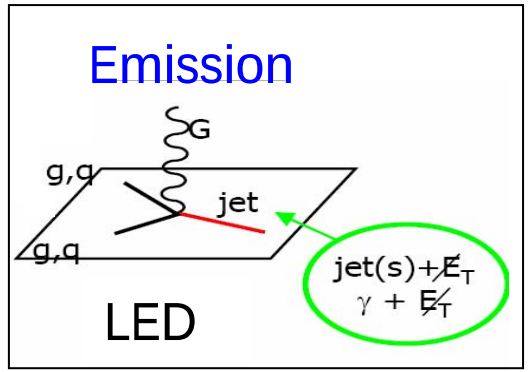
Signature		Experiment	Model
Graviton Emission	$\gamma + ME_T$	LEP, CDF	LED
	jets$+ME_T$	CDF, D0	
Graviton Exchange	$\mu\mu$	CDF, D0	LED, RS
	ee	CDF, D0	
	ee$+\gamma\gamma$	D0	
	$\gamma\gamma$	CDF	
	$e^{+/-}X$	H1	LED
Boson Exchange	ee		TeV^{-1}

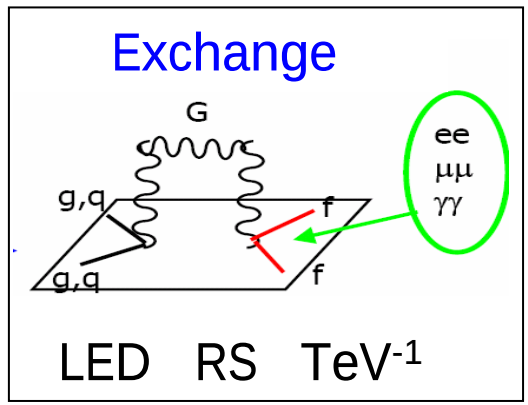




ED Searches

Signature		Experiment	Model
Graviton Emission	$\gamma + ME_T$	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}

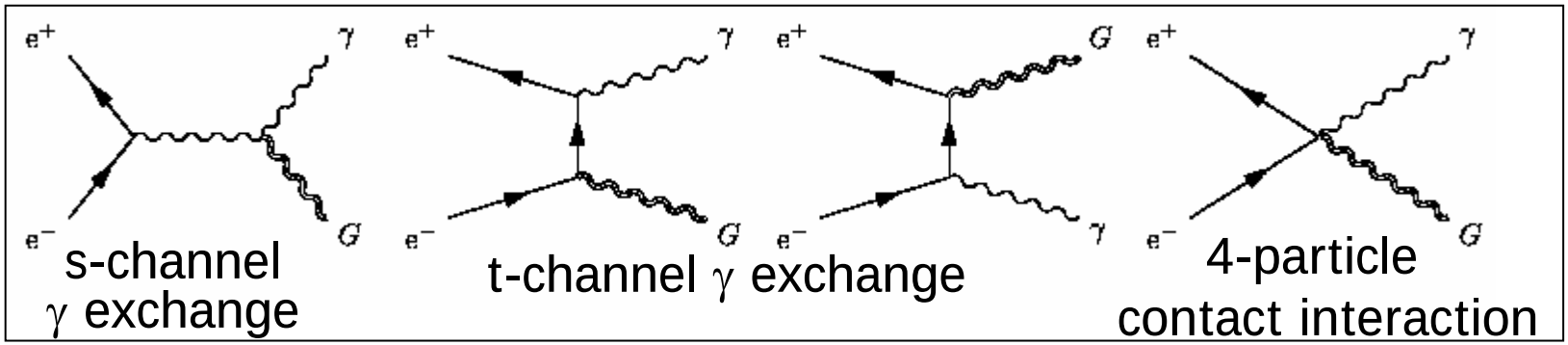




G emission: LEP $\gamma + ME_T$

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

G escapes detection: enhanced rate of $\gamma + ME_T$ events

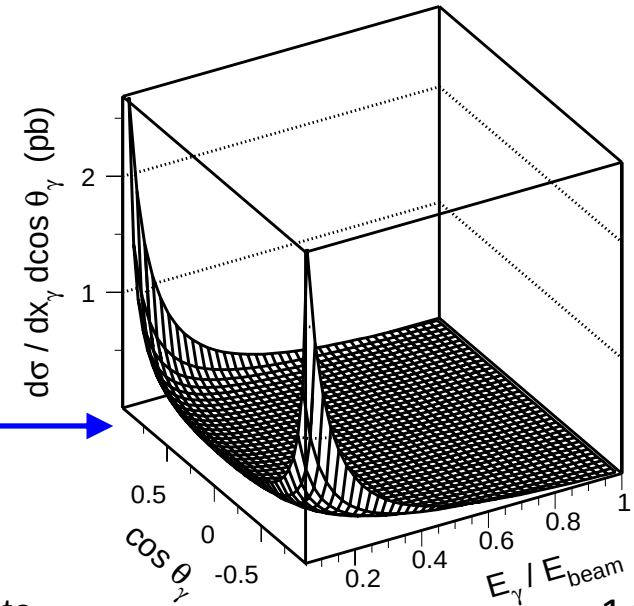


$$\frac{d^2\sigma}{dx_\gamma d\cos\theta_\gamma} = \frac{\alpha}{32s}\frac{\pi^{n/2}}{\Gamma(n/2)}\left(\frac{\sqrt{s}}{M_D}\right)^{n+2} f(x_\gamma, \cos\theta_\gamma)$$

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

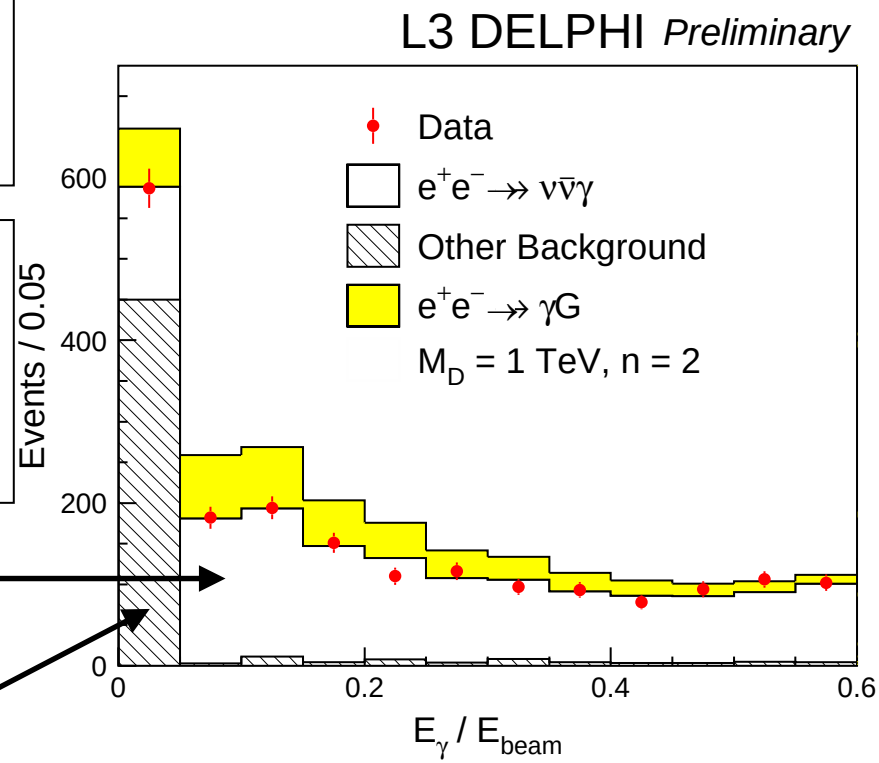


G emission: LEP $\gamma + ME_T$

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
$e^+e^- \rightarrow \nu\nu\gamma$
Other Background
$e^+e^- \rightarrow e^+e^-\gamma(\gamma)$



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

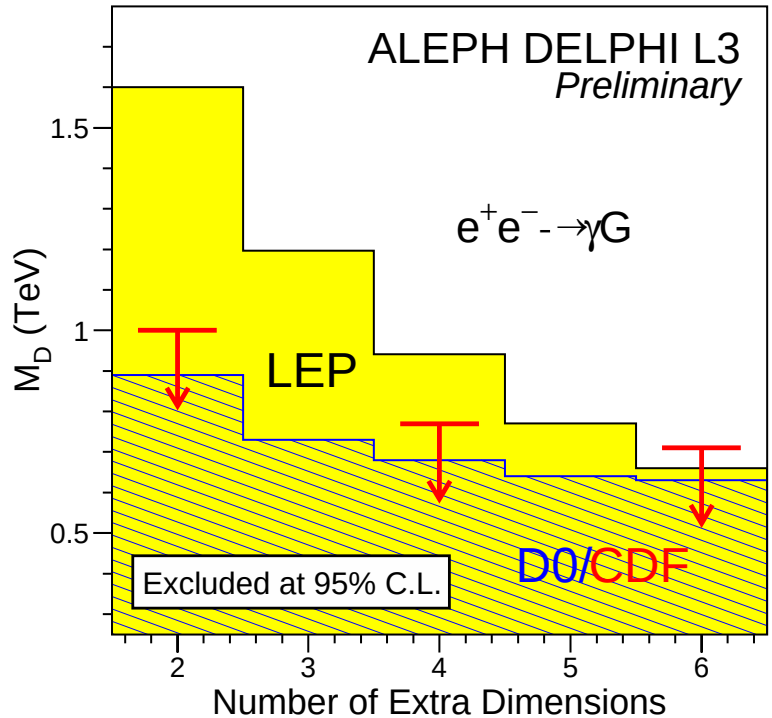
Good agreement with SM observed by all experiments

G emission: LEP $\gamma + ME_T$

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
$W\gamma$ ($\nu\gamma$)	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

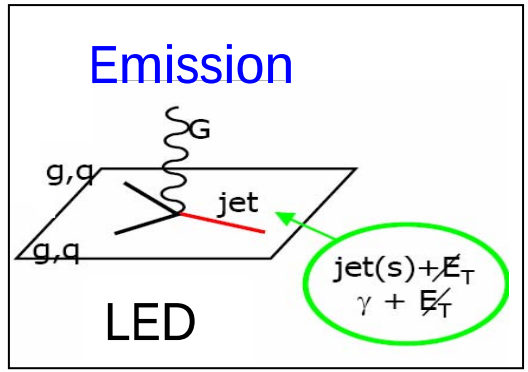
n=6 M_D > 0.58 TeV

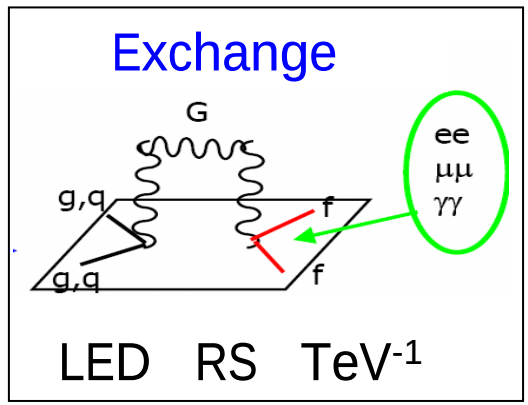
n=8 M_D > 0.60 TeV

Limits not as restrictive as LEP

ED Searches

Signature		Experiment	Model
Graviton Emission	$\gamma + ME_T$	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}



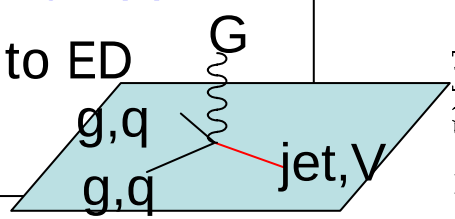


Real G Emission: jet(s)+ME_T

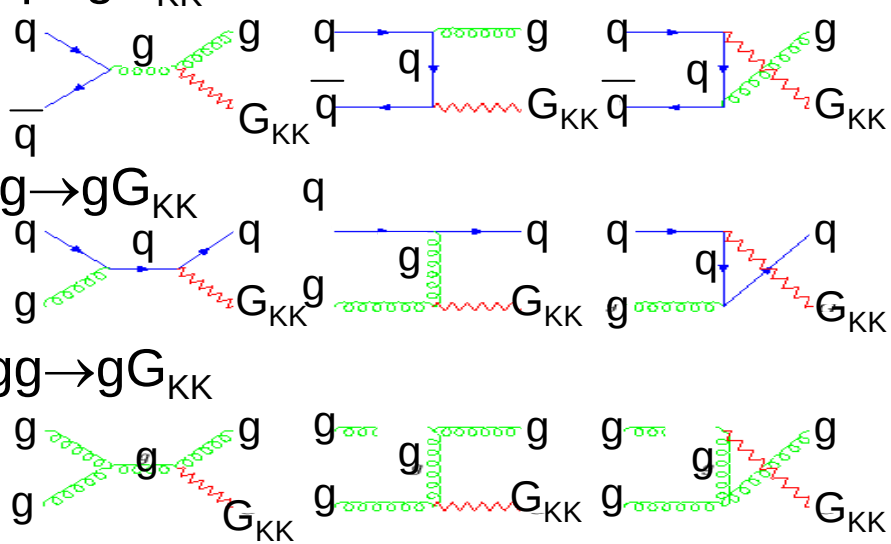
Better limits on G emission at the Tevatron from the jets + ME_T searches

Search Signature: pp → jet(s) + G

G escapes to detection into ED
→Events with large ME_T
Recoil jet very energetic

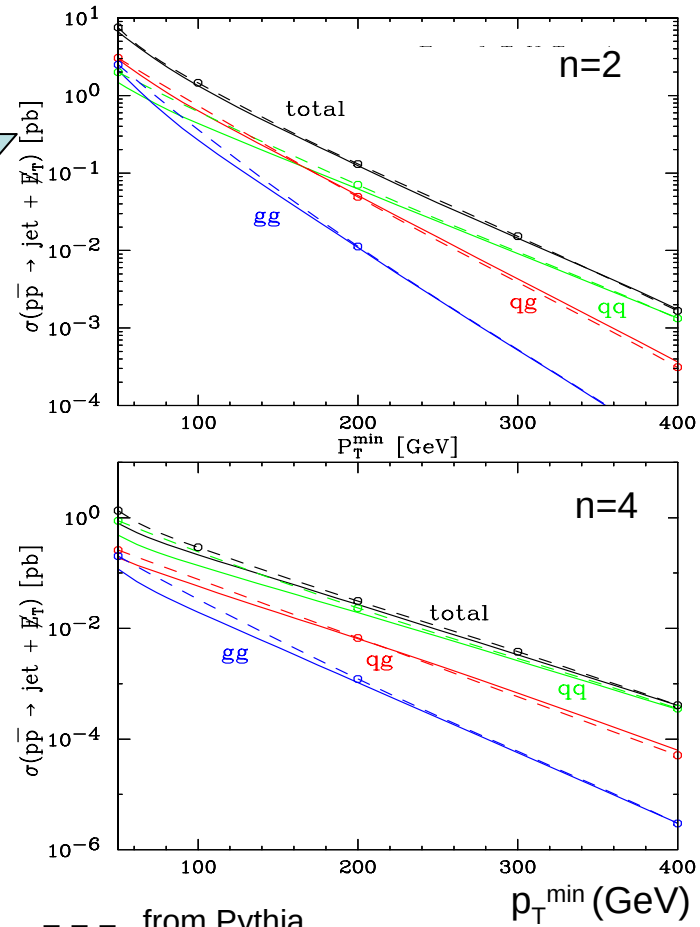


$q\bar{q}\to gG_{KK}$ dominate sub-process for n>2



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

Tevatron √s=2 TeV M_D = 1.2 TeV



- - - from Pythia

——— prediction from Giudice, Rattazi and Wells (hep-ph9811291)

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

Search Selection 84 pb^{-1} Run Ib

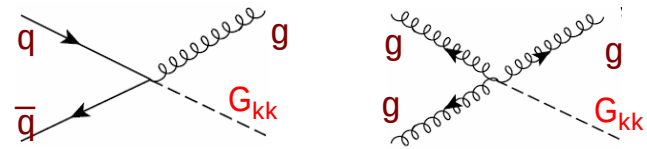
jet $E_T^{1st} \geq 80$ GeV, $|\eta| < 1.1$ and $ME_T > 80$ GeV
a second jet is allowed if $E_T^{2nd} > 30$ GeV
no isolated tracks in event ($p_T \geq 10$ GeV)

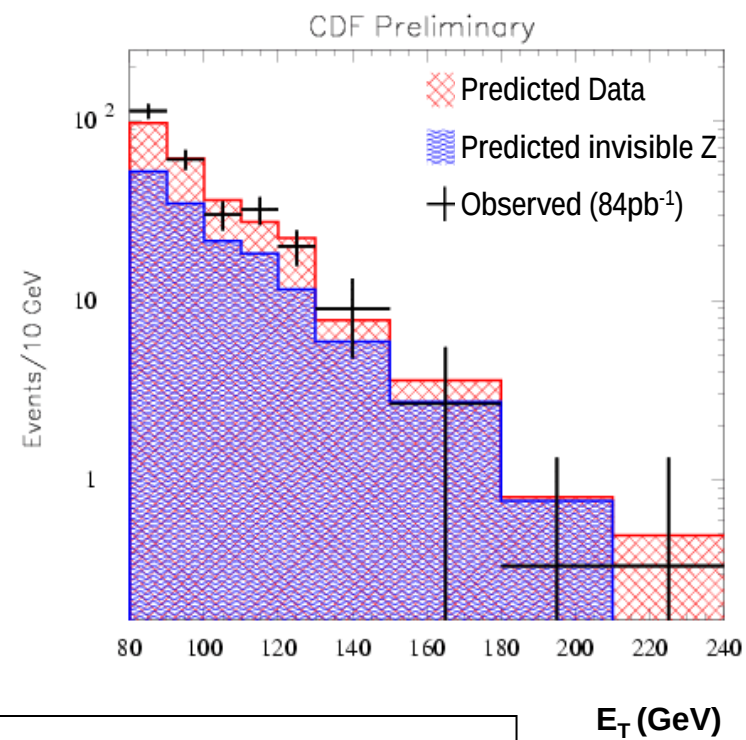
Main background

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 %





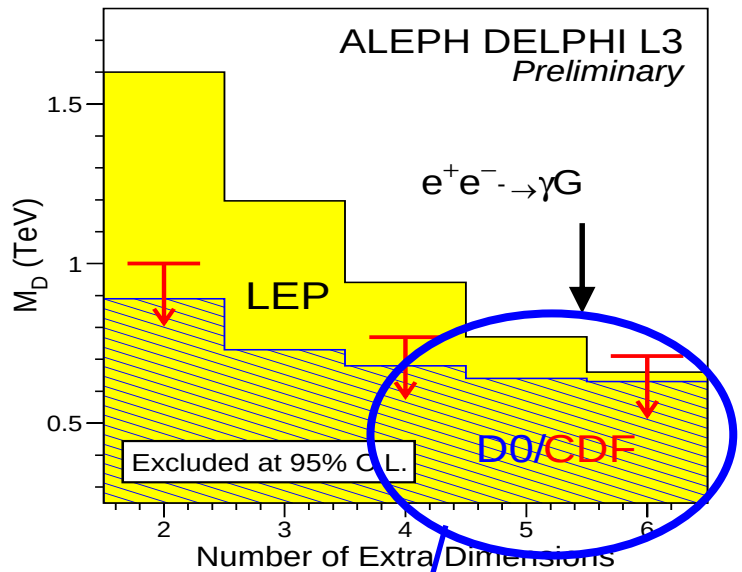
D0 have/also search for G emission (Run I & II): Monojet +ME_T
presently their limits are not as restrictive as CDFs

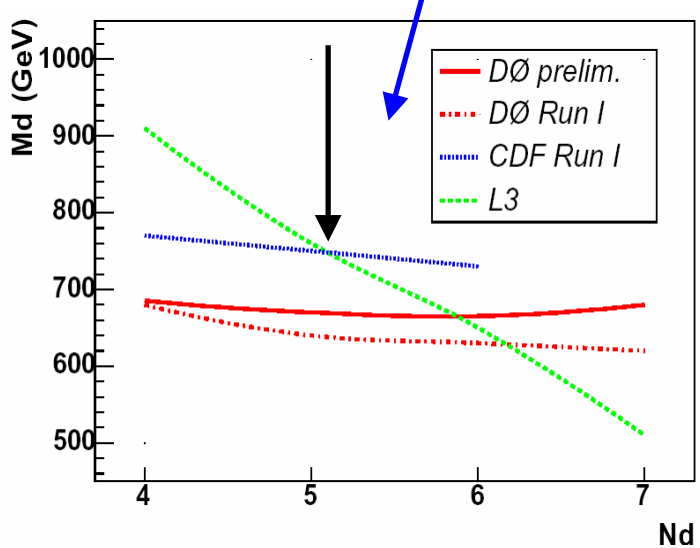
G Emission Summary

LEP and Tevatron results are complementary

For n<6:
LEP limits best $\gamma+ME_T$

LEP use $\gamma+ME_T$, 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

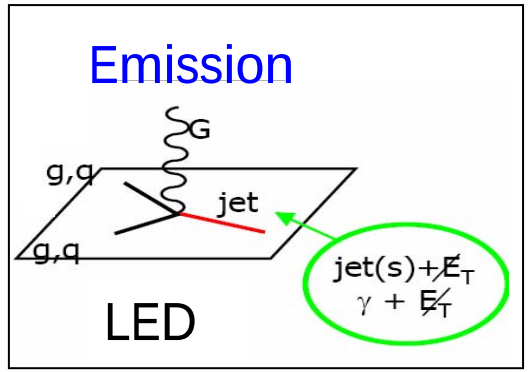
Tevatron better at large values of n,
because of the higher energy, which is a bigger effect at larger values of n.

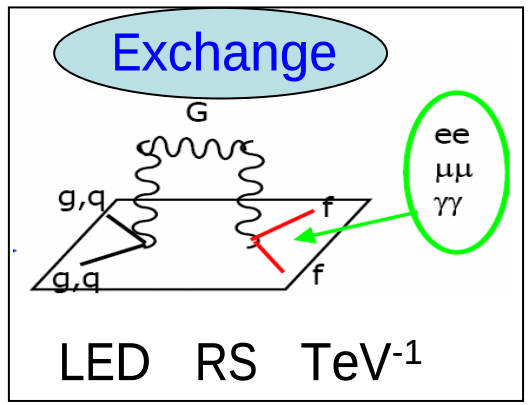
$\sigma \propto$ total number of possible modes in the KK tower N_{KK}
$\sigma \propto N_{KK} \propto \sqrt{(s\text{-hat})}$
But this is true for each ED, so $\sigma \propto (\sqrt{(s\text{-hat})})^n$

$\Rightarrow$the difference in energy is a bigger effect for n=6 than n=2

ED Searches

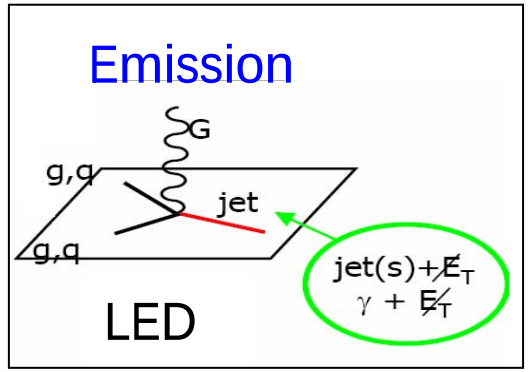
Signature		Experiment	Model
Graviton Emission	$\gamma + ME_T$	LEP, CDF	LED
	jets$+ME_T$	CDF, D0	
Graviton Exchange	ee$+\gamma\gamma$	D0	LED, RS
	ee	CDF, D0	
	$\mu\mu$	CDF, D0	
	$\gamma\gamma$	CDF	
	$e^{+/-}X$	H1	LED
Boson Exchange	ee		TeV^{-1}

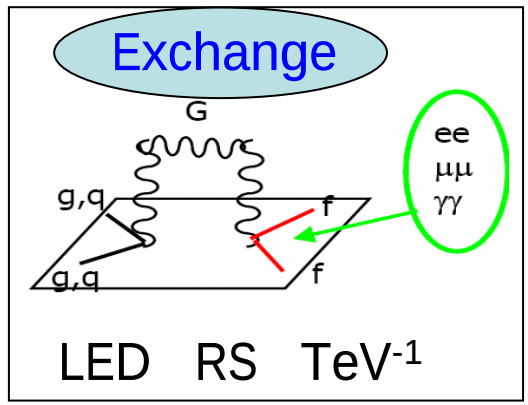




ED Searches

Signature		Experiment	Model
Graviton Emission	$\gamma + ME_T$	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}





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

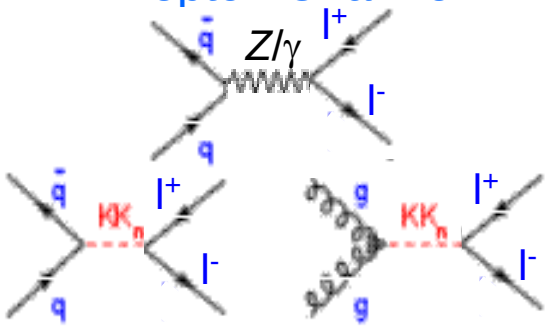
Search for G Exchange?

Similarities

Search Signature

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

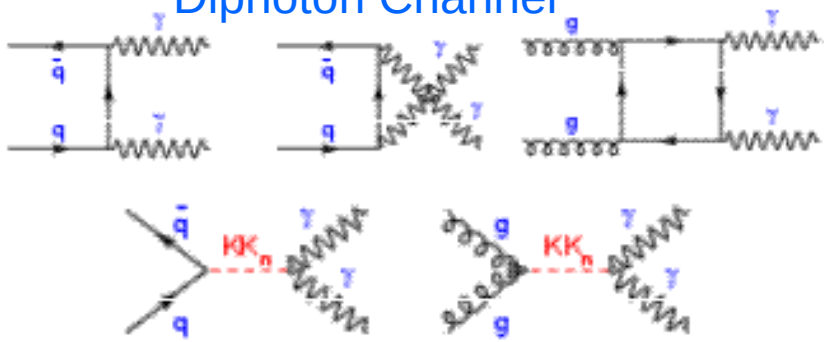
Dilepton Channel



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

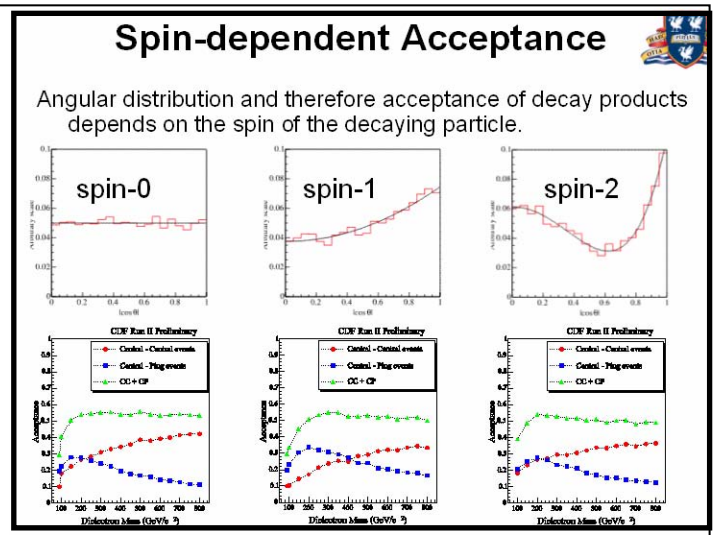
Spin 2 graviton – used to distinguish between other new physics

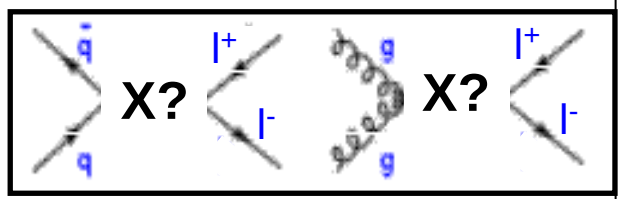
Tevatron Exchange Search Strategies

CDF Search Strategy: ee, μμ, γγ

- 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 & μμ): Spin-0 : RPV sneutrinos
Spin-1 : Z', Technicolor ρ, ω
Spin-2 : RS G, LED, etc..



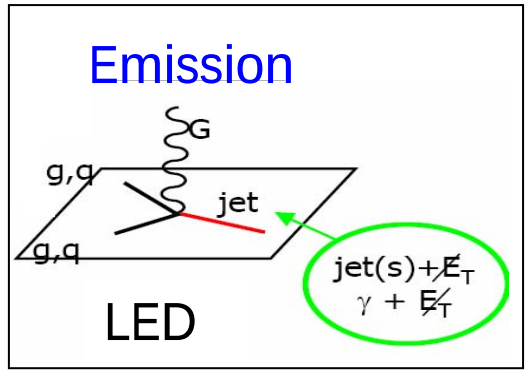


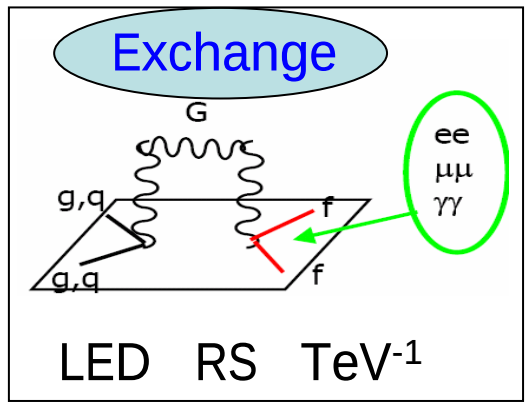
D0 Search Strategy: ee, μμ, γγ

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

ED Searches

Signature		Experiment	Model
Graviton Emission	$\gamma + ME_T$	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*

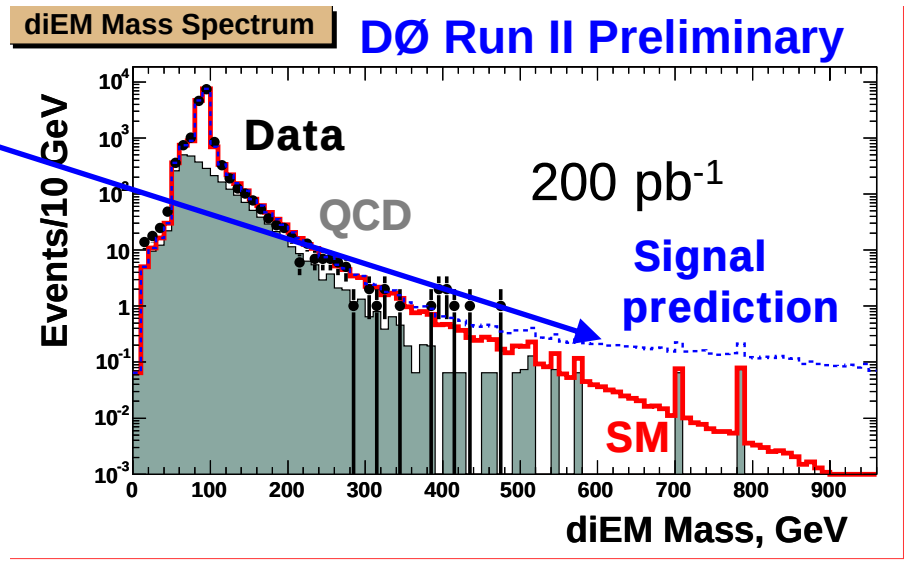
Search for spin-2 broad σ change

⇒ 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....

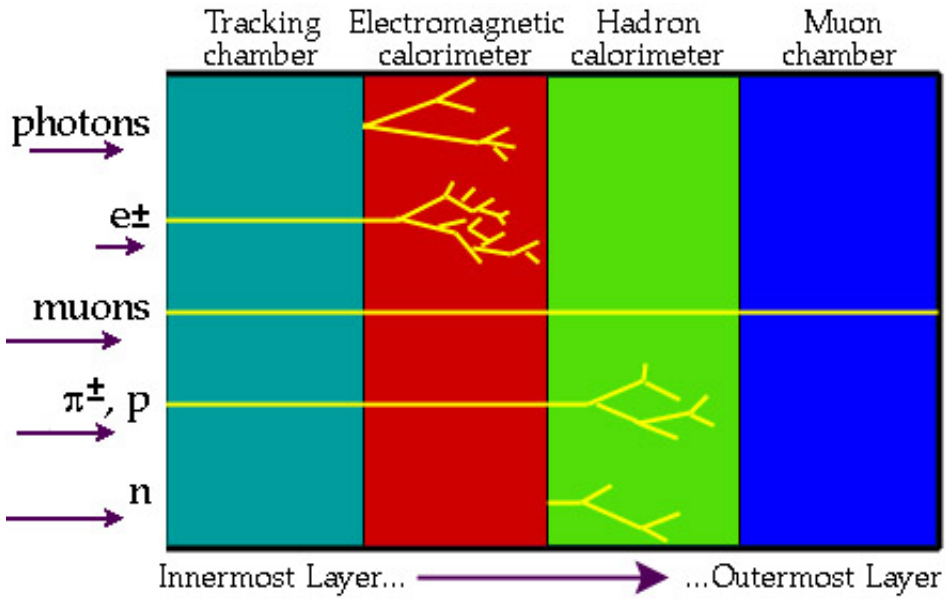
e/γ Id/Misid-entification in Detectors

Similarities

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

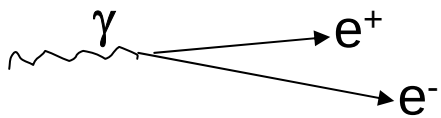
Differences

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



Inefficiencies arise if:

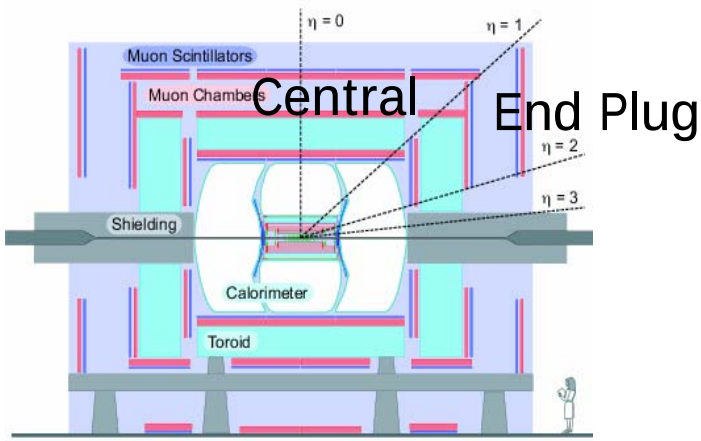
- γ ID requires no track, but γ converts (→ee)
- e ID requires a track, but loose track due to imperfect track reconstruction/crack



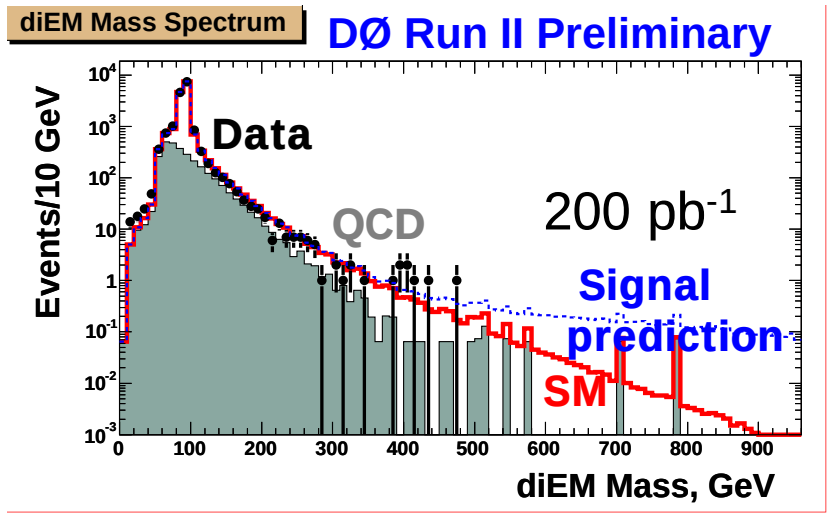
To maximise reconstruction efficiency: D0 combine ee+γγ ⇒ diEM search

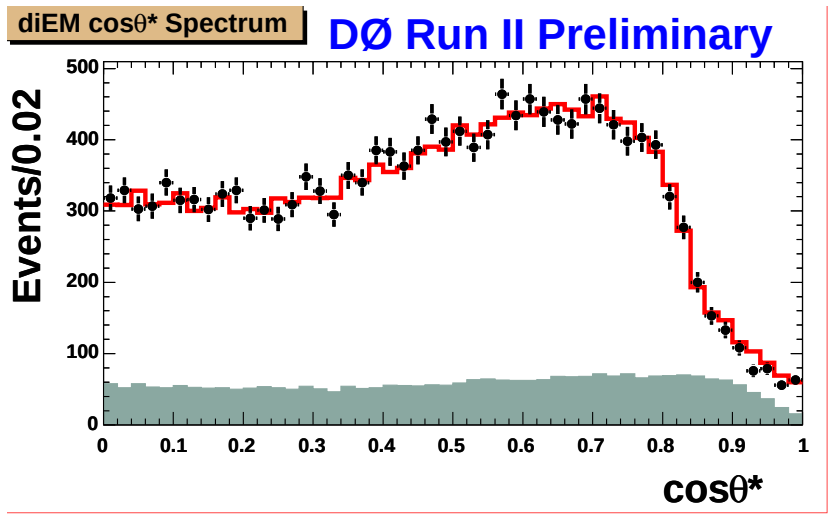
G Exchange: D0 ee+$\gamma\gamma$ ADD LED

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



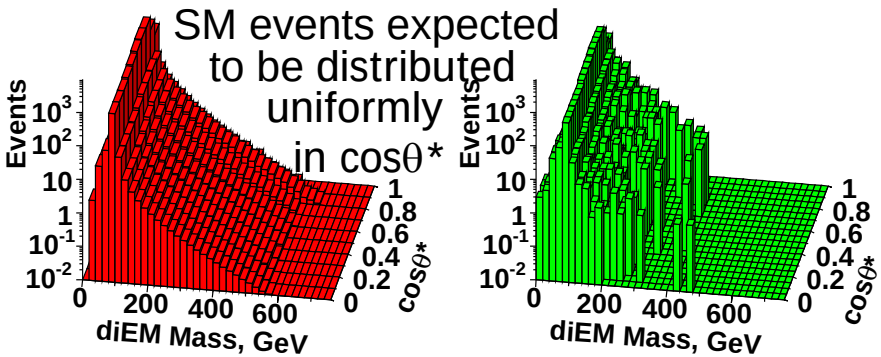


D0 ee+$\gamma\gamma$ ADD LED

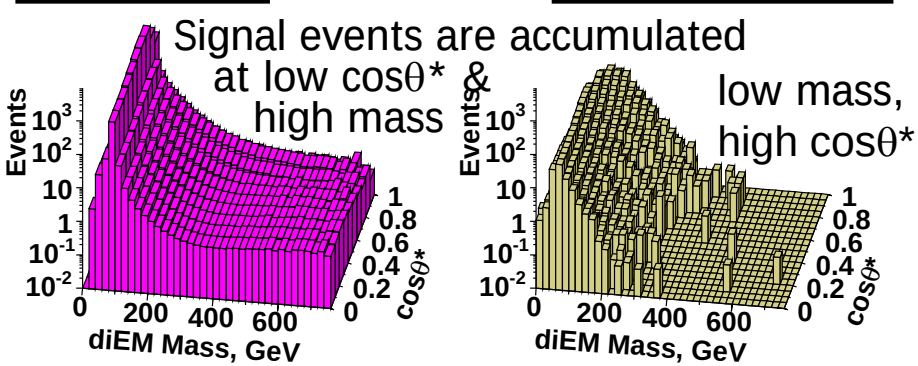
D0 perform a combined fit of the invariant mass and angular information

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

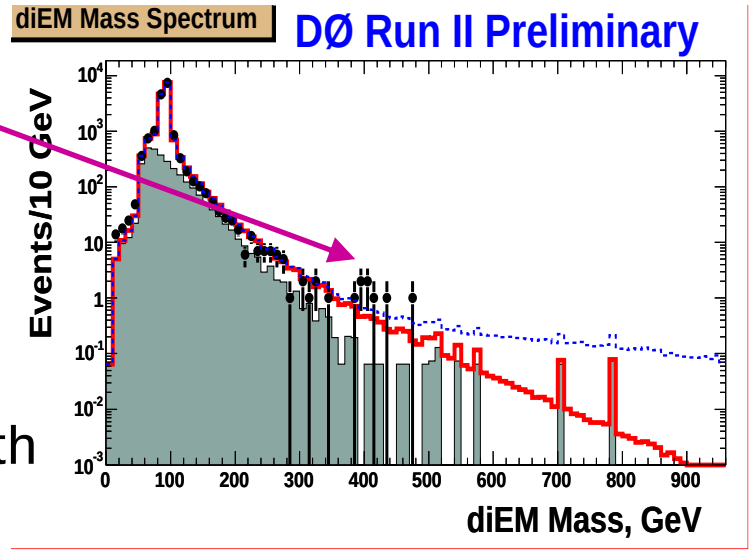
$$\eta = \lambda / M_s^4$$

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

- 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 γγ

⇨ excellent candidates for new physics beyond the SM!

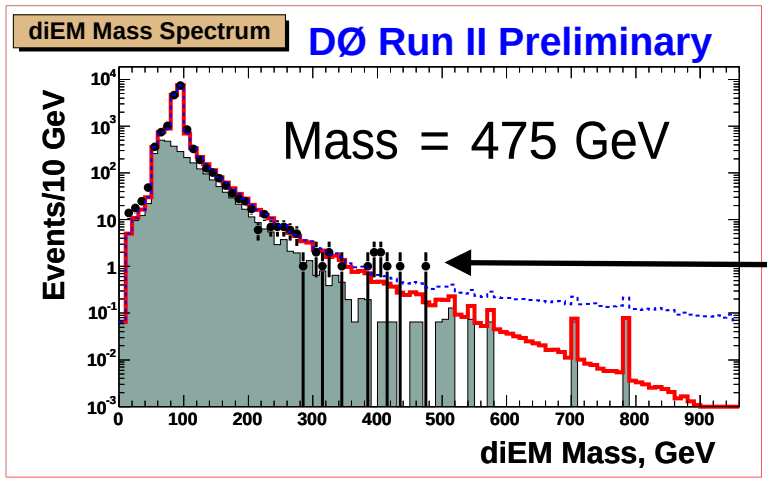
i.e. possess kinematics typical of signal from large ED. (Very high scattering angle: close to π/2.)

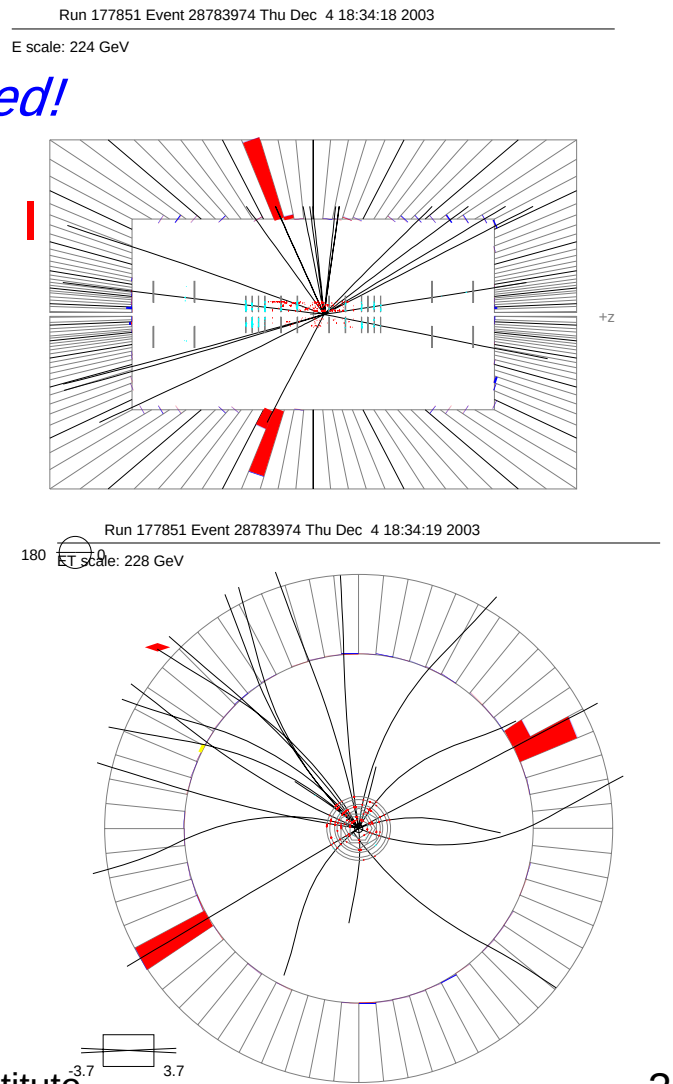
Intriguing events – but consistent with the SM

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

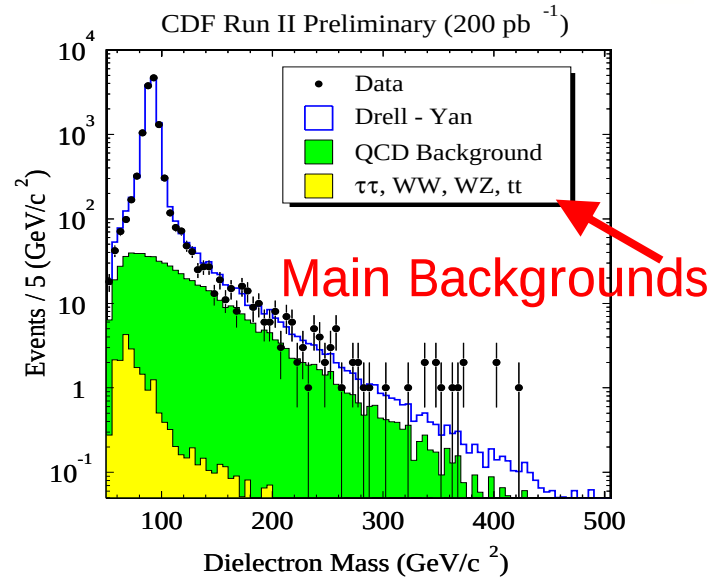
2 central e (CC)

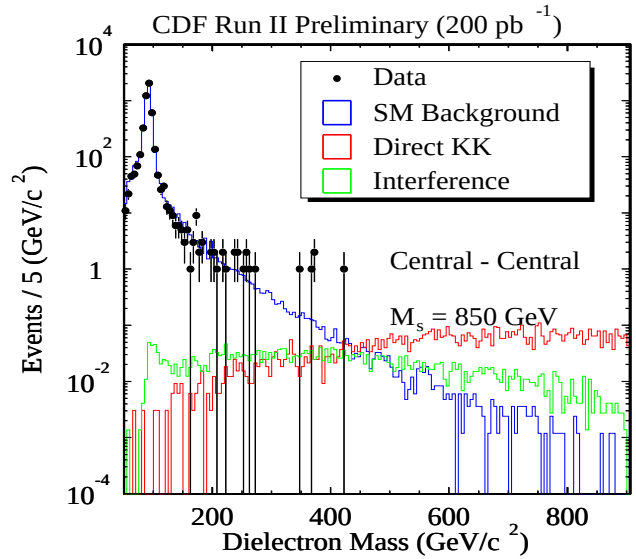
or 1 central and 1 forward e (CP)

N_{exp}=11.1 N_{obs}=14 for M_{ee}>300 GeV/c^2

N_{exp}= 4.6 N_{obs}= 9 for M_{ee}>350 GeV/c^2

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





D0 μμ ADD LED

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

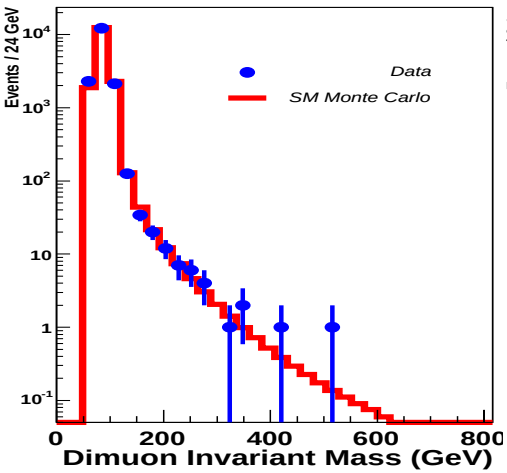
Search Selection 250 pb^{-1}

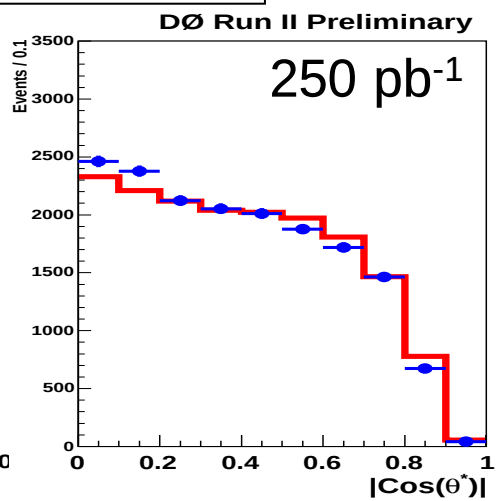
$p_T^{\mu1,\mu2}$>15 GeV

Isolated tracks

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

Cosmics removed

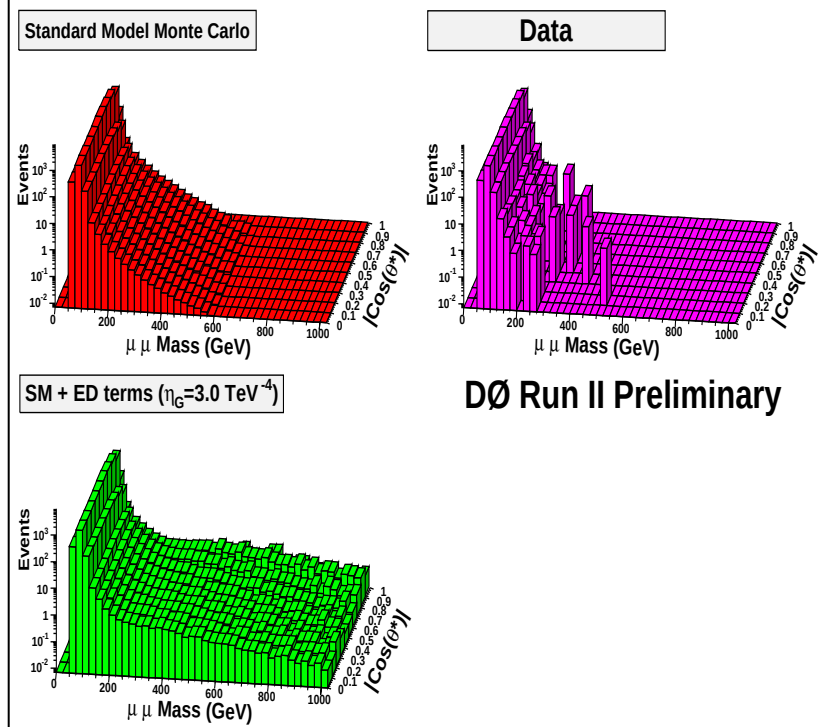




N_{exp}=6.4 N_{obs}=5 for M_{ee}>300 GeV/c^2

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

3D fits to extract limits



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:

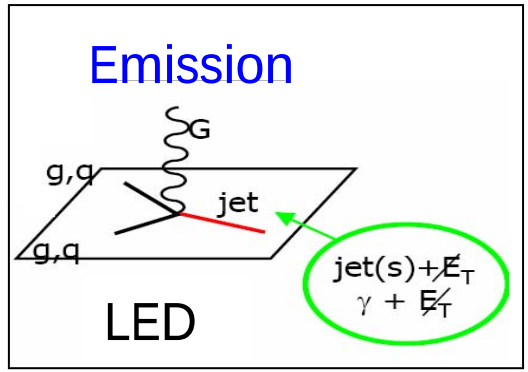
	GRW	HLZ for n=						Hewett
		2	3	4	5	6	7	λ=+1/-1
D0 Run II: $\mu\mu$	1.09	1.00	1.29	1.09	0.98	0.91	0.86	0.97/0.95
D0 Run II: ee+$\gamma\gamma$	1.36	1.56	1.61	1.36	1.23	1.14	1.08	1.22/1.10
D0 Run I+II: ee+$\gamma\gamma$	1.43	1.61	1.70	1.43	1.29	1.20	1.14	1.28/NA
CDF Run II: ee	1.11		1.32	1.11	1.00	0.93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

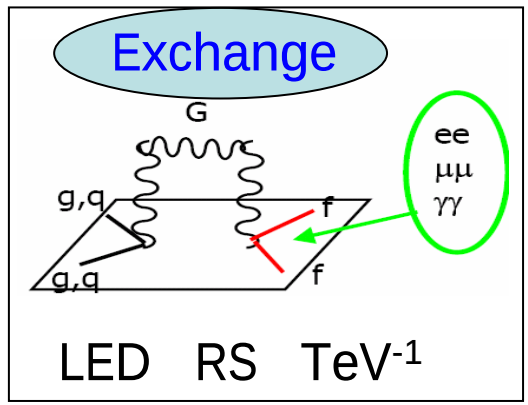
D0 Run II $\mu\mu$ result: tightest limits on LED from a single measurement in this channel!

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	$\gamma + ME_T$	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}





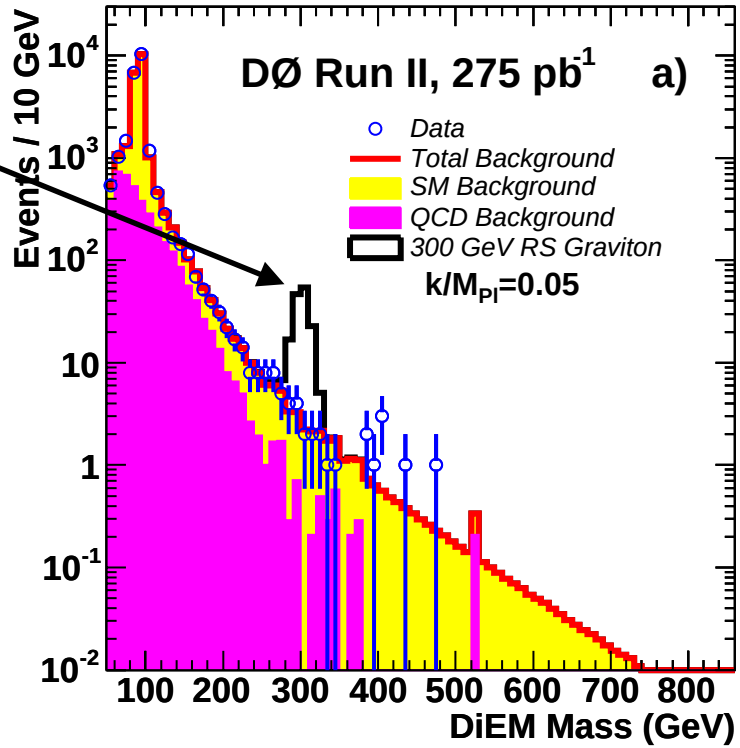
G Exchange: D0 RS ee+$\gamma\gamma$

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

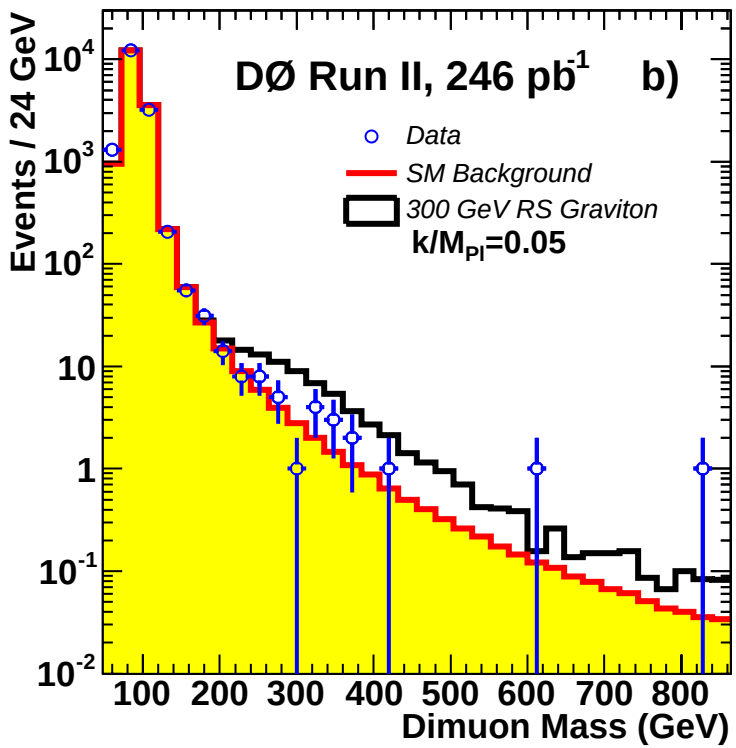


G exchange: D0 RS μμ

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



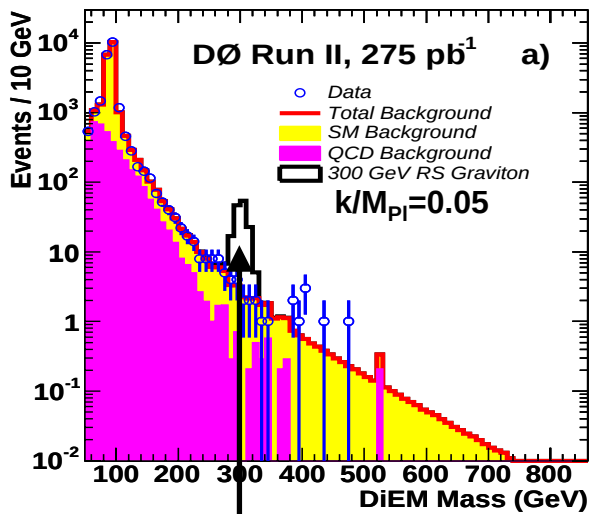
N_{obs}=17128

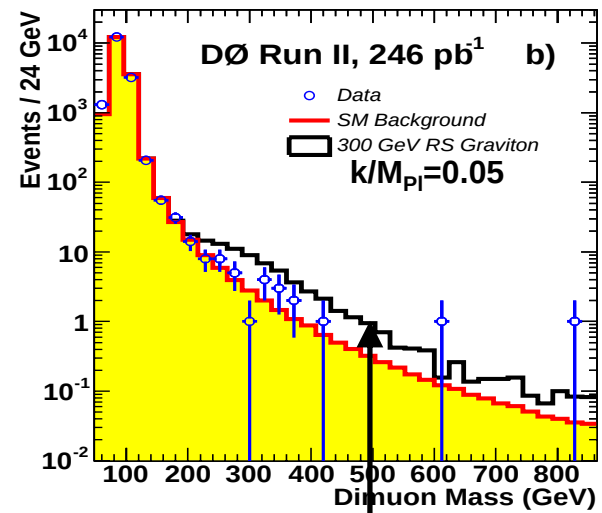
Good agreement between data and expected background

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





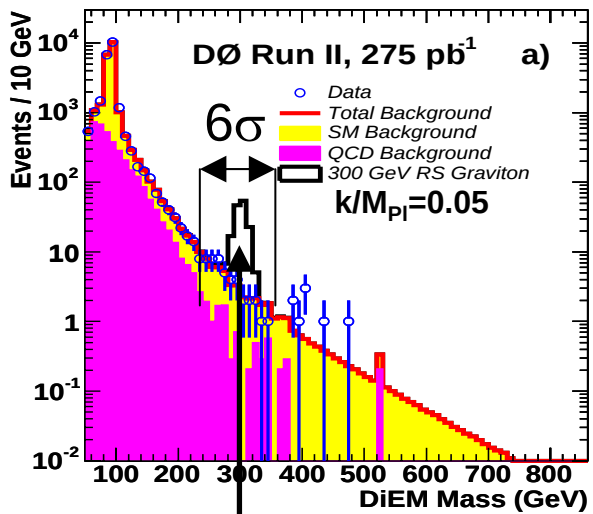
ee+$\gamma\gamma$: EM energy determined using calorimeters

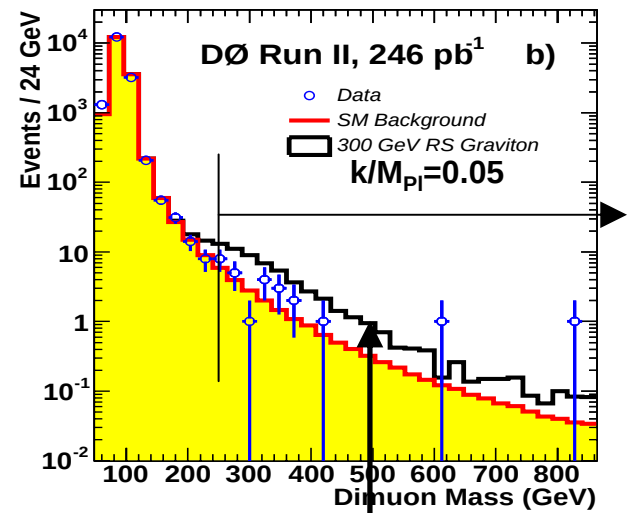
$\mu\mu$: p_T measured in tracker

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





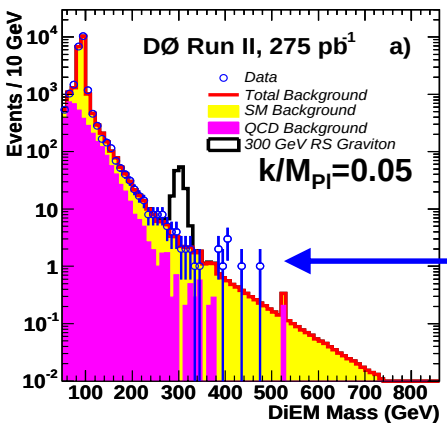
ee+$\gamma\gamma$: EM energy determined using calorimeters

$\mu\mu$: p_T measured in tracker

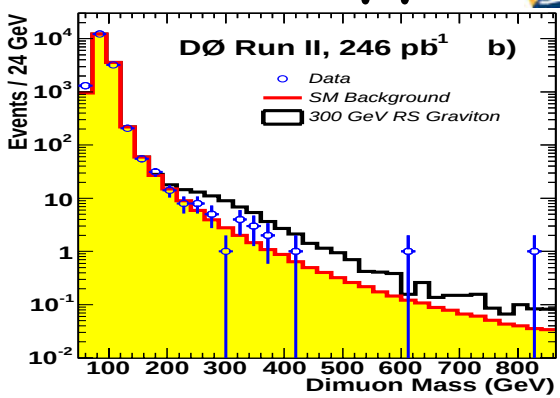
⇒ Symmetric windows
width 6 x detector resolution

⇒ 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

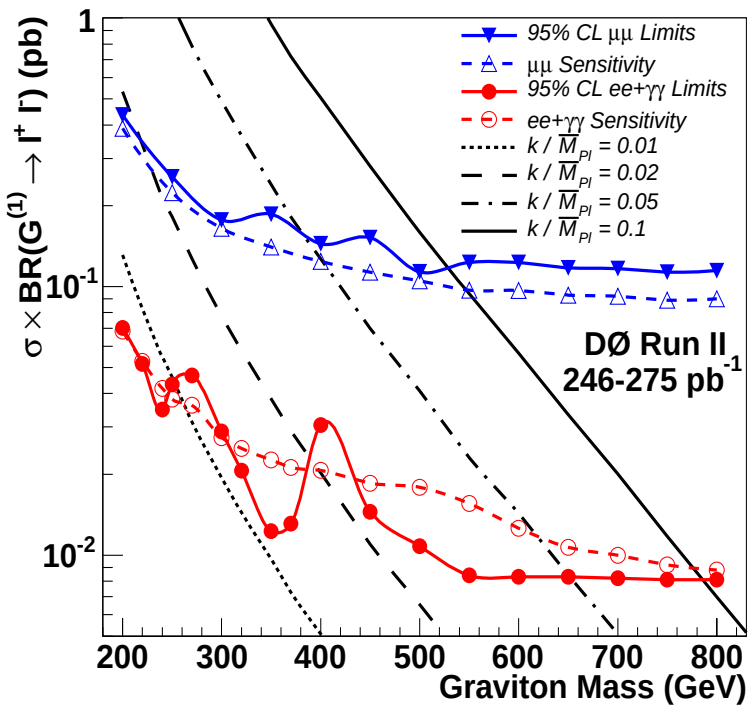


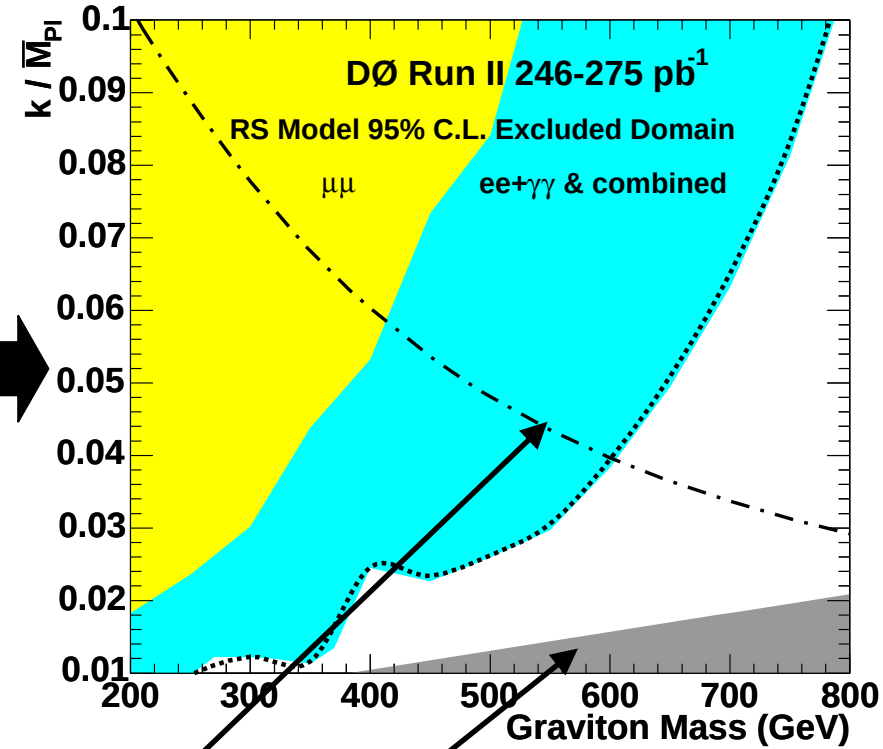
Small excess in μ channel

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!

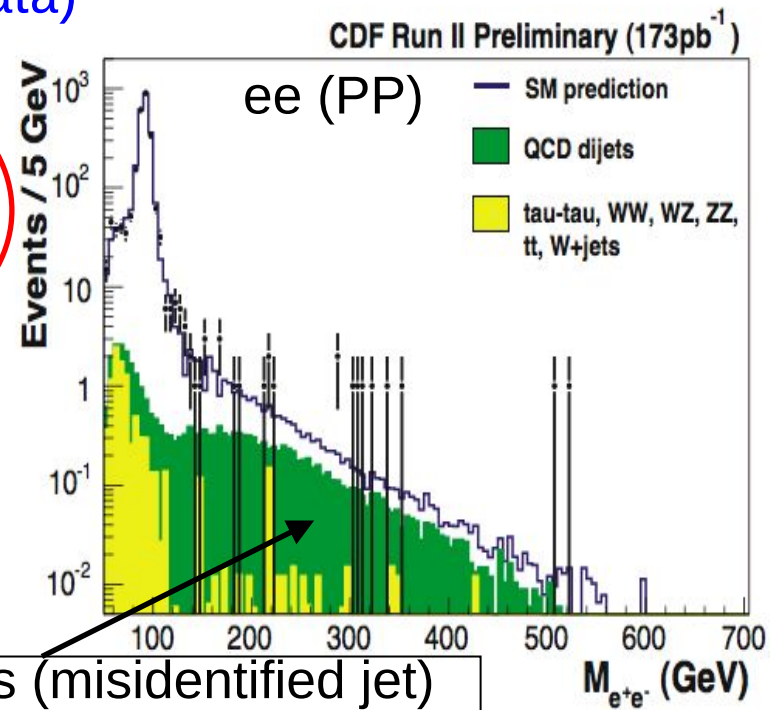
G exchange: CDF RS ee (PP)

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

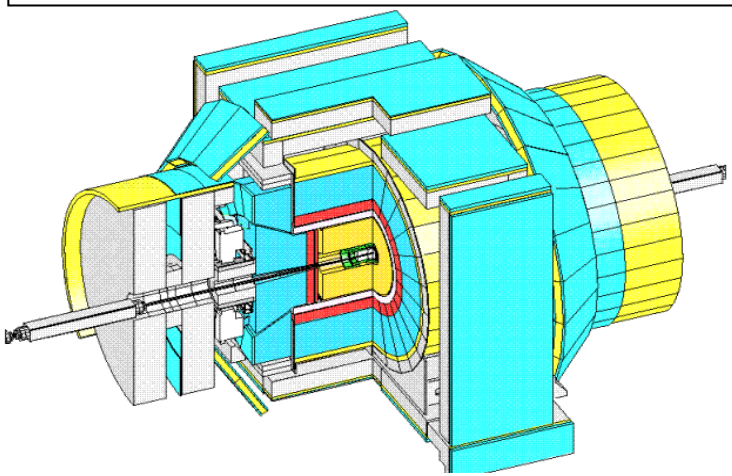
- include CC + CP (same as ADD ee data)
- add PP ee events

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

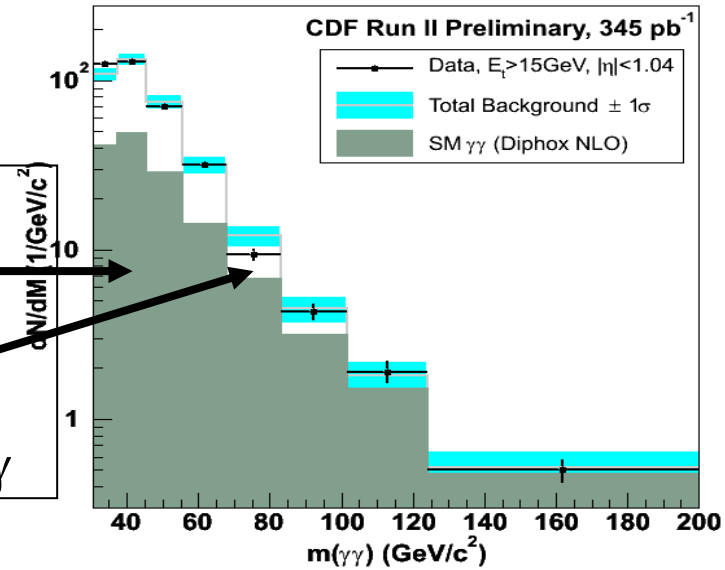
G exchange: CDF RS $\gamma\gamma$

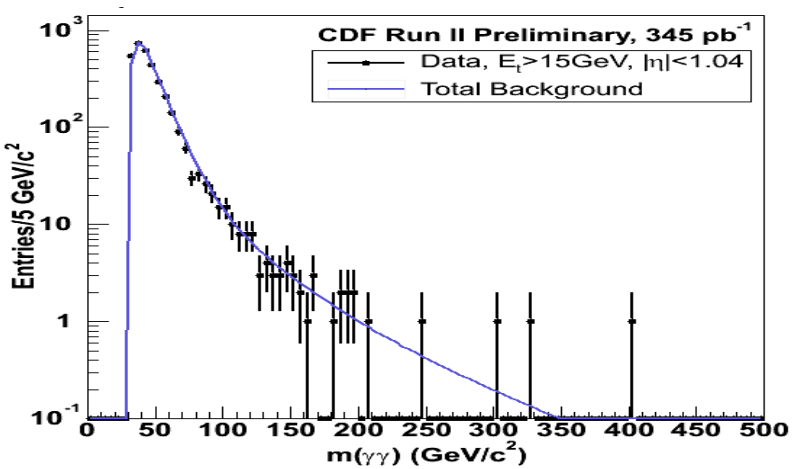
Search Selection

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 $\pi^0 \rightarrow \gamma\gamma$



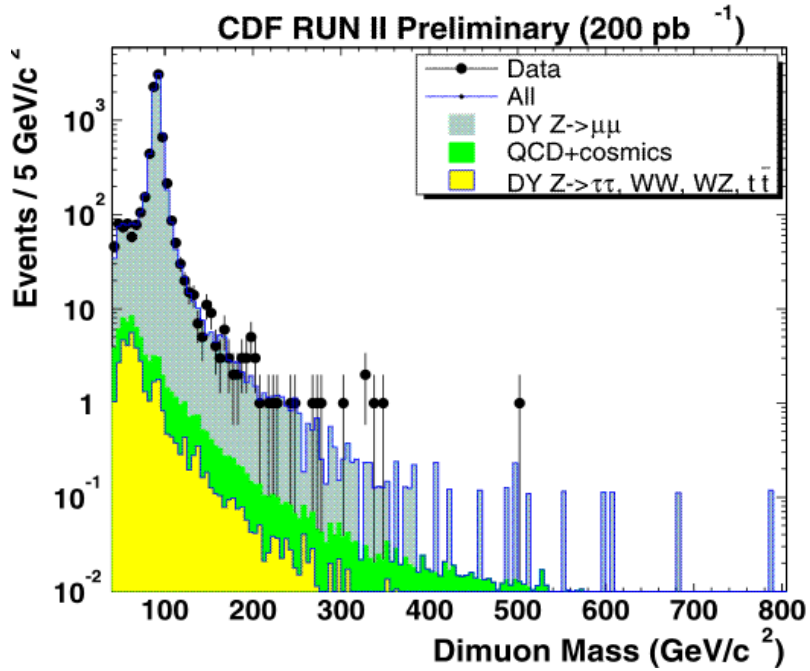


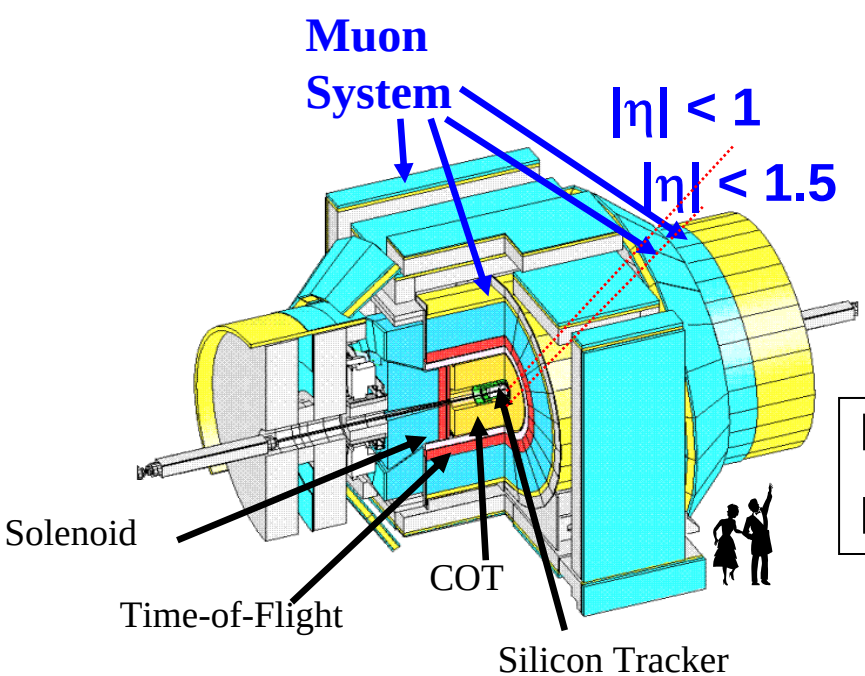
N_{exp}=4.2±1.0 N_{obs}=1 for M_{ee}>300 GeV/c^2

N_{exp}=1.5±0.5 N_{obs}=1 for M_{ee}>350 GeV/c^2

G Exchange: CDF RS μμ

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





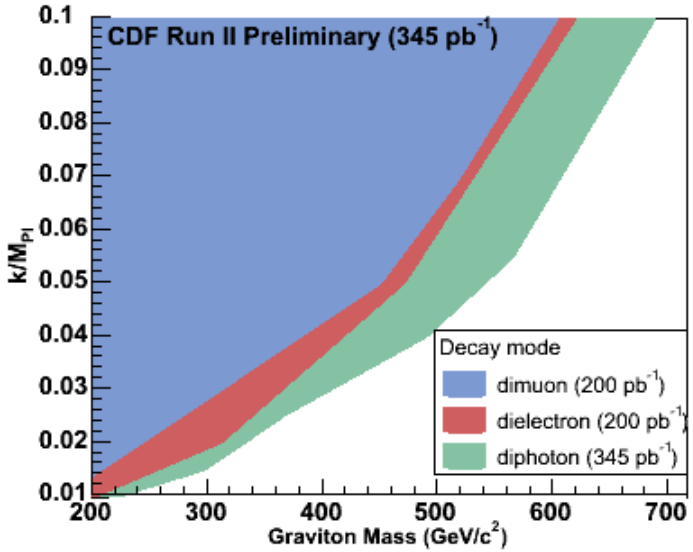
N_{exp}=5.2 ± 0.3 N_{obs}=6 for M_{ee}>300 GeV/c^2
N_{exp}=3.2 ± 0.2 N_{obs}=1 for M_{ee}>350 GeV/c^2

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

CDF RS Graviton Limits

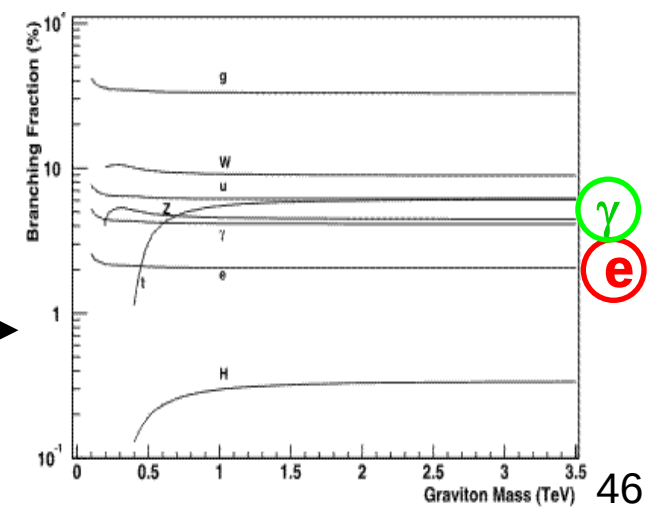
Setting 95 % C.L. upper limits on σ.BR($\sigma \rightarrow \gamma\gamma$/ll):

- $\gamma\gamma$: Like D0 ee+$\gamma\gamma$, CDF use $\pm 3\sigma$ windows around M_G, but in 1D only
- ee+$\mu\mu$: 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
$\mu\mu$	200	170	610
ee+$\mu\mu$	200	200	700
$\gamma\gamma$	345	220	690

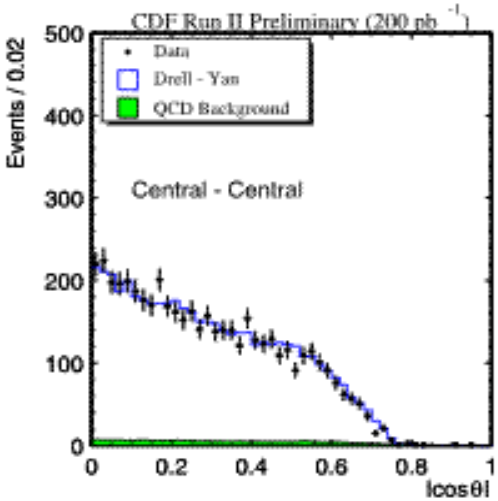
- **ee** has largest acceptance at low mass
- $\gamma\gamma$ has largest acceptance at high mass
- BR(**G**$\rightarrow\gamma\gamma$) = 2 * BR(**G**$\rightarrow$**ee**)

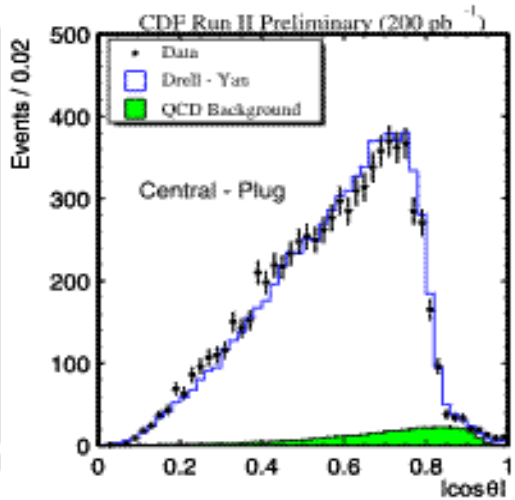


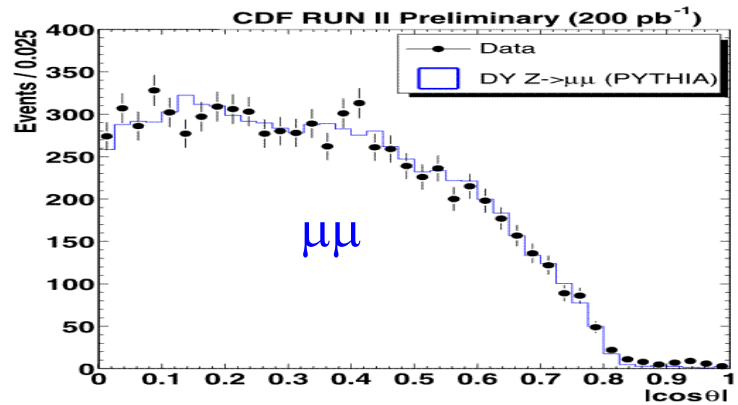
CDF limits not as exclusive as D0's

G exchange: CDF RS Searches

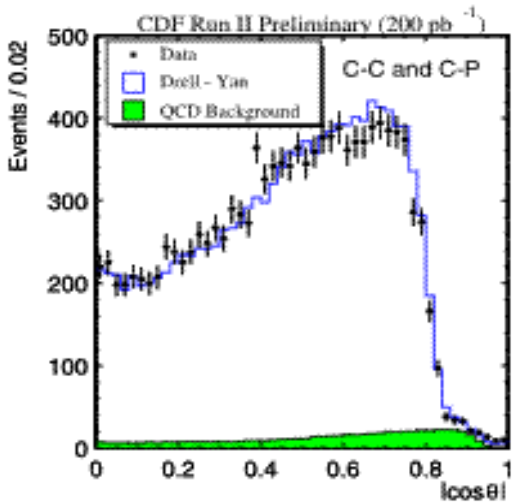
CDF perform 1-D fits, but also study (ee, $\mu\mu$, $\gamma\gamma$) angular distributions

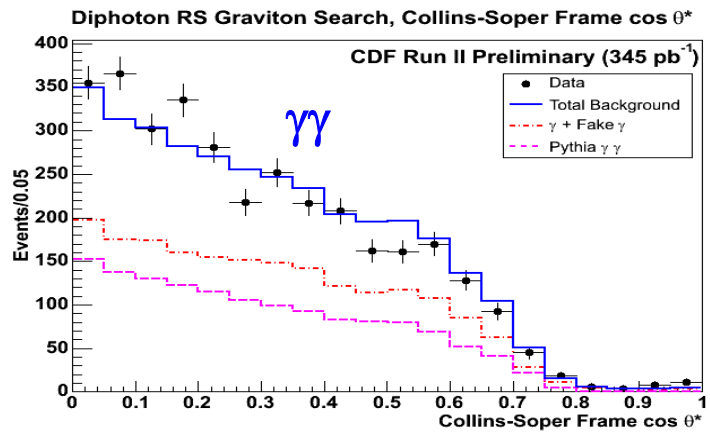






ee

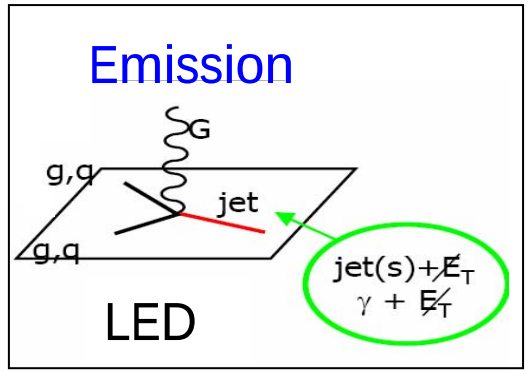


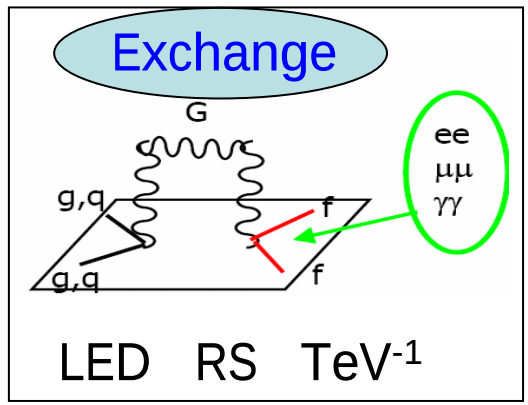


Good agreement with SM prediction

ED Searches

Signature		Experiment	Model
Graviton Emission	$\gamma + ME_T$	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}



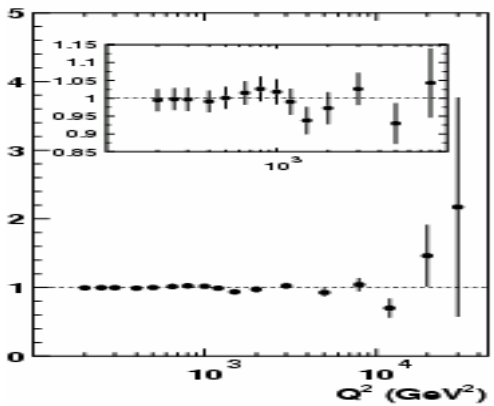


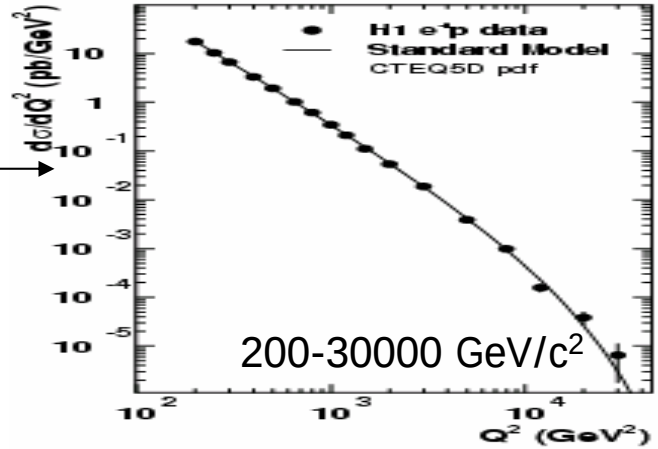
H1 LED Searches

H1 Search Strategy

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





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

- 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)

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.

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

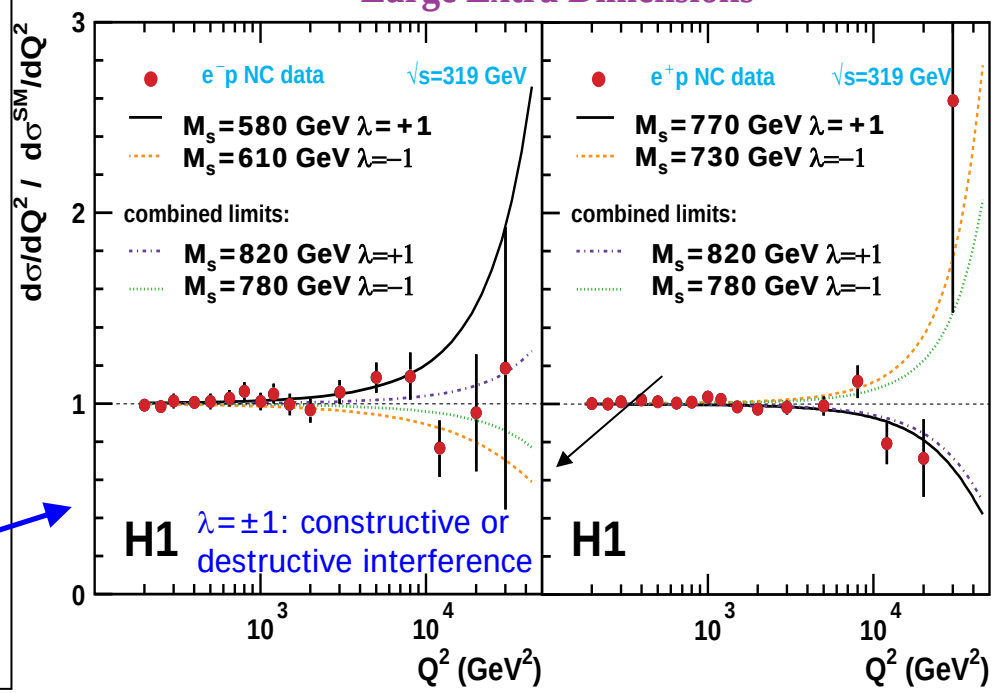
To Set Limits

- Parameterise σ in terms of $\eta = \lambda / M_s^4$

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

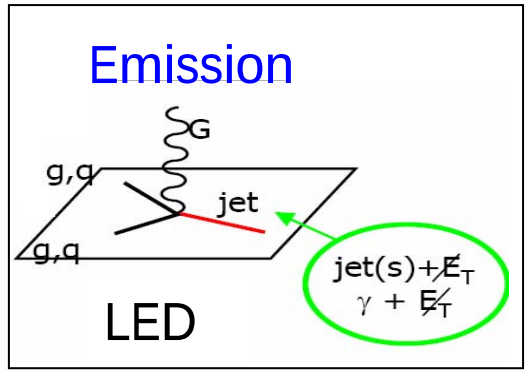
- Fit the differential σ to the formula above treating λ/M_s^4 as a free parameter
- Extract limits on M_s

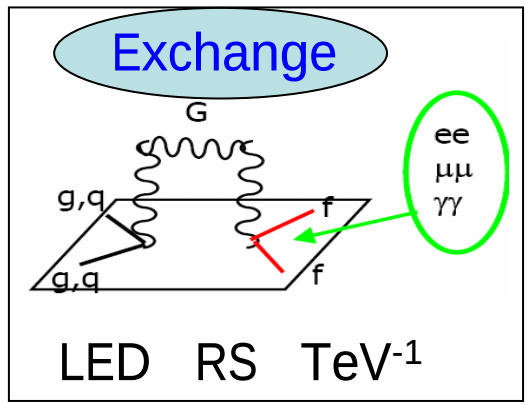
Large Extra Dimensions



ED Searches

Signature		Experiment	Model
Graviton Emission	$\gamma + ME_T$	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

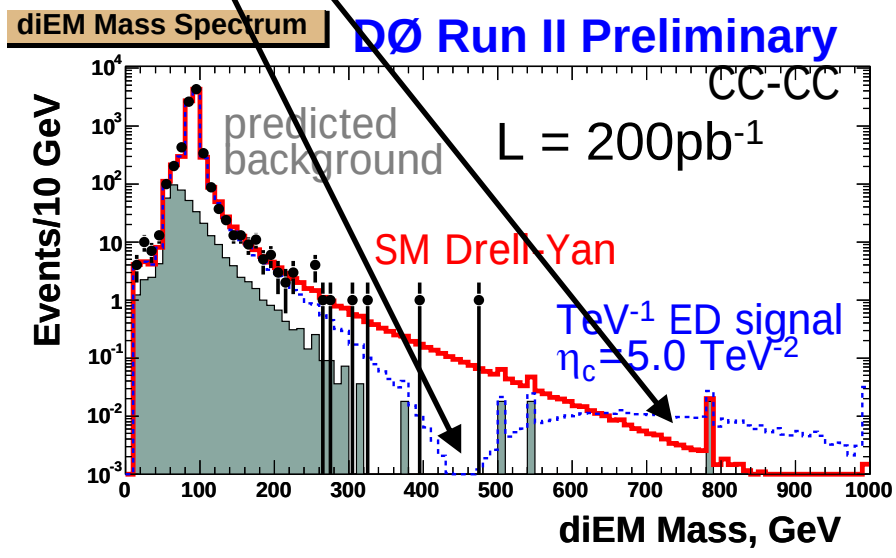
Search Signature: Signal has 2 distinct features:

- 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 $200pb^{-1}$

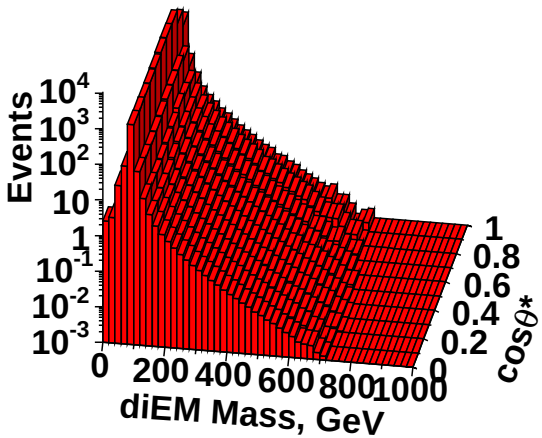
Same as LED diEM search except: at least 1 EM cluster has to have a matching track & no track isolation requirement

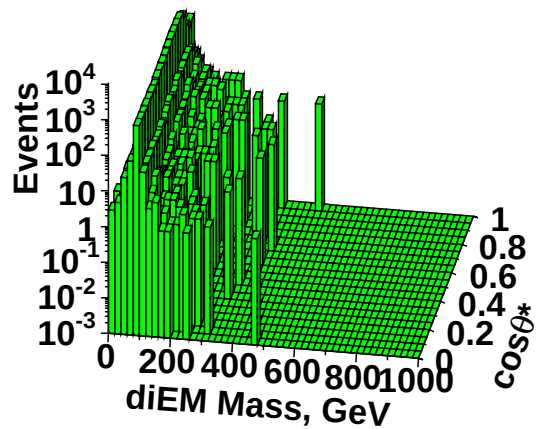
Data are in excellent agreement with Drell-Yan production, so proceed to set limits...



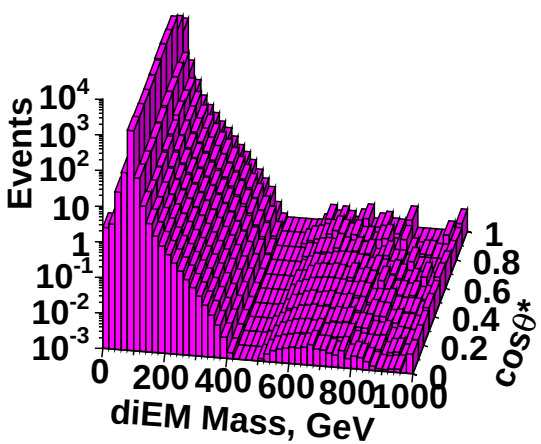
TeV^{-1} ee D0

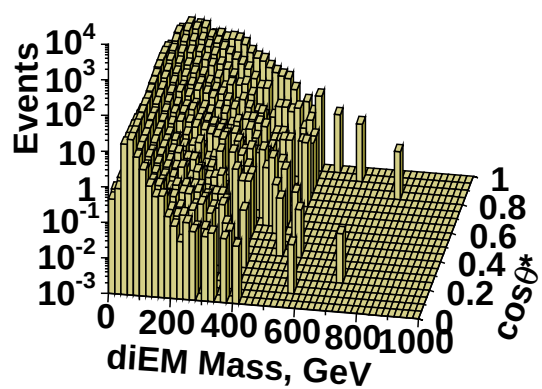
SM Prediction **DØ Run II Preliminary** **Data**





ED Signal **QCD Background**





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

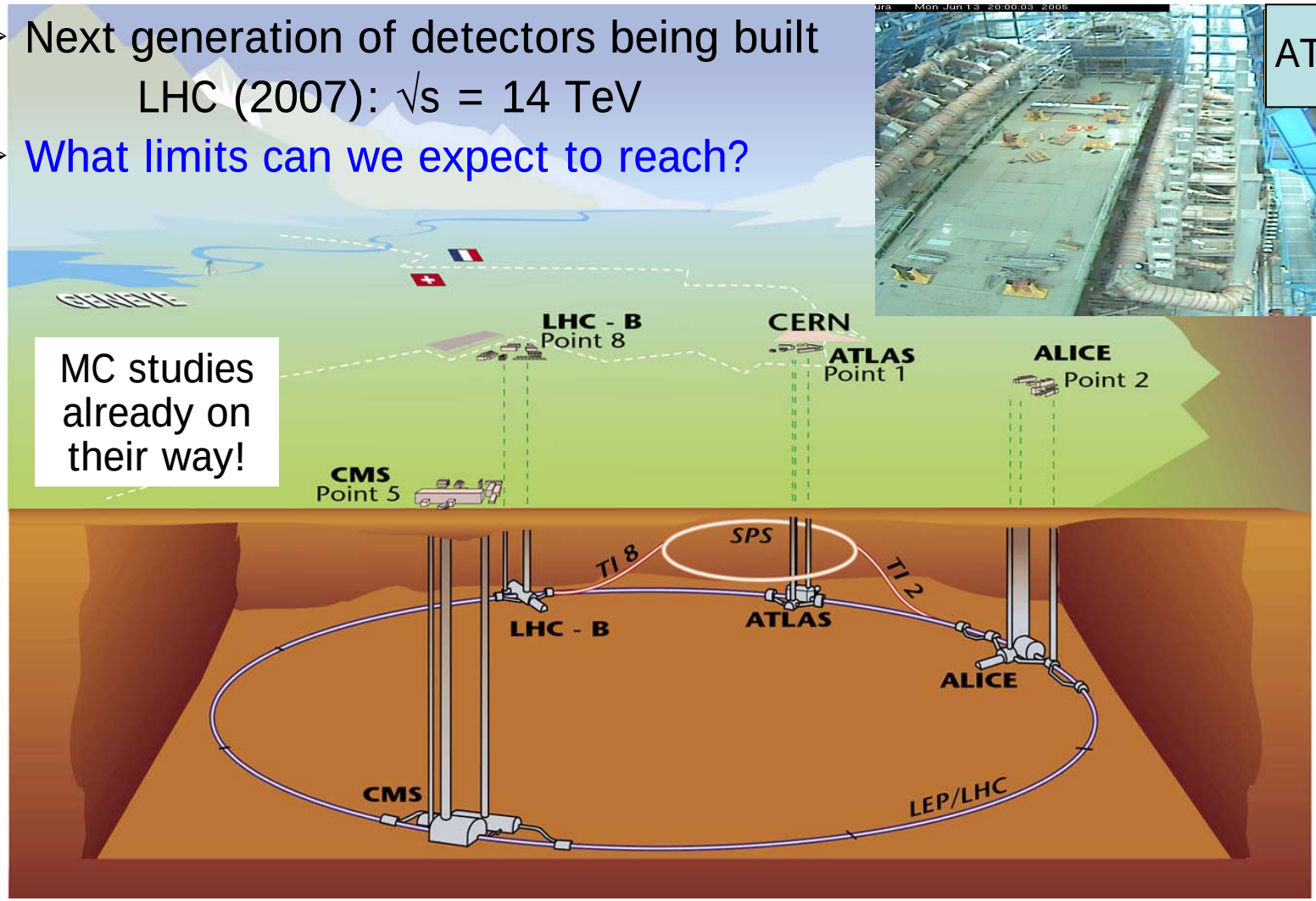
RS: m_1 from 0.5 to 1 TeV for k/M_{Pl} 0.01 to 0.1

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)	δ=2
HL 100fb^{-1}	4

ATLAS

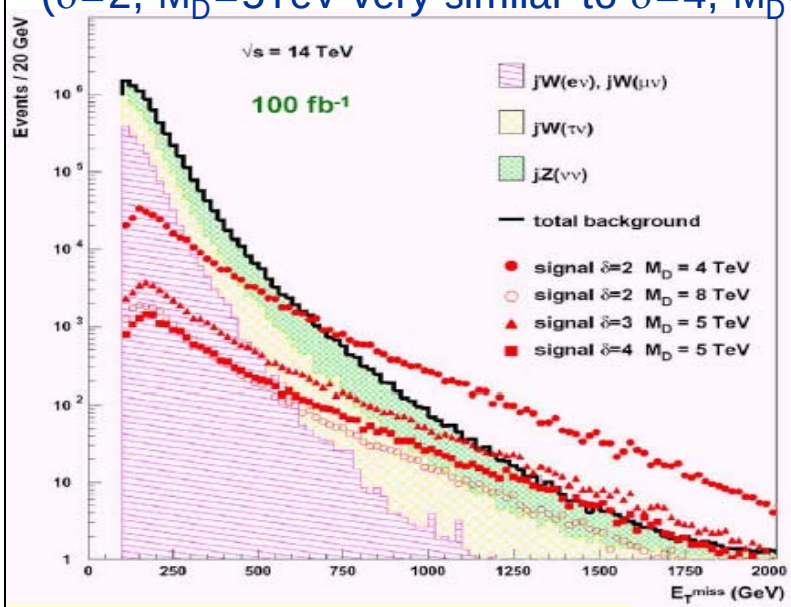
jet+ ME_T

M_D^{MAX} (TeV)	δ=2	δ=3	δ=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

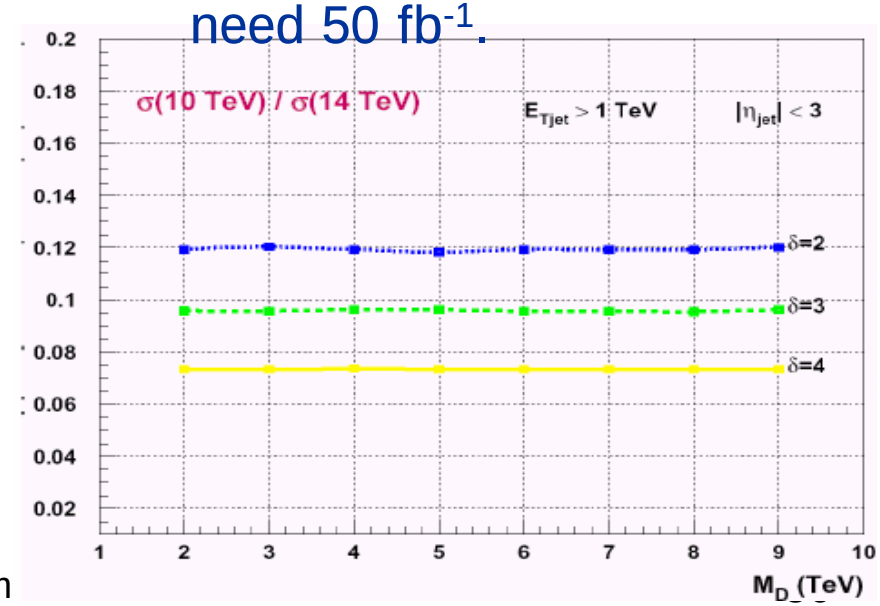
(δ=2, M_D=5TeV very similar to δ=4, M_D=4TeV)



Disentangle δ and M_D:

Run at two different $\sqrt{s}$

e.g. 10 TeV and 14 TeV => need 50 fb^{-1}.

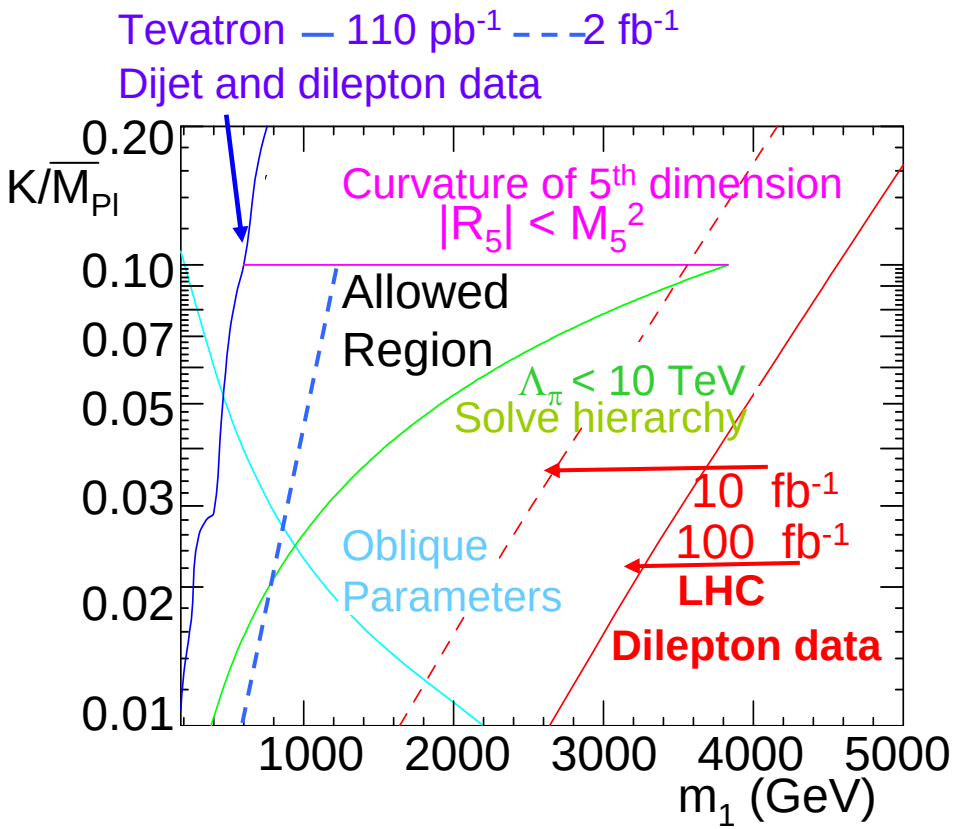


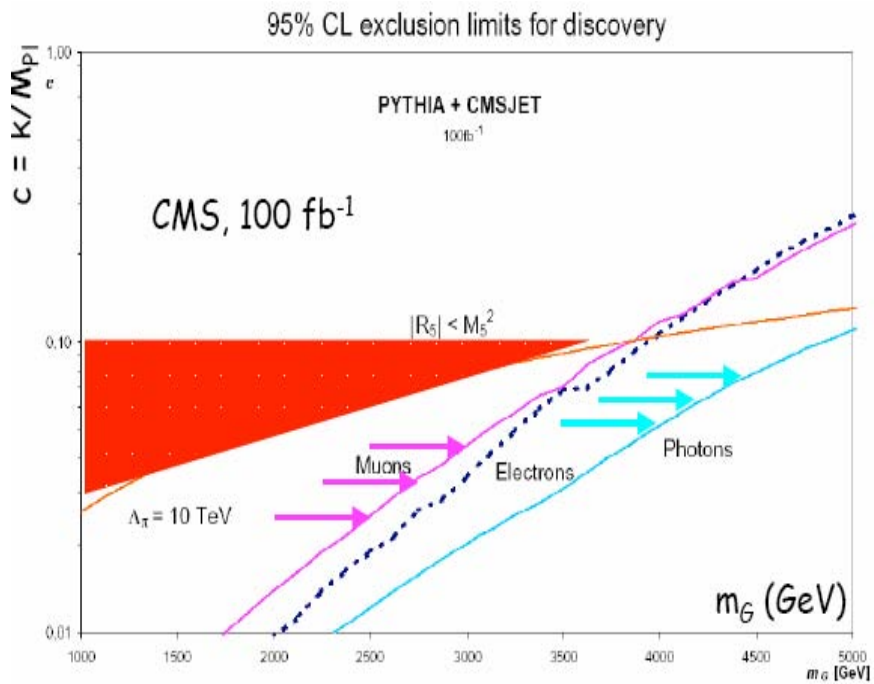
LED ADD: Virtual G Exchange

channel	Luminosity		δ = 2	δ = 3	δ = 4	δ = 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





$BR(G \rightarrow \gamma\gamma) = 2 * BR(G \rightarrow ee)$

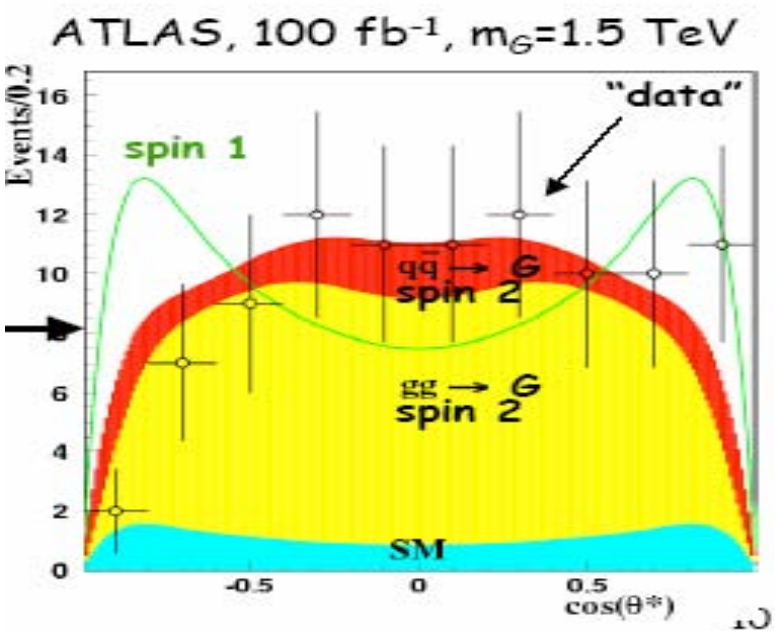
LHC completely covers the region of interest

(hep-ph 0006041)

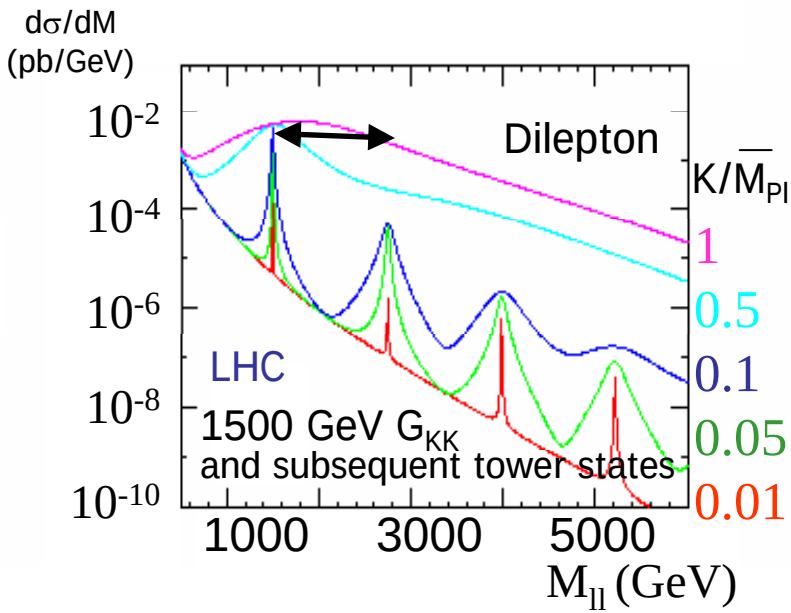
RS constraints

Distinguish RS model from other new physics

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



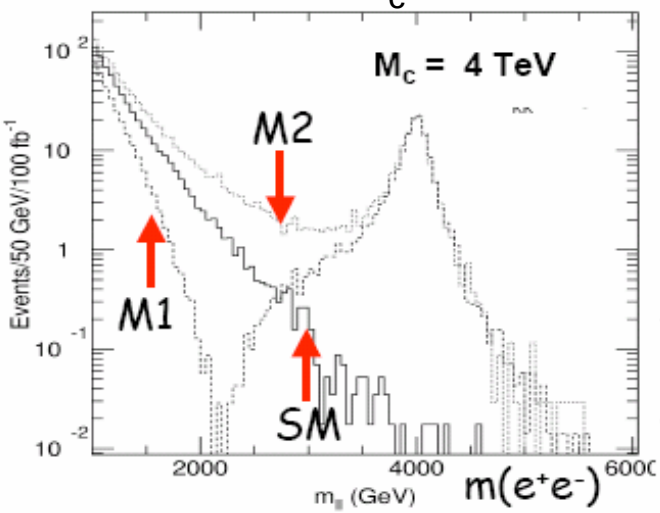
- If many resonances observed: study separation: is it characteristic Bessel spacing?



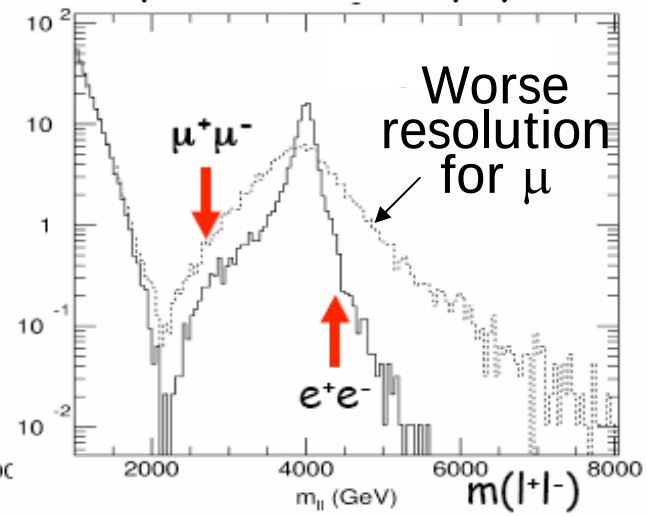
TeV^{-1} Sized ED & KK Gauge Boson

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, …**

ATLAS M_c=4 TeV



$\gamma^{(1)}/Z^{(1)} \rightarrow e^+e^-/\mu^+\mu^-$



- 2 TeV e in ATLAS: $\Delta E/E \sim 0.7$ ~20% for μ
- Acceptance for leptons: $|\eta|<2.5$

Reach: Possible to detect resonance up to 5.8 TeV

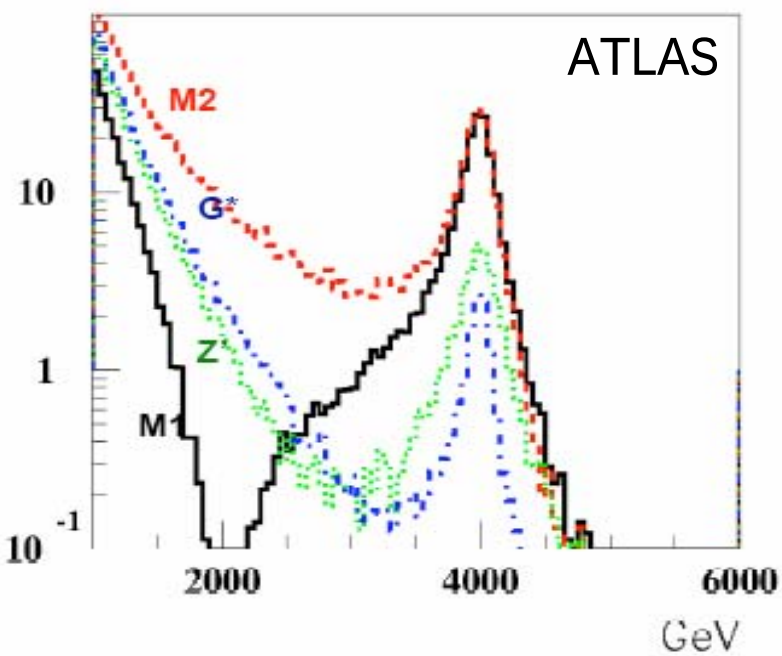
In absence of peak a 95% CL of 13.5 TeV can be achieved

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

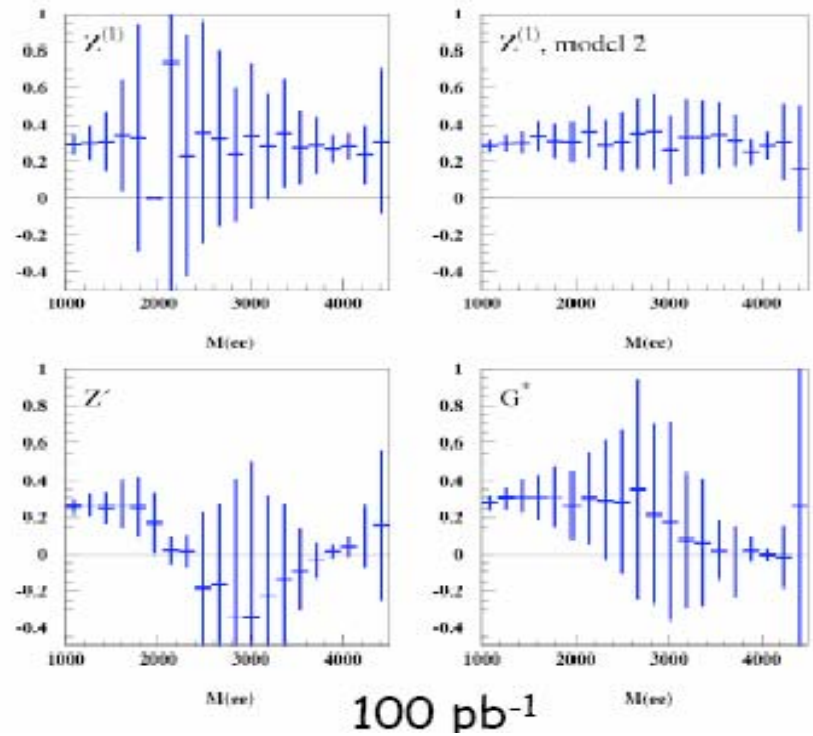
TeV^{-1} Sized ED & KK Gauge Boson

Distinguish RS model from other new physics

$Z^{(1)}$ or Z' or RS Graviton?



Forward-backward asymetries:



Concluding Remarks

- No significant sign of new physics!
- Increasing number of channels being used to search for EDs
  Many searches underway:
  e.g. $pp \rightarrow \tau\tau$, $pp \rightarrow$ jet jet, $pp \rightarrow G \rightarrow ZZ$
- Existing analyses being refined & improved
  Updates imminent e.g. $pp \rightarrow ee$, $pp \rightarrow jet + ME_T$,
- Present limits are up to ~ 1TeV
- LHC will enable searches probe up to ~ 5-6 TeV

Will HERA/Tevatron discover new physics before LHC?