Search for Randall-Sundrum Gravitons in the $\gamma\gamma$ Channel at CDF

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Outline

- RS Model – Motivation for ED searches
- CDF Detector
- $\gamma\gamma$ Search Analysis
  - Selection Criteria
  - Efficiency and Acceptance from MC
  - Systematic Uncertainties
  - Backgrounds
  - Systematic Uncertainties on Backgrounds
- Limits
- Future Prospects

Extra Dimensions: Motivations

In the late 90's Large Extra Dimensions (LED) were proposed as a solution to the hierarchy problem **M_{EW} (1 TeV) << M_{Planck} (10^{19} GeV)?**

ADD

Arkani-Hamed, **D**imopoulos, **D**vali,
Phys Lett B429 (98)

Many (δ) large compactified EDs
In which G can propagate

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

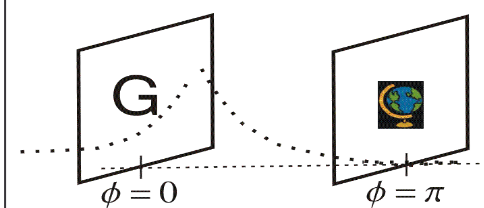
Effective $M_{Pl} \sim$ 1TeV $\rightarrow$ if compact space (R^{δ}) is large

RS

Randall, **S**undrum,
Phys Rev Lett 83 (99)

1 highly curved ED
Gravity localised in the ED

Planck TeV brane



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

$\Lambda_{\pi} \sim$ TeV

if warp factor kR_c ~11-12

Since then, new Extra Dimensional models have been developed and been used to solved other problems:
Dark Matter, Dark Energy, SUSY Breaking, etc

Some of these models can be/have been experimentally tested at high energy colliders

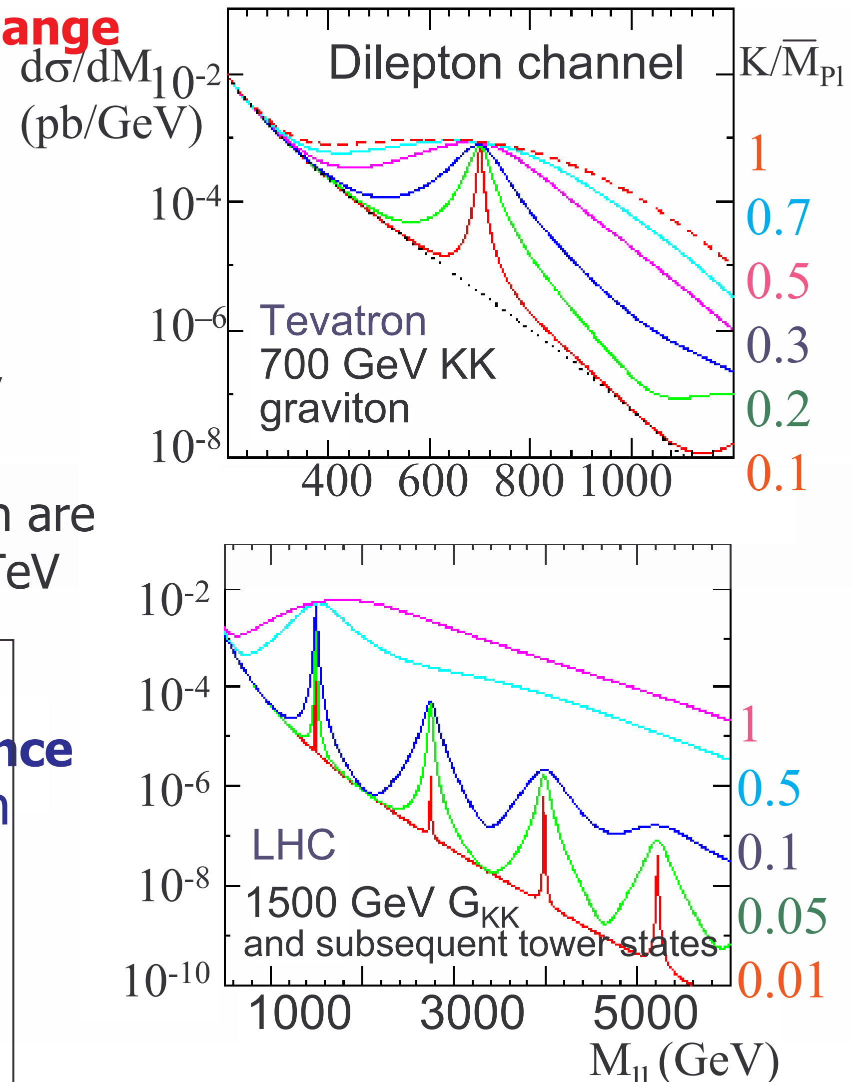
Experimental Signature for RS Model

Detect effects of Virtual Graviton exchange

$q\bar{q}, gg \rightarrow G_{KK} \rightarrow e^+e^-, \mu^+\mu^-, \gamma\gamma, jet + jet$

Signature:
Narrow, high-mass resonance states in dilepton/dijet/diboson channels

- KK excitations can be excited individually on resonance
- Couplings of each individual KK excitation are determined by the scale, $\Lambda_\pi = M_{pl}e^{-kR_c\pi} \sim$ TeV



Davoudiasl, Hewett, Rizzo
hep-ph0006041

Model parameters:

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

  1st graviton excitation mass: m_1 → position (**Resonance**)

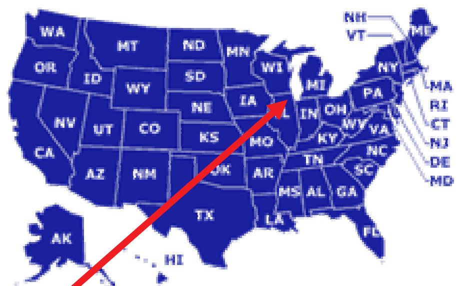
  $\Lambda_\pi = m_1 M_{pl}/kx_1$, & $m_n = kx_n e^{krc\pi}(J_1(x_n)=0)$
- Coupling constant: $c = k/M_{Pl}$

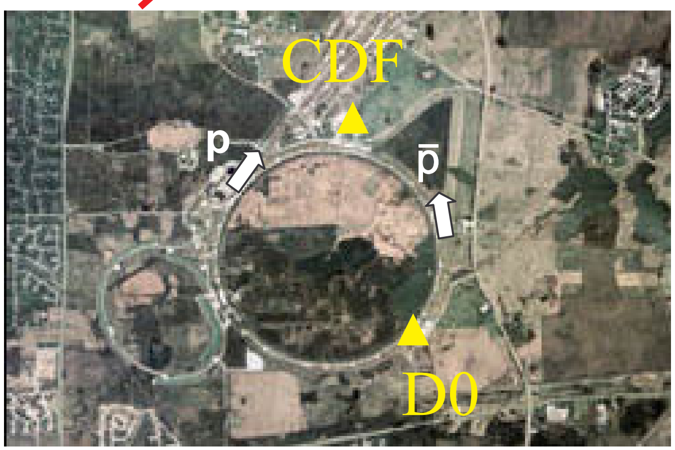
  $\Gamma_1 = \rho m_1 x_1^2 (k/\overline{M}_{pl})^2$ → width

k = curvature, R = compactification radius

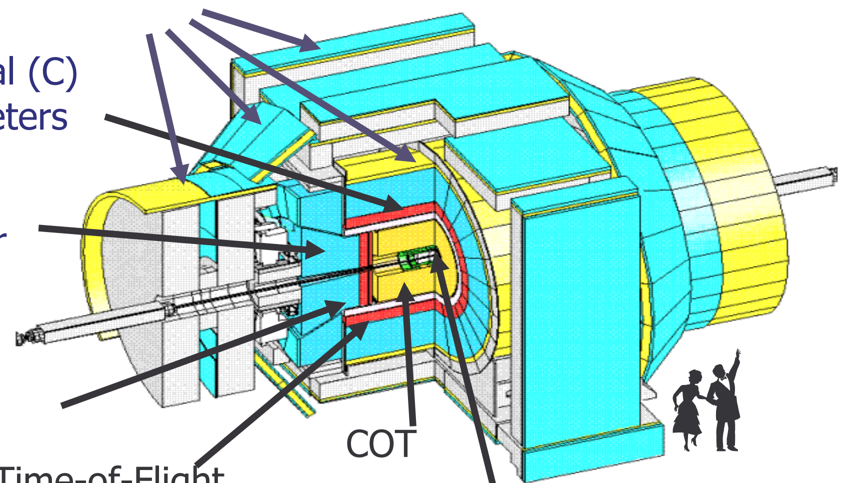
CDF @ Tevatron $p\bar{p}$ Collider

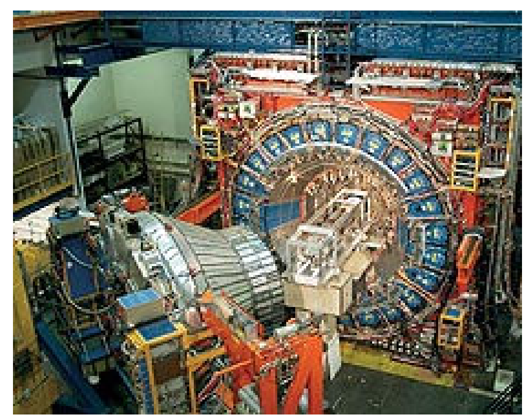
Highest energy *operational* collider in the world!





$\sqrt{s} \approx 1.96$ TeV





Data Sample

Data

- Triggers : DIPHOTON_12/_18
  ULTRA PHOTON_50 and SUPER PHOTON_70 EM & JET
- GoodRun List
- Luminosity: 1155 pb^{-1} CC
  1070 pb^{-1} CP

To keep high efficiency at high mass:
Had/Em inefficient at high E_T as
EM E saturates, so is miscalculated.
PHOTON 70 has no HAD/EM cut

Selection Cuts

- $E_T > 15$ GeV
- $M_{\gamma\gamma} > 30$ GeV
- 2 highest E_T photons selected to assign region (CC, CP, PP)
- Good vertex
- Standard high-P_T selection cuts….

Selection Cuts

High-P_T photon cuts in order applied.

CEM selection cuts

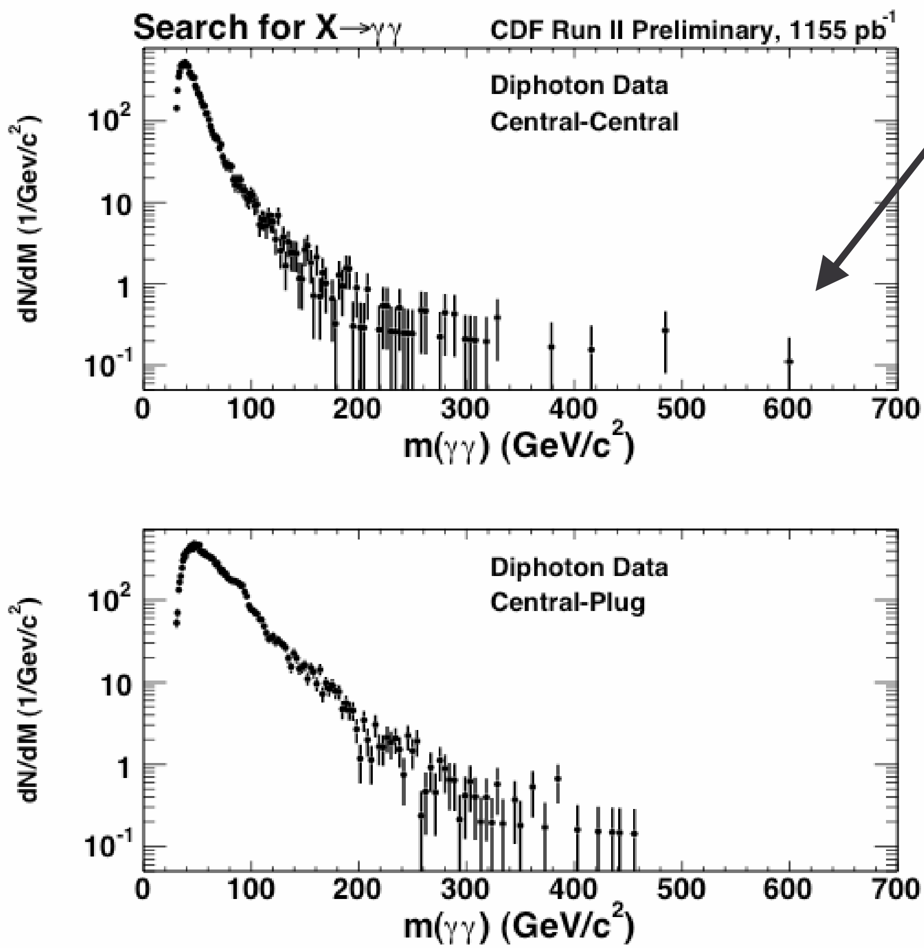
Variable	Cut
CES X and Z Fiducial	Ces $\|X\| < 21$ cm, $9 <$ Ces $\|Z\| < 230$ cm
HAD/EM	$< 0.125 \|\| < 0.055 + 0.00045$*ECorr
Isolation E_T (Cone 0.4)	EtCorr < 20: < 0.1*EtCorr
	EtCorr > 20: $< 2.0 + 0.02$*(EtCorr-20.0)
χ^2 (Strips + Wires)/2.0	< 50
N track (N3D)	≤ 1
Track p_T	$< 1 + 0.005$*EtCorr GeV
Track Isolation (Cone 0.4)	$< 2.0 + 0.005$*EtCorr
2nd CES Cluser E*sinθ	EtCorr < 18: < 0.14*EtCorr
	EtCorr > 18: $< 2.4 + 0.01$*EtCorr

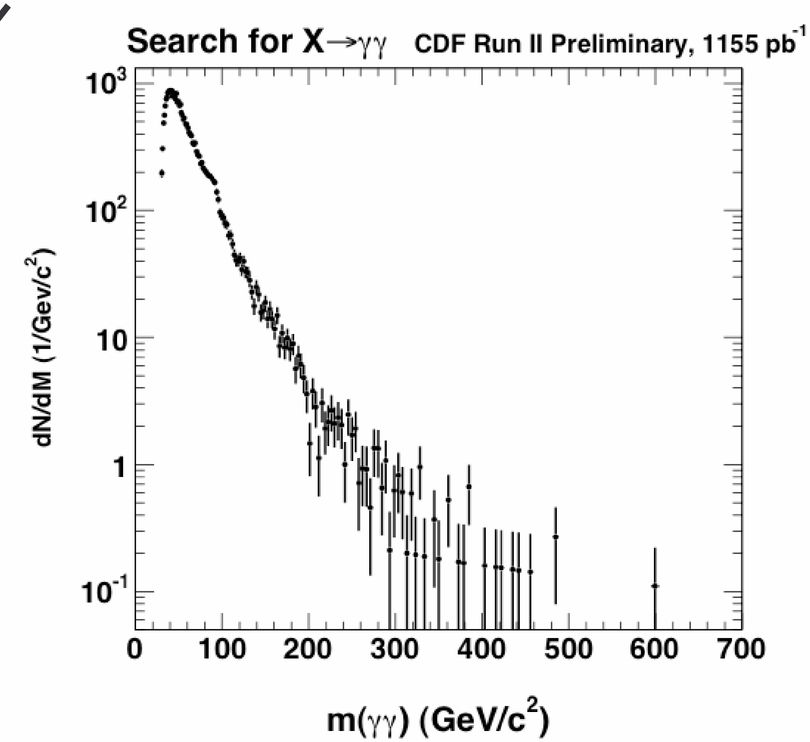
PEM selection cuts

Variable	Cut
PES U and V Fiducial	$1.2 < \|\eta\| < 2.8$
HAD/EM	< 0.05 for ECorr ≤ 100 GeV
	$< 0.05 + 0.026$*ln(ECorr/100) for ECorr > 100 GeV
Isolation E_T (Cone 0.4)	< 0.1*EtCorr for EtCorr < 20 GeV
	$< 2.0 + 0.02$*(EtCorr-20.0) for EtCorr > 20
PEM χ^2	< 10
PES 5x9	> 0.65
Track Isolation (Cone 0.4)	$< 2.0 + 0.005$*EtCorr

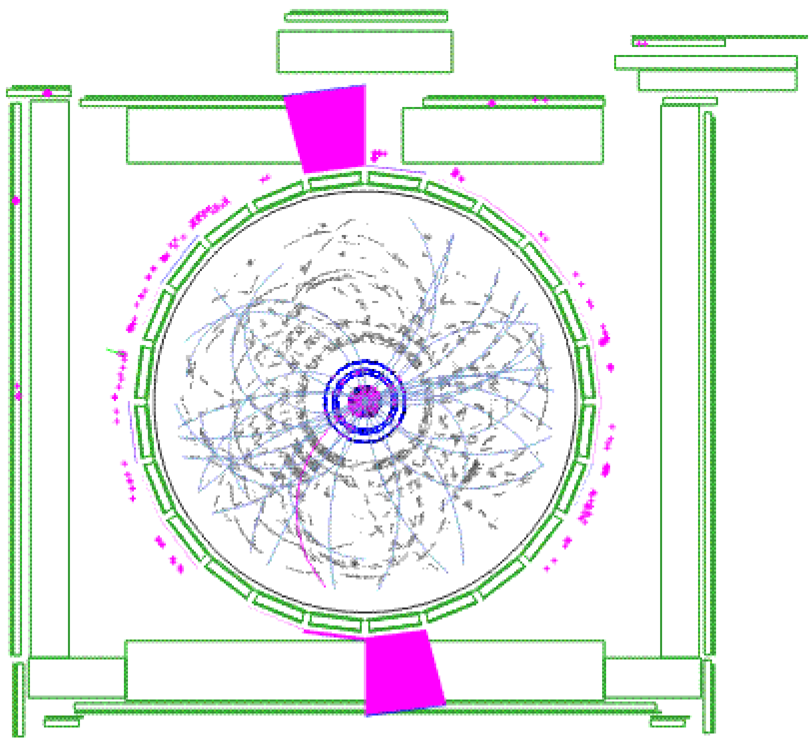
Mass Spectra

Highest mass CC event: 602 GeV

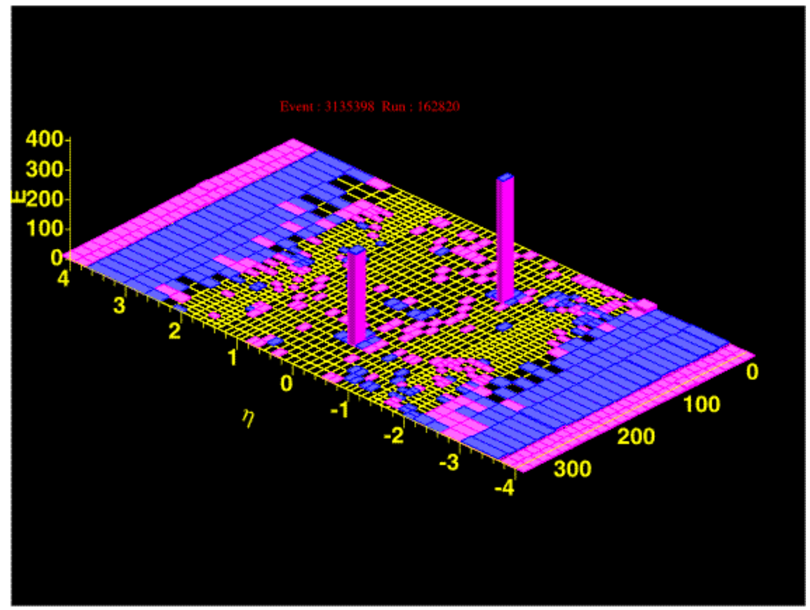




Highest Mass CC event



Diphoton Mass = 602 GeV



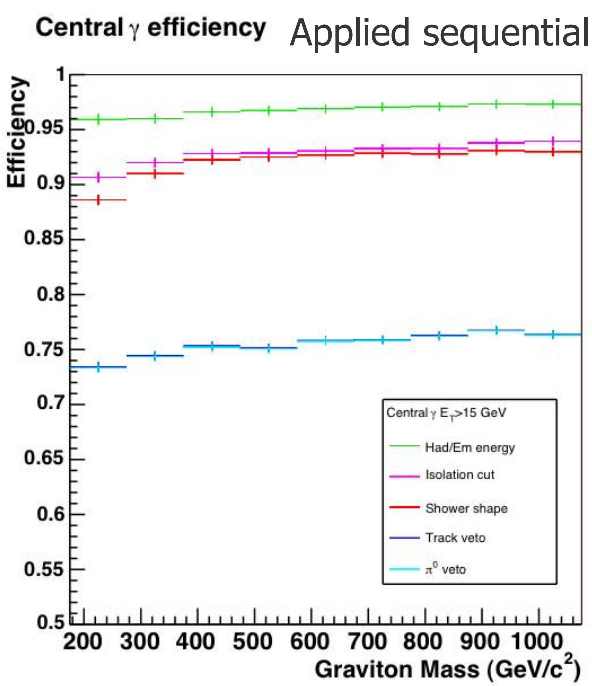
Photon ID Efficiencies

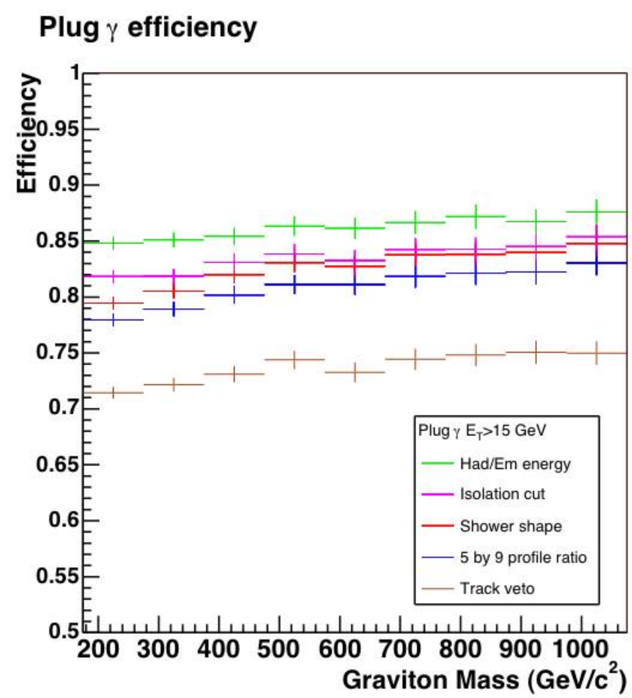
Calculated using Monte Carlo (MC)
Scaled by factors derived from $Z \rightarrow ee$ MC & Data study
CEM scaled by 1.00 and PEM by 0.91

Monte Carlo:

- Randall-Sundrum $G \rightarrow \gamma\gamma$ MC generated using HERWIG version 6.510 with k/M_{Pl} = 0.1 and CTEQ5L pdf.
- 10000 events generated between 200GeV<M_G<1050GeV in 50 GeV steps

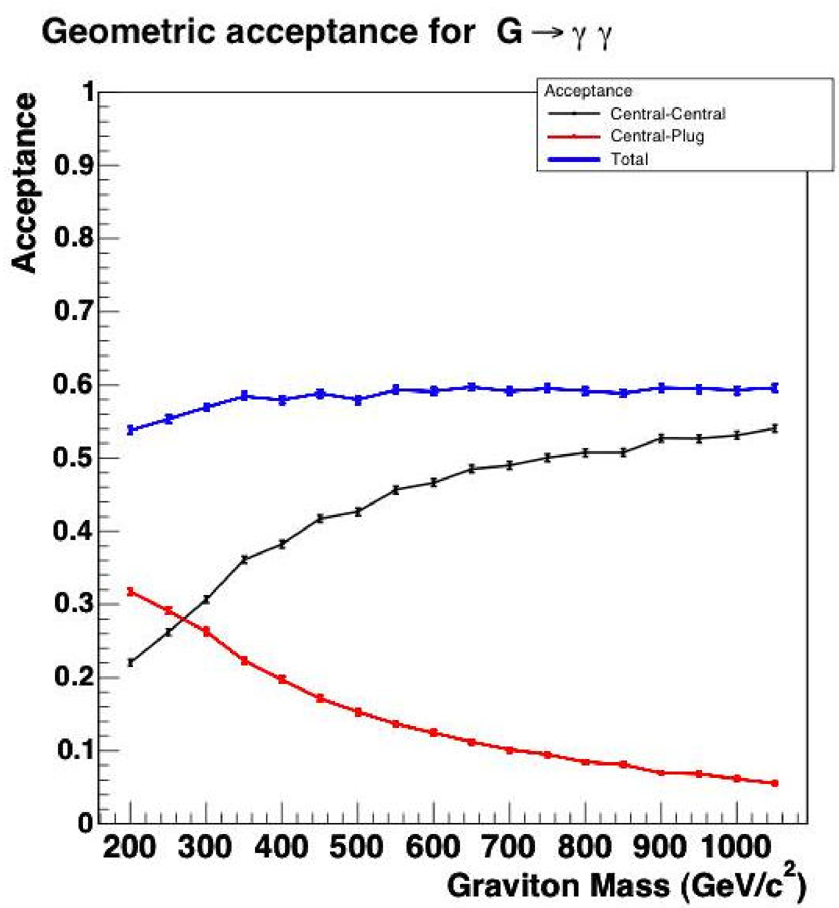
Applied sequentially

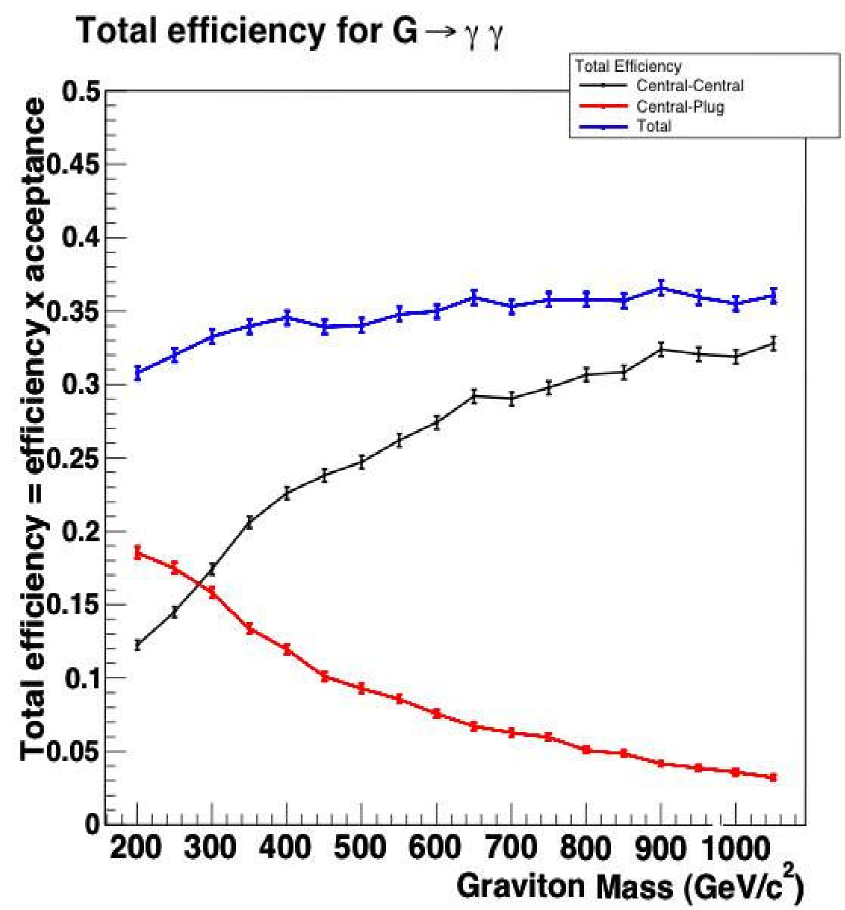




Scaled Total Efficiency and Acceptance

From Monte Carlo





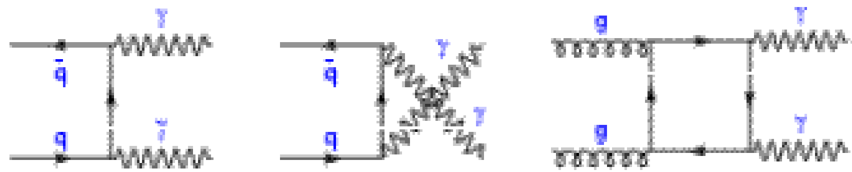
Systematic Uncertainties

- Acceptance Systematic Uncertainty
  - E_T scale (0.2% CEM and 0.8% PEM)
  - PDF (4%)
  - FISR (4%)
  - Luminosity (6%)
- Efficiency Systematic Uncertainty
  - Z efficiency scale factor (1% per photon leg)
  - Trigger efficiency
  - Z vertex (0.2%)
  - Photon conversion (2%)
- Background Systematic Uncertainty
  - Diphox NLO MC
  - QCD fake photons from sideband variations

Expected Diphoton Spectrum

- Standard Model Diphoton Production estimated using Diphox (NLO), absolutely normalised

  mass spectrum corrected for efficiency from Pythia SM $\gamma\gamma$ prod.



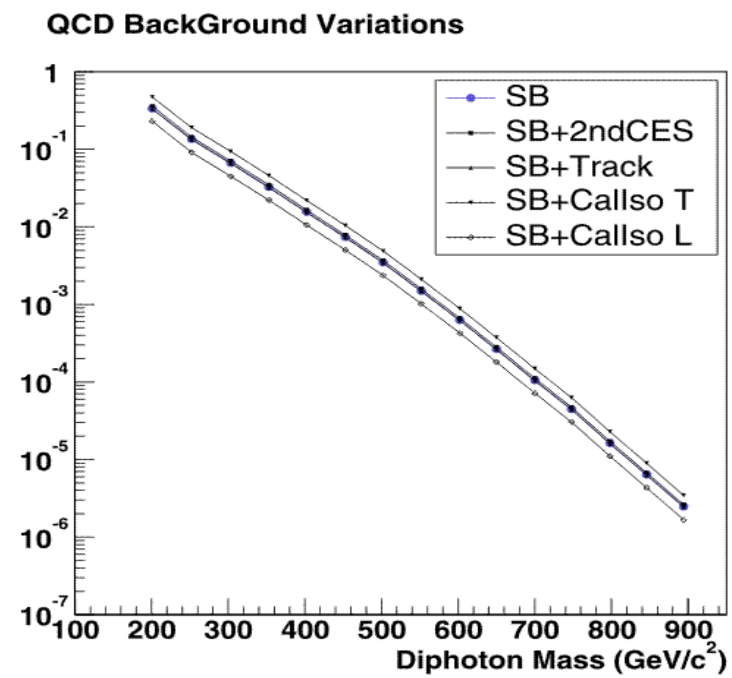
- Jets Faking Photons: γ-jet and jet-jet

  estimated using sidebands

  - loosen $\gamma\gamma$ selection criteria
  - exclude tight $\gamma\gamma$ events
  - apply various tighter cuts
  - fit to the spectrum

  Normalised in the low mass region

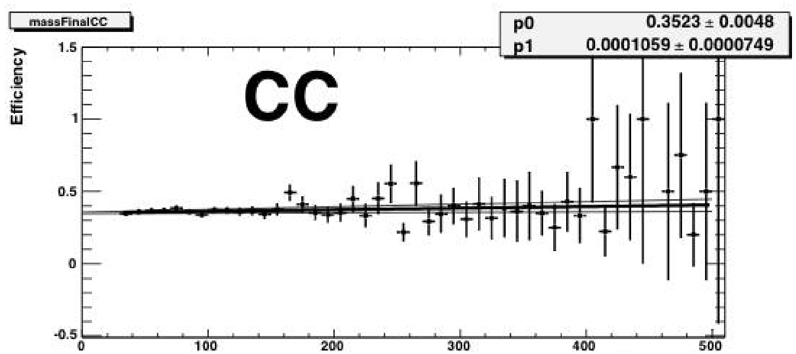
  $\int_{30}^{100} N_{data} = \int_{30}^{100} N_{diphox} + \int_{30}^{100} N_{SB}$



- e^+e^- Production

SM Diphoton Background

- Estimated from Diphox NLO MC.
  Gives mass distribution for events passing E_T and η selection.
- Cross section modified by mass-dependant photon ID efficiency (SM MC PYTHIA).



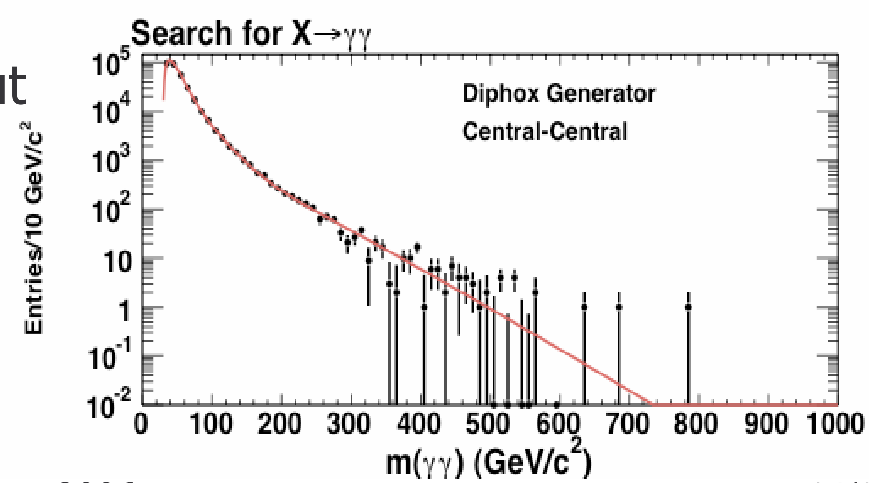
Efficiency = number of reconstructed events passing all cuts divided by number at generator level passing acc. Shows fit and uncertainty.

- Mass distribution for SM diphoton production fit to general function:

$$y = (x^{0.1} + \alpha_5 x^{\alpha 6})(e^{x/\alpha 0} + \alpha_1 e^{x/\alpha 2} + \alpha_3 e^{x/\alpha 4})$$

Where x = mass - mass threshold cut (30 GeV/c^2)

α = free fit parameter



Fake Photon Background

- Jets faking photons

  Fakes estimated by loosening selection criteria and removing events with 2 good photons.

  The remaining events constitute the sidebands ($M_{\gamma\gamma} > 30$ GeV/c^2 also required).

Variable	Cut
CES X and Z Fiducial	Ces $\|X\| < 21$ cm, $9 <$ Ces $\|Z\| < 230$ cm
E_T	> 15 GeV
HAD/EM	< 0.125
Isolation E_T (Cone 0.4)	EtCorr < 20: < 0.15*EtCorr EtCorr > 20: $< 3.0 + 0.02$*(EtCorr-20.0)
Track P_T	$< 0.25 * E_T Corr$
Track Isolation (Cone0.4)	<5.0

CEM loose selection criteria

Variable	Cut
PES U and V Fiducial	$1.2 < \|\eta\| < 2.8$
E_T	> 15 GeV
HAD/EM	< 0.125
Isolation E_T (Cone 0.4)	EtCorr < 20: < 0.15*EtCorr EtCorr > 20: $< 3.0 + 0.02$*(EtCorr-20.0)
Track Isolation (Cone0.4)	<5.0

PEM loose selection criteria

Fake Photon Background

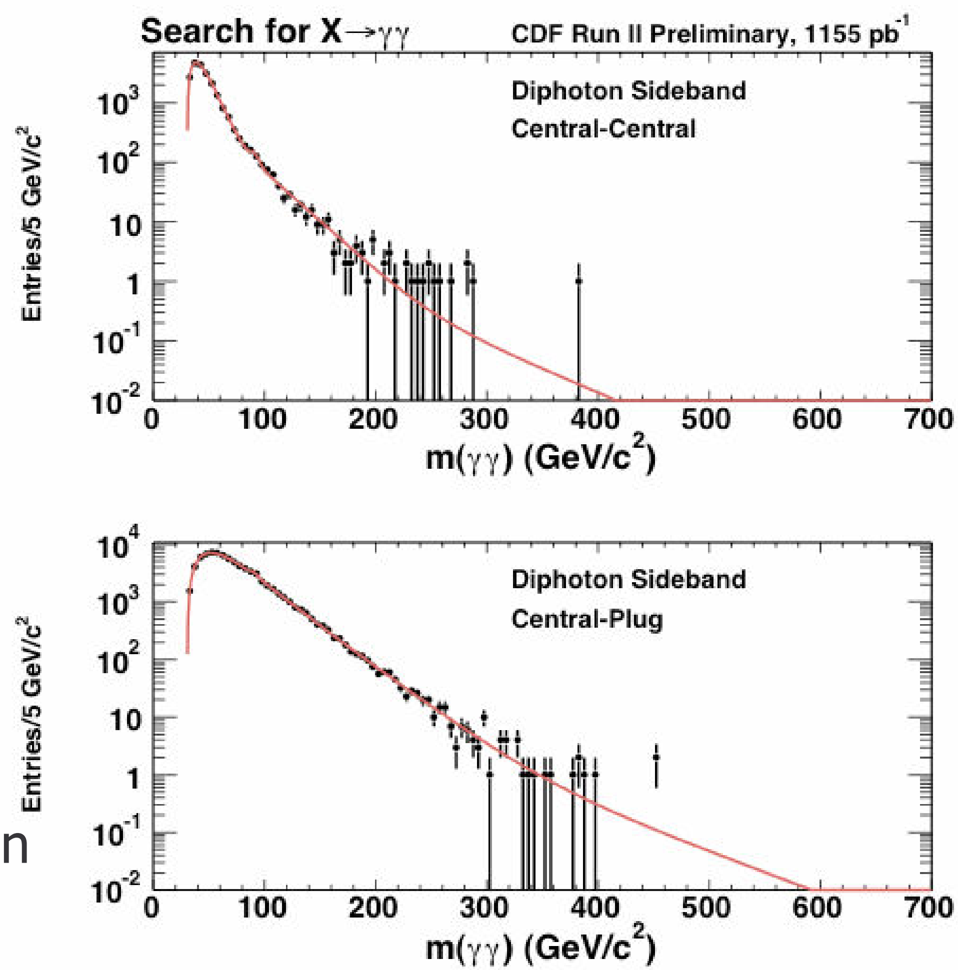
–There will be some true diphoton contribution in the sidebands.

–Estimate the ratio of photons in data to sidebands from pythia diphoton MC.

–Sidebands fit with same function but set α_3 to zero and include predicted contribution from true events by including fixed number of events from Diphox distribution.

Normalised in the low mass region

$$\int_{30}^{100} N_{data} = \int_{30}^{100} N_{diphox} + \int_{30}^{100} N_{SB}$$



Background Systematic Uncertainties

From Diphox:

Varying Q by a factor of 2 gives ~ 20% variation in normalisation from cross section.

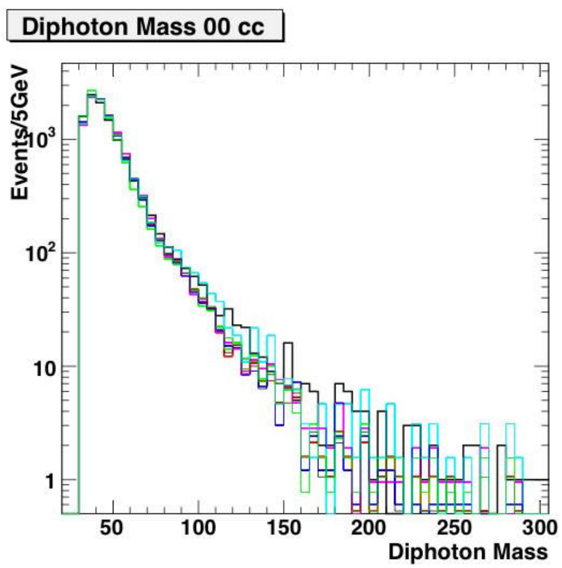
Uncertainty from fit:

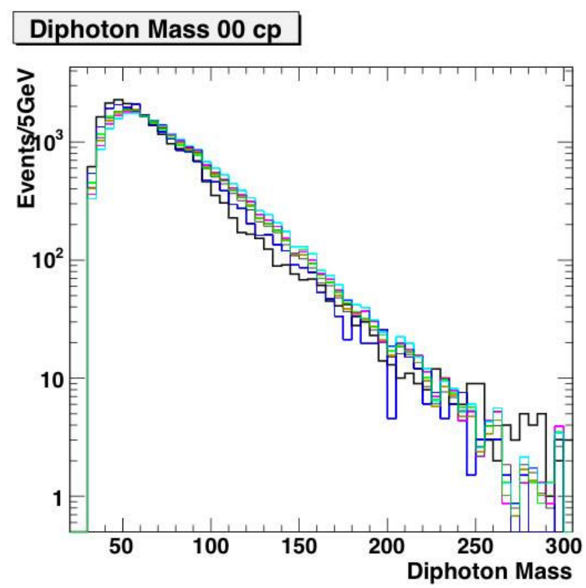
Translates to ~ 0.0002*mass (uncertainties on efficiency small in comparison).

Uncertainties on SB:

Estimated from varying SB cuts.

Relative difference between variations and standard SBs is ~20 %



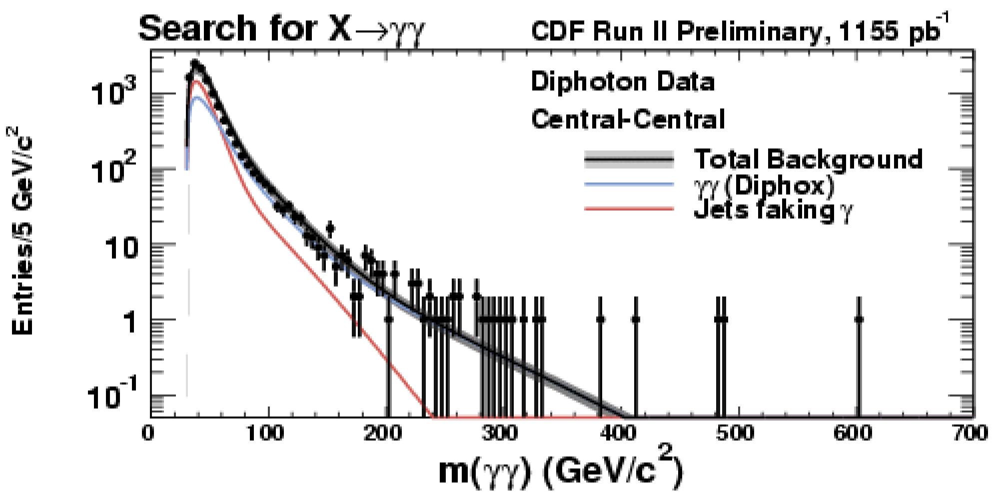


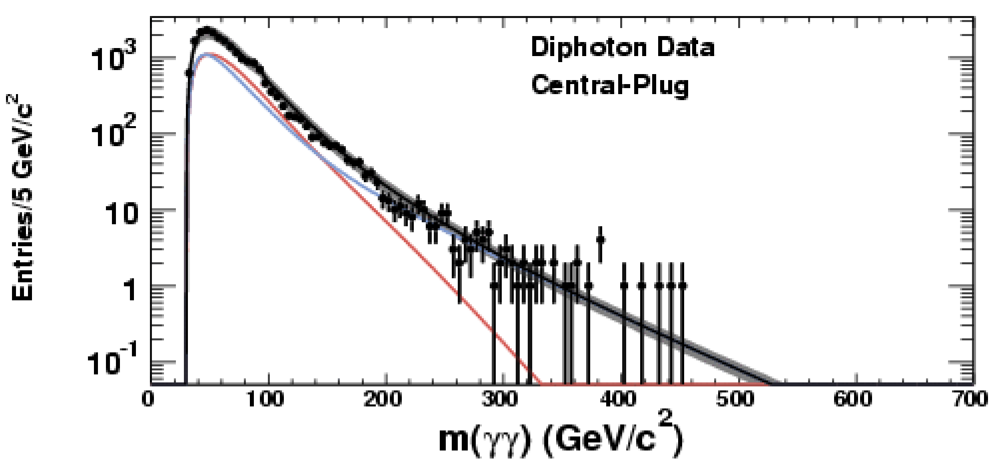
e^+e^- production

- Background from $e^+ e^-$ production:
  - Where e tracks have not been reconstructed.
  - Probability of losing a track is ~ 1%
  - From e analysis estimate background contribution:
    - 100 events above 200 GeV for 450 pb^{-1}
    - Scale by 2 for luminosity
    - Add probability of 0.01 for losing a track (twice for CC, once for CP)
    - Leaves 0.5 events out of 198

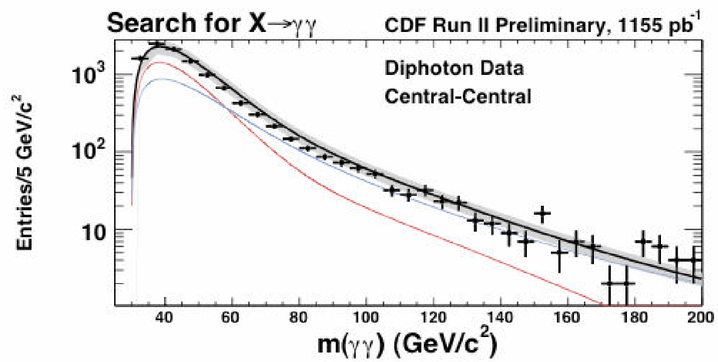
  - Background is less than 0.1% bkg for CC and 1% for CP above mass of 200 GeV.

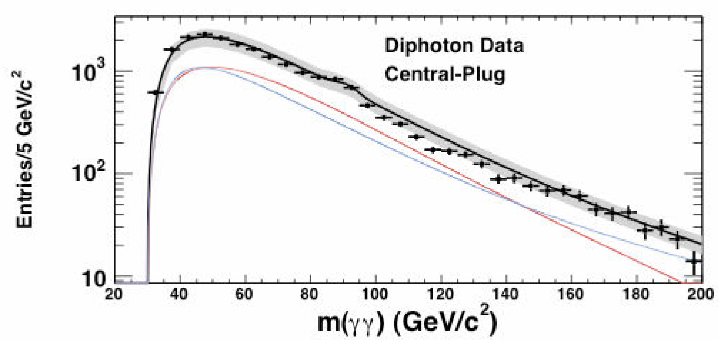
CC and CP Mass Distributions





Low mass region





Limits

Likelihood that binned diphoton data (N^d_i) is described by a predicted background (N^b_i) and hypothetical signal (N^s_i):

$$L(\sigma) = \prod_{i=1}^{N_{bins}} \frac{\mu(\sigma)_i^{N_i^d} e^{-\mu(\sigma)_i}}{N_i^d!} \qquad \mu(\sigma)_i = A\epsilon\mathcal{L}\sigma N_i^s / N_{tot}^s + N_i^b$$

- incorporate systematics by smearing the likelihood
- smear by integrating over all possible cross-sections weighted by a Gaussian with a mean and sigma equal to the given cross-section and its error

$$L^{smear}(\sigma) = \int_0^\infty L(\sigma') \frac{e^{-\frac{(\sigma'-\sigma)^2}{2\Delta\sigma^2}}}{\sqrt{2\pi\Delta\sigma^2}} d\sigma'$$

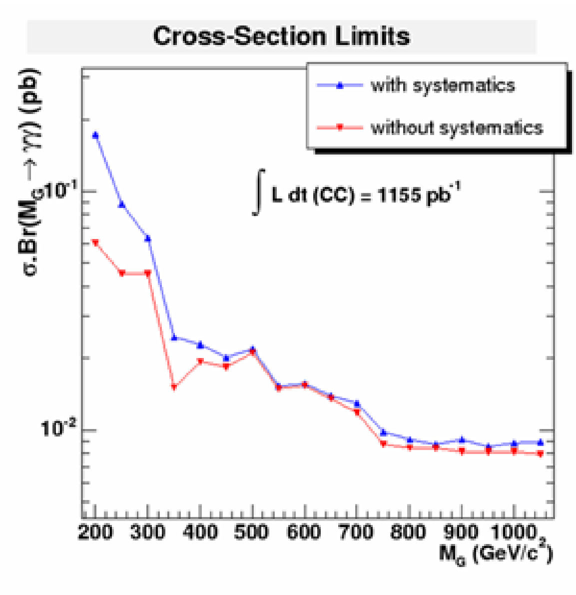
95 % confidence level obtained by integrating likelihood wrt σ such that

$$\frac{\int_{\sigma=0}^{\sigma^{95}} L(\sigma)}{\int_{\sigma=0}^{\infty} L(\sigma)} = 0.95$$

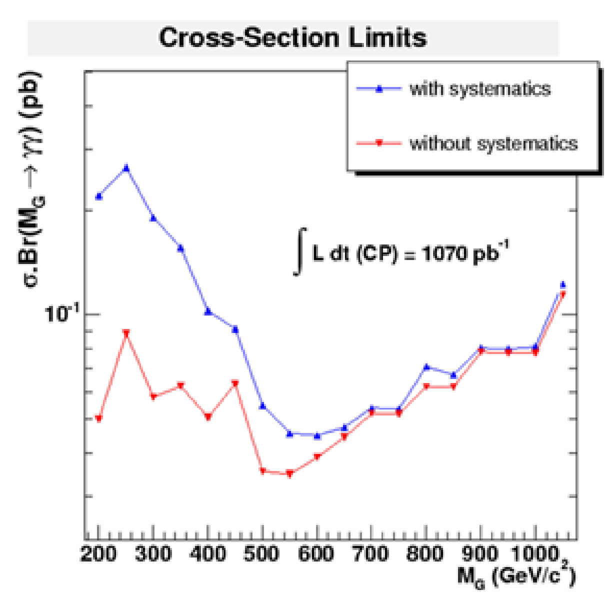
CC and CP channels combined by multiplying individual likelihoods.

CC, CP and Combined Limits

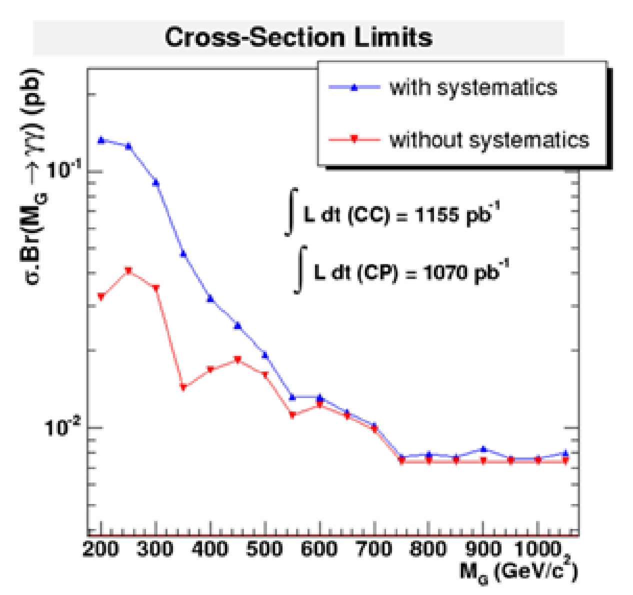
CC



CP



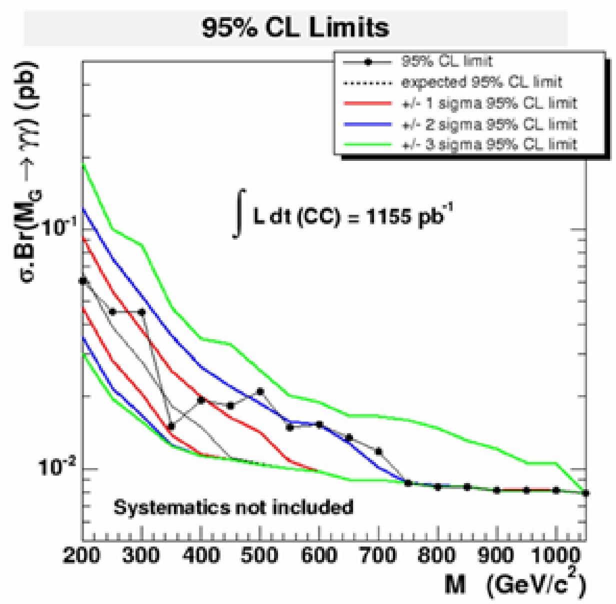
Combined channels



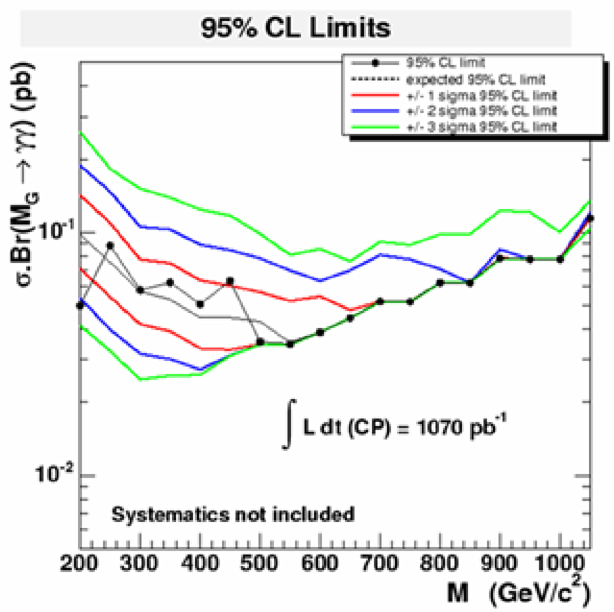
CC, CP and Combined Limits

Compare observed limit to that expected if only background was present: 10 000 pseudo-experiments generated for each mass point and limit calculated. Median taken as expected limit.

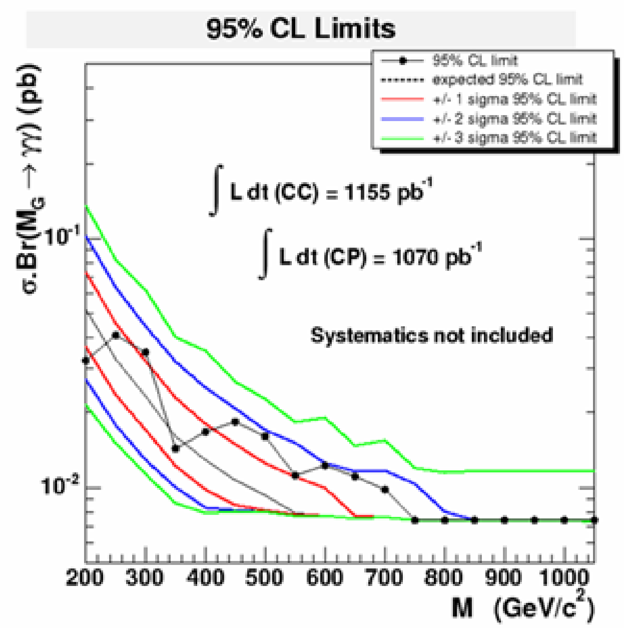
CC



CP



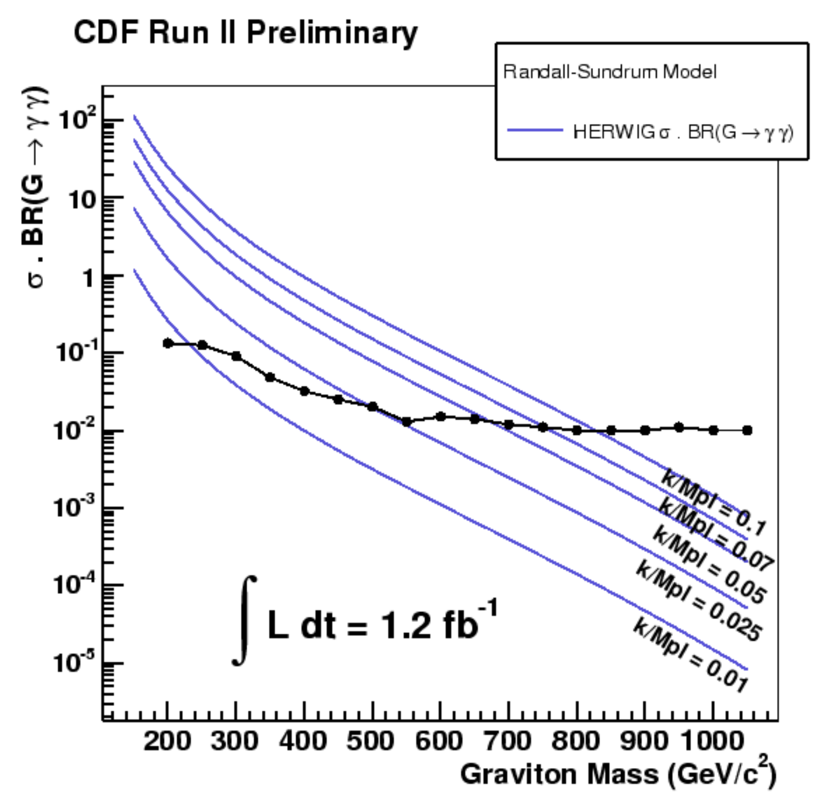
Combined channels



Lower Limits on M_G

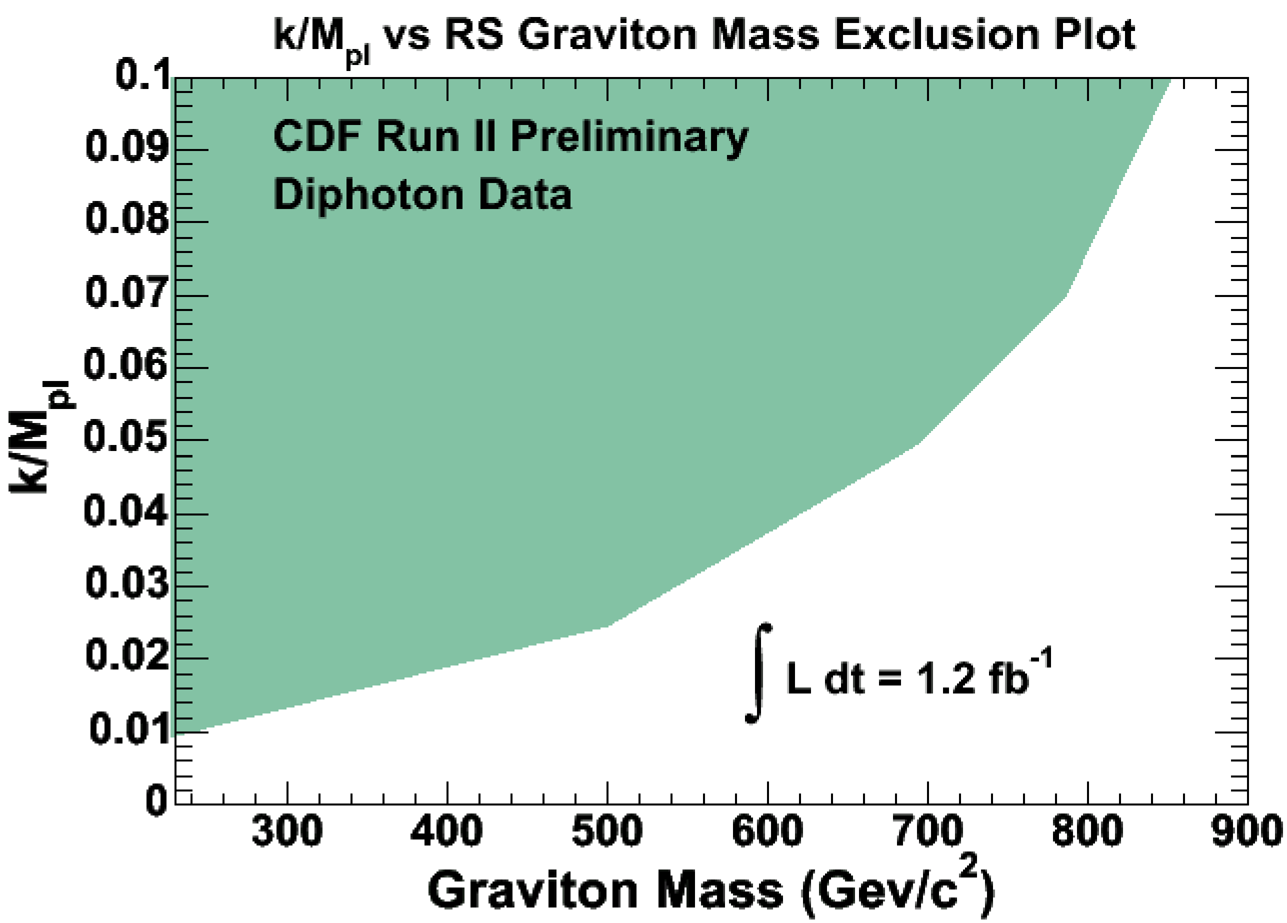
Upper limit on cross-section shown with theoretical predicted cross-sections from scaling HERWIG and using correction factor $K_f = 1.3$

K/M_{Pl}	Lower mass limit (GeV/c^2)
0.1	850
0.07	784
0.05	694
0.025	500
0.01	230



Excluded Region

95% C.L. excluded region on the plane for M_G vs k/M_{Pl} for diphoton decay mode



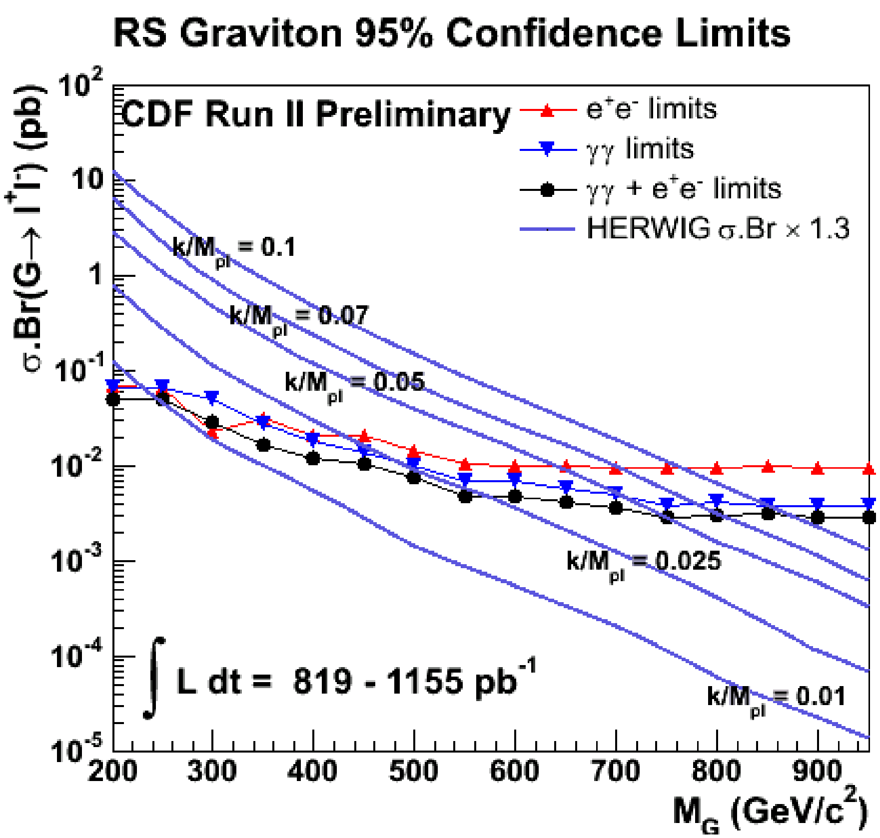
Systematic Errors

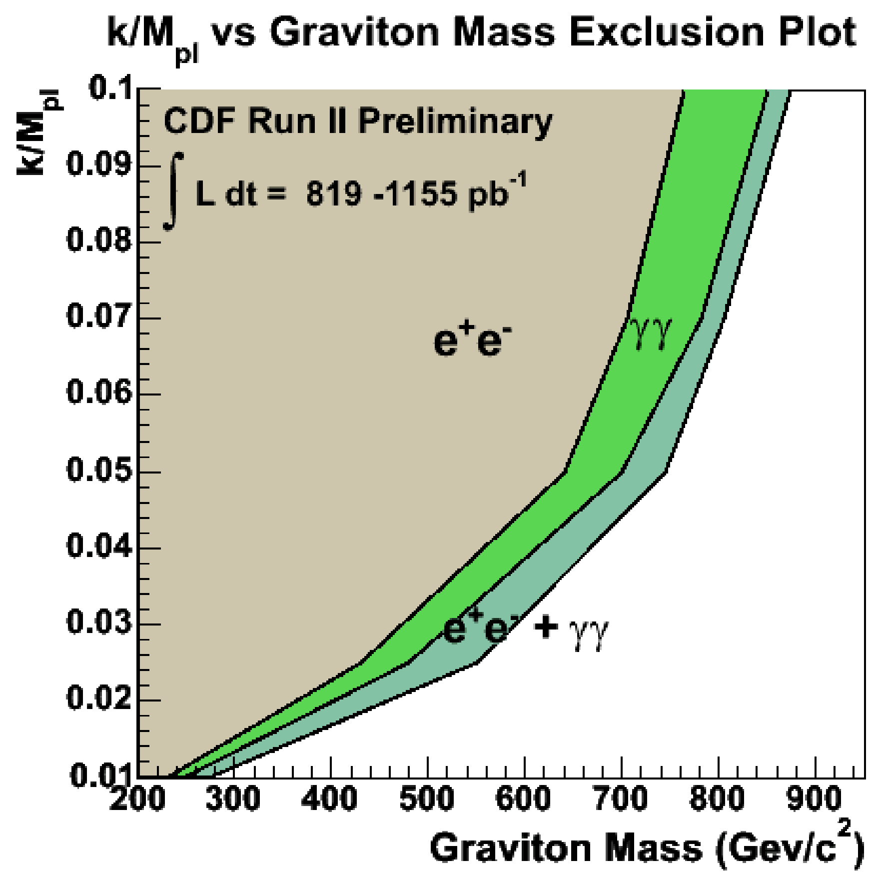
Combining di-photon + di-electron analysis
Identical to combining CC+CP channels: just multiply the likelihoods
Only issue is the systematic errors

combining in the presence of non-systematics is trivial
just need to sort out the correlations

- 100% Correlated Errors (all errors on acceptance or lumi)
  - luminosity
  - ISR
  - energy scale
  - energy resolution
  - efficiency uncertainty (inflated errors to 2% for CEM/PEM)
  - PDFs (di-electron changed error to 3.9% CC, 5.2% CP)
  - photon conversion uncertainty
  - z vertex efficiency uncertainty
- Uncorrelated (all bkg errors)
  - QCD ele bkg shape + norm (ele bkg)
  - Z MC norm (ele bkg)
  - EWK cross section (ele bkg)
  - Pho bkg fit uncertainties (pho bkg)

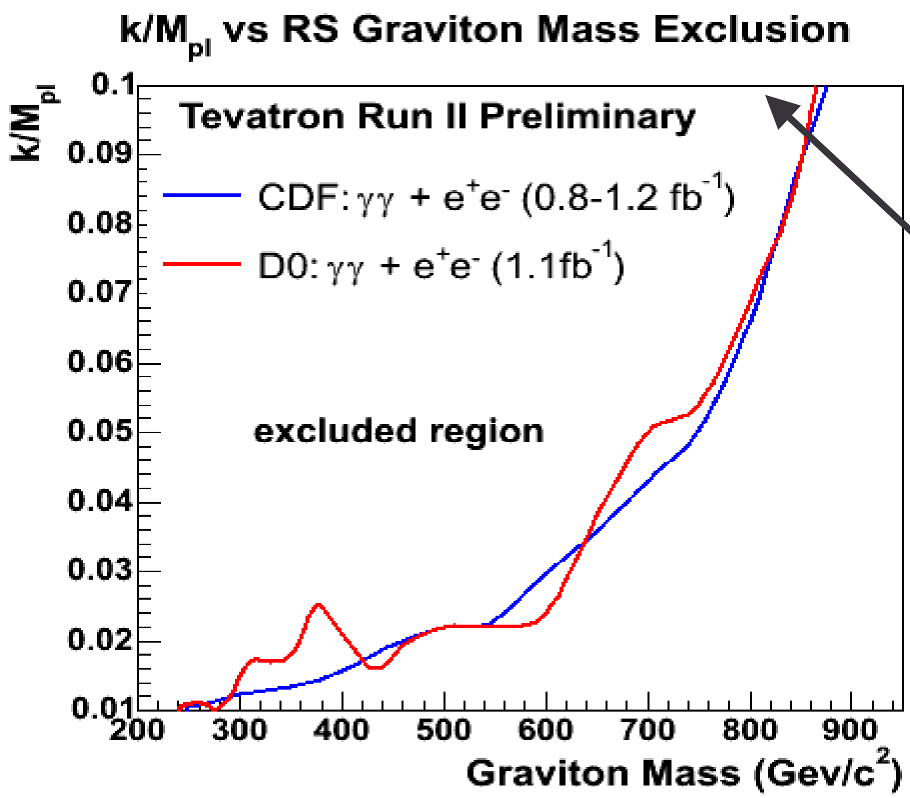
Combined Limits





Present Limits on RS Model

CDF performed ee & $\gamma\gamma$ search, then combine
D0 perform a di-EM object search



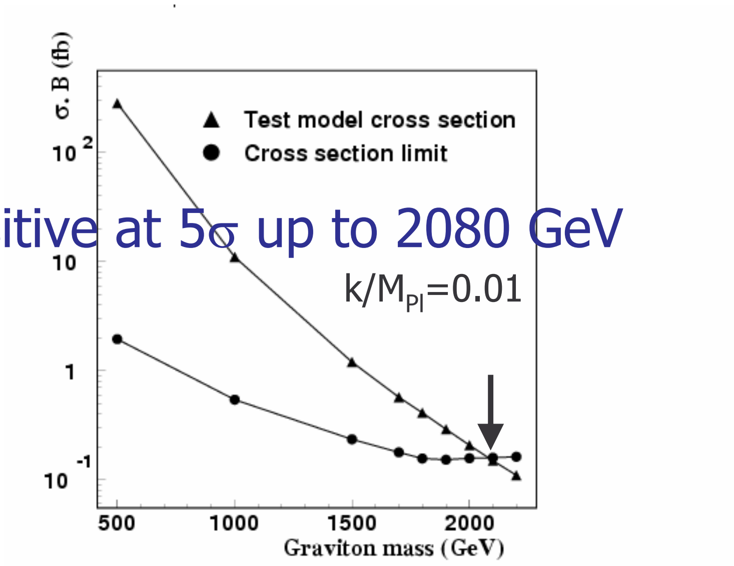
Present Experimental Limits

Theoretical Constraints

- c>0.1 disfavoured as bulk curvature becomes to large (larger than the 5-dim Planck scale)
- Theoretically preferred Λ_π<10TeV assures no new hierarchy appears between m_{EW} and Λ_π

Future Prospects

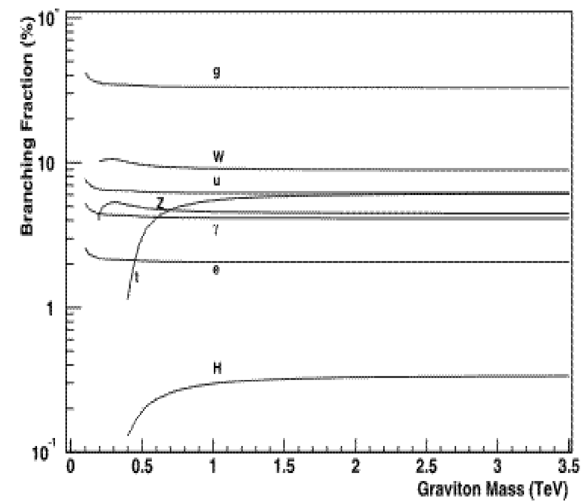
- Best channels to search in are G(1)→e+e- and G(1)→γγ due to the energy and angular resolutions of the LHC detectors
- G(1)→e+e- best chance of discovery due to relatively small bkdg, from Drell-Yan*

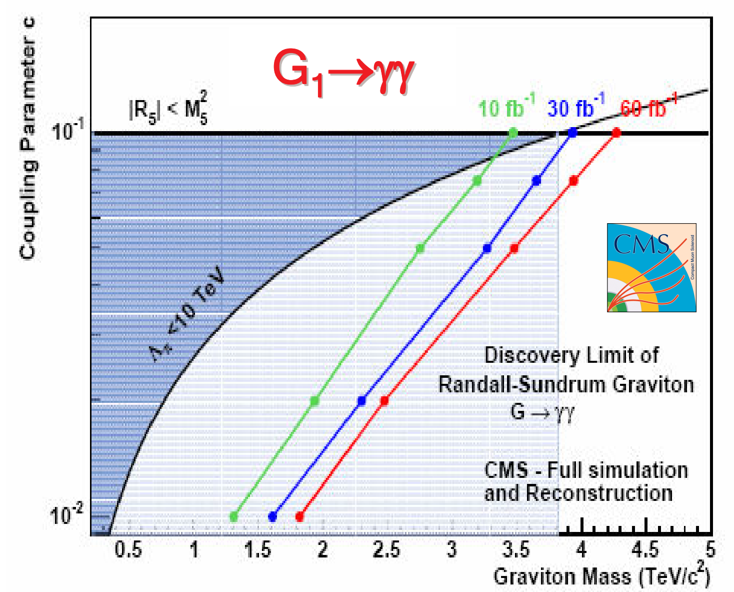


Sensitive at 5σ up to 2080 GeV

$k/M_{Pl}=0.01$

Allenach et al, hep-ph0006114
Allenach et al, hep-ph0211205





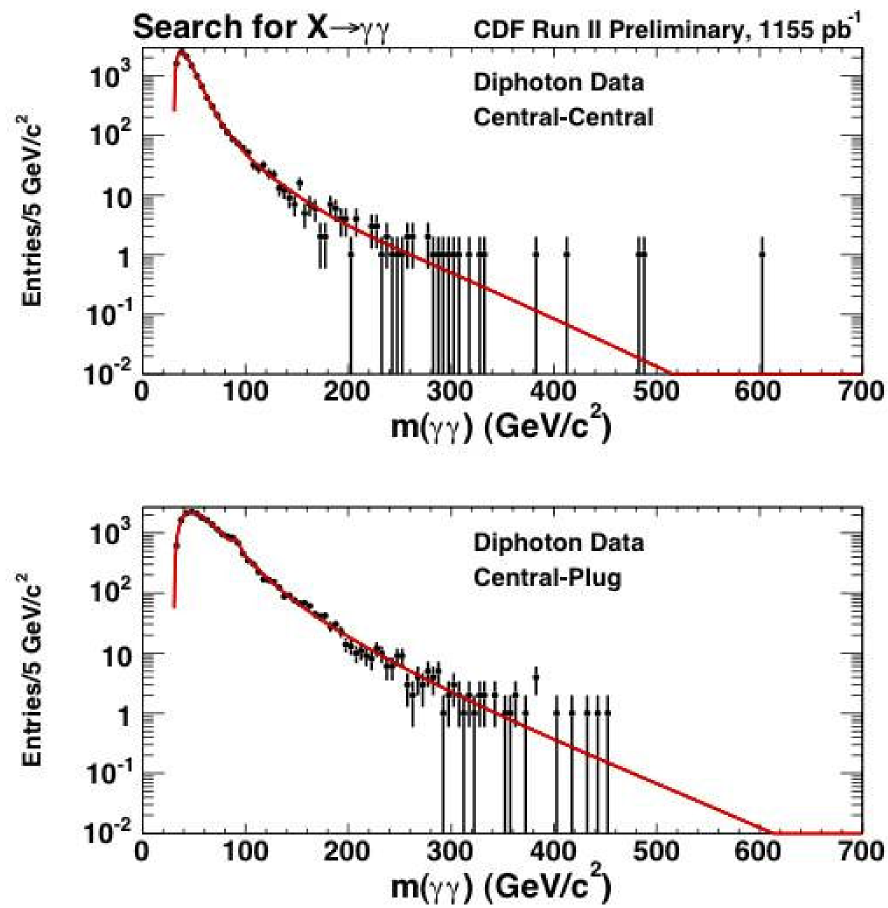
LHC completely covers the region of interest

M.-C. Lemaire et al.
CMS NOTE 2006/051
CMS PTDR 2006

Backup

Limit Fits

CC and CP mass spectra fit with same general function, removing one of the exponentials and including predicted contribution from true diphotons using number of events from DiPhox distribution, the shape of which is allowed to float.



Acceptance Systematics

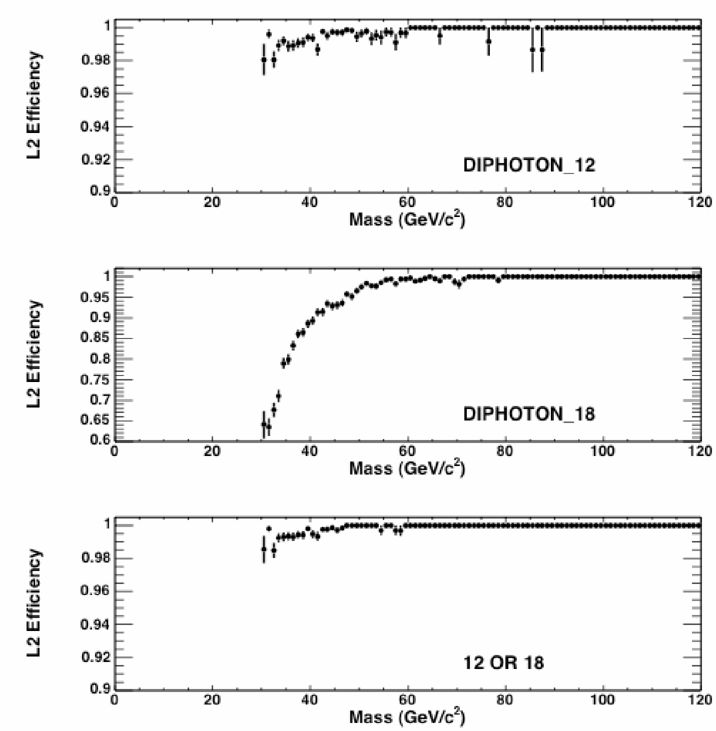
- E_T scale:
  - E_T threshold varied by ± 1% (from Z mass MC/ data comparison)
  - 0.2% CEM and 0.8% PEM
- PDF:
  - Relative change calculated for acceptance values generated using different PDFs (high/ low gluon and high/ low α_s)
  - 4%
- ISR:
  - Parameter varied in Pythia with CTEQ5L PDFs for more and less ISR
  - 4%
- Luminosity:
  - 6%

Efficiency Systematics

- Z efficiency scale factor:
  - from Z MC/ data comparison for photon selection criteria
  - Systematic error of 1% per photon leg

- Trigger efficiency:
  - L2 eff given by offline cuts + L2 trigger/ offline cuts
  - Had/Em inefficient at high E_T as EM E saturated, so miscalculated. 50 (E_T and Had/Em) and 70 (E_T) triggers therefore included to prevent loss of events.

  Trigger eff taken as 100% efficient



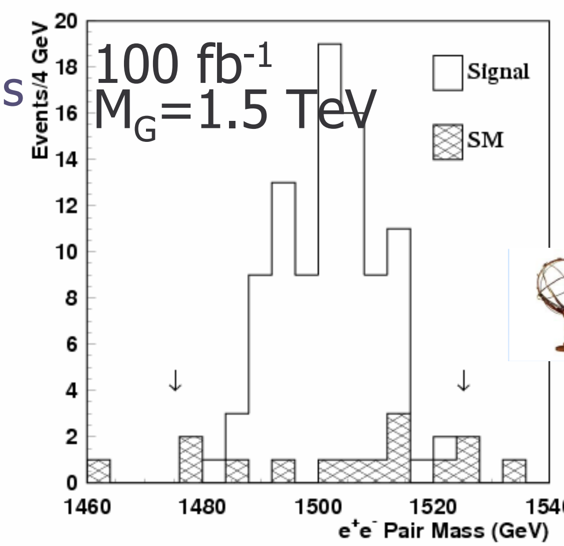
41/11088 CC signal events from 50/70 triggers (23 pass both, 18 pass 50 only) and 84/20933 CP signal events (22 pass both, 62 pass 50 only) .

Efficiency Systematics

- Z Vertex:
  - Event selection requires Z vertex falls within ± 60 cm of centre of detector.
  - Some events may occur outside this region, efficiency for this measured in MC, 97% eff.
  - Q. from full status: MC does not include run dependent variations of generated Z vertex position- generated using single run.
  - Efficiency of Z vertexing 96% +/- 0.2% (syst) +/- 0.04% (stat) (cdf note 8318, W. Sakumoto)
  - 0.2% uncertainty and 0.96/0.97 (=0.99) Z vertex eff.
- Photon Conversion:
  - 10 % conversion probability, amount of detector material known to ~ 10%
  - take 1% uncertainty on probability of converting per leg, total of 2%.

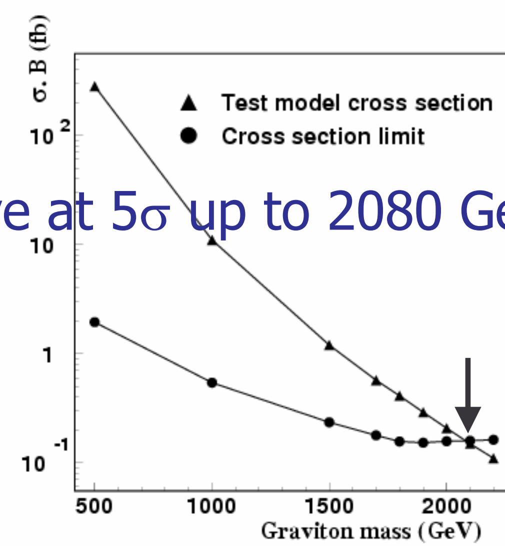
RS1 Discovery Limit

- Best channels to search in are G(1)→e+e- and G(1)→γγ due to the energy and angular resolutions of the LHC detectors
- G(1)→e+e- best chance of discovery due to relatively small bkdg, from Drell-Yan*



Di-electron

- ❑ HERWIG
- ❑ Main Bkdg: Drell-Yan
- ❑ Model-independent analysis
- ❑ RS model with $k/M_{Pl}=0.01$ as a reference (pessimisitc scenario)
- ❑ Fast Simulation



Sensitive at 5σ up to 2080 GeV

*Reach goes up to 3.5 TeV for c=0.1 for a 20% measurement of the coupling.

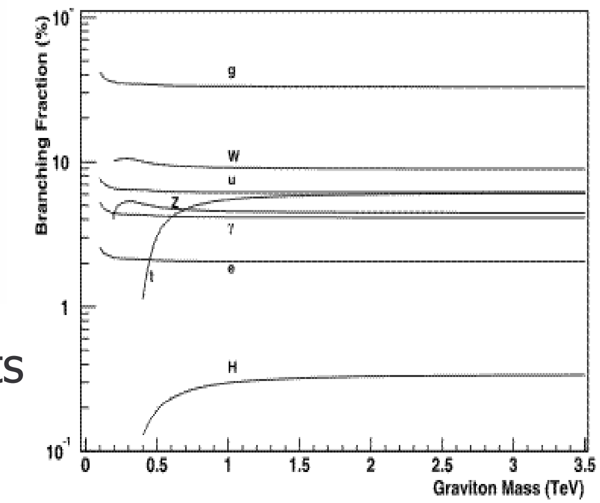
Allenach et al, hep-ph0006114

*Allenach et al, hep-ph0211205

RS1 Model Parameters

A resonance could be seen in many other channels: $\mu\mu$, $\gamma\gamma$, jj, bbbar, ttbar, WW, ZZ, hence allowing to check universality of its couplings:

Channel	Point m_G, Λ_π (TeV)							
	1,10	1,20	1,30	2,10	2,20	2,30	3,10	3,20
e^+e^-	1.6	3.3	5.3	5.4	11.0	17.1	15.1	30.7
$\mu^+\mu^-$	1.9	4.5	8.2	6.2	15.2	28.2	15.1	32.7
$\gamma\gamma$	1.2	2.9	5.2	3.9	8.8	15.2	10.5	23.0
WW	11.6	44.9	-	38.2	-	-	-	-
ZZ	13.7	50.1	-	52.7	-	-	-	-
jj	19.0	77.0	-	31.0	-	-	59.0	-



Relative precision achievable (in %) for measurements of σ.B in each channel for fixed points in the M_G,Λ_π plane. Points with errors above 100% are not shown.

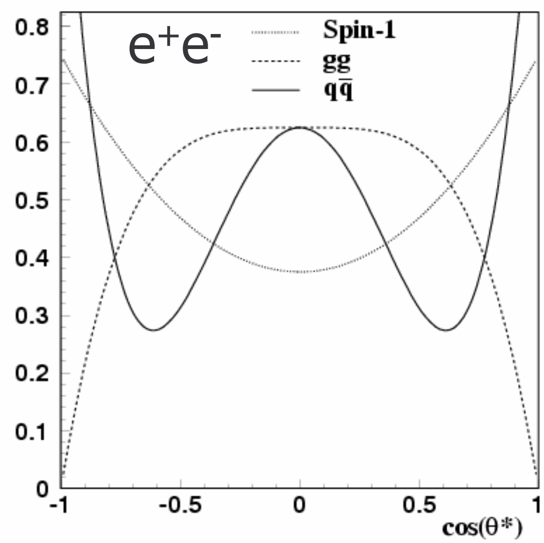
Also the size (R) of the ED could also be estimated from mass and cross-section measurements.

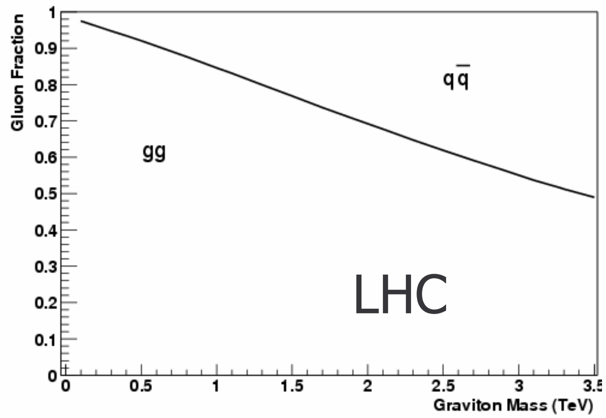
Allenach et al, hep-ph0211205

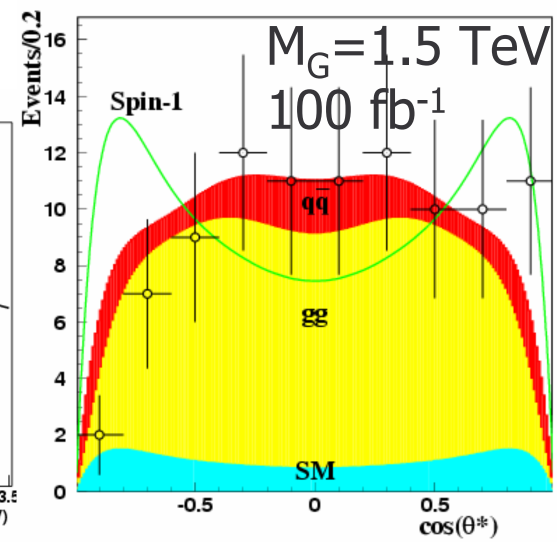
Allenach et al, JHEP 9 19 (2000), JHEP 0212 39 (2002)

RS1 Model Determination

Spin-2 could be determined (spin-1 ruled out) with 90% C.L. up to M_G = 1720 GeV







Note: acceptance at large pseudo-rapidities is essential for spin discrimination (1.5<|eta|<2.5)

Allanach et al, hep-ph 0006114