Search for Extra Dimensions in the Diphoton Channel at CMS

Selda Esen

Brown University

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Introduction

• *Hierarchy Problem* in the Standard Model:

➔ Why the fundamental scale of Gravity (M_{Pl} ~ 10^{19} GeV) is so much higher than the electroweak (M_{EWSB} ~ 10^{3} GeV)?

➔ Many extensions of the Standard Model (SM) are motivated by the hierarchy problem.

• Possible Solution: ***Extra Dimensions (EDs)***

➔ ED effects are revealed from the existence of series of Graviton states (Kaluza Klein)

▪ Focus on:

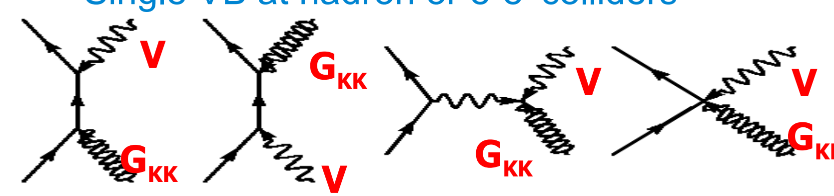
➔ *Large ED (ADD)*
Proposed by Arkani-Hamed, Dimopoulus and Dvali.
Phys Lett B429, 257-263 (1998)

➔ *Warped ED (RS)*
Proposed by Randall and Sundrum.
Phys Rev Lett 83, 3370-3373 (1999))

Real Graviton Emission

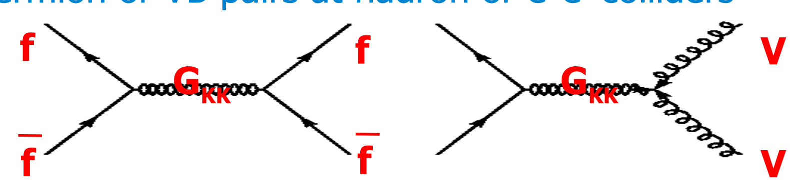
Monojets at hadron colliders

Single VB at hadron or e^+e^- colliders



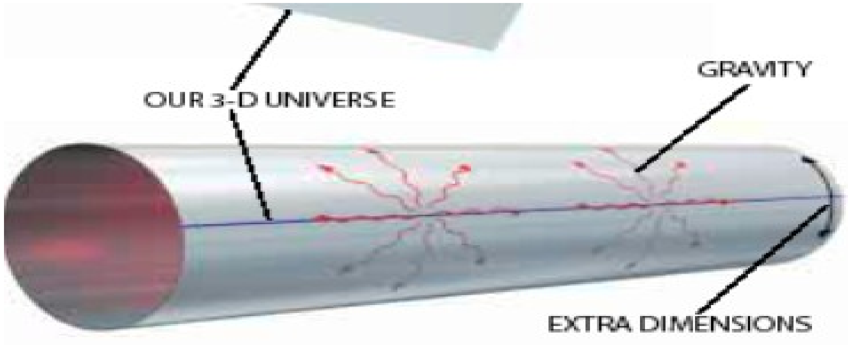
Virtual Graviton Exchange

Fermion or VB pairs at hadron or e^+e^- colliders



Large Extra Dimensions

- SM lives on bulk (3+1 dimensions), but gravity propagates through extra dimensions (n_{ED})
  - Fundamentally strong force, but we don't feel that
    - Strength is diluted (Gauss' Law)



- In the presence of n_{ED}, the fundamental Planck Scale in 4+n dimensions can be lowered to the TeV range (~1 TeV)
  - To the value comparable to the scale that characterizes the other forces

- The fundamental Planck scale: $M_D^{(n_{ED}+2)} \approx M_{Pl}^2 / R^{n_{ED}}$

  - For $M_D \sim M_{EWSB} \rightarrow r \sim 10^{30/nED\ -19}$ m
    - $n_{ED}>1$, ED implies ~mm scales,

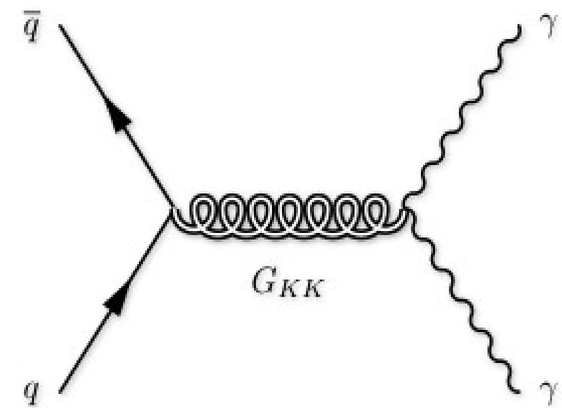
- Fairly large compared to the characteristic distance scales .

Large ED: Signature

- *Virtual Graviton* can decay, and give *diboson and difermion* final state

- Effective cross section has three terms with one parameter :

$$\sigma = \sigma_{SM} + \eta_G \sigma_{\text{int}} + \eta_G^2 \sigma_{\text{KK}} \qquad \eta_G = F / M_s^4$$



- *Enhancement* at the high end of the invariant mass spectrum of the pair of the final state particles

- Focus on *diphoton* final state

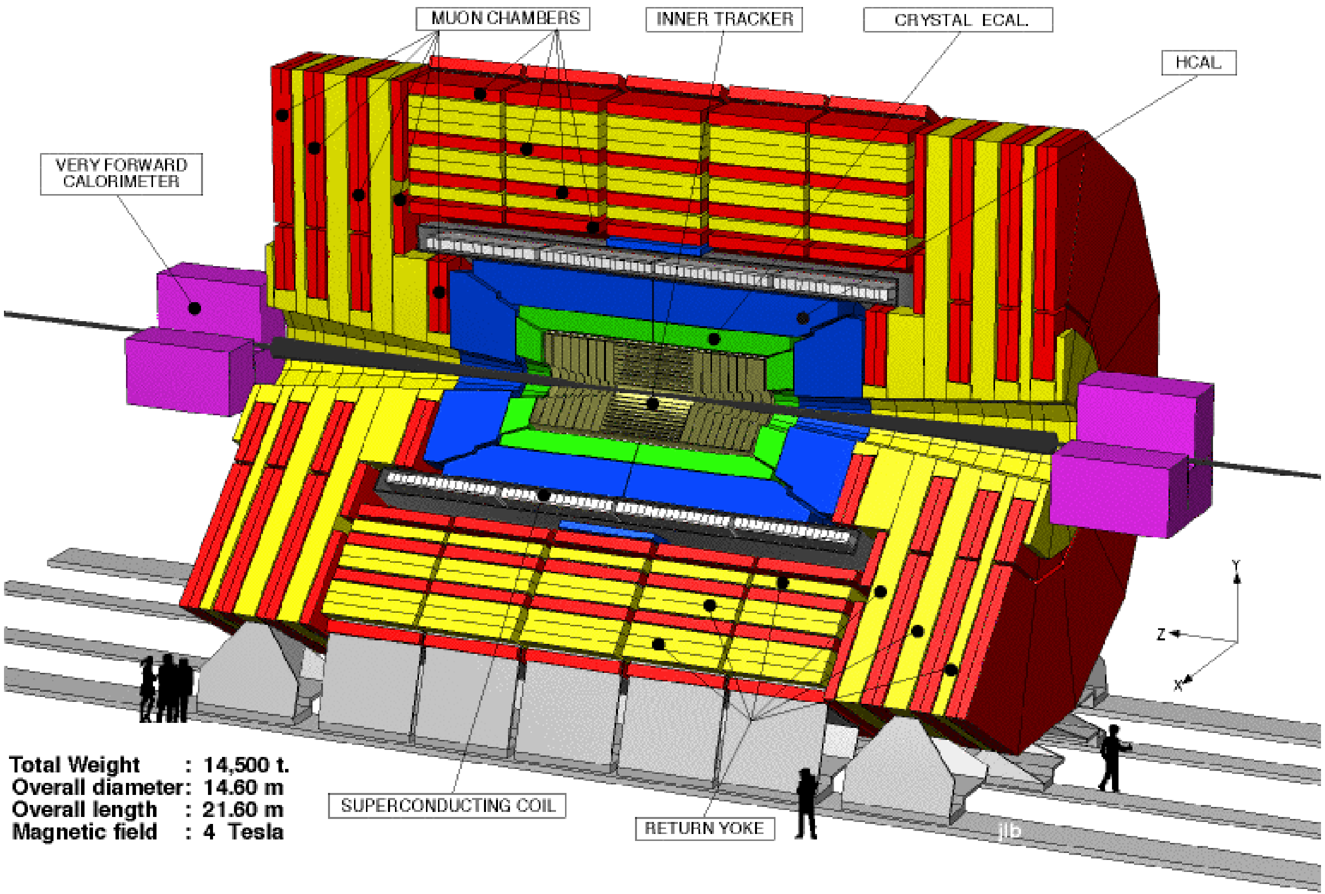
→ Easy to reconstruct; higher branching fraction, as spin-2 gravitons decay into a pair of photon in the s-wave.

- Search strategy: Likelihood fits as a function of η_G

- Translate into 95% CL lower limits on M_s for simplified *HLZ* (Han, Lykken, Zhang) convention.
  - → *Phys. Rev. **D 59**, 105006 (1999)*

$$\mathcal{F} = \begin{cases} \log\left(\frac{M_S^2}{\hat{s}}\right), & n = 2 \\ \frac{2}{n-2}, & n > 2 \end{cases}$$

The CMS Detector



Muon Chambers
HCAL
ECAL
Inner Tracker

- LHC *p-p* collider.
- CMS is one of the LHC experiments.
- Studies here are for $\sqrt{s}$ = 10 TeV.
- Data taking is starting this fall (hopefully)!

Photon ID @ CMS

To become a *photon* in the CMS software:

- You must have a deposition of energy in the ECAL (a supercluster)
- Pass an E_T threshold (currently set at 10 GeV)
- Pass some minimal and efficient (loose) isolation cuts

Which means:

- All real photons will pass the photon ID requirements
- All real electrons will pass the photon ID requirements
- A lot of jets will pass the photon ID requirements

Photon ID in this analysis:

- Require tighter *isolation* cuts to reduce the background from jets
  - Isolations: ECAL, HCAL, Tracking, HadronicOverEM (H/EM)
  - The cuts were optimized for this analysis
- Require that the ECAL superclusters don't have associated pixel detector hits, *pixel veto*, to get rid of background from electrons/positrons

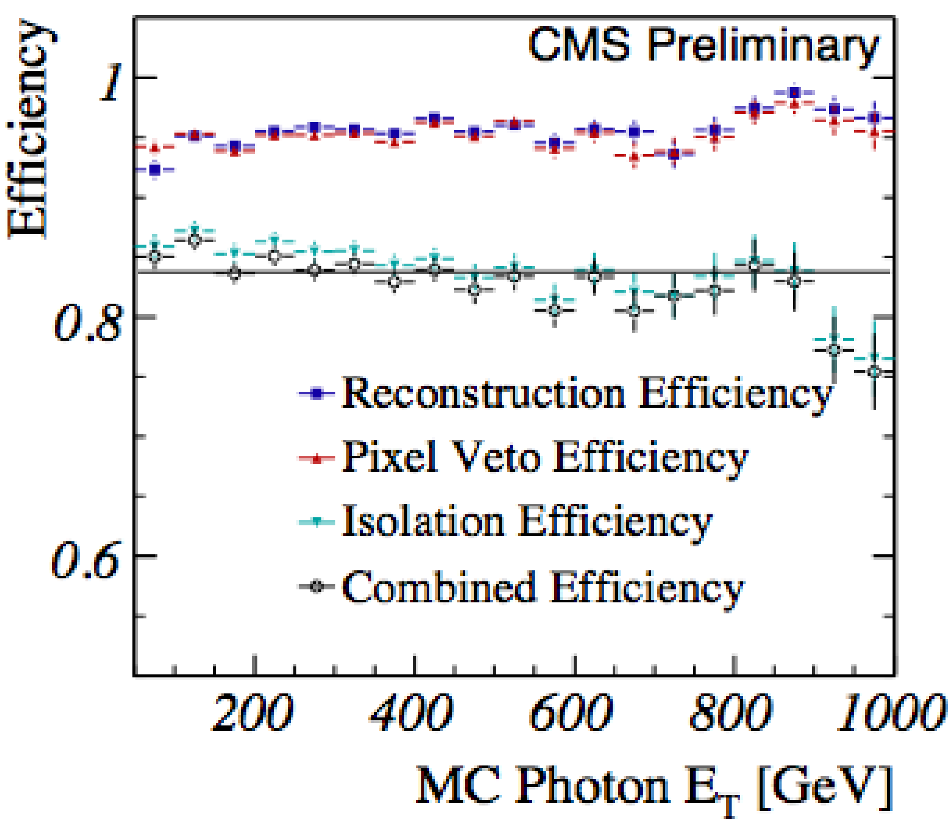
Kinematic cuts: E_T>50 GeV, |η|<1.5, $M_{\gamma\gamma}$ >700 GeV

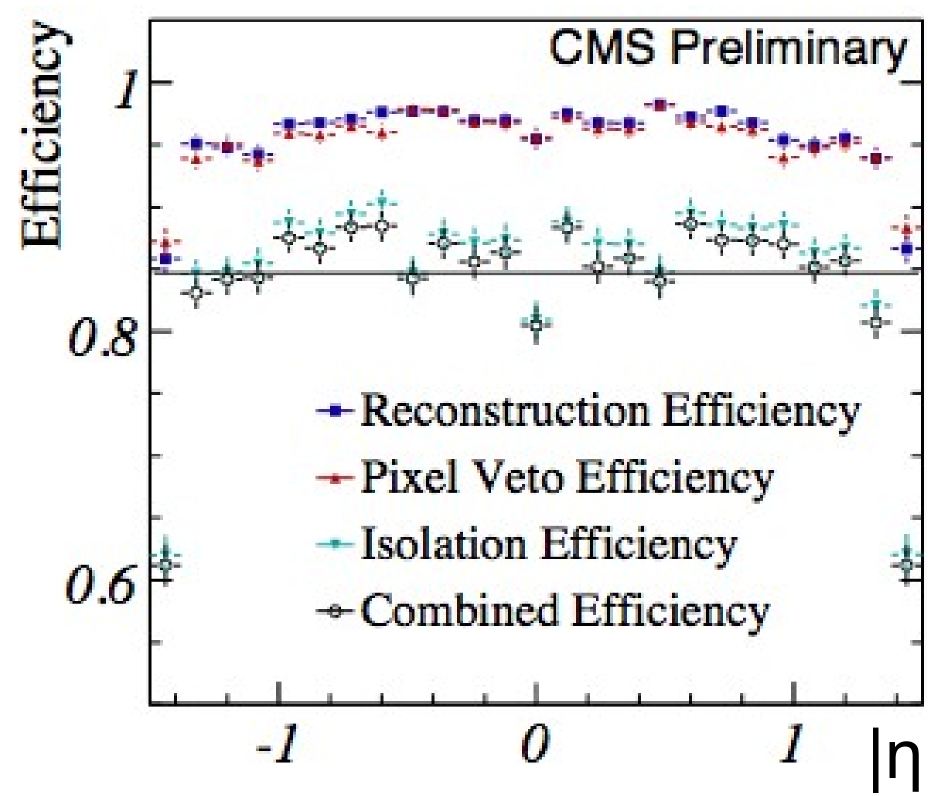
Photon ID: MC Efficiency

- Photon efficiency includes reconstruction, pixel veto and photon isolation

→ Measure it as a function of E_T and $|\eta|$

- $\varepsilon_\gamma = 0.85 \pm 0.04$
- $\varepsilon_{\gamma\gamma} = 0.72 \pm 0.07$





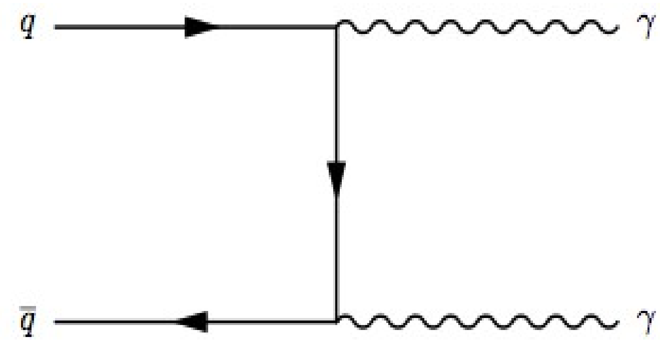
Backgrounds (I)

There are two types of background:

•Irreducible:

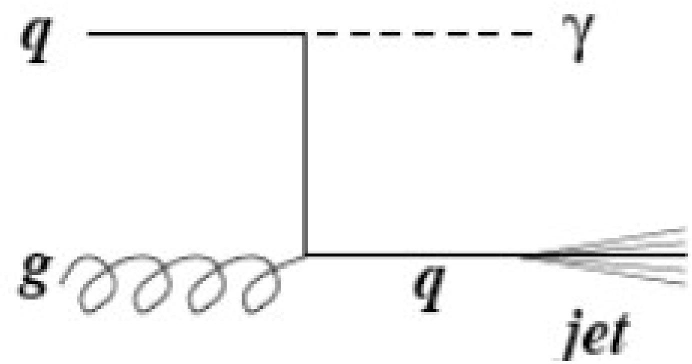
➔SM production of diphotons principally through t-channel diagrams.

- ➔ Born and Box
- ➔ Box contribution is negligible above 200 GeV

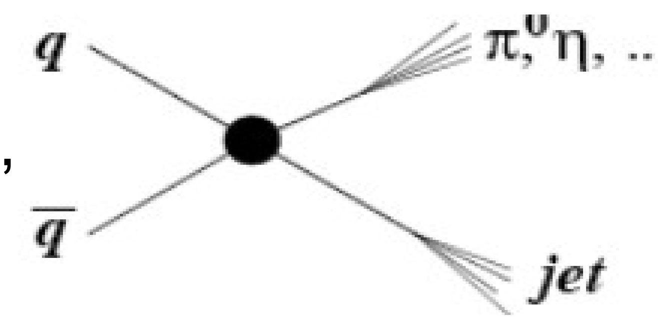


•Instrumental:

➔ $\gamma + jets$, *QCD dijets*: Typically when jet is dominated by neutral hadron, which decays to photons.



➔ *Drell-Yan* ($e^+ e^-$): from electron bremms or mis-reconstruction of tracks.



•Strategy: Reduce the instrumental background, so it is negligible compared to the irreducible direct background.

Backgrounds (II)

- *Dijet and photon+jets*
  - Apply the jet-faking-photon fake rate ($f_{jet \to \gamma}$) to the jets in the dijet and $\gamma + jets$ events
  - $f_{jet \to \gamma}$: E_T spectrum of photons divided by E_T spectrum of jets (using MC dijet events): $f_{jet \to \gamma} \approx 10^{-3} - 10^{-4}$

- Data-Driven:
  - Overestimate if we fail to subtract out direct γ contamination in real dijet data
  - Use conversions ($\gamma \to ee$) to determine the fraction of jets and direct photons
  - Calculate the total E_T of the supercluster divided by the total sum p_T of the two associated tracks, $E_T / \sum p_T$, which is lower for the prompt photons
  - Demonstrated the method works well

- *Drell-Yan*
  - Completely data-driven:
  - Use ee and $e\gamma$ in the Z *events*
  - Apply the electron-faking-photon fake rate ($f_{e \to \gamma}$) to the high mass Drell-Yan samples
  - The fake rate:

$$f_{e \to \gamma} = 1 - 2N_{ee} / (2N_{ee} - N_{e\gamma})$$

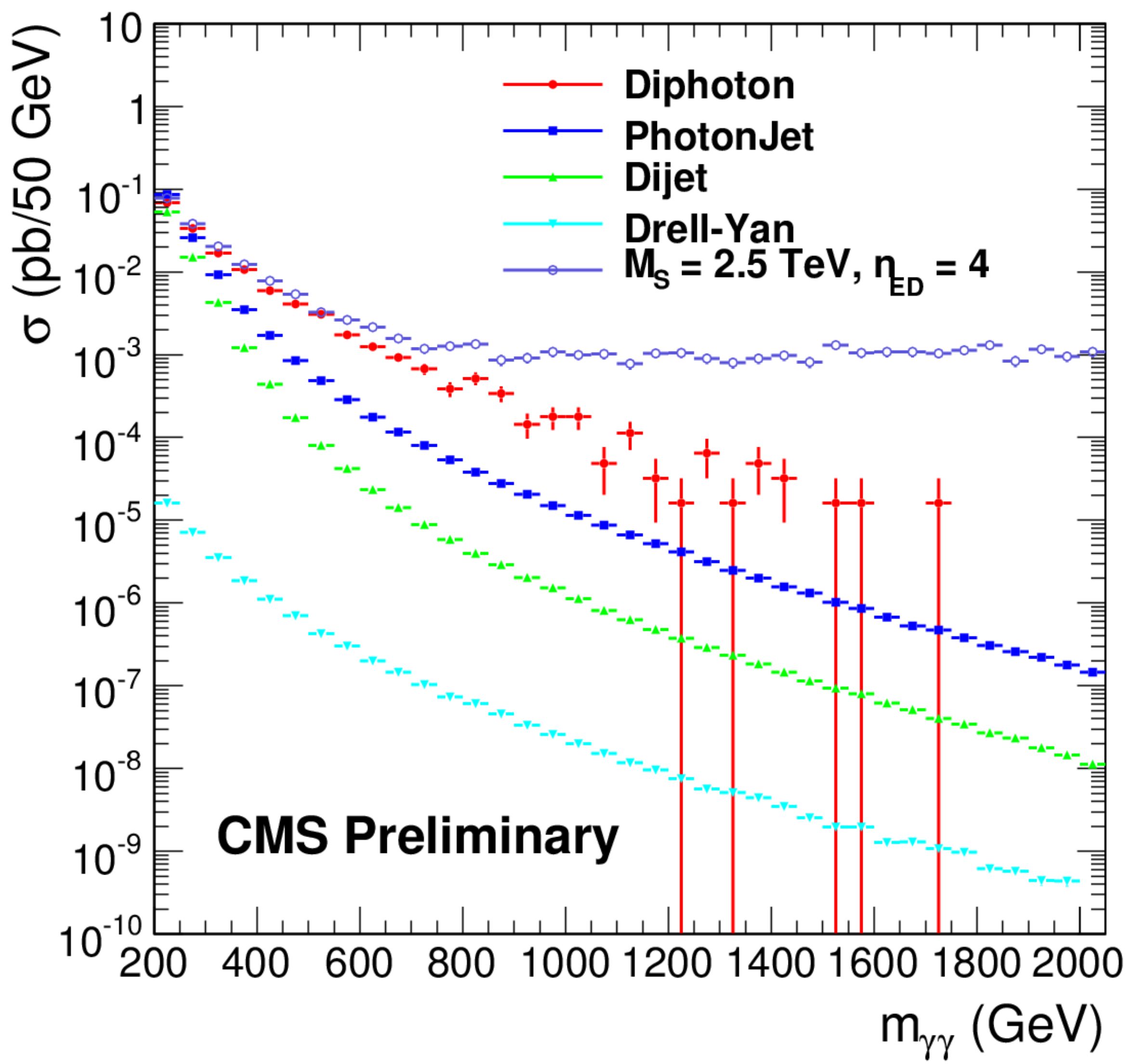
$$f_{e \to \gamma} \approx 0.86\,\%$$

- *SM Diphotons*
  - Determined via normalization in $200 < M_{\gamma\gamma} < 500$ GeV range with ~35% uncertainty
  - In $200 < M_{\gamma\gamma} < 300$ GeV region, the dijet and direct γ background is not negligible
    - Needed to be subtracted out

Backgrounds and Large ED Signal

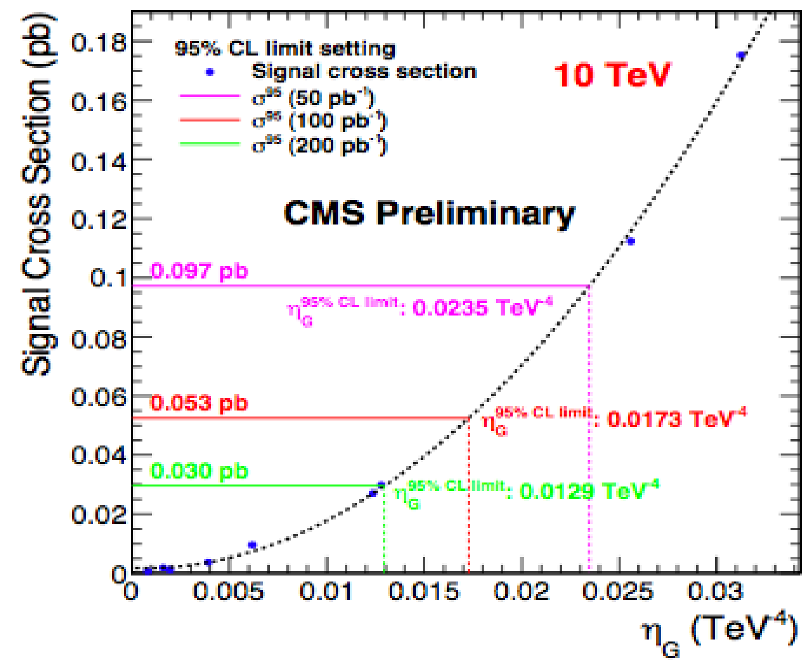
- Large ED creates an *enhancement* at high $M_{\gamma\gamma}$
- SM diphoton is the *dominant* background

- **Systematics:**
  - 10% uncertainty in the efficiency and luminosity
  - 10% uncertainty on the signal cross section, mainly due to the K factor uncertainty
  - ~35% uncertainty on the background estimation, luminosity dependent



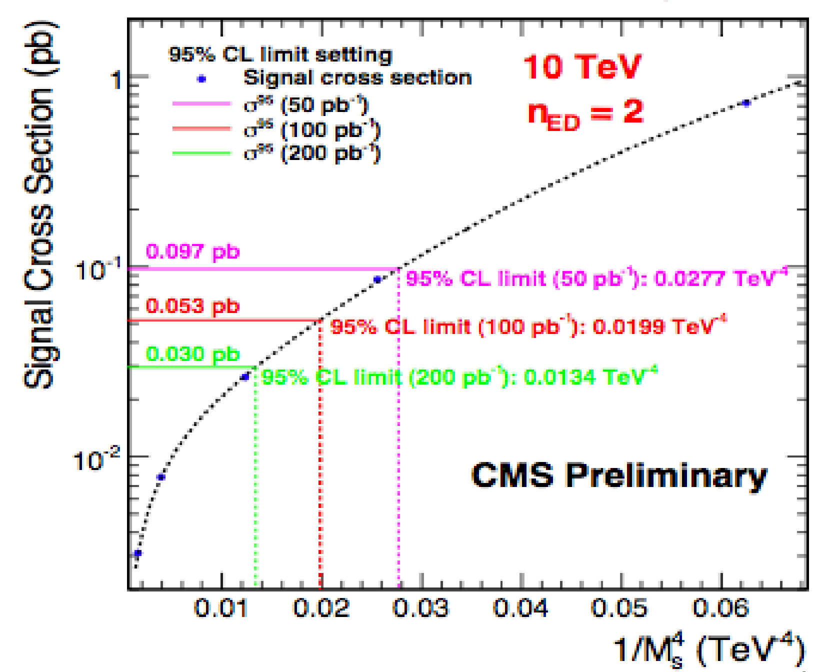
Expected 95% CL Limits

- Current 95% CL best limit on Ms:
  - LEP: 1.1-1.2 TeV
    - depends on sign of the interference term (convention by J. Hewett)
      - *Phys. Rev. Lett.* ***82****, 4765 (1999)*
    - ~ 1.2 at n_{ED} = 5 for λ = +1 (in HLZ)
  - Tevatron: 1-2 TeV
    - depends on n_{ED} (HLZ)
      - *Phys. Rev. Lett.* ***102****, 051601 (2009)*



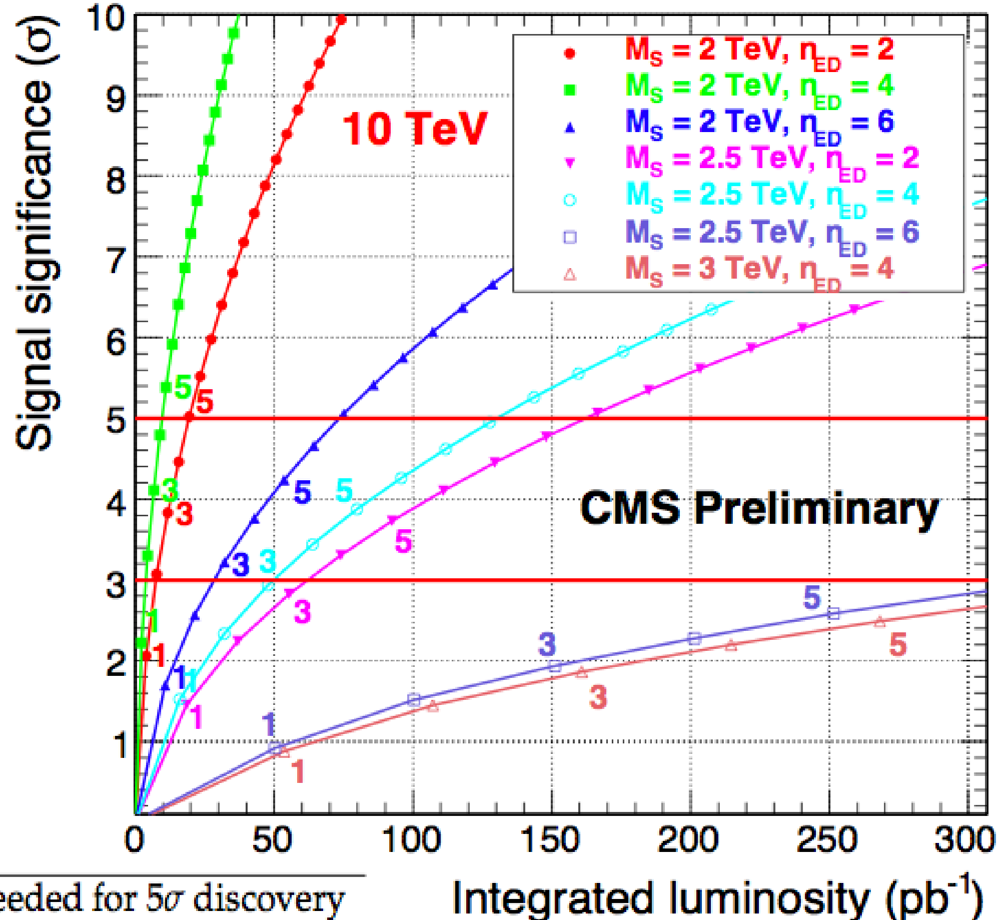
- The limits on M_S for 100 pb^{-1} are approximately twice current limits achieved at Tevatron

n_{ED}	95% CL Limit on M_S		
	50 pb^{-1}	100 pb^{-1}	200 pb^{-1}
2	2.5 TeV	2.7 TeV	2.9 TeV
3	3.0 TeV	3.3 TeV	3.5 TeV
4	2.6 TeV	2.8 TeV	3.0 TeV
5	2.3 TeV	2.5 TeV	2.7 TeV
6	2.1 TeV	2.3 TeV	2.5 TeV
7	2.0 TeV	2.2 TeV	2.4 TeV



Discovery Potential for Large ED

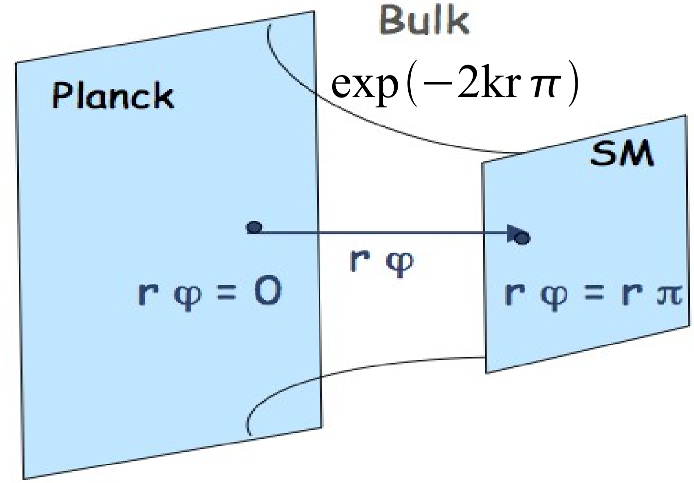
- Calculate the Poisson probability for background to fluctuate to or above the number of observed events, n_{obs}
- Convert the probability of one-side Gaussian significance and express this as a number of sigmas (σ)
- Further require $n_{obs} \geq 3$ and $n_{obs} \geq 5$
- At ~130 pb^{-1}, we can observe M_S = 2.5 TeV, n_{ED} = 4 at 5σ



ED Parameters	$\int Ldt$ needed for 3σ evidence	$\int Ldt$ needed for 5σ discovery
$M_s = 2$ TeV, $n_{ED} = 2$	~ 12 pb^{-1}	~ 20 pb^{-1}
$M_s = 2$ TeV, $n_{ED} = 4$	~ 7 pb^{-1}	~ 11 pb^{-1}
$M_s = 2$ TeV, $n_{ED} = 6$	~ 32 pb^{-1}	~ 72 pb^{-1}
$M_s = 2.5$ TeV, $n_{ED} = 2$	~ 62 pb^{-1}	~ 162 pb^{-1}
$M_s = 2.5$ TeV, $n_{ED} = 4$	~ 51 pb^{-1}	~ 129 pb^{-1}
$M_s = 2.5$ TeV, $n_{ED} = 6$	~ 342 pb^{-1}	~914 pb^{-1}
$M_s = 3$ TeV, $n_{ED} = 2$	~ 314 pb^{-1}	~846 pb^{-1}
$M_s = 3$ TeV, $n_{ED} = 4$	~ 387 pb^{-1}	~1050 pb^{-1}

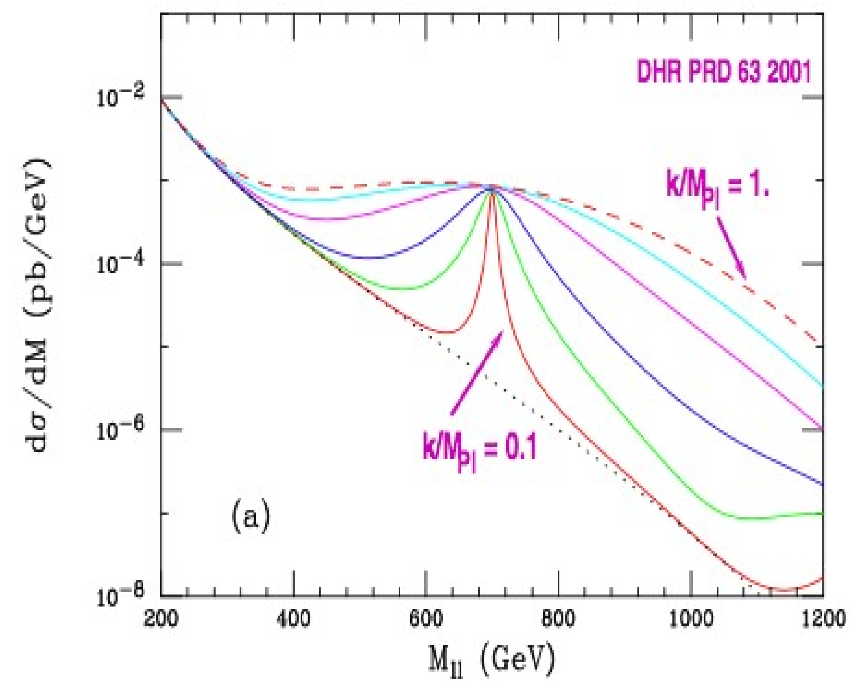
Warped Extra Dimension (RS)

- Study the simplest RS1 model, in which all particles, except the graviton, are localized on (3+1)-dim SM brane, separated by a warped extra dimension (k: warp factor)



- Gravitons appears as a series of high mass resonances (Kaluza-Klein modes)

- Two free parameters:
  M_1 (M_G): lowest excitation mass
  $\tilde{k} = k / M_{Pl}$: coupling parameter

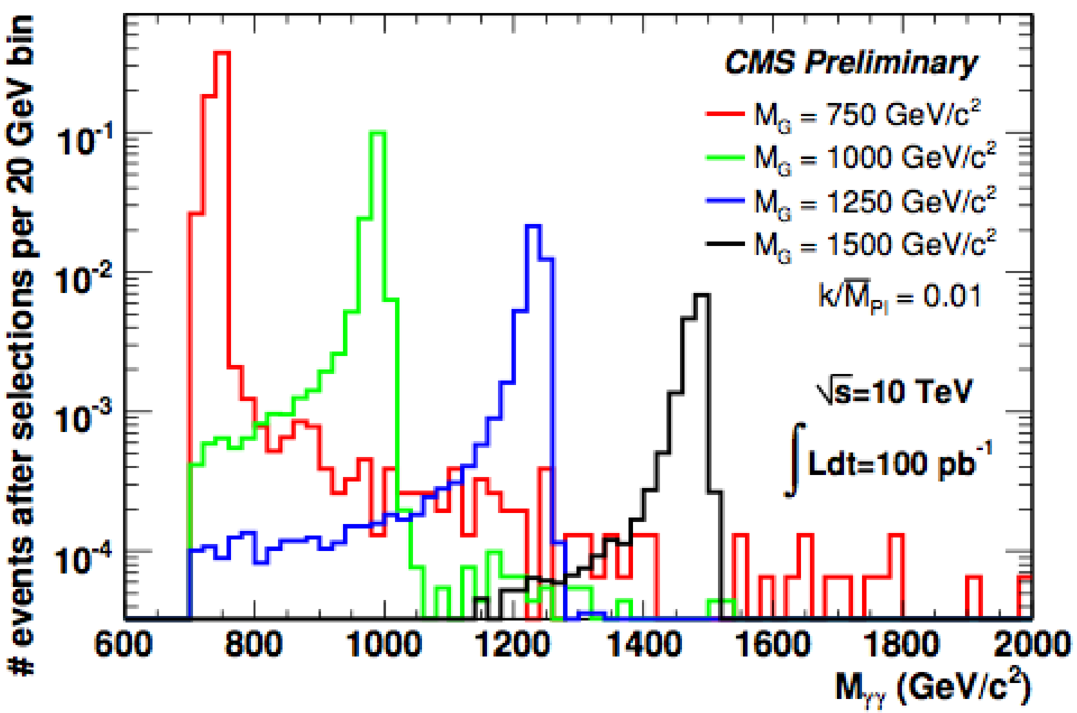


- We probe the feasibility of discovering RS gravitons in the diphoton channel

- Strategy: Use the results of the search for Large ED in the diphoton channel to extract the limits on the RS model.

Signal & Event Selection for Warped ED

- High mass diphoton resonance ($G_{KK} \rightarrow \gamma\gamma$)
- Use the samples produced with the parameters:
  - ➔ $\tilde{k}$ = 0.01 & M_G = 750, 1000, 1250, 1500 GeV
- We apply the selection optimized for the Large ED:
  - ➔ E_T>50 GeV, $|\eta|$<1.5, $M_{\gamma\gamma}$>700 GeV

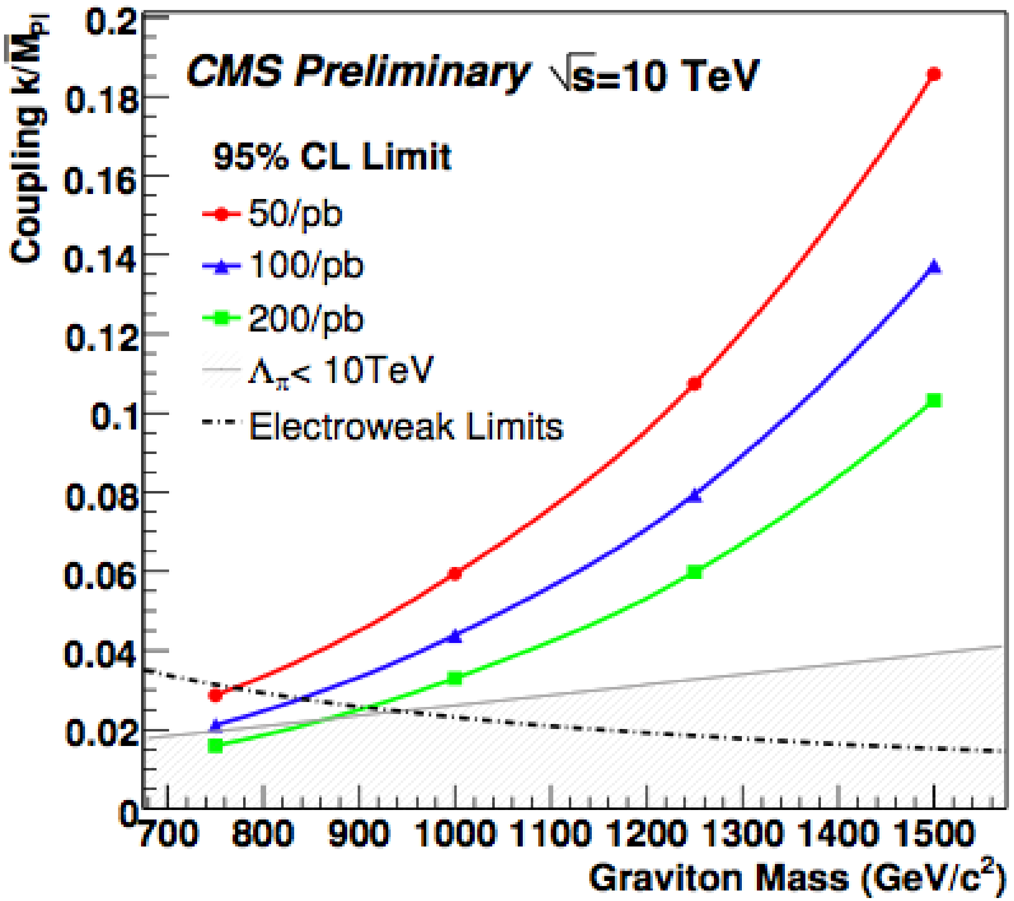


Photon efficiency: 63%-59%

Photon acceptance: 50%-67%

Expected 95 % CL on Warped ED

- Use the results of the search for Large ED in the diphoton channel to extract the limits on the RS model.
  - Correct for the differences in efficiency and acceptance between Large ED and RS.



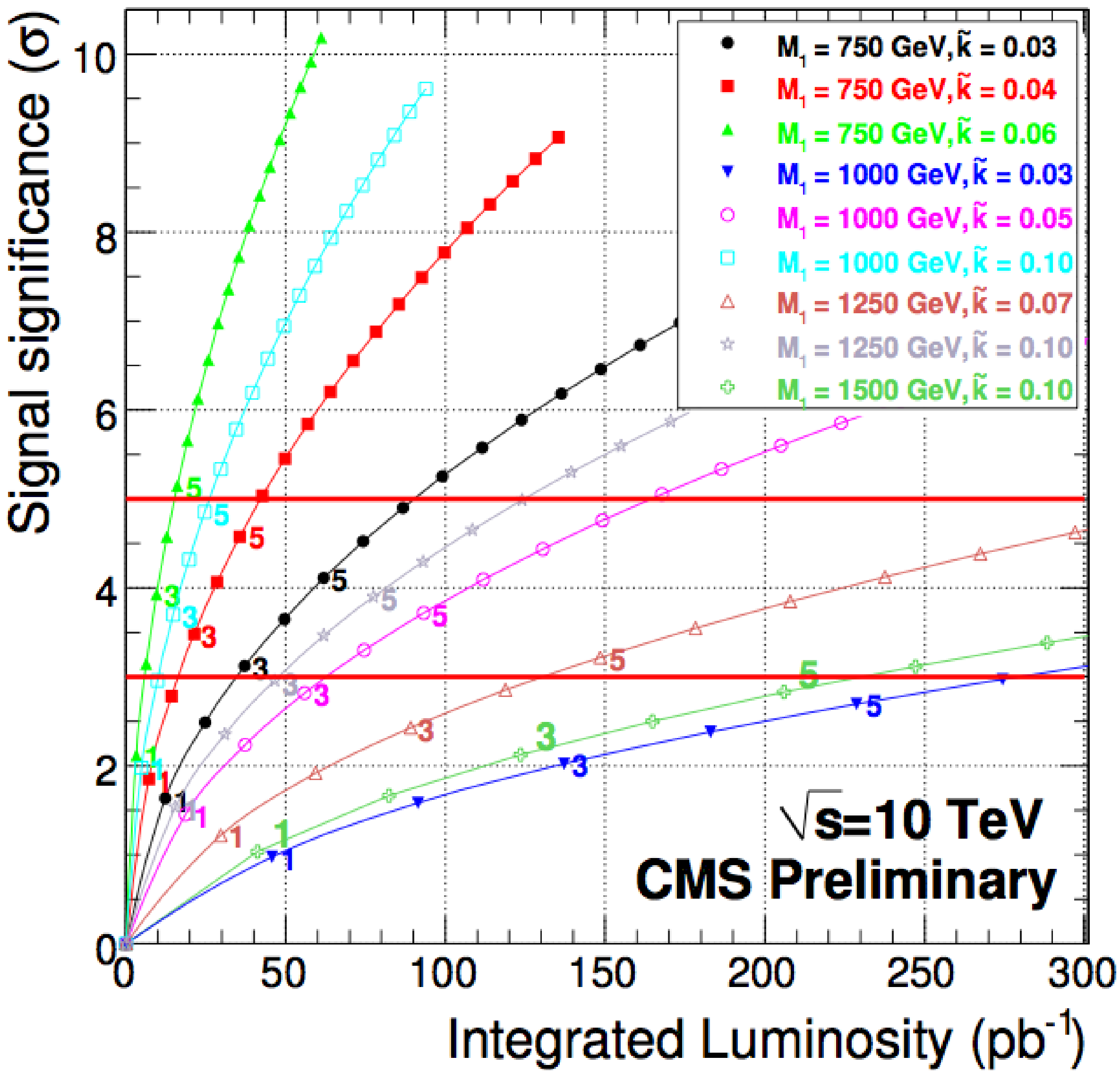
- With 50 pb^{-1}, we can exclude a RS graviton up to:
  M_1=1.2 TeV, $\tilde{k}$ = 0.1
- With 100 pb^{-1}, we can exclude up to:
  M_1=1.35 TeV, $\tilde{k}$ = 0.1

- Current Limits at Tevatron:

→95%CL at D0 (CDF) for $\tilde{k}$ =0.1
M_1 = 900 (850) GeV for di-EM ($\gamma\gamma$)

*PRL **100**, 091802 (2008)*
*PRL **99**, 171801 (2007)*

Discovery Reach for Warped ED



Plot showing luminosity required for signal discovery for various values of M_1 and $\tilde{k}$

With as little as 30 pb^{-1}, we can claim discovery if M_1<1.0 TeV, $\tilde{k}$=0.1

With 100 pb^{-1}, we can claim discovery if M_1=750 GeV, $\tilde{k}$=0.03

With 130 pb^{-1}, we can claim if M_1=1.25 TeV, $\tilde{k}$ =0.1

Conclusions

- We have designed an analysis to search for Large Extra Dimensions through virtual KK Graviton production in the diphoton channel.
  - With 100 pb^{-1} data, we expect to set 95% CL limit on the cutoff scale, Ms, between 2.2-3.3 TeV depending on the number of Extra Dimensions
  - We expect observation and discovery to be possible with early data, even for Ms~2.5 TeV
- We have extended the results of Large Extra Dimensions analysis to place a limit and probe the discovery reach of RS gravitons in the diphoton decay channel
  - With 100 pb^{-1} we can place 95% CL limit on a graviton mass up to 3 TeV with $\tilde{k}$ >0.1. Likewise, with 100pb^{-1}, we can claim a 5σ discovery for a 750 GeV graviton if $\tilde{k}$ >0.03

Photon ID: Isolation Requirement

- We want to ID prompt photons with E_T>50 GeV
  - ➔Start with the superclusters
  - ➔Use isolation variables to reduce the jet fake background
- Isolation Criteria:

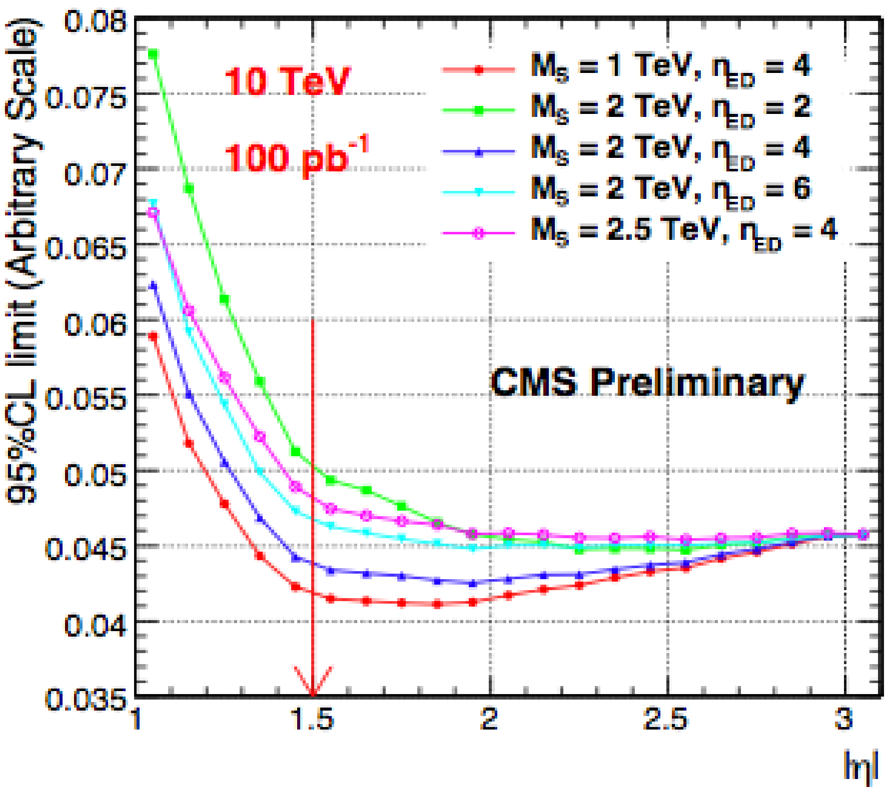
HadronicOverEM: Hadronic energy divided by EM energy
The cut used: <0.05

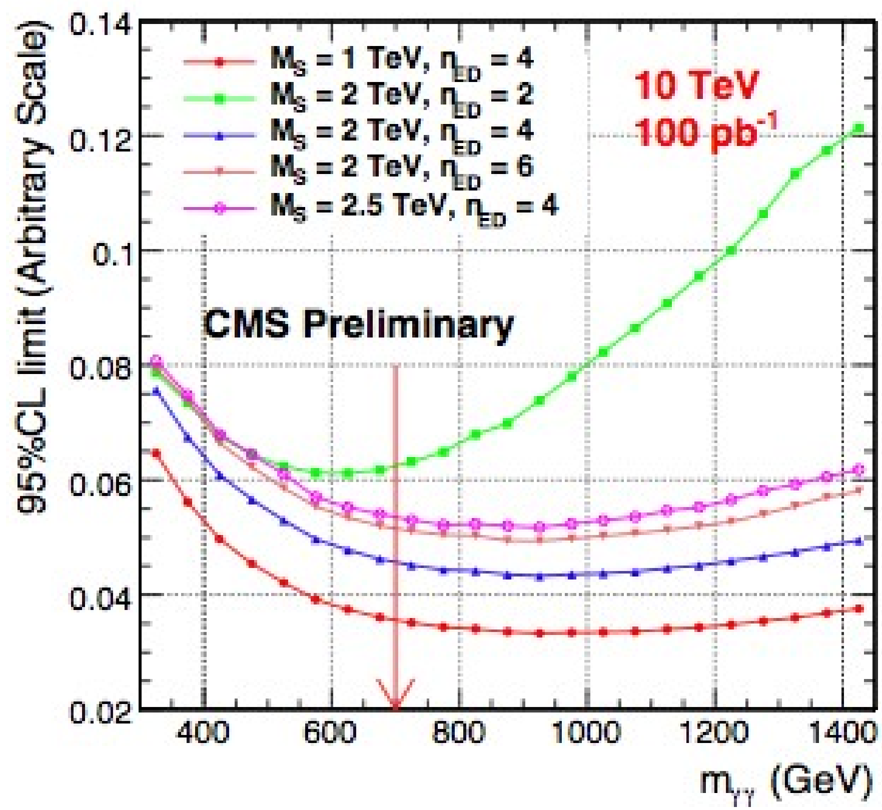
Tracking Isolation: Sum of the p_T in the hollow cone of dR = 0.04-0.40
The cut used: <5 GeV

ECAL Isolation: Sum E_T in a hollow cone of dR = 0.06-0.40
The cut used: <10 GeV

HCAL Isolation: Sum E_T in a hollow cone of dR = 0.1-0.4
E_T sliding window cut used: $< 4.7 + 0.003 * E_T$

Kinematic optimization





- Minimize 95% CL cross section limit with respect to photon |η| and $M_{\gamma\gamma}$
- Only consider diphoton SM background
- Chosen cuts: |η| < 1.5 and $M_{\gamma\gamma}$ > 700 GeV

Photon Acceptance and Efficiency for RS

M_1 (GeV/c^2)	$\tilde{k}$	$N_{expected\ 100pb^{-1}}$	MC acceptance	photon ID/reco eff
750	0.01	0.595 $\pm$0.007	0.499 $\pm$0.004	0.631 $\pm$0.005
1000	0.01	0.150 $\pm$0.001	0.563 $\pm$0.003	0.633 $\pm$0.004
1250	0.01	0.0462 $\pm$0.0004	0.616 $\pm$0.003	0.599 $\pm$0.004
1500	0.01	0.0155 $\pm$0.0001	0.672 $\pm$0.003	0.588 $\pm$0.004

- We separate the acceptance for MC truth particles applying only the kinematic selection and the photon efficiency

- Photon efficiency includes reconstruction, pixel veto, photon identification

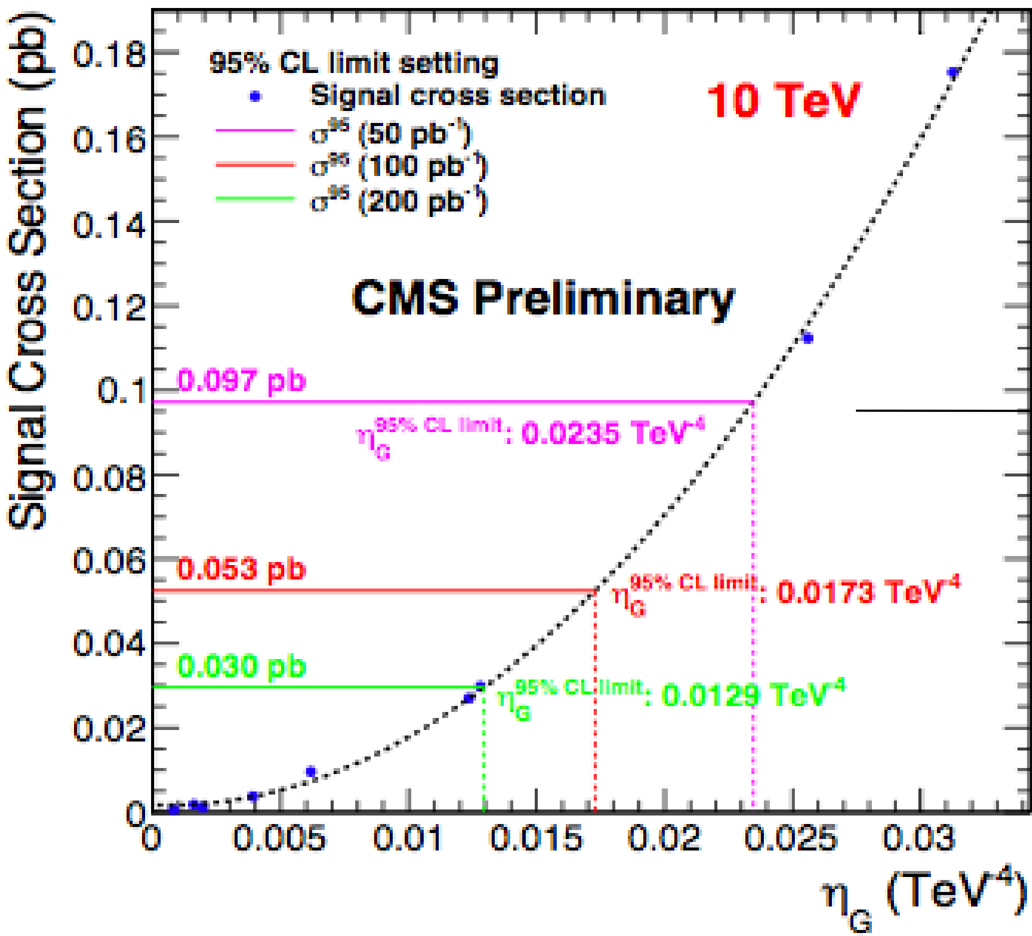
- Photon identification includes H/EM, Tracker, ECAL, and HCAL isolations

- The photon efficiency for large ED analysis is a flat ~ 0.72+/-0.07

- The efficiency here is also flat but significantly lower, so we use the actual RS efficiency to calculate limits and reach. The difference in efficiency is possibly due to differences in sample composition and MC simulation details

Extrapolations of Limits for RS

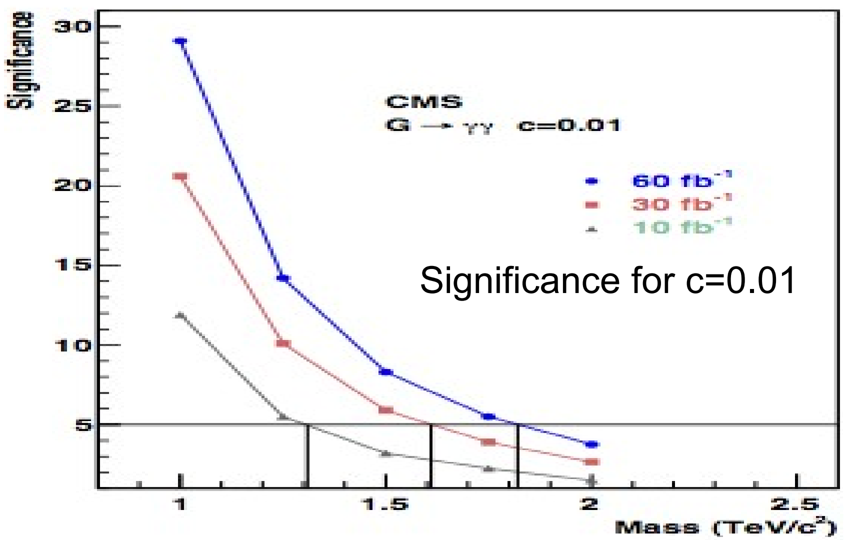
•We use the acceptances calculated to extrapolate the limits from Large ED diphoton Analysis to limits on the RS model

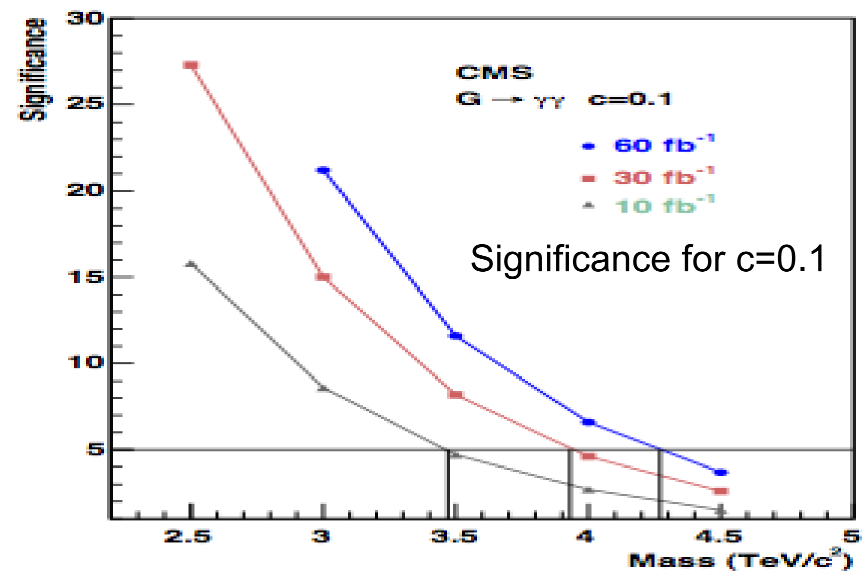


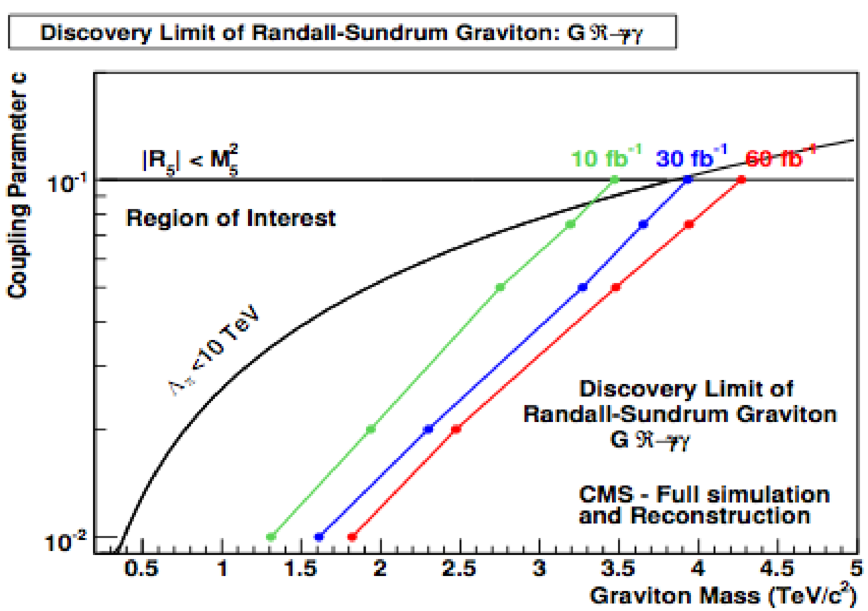
$$\tilde{k}^{95} = \tilde{k}\sqrt{\frac{\sigma^{95} \times (\epsilon_{ID}/\epsilon_{ID}^{RS})}{\sigma_{RS}^{LO}(\gamma\gamma) \times K \times A}}$$

- $\tilde{k}^{95}$ = 95% CL on RS coupling
- $\tilde{k}$ = RS coupling = 0.01
- e_{ID} = photon eff for large ED
- e_{ID}^{RS} = photon eff for RS
- σ^{95} = 95% CL large ED signal c.s.
- σ^{LO} = LO RS signal c.s.
- K = K factor = 1.3
- A = acceptance for RS signal

Previous CMS RS Results (PTDR-II)







Where c is the coupling parameter = $\tilde{k}$

- For 10 fb^{-1}:
- →5σ discovery reaches to: M_G-1.31 TeV if c= 0.01.
- →5σ discovery reaches to M_G=2.47 TeV if c=0.1