Search for New Physics in the Diphoton Channel

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LPC J-Term 4 Workshop
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Outline

- Motivation & Introduction
- Photon ID
  - Efficiency
- Background Measurements
- Large Extra Dimensions
  - Backgrounds & Signal
  - 95% CL Limits
- Warped Extra Dimensions
  - Signal
  - 95% CL Limits
- Conclusions

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The Compact Muon Solenoid Experiment
Analysis Note
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22 April 2009 (v7, 14 July 2009)

Search for Large Extra Dimensions in the Diphoton Final State

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The Compact Muon Solenoid Experiment
Analysis Note
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24 May 2009 (v5, 09 July 2009)

Search for Randall-Sundrum Gravitons in the Diphoton Final State

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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

▪Focus on:

➔*Large ED (ADD)*

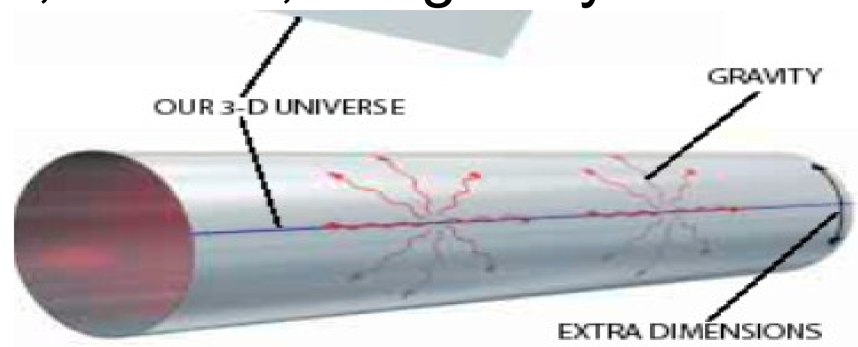
- ➔ Proposed by Arkani-Hamed, Dimopoulus and Dvali.
  Phys Lett B429, 257-263 (1998)

➔*Warped ED (RS)*

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

Large Extra Dimensions

- SM lives on 3+1 space-time dimensions, “brane”, but gravity propagates through the entire multidimensional extra space, “bulk”.
  - ➔ Fundamentally strong force, but we don't feel that
    - ➔ Strength is diluted (Gauss' Law)



- In the presence of extra dimensions, 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: $M_D^{(n_{ED}+2)} \approx M_{Pl}^2 / R^{n_{ED}}$

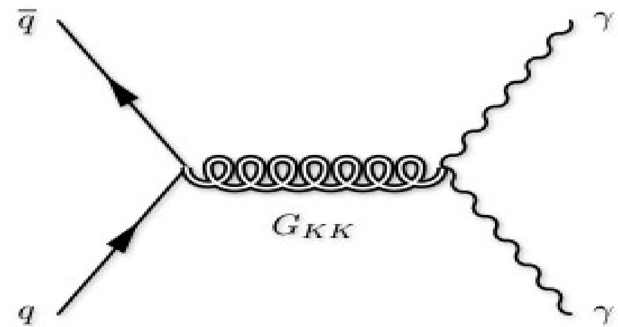
  - ➔ For $M_D \sim M_{EWSB} \sim 1\text{TeV} \rightarrow R \sim 10^{30/nED\ -19}$ m
    - ➔ $n_{ED}>1$, ED implies ~mm scales

- Fairly large compared to the characteristic distance scales .

Large ED: Signature

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

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



- 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

- Use simplified *HLZ* (Han, Lykken, Zhang) convention.
  - → *Phys. Rev.* ***D 59****, 105006 (1999)*

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

Photon Identity

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
  - See the "Photons" talk for the details at the J-Term 4 given by A. Askew

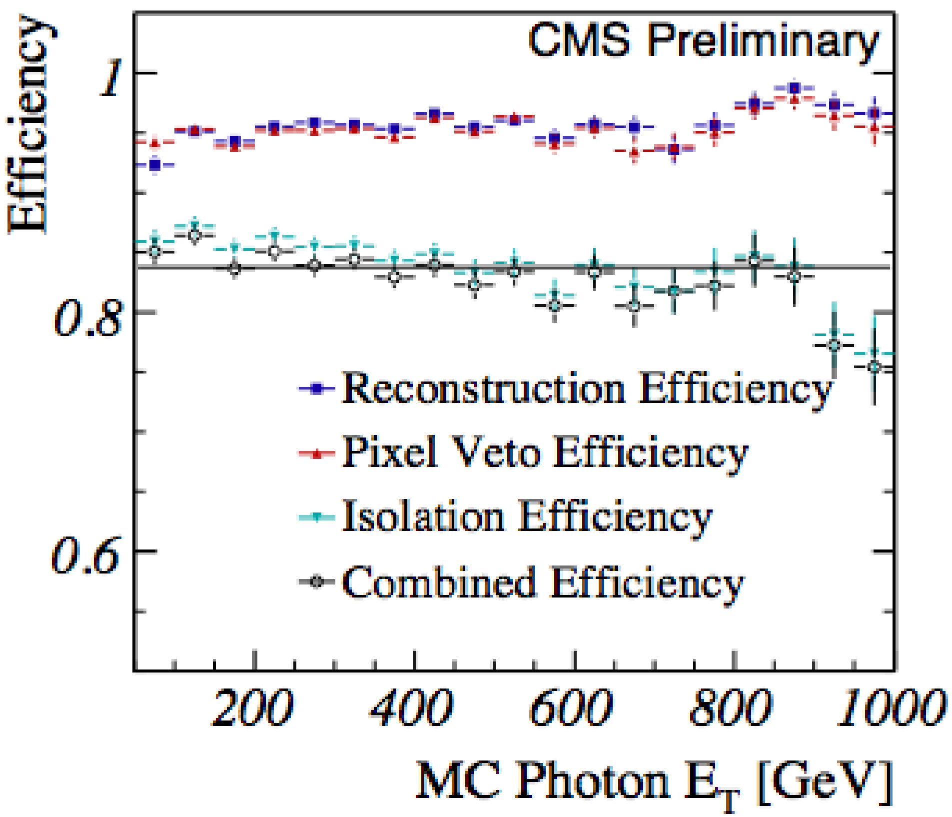
Kinematic cuts: E_T>50 GeV, $|\eta|$<1.5, $M_{\gamma\gamma}$ >700 GeV

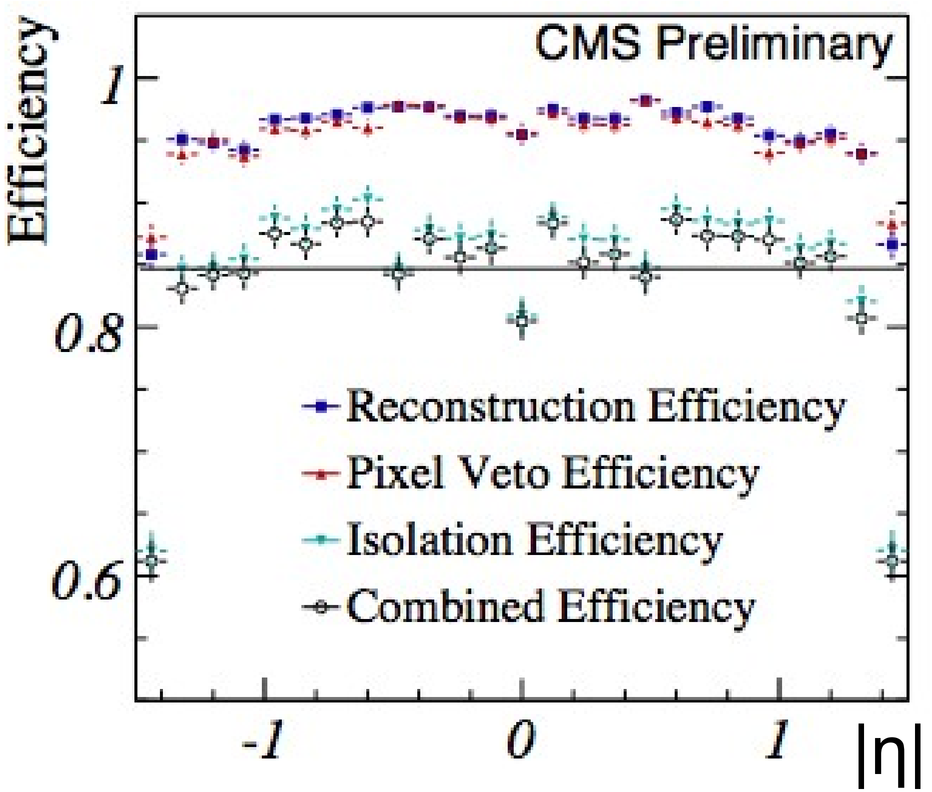
Photon ID: MC Efficiency

- Photon efficiency includes reconstruction, pixel veto and photon isolation

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

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

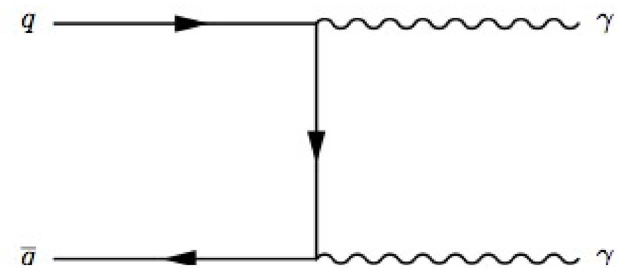


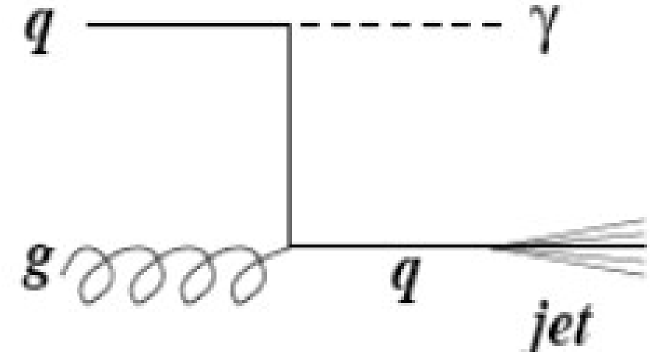


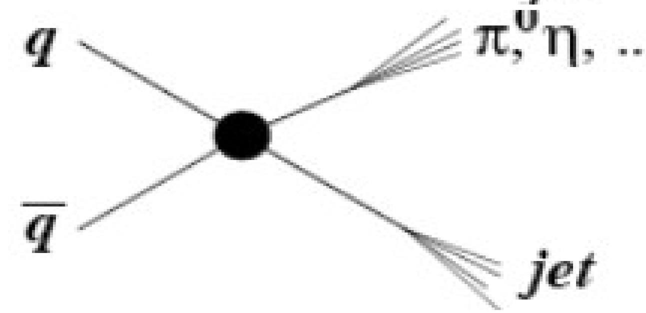
Backgrounds: Introduction

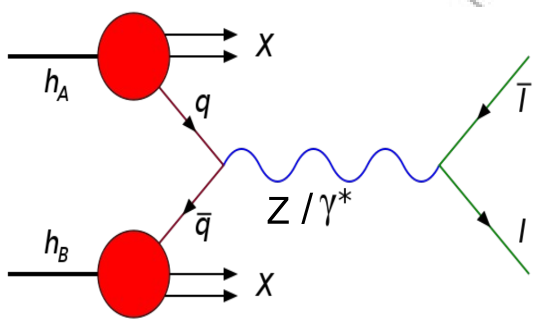
There are two types of background:

- **Irreducible:** The same final state as the signal
  - SM diphoton processes via quark annihilation (Born) and gluon fusion (Box)
    - Box contribution is negligible above 200 GeV
- **Instrumental:** Arise from processes with one or two fake fake photons: $\gamma + jets$, multijet, Drell-Yan $e^{+}e^{-}$ production
  - $\gamma + jets$, *QCD dijets*: Typically when jet is dominated by neutral hadron, which decays to photons.
  - *Drell-Yan ($e^{+}e^{-}$):* from electron bremmsstrahlug or mis-reconstruction of tracks.





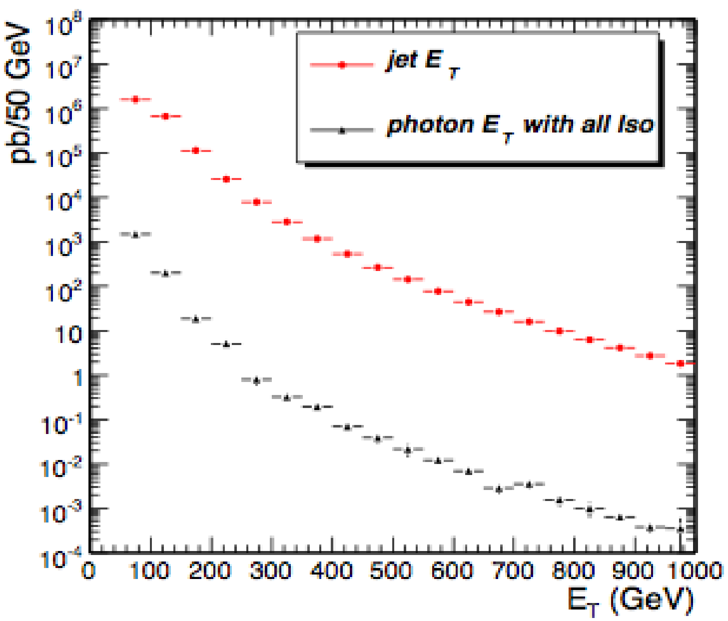




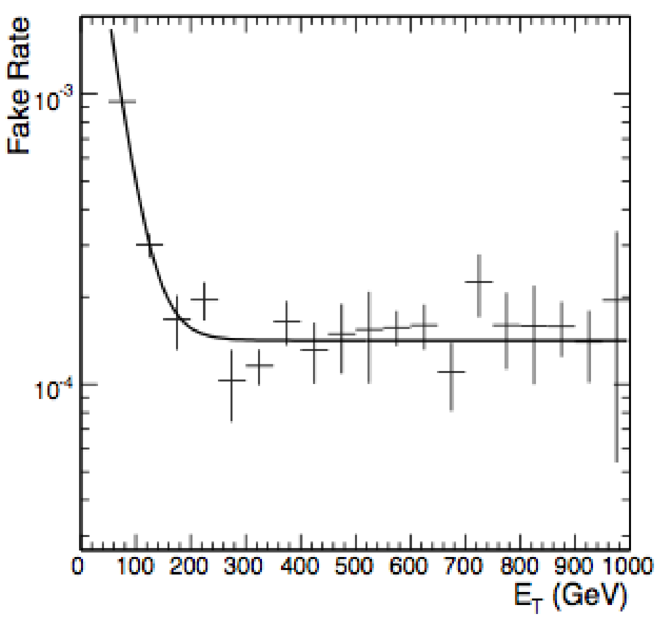
Backgrounds: Jet-Faking-Photons

- Jets can fake the isolated photons by fluctuating to a hard π^0, η
  - Measure the jet-faking-photon rate in a multijet sample
  - Define the rate as the reconstructed photon E_T spectrum divided by the photon E_T spectrum
  - Apply to the jet(s) in photon+jets and multijet events to get the background

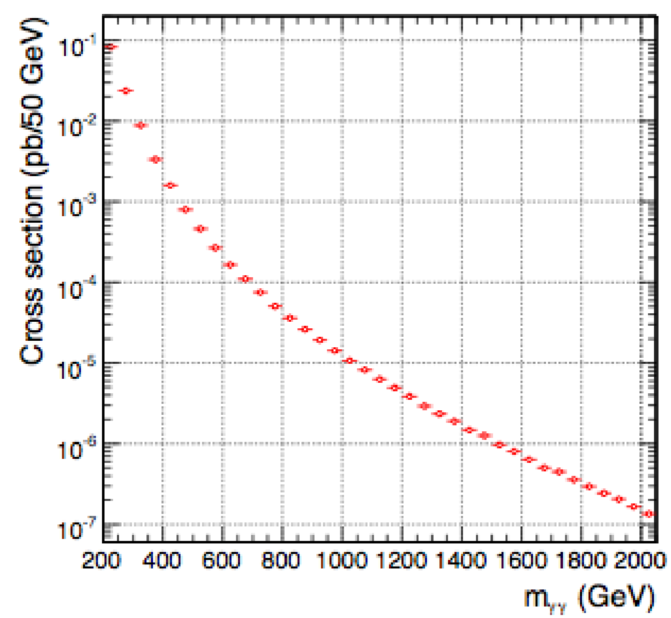
Photon and Jet E_T distributions



Jet-Faking-Photon rate



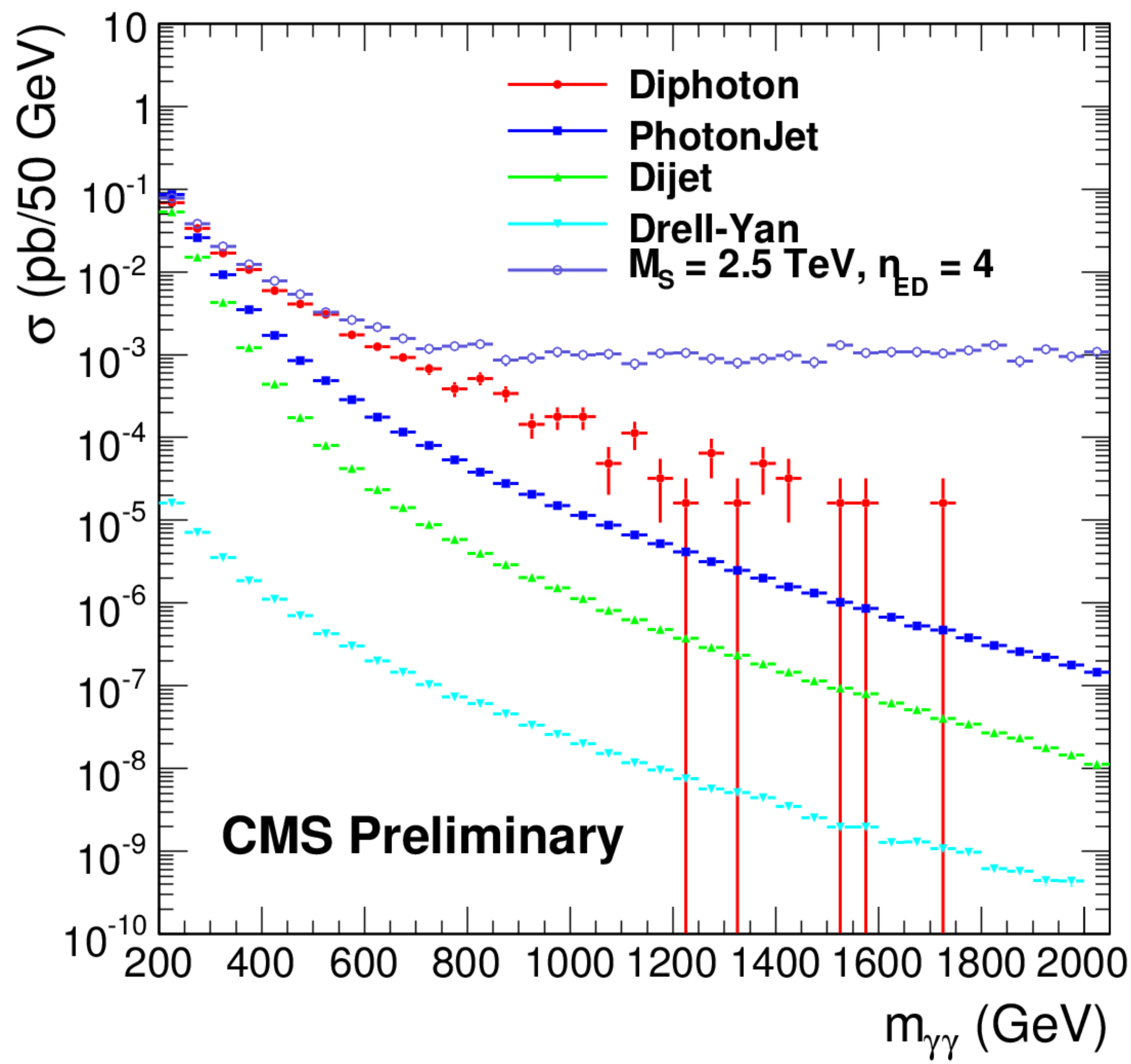
Background from $\gamma + jets$



Backgrounds and Large ED Signal

- Large ED creates an
- *enhancement* at high mass

- SM diphoton is the *dominant* background



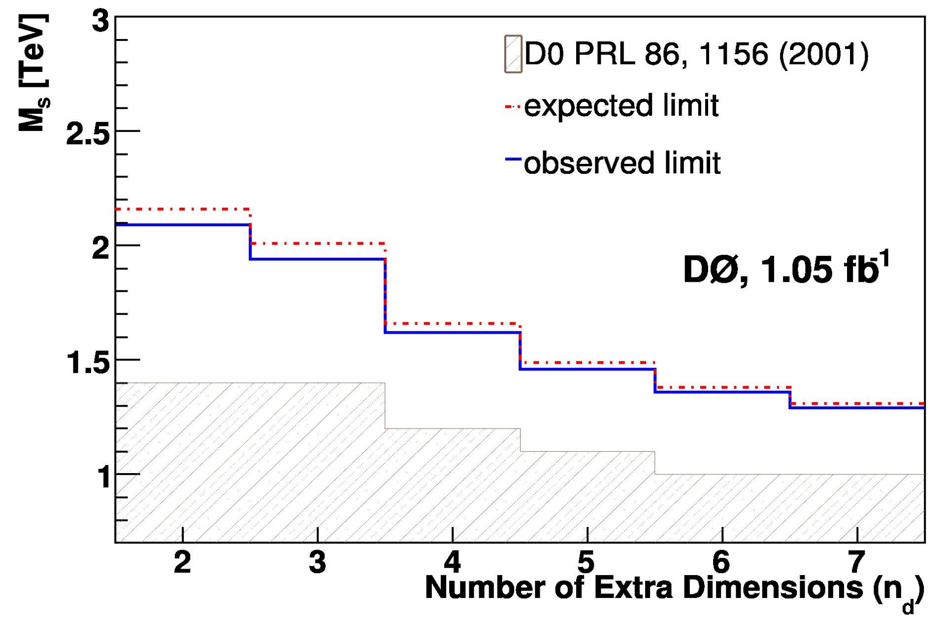
Expected 95% CL Limits

- Current 95% CL best limit on Ms
  - ➔ Tevatron: 1-2 TeV
    - ➔ depends on n_{ED} (HLZ)

- For instance n_{ED} = 4
  - ➔ M_S=1.6 TeV at Tevatron
  - ➔ M_S=2.8 TeV at CMS for 100 pb^{-1}

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

Tevatron



CMS Preliminary

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

Warped Extra Dimension (RS)

▪Study the simplest *RS1* model:

➔5-dimensional space, in which all particles, except the graviton, are localized on (3+1)-dim SM brane, separated by a warped extra dimension

➔Gravitons appear as a series of high mass resonances with widths dtermined by the

➔ Two free parameters:

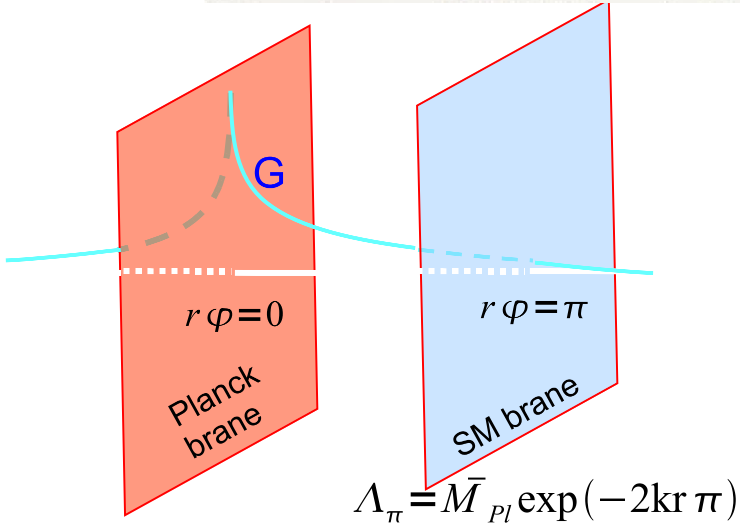
M_1 (M_G) : first excitation mass of Graviton

$\tilde{k} = k / M_{Pl}$: coupling parameter

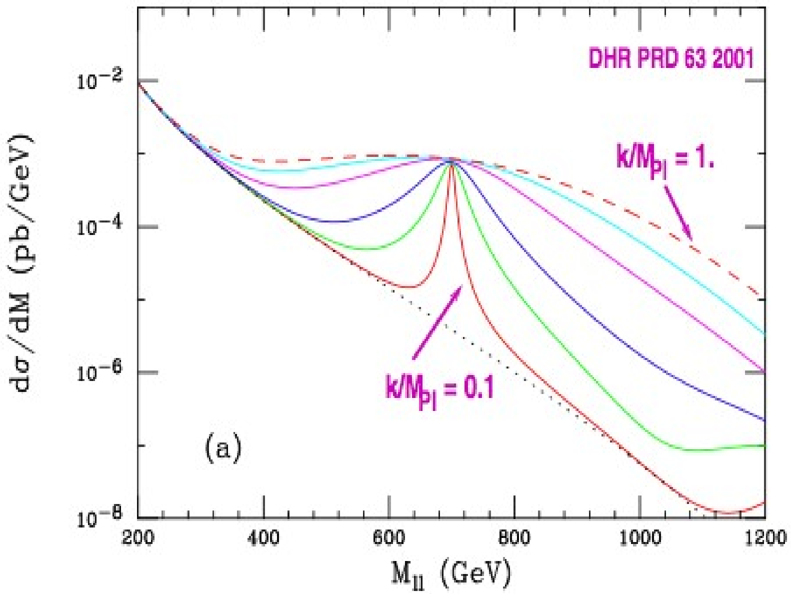
▪We probe the feasibility of discovering RS gravitons in the diphoton channel

Anti-deSitter space-time metric:

$$ds^2 = e^{-2kr|\phi|}\eta_{\mu\nu}dx^\mu dx^\nu - r^2 d\phi^2$$



$\Lambda_\pi = \bar{M}_{Pl} \exp(-2kr\pi)$

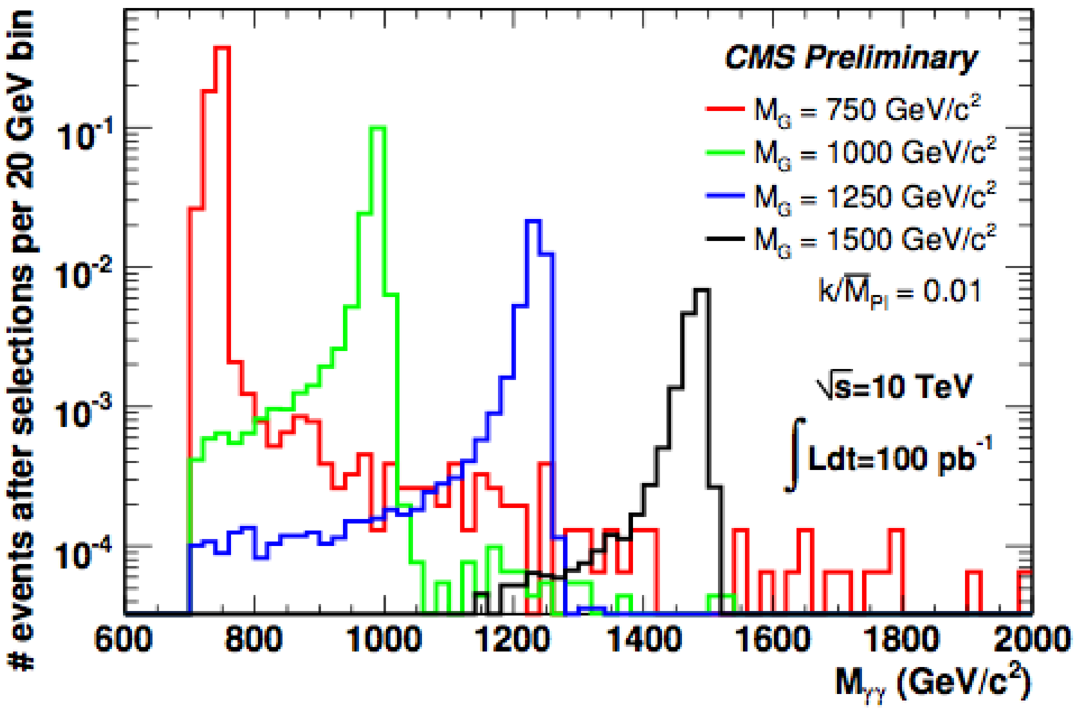


Signal & Event Selection for Warped ED

- High mass diphoton resonance ($G_{KK} \rightarrow \gamma\gamma$)

- Use the samples produced with the masses:
  - 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

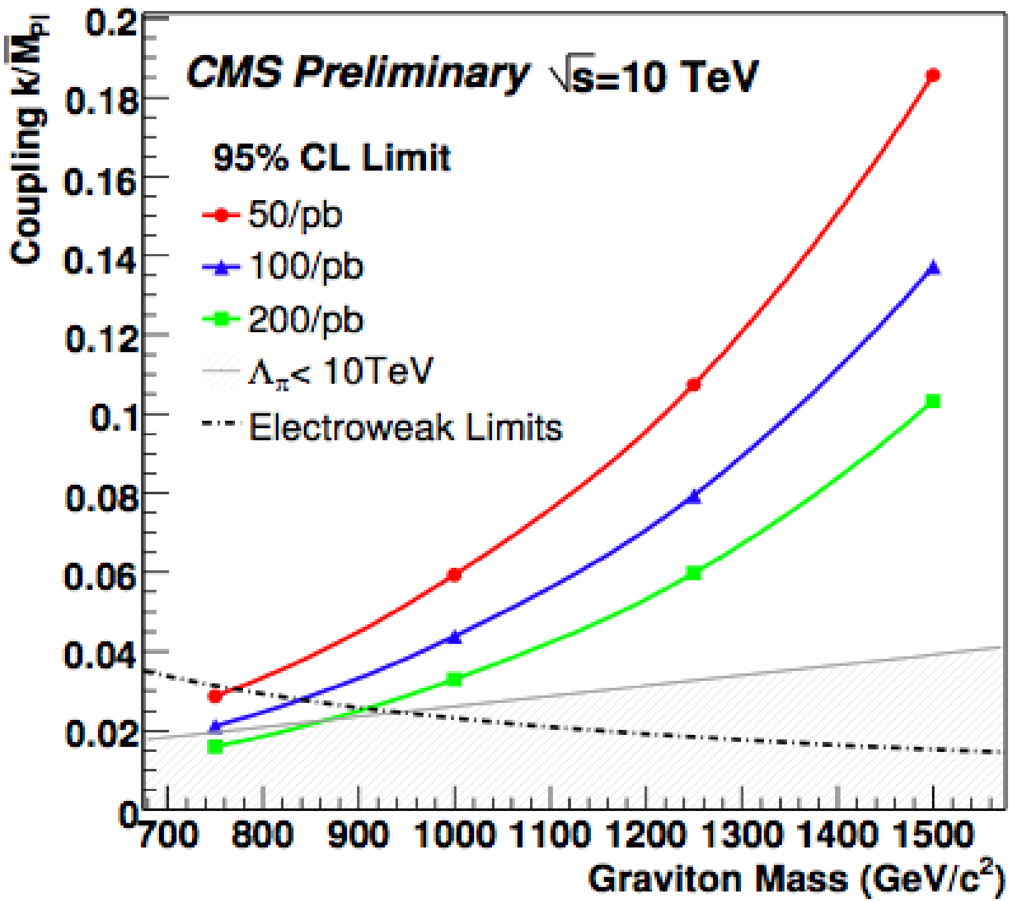


Photon efficiency: 63%-59%

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 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

- We extend the sensitivity significantly beyond the reach obtained at the Tevatron!

...more with Diphotons

- Also studied:

Available on CMS information server **CMS AN -2009/096**

The Compact Muon Solenoid Experiment

Analysis Note

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25 May 2009 (v2, 14 July 2009)

EXO-09-011

Search for Scalar and Tensor Unparticles in the Diphoton Final State

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Abstract

This note discusses a search for scalar and tensor virtual unparticle effects in the diphoton final state produced in *pp* collisions at 10 TeV center-of-mass energy, with the CMS detector. The analysis focuses on the data sample corresponding to the integrated luminosity of 100/pb, expected to be collected in the first LHC run. The study is based on the results obtained in the search for large extra dimensions [1], where the virtual KK graviton decays into two photons. The discovery potential and exclusion reach for unparticle model parameters are presented.

Did'nt have time to include...
- → Hope next time

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 Ms between 2.2-3.3 TeV depending on the number of Extra Dimensions (n_{ED}).

- 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 k>0.1.

- All diphoton analysis were documented, and publicly available!

- ...BUT, we were NOT alone during these analysis: Got a lot of help on Photon ID issues from the LPC Photon+X Working Group!
  - Excellent experts on photons right here, at the LPC!
  - They carried their experience from the Tevatron, LEP etc. to the LPC!
  - You can find the answers to your questions right away, as well!

Acknowledgement

Many thanks to:

Andrew Askew, Oleksiy Atramentov, Marat Gataullin, Yuri Gershtein, John Conway, Marco Paganoni, Paolo Checchia, Marco Pieri, Sam Haper, Conor Henderson, Bernadette Heyburn, Albert De Roeck

for many useful discussions and help with various photon ID tool!

(Wonderful to have excellent experts on photons at the LPC!)

Photon Identification: 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

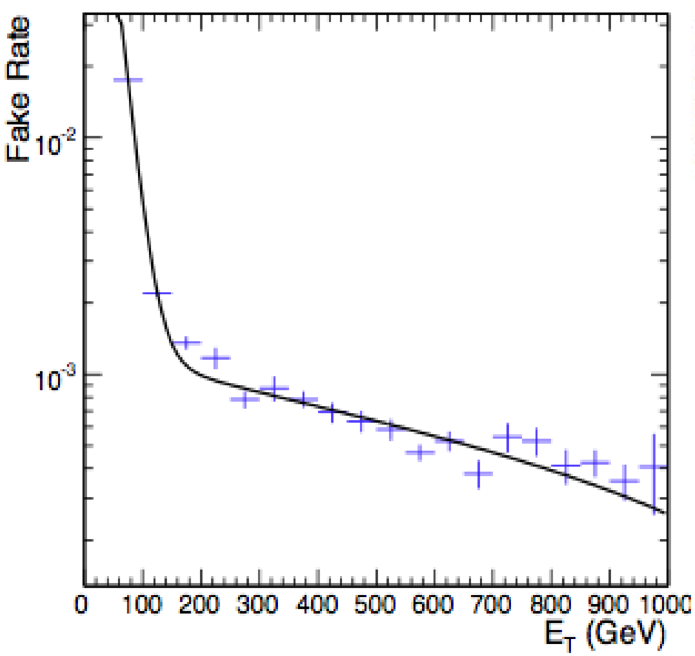
Tracking Isolation: Sum of the p_T in the hollow cone of dR = 0.04-0.40
The cut used: <5 GeV

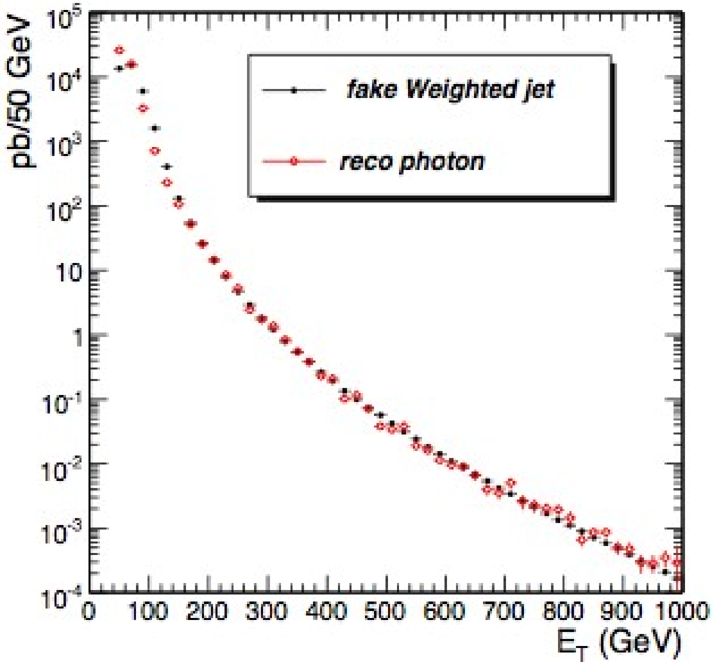
ECAL Isolation: Sum E_T in a hollow cone of dR = 0.06-0.40
The cut used: <10 GeV

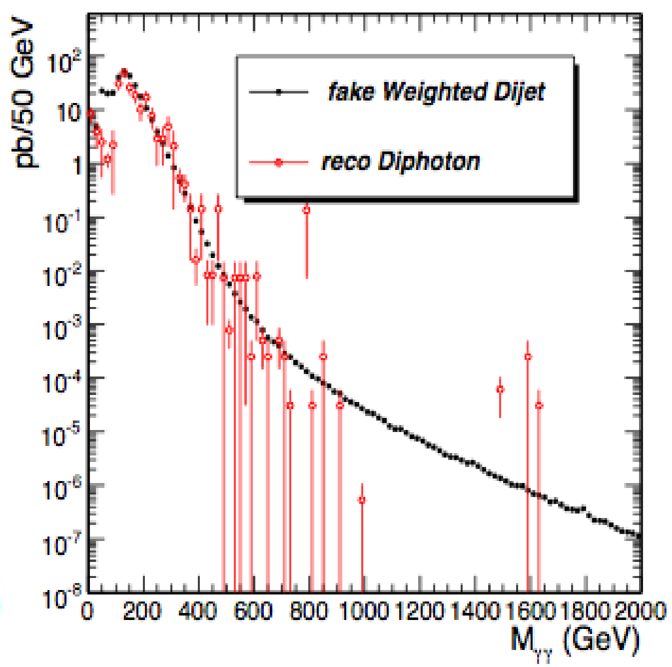
HCAL Isolation: Sum E_T in a hollow cone of dR = 0.1-0.4
E_T sliding window cut used: $< 4.7 + 0.003*E_T$

Jet-Faking-Photons: Fake Rate Validation

- Statistic becomes an issue when applying all isolation cut together
- Validate the fake rate by loosening the isolation cuts:
  - Use only one of them
    - Here, we used only H/EM cut
- Apply to the jet(s) in multijet events for the ET and mass distributions to get the predicted distributions
- Compare to the observed ET and mass distributions







Backgrounds: Drell-Yan

- Completely data-driven

- Use ee and $e\gamma$ event in Z-events for electron-faking-photon fake rate, $f_{e\to\gamma}$.

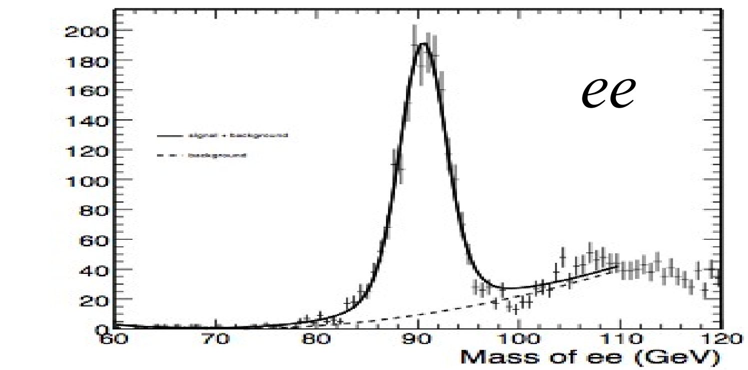
- Apply to high-mass Drell-Yan events

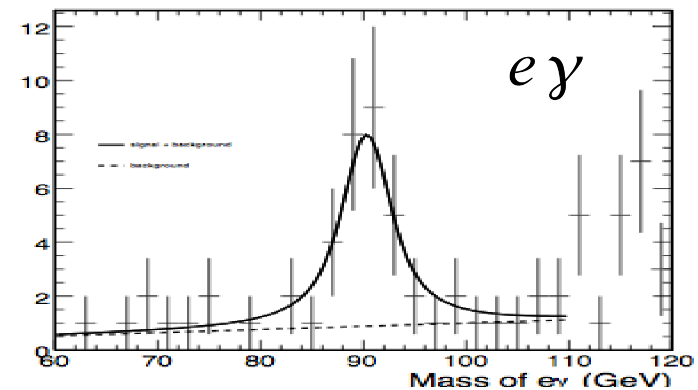
$$\left.\begin{aligned} N &= N_{ee} + N_{e\gamma} + N_{\gamma\gamma} \\ N_{ee} &= N(1 - f_{e\to\gamma})^2 \\ N_{e\gamma} &= 2\mathrm{N}\mathrm{f}_{e\gamma}(1 - f_{e\to\gamma}) \\ N_{\gamma\gamma} &= N f_{e\to\gamma}^2 \end{aligned}\right\}$$

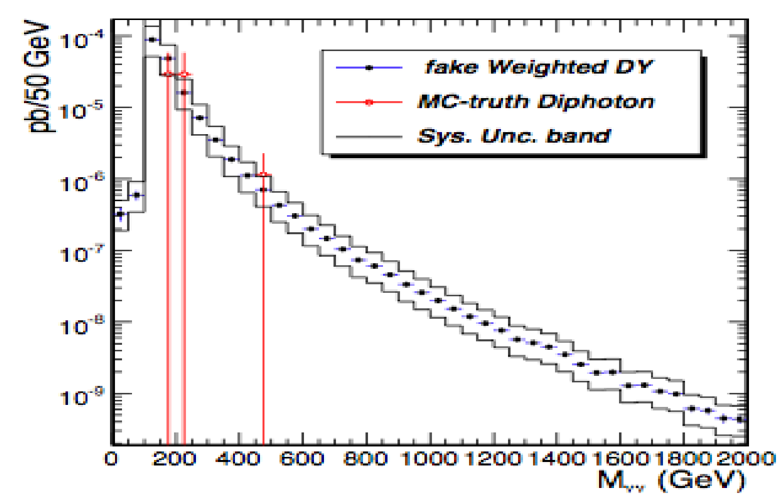
Solve for : $f_{e\to\gamma}$

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

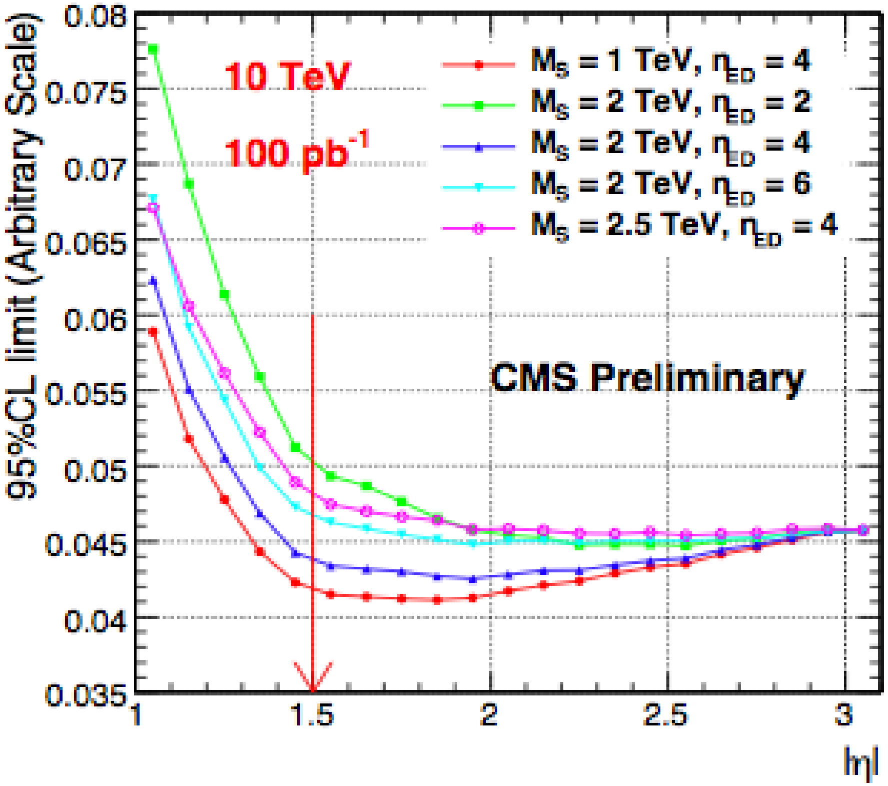
$$f_{e\to\gamma} \approx 0.86\,\%$$

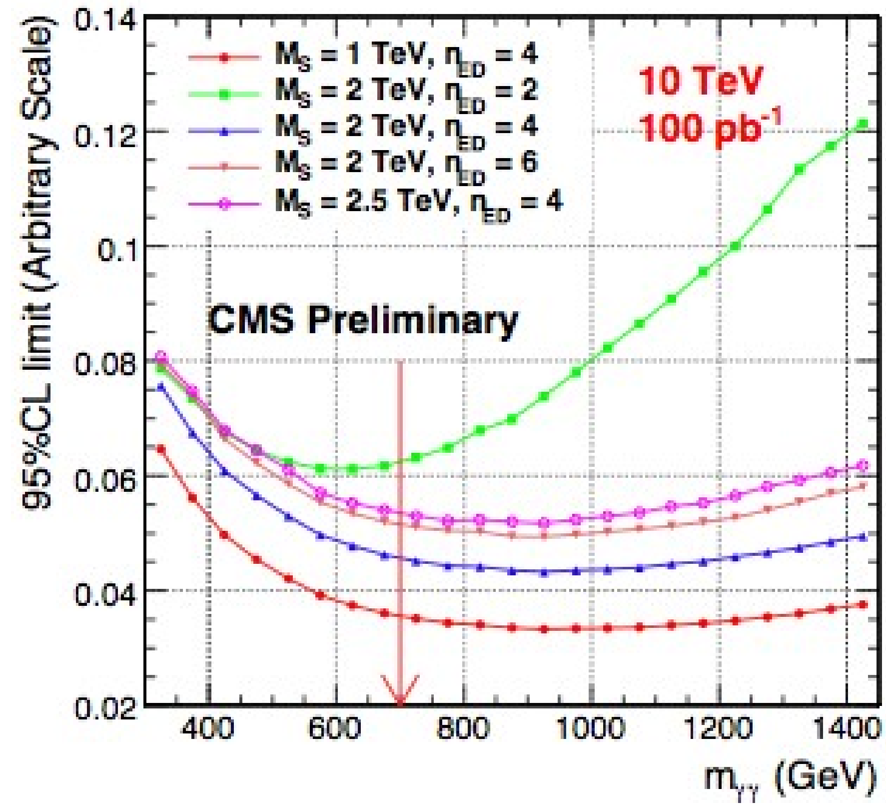






Kinematic optimization

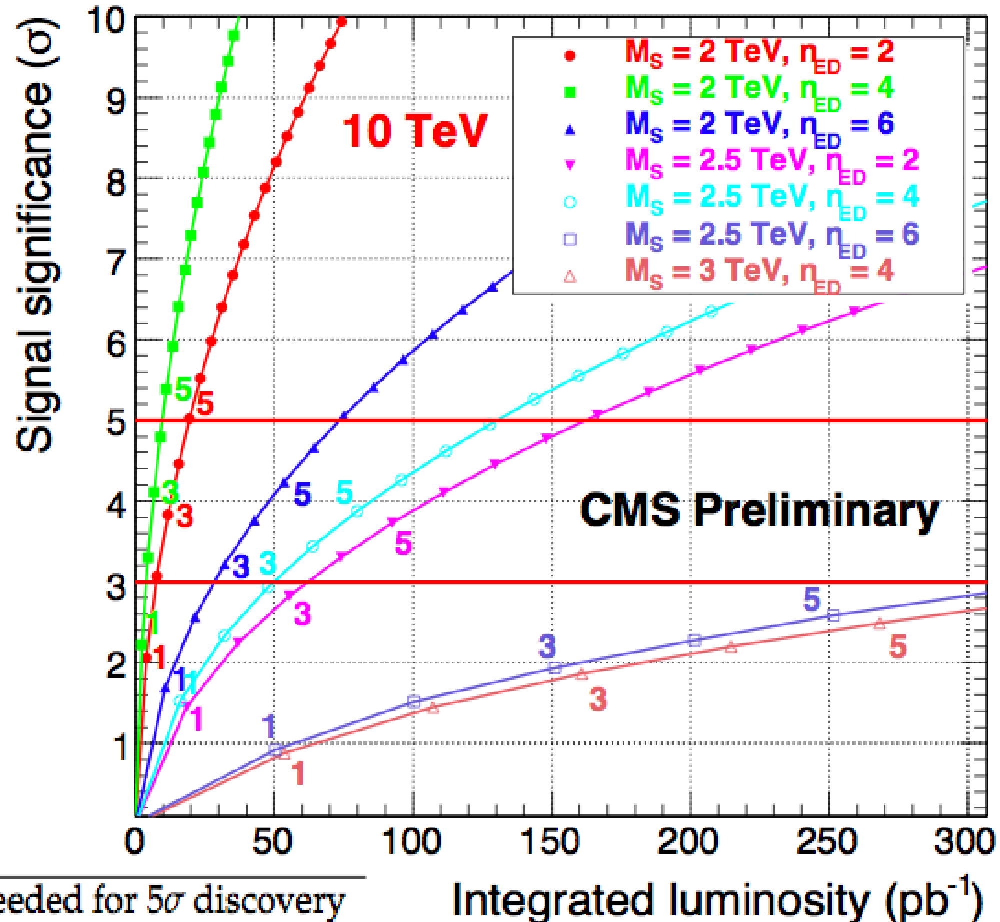




- Minimize 95% CL cross section limit with respect to photon |η| and $M_{\gamma\gamma}$
- Only consider diphoton SM background
- Chosen cuts: |η| < 1.5 and $M_{\gamma\gamma}$ > 700 GeV

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}

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 ±0.007	0.499 ±0.004	0.631 ±0.005
1000	0.01	0.150 ±0.001	0.563 ±0.003	0.633 ±0.004
1250	0.01	0.0462 ±0.0004	0.616 ±0.003	0.599 ±0.004
1500	0.01	0.0155 ±0.0001	0.672 ±0.003	0.588 ±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

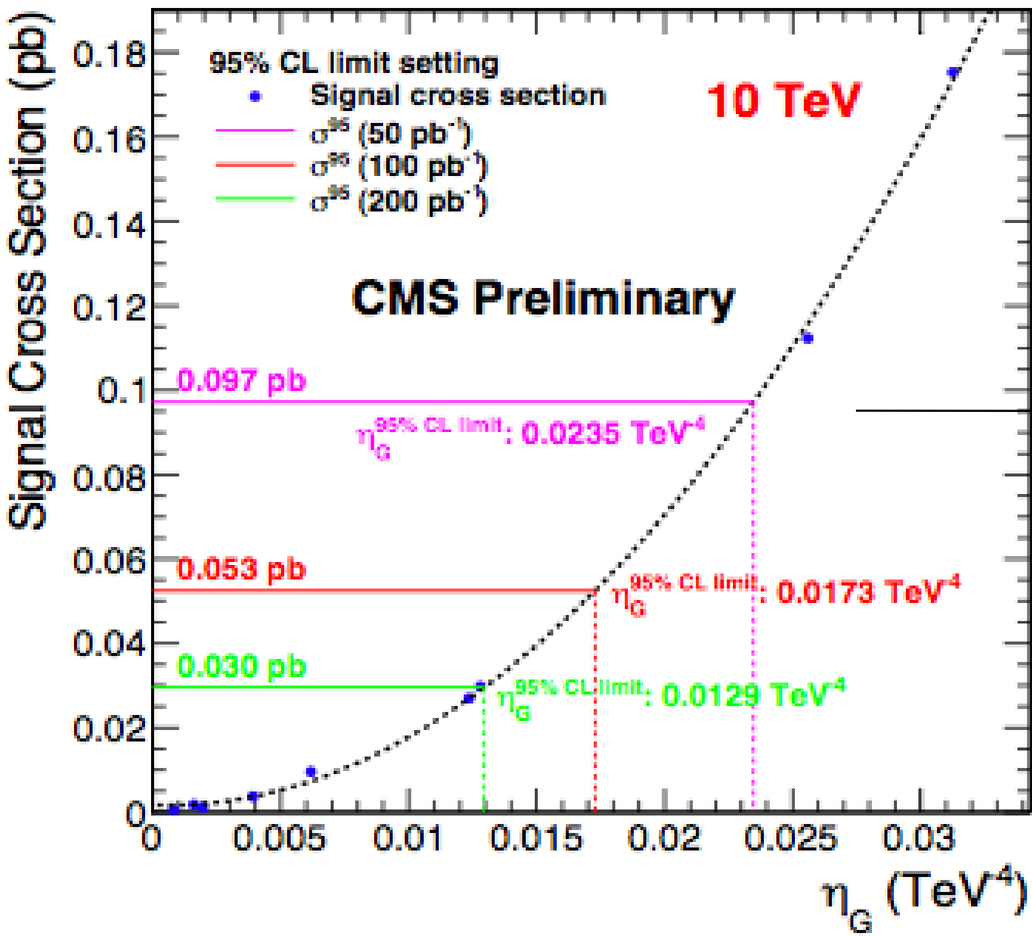
- Photon identification includes H/EM, Tracker, ECAL, and HCAL isolations

- 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

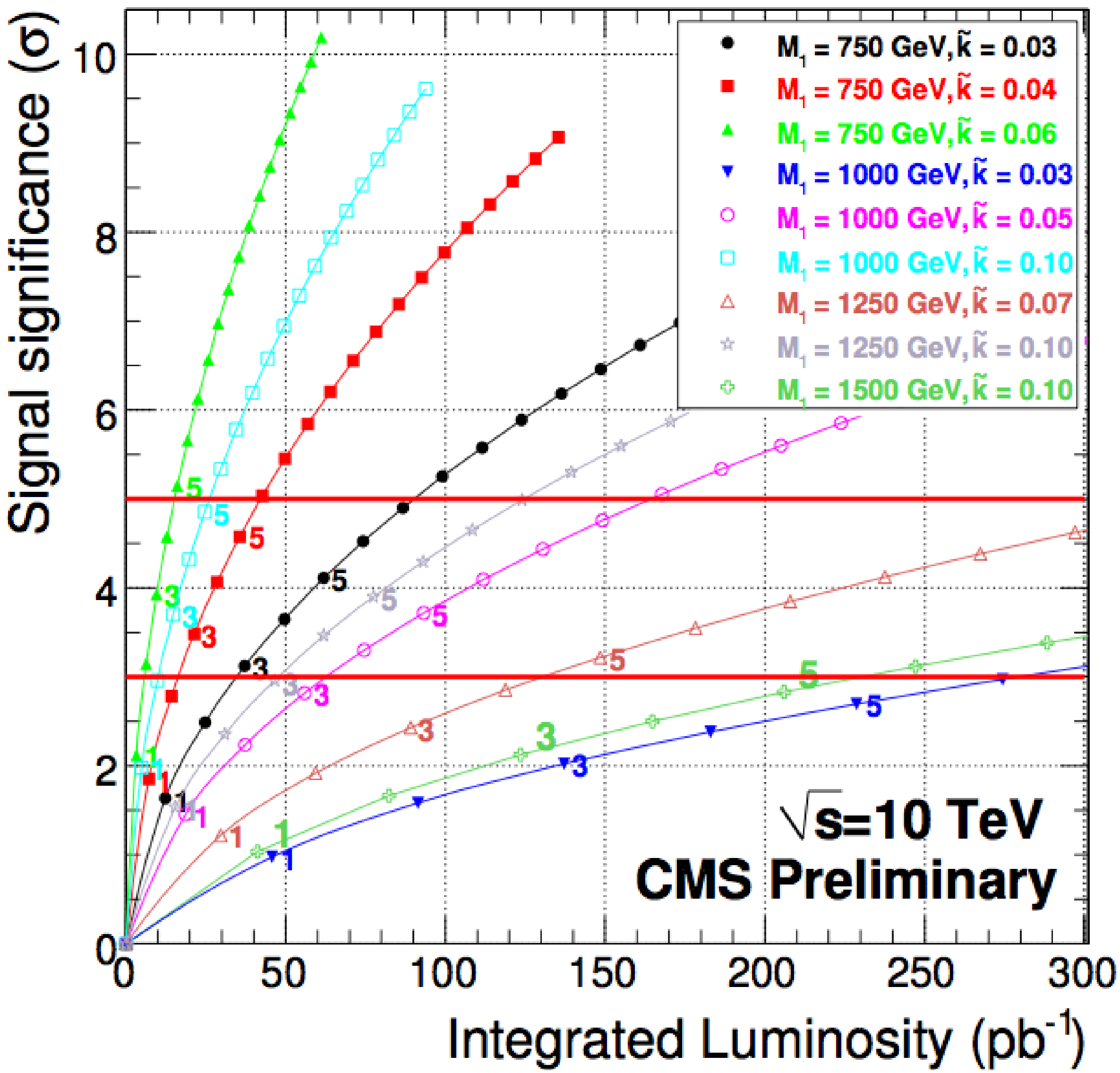
•We use the acceptances calculated to extrapolate the limits from Large ED diphoton Analysis to limits on the RS model



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

- $\tilde{k}^{95}$ = 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

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