A la recherche de dimensions supplémentaires au LHC

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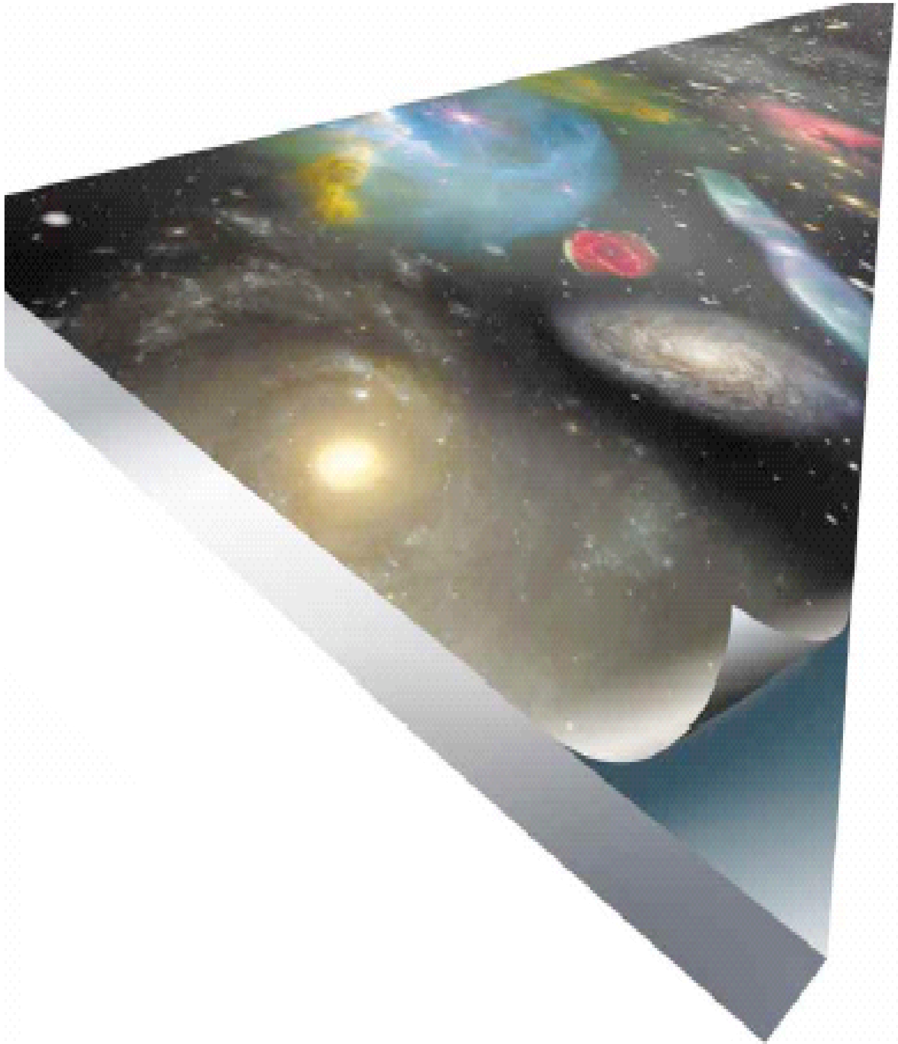
Figure from Scientific American



L'univers dans lequel nous vivons pourrait être une membrane à l'intérieur d'un espace-temps possédant un plus grand nombre de dimensions.

Quelle part de fiction y a-t-il dans la Science Fiction ? D'où proviennent les idées de dimensions supplémentaires et d'univers parallèles ?

Plan du Séminaire

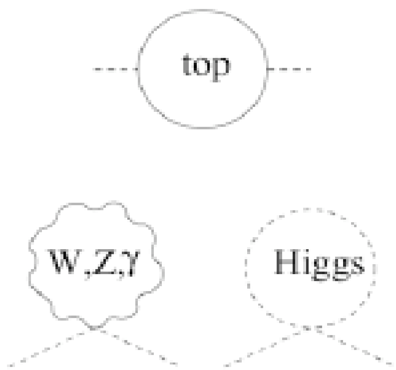
- Introduction :
  - Motivation des dimensions supplémentaires
  - Comment les détecter?
  - Le rôle du LHC
- Les 3 modèles de dimensions supplémentaires : Introduction & Recherche au LHC
  - Les grandes dimensions supplémentaires (ADD)
  - Les dimensions supplémentaires de la taille TeV^{-1}
  - Les dimensions supplémentaires voilées (RS)
- Conclusions

Introduction

- Many extensions of the Standard Model are motivated by the Hierarchy problem :
  - o Electroweak Scale ~ 100 GeV
    - M_W = 80 GeV, M_Z = 91 GeV
  - o Planck Scale ~ 10^{19} GeV
    - Energy where the relativistic and quantum effects are important for gravity
  - o The Higgs mass diverges in the Standard Model because of radiative corrections.
    - $M_H^2 = [M_H^0]^2 + O(\Lambda^2) + \ldots$

      with Λ : the scale of validity for the Standard Model

      Fine tuning which can provide cancellations ?

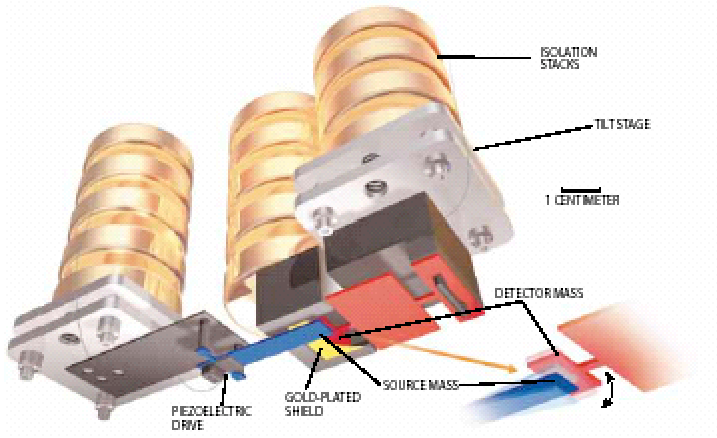


Introduction

- The Standard Model is an effective theory. The new theory takes over at a scale Λ comparable to the Higgs boson mass, i.e. $\Lambda \sim 1$ TeV.
- Possible solution?
  - Supersymmetry : for each SM particle a Susy partner is introduced. SM and Susy particle contributions to Higgs mass have opposite sign.
  - Extra Dimensions : strong gravity at TeV scale.

    ED already introduced in string theory (theory for describing the gravity quantically with 10 or 11 dimensions, in which extra dimensions are compactified).
  - ...

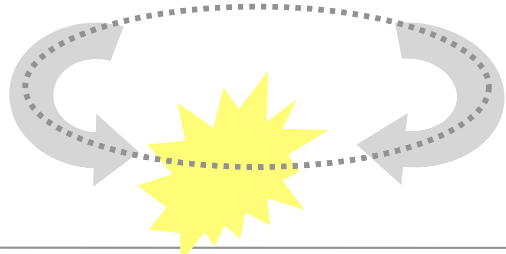
How to detect these extra dimensions?



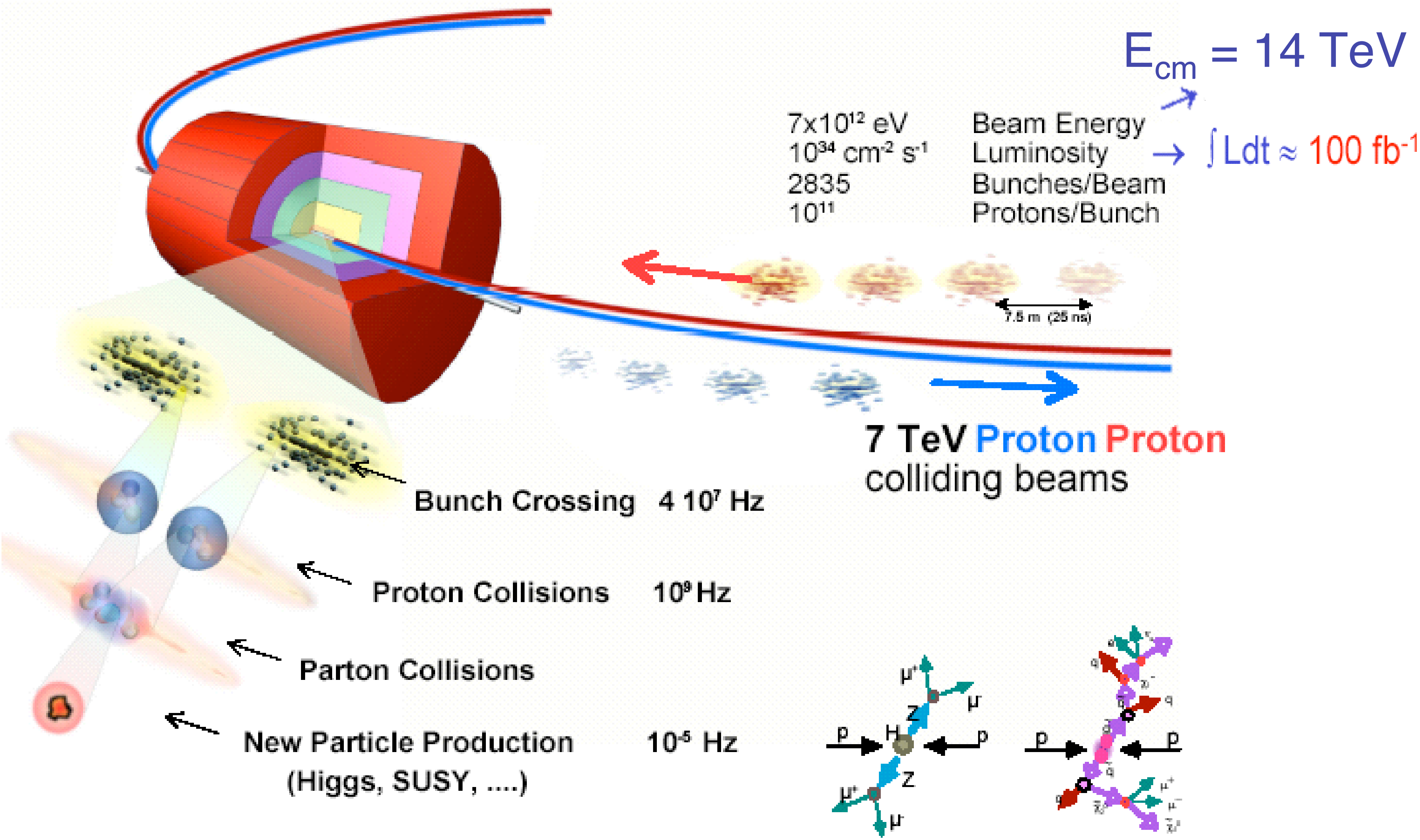
Astrophysics : Study of the sky activity

Gravity :Test of the Newton's Law

Particle Physics : Search for their effects on reactions produced in colliders

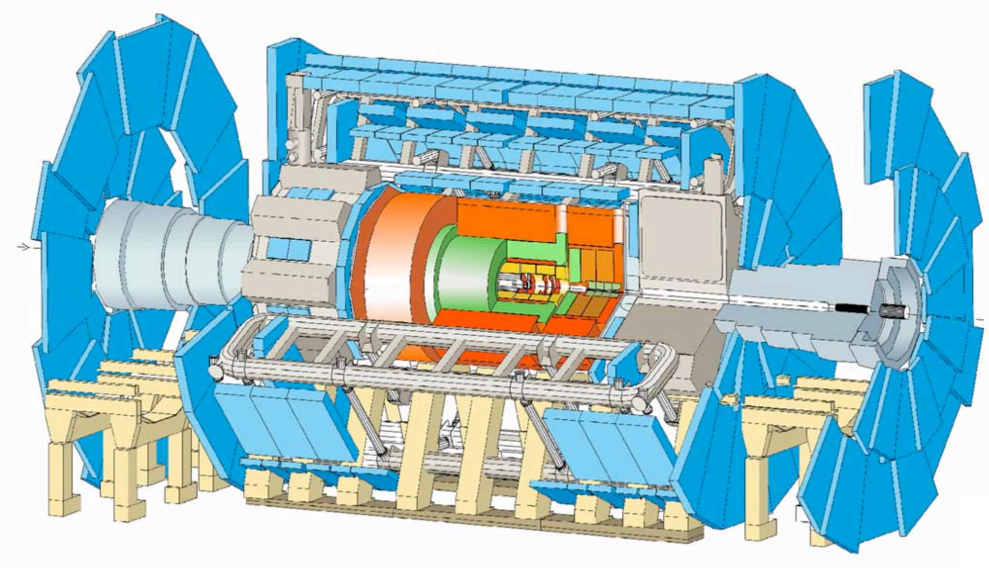


The LHC



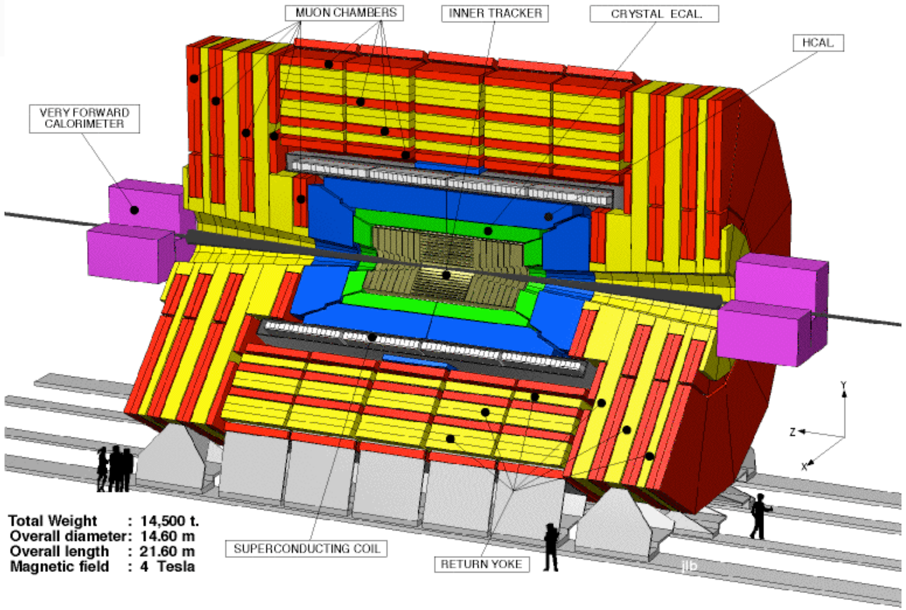
E_cm = 14 TeV
7x10^12 eV Beam Energy
10^34 cm^-2 s^-1 Luminosity
2835 Bunches/Beam
10^11 Protons/Bunch
∫Ldt ≈ 100 fb^-1
7.5 m (25 ns)
7 TeV Proton Proton
colliding beams
Bunch Crossing 4 10^7 Hz
Proton Collisions 10^9 Hz
Parton Collisions
New Particle Production 10^-5 Hz
(Higgs, SUSY, ...)
p
p
H
Z
Z
μ+
μ-
μ+
μ-

The 2 Experiments of the LHC



ATLAS

CMS



The total mass of CMS is approximately 12500 tonnes - double that of ATLAS (even though ATLAS is ~8x the volume of CMS)

Models with Extra Dimensions

1. The cisplanckian physics (√s << gravity scale)

Large extra dimensions

Kaluza-Klein Excitations of gravitons

by direct production or virtual effects

The TeV^{-1} size extra dimensions

Kaluza-Klein Excitations

of gauge bosons

The warped extra dimensions

Kaluza-Klein Excitations of gravitons

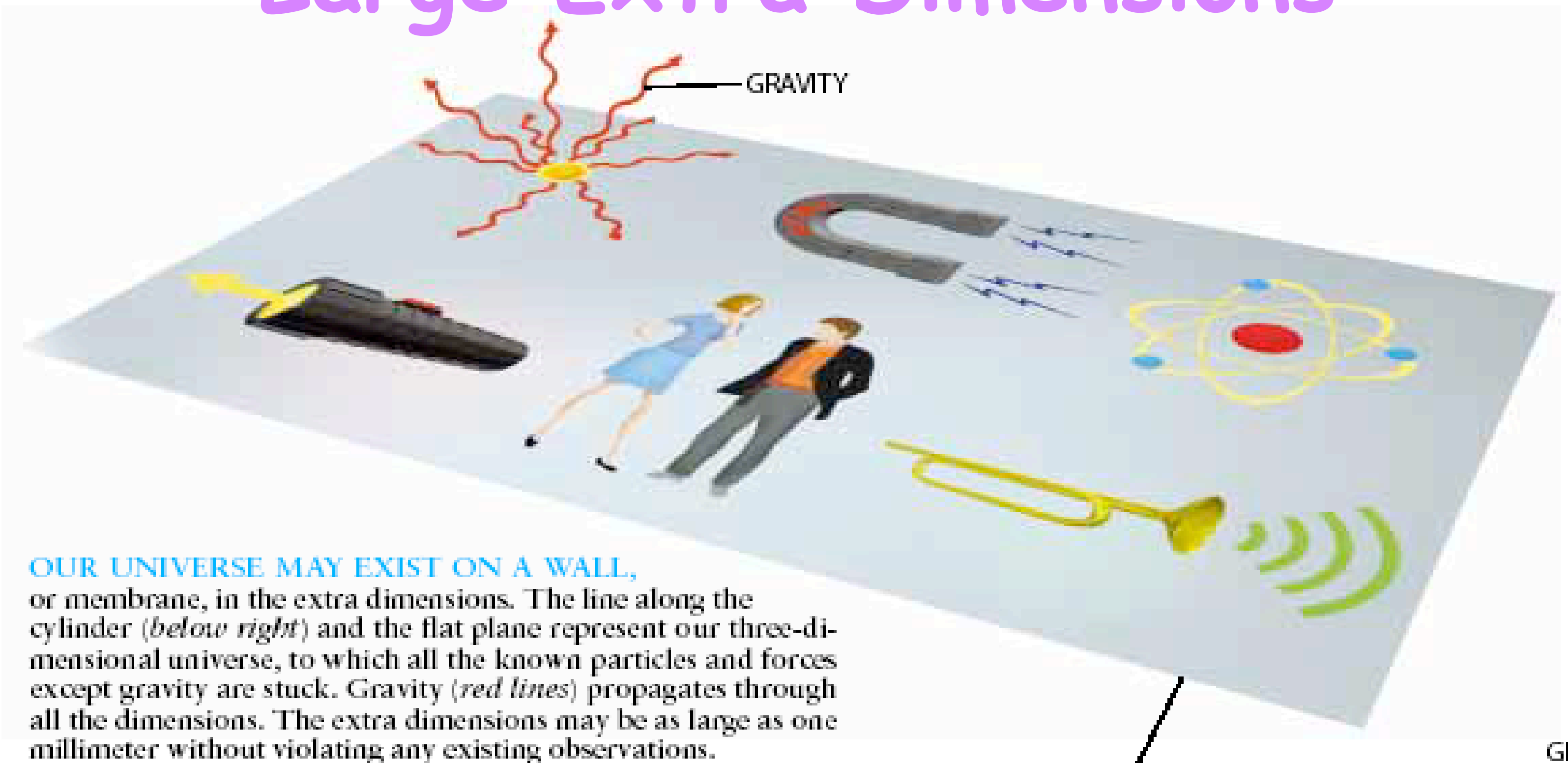
(The radion)

Size of the extra dimensions

2. (The transplanckian physics (√s >> gravity scale)

- Black holes & string balls)

Large Extra Dimensions



Model of Arkani-Hamed, Dvali, Dimopoulos: Standard Model particles are localized on a 3-D brane. Gravity propagates inside the bulk (a more dimensional space)

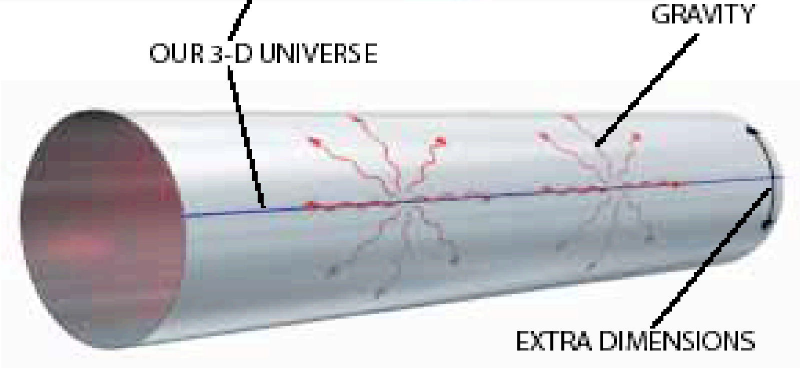
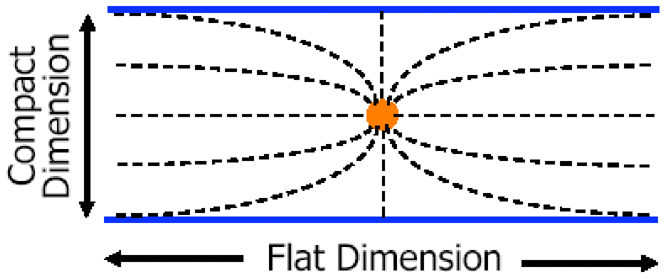


Figure from Scientific American

Large Extra Dimensions

- Model of Arkani-Hamed, Dvali, Dimopoulos:
  - World at 4 + n dimensions. Only the gravitons may propagate in extra dimensions. Gravity appears to be diluted.

$$V(r) = \frac{1}{M_{Pl}^2}\frac{m_1 m_2}{r} \rightarrow \frac{1}{\left(M_{Pl}^{[3+n]}\right)^{n+2}}\frac{m_1 m_2}{r^{n+1}}$$



$$V(r) \propto \frac{1}{\left(M_{Pl}^{[3+n]}\right)^{n+2}}\frac{m_1 m_2}{R^n r} \quad \text{for } r >> R$$

The Newton's Law is verified up to distances ~0.2 mm. Extra dimensions must be smaller than 0.2 mm and compactified.

The real Planck mass $M_D = M_{PL}^{[n+4]}$:

$$(M_D)^{(2+n)} = (M_{PL}^{[4]})^2 R^n$$

If M_D ~ 1 TeV (= no more hierarchy problem):

$$R = \frac{1}{2\sqrt{\pi} M_D}\left(\frac{M_{Pl}}{M_D}\right)^{2/n} \propto \begin{cases} 8\times10^{12}\, m, & n=1 \\ 0.7\, mm, & n=2 \\ 3\, nm, & n=3 \\ 6\times10^{-12}\, m, & n=4 \end{cases}$$

Large Extra Dimensions

- Particle in compact extra dimension:
  - Wavelength set by periodic boundary conditions
  - States will be evenly spaced in mass → tower of Kaluza-Klein (KK) modes
  - Spacing depends on the scale of ED

A tower of massive KK excitations of gravitons:

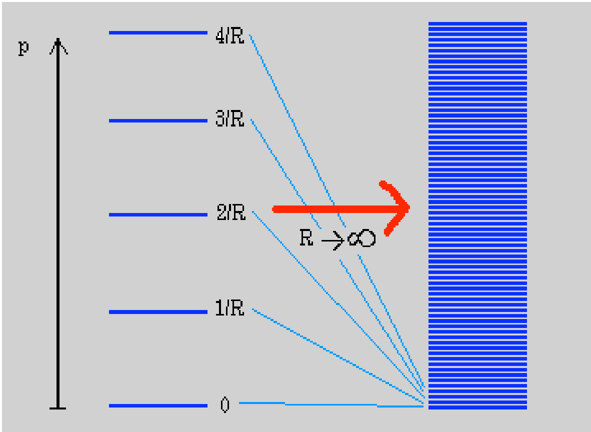
$M_n^2 = M_0^2 + n^2/R^2$ for the n^{th} state.

They couple to Standard Model particles:

$L = 1/M_{PL}\, G_{\mu\nu}^{(n)}\, T^{\mu\nu}$

The large number of states (degenerated in mass) compensates the low coupling ($1/M_{PL}$):

$\sigma \sim (\sqrt{s}/M_D^2)^n$



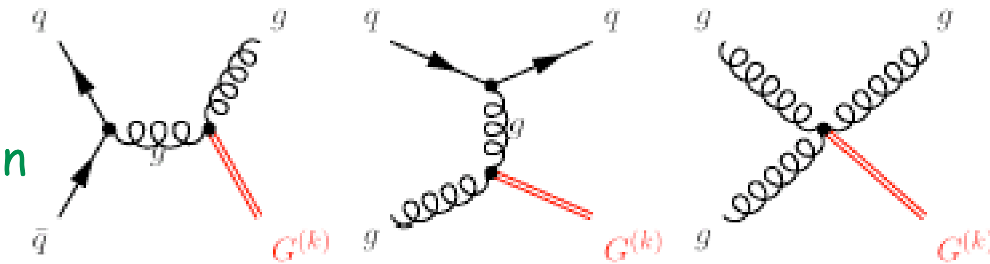
Constraints on this model

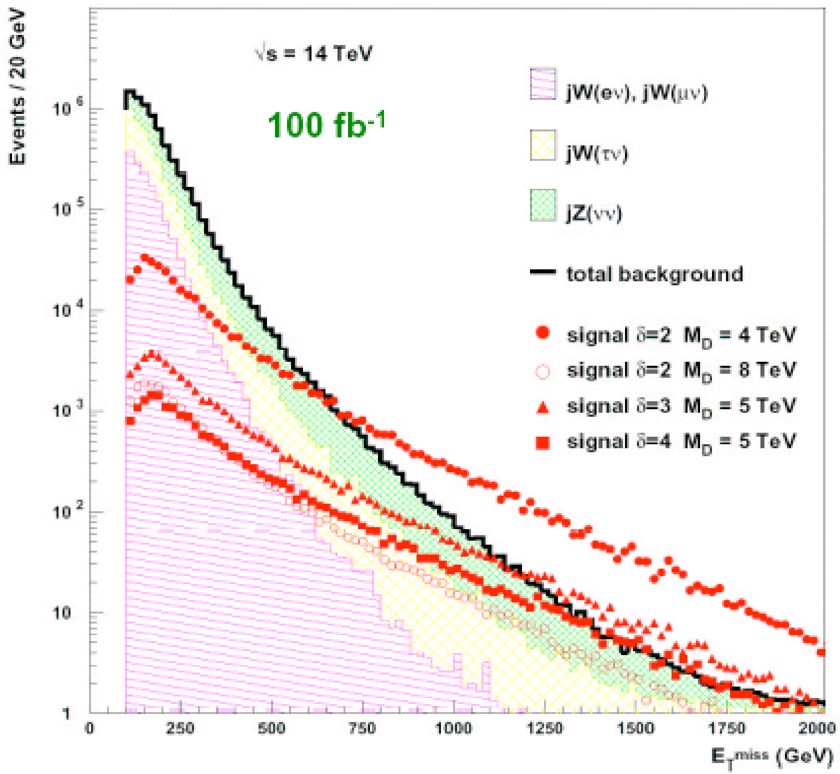
G.F. Giuduce and J. March-Russel, PDG review 2002

Constraint	n=2		n=3	
	max R_D (mm)	min M_D (TeV)	max R_D (mm)	min M_D (TeV)
Gravity law	0.2	0.6		
Cooling of supernovae by emission of gravitons	7×10^{-4}	10	9×10^{-7}	0.8
Diffused background of cosmic rays ($G_{KK} \rightarrow \gamma\gamma$)	9×10^{-5}	25	2×10^{-7}	1.9
Heating of neutron stars (trapped G_{KK} which decay)	8×10^{-6}	90	3.5×10^{-8}	5
LEP : γG, ZG, virtual exchanges		~ 1 TeV		
Tevatron		~ 1 TeV		

Search at LHC: Large Extra Dimensions

- Direct Search
  - Monojet with a large missing transverse energy (stable non detected G_{KK})





ATLAS

δ	M_D^{max} (TeV) LL, 30 fb^{-1}	M_D^{max} (TeV) HL, 100 fb^{-1}	M_D^{min} (TeV)
2	7.7	9.1	~ 4
3	6.2	7.0	~ 4.5
4	5.2	6.0	~ 5

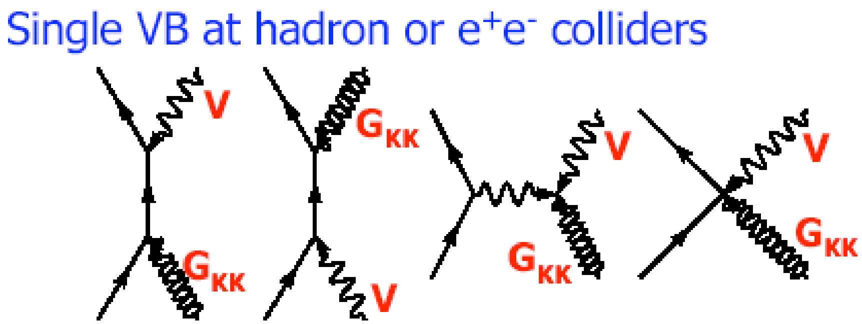
Limit on M_D^{min}:

Validity of the effective theory: $\sqrt{s} < M_D$.
Above this limit: sensitivity to new physics.
→ Truncation of σ when $\sqrt{s} > M_D$.

Search at LHC: Large Extra Dimensions

- Isolated Photon with a large missing transverse energy (non detected G_{KK})

Channel which will allow to confirm the discovery in the monojet channel

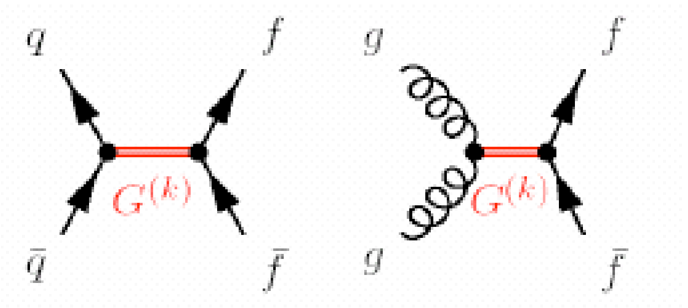


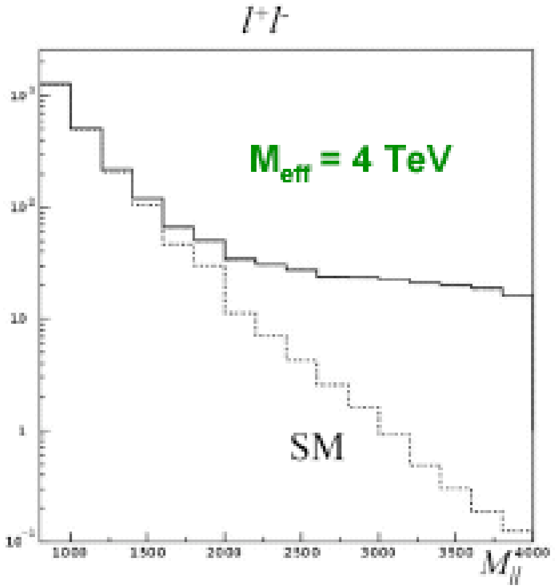
ATLAS

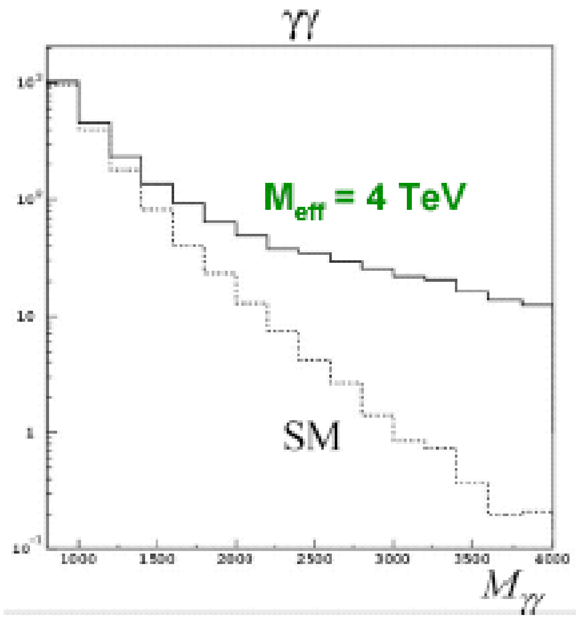
δ	M_D^{max} (TeV) HL, 100 fb^{-1}	M_D^{min} (TeV)
2	4	~ 3.5

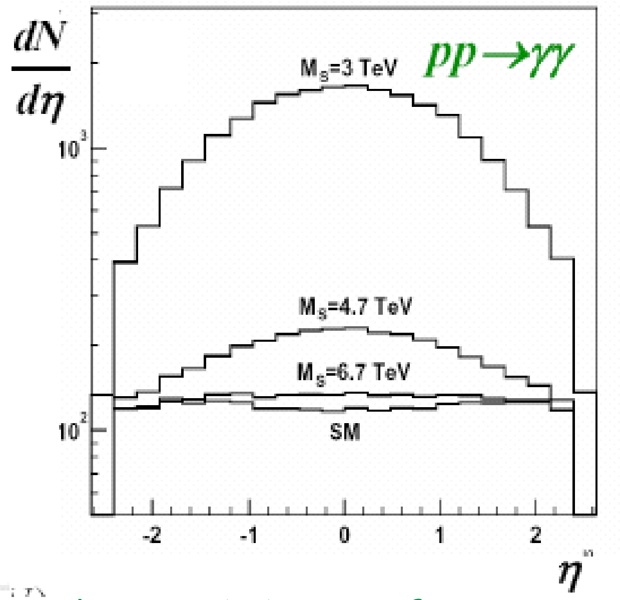
Search at LHC: Large Extra Dimensions

- Indirect Search
  - o G_{KK} is a propagator. Search for deviations in σ or in asymmetries compared to SM.
  - o M_S is a cut-off (UV divergence).









ATLAS @ 100 fb^{-1} : M_S < 5.1 TeV for the ll channel and M_S < 6.6 TeV for $\gamma\gamma$

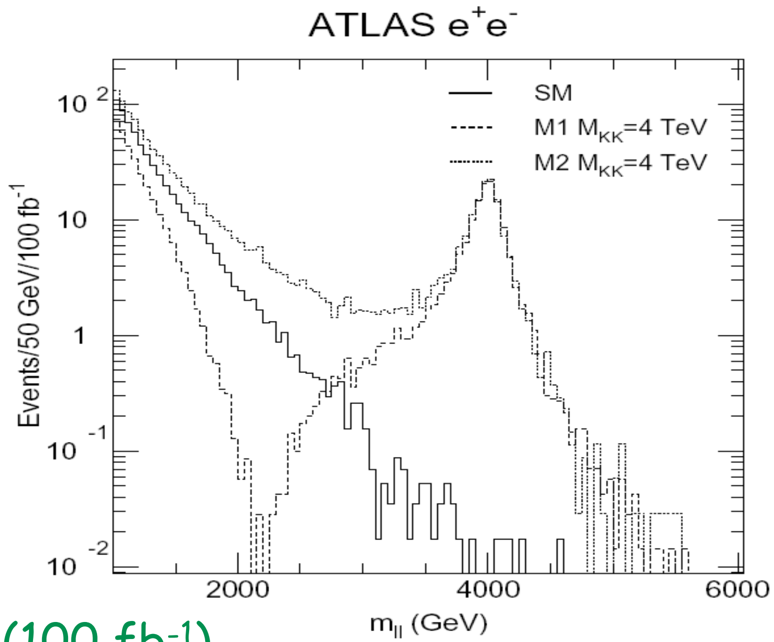
The TeV^{-1} size Extra Dimensions

Variation of the previous model : In addition to the large extra dim, smaller ones are introduced (of TeV^{-1} size) in which gauge bosons can propagate while fermions are confined on the 4dim branes.

The KK modes of the gauge bosons $\gamma^{(n)}$, $Z^{(n)}$, $W^{(n)}$, $g^{(n)}$ are massive

$$M_n^2=(n\,M_c)^2 + M_0^2$$

and their coupling goes like SM (* √2)



Constraints for $\gamma^{(1)}$ and $Z^{(1)}$:

- LEP2+Tevatron+Hera: $M_c > 6.8$ TeV

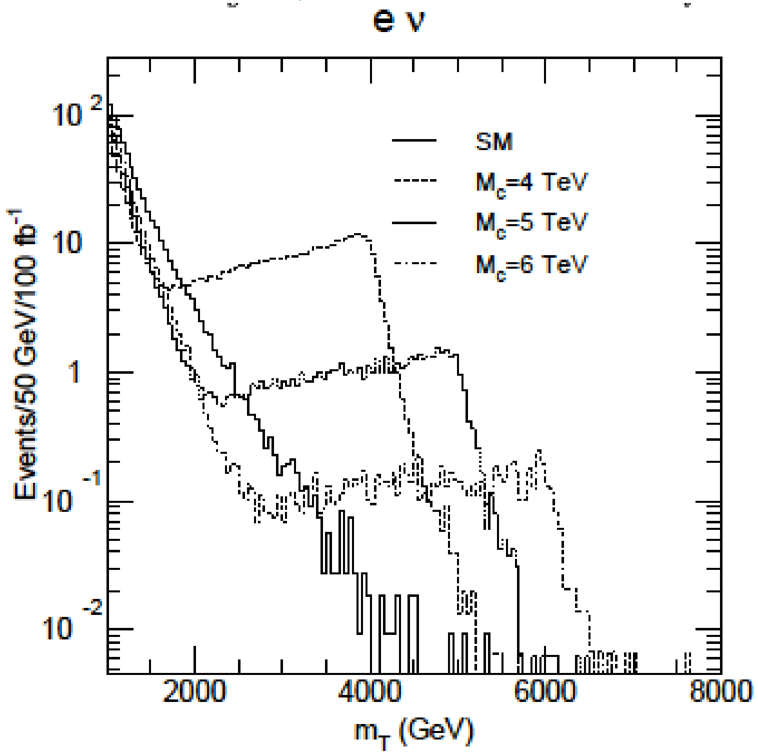
At LHC (mostly from ATLAS):

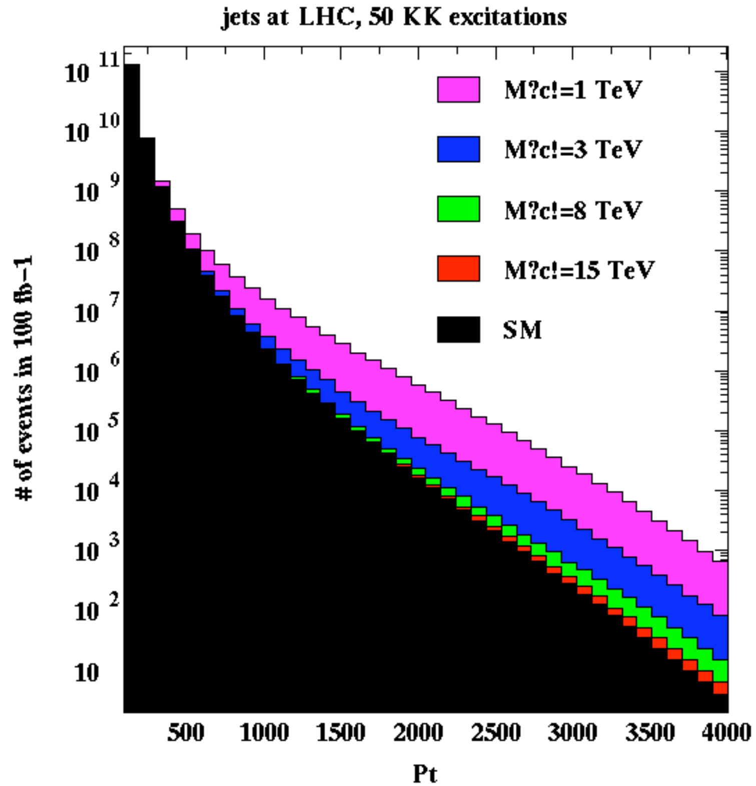
- Sensitivity in the peak: M_c^{max}= 5.8 TeV (100 fb^{-1})
- From interference study: M_c^{max}=9.5 TeV (e) for 100 fb^{-1} and 13.5 TeV for 300 fb^{-1} (e+μ)

The TeV^{-1} size Extra Dimensions

Sensitivity from ATLAS with 100 fb^{-1} :

- for $W^{(1)}$: -Sensitivity in the peak: M_c^{max}= 6 TeV
  -From interference study: M_c^{max}=9 TeV
- for $g^{(1)}$: up to 15 TeV





The Warped Extra Dimensions

The Randall-Sundrum Model

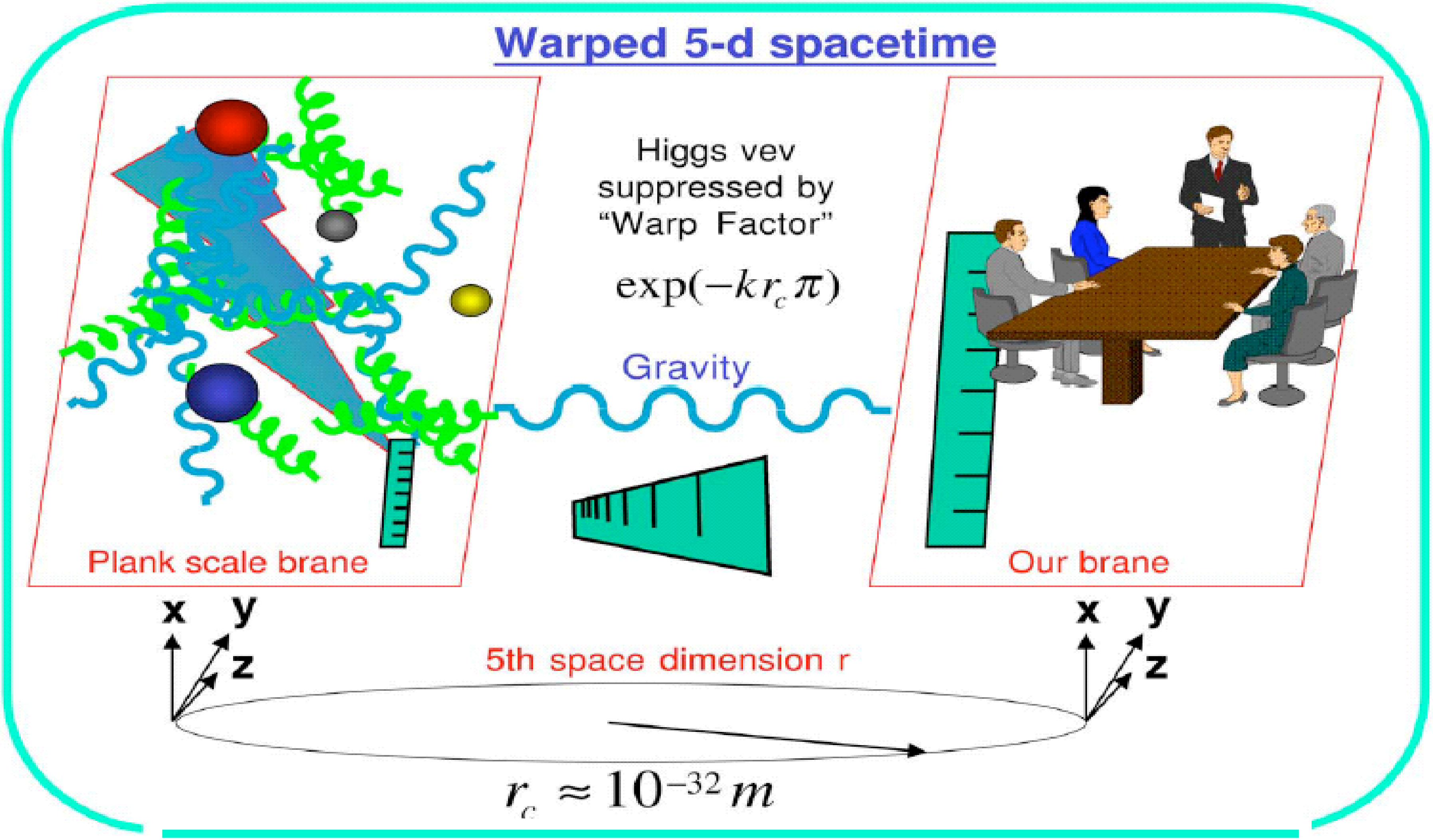
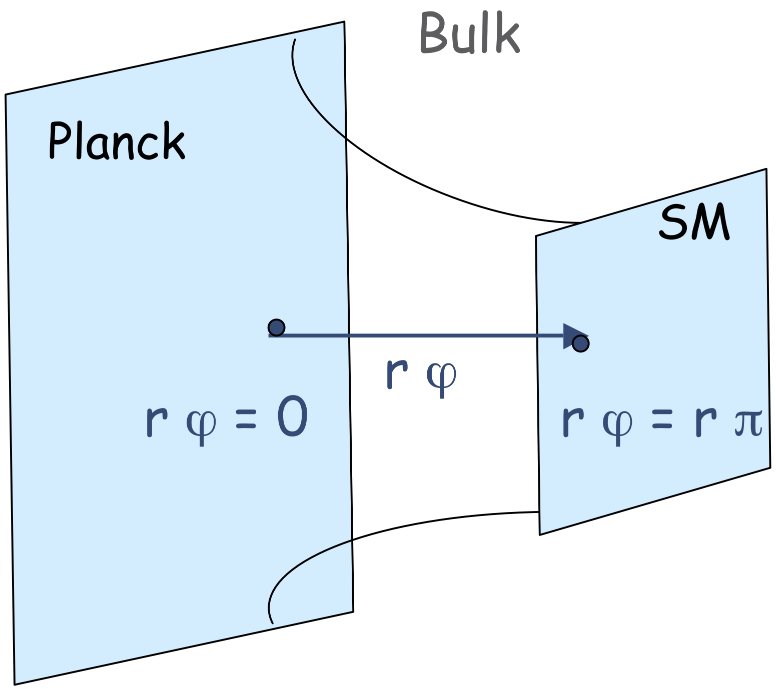


Figure de A. Parker

The model of Randall and Sundrum

The extra dimension allows to explain the hierarchy problem ($M_{EW} \ll M_{PL}$).



o Special geometry :

$$e^{-2kr\varphi}\, \eta_{\mu\nu}\, dx^{\mu}\, dx^{\nu} + r^2\, d\varphi^2$$

k = curvature of the space and r = compactification radius of the extra dim.

Specificity of this model: the exponential factor ("warp factor")

o Gravity :

$$\Lambda_{\pi} = M_{PL}\, e^{-kr\pi} \sim 1\text{TeV}$$

i.e. no hierarchy if kr ≈ 11-12 which can be stabilised with the introduction of the Radion field

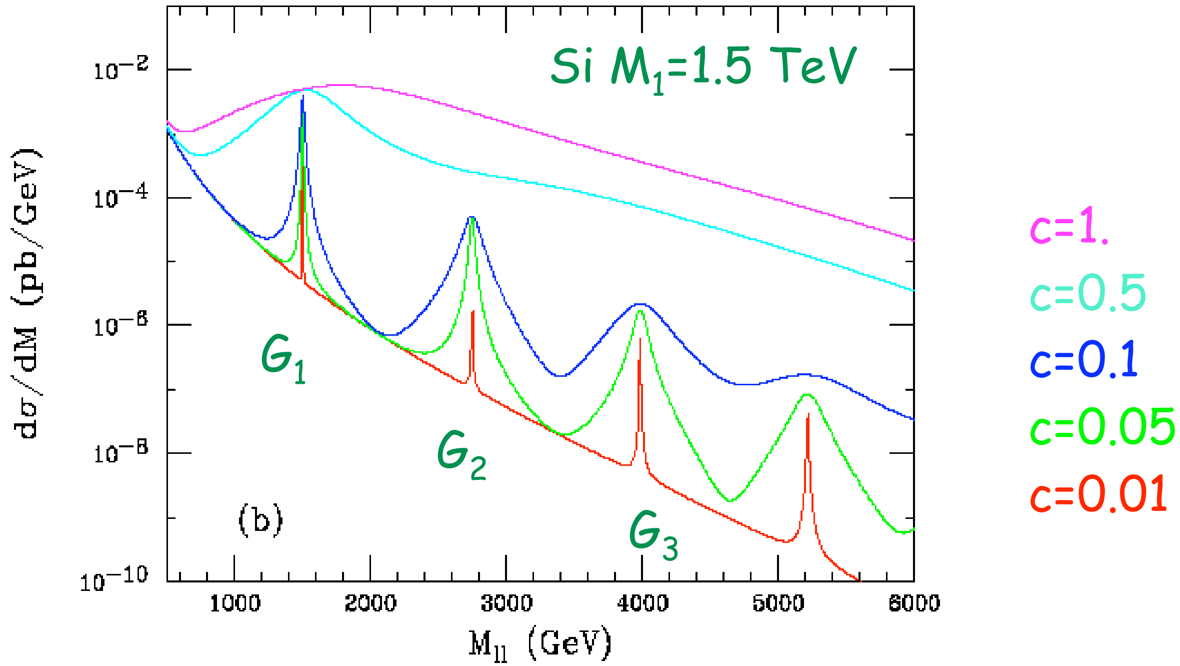
The model of Randall and Sundrum

o Gravitons at 5 Dim → KK excitations of gravitons at 4 Dim (development in Bessel series and not in Fourier series like for the large extra dim.)

$$M_n = k\, x_n\, e^{-kr\pi} \quad \text{with } J_1(x_n)=0$$

$$\Gamma_n = \rho\, M_n\, x_n^2\, c^2$$

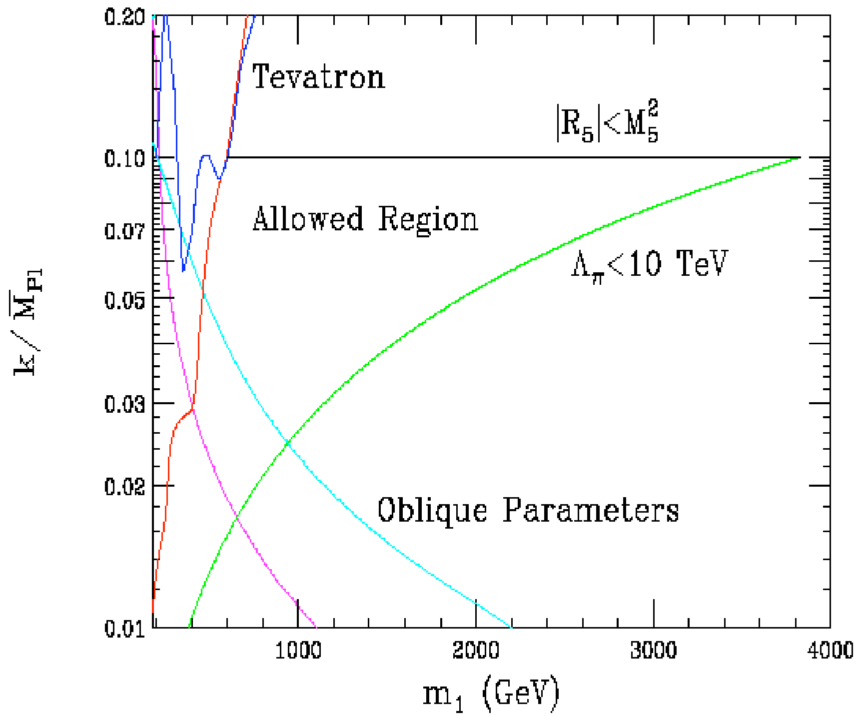
H.Davoudiasl, J.Hewett, T.Rizzo, hep-ph/0006041



o 2 free parameters in the model: $M_G=M_1$ and $c=k/M_{PL}$

The model of Randall and Sundrum

Constraints on the two free parameters of the model: M_G and $c=k/M_{PL}$



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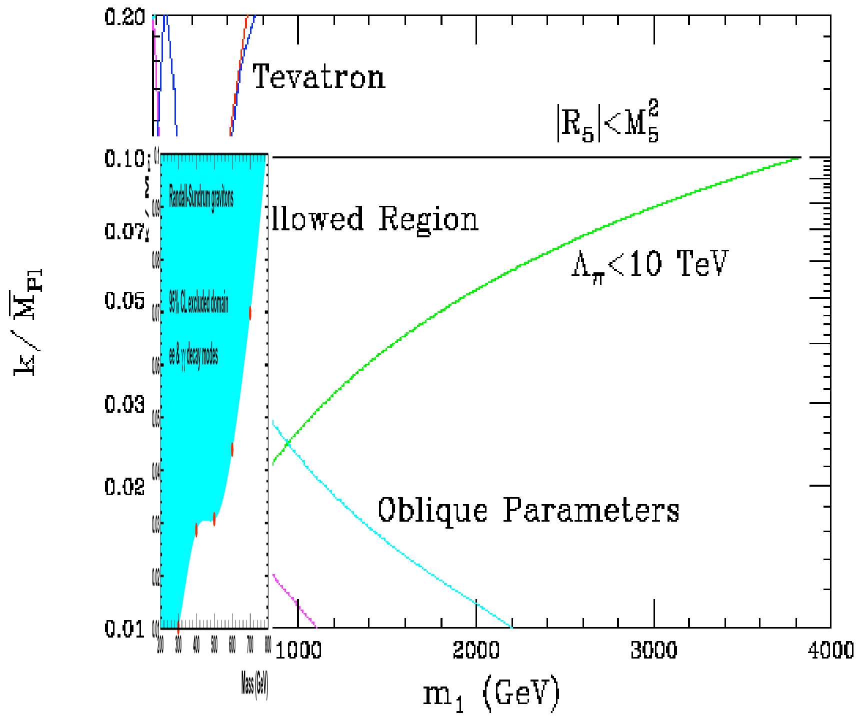
The model of Randall and Sundrum

Constraints on the two free parameters of the model: M_G and $c=k/M_{PL}$



H.Davoudiasl, J.Hewett, T.Rizzo, hep-ph/0006041

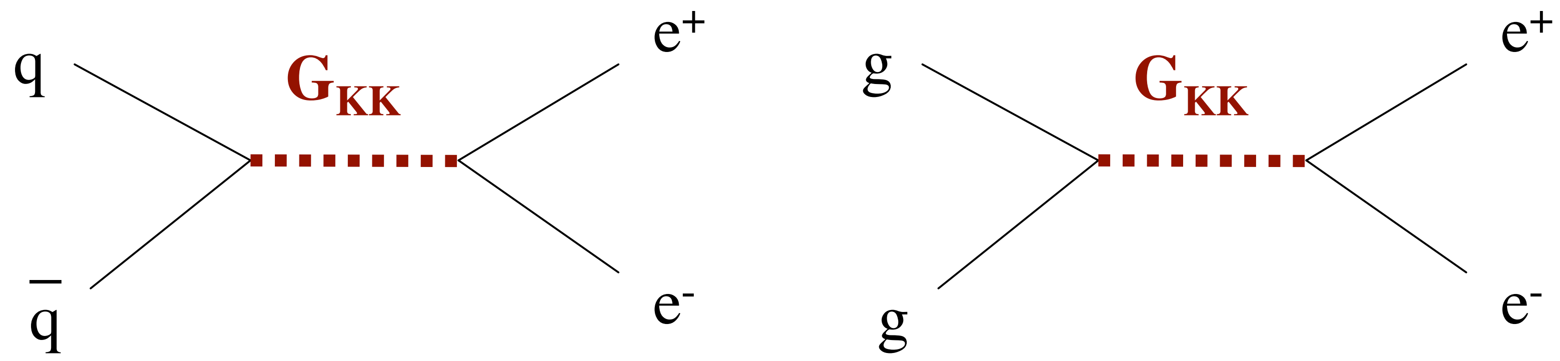
D0 Run II Preliminary
95% CL excluded domain
ee & γγ modes

Which part of the plane can be access with CMS?

The e^+e^- channel

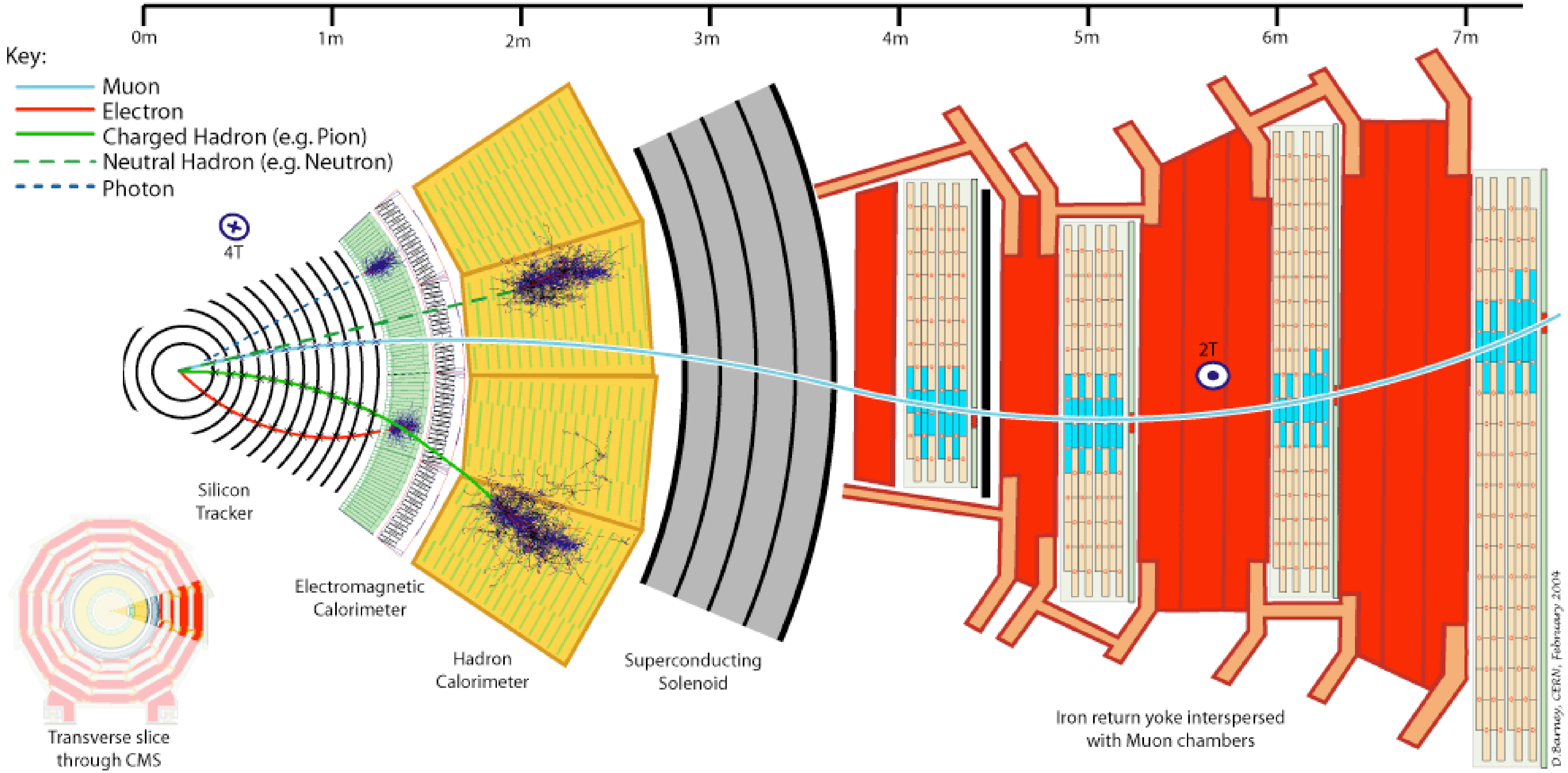
- Signal: $pp \rightarrow G \rightarrow e^+e^-$ (K Factor =1)

  The e^+e^- decay channel has a low branching ratio (BR=2%) but the clear signal in the electromagnetic calorimeter ECAL allows it to be the **discovery channel for Randall-Sundrum Gravitons.**



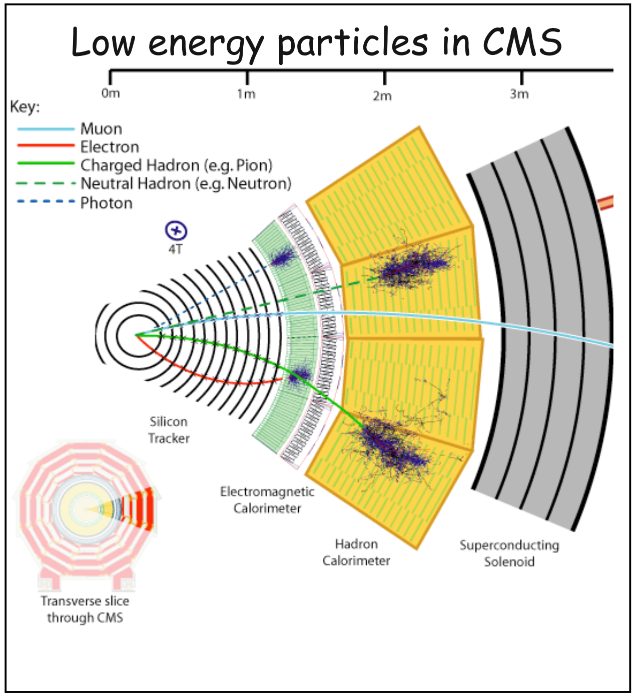
- Background: 2 electrons in the final state
  - Drell-Yan: $pp \rightarrow \gamma/Z \rightarrow e^+ e^-$ (K Factor=1.3)
  - [Jet faking an electron: Dijet, γ-jet, e-jet which is negligible in comparison to Drell-Yan]

Electron Reconstruction



Full Simulation & Reconstruction Analysis

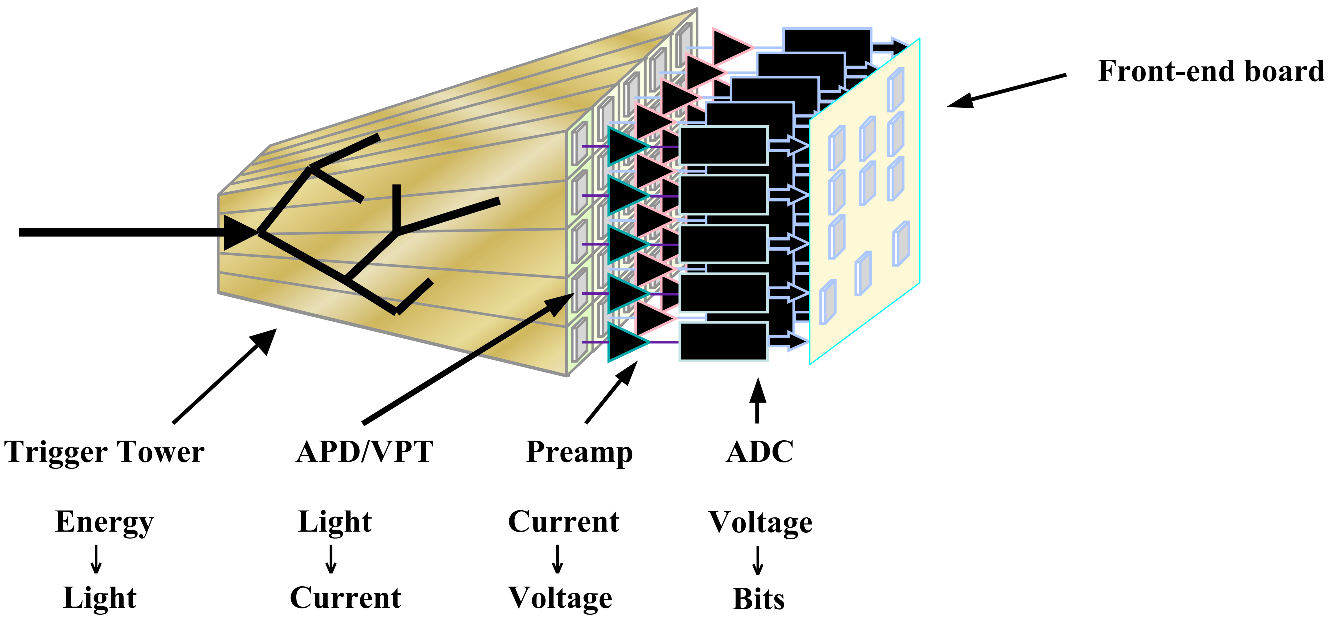
Generation with PYTHIA with a correct description of the energy evolution of the squared amplitude + inner Bremsstrahlung with PHOTOS



Full Simulation and Reconstruction chain of CMS (CMSIM & ORCA without pile-up):

- -Very high energetic electrons! Work on the electron reconstruction
- -Synchrotron radiation is included but found to be negligible in comparison to Bremsstrahlung in the tracker
- -Possible saturation of the ECAL electronics

Saturation of the ECAL electronics

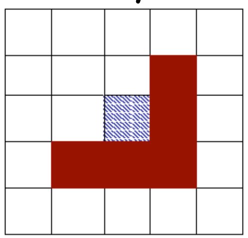


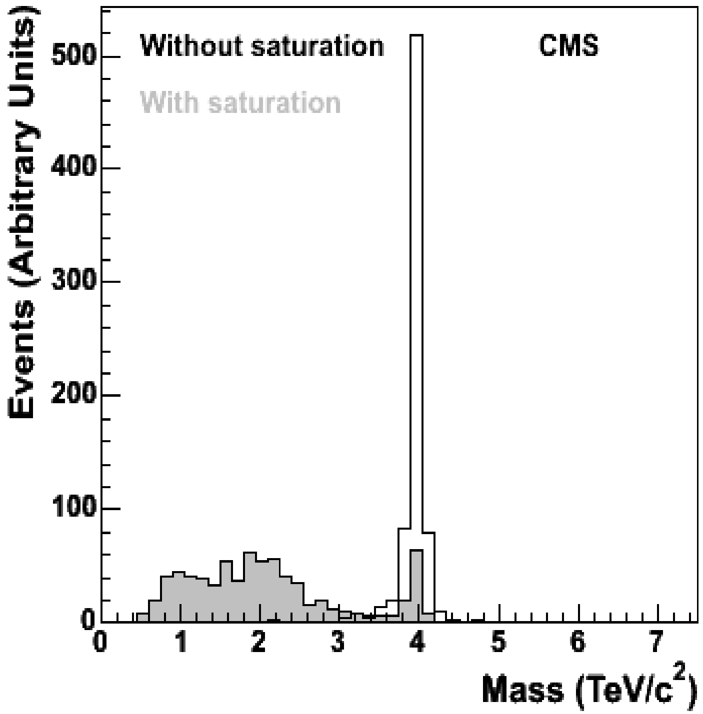
- Possible saturation of the ECAL electronics (pre-amplifiers in VFE cards) is studied:
  - Saturation expected at 1.7 TeV in the barrel with measured crystal light yield (4.5 photo-electrons/MeV)
  - Study here for saturation at 1.25 TeV (i.e. 6 p.e./MeV)
  - A simple correction is found.

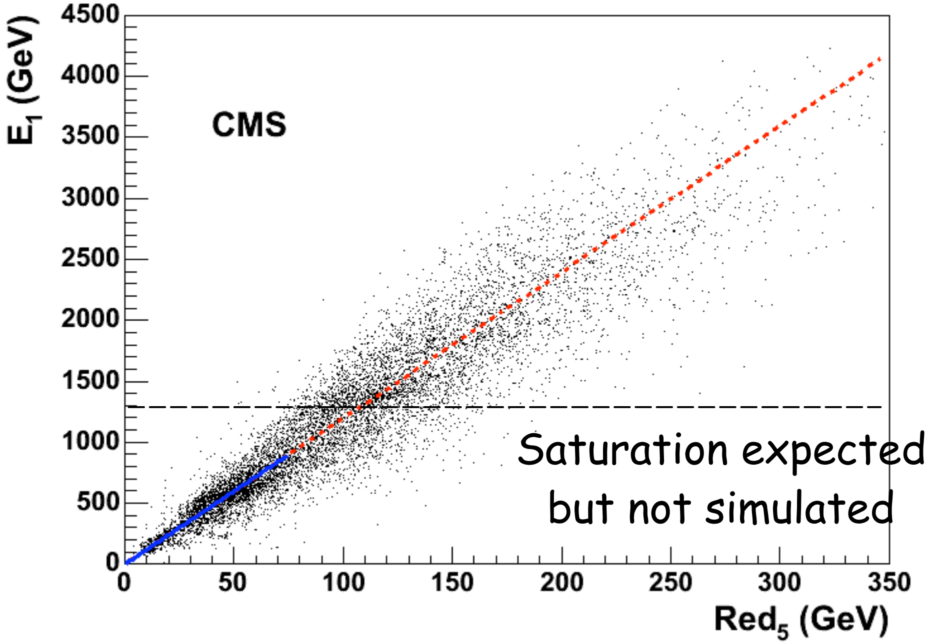
Saturation of the ECAL electronics

- The saturation has a big effect on the mass reconstruction of heavy resonances.

Idea for correction:
Correlation between
Red$_5$=E$_9$-E$_4$ and E$_1$

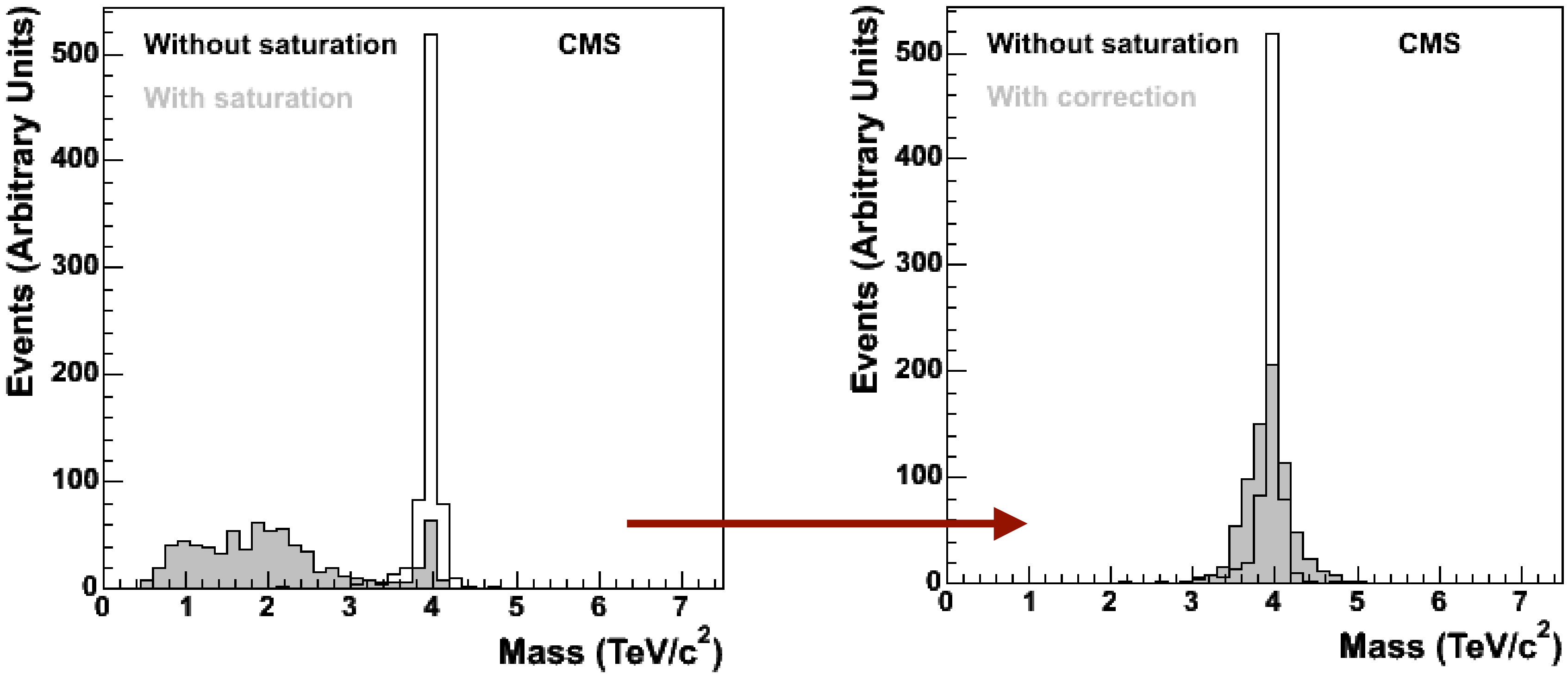






Saturation of the ECAL electronics

- This correction of the saturation allows to reconstruct heavy mass resonances.



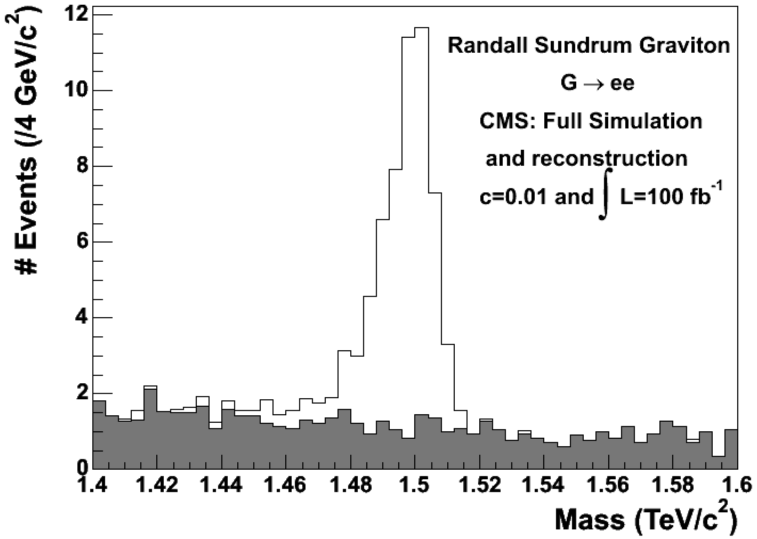
Selection Cuts

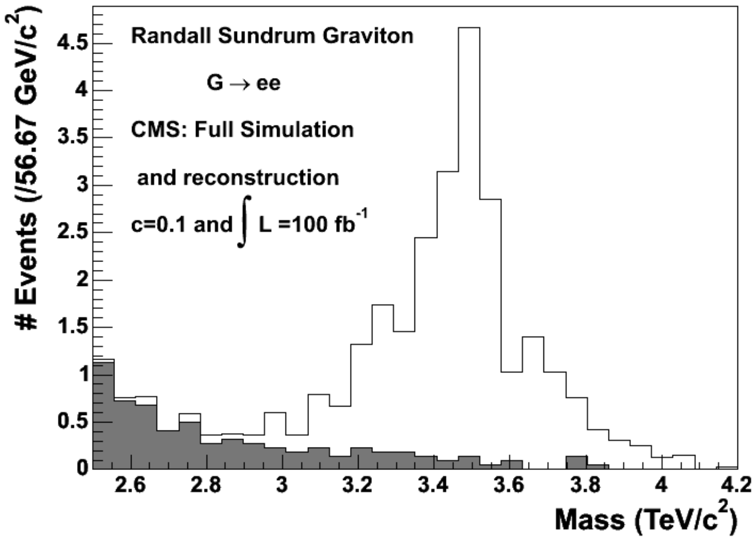
$pp \rightarrow G \rightarrow e^+e^-$

- Trigger up to Level 2.5
- 2 electrons
  - Super-Clusters:
    - $p_T > 100$ GeV,
    - $|\eta|<1.4442$ (barrel)

      or $1.566 < |\eta| < 2.5$ (endcaps)
  - Isolated: $E_T^{cone} < 0.02\ E_T^{SC}$ in cone $\Delta r<0.5$ (to kill big jets)
  - Electromagnetic: $H/E < 0.1$ (to kill π^+/π^-)
  - Charged: 2 tracks with at least 2 hits (to kill π^0/γ)

Search for a resonance

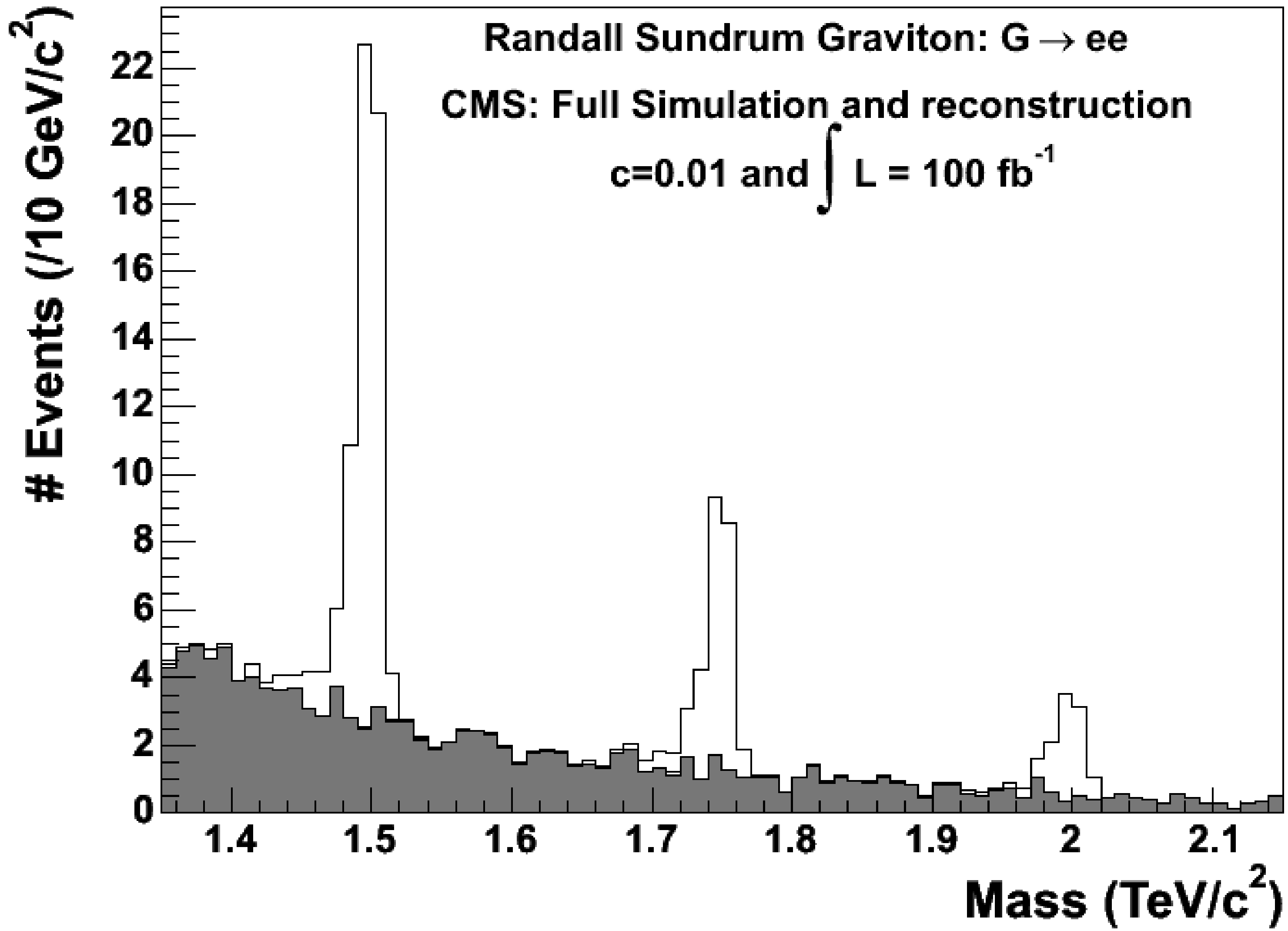




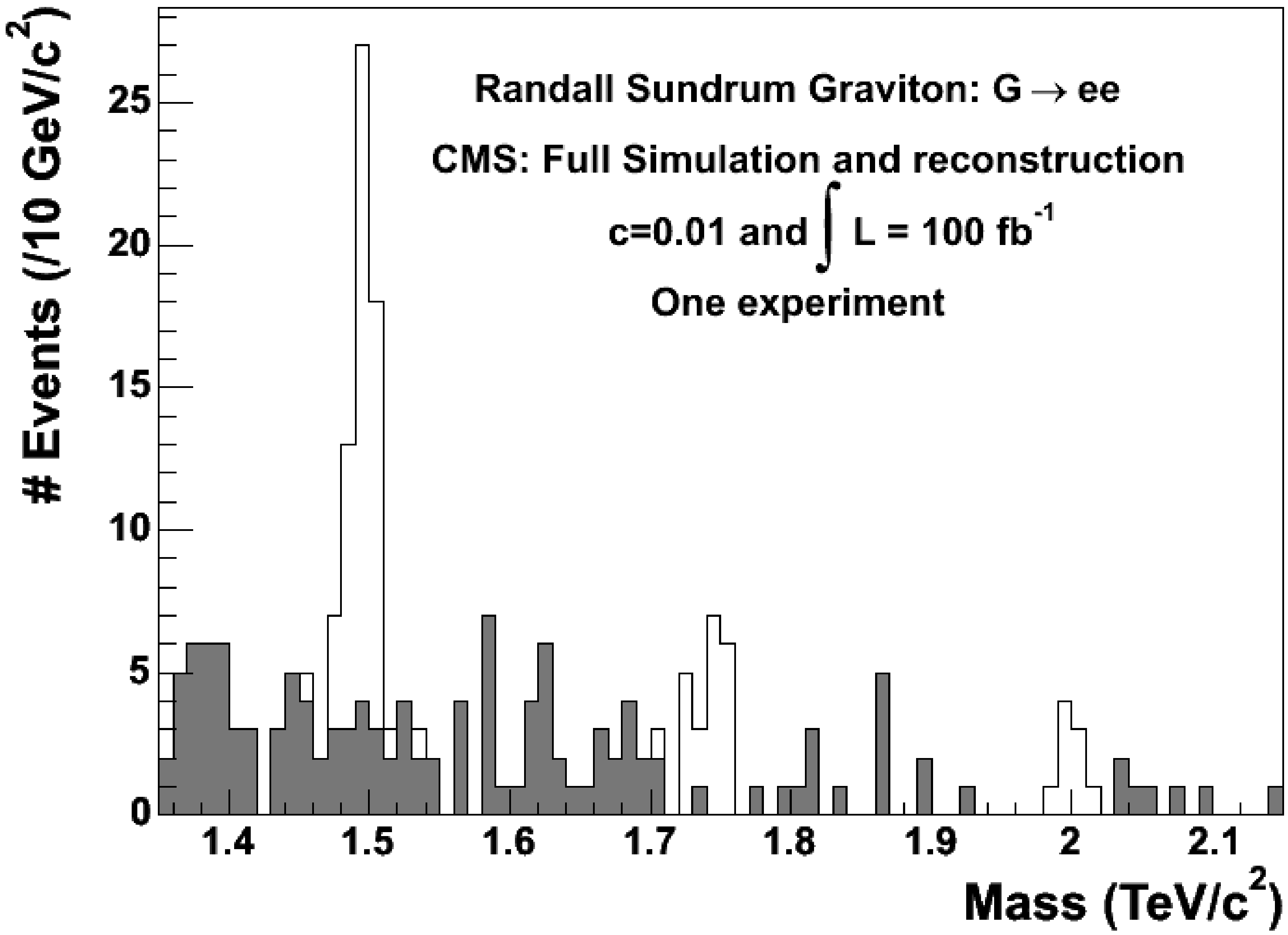
- Fit of a Gaussian to the signal distribution
- Mass window for N_S and N_B estimation: $\langle M \rangle \pm 3\sigma$

- For low coupling values: $E_1 < 1.25$ TeV (no saturation)
- For large coupling values: correction of the saturation coming from the ECAL electronics

Results for c=0.01

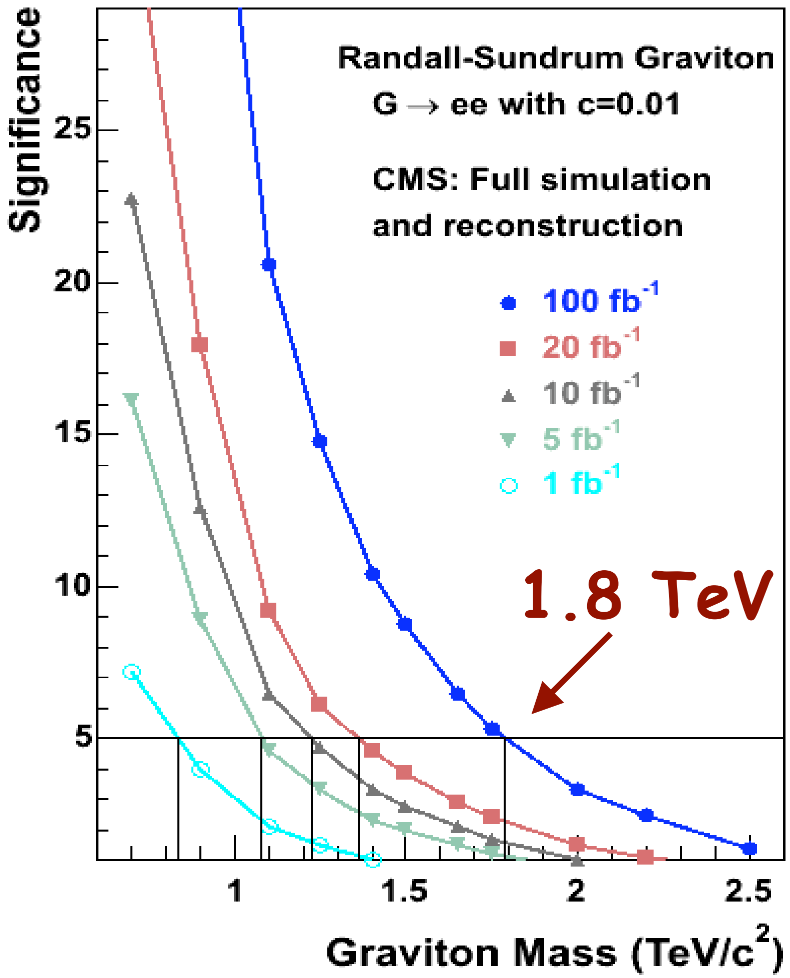


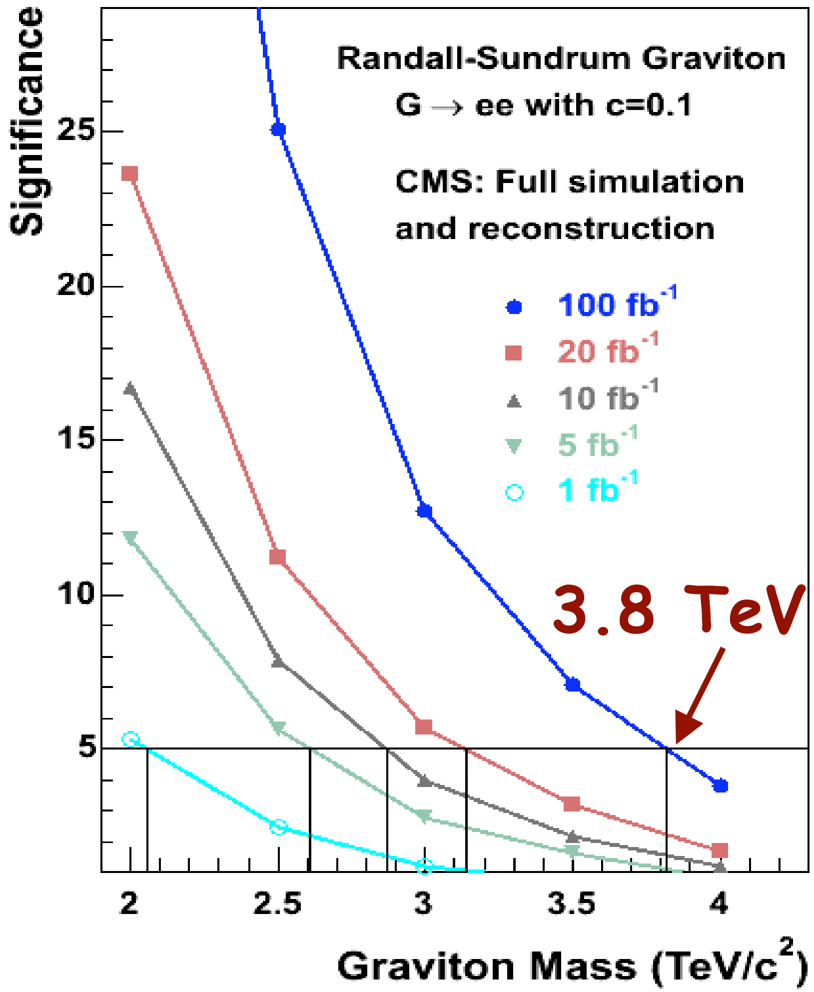
Results for c=0.01



Significance

$$S = 2(\sqrt{N_S + N_B} - \sqrt{N_B}).$$

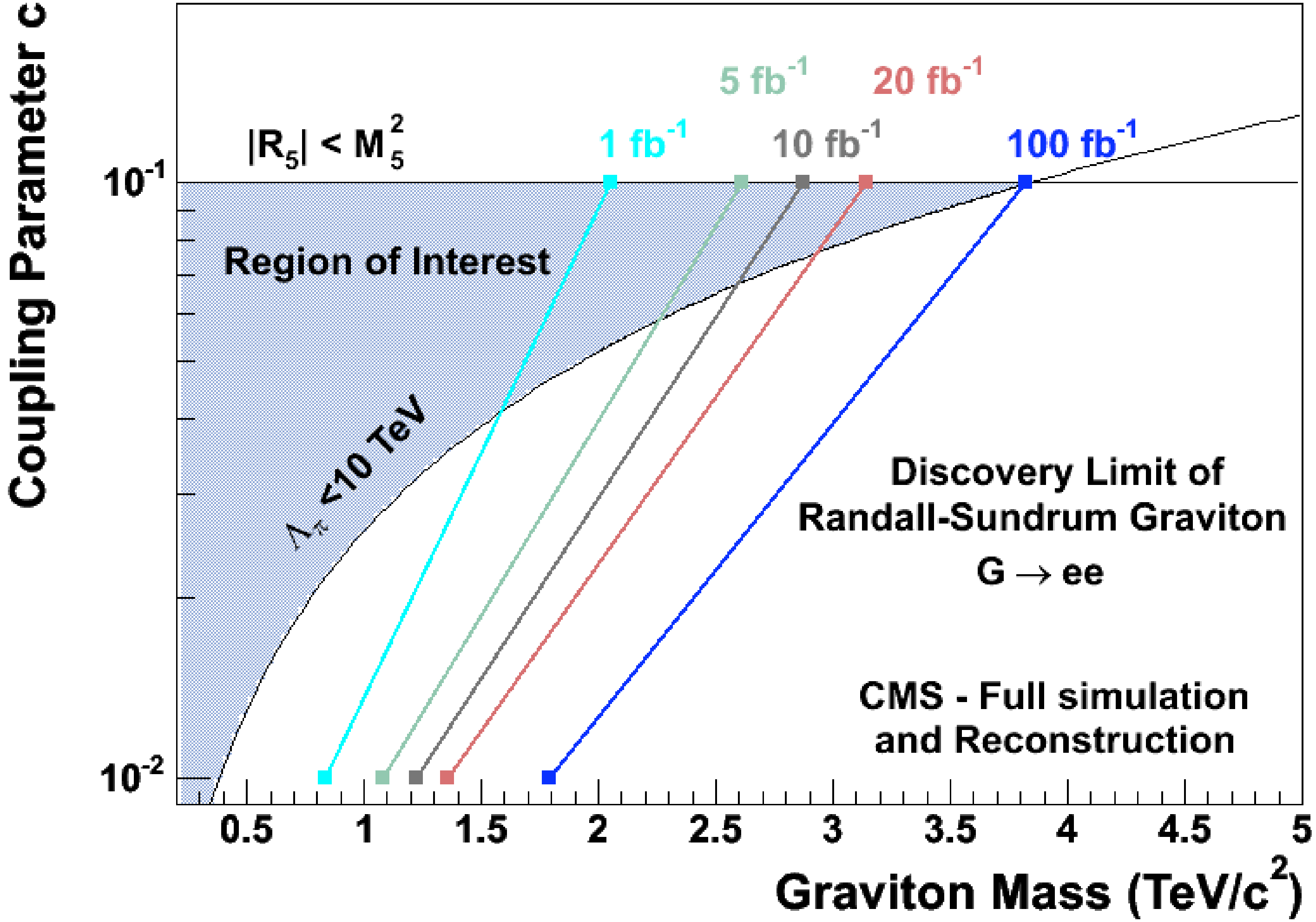




G→e⁺e⁻ : Discovery plane

CMS NOTE 2004-024

(Accepted by Eur. Phys. J-direct C)



$G \to e^+e^-$: Discovery plane

CMS NOTE 2004-024

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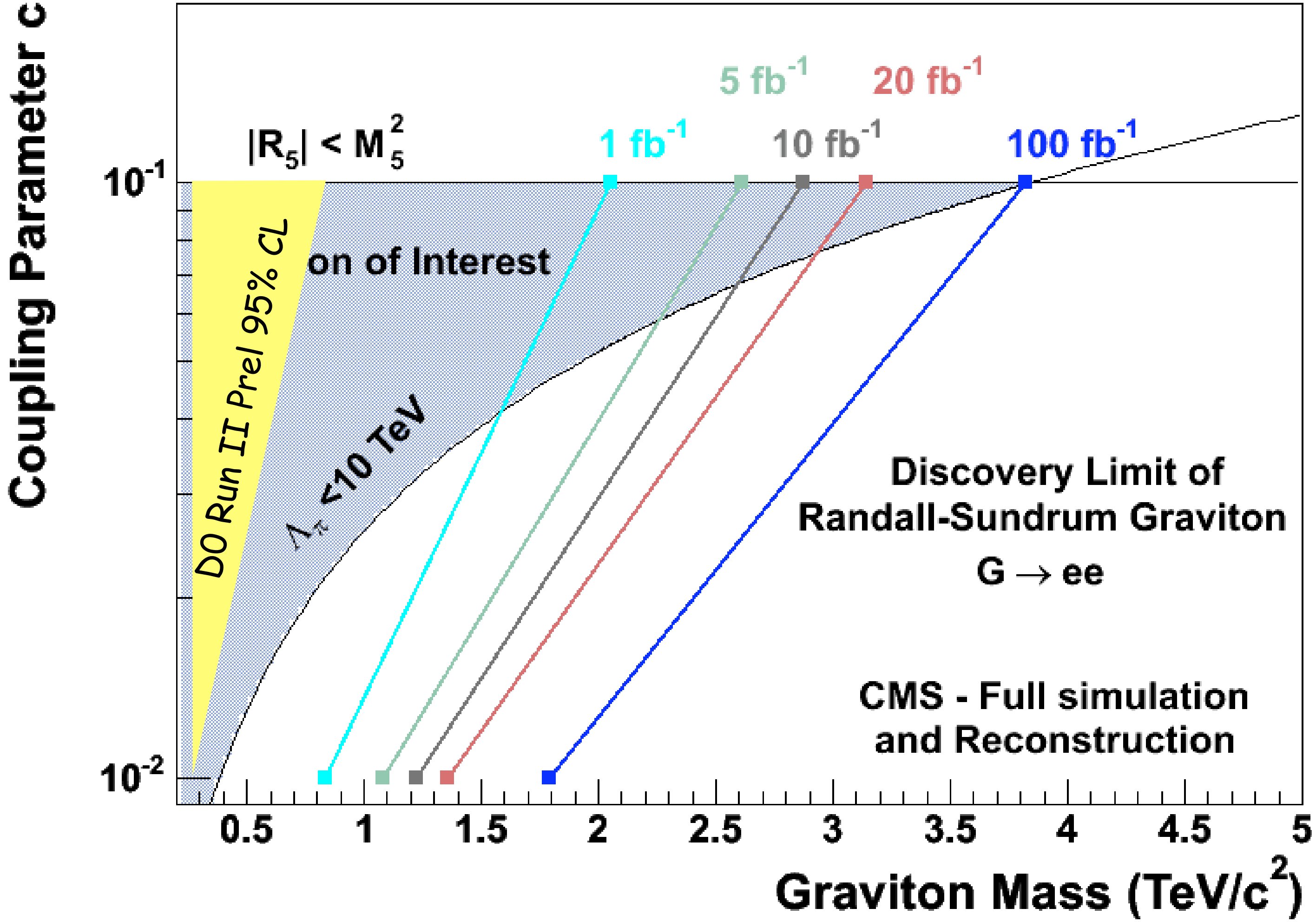
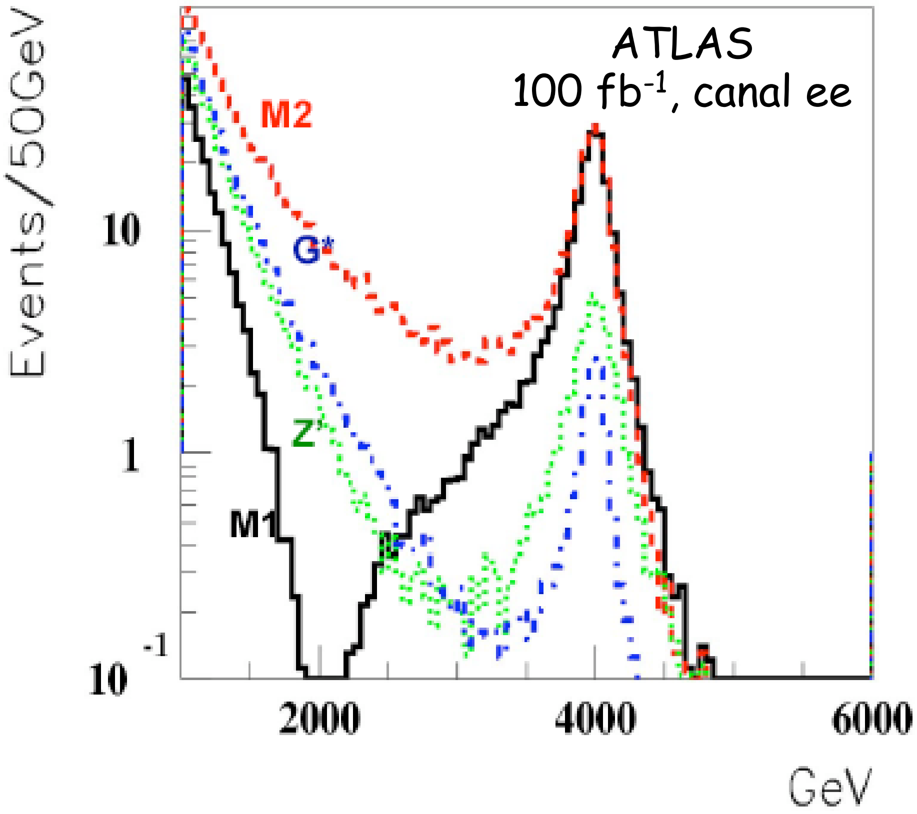


Identification



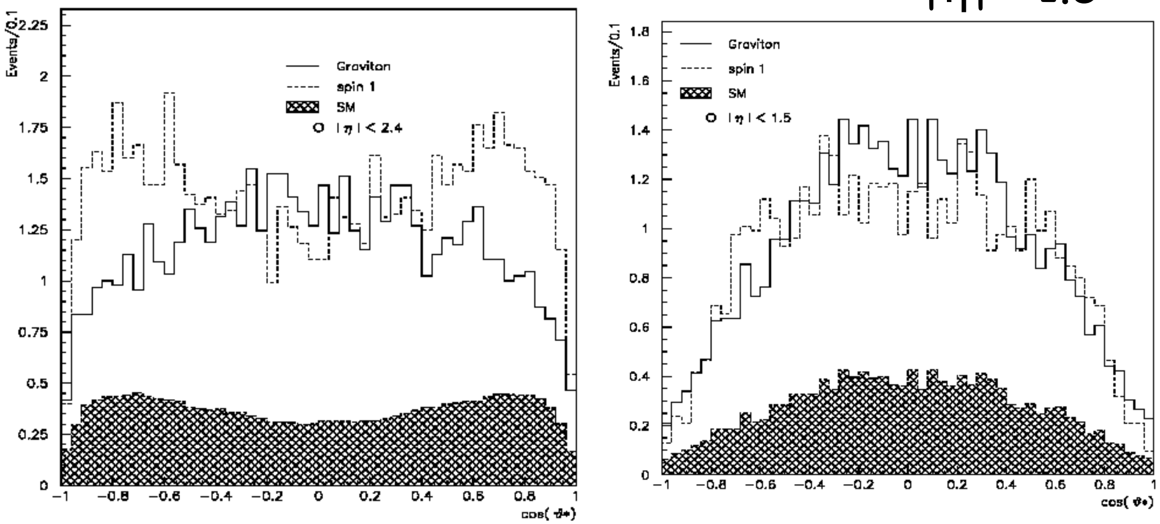
How to distinguish Gravitons from other particles?

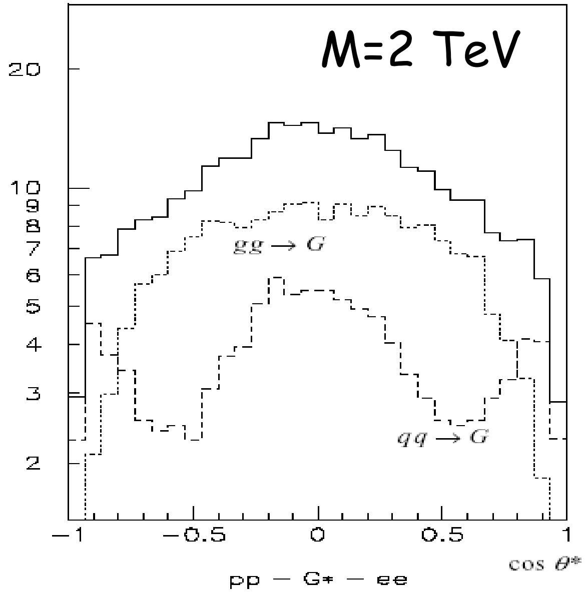
- Angular Distribution Study (Graviton is spin-2)
- Other Channel Study (Universal couplings of Graviton)

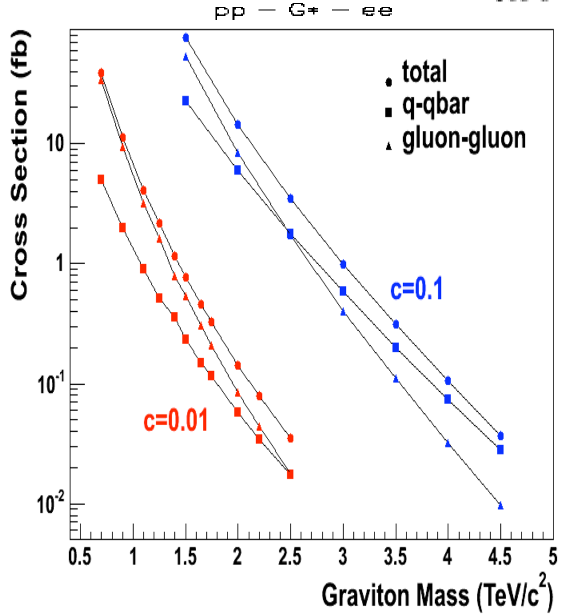
Angular Distribution

Analysis with fast simulation (CMSJET)

$|\eta| < 2.4$ M=1.5 TeV $|\eta| < 1.5$







- Need of the endcaps!
- Dependence on the Graviton mass

⇨ Need to do the study with the full simulation and reconstruction chain of CMS

Conclusions on the RS analysis

Full simulation & reconstruction analysis

- Study of very energetic electrons and search for massive resonances
- Discovery plane for the Randall-Sundrum gravitons $G \rightarrow e^+ e^-$:
  - o With 100 fb^{-1}: the region of interest will be covered by CMS.
  - o With 1 fb^{-1}: a large part of this region of interest will be accessible at the first beginning of the LHC running.
- For the Future: Work on the Identification of the Graviton nature
  - o Angular Distribution (Graviton is spin 2)
  - o Other channels:

    $G \rightarrow \gamma\gamma$ is allowed but not $Z' \rightarrow \gamma\gamma$.

    Test the universality of the Graviton couplings.

Conclusions : The extra dim

- A large number of models exists. I have only presented 3 of them here, which propose quite interesting signatures to be detected at LHC.

- If we don't find candidates for new physics, the LHC will provide strong constraints on the different models.
- In case of discovery (which may appear quickly), big efforts should be done to identify the nature of the signal. Help will come from linear colliders.

- Important to be ready for the start of LHC!