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Searches for New Physics at the LHC

Introduction

Many extensions of the Standard Model are motivated by the hierarchy problem

- The Planck scale (10^{19} GeV) >> EW scale (10^{2} GeV)
- Radiative corrections drive the Higgs mass to the upper scale, unless an exceptionally fine tuning of parameters provides cancellations

Possible solutions:

- **Supersimmetry:** for each SM particle a susy partner is introduced. SM and susy particle contributions to Higgs mass have opposite sign.
- **Little Higgs model:** The SM gauge group is part of a larger group broken at a few TeV. Additional particles provide cancelations of SM contributions to m_H
- **Extra spatial dimensions:** strong gravity at TeV scale

To avoid fine tuning, the new physics must appear at the TeV scale

This talk covers Little Higgs and Extra Dimensions searches

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Little Higgs Models

Known and new Higgs, gauge bosons coming from breaking a SU(5) simmetry at scale *v* (few TeV). A new heavy quark (color singlet) is introduced as well.
Divergent contribution to the Higgs mass from top, W, Z and Higgs loops are canceled by the new particles:

- Heavy gauge bosons Z_H, W_H, A_H — $m < 6$ TeV $(m_h/200\ \mathrm{GeV})^2$
- Heavy quark T (electroweak singlet) — $v\sqrt{2} < m < 2$ TeV $(m_h/200\ \mathrm{GeV})^2$
- New Higgs bosons $\Phi^0\ \Phi^+\ \Phi^{++}$ — $m < 8$ TeV $(m_h/200\ \mathrm{GeV})^2$

"Littlest Higgs model" (T. Han et al., Phys. Rev. D67, 095004) used for a detailed ATLAS study (G. Azuelos et al. , hep-ph/0402037).
CMS study for generic heavy gauge bosons is also relevant (M. Dittmar et al., hep-ph/0307020).

New Quark T

Parameters: M_T, λ_1/λ_2

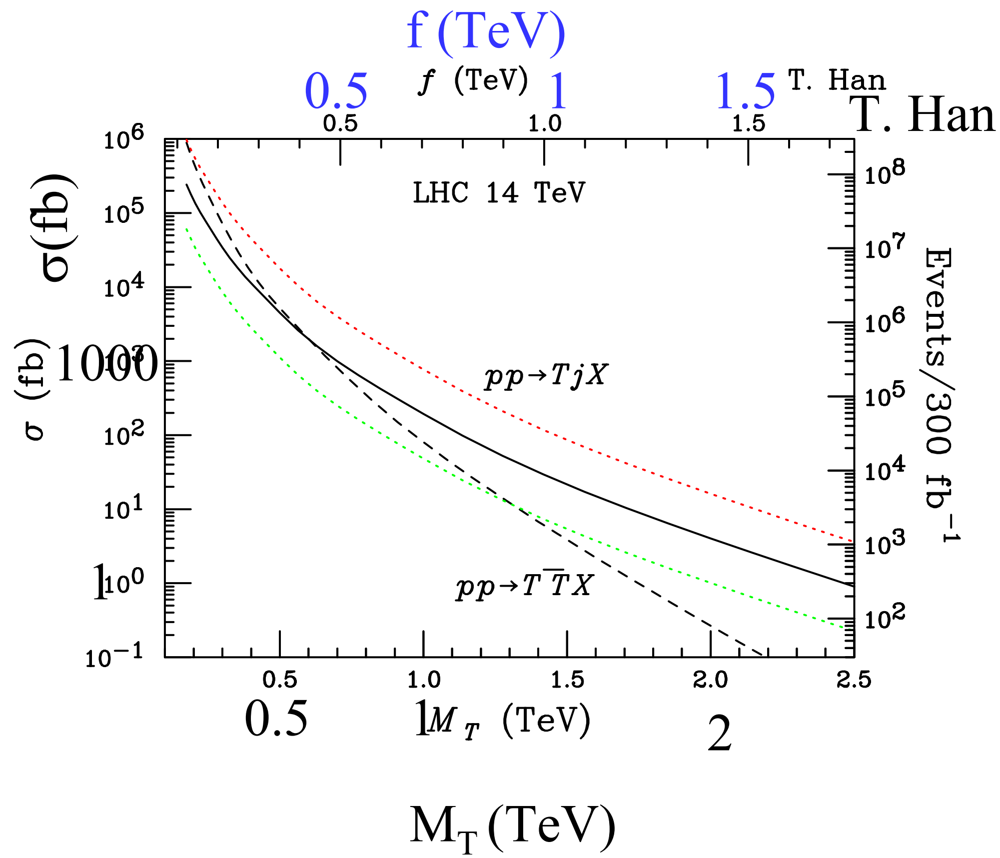
Decays:

- $T \rightarrow Wb$ 50%
- $T \rightarrow Zt$ 25%
- $T \rightarrow Zh$ 25%

Narrow resonance:

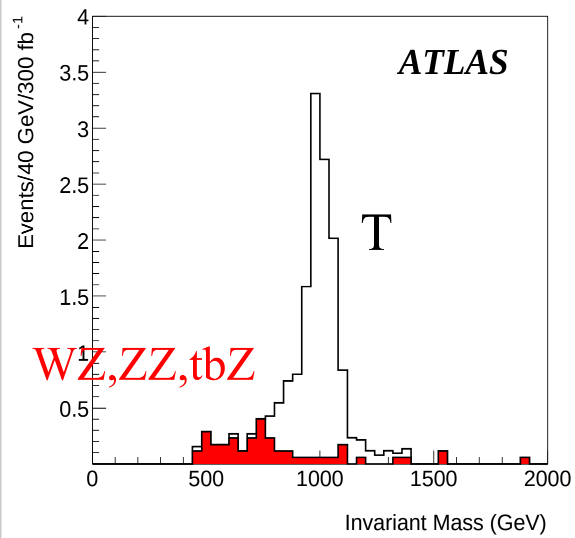
$\Gamma = k^2/32\pi\ M_T$

$k = \lambda_1/\sqrt{\lambda^2{}_1+\lambda^2{}_2}$



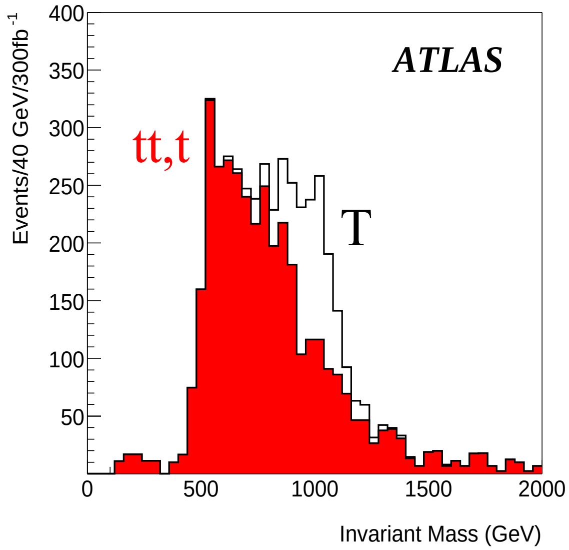
T Quark Search

- ATLAS study (hep-ph/0402037)
- Plots for 300 fb^{-1}



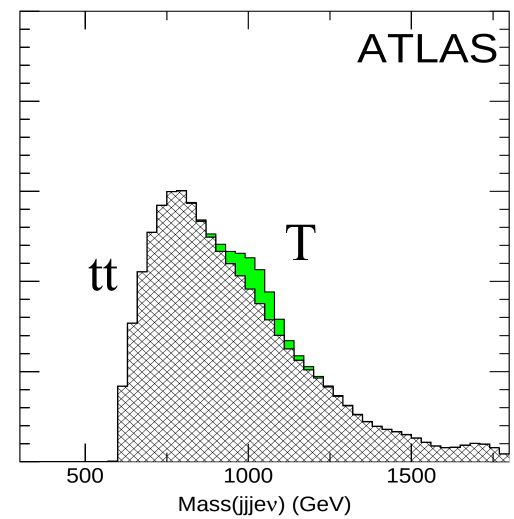
$T \to Zt \to l^+l^-l\nu b$

$M_T < 1050$ (1400) GeV



$T \to Wb \to l\nu b$

$M_T < 2000$ (2500) GeV

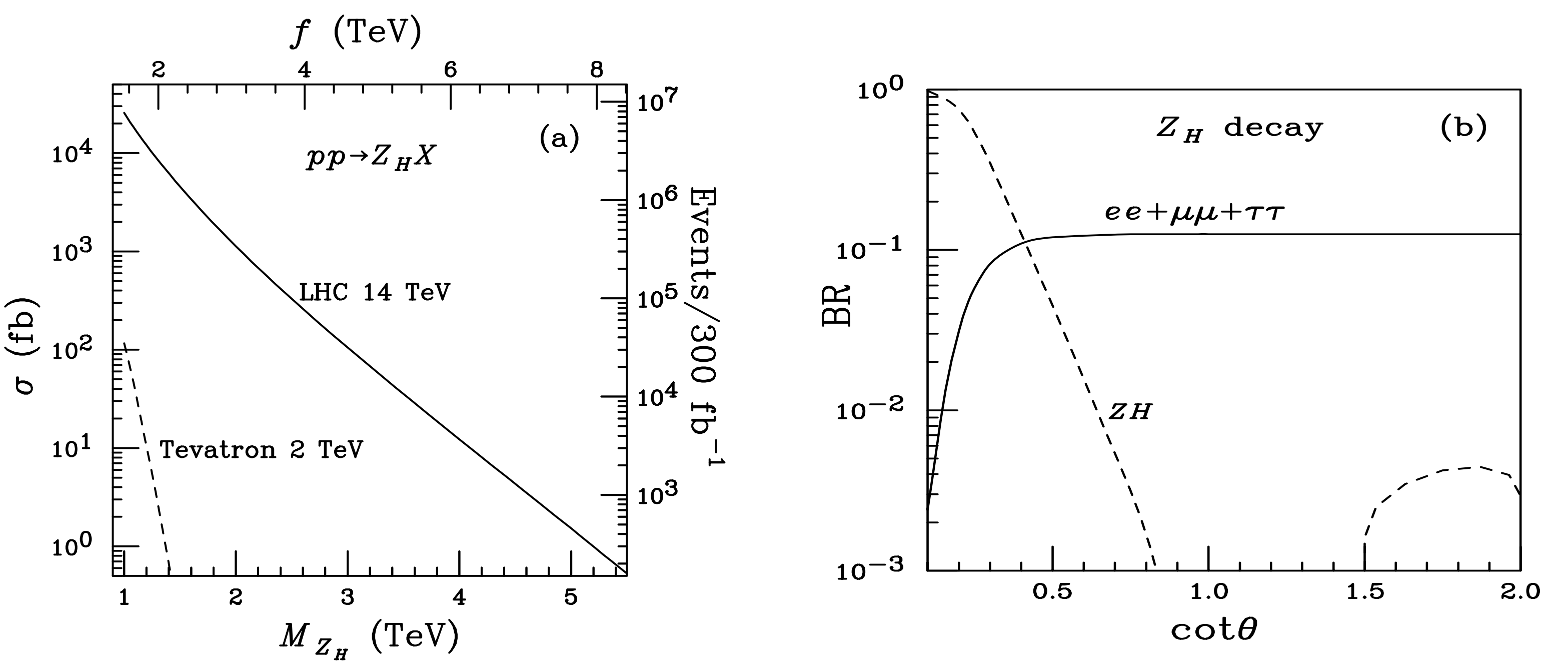


$T \to ht \to bbl\nu b$

4σ significance at $M_T = 1000$ GeV
Somewhat lower at $M_T = 700$ GeV (more tt background)

New Gauge Bosons

- Parameters: M, cotθ (for Z_H) cotθ' (for A_H)
- Production ~ $(\cot \theta)^2$



Gauge boson searches

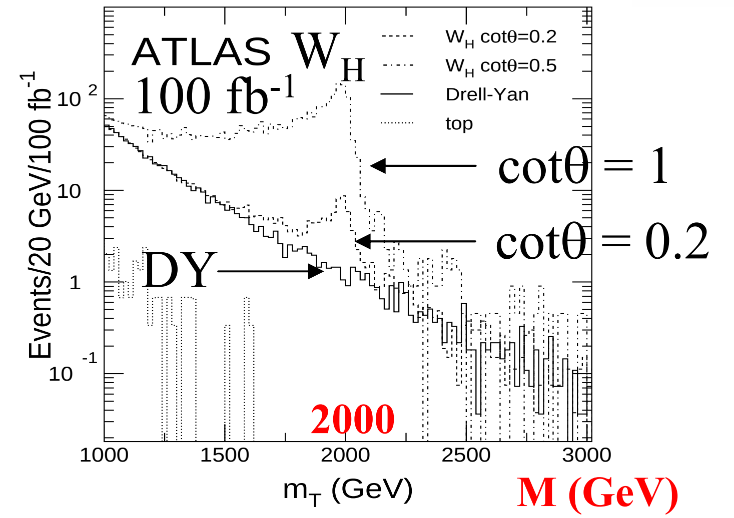
- Discovery:

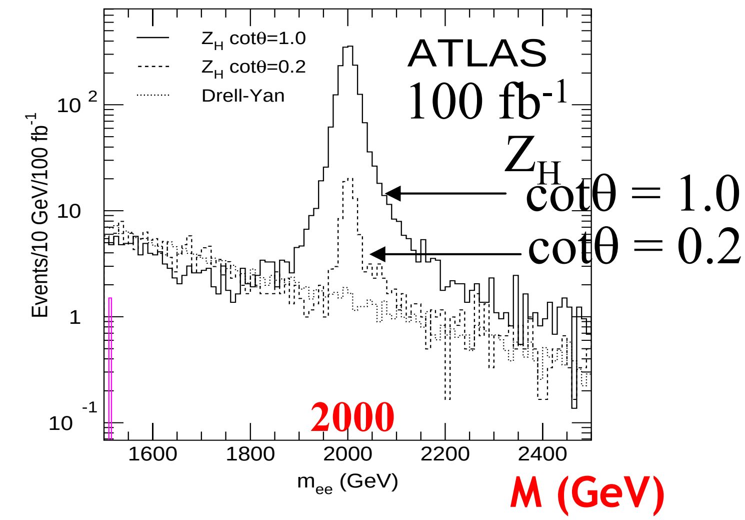
  $A_H \to ee, \mu\mu$

  $Z_H \to ee, \mu\mu$

  $W_H \to e\nu, \mu\nu$

- Up to ~5 TeV, except for small $\cot\theta$ (Z_H, W_H) and $\tan\theta` \approx 1.3$ (A_H)
- CMS reach similar
- Cross section, width measure θ





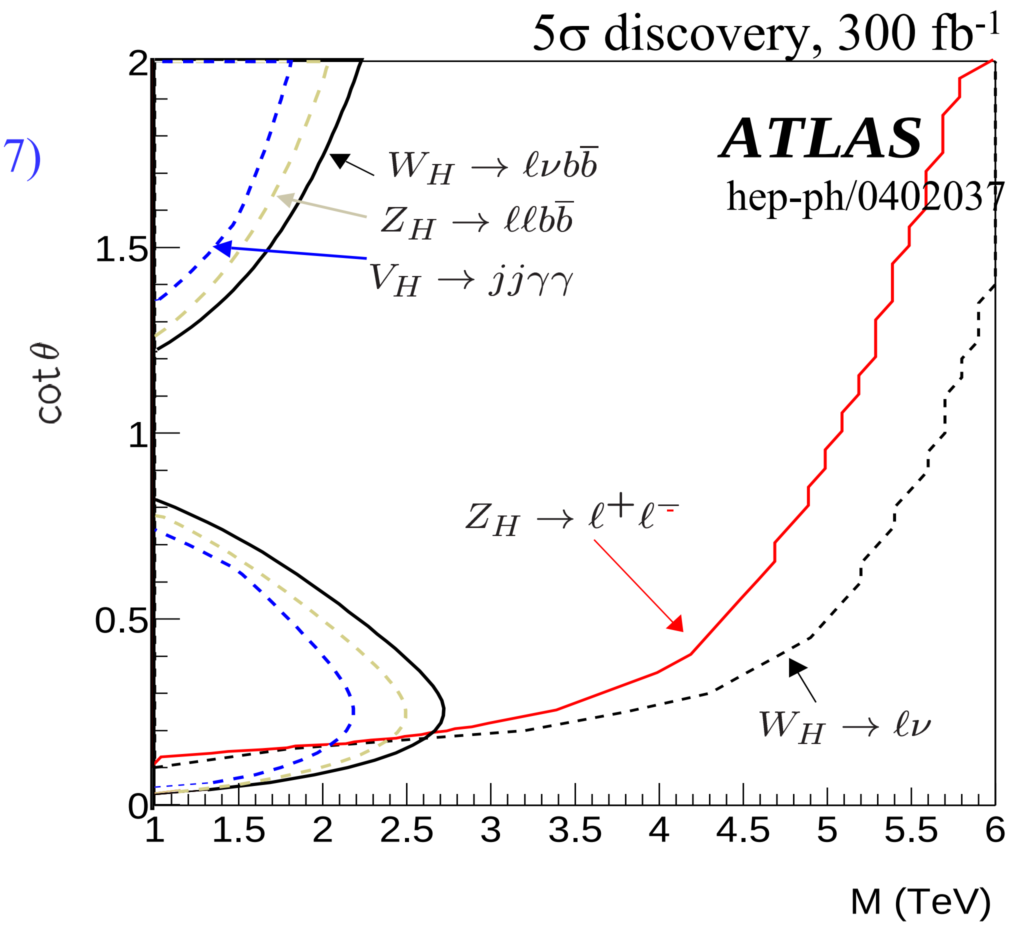
Gauge Bosons: Higgs channel

- Specific of L dels
- Atlas study (h 402037) assuming m_h :

$Z_H \rightarrow Zh \rightarrow llbb$

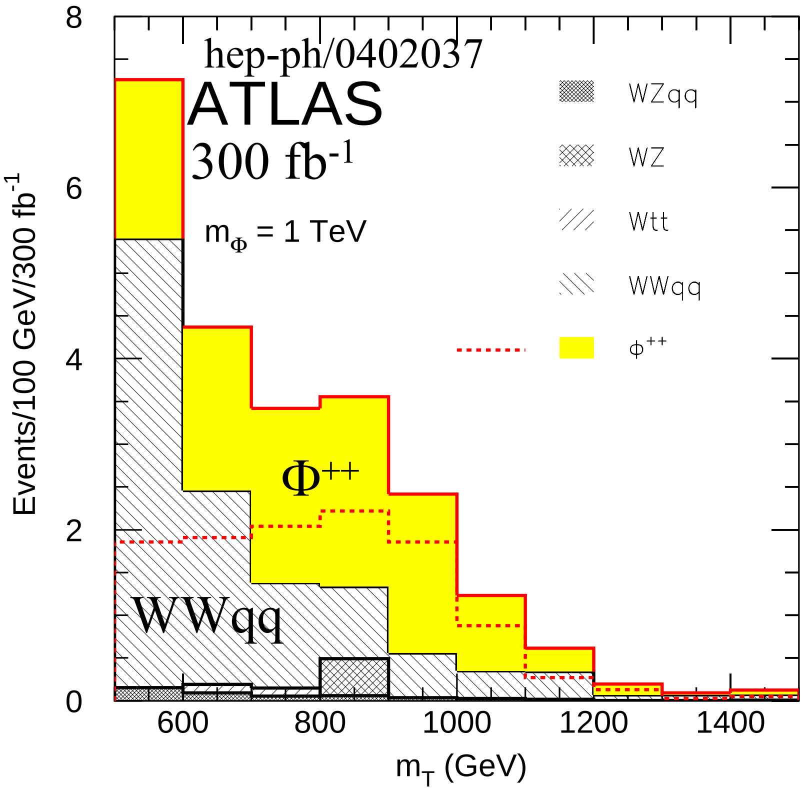
$W_H \rightarrow Wh \rightarrow l\nu bb$

$W_H/Z_H \rightarrow W/Z\ h \rightarrow qq\gamma\gamma$



Heavy Higgs

- Less constrained in mass
- $qq \rightarrow \varphi^{++}\varphi^{--} \rightarrow 4l$ (too small cross section)
- $qq \rightarrow q'q'\varphi^{++} \rightarrow q'q'W^{+} W^{+} \rightarrow q'q' ll\nu$
- Coupling φWW depends on v' (VEV of Higgs triplet)
- From EW data v' < 15 MeV
- For m_{ϕ} = 1000 (1500) GeV discovery requires v' > 29(54) MeV
- Φ^{+} and Φ^{0} probably even more difficult



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Extra Dimensions

Several models (review in hep-ph/0205106):

- Large Extra Dimensions

  Direct production and virtual effects of gravitons
- TeV^{-1} size extra dimension

  Kaluza-Klein excitations of gauge bosons
- Small Warped extra dimension

  graviton narrow resonance – radion

Large Extra Dimensions

ADD model: **A**rkani-Hamed, **D**imopoulos and **D**vali.

N. Arkhani-Hamed et al., Phys. Lett. B429, 263
N. Arkhani-Hamed et al., Phys. Rev. D59, 086004
I. Antoniadis et al., Phys. Lett. B436, 257

- δ new dimensions of size $TeV^{-1} \ll R_0 < 0.2$ mm
- Gravity propagates in the whole space (bulk) → increases as $R^{-(2+\delta)}$ for $R < R_0$ and is strong at scale M_D (~ TeV).
- $M_D^{\delta+2} R_0^{\delta} = M_{Planck} \rightarrow R_0 \sim 1$ mm (δ=2) or 10 fm (δ=6)
- Direct tests of Newton's law exclude δ=1, δ=2 marginal ($R_0 < 190$ μm)
- Stringent (but model-dependent) astrophysical limits
- Low-energy Kaluza-Klein graviton excitations. Universal and weak coupling to SM particles. Large number of states (~ continuum).

Large extra dimension: direct searches

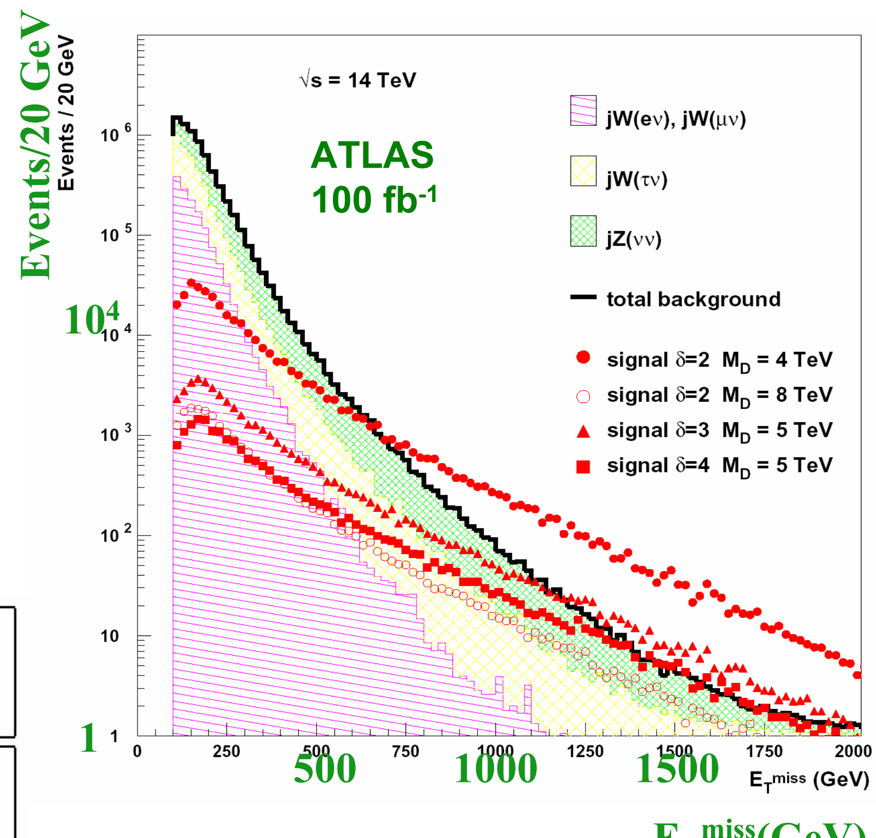
Direct production of KK gravitons

$$\left.\begin{array}{l} \bar{q}q \rightarrow gG^{(k)}, \gamma G^{(k)} \\ qg \rightarrow qG^{(k)} \\ gg \rightarrow gG^{(k)} \end{array}\right\} \text{jets} + \not{E}_T,\ \gamma + \not{E}_T$$

LEP+Tevatron+Hera limits ~ 1.4/0.6 TeV (δ=2/6)

ATLAS search (L. Vacavant and I. Hinchliffe, J. Phys. G27 , 1839)

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

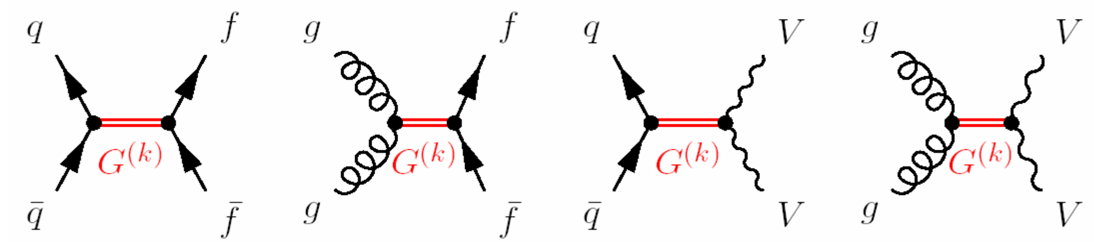


Lower limit is from validity of low-energy effective theory

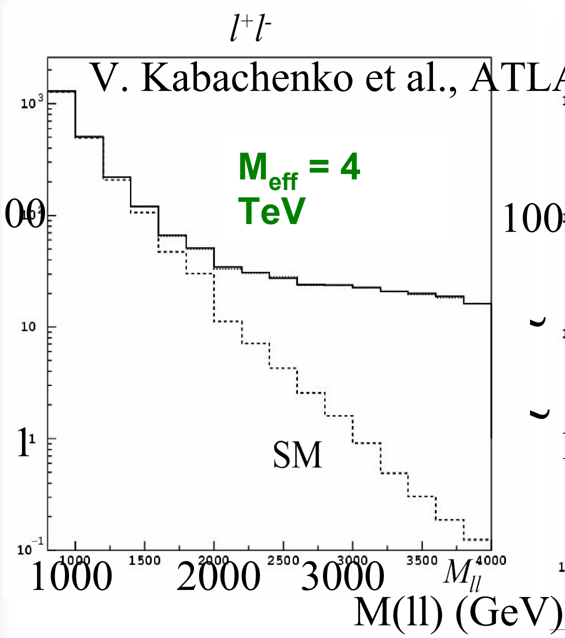
Large ED: indirect searches

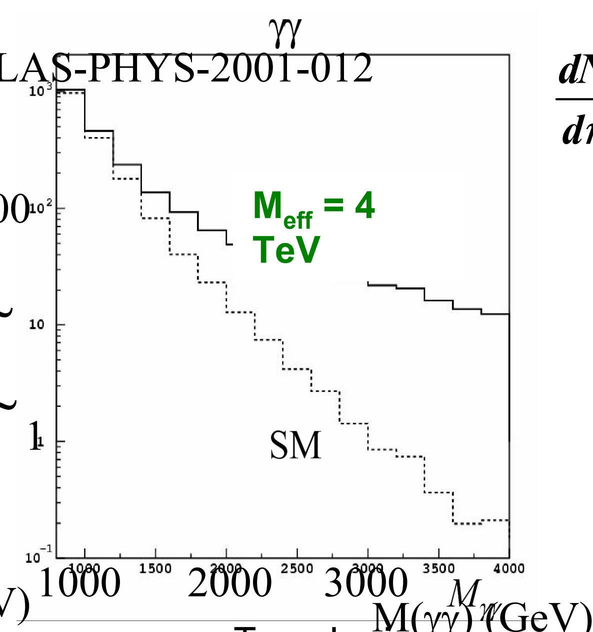
- Virtual exchange of gravitons modify Drell-Yan X-sections , asymmetries
- UV divergence, ignorance of full theory – use cut-off M_S

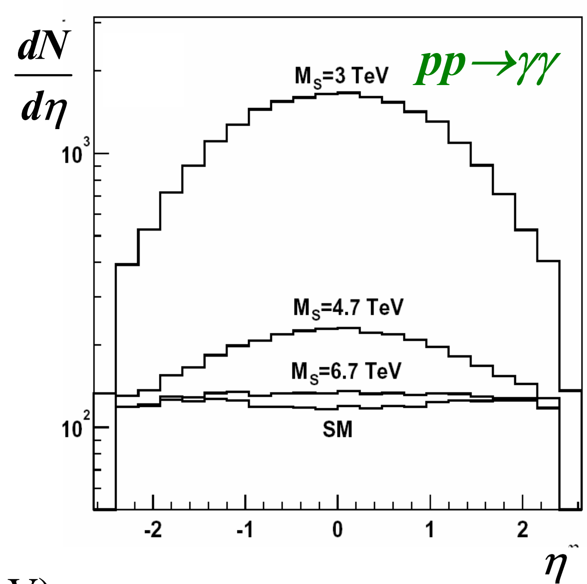
ATLAS, 100 fb^{-1}
$M_S < 5.1$ TeV ll
$M_S < 6.6$ TeV γγ



V. Kabachenko et al., ATLAS-PHYS-2001-012







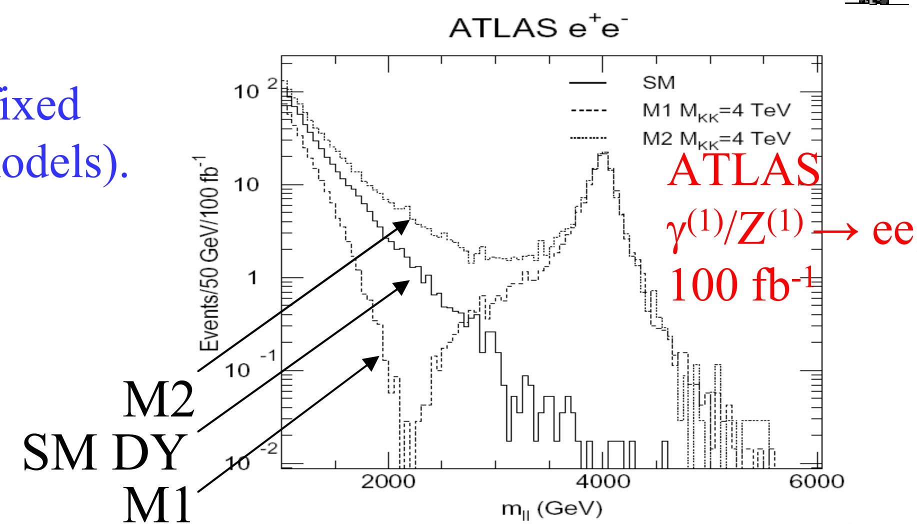
TeV^{-1} Search

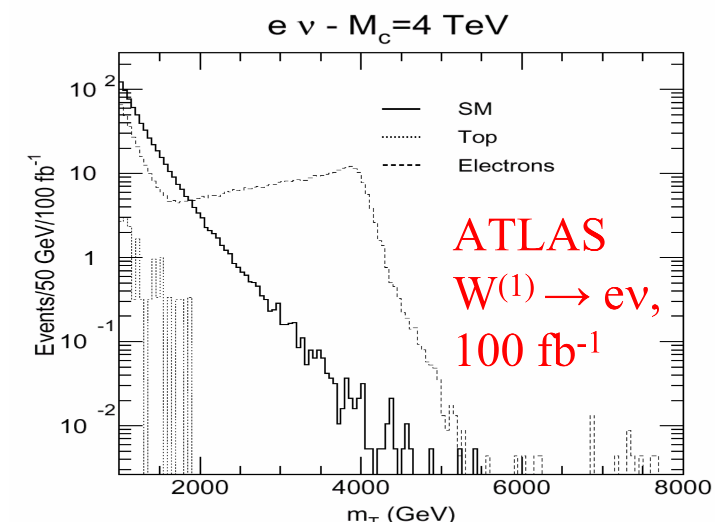
- One ED, gauge bosons in the bulk fermions on 4D brane at one/two fixed points in 5th dimension (M1/M2 models).
- KK spectra for $Z^{(k)}, W^{(k)}$: $m_k^2 = m_0^2 + k^2 M_C^2$
- EW data: $M_C > 4$ TeV
- Only first resonance observable
- Discovery with ee, μμ, eν, μν
- Precision measurements with electrons

ΔE/E	2 TeV e	2 TeV μ
ATLAS	0.7 %	20 %
CMS	0.6 %	6%

$Z^{(1)}/\gamma^{(1)}$: G.Azuelos and G.Polesello, in hep-ph/0204031

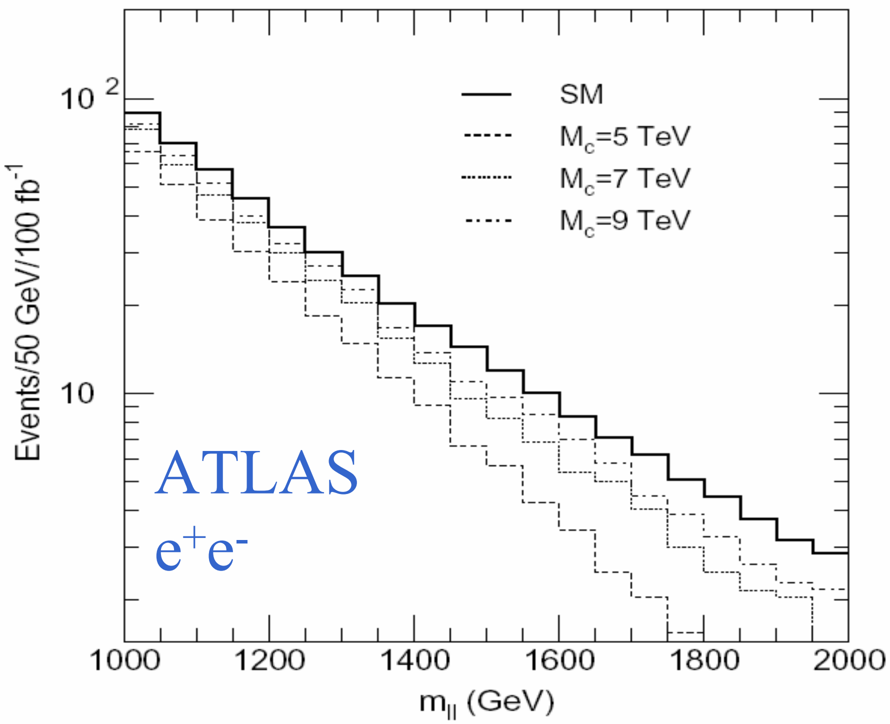
$W^{(1)}$: G.Polesello, M.Prata





TeV^{-1} Sized ED Reach

Sensitivity to peak (100 fb^{-1}, $S/\sqrt{B}>5$, $S>10$): 5.8 TeV
Reach (with interference in tail, el.,100 fb^{-1}): 9.5 TeV
Ultimate (with interference, el.+muons, 300 fb^{-1}): 13.5 TeV



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Discrimination of Models

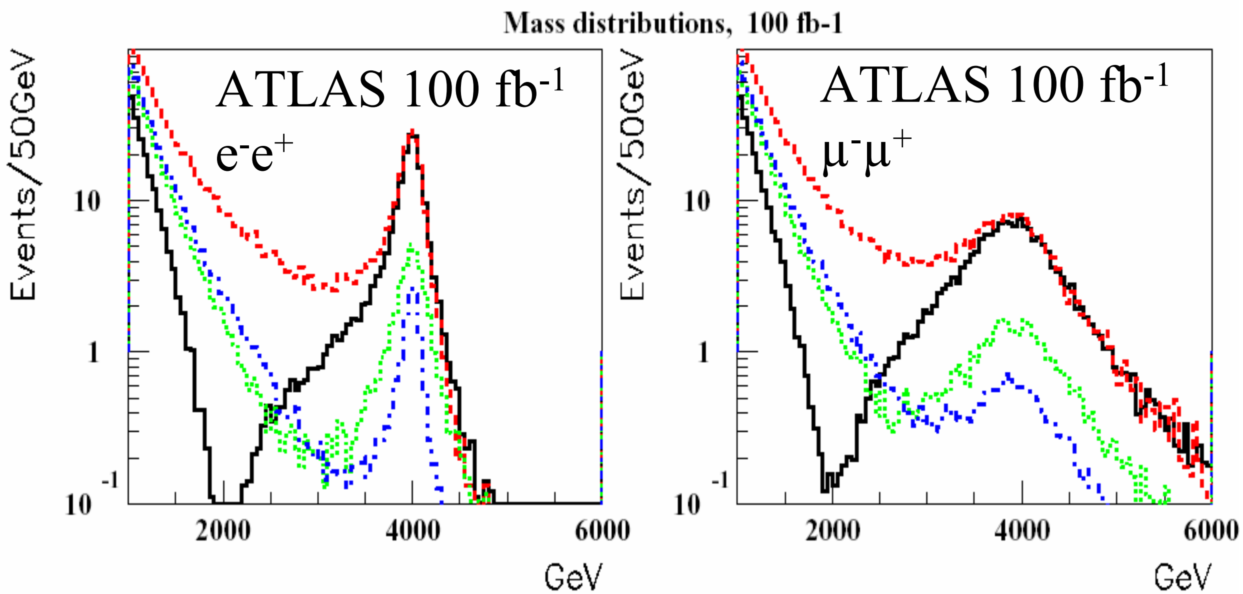
- Cross section, width, resonance shape

Not shown: asymmetries

- Discrimination Z $^{(1)}$/Z'/G* possible

W$^{(1)}$/W' difficult

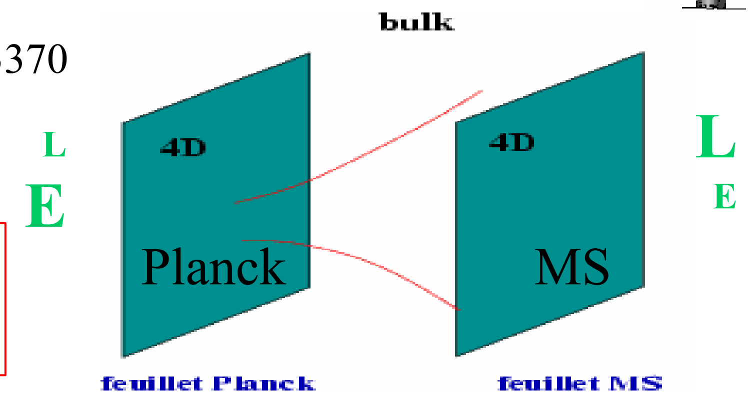
process	$\sigma \times BR(Z^* \to e^+e^-)$ (fb)
$Z^{(1)}/\gamma^{(1)}$	4.05
$Z^{(1)}/\gamma^{(1)}$-M2	11.75
Z'	4.65
$qq \to G^*$	0.20
$gg \to G^*$	0.13
$qq \to e^+e^-$	4.83



- Z/γ M1
- Z/γ M2
- Z'
- G*+SM Drell-Yan resonance

Randall-Sundrum model

L. Randall and R. Sundrum, Phys. Rev. Lett. 83, 3370



- Only one ED:

$$ds^2 = e^{-2ky}\eta_{\mu\nu}dx^\mu dx^\nu + dy^2, \quad y = r_c\phi$$

$\Rightarrow$ distances in 3D shrink as fonction of y

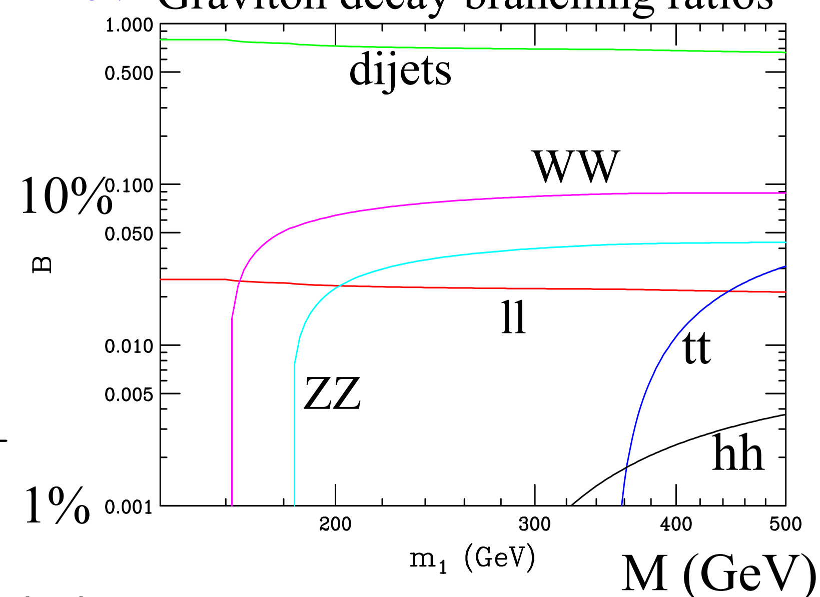
- $k \sim M_{Pl}$; Gravity scale $\Lambda_\pi \sim M_{Pl}\, e^{-kr\pi} \sim$ TeV if $kr \sim 12$
- Graviton KK excitations:

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

2 parameters: m_G and k/M_{Pl}

coupling of KK states $\sim 1/\Lambda_\pi$,

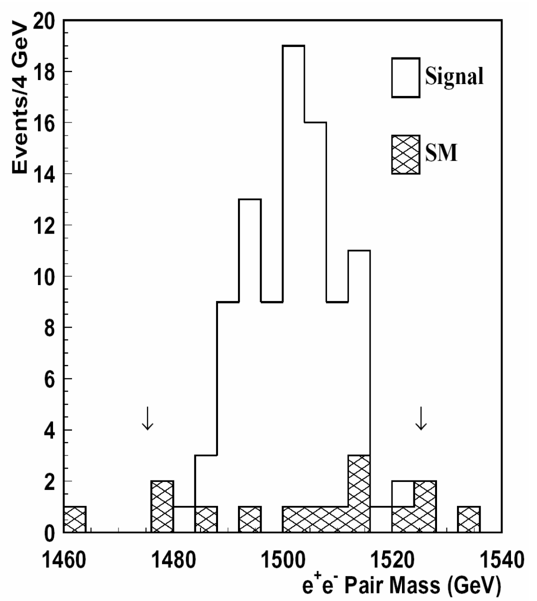
with $\Lambda_\pi = M_{pl} e^{-kr_c\pi} = \dfrac{m_G}{3.83 \times k/M_{Pl}}$



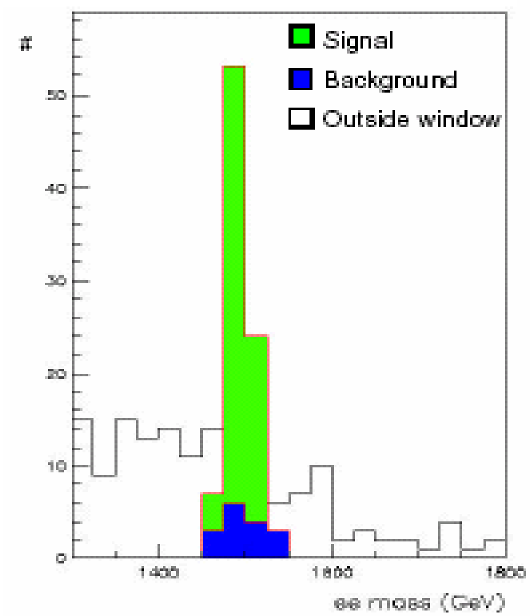
RS Graviton Searches

• The RS scenario has been studied both by ATLAS (B.C. Allanach et al., hep-ph/0211205) and CMS (P. Traczyk et al., hep-ex/0207061)

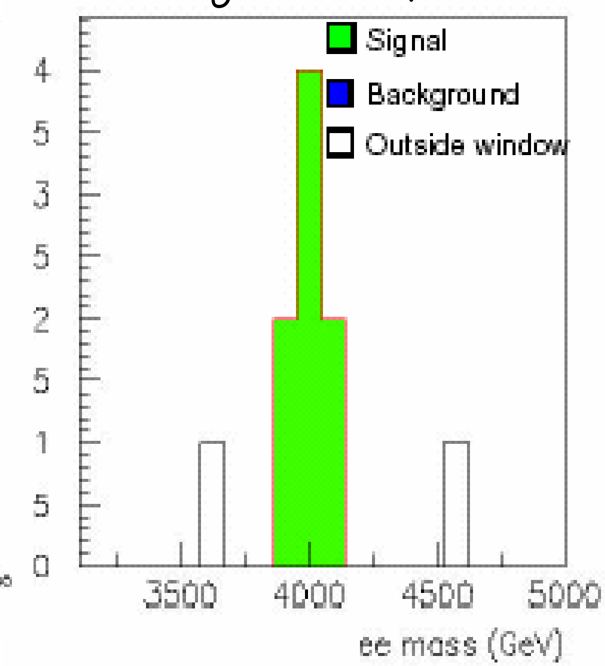
ATLAS, e^+e^-
m_G= 1.5 TeV, c = 0.01



CMS, e^+e^-
m_G= 1.5 TeV, c = 0.01



CMS, e^+e^-
m_G= 4 TeV, c = 0.1

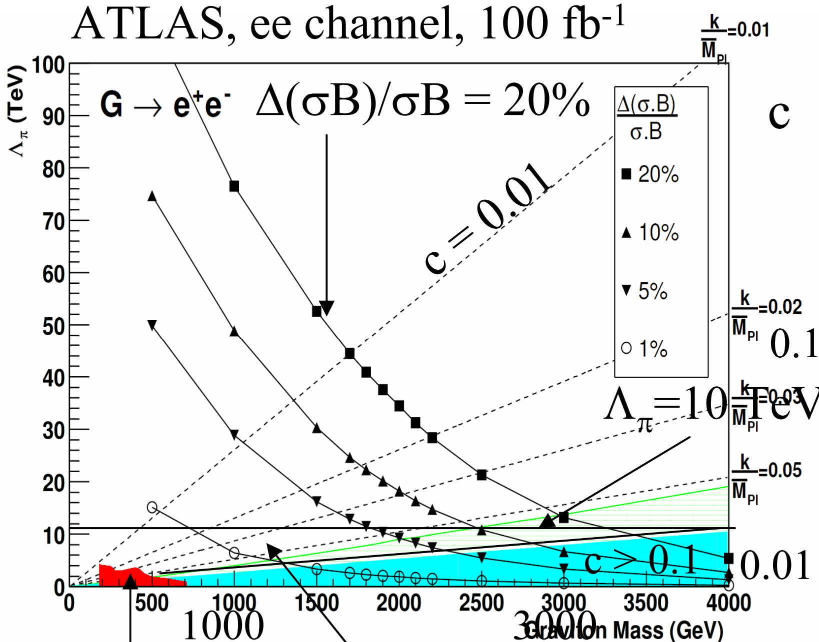


RS Graviton Reach

Channels: G → ee, μμ, γγ, WW, ZZ, jj

LHC is sensible to first three channels over all the parameter space constrained by c < 0.1 (theoretical requirement on curvature) and Λ_π < 10 TeV : (no new hierarchy)

ATLAS, ee channel, 100 fb^{-1}

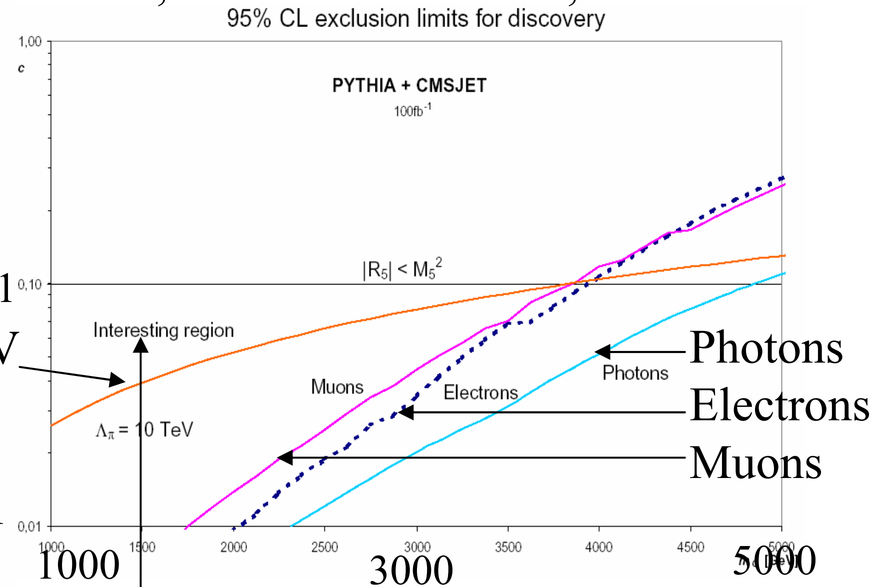


Tevatron limit

Interesting region

M_G (GeV)

CMS, 95% exclusion limit, 100 fb^{-1}

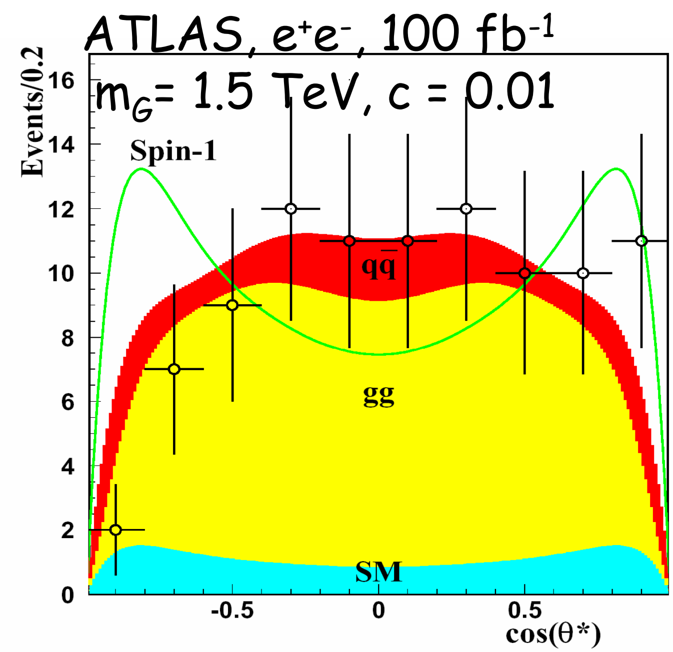


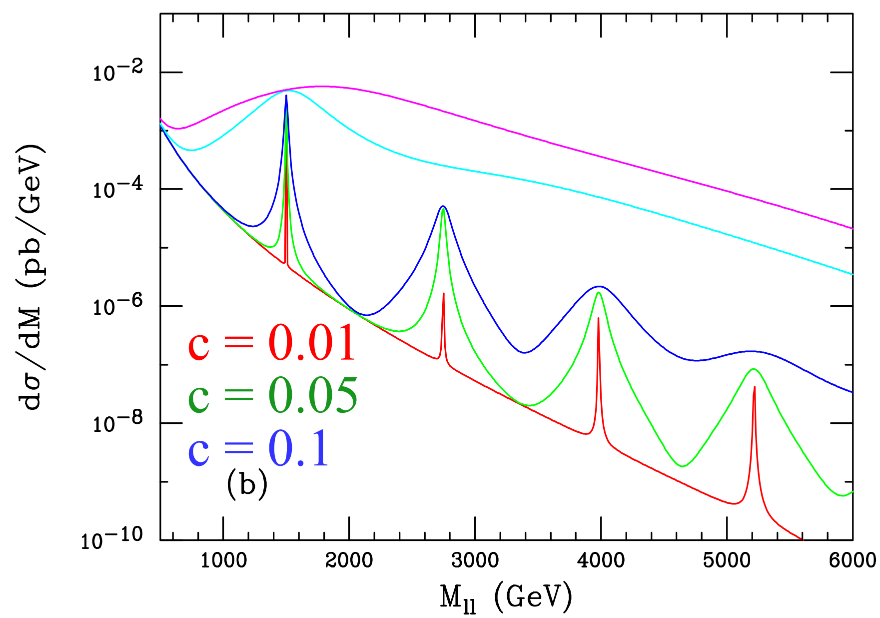
Interesting region

M_G (GeV)

RS Graviton Studies

- Model parameters from resonance mass, width and x-section
- May be possible to observe second resonance (spaced as Bessel function zeros)
- Spin measurement possible over most of parameter space (endcaps needed!)

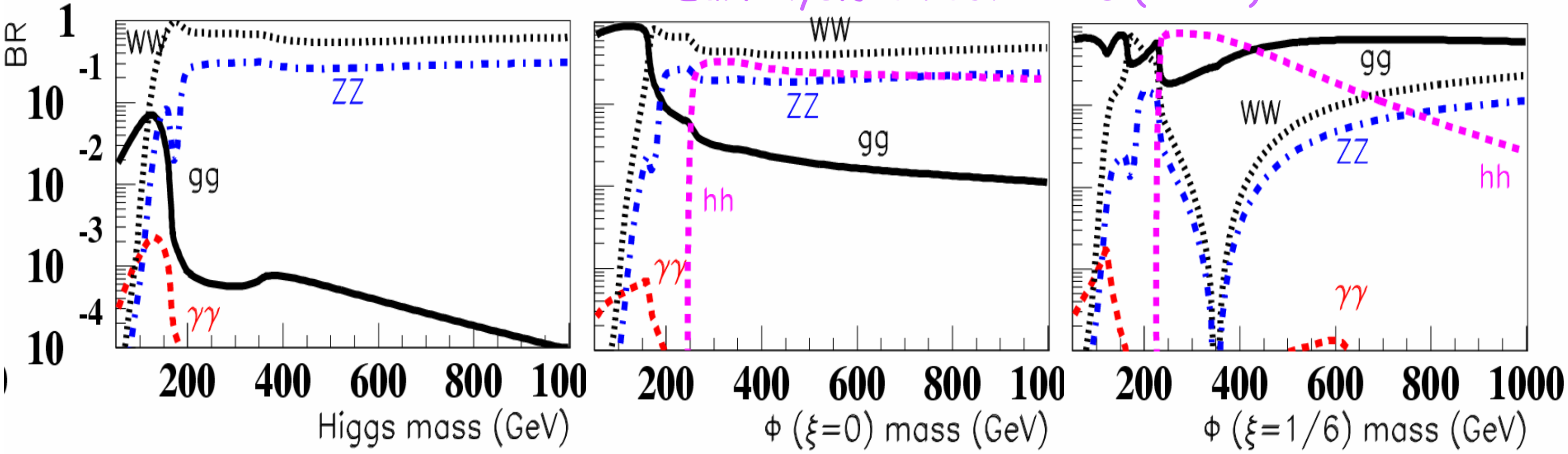




Radion

- A scalar field is introduced to stabilize the distance between branes.
- Possibly lighter than $G^{(1)}$ W.D. Goldberger, M.B. Wise, PRL **83** 4922 (1999)
- Coupling similar to Higgs, mixes with Higgs (angle ξ)
- More coupling to gluons, narrow width
- See talk of L. Fano G.Giudice, R.Rattazzi, J.D.Wells, hep-ph/0002178

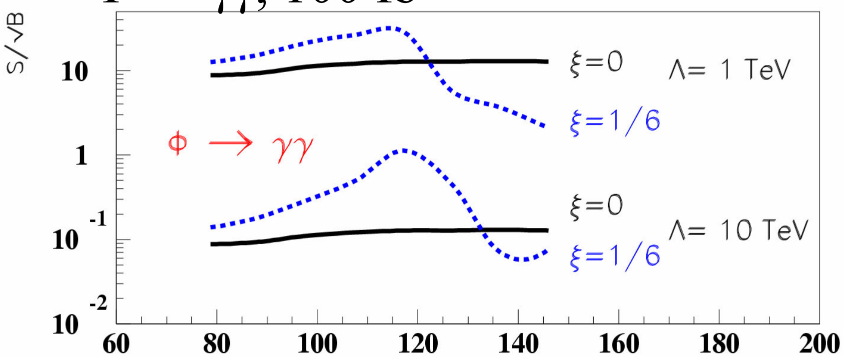
ATLAS: G.Azuelos, D.Cavalli, H.Przysiezniak,LV
Eur.Phys.J direct **C4** 16 (2002)



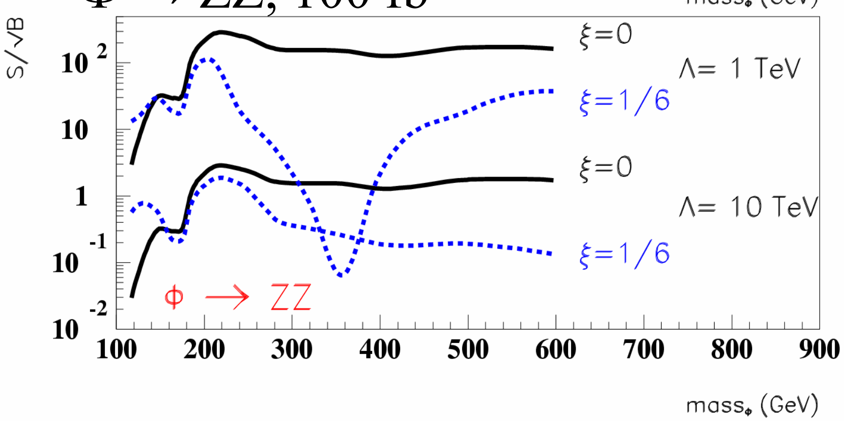
Radion searches

Again, see L. Fano talk

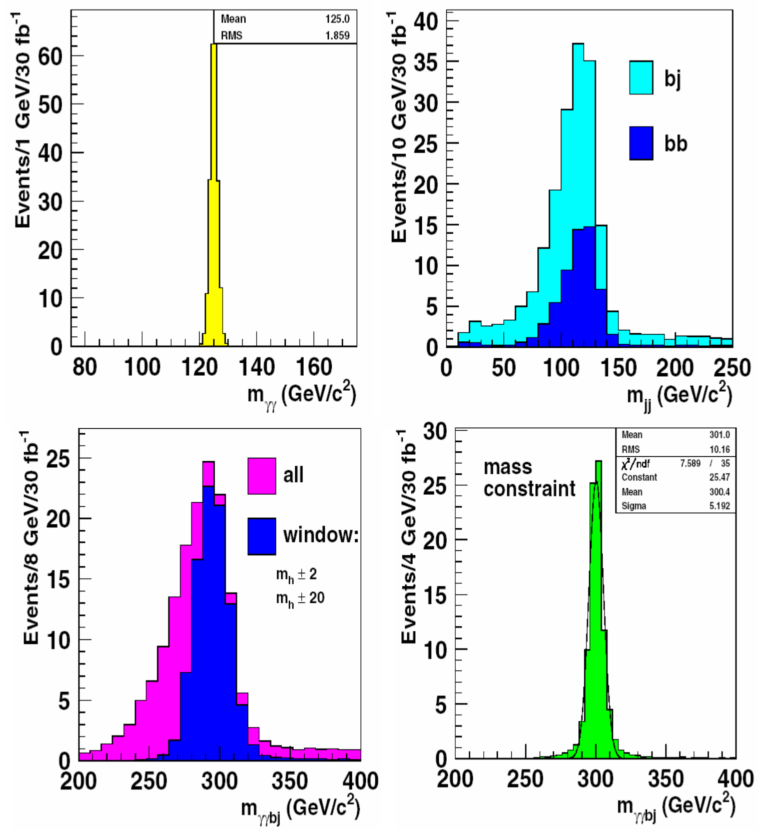
$\Phi \rightarrow \gamma\gamma$, 100 fb^{-1}



$\Phi \rightarrow ZZ$, 100 fb^{-1}



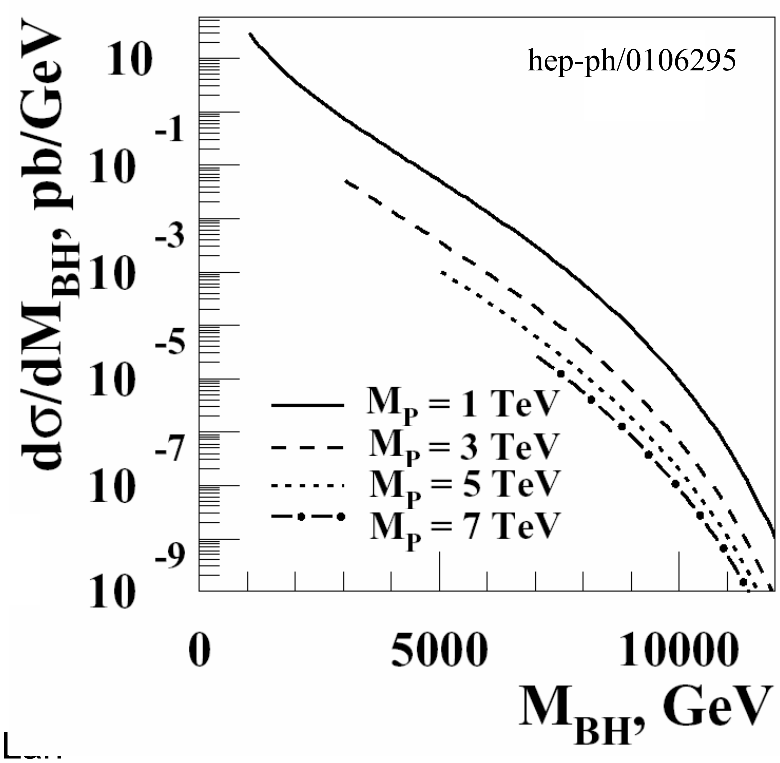
$\Phi \rightarrow hh \rightarrow \gamma\gamma bb$



Black Holes production

S. Dimopoulos and G. Landsberg, Phys. Rev. Lett. 87, 161602
S.B. Giddins and S. Thomas, Phys. Rev. D65, 056010

- When $\sqrt{s} > M_{Pl}$ (gravity scale) black hole production is possible
- $\sigma \sim \pi R_s^2$ (large, but suppressed by parton pdf)
- $\sigma_{tot} = 0.5$ nb ($M_p = 2$ TeV, $\delta=7$)
- $\sigma_{tot} = 120$ fb ($M_p = 6$ TeV, $\delta=3$)
- Uncertainties because of missing quantum gravity theory
- Decay via Hawking radiation with T ~ 100 GeV (10^{15} K)
- Multeplicity ~ 10, all particles with m << T produced with equal probability



Black Hole Events

Tag event with at least 4 jets + photon or electron → SM background small

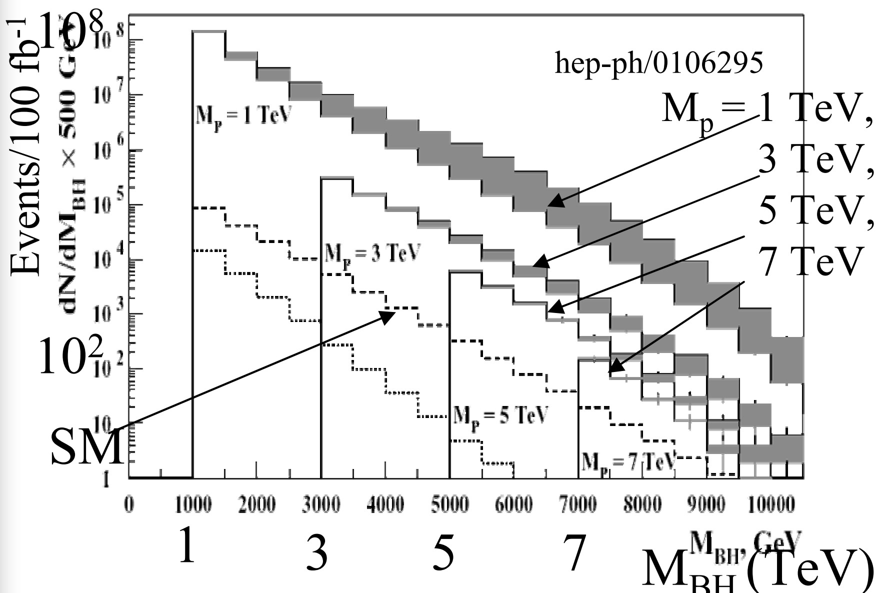
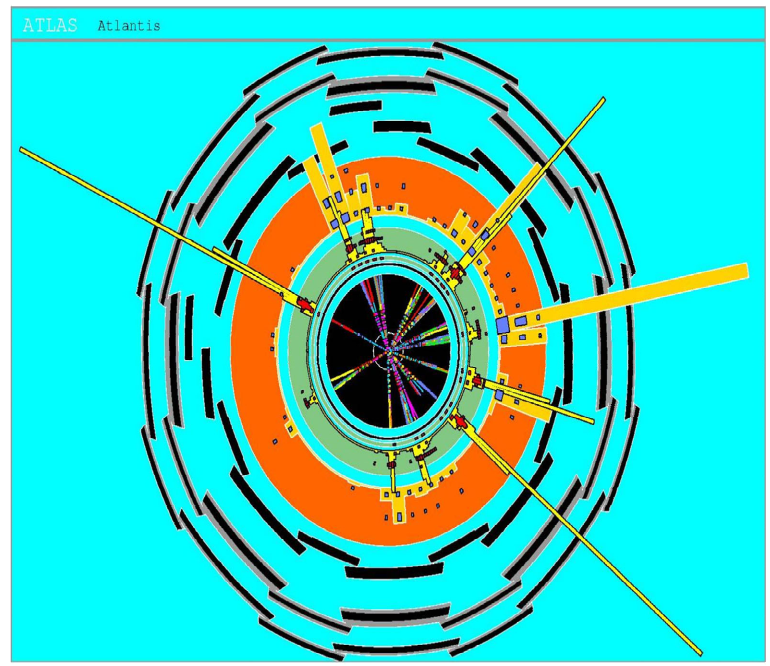


FIG. 2: Number of BHs produced at the LHC in the electron or photon decay channels, with 100 fb^{-1} of integrated luminosity, as a function of the BH mass. The shaded regions correspond to the variation in the number of events for n between 2 and 7. The dashed line shows total SM background



10 Hz @ M_p = 1 TeV
few fb @ M_p = 7 TeV

Black Holes activities

- Measure δ from T_H-M_{BH} relation: $\log(T_H) = \frac{-1}{n+1}\log(M_{BH}) + const$

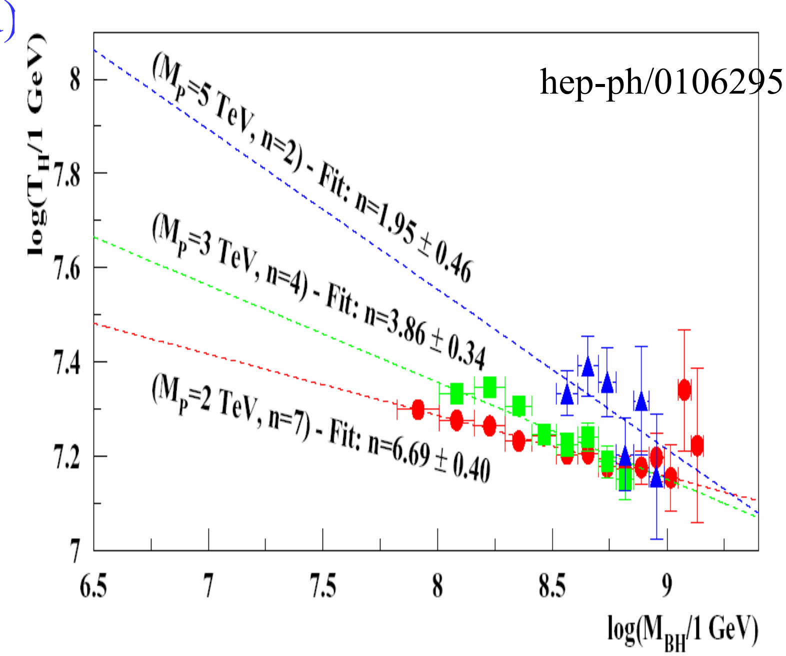
  M_{BH} measured for each event

  T_H from lepton/photon energy distribution in bins of M_{BH}

  However: affected by quantum gravity effects

- BH as factories of Higgs and other heavy particles (tag with BH signatures eliminates SM background)

  Can see a light Higgs with 1 hour statistic



Conclusions

- Models beyond the SM present a rich and exciting phenomenology
- The LHC will be able to study most of it over most of the favoured parameter space
- Many other studies not included in this talk
- Looking forward to the first data!

Backup slides

Torino, 15-04-2004

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Slide of L. Vacavant talk at EPS Aachen – Jul 03

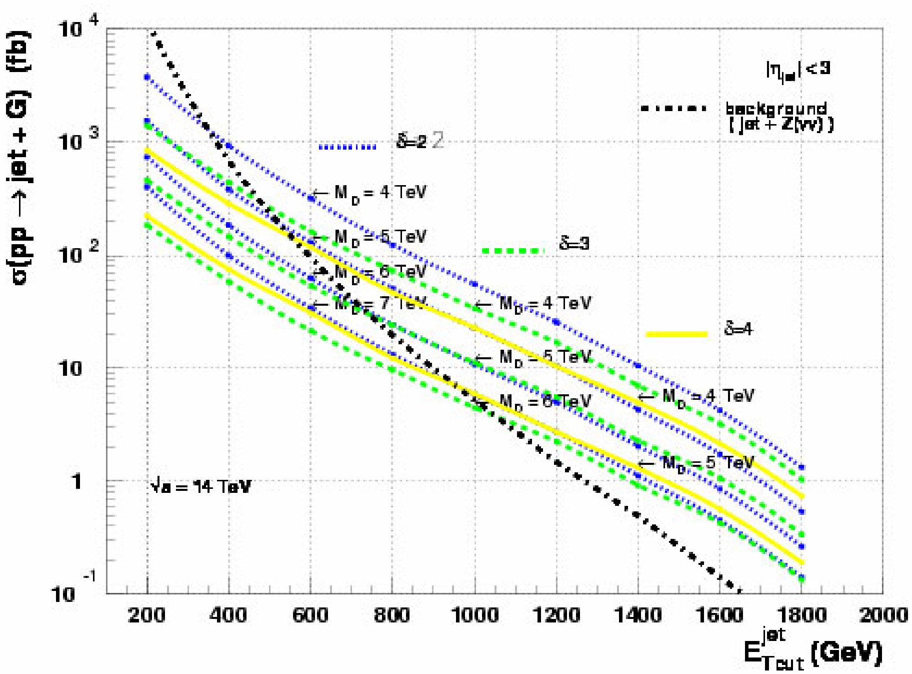
Characterization of the model: ➔ measure both M_D and δ

Precise measurement of Xsection:

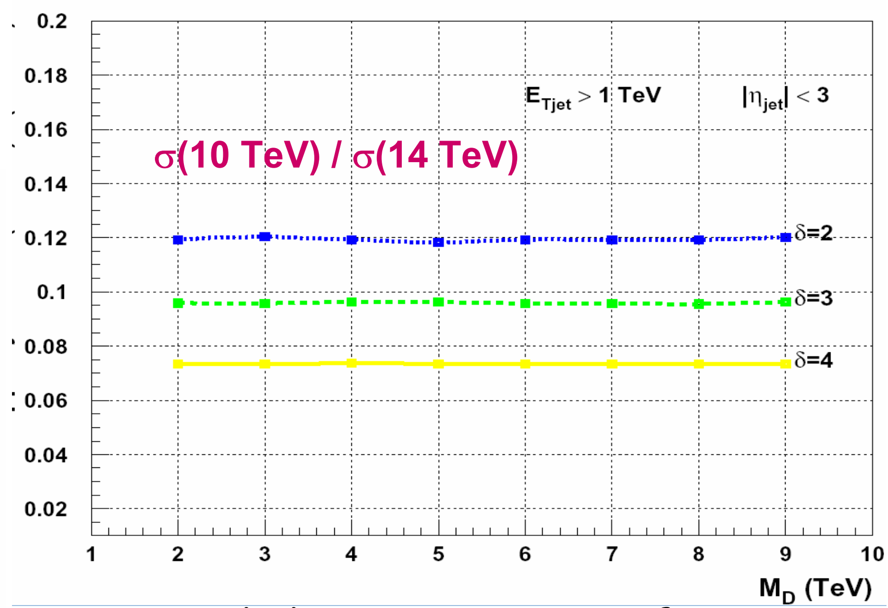
- difficult:

case (δ=2, M_D= 5 TeV) very similar to the case (δ=4, M_D= 4 TeV) for instance

- not (yet) investigated in details



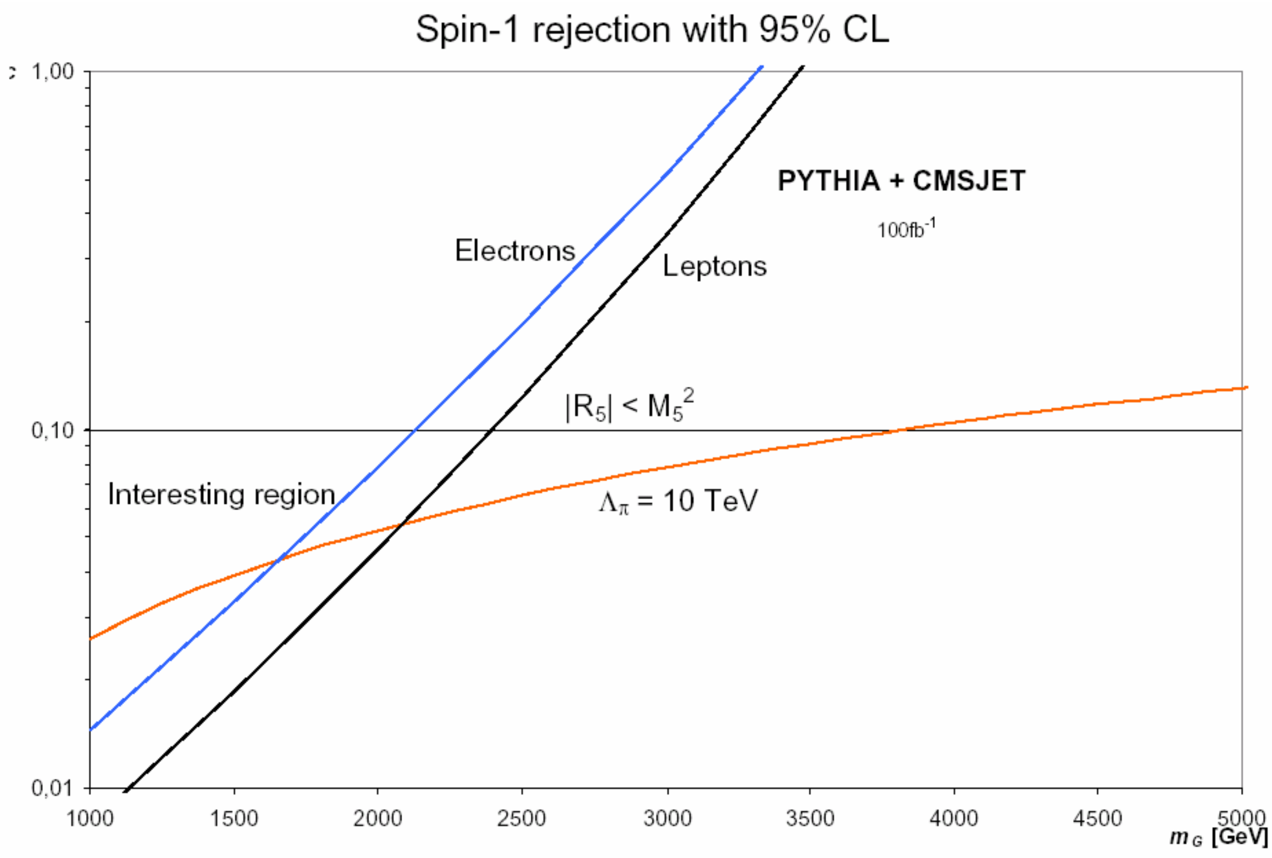
Run at a different CME:



- good discrimination if
  - 5% accuracy on $\sigma(10)/\sigma(14)$
  - > 50 fb^{-1} @ 10 TeV
- new CME close to 14 TeV

(otherwise small overlap of regions allowed by eff. theory)

CMS spin-1 rejection



Torino, 15-04-2004 T. Lari

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