Beyond Standard Model

L. Poggioli, LAPP

- Introduction
- Strong Symmetry Breaking
- Extra Dimensions
- Compositeness
- New particles
- Other

Introduction

- ✓ Hierarchy problem
  - SUSY : See Lecture # 2
  - Strong Symmetry Breaking
    - New strong interactions ~ 1 TeV
  - Extra Dimensions
    - Gravity scale brought down to ~ 1 TeV
  - Little Higgs
    - Composite H with compositeness scale ~ 10 TeV
- ✓ Possible new physics
  - Excited fermions, contact interactions
- ✓ Extension of EW gauge group
  - New gauge Bosons
- ✓ Unexpected

Strong Symmetry Breaking

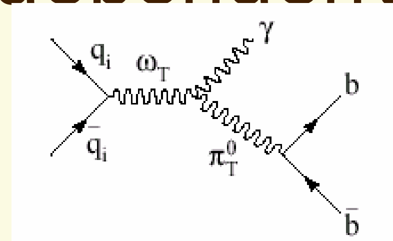
- Technicolor
- Chiral Lagrangian Model

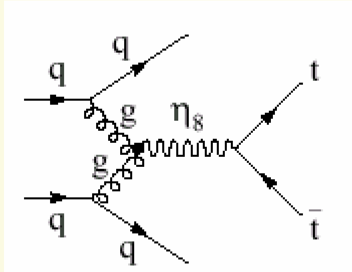
Technicolor (1)

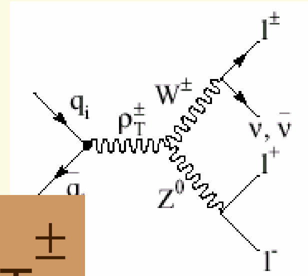
- ✓ New strong interaction O(TeV) with Techniquarks condensates -> EWSB
- ✓ Pros
  - Solves hierarchy problem(no fund. scalar)
- ✓ Cons
  - No account for fermion masses (ETC ?)
  - In conflict with S,T @ LEP (Walking TC ?)
- ✓ Predictions
  - Technimesons resonances in $W_L W_L$ and $W_L Z_L$ scattering

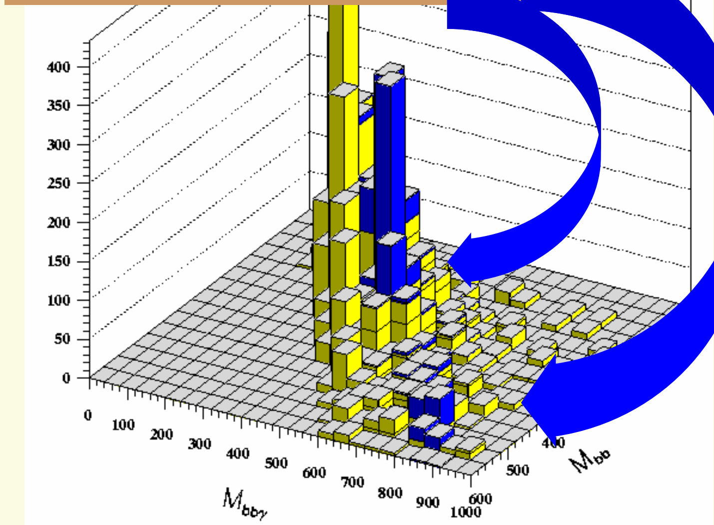
Technicolor (2)

- ✓ ω_T, $\rho_T^{\pm}$, $t\bar{t}$ (mass spectra model dependent)



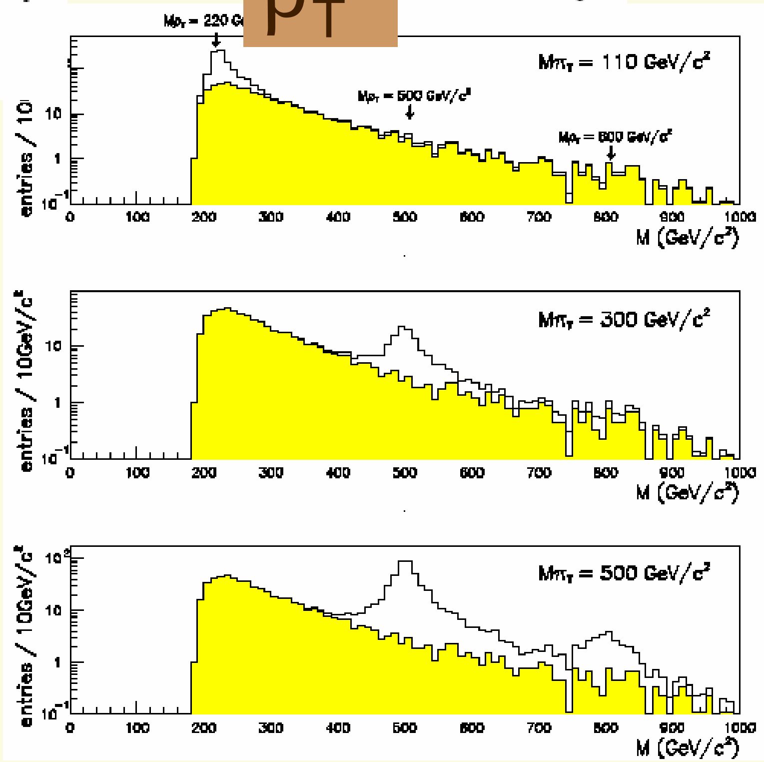






m(ω_T,π_T) = (800, 500)
(500,300)

$\rho_T^{\pm}$



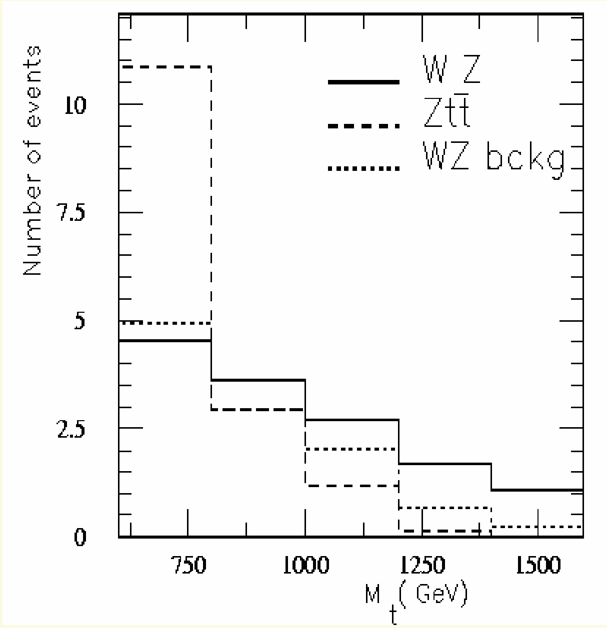
Chiral Lagrangian Model

✓ Based on Chiral Perturbation Theory

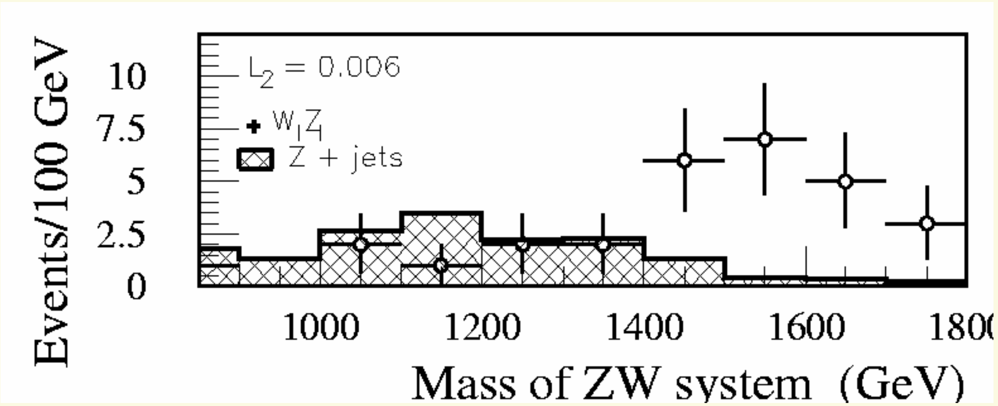
✓ Use Inverse Amplitude Method with 2 parameters L1 & L2

– Non-Resonant scattering

– Resonant scattering



$W_L^{\pm} Z_L \rightarrow W_L^{\pm} Z_L \rightarrow l\nu ll$



$qq \rightarrow W_L Z_L \rightarrow l\nu jj$

Cf. Anomalous TGC

Extra Dimensions

- Large extra dimensions
- Small extra dimension
- Randall-Sundrum model
- Universal extra dimensions
- Black Holes

Introduction

- ✓ Large extra dimensions (>> 1/TeV)
  - ADD model (Arkani, Dimopoulos, Dvali)
  - SM particules in brane
  - Gravity propagates in bulk (Xtra Ds)
    - Hence new gravity scale $M_{PL}^2 \sim M_D^{2+\delta} R^\delta$
    - KK graviton excitations $M_D \sim$ TeV for $R <$ mm
- ✓ TeV^{-1} Xtra Ds
  - KK excitation of SM gauge fields

KK: Kaluza-Klein

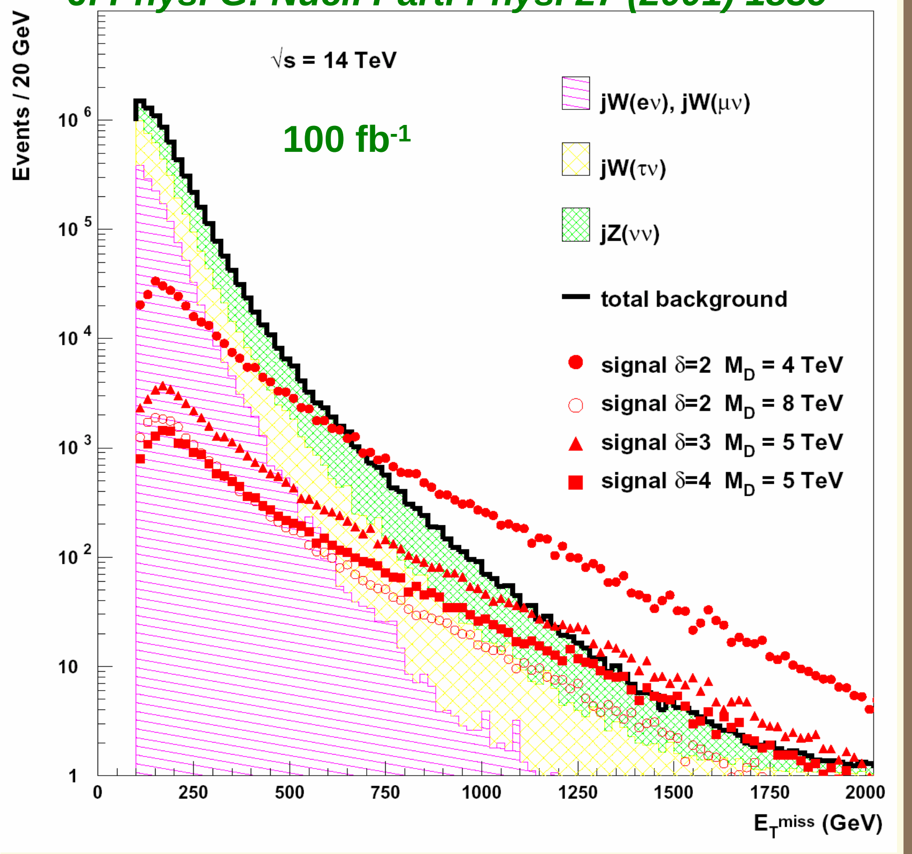
- ✓ Randall-Sundrum : 1 small Xtra D
  - Warped metric
  - Narrow Graviton resonance
  - Radion

ADD: Graviton emission

✓ Process

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

L. Vacavant and I. Hinchliffe,
J. Phys. G: Nucl. Part. Phys. 27 (2001) 1839



✓ Reach

– gG

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

– γG

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

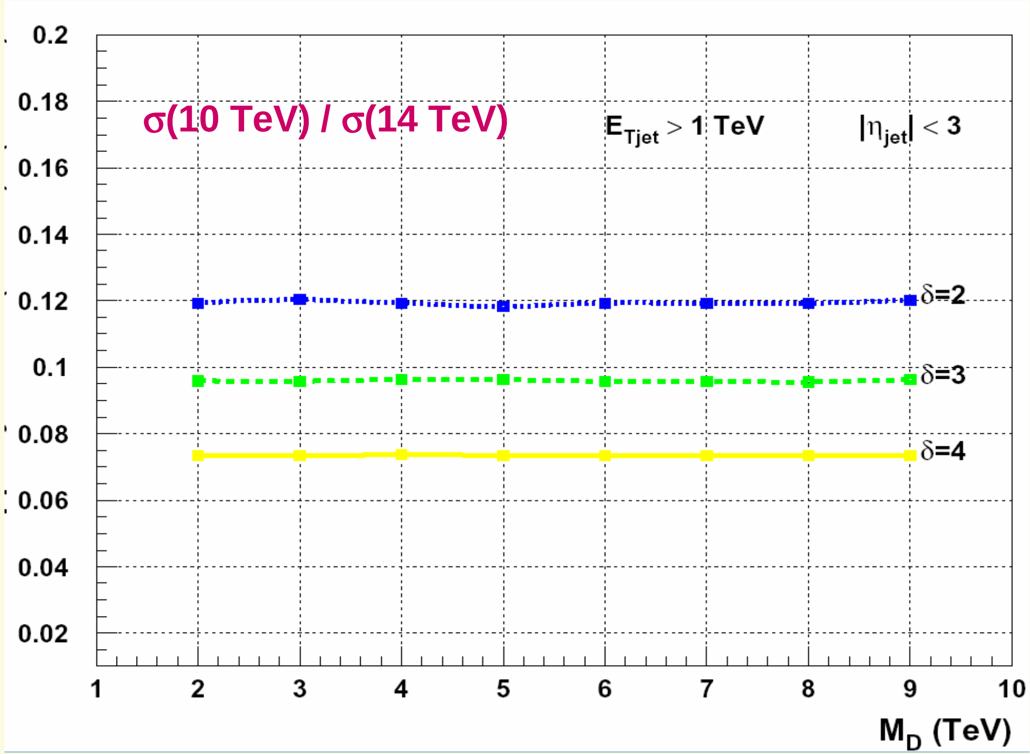
Background calibrated by Z j -> ll j

ADD: Graviton emission

✓ Disentangling M_D and δ

– Run LHC @ 2 energies

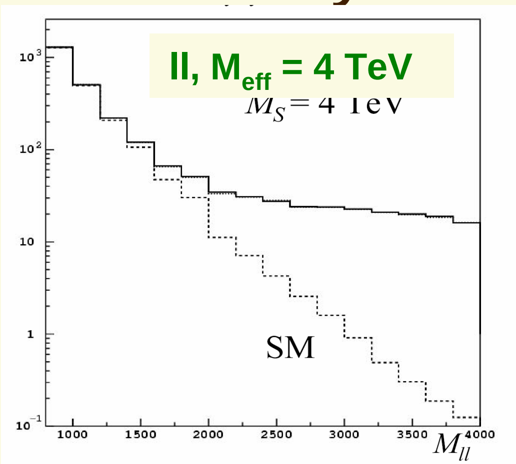
– **50 fb^{-1}** necessary

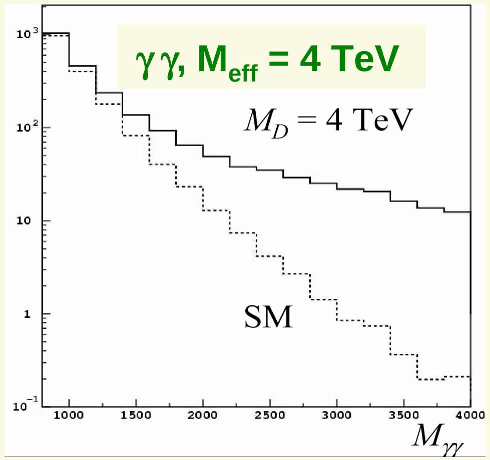


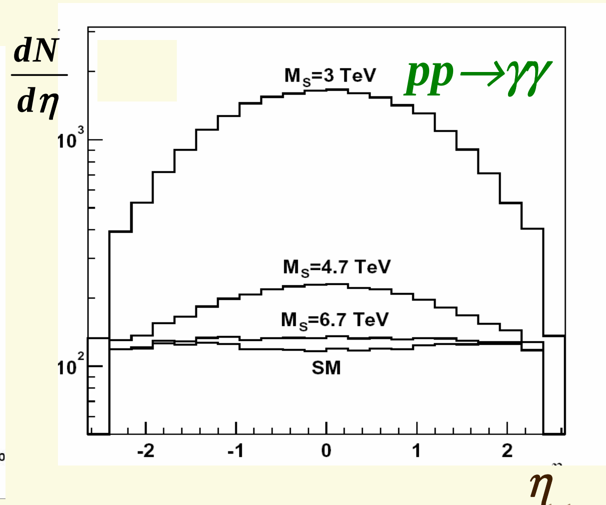
ADD: Virtual Graviton

- ✓ Final state $q\bar{q}, gg \rightarrow \gamma\gamma, \ell\ell, \quad (WW, t\bar{t} \ldots)$
  - Use effective scale M_s (σ diverges if $\delta \geq 2$)
- ✓ Observables
  - Excess in ll & $\gamma\gamma$
  - $\gamma\gamma$ more central than SM
  - PDF systematics

reach: $\begin{cases} \ell\ell: & M_S \sim 5.1 \text{ TeV} \\ \gamma\gamma: & M_S \sim 6.6 \text{ TeV} \end{cases}$







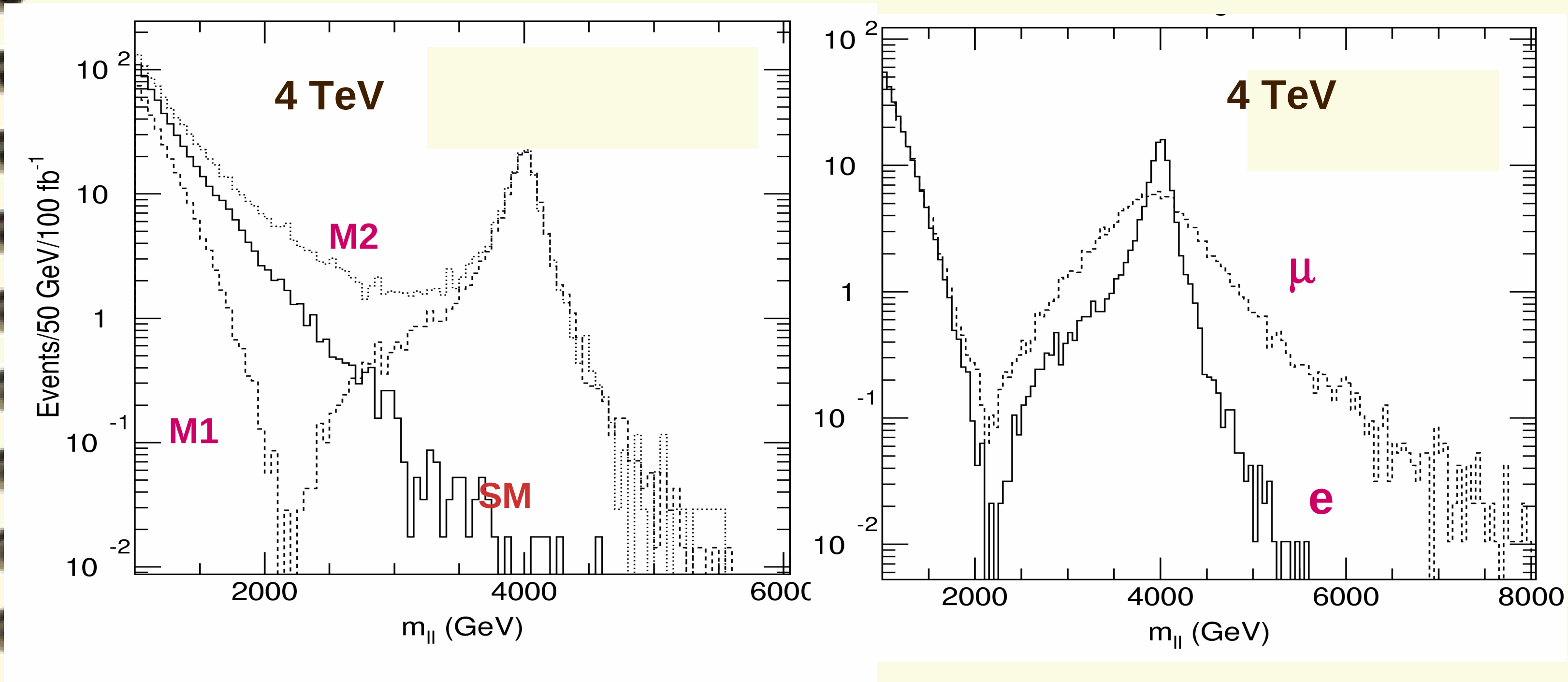
TeV^{-1}: Introduction

- ✓ Compactification radius small enough to allow SM in bulk
  - e.g $R = \hbar c / 1\ \mathrm{TeV}^{-1} = 2\times 10^{-4}$ fm $[M_D$ □ 10^{15} GeV pour $n=1]$
- ✓ Indirect constraints from LEP EW
  - $R^{-1} > 3.9 - 6.8$ TeV   Rizzo, Cheung, Landsberg
- ✓ Model (T. Rizzo)
  - 1 X Dim $m_k^2 = m_0^2 + k^2 M_C^2 \approx k^2 M_C^2$
  - Gauge Bosons & H in bulk
    - Coupling to fermions $\times\sqrt{2}$
  - Dilepton resonances from $\gamma^{(1)} / Z^{(1)}$

TeV^{-1}: Direct $\gamma^{(1)}/Z^{(1)}$

✓ Compactification radius small enough to allow SM in bulk

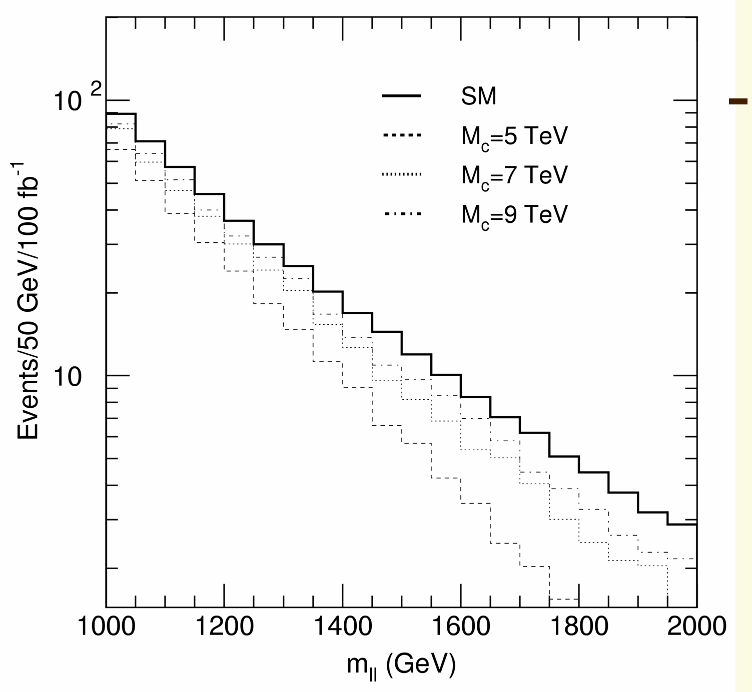
– Look at resonance in ll spectrum



– Observation up to ~ 6 TeV with 100 fb^{-1}

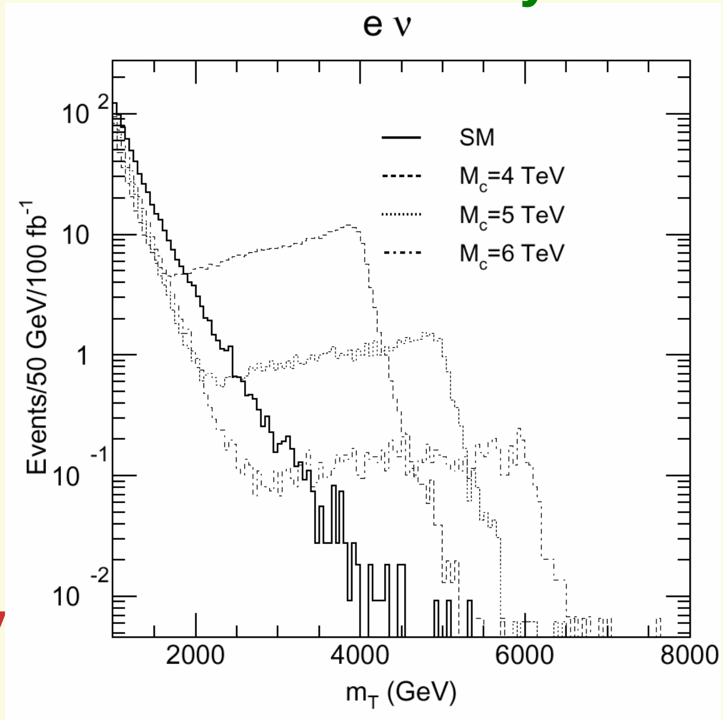
TeV^{-1}: Drell-Yan, W$^{(1)}$

✓ Drell-Yan tail



- Reach ~ 10 TeV
- Large systematics

ATLAS Preliminary

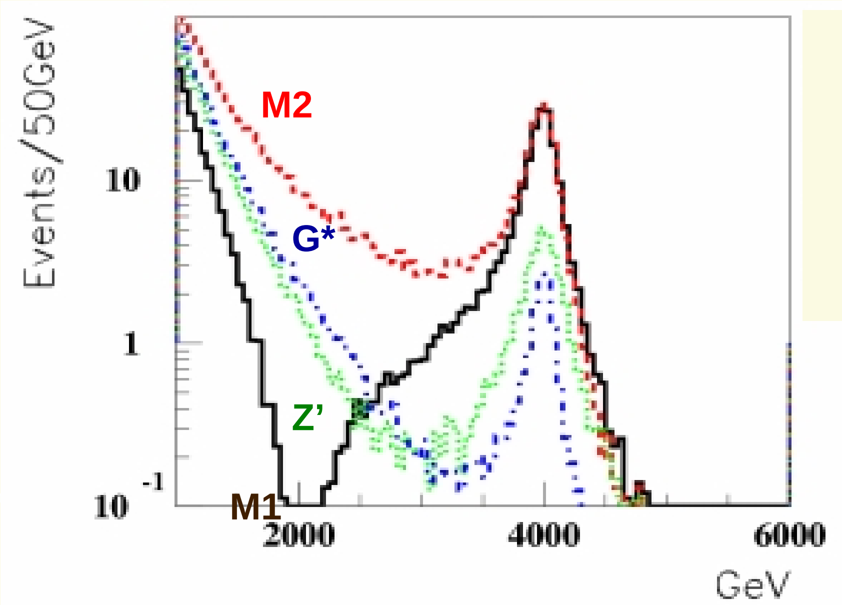


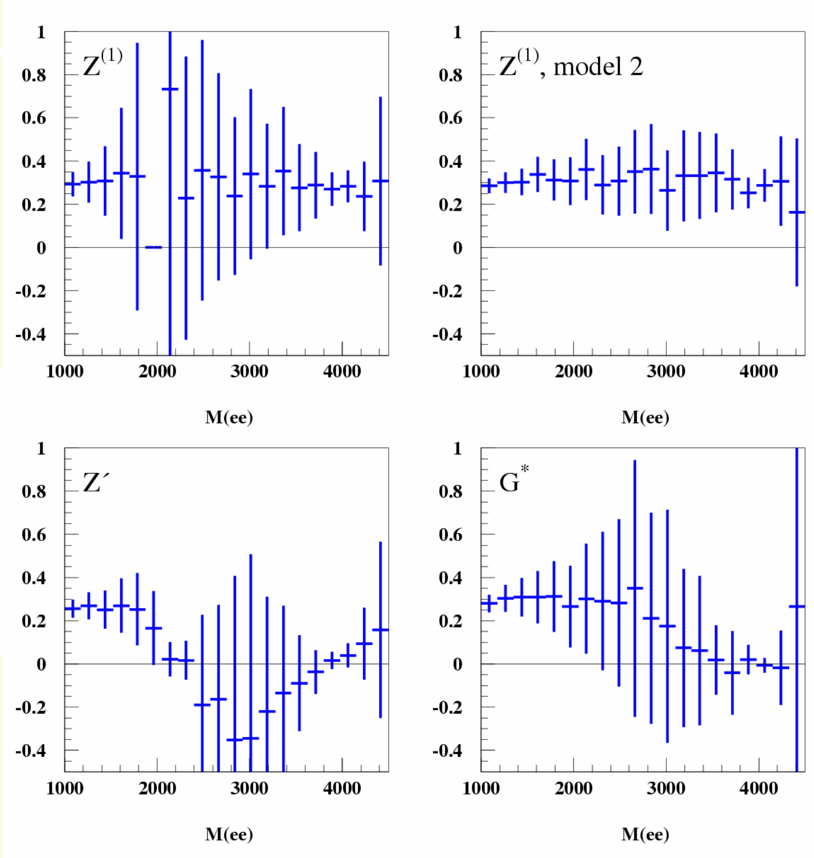
✓ Also W$^{(1)}$

– Direct reach ~ 6 TeV

TeV^{-1}: Asymmetry

- ✓ Look at Forward-Backward asymmetry





- ✓ Model discrimination

Randall-Sundrum

✓ Motivation

– 2 branes (Ours & Planck scale's) connected by 1 warped ED

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

– Coupling of KK states ~ $1/\Lambda_\pi$

$$\Lambda_\pi = M_{pl}e^{-kr_c\pi}; \qquad kr_c\pi \quad 35 \Rightarrow \Lambda_\pi \quad \text{TeV}$$

– Graviton excitations

$$m_n = kx_n e^{-k\pi r_c}, \quad \text{avec} \quad J_1(x_n) = 0$$

$$m_1 = 3.83\frac{k}{M_{Pl}}\Lambda_\pi$$

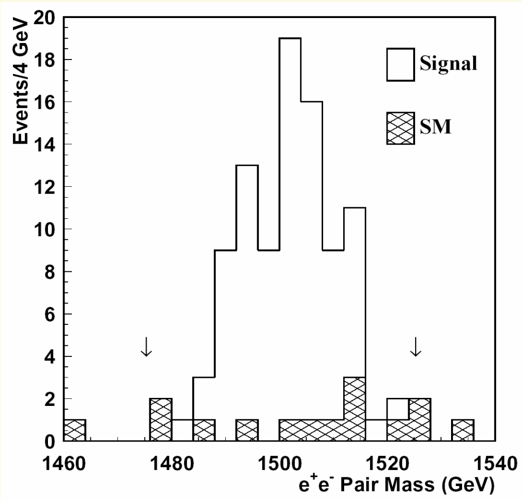
– Constraints

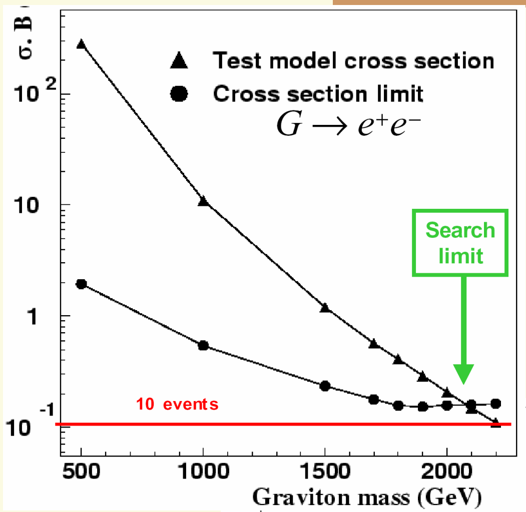
$0.01 < k/M_{pl} < 0.1$

RS: Graviton resonance

✓ Narrow Graviton resonance

$G^{(1)} \rightarrow e^+e^-, \mu^+\mu^-, \gamma\gamma, (WW, ZZ, t\bar{t})$

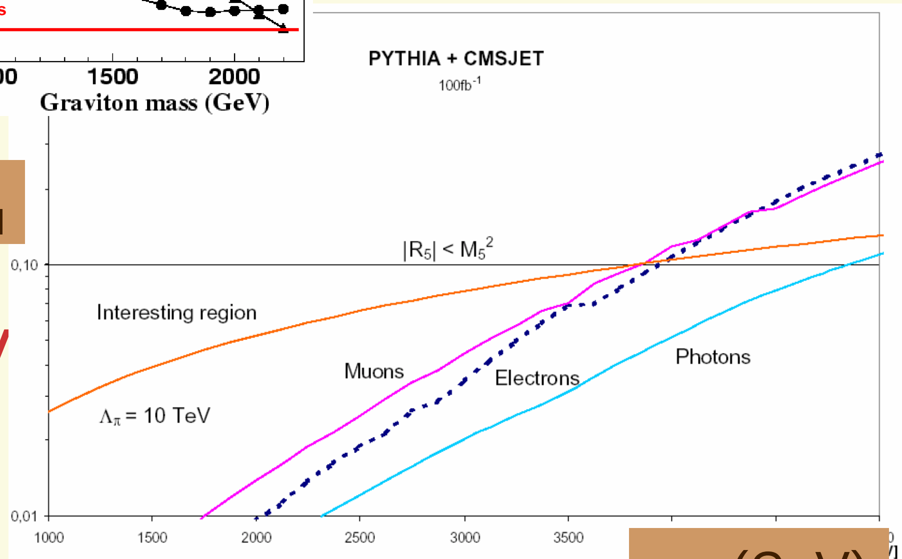




✓ Reach

– Range ~ 2-4 TeV

k/M$_{Pl}$

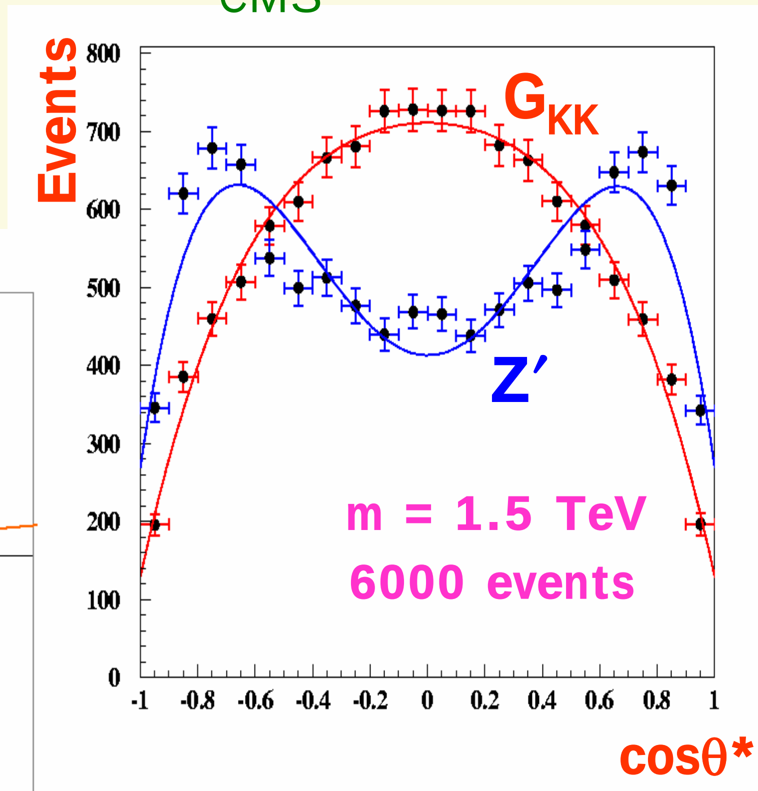


m$_G$ (GeV)

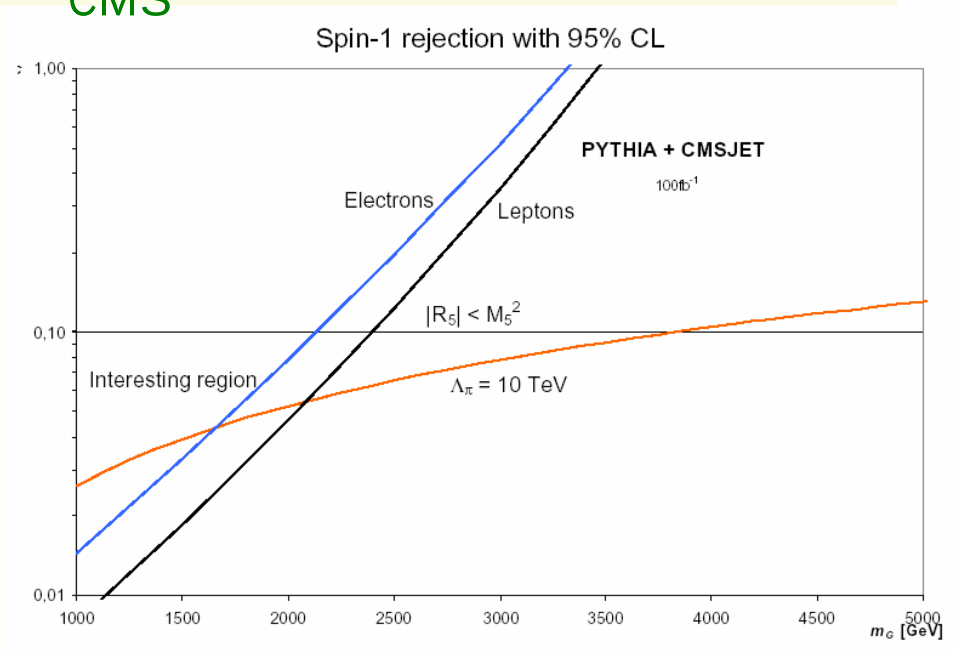
RS: Graviton Spin

- ✓ Look at angular distribution
  - 90% exclusion of spin-1 for m_G < 2.3 TeV

CMS



CMS



Radion (1)

✓ Motivation

– Scalar field representing fluctuations of the distance of the 2 branes

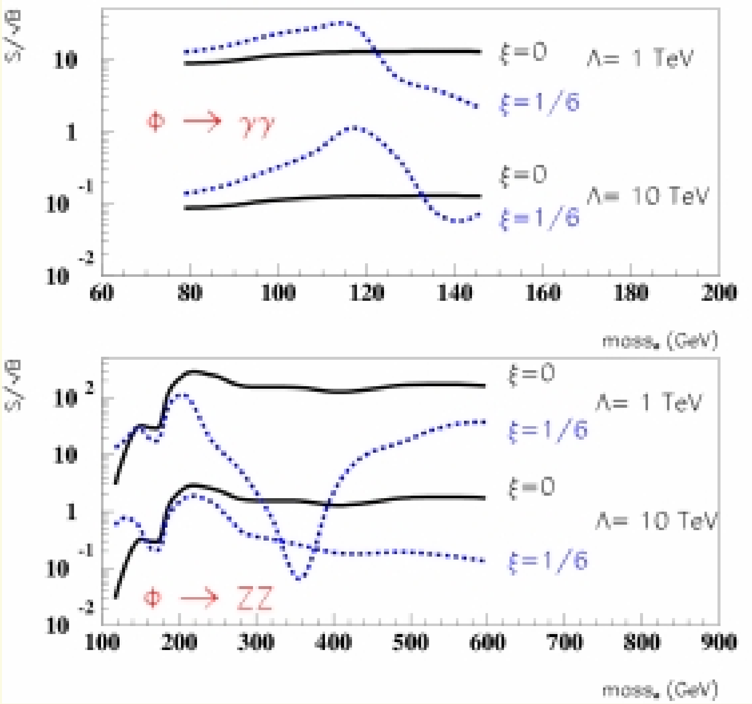
– To stabilize $kr_c\pi \sim 35$ (Golberger & Wise)

✓ Radion properties

– Higgs-like couplings

– Mixing to Higgs ξ

✓ Signal $\phi \rightarrow \gamma\gamma,\ \ \phi \rightarrow ZZ$

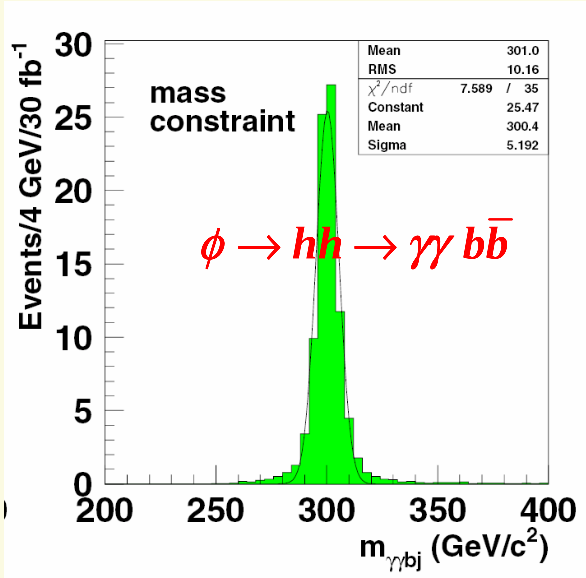


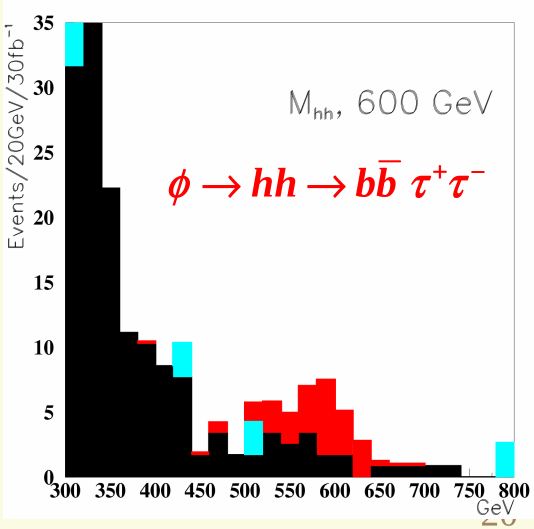
Radion (2)

- ✓ Other signals
  - $\phi \to hh \to \gamma\gamma\, b\bar{b}$

ξ	Λ_ϕ (TeV)	m_ϕ=300	m_ϕ=600
0	1	4	43
0	10	333	-
1/6	1	2	57
1/6	10	250	-

Required luminosity (fb^{-1}) for 5σ discovery



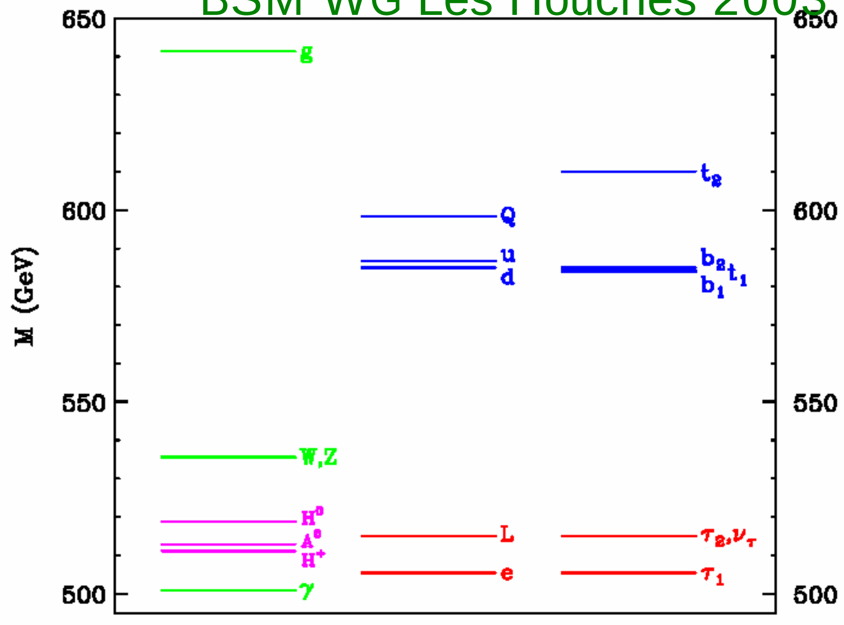


- ✓ Discrimination Higgs/Φ
  - Difficult at LHC
  - Look at Γ & BR mods (Rizzo et al)

Universal ED

- ✓ Idea
  - All particles are in the bulk
  - Conserved KK number $m_n^2 = an^2 + m^2$
  - Radiative mass splittings
  - Can fake SUSY
- ✓ Disentangle ?
  - Assess feasibility at LHC
  - Undertaken in Les Houches

BSM WG Les Houches 2003



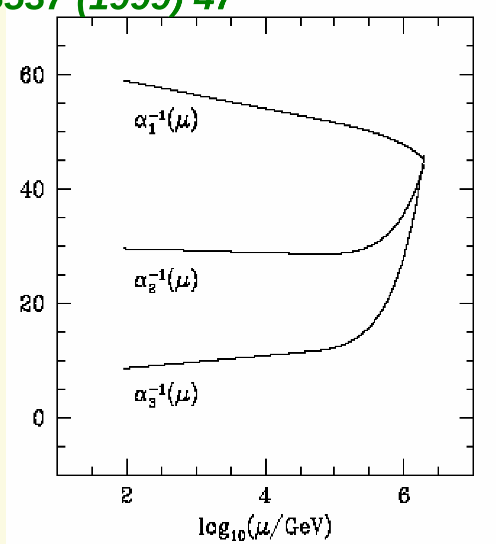
Universal ED (2)

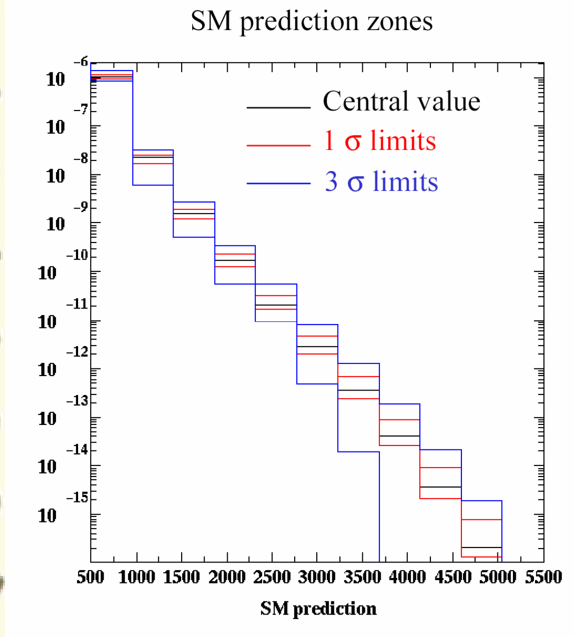
- ✓ jj+E_t^{miss} from $q\,q \rightarrow q^{\bullet} q^{\bullet} \rightarrow qG\,qG$
  - Difficult
- ✓ KK excitation of q and g decay down to LKP (Lightest KK Particle) γ^*
  - LKP stable jj+ E_t^{miss} *TOUGH*
  - LKP not stable $\gamma\gamma + E_t^{miss}$
    - $\gamma^* \rightarrow \gamma\, G$
    - If γ^* heavy, large p_T (γ)
    - Separation with SM background easier
    - Under implementation in COMPHEP

Coupling Unification at TeV

- ✓ KK states affect running of gauge couplings
  - – Above 1/R power law
- ✓ Dijet cross-section

K.R. Dienes, E. Dudas and T. Gherghetta, *Nucl.Phys. B537 (1999) 47*





-Sensitivity of deficit in jet cross section, ~ 10 TeV, at parton level

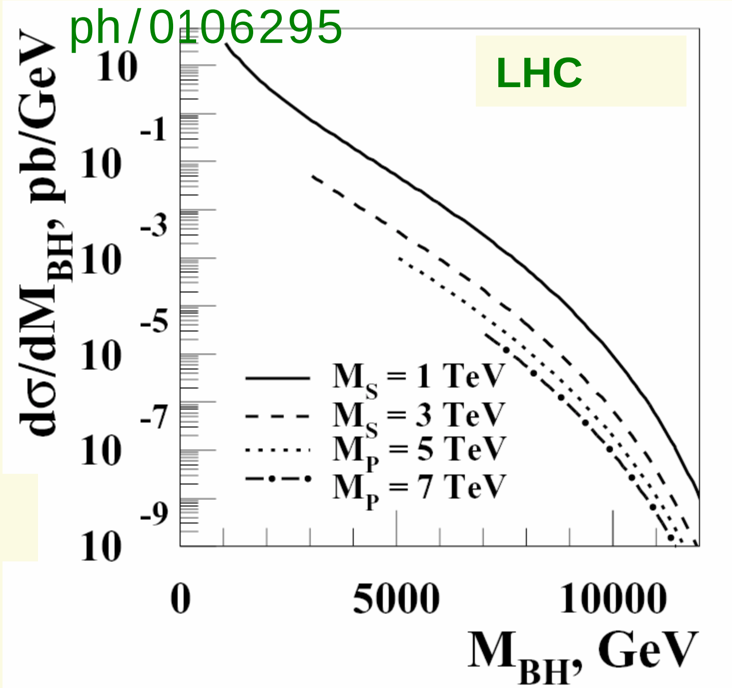
-PDF uncertainties limit reach to 1 TeV

Black Holes (1)

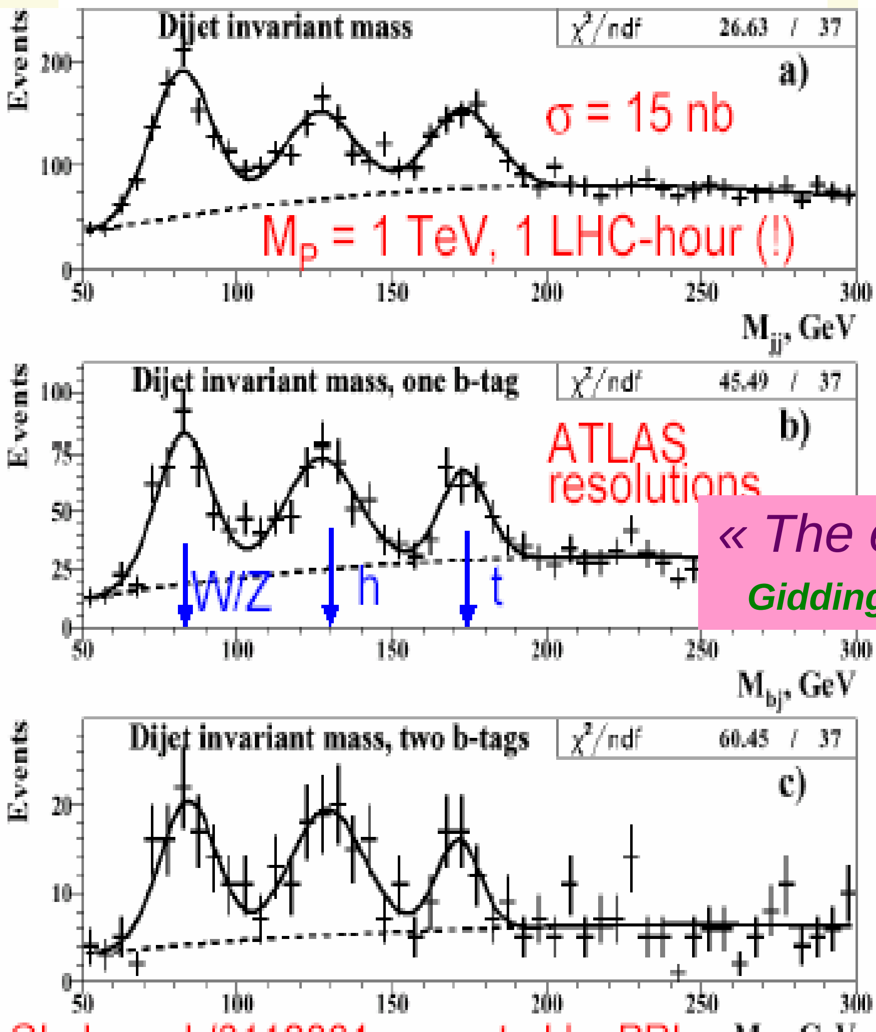
- ✓ Motivation
  - Object confined in R < R_s
- ✓ Features
  - T is mass dependent
  - Black body radiation
- ✓ Uncertainties
  - Cross-section
  - Decays
    - Various phases

Implementation in Herwig & simulated in ATLAS

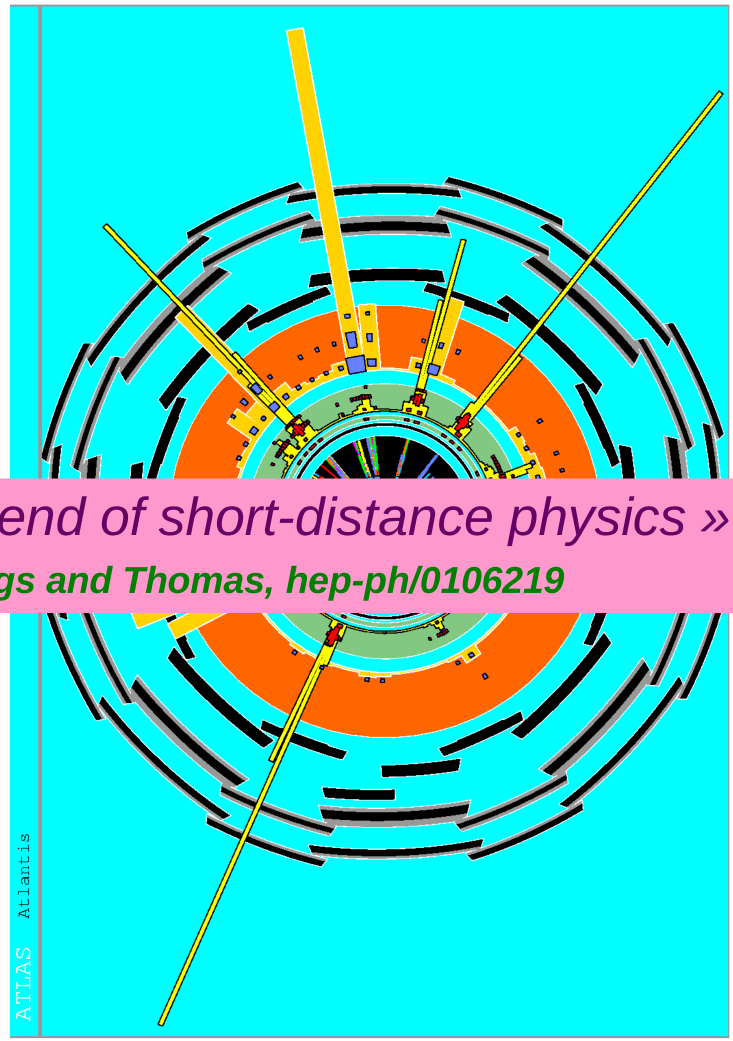
Dimopoulos et Landsberg, hep-ph/0106295



Black Holes (2)



GL, hep-ph/0112061, accepted by PRL



« The end of short-distance physics »

Giddings and Thomas, hep-ph/0106219

Compositeness

- Excited quarks and leptons
- Deviation to QCD

Introduction

✓ Motivation

– Fermionic generation explained by compositeness

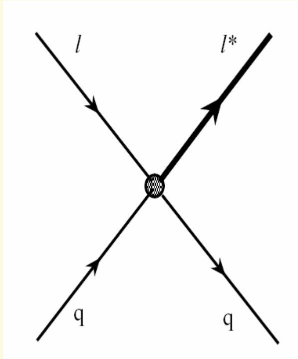
– Quarks & leptons: bound states of 3 fermions or 1 fermion + 1 boson

✓ Interaction

– Contact interactions – Scale Λ

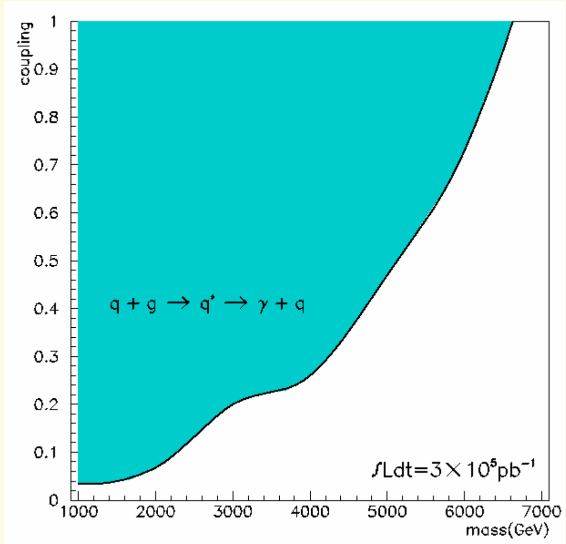
– Spectrum of excited states

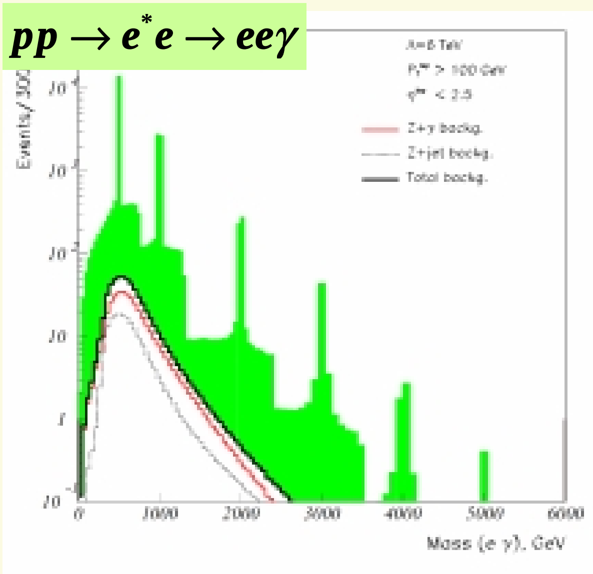
– Deviation to QCD

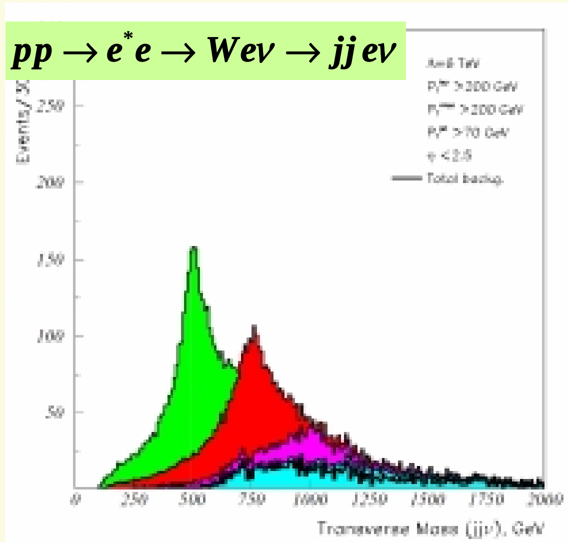


Excited quarks & leptons

- ✓ Excited quarks
  - Reach limit for q* -> q γ
- ✓ Excited leptons
- ✓ **Reach: ~ 1 – 4 TeV for Λ = 6 TeV, 300fb^{-1}**

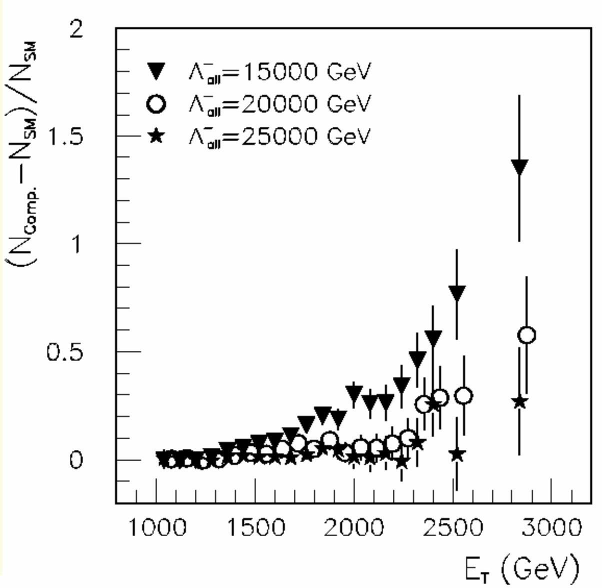


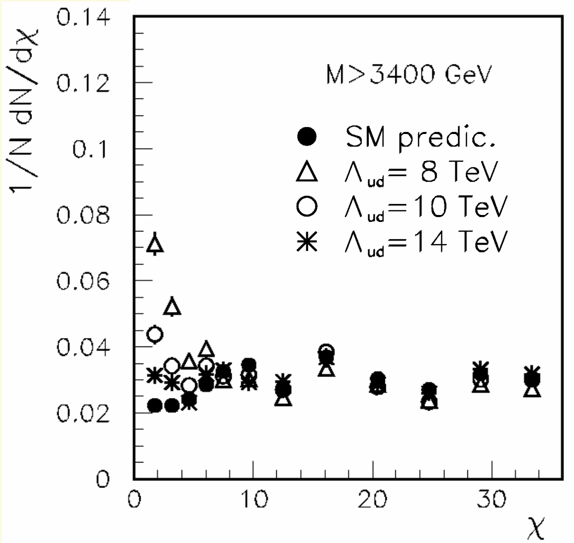




Deviation to QCD

- ✓ Look at high P_T di-jets
  - – Sensivity in E_T distribution
- ✓ Systematics
  - – Non-linearities under control
  - – Structure functions
- ✓ Angular distribution in cms
  - – $\chi = (1+\cos\theta^*)/(1-\cos\theta^*)$
  - – Need high mass
  - – Access to Λ



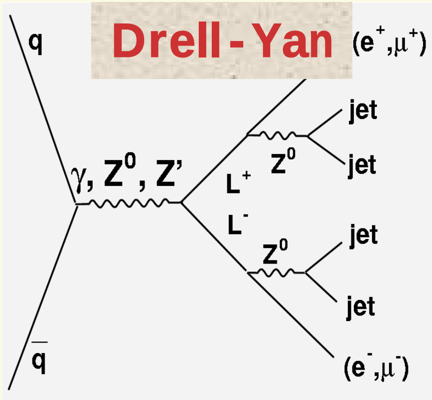


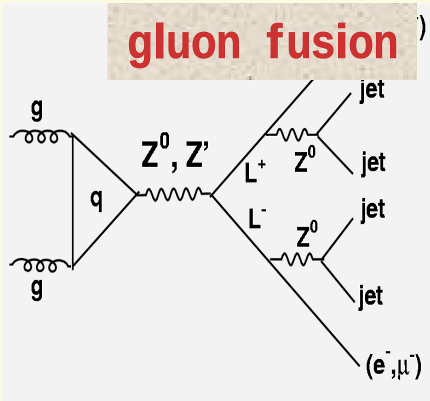
New particles

- Heavy leptons
- New gauge bosons
- Leptoquarks

Heavy Leptons (1)

- ✓ Basics
  - Look at sequential lepton: 4^{th} family
  - Other models: VSM, VDM, FMFM
  - Final state llZZ
- ✓ Analysis
  - gg & DY
  - 2l, 2Z (4jets)
  - Bdg: tt, VV+jets



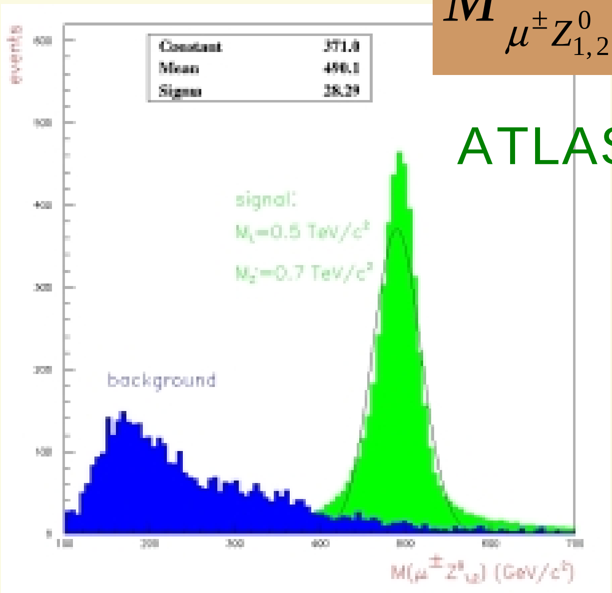


Heavy Leptons (2)

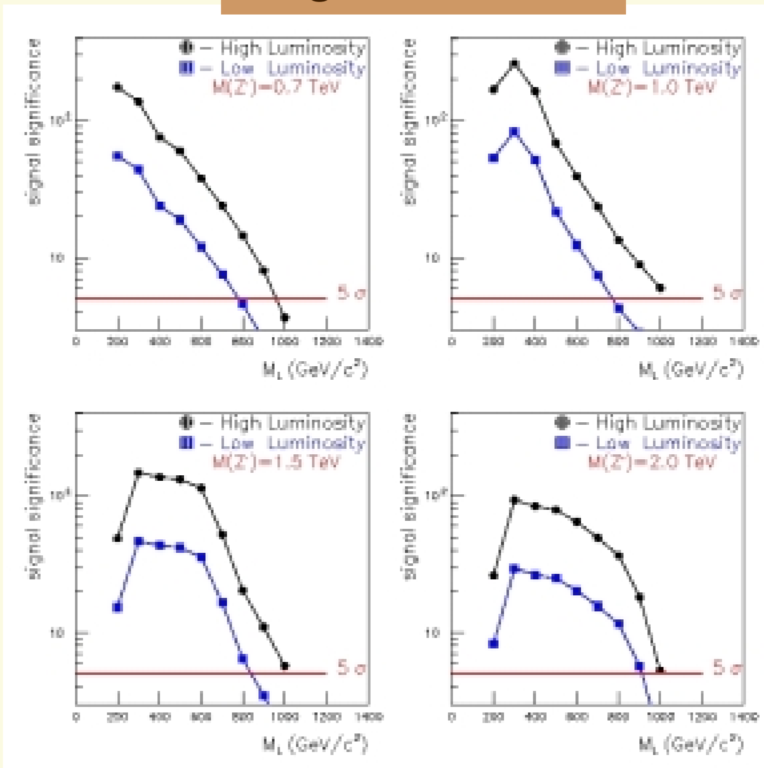
✓Yield

$M_{\mu^{\pm}Z^{0}_{1,2}}$ **distribution for L→ μ Z⁰**

ATLAS



Significance



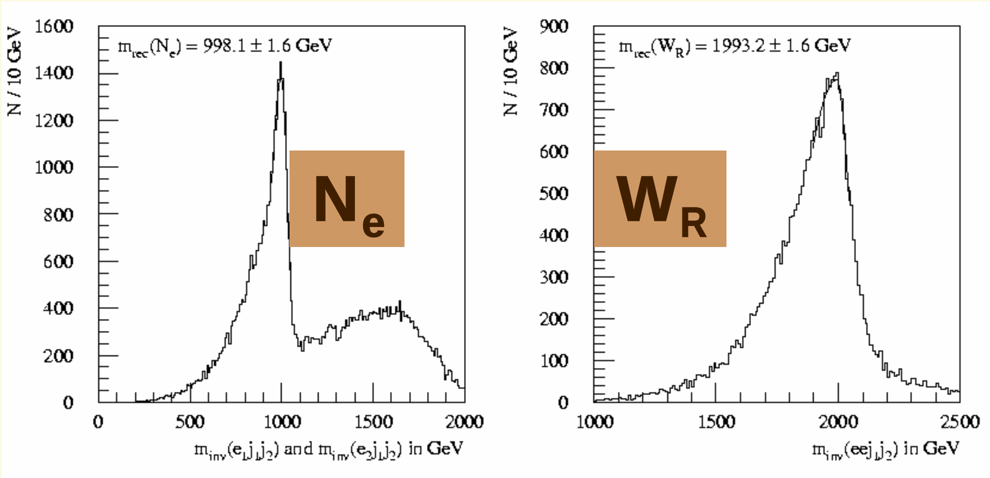
✓Reach

– ~ 1 TeV (e & μ)

– Depend on Z' mass

New Gauge Bosons (1)

- ✓ Models
  - – Breaking of larger group E6
  - – Left-Right Symmetric Model
    - Restores parity symmetry @ high energy
    - Introduces W^+_R, W^-_R, Z', R-handed ν Ne
- ✓ W_R & Ne
  - $pp \to W_R \to eN_e \to eeW^*_R \to ee{+}q_iq_j$
  - – Reach **300 fb^{-1}**
    $m_{WR} > 4$ TeV
    $m_{Ne} > 6$ TeV

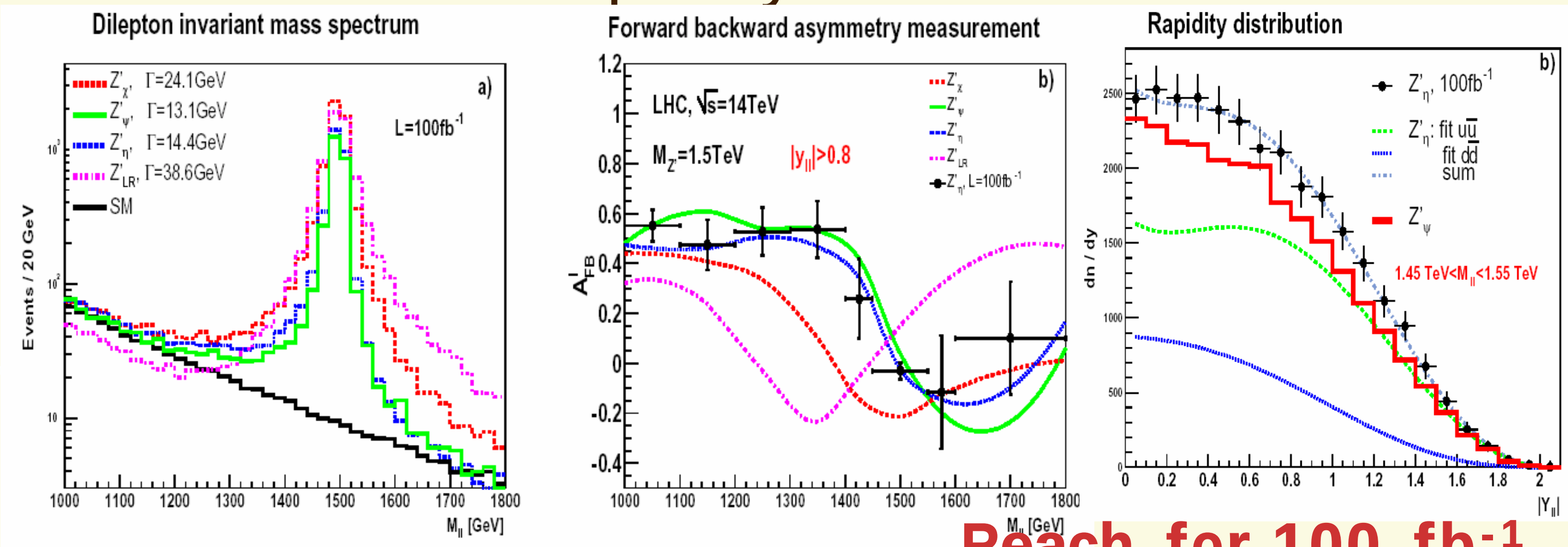


New Gauge Bosons (2)

CMS

Z' -> ll

- ✓ Discriminating between models
  - Look at σxΓ, Asymmetry F-B
  - Looak at Z' rapidity



  - Nicollerat, Dittmar, Djouadi

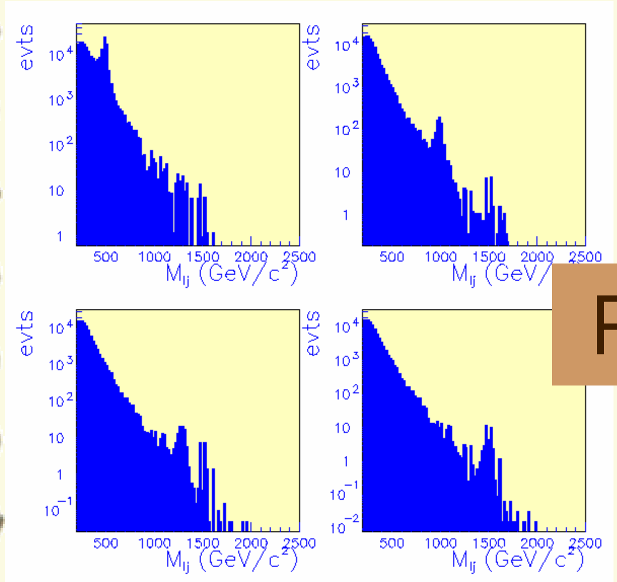
Reach for 100 fb^{-1}

- **4 – 5 TeV**
- **ID up to 2.5 TeV**

Leptoquarks

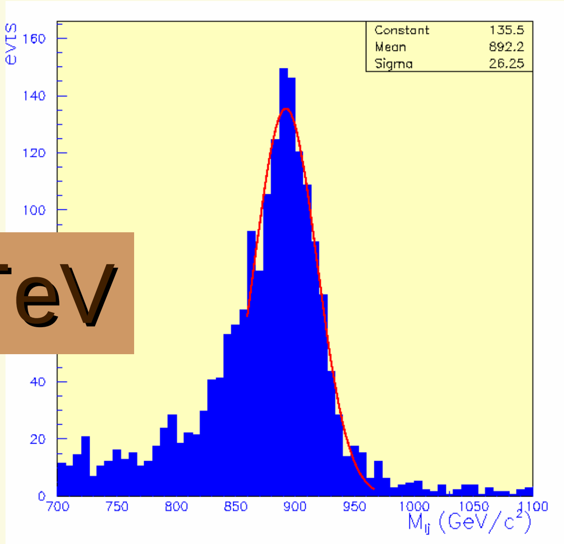
- ✓Motivation
  - SM extension: lepton-quark symmetry
- ✓Study: Scalar LQ pair-produced
  - Final state lljj

CMS ejet σ~27 GeV



CMS

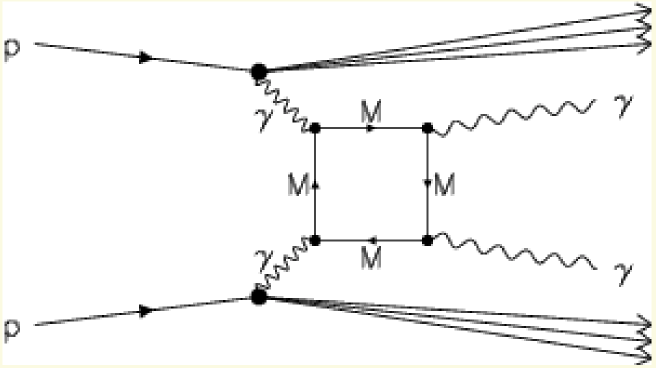
Reach ~1.5 TeV

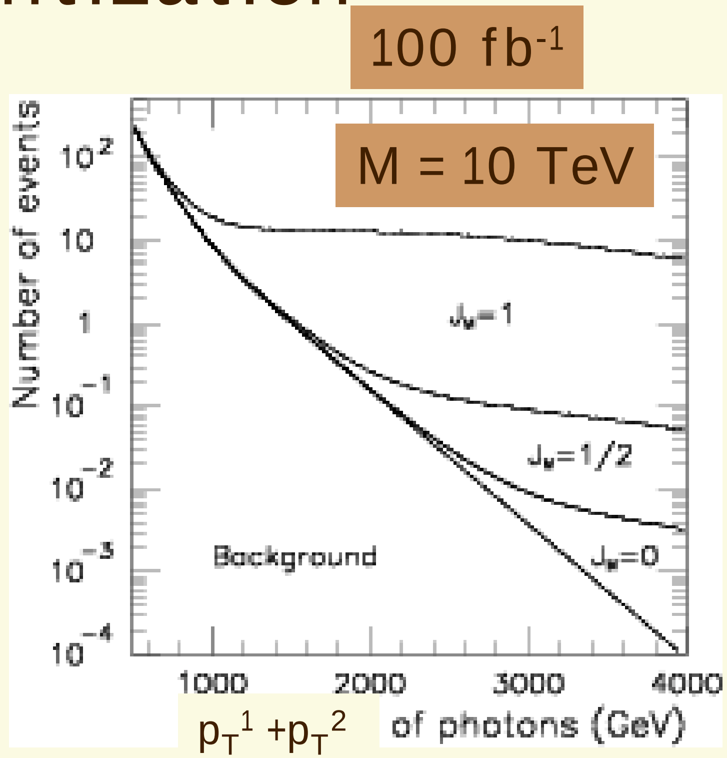


Monopoles

✓Motivation

– Restores Maxwell's equ'ns symmetry & explains charge quantization





✓Reach

– 10-20 TeV (spin dependent)

Little Higgs

Recall (see E. Ros's lecture)

✓ Motivation

- H is ~ Goldstone boson of larger group
- Cut-off Λ introduced ~ 10 TeV
- Divergences canceled by
  - $\delta m^2_{H|top}$ New colored fermion T
  - $\delta m^2_{H|gauge}$ New bosons W_H, Z_H, A_H
  - $\delta m^2_{H|Higgs}$ Higgs triplet

✓ Issues

- EW precision tests
  - LEP and Tevatron give **f > 4 TeV at 95% ($\Lambda = 4\pi f$)**
  - Fine tuning > 100 needed to keep m_h ~200 TeV
- Integrating GUTs

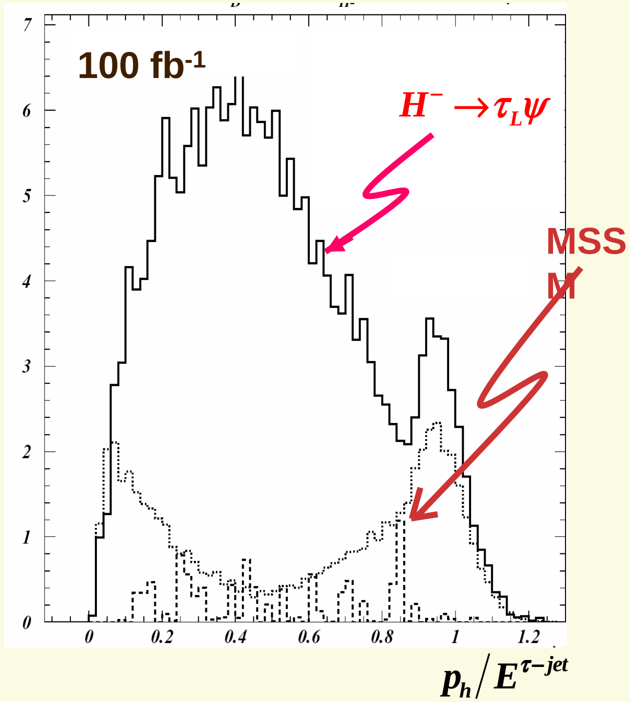
Other

- Models with singlet neutrino
- Lepton Flavor Violation
- SLHC

$H^- \rightarrow \tau^- \nu$

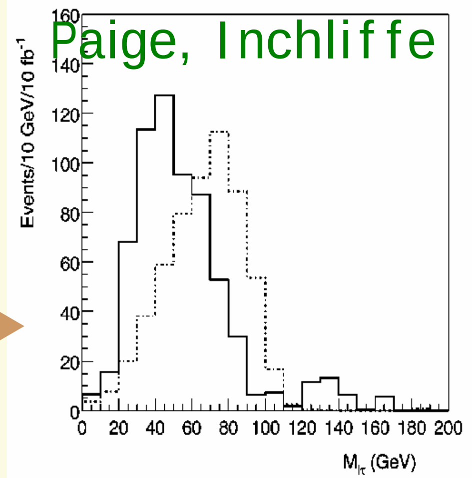
- In models with singlet neutrino
  - Low ν mass without see-saw
    N. Arkani-Hamed, S. Dimopoulos, G. Dvali, J. March-Russell, *hep-ph/9811448*
  - Single neutrino in bulk
  - 2HDM-II
    - MSSM only $H^- \rightarrow \tau_R \nu$ allowed
    - with presence of singlet bulk neutrino
      $H^- \rightarrow \tau_R \nu + \tau_L \Psi$
    - Assymmetry to distinguish

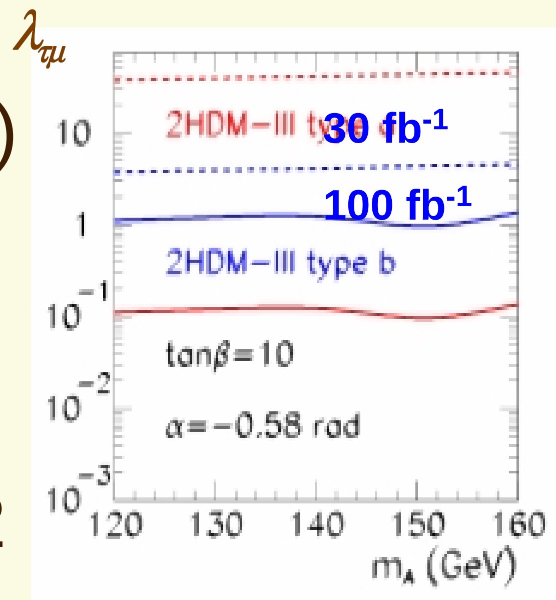
ATLAS



Lepton Flavor Violation

- ✓ $\tau \to \mu\,\gamma$
  - Expect **5x10^{-7}** from $Z \to \tau\,\tau$
- ✓ $\tau \to \mu\mu\mu$: Under study
- ✓ mSUGRA $\tilde{\chi}_2^0 \to \tilde{\tau}\tau \to \tilde{\chi}_1^0 \mu\tau$
  - LFV decays give $\mu^+\tau^-$ signal
  - asymmetry in $\mu^+\tau^-$ & $e^+\tau^-$
  - Expect sensitivity ~ O(10^{-9})
- ✓ A/H $\to \tau\,\mu$
  - LFV appears at tree-level in 2-doublet Higgs Models
  - Strong constraint from g-2





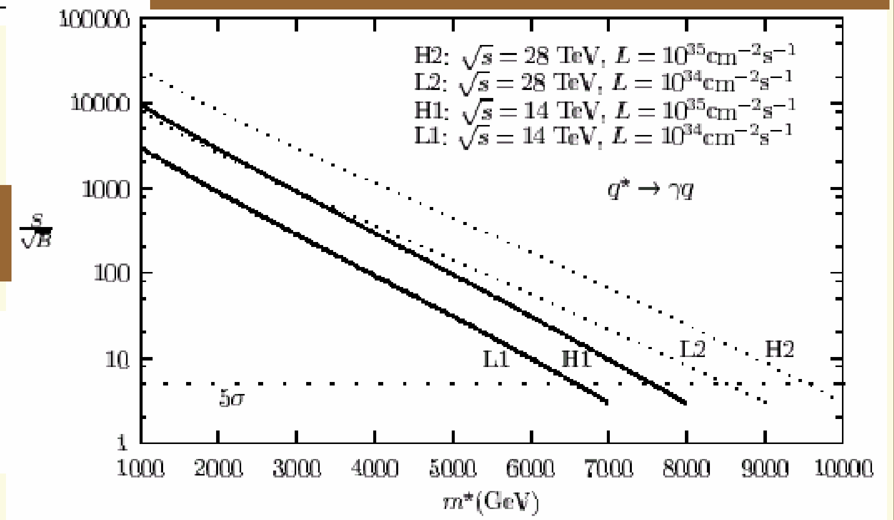
Super LHC

- ✓ 2 options
  - 1000 fb^{-1} or 28 TeV (more difficult)
- ✓ Potential

Large XD- MD reach: Direct Graviton

δ	14 TeV 100 fb^{-1}	14 TeV 1000 fb^{-1}	28 TeV 100 fb^{-1}	28 TeV 1000 fb^{-1}
2	9	12	15	19
3	6.8	8.3	11.5	14
4	5.8	6.9	10	12

Excited quarks: q* -> qγ



New gauge bosons: Z' -> μμ

14 TeV 100 fb^{-1}	14 TeV 1000 fb^{-1}	28 TeV 100 fb^{-1}	28 TeV 1000 fb^{-1}
4.5	5.4	7.0	9.5

Prospects

- ✓ LHC will be able to probe various physics beyond SM
- ✓ Detector performance adequate
  - b-tag & Lepton-ID @ high p_T
- ✓ Lot of recent & exciting studies
  - Xtra dimensions
  - Little Higgs
  - Link to Astrophysics (Black holes)
- ✓ Ongoing: Assessing observations
  - SUSY vs UED
  - Higgs vs Radion