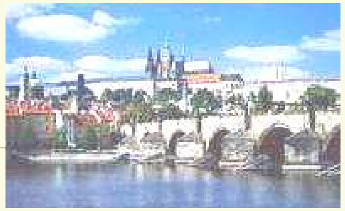
Beyond SM: LHC potential

L. Poggioli, LAPP (Annecy)

- Strong Symmetry Breaking
- Extra Dimensions
- Compositeness
- New particles
- Little Higgs
- Other

Introduction



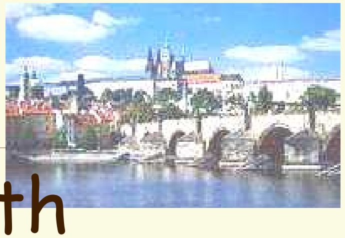
- ✓ Hierarchy problem
  - SUSY : Elegant, *not discussed here*
  - Technicolor
    - New strong interactions ~ 1 TeV
  - Extra Dimensions
    - Gravity scale brought down to ~ 1 TeV
  - Little Higgs
    - Composite H with compositeness scale ~ 10 TeV
- ✓ Possible new physics
  - Excited fermions, contact interactions
- ✓ Extension of EW gauge group
  - New gauge Bosons
- ✓ Unexpected

Strong Symmetry Breaking

- Technicolor
- Chiral Lagrangian Model

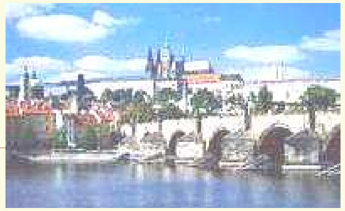
[redacted]

Technicolor (1)

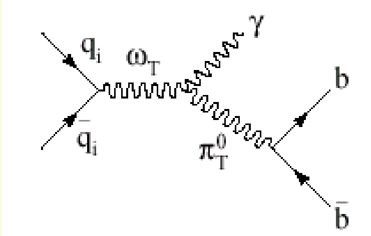


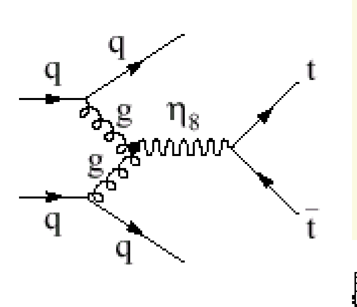
- ✓ New strong interaction O(TeV) with Techniquarks condensates -> EWSB
- ✓ Pros
  - Solves hierarchy problem(no fund. scalar)
- ✓ Cons
  - No account for fermion masses (ETC ?)
  - In conflict with S,T @ LEP (Walking TC ?)
- ✓ Predictions
  - Technimesons resonances in $W_L W_L$ and $W_L Z_L$ scattering

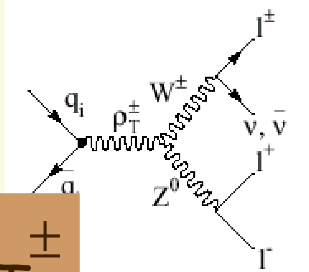
Technicolor (2)



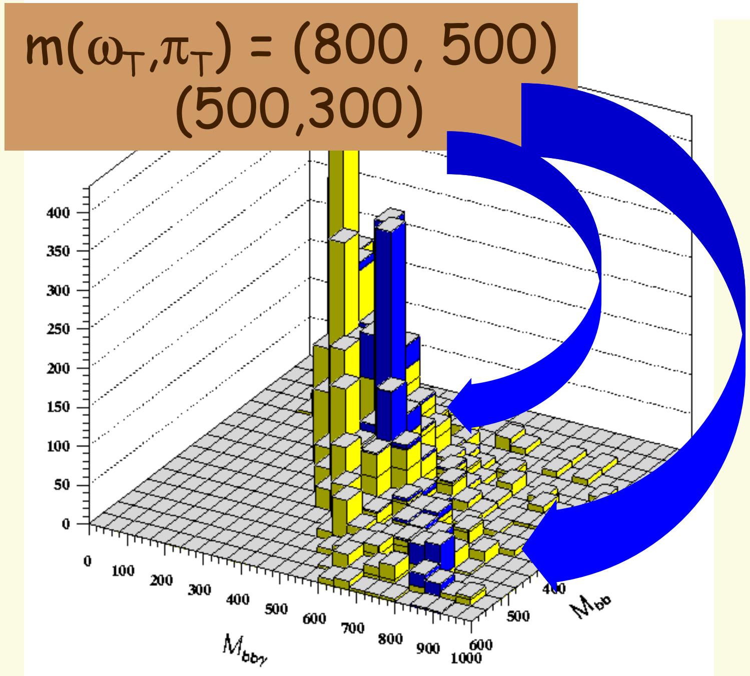
- ✓ ω_T, $\rho_T^{\pm}$, tt (mass spectra model dependent)


q_i
ω_T
γ
b
q̄_i
π_T^0
b̄

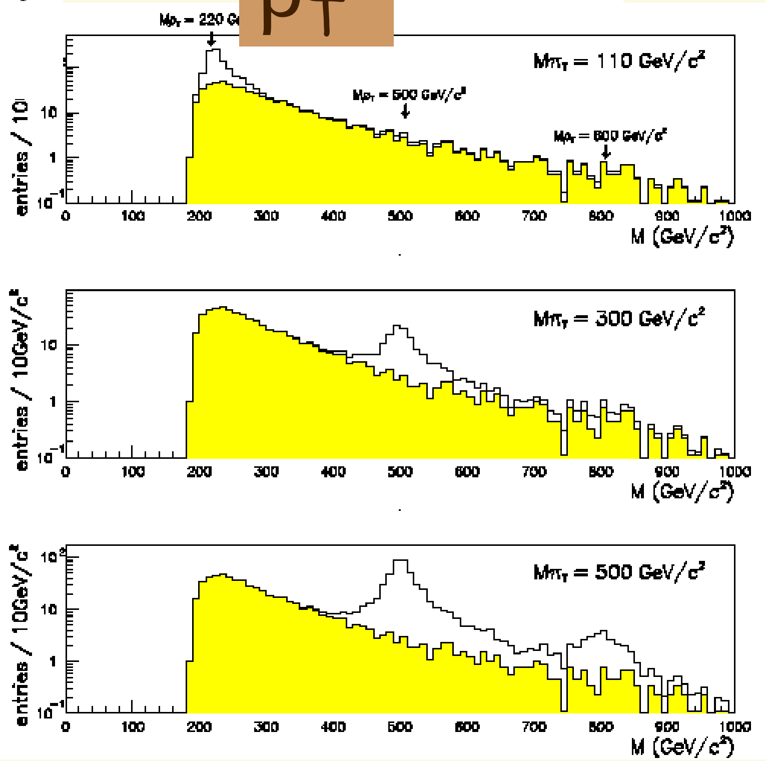

q
q
g
η_8
t
g
q
q
t̄


q_i
ρ_T^±
W^±
l^±
ν, ν̄
l^+
Z^0
l^-

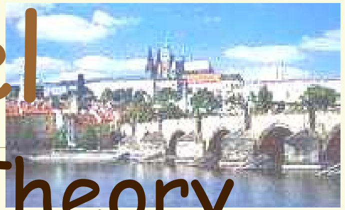
$m(\omega_T,\pi_T)$ = (800, 500)
(500,300)



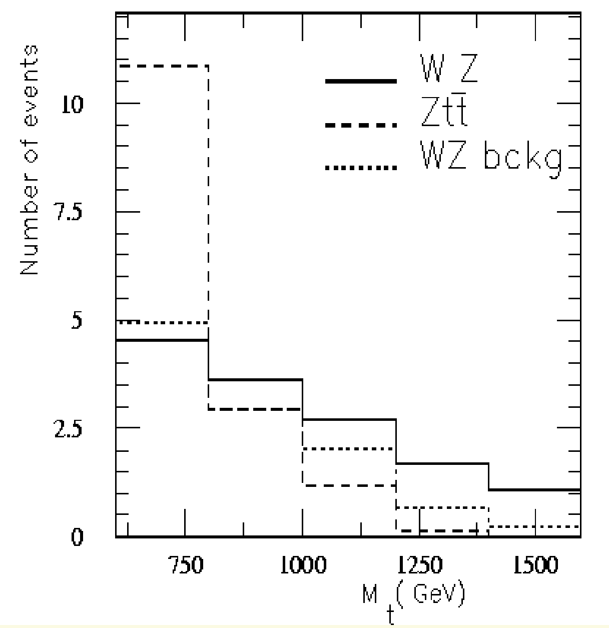
$\rho_T^{\pm}$



Chiral Lagrangian Model

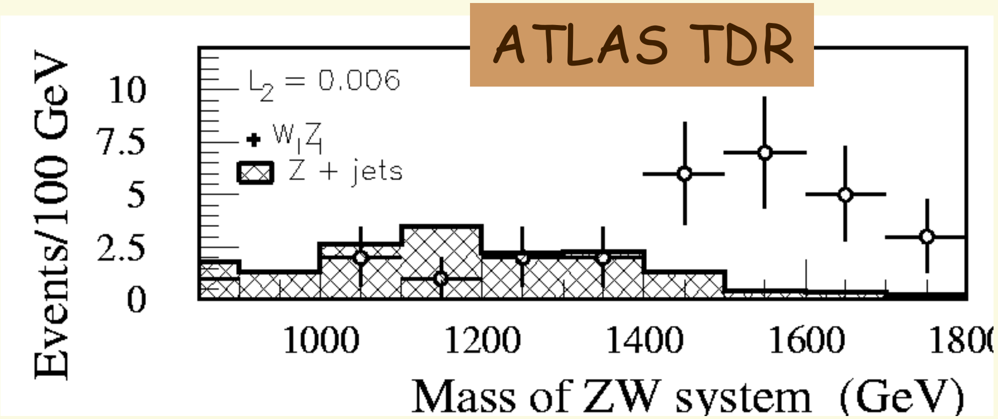


- ✓ Based on Chiral Perturbation Theory
- ✓ Use Inverse Amplitude Method with 2 parameters L1 & L2
  - Non-Resonant scattering
  - Resonant scattering

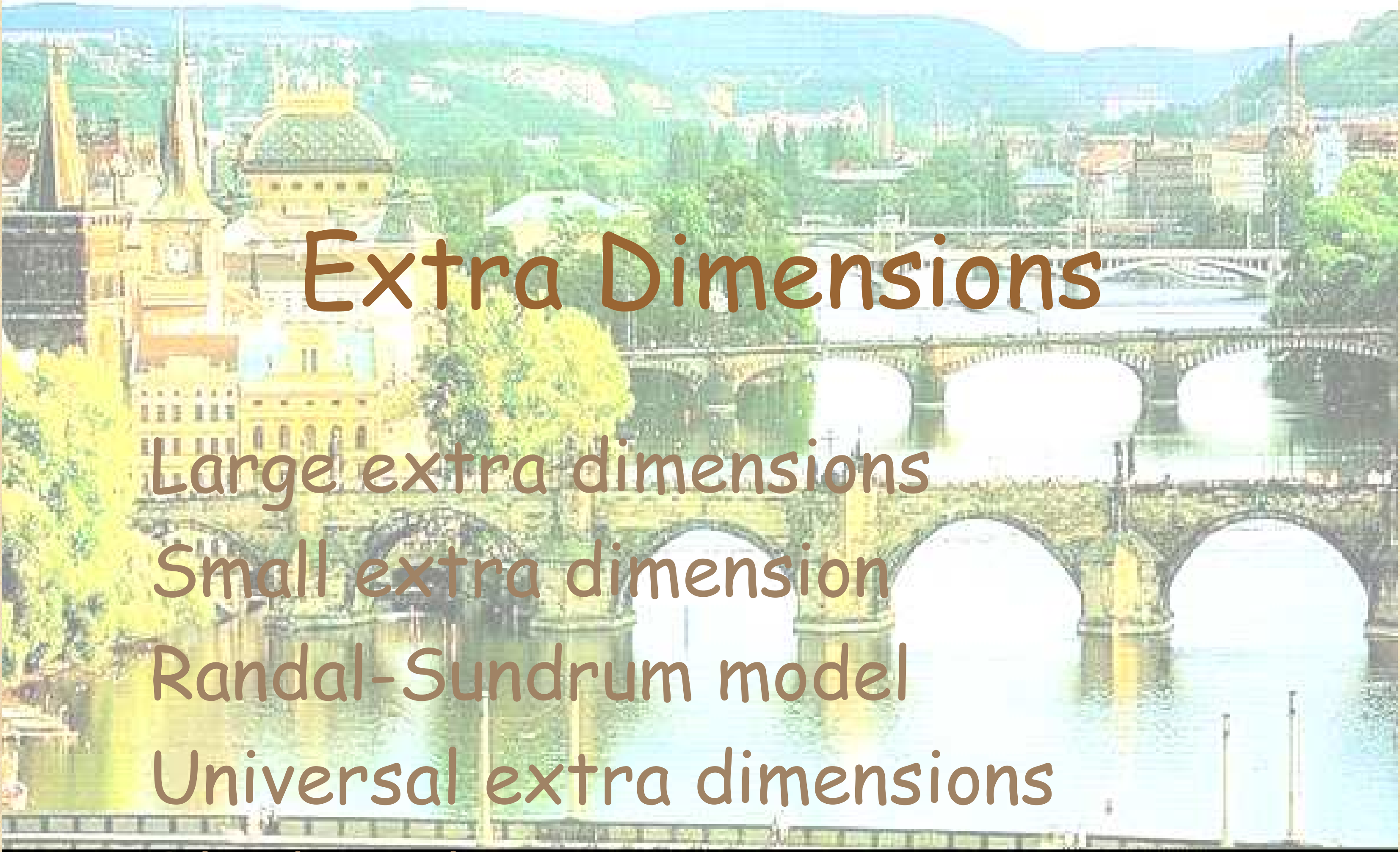


$W_L^\pm Z_L \rightarrow W_L^\pm Z_L \rightarrow l\nu ll$

ATLAS TDR



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



Extra Dimensions

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

Introduction

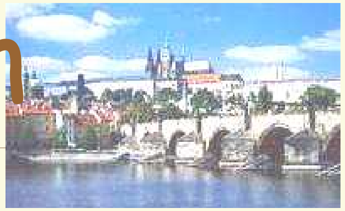
- ✓ Large extra dimensions (>> 1/TeV)
  - ADD model (Arkani, Dimopoulos, Dvali)
  - SM particules in brane
  - Gravity propagates in bulk (Xtra Ds)
    - Hence new gravity scale
    - KK graviton excitations

$M_{PL}^2 \sim M_D^{2+\delta} R^\delta$

$M_D \sim$ TeV for $R <$ mm

- ✓ TeV^{-1} Xtra Ds
  - KK excitation of SM gauge fields
- ✓ Randall-Sundrum : 1 small Xtra D
  - Warped metric
  - Narrow Graviton resonance
  - Radion

ADD: Graviton emission



✓ Process

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

✓ Reach

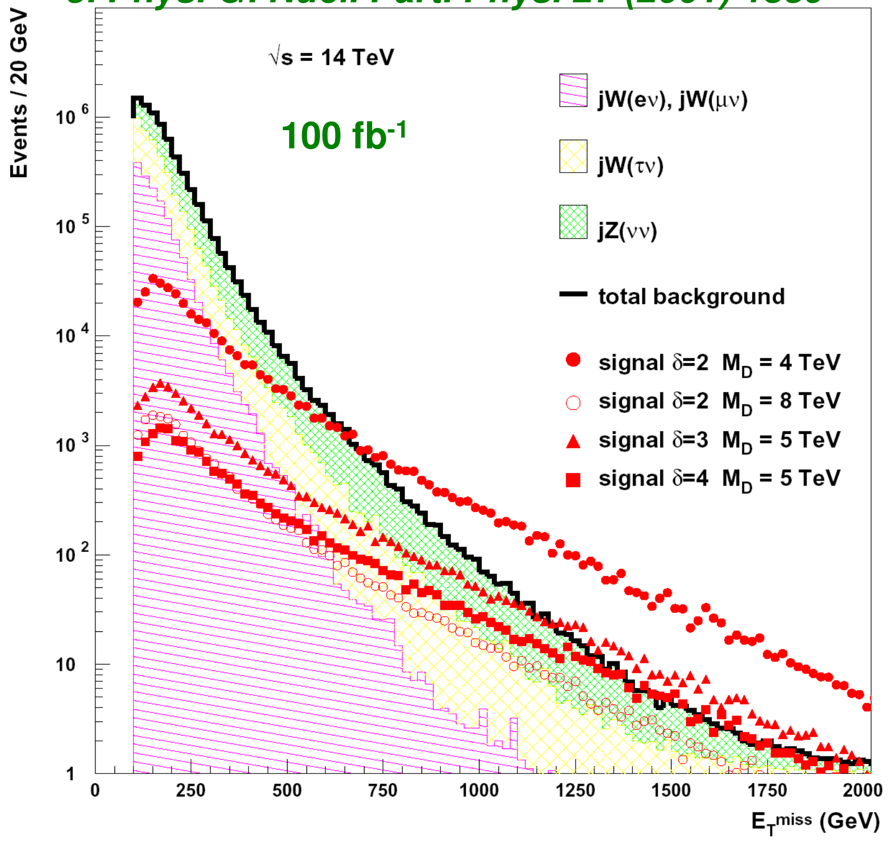
- gG

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

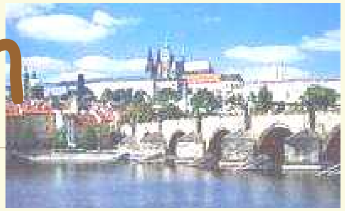
δ	M_D^{max} (TeV) HL, 100 fb^{-1}	M_D^{min} (TeV)
2	4	~ 3.5

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

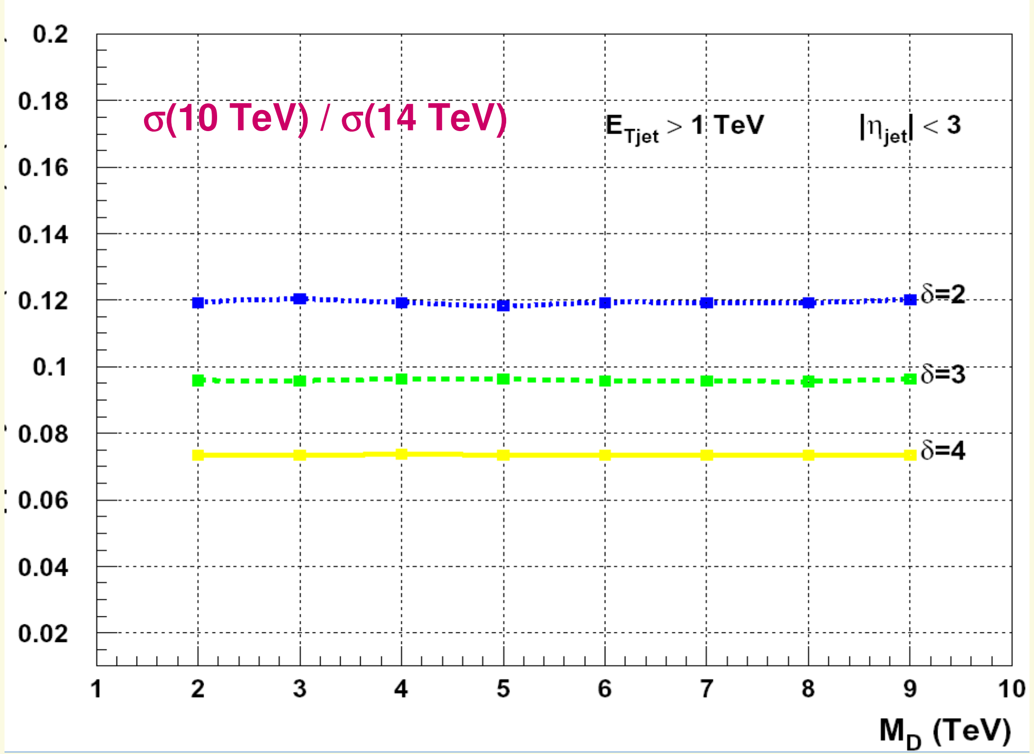


Background calibrated by Z j -> ll j

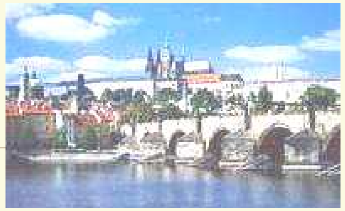
ADD: Graviton emission



- ✓ Disentangling M_D and δ
  - Run LHC @ 2 energies
  - **50 fb^{-1}** necessary



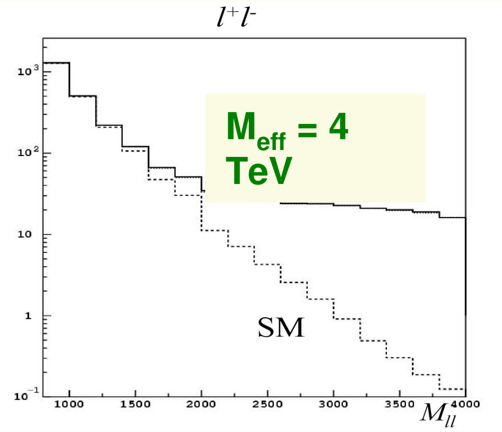
ADD: Virtual Graviton

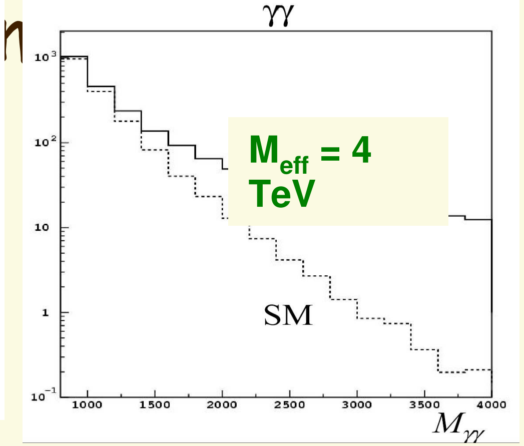


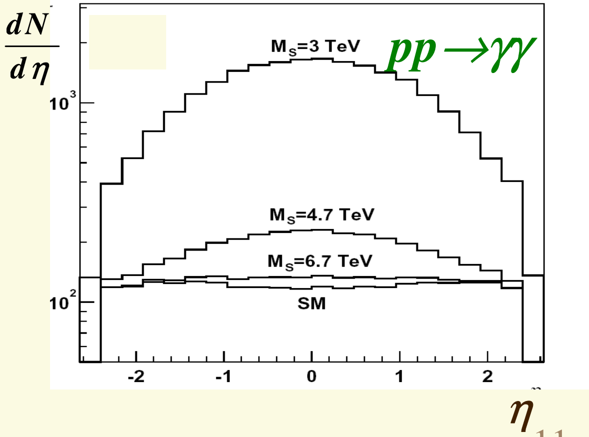
- ✓ Final state $q\bar{q}, gg \to \gamma\gamma, \ell\ell, \quad (WW, t\bar{t} \ldots)$
  - Use effective scale M_s (σ diverges if $\delta \geq 2$)
- ✓ Observables
  - Excess in ll & γγ
  - γγ more central than SM

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

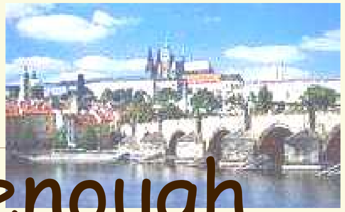
V. Kabachenko and A. Miagkov





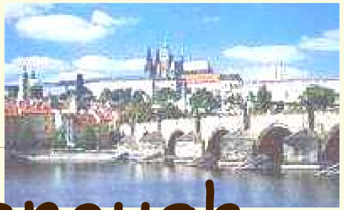


TeV^{-1}: Introduction

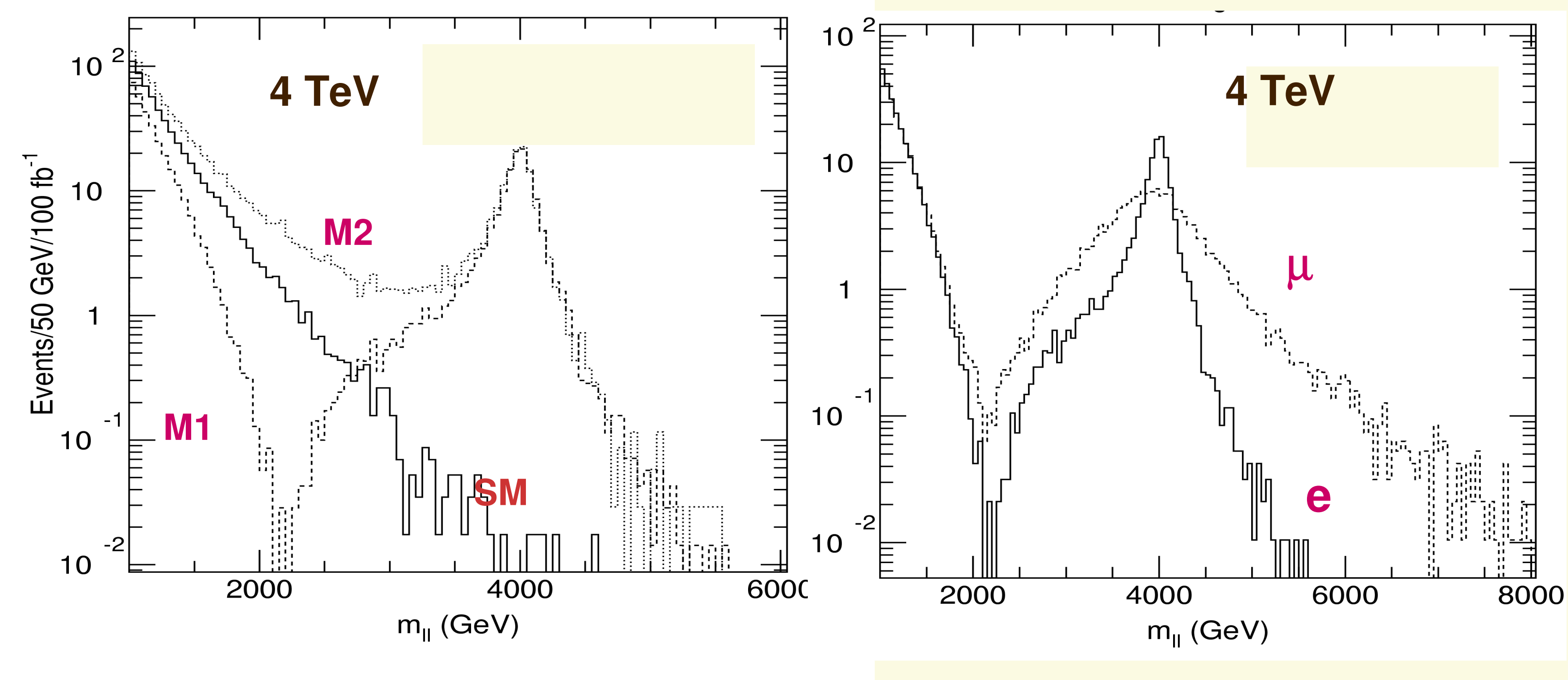


- ✓ Compactification radius small enough to allow SM in bulk
  - Eg $R = \hbar c / 1\ \mathrm{TeV}^{-1} = 2\times10^{-4}\ \mathrm{fm}$ $[M_D \square 10^{15}\ \mathrm{GeV\ pour}\ n=1]$
- ✓ Indirect constraints from LEP EW
  - R^{-1} > 3.9- 6.8 TeV Rizzo, Cheung, Landsberg
- ✓ Model (T. Rizzo)
  - 1 X 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 $\gamma^{(1)}/Z^{(1)}$

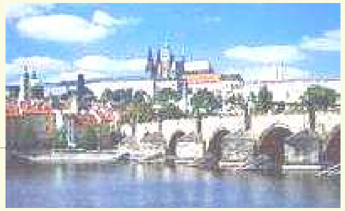


- ✓ Compactification radius small enough to allow SM in bulk
  - Look at resonance in ll spectrum

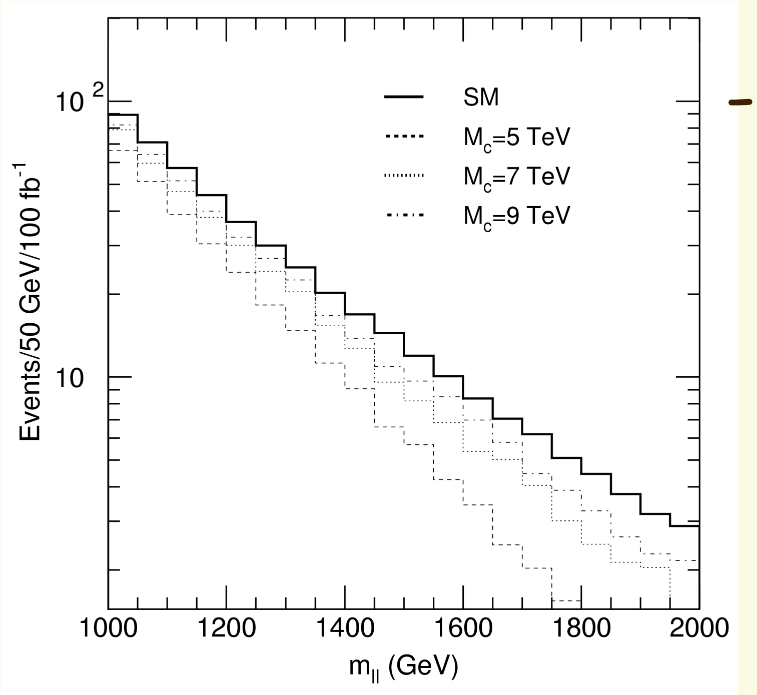


  - Observation up to ~ 6 TeV with 100 fb^{-1}

TeV-1: $W^{(1)}$

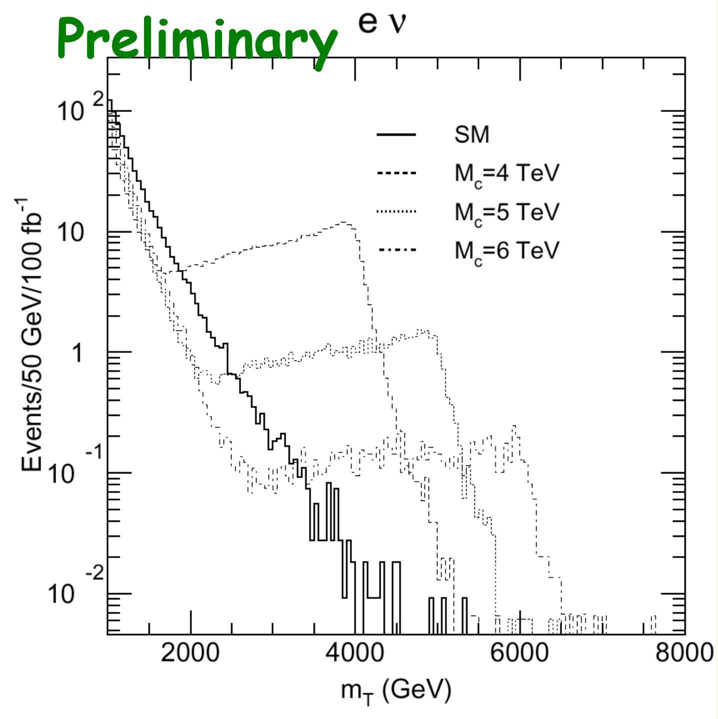


- ✓ Drell-Yan tail



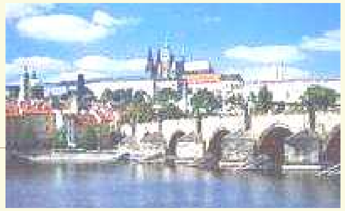
  - Reach ~ 10 TeV
  - Large systematics

G. Polesello & M. Prata
Preliminary

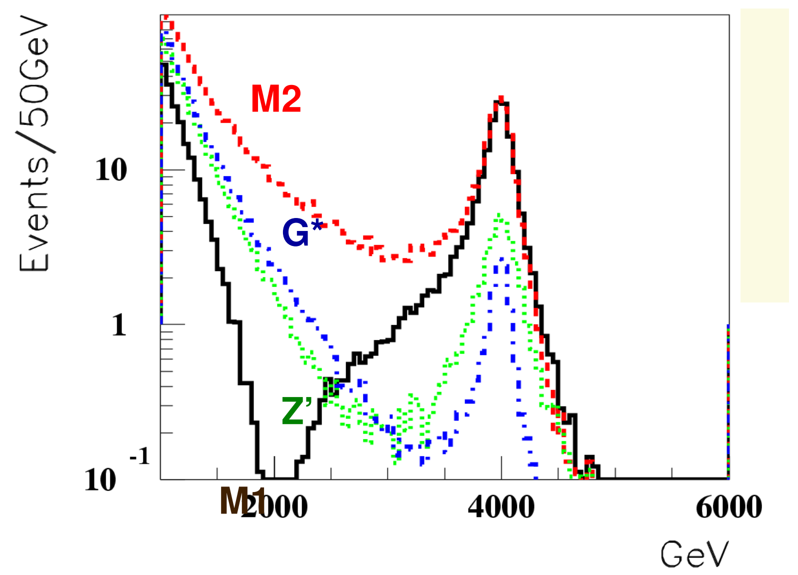


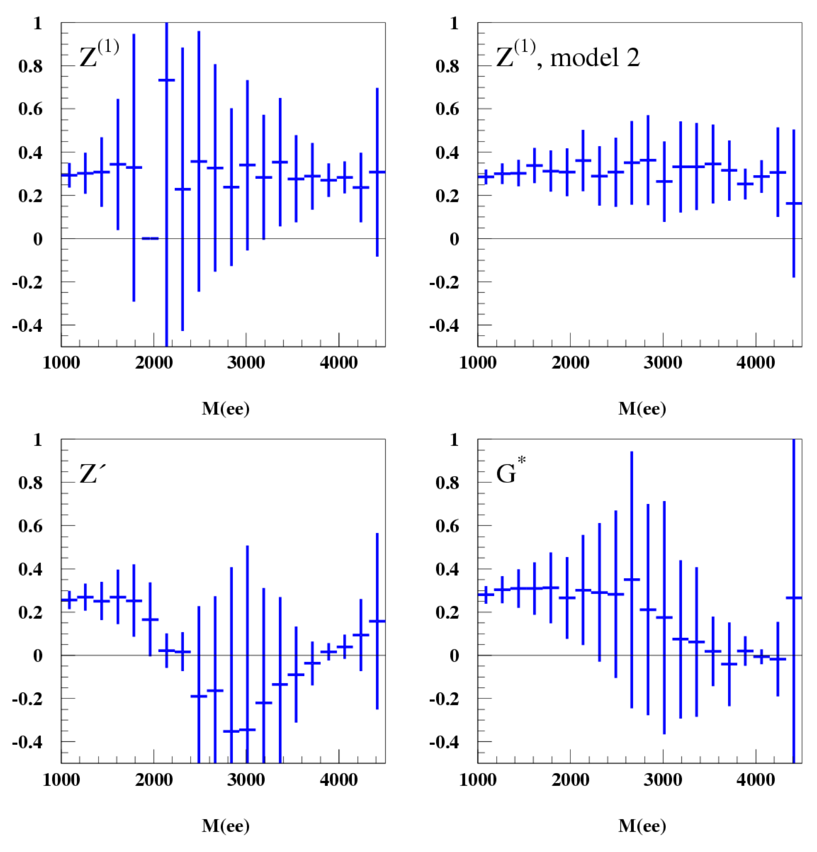
- ✓ Also $W^{(1)}$
  - Direct reach ~ 6 TeV

TeV-1: Asymmetry



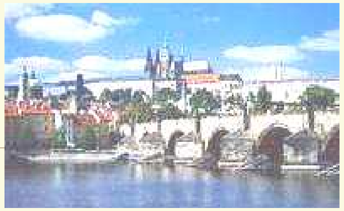
- ✓ Look at Forward-Backward asymmetry





- ✓ Model discrimination (see also S. Shmatov)

Randall-Sundrum



✓ Motivation

- 2 branes (Ours & Plank' scal) 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 ~ $1/\Lambda_\pi$

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

- Graviton excitations

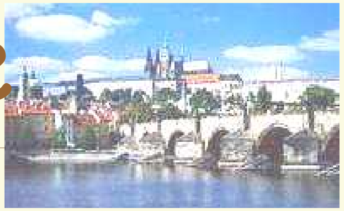
$$m_n = kx_n e^{-k\pi r_c}, \quad \text{avec } J_1(x_n) = 0$$

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

- Constraints

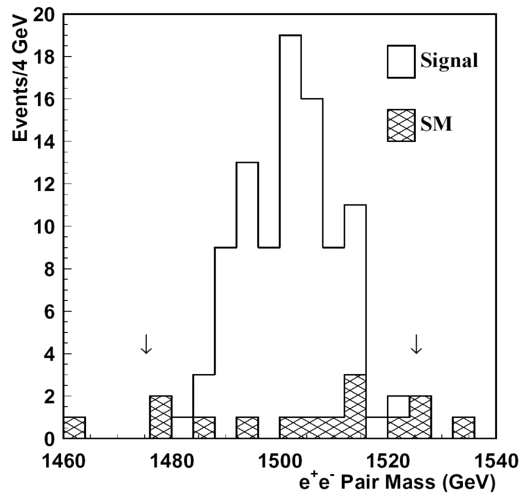
$0.01 < k/M_{pl} < 0.1$

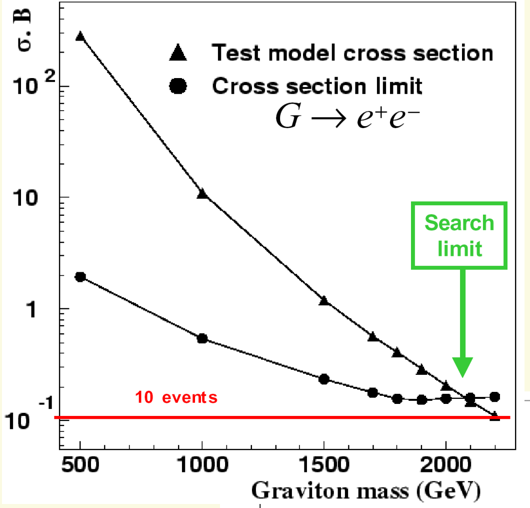
RS: Graviton resonance



- ✓ Narrow Graviton resonance

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



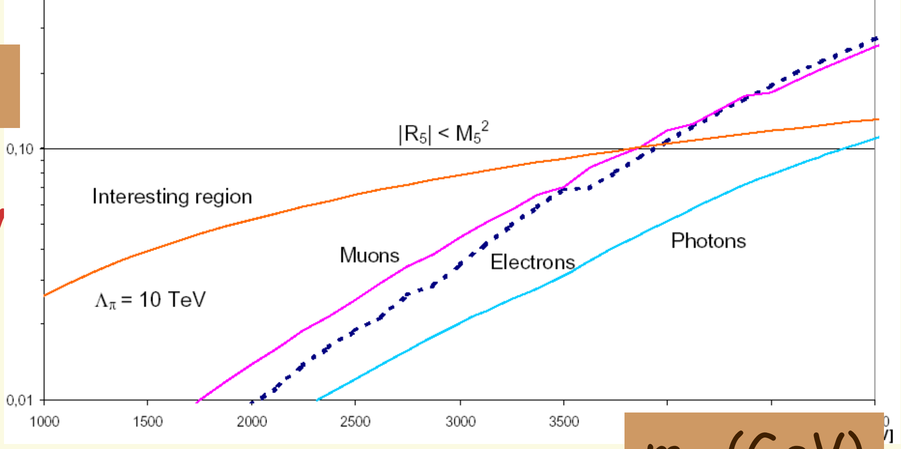


Allanach, Odagiri, Parker
and Webber, *JHEP 9 (2000) 19*

P. Traczyk

- ✓ Reach
  - Range ~ 2-4 TeV

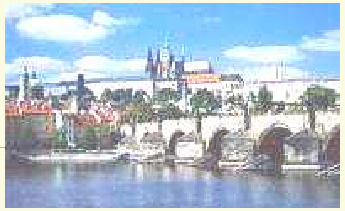
PYTHIA + CMSJET
$100fb^{-1}$



k/M$_{Pl}$

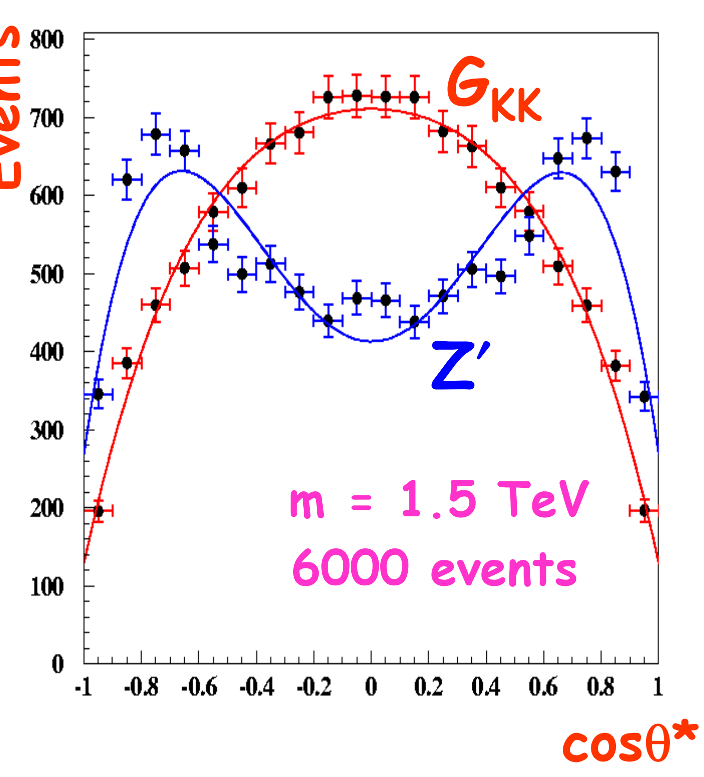
m$_G$ (GeV)

RS: Graviton Spin

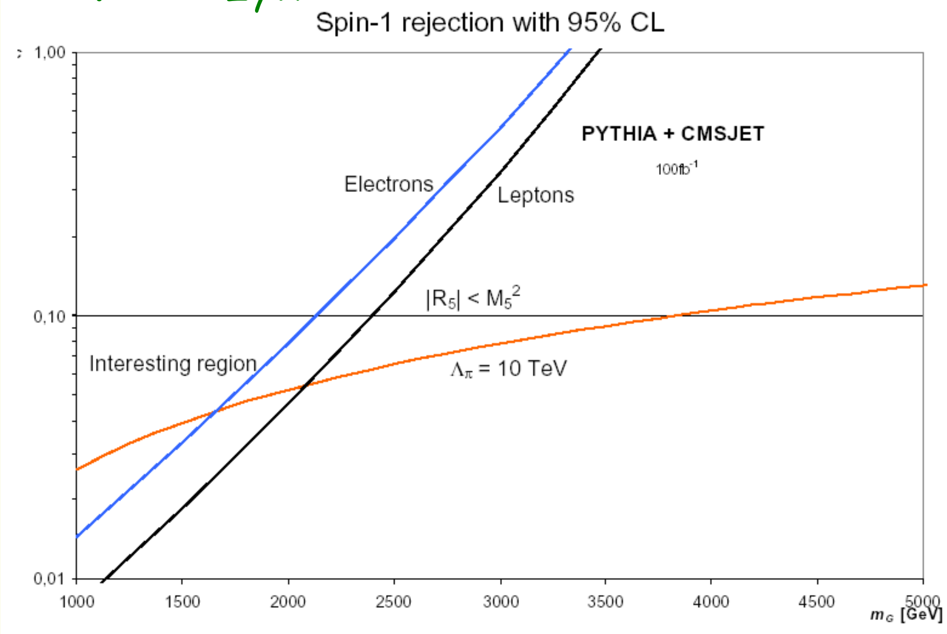


- ✓ Look at angular distribution
  - 90% exclusion of spin-1 for $m_G < 2.3$ TeV

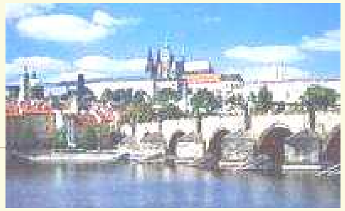
S. Shmatov



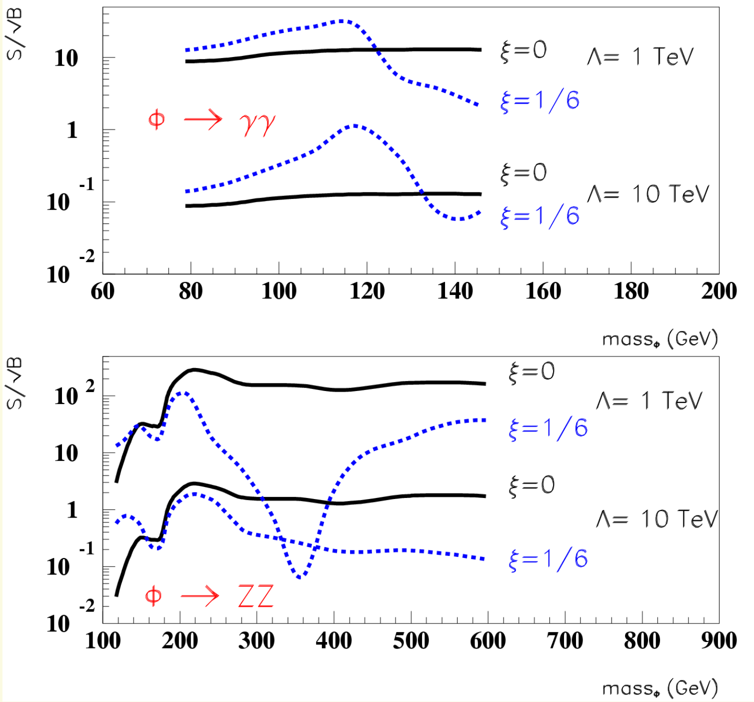
P. Traczyk



Radion (1)

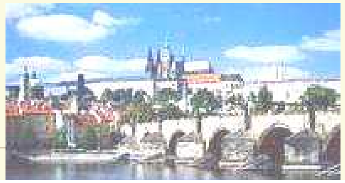


- ✓ Motivation
  - Scalar field representing fluctuations of the distance of the 2 branes
  - To stabilize $kr_c\pi \sim 35$ (Golberger & Wise)
- ✓ Radion properties
  - Higgs-like couplings
  - Mixing to Higgs ξ
- ✓ Signal $\phi \rightarrow \gamma\gamma, \quad \phi \rightarrow ZZ$



Azuelos., Cavalli, H. Przysiezniak, Vacavant *SN-ATLAS-2002-019*

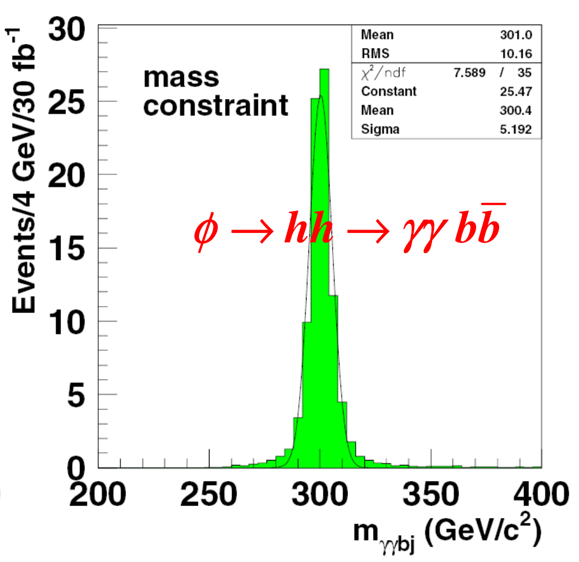
Radion (2)

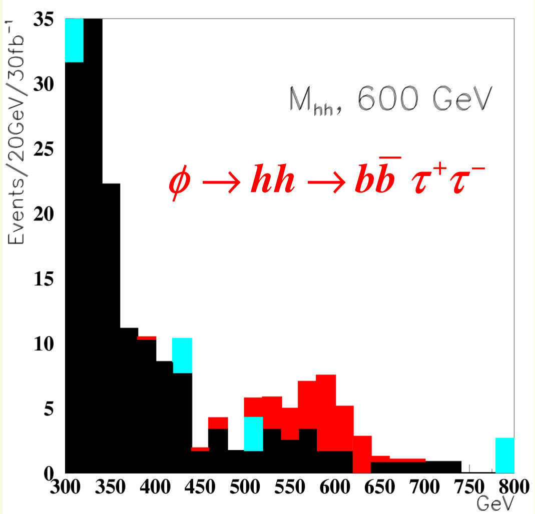


- ✓ Other signals — See L. Fano
  - $\phi \rightarrow hh \rightarrow \gamma\gamma\, b\bar{b}$

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	-

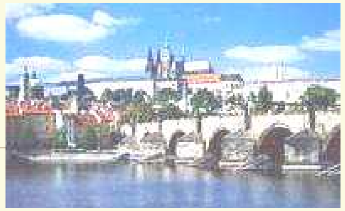
Required luminosity (fb^{-1}) for 5σ discovery



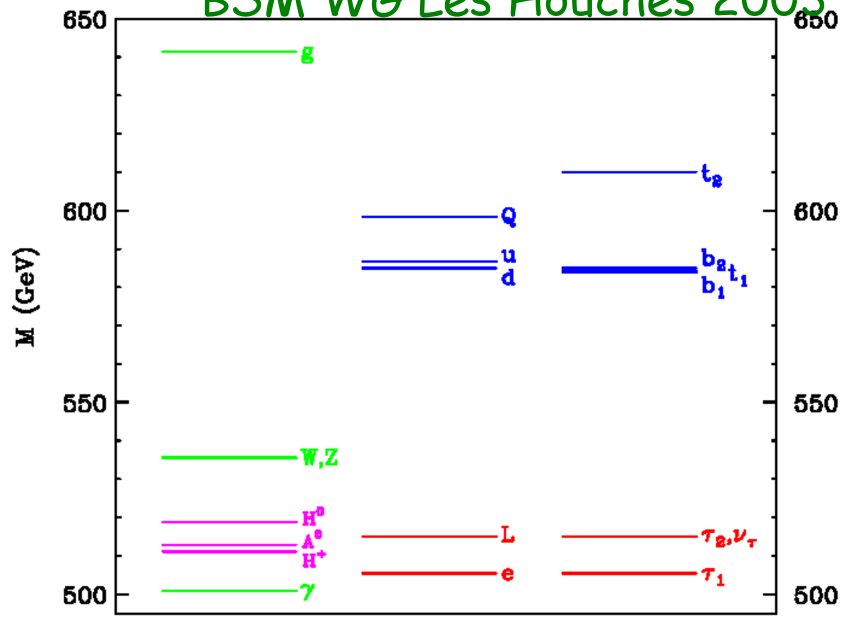


- ✓ Discrimination Higgs/Φ
  - Difficult at LHC
  - Look at Γ & BR mods (Rizzo et al)

Universal ED



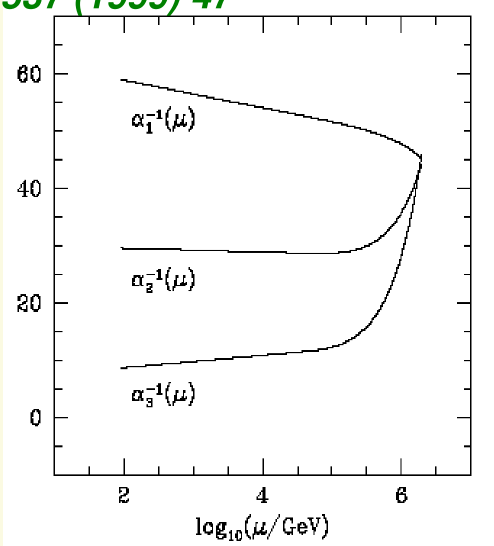
- ✓ Idea
  - All particles are in the bulk
  - Conserved KK number $m_n^2 = an^2 + m^2$
  - Radiative mass splittings
  - Can fake SUSY
- ✓ Disentangle ?
  - Assess feasibility at LHC
  - Undertaken in Les Houches


BSM WG Les Houches 2003

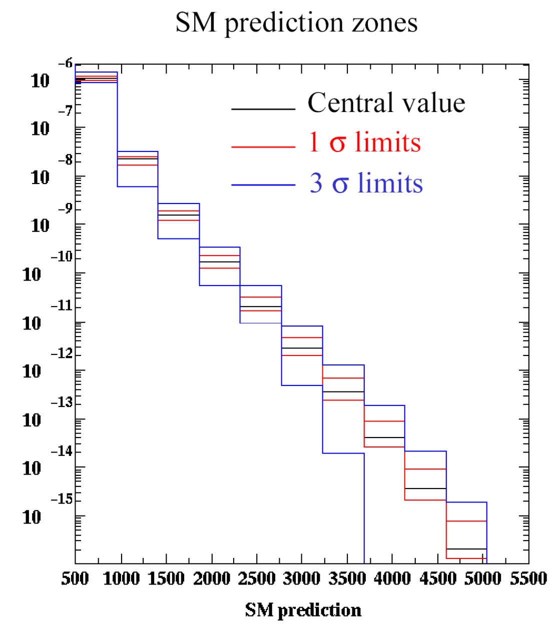
Coupling Unification at TeV

- ✓ KK states affect running of gauge couplings
  - Above 1/R power law

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



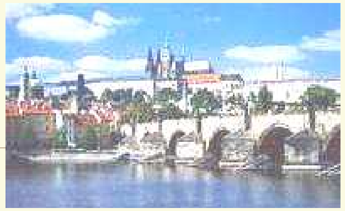
- ✓ Dijet cross-section



-Sensitivity of deficit in jet cross section, ~ 10 TeV, at parton level
Balázs, B. Laforge, *hep-ph/0110217*

-PDF uncertainties limit reach to 1 TeV Ferrag, Escalier, Laforge

Black Holes (1)

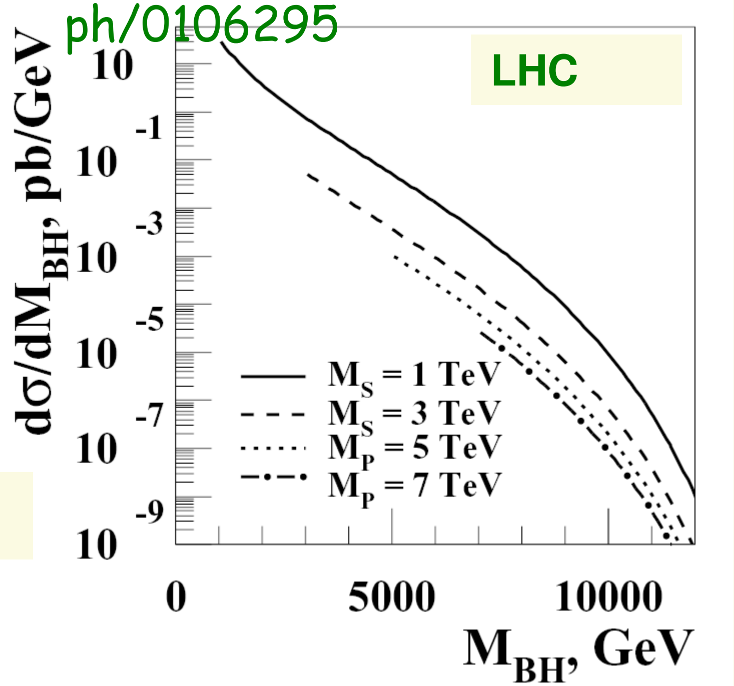


- ✓ Motivation
  - Object confined in $R < R_s$
- ✓ Features
  - T is mass dependent
  - Black body radiation
- ✓ Uncertainties
  - Cross-section
  - Decays
    - Various phases

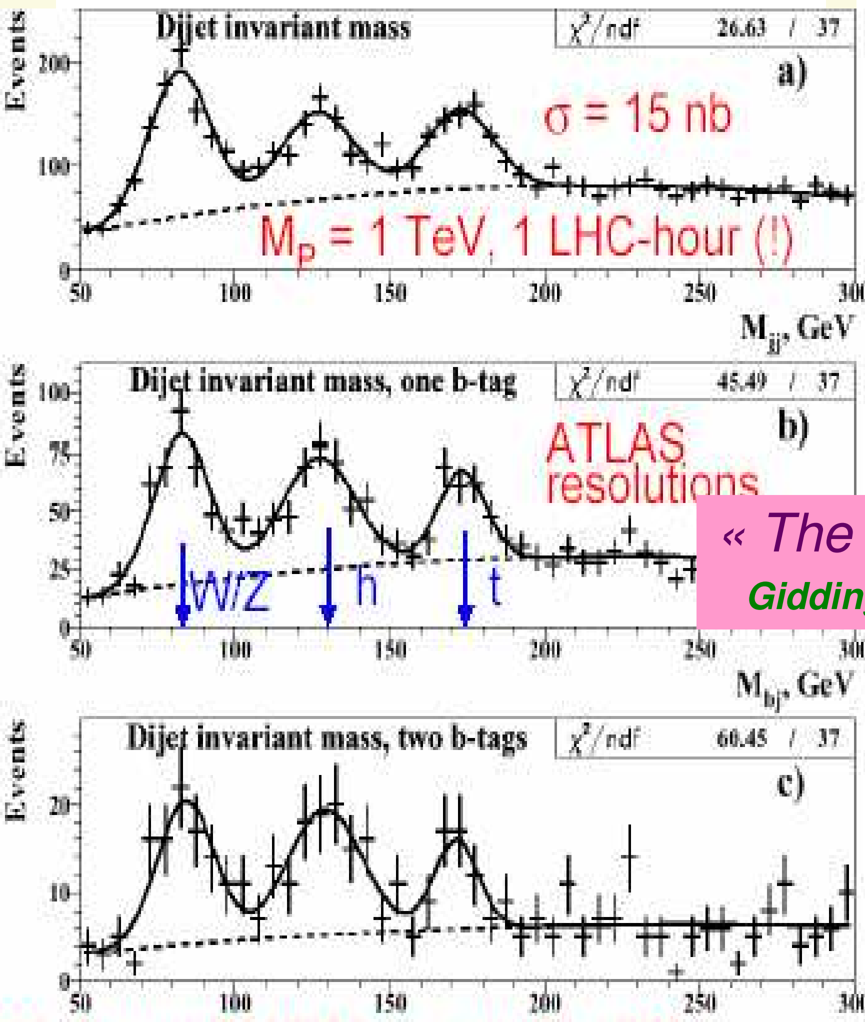
Implementation in Herwig & simulated in ATLAS

See Ch. Lester

Dimopoulos et Landsberg, hep-ph/0106295



Black Holes (2)



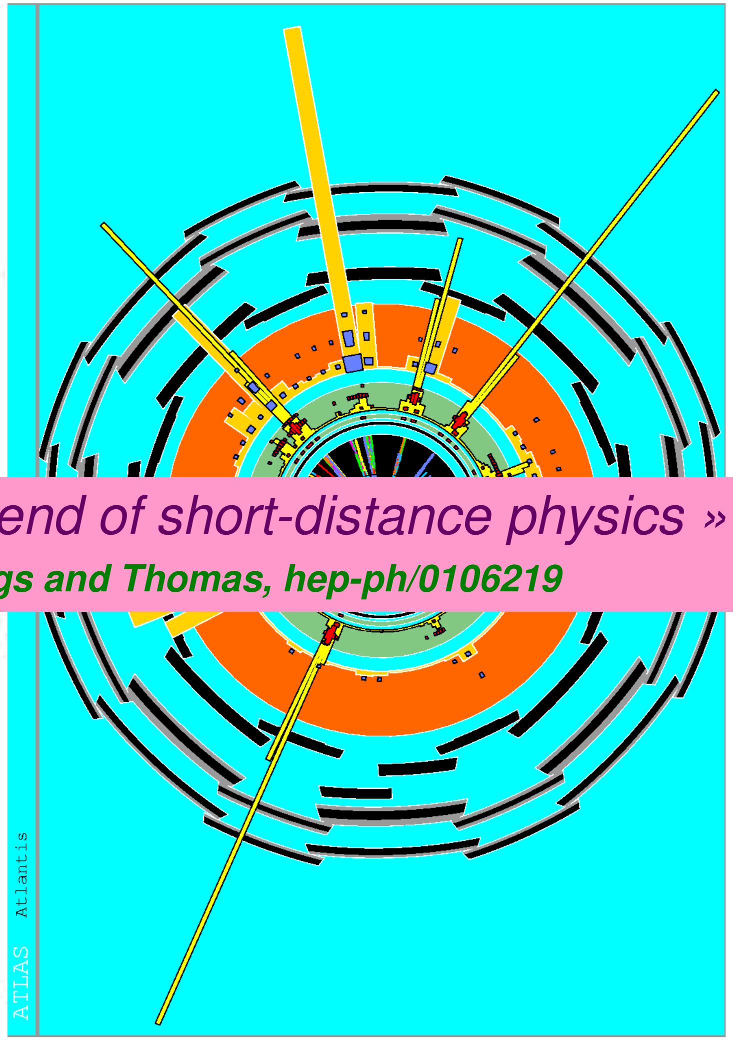
σ = 15 nb

M_P = 1 TeV, 1 LHC-hour (!)

ATLAS resolutions

W/Z h t

GL, hep-ph/0112061, accepted by PRL



« The end of short-distance physics »

Giddings and Thomas, hep-ph/0106219

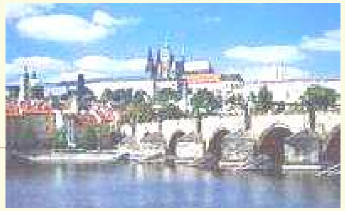
Compositeness

Excited quarks and leptons

Deviation to QCD

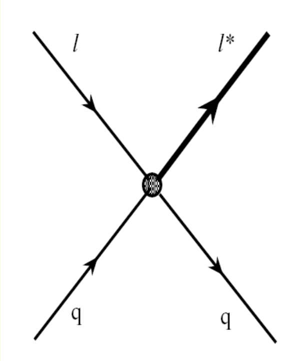
[redacted]

Introduction

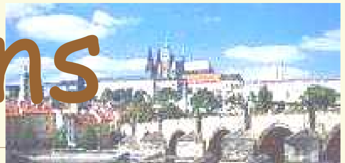


✓ Motivation
  - Fermionic generation explained by compositeness
  - Quarks & leptons: bound states of 3 fermions or 1 fermion + 1 boson

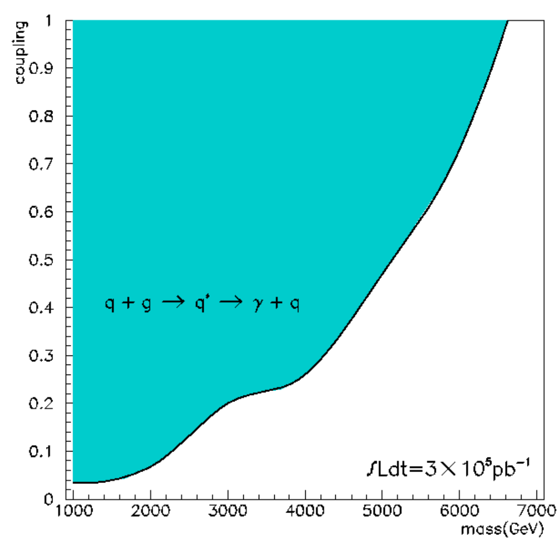
✓ Interaction
  - Contact interactions – Scale Λ
  - Spectrum of excited states
  - Deviation to QCD



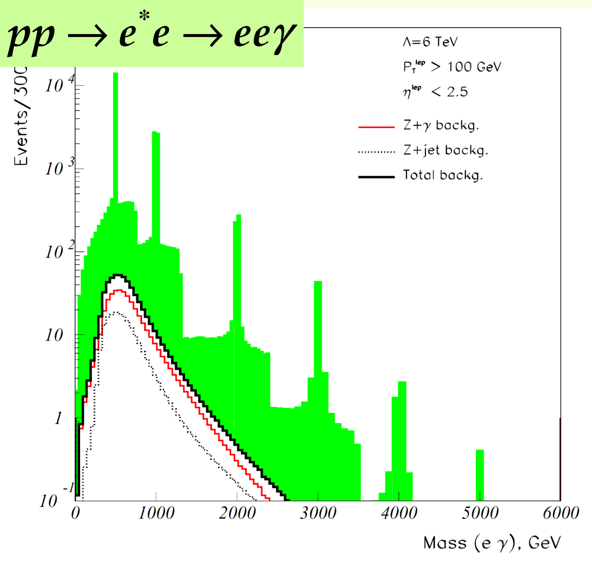
Excited quarks & leptons



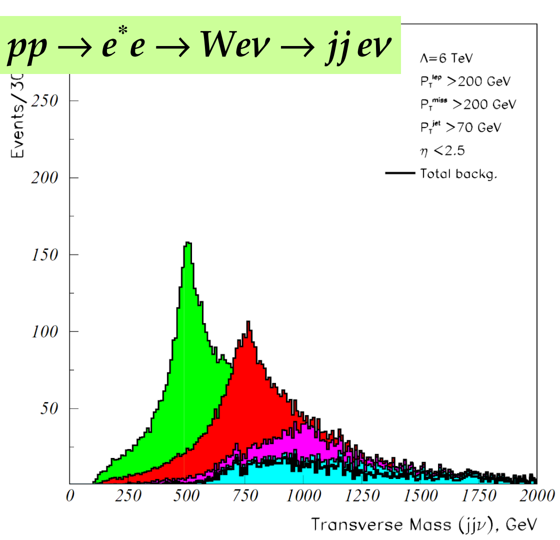
- ✓ Excited quarks
  - Reach limit for q* -> q γ
- ✓ Excited leptons
- ✓ **Reach: ~ 1 - 4 TeV for Λ = 6 TeV, 300fb^{-1}**



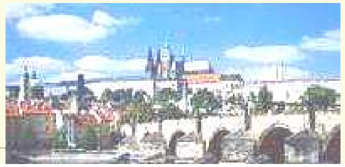
$pp \to e^* e \to ee\gamma$



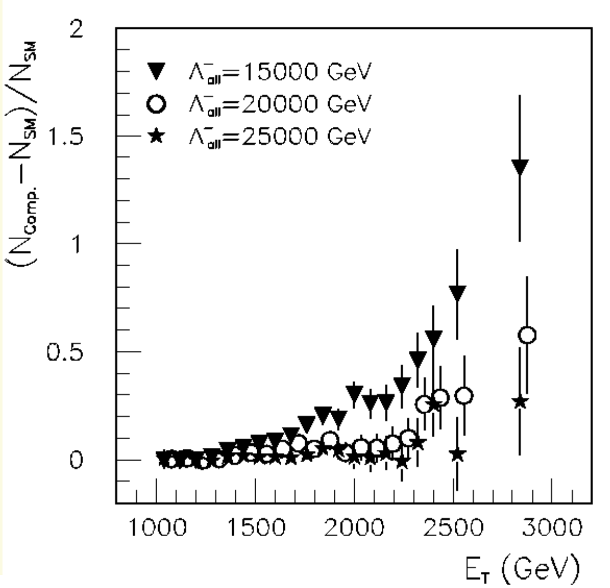
$pp \to e^* e \to We\nu \to jj\,e\nu$

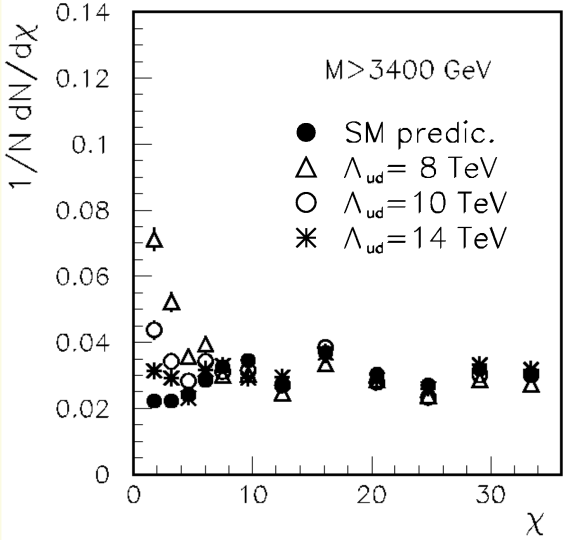


Deviation to QCD



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





New particles

- Heavy leptons
- New gauge bosons
- Leptoquarks

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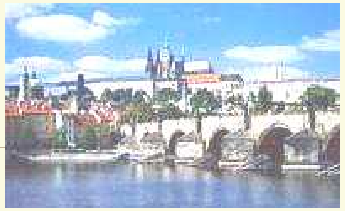
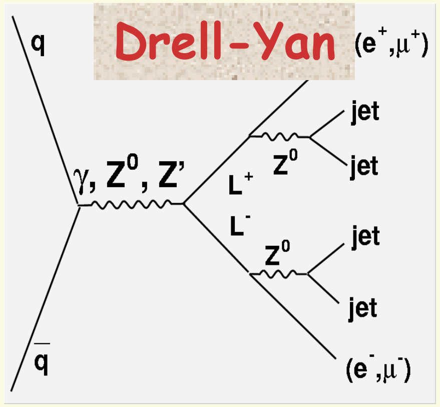
Heavy Leptons (1)

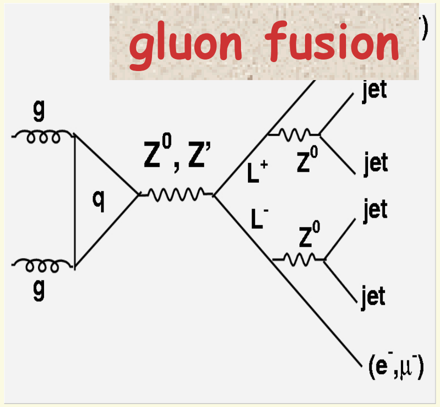


- ✓ Basics
  - Look at sequential lepton: 4th family
  - Other models: VSM, VDM, FMFM
  - Final state llZZ
- ✓ Analysis
  - gg & DY
  - 2l, 2Z (4jets)
  - Bdg: tt, VV+jets



Drell-Yan

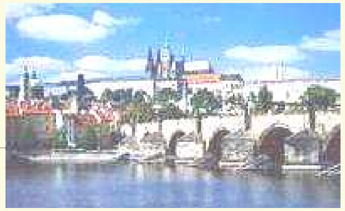
q
(e^+,μ^+)
jet
jet
γ, Z^0, Z'
L^+
Z^0
L^-
Z^0
jet
jet
$\bar{q}$
(e^-,μ^-)



gluon fusion

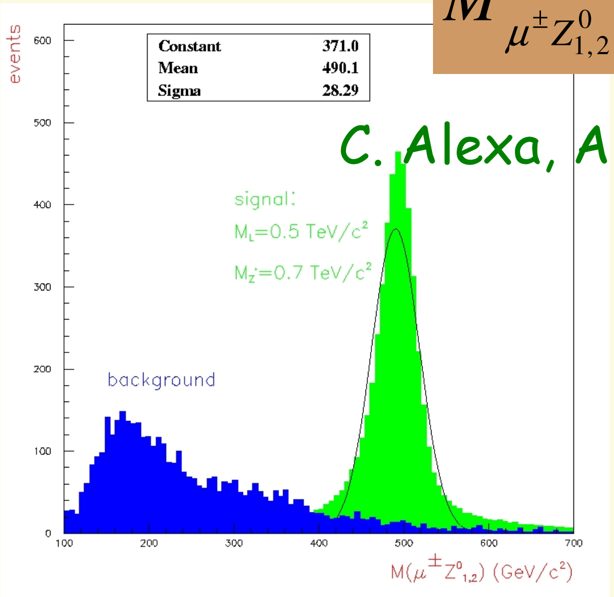
g
Z^0, Z'
jet
jet
q
L^+
Z^0
L^-
Z^0
jet
g
jet
(e^-,μ^-)

Heavy Leptons (2)



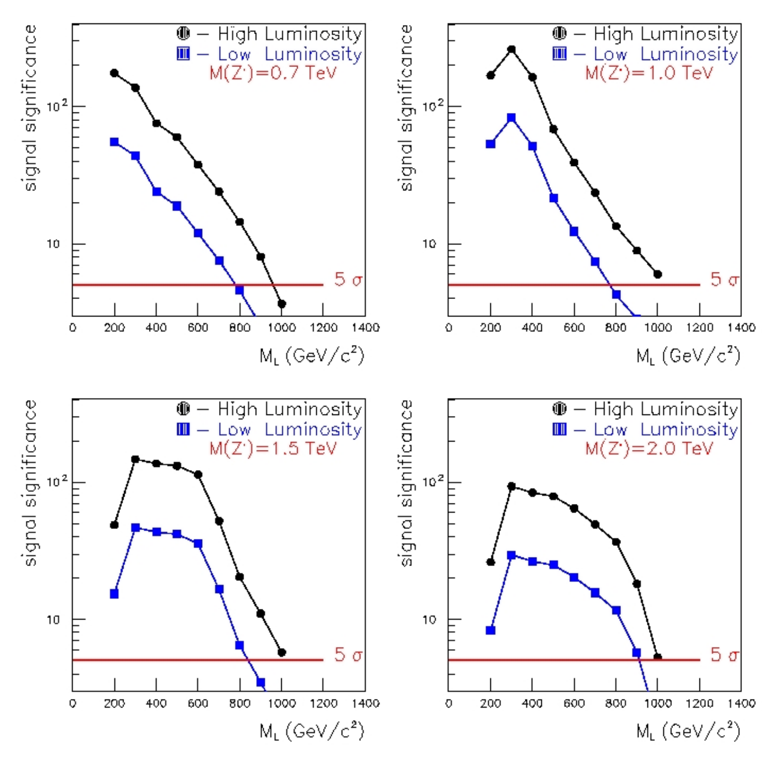
✓Yield

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



C. Alexa, ATLAS

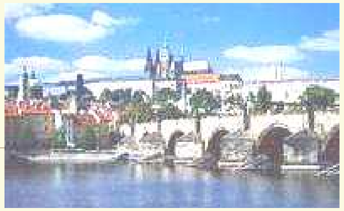
Significance



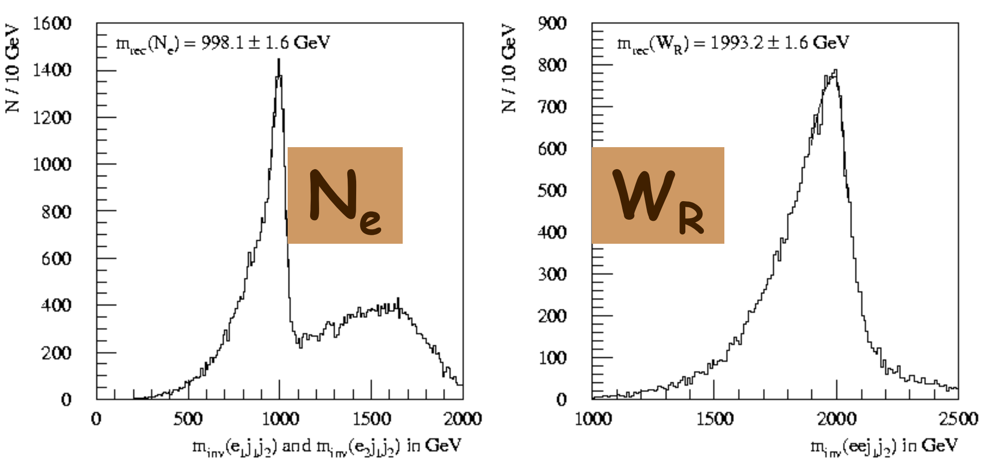
✓Reach

- ~ 1 TeV (e & μ)
- Depend on Z' mass

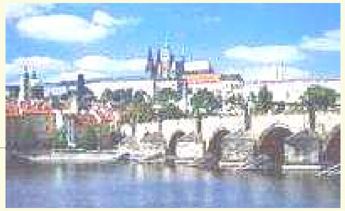
New Gauge Bosons (1)



- ✓ 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



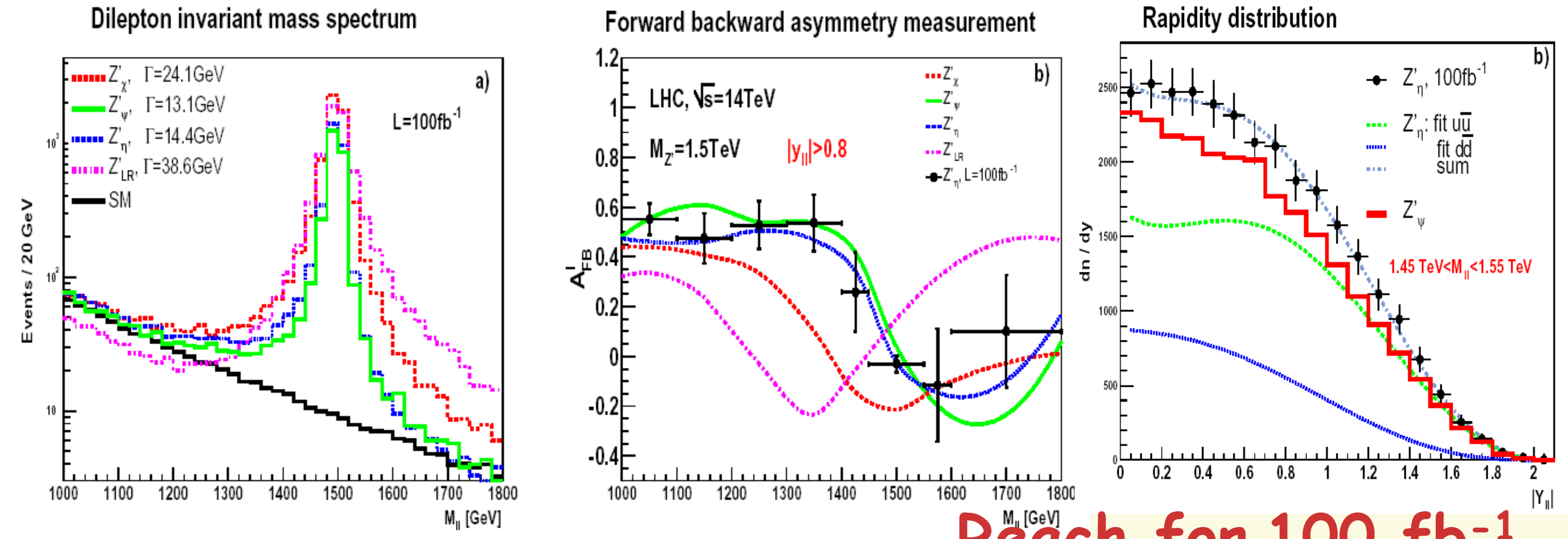
New Gauge Bosons (2)



CMS

Z' -> ll

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

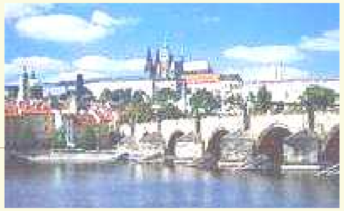


  - Nicollerat, Dittmar, Djouadi
  - See also S. Shmatov's talk

Reach for 100 fb^{-1}

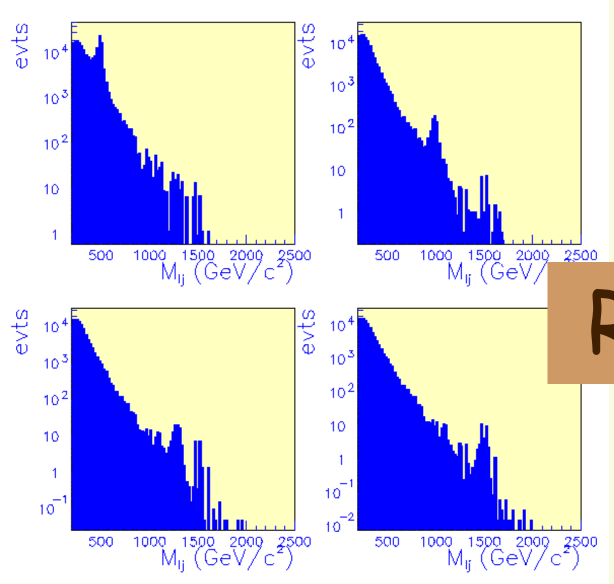
- 4 – 5 TeV
- ID up to 2.5 TeV

Leptoquarks



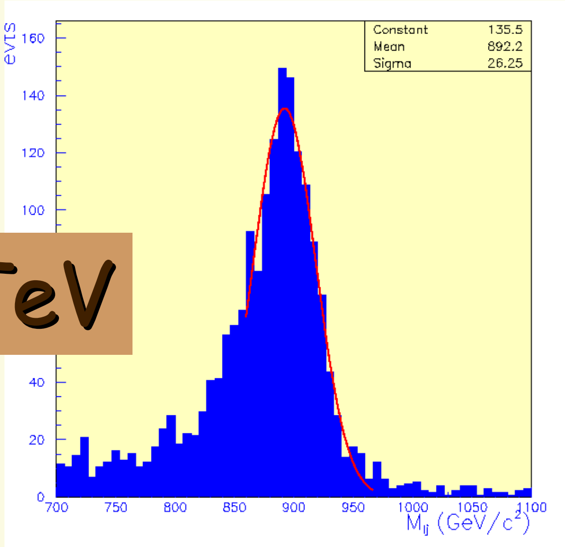
- ✓ Motivation
  - SM extension: lepton-quark symmetry
- ✓ Study: Scalar LQ pair-produced
  - Final state lljj

CMS ejet σ~27 GeV

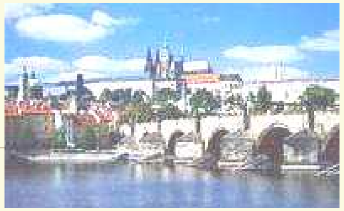


F. Charles et al

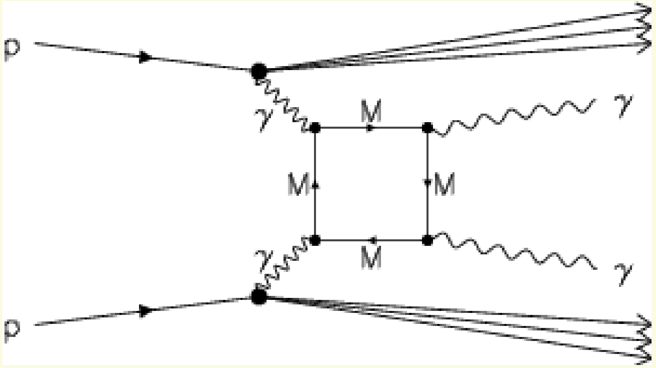
Reach ~1.5 TeV



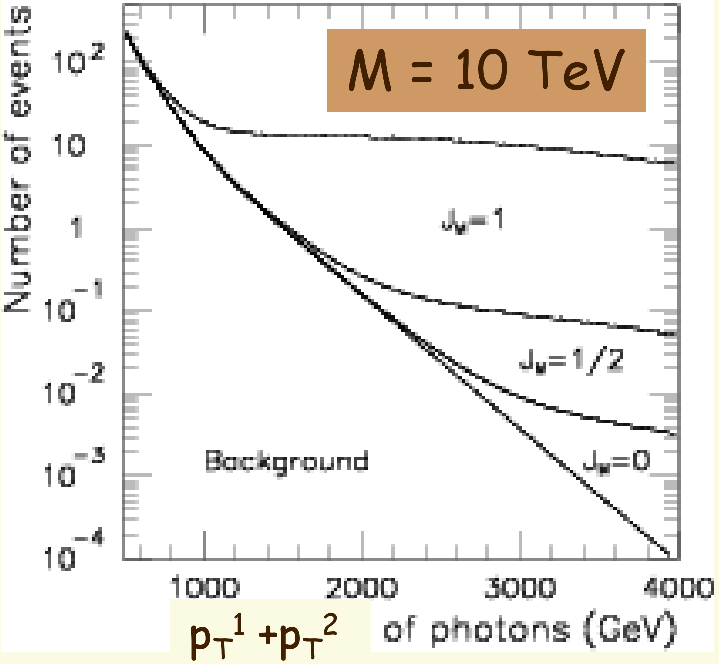
Monopoles



- ✓ Motivation
  - Restores Maxwell's equ'ns symmetry & explains charge quantization



100 fb^{-1}



M = 10 TeV

- ✓ Reach
  - 10-20 TeV (spin dependent)

Little Higgs

- Motivation
- Signatures

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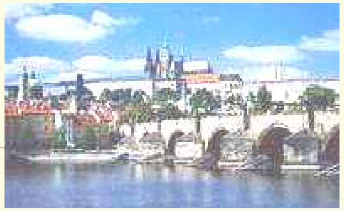
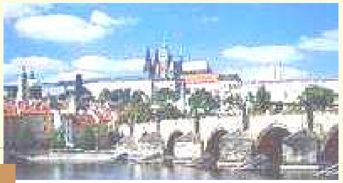
Introduction

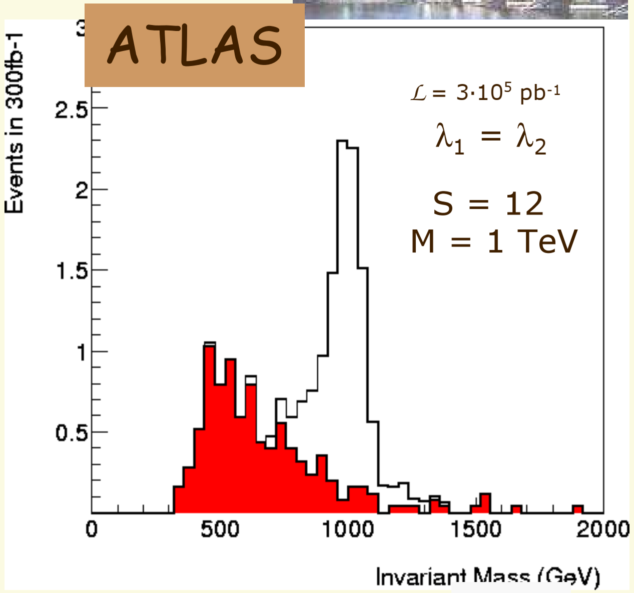


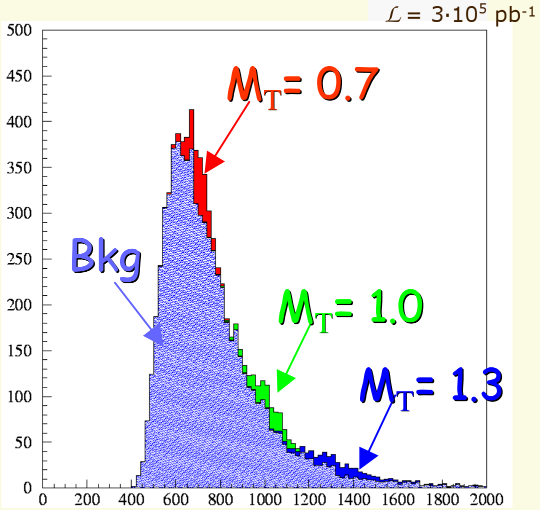
- ✓ Motivation   See M. Lechowski
  - H is ~ Goldstone boson of larger group
  - Cut-off Λ introduced ~ 10 TeV
  - Divergences canceled by
    - $\delta m^2_{H|top}$ New colored fermion T
    - $\delta m^2_{H|gauge}$ New bosons W_H, Z_H, A_H
    - $\delta m^2_{H|Higgs}$ Higgs triplet
- ✓ Issues
  - EW precision tests
    - LEP and Tevatron give **f > 4 TeV at 95% (Λ = 4πf)**
    - Fine tuning > 100 needed to keep m_h ~200 TeV
  - Integrating GUTs

Heavy T

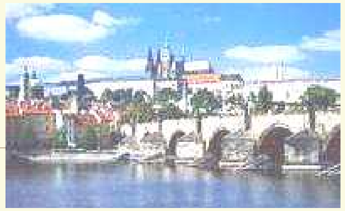


- ✓ Decay
  - bW (50%), tZ (25%), th (25%)
- ✓ tZ mode
  - 3 leptons + 1 b-jet
- ✓ th mode
  - Confirmation mode
  - 3 b-jets + 1 lepton

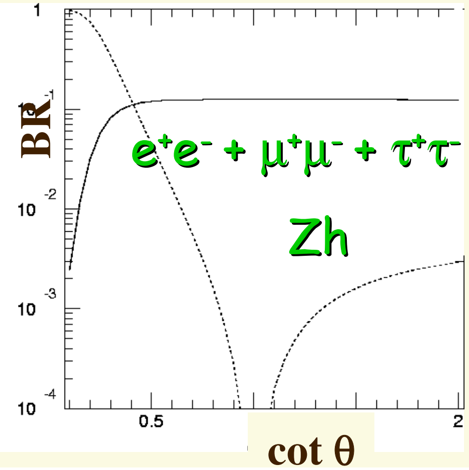


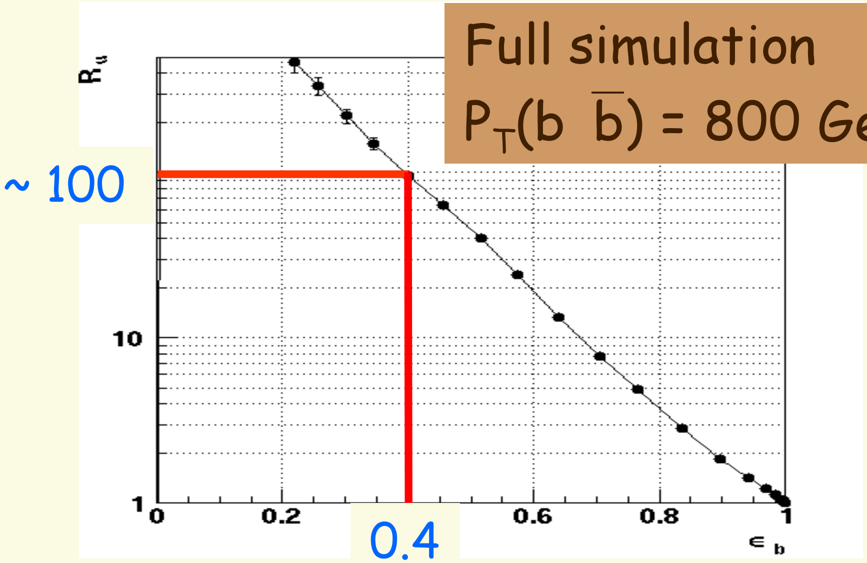


A_H, Z_H



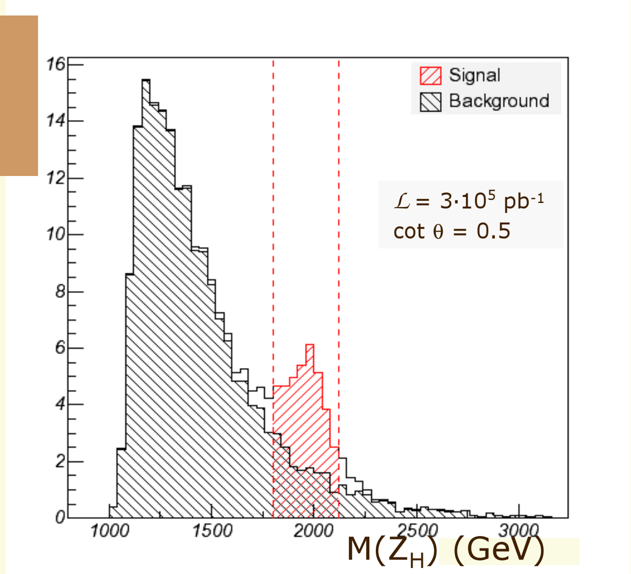
- ✓ Decay : ll and Zh
  - ll mode (ee for resolution)
  - Zh
    - Final state llbb
    - B-tagging crucial



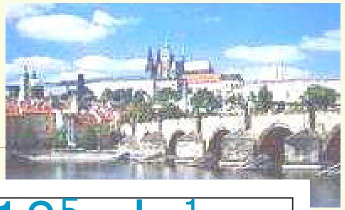


Full simulation

$P_T(b\ \bar{b})$ = 800 GeV



New Higgs Φ^{++}



ATLAS

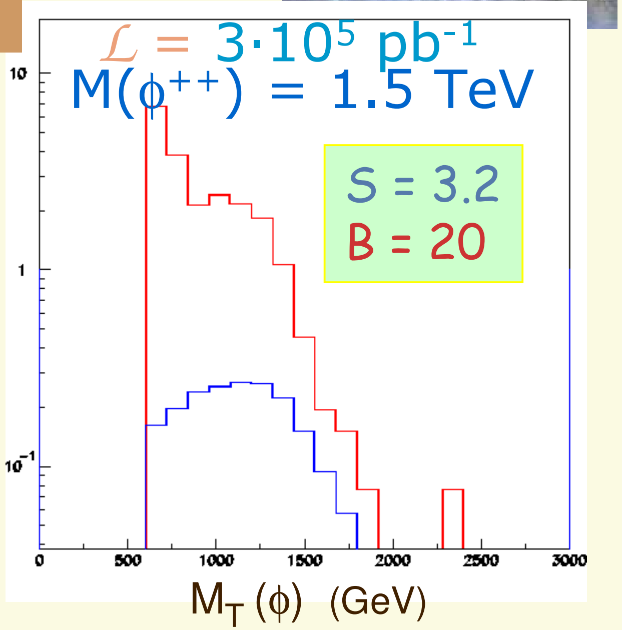
✓ Production

- Via WW fusion

Forward jet tag essential

✓ Decay

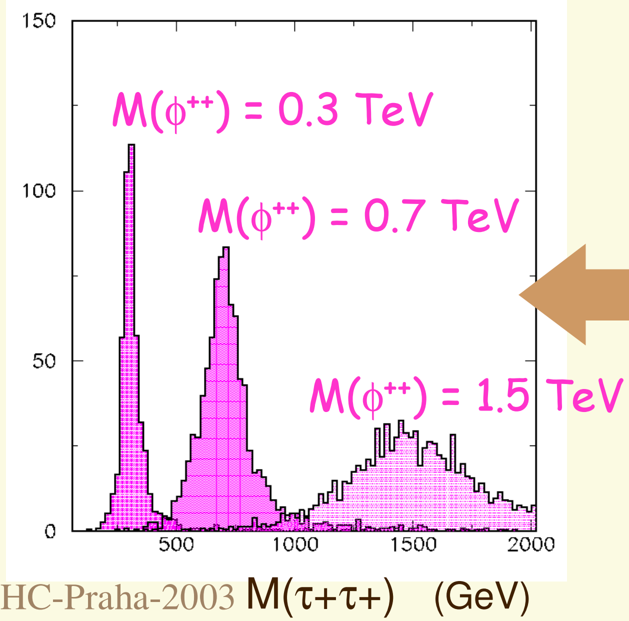
- W^+W^+ to $l^+\nu l^+\nu$



-WW to ee, μμ

-WW to $\tau^+\tau^+$ to l^+ jets

- May be suppressed



Other

- Models with singlet neutrino
- Left-Right symmetry model
- Lepton Flavor Violation
- SLHC

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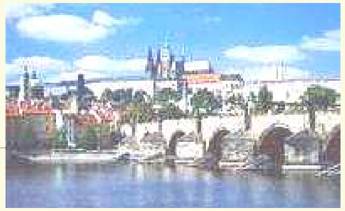
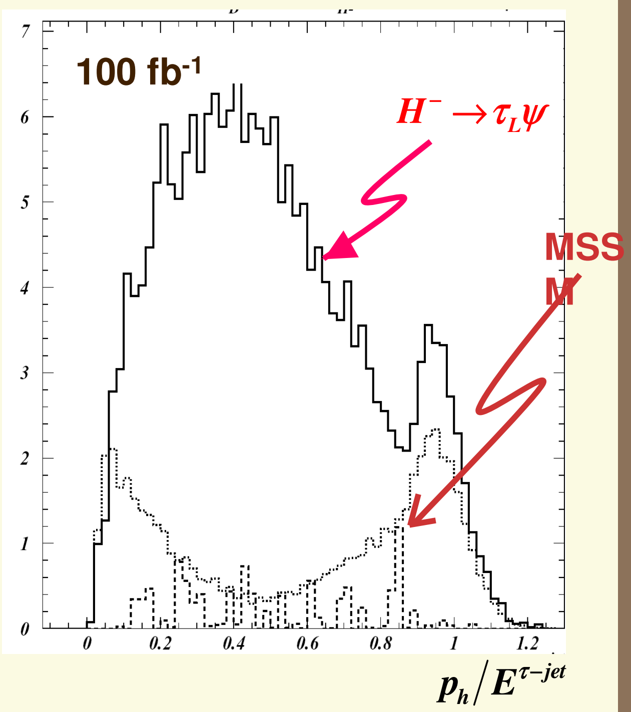
$H^- \rightarrow \tau^- \nu$

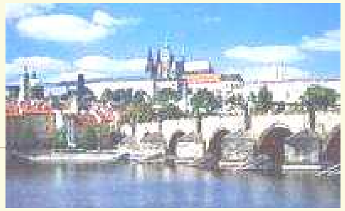


- ✓ In models with singlet neutrino
  - Low ν mass without see-saw
    N. Arkani-Hamed, S. Dimopoulos, G. Dvali, J. March-Russell, *hep-ph/9811448*
  - Single neutrino in bulk
  - 2HDM-II
    - MSSM only $H^- \rightarrow \tau_R \nu$ allowed
    - with presence of singlet bulk neutrino
      $H^- \rightarrow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

ATLAS



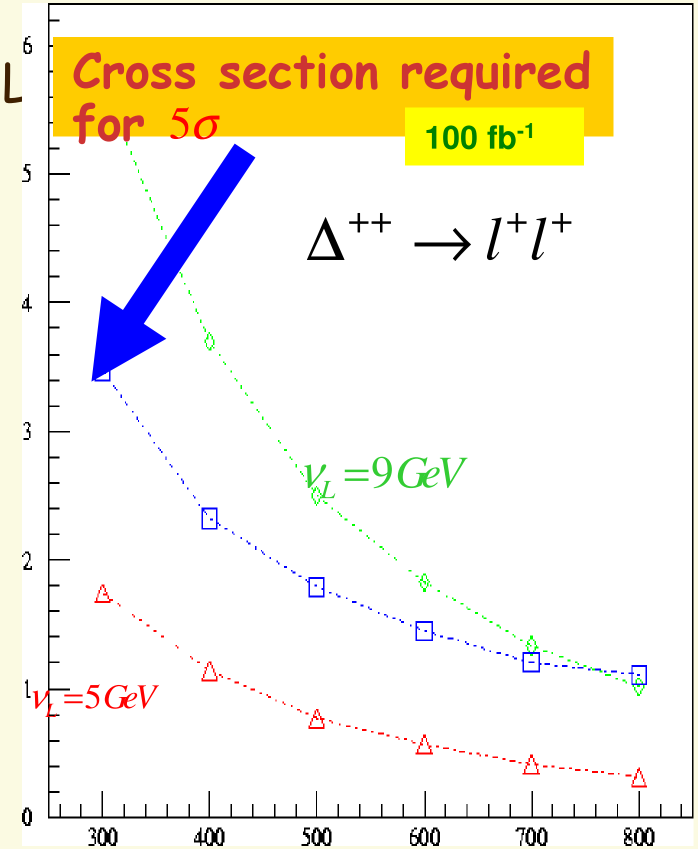
L-R symmetric model



- ✓ Motivation
  - Natural extension of SM
  - $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$
  - Predicts bi-doublet H
- ✓ Observation
  - Preliminary

ATLAS

$$W_L^+W_L^+ \to \Delta_L^{++} \to \ell^+\ell^+$$
$$\to \tau^+\tau^+ \qquad \tau \to l\nu\nu$$
$$\to \tau^+\tau^+ \to l^+ h \ X$$
$$\to W^+W^+ \to l^+\nu \ l^+\nu$$

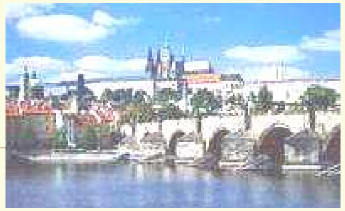


Cross section required for 5σ

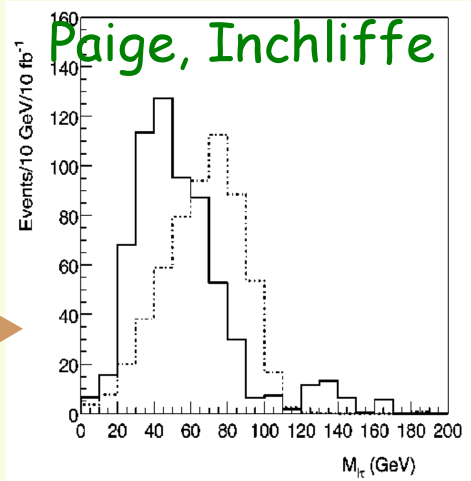
100 fb^{-1}

$\Delta^{++} \to l^+l^+$

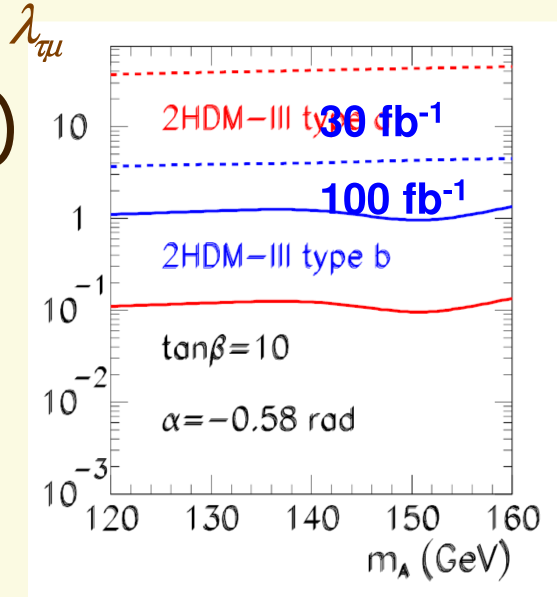
Lepton Flavor Violation



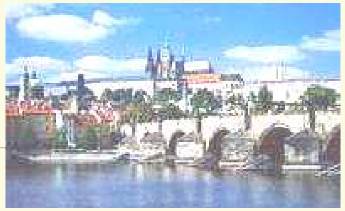
- ✓ τ -> μ γ See K. Mazumdar
  - Expect 5x10^{-7} from Z -> τ τ
- ✓ τ -> μμμ : Under study
- ✓ mSUGRA $\tilde{\chi}_2^0 \to \tilde{\tau}\tau \to \tilde{\chi}_1^0 \mu\tau$
  - LFV decays give $\mu^+ \tau^-$ signal
  - asymmetry in $\mu^+ \tau^-$ & $e^+ \tau^-$
  - Expect sensitivity ~ O(10^{-9})
- ✓ A/H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



Paige, Inchliffe



Super LHC

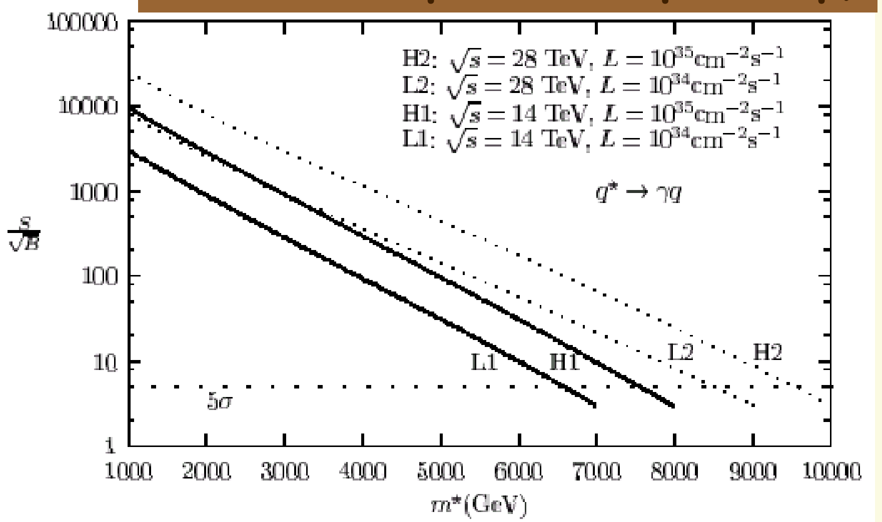


- ✓ 2 options
  - 1000fb^{-1} or 28 TeV (more difficult)
- ✓ Potential

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

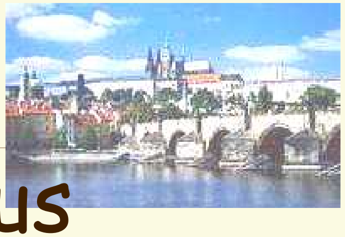
Excited quarks: q* -> qγ



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