Prospects for BSM searches at LHC

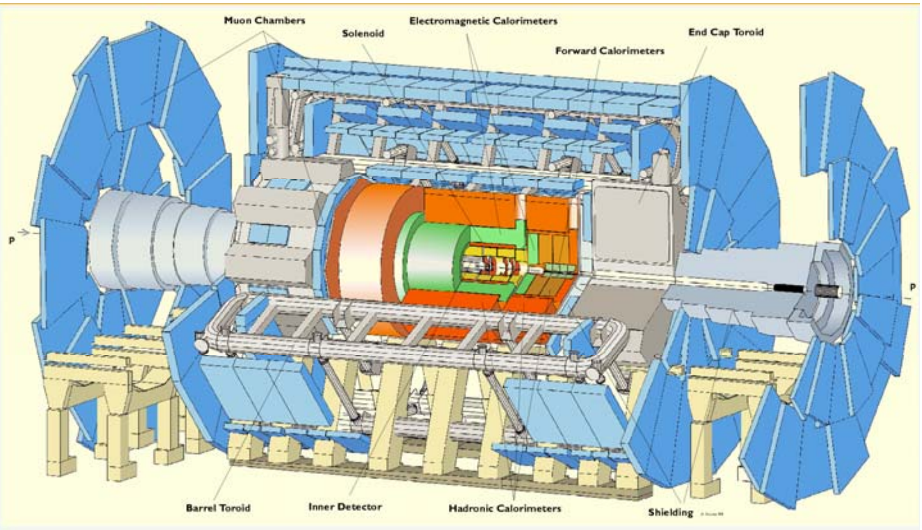
- Supersymmetry
- Dynamical symmetry breaking
- extended gauge symmetry
- compositeness
- extra dimensions

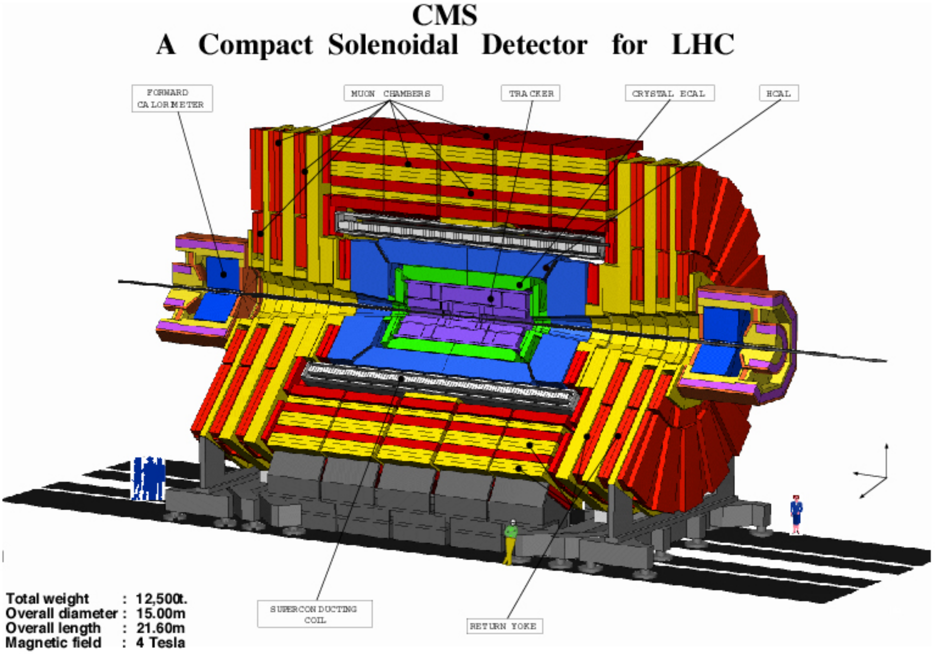
Apologies: - biased selection of physics processes
- bias towards ATLAS

LHC parameters

pp collider, $\sqrt{s} = 14\ \mathrm{TeV}$ starting: 2007, 2 detectors

ATLAS





First year proton parameters: (see web page here)

- luminosity: 1.2 × 10^{33} cm^{-2}s^{-1}
- bunch crossing: 25 ns

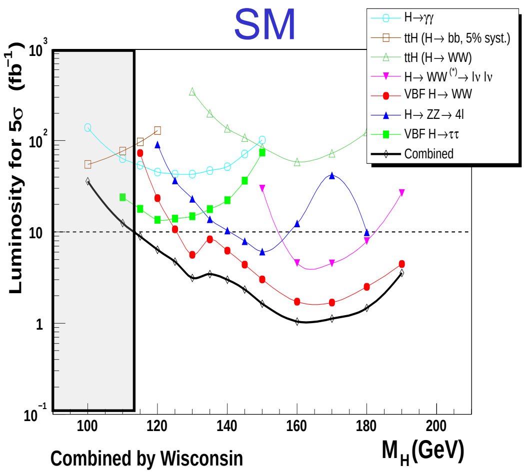
Nominal parameters: (see here)

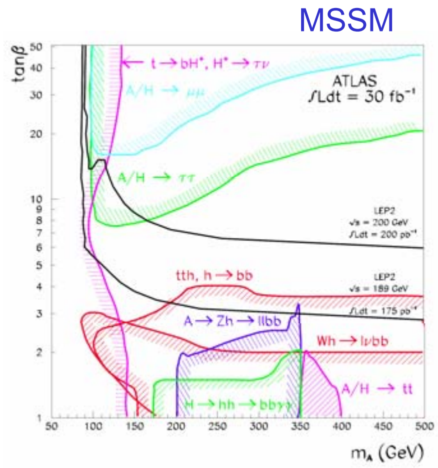
- luminosity: 1.0 × 10^{34} cm^{-2}s^{-1}
- bunch crossing: 25 ns

➔ ~ 23 min. bias events per bunch crossing

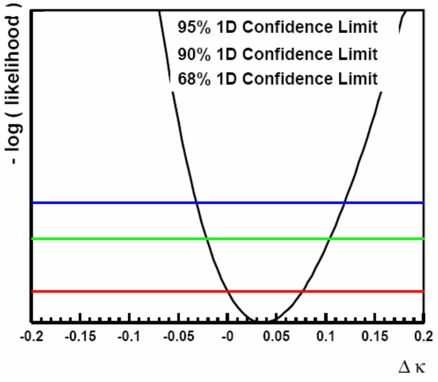
I shall not talk about BSM in …

- **Higgs →** ***see previous talk by A. Nikitenko***





- **top quark physics →** ***see next talk by E. Thomson***
- **B physics**
- **precision EW, TGC, etc**
- **QCD**
- **Heavy ions …**



Supersymmetry

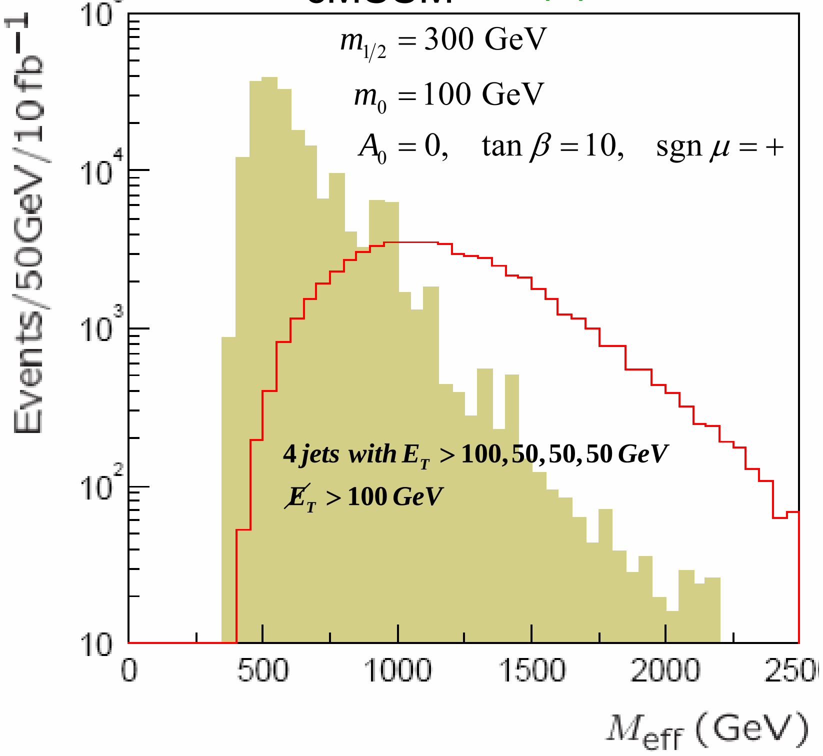
Inclusive signal with jets (R-conservation)

- trigger: Jets + $\not{E}_T$
- main background: SUSY

$$\boxed{\tilde{g}\tilde{g} \to \ldots \text{ cascade } \to \tilde{\chi}_1^0\tilde{\chi}_1^0 + jets + leptons}$$

F. Paige
hep-ph/0307342

cMSSM

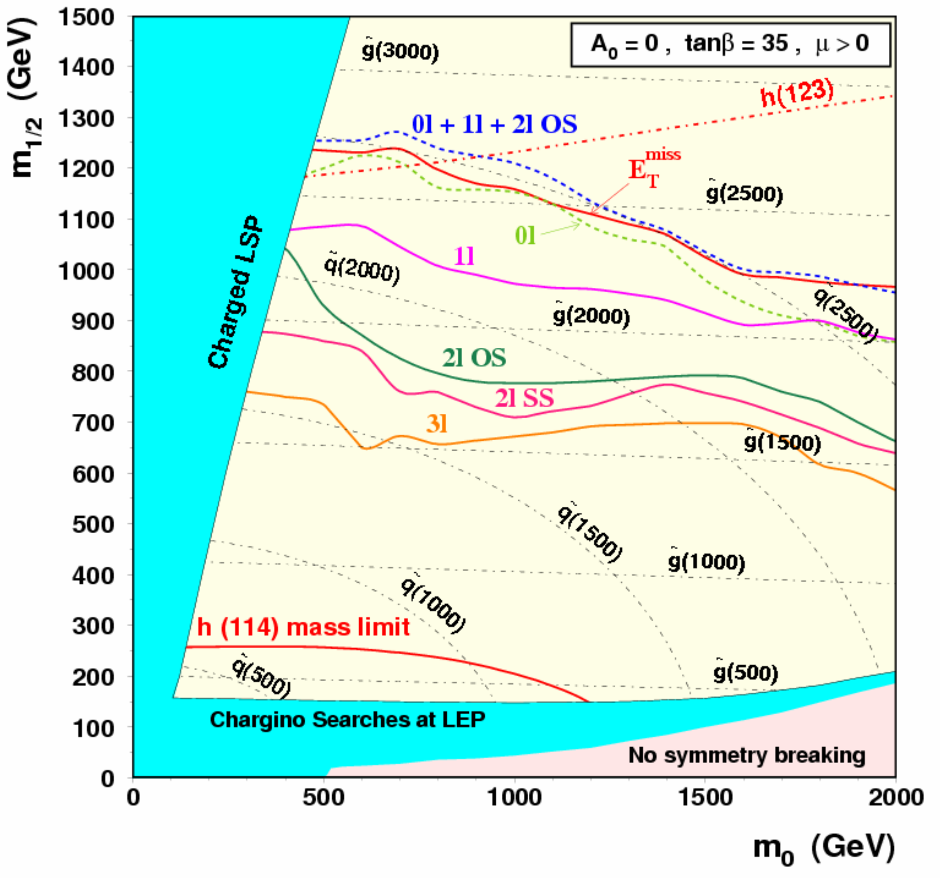


$$M_{eff} \equiv \sum_{jets} E_T^{jets} + \not{E}_T$$: good measure of M_{SUSY}

$\Rightarrow$ preselect SUSY-rich sample

LHC reach, 100 fb^{-1}, various signals:

CMS Note 1998/073

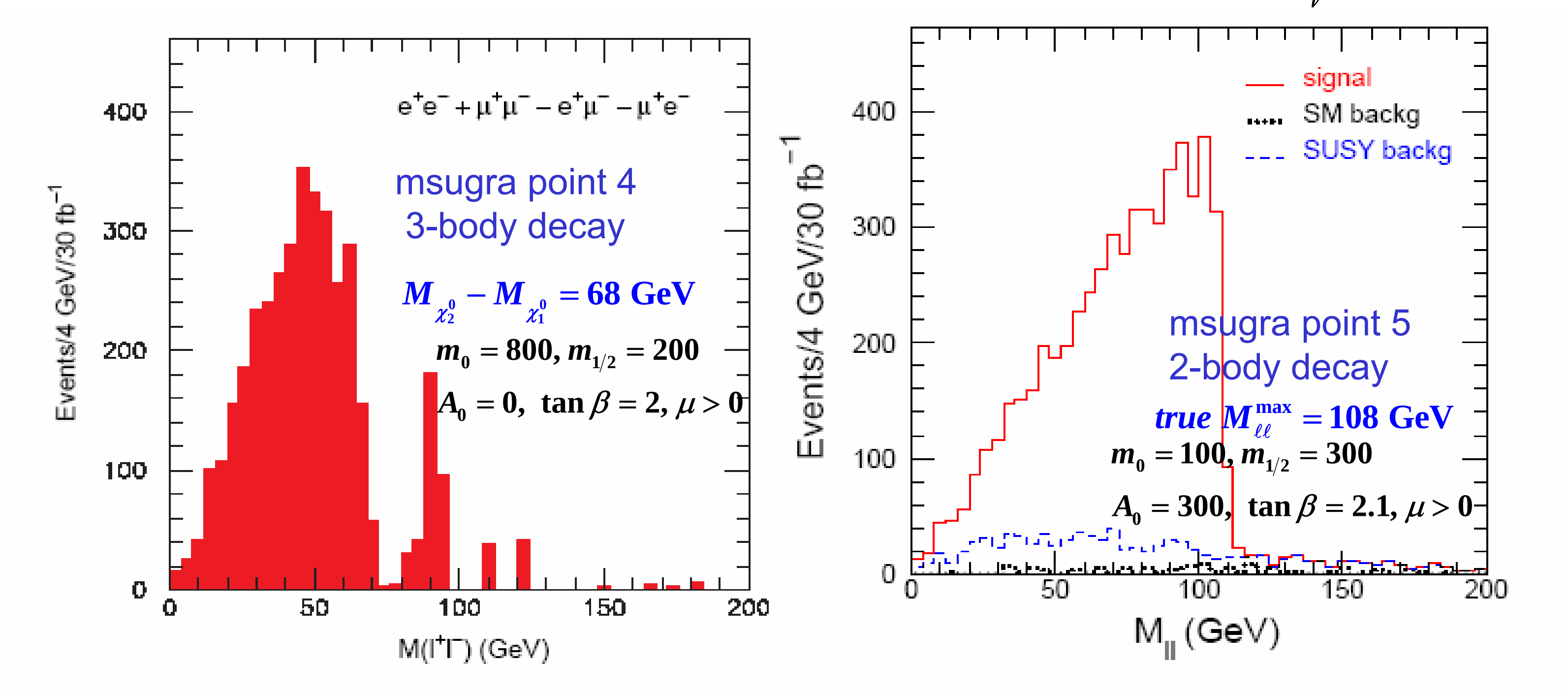


Supersymmetry

- **Mass reconstruction from di-lepton endpoints**

3-body decay: $\tilde{\chi}^0_2 \rightarrow \tilde{\chi}^0_1 \ell^+ \ell^- \Rightarrow M_{\ell\ell} < M_{\tilde{\chi}^0_2} - M_{\tilde{\chi}^0_1}$

2-body decay: $\tilde{\chi}^0_2 \rightarrow \tilde{\ell}^\pm \ell^\mp \rightarrow \tilde{\chi}^0_1 \ell^+ \ell^- \Rightarrow M_{\ell\ell} < \dfrac{\sqrt{(M^2_{\tilde{\chi}^0_2} - M^2_{\tilde{\ell}})(M^2_{\tilde{\ell}} - M^2_{\tilde{\chi}^0_1})}}{M_{\tilde{\ell}}}$



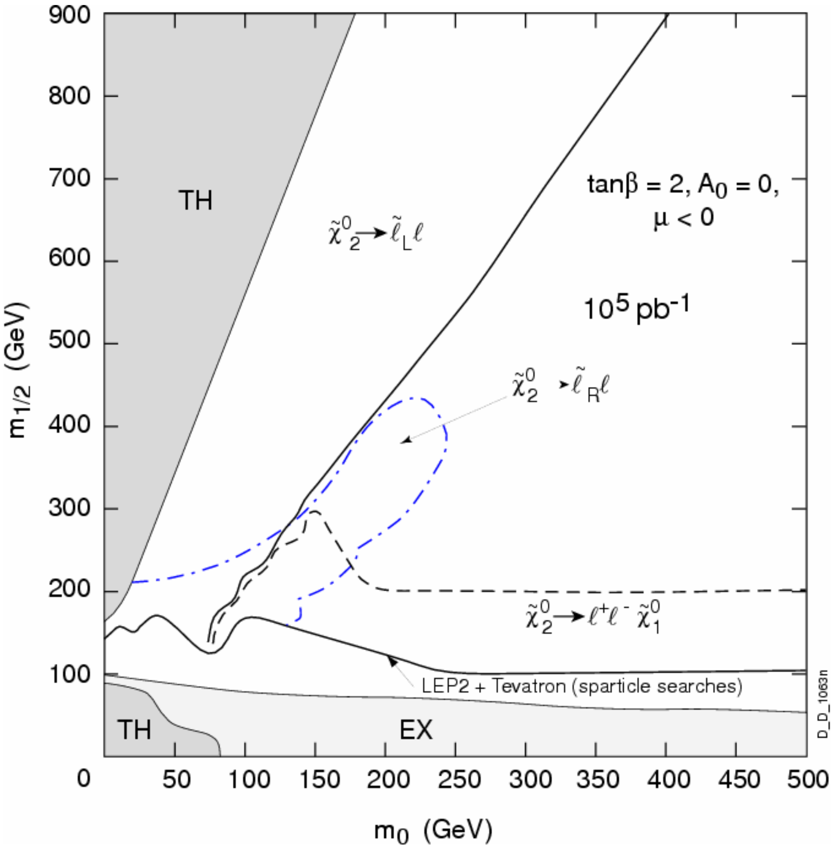
SM background removed by subtracting distributions with opposite flavor leptons
precision in end-point measurement: ~ 1-2 %

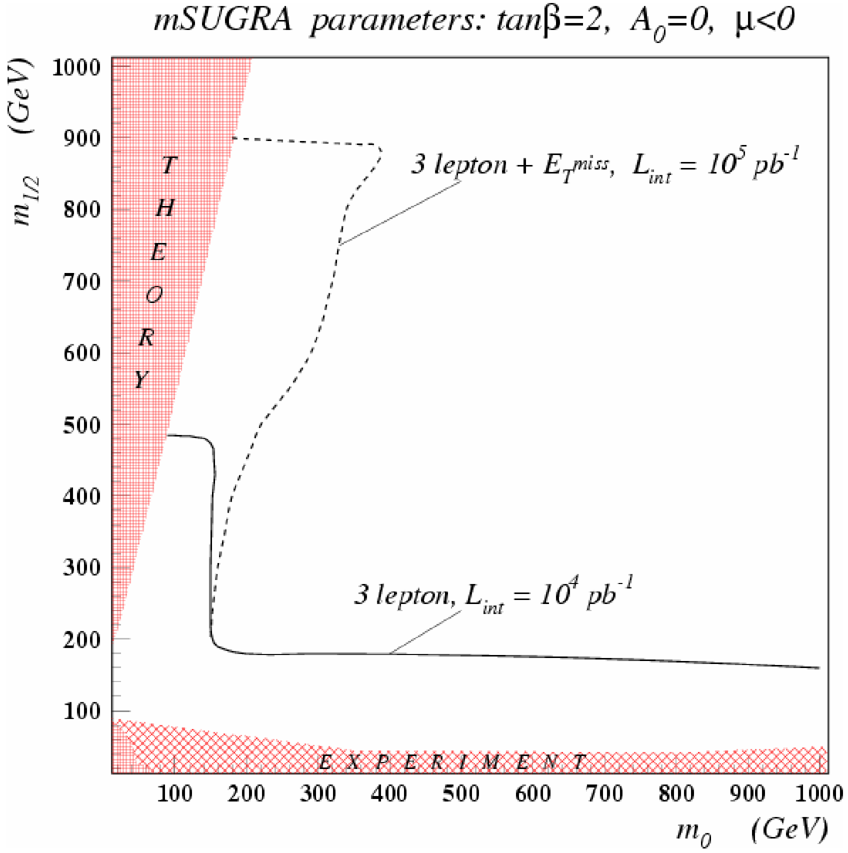
Supersymmetry

- **Inclusive signal from di-lepton endpoint**

2 leptons + E_T^{miss} + jets

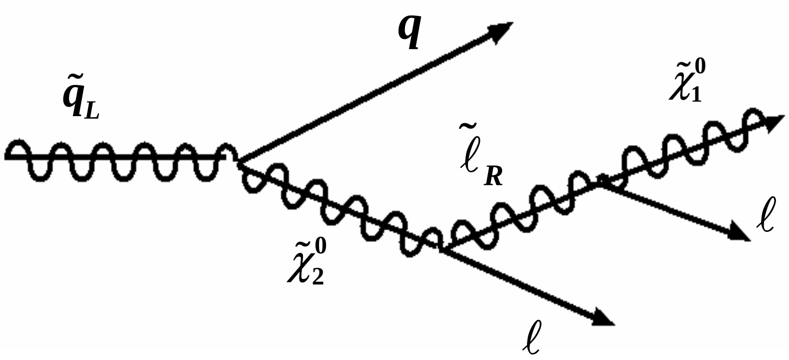
Direct $\tilde{\chi}_1^+ \tilde{\chi}_2^0$production $\rightarrow \ell \tilde{\nu} \;\; \ell\ell\tilde{\chi}_1^0$





CMS

Supersymmetry



reconstruction higher up in the chain possible

mass relations with ~ 1% precision

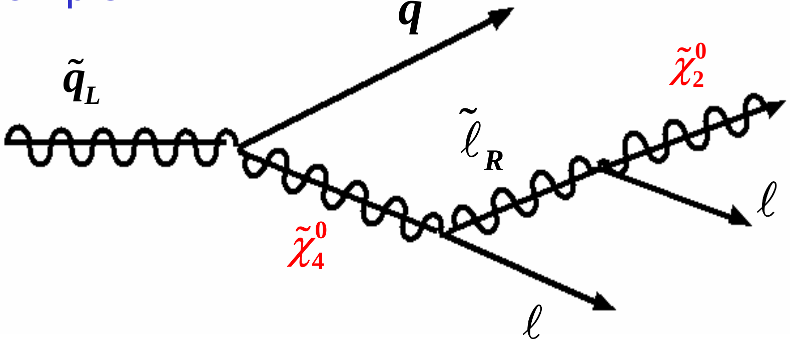
$\tilde{\chi}_1^0$ mass: ~ 10%

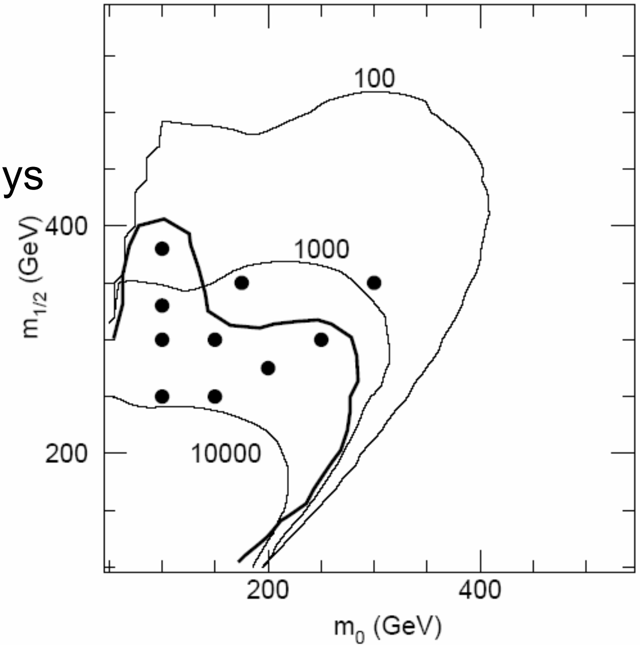
Heavy gauginos

$\tilde{\chi}_4^0, \tilde{\chi}_2^\pm$ have non-negligible gaugino content

→ participate in squark and gluino decays

example:





LHC reach, 100 fb^{-1}

F. Paige,
Physics at LHC, Vienna

Supersymmetry

3rd generation squarks

$\tilde g \to \bar t\ \tilde t_1$

$\hookrightarrow b\tilde\chi_1^+$ or $c\tilde\chi_1^0$

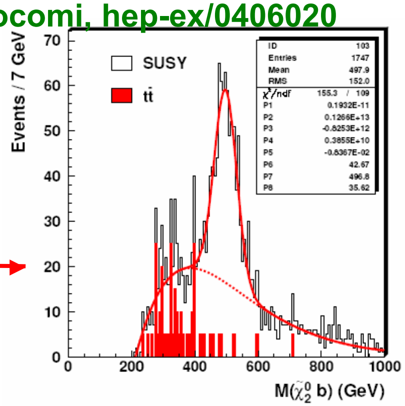
$\tilde g \to \tilde b_1\ b$

$\hookrightarrow \tilde\chi_2^0 \bar b$

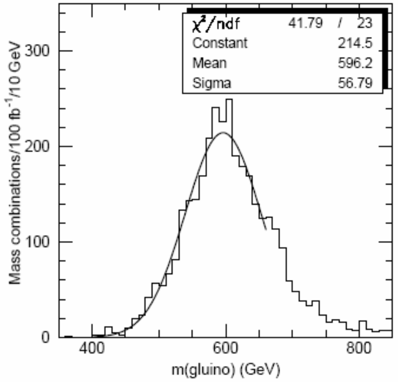
$\hookrightarrow \chi_1^0 \ell\ell$

- important for distinguishing between SUSY models
- difficult, but possible to measure combination of masses (m_{tb})
- knowing $\tilde\chi$ masses, can reconstruct $\tilde g$ and $\tilde b$
- mass relation method:
  - constraint: require same masses in several events

A. Trocomi, hep-ex/0406020



Nojiri et al, hep-ph/0312317

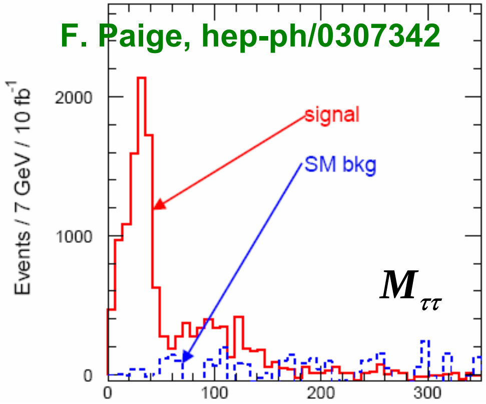


$\tilde\tau$'s

- identification of τ's in leptonic decays difficult because of E_T^{miss}
  → use hadronic decays, but high background
- polarisation measurement appears possible

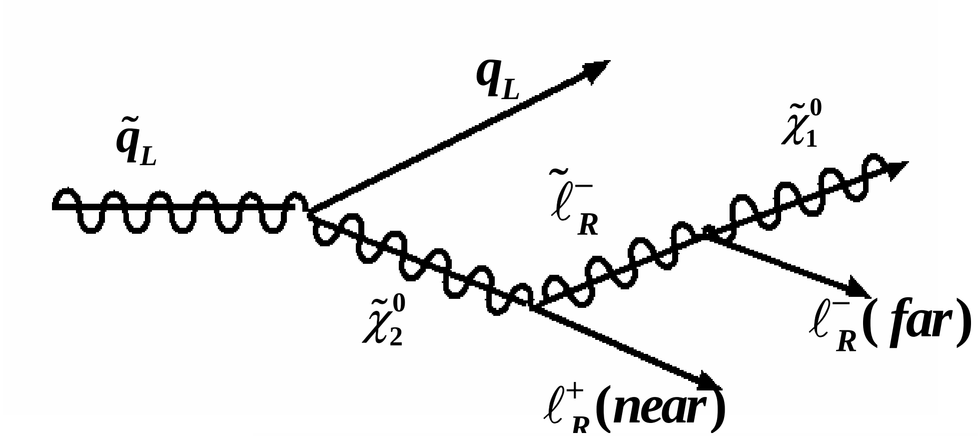
$\chi_2^0 \to \tilde\tau\tau$

$\hookrightarrow \tau\chi_1^0$



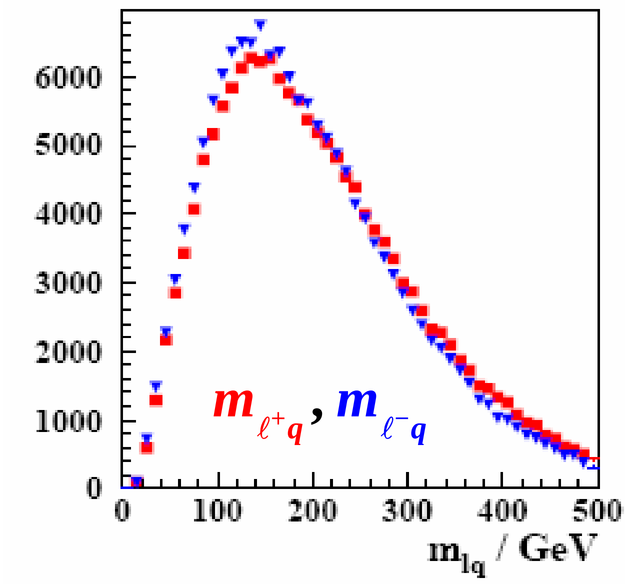
Supersymmetry – other topics

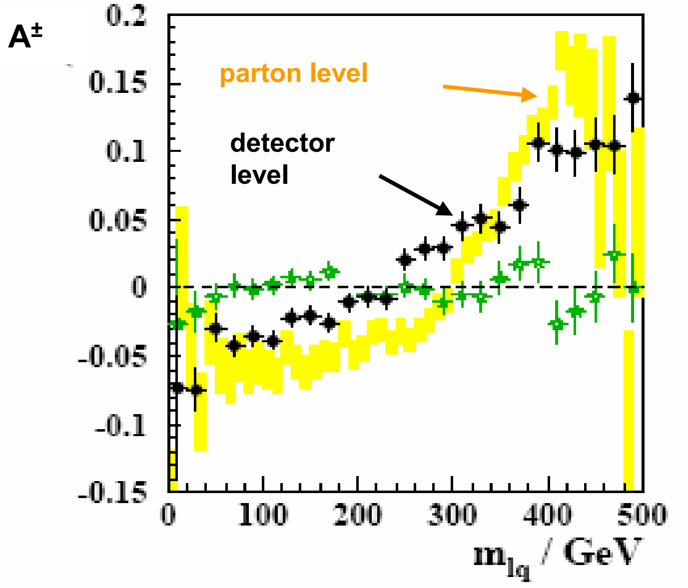
- **Spin measurements** **A.J. Barr, hep-ph/0405052**
  - evidence for supersymmetry (vs extra dimensions, for example)



polarization of χ_2^0 induces asymmetry

seems feasible, with 150 fb^{-1}





Supersymmetry – other topics

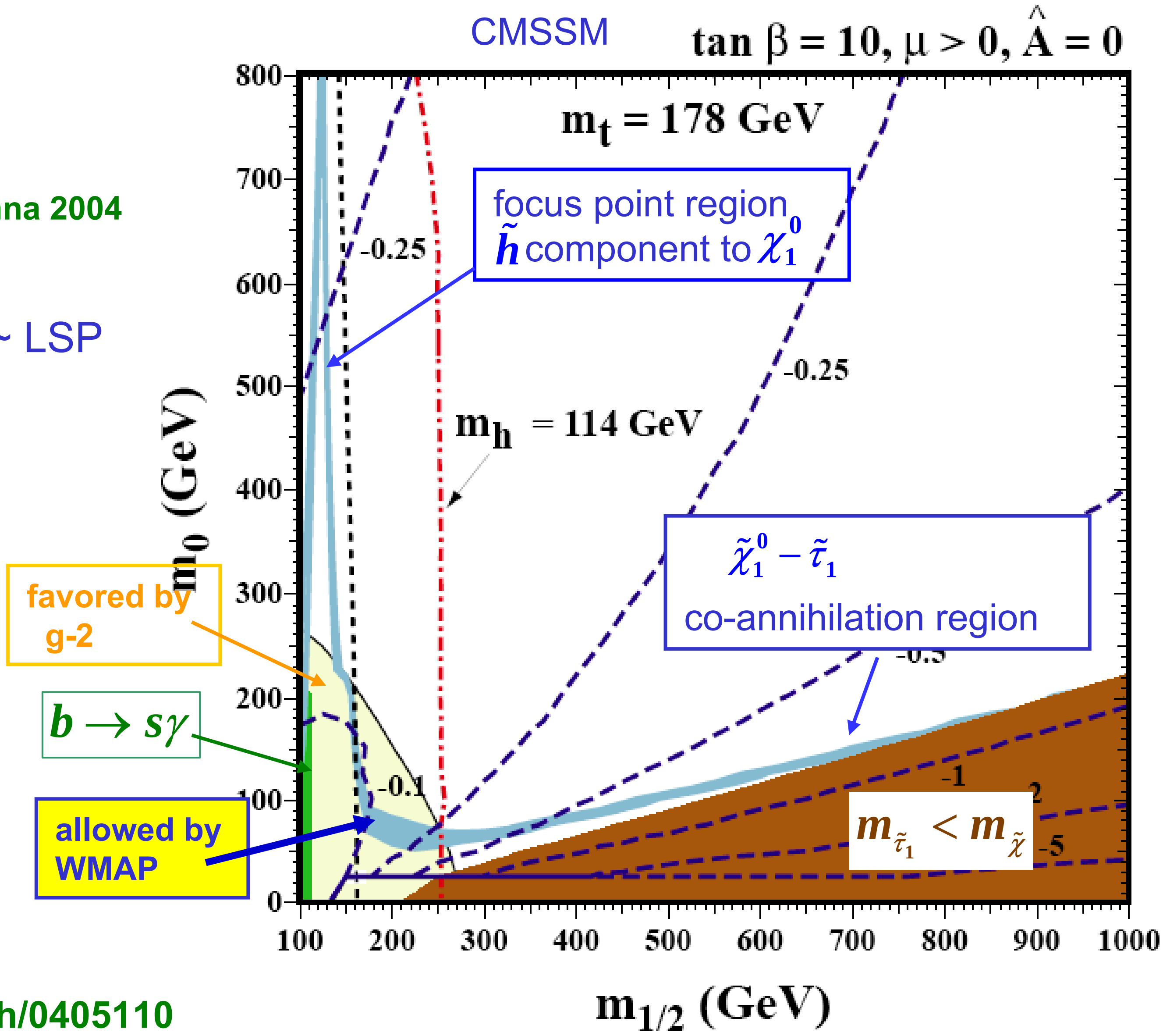
- **GMSB**
  - $LSP : \tilde{G}, \quad NLSP : \tilde{\chi}_1^0$ or $\tilde{\ell}\ (\tilde{\tau}_R)$
  - jets + E_t^{miss}: ~ similar reach as MSugra
  - signatures: **Kawagoe, Vienna 2004**
    - $\tilde{\chi}_1^0 \to \tilde{G}\,\ell^+\ell^-$ for short lifetimes, or
    - $\tilde{\chi}_1^0 \to \tilde{G}\,\gamma$: non-pointing photons for long lifetimes
    - $\tilde{\ell} \approx$ slow “muon” $\Rightarrow$ TOF measurements
    - $\tilde{\ell} \to \ell\chi_1^0 \to \ell\,\gamma\tilde{G}$: non-pointing photons
- **AMSB**
  - light $\tilde{W}$ or $\tilde{\nu}$
  - $\tilde{\ell}$ pairs: $p\bar{p} \to \tilde{\nu}_L \tilde{\ell}_L^{\pm} \to \ell^{\mp}\tilde{W}^{\pm}\ \ell^{\pm}\tilde{W}^{0};$ displaced vtx from $\tilde{W}^{\pm} \to \tilde{W}^{0}\pi^{\pm}$
- **Generic SUSY search by statistical method**

Duchovni, SN-ATLAS-2004-043

- **R-parity violating processes**
- **Split Supersymmetry**
  - heavy, stable gluino → R-hadron

Supersymmetry vs WMAP

- **Focus point**
  - heavy scalars
  - sensitive to m_t
  - **see T. Lari, at Vienna 2004**
- **co-annilation**
  - mass: slepton ~ LSP



CMSSM $\tan\beta = 10, \mu > 0, \hat{A} = 0$

focus point region
$\tilde{h}$ component to χ_1^0

$\tilde{\chi}_1^0 - \tilde{\tau}_1$
co-annihilation region

favored by g-2

$b \to s\gamma$

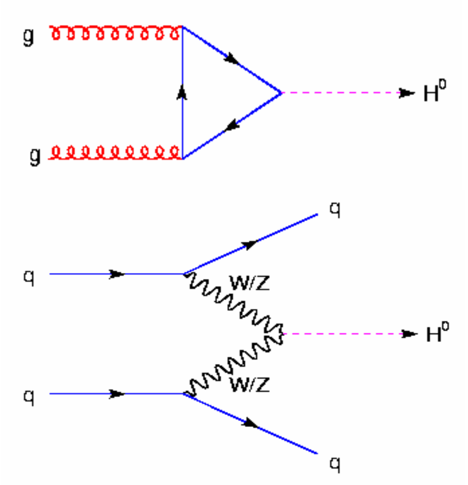
allowed by WMAP

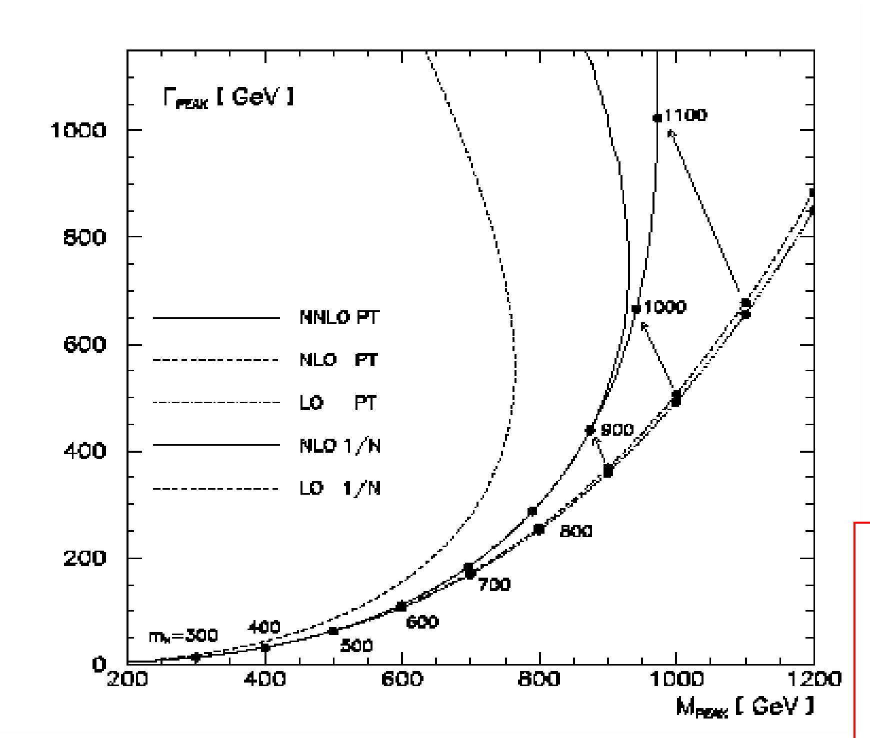
$m_{\tilde{\tau}_1} < m_{\tilde{\chi}}$

J. Ellis et al., hep-ph/0405110

Strong symmetry breaking

- As m_H increases, $V_L V_L$ coupling increases
  - vector boson fusion process becomes important
    - forward jet tagging!
  - saturation of width of Higgs boson





Perturbative and nonperturbative Higgs signals
Adrian Ghinculov and Thomas Binoth hep-ph/9807227

Experimental considerations:
- forward jet tagging
- central jet veto

- **In the absence of SM Higgs**
  - violation of perturbative unitarity for $m_H \gtrsim \text{TeV}$
- **hierarchy problem**

⇒ "guaranteed" new physics at LHC in EW sector

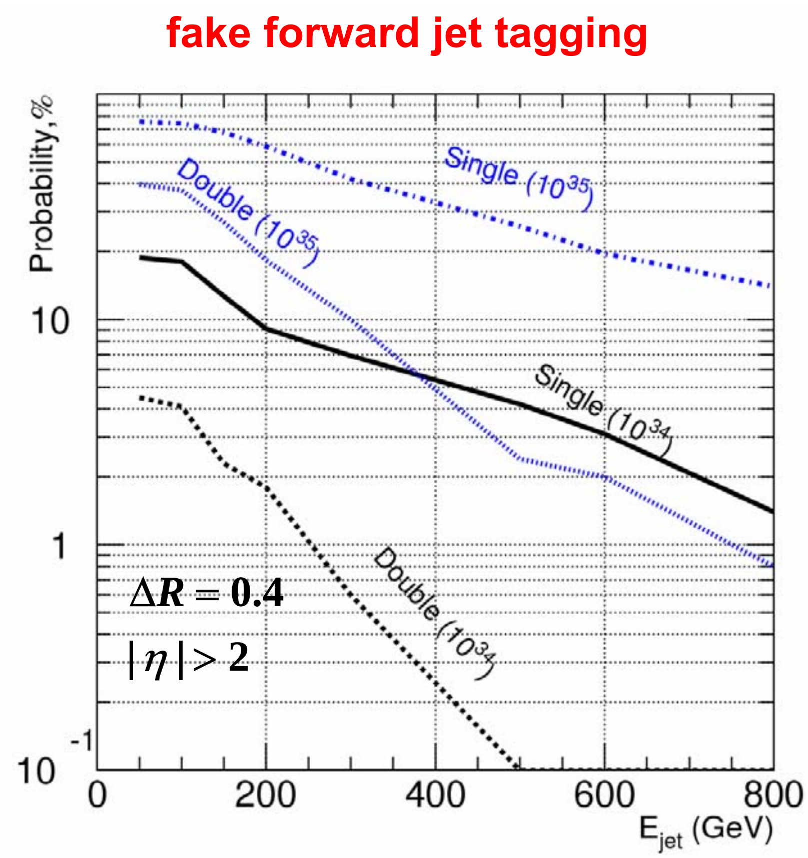
Strong Dynamics

Forward jet tagging and central jet veto:
- essential for $t\bar{t}$ and $W+j$ rejection
- need to understand fake tagging and fake central jet due to pileup

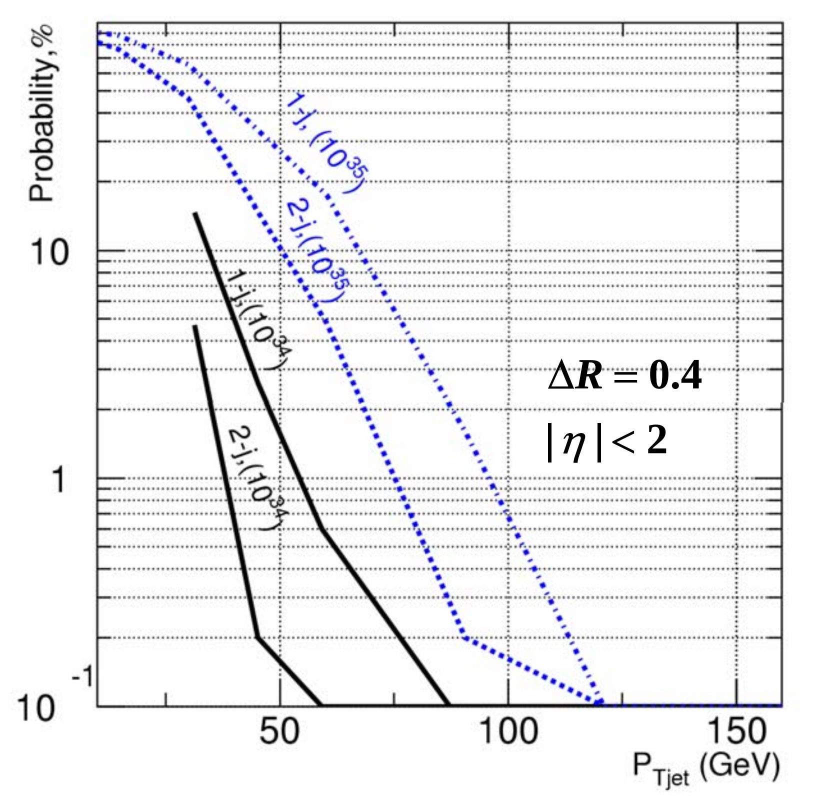
G.A: in superLHC study, hep-ph/0204087
also: D. Costanzo, ATL-PHYS-2002-008

Rough estimates

fake forward jet tagging



extra central jet



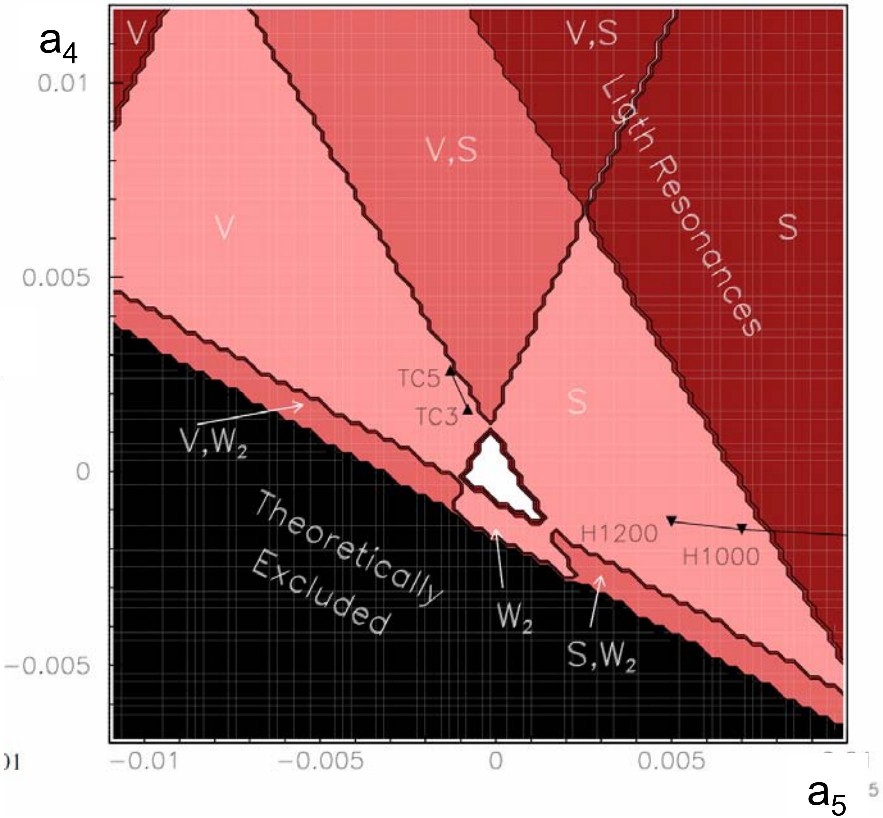
Chiral Lagrangian Model

- **Effective theory: expansion in derivatives (momenta)**
  - couples Goldstone bosons to gauge bosons, respect SU(2) x U(1) invariance

$$
\begin{aligned}
\mathcal{L}_{\rm EChL} = {} & \frac{v^2}{4}{\rm Tr}D_\mu U(D^\mu U)^\dagger + a_0\frac{g'^2v^2}{4}[{\rm Tr}(TV_\mu)]^2 \\
& + a_1\frac{igg'}{2}B_{\mu\nu}{\rm Tr}(T\mathcal{W}^{\mu\nu}) + a_2\frac{ig'}{2}B_{\mu\nu}{\rm Tr}(T[V^\mu,V^\nu]) \\
& + a_3 g{\rm Tr}(\mathcal{W}_{\mu\nu}[V^\mu,V^\nu]) + a_4[{\rm Tr}(V_\mu V_\nu)]^2 \\
& + a_5[{\rm Tr}(V_\mu V^\mu)]^2 + a_6{\rm Tr}(V_\mu V_\nu){\rm Tr}(TV^\mu){\rm Tr}(TV^\nu) \\
& + a_7{\rm Tr}(V_\mu V^\mu)[{\rm Tr}(TV^\nu)]^2 + a_8\frac{g^2}{4}[{\rm Tr}(T\mathcal{W}_{\mu\nu})]^2 \\
& + a_9\frac{g}{2}{\rm Tr}(T\mathcal{W}_{\mu\nu}){\rm Tr}(T[V^\mu,V^\nu]) \\
& + a_{10}[{\rm Tr}(TV_\mu){\rm Tr}(TV_\nu)]^2 \\
& + \text{e.o.m. terms} + \text{standard YM terms}
\end{aligned}
$$

VB scattering

CERN 2000-004
Pelaez, hep-ph/9912224
Pelaez, hep-ph/9609427



[details](#)

after unitarization

extra

$$U(x) = \exp\left(\frac{i\omega^a(x)\tau^a}{v}\right)$$

$$T \equiv U\tau^3U^\dagger; \quad V_\mu \equiv (D_\mu U)U^\dagger$$

$$\begin{aligned}
D_\mu U &\equiv \partial_\mu U - g\mathcal{W}_\mu U + g' U\mathcal{B}_\mu, \\
\mathcal{W}_\mu &\equiv \frac{-i}{2}\,\vec{W}_\mu \cdot \vec{\tau}, \quad \mathcal{B}_\mu \equiv \frac{-i}{2}\,B_\mu\,\tau^3, \\
\mathcal{W}_{\mu\nu} &\equiv \partial_\mu \mathcal{W}_\nu - \partial_\nu \mathcal{W}_\mu - g[\mathcal{W}_\mu, \mathcal{W}_\nu], \\
B_{\mu\nu} &\equiv \partial_\mu B_\nu - \partial_\nu B_\mu.
\end{aligned}$$

Strong Symmetry Breaking

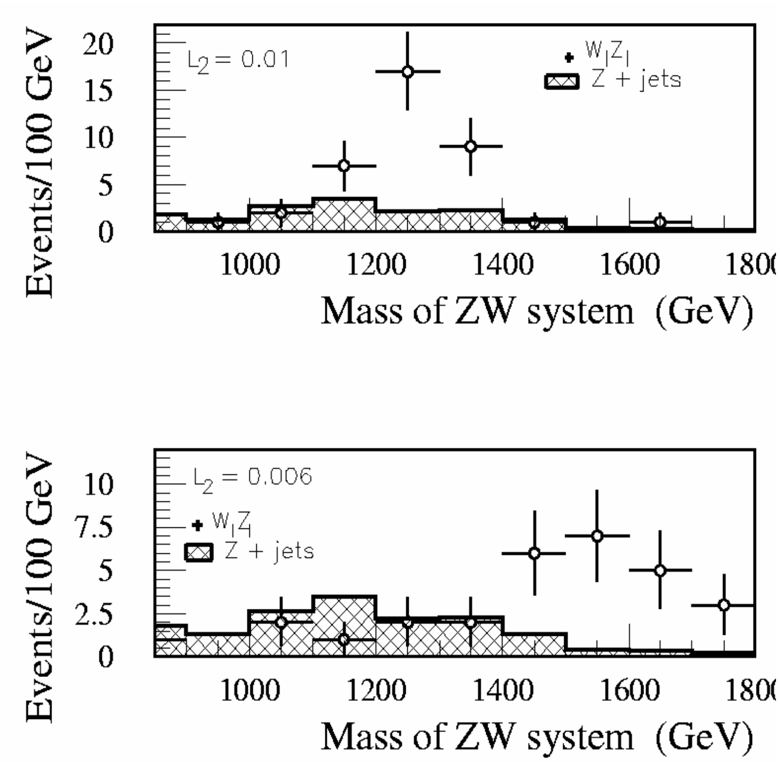
- ***WZ (I,J = 1,1)*** **scattering in ChL Model, with IAM, with parameters for resonance at 1.2 and 1.5 TeV:**

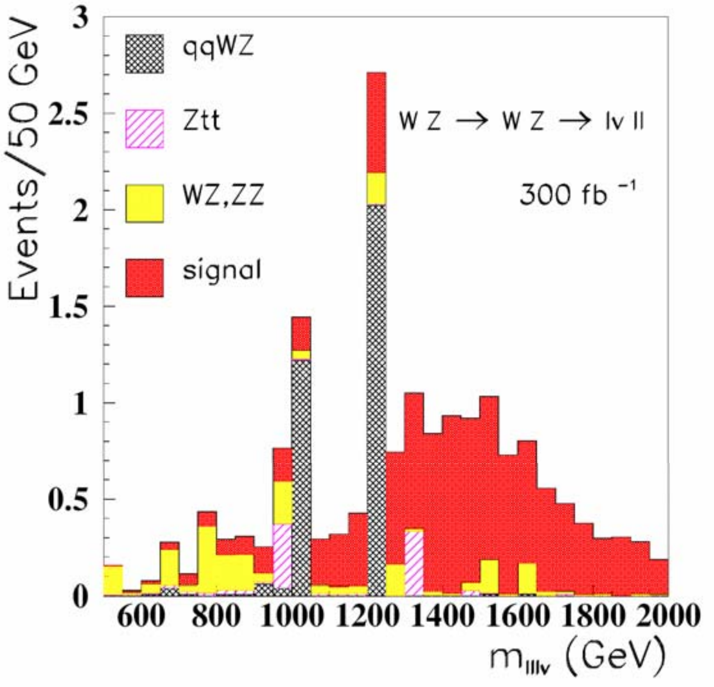
$$qq \to qq\,WZ \to qq\;j\,j\,\ell\ell$$

with forward jet tagging, 300 fb^{-1}

A. Miagkov, ATL-PHYS-99-06

GA, superLHC: hep-ph/0204087





Worst case scenario: non-resonant excess
→ W^+W^+ scattering, … need good understanding of backgds.

Technicolor

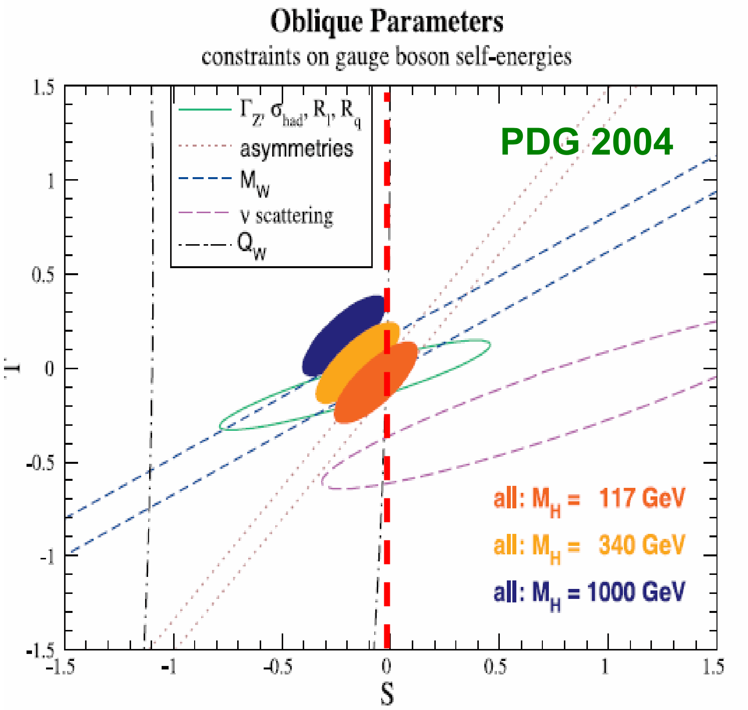
- **analogy with QCD: a new interaction technicolor between techniquarks, with chiral symmetry broken by condensates**
  - (light) technipions produced → longitudinal component of gauge bosons → mass

problem:

$S = -0.03 \pm 0.11\,(-0.08)$ (PDG 2002)

but $S \approx 0.25\, N \left(\frac{N_{TC}}{3} \right)$

⇒ “minimal” technicolor ruled out



→ old plot

- extended technicolor to give mass to fermions
- walking technicolor to inhibit FCNC ’s

S –parameter not necessarily positive
⇒ not ruled out

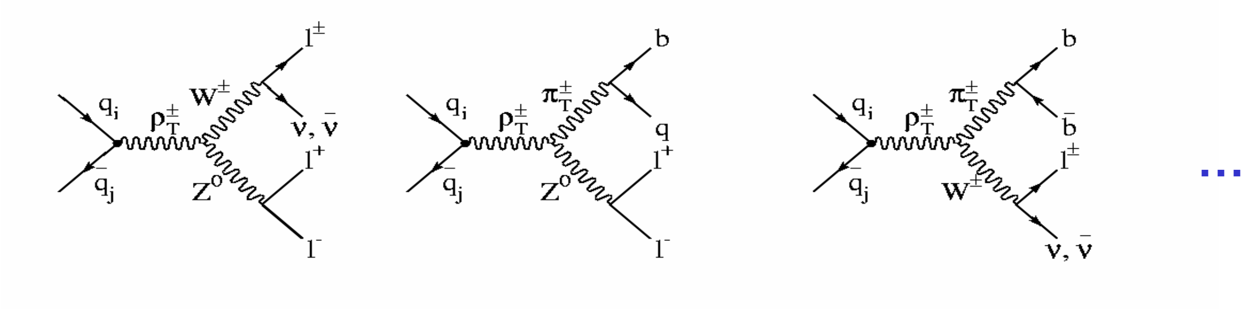
- TopColor assisted TC, or TC2:
  new top interaction (partially) responsible for top mass

Low scale technicolor

- **model of K. Lane et al.** **(hep-ph/0202255, hep-ph/9903372,hep-ph/9610463)**
  - Low scale technicolor model, SU(N_{TC}) –
    (older version in PYTHIA) → needs to be redone with new version, as in Tevatron
    - many technipions, including color octets
    - mixing between long. Gauge bosons and technipions

$$|\Pi_T\rangle = \sin\chi\,|W_L\rangle + \cos\chi\,|\pi_T\rangle$$

  - Resonances predicted, as in QCD: ρ_T, ω_T
  - With a given choice of parameters, cross sections and BR 's can be evaluated
    - resonances decay mostly to heavy quarks (except top)

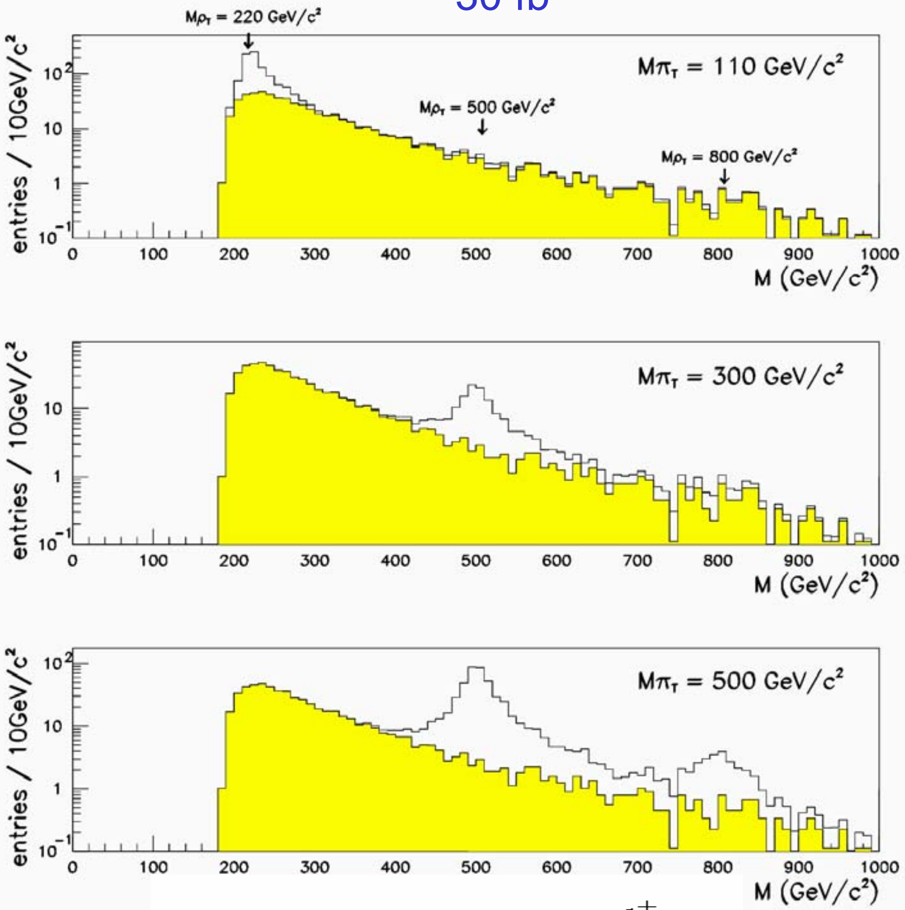


Experimental considerations:
- b-tagging at high energy
- $E_t$miss
- backgrounds (*W + j*, *Z +j*)

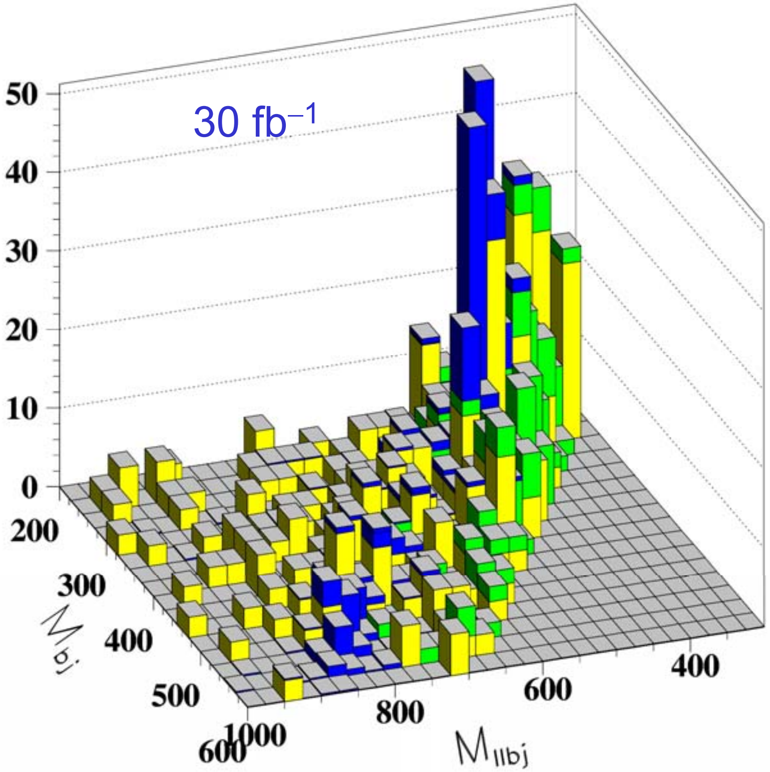
Strong Dynamics

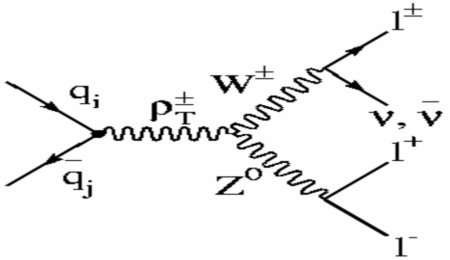
ATL-PHYS-99-020

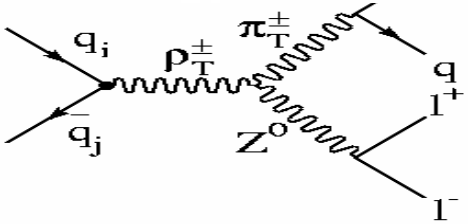
30 fb^{-1}



results depend on parameters

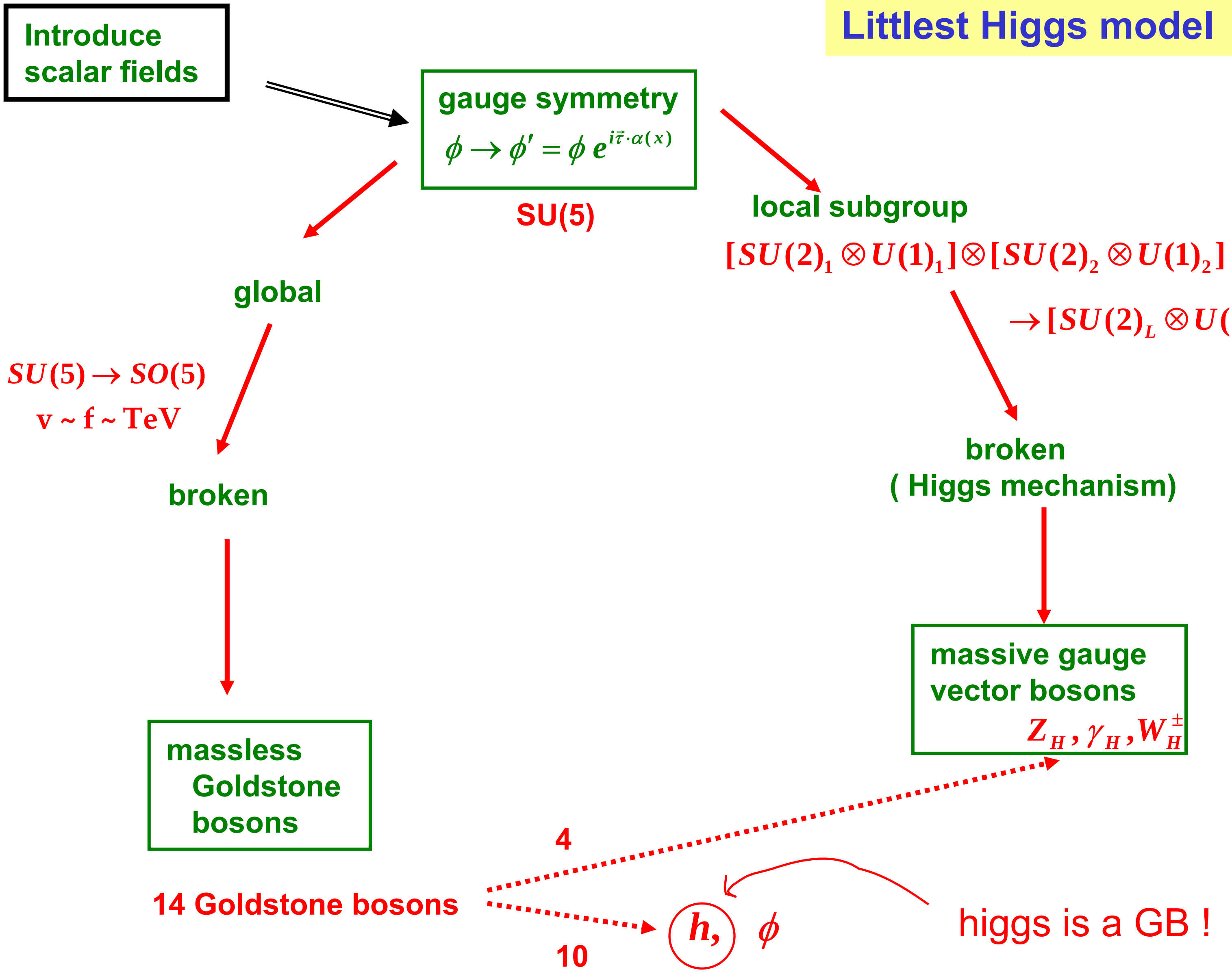






Why hierarchy of scales? ⟹ Little Higgs?

Littlest Higgs model



Introduce scalar fields

gauge symmetry

$\phi \to \phi' = \phi\, e^{i\vec{\tau}\cdot\alpha(x)}$

SU(5)

global

$SU(5) \to SO(5)$

$v \sim f \sim \mathrm{TeV}$

broken

massless Goldstone bosons

local subgroup

$[SU(2)_1 \otimes U(1)_1] \otimes [SU(2)_2 \otimes U(1)_2]$

$\to [SU(2)_L \otimes U(1)_Y]$

broken
(Higgs mechanism)

massive gauge vector bosons
$Z_H, \gamma_H, W_H^{\pm}$

14 Goldstone bosons

4

10

$h,\ \phi$

higgs is a GB !

The littlest Higgs Model - particles

In $SU(2)_L \times U(1)_Y$ basis, $(2\tau+1)_{Y/2}$

$Q = \tau_3 + \frac{Y}{2}$

$$\left.\begin{matrix} X & Y \\ 1_0 & 3_0 \end{matrix}\right\} \rightarrow$$ eaten $\Rightarrow$ 4 heavy bosons: $Z_H, \gamma_H, W_H^{\pm}$

$$\left.\begin{matrix} h & h^\dagger \\ 2_{1/2} & 2_{-1/2} \end{matrix}\right\} \rightarrow$$ complex higgs doublet, massless

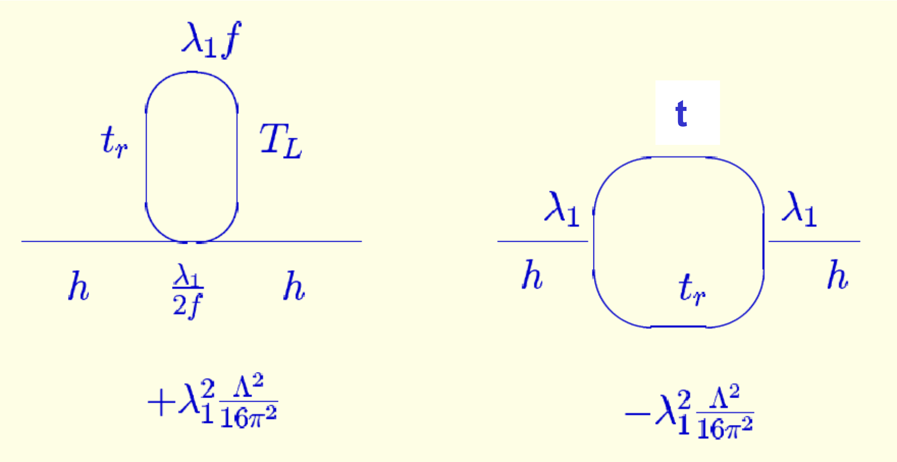
vev for h → triggers EW symm. breaking → mass to Z, W, h massless

$$\left.\begin{matrix} \phi & \phi^\dagger \\ 3_1 & 3_{-1} \end{matrix}\right\} \rightarrow$$ complex triplet

acquires mass from one-loop gauge interactions

1-loop gauge interactions:

To cancel the top loop, introduce $SU(2)_L$ singlet quark T_L, and T_R →



$$\lambda_1 (iQht_r + fT_L t_r hh^\dagger) + \lambda_2 f (T_L T_R)$$

The littlest Higgs Model - remarks

- the small Higgs mass results from non-exact symmetry
  → pseudoGoldstone boson
  (pions have mass because quark masses and e.m. break chiral symmetry)

- quadratic divergences occur at two-loop level ~ 10 TeV
  → model is not complete
  UV completion required at ~ 10 TeV

- Low energy EW constraints rather severe
  - FCNC's at ~ 100 TeV

- New particle content

$$W_H^{\pm}, Z_H, \gamma_H : \sim 1 \ \text{TeV}$$

$$T : \sim 1 \ \text{TeV}$$

$$\phi^{\pm\pm}, \phi^{\pm}, \phi^{0} : \sim 10 \ \text{TeV}$$

Search for the heavy T quark

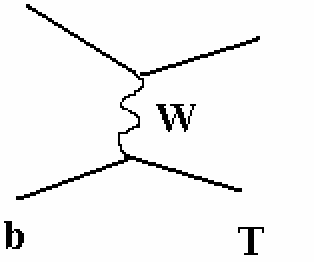
Couplings: $\lambda_1(iQht_r + fT_Lt_rhh^\dagger) + \lambda_2 f(T_LT_R)$

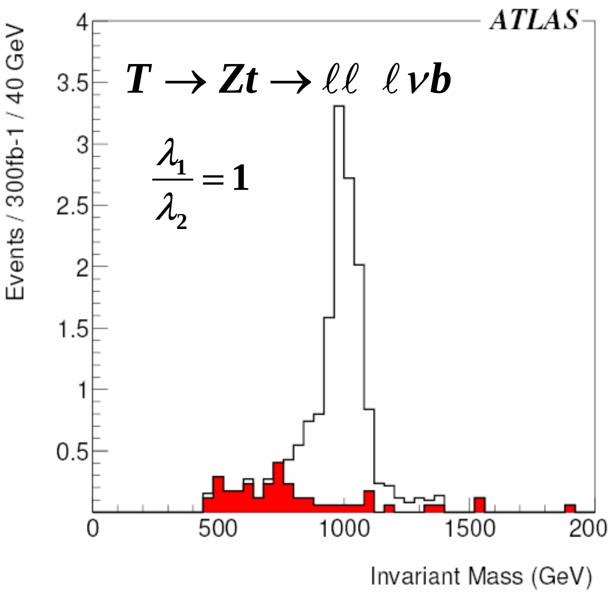
→ **3 parameters: m_t, m_T, and λ_1/λ_2**

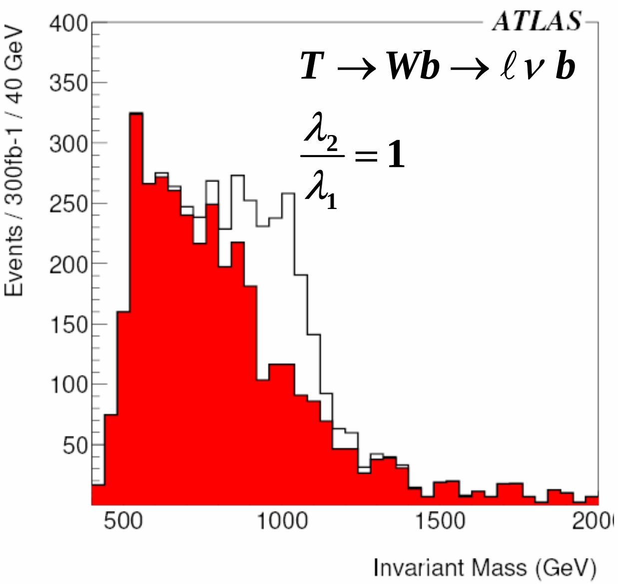
Widths: $$\Gamma(T \to t\,h) = \Gamma(T \to tZ) = \frac{1}{2}\Gamma(T \to bW) = \frac{\kappa^2}{32\pi}M_T$$

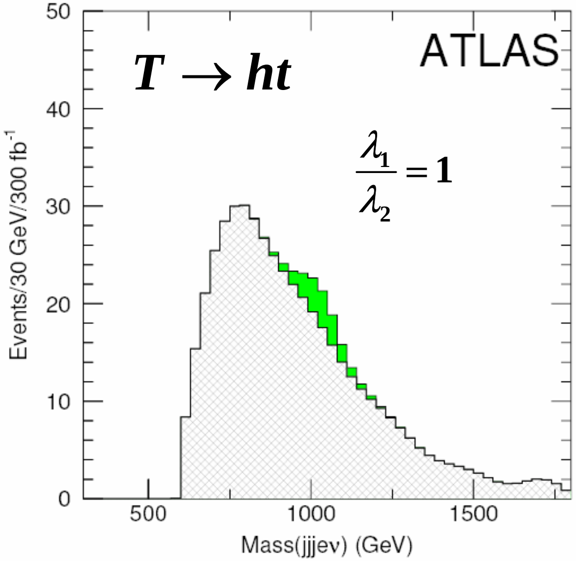
$$\kappa = \frac{\lambda_1^2}{\sqrt{\lambda_1^2 + \lambda_2^2}}$$

Single production:







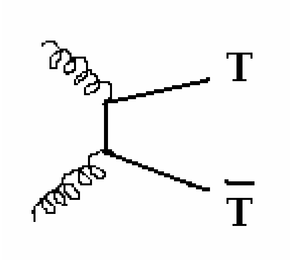


SN-ATLAS-2004-038

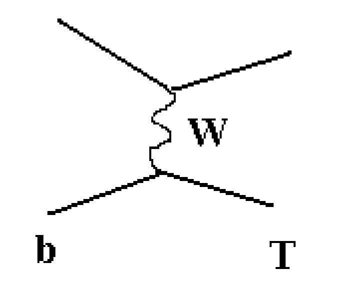
detail

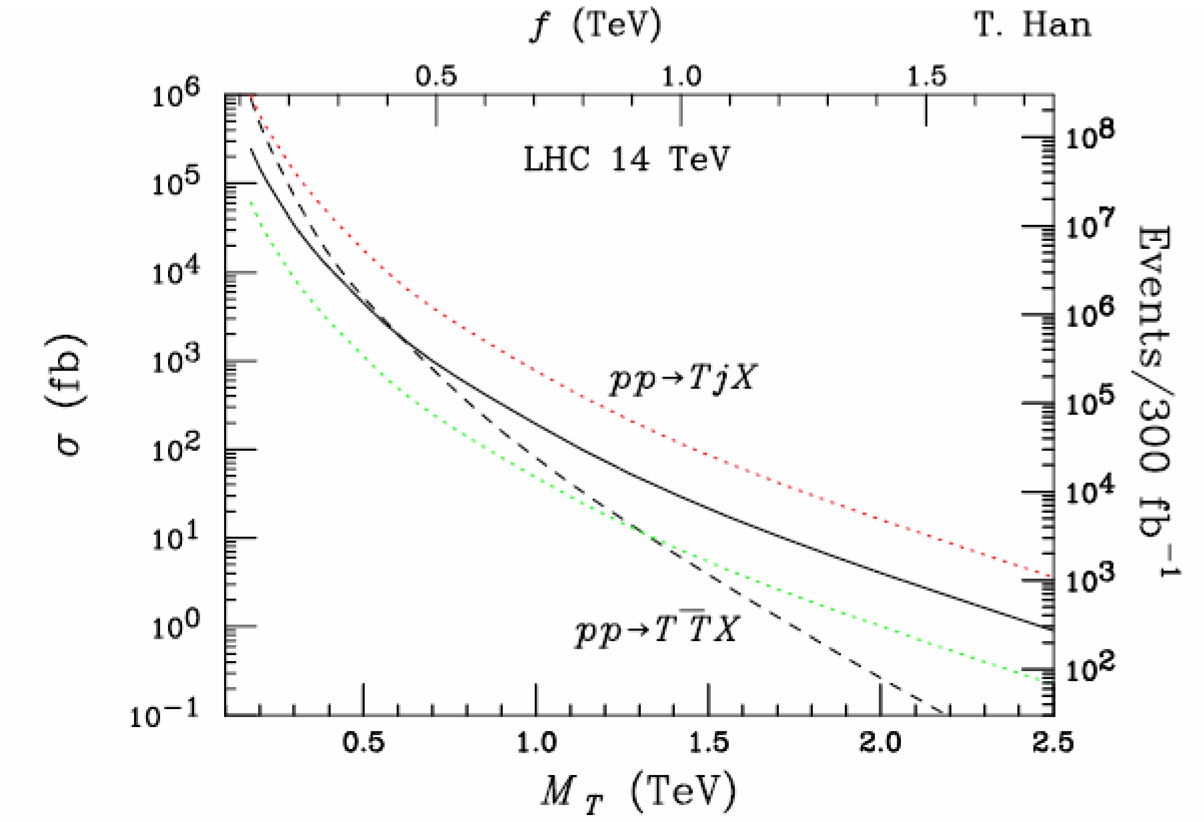
Search for the heavy T quark

Pair production →



Single production:

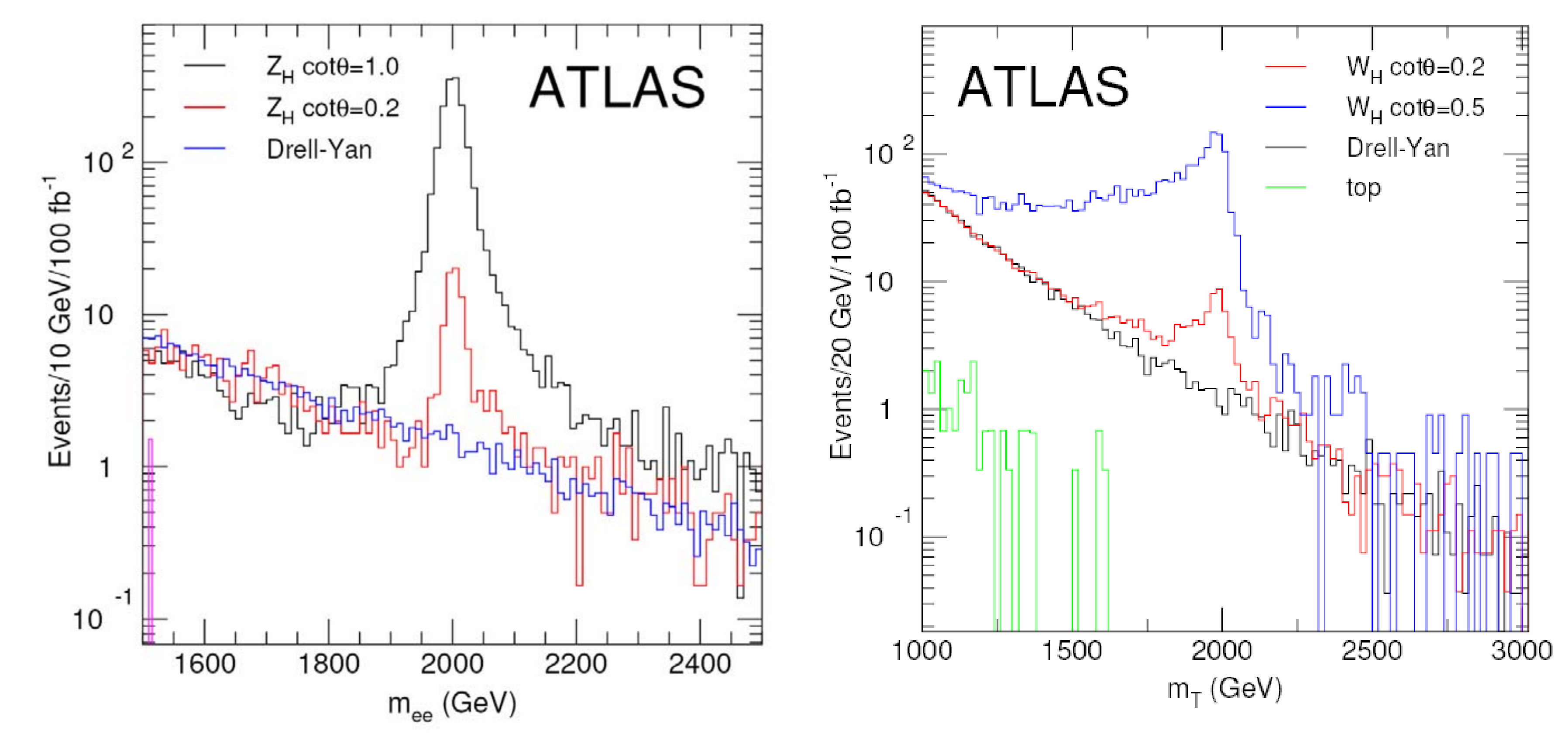




Heavy Gauge Bosons: Z_H

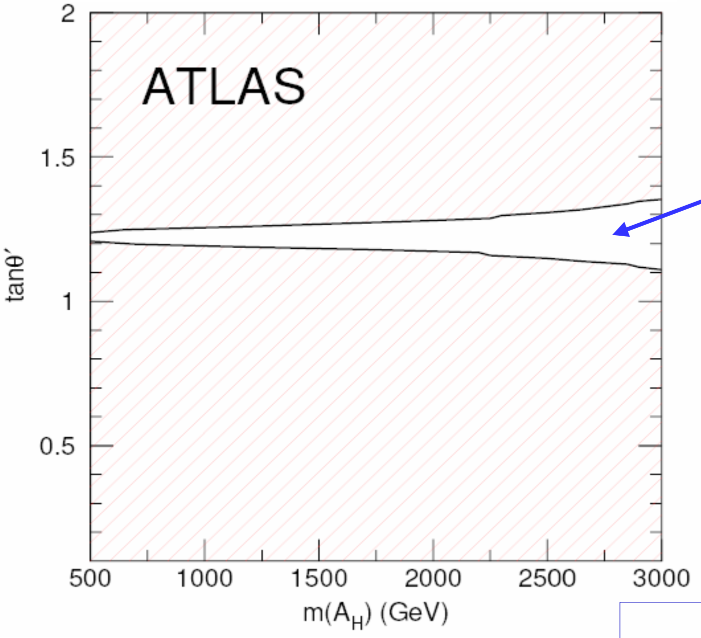
W_H, Z_H, A_H arise from $[SU(2) \otimes U(1)]^2$ symmetry

→ 2 mixing angles (like θ_W): θ for Z_H
θ' for A_H



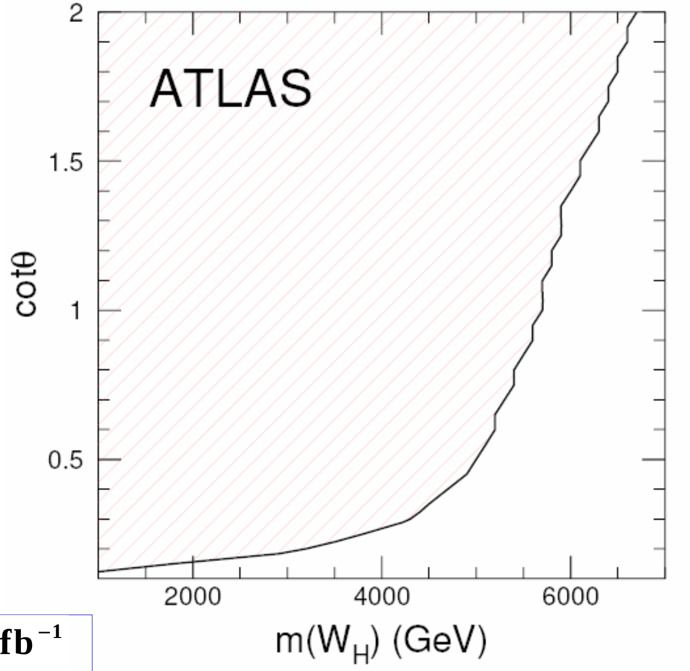
Heavy Gauge Bosons: Z_H, γ_H

$A_H \rightarrow e^+e^-$ reach for 300 fb^{-1}

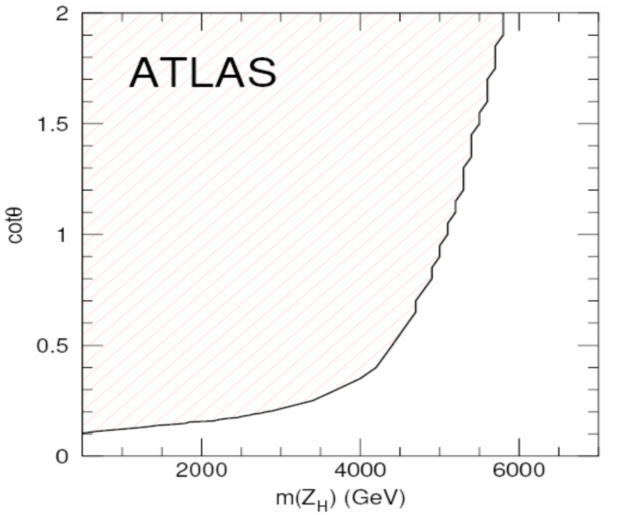


low BR

$W_H \rightarrow e\nu$ 5 σ reach for 300 fb^{-1}

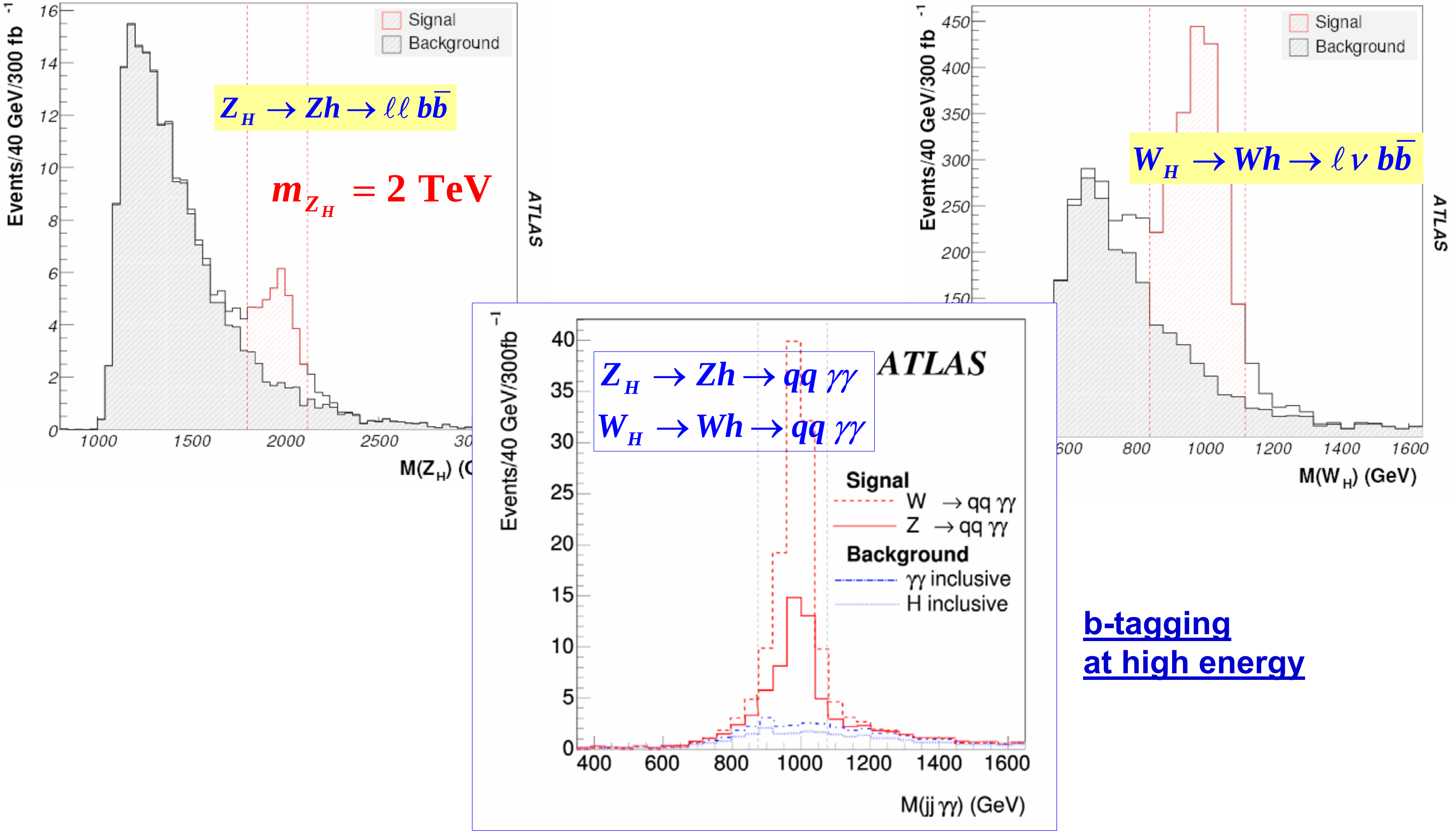


$Z_H \rightarrow e^+e^-$ reach for 300 fb^{-1}



Higgs-Gauge boson couplings

Measurement of Z_HZh and W_HWh couplings needed to test model



b-tagging at high energy

b-tagging

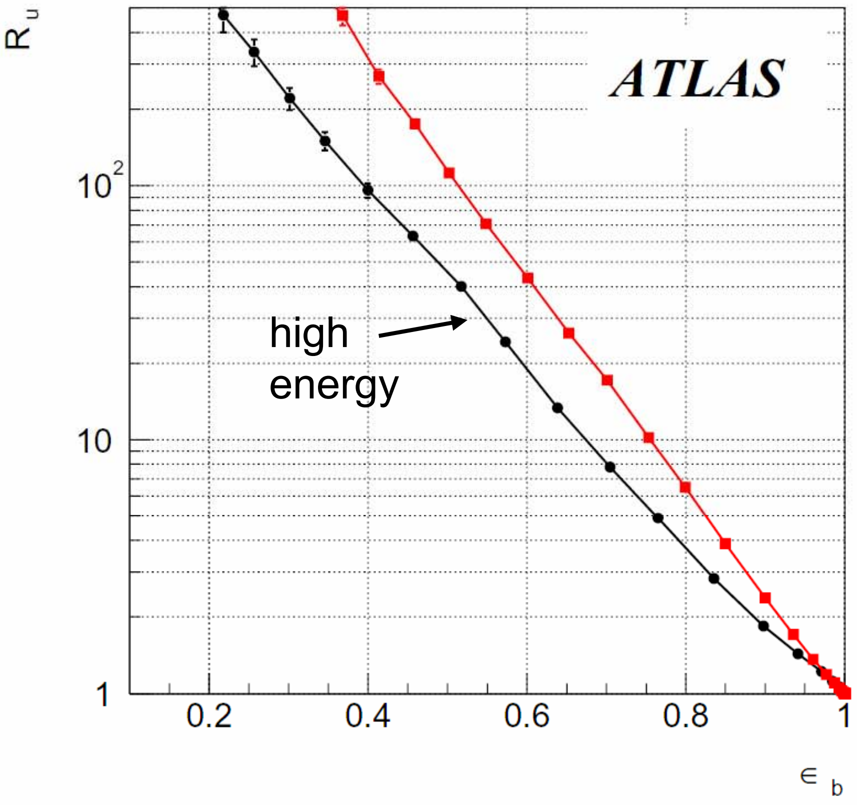
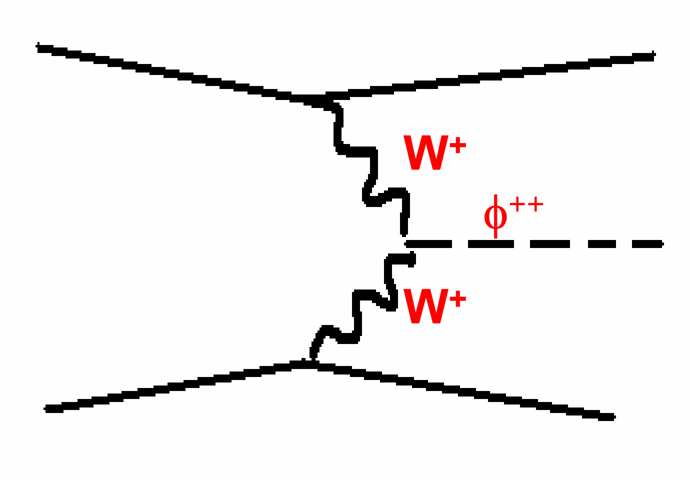


Figure 13: Plot showing the tagging efficiency for $b-$jets as a function of the rejection factor against light quark jets. The upper curve shows the result from the benchmark ATLAS sample of bottom quarks from a Higgs decay of mass 400 GeV produced in association with a W [13]. The lower curve shows the result from the higher energy $b-$quarks from the $Z_H \to Zh$ sample.

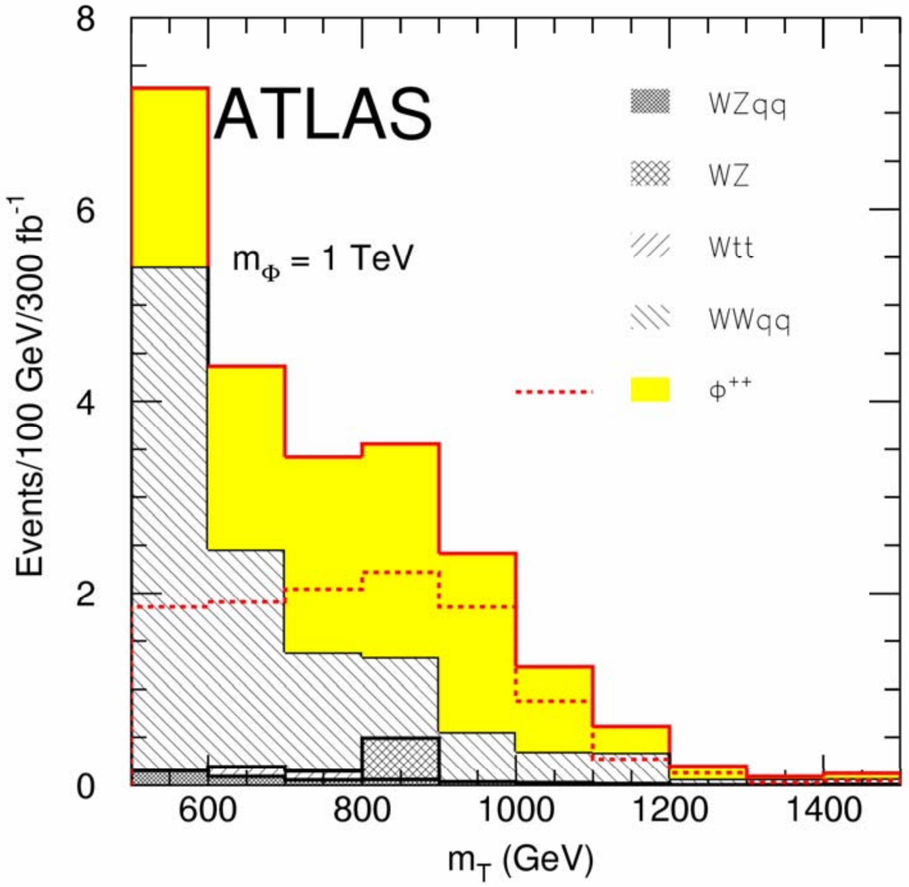
Triplet Higgs



Single production

$$qq \to qq\phi^{++}$$

↳ $W^+W^+ \to \ell^+\nu\,\ell^+\nu$

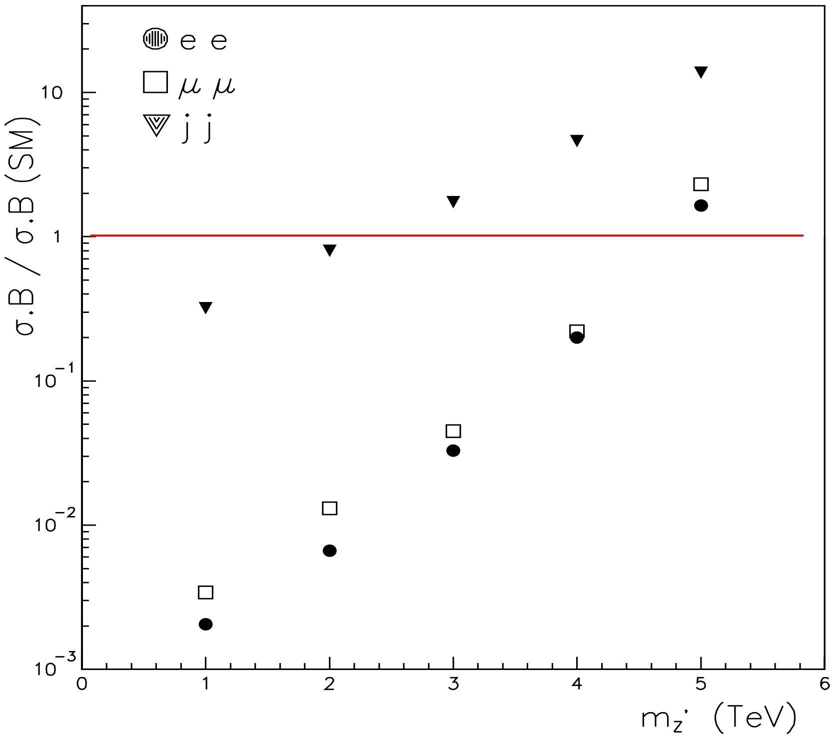


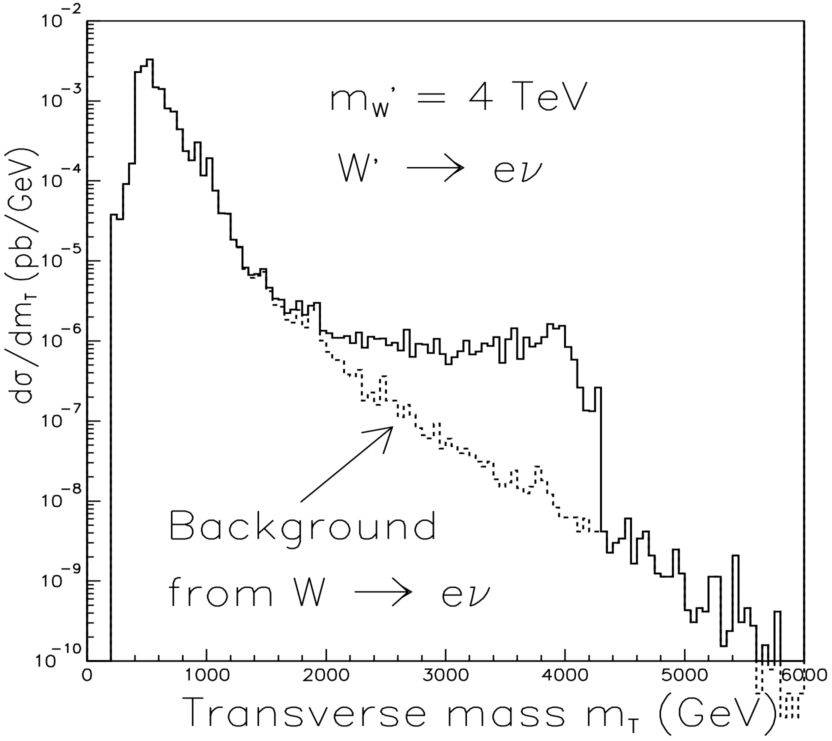
Main background from W_TW_T scattering

Sequential Z', W'

Generic Z', W'

clean signals, little background





from TDR **100 fb^{-1}**

experimental considerations:
- **energy calibration, resolution, ID, efficiencies for high energy e, μ, jets**
- **charge assignment for e, μ**

Right-handed interactions?

Z' : first sign of extended gauge group ?

- **Left-Right Symmetric Model:**

triplet Higgs

$$SU(2)_L \times SU(2)_R \times U(1)_{B-L} \xrightarrow{\Delta} SU(2)_L \times U(1)_Y$$

$$\begin{array}{ccccc} \downarrow & \downarrow & \downarrow & \downarrow & \downarrow \\ \mathbf{W}_{\mathrm{L}}^{i} & \mathbf{W}_{\mathrm{R}}^{i} & \mathbf{C} & \mathbf{W}_{\mathrm{L}}^{i} & \mathbf{B} \\ \mathbf{g}_{\mathrm{L}} & \mathbf{g}_{\mathrm{R}} & \mathbf{g'} & \mathbf{g}_{\mathrm{L}} & \mathbf{g}_{\mathrm{Y}} \end{array}$$

- right-handed fermions in doublets ➔ heavy Majorana $\nu_R = N$
  - explains low mass of ν_L (see-saw mechanism)
- W_R, Z_R associated with right-handed sector $W_R \to eN, \quad Z_R \to ee$

- **larger GUT groups (includes LRSM)**

$$E_6 \to SO(10) + U(1)_\psi$$

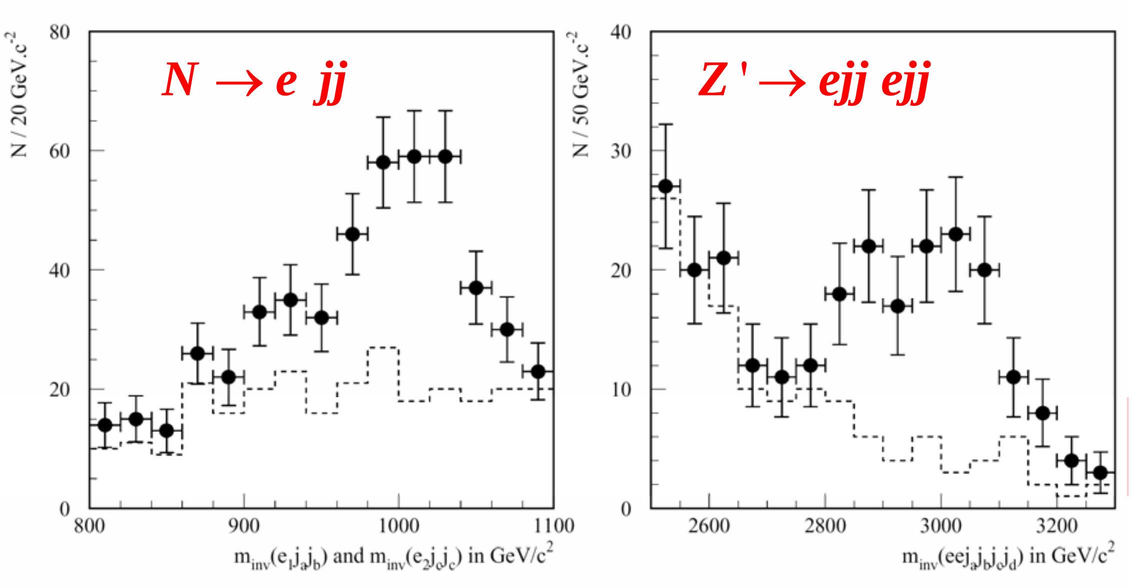
$$\hookrightarrow SU(5) + U(1)_\chi$$

$$Q_{E_6} = \cos\beta\, Q_\chi + \sin\beta\, Q_\psi : \quad \Rightarrow \quad Q_\eta = \sqrt{\frac{3}{8}}\, Q_\chi - \sqrt{\frac{5}{8}}\, Q_\psi$$

Z', W' in LRSM

$p\,p \to Z_R \to N_\ell N_\ell \to \ell jj\ \ell jj$

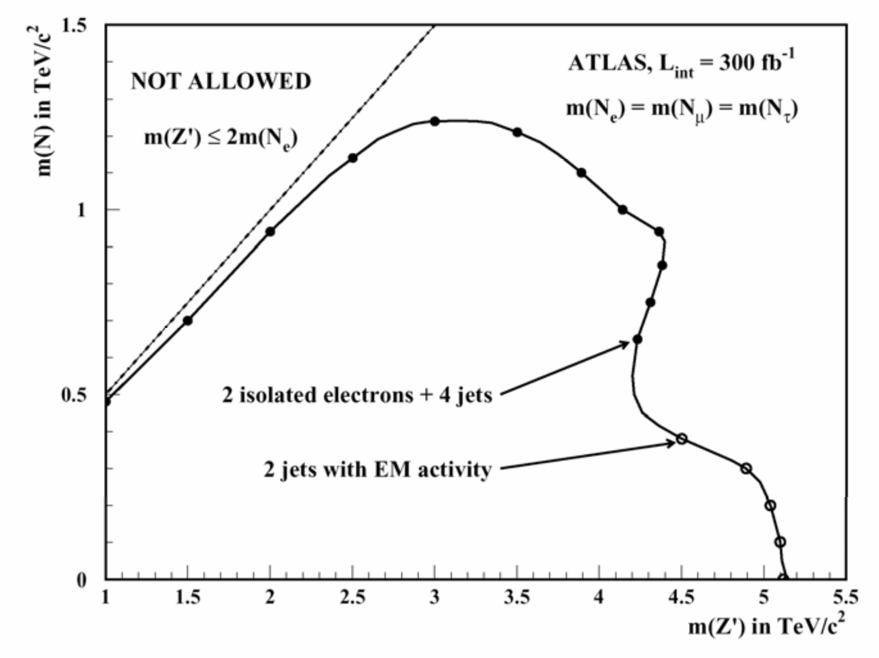
J. Collot, A. Ferrari
ATL-PHYS-98-124,
ATL-PHYS-99-034



backgrounds:

t tbar
DY, WW, ZW, ZZ
LRSM bckg: W_R,…

⇒ cuts on m_{ee}, pT(jets)



FB asymmetry gives a measure of $\kappa = g_R/g_L$

$$m_{Z'} = \sqrt{\frac{2\kappa^2 \cot^2\theta_W}{\kappa^2 \cot^2\theta_W - 1}}\; m_{W_R}$$

$$= 1.7\, m_{W_R} \quad \text{if } \kappa=1$$

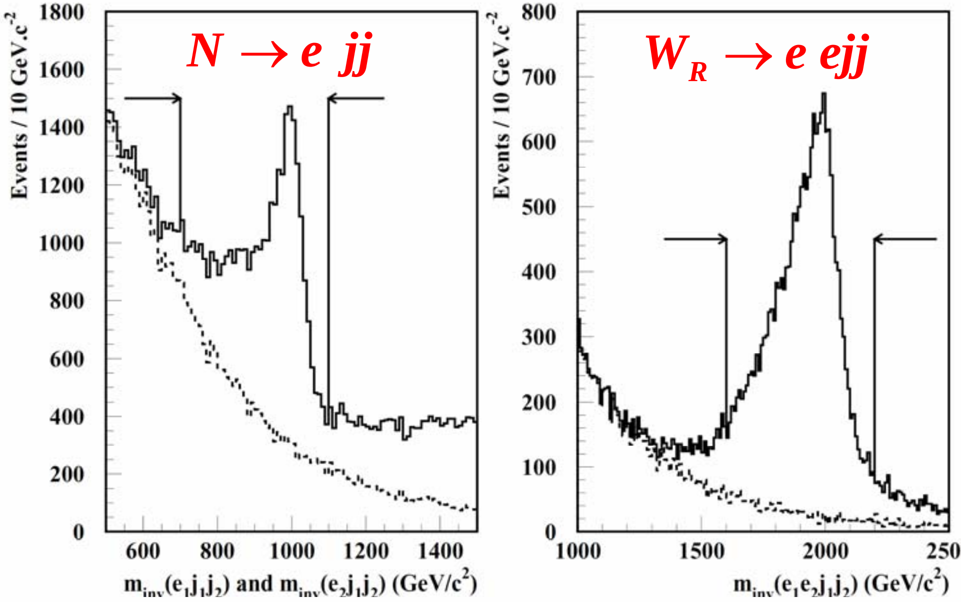
Z', W'

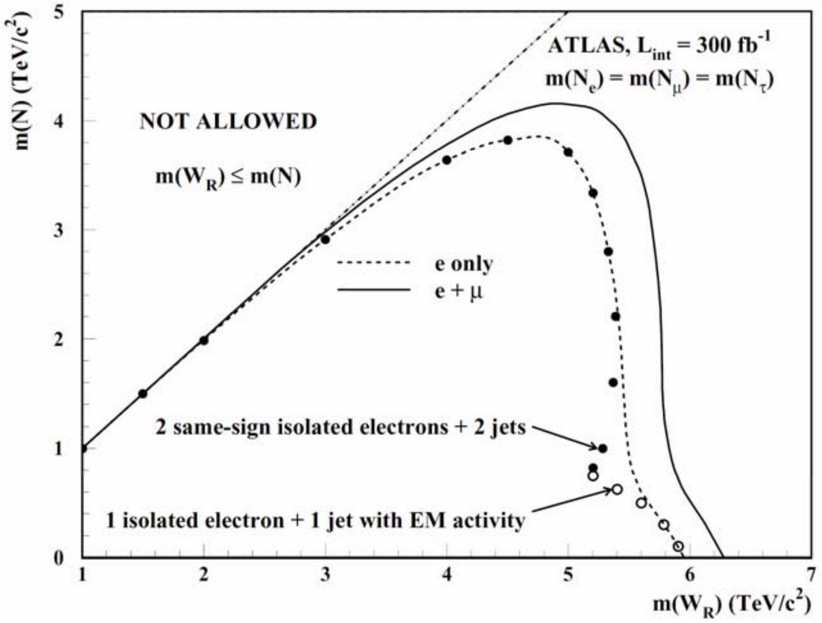
$p\,p \rightarrow W_R \rightarrow \ell N_\ell \rightarrow \ell\,\ell jj$

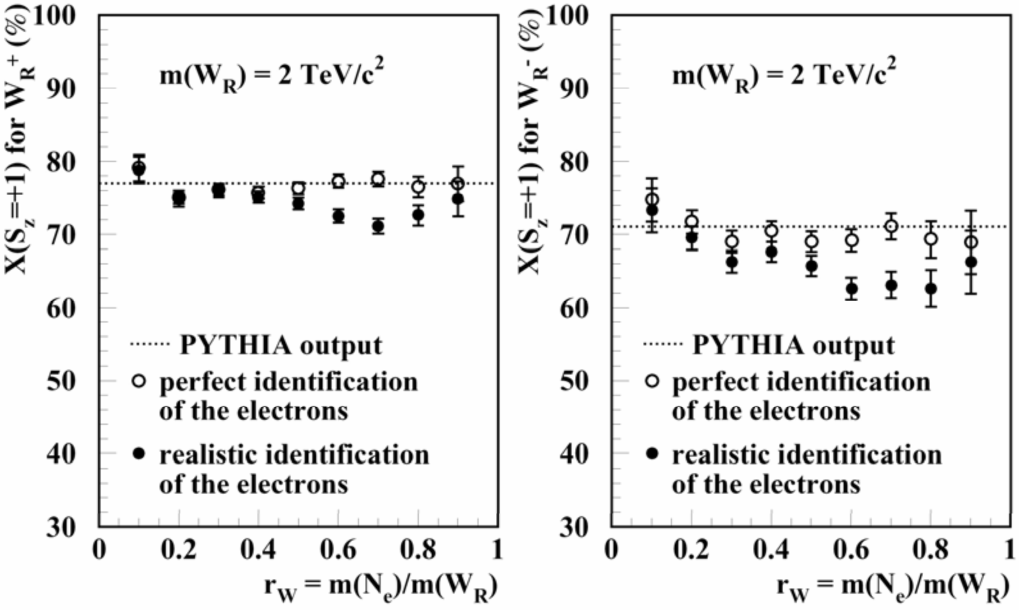
J. Collot, A. Ferrari
ATL-PHYS-98-124,
ATL-PHYS-99-018

backgrounds:

t tbar
DY, WW, ZW, ZZ

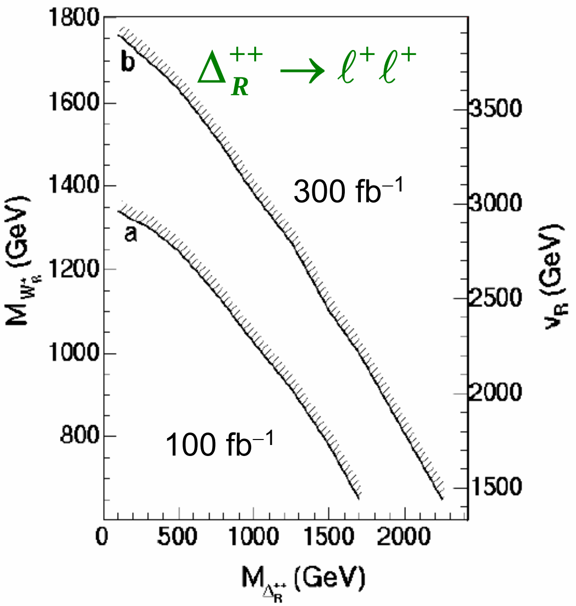


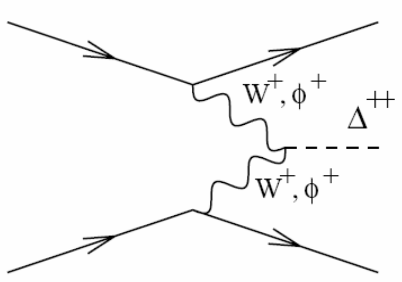




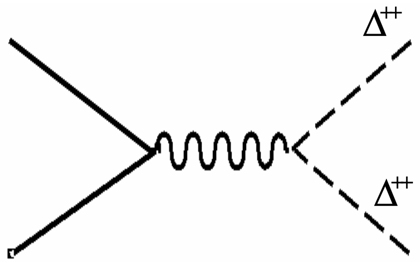
H^{++} in LRSM

ATL-PHYS-2004-025



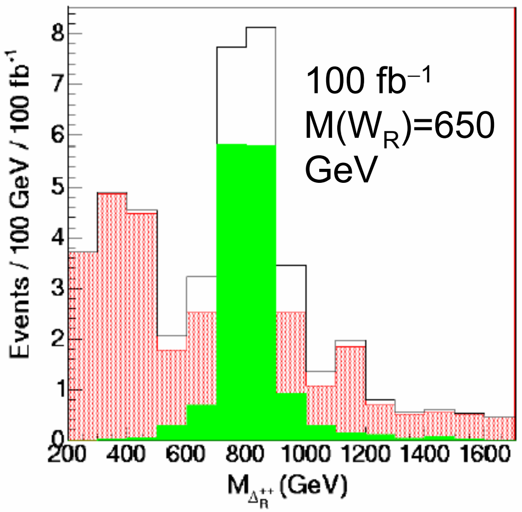


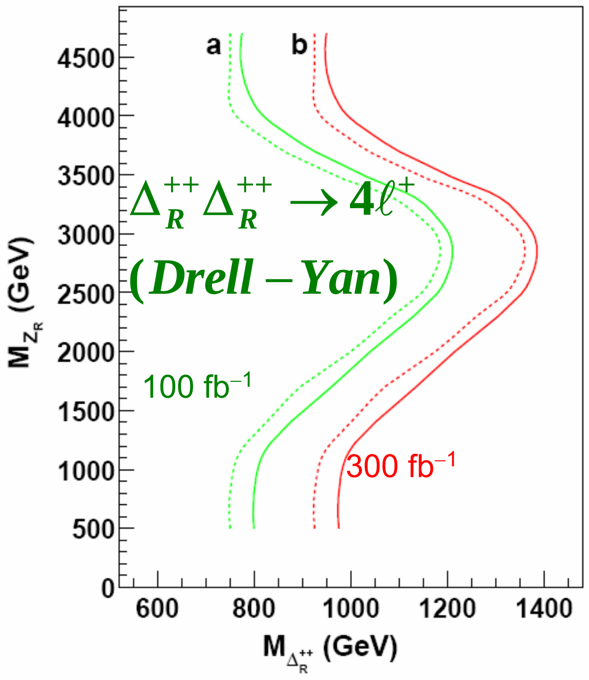
VBF

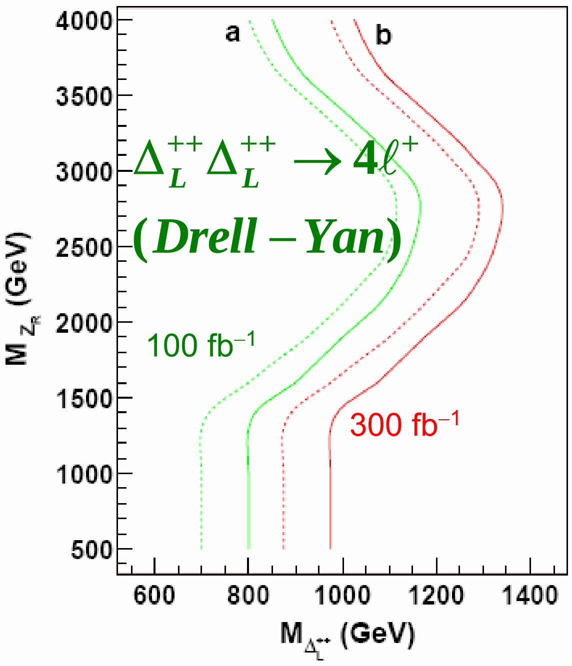


D-Y

$\Delta_R^{++} \rightarrow \tau^+\tau^+ \rightarrow \ell^+\ell^+ + \not{p}_T$







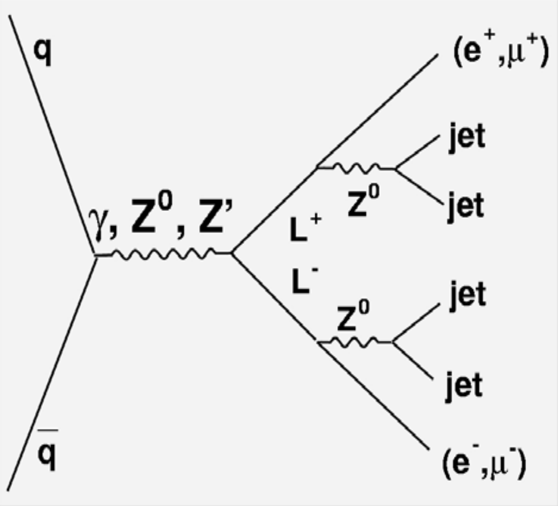
Heavy leptons

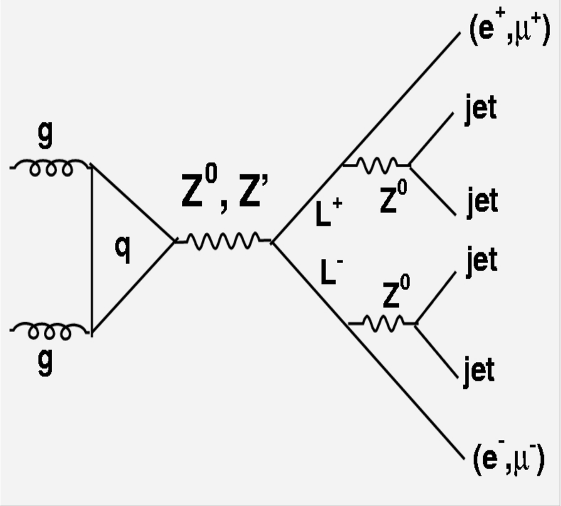
C. Alexa

ATL-PHYS-2003-014

backgrounds:
ttbar, WW, WZ, ZZ

also:
6-lepton channel





Experimental considerations:
- **high energy leptons, jets**

Systematics:
- **large NLO corrections**

conclusion:

ATLAS can discover sequential charged heavy leptons up to
M_L = 0.9 / 1.0 TeV
(low/high luminosity)

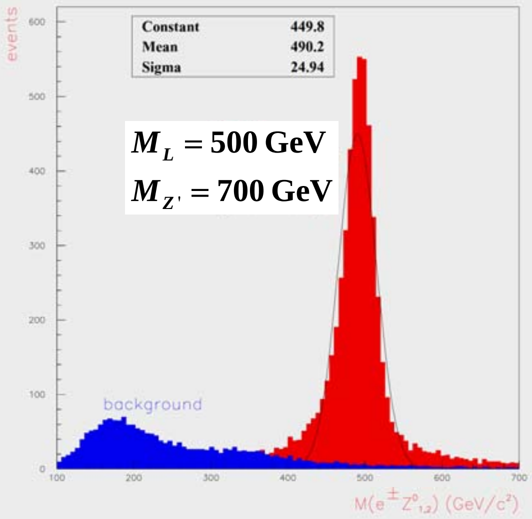
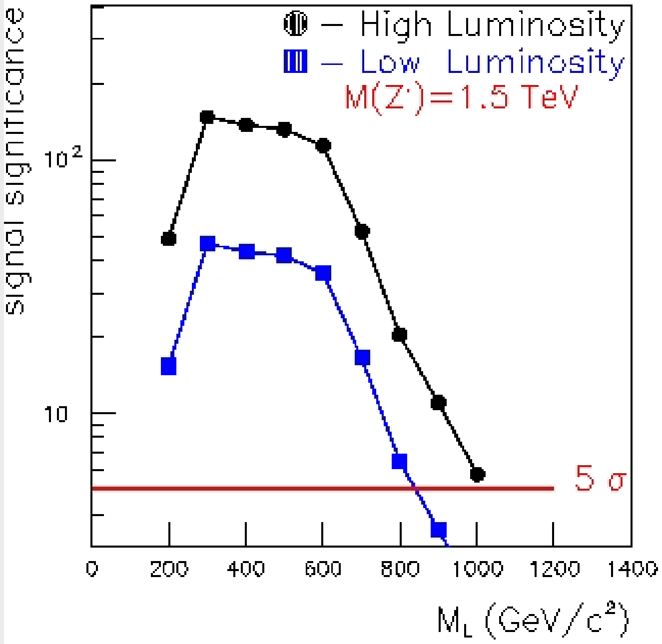
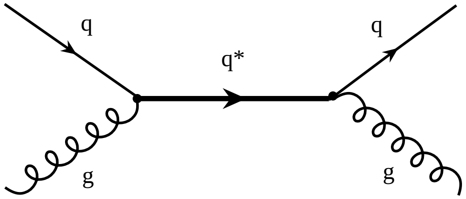


Figure 13: Signal to background comparison for $M_L = 0.5\ TeV/c^2$ and $M_{Z'} = 0.7\ TeV/c^2$, for $L \to e + Z^0$ channel.



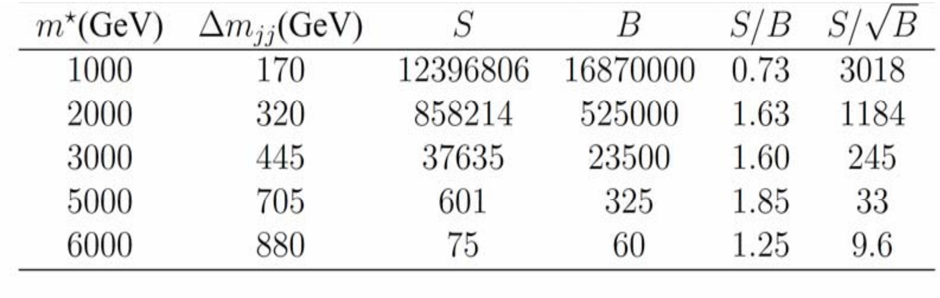
Excited quarks



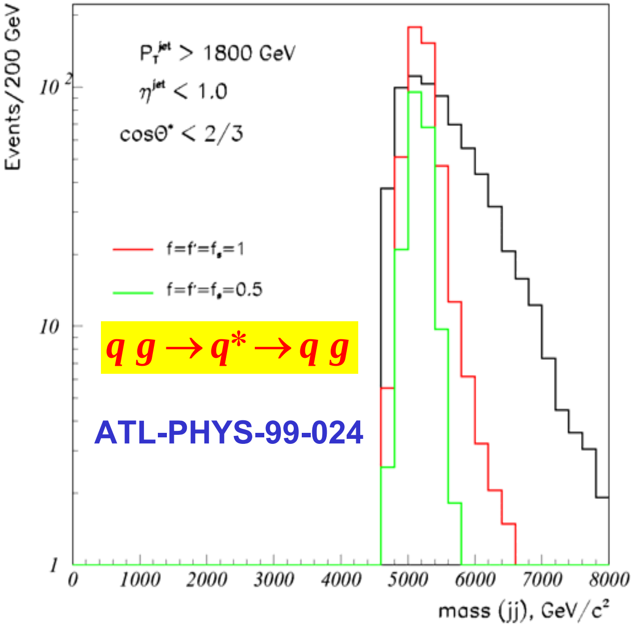
$$L = \frac{1}{2\Lambda}\bar{q}^{*}_{R}\sigma^{\mu\nu}\left(g_s f_s G^{a}_{\mu\nu} + g\, f\,\frac{\tau}{2}W_{\mu\nu} + g'\, f'\,\frac{Y}{2}B_{\mu\nu}\right)q_L + h.c.$$

take as reference : $\Lambda = m^*, \quad f_s = f = f' = 1$

O. Çakir, C. Leroy, R. Mehdiyev,
ATL-PHYS-2002-014

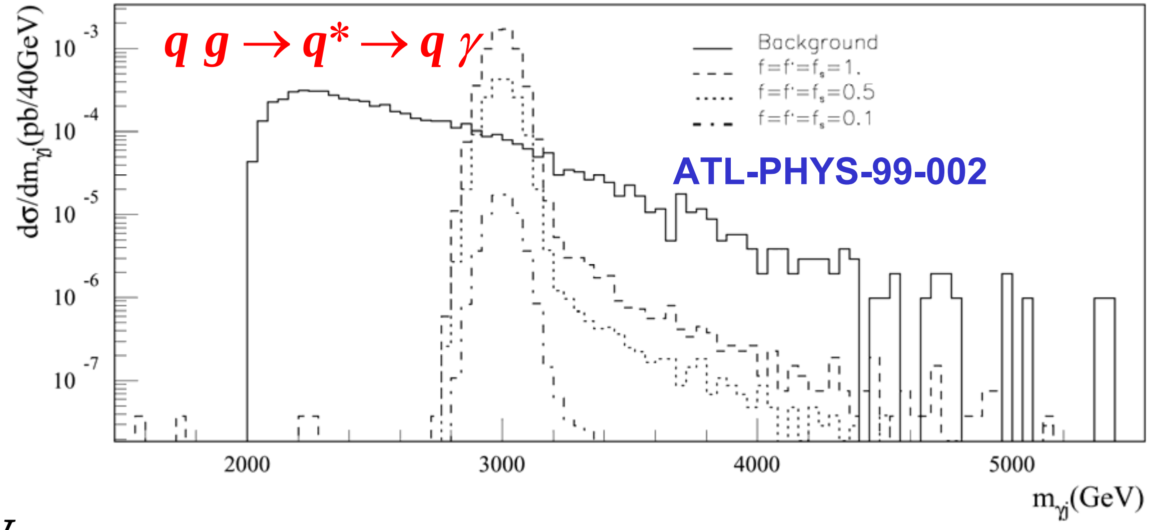


$m^\star$(GeV)	Δm_{jj}(GeV)	S	B	S/B	$S/\sqrt{B}$
1000	170	12396806	16870000	0.73	3018
2000	320	858214	525000	1.63	1184
3000	445	37635	23500	1.60	245
5000	705	601	325	1.85	33
6000	880	75	60	1.25	9.6



$q\,g \rightarrow q^* \rightarrow q\,g$

ATL-PHYS-99-024



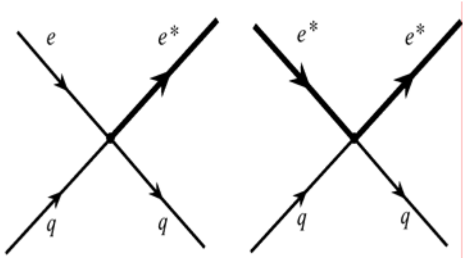
$q\,g \rightarrow q^* \rightarrow q\,\gamma$

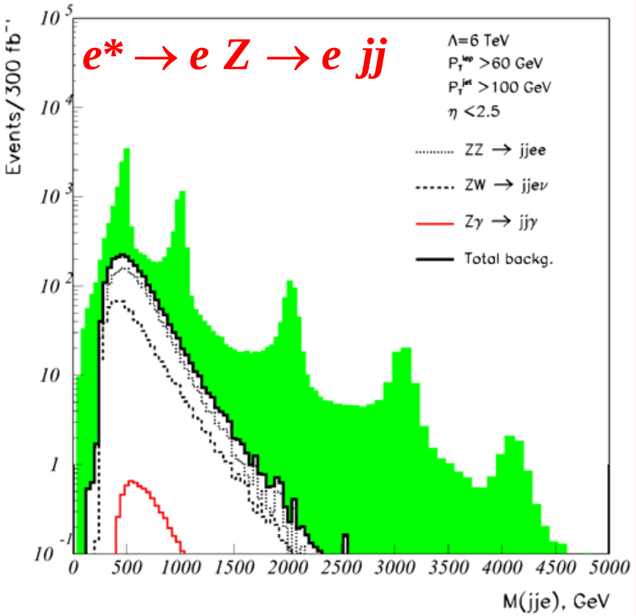
ATL-PHYS-99-002

Also : $\quad q^* \rightarrow qZ; \quad q^* \rightarrow \bar{q}'W$

excited leptons

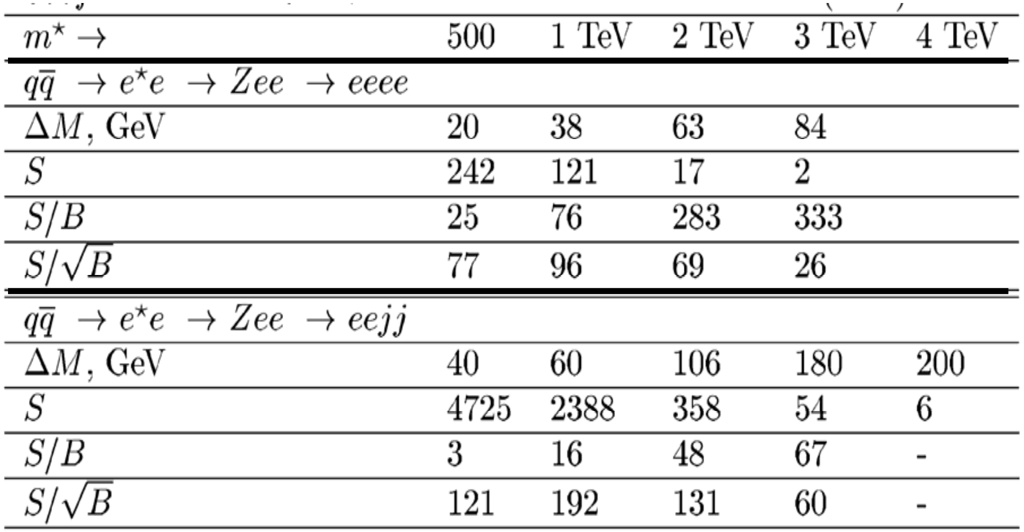
contact interaction : $L_C = \frac{g_*^2}{2\Lambda^2} J_\mu J^\mu$



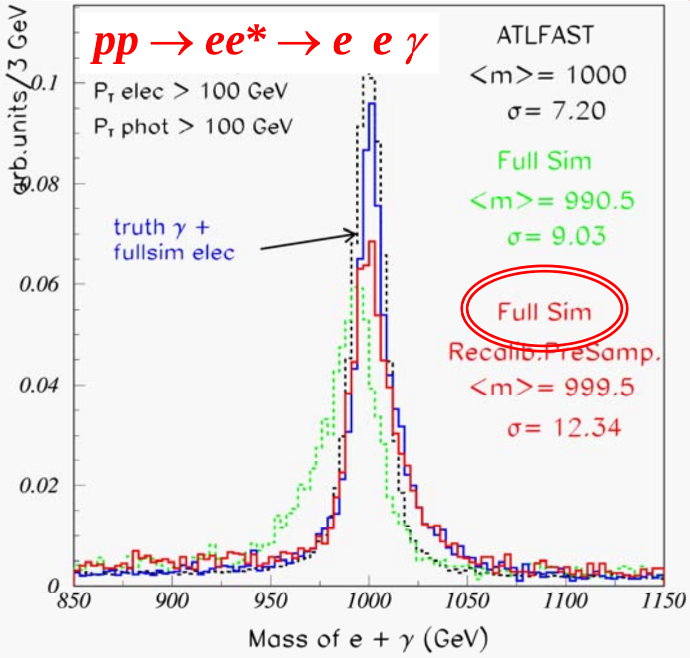


Experimental considerations:
- high energy e, γ
- Z → jj, W → jj

L = 300 fb^{-1}, Λ = 6 TeV

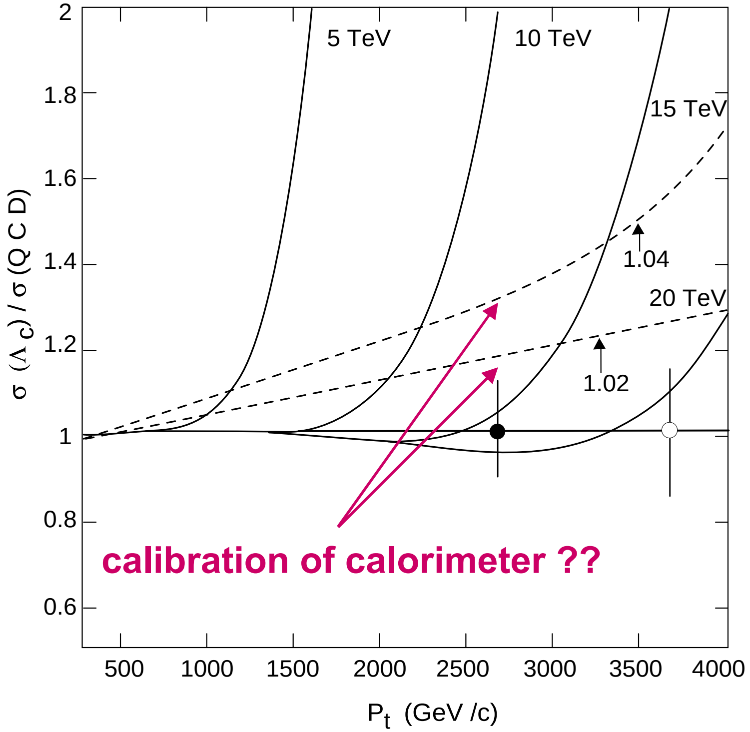


$m^\star \rightarrow$	500	1 TeV	2 TeV	3 TeV	4 TeV
$q\bar{q} \rightarrow e^\star e \rightarrow Zee \rightarrow eeee$					
ΔM, GeV	20	38	63	84	
S	242	121	17	2	
S/B	25	76	283	333	
$S/\sqrt{B}$	77	96	69	26	
$q\bar{q} \rightarrow e^\star e \rightarrow Zee \rightarrow eejj$					
ΔM, GeV	40	60	106	180	200
S	4725	2388	358	54	6
S/B	3	16	48	67	-
$S/\sqrt{B}$	121	192	131	60	-



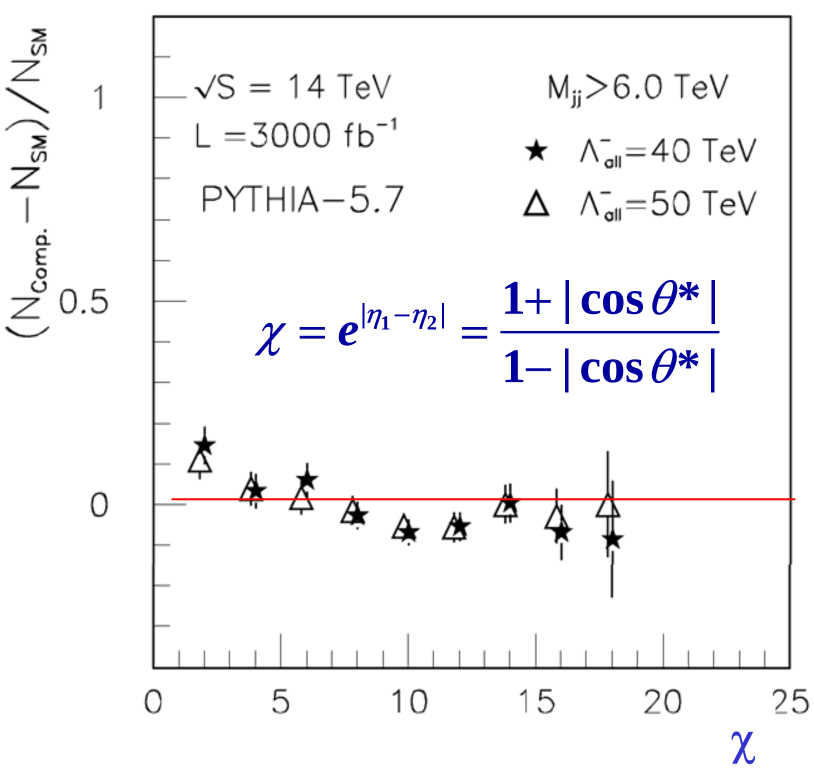
quark substructure

Contact interactions:
scale of compositeness Λ >> m*



calibration of calorimeter ??

di-jets, relative to SM QCD, from TP



$$\chi = e^{|\eta_1 - \eta_2|} = \frac{1 + |\cos\theta^*|}{1 - |\cos\theta^*|}$$

angular distribution

less dependent on calibration

Z. Usubov

(from superLHC)

Extra dimensions

- **well motivated**
  - string theory requires 10 dimensions!
    - theoretical approach towards a quantum description of gravity
    - includes supersymmetry
  - $1/r^2$ law not verified for dimensions $\lesssim$ 0.2 mm
- **ADD: Large, flat compactified extra dimensions**
  - Gauss' law: →
  - SM particles on 3-brane

$$G_N \frac{m_1 m_2}{r^2} = G' \frac{m_1 m_2}{r^2 (2\pi r)^n}, \quad \text{for} \quad r = R \;\Rightarrow\; G' = G_N (2\pi R)^n$$

$$M_D^{2+n} = \frac{M_{Pl}^2}{8\pi (2\pi R)^n} \;\Rightarrow\; M_D \sim \text{TeV for values of } R \le \text{mm}$$

for compactification in circles: graviton field periodic in extra dimensions *(y)*

$$\phi(x,y) = \sum_{k_1=-\infty}^{\infty} \sum_{k_2=-\infty}^{\infty} \cdots \sum_{k_n=-\infty}^{\infty} \phi^{(k)}(x)\, e^{i \vec{k}\cdot\vec{y}/R}$$

towers of Kaluza-Klein states of graviton with p_T ~ mass = k/R

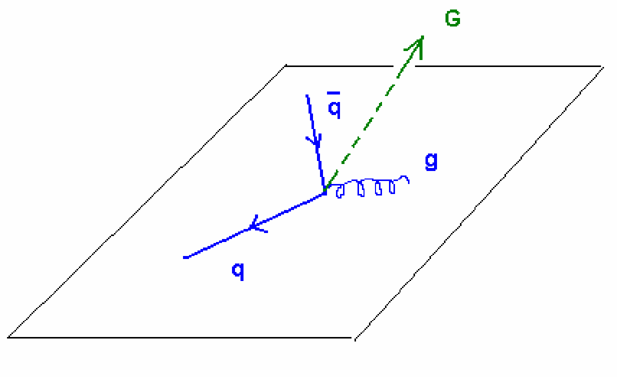
KK mode separation is very small: → continuous spectrum

→ high density of states compensates low coupling (~$1/M_{Pl}$)

→ chance to observe effects at LHC

Direct Graviton production

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



- **Signals in ATLAS:**

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

  - Implemented in ISAJET, with cross sections from

    Giudice, Rattazzi & Wells, Nucl.Phys. B544 (1999) 3 (hep-ph/9811291)

$$\frac{d^2\sigma}{dt\,dm} = S_{n-1}\frac{1}{M_D^{2+n}}m^{n-1}\frac{1}{s}F\left(t/s, m^2/s\right)$$

density of KK modes: $S_{n-1} = \frac{2\pi^{n/2}}{\Gamma(\frac{n}{2})}$

$$\frac{dN}{dm} = S_{n-1}\frac{\bar{M}_{Pl}^2}{M_D^{n+2}}m^{n-1}$$

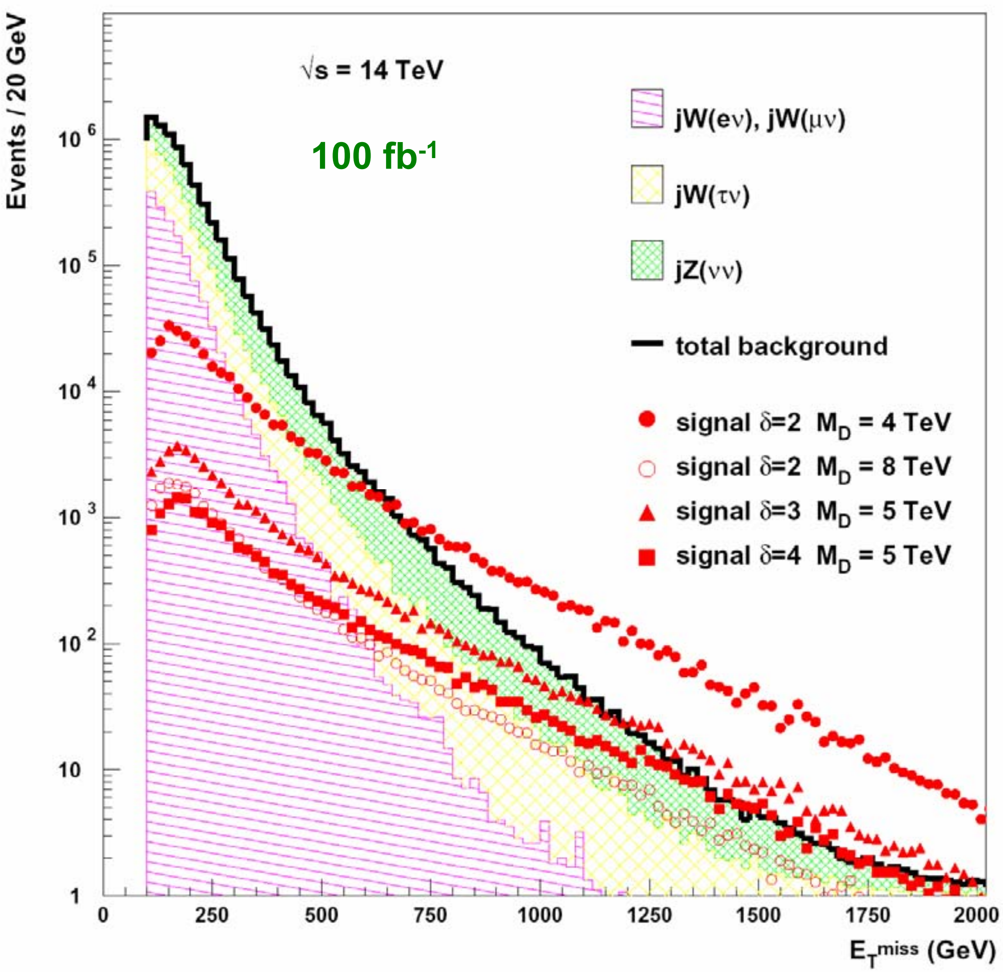
Direct graviton production: Jets + missing E_T

Detector effects: ATLFAST

- Jets and leptons reconstructed in $|\eta| < 5, 2.5$

Minimum of validity

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



Uncertainty in σ(Z+jets) will lower the reach

calibrate background level by $Z + j \rightarrow \ell^+\ell^- + j$

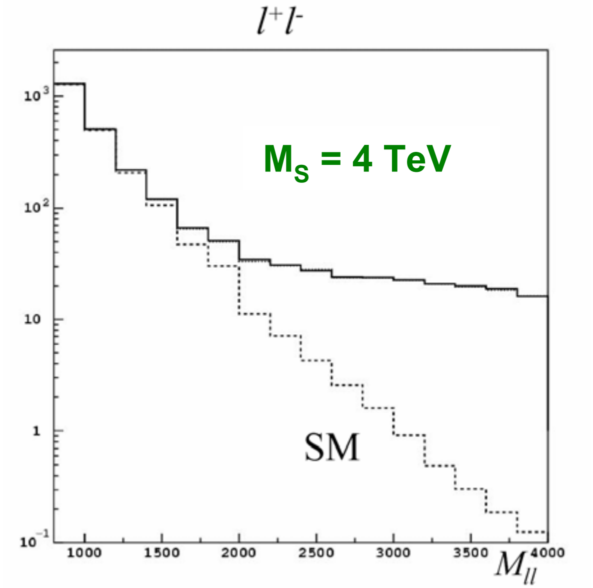
Reach in M_D for γG

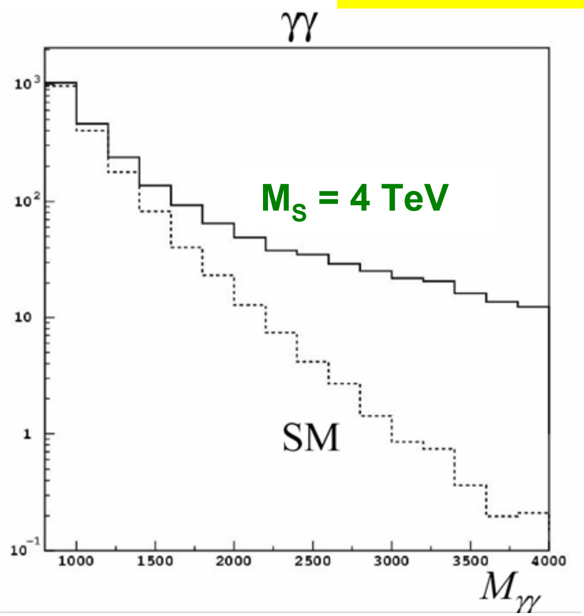
δ	M_D^{max} (TeV) HL, 100 fb^{-1}	M_D^{min} (TeV)
2	4	~ 3.5

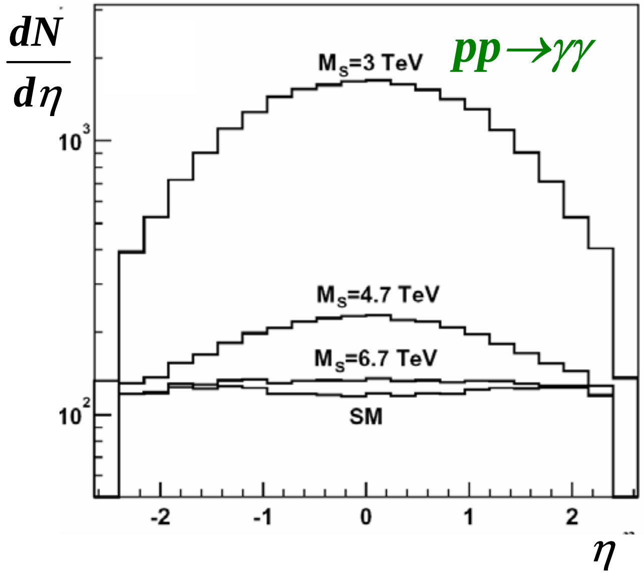
Virtual Graviton Exchange

- **Signals:** $q\bar{q},\, gg \rightarrow \gamma\gamma,\, \ell\ell, \quad (WW, t\bar{t}\ldots)$
  - We require that : $M_{\gamma\gamma,\ell\ell} < 0.9\, M_S$ (effective theory)
  - Excess in di-leptons mass distribution (same for di-photons)
  - event distribution of $\gamma\gamma$ (s-channel) more central than in SM (t and u channels)
  - can measure FB asymmetry

Sensitivity for 100 fb^{-1} ~ 5-6 TeV







detail

Extra dimensions of ~TeV^{-1} size

G. A. and G. Polesello *Proceedings of Les Houches 2001*

- **Compactification radius is small enough to allow SM particles in the bulk**

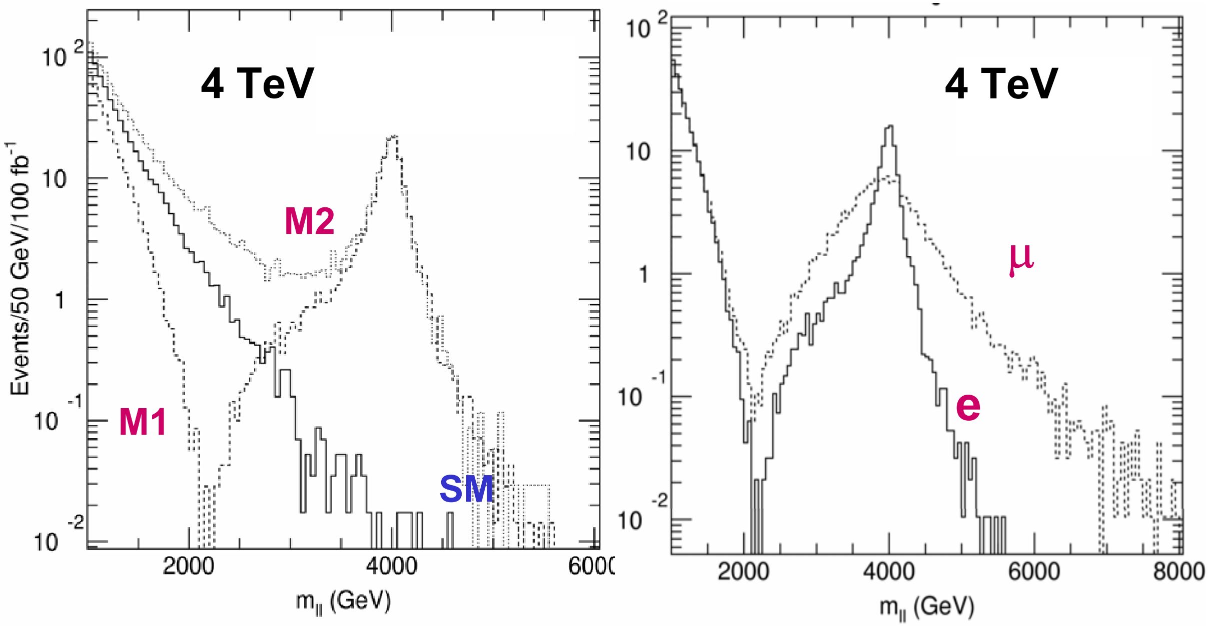
  note: $R = \hbar c / 1\ \mathrm{TeV}^{-1} = 2\times10^{-4}\ \mathrm{fm}\ [M_D \sim 10^{15}\ \mathrm{GeV\ for}\ n=1]$

- ***indirect* constraints from LEP EW measurements:**
  - limits from gauge boson couplings, mixings and virtual exchanges
    - $R^{-1} \geq 3.3 - 6.8$ TeV   K. Cheung and G. Landsberg, Phys.Rev. D65 (2002) 076003 (*hep-ph/0110346*)

- **Z/γ excitation:**

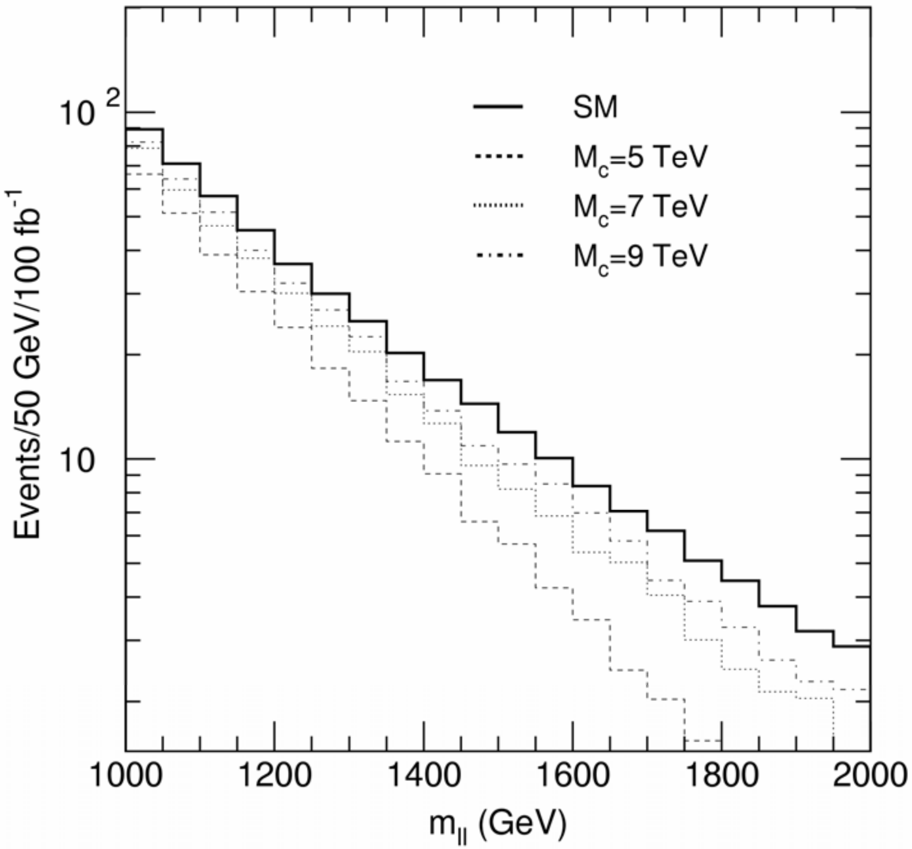
(following T. Rizzo, Phys. Rev. D61 (2000) 055005)

resonance observable up to ~ 5.8 TeV with 100 fb^{-1}



Extra dimensions of ~TeV^{-1} size : Z/γ excitation

- effect on shape of Drell-Yan tail



Optimal analysis of mass from tail

- uses full information

$$x_1,\ x_2, \cos\theta$$

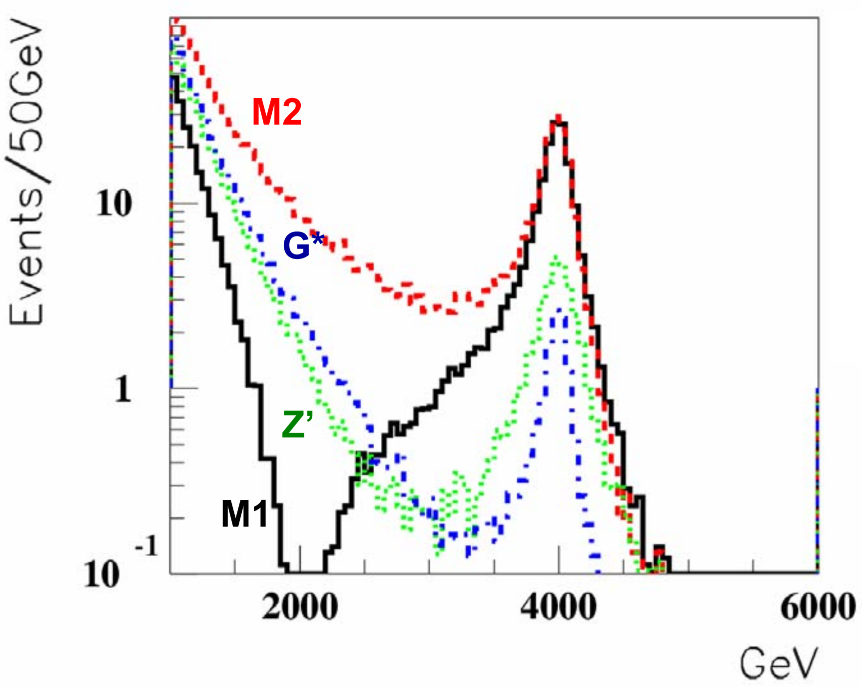
- unbinned max. likelihood

electrons			e+μ
100 fb^{-1}	200 fb^{-1}	300 fb^{-1}	300 fb^{-1}
9.5 TeV	11 TeV	12 TeV	13.5 TeV

- systematics:
  - linearity in energy calibration
  - QCD and EW higher order corrections
  - structure functions

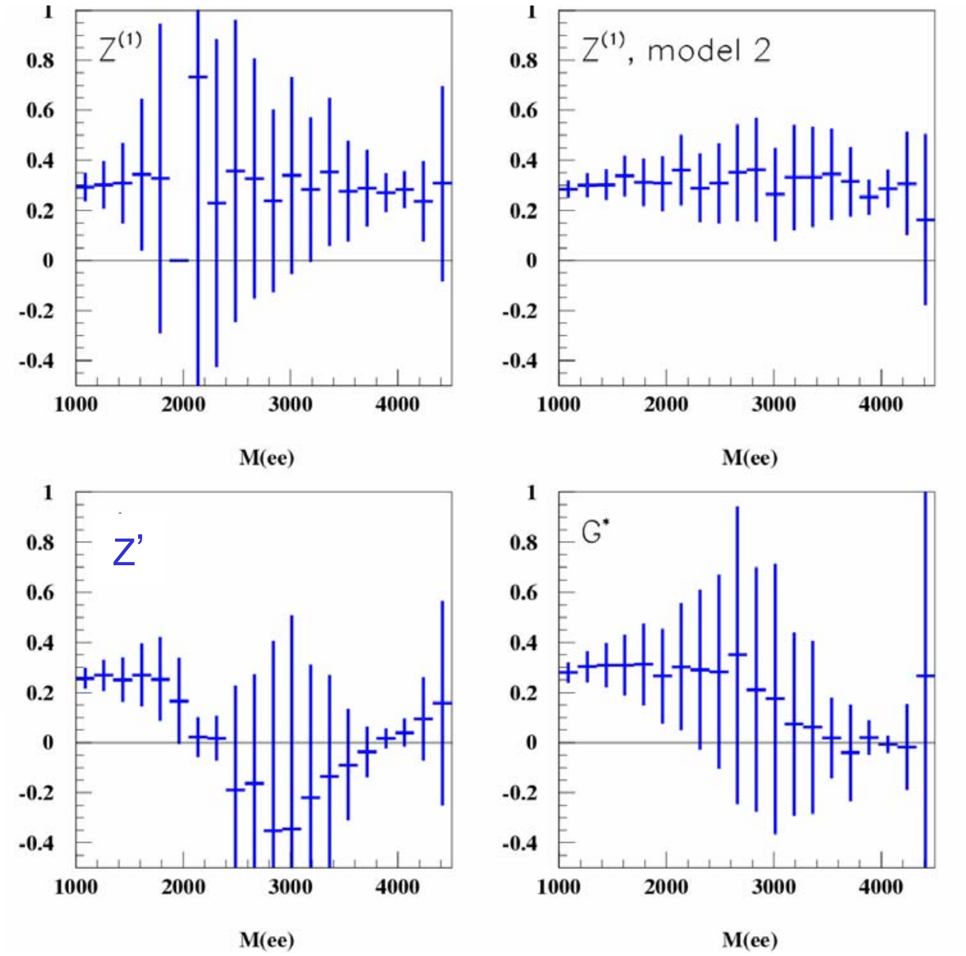
Extra dimensions of ~TeV^{-1} size: Z/γ excitation

- **angular distribution and FB asymmetry**
  (with respect to direction of e^+e^- pair)



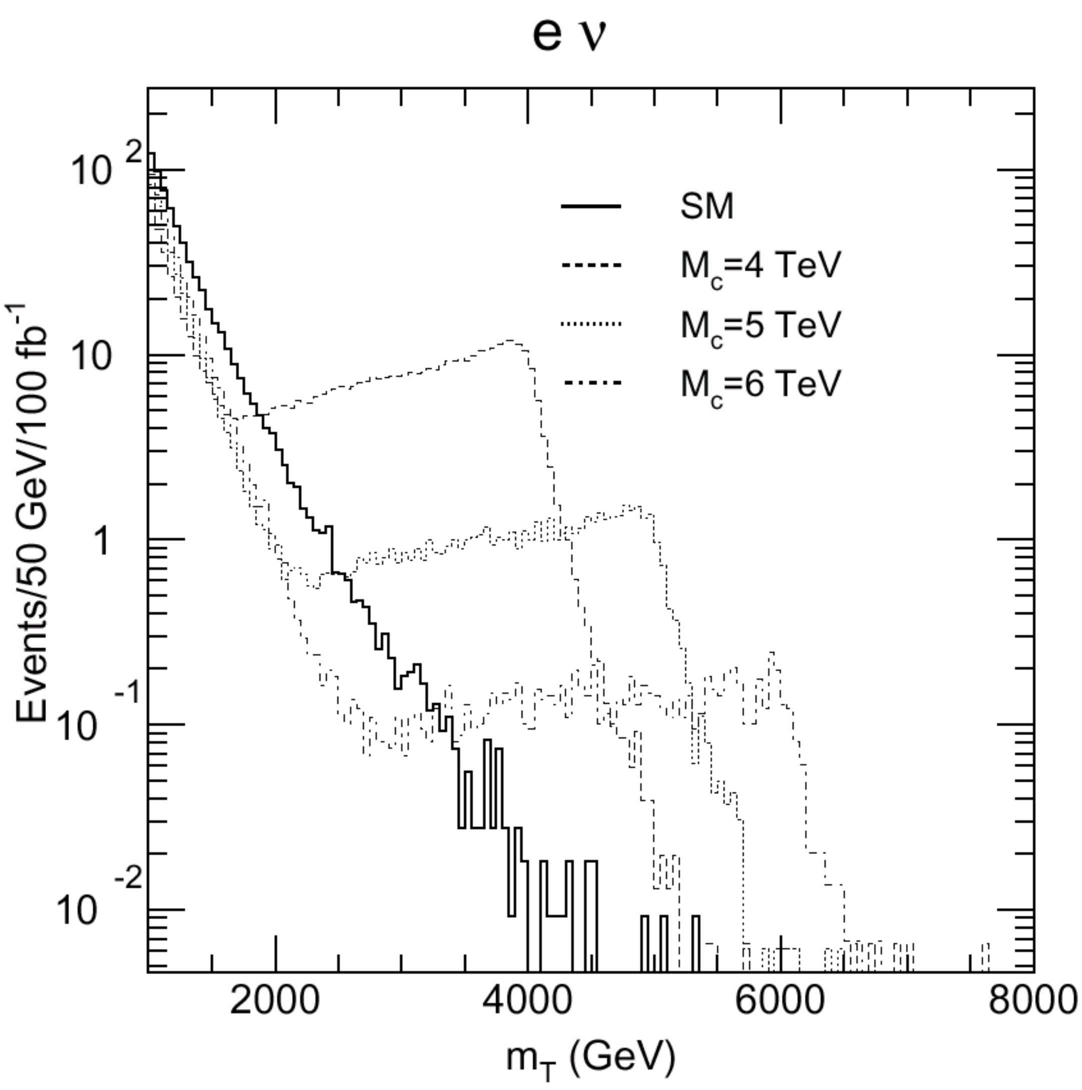
Different narrow resonances

100 fb^{-1}



Extra dimensions of ~TeV^{-1} size: W excitation

- **Same for W$^{(1)}$**
  - direct observation
    up to 6 TeV
  - indirect
    up to ~ 9 TeV
- **more difficult to distinguish from a W'**



G. Polesello et M. Prata
EPJDirect (SN-ATLAS-2003-036)

Randall-Sundrum Model

L. Randall and R. Sundrum, Phys.Rev.Lett. 83 (1999) 3370 (hep-ph/9905221)

- **1 extra dimension *y* with non-factorizable metric**
  - 5D space, bounded by 2 branes
    - SM brane (TeV) at y = π r_c
    - Planck brane at y =0

$$ds^2 = e^{-2ky}\eta_{\mu\nu}dx^\mu dx^\nu + dy^2, \quad y = r_c\phi \text{ , } (k \sim M_{Pl}) \Rightarrow \text{ 3D distances shrink with } y$$

- 5-D Planck scale $M_5 \sim M_{Pl}$: $M_{Pl}^2 = \frac{M_5^3}{k}\left(1 - e^{-2kr_c\pi}\right)$ curvature scalar $|R_5| = 20k^2$
- new physics scale at SM brane = $\Lambda_\pi = M_{pl}e^{-kr_c\pi}$; $kr_c\pi \sim 35 \Rightarrow \Lambda_\pi \sim \text{TeV}$
  - coupling of KK states ~ $1/\Lambda_\pi$
- KK masses:
  - $m_n = kx_ne^{-k\pi r_c}$, with $J_1(x_n) = 0 \quad \Rightarrow \quad m_1 = 3.83\frac{k}{M_{Pl}}\Lambda_\pi$

3 parameters: k, r_c, Λ_π
(2 independent)

constraints: $0.01 \le \frac{k}{M_{Pl}} \le 0.1$

Note: astrophysical bounds not applicable in this model

Narrow Graviton Resonance

B. C. Allanach, K. Odagiri, A. Parker and B. Webber,
JHEP 9 (2000) 19

- **signal:** $G^{(1)} \rightarrow e^+e^-, \mu^+\mu^-, \gamma\gamma, (WW, ZZ, t\bar{t})$
  - implemented in HERWIG
  - model-independent analysis

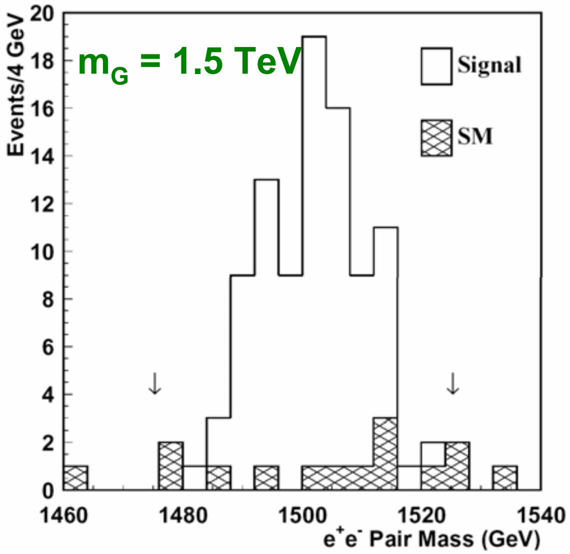
e^+e^- channel,

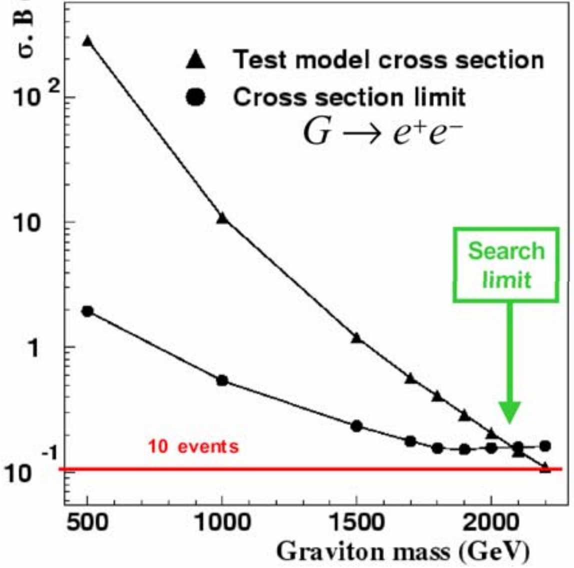
100 fb^{-1}

RS model uses as reference with

$$\frac{k}{M_{Pl}} = 0.01$$

(pessimistic scenario)





Energy resolution

$$\frac{\Delta E}{E} = \frac{12\%}{\sqrt{E(GeV)}} \oplus \frac{24.5\%}{E_T} \oplus 0.7\%$$

Sensitive at 5σ up to 2080 GeV

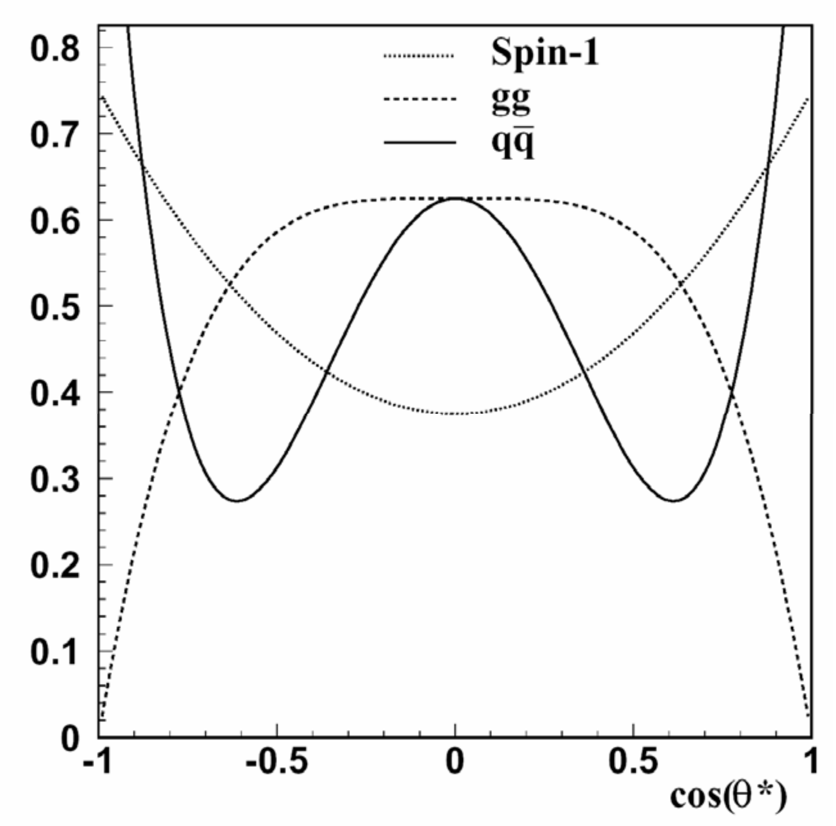
mass resolution

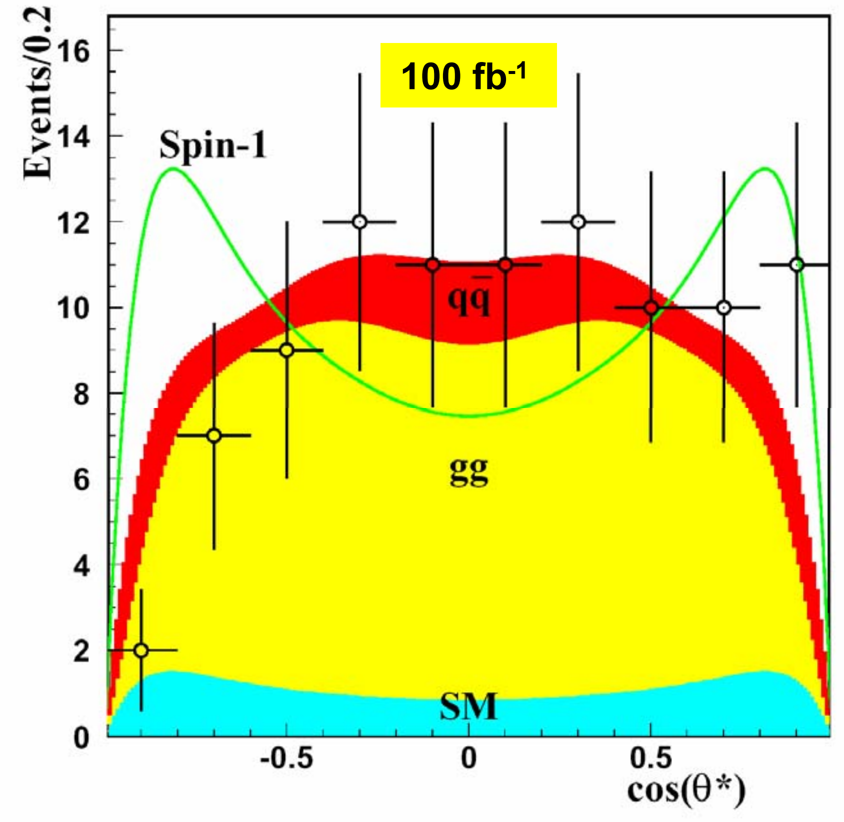
$$\frac{\sigma_m}{m} \sim 0.8\%$$

similar results with *$\gamma\gamma$, ($\mu\mu$)*

Narrow Graviton Resonance

Spin determination

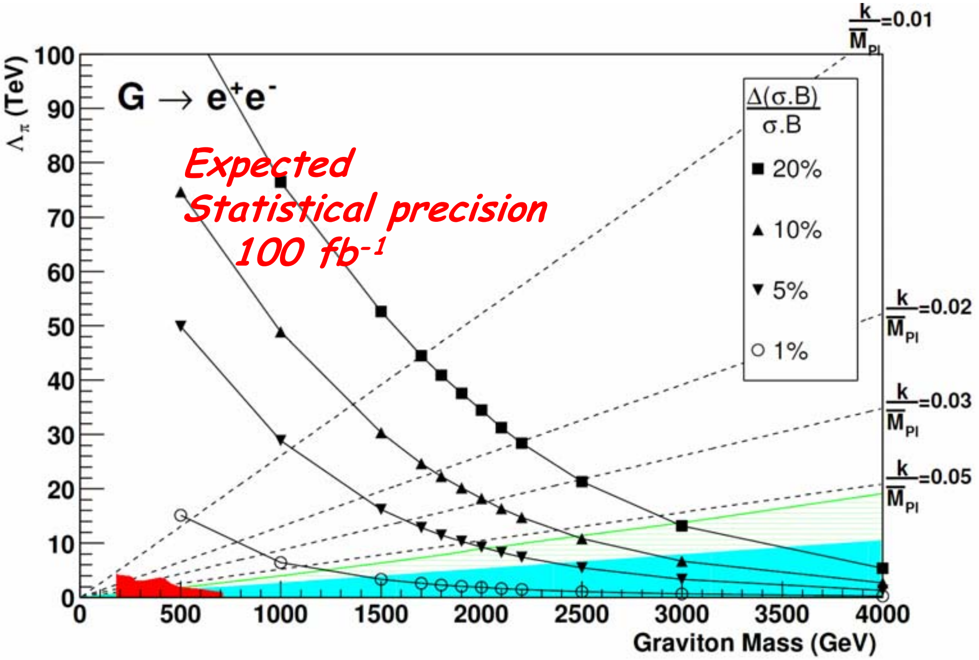




spin-2 could be determined (spin-1 ruled out) with 90% CL up to graviton mass of 1720 GeV

Allanach et al., ATL-PHYS-2002-031

- also G → WW , ZZ, jj, mm, tt, hh

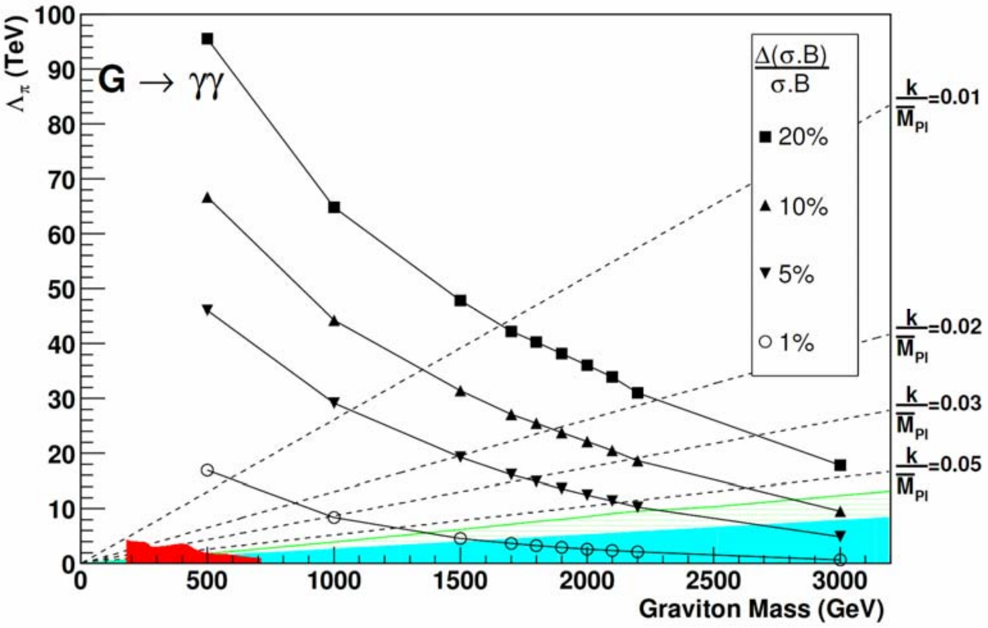


Expected Statistical precision $100\ fb^{-1}$

$$\Lambda = \frac{m_G}{x_1 \cdot k / M_{Pl}},$$

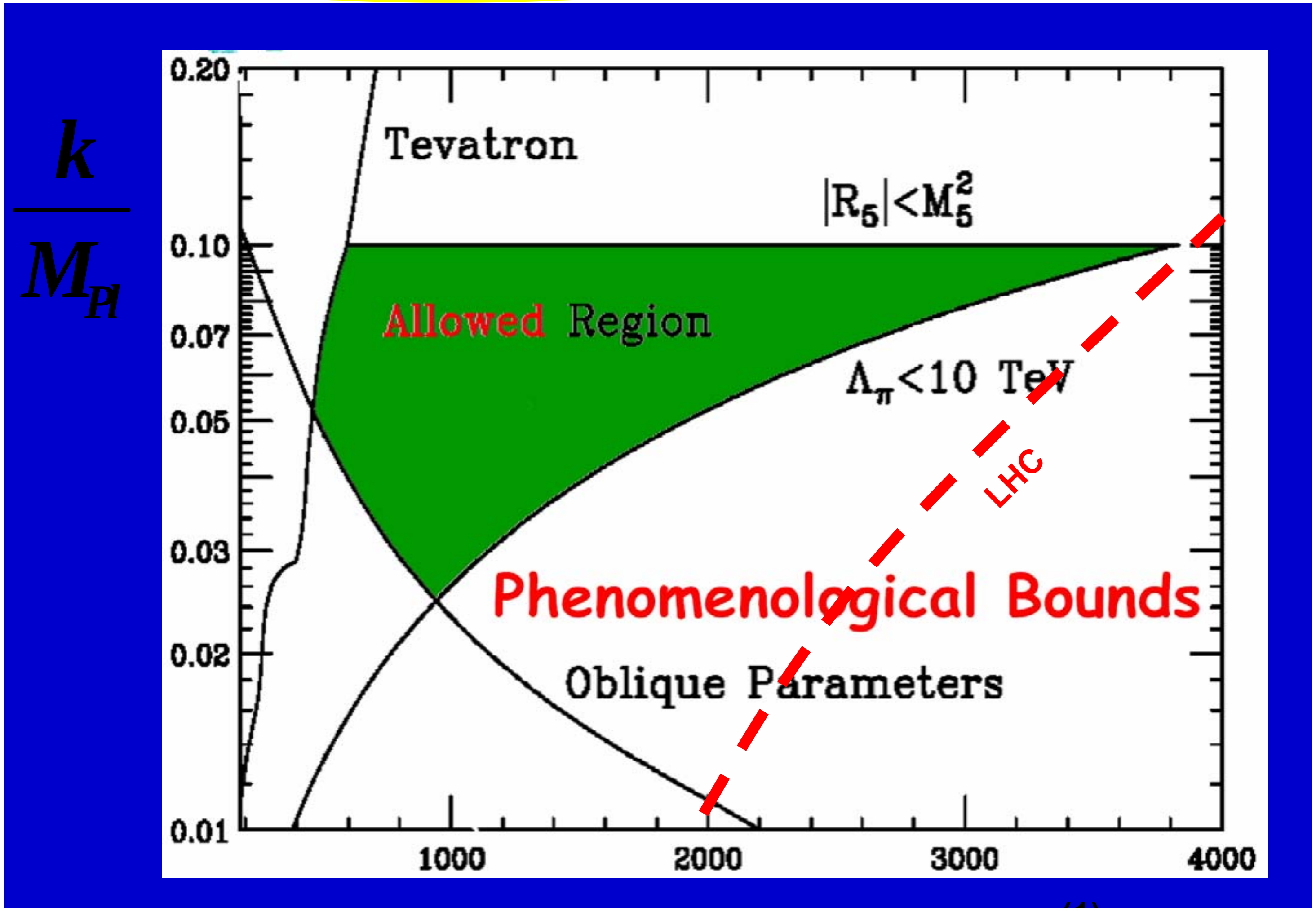
$x_1 = 3.83 = 1^{st}$ root of Bessel function

e.g.: for a resonance observed at
m_G = 1.5 TeV in ee channel
$\Delta m_G < 10.5$ GeV (energy scale error)
$\Delta\sigma.B \sim 18\%$
if $k/r_c = 0.01$ (pessimistic)
⟹ $r_c = (82 \pm 7) \times 10^{-33}$ m !!



Narrow Graviton Resonance

Interesting region covered by LHC

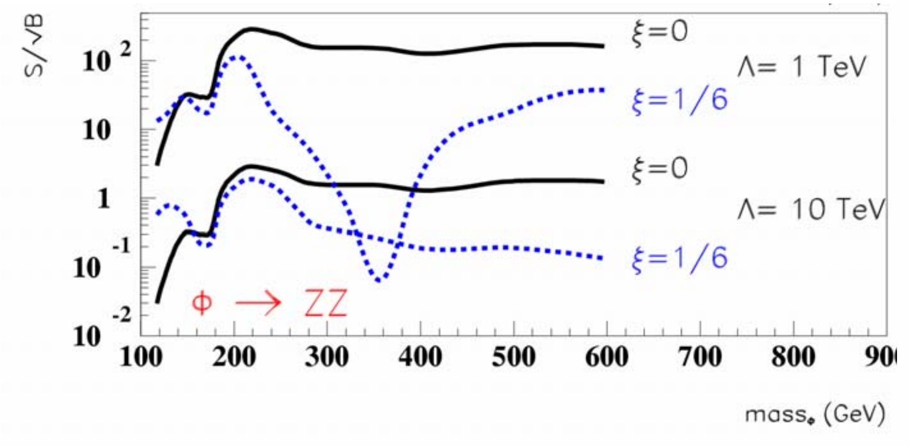


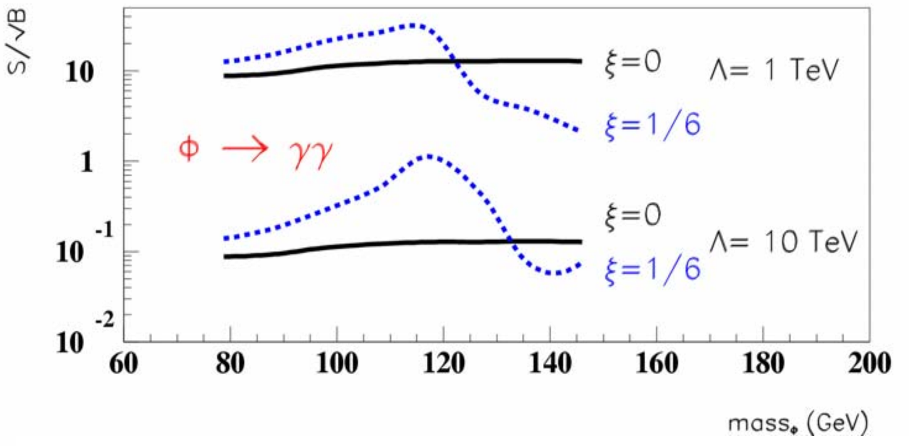
H. Davoudiasl, J. Hewett and T. Rizzo, Phys.Rev. D63 (2001) 075004 (*hep-ph/0006041)*

Randall-Sundrum model: the radion

- **stabilize $kr_c\pi \sim 35\ \ (kr_c \sim 12)$**
  - *Goldberger and Wise (PRL 83 (1999) 4922) proposed a mechanism which stabilizes $kr_c\pi$*
    - *introduce a radion: a scalar field representing fluctuations of the distance between the two branes*
    - *radion has mass: $m_\phi < m(KK=2)$*
  - higgs-like couplings ⇒ mixes with Higgs
- **reinterpreting SM Higgs search studies…**

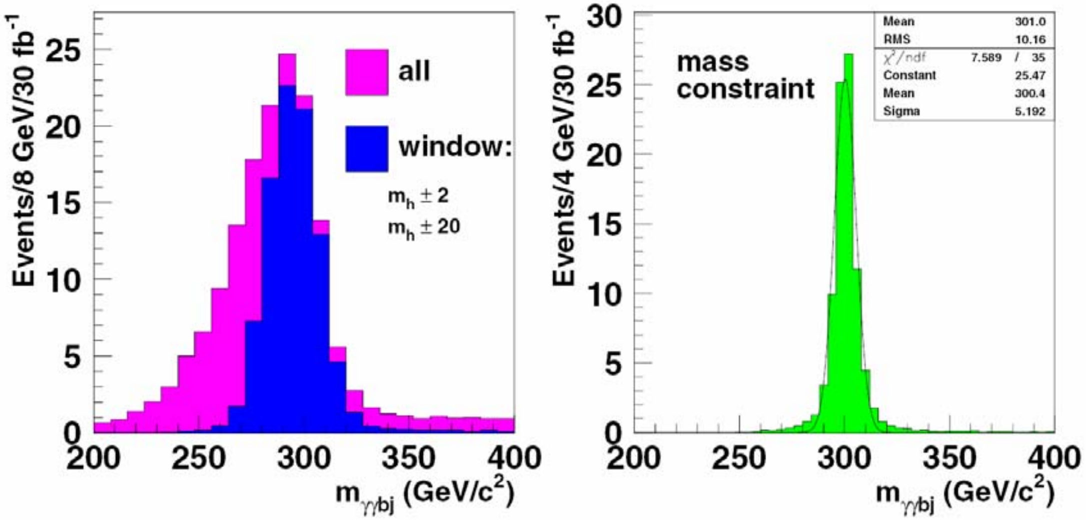
G.A., D. Cavalli, H. Przysiezniak, L. Vacavant
SN-ATLAS-2002-019





Randall-Sundrum model: the radion

- **signal:** $\phi \rightarrow hh \rightarrow \gamma\gamma\, b\bar{b}$
  - similar to MSSM, but with appropriate corrections for width and branching ratios
  - consider cases: m_ϕ = 300, 600 GeV, m_h = 125 GeV
- **backgrounds negligible**
  - $gg \rightarrow \gamma\gamma$ with QCD radiation
  - γj, with jet misidentified as photon



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

Luminosity (fb^{-1}) required for 5 σ discovery

reach: 2.2 TeV or 0.6 TeV for $m\phi$ = 300 or 600 GeV, respectively, with 30 fb^{-1}

Black Holes

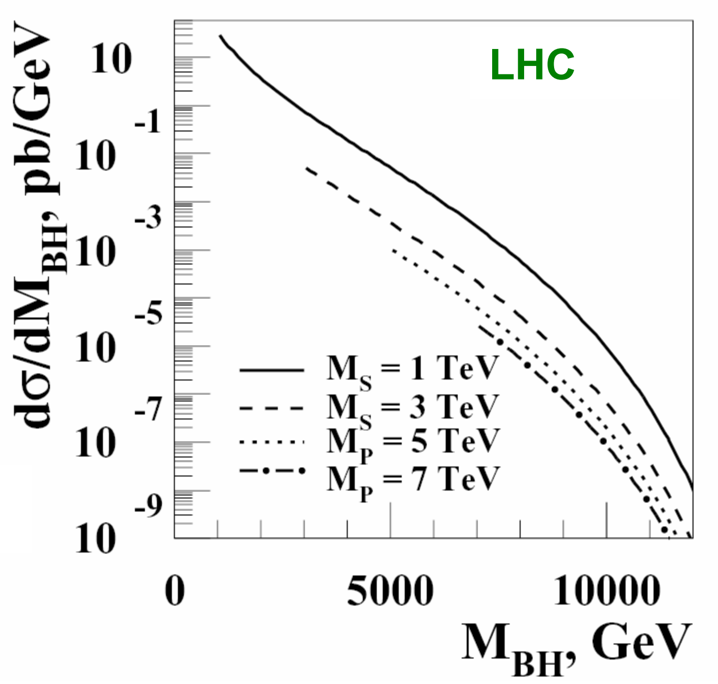
definition

- object confined in a volume of radius R< R_S

For n+3 dim., $$R_S^{(n)} = \frac{1}{\sqrt{\pi} M_P}\left[\frac{M_{BH}}{M_P}\left(\frac{8\Gamma\left(\frac{n+3}{2}\right)}{n+2}\right)\right]^{\frac{1}{n+1}}$$

$$M_P \sim \mathrm{TeV} \quad \Rightarrow \quad \pi R_S^2 \sim \mathrm{O}(100\,\mathrm{pb})$$

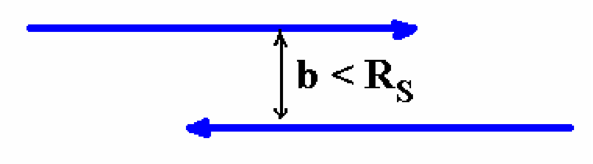
(**This approximation is contested:**
- **M. B. Voloshin, *PL B518 (2001) 137, PL B524 (2002) 376***
- **V. S. Rychkov, *hep-ph/0401116***)



Dimopoulos et Landsberg, hep-ph/0106295

Production at the LHC

- For impact parameters $b < R_S\left(\sqrt{s}\right)$



⇒ formation of black holes

> *« The end of short-distance physics »*
>
> ***Giddings and Thomas, hep-ph/0106219***

Black Holes

Theoretical Uncertainties

- production cross section
- disintegration
  - emission of gravitational radiation (balding phase)
  - main phase ? = Hawking radiation, or evaporation
    - spin-down phase: loss of angular momentum
    - Schwarzschild phase: emission of particles
      - quantum numbers conserved?
  - Planck phase: impossible to calculate

⇒ new generator, CHARYBDIS : time evolution, grey-body factors, Planck phase

CM Harris, P. Richardson and BR Webber, JHEP 0308 (2003) 033 (hep-ph/0307305)

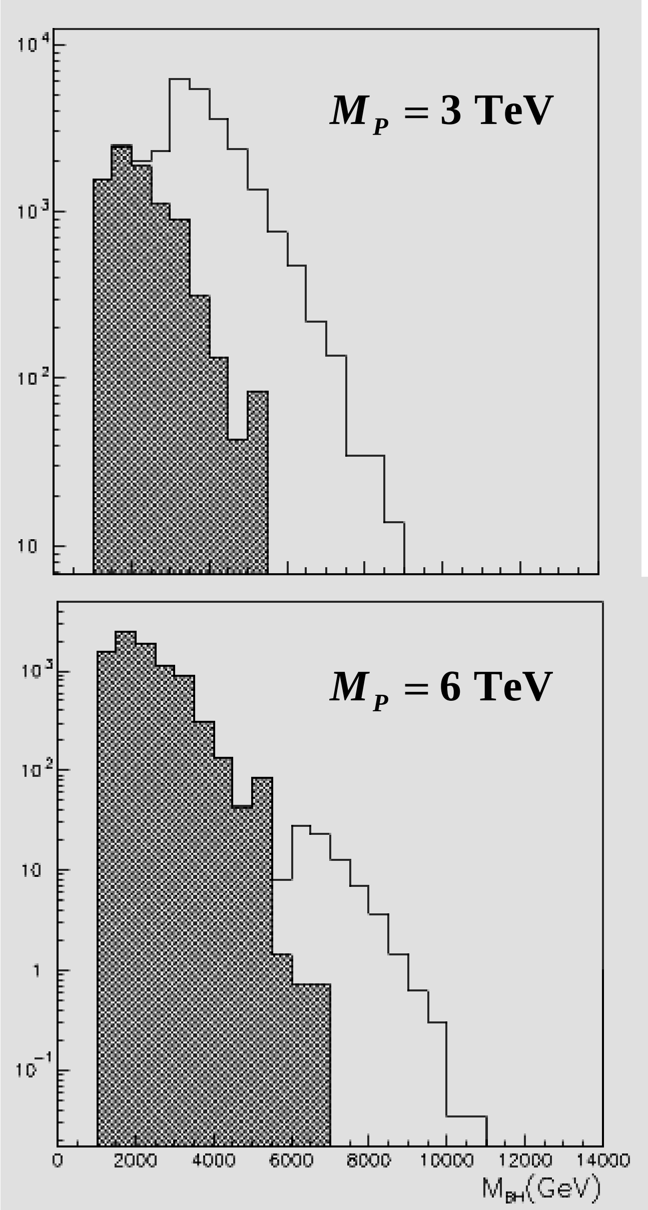
Characteristics

- temperature: depends on the mass

$$T_H(M_P, n, M_{BH}) = M_P \frac{n+1}{4\sqrt{\pi}} \left(\frac{M_P}{M_{BH}} \frac{n+2}{8\Gamma\left(\frac{n+3}{2}\right)} \right)^{\frac{1}{n+1}} = \frac{n+1}{4\pi R_S^{(n)}}$$

- black body radiation: emission of particles
  - high multiplicity
  - “democratic” emission
  - spherical distribution

Black Holes



M_{BH}

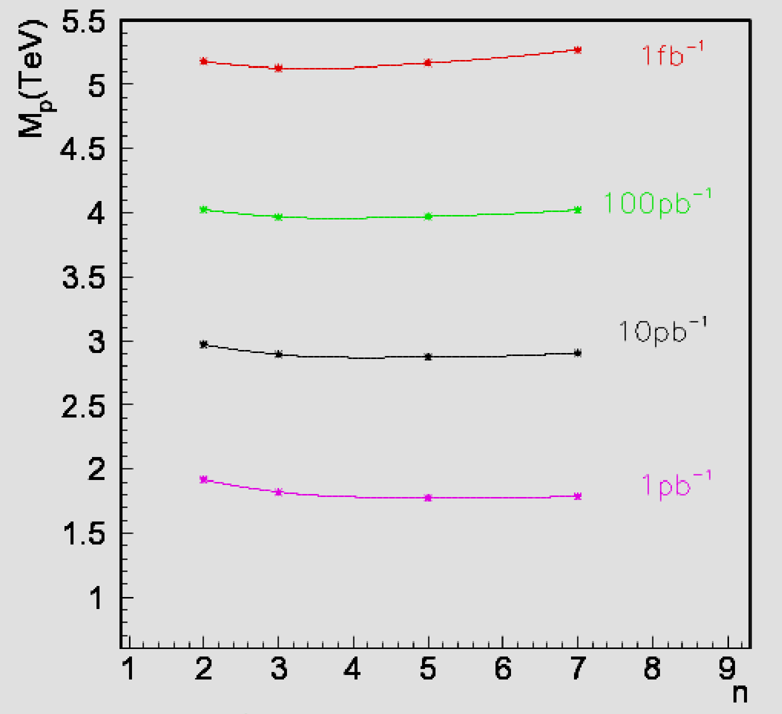
simulation in ATLAS

- selection of spherical events
- **M_{BH}** reconstructed for each event
- reconstruction of **M_P** from the cross section

ds/dM_{BH}

- given the energy distribution for M_{BH} ⇒ **T_H**

n deduced from T_H, M_{BH} and M_P
(Hawking radiation formula)



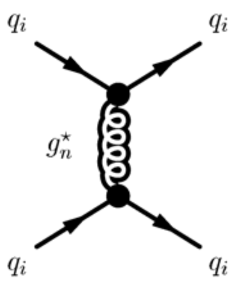
J. Tanaka et al., ATL-PHYS-2003-037

Other models and ideas…

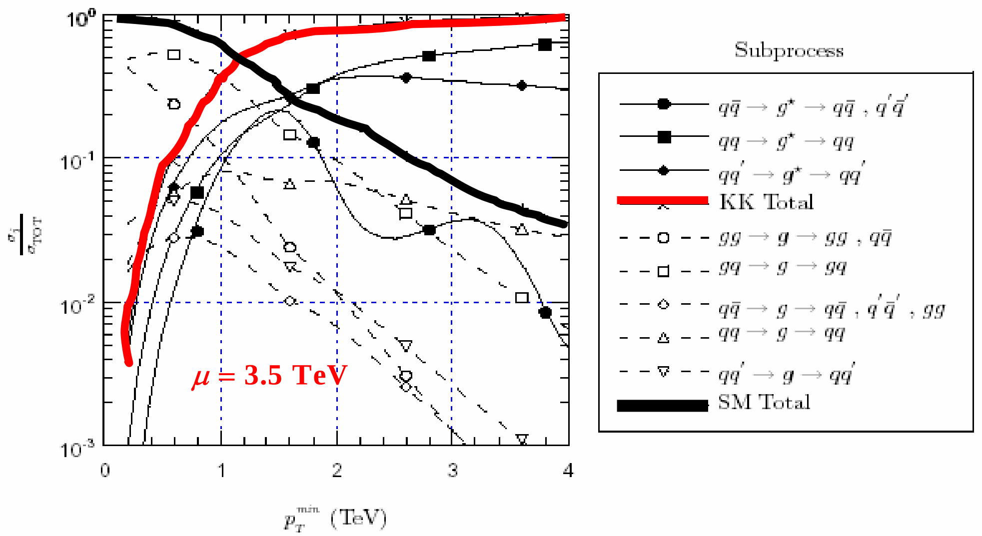
- **TeV^{-1}-size:**

DA Dicus, CD McMullen and S. Nandi hep-ph/0012259

  - virtual g* excitation ⇒ enhanced di-jet cross section



ATLAS study in progress…



- **Universal Extra dimensions**

T. Appelquist, HC Cheng and BA Dobrescu, PR D64 (2001) 035002

  - All SM particles in bulk

⇒ conservation of momentum in extra dimensions

⇒ conservation of KK number

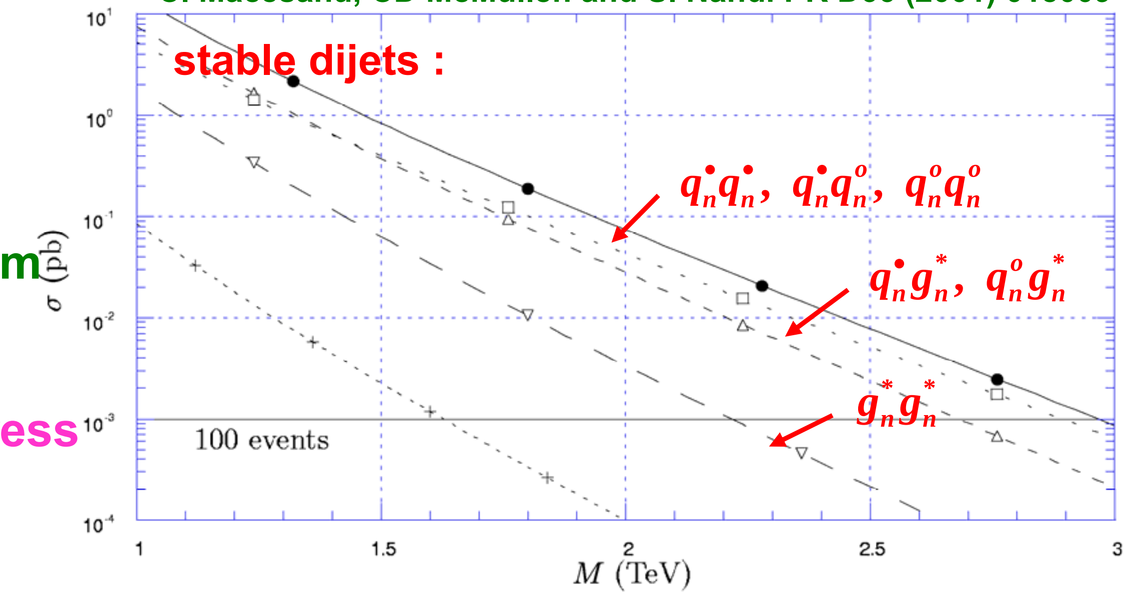
⇒ pair production of KK states

⇒ lower collider bounds: ~ 350-400 GeV

Universal Extra Dimensions

- **dijet signals**
  - **stable**
  - **unstable:**
    fat brane absorbs unbalanced momentum from KK number violation
  - **ATLAS study in progress**

C. Macesanu, CD McMullen and S. Nandi PR D66 (2001) 015009



- **LKP:** γ^*

$$q_1^\bullet q_1^\bullet \to (\ldots+\gamma^*)(\ldots+\gamma^*)\left(\to \gamma G + \gamma G + X\right)$$

C. Macesanu, CD McMullen and S. Nandi
Phys.Lett. B546 (2002) 253

  - **can be fooled by SUSY**

HC Cheng, KT Matchev, and M Schmaltz
Phys.Rev. D66 (2002) 056006 (hep-ph/0205314)

  - **ATLAS study in progress**

Many other topics…

- **leptoquarks**
  - see talk by S. Rolli, in “landscape” // session, yesterday
    - reach: ~ 1.5 TeV
- **scalars in the bulk**
  - → coupling to Higgs, Cosm. constant problem?
  - mixing with higgs
- **higgless model**
  - → *Z’* with anomalous couplings
- **LFV:**
  - $\tau \rightarrow 3\ \mu$
  - in SUSY decays
- **monopoles**
- **…**

Benefit from Tevatron experience

- **experience with real data,**
  - limit of low rates, sometimes limit of detector performance, at LHC
  - sources of systematic errors, experimental and theoretical
  - calibration and scale of high energy tracks, jets
  - particle ID: b-jets, photons, electrons
  - jet pair reconstruction
  - pileup: min. bias models cannot be extrapolated
    - central jet veto
  - analysis techniques: NN,
- **overlap region**
  - 95% exclusion means 5% possibility of signal
  - trigger