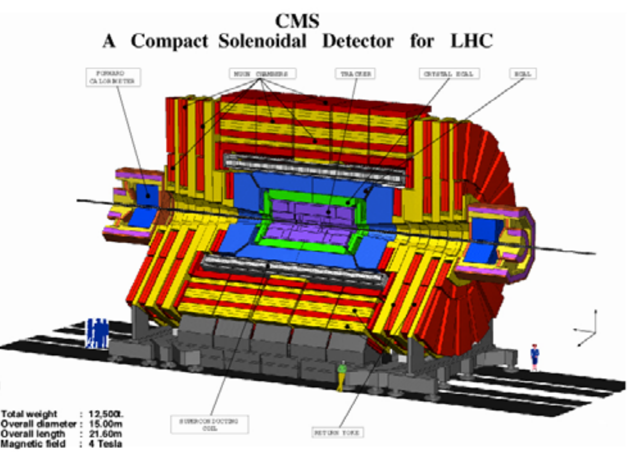
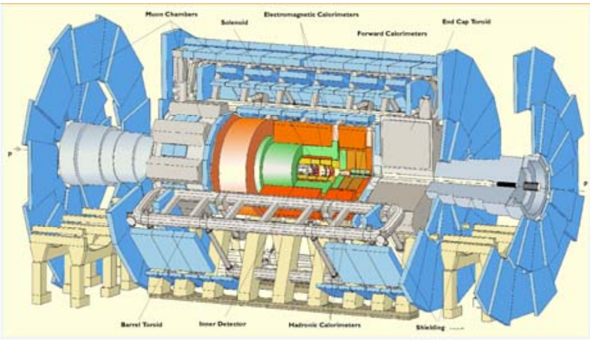
LHC Physics Landscape

What more will we know a few years from now?
Possible scenarios

G. Azuelos
TRIUMF/ U. Montreal





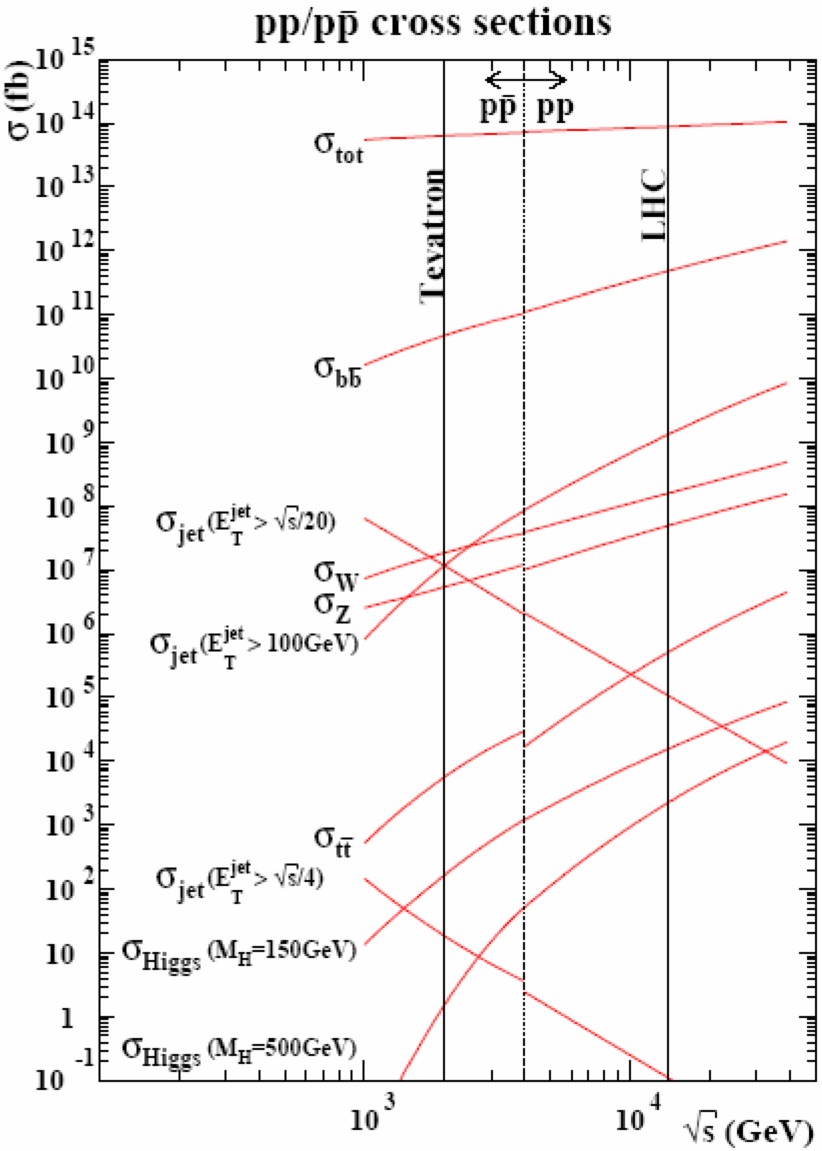
apologies for ATLAS bias…

Vast Physics programme

- **EWSB**
  - SM Higgs
  - SUSY
    - Higgs
    - particle spectrum → *talk by Gudrid Moortgat-Pick*
  - alternatives: little Higgs, Higgless models,
    (strong EWSB → talk by Tim Barklow)
- **gauge theories with extended symmetry**
  - *Z', W' → talk by Steve Godfrey*
  - LR model, E6
- **ew precision measurements**
  - ***top → talk by Aurelio Juste on top couplings***
- **compositeness**
- **extra dimensions**
- **other topics…**
- *QCD*
- *B (LHCb), Heavy Ions (ALICE)*

For an excellent review:
Physics Interplay of the LHC and the ILC, G. Weiglein, ed., (hep-ph/0410364)

LHC: basic features



from: **G. Weiglein et al.,** ***Physics Interplay of the LHC and the ILC*****, hep-ph/0410364**

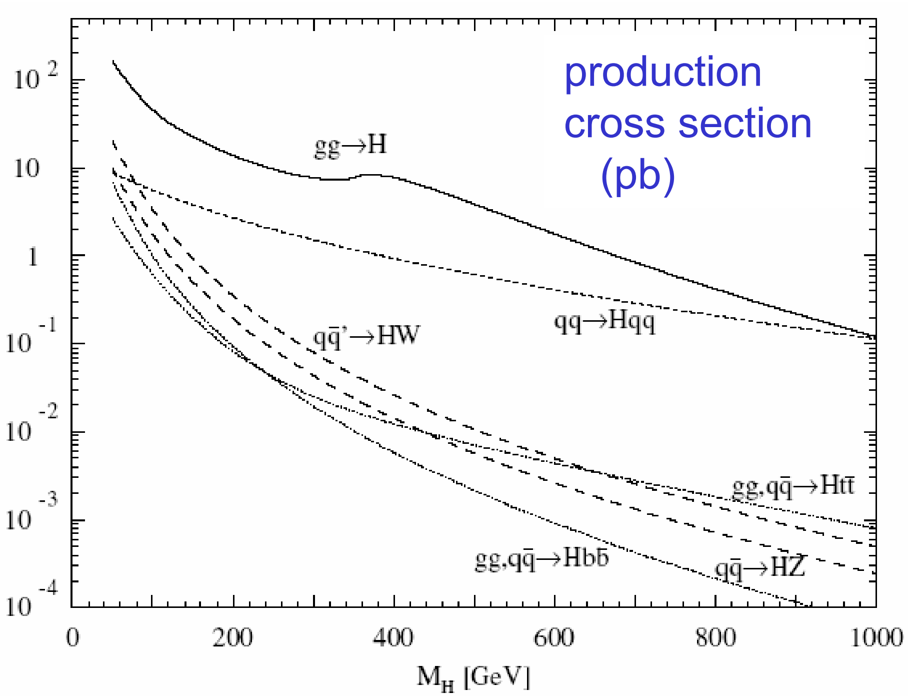
- **p p collider,** $\sqrt{s} = 14$ TeV
  - (also heavy ions)
- **startup:** 2007-2008
- **nominal luminosity:** $10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$
- **bunch crossing:** every 25 ns

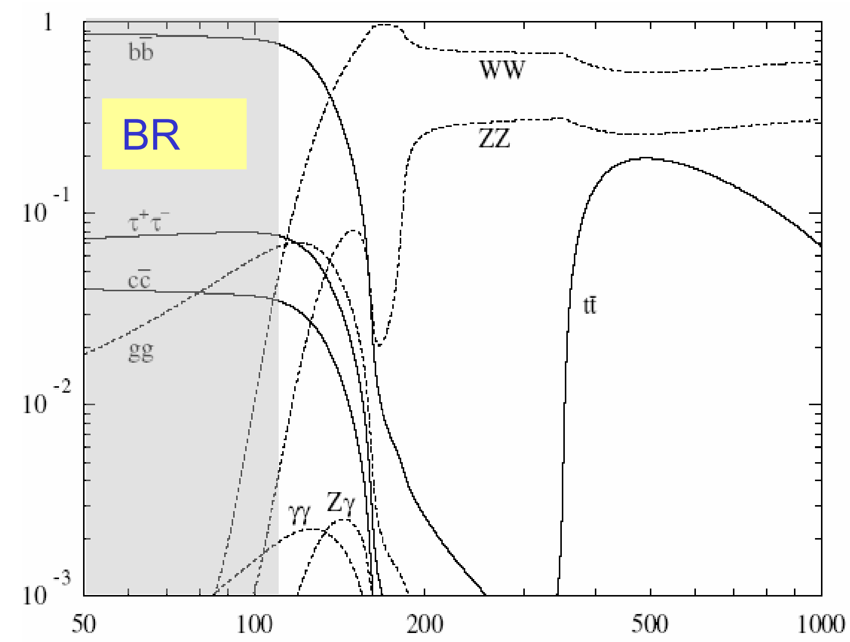
☺ **high energy:**
- parton collisions spanning up to $\sqrt{\hat{s}} \sim 7$ TeV (gg collisions)

☹ **very high QCD cross section**
- NLO corrections important
- pileup: ~ 20 min. bias events/bunch crossing
  - resolution effects and backgrounds
- overwhelming background for ew processes
  - good particle ID crucial

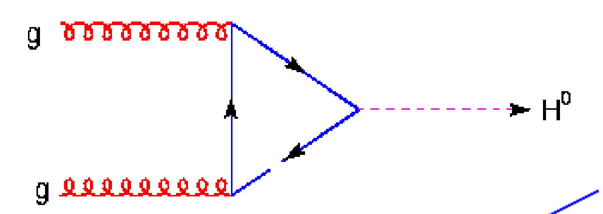
- **ILC:**
  - ☹ lower energy, fixed cm energy but
  - ☺ precision measurements, with clean events, known cm energy, luminosity, and polarization

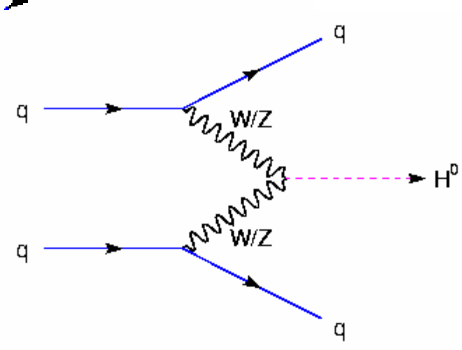
EWSB: Standard Model Scenario



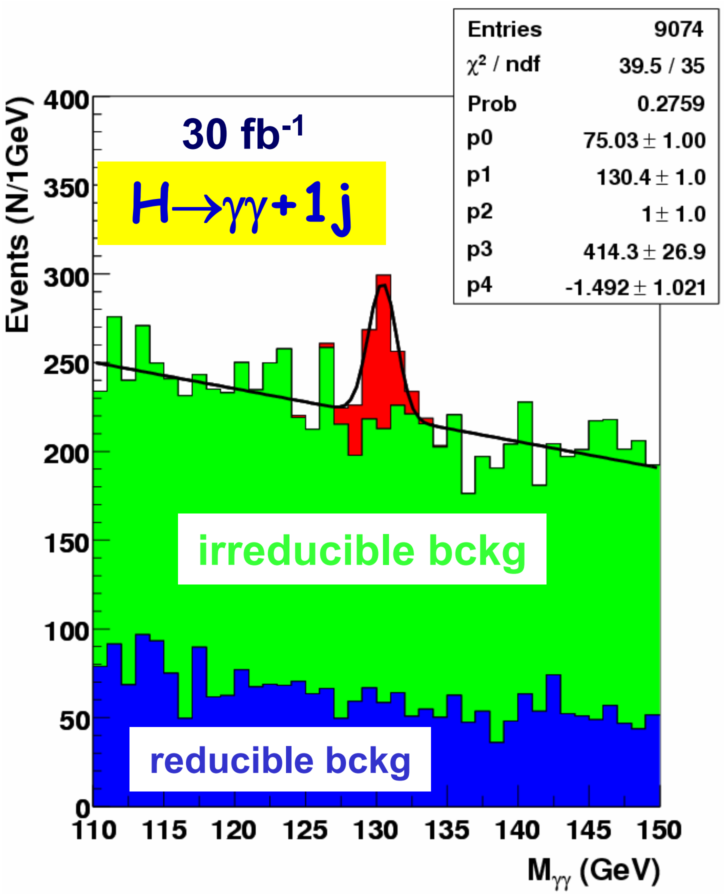


- **production principally by gg fusion, but also by VB fusion**
- **QCD background limits study of H decay channels**
- **need to measure properties:**
  mass, gauge and Yukawa couplings, spin, CP quantum number, self-couplings



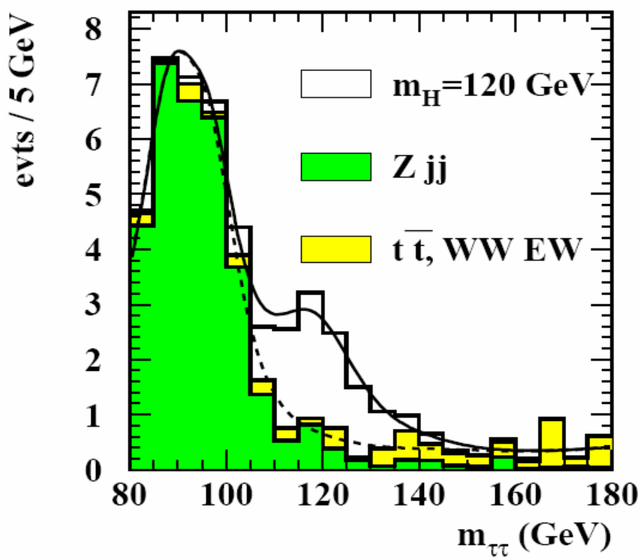


EWSB: Standard Model Scenario: light Higgs



B. Mellado, ATLAS Phys workshop, 7/06/05

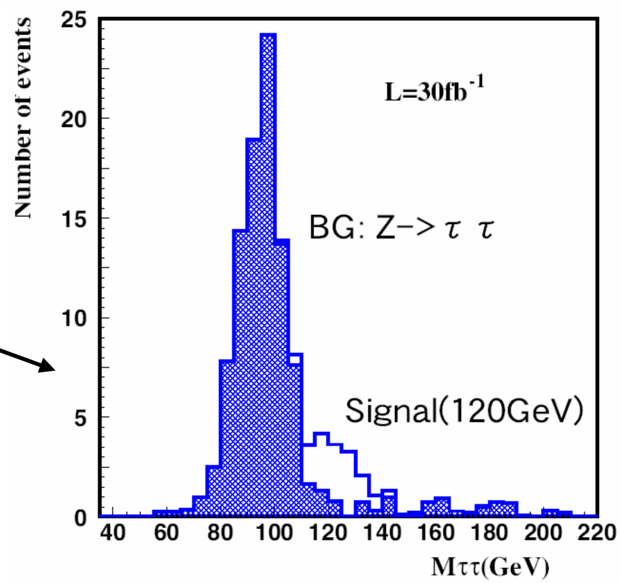
$qqH \rightarrow qq\tau\tau$ 30 fb^{-1}



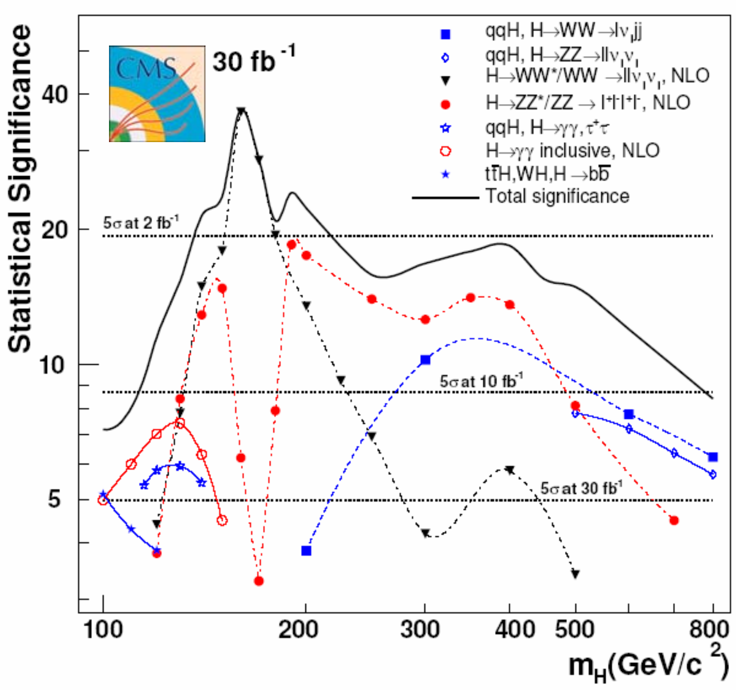
Asai et al.,
Eur.Phys.J. C32S2 (2004) 19
(hep-ph/0402254)

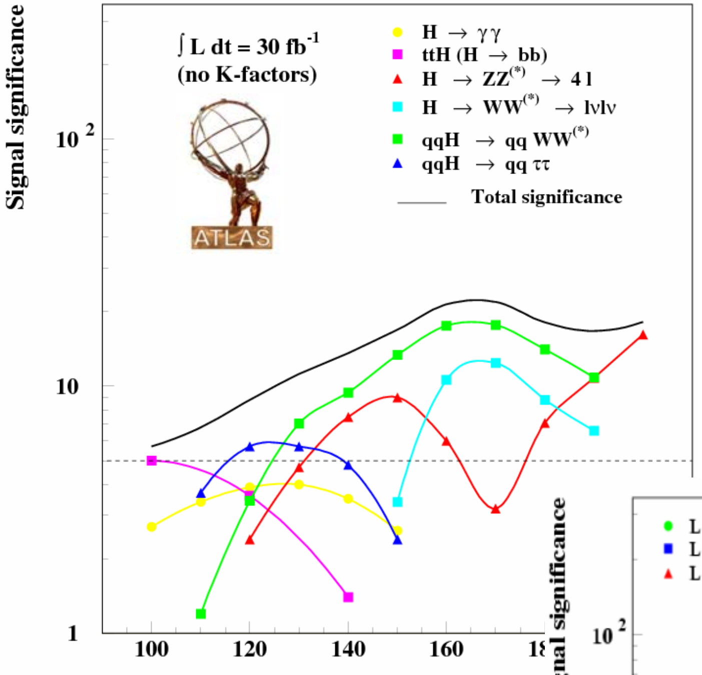
$\tau\tau \rightarrow ll + \not{E}_T$

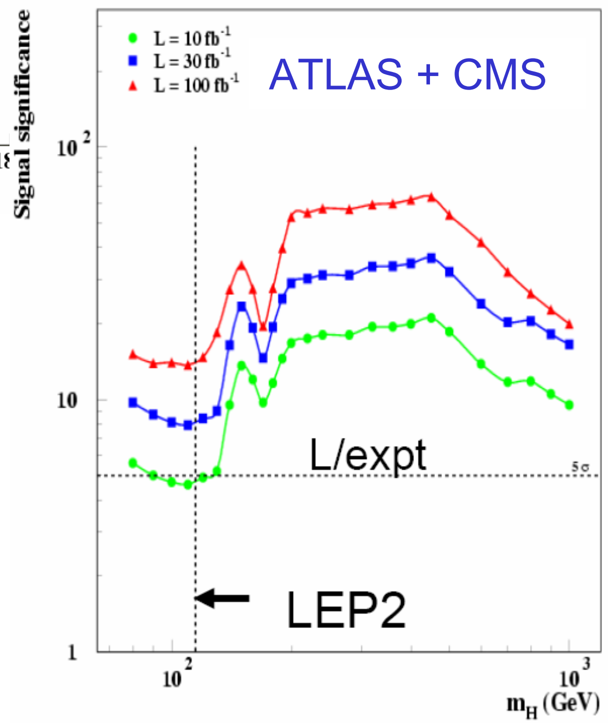
$\tau\tau \rightarrow lh + \not{E}_T$



EWSB: Standard Model Scenario







- Discovery assured in full mass range with ~ 10 fb^{-1}

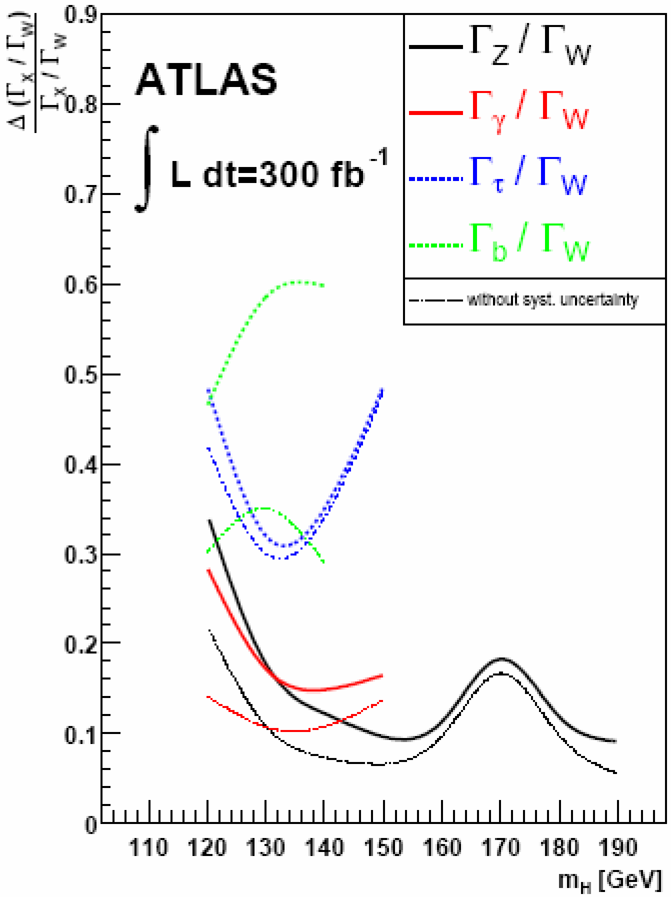
- more than one channel of discovery

at ILC,
a final-state-independent mass determination is possible from mass recoil against Z in HZ production.

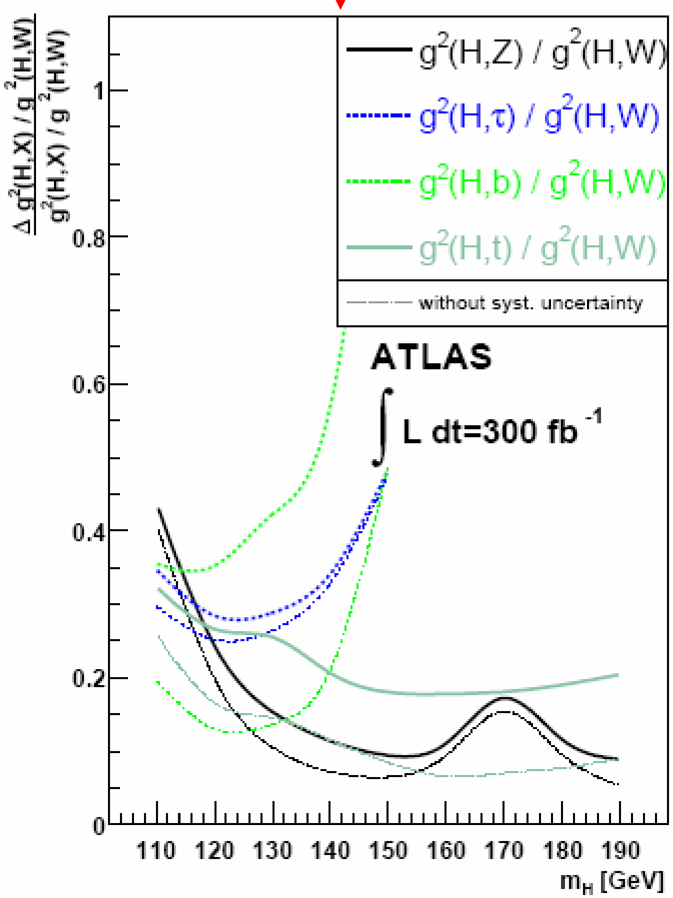
EWSB: – Is this the SM Higgs ??

Fractional errors

ratios of BR's



ratios of couplings



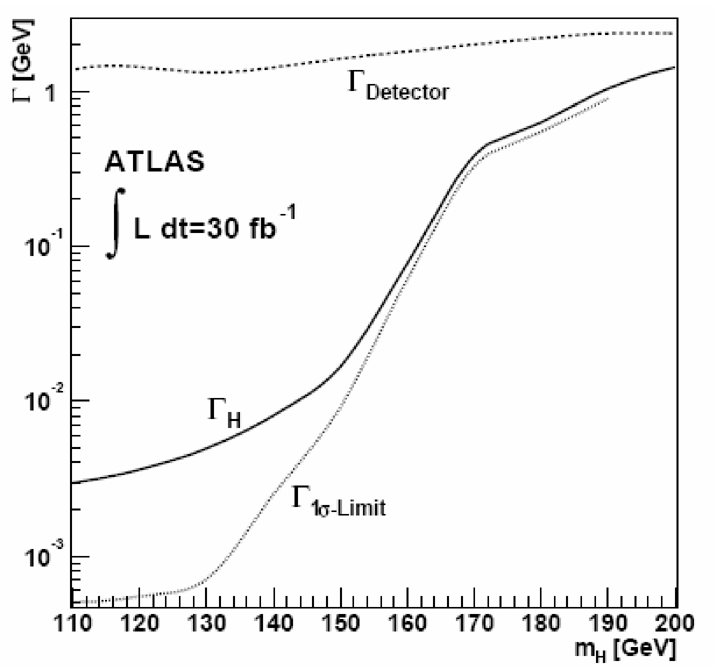
assume:

- CP even, spin-0 scalar
- only one Higgs boson
- no extra fermions

some theoretical model-dependence in evaluation of production and decay diagrams

from a compilation of various ATLAS studies, **M. Dührssen, ATL-PHYS-2003-030**

Absolute couplings

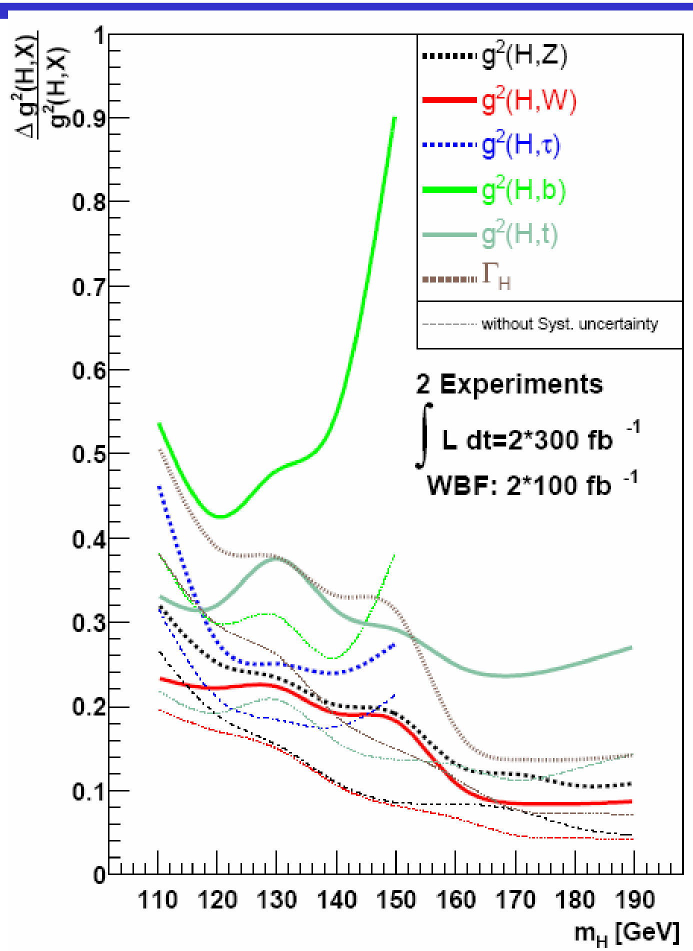


lower limit on width of H boson

(from sum of all detectable decays)

M. Dührssen ATL-PHYS-2003-030

at ILC, much higher precision attainable (top-Yukawa requires high energy)



M. Dührssen et al., XXXIXth Rencontres de Moriond, La Thuile, March 2004 (hep-ph/0407190)

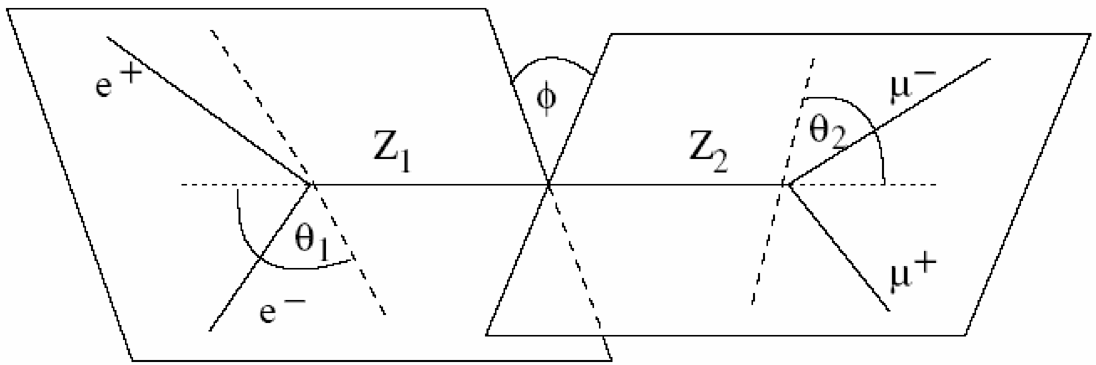
assumes gauge boson couplings not larger than in SM

(valid for generic 2HDM)

Spin and CP Eigenstate

- production vertex not measurable
  gg fusion rules out spin 1 (Yang's theorem)
- decay vertex: decay to resonance pair necessary to measure CP

For $m_H > 2m_Z$:

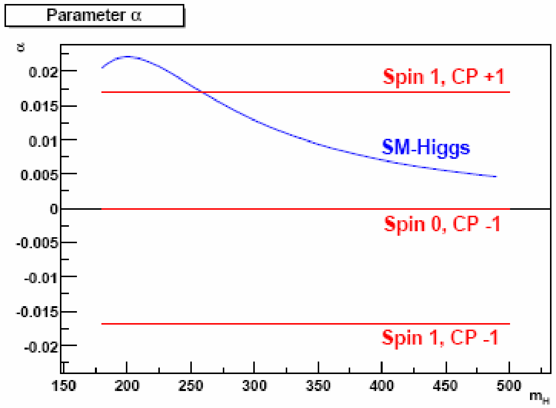


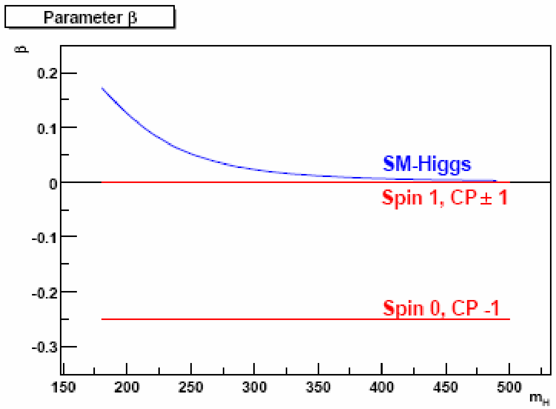
$$F(\phi) = 1 + \alpha \cos(\phi) + \beta \cos(2\phi)$$

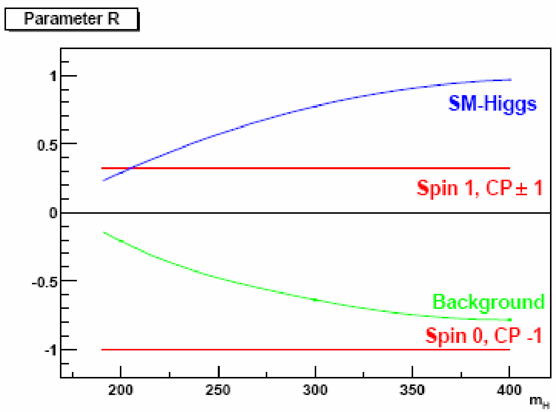
$$G(\theta) = T\,(1 + \cos^2\theta) + L\,\sin^2\theta$$

$$R = \frac{L - T}{L + T}$$

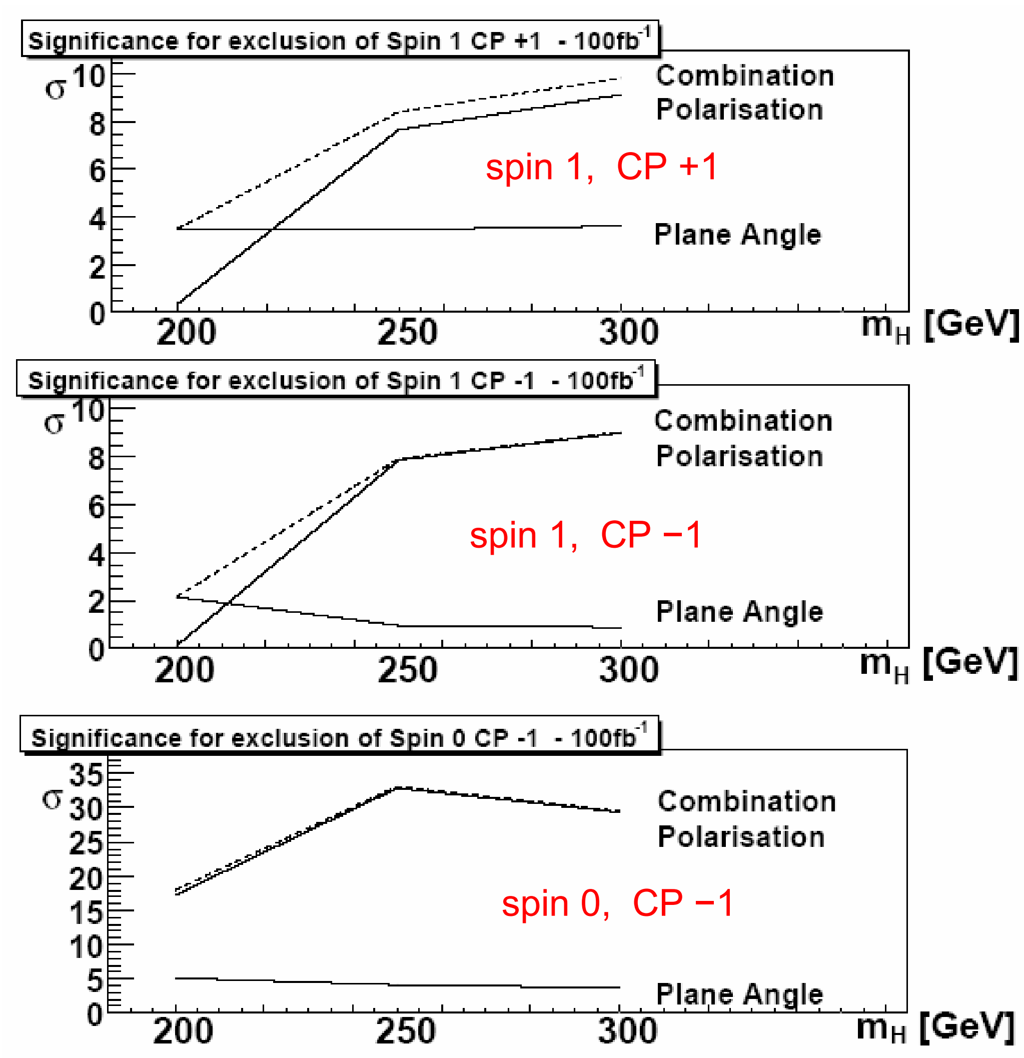
C.P. Buszello et al., *Eur. Phys. J C32 (2004) 209* (hep-ph/0212396)







Spin and CP Eigenstate



C.P. Buszello et al., *Eur. Phys. J C32 (2004) 209* (hep-ph/0212396)

- rule out spin 1
  - for $m_H > 230$ GeV with 100 fb^{-1}
  - for $m_H \sim 200$ GeV, higher Luminosity
- rule out J=0, CP= −1
  - for $m_H > 200$ GeV with 100 fb^{-1}

In a general 2HDM, or MSSM with CP violation, the 3 neutral H bosons mix. Measuring the amount of CP violation will need combination of LHC/ILC.

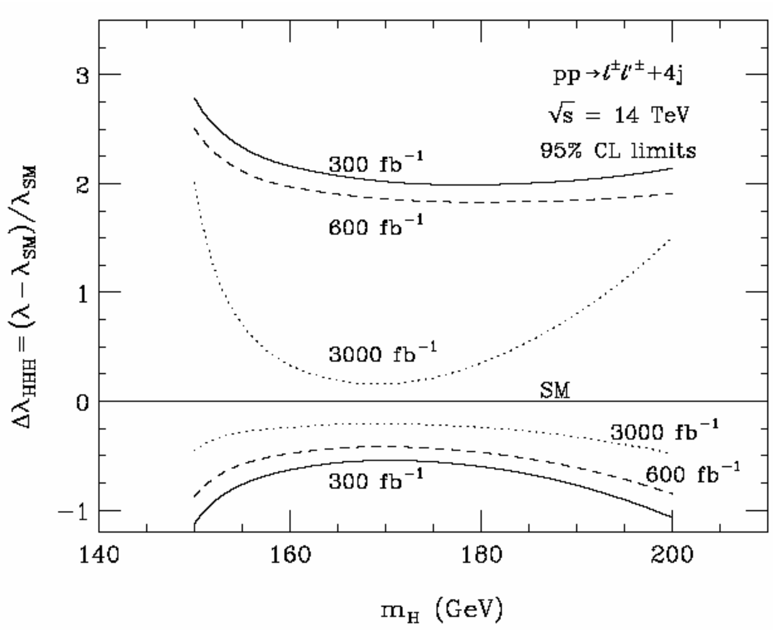
Higgs self-coupling

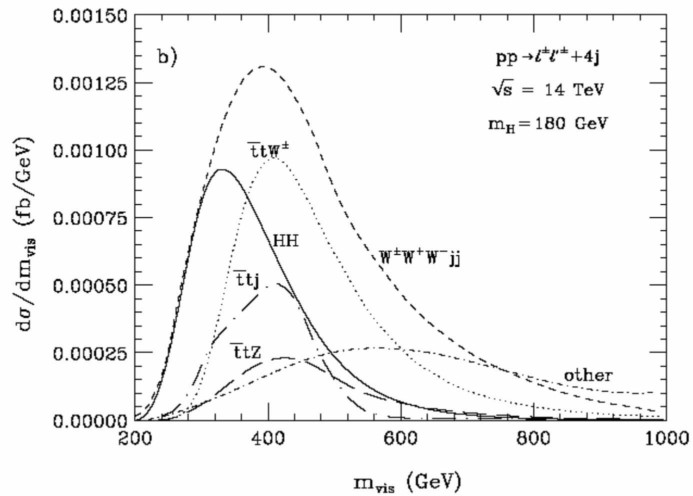
- **Higgs self-coupling is a crucial ingredient of the SM**

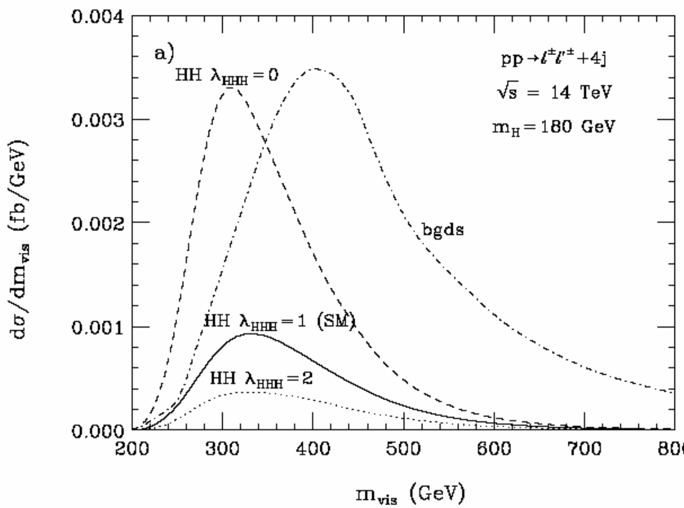
  Higgs potential: $V(\phi) = -\mu^2\left(\phi^\dagger\phi\right) - \lambda\left(\phi^\dagger\phi\right)^2$

  $\hookrightarrow \mu^2 = -\lambda v^2 = -m_H^2/2$

- **cross section for Higgs pair production at LHC very low, and backgrounds important, but some limits can be set**





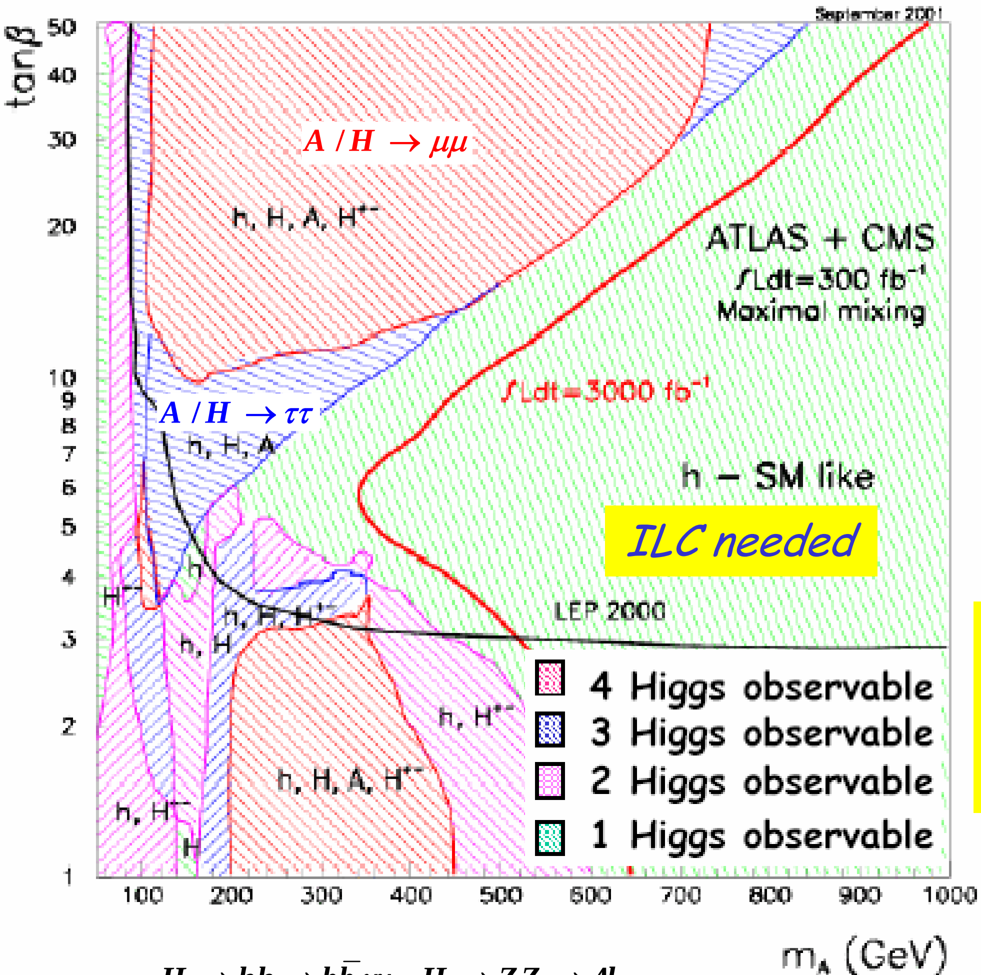


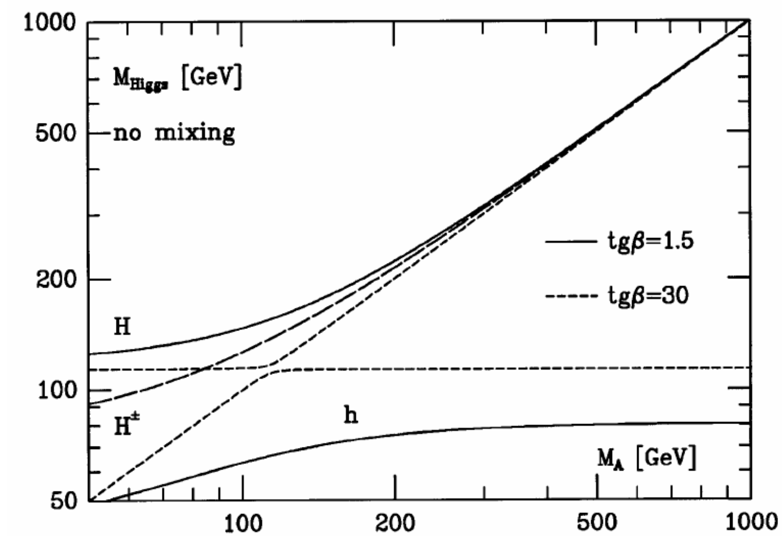
at ILC (1 TeV), higher precision for $m_H < 140$ GeV (bb bb channel at ILC, γγ bb at LHC). Precision Higgs properties important for LHC measurement at higher mass (top Yukawa, HWW coupling, total width…) → see talk by T. Barklow

U. Baur, T. Plenh and D. Rainwater, Phys.Rev. D67 (2003) 033003; and LHC/ILC study

EWSB: MSSM scenario

- **5 Higgs bosons, two parameters:**





ILC needed

$H \to hh \to b\bar{b}\gamma\gamma$ $\quad H \to ZZ \to 4l$

$A \to Zh \to l\bar{l}b\bar{b}$ $\quad A/H \to t\bar{t}$

in the decoupling limit, the ILC can help:
- *precision measurements*
- *HA and H^+H^- production (need high energy)*
- *$\gamma\gamma \to H/A$ possible*

In general, in the presence of SUSY particles, the discovery reach changes

Other EWSB scenarios

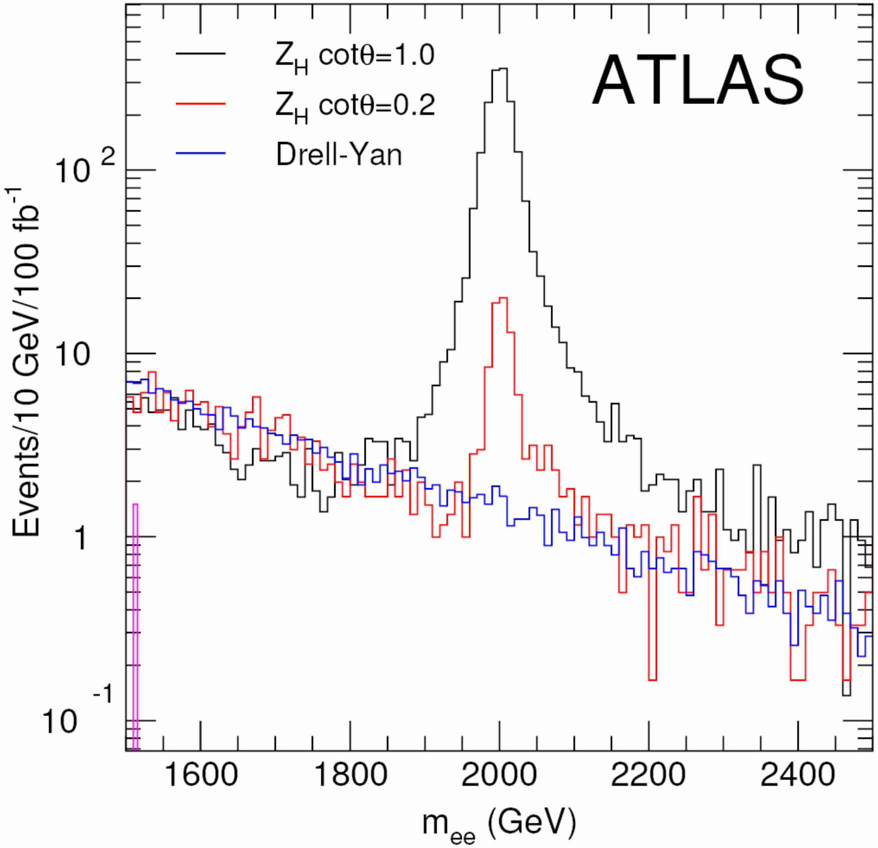
- **NMSSM**
  - extend MSSM by adding one singlet superfield $\rightarrow$ new h_3 and A_2
    - LHC: $WW \rightarrow h \rightarrow aa \rightarrow bb\ \tau\tau$
    - ILC : also $Z\,h \rightarrow Z\,aa;\ \ a \rightarrow bb$ or $\tau\tau$, $\rightarrow$ talk by J. Gunion
- **invisible channel**
  - difficult at LHC (VBF), but easier at ILC (Zh)
- **radion (or other scalars)**
  - scalar state in Randall-Sundrum extra-dimension model
    - mixes with SM Higgs, can decay to hh
    - some channels of discovery at LHC,

$$\phi \rightarrow hh \rightarrow \gamma\gamma\, b\bar{b}, \tau\tau\, b\bar{b};\quad \phi \rightarrow ZZ^{(*)} \rightarrow 4\mathrm{l}$$

      but distinguishing from MSSM Higgs difficult in some mass regions
- **fermiophobic Higgs**
  - if mass originates from other mechanism…
    - use $\gamma\gamma$ production at ILC

little Higgs model

- Higgs is naturally light (pseudo Goldstone boson from breaking of higher symmetry)
- new states from higher symmetry (and isosinglet top) cancel quadratic divergences from radiative corrections
- LHC: discovery possible of new states in large part of parameter space
- with T-parity: missing energy signal could fake SUSY
- ILC: sensitive to presence of new particles in loops (TGC, $h\gamma\gamma$,…)

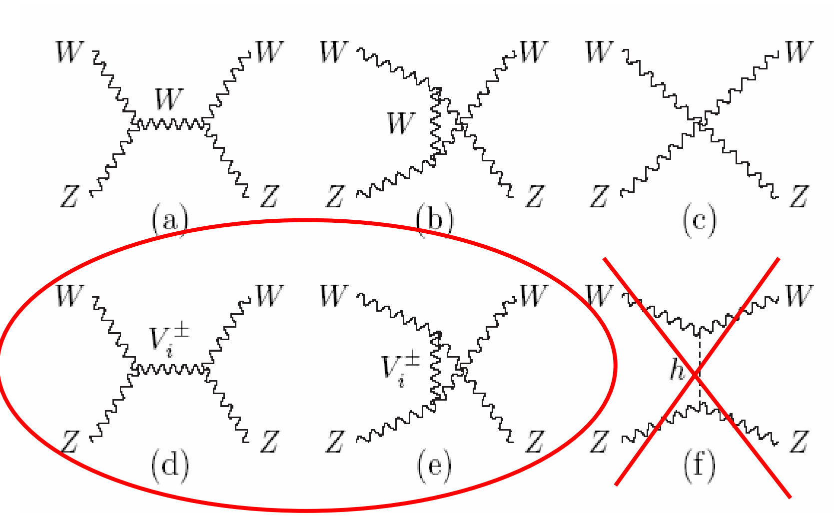


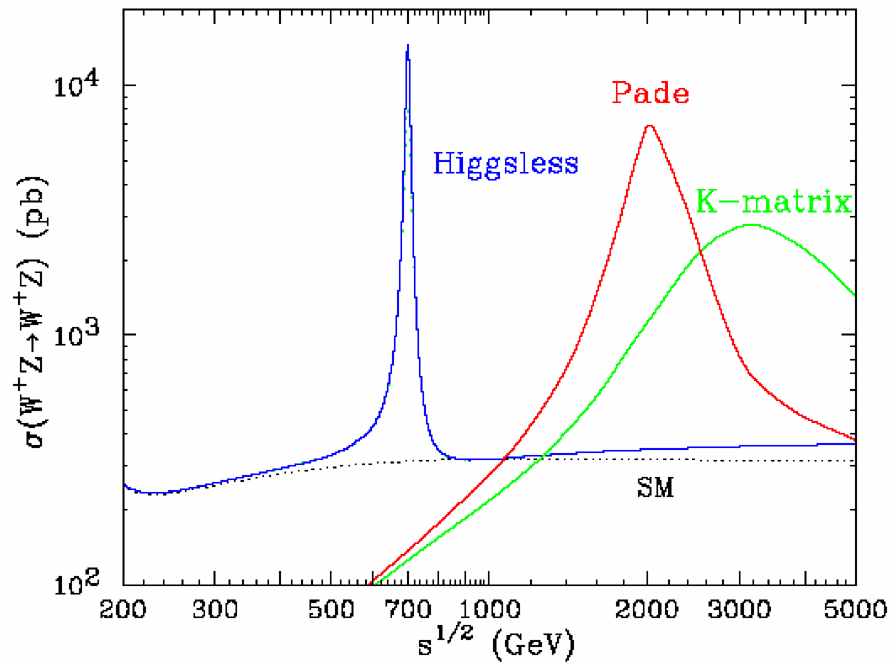
SN-ATLAS-2004-038

Higgsless model

- EWSB from boundary conditions between branes in warped 5th dimension

C. Csaki, et al., Phys. Rev. D 69, 055006 (2004) [hep-ph/0305237





Higher KK levels of vector bosons contribute and regularize the cross section, in the absence of a Higgs boson

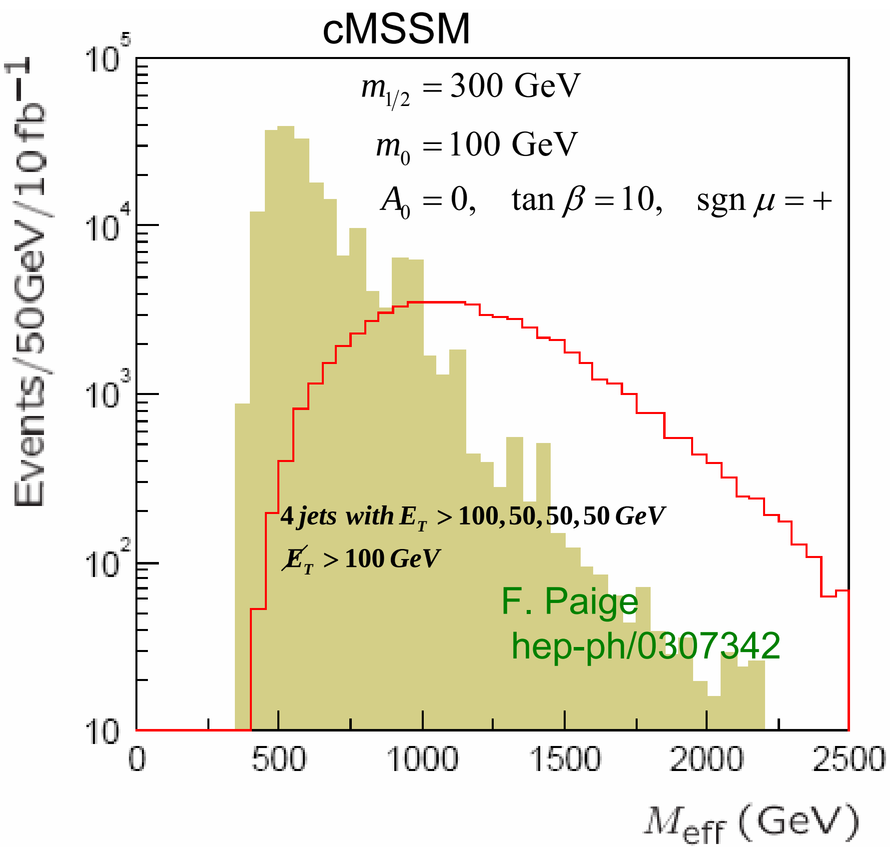
A. Birkedal, K. T. Matchev, and M. Perelstein, hep-ph/0412278, 0508185

LHC: How to distinguish from technicolor (QCD-like) resonance? need to see more KK states, but insufficient energy…

Supersymmetry

- **Inclusive signal with jets (R-conservation)**
  - trigger: Jets + $\not{E}_T$
  - main background: SUSY

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



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

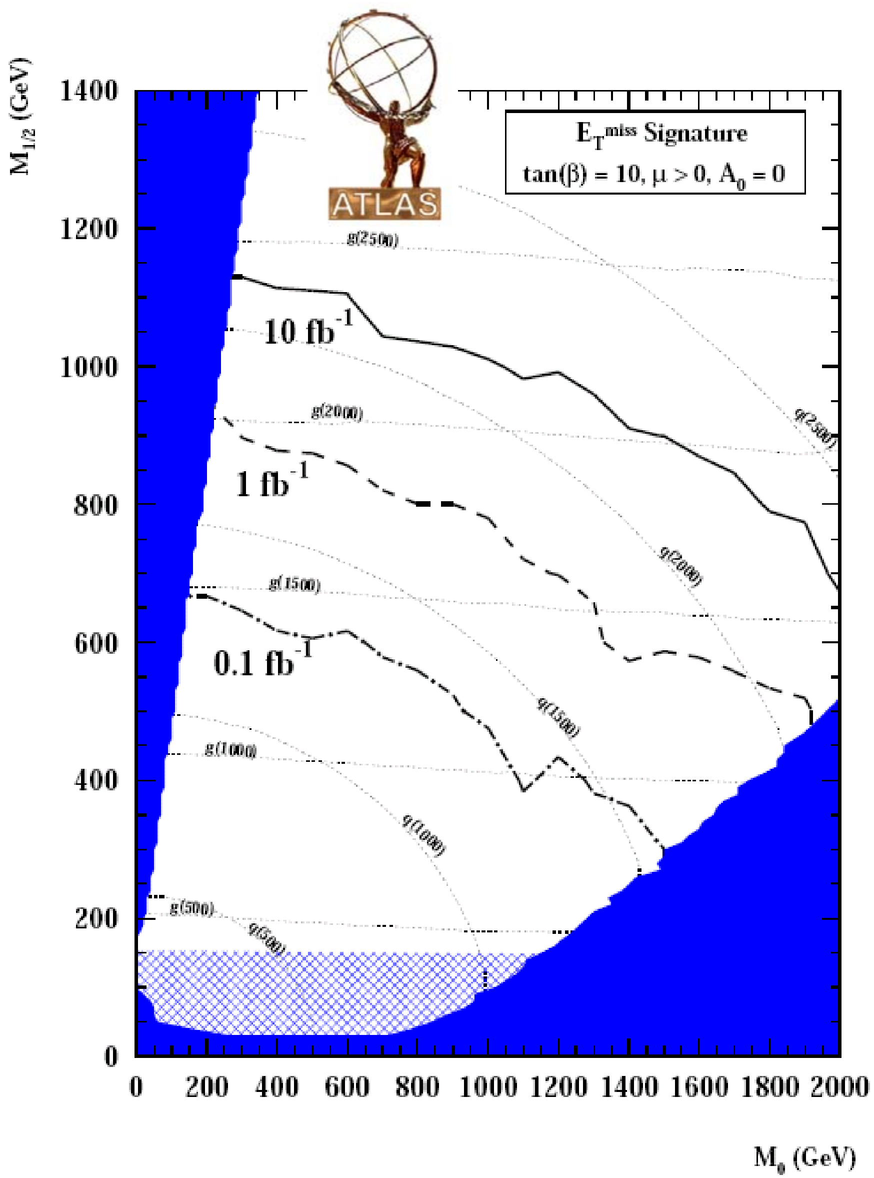
(linear relation)

$\Rightarrow$ preselect SUSY-rich sample

note:

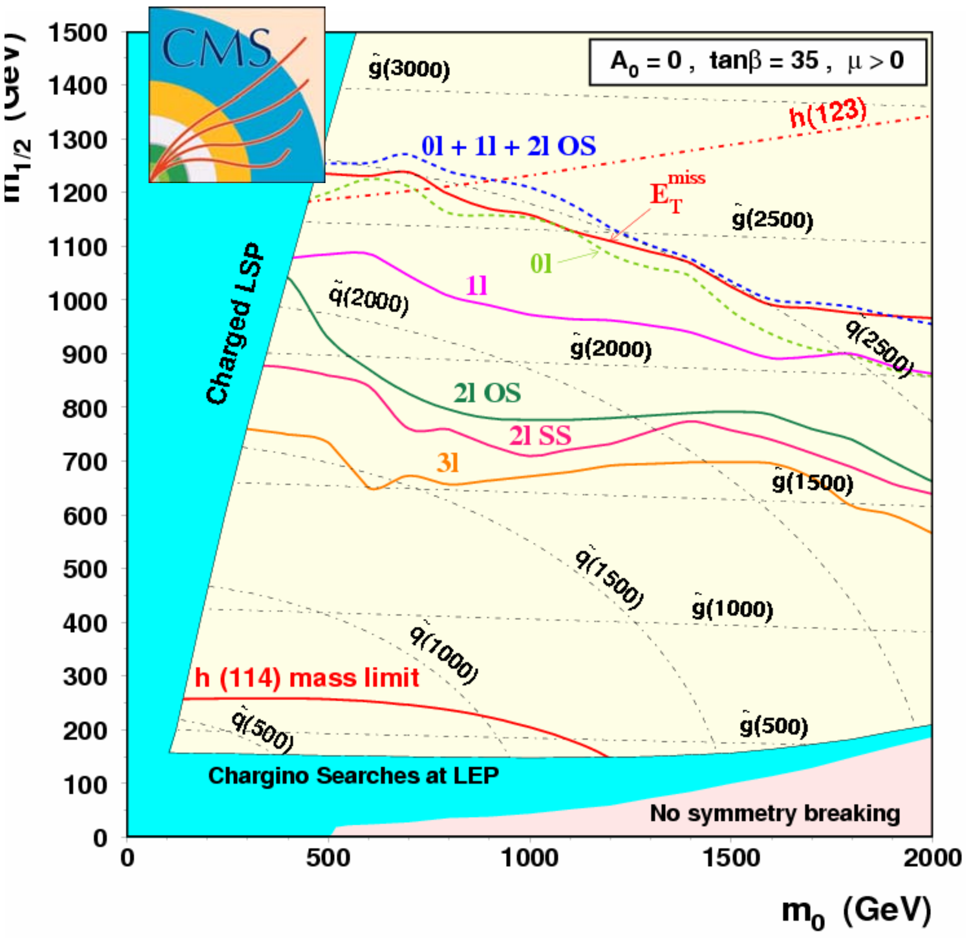
background ($t\bar{t}, W+j, Z+j$, QCD) increases by factor 2-4 with multi-parton (ME-PS) generators

SUSY - inclusive search



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

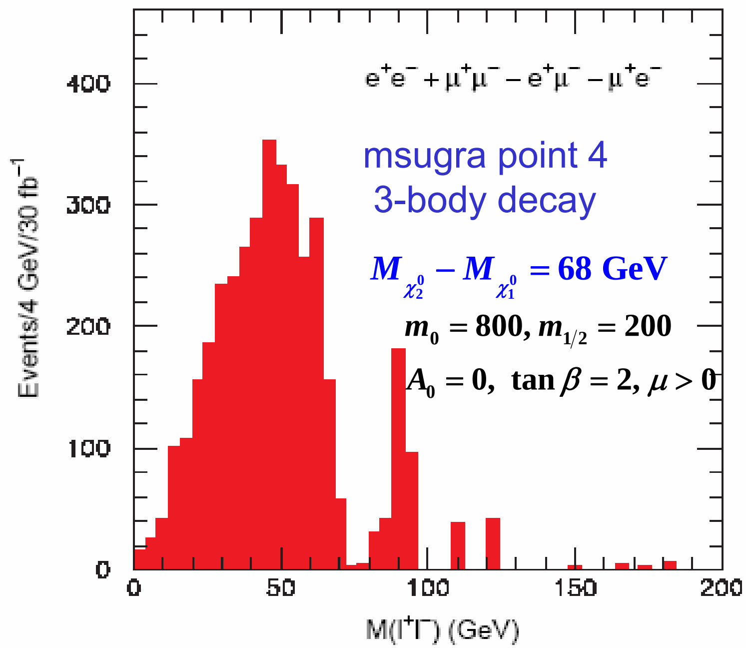
CMS Note 1998/073

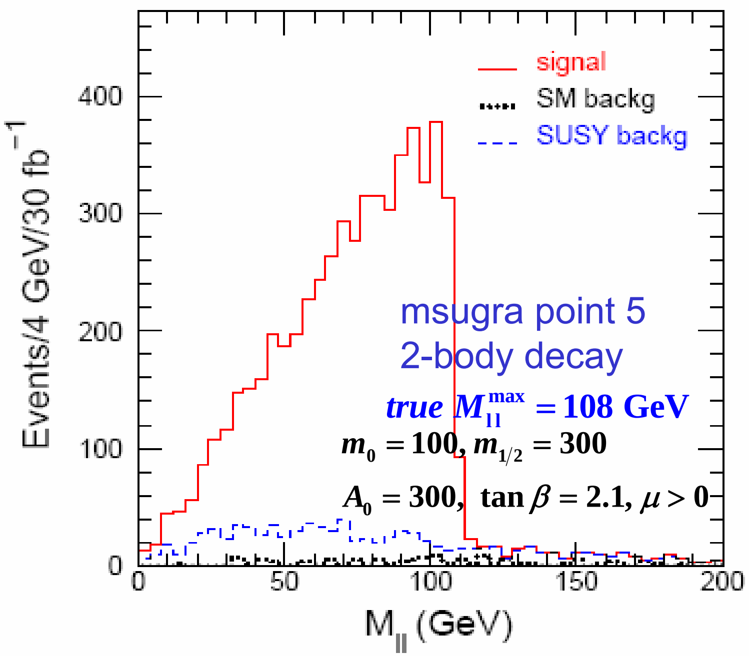


Mass reconstruction from di-lepton endpoints

3-body decay: $\tilde{\chi}^0_2 \to \tilde{\chi}^0_1 l^+ l^- \Rightarrow M_{ll} < M_{\tilde{\chi}^0_2} - M_{\tilde{\chi}^0_1}$

2-body decay: $\tilde{\chi}^0_2 \to \tilde{l} l^{\mp} \to \tilde{\chi}^0_1 l^+ l^- \Rightarrow M_{ll} < \frac{\sqrt{(M^2_{\tilde{\chi}^0_2} - M^2_{\tilde{l}})(M^2_{\tilde{l}} - M^2_{\tilde{\chi}^0_1})}}{M_{\tilde{l}}}$



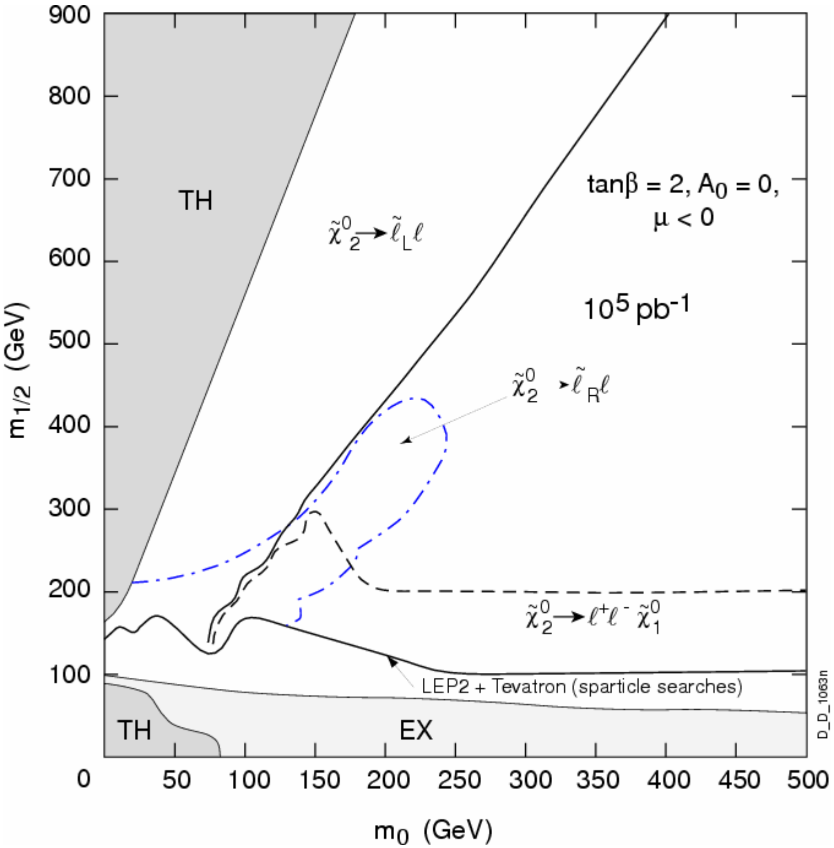


SM background removed by subtracting distributions with opposite flavor leptons
precision in end-point measurement: ~ 1-2 %

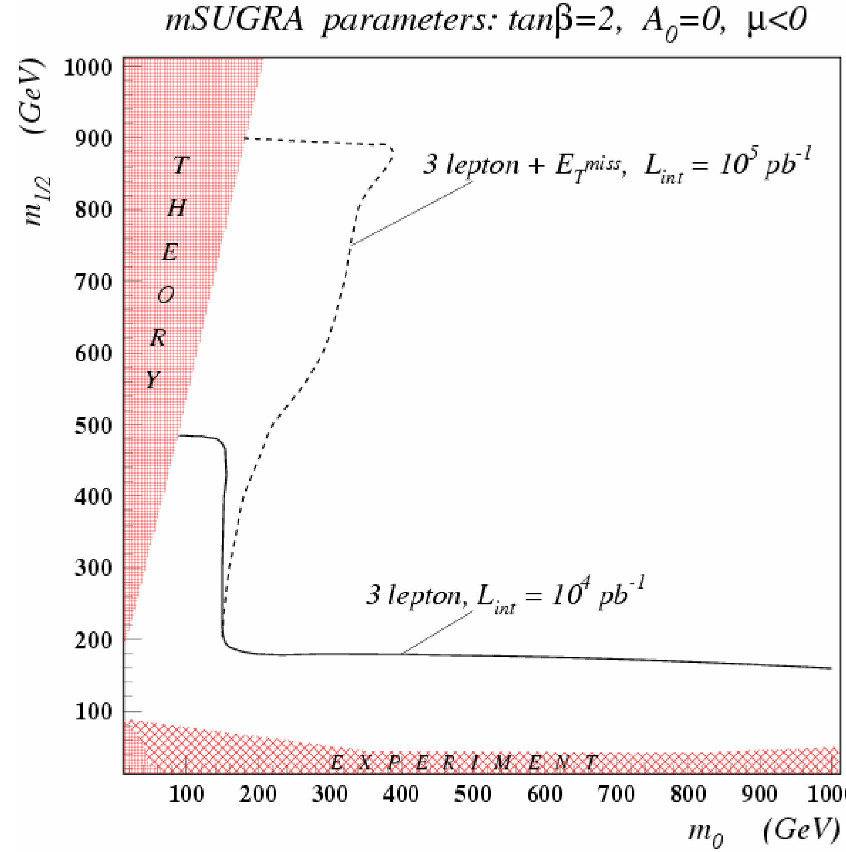
example of SPS1a point fully studied in LHC/ILC report:

Inclusive signal from di-lepton endpoint

2 leptons + E_T^{miss} + jets



Direct $\tilde{\chi}^\pm_1 \tilde{\chi}^0_2$ production → $l \nu \tilde{\chi}^0_1 l l \tilde{\chi}^0_1$

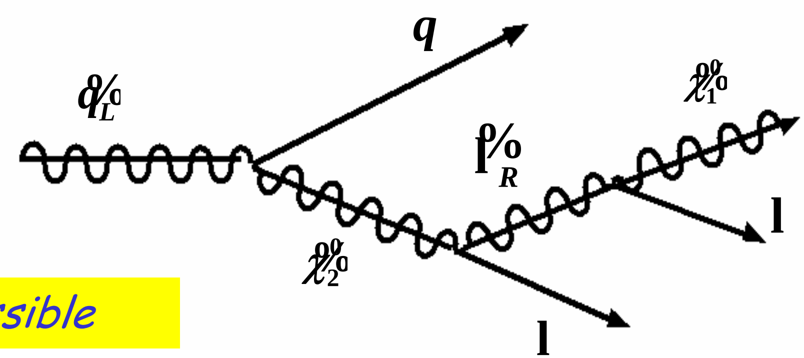


CMS

reconstruction higher up in the chain possible

- mass relations with ~ 1% precision
  - $\tilde{\chi}_1^0$ mass: ~ 10%

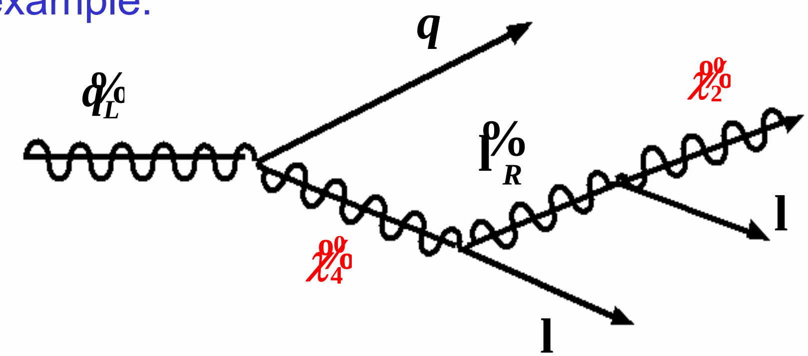
at ILC: precision of ≤ 1% possible

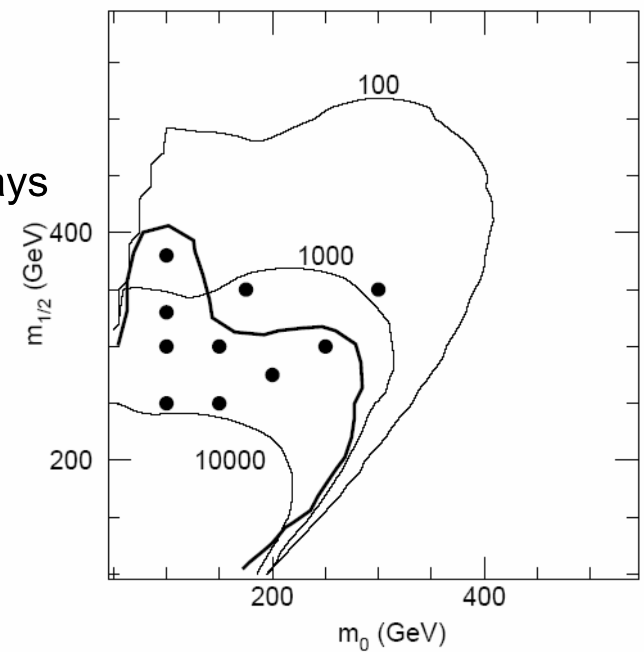


Heavy gauginos

$\tilde{\chi}_4^0$, $\tilde{\chi}_2^\pm$ have non-negligible gaugino content
→ participate in squark and gluino decays

example:





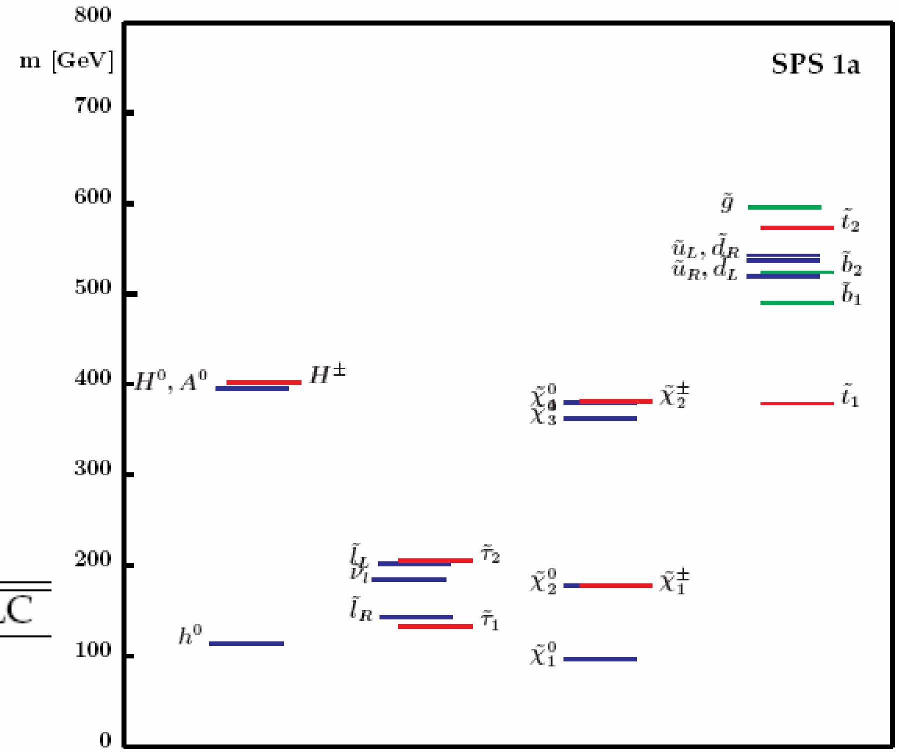
LHC reach, 100 fb^{-1}

F. Paige,
Physics at LHC, Vienna

SUSY masses and parameters

	LHC	LHC+LC
$\Delta m_{\tilde{\chi}_1^0}$	4.8	0.05 (LC input)
$\Delta m_{\tilde{\chi}_2^0}$	4.7	0.08
$\Delta m_{\tilde{\chi}_4^0}$	5.1	2.23
$\Delta m_{\tilde{l}_R}$	4.8	0.05 (LC input)
$\Delta m_{\tilde{\ell}_L}$	5.0	0.2 (LC input)
Δm_{τ_1}	5-8	0.3 (LC input)
$\Delta m_{\tilde{q}_L}$	8.7	4.9
$\Delta m_{\tilde{q}_R}$	7-12	5-11
$\Delta m_{\tilde{b}_1}$	7.5	5.7
$\Delta m_{\tilde{b}_2}$	7.9	6.2
$\Delta m_{\tilde{g}}$	8.0	6.5

	LHC (0.5% jet scale)	LHC (0.5% jet scale) + LC
$\Delta m_{\tilde{q}_L}$	7.8	2.6
$\Delta m_{\tilde{b}_1}$	6.0	3.7
$\Delta m_{\tilde{b}_2}$	6.4	4.3
$\Delta m_{\tilde{g}}$	6.0	3.7



SPS 1a :
$m_0 = 100$ GeV,
$m_{1/2} = 250$ GeV,
$A_0 = -100$ GeV,
$\tan\beta = 10, \ \mu > 0$

SUSY Parameters				Mass Predictions	
M_1	M_2	μ	$\tan\beta$	$m_{\tilde{\chi}_2^\pm}$	$m_{\tilde{\chi}_3^0}$
99.1 ± 0.1	192.7 ± 0.3	352.4 ± 2.1	10.2 ± 0.6	378.5 ± 2.0	358.8 ± 2.1

Table 5.23: *SUSY parameters with 1σ errors derived from the combined analysis of the LHC and LC data with $\delta m_{\tilde{\chi}_2^0} = 0.08$ GeV and $\delta m_{\tilde{\chi}_4^0} = 2.23$ GeV derived from the LHC when using the LC input of $\delta m_{\tilde{\chi}_1^0} = 0.05$ GeV.*

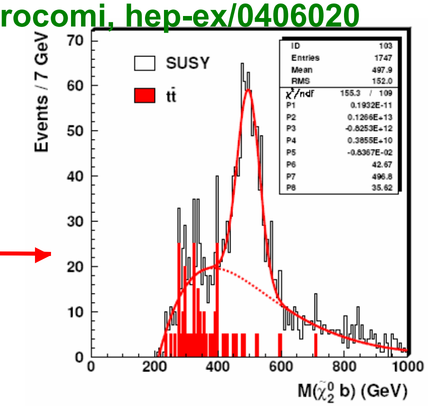
from LHC/ILC report

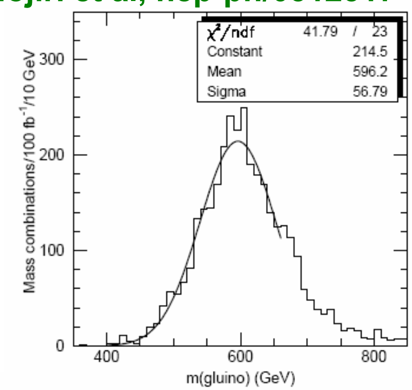
Supersymmetry

- **3rd generation squarks**

$\tilde{g} \to \bar{t}\,\tilde{t}_1$
$\quad \hookrightarrow b\,\tilde{\chi}_1^{\pm}$ or $c\,\tilde{\chi}_1^{0}$

$\tilde{g} \to \tilde{b}_1 b$
$\quad \hookrightarrow \tilde{\chi}_2^0 \bar{b}$
$\quad\quad \hookrightarrow \chi_1^0 l l$



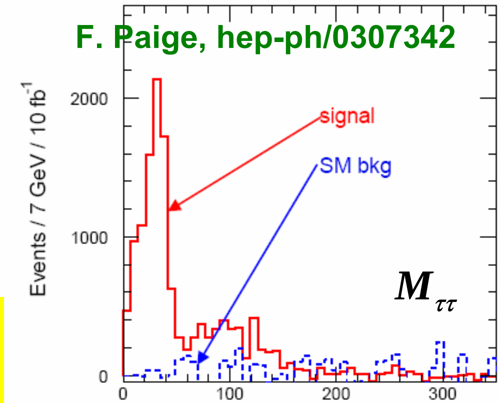


  - important for distinguishing between SUSY models
  - difficult, but possible to measure combination of masses (m_{tb})
  - knowing $\tilde{\chi}$ masses, can reconstruct $\tilde{g}$ and $\tilde{b}$
  - mass relation method:
    - constraint: require same masses in several events

- **$\tilde{\tau}$s**

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

$\chi_2^0 \to \tilde{\tau}\tau$
$\quad \hookrightarrow \tau\chi_1^0$



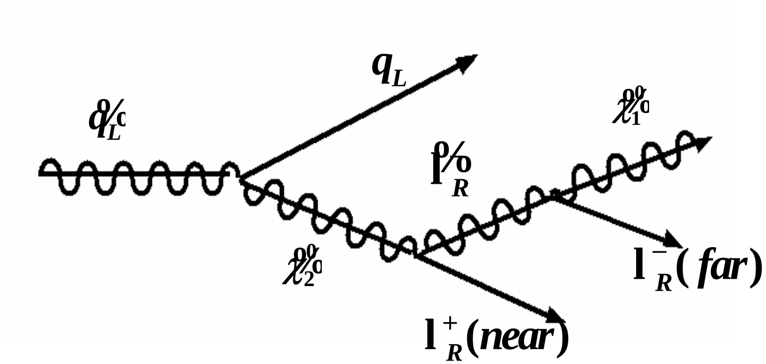
mixing angles and masses possible by combining LHC and ILC data

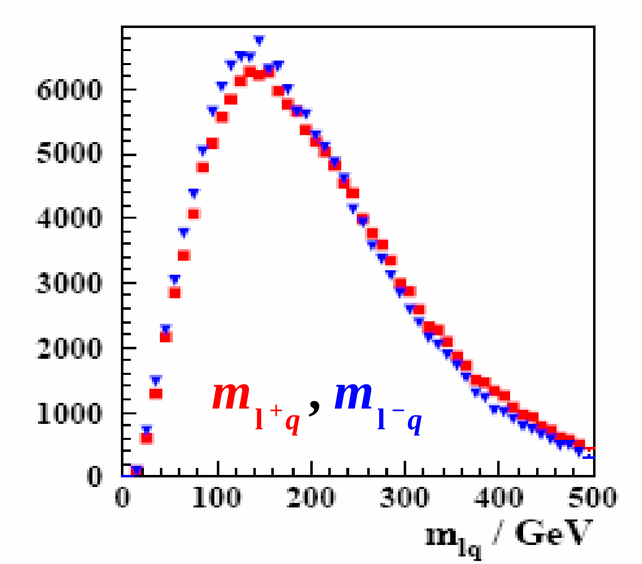
heavy sfermions: → see talk by G. Moortgat-Pick

Spin measurements

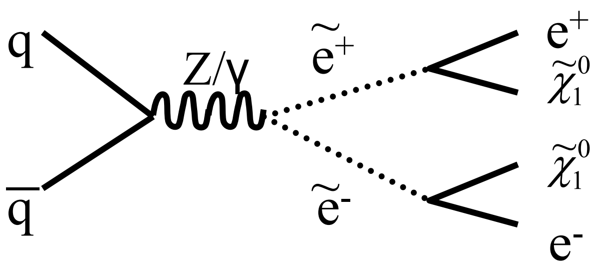
A.J. Barr, hep-ph/0405052

- evidence for supersymmetry (vs extra dimensions, for example)
  - polarization of χ_2^0 induces asymmetry
  - seems feasible, with 150 fb^{-1}, but very difficult





- slepton spin can be measured from angular distribution: $1 - \cos^2\theta$ for SUSY



polarization measurements with ILC and threshold measurements

A. Barr, ATLAS presentaiton, Oct.2005

Supersymmetry – other topics

- **GMSB**
  - $LSP: \tilde{G},\quad NLSP: \tilde{\chi}_1^0$ or $\tilde{l}\ (\tilde{\tau}_R)$
  - jets + E_t^{miss}: ~ similar reach as MSugra
  - signatures:
    - $\tilde{\chi}_1^0 \to \tilde{G}\, l^+ l^-$ for short lifetimes, or
    - $\tilde{\chi}_1^0 \to \tilde{G}\gamma$: non-pointing photons for long lifetimes
    - $\tilde{l}$ ≈ slow "muon" ⇒ TOF measurements
    - $\tilde{l} \to l\, \chi_1^0 \to l\, \gamma \tilde{G}$: non-pointing photons

Kawagoe, Vienna 2004

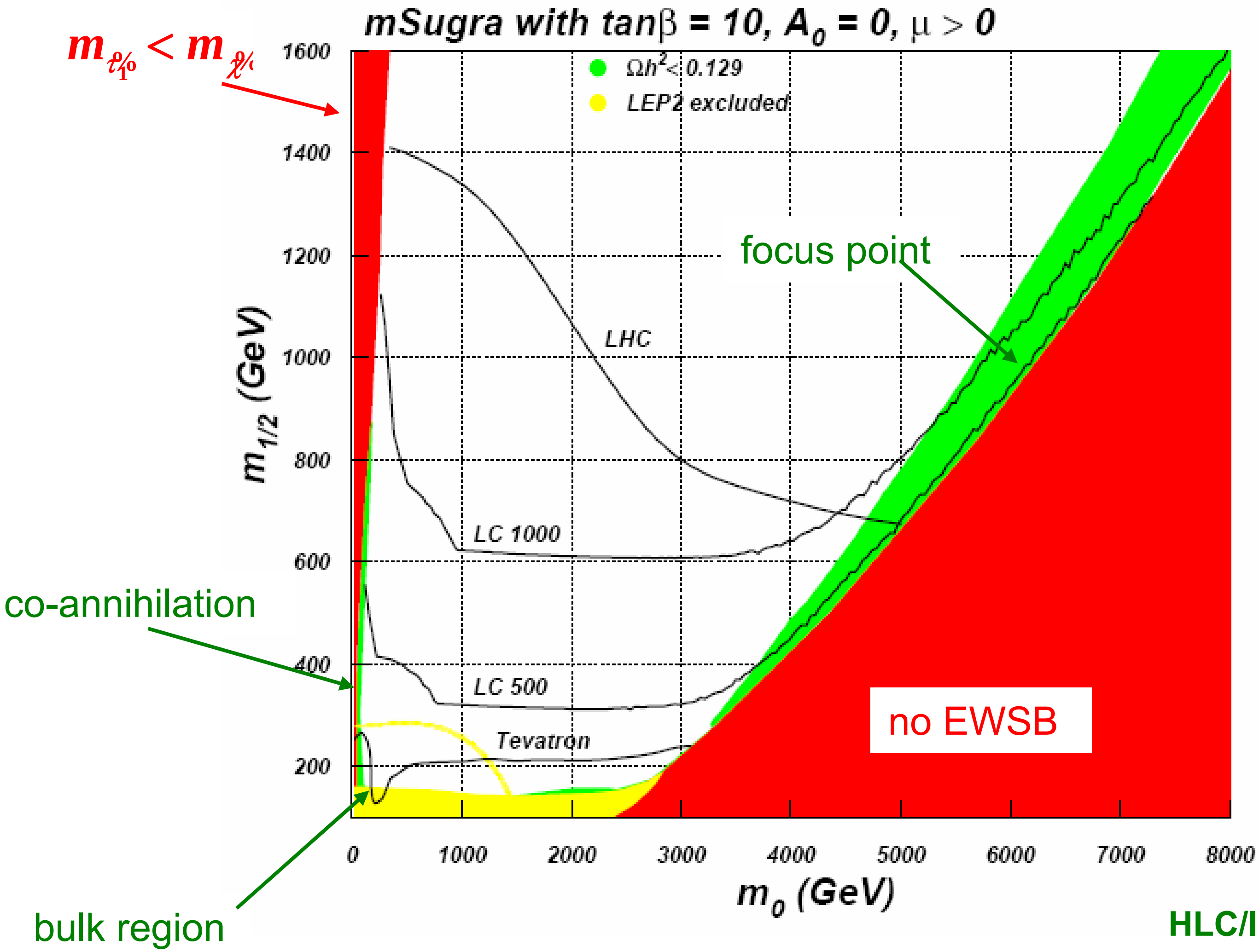
ILC: help discriminate between scenarios
extrapolation to GUT scale

- **AMSB**
  - light $\tilde{W}$ or $\tilde{\nu}$ $\quad p\bar{p} \to \tilde{\nu}_L \tilde{l}_L \to l^{\mp} \tilde{W}^{\pm}\, l^{\pm} \tilde{W}^0;$ displaced vtx from $\tilde{W}^{\pm} \to \tilde{W}^0 \pi^{\pm}$
  - $\tilde{l}$ pairs:
- **Generic SUSY search by statistical method**

Duchovni, SN-ATLAS-2004-043

- **R-parity violating processes**
- **Split Supersymmetry**
  - heavy, stable gluino → R-hadron
- **LFV (τ – μ sector)**

SUSY vs WMAP (and PLANCK)



see T. Lari, at Vienna 2004

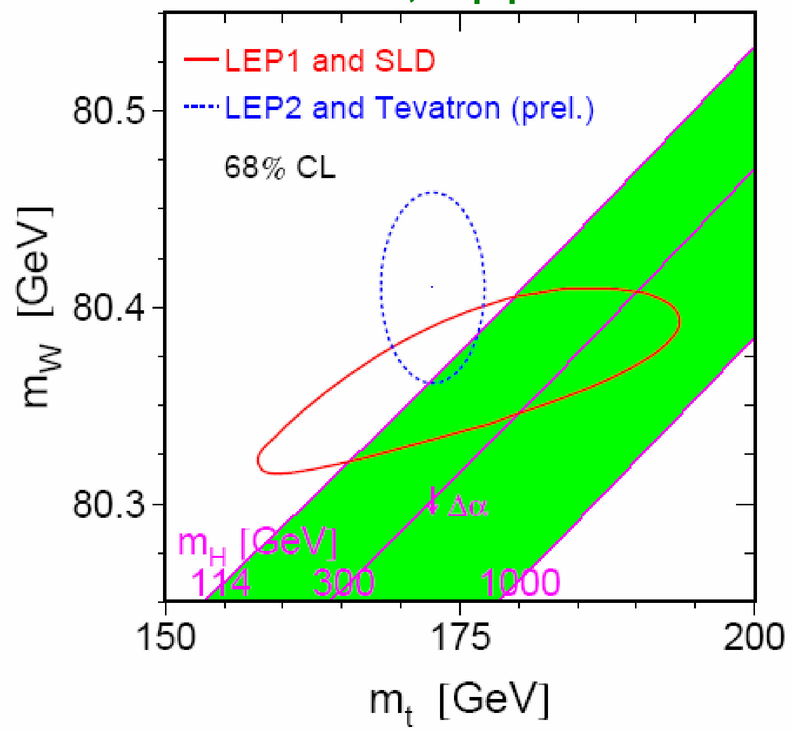
HLC/ILC workshop

ILC: High precision measurement necessary to match experimental predictions from WMAP and PLANCK, assuming cosmological model

Electroweak

- **precision mass measurements:**
  - m_W: use $Z \rightarrow ee$ as a reference for an accurate measure of the em energy scale **(N. Besson, M. Boonekamp, ATL-PHYS-2006-007)** $\Rightarrow$ syst. uncertainty of 4 MeV
  - m_t: from ttbar; various decay channels investigated. di-lepton channel clean, but more than one solution and MC weights required
  - V_{tb} from single top measurement

LEP EWWG, hep-ph/0511027

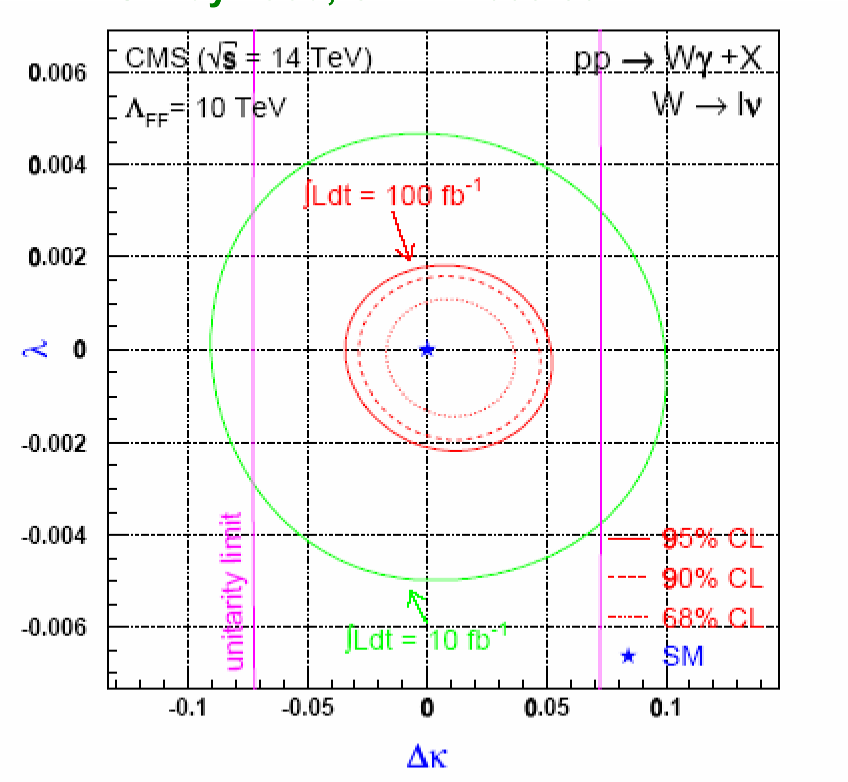


LHC/ILC report (Table 6.5)

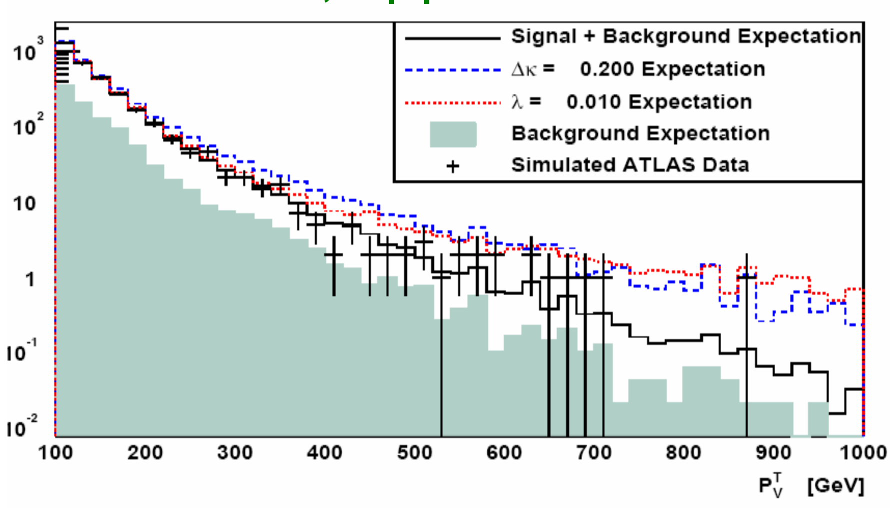
	now	Tev. Run IIA	Run IIB	LHC	LC	GigaZ
$\delta \sin^2\theta_{\text{eff}}(\times 10^5)$	17	78	29	14–20	(6)	1.3
δM_W [MeV]	34	27	16	15	10	7
δm_t [GeV]	5.1	2.7	1.4	1.0	0.2–0.1	0.1
δm_h [MeV]	—	—	$\mathcal{O}(2000)$	200	50	50

Triple Gauge Boson Couplings

S. Haywood, CERN 2000-004



M. Dobbs, hep-ph/0506174



ILC: considerable improvement for all parameters: $\Delta\kappa_\gamma, \Delta\lambda_\gamma, \Delta\kappa_Z, \Delta\lambda_Z, \Delta g_Z$

(LHC/ILC report, Sect. 6.2)

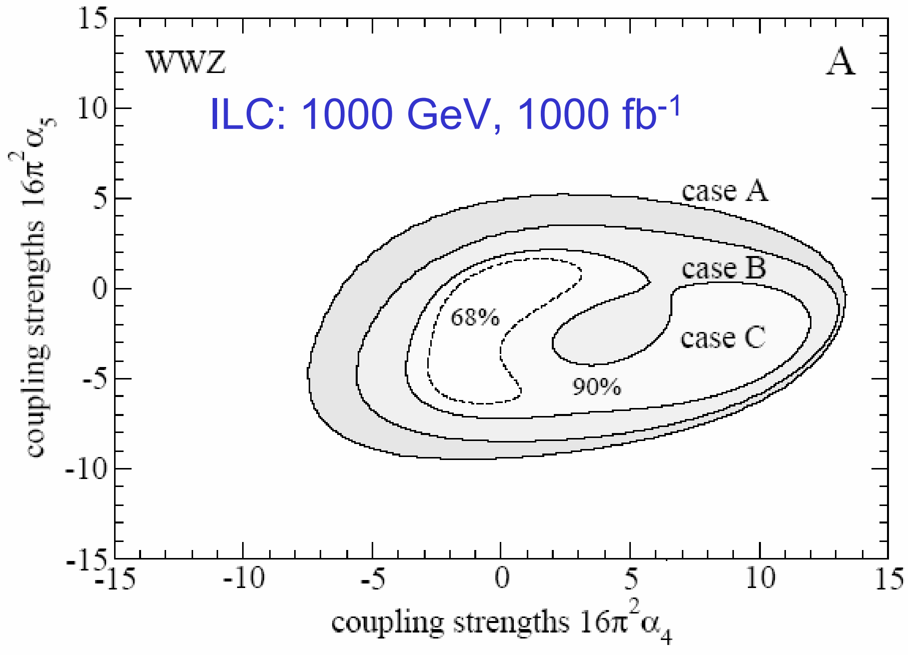
sensitivity to quartic couplings

high mass vector boson scattering.

at LHC: c.m. energy sufficient to explore resonances (unitarization procedure)

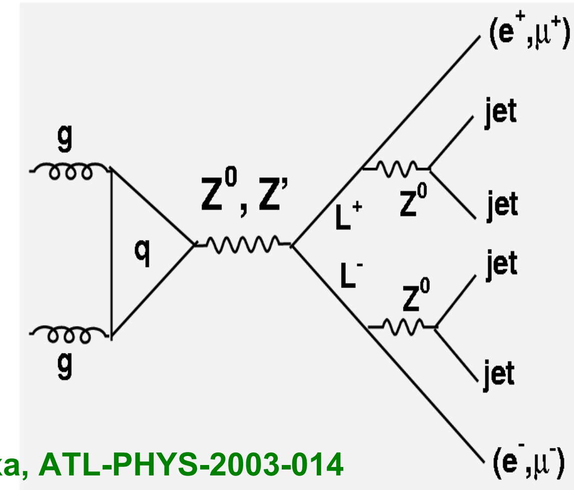
$\rightarrow$ see talk by T. Barklow

M. Beyer, hep-ph/0604048

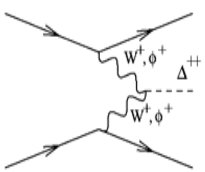


$$
\begin{aligned}
\mathcal{L}_4 &= \alpha_4 \left[\mathrm{Tr}\left(V_\mu V_\nu\right)\right]^2 \ , \\
\mathcal{L}_5 &= \alpha_5 \left[\mathrm{Tr}\left(V_\mu V^\mu\right)\right]^2 \ , \\
\mathcal{L}_6 &= \alpha_6 \ \mathrm{Tr}\left(V_\mu V_\nu\right) \mathrm{Tr}\left(T V^\mu\right) \mathrm{Tr}\left(T V^\nu\right) \\
\mathcal{L}_7 &= \alpha_7 \ \mathrm{Tr}\left(V_\mu V^\mu\right) \left[\mathrm{Tr}\left(T V^\nu\right)\right]^2 \ , \\
\mathcal{L}_{10} &= \frac{\alpha_{10}}{2} \left[\mathrm{Tr}\left(T V_\mu\right) \ \mathrm{Tr}\left(T V_\nu\right)\right]^2 \ .
\end{aligned}
$$

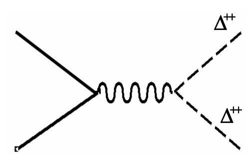
- **E6 and other grand unified theories**
  - include LR symmetric model
    - Z', W'
    - heavy leptons, Majorana neutrino
    - triplet Higgs (H^{++})

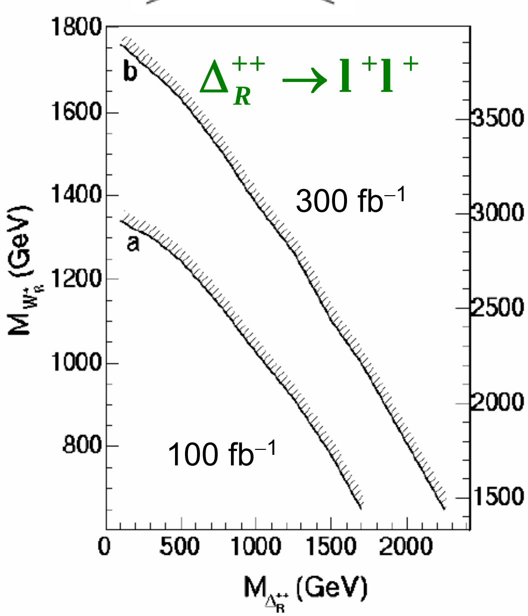


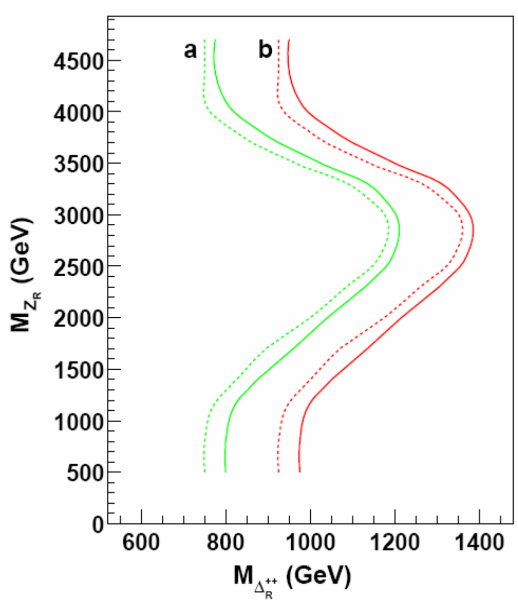
C. Alexa, ATL-PHYS-2003-014

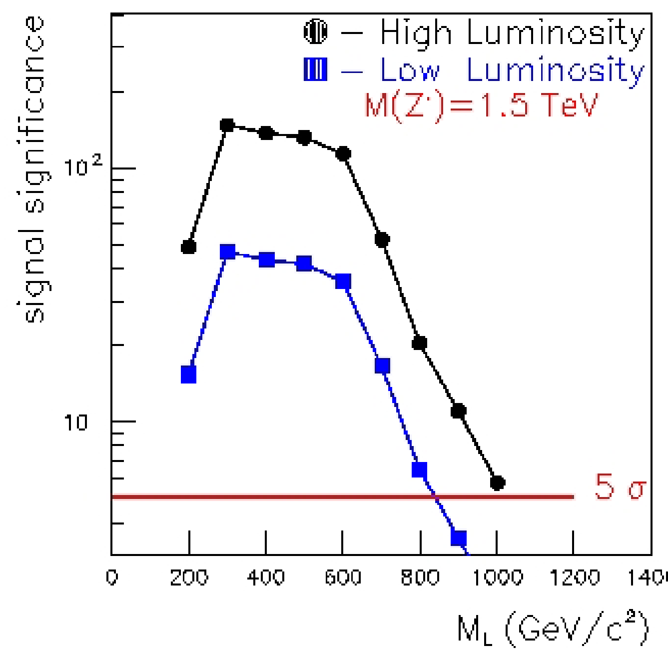


ATL-PHYS-2004-025

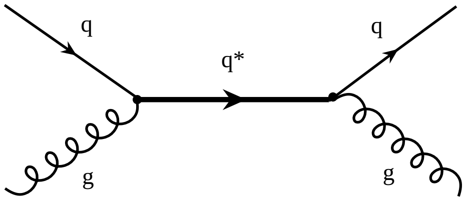








Excited quarks and leptons

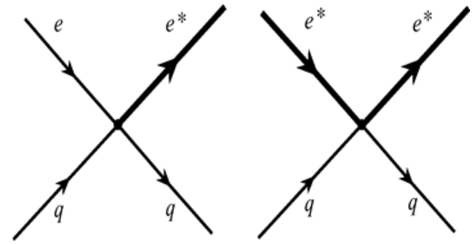


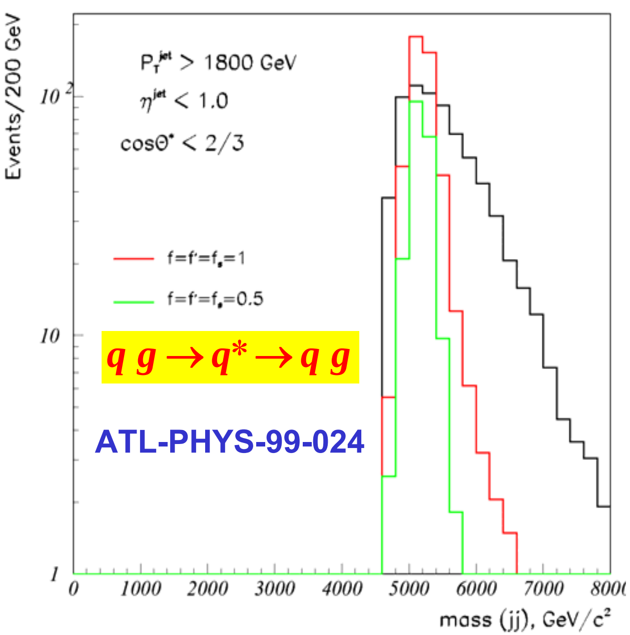
$$L = \frac{1}{2\Lambda}\bar{q}^*_R \sigma^{\mu\nu}\left(g_s f_s G^a_{\mu\nu} + g\, f \frac{\tau}{2} W_{\mu\nu} + g'\, f' \frac{Y}{2} B_{\mu\nu} \right) q_L + h.c.$$

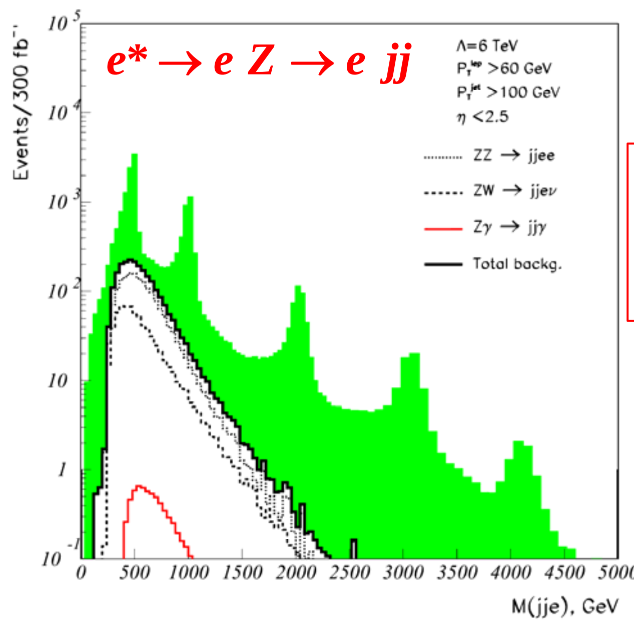
take as reference : $\Lambda = m^*, \quad f_s = f = f' = 1$

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

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





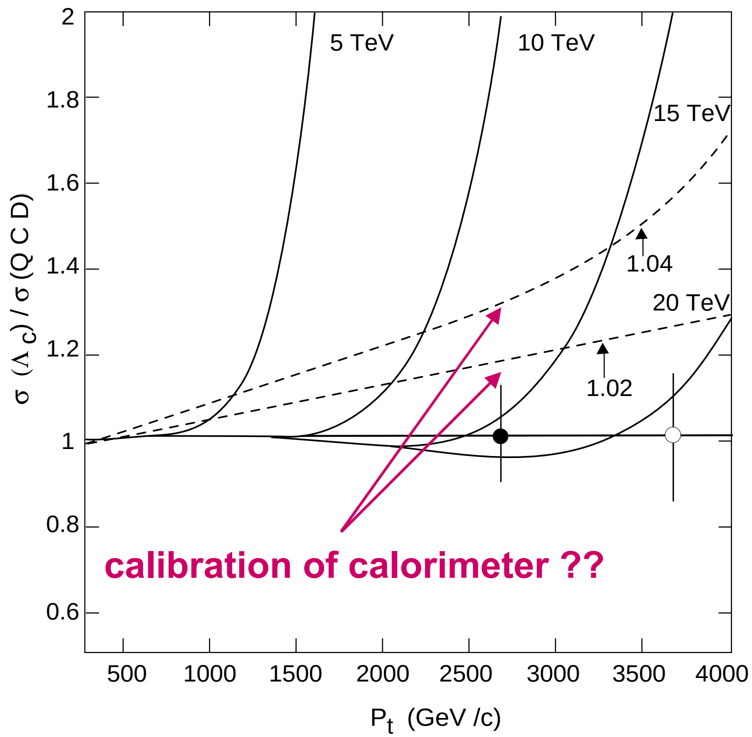


Also :
$q^* \rightarrow q\gamma; \quad q^* \rightarrow qZ; \quad q^* \rightarrow \bar{q}'W$
$e^* \rightarrow e\gamma$

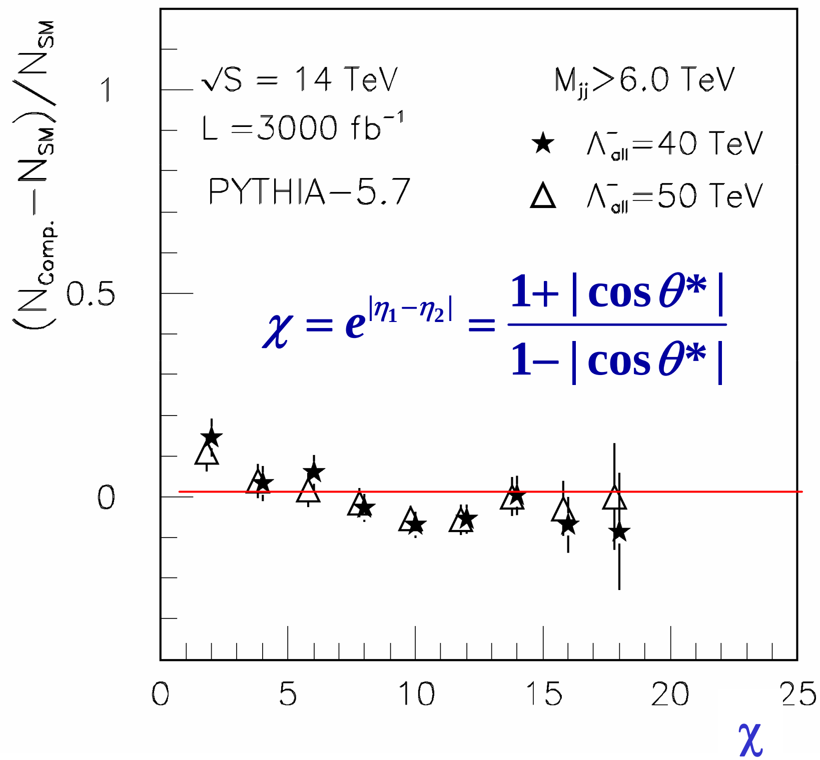
clean signals up to few TeV, depending on Λ

quark substructure

Contact interactions:
scale of compositeness $\Lambda >> m^*$



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

extraD signal?
- virtual G exchange,
- virtual g* exchange in UED?
- early gauge coupling unification?

Z. Usubov

(from superLHC)

Extra dimensions

- **ADD: Large, flat compactified extra dimensions**
  - Gauss' law: →
  - SM particles on 3-brane

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

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

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

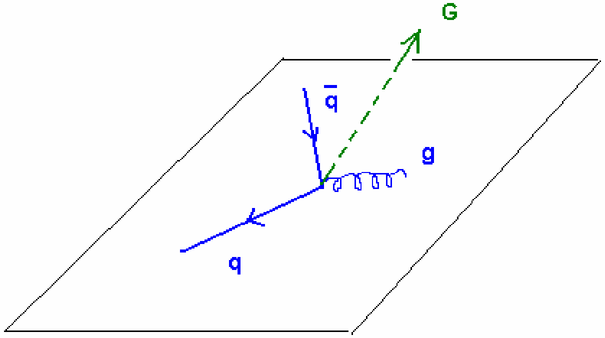
$$\phi(x,y) = \sum_{k_1=-\infty}^{\infty} \sum_{k_2=-\infty}^{\infty} \cdots \sum_{k_n=-\infty}^{\infty} \phi^{(k)}(x)\, e^{i \vec{k}\cdot\vec{y}/R}$$

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

at LHC:

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



Direct graviton production: Jets + missing E_T

- **Detector effects: ATLFAST**
  - Jets and leptons reconstructed in $|\eta| < 5, 2.5$

Minimum of validity

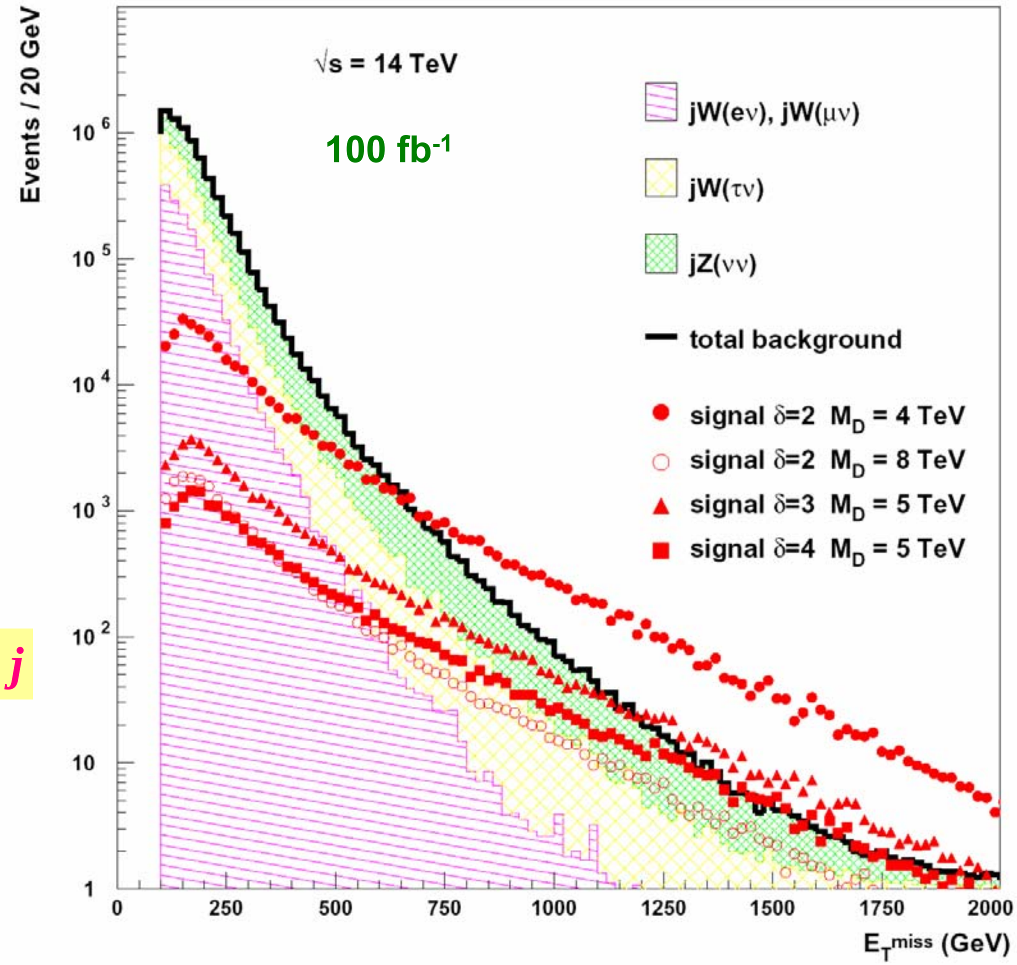
δ	M_D^{max} (TeV) LL, 30 fb^{-1}	M_D^{max} (TeV) HL, 100 fb^{-1}	M_D^{min} (TeV)
2	7.7	9.1	~ 4
3	6.2	7.0	~ 4.5
4	5.2	6.0	~ 5

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

Uncertainty in $\sigma(Z+jets)$ will lower the reach

Reach in M_D for γG

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



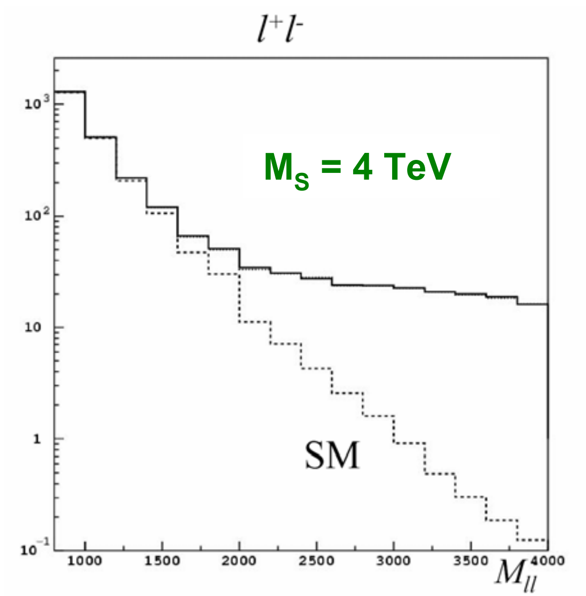
ILC: disentangle δ and M_D by running at 2 cm energies

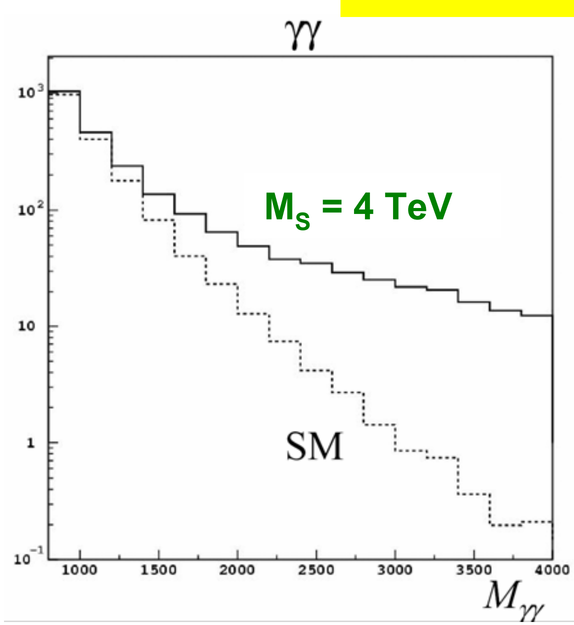
L. Vacavant and I. Hinchliffe, *J. Phys. G: Nucl. Part. Phys. 27 (2001) 1839*

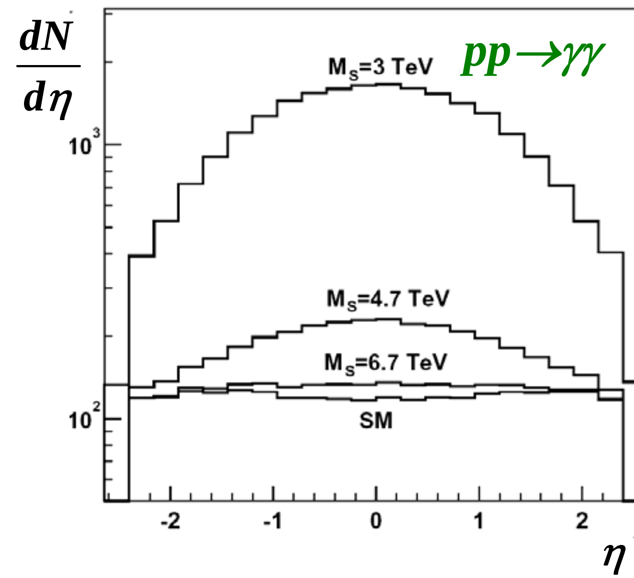
Virtual Graviton Exchange

- **Signals:** $q\bar{q}, gg \to \gamma\gamma, ll, \quad (WW, t\bar{t} \ldots)$
  - We require that : $M_{\gamma\gamma,ll} < 0.9\, M_S$ (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*

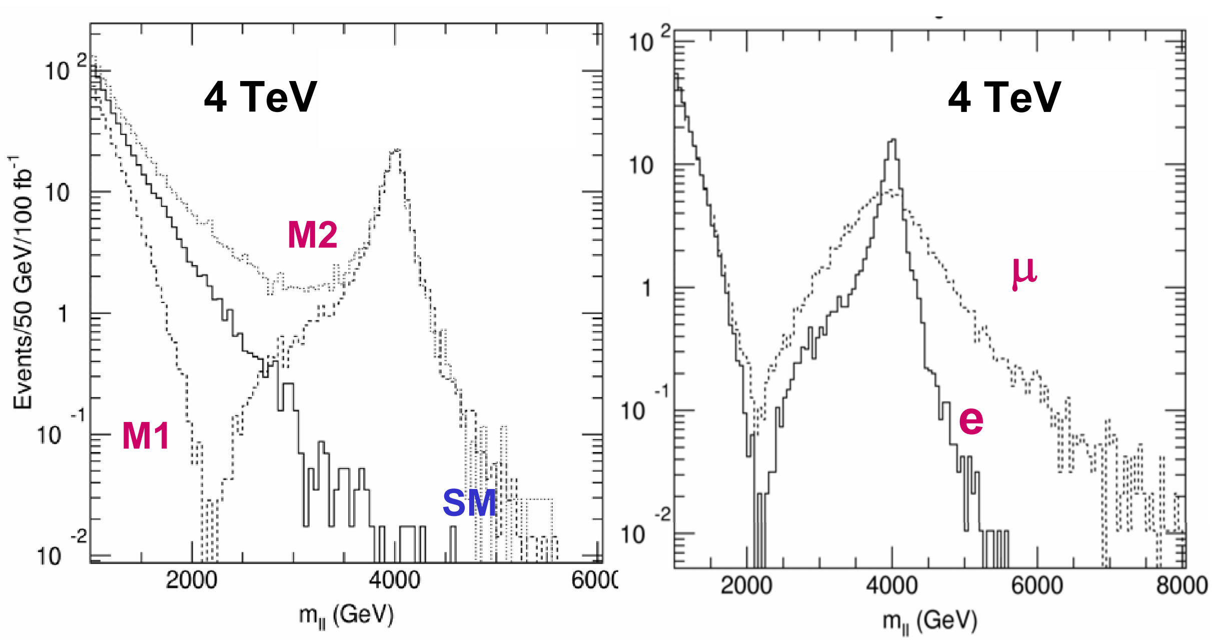
- **Compactification radius is small enough to allow SM particles in the bulk**

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

- ***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)

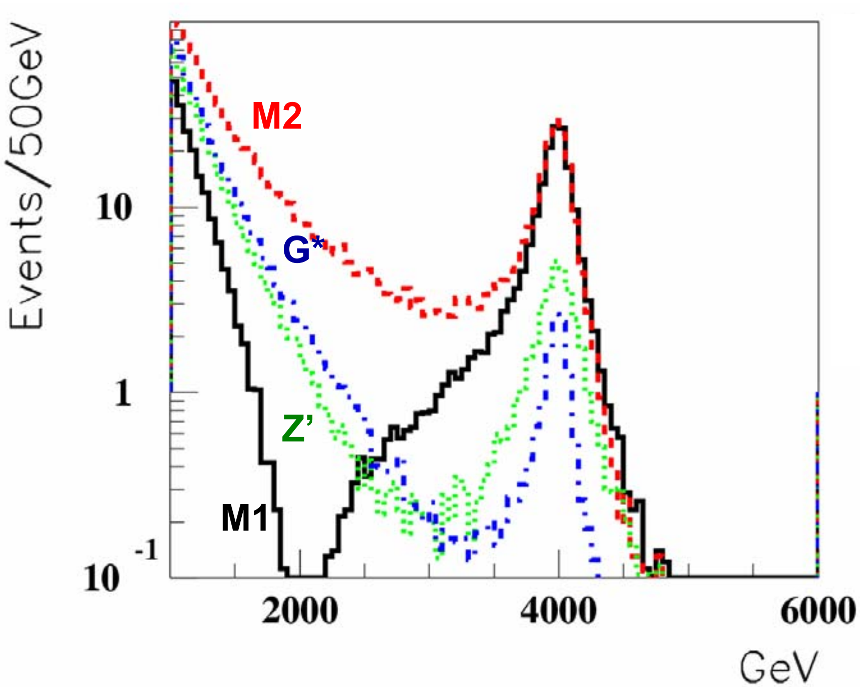


resonance observable up to ~ 5.8 TeV with 100 fb^{-1}

sensitivity to DY tail up to 13.5 TeV (e-μ) combined

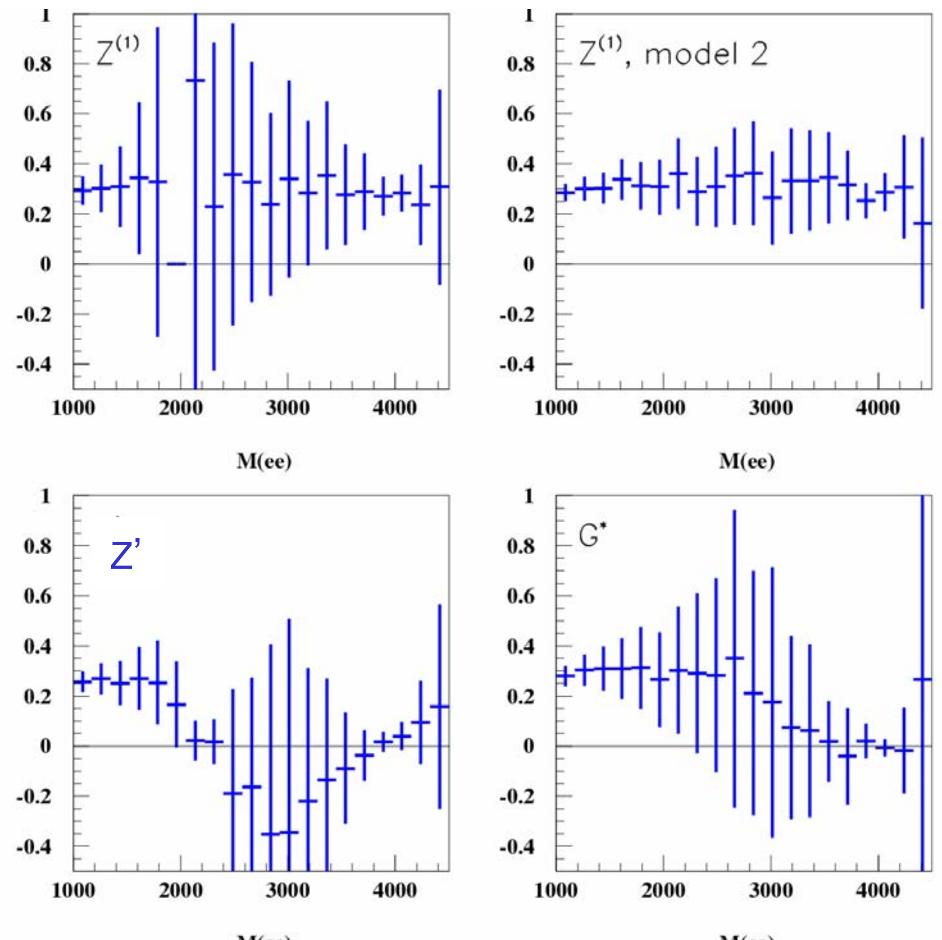
Extra dimensions of ~TeV^{-1} size: Z/γ excitation

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



Different narrow resonances

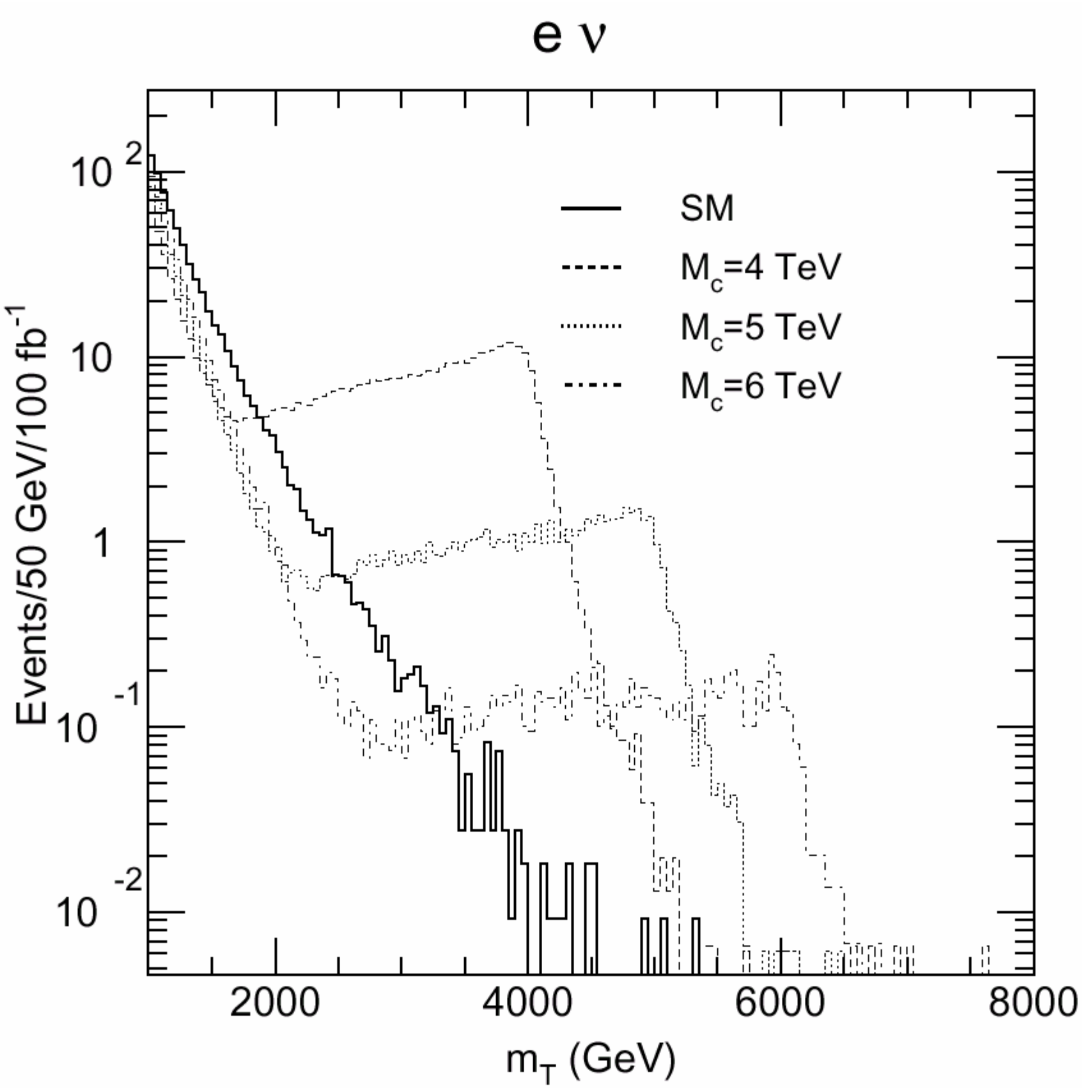
100 fb^{-1}



ILC: precision measurements of FB asymmetry and DY help discriminate between models

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

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

  - 5-D Planck scale M_5 ~ 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 = $\Lambda_\pi = M_{pl}e^{-kr_c\pi};\ kr_c\pi : 35 \Rightarrow \Lambda_\pi : \text{ TeV}$
    - coupling of KK states ~ $1/\Lambda_\pi$
  - KK masses:
    - $m_n = kx_n e^{-k\pi r_c}$, with $J_1(x_n) = 0 \Rightarrow m_1 = 3.83\frac{k}{M_{Pl}}\Lambda_\pi$

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

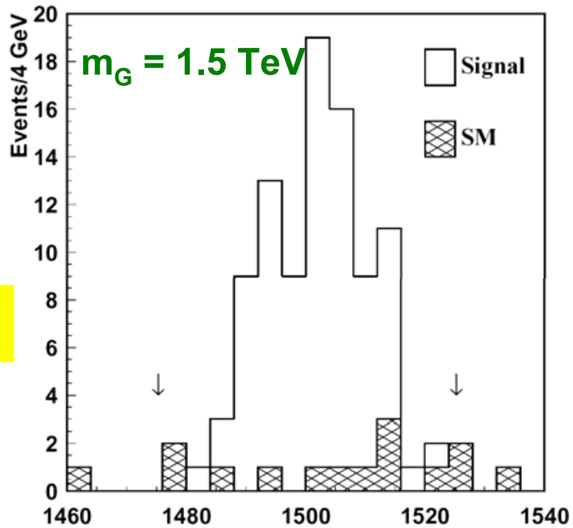
e^+e^- channel,

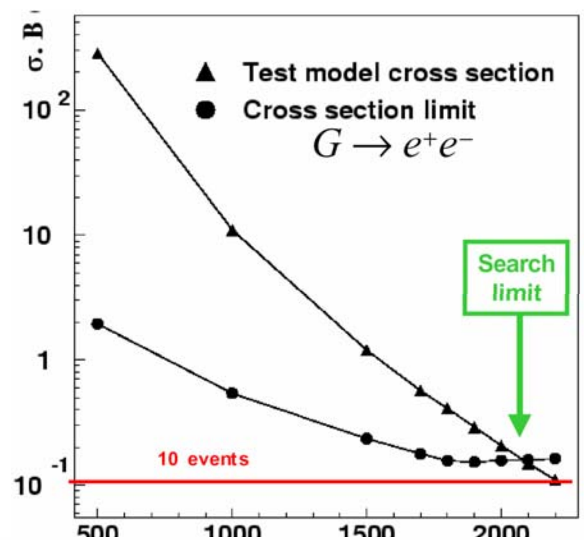
100 fb^{-1}

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

Sensitive at 5σ up to 2080 GeV

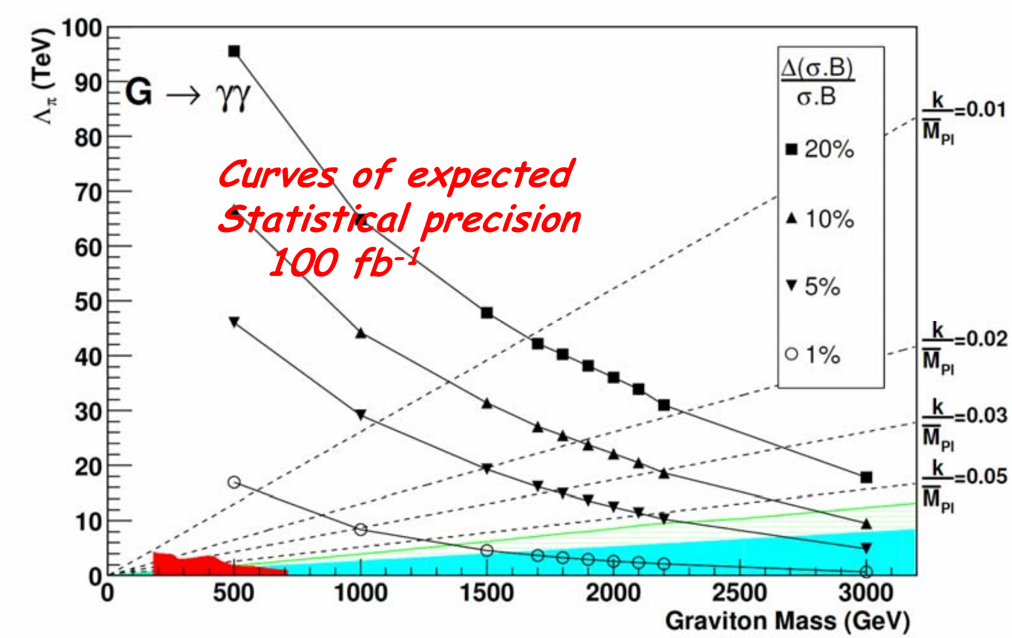
B. C. Allanach, K. Odagiri, A. Parker and B. Webber,
JHEP 9 (2000) 19





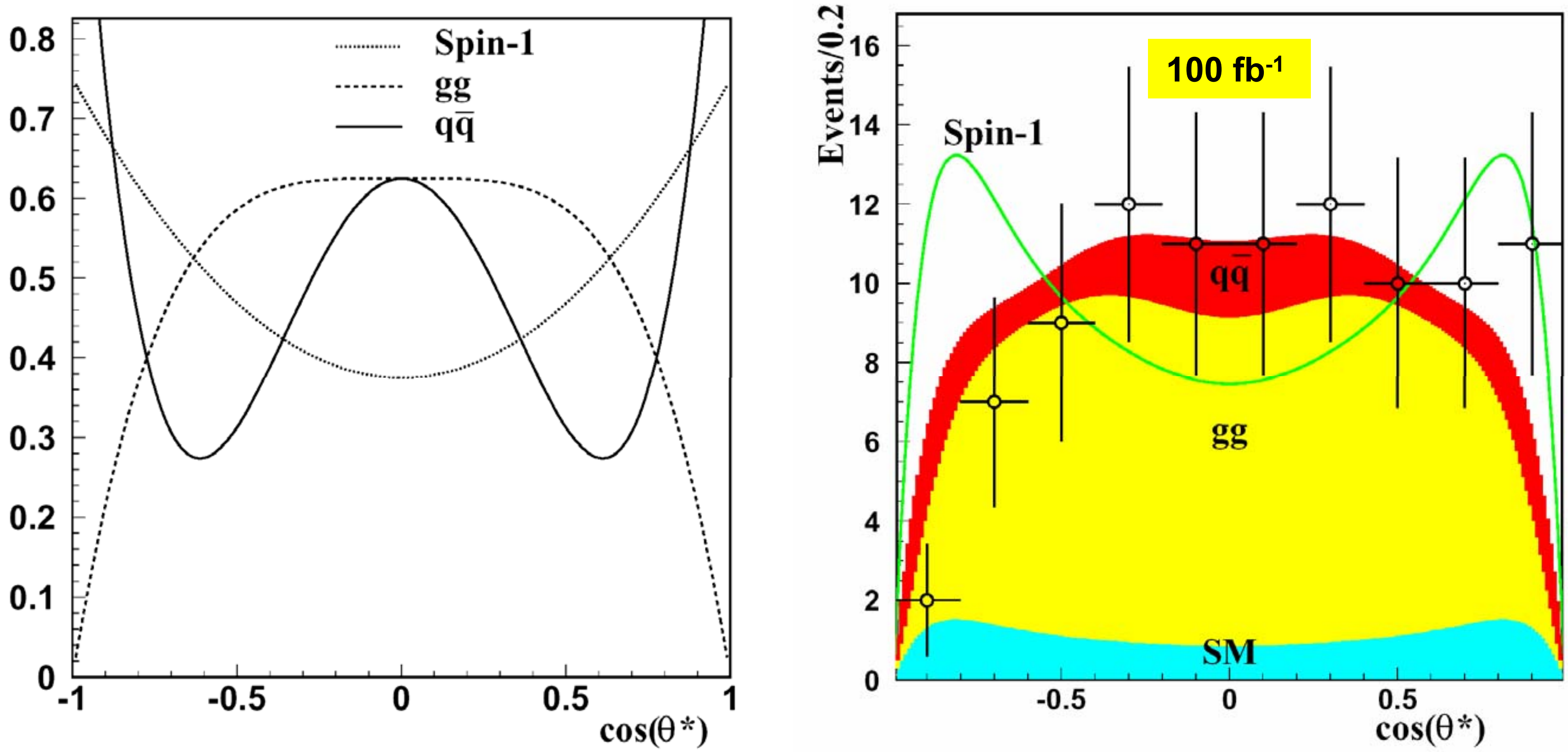
- also G → WW , ZZ, jj, μμ, tt, hh

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



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

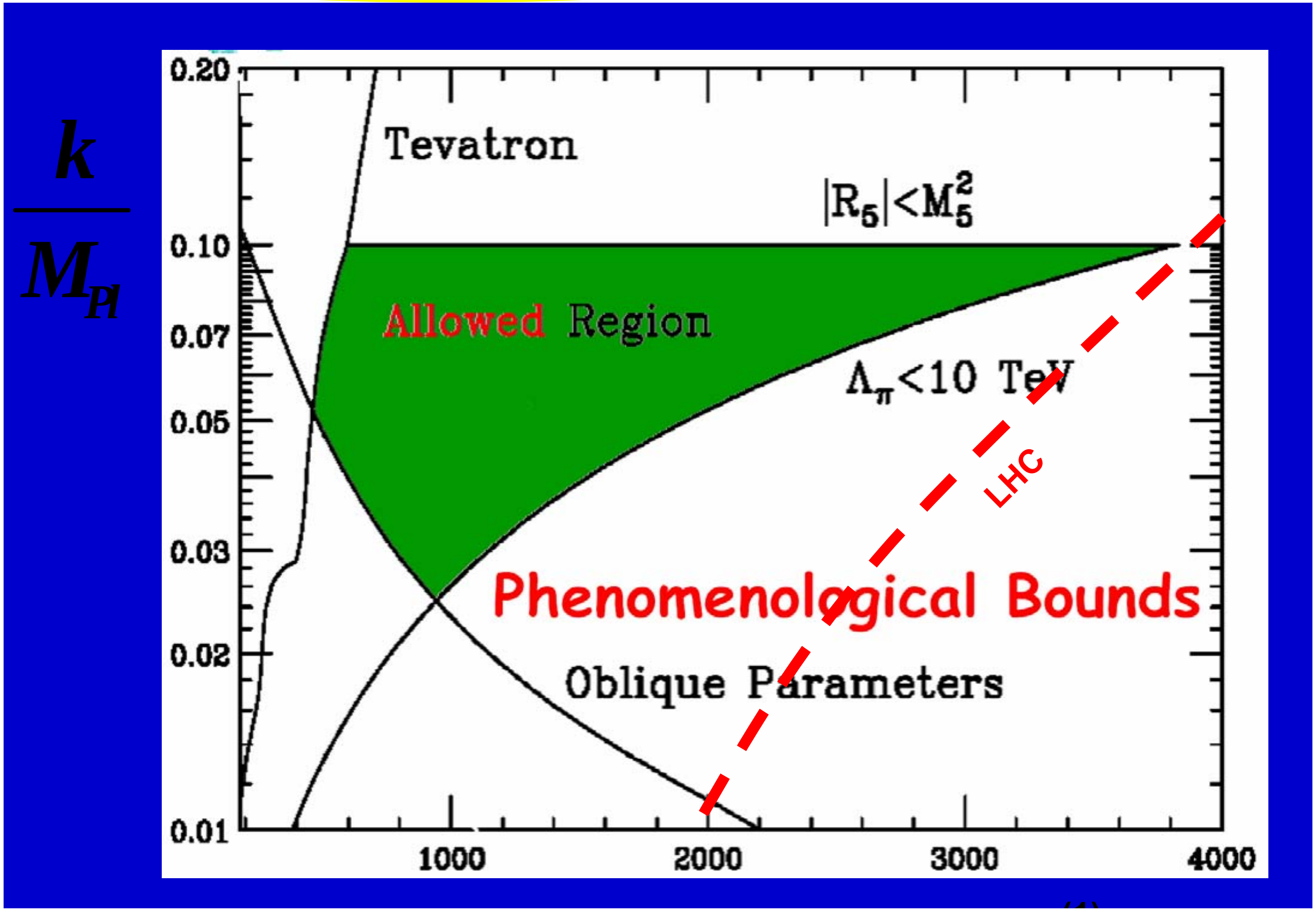
Spin determination



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

Narrow Graviton Resonance

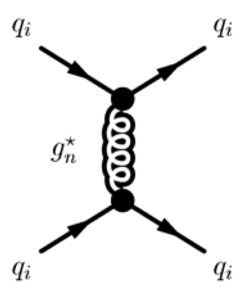
Interesting region covered by LHC

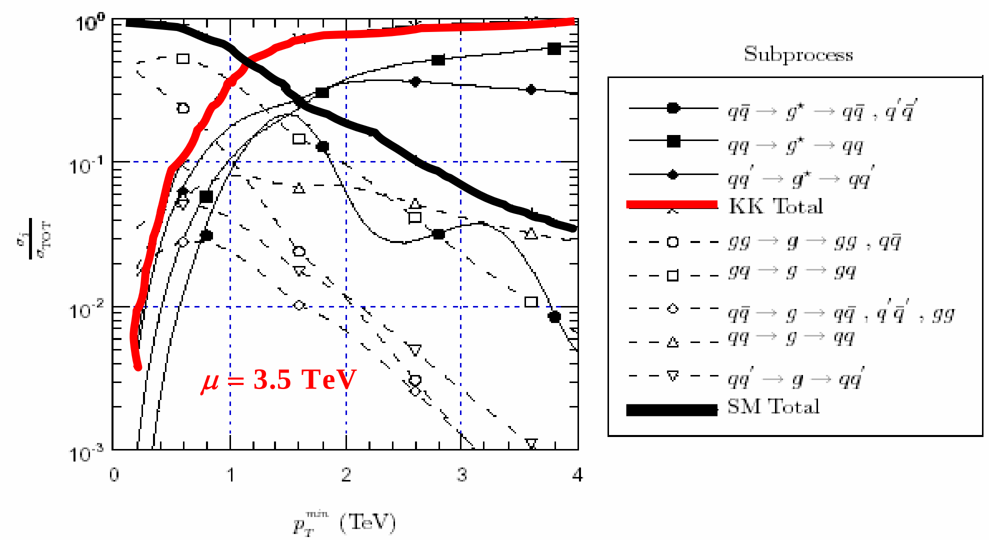


H. Davoudiasl, J. Hewett and T. Rizzo, Phys.Rev. D63 (2001) 075004 (*hep-ph/0006041)*

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

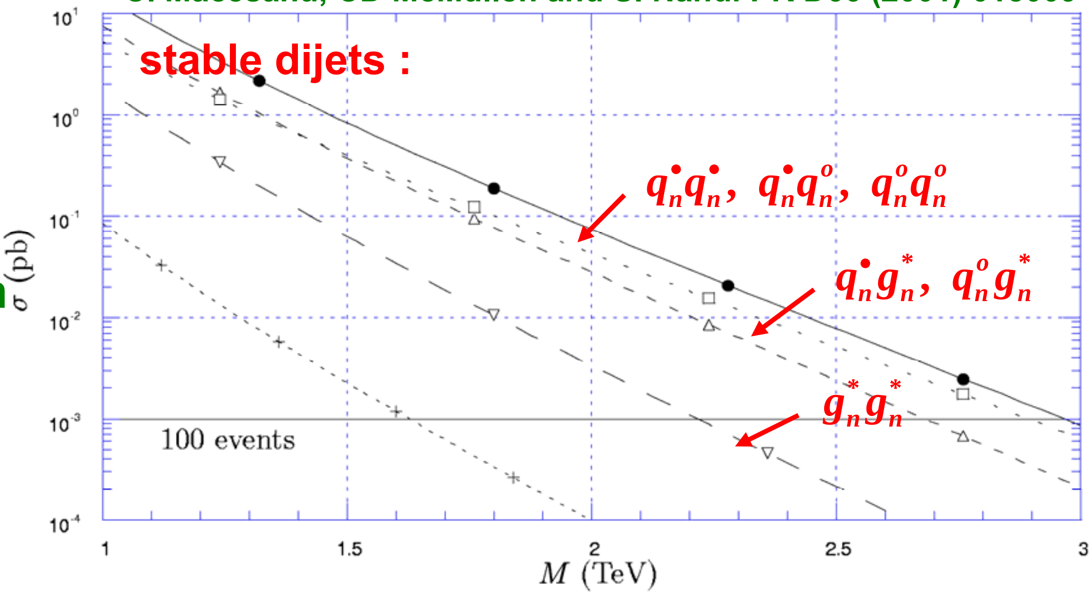
⇒ pair production of KK states

⇒ lower collider bounds: ~ 350-400 GeV

Universal Extra Dimensions

- dijet signals
  - stable
  - unstable:
    fat brane absorbs unbalanced momentum from KK number violation

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



- LKP: γ^*

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

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)

ILC: spin can distinguish between SUSY and UED better than at LHC

Many other topics…

- **QCD:**
  - measurement of α_s through high E_T jets (ILC: use event shapes)
  - parton densities
  - tests of NNLO corrections
  - forward physics
- **leptoquarks**
  - reach: ~ 1.5 TeV
- **scalars in the bulk**
  - $\rightarrow$ coupling to Higgs
  - mixing with Higgs
- **Lepton Flavor Violation:**
  - $\tau \rightarrow 3\,\mu$
  - in SUSY decays
- **monopoles**
- **isosinglet quarks…**
- **black holes**

Conclusions

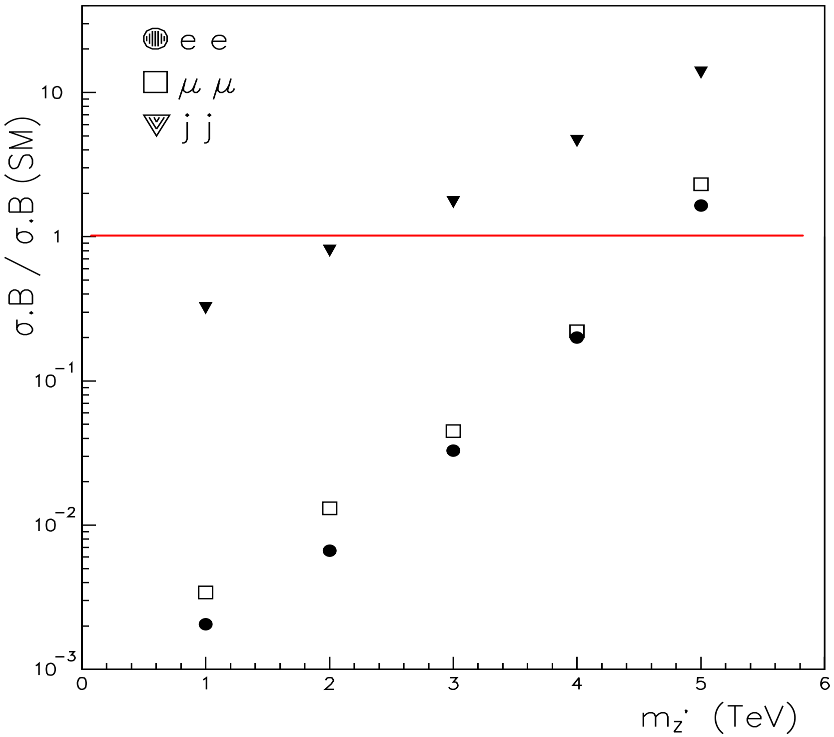
- **LHC: a discovery machine with a very rich programme of physics**
  At the start of ILC, we can expect
  - some manifestation from source of EWSB, and resolution of hierarchy problem?
    (SM, SUSY, little Higgs? extra Dimensions?)
    - « guarantee » of some new phenomena to be observed
    - **ILC should refine understanding and help discriminate between models through clean precision measurements and new processes**
      - **telescope and microscope for much better measurement of couplings, consistency**
  - exotic physics
    - extended gauge groups?
    - extra dimensions?
    - compositeness?
    - 3rd family couplings?
- **Observation of a resonance or other signal is not enough. What is the nature of the new physics ??**
  - **ILC will allow to observe the new discoveries from a different angle and correlate precision measurements of different observables**

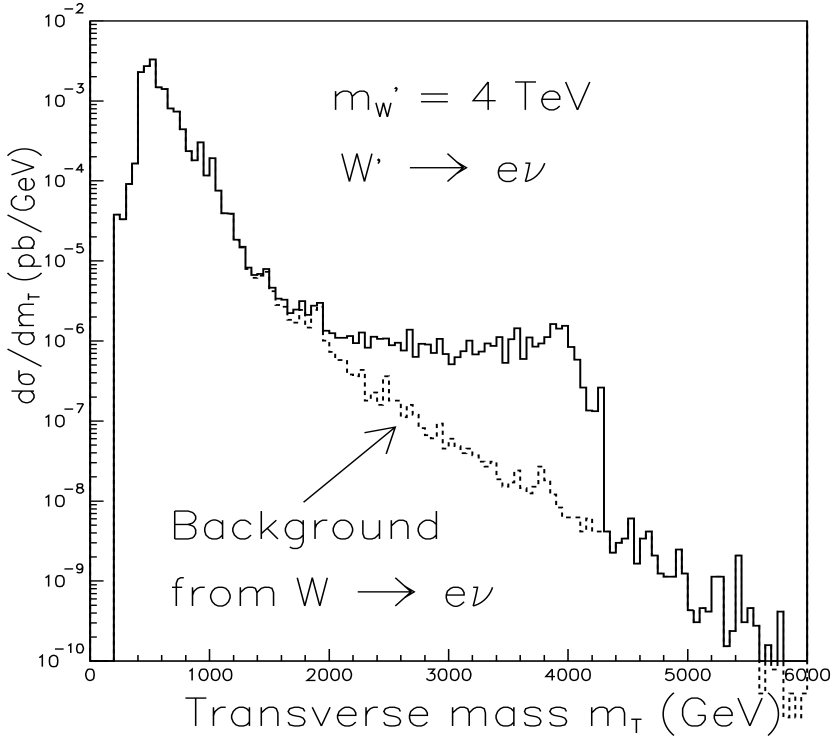
backup

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

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

$SU(2)_L$	$SU(2)_R$	$U(1)_{B-L}$	$SU(2)_L$	$U(1)_Y$
$\downarrow$	$\downarrow$	$\downarrow$	$\downarrow$	$\downarrow$
$\mathbf{W}_L^i$	$\mathbf{W}_R^i$	$\mathbf{C}$	$\mathbf{W}_L^i$	$\mathbf{B}$
g_L	g_R	g'	g_L	g_Y

- 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

$p\,p \to Z_R \to N_l N_l \to l jj\, l jj$

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

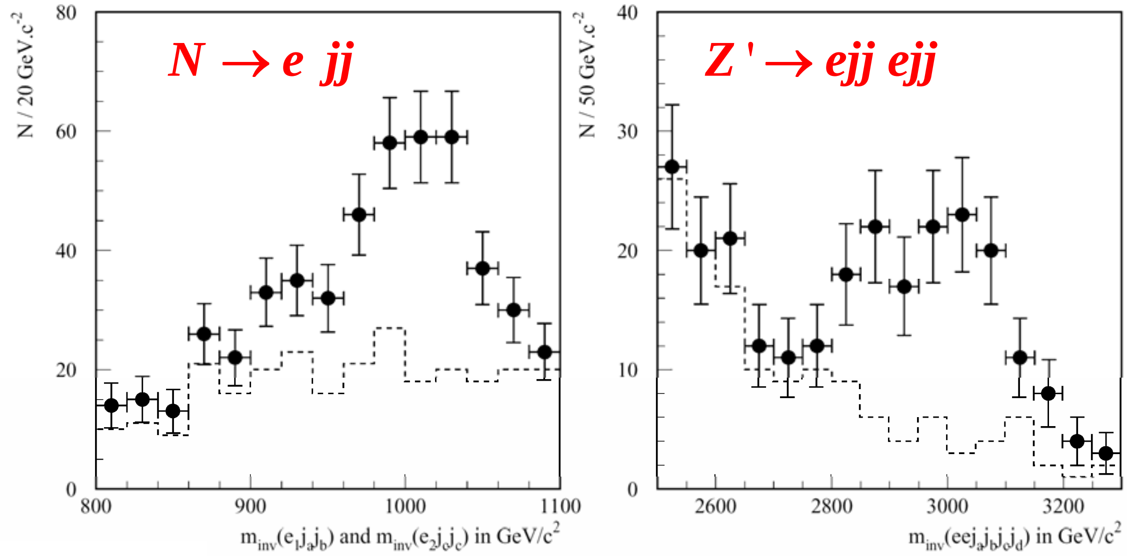
backgrounds:

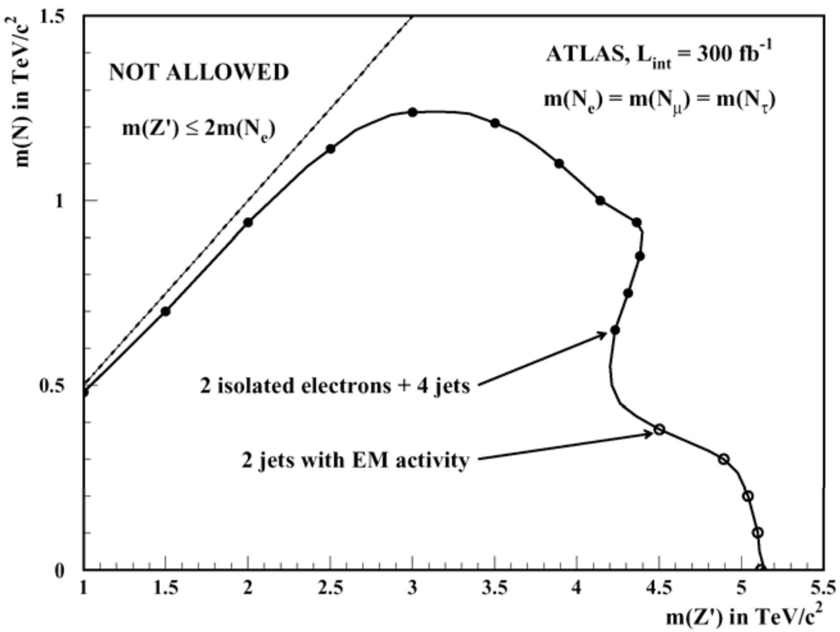
t tbar

DY, WW, ZW, ZZ

LRSM bckg: W_R,…

⇒ cuts on m_{ee}, pT(jets)





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

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

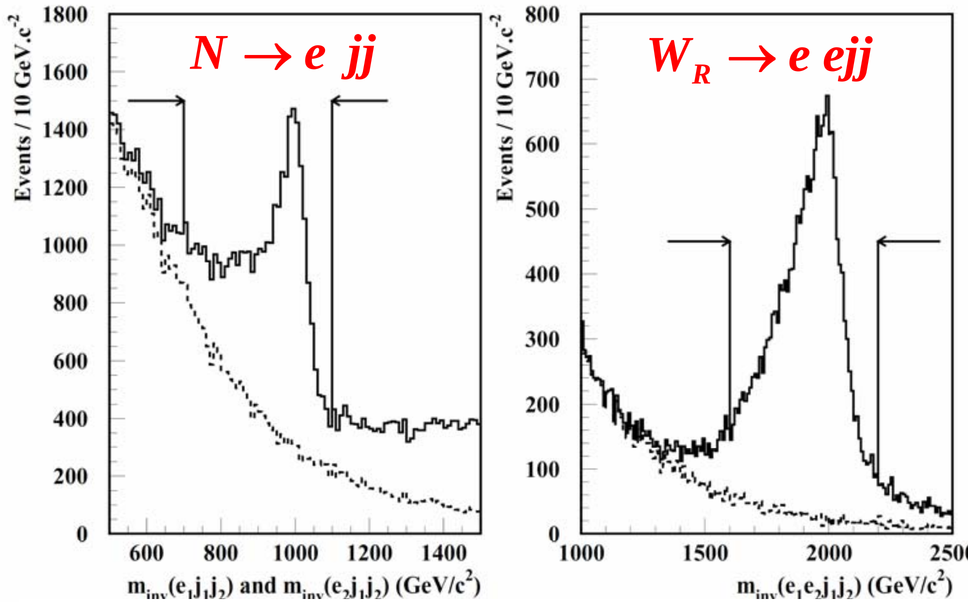
$$= 1.7\, m_{W_R} \quad \text{if } \kappa = 1$$

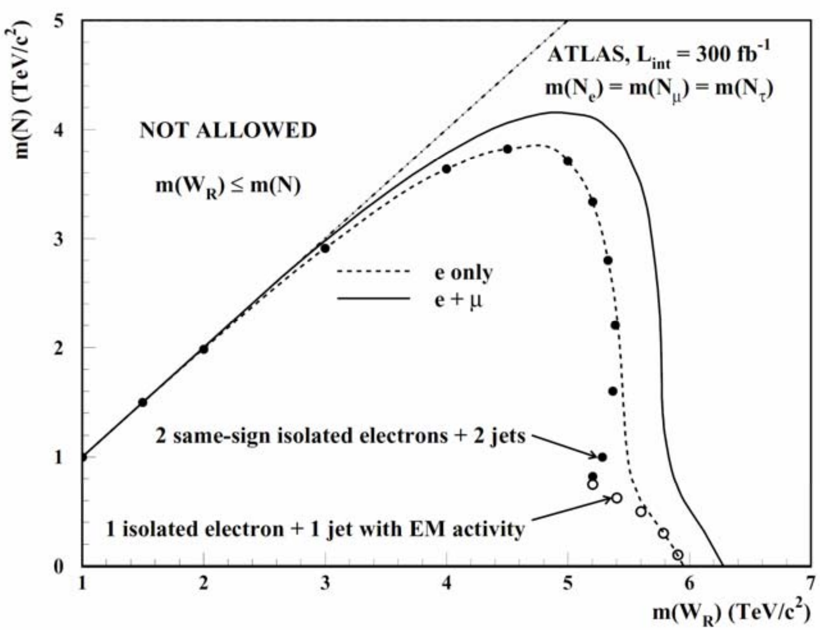
Z', W'

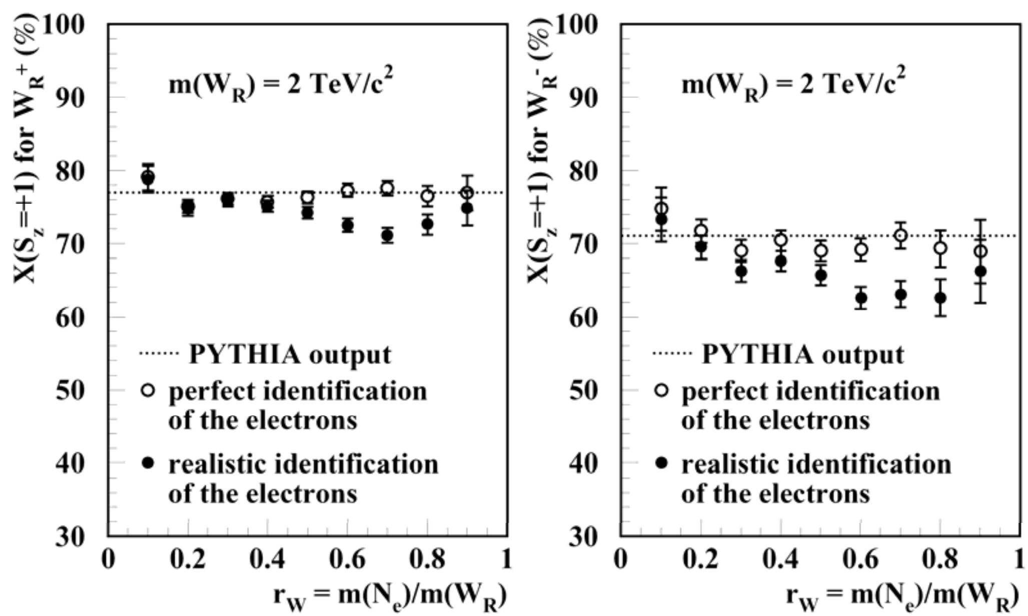
$p\,p \rightarrow W_R \rightarrow l\,N_l \rightarrow l\,l\,jj$

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

backgrounds:
t tbar
DY, WW, ZW, ZZ

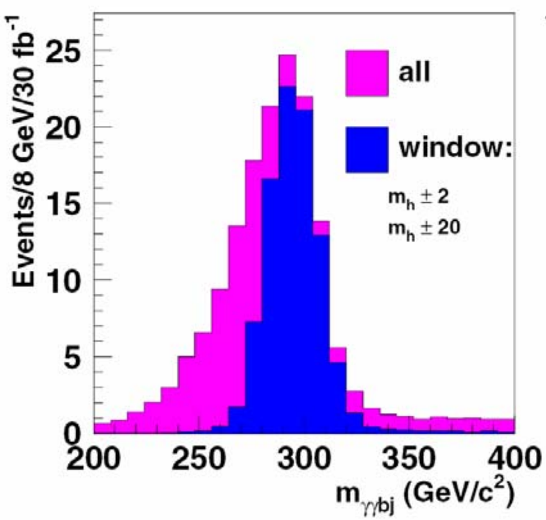


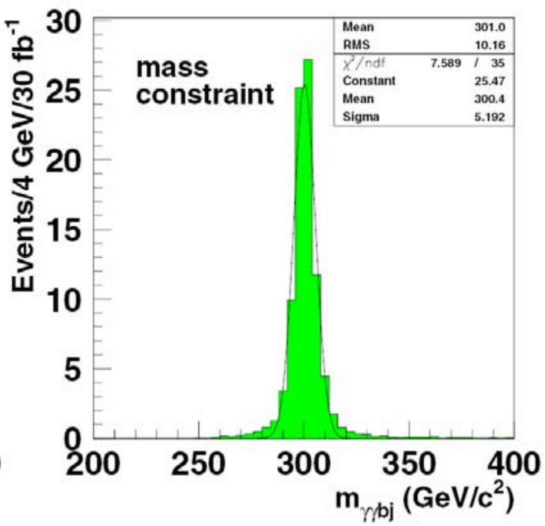




Randall-Sundrum model: the radion

- **signal:** $\phi \to hh \to \gamma\gamma\, b\bar{b}$
  - 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**
  - $gg \to \gamma\gamma$ 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}

$SPS1a:$

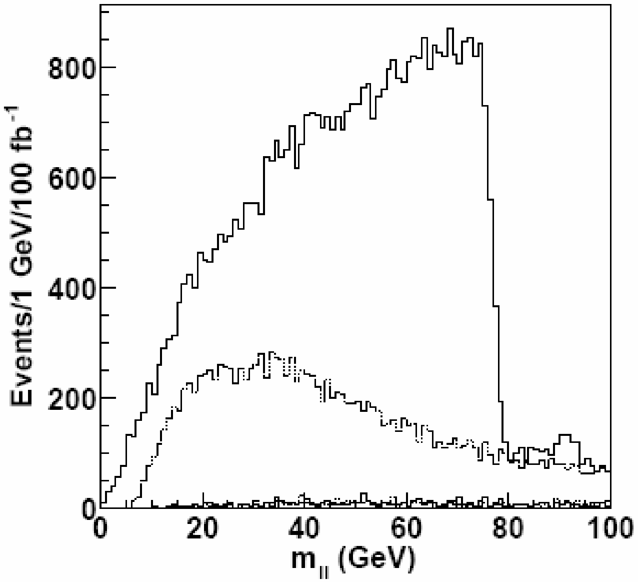
$m_0 = 100$ GeV,

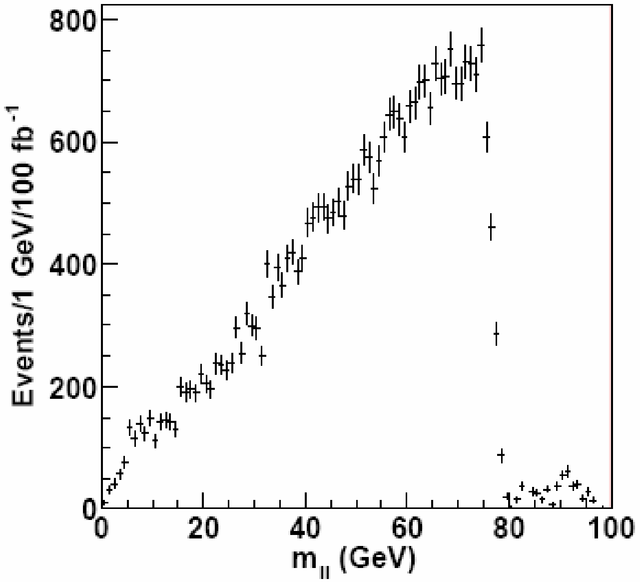
$m_{1/2} = 250$ GeV,

$A_0 = -100$ GeV,

$\tan\beta = 10, \ \mu > 0$

100 fb^{-1}





A. Belyaev, Phys Rev D59 1998 015022