Leptonic (and more) Resonances at the LHC

- di-lepton resonances
  - **Z'-like resonances**
  - **W'**
- 3[rd] family resonances
- Little Higgs
- leptoquarks
- excluding: Higgs, SUSY, excited fermions

Resonances: early LHC physics

Resonances should be relatively easy and quick to discover, but:

- what are they?, in what model do they fit? what are the couplings to fermions and bosons?
- what can we measure, and with what precision?
  - production cross section and decay branching ratios
  - width
  - interferences (and interference with Drell-Yan for Z')
  - FB asymmetry
  - rapidity distribution
  - associated with what other new physics?

LHC: a discovery machine

ILC: precision measurements

2-body resonances

	e/μ	τ	ν	j	b	t	γ	W/Z	h
e/μ	Z', G*, ρ_{TC}, H^{++}	LFV	W'	LQ, (2l-2j)	LQ , (2l-2j)	LQ , (2l-2j)	e*, μ*	e*, μ*, ν*, e', μ'	
τ		Z', G*, ρ_{TC}, H^{++}, A/H	W'	LQ , (2l-2j)	LQ , (2l-2j)	LQ , (2l-2j)	τ*	τ* ,τ', ν*	
ν				LQ , (2l-2j)	LQ , (2l-2j)	LQ , (2l-2j)	ν*(?)	ν*, ν'	
j				Z', G*, ρ_{TC}, H	π_{TC}	π_{TC}	q*	q*, q', D	D
b					Z', G*, ρ_{TC}, H, h	W'	b*	b*, b', T	D
t						Z', G*, ρ_{TC}, H, g_{KK}	t*	T	T
γ							G*, ρ_{TC}, H	W'	
W/Z								Z', G*, ρ_{TC}, H, W'	W', Z', H
h									H/A

Z'-like resonances

- **from new U(1)**
  - E_6, L-R symmetric model,
  - little Higgs (including Z_H, A_H)
  - 3-3-1(including doubly charged)
- **from extraD's**
  - Z_{KK}/γ_{KK} in bulk, TeV-1-size ED: EW constraints ➔ $m_{Z'} \geq \sim 4$ TeV
    - including RS bulk: Z'/γ :
      flavor dependent coupling [Ledroit et al., hep-ph/0703262]
    - fermiophobic Z', W' (3-site model, see talk by S. Chivukula)
  - gravitons in RS
    - Higgsless models
    - measure spin-2 and observe other channels
    - RS in bulk: lepton and photon couplings negligible ➔ look for top or VB pairs [Agashe et al., hep-ph/0701186]
  - gluon: look for decay to top pairs and polarization
- **technicolor**
  - ρ_{TC}, π_{TC} BESS
- **Higgs ($H/A \rightarrow \mu\mu, \tau\tau$, bb, tt)**
- **Hidden Valley ….**

Experimental issues at LHC

e^+e^-, $\mu^+\mu^-$: clean signal, little background (Drell-Yan)

- measure σ, Γ, A_{FB}

$\tau^+\tau^-$: reconstruction difficult, but possible

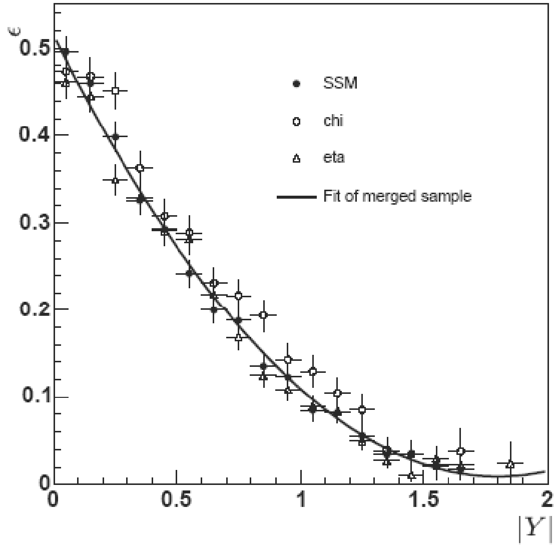
- measure τ polarization and spin correlations

$t\bar{t}$: very large QCD background

- can be seen if due to strong interaction resonance $g_{KK} \to t\bar{t}$

A_{FB} is an important observable

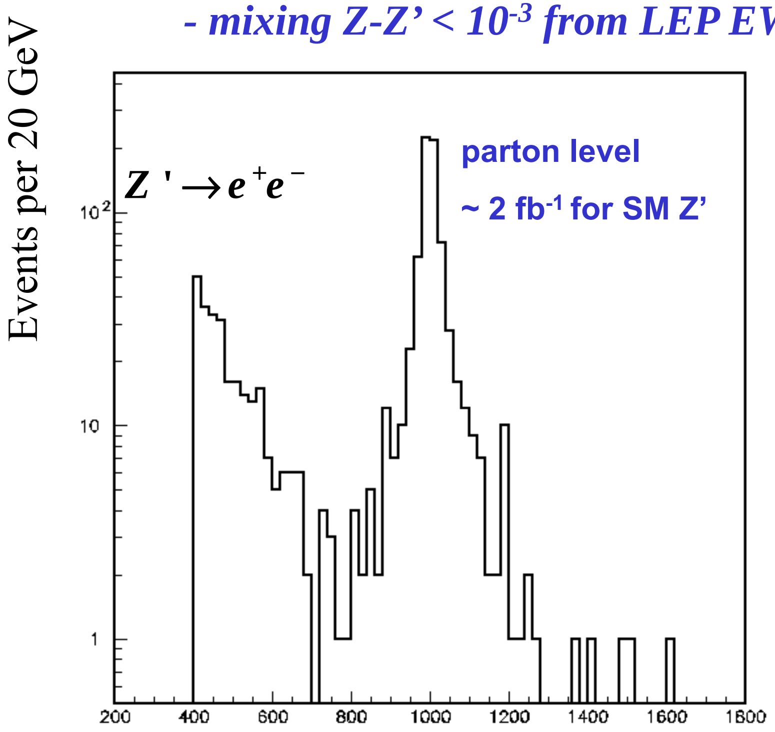
- In a pp collider, we must resort to "guess" that Z' boost is in direction of quark (by opposition to antiquark) forming it
  - reliable for large values of boost (rapidity of Z')
    - but pseudorapidity cut on leptons: $|\eta| < 2.5$
  - can correct for dilution to a large extent
    - efficiency depends only on Y (given incoming type of quarks) because of the smmetr of the detector
    - some systematic uncertainties (PDF's…)

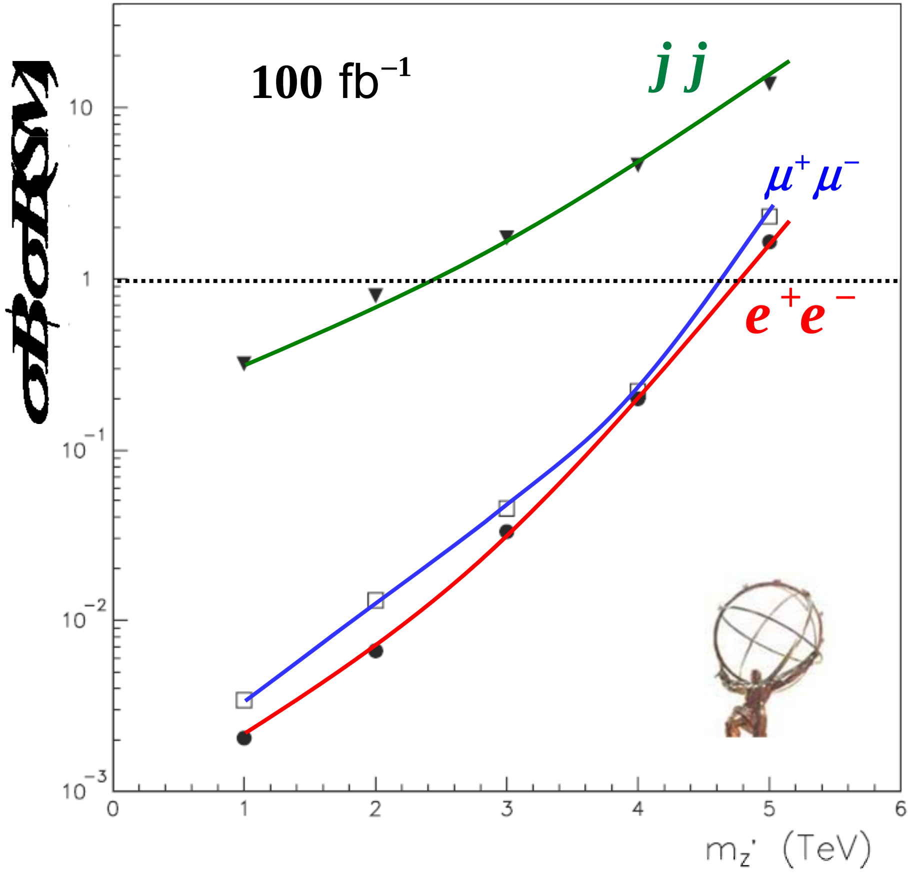


Probability to be wrong vs Y
Ledroit et al., hep-ph/0703262

Z' resonance discovery at the LHC

- *present limits ~ 600 GeV if SM couplings* ➔ *not interesting for 500 GeV ILC, unless couplings are lower than SM*
- *mixing Z-Z' < 10^{-3} from LEP EW measurements*





SM-like Z':

- width ~ 3% of mass for SM Z'
  - could increase if $Z' \to WW, Zh$
- very little background
- typical resolution: $\frac{\sigma(E)}{E} \sim 0.75\%$

ATLAS Physics TDR

E6 extensions of SM (superstring inspired)

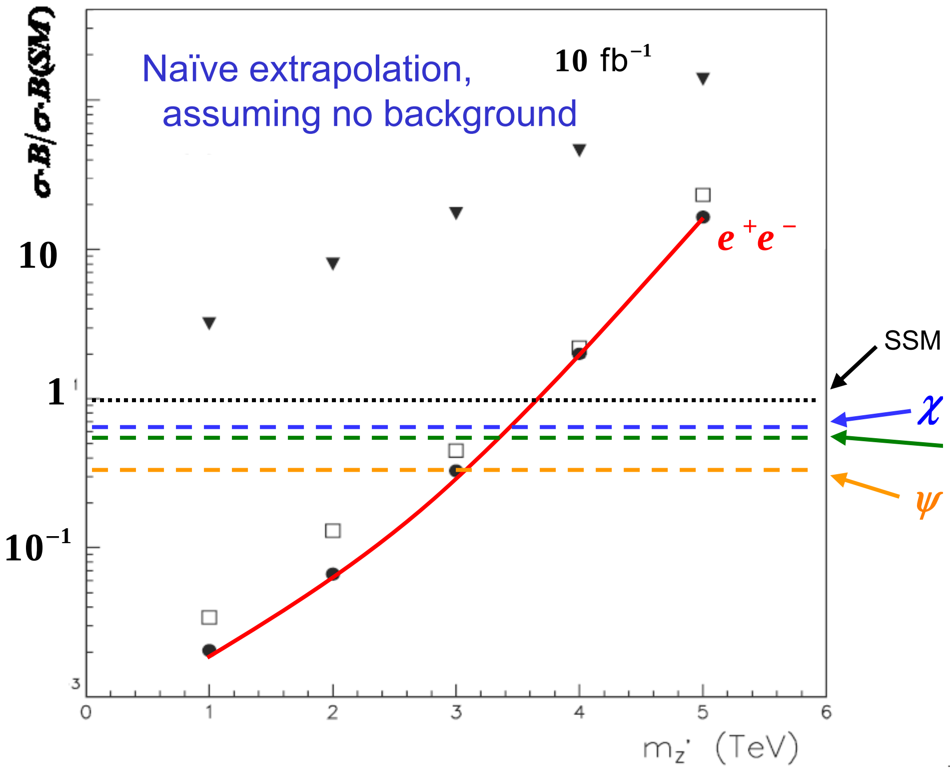
$$E_6 \rightarrow SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_\eta \quad \text{(rank 5)}$$

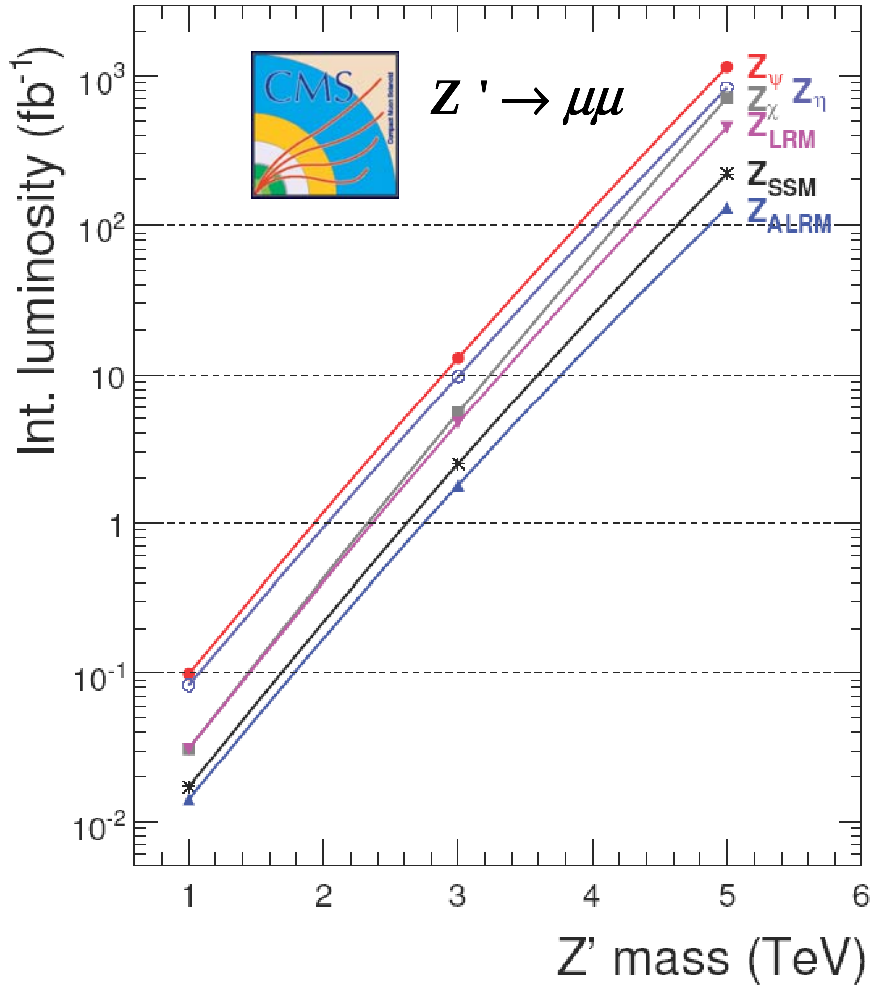
$$E_6 \rightarrow SO(10) \times U(1)_\psi$$

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

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

J. Hewett and T. Rizzo, Phys Rep 183 (1989) 193
F. del Aguila, hep-ph/9404323

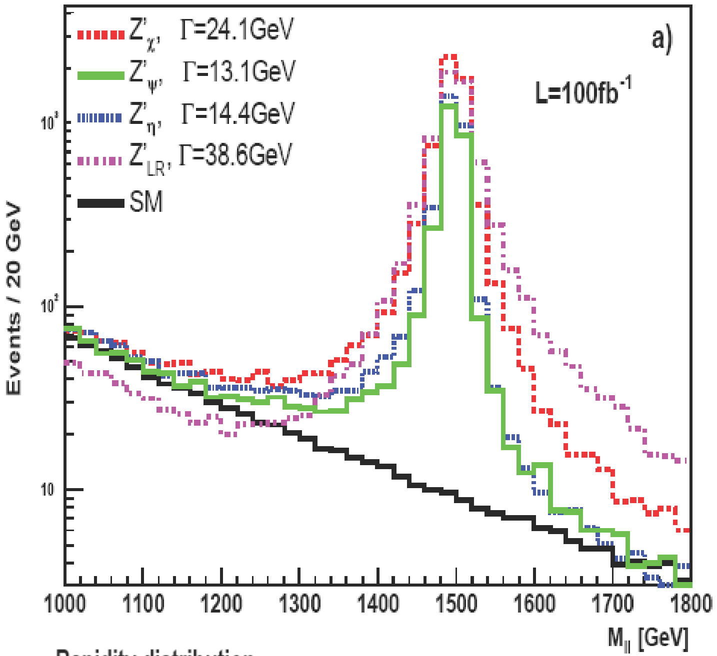




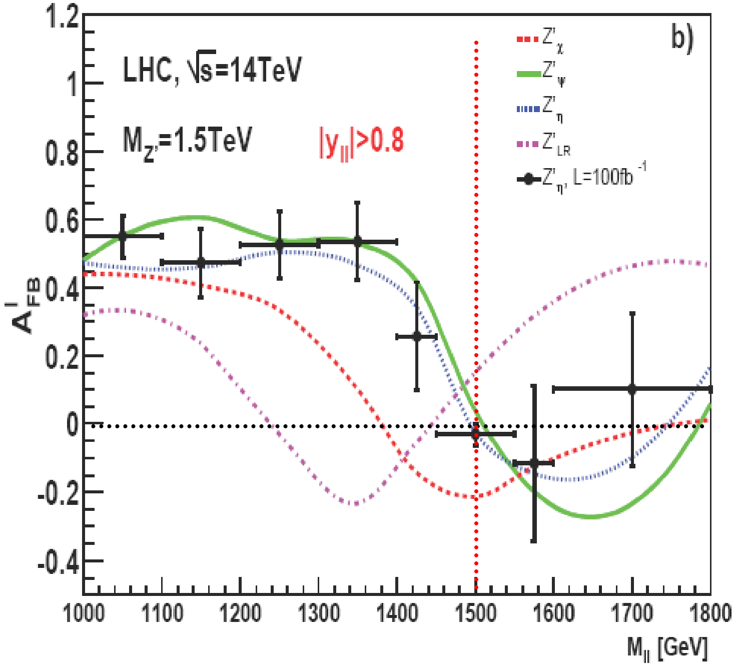
Statistics not a problem: ILC helps with precision or investigation of some rare couplings

Observables

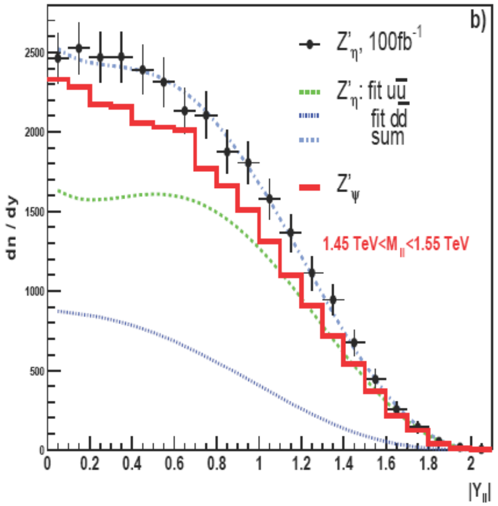
Dilepton invariant mass spectrum



Forward backward asymmetry measurement



Rapidity distribution



$$\frac{d\sigma}{d\cos\theta^*} \propto \frac{3}{8}\left(1+\cos^2\theta^*\right) + A_{FB}\cos\theta^*$$

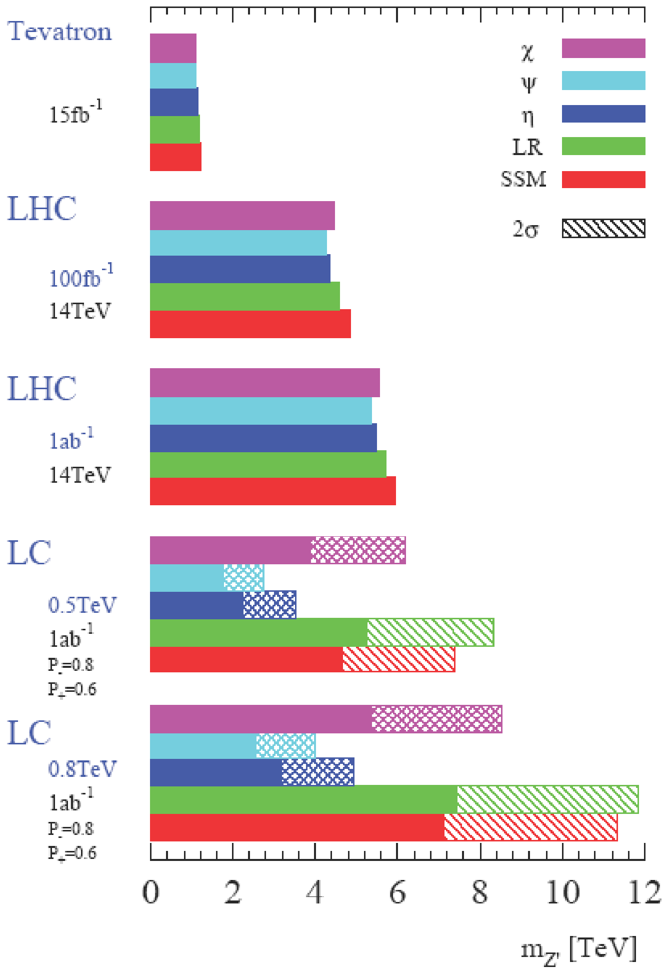
Also, Z' rapidity distribution depends on u/d couplings

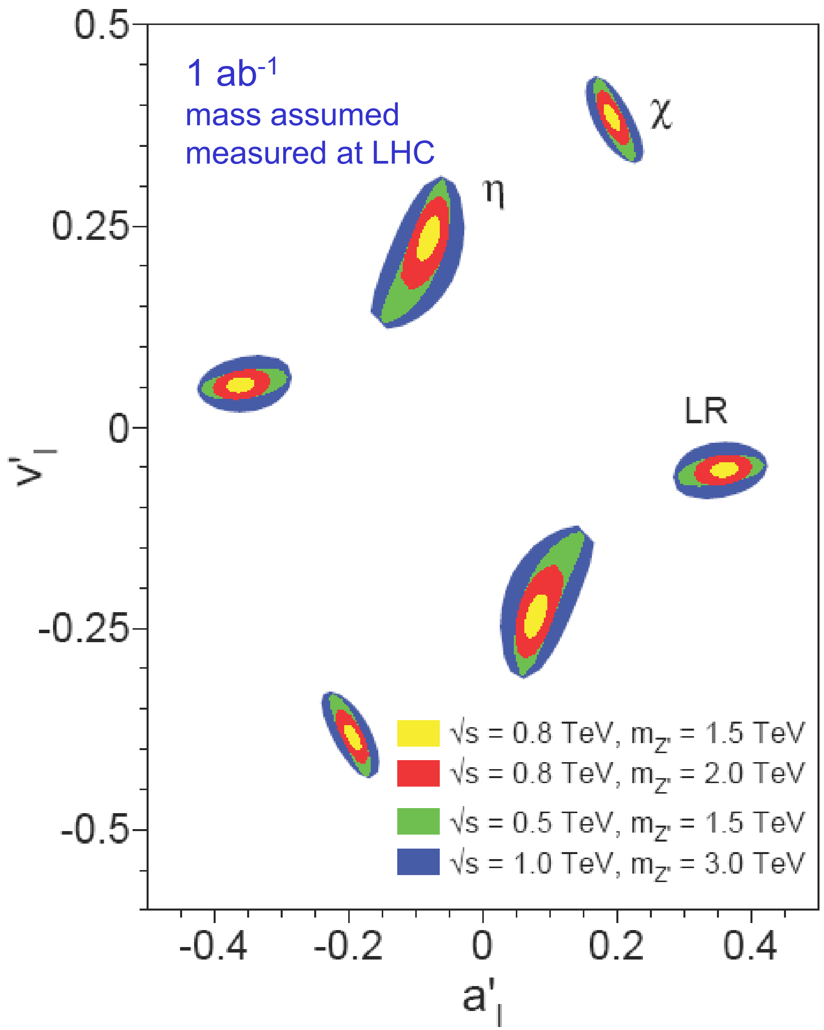
M Dittmar, A Djouadi, A-S Nicollerat, Phys.Lett. B583 (2004) 111

Z’ at the ILC

At the ILC, sensitivity s from Z’-Z interference

- can also be sensitive to high masses (contact-like interaction)





LHC/ILC Interplay, G. Weiglein et al, hep-ph/04103(

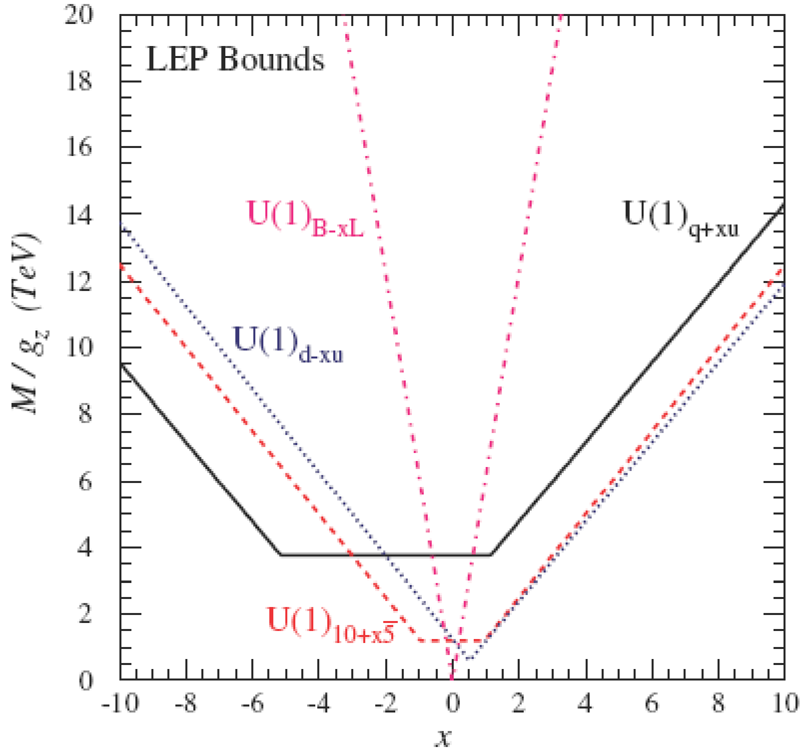
CDDT parametrization

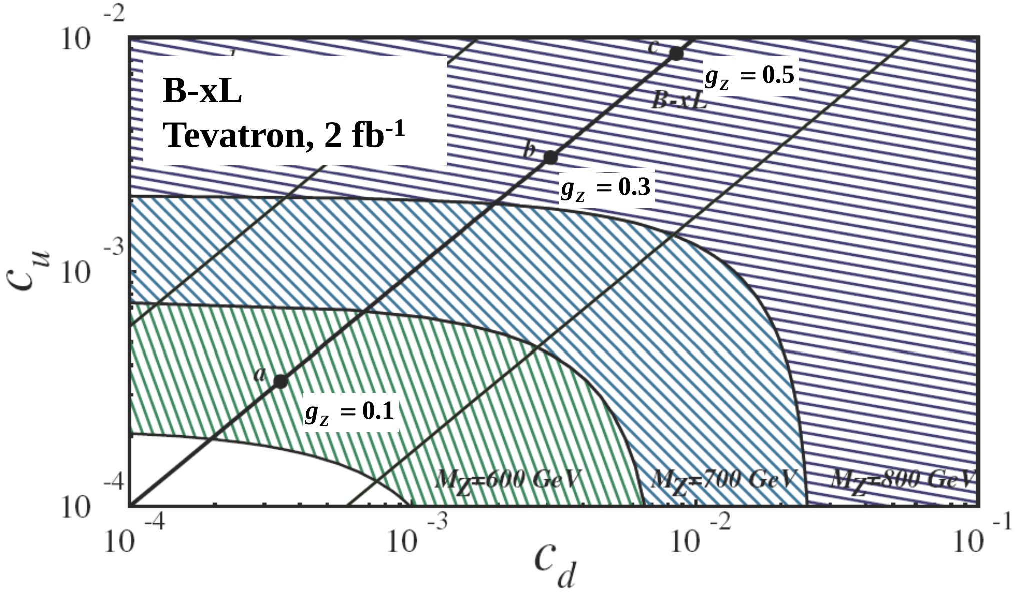
M Carena, A. Daleo, B. Dobrescu and T. Tait, PR D70 (2004) 093009

- very general model with 2 Higgs doublets
- 15 fermion couplings z_f: $f = e_R^j, l_L^j, u_R^j, d_R^j, q_L^j \quad j = 1, 2, 3$
- couplings to quarks are generation-independent $U(1)_z$ charges
  - z_u, z_d, z_q and $z_{l_j}, z_{e_j}, j = 1-3$
  - anomaly cancellations and possible new fermions must be taken into account
    - "realistic models" for Tevatron

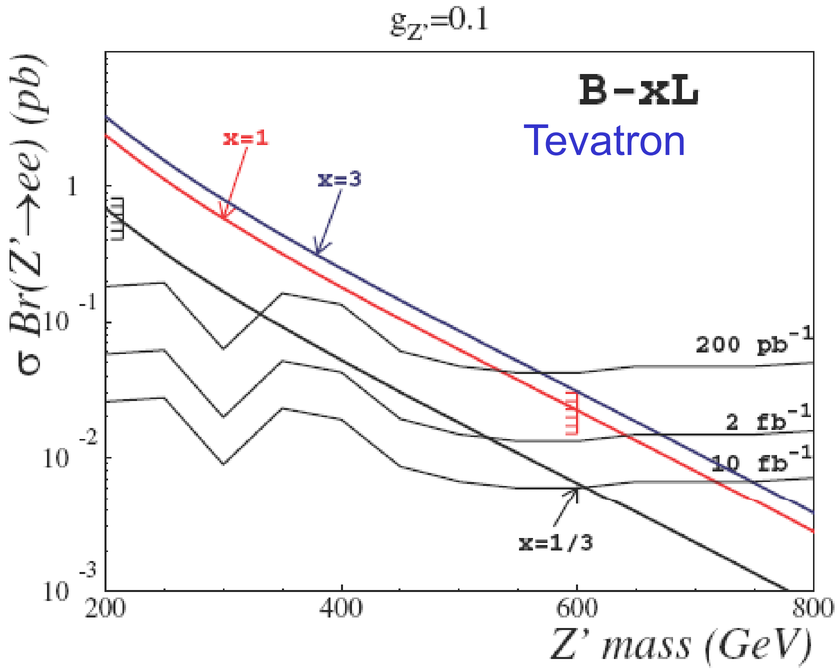
$$U(1)_{B-xL}, \bar{U}(1)_{q-xu}, U(1)_{d-xu}, U(1)_{10-x\bar{5}}$$

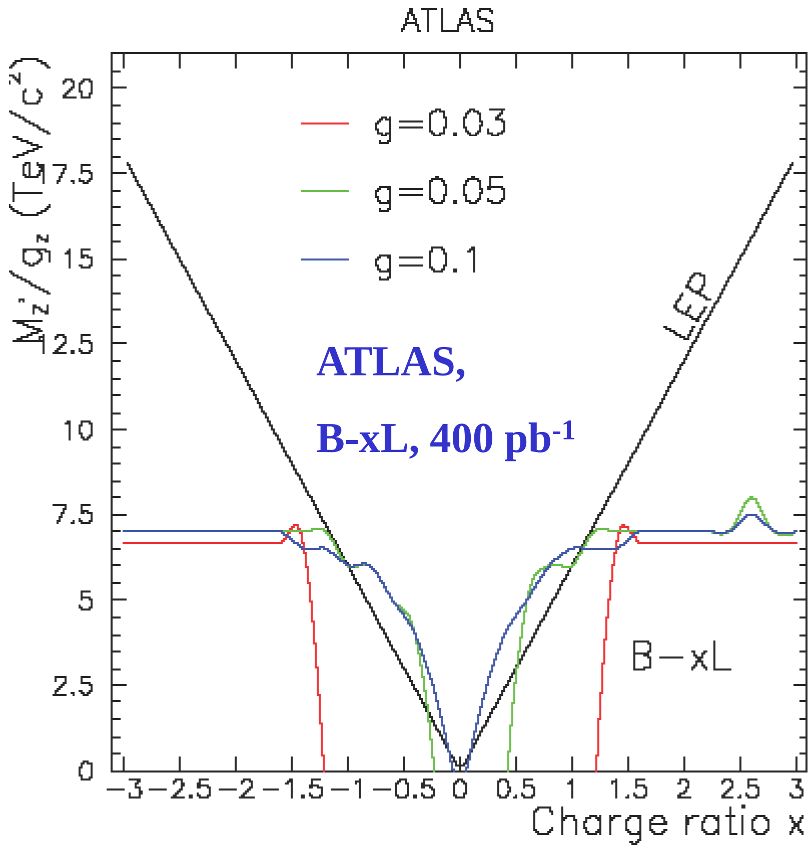
LEP bounds from contact interactions:





$$c_{u,d} = g_z^2(z_q^2 + z_{u,d}^2)\mathrm{Br}(Z' \rightarrow l^+ l^-)$$

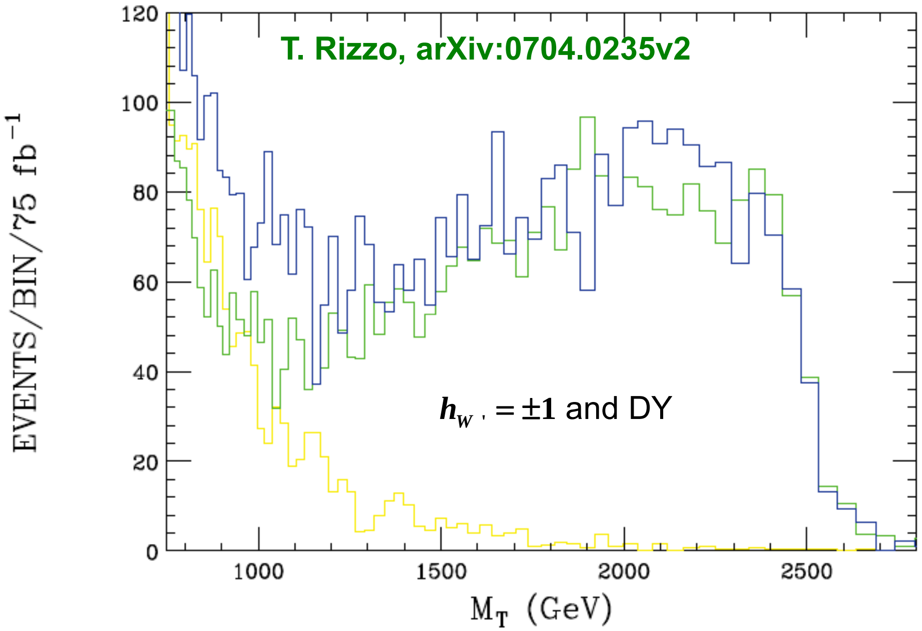


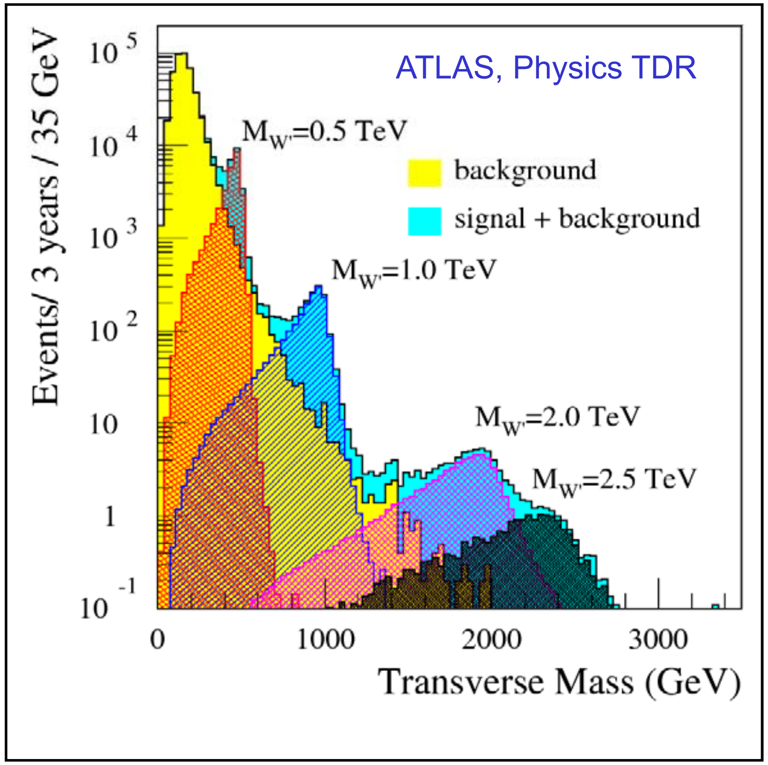


Ledroit et al., hep-ph/0703262

W’ → ℓ ν

- **W’ mass difficult to reconstruct:**
  - only transverse mass observable
- **A_{FB} not easily measurable**
  (assume light RH neutrino)
  - ν direction unknown
  - m_T is max when cos(θ) =0
  - can be measured in interference region
  - possibly also in W’ → t b, with t polarization



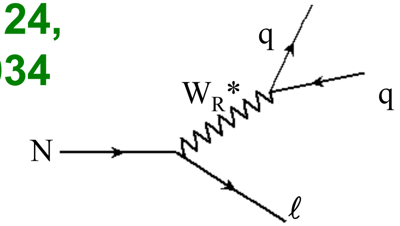


W’ couplings more easily measurable at ILC, where cm is known, but is there enough mass? (produced in pairs?)

Z', W' in LRSM

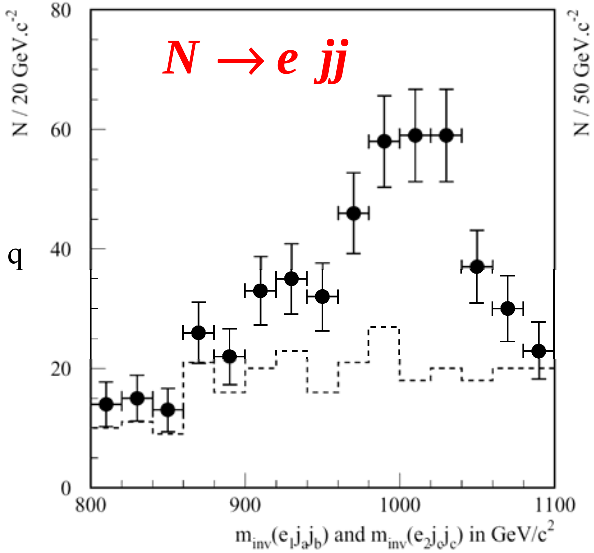
$p\,p \rightarrow Z_R \rightarrow N_\ell N_\ell \rightarrow \ell jj\ \ell jj$

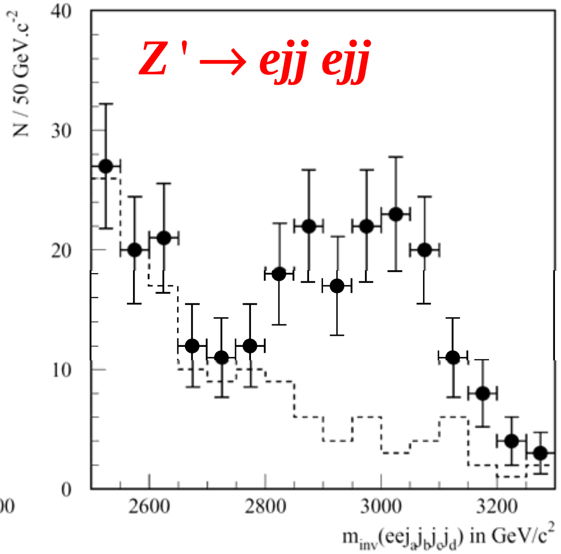
J. Collot, A. Ferrari
ATL-PHYS-98-124,
ATL-PHYS-99-034

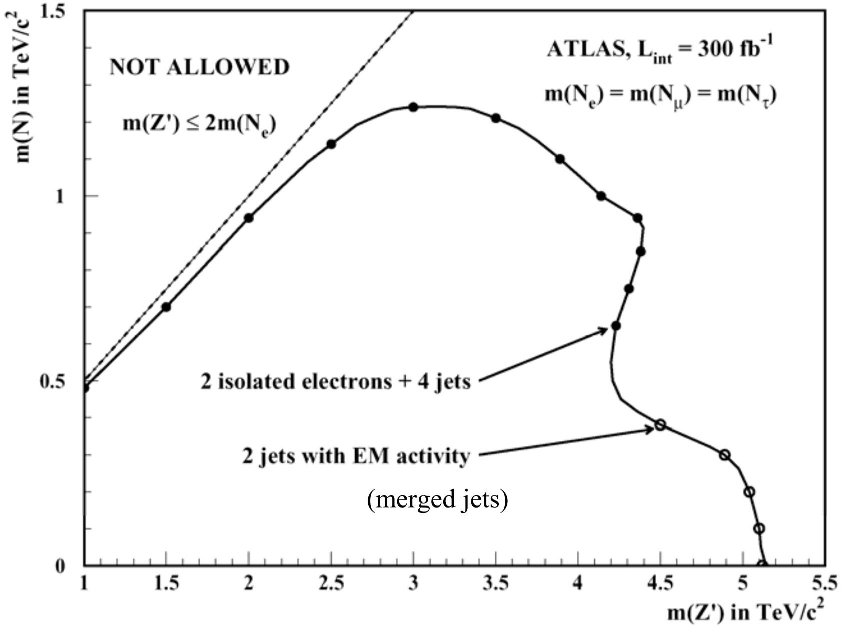


backgrounds:

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







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'

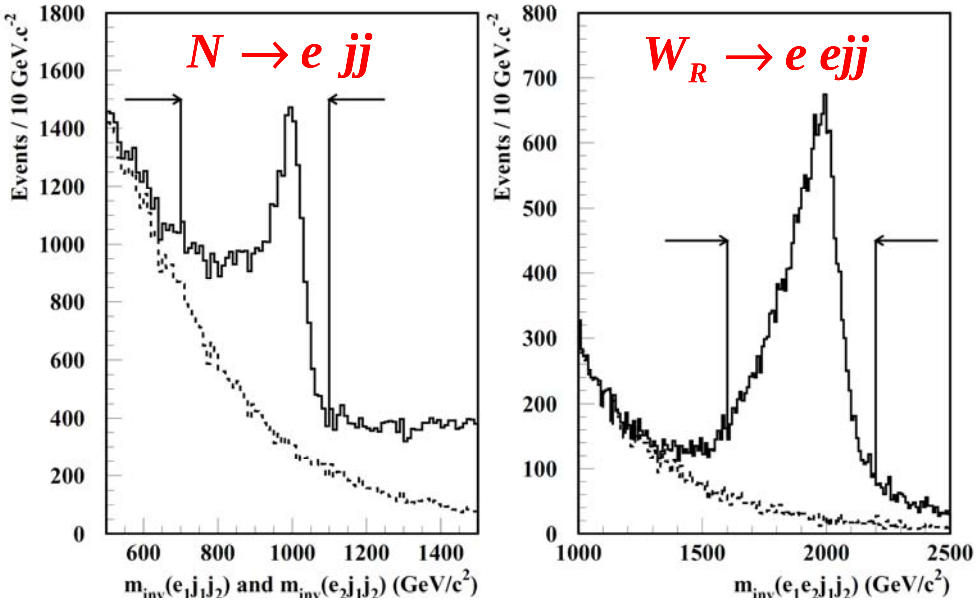
$p\,p \to W_R \to \ell N_\ell \to \ell\,\ell jj$

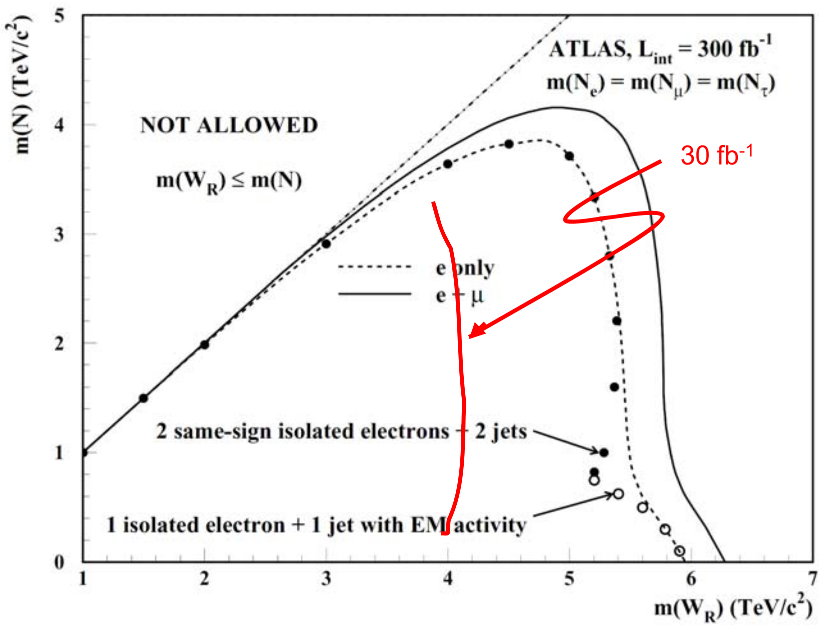
J. Collot, A. Ferrari
ATL-PHYS-98-124,
ATL-PHYS-99-018

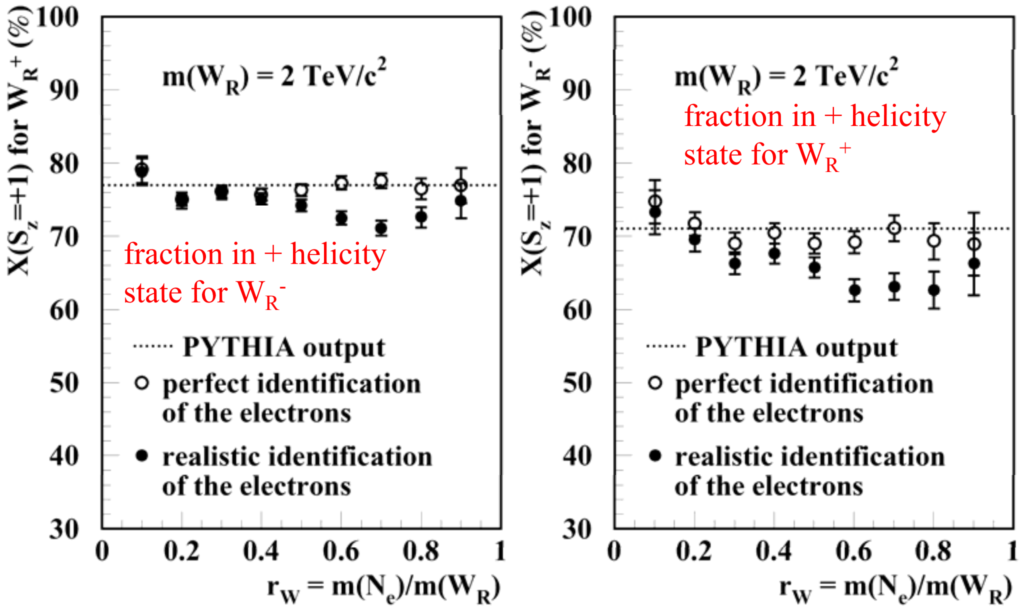
backgrounds:

t tbar

DY, WW, ZW, ZZ

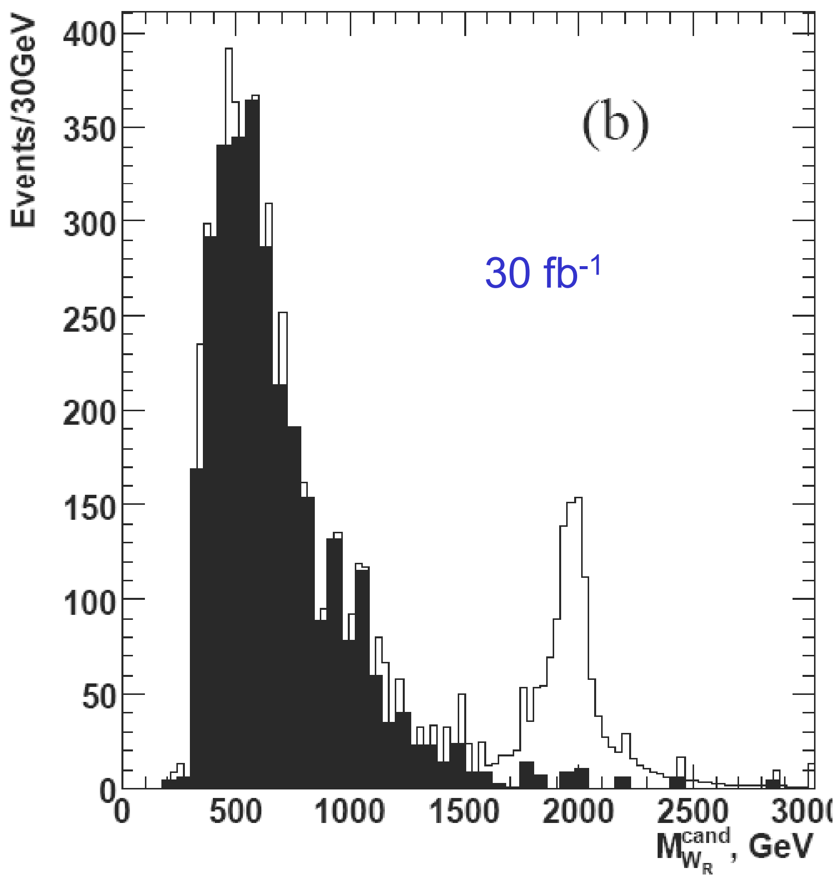


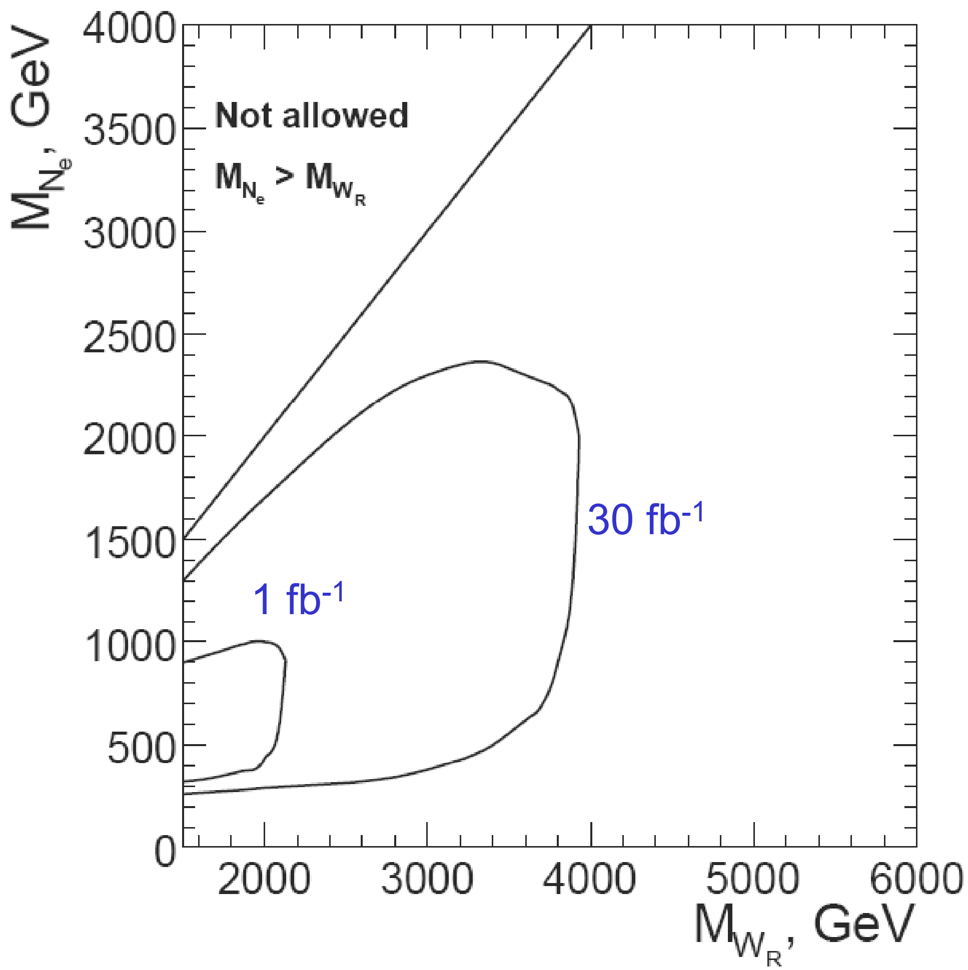




CMS result on W_R'

Full GEANT detector simulation and reconstruction





CMS Physics TDR, CERN/LHCC 2006-021

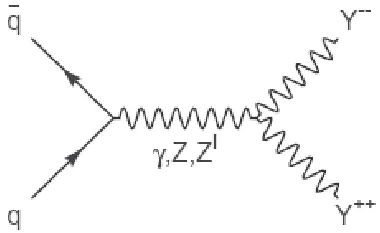
vector bi-leptons

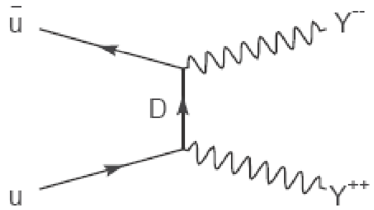
3-3-1 model: $SU(3)_C \times SU(3)_L \times U(1)_X$

- explains 3 families: anomalies cancel, taking all 3 generations together

fermions: $\begin{pmatrix} e^- \\ \nu_e \\ e^c \\ u \\ d \\ D \end{pmatrix}_L \begin{pmatrix} \mu^- \\ \nu_\mu \\ \mu^c \\ c \\ s \\ S \end{pmatrix}_L \begin{pmatrix} \tau^- \\ \nu_\tau \\ \tau^c \\ t \\ b \\ T \end{pmatrix}_L$ D, S, T have charges +5/3, -4/3, -4/3

new vector gauge bosons: $Z', W'^{\pm}, Y^{\pm\pm}$





$Y^{\pm\pm} \rightarrow \ell^{\pm}\ell^{\pm}$

-essentially no background, and detection possible up to ~ 1.4 TeV

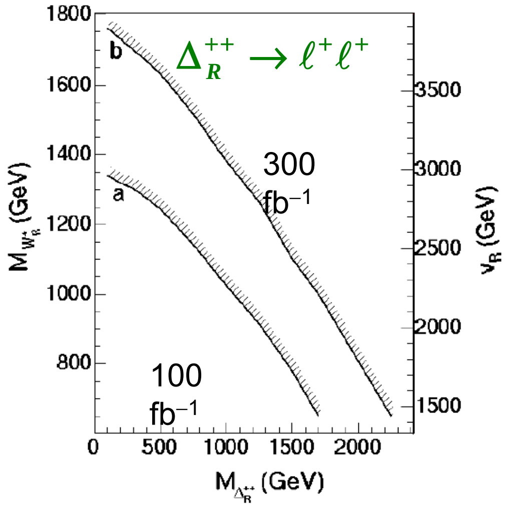
- can measure FB asymmetry, Z' mass

B. Dion et al., Phys.Rev. D59 (1999) 075006,
B. Brelier and G.A., ATLAS internal note

- at ILC, different 331 models can be distinguished (Barreto et al, hep-ph/0703099)

Scalar bileptons

doubly (and singly) charged Higgs in Higgs triplet models (as in LR symmetric model)



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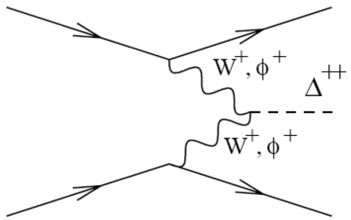
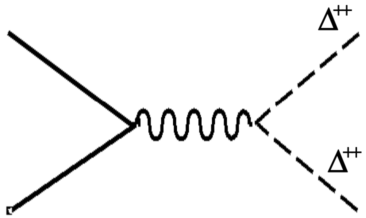


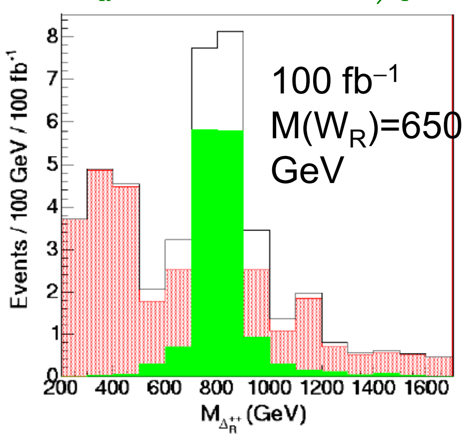
VBF

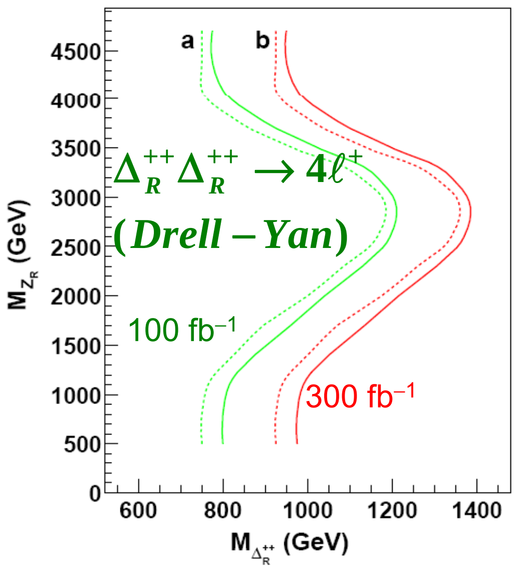


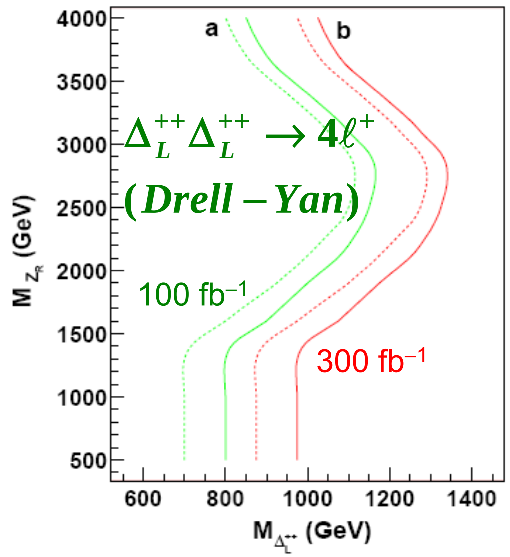
D-Y

$$m_{W_R}^2 = g_R^2 v_R^2 / 2$$

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







The littlest Higgs Model - remarks

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

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

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

- New particle content

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

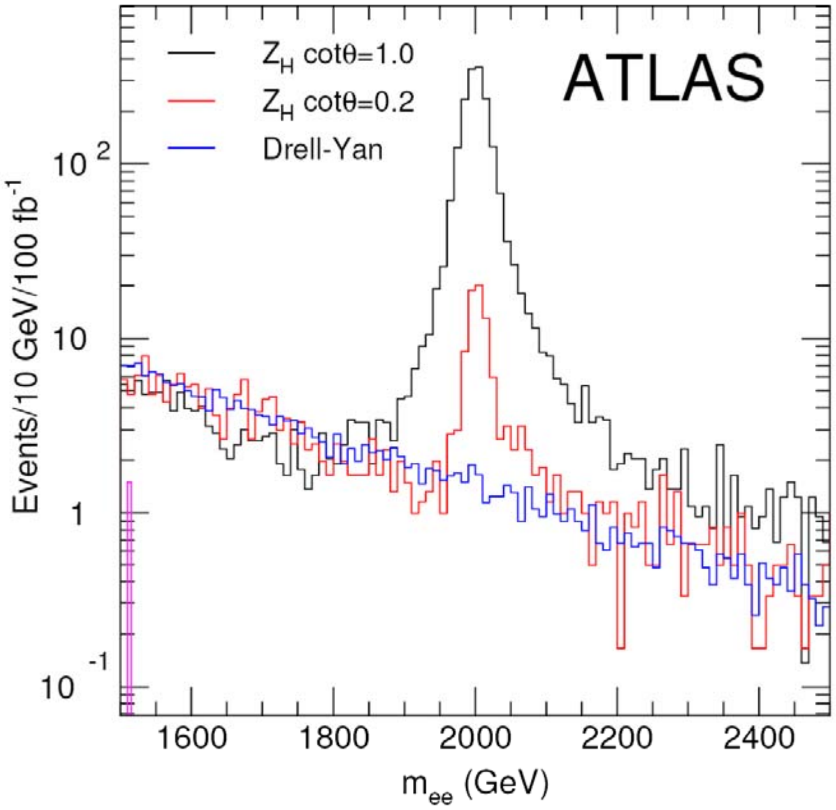
$$T : \sim 1 \ \text{TeV}$$

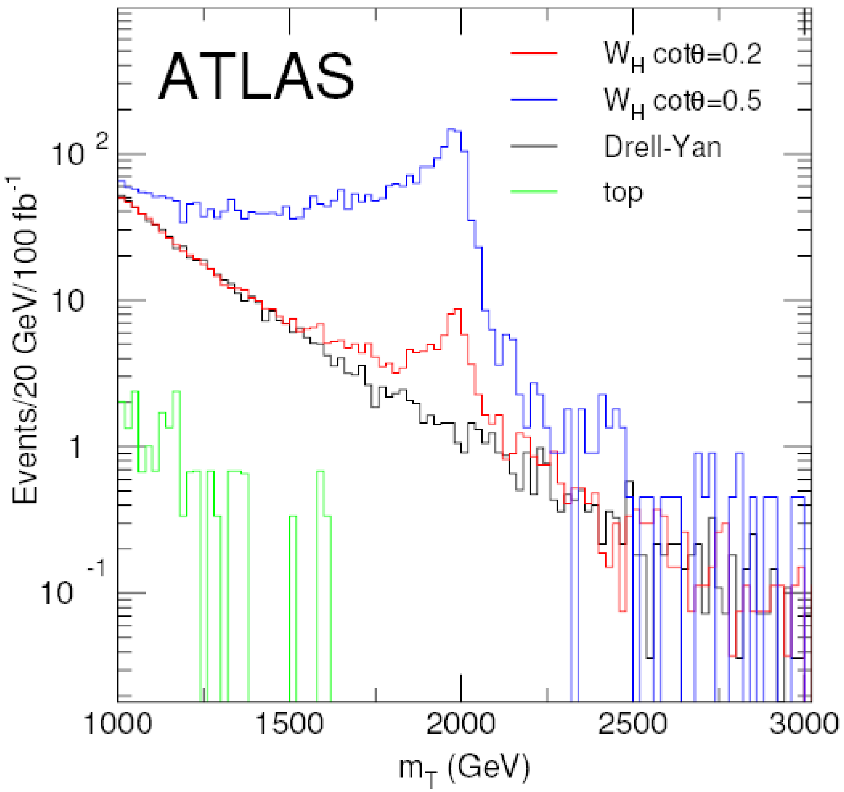
$$\phi^{\pm\pm}, \phi^{\pm}, \phi^{0} : \ \gtrsim \ \text{TeV}$$

Heavy Gauge Bosons: Z_H

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

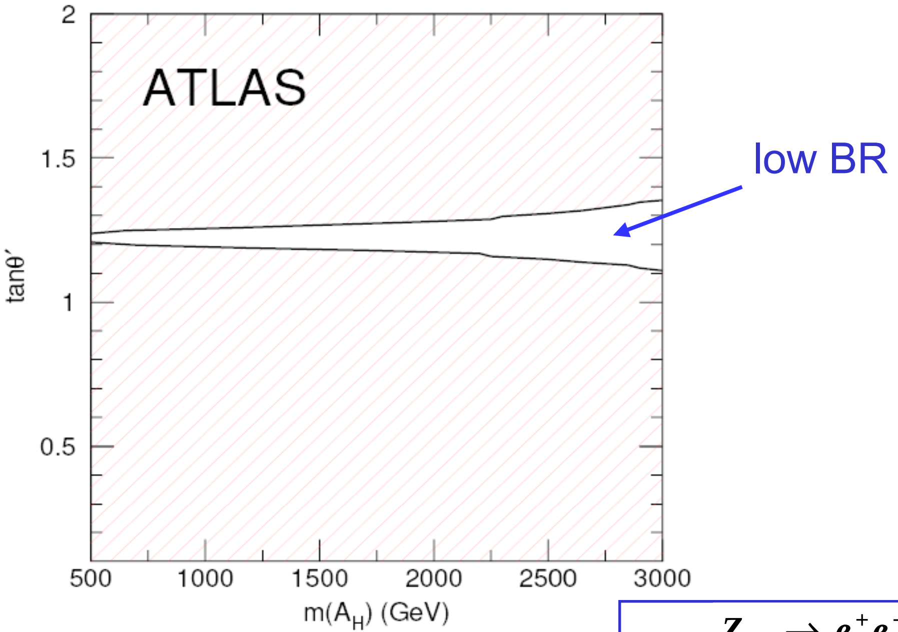
$\rightarrow$ 2 mixing angles (like θ_W): θ for Z_H
θ' for A_H



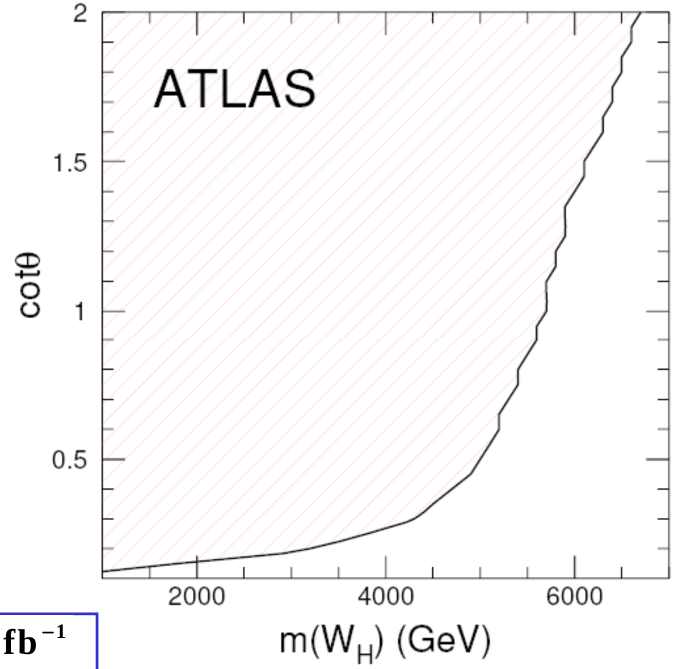


Heavy Gauge Bosons: Z_H, γ_H

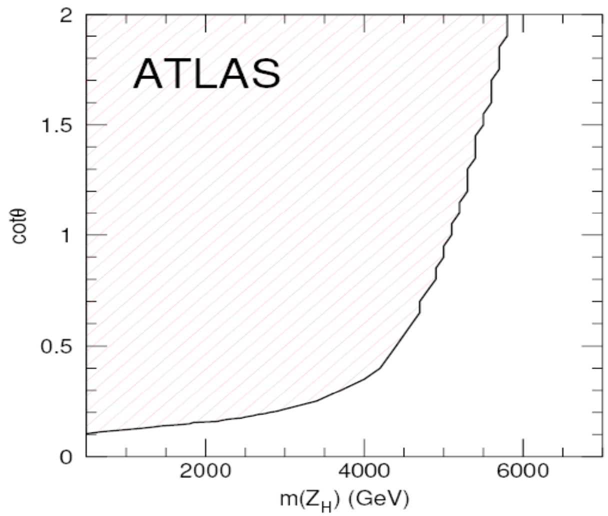
$A_H \to e^+e^-$ reach for 300 fb^{-1}



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

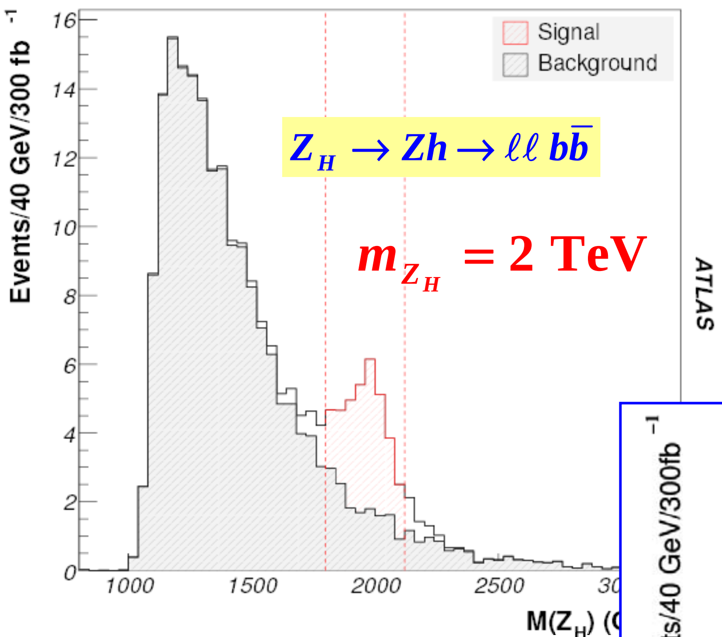


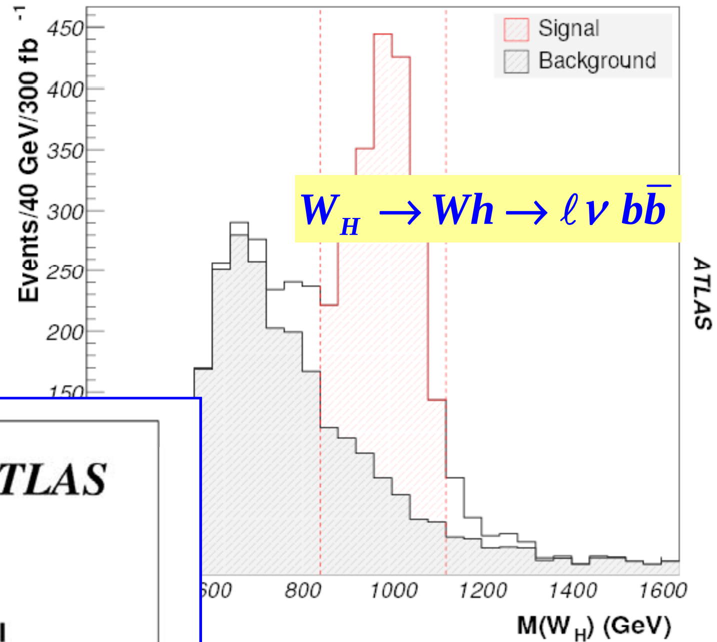
$Z_H \to e^+e^-$ reach for 300 fb^{-1}

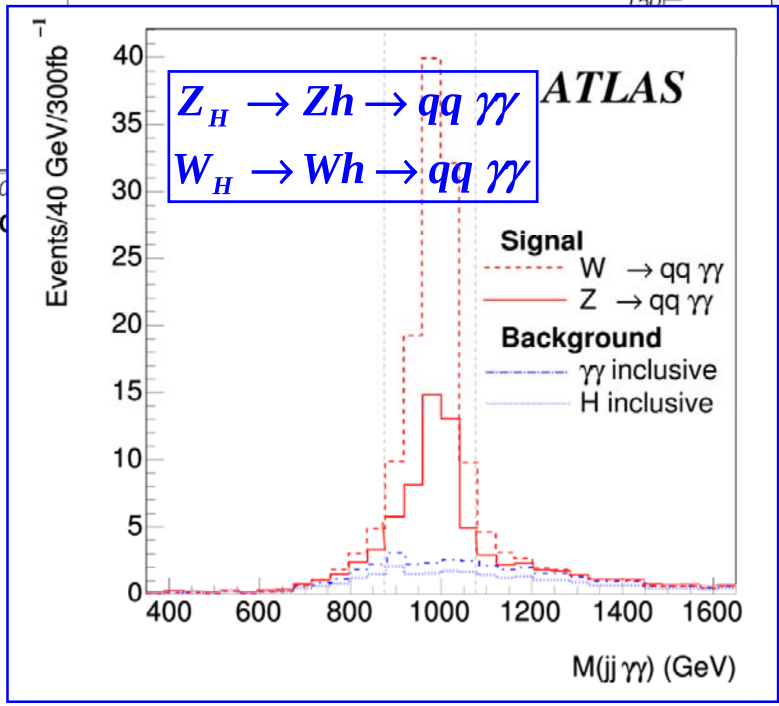


Higgs-Gauge boson couplings

Measurement of $Z_H Zh$ and $W_H Wh$ couplings needed to test model



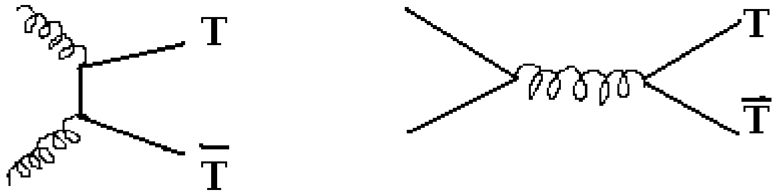




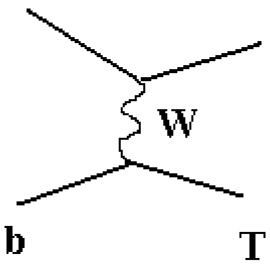
b-tagging
at high energy

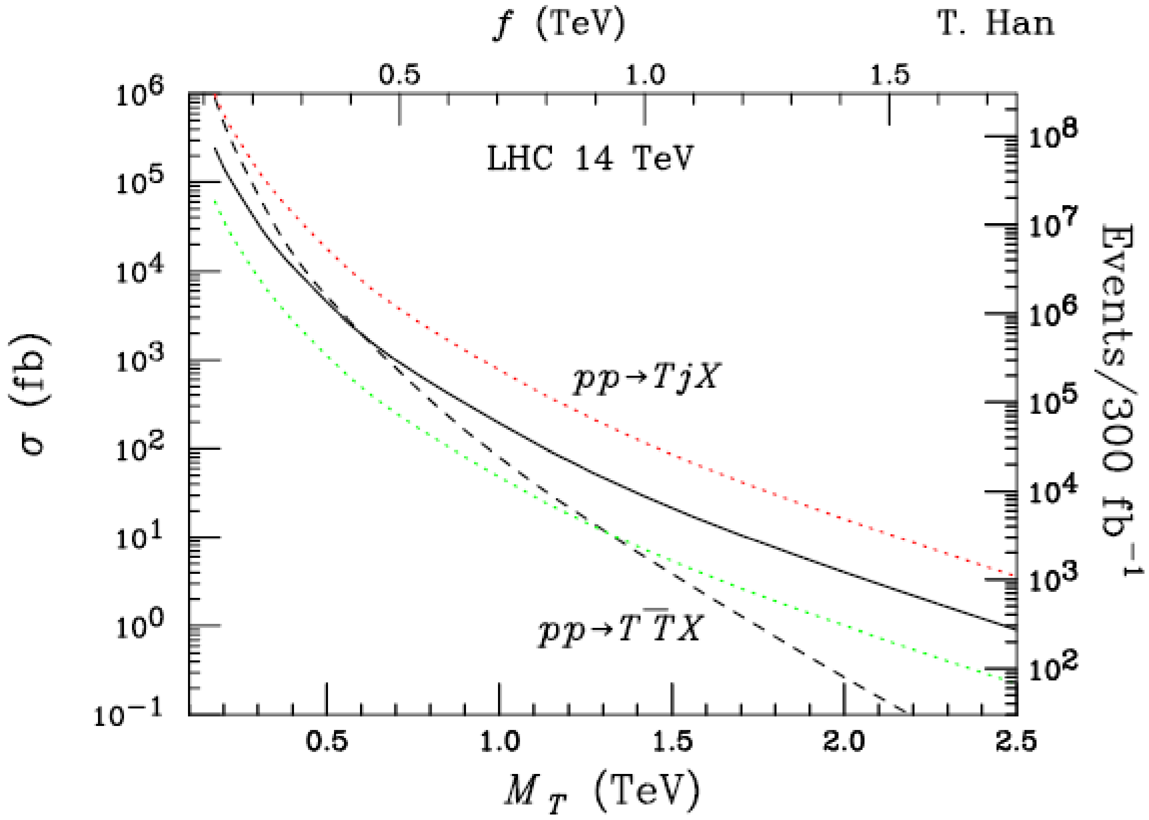
Search for the heavy T quark

Pair production →



Single production:





Search for the heavy T quark

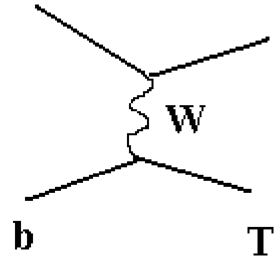
Couplings: $\lambda_1 (iQht_r + fT_L t_r hh^{\dagger}) + \lambda_2 f (T_L T_R)$

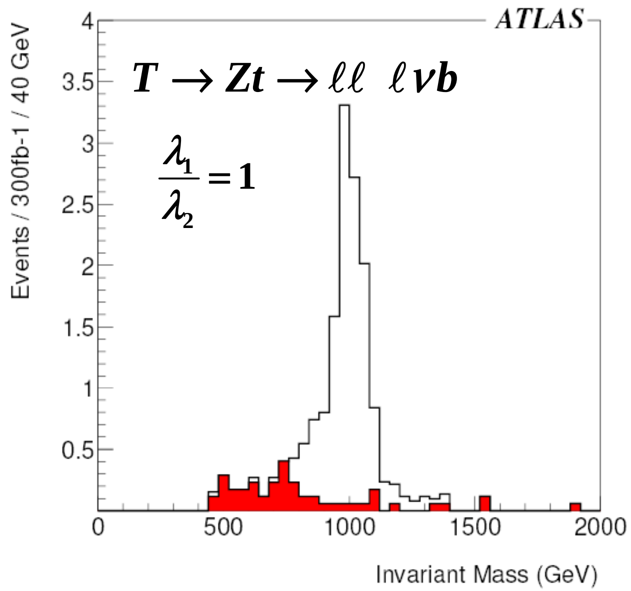
$\rightarrow$ **3 parameters: m_t, m_T, and λ_1/λ_2**

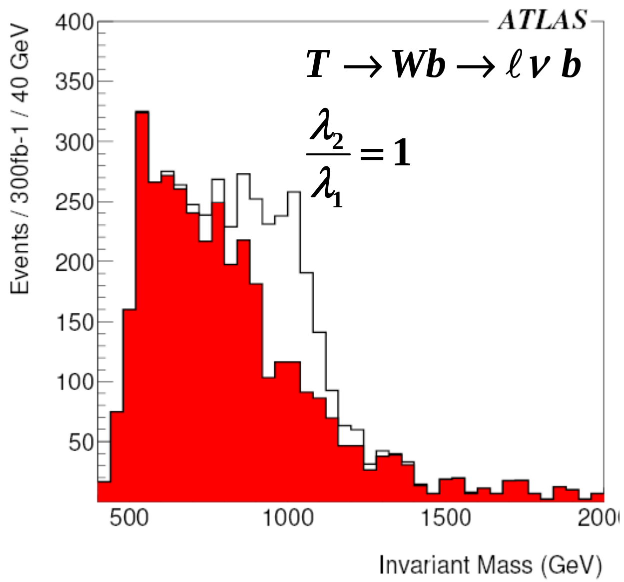
Widths: $$\Gamma(T \rightarrow t\,h) = \Gamma(T \rightarrow tZ) = \frac{1}{2}\Gamma(T \rightarrow bW) = \frac{\kappa^2}{32\pi} M_T$$

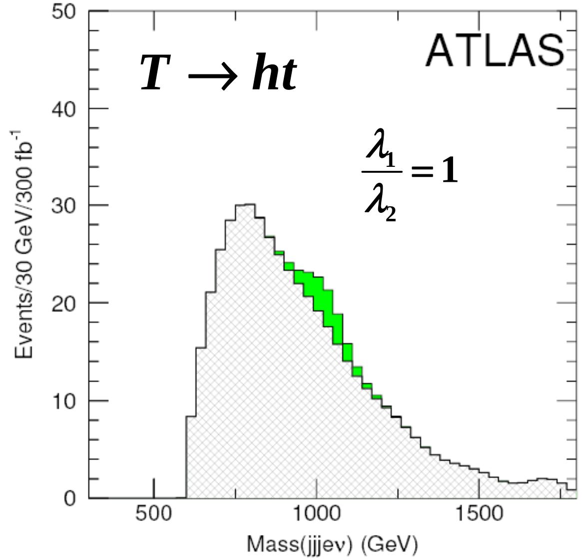
$$\kappa = \frac{\lambda_1^2}{\sqrt{\lambda_1^2 + \lambda_2^2}}$$

Single production:









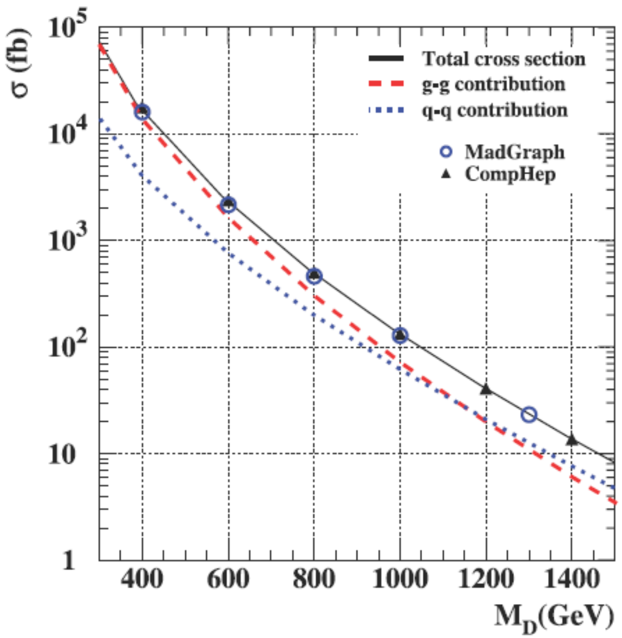
SN-ATLAS-2004-038

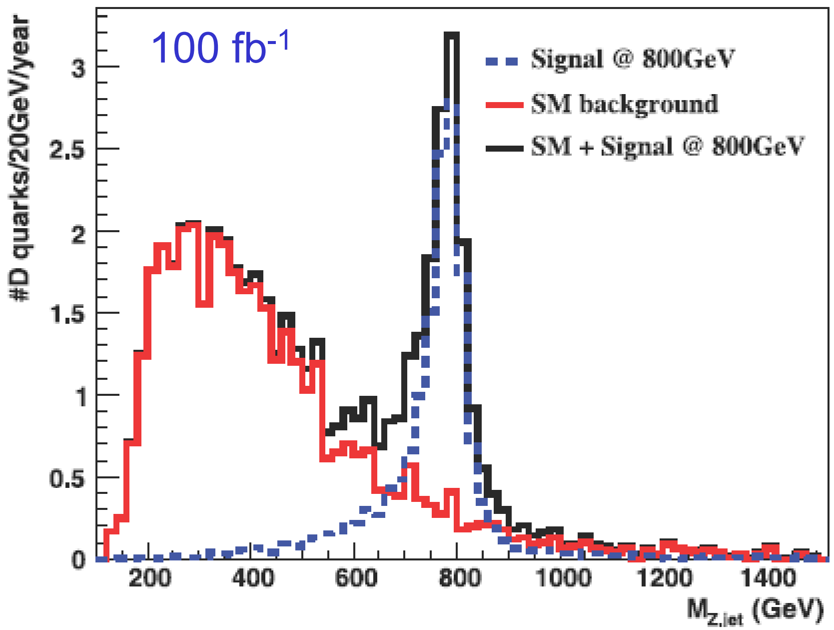
detail

E_6 isosoinglet quarks

- **quark sector in E_6 :** $\left[\begin{pmatrix} u \\ d \end{pmatrix}_L, u_R, d_R, D_L, D_R\right] \times 3$ families
  - present limit: m_D > 199 GeV (PDG)
  - 3 x 4 CKM matrix → constraint D-u mixing : $\sin\varphi < 0.07$
  - decays: $D \to W\,u\ (50\%);\quad D \to Z\,d\ (25\%);\quad D \to d\,H\ (25\%)$
- **ATLAS study:** $p\,p \to D\,\bar{D} \to Z\,d\ Z\,\bar{d} \to \ell\bar{\ell}d\ \ell\bar{\ell}\bar{d}$
  - process implemented in CompHep and MADGRAPH
    - reach: 920 GeV with 300 fb^{-1}

R. Mehdiyev et al., Eur Phys J C49 (2007) 613





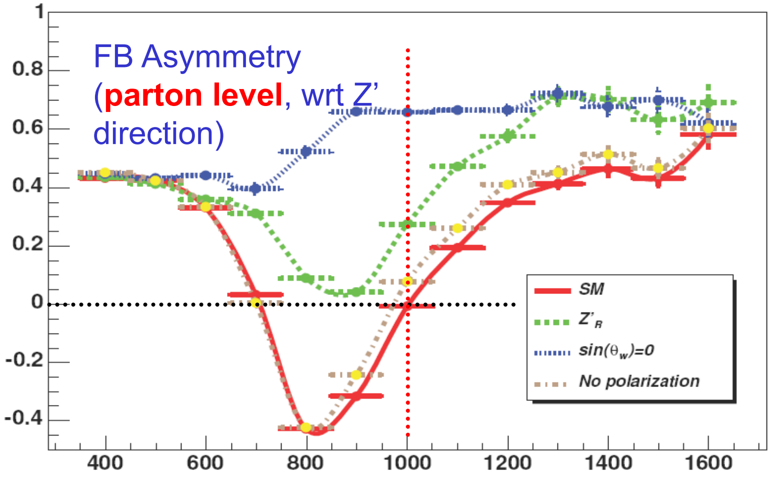
3^{rd} family

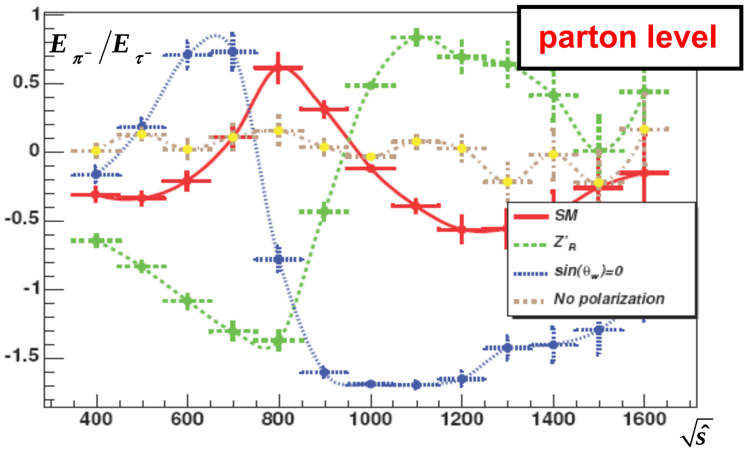
- **Possibly different couplings to the 3^{rd} family:**
  - LEP constraints weaker
  - topcolor
- **distinguish between scalar (A/H) from vector (Z')**
- **… but difficult to measure**
  - Z' → τ τ : poor resolution in mass reconstruction
    - method assumes collinear approximation:
      neutrino in same direction as τ, with the τ massless
      2 x 3-vectors for charged particles, 1 x 2-vector for missing pT
      → 8 input + 2 constraints for 4 x 3 – 2 = 10 deg. of freedom
      – works when τ's are not back to back (not too heavy Z')
    - good reconstruction at ILC, where $\sqrt{s}$ and P_{miss} is known !
  - Z' → bb : huge QCD background
  - Z' → t t : too much background from QCD production of top
    - except if resonance is from a strong interaction process
    - good for ILC, but limited by mass

further observables for 3rd generation

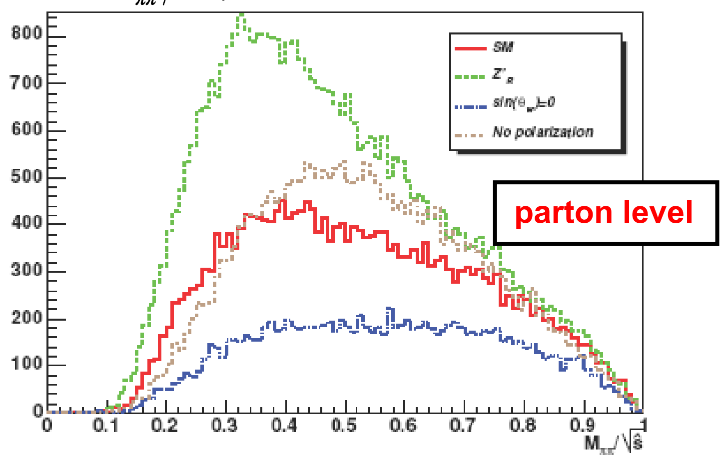
- can measure FB asymmetry wrt to Z' direction
- possibility to measure polarization or spin correlations through decay of τ or t

$Z' \to \tau\tau$, $\tau \to \pi\nu$ $\quad m(Z') = 1\ TeV$

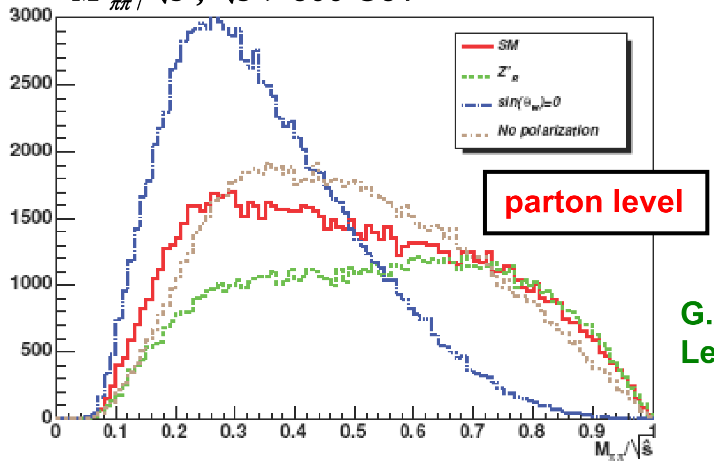




$M_{\pi\pi}/\sqrt{\hat{s}}$, $\sqrt{\hat{s}} < 800$ GeV



$M_{\pi\pi}/\sqrt{\hat{s}}$, $\sqrt{\hat{s}} > 800$ GeV

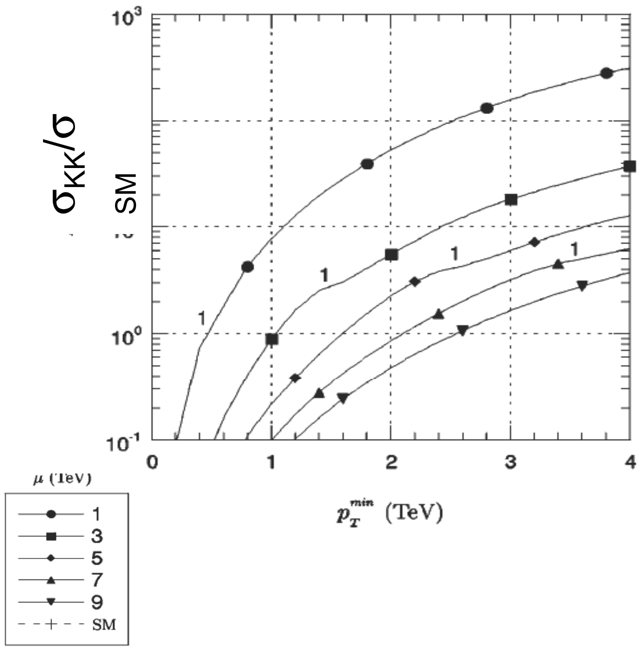


G.A. et al.,
Les Houches 2005

KK excitation of the gluon

UED scenario

D.A. Dicus, C.D. McMullen and S. Nandi, PR D65 (2002) 076007



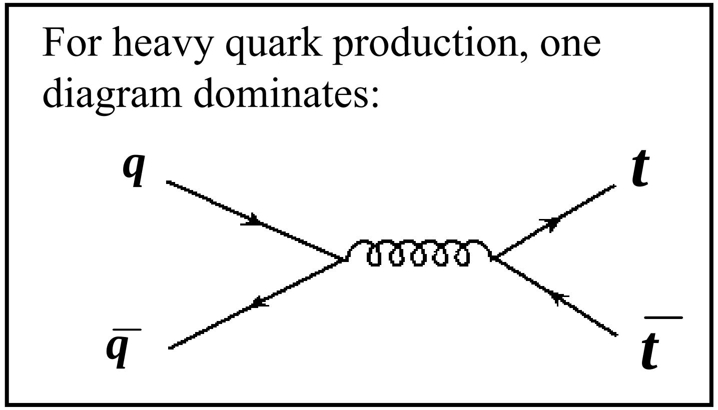
top resonance from bulk RS KK gluon

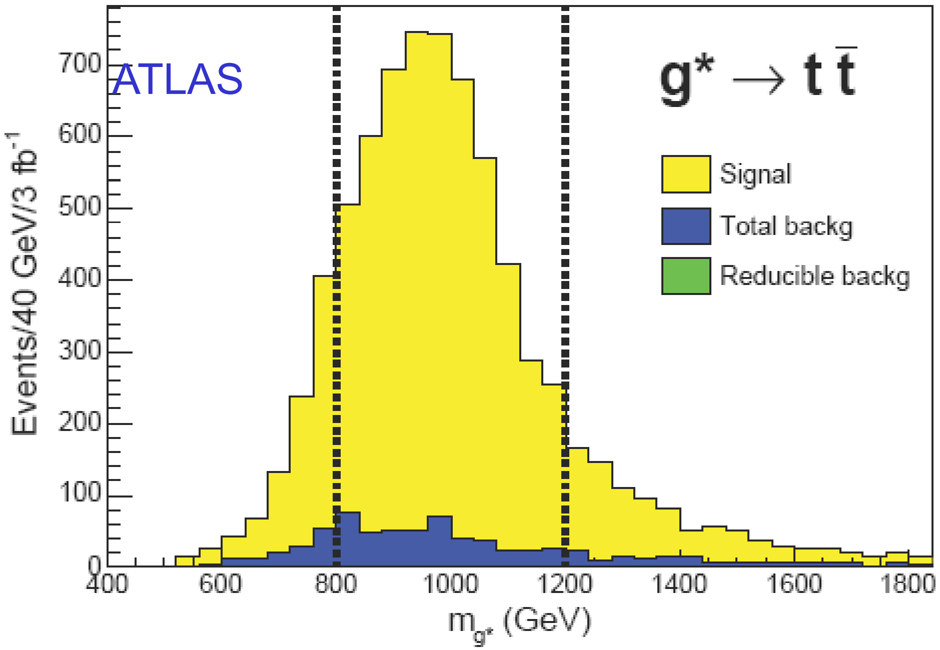
- large overlap of KK gluon and top quark wave functions because both are localized towards TeV brane

B. Lillie, L. Randall and L-T Wang, hep-ph/0701166

- can also measure spin correlations
- graviton resonance to top pairs (or WW)

Agashe et al., hep-ph/0701186





March, L; Ros, E; Salvachúa, B; **ATL-PHYS-PUB-2006-002**

Jet splitting

- **Highly boosted di-jet looks like one jet**
  → use algorithm to see if jet splits into two when narrower cone is used

jets with p_T > 250 GeV

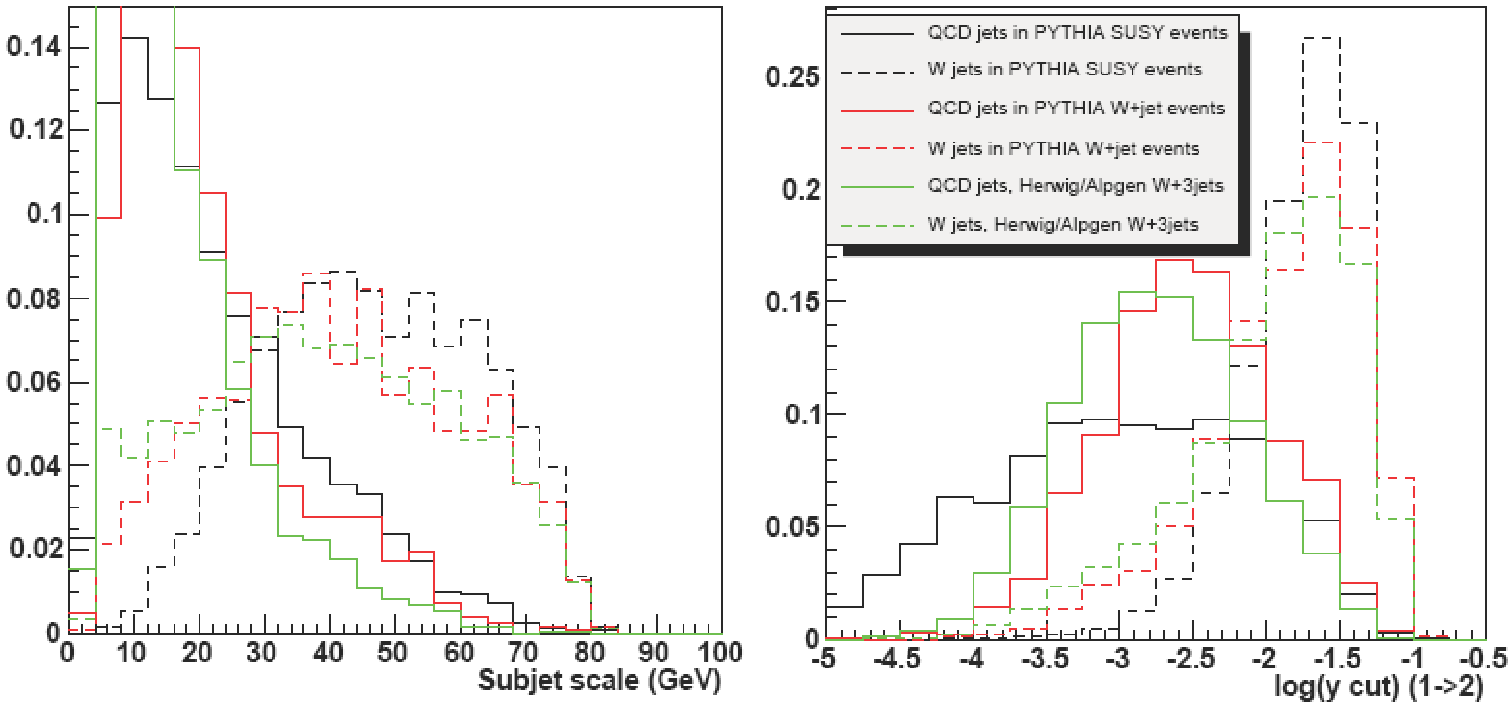
Once a jet is found, apply the inclusive kT algorithm to clusters composing it

$$d_{kl} = \min\left(p_{T_k}^2, p_{T_k}^2\right) R_{kl}^2 / R^2$$

$$y \equiv \frac{d_{kl}}{\left(p_T^{jet}\right)^2}$$

y_{cut} at which jet splits into 2 subjets

scale: $p_T^{jet}\sqrt{y} = \sqrt{d_{kl}}$

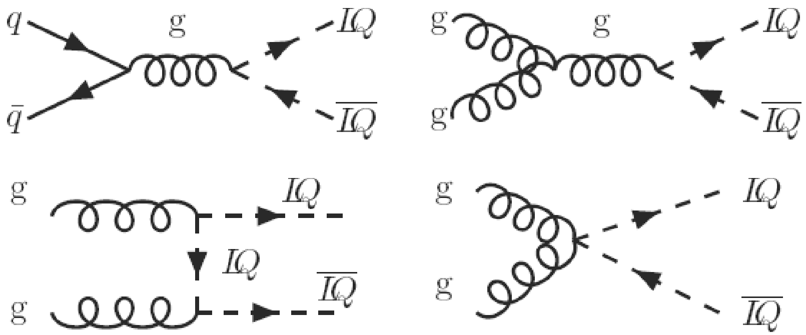


J.M. Butterworth, J.R. Ellis, A.R. Raklev, hep-ph/0702150

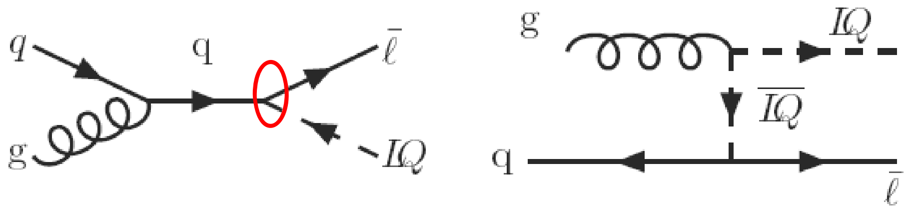
Leptoquarks

implemented in CompHep/CalcHep   A. Belyaev et al., ***J. High Energy Phys. 09 (2005) 005***

Pair production



Single production



(no single production at ILC)

Characterized by: Fermion number: 0 ($\ell^+ \boldsymbol{q}$) or 2 ($\ell^- \boldsymbol{q}$)

spin: scalar or vector (g-Φ^μ-Φ_μ coupling depends on κ_g and λ_G)

isospin: 0, ½, 1

charge: ±1/3, ±2/3, -4/3, -5/3

$$\mathcal{L}^f_{|F|=0} = (h_{2L}\bar{u}_R\ell_L + h_{2R}\bar{q}_L i\tau_2 e_R)R_2 + \tilde{h}_{2L}\bar{d}_R\ell_L\tilde{R}_2 + (h_{1L}\bar{q}_L\ell_L + h_{1R}\bar{d}_R\gamma^\mu e_R)U_{1\mu} + \\ + \tilde{h}_{1R}\bar{u}_R\gamma^\mu e_R\tilde{U}_{1\mu} + h_{3L}\bar{q}_L\vec{\tau}\gamma^\mu\ell_L\vec{U}_{3\mu} + \text{h.c.}\,,$$

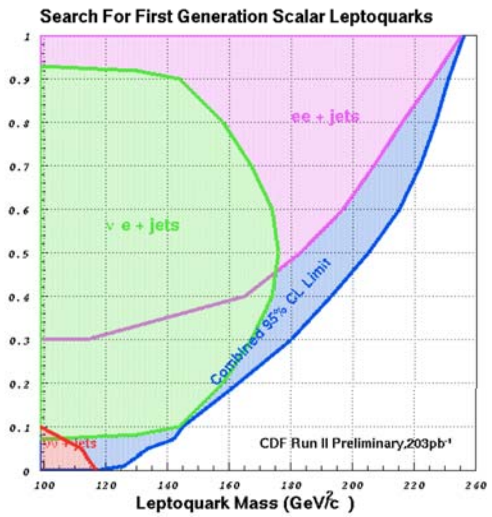
$$\mathcal{L}^f_{|F|=2} = (g_{1L}\bar{q}^c_L i\tau_2\ell_L + g_{1R}\bar{u}^c_R e_R)S_1 + \tilde{g}_{1R}\bar{d}^c_R e_R\tilde{S}_1 + g_{3L}\bar{q}^c_L i\tau_2\vec{\tau}\ell_L\vec{S}_3 + \\ + (g_{2L}\bar{d}^c_R\gamma^\mu\ell_L + g_{2R}\bar{q}^c_L\gamma^\mu e_R)V_{2\mu} + \tilde{g}_2\bar{u}^c_R\gamma^\mu\ell_L\tilde{V}_{2\mu} + \text{h.c.}\,,$$

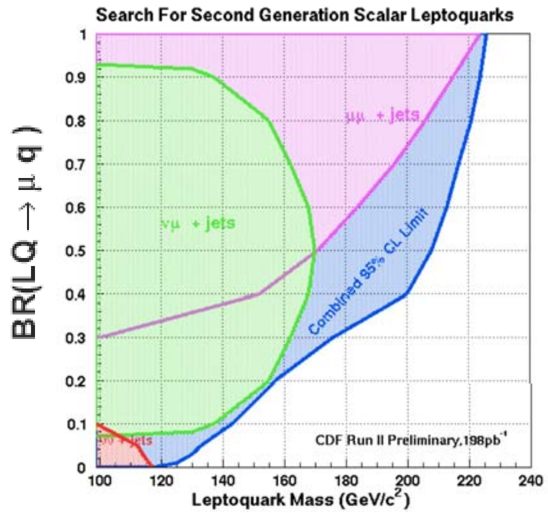
LQ limits

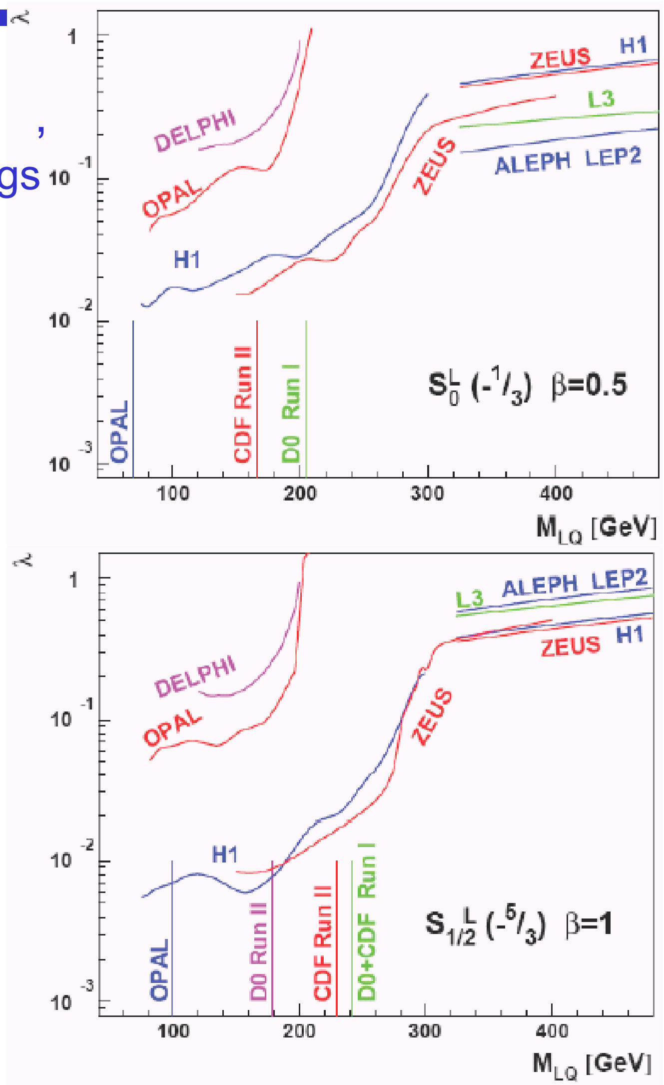
In effect, only 3 parameters: M_{LQ}, λ_L ***and*** λ_R

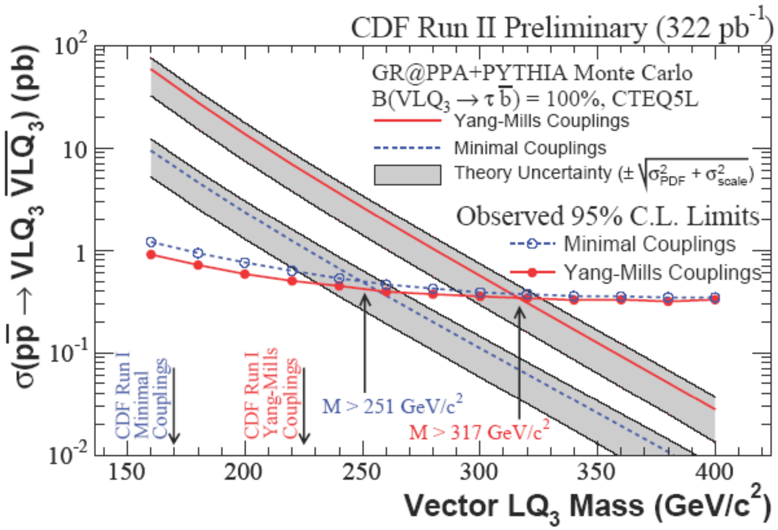
total width depends on $\lambda_{eff}^2 = \lambda_L^2(lq) + \lambda_R^2(lq) + \lambda_L^2(\nu q')$,

where λ are linear combinations of $g, h, \tilde{g}, \tilde{h}$ couplings









from CDF:

http://ncdf70.fnal.gov:8001/lq/LQ_comb/Combinations.html

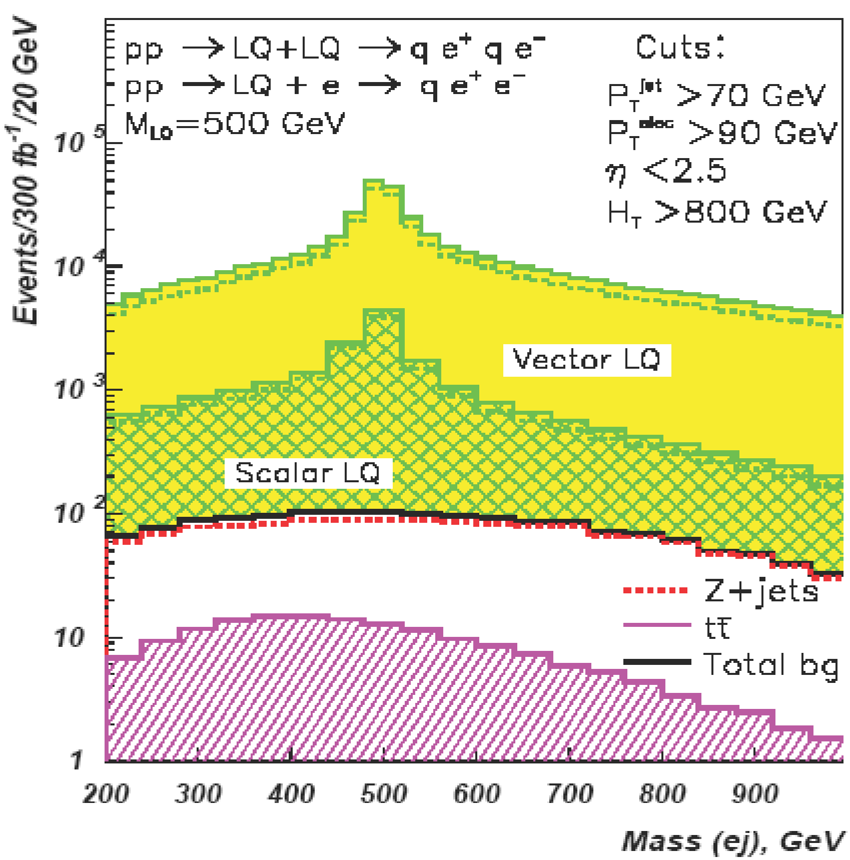
http://www-cdf.fnal.gov/physics/joint_physics/public/ichep/CDF_Physics_2006.html

similar results from D0:

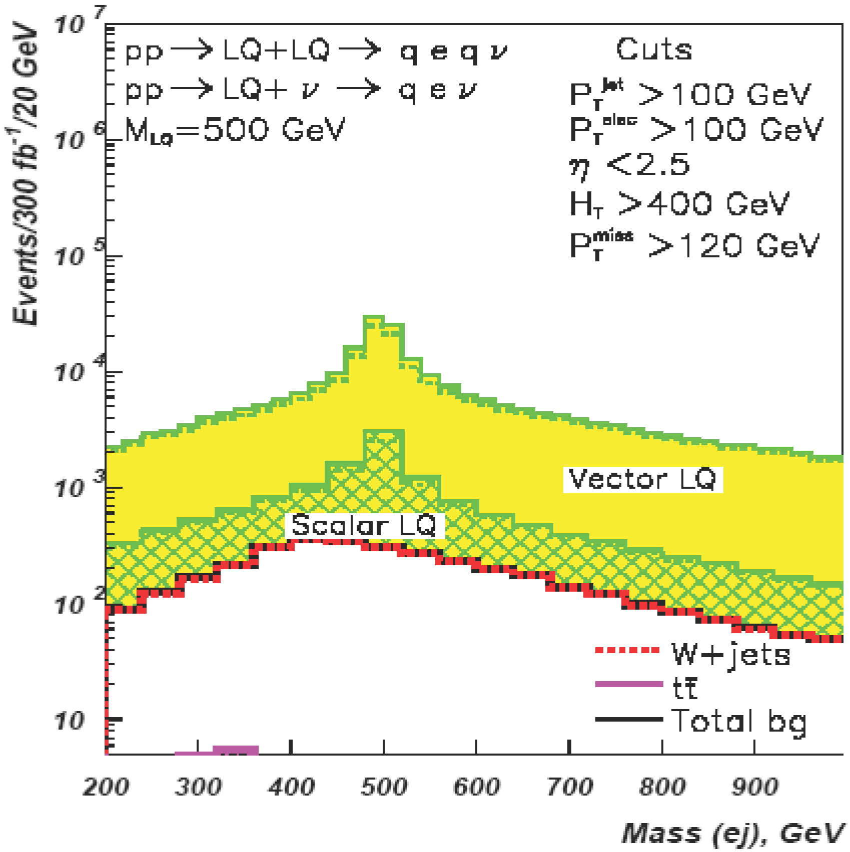
http://www-d0.fnal.gov/Run2Physics/WWW/results/np.htm

ATLAS study

"type 1": 2 leptons + jets



"type 2": 1 lepton + jets + E_T^{miss}



Combine single and pair production

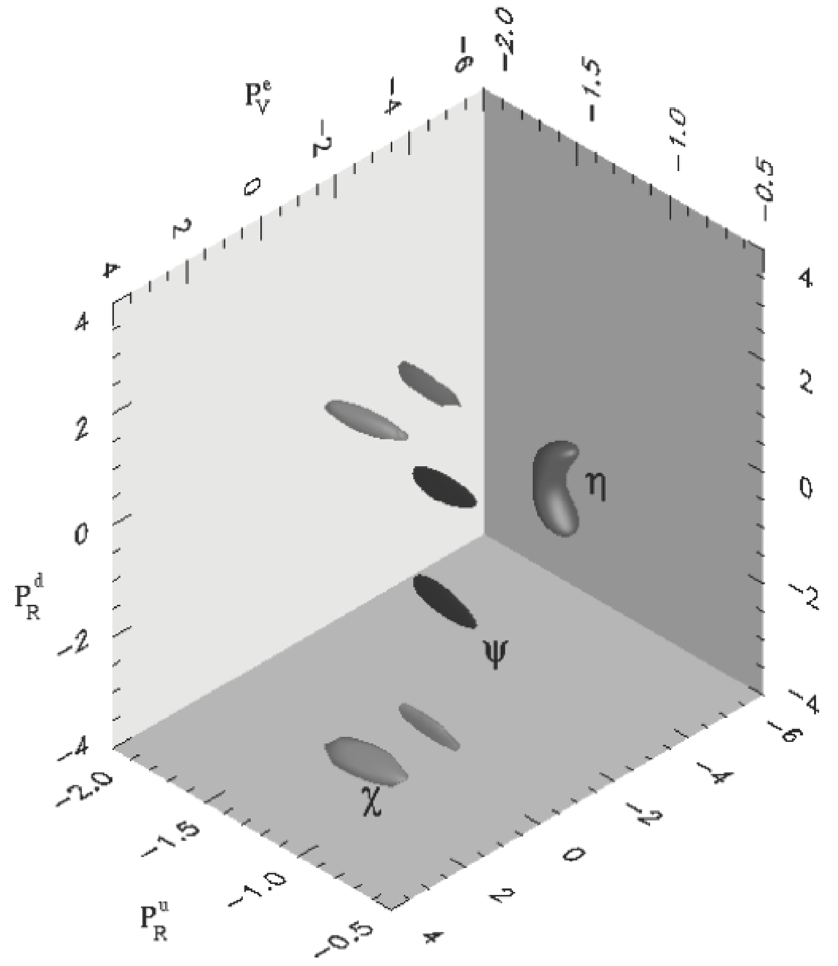
A. Belyaev et al., ***J. High Energy Phys. 09 (2005) 005***

Reach with 10 fb^{-1}: ~ 800 and 900 GeV for S (types 1 and 2 respect.)
~ 1000 and 1300 GeV for V (types 1 and 2 respect.)
assuming Λ_{eff} ~ α and minimal couplings for vector LQs

Conclusions

- **All possible types of 2-body resonances are predicted by new models**
- **In general, exotic physics probes high masses with high luminosity**
  - ➔ push for highest energy machine, or at least possibility of upgrade
- **but**
  - possibilities of weak couplings buried in background at LHC
  - higher precision attainable at ILC

Backups

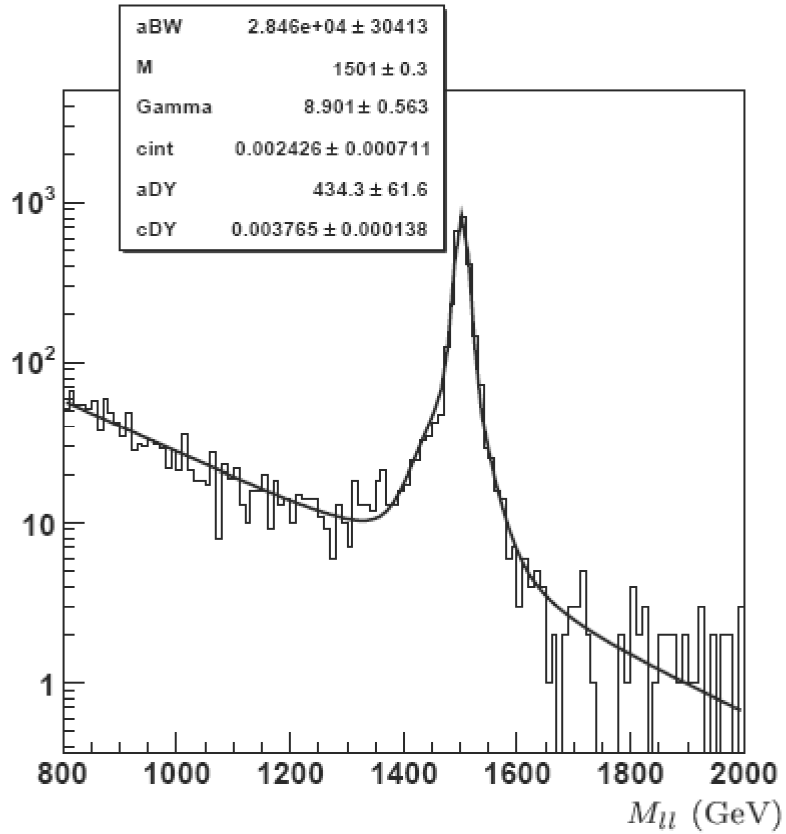


from Cvetic and Godfrey, hep-ph/9404216

Figure 6: 90% confidence level ($\Delta\chi^2 = 6.3$) regions for the χ, ψ, and η models with $M_{Z'} = 1$ TeV are plotted for P_R^u versus P_R^d versus P_V^ℓ at the LHC. The figure reflects a few-fold ambiguity in the determination of these couplings at the LHC.

excess fermions

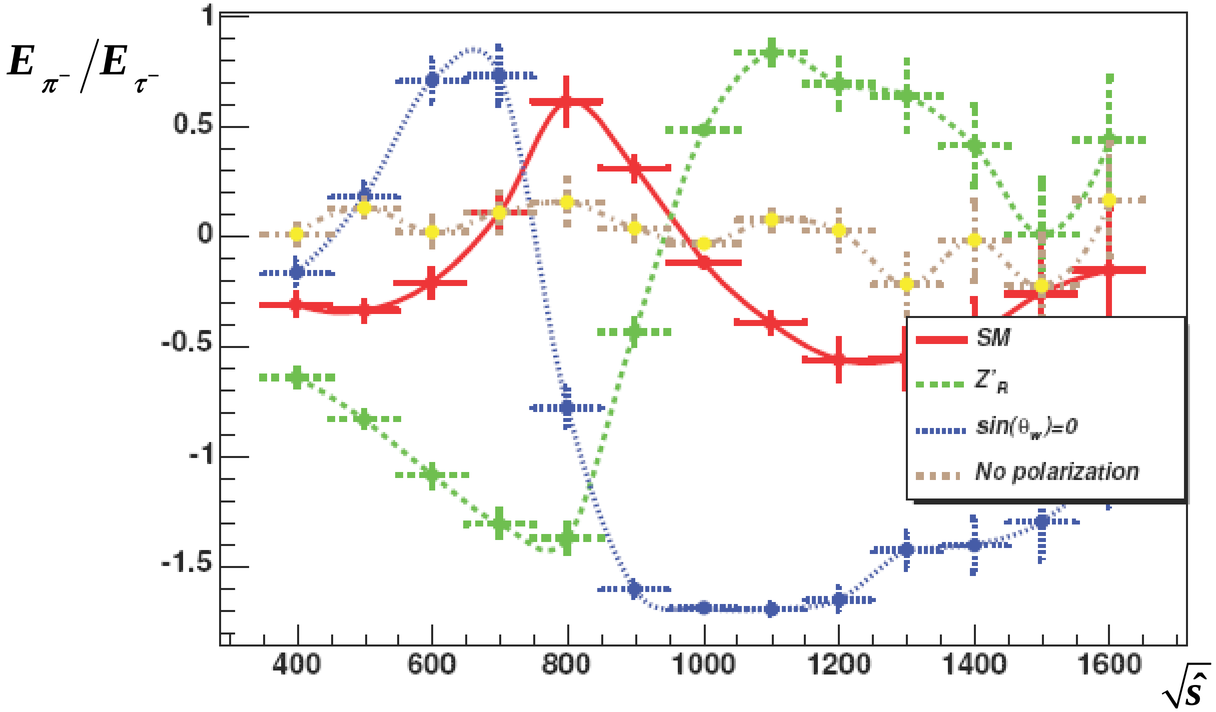
- **contact interaction**
- **virtual gravitons**
- **torsion**



Ledroit atl-phys-pub-2005-010

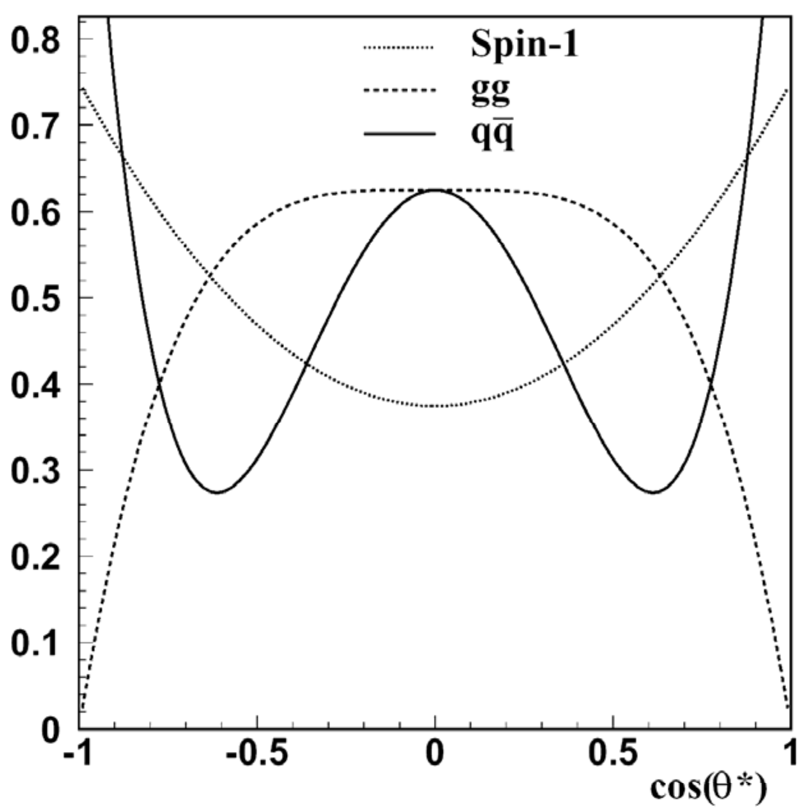
$Z' \to \tau\tau$ $\quad$ $m(Z') = 1\ TeV$

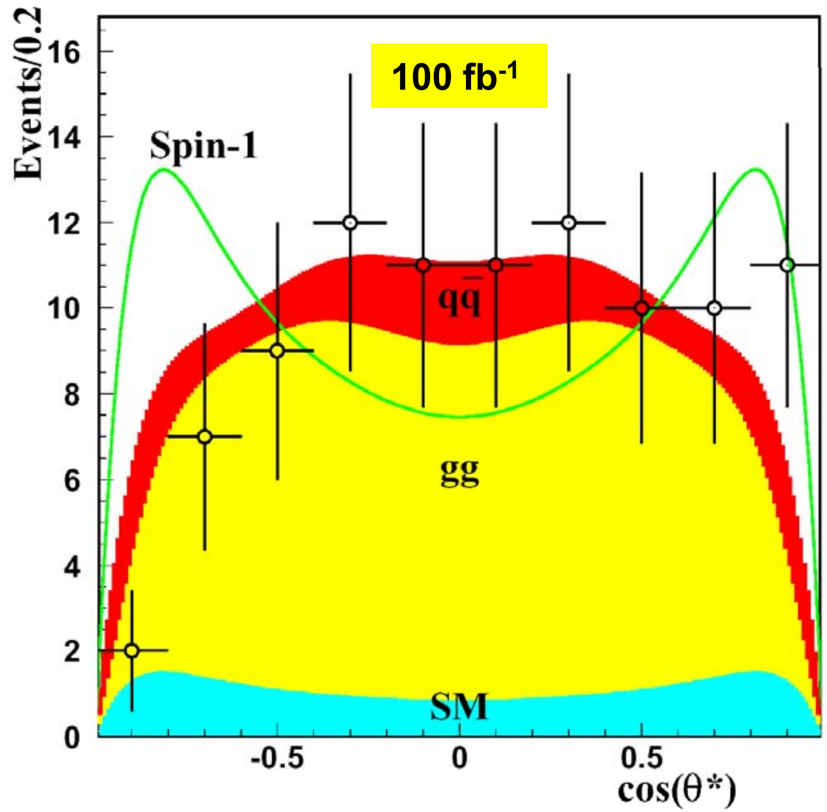
$\hookrightarrow \pi\nu$



Narrow Graviton Resonance

Spin determination

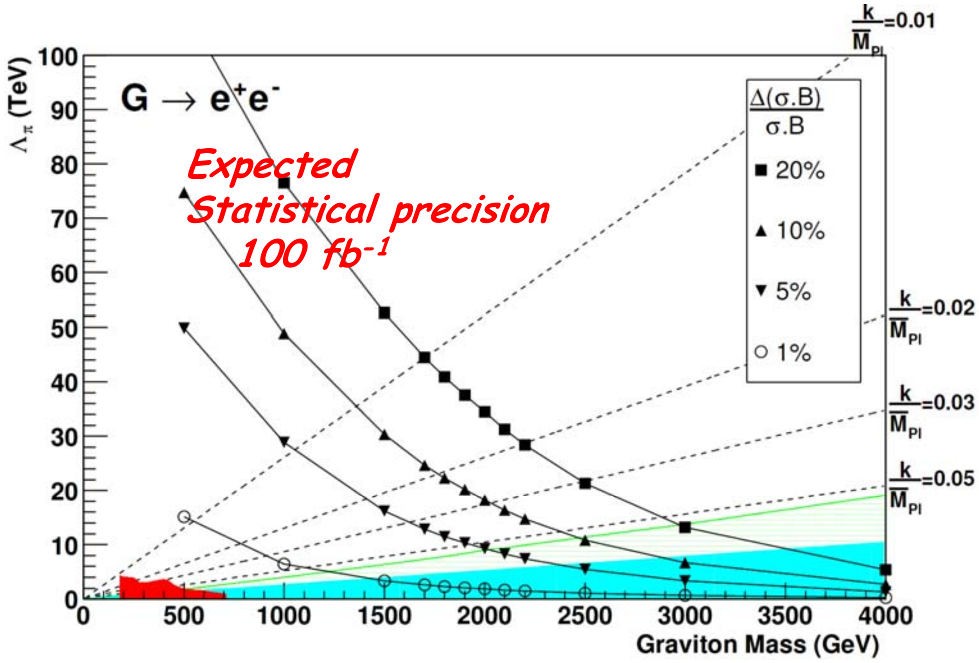




spin-2 could be determined (spin-1 ruled out) with 90% CL up to graviton mass of 1720 GeV

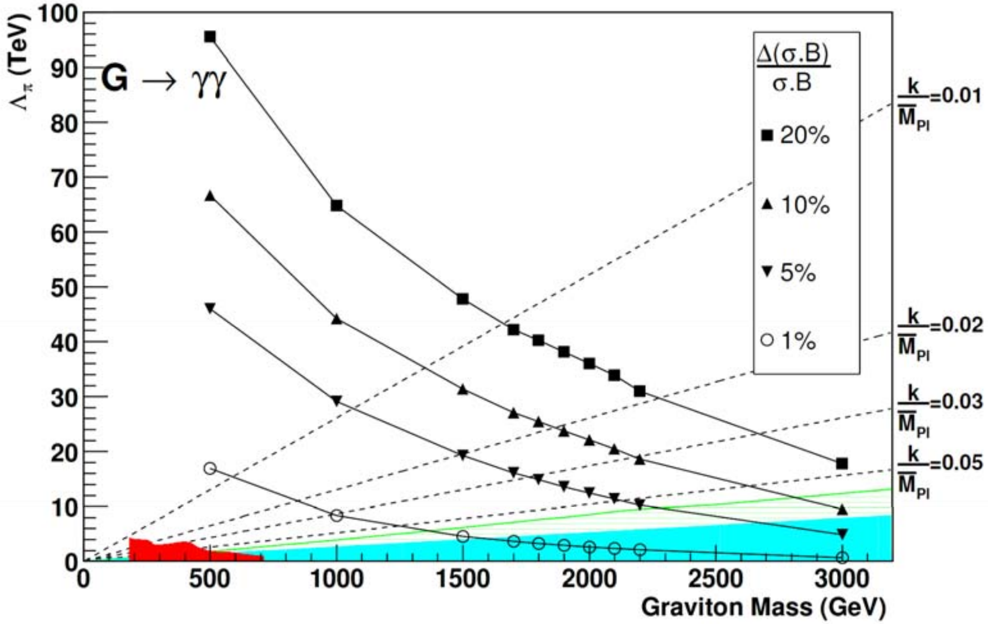
Allanach et al., ATL-PHYS-2002-031

- *also G → WW , ZZ, jj, mm, tt, hh*



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

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



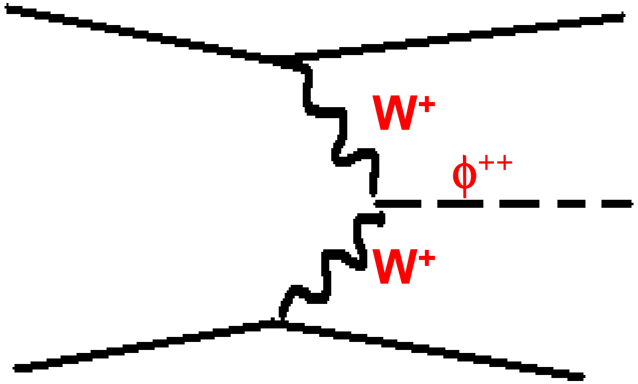
e.g.: for a resonance observed at
m_G = 1.5 TeV in ee channel
Δm_G < 10.5 GeV (energy scale error)
$\Delta\sigma.B \sim 18\%$
if $k/r_c = 0.01$ (pessimistic)
⟹ $r_c = (82\pm7) \times 10^{-33}$ m !!

LQ	F	I_3	$Q_{\rm em}$	decay	coupling	β
S_0	2	0	$-1/3$	$e_L^- u_L$ $e_R^- u_R$ $\nu_e d_L$	λ_{LS_0} λ_{RS_0} $-\lambda_{LS_0}$	$\frac{\lambda^2_{LS_0}+\lambda^2_{RS_0}}{2\lambda^2_{LS_0}+\lambda^2_{RS_0}}$
$\tilde{S}_0$	2	0	$-4/3$	$e_R^- d_R$	$\lambda_{R\tilde{S}_0}$	1
S_1	0 2	1	$2/3$	$\nu_e u_L$	$\sqrt{2}\lambda_{LS_1}$	0
		0	$-1/3$	$\nu_e d_L$ $e_L^- u_L$	$-\lambda_{LS_1}$ $-\lambda_{LS_1}$	$1/2$
		-1	$-4/3$	$e_L^- d_L$	$-\sqrt{2}\lambda_{LS_1}$	1
$S_{1/2}$	0	$1/2$	$-2/3$	$\nu_e \overline{u}_L$ $e_R^- \overline{d}_R$	$\lambda_{LS_{1/2}}$ $-\lambda_{RS_{1/2}}$	$\frac{\lambda^2_{RS_{1/2}}}{\lambda^2_{LS_{1/2}}+\lambda^2_{RS_{1/2}}}$
		$-1/2$	$-5/3$	$e_L^- \overline{u}_L$ $e_R^- \overline{u}_R$	$\lambda_{LS_{1/2}}$ $\lambda_{RS_{1/2}}$	1
$\tilde{S}_{1/2}$	0	$1/2$	$1/3$	$\nu_e \overline{d}_L$	$\lambda_{L\tilde{S}_{1/2}}$	0
		$-1/2$	$-2/3$	$e_L^- \overline{d}_L$	$\lambda_{L\tilde{S}_{1/2}}$	1

LQ	F	I_3	$Q_{\rm em}$	decay	coupling	β
V_0	0	0	$-2/3$	$e_L^- \overline{d}_R$ $e_R^- \overline{d}_L$ $\nu_e \overline{u}_R$	λ_{LV_0} λ_{RV_0} λ_{LV_0}	$\frac{\lambda^2_{LV_0}+\lambda^2_{RV_0}}{2\lambda^2_{LV_0}+\lambda^2_{RV_0}}$
$\tilde{V}_0$	0	0	$-5/3$	$e_R^- \overline{u}_L$	$\lambda_{R\tilde{V}_0}$	1
V_1	0	1	$1/3$	$\nu_e \overline{d}_R$	$\sqrt{2}\lambda_{LV_1}$	0
		0	$-2/3$	$\nu_e \overline{u}_R$ $e_L^- \overline{d}_R$	λ_{LV_1} $-\lambda_{LV_1}$	$1/2$
		-1	$-5/3$	$e_L^- \overline{u}_R$	$\sqrt{2}\lambda_{LV_1}$	1
$V_{1/2}$	2	$1/2$	$-1/3$	$\nu_e d_R$ $e_R^- u_L$	$\lambda_{LV_{1/2}}$ $\lambda_{RV_{1/2}}$	$\frac{\lambda^2_{RV_{1/2}}}{\lambda^2_{LV_{1/2}}+\lambda^2_{RV_{1/2}}}$
		$-1/2$	$-4/3$	$e_L^- d_R$ $e_R^- d_L$	$\lambda_{LV_{1/2}}$ $\lambda_{RV_{1/2}}$	1
$\tilde{V}_{1/2}$	2	$1/2$	$2/3$	$\nu_e u_R$	$\lambda_{L\tilde{V}_{1/2}}$	0
		$-1/2$	$-1/3$	$e_L^- u_R$	$\lambda_{L\tilde{V}_{1/2}}$	1

from LQ - OPAL

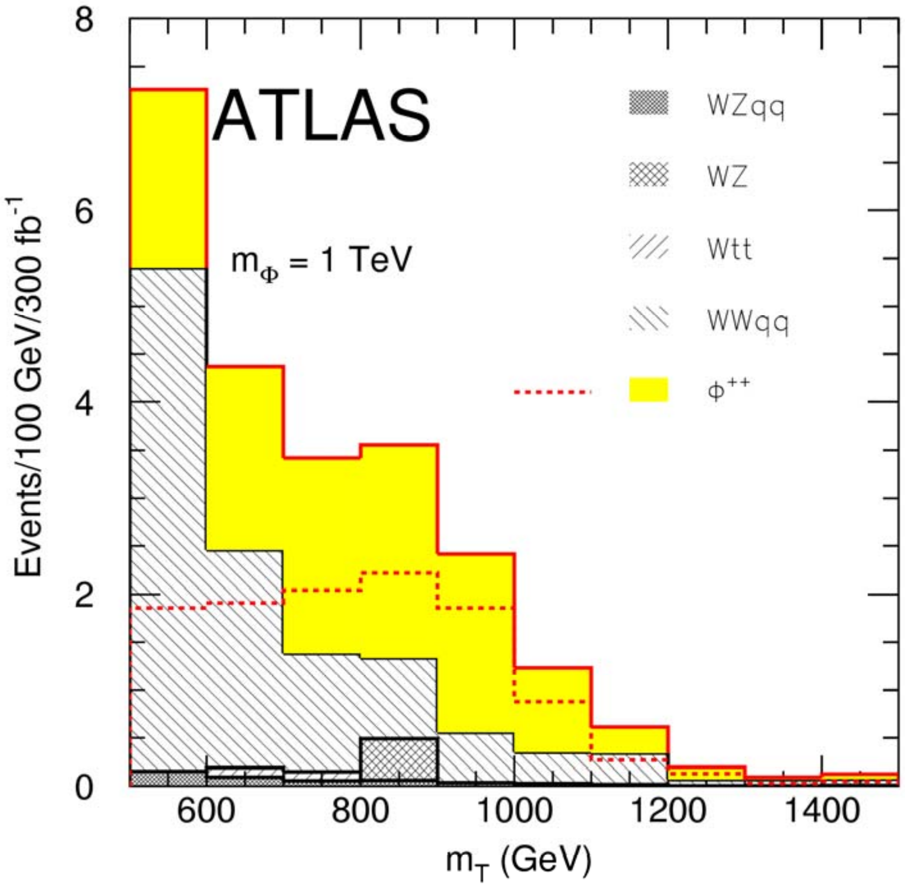
Triplet Higgs



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

$$\hookrightarrow W^+W^+ \rightarrow \ell^+\nu\,\ell^+\nu$$

Single production



Main background from W_TW_T scattering

Right-handed interactions?

Z' : first sign of extended gauge group ?

- **Left-Right Symmetric Model:** triplet Higgs

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

$SU(2)_L$	$SU(2)_R$	$U(1)_{B-L}$	$SU(2)_L$	$U(1)_Y$
$\downarrow$	$\downarrow$	$\downarrow$	$\downarrow$	$\downarrow$
W_L^i	W_R^i	C	W_L^i	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)**

$$E_6 \to SO(10) + U(1)_\psi$$
$$\hookrightarrow SU(5) + U(1)_\chi$$

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

	χ-Model		η-Model		ψ-Model	
	g_V	g_A	g_V	g_A	g_V	g_A
$Z'\bar{e}e$	$-\frac{g\tan\theta_W}{\sqrt{6}}$	$-\frac{g\tan\theta_W}{2\sqrt{6}}$	$-\frac{g\tan\theta_W}{4}$	$-\frac{g\tan\theta_W}{12}$	0	$\frac{-g\tan\theta_W\sqrt{10}}{12}$
$Z'\bar{\nu}_e\nu_e$	$-\frac{3g\tan\theta_W}{4\sqrt{6}}$	$-\frac{3g\tan\theta_W}{4\sqrt{6}}$	$-\frac{g\tan\theta_W}{12}$	$\frac{-g\tan\theta_W}{12}$	$-\frac{g\tan\theta_W\sqrt{10}}{24}$	$-\frac{g\tan\theta_W\sqrt{10}}{24}$
$Z'\bar{u}u$	0	$\frac{g\tan\theta_W}{2\sqrt{6}}$	0	$\frac{g\tan\theta_W}{3}$	0	$-\frac{g\tan\theta_W\sqrt{10}}{12}$
$Z'\bar{d}d$	$\frac{g\tan\theta_W}{\sqrt{6}}$	$-\frac{g\tan\theta_W}{2\sqrt{6}}$	$\frac{g\tan\theta_W}{4}$	$\frac{g\tan\theta_W}{12}$	0	$-\frac{g\tan\theta_W\sqrt{10}}{12}$

TABLE III: Couplings between Z' and fermions in ψ, η and χ models where θ_W is the Weinberg angle.

from Almeida et al., arXiv:hep-ph/0702137v1

The littlest Higgs Model - particles

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

X	Y	$\to$ eaten $\Rightarrow$ 4 heavy bosons: $Z_H, \gamma_H, W_H^{\pm}$	
1_0	3_0		
h	$h^{\dagger}$	$\to$ complex higgs doublet, massless	
$2_{1/2}$	$2_{-1/2}$		
ϕ	$\phi^{\dagger}$	$\to$ complex triplet	
3_1	3_{-1}		

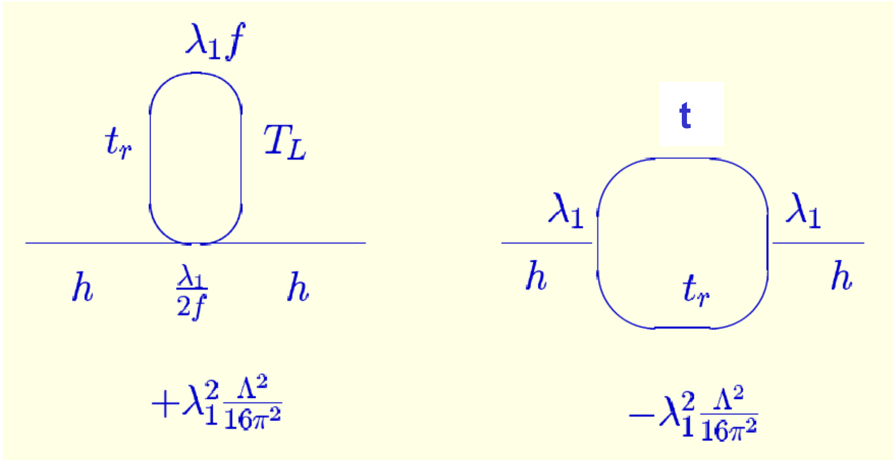
$Q = \tau_3 + \frac{Y}{2}$

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

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

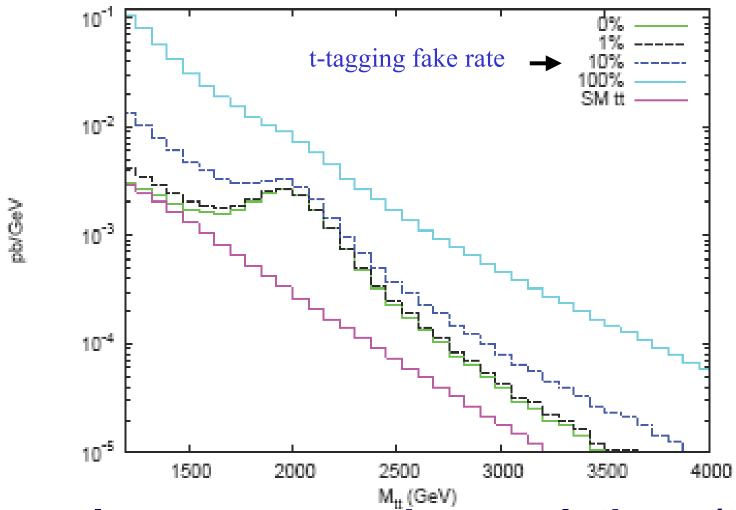


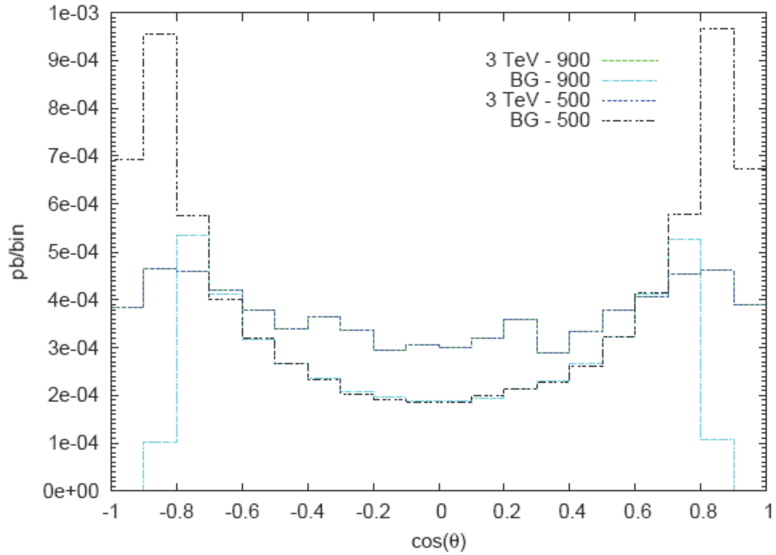
$$\lambda_1(iQht_r + fT_L t_r hh^{\dagger}) + \lambda_2 f (T_L T_R)$$

top resonance from bulk RS KK gluon

B. Lillie, L. Randall and L-T Wang, hep-ph/0701166

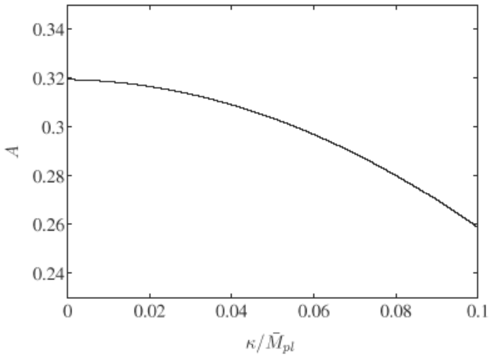
- **large overlap of KK gluon and top quark wave functions because both are localized towards TeV brane**





- **can also measure spin correlations (t_R coupling?)**
- **experimental issues:**
  - **b-tagging**
  - **strong collimation of jets from top and from W's**
    - **jet mass can be used, as in:**

      W. Skiba, D. Tucker-Smith hep-ph/0701247



spin asymmetry vs k/M_{Pl} (in classical RS model),
M. Arai et al., hep-ph/0701157

- **can also have graviton resonance to top pairs (or WW), but higher mass** (Agashe et al., hep-ph/0701186)