# $Z'$ Phenomenology at LHC (hep-ph/0610104)

- Model Sampler ( ~$10^3$'s on the market.... ) → Common in many models
- Existing Constraints ( indirect + direct ... )
- Goals for LHC :
  - Exclude a $Z'$ up to some mass (boring)
  - Discover a $Z'$ → work is just beginning !!

⟹ { Is it REALLY a $Z'$? Which one ? Something new ? Larger framework ? .....

→ Measure everything ( $M$, $\Gamma$, $\sigma_{pk}$, couplings, $Z$-$Z'$ mixing ($\phi$), ... )

- very ambitious goals for LHC ... what are the "tools"?

¿ Are they enough ?? ( I don't think so.... )

⇒ more work needed...



T.G. Rizzo

# $Z'$ Model Sampler

- $E_6 \to SO(10) \times U(1)_\psi \to SU(5) \times U(1)_\chi \times U(1)_\psi \to SM \times U(1)_\theta$ ← $Z'$ { "string-inspired" models from the 80's

  $c_\theta U(1)_\psi - s_\theta U(1)_\chi$

  ( $\theta$ is a free parameter... )

  special cases { $\psi$ ($\theta = 0$), $\chi$ ($\theta = -90°$), $\eta$ ($\theta \simeq 37.76°$), $I$ ($\theta \simeq -52.24°$) }

- Left-Right Model (LRM) : $E_6 / SO(10) \to SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ ↑ $Z' + W'$ !

  ($\kappa \equiv g_R / g_L$) is $\simeq$ a free parameter

- Little-Higgs models (LH) : new global symmetries protect Higgs mass from 1-loop quadratic divergence ; ( $\cot \theta_H$ is a free parameter )

- 'Sequential' SM (SSM) ! $Z'$ just a heavy copy of $Z_{SM}$ ... not a real model ... 'Standard' candle..

.... there are Hundreds more !!

( → enough for us ! )

# Indirect Constraints $(Q^2 \ll M_{Z'}^2)$

$\Rightarrow$ Many !! $\begin{cases} \text{Low Energy}^* \\ \text{High Energy} \Rightarrow \text{LEP II} \end{cases}$

* e.g., **E-158**: Very high precision polarized Møller scattering

$$A_{LR} \sim -\frac{1}{2} + 2\sin^2\theta_{eff}, \qquad \sin^2\theta_{eff} = \sin^2\theta_{SM} - \frac{1}{\sqrt{2}G_F}\underbrace{\frac{g_{Z'}^2}{M_{Z'}^2} v_e' a_e'}$$

Calculable for your favorite model

$\rightarrow M_{Z'_\chi} > 960\,\text{GeV}$ (@ 90% CL) !!
$(\phi = 0)$

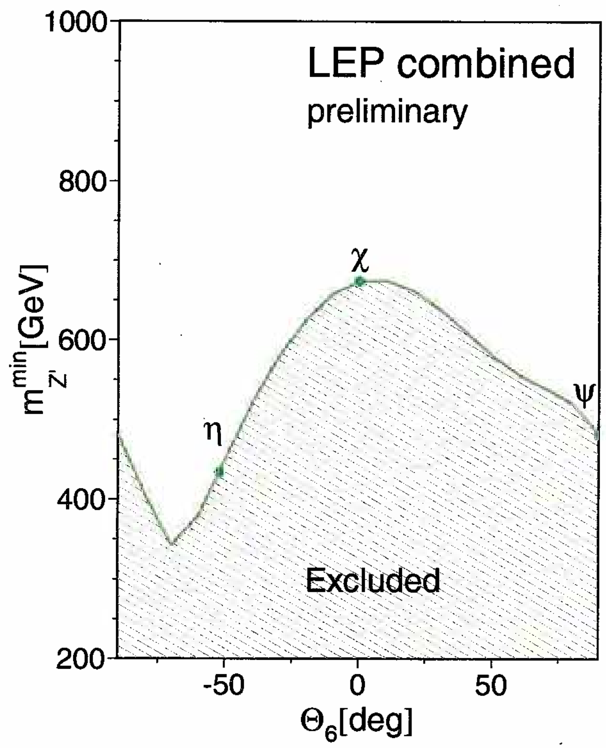
· Atomic Parity Violation : "weak-charge" of nucleus, $Q_W$

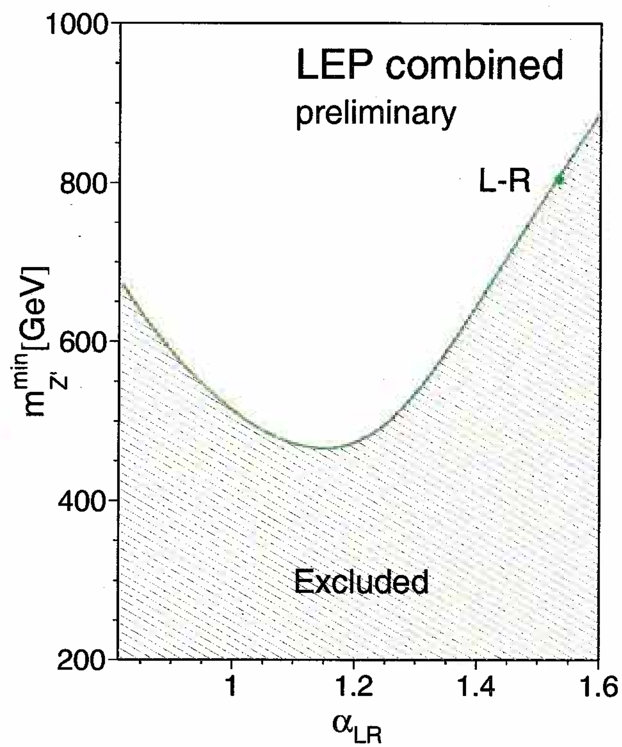
$$\Delta Q_W [Cs^{133}] \rightarrow M_{Z'_{LRM,\,k=1}} > 0.67\,\text{TeV} \;(95\%\,\text{CL}) \quad [\phi = 0]$$

$\Rightarrow$ Low Energy but High precision exp's have ~ TeV scale sensitivity!

LEP II $\Rightarrow$ look for deviations from SM predictions in $d\sigma/d\cos\theta$ from heavy states, e.g., $Z'$.. $(m_{Z'} \approx \text{few} \sqrt{s})$

LEPEWWG




κ = 1

Figure 10: The 95% confidence level limits on $M_{Z'}$ as a function of the model parameter $\theta_6$ for $E_6$ models and $\alpha_{LR}$ for left-right models. The Z-Z′ mixing is fixed, $\Theta_{ZZ'} = 0$.

| Z′ model | $\chi$ | $\psi$ | $\eta$ | L-R | SSM |
|---|---|---|---|---|---|
| $M_{Z'}^{limit}$ (GeV/$c^2$) | 673 | 481 | 434 | 804 | 1787 |

Table 15: The 95% confidence level lower limits on the Z′ mass for $\chi$, $\psi$, $\eta$, L-R and SSM models.

Constraints on $\Delta\left(\frac{d\sigma}{d\cos\theta}\right)(\ell, c, b)$ → bound on Z′

→ Model dependent!

# Direct Tevatron Searches

- $p\overset{(-)}{p} \rightarrow \ell^+\ell^- + X$ (Drell-Yan process), $Z'$ appears as a peak just like $Z_{SM}$ ... but heavier!

- given understanding of backgrounds → constrain $\sigma_{Z'} \cdot B(Z' \rightarrow \ell^+\ell^-)$* as a function of $M_{Z'}$, then compare w/ theory calculations.

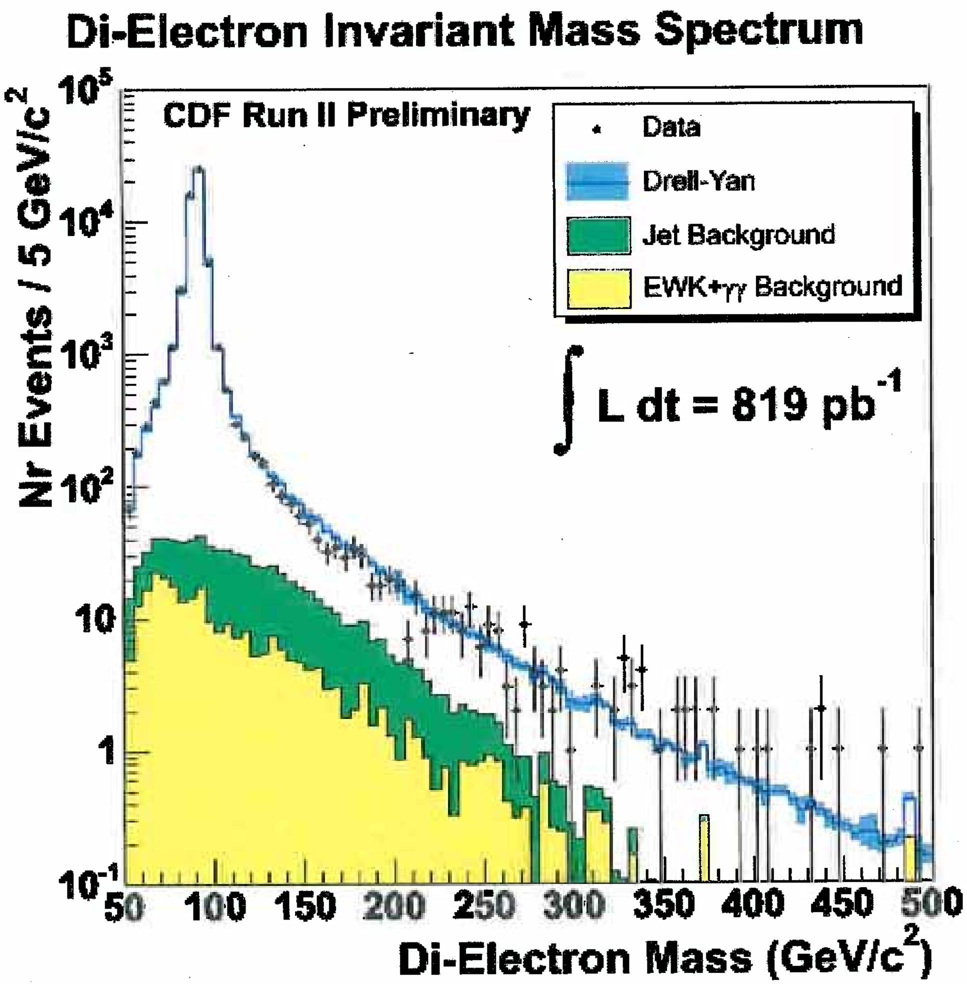
- usually first done for $Z_{SM}$ → other models

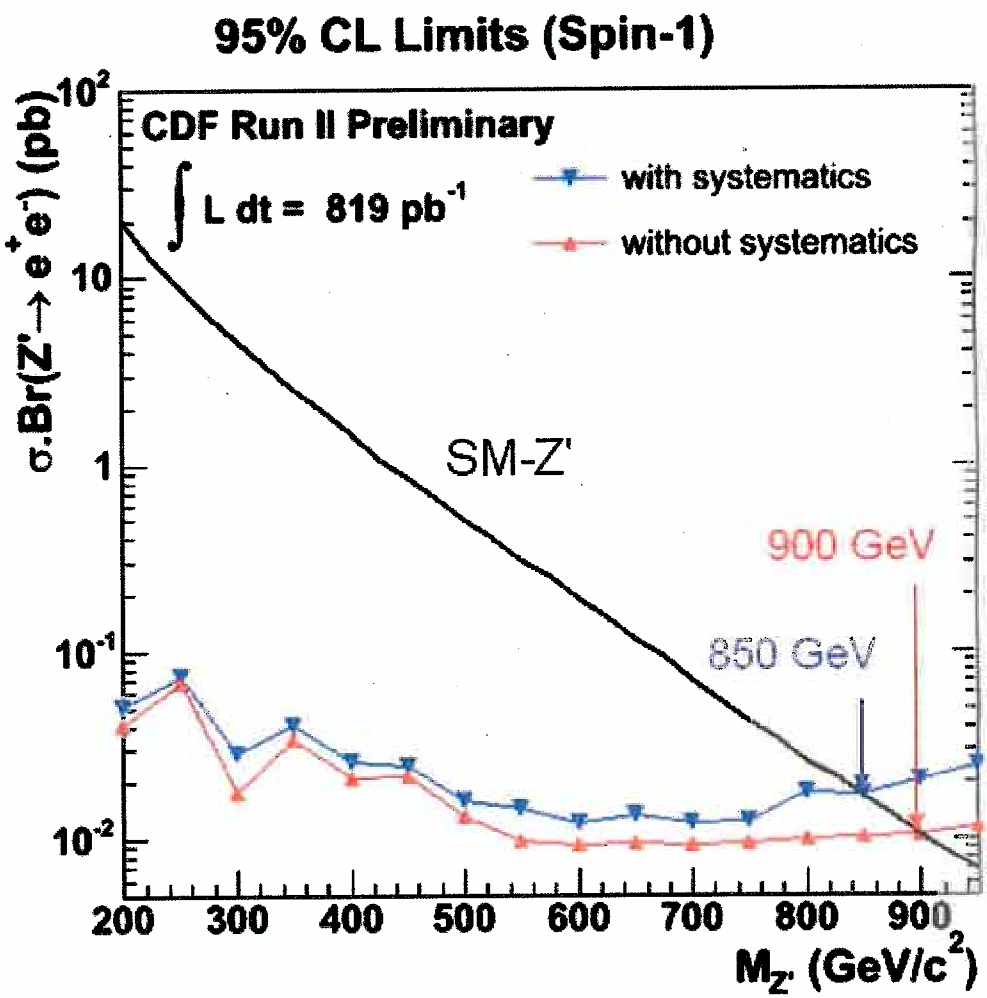
- with no signal, bounds will improve as $\mathcal{L}$ ↑ ...

  { $\mathcal{L}$ now approaching $\approx 2\,fb^{-1}$, but only $\approx 0.8\,fb^{-1}$ analyzed as of summer '06

*Note: limit is sensitive to $B(Z' \rightarrow \ell^+\ell^-)$ ... assume $Z' \rightarrow SM$ only!

# CDF update – preliminary results in the electron channel w/ 819 $pb^{-1}$




m. Schmitt

ICHEP06

*M > 850 GeV at 95% CL, for a sequential Z'*

(no AFB!)

# Other Z′ models...

| $Z'$ Model | $Z_{SM}$ | $Z_\chi$ | $Z_\psi$ | $Z_\eta$ | $Z_I$ | $Z_N$ | $Z_{\text{sec}}$ | $Z_H^{0.3}$ | $Z_H^{0.5}$ | $Z_H^{0.7}$ | $Z_H^{1.0}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Exp. limit (GeV/$c^2$) | 860 | 735 | 725 | 745 | 650 | 710 | 675 | 625 | 765 | 835 | 910 |
| Obs. limit (GeV/$c^2$) | 850 | 740 | 725 | 745 | 650 | 710 | 680 | 625 | 760 | 830 | 900 |

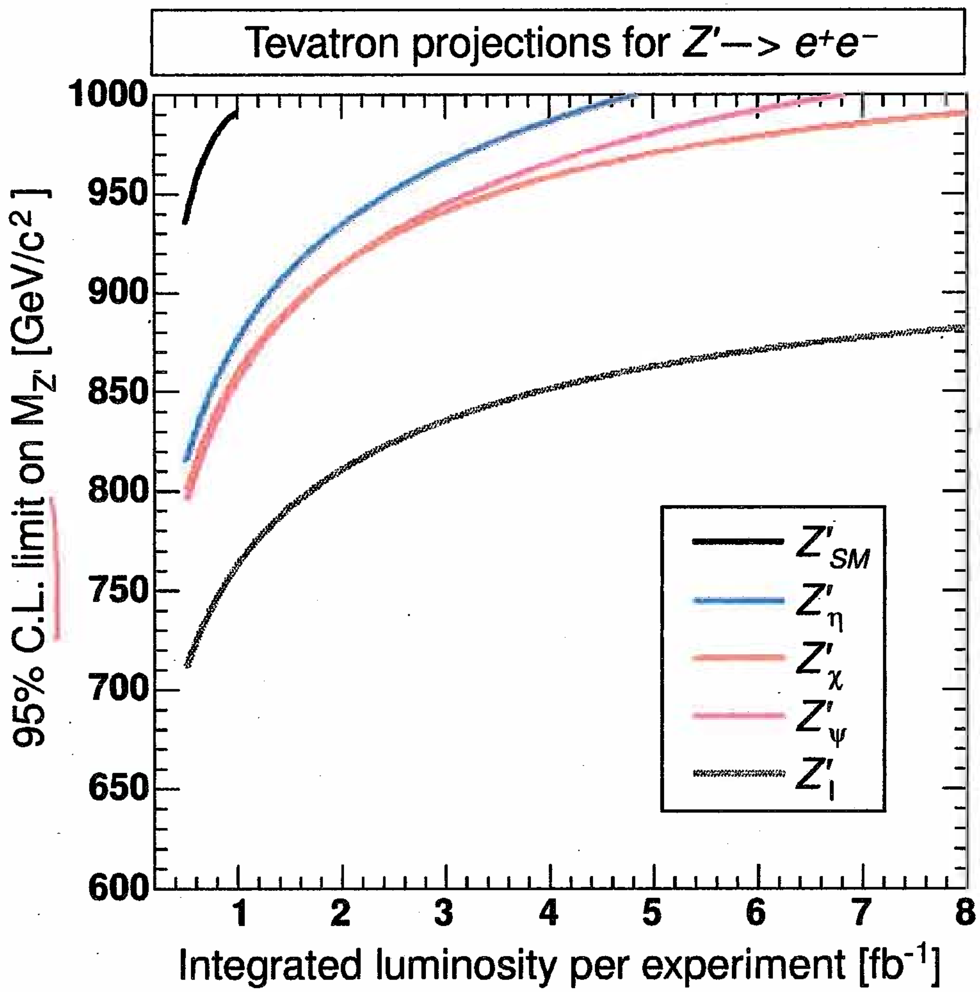
↑ SSM (under $Z_{SM}$); $E_6$ (bracket over $Z_\chi$ to $Z_N$); LH (bracket over $Z_H^{0.3}$ to $Z_H^{1.0}$)

- As the possible Z′ couplings vary the 95% CL lower bound moves around; <u>Generally</u> $Z'_{SSM}$ is the <u>most</u> strongly constrained as it has <u>large</u> couplings... Watch out for weakly coupled/narrow Z′ that may slip by...

- What about the future of Z′ searches at the Tevatron before 14 TeV results from LHC?

  ... hit the wall ~1 TeV!

Rapidly falling PDF's limit the Tevatron Z' reach..

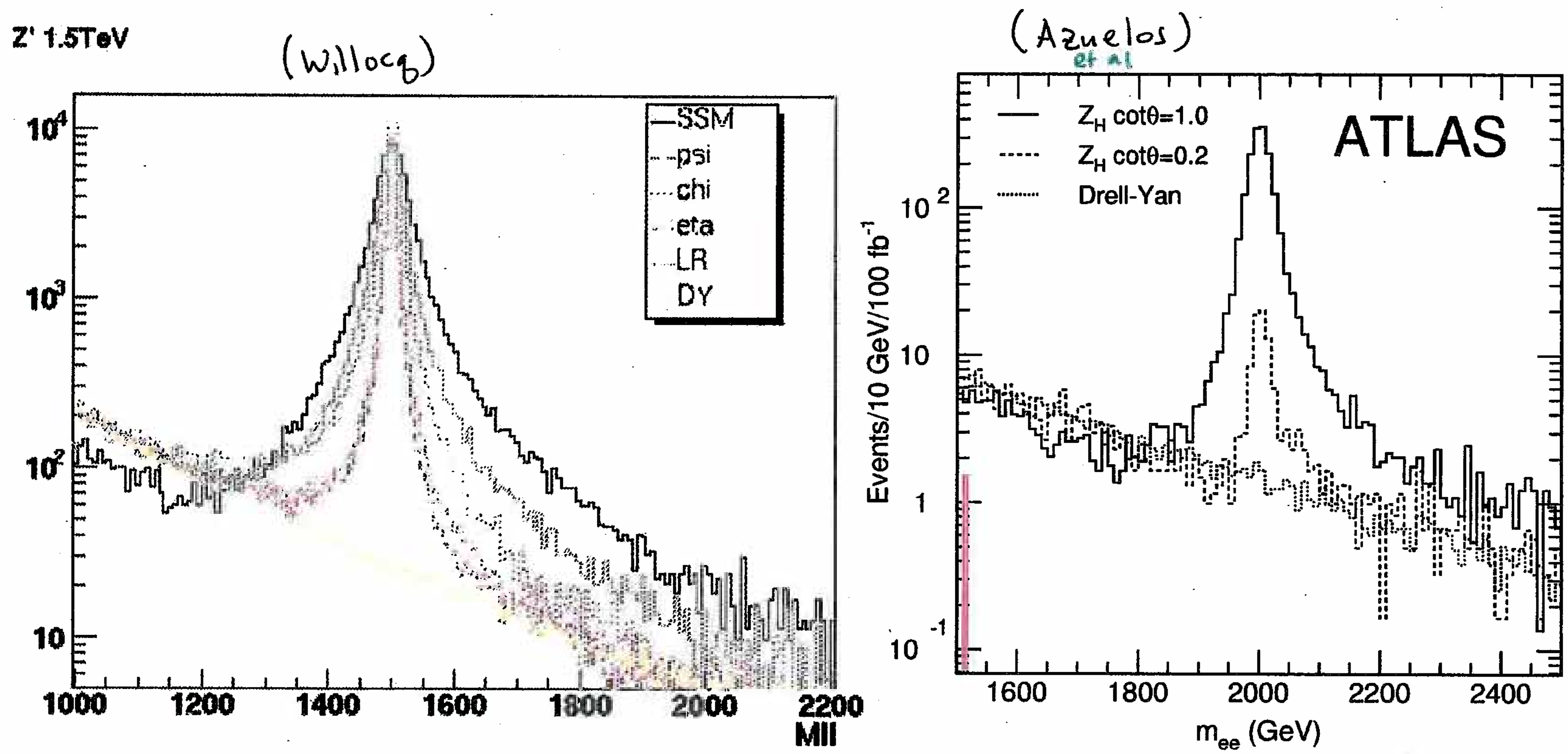



not discovery!

Fig. 1.6. Extrapolation of the Z' reach for a number of different models at the Tevatron as the integrated luminosity increases. Results from CDF and D0 are combined.

Searches "die" at ~ 1TeV; $M_{Z'} \gtrsim 1$ TeV is open for LHC !!

[ "narrow" Z' maybe missed ]



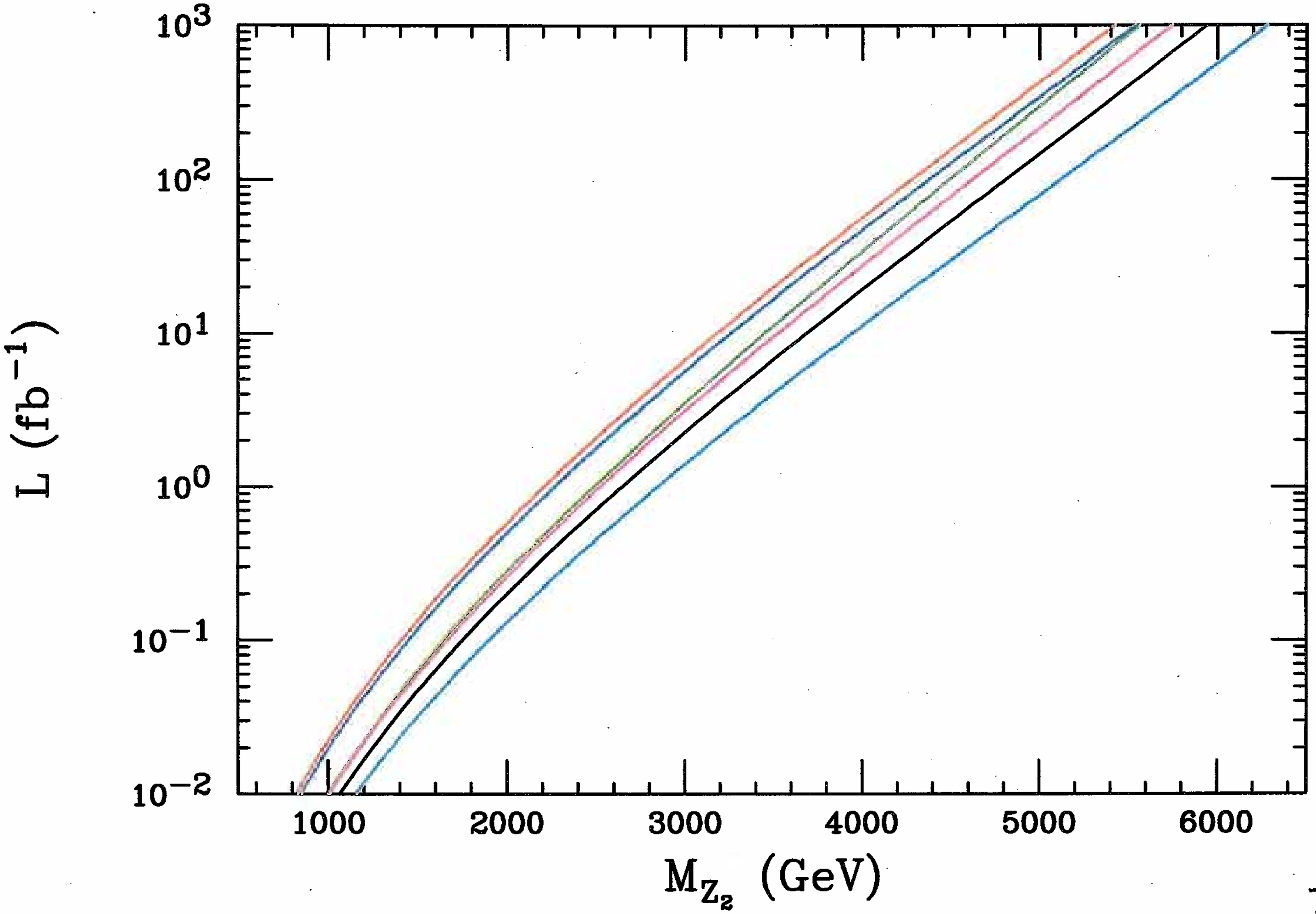

(a) (b)

Fig. 1.8. Resonance shapes for a number of Z' models as seen by ATLAS assuming $M_{Z'} = 1.5$ TeV. The continuum is the SM Drell-Yan background.

Z' are 'easy' to spot at LHC; clean w/ well understood backgrounds; $\left( \frac{\Delta \sigma_{Z'}}{\sigma_{Z'}} = 5\,(15, 25)\,\% \text{ at } M_{Z'} = 1\,(3, 5) \text{ TeV} \right)$ mostly from PDF's

"Cleaning up" $\lesssim$ 1 TeV at LHC requires ONLY 25 $pb^{-1}$ !!!

95% CL lower bound if nothing seen...




~5 TeV exclusion at ~100 $fb^{-1}$

- red — $\psi$
- green — $\chi$
- blue — $\eta$
- magenta — LRM ($\kappa$=1)
- cyan — SSM
- black — ALRM

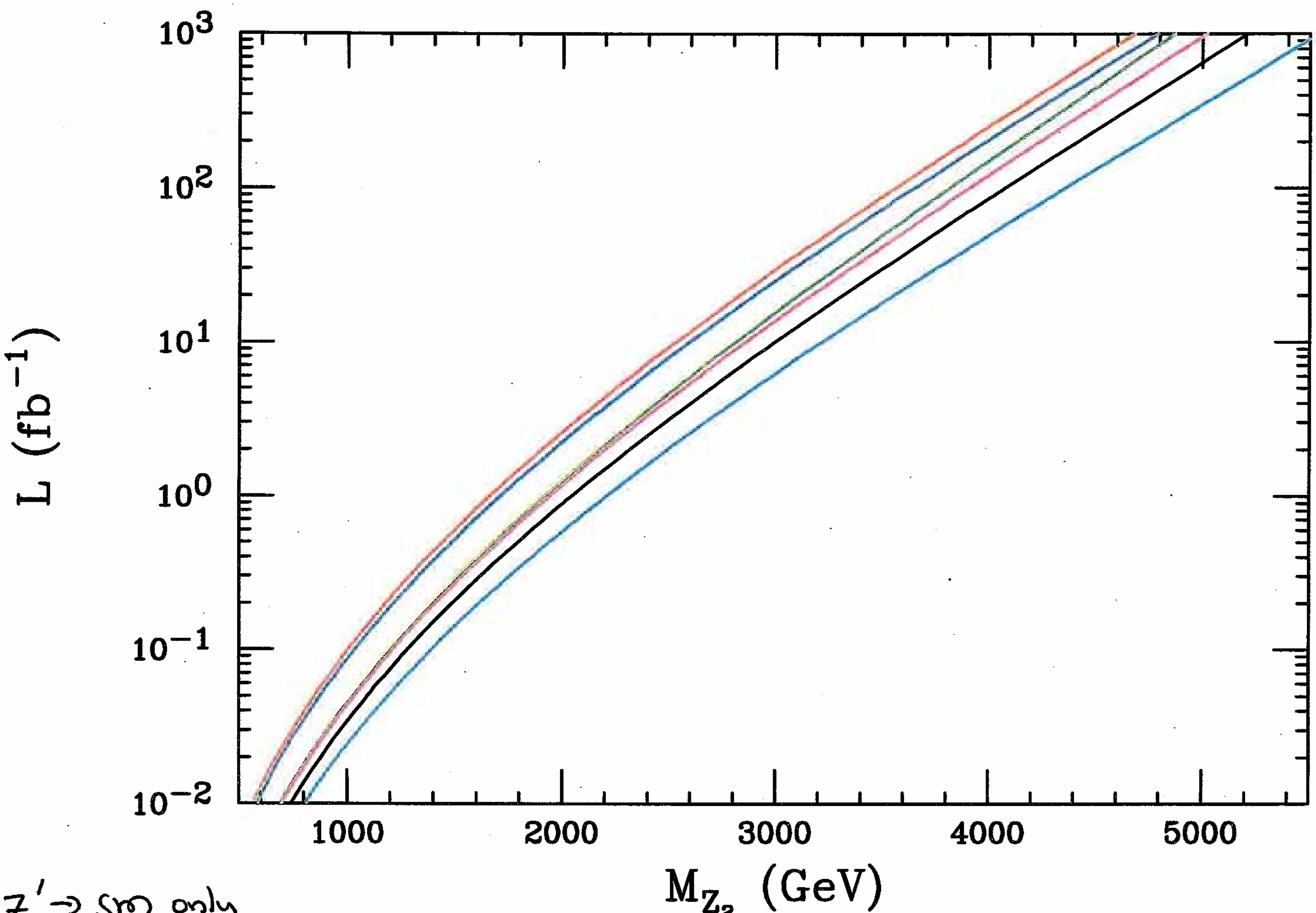
⇛ $Z' \to$ SM only!

$B \to B/2$ ↓ 10%

→ $Z'$ @ 1TeV discovery w/ only 100 $pb^{-1}$ !!

First new physics ??

5 $\sigma$ Discovery of $Z'$




~ 4 TeV w/ 100 $fb^{-1}$

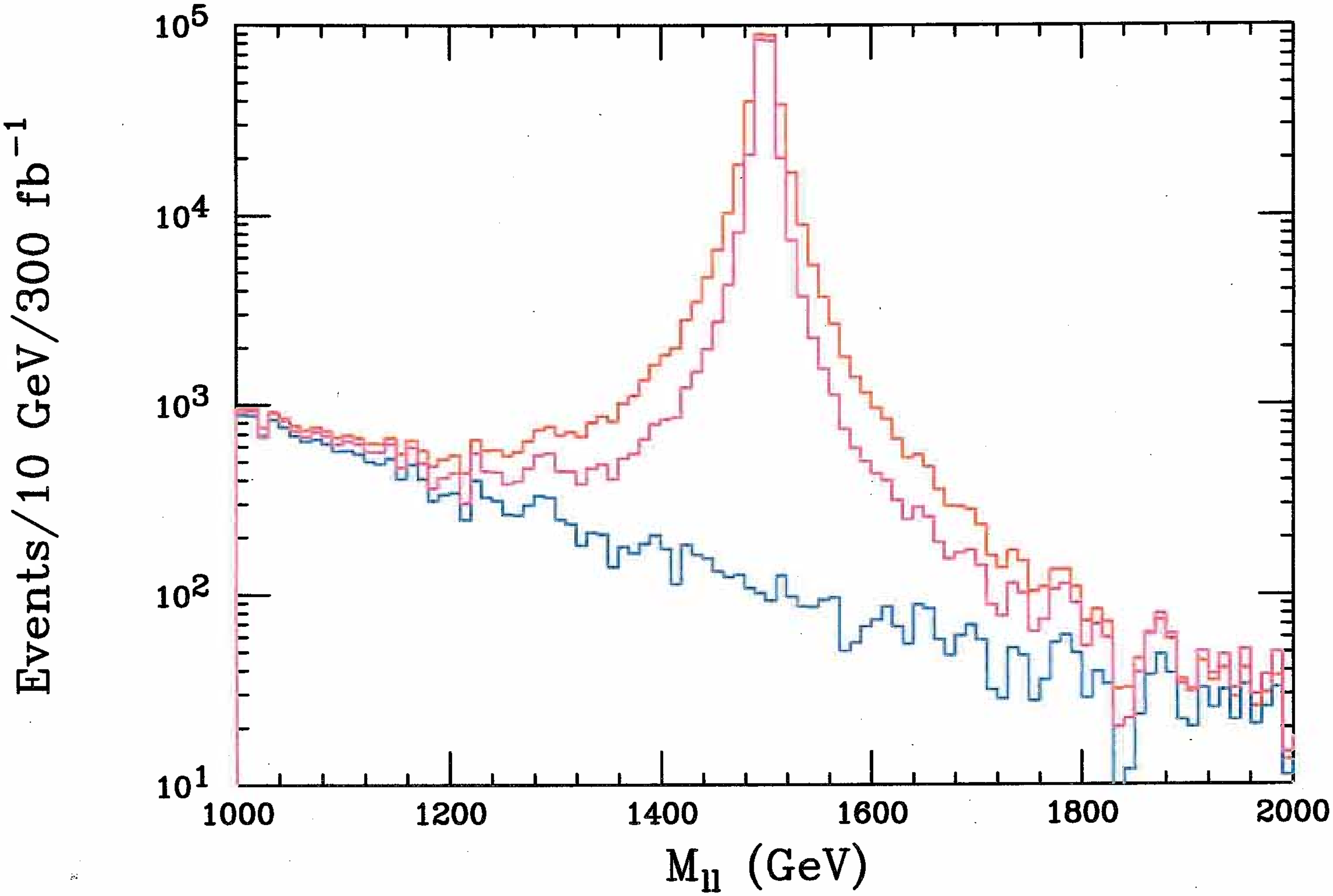
- red $\psi$
- green $\chi$
- blue $\eta$
- magenta LRM ($\kappa$=1)
- cyan SSM
- black ALRM

$Z' \to$ SM only

$B \to \frac{B}{2}$ reach ↓ 10%

... but is IT REALLY a $Z'$ ?

Is it a Z' ???




other models can fake a Z' signature...

no!!

# Drell-Yan Formulae

$$\frac{d\sigma}{dM\,dy\,dz} = \frac{K}{48\pi M^3} \sum_q \left\{ S_q G_q^+ (1+z^2) + 2 A_q G_q^- z \right\} \quad ; \quad z \equiv \cos\Theta_{\ell^- q}$$

$K$ : 'K-factor' (NLO + NNLO QCD ⊕ EWK corrections) [≈1.3]

PDF's →

$$G_q^{\pm} \equiv x_a x_b \left\{ q(x_a, M^2)\, \bar{q}(x_b, M^2) \pm q(x_b, M^2)\, \bar{q}(x_a, M^2) \right\}$$

couplings of exchanges →

$$S_q \equiv \sum_{ij} P_{ij}\, (v_i v_j + a_i a_j)_q\, (v_i v_j + a_i a_j)_\ell$$

$$A_q \equiv \sum_{ij} P_{ij}\, (v_i a_j + v_j a_i)_q\, (v_i a_j + v_j a_i)_\ell$$

Masses + widths of exchanges $\gamma, Z, Z', \ldots$ →

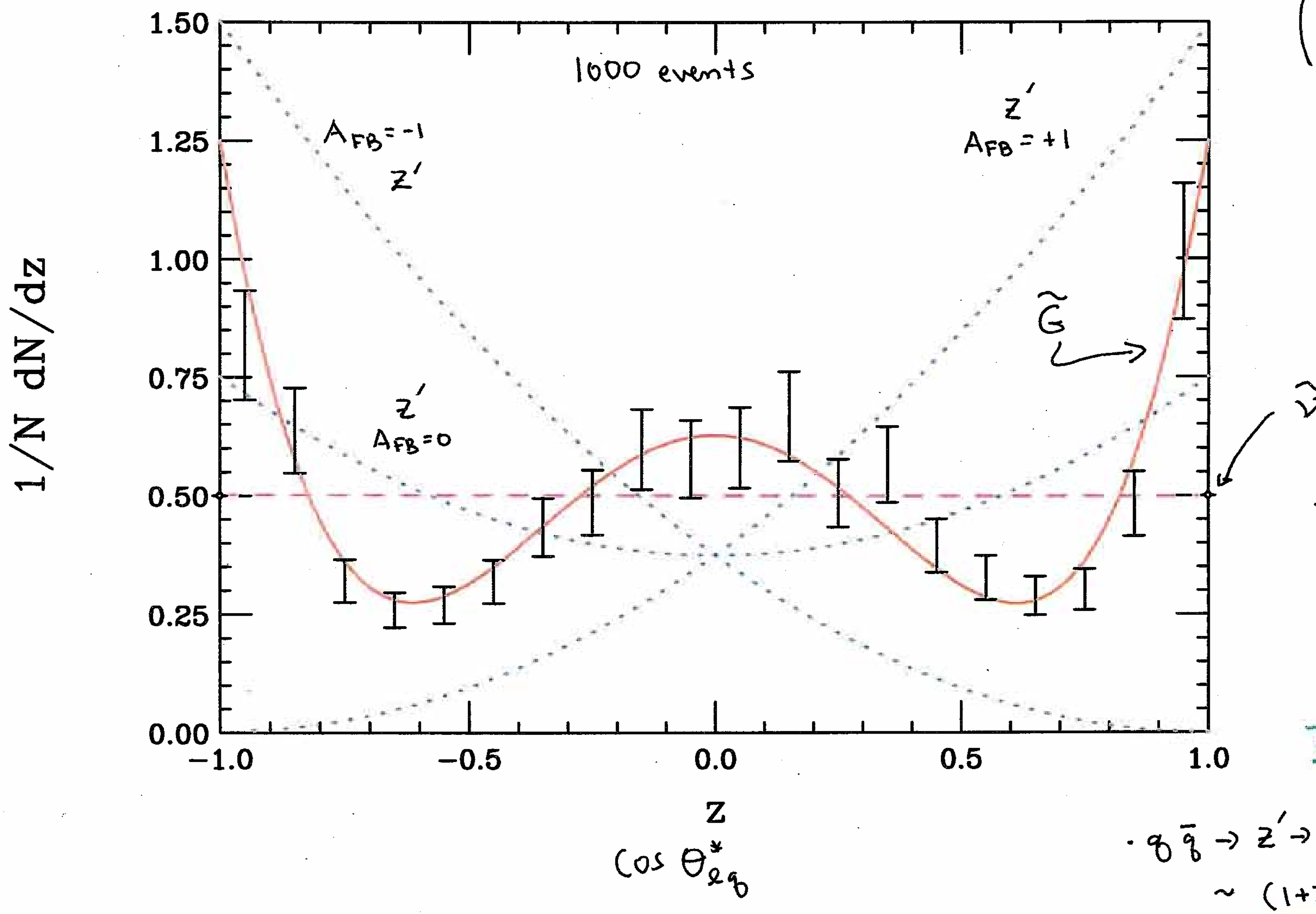
- $$P_{ij} \equiv M^4 \cdot \frac{(M^2 - M_i^2)(M^2 - M_j^2) + (M_i \Gamma_i)(M_j \Gamma_j)}{\left[(M^2 - M_i^2)^2 + (\Gamma_i M_i)^2\right]\left[\, i \to j \,\right]}$$

$$\frac{d\sigma^{\pm}}{dM\,dy} \equiv \left[ \int_0^{z_0} \pm \int_{-z_0}^{0} \right] dz \left( \frac{d\sigma}{dM\,dy\,dz} \right)$$

$$\frac{d\sigma^{\pm}}{dM} \equiv \left[ \int_{y_1}^{Y} \pm \int_{-Y}^{-y_1} \right] dy \left( \frac{d\sigma^{\pm}}{dM\,dy} \right) \Rightarrow A_{FB}(M) = \frac{d\sigma^-/dM}{d\sigma^+/dM}$$

NOTE!!

Measurements of lepton angular distributions are <u>necessary</u> to determine "Z′" spin



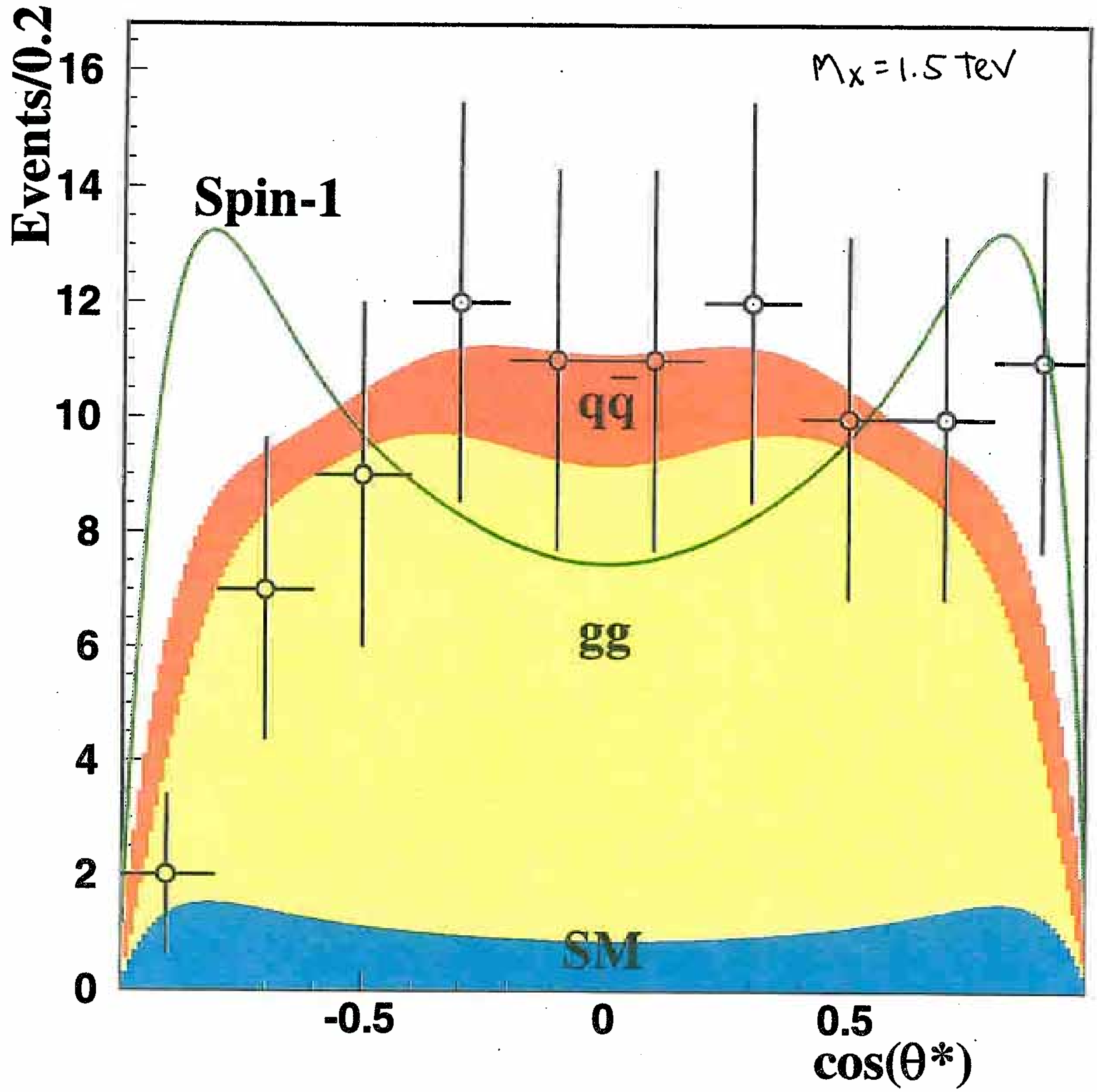

(spin-0 : $\tilde{\nu}$ ~~R~~
spin-2 : KK grav)

- $q\bar{q} \to \tilde{\nu} \to \ell^+\ell^-$ is <u>flat</u>
- $q\bar{q} \to G \to \ell^+\ell^-$ $\sim 1-3z^2+4z^4$
- $gg \to G \to \ell^+\ell^-$ $\sim 1-z^4$

→ Need a few hundred events!

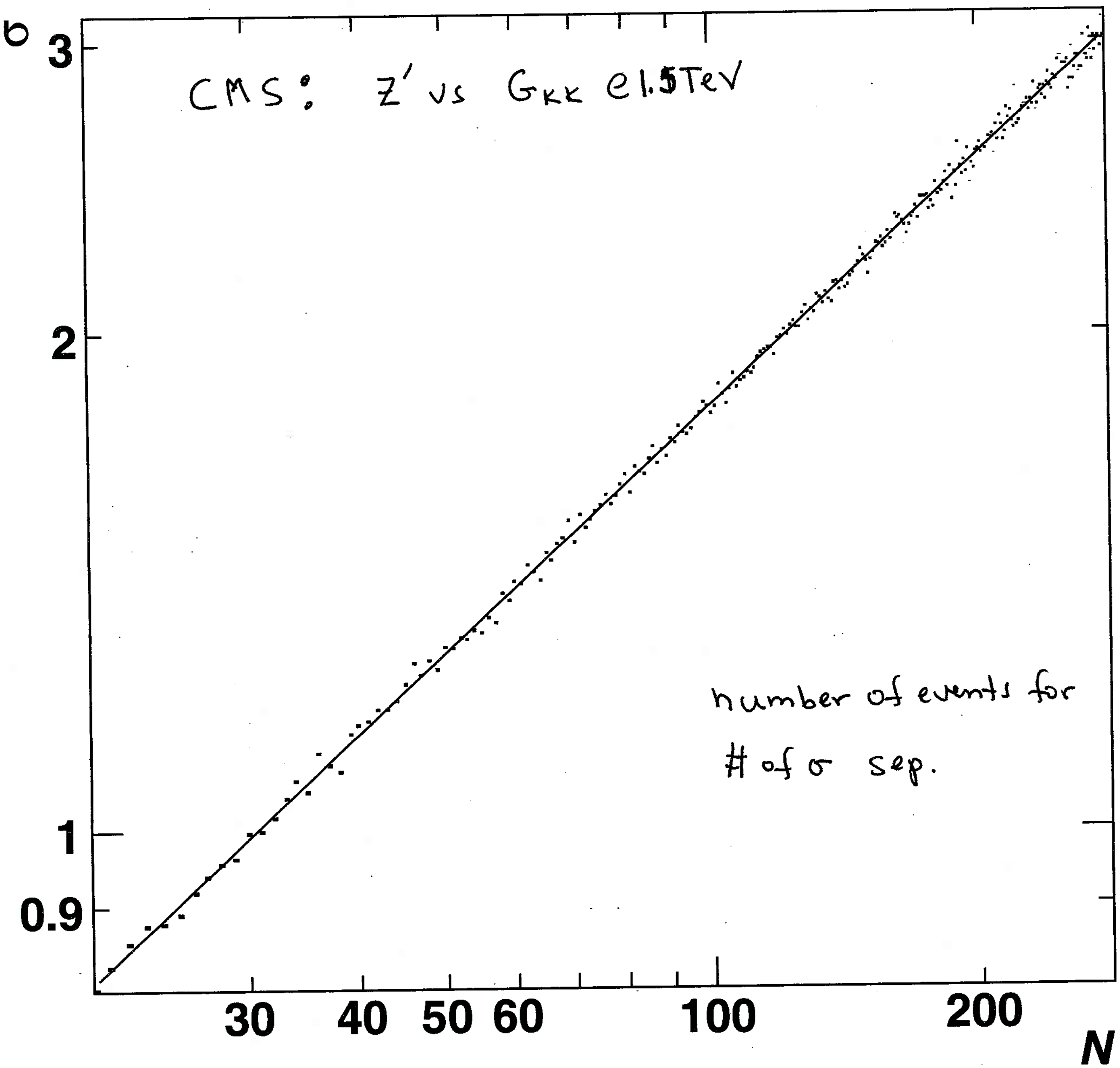
<u>But</u>:

- $q\bar{q} \to Z' \to \ell^+\ell^-$ $\sim (1+z^2) + \frac{8}{3} A_{FB}\, z$




Z′ vs Graviton KK in ATLAS

Allanach etal (hep-ph/0006114)




Cousins et al

JHEP 0511 046 ('05)

← <u>3σ</u> sep requires

~<u>300 events</u>

- Many more than discovery!

∴ spin analysis <u>cannot</u> be done for <u>very</u> <u>heavy</u> Z′..

~ 2.5-3 TeV ??

($\sim 1\,ab^{-1}$)

## A few comments:

- The $d\sigma/dM$ values in the region below the peak are very important...

  → is there interference w/ SM contributions?

  - No! (if spin-0 or 2) { note also: $Z' \not\to \gamma\gamma$ but, eg, $G \to \gamma\gamma$ }

- This region can also be very important for $Z'$ vs KK differentiation

- Generally $\frac{\Delta M}{M} \sim \left(\frac{\Gamma}{M}\right)_{Z'} \sim 0.01$ (as in all the cases shown here)

⇒ But beware! There are (many) models w/ narrow resonances ($\Gamma/M \ll 0.01$) which are smeared out by resolution....

∴ have reduced S/B ... such cases have not been well-studied

- After establishing the $Z'$ spin-1 nature, what next?

  - measure the 'obvious' : $M_{Z'}$, $\Gamma_{Z'}$, $\sigma_{\ell\ell}$ !

  $\Rightarrow$ How well can this be done? (eg, w/ $L = 10\,fb^{-1}$)

  **Not Bad !**

→ But, we want **couplings** ! + we want to be model-independent !

**Both** $\Gamma_{Z'}$ + $\sigma_{\ell\ell}$ are sensitive to $Z' \to$ non-SM particles

[ SUSY, exotic fermions, who knows what? ]

But $\boxed{\Gamma_{Z'} \cdot \sigma_{\ell\ell}}$ is **insensitive** !

What else can we measure ??

ATLAS DC1 Study

Shäfer, Ledroit & trocme

Atl-phys-pub-2005-010

| | | $M_{rec}$ (GeV) | $\Gamma_{rec}$(GeV) | $\Gamma_{gen}$(GeV) | $\Gamma_{theo.}$(GeV) |
|---|---|---|---|---|---|
| $M = 1.5$ TeV | $SSM$ | 1500.7± 0.7 | 46.6± 1.4 | 47.0± 0.9 | 44.7 |
| | $\psi$ | 1500.2± 0.3 | 7.8± 0.6 | 7.1± 0.5 | 8.0 |
| | $\chi$ | 1500.8± 0.4 | 17.1± 0.9 | 18.4± 0.5 | 17.6 |
| | $\eta$ | 1500.6± 0.3 | 8.9± 0.6 | 9.5± 0.4 | 9.5 |
| | $LR$ | 1499.5± 0.6 | 29.7± 1.3 | 32.2± 0.8 | 30.6 |
| $M = 4$ TeV | $SSM$ | 4002. ± 15. | 94. ± 33. | 97. ± 19. | 119. |
| | $KK$ | 3982. ± 6. | 168. ± 14. | 173. ± 8.4 | |

Table 8: *Results of the fit to the reconstructed dilepton mass for all studied models*

.. as expected, some cases are better than others due to statistics & coupling variations

| | | $\sigma_{ll}^{gen}$(fb) | $\sigma_{ll}^{rec}$(fb) | $\sigma_{ll}^{rec} \times \Gamma_{rec}$(fb.GeV) |
|---|---|---|---|---|
| $M = 1.5$ TeV | $SSM$ | 78.4±0.8 | 78.8±1.8 | 3668±138 |
| | $\psi$ | 22.6±0.3 | 22.7±0.6 | 178±13 |
| | $\chi$ | 47.6±0.6 | 48.4±1.3 | 828±48 |
| | $\eta$ | 26.2±0.3 | 25.1±0.6 | 223±15 |
| | $LR$ | 50.8±0.6 | 51.1±1.3 | 1515±75 |
| $M = 4$ TeV | $SSM$ | 0.16±0.02 | 0.15±0.03 | 14±6 |
| | $KK$ | 2.2±0.07 | 2.2±0.12 | 376±37 |

Table 9: *Results on $\sigma_{ll}$ and $\sigma_{ll} \times \Gamma$ for all studied models*

(generator = PYTHIA)

# $A_{FB}$

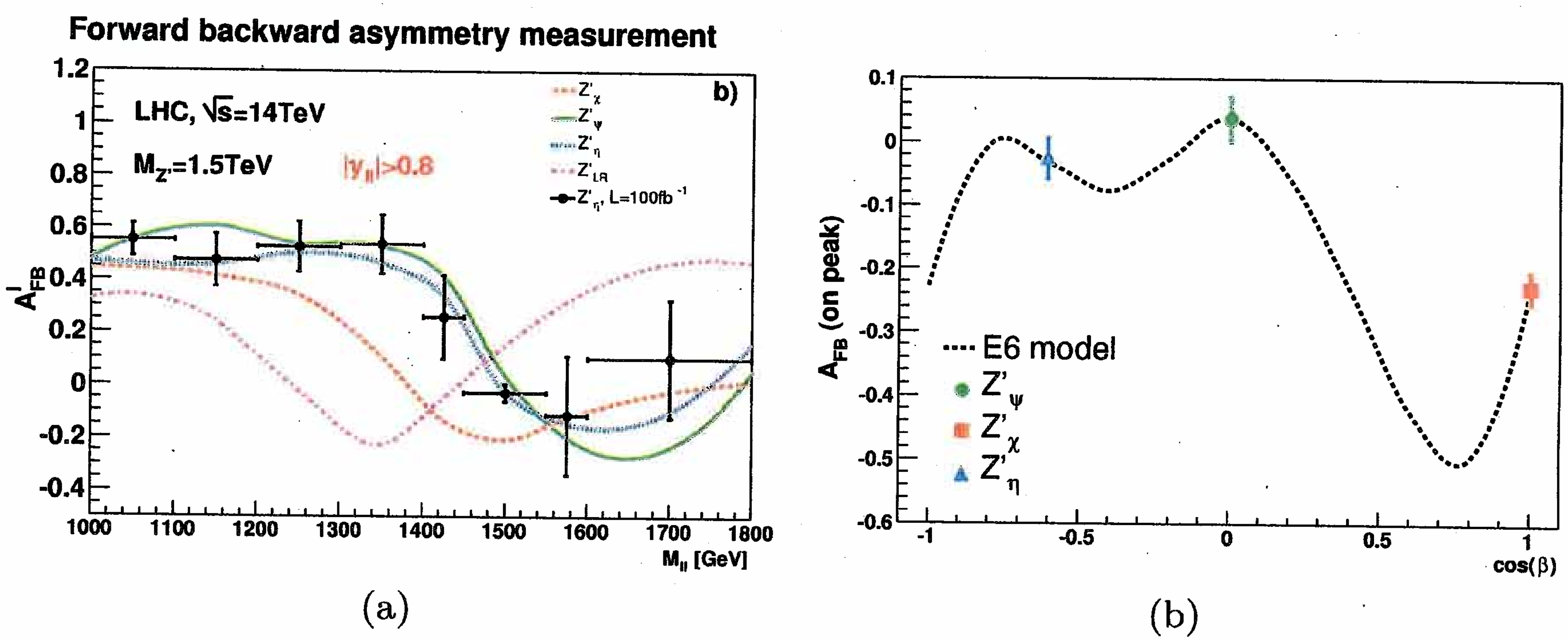



Fig. 1.10. (a)$A_{FB}$ near a 1.5 TeV Z' in a number of models. (b)On-peak differentiation of $E_6$ models using $A_{FB}$ showing statistical errors for a 1.5 TeV Z'.

- Dittmar, Nicollerat + Djouadi
  hep-ph/0307020

→ $A_{FB}$ is coupling sensitive + since $A_{FB} \simeq \frac{d\sigma^-/dM}{d\sigma^+/dM}$, it is insensitive to 'exotic' Z' decays.. (but the statistics do!)
until data is available

| Model | $\int \mathcal{L}(fb^{-1})$ | Generation | Observed | Corrected |
|---|---|---|---|---|
| 1.5 TeV | | | | |
| $SSM$ | 100 | $+0.088 \pm 0.013$ | $+0.060 \pm 0.022$ | $+0.108 \pm 0.027$ |
| $\chi$ | 100 | $-0.386 \pm 0.013$ | $-0.144 \pm 0.025$ | $-0.361 \pm 0.030$ |
| $\eta$ | 100 | $-0.112 \pm 0.019$ | $-0.067 \pm 0.032$ | $-0.204 \pm 0.039$ |
| $\eta$ | 300 | $-0.090 \pm 0.011$ | $-0.050 \pm 0.018$ | $-0.120 \pm 0.022$ |
| $\psi$ | 100 | $+0.008 \pm 0.020$ | $-0.056 \pm 0.033$ | $-0.079 \pm 0.042$ |
| $\psi$ | 300 | $+0.010 \pm 0.011$ | $-0.019 \pm 0.019$ | $-0.011 \pm 0.024$ |
| $LR$ | 100 | $+0.177 \pm 0.016$ | $+0.100 \pm 0.026$ | $+0.186 \pm 0.032$ |
| 4 TeV | | | | |
| $SSM$ | 500 | $+0.138 \pm 0.099$ | $+0.006 \pm 0.183$ | $+0.265 \pm 0.260$ |
| $KK$ | 500 | $+0.491 \pm 0.028$ | $+0.189 \pm 0.057$ | $+0.457 \pm 0.073$ |

Table 11: *Measured on peak $A_{FB}$ for all studied models in the central mass bin.*

| Model | $\int \mathcal{L}(fb^{-1})$ | Generation | Observed | Corrected |
|---|---|---|---|---|
| 1.5 TeV | | | | |
| $SSM$ | 100 | $+0.077 \pm 0.025$ | $+0.086 \pm 0.038$ | $+0.171 \pm 0.045$ |
| $\chi$ | 100 | $+0.440 \pm 0.019$ | $+0.180 \pm 0.032$ | $+0.354 \pm 0.039$ |
| $\eta$ | 100 | $+0.593 \pm 0.016$ | $+0.257 \pm 0.033$ | $+0.561 \pm 0.039$ |
| $\psi$ | 100 | $+0.673 \pm 0.012$ | $+0.294 \pm 0.033$ | $+0.568 \pm 0.039$ |
| $LR$ | 100 | $+0.303 \pm 0.022$ | $+0.189 \pm 0.033$ | $+0.327 \pm 0.040$ |

Table 12: *Measured off peak $A_{FB}$ for all studied models at M=1.5 TeV*

$0.8 \le M_{ee} \le 1.4$ TeV

Atlas DC1 study

Shäfer, Ledroit + Trocme

Atl-phys-pub-2005-010

Dilution effects :

- determination of q direction
  → rapidity cut
- gluon radiation ....

etc

→ needs NNLO study..

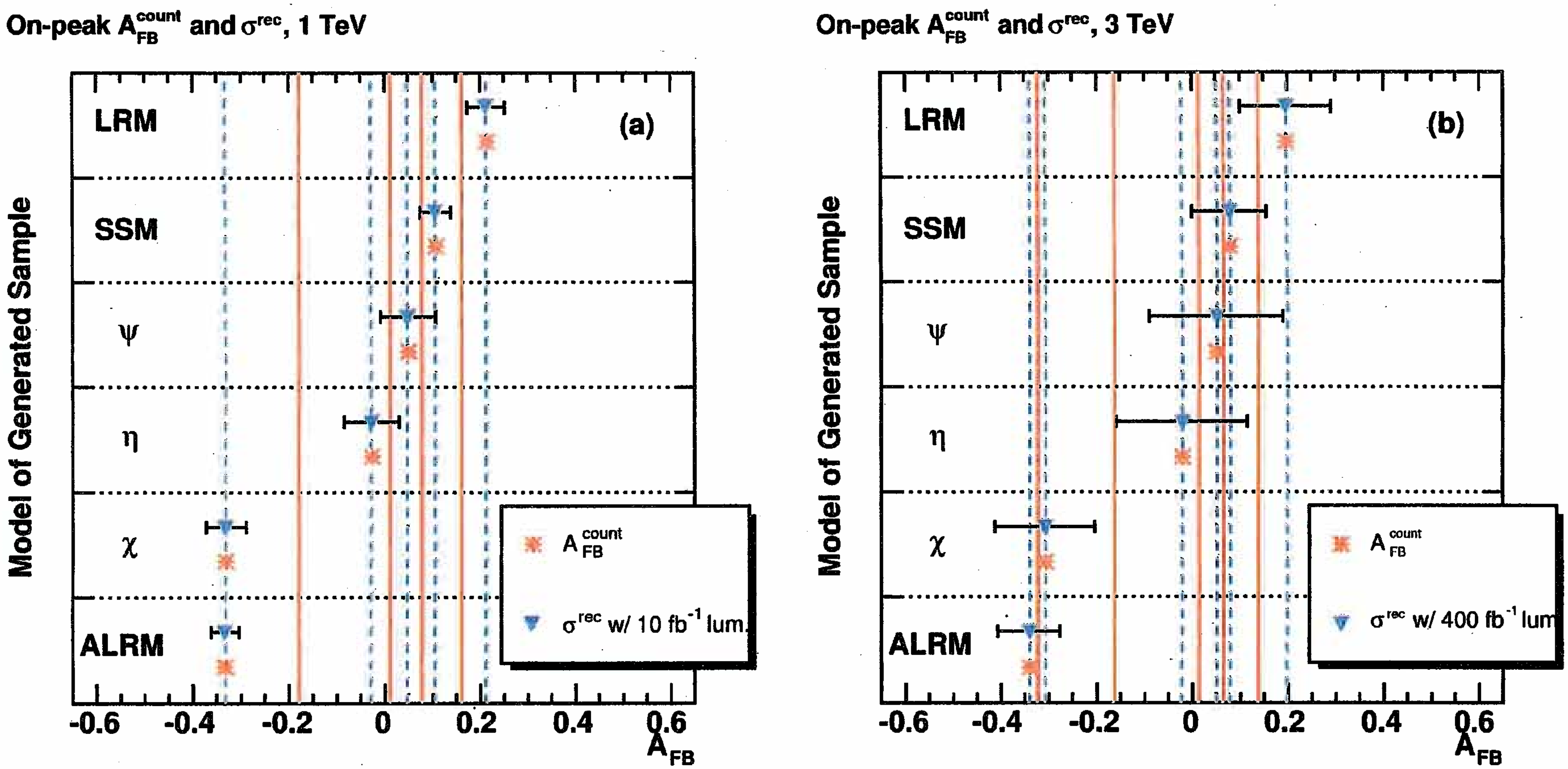



Fig. 1.11. CMS analysis of Z' model differentiation employing $A_{FB}$ assuming $M_{Z'} = 1$ or 3 TeV.

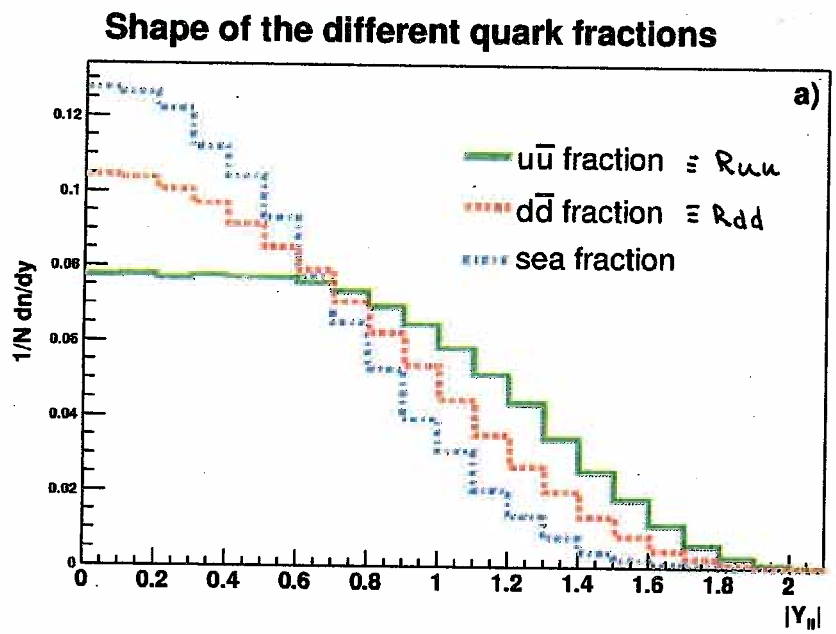
Cousins, Mumford + Valuev  CMS note 2005/022

→ Relatively, easy to sep. models...

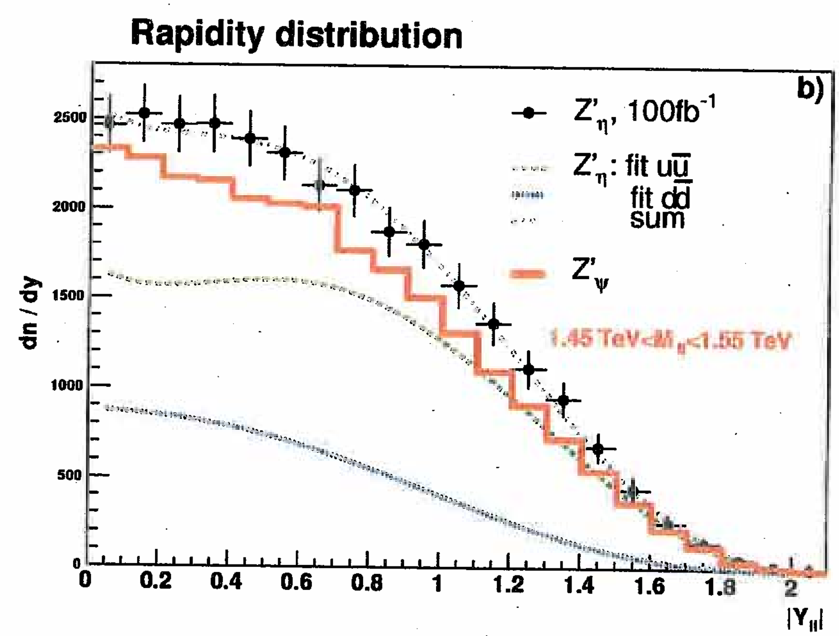
What about other leptonic observables?

22)

# Rapidity Shape Differences




(a)




(b)

Fig. 1.12. (a)Rapidity distributions for different $q\bar{q}$ induced events. (b)Rapidity distribution differentiation of Z' models. (Dittmar et.al)

- $u\bar{u}$ + $d\bar{d}$ induced 'events' → different rapidity distributions for leptons. The Z' couplings determine the weight. <u>if</u> PDF's are <u>known</u>, the $R_{uu,dd} \rightarrow (v_u'^2 + a_u'^2)/(v_d'^2 + a_d'^2)\ldots$

DC1 Study by ATLAS

$M_{Z'} = 1.5$ TeV

| ATLAS | Generation level Fitted values (%) | | Reconstruction level Fitted values (%) | |
|---|---|---|---|---|
| **Model** | Prop(Z'←dd) | Prop(Z' ←uu) | Prop(Z'←dd) | Prop(Z'←uu) |
| SSM | 41.±10. | 52.±12. | 22.±16. | 60.±16. |
| $\chi$ | 62.±12. | 29.±14. | 79.±17. | 17.±19. |
| $\eta$ | 23.±13. | 75.±14. | 33.±6. | 67.±8. |
| $\psi$ | 36.±12. | 61.±13. | 32.±15. | 62.±17. |
| LR | 57.±4. | 43.±14. | 53.±13. | 46.±15. |

Fig. 1.13. Comparison of $R_{q\bar{q}}$ values determined at the generator level and after detector simulation by ATLAS.

Morel + Ledroit, talk at LPSC-Grenoble, July '05

- Both $R_{uu,dd}$ poorly determined unless high-lumi available.
- Any thing else w/ leptons ?

A more global observable using the lepton's rapidity...

**Rapidity Ratio**

$$R \equiv \frac{\int_{-y_1}^{y_1} \left(\frac{d\sigma^+}{dy}\right) dy}{\left[\left(\int_{y_1}^{Y} + \int_{-Y}^{-y_1}\right) dy\right] \left(\frac{d\sigma^+}{dy}\right)} \qquad y_1 \approx 1.0$$

• del Aguila et al ('93)

$\approx$ central / forward leptons

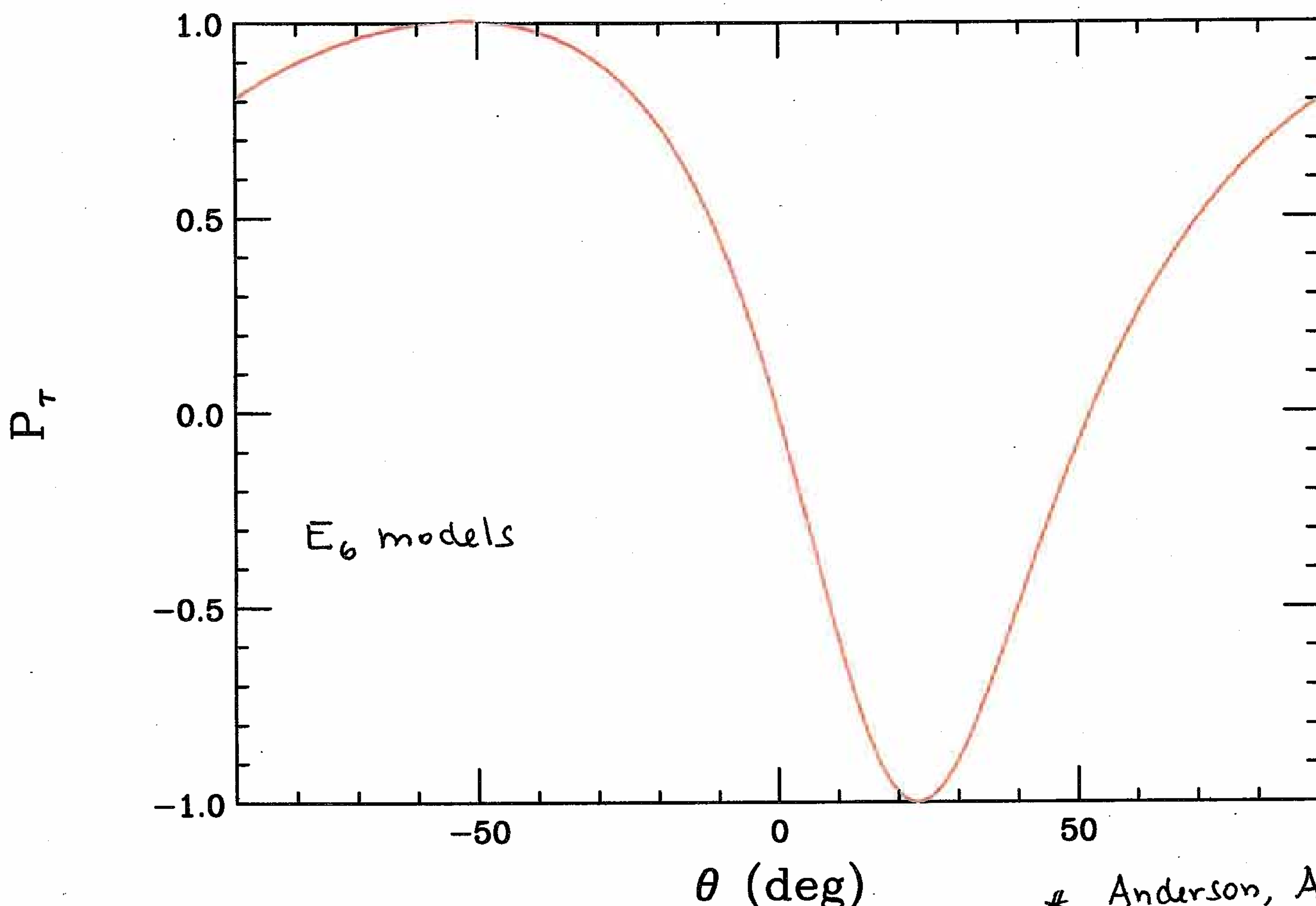
→ no detector studies (yet)

... that's about all we can do w/ e's + μ's

What about τ's ? τ's are not useful if the Z' has generation independent couplings ...

except for ...

Tau Polarization Asymmetry




$P_\tau^{NWA} = \frac{2 v_e' a_e'}{v_e'^2 + a_e'^2}$

Clearly has coupling sensitivity...

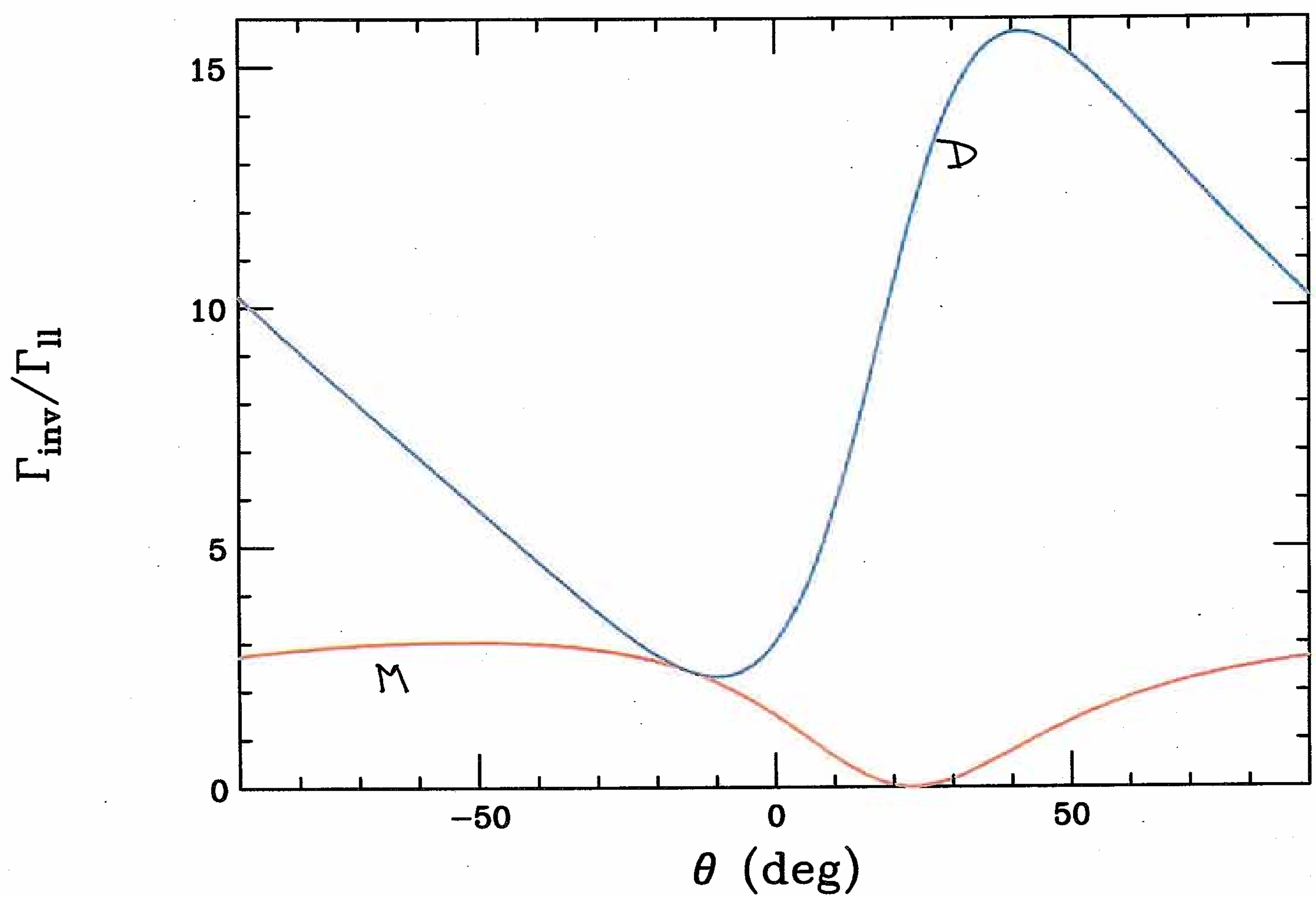
Old idea*, but can it be done? No Study yet (Azuelos?)

(B insensitive)

* Anderson, Austern + Cahn, PRD 46, 280 '92; PRL 69, 25 '92

20)

# Dirac vs Majorana neutrinos ??



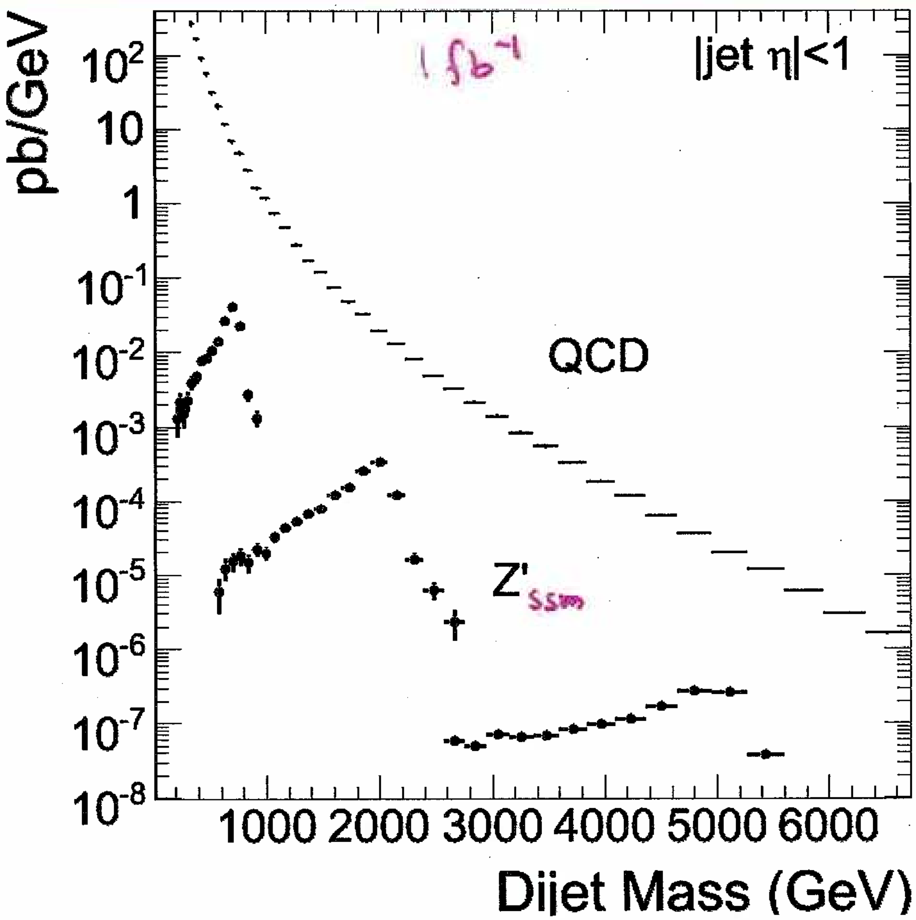

.. this may be the only clean way to ever know!

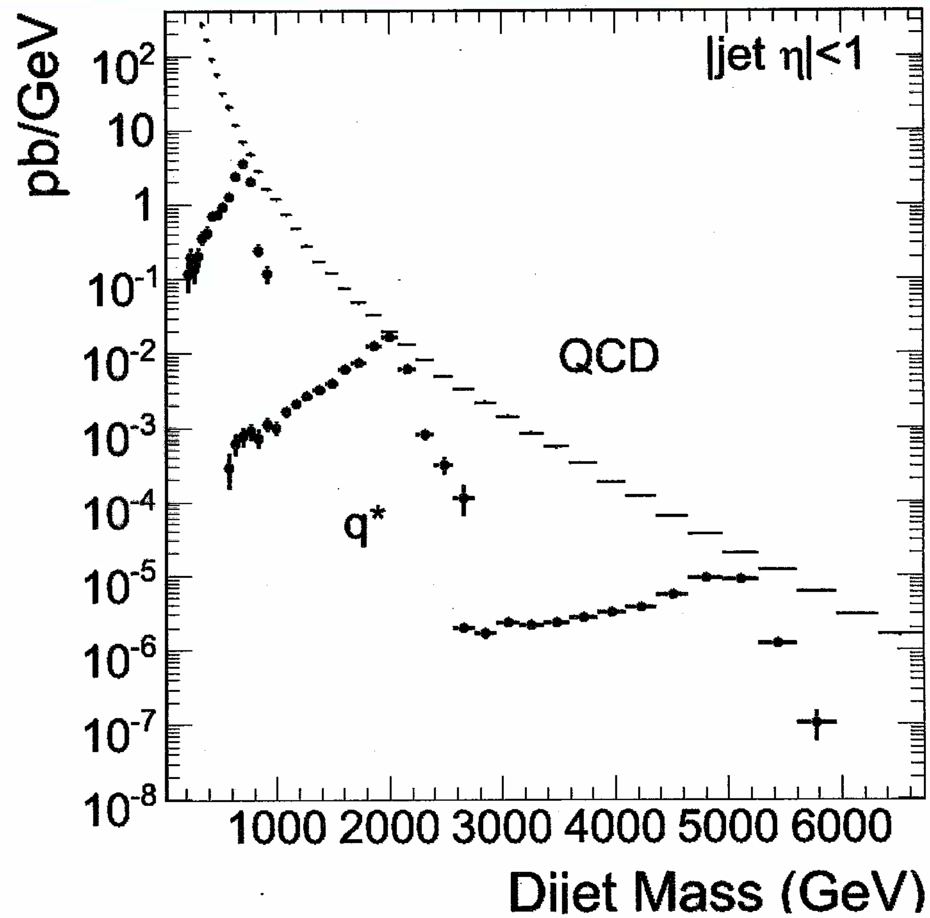
Too bad....

.. what about Z′ in jj mode? Can we get info there?

Very difficult to see $Z' \to jj$

# Signal and Background




- QCD cross section falls smoothly as a function of dijet mass.
- Resonances produce mass bumps we can see if xsec is big enough.

Gumus et al
CMS note 2006/070

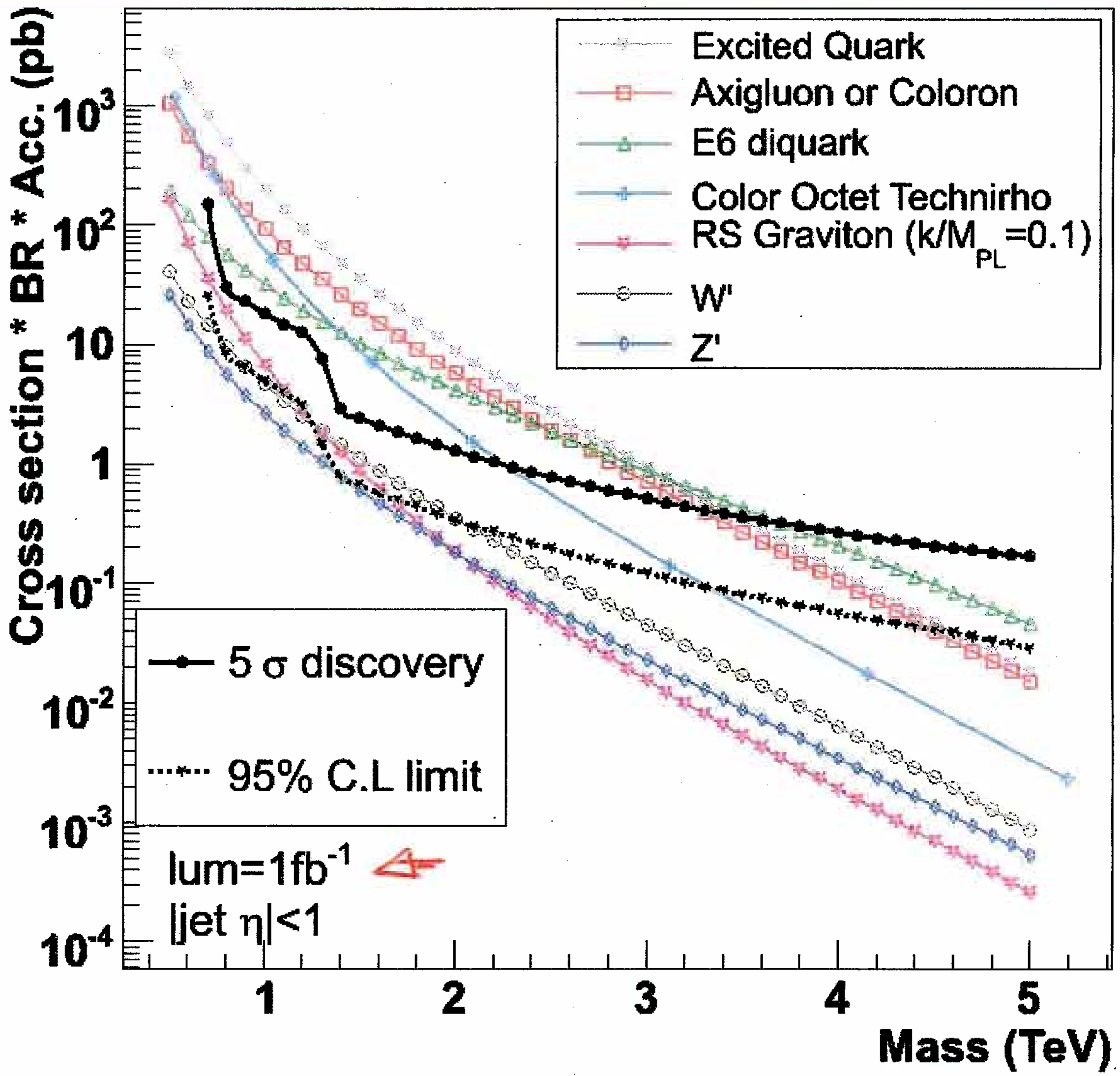


28)

$Z' \to jj$ will be very hard!

# Sensitivity to Resonance Cross Section

- Cross Section for Discovery or Exclusion
  - Shown here for 1 $fb^{-1}$
  - Also for 100 $pb^{-1}$, 10 $fb^{-1}$
- Compared to cross section for 8 models
- CMS expects to have sufficient sensitivity to
  - Discover with $5\sigma$ significance any model above solid black curve
  - Exclude with 95% CL any model above the dashed black curve.
- Can discover resonances produced via color force, or from valence quarks.






What about $Z' \to b\bar{b}, t\bar{t}$??

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# $Z' \to$ heavy flavors ??

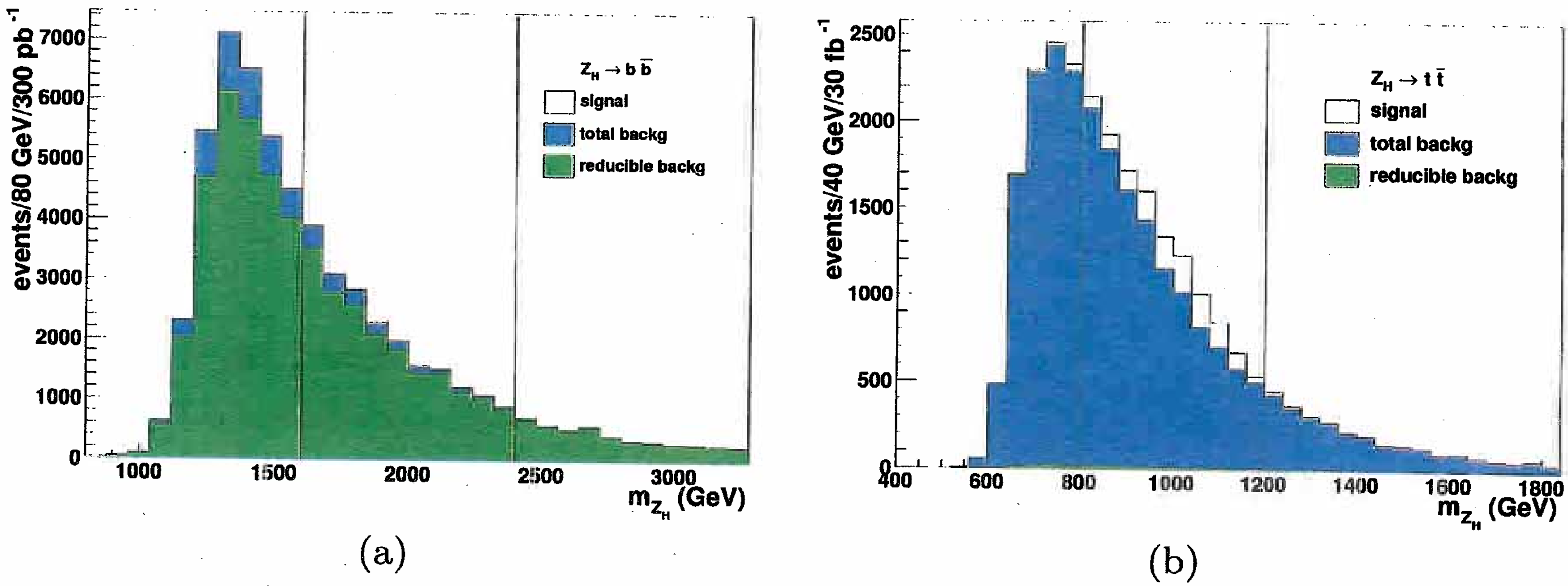



Fig. 1.16. Search for heavy flavor decays of the Z' in the Little Higgs model by ATLAS. $\cot\theta_H = 1$ has been assumed. $Z' \to b\bar{b}$ assuming $M_{Z'} = 2$ TeV and a luminosity of 300 $fb^{-1}$(a) and $t\bar{t}$(b) for $M_{Z'} = 1$ TeV and a luminosity of 30 $fb^{-1}$.

Hoz, March + Ros, Atl-phys-pub-2006-003

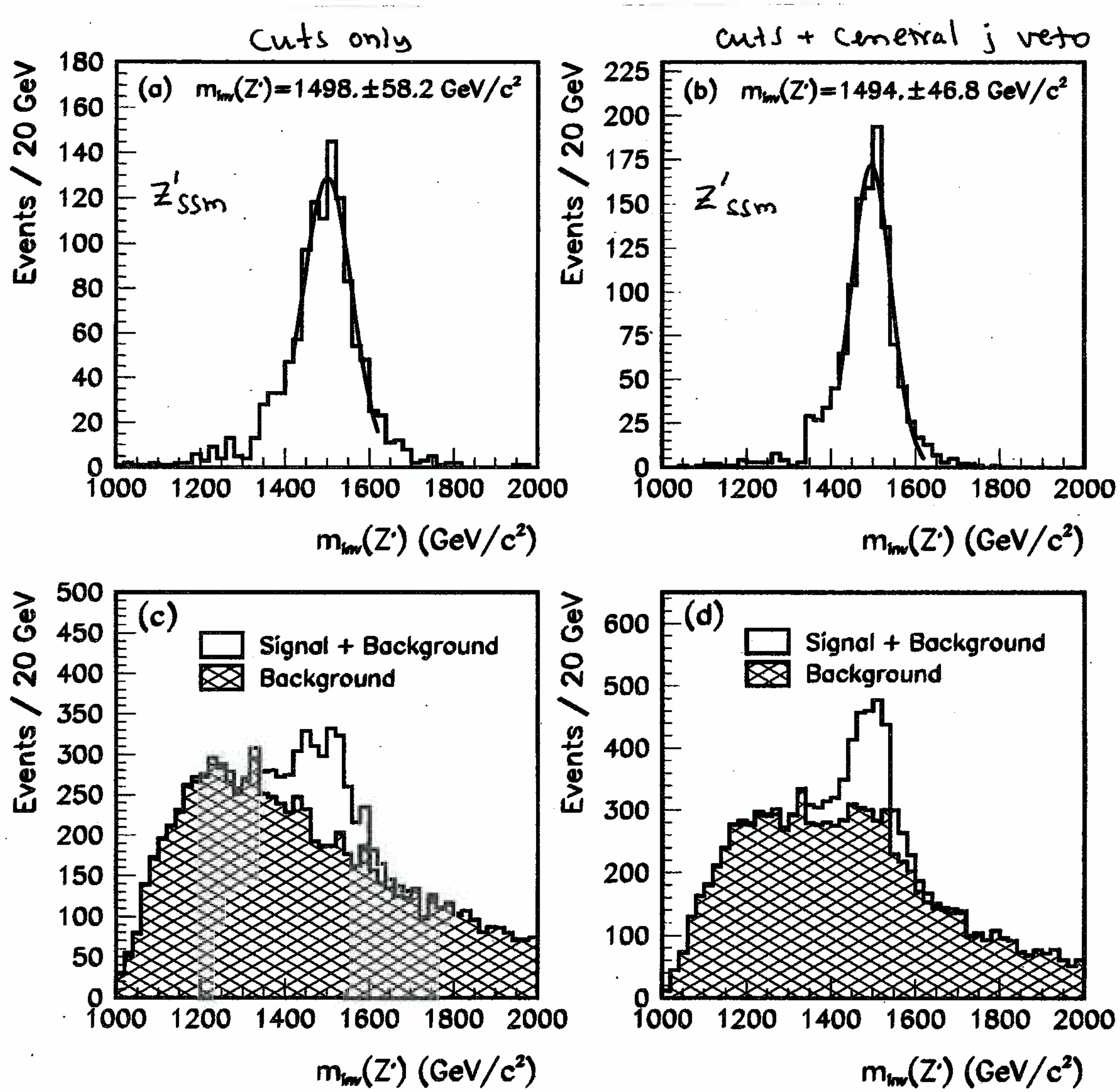
- Doesn't look too promising .. more work necessary for $t\bar{t}$ case .. but $Z' \to b\bar{b}$ (in this case) looks invisible

→ More general study needed !

$Z' \to W^+W^-$

(can be mixing induced)

$\frac{\Gamma}{\Gamma_{Z'}} \sim \phi^2 \frac{M_{Z'}^4}{M_W^4}$




This is a good way to get at Z-Z' mixing in many models

Fig. 1.17. Results of two <u>ATLAS</u> analyses showing the Z'→ WW signal above SM backgrounds and Z' mass reconstruction in this channel for the SSM model assuming $M_{Z'} = 1.5$ TeV and $\beta = 1$. ( $\phi \simeq \beta (M_Z/M_{Z'})^2$ )

Benchekroun, Driouichi + Hoummada – old analysis

SN-Atl-2001-001

Update ? (DeRoeck) (CMS)

$Z' \to Zh$ in Little Higgs models

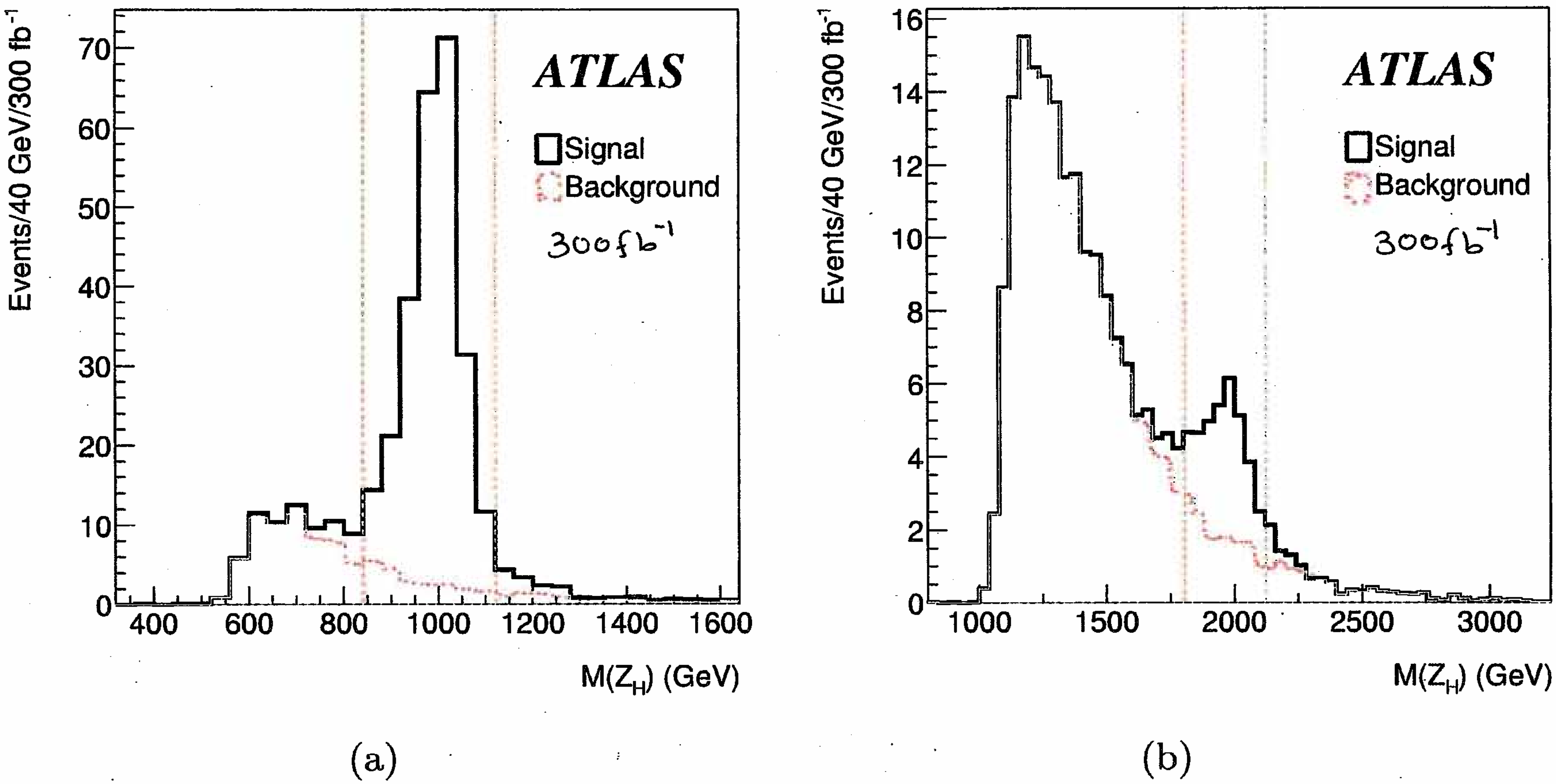


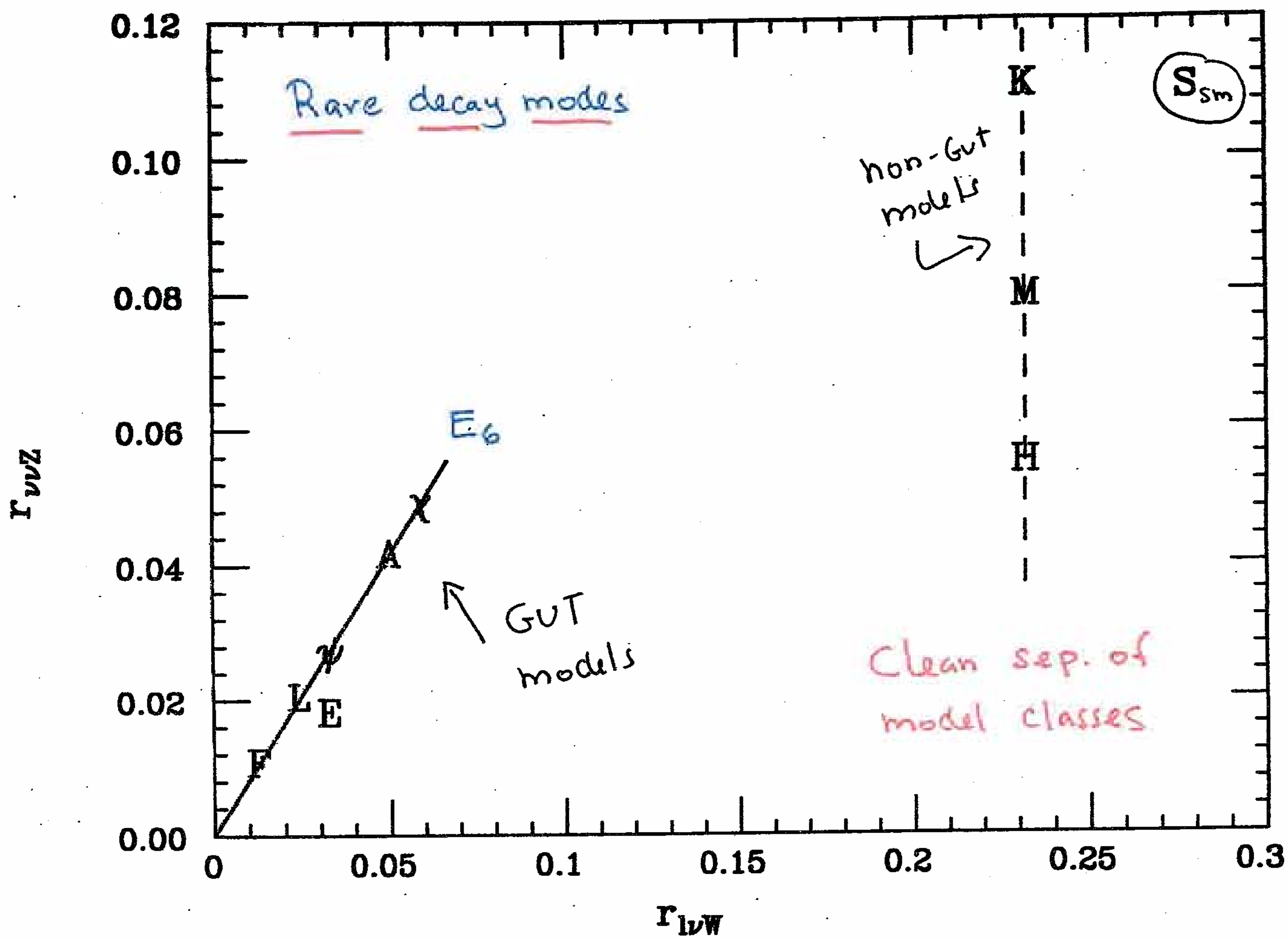

Fig. 1.18. Search study for the decay $Z' \to ZH$ by ATLAS in the Little Higgs model assuming $\cot\theta_H = 0.5$ for the $l^+l^-b\bar{b}$ mode assuming $M_{Z'}$=1 (a) or 2(b) TeV.

Azuelos et al, EPJ C39 s2 s13-s24 (2004)
Ros, Atl-phys-conf-2006-007

- This is also sensitive but less clean than $W^+W^-$ mode w/ lower statistics

$$r_{ff'V} \equiv \frac{\Gamma(Z' \to f f' V)}{\Gamma(Z' \to \ell^+ \ell^-)}$$

del Aguila, Cvetic + Langacker; Rizzo; Cvetic + Langacker; Hewett + Rizzo (187-192)




Clean model sep.

- no detector studies yet.

Huge lumi's required!

But: they are rare! need $\sim 10^4$ $Z \to \ell^+\ell^-$ events

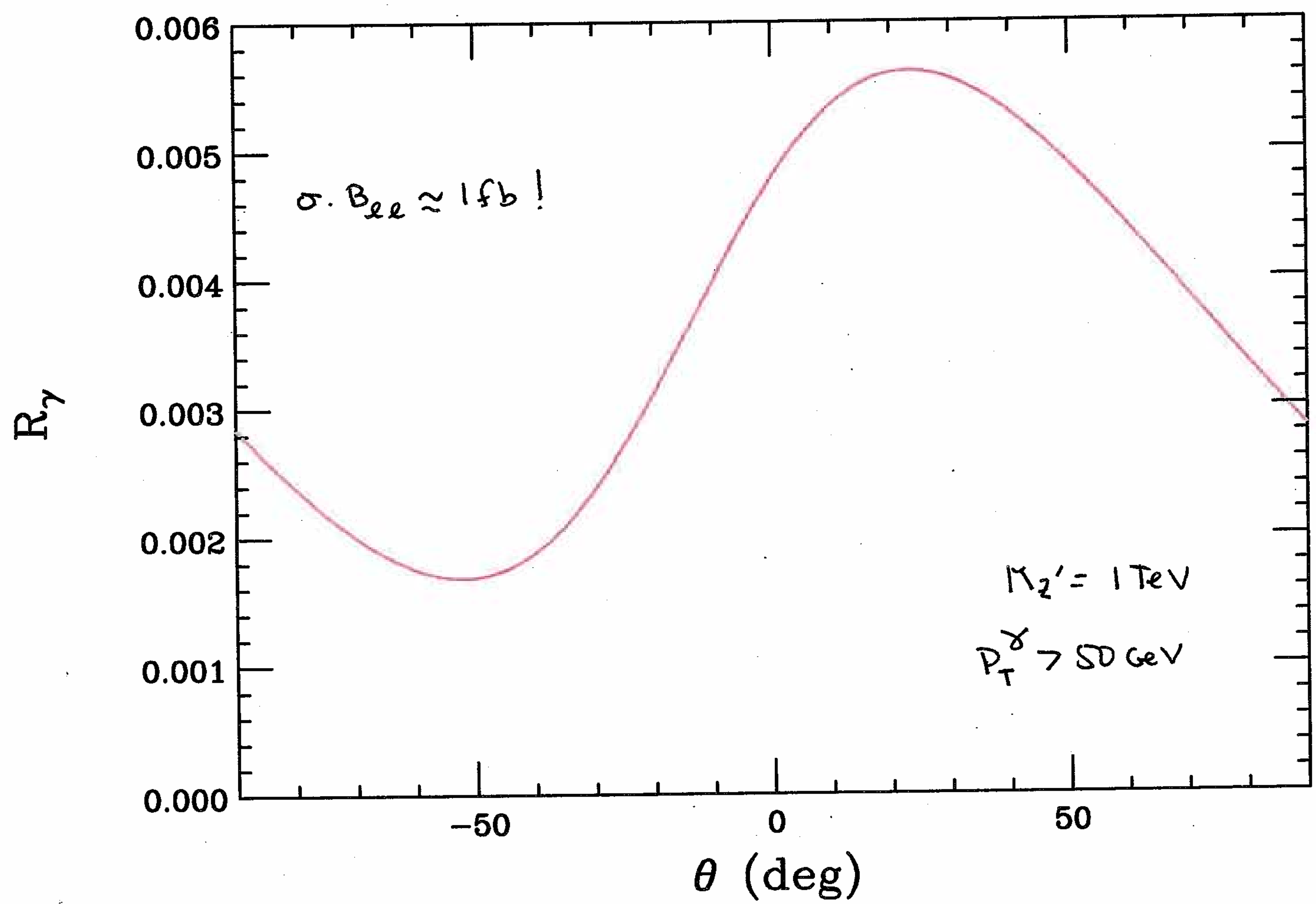
$\therefore$ $M_{Z'} \lesssim 1.5$ TeV only

## Associated Z' production

$$R_V = \frac{\sigma(q\bar{q} \to Z'V)}{\sigma(q\bar{q} \to Z')}.$$

reweights Z' couplings e.g, V=W $\sigma \sim (v_q + a_q)^2$

→ strong model sensitivity.




{ Rizzo ('93)
{ Langacker + Cvetic

− no experimental studies yet.*

low statistics

* See { Nepomuceno + Marroquim
Dilep/diphot subgroup of Exotics 9/28/06

→ Low rates → not useful if $M_{Z'} \gtrsim 1.5$ TeV

## Conclusions

- A light ($\sim 1$ TeV) $Z'$ can be rapidly discovered - measure spin!
- LHC data <u>WILL</u> be able to distinguish models w/ (a few) hundred event samples
- Going beyond the $\ell^+\ell^-$ mode will be difficult (but studies are still needed)
- True coupling determinations for $M_{Z'} \gtrsim 1$ TeV looks unlikely (though many studies still <u>not</u> done)
- ILC may (more than likely) be needed to 'clean-up' $Z'$ physics + discover "the framework"...

⇒ Of course, things 'Probably will Change' (if) a $Z'$-like object <u>is</u> discovered.. Experimenters are <u>clever</u> w/ data!!

LHC physics will be exciting!!