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

- Model Sampler ($\sim 10^3$'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, Γ, σ_{pk}, couplings, Z-Z' mixing (ϕ), ...)

- 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 }

  $U(1)_\theta$ = $C_\theta U(1)_\psi - S_\theta U(1)_\chi$

  (θ 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) : $E_6/SO(10) \to SU(2)_L \times SU(2)_R \times U(1)_{B-L}$

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

  ↑ Z'+W' !

- 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 !! { Low Energy* ; High Energy $\Rightarrow$ LEP II

* 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

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

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

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

$\Rightarrow$ 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, eg, Z'.. ($m_{Z'} \approx$ few $\sqrt{s}$)

LEPEWWG

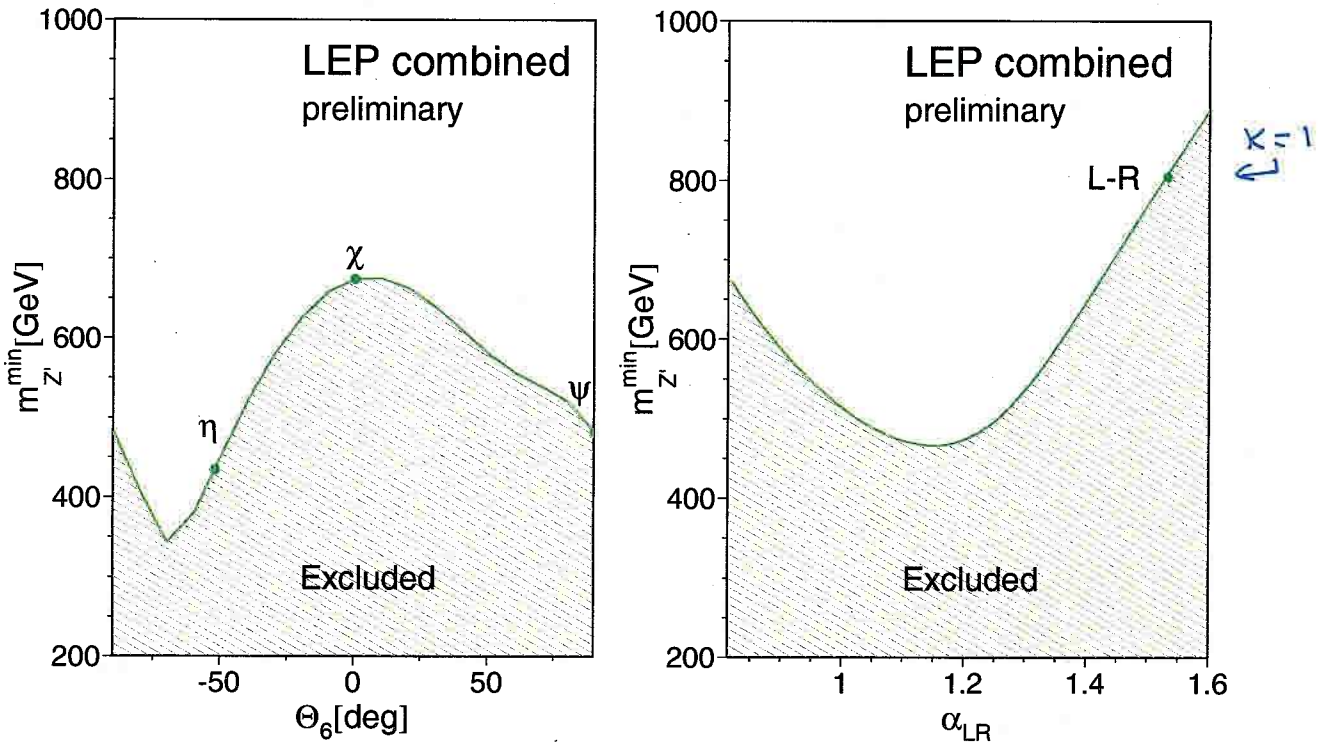


Figure 10: The 95% confidence level limits on $M_{Z'}$ as a function of the model parameter θ_6 for E_6 models and α_{LR} for left-right models. The Z-Z′ mixing is fixed, $\Theta_{ZZ'} = 0$.

Z′ model	χ	ψ	η	L-R	SSM
$M^{limit}_{Z'}$ (GeV/c^2)	673	481	434	804	1787

Table 15: The 95% confidence level lower limits on the Z′ mass for χ, ψ, η, L-R and SSM models.

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

→ Model dependent !

4)

Direct Tevatron Searches

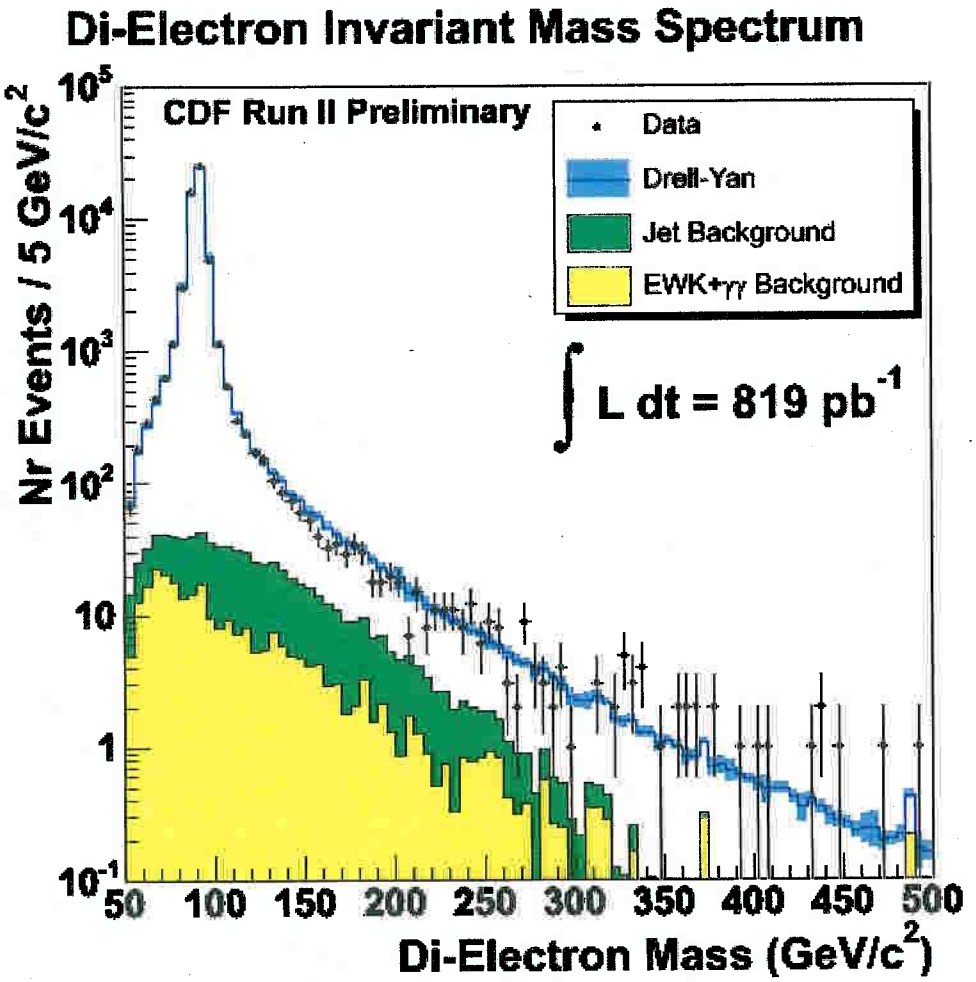
- $p\bar{p}^{(-)} \to l^+l^- + X$, Z' appears as a peak just like Z_{SM} ... but heavier!

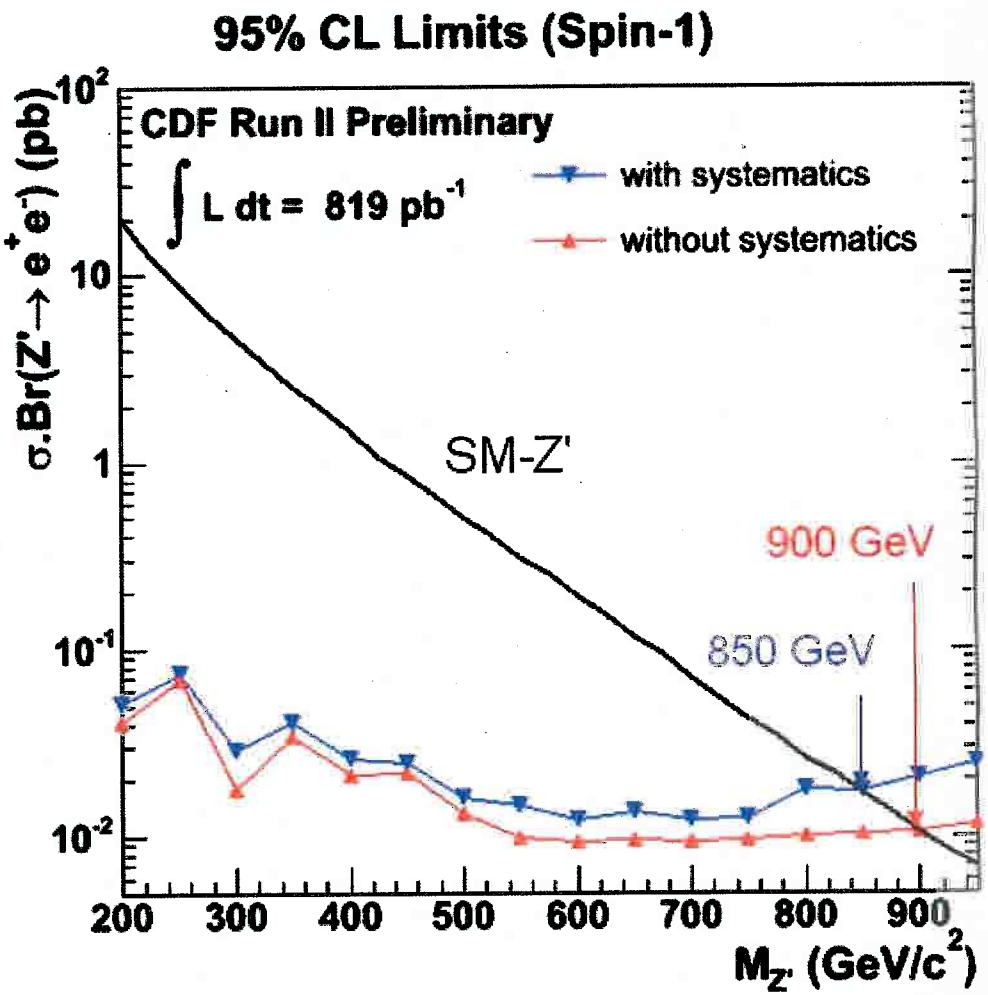
  Drell-Yan process

- given understanding of backgrounds → constrain $\sigma_{Z'} \cdot B(Z' \to l^+l^-)^*$ 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 $\mathcal{L} \uparrow$ ...
  - $\mathcal{L}$ now approaching $\approx 2\,fb^{-1}$, but only $\approx 0.8\,fb^{-1}$ analyzed as of Summer '06

* Note: limit is sensitive to $B(Z' \to l^+l^-)$ ... assume $Z' \to SM$ 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 A_{FB} !)

6)

Other Z′ models...

Z' Model	Z_{SM}	Z_χ	Z_ψ	Z_η	Z_I	Z_N	$Z_{\rm sec}$	$Z_H^{0.3}$	$Z_H^{0.5}$	$Z_H^{0.7}$	$Z_H^{1.0}$
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

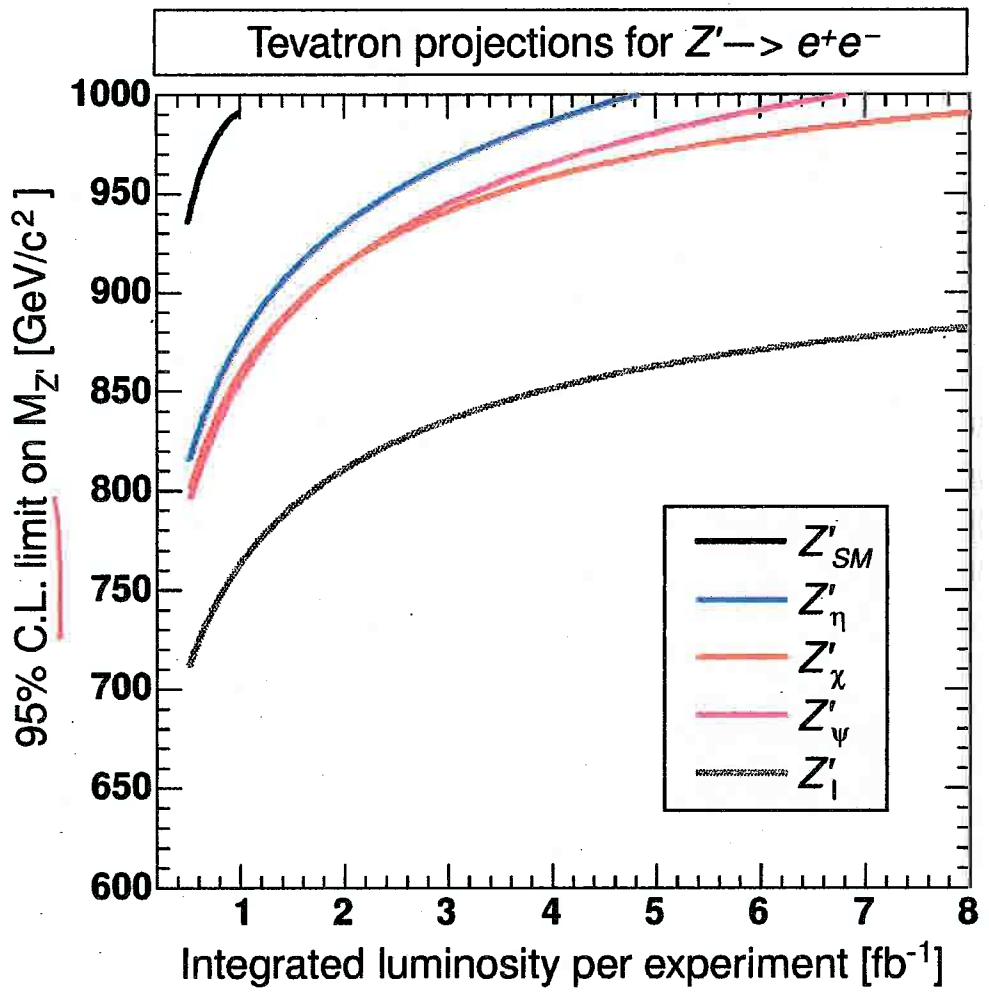
↑ ssm — E_6 — LH

- As the possible Z′ couplings vary the 95% CL lower bound moves around; Generally Z'_{ssm} is the most strongly constrained as it has large 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 ~ 1 TeV; $M_{Z'} \gtrsim 1$ TeV is open for LHC !! ["narrow" Z' maybe missed]

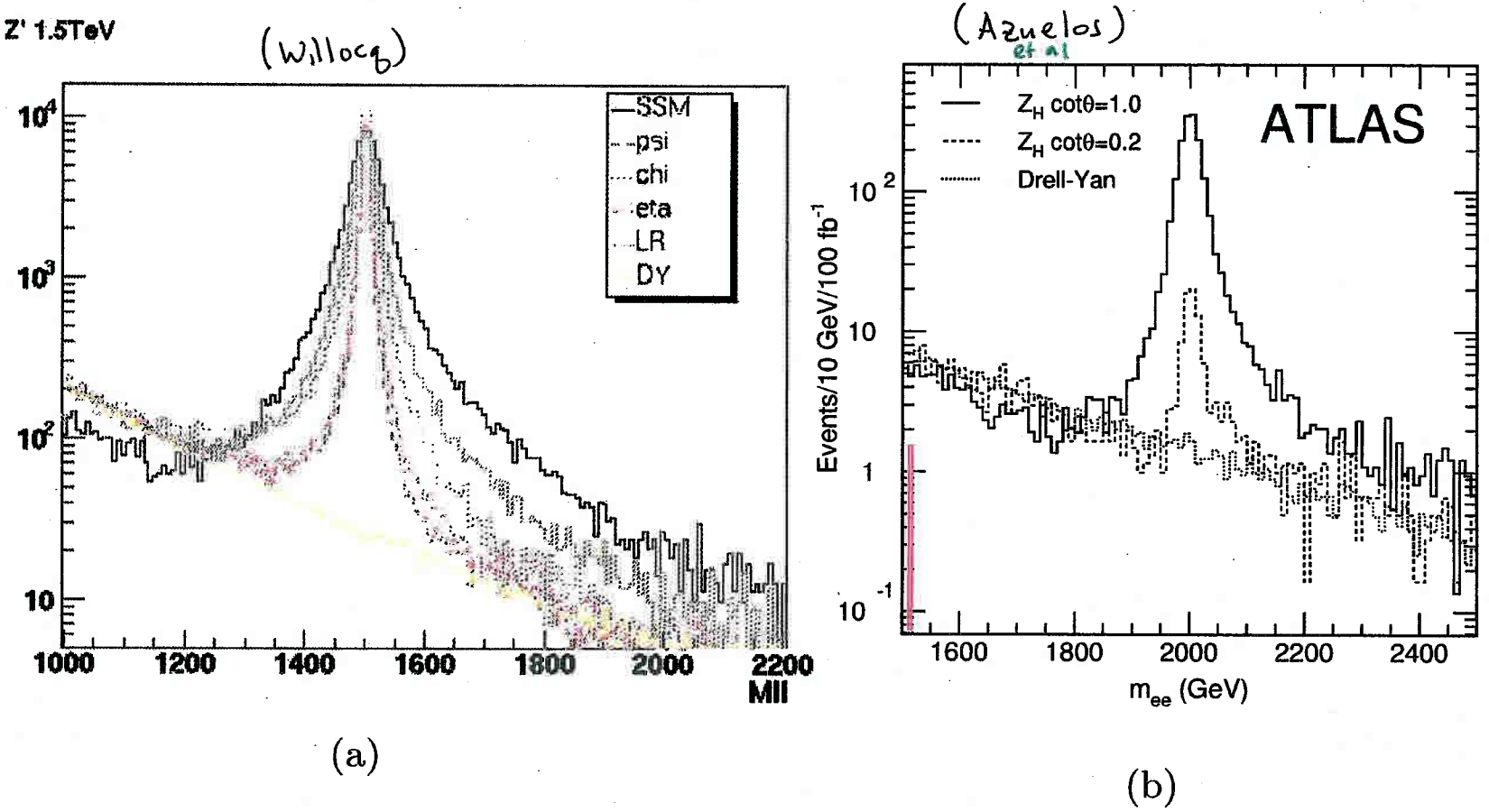


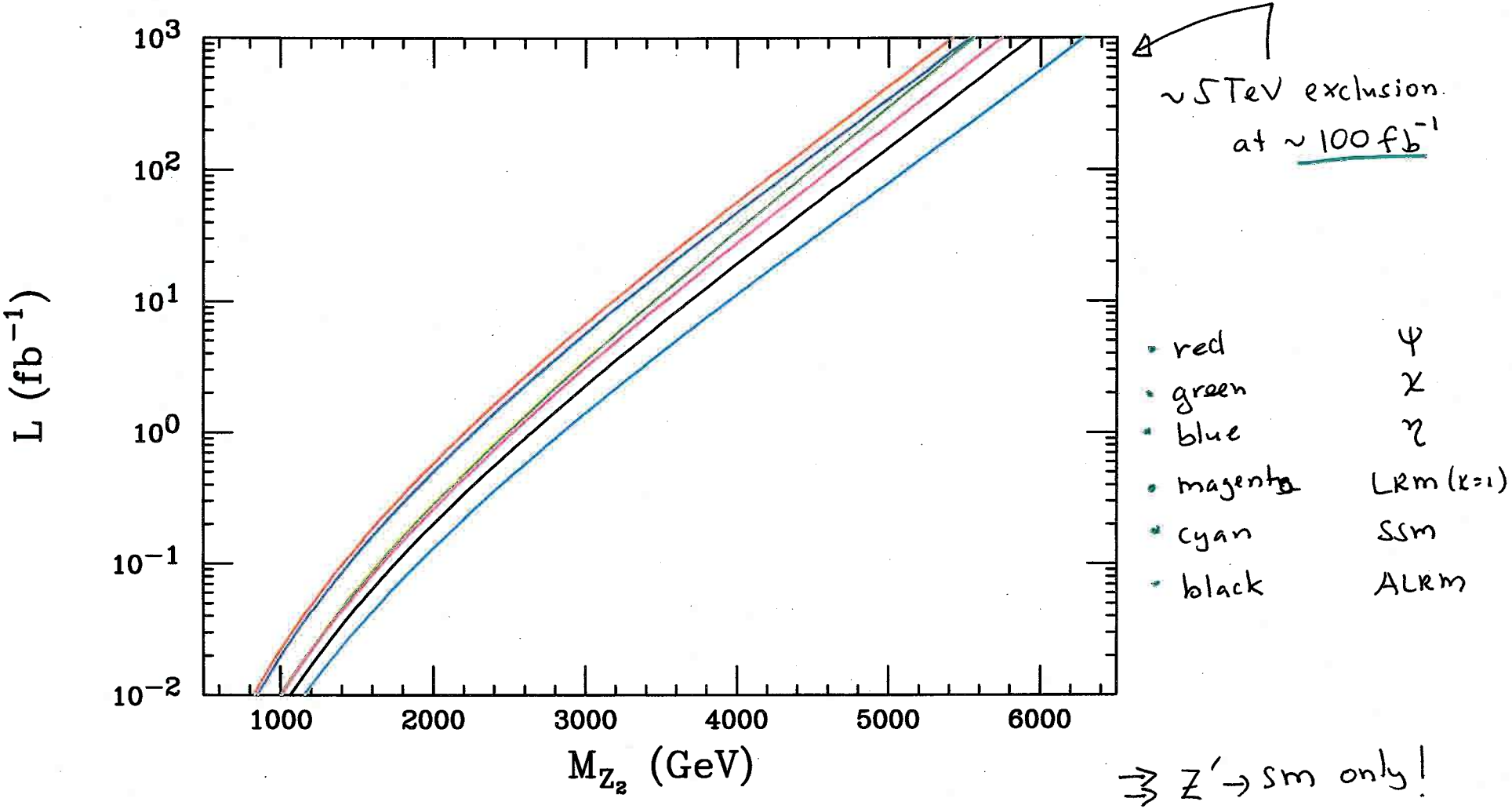
Fig. 1.8. Resonance shapes for a number of Z' models as seen by ATLAS assuming $M_{Z'} = 1.5$ TeV. The continuum is the SM Drell-Yan background.

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

a)

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

95% CL lower bound if nothing seen...



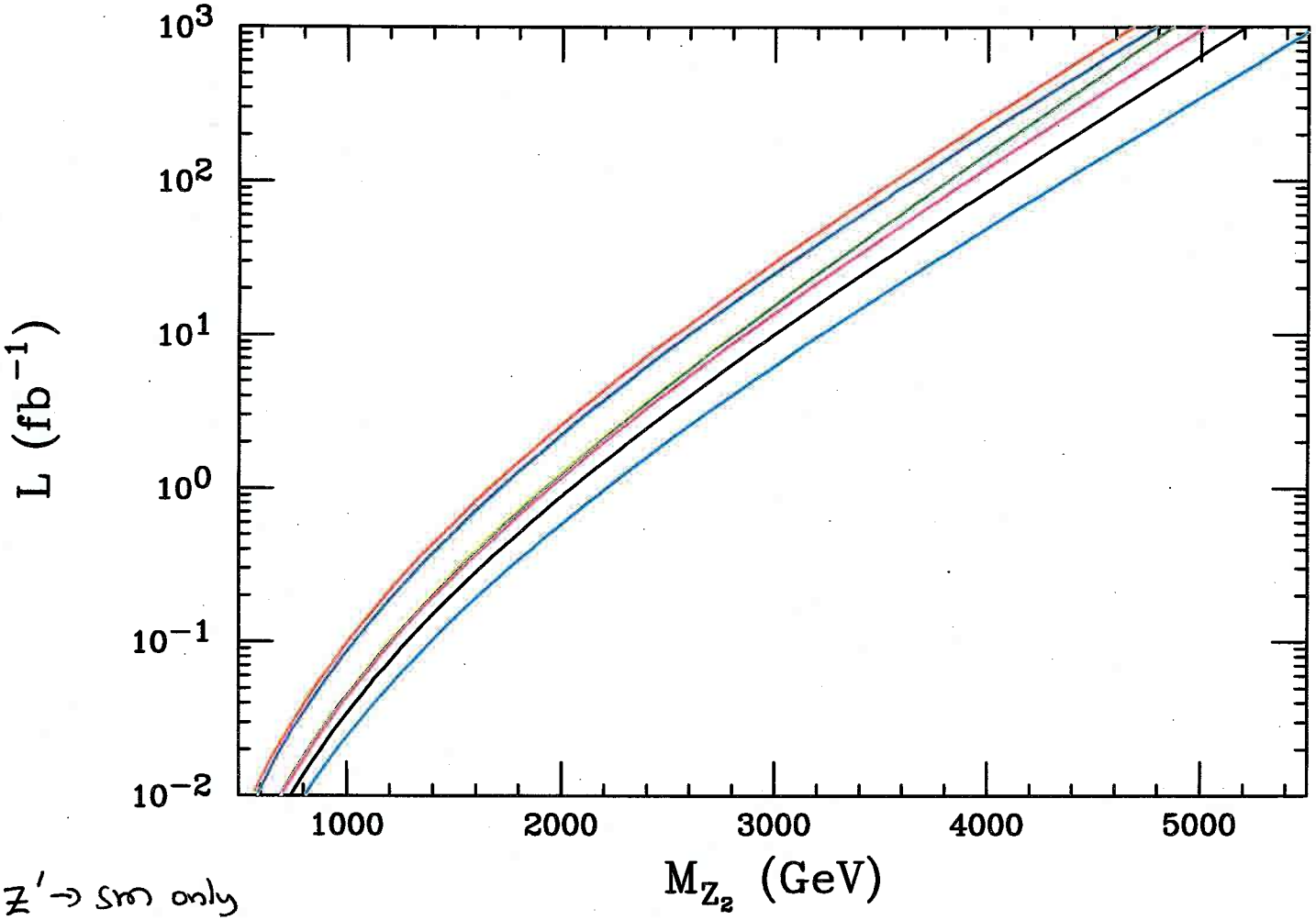
⇒ $Z' \to$ sm only!

$B \to B/2$ ↓ 10%

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

First new physics ??

5σ Discovery of Z'



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

- red ψ
- green χ
- blue η
- magenta LRm (k=1)
- cyan Ssm
- black ALRm

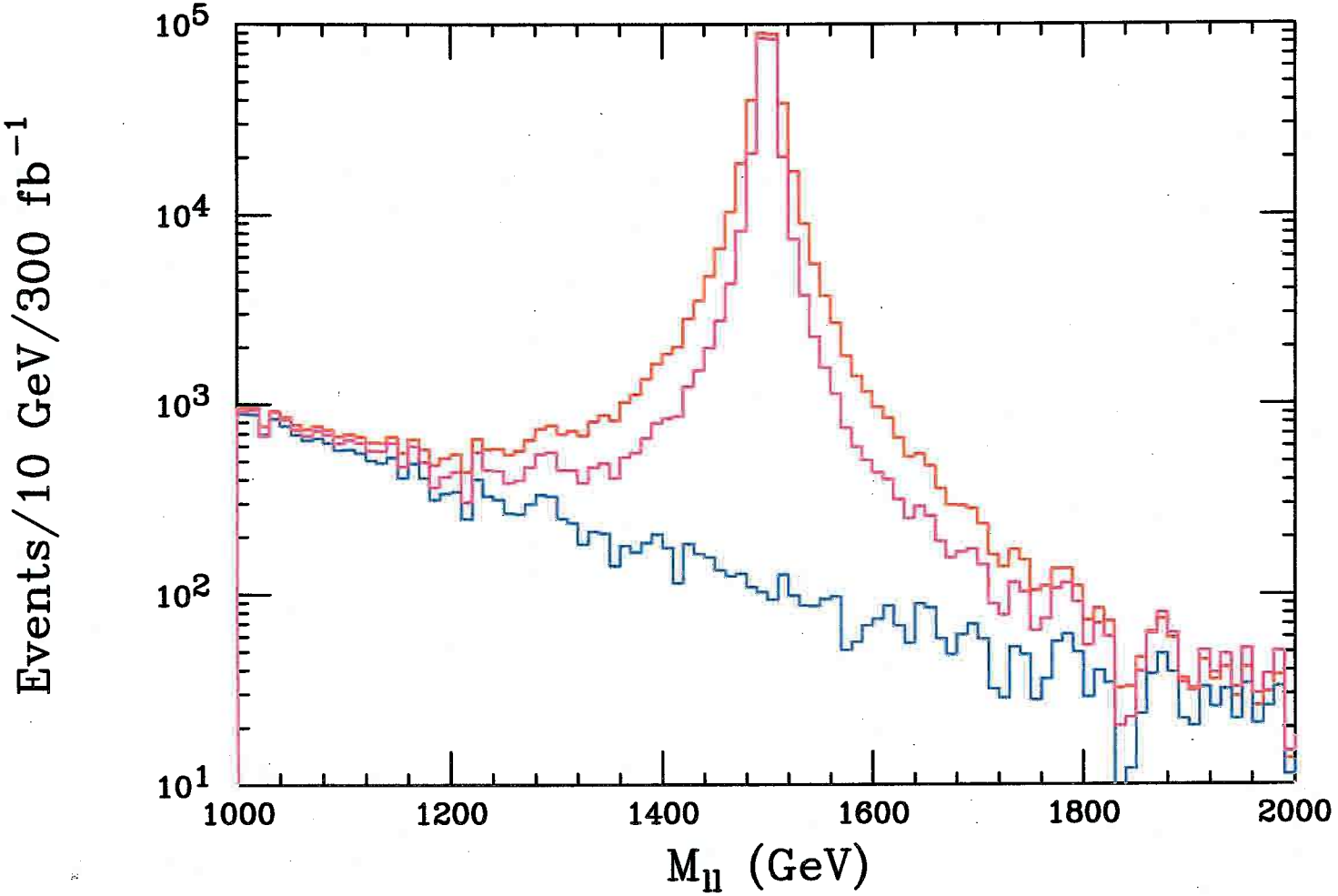
$Z' \to$ sm only

$B \to \frac{B}{2}$ reach ↓ 10%

... but is IT REALLY a Z' ?

11)

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) $[\approx 1.3]$

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

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

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

masses + widths of exchanges

$\gamma, Z, Z', \ldots$

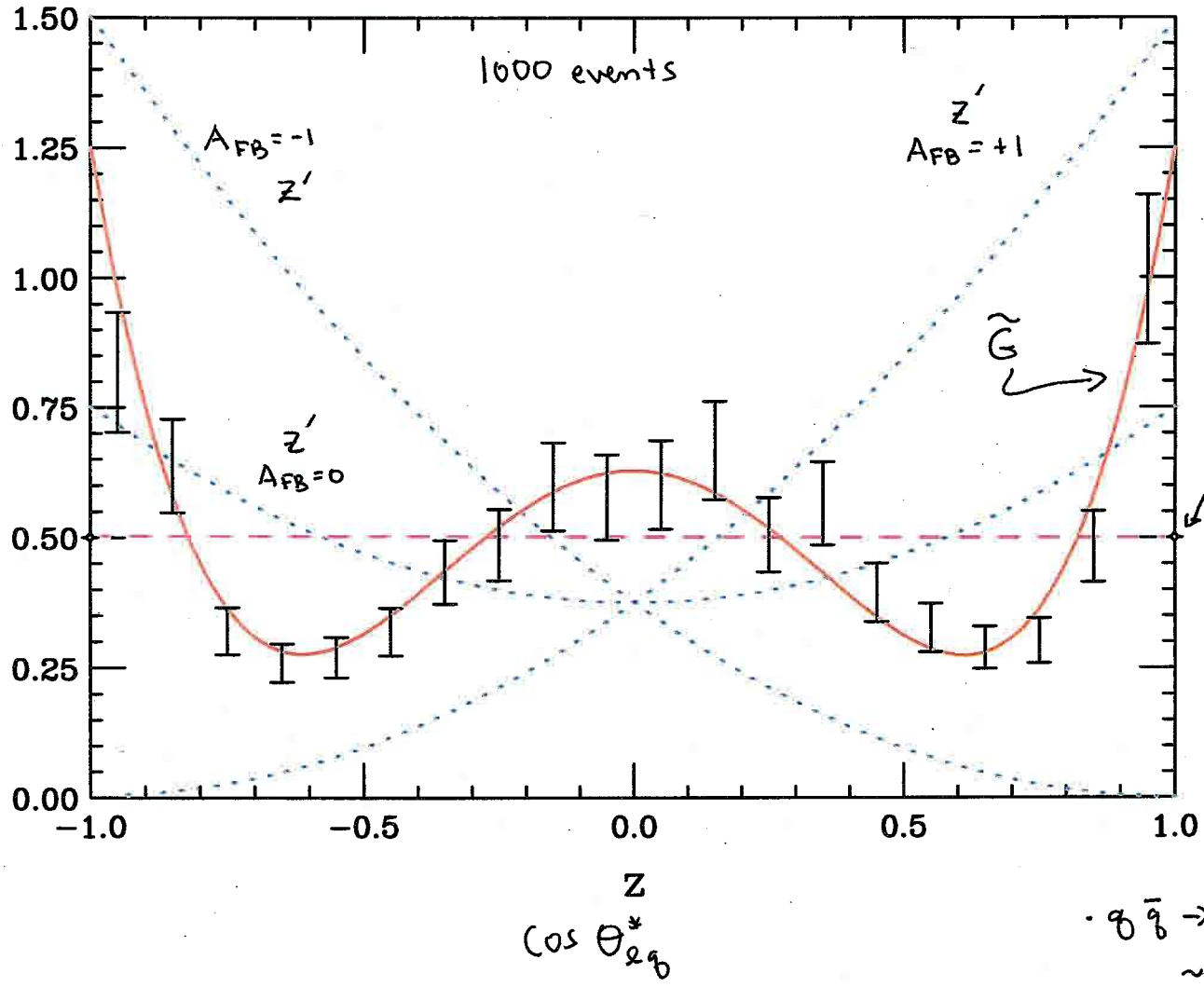
$$\bullet\ P_{ij} \equiv M^4 \cdot \frac{(M^2 - M_i^2)(M^2 - M_j^2) + (M_i \Gamma_i)(M_j \Gamma_j)}{\left[(M^2 - M_i^2)^2 + (\Gamma_i M_i)^2\right]\left[\, i \to j \,\right]}$$

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

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

NOTE!!

Measurements of lepton angular distributions are necessary to determine "Z'" spin



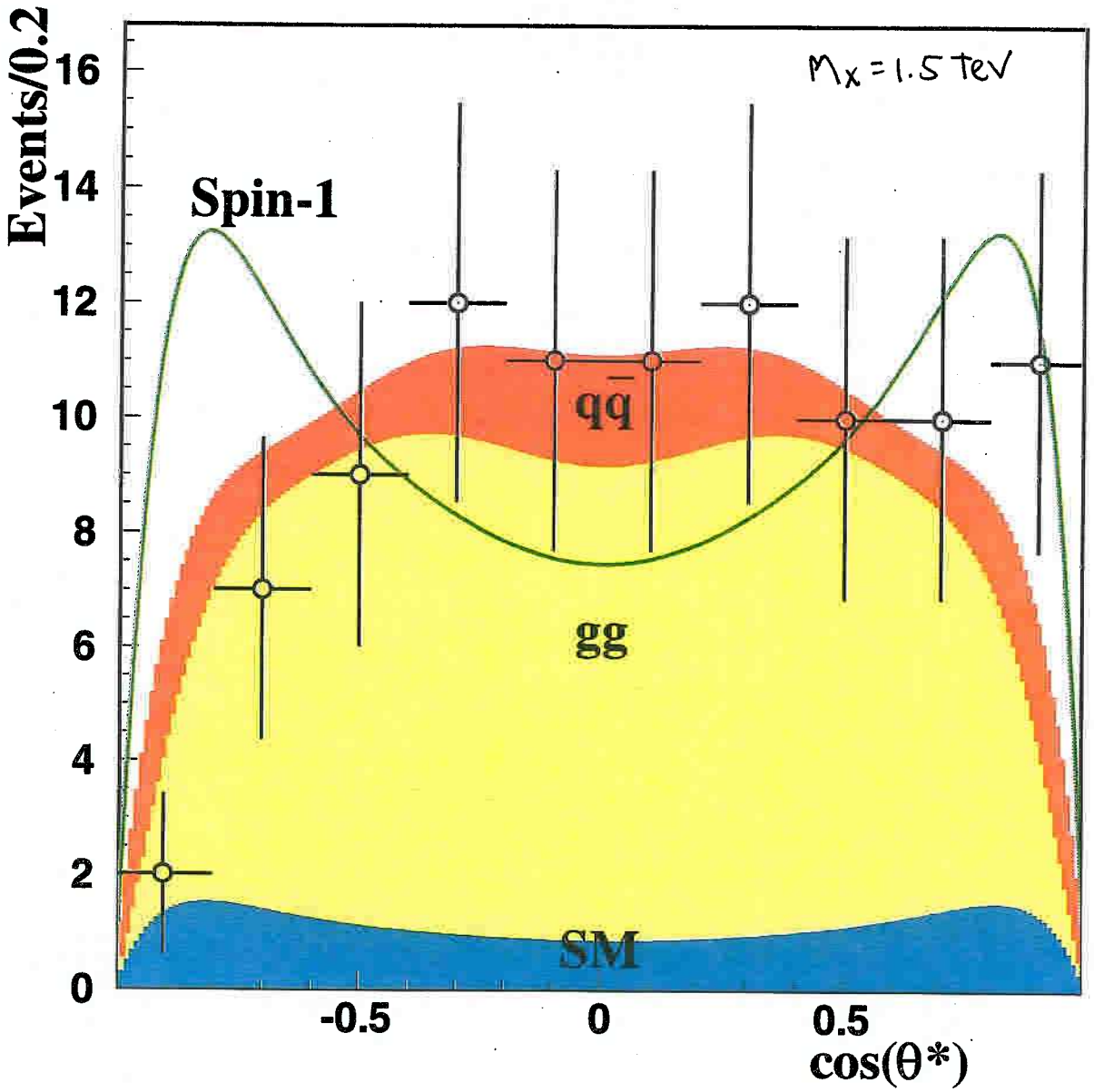
(spin-0 : $\tilde{\nu}$ ✗
spin-2 : KK grav ✓)

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

→ Need a few hundred events!

But!

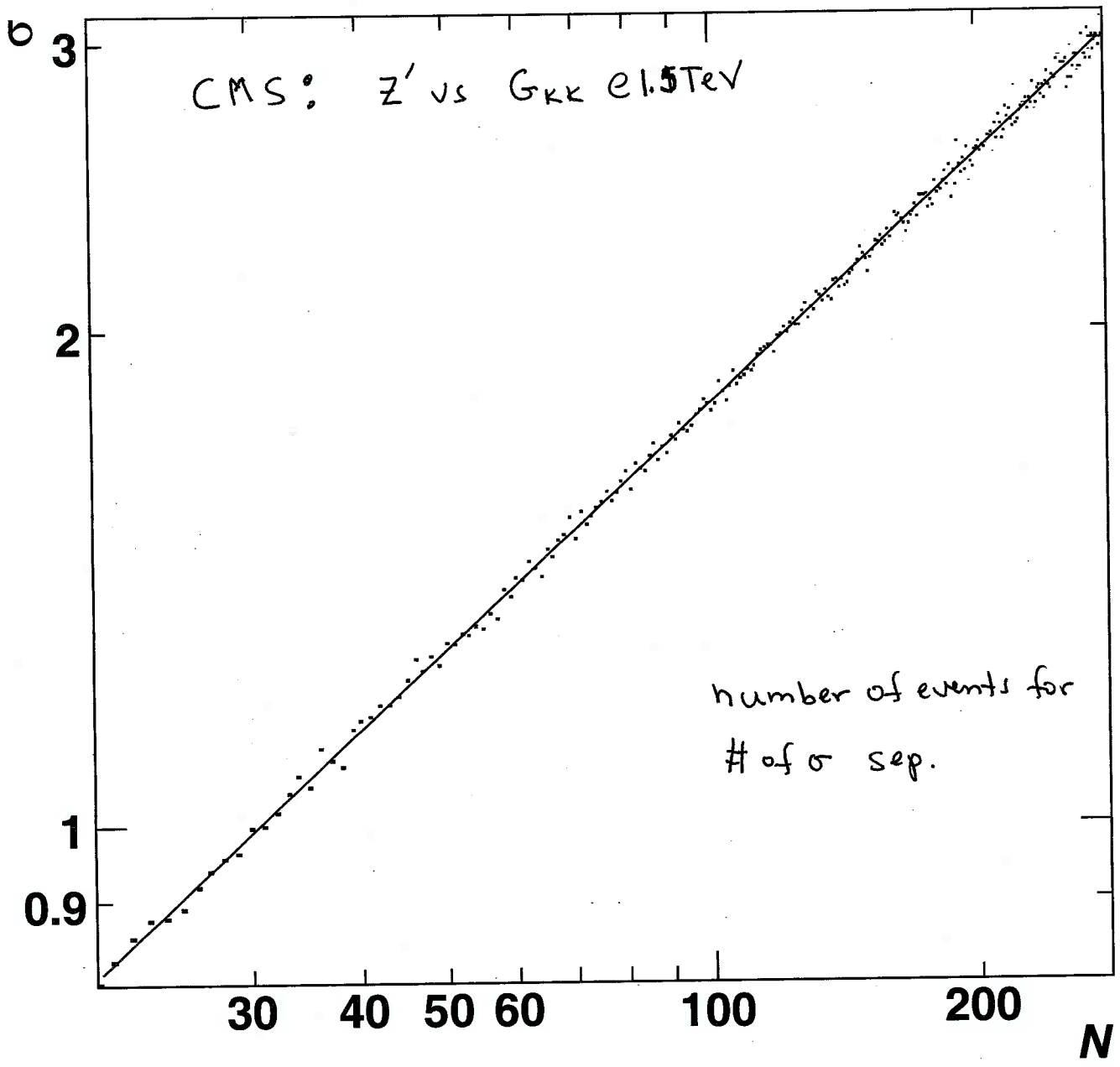
- $q\bar{q} \to Z' \to \ell^+\ell^-$ $\sim (1+z^2) + \frac{8}{3} A_{FB}\, z$



Z' vs Graviton kk

in ATLAS

Allanach etal (hep-ph/0006114)



Cousins et al
JHEP 0511 046 ('05)

← 3σ sep requires
~300 events

- Many more than discovery!

∴ spin analysis cannot be done for very heavy Z′..
~ 2.5-3 TeV ??
(~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' : $M_{Z'}$, $\Gamma_{Z'}$, σ_{ll} !

$\Rightarrow$ 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 $\Gamma_{Z'}$ + σ_{ll} are sensitive to $Z' \rightarrow$ non-SM particles

[susy, exotic fermions, who knows what ?]

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

What else can we measure ? ?

ATLAS DC1 Study

Shäfer, Ledroit & Trocme

Atl-phys-pub-2005-010

		M_{rec} (GeV)	Γ_{rec}(GeV)	Γ_{gen}(GeV)	$\Gamma_{theo.}$(GeV)
$M = 1.5$ TeV	SSM	1500.7± 0.7	46.6± 1.4	47.0± 0.9	44.7
	ψ	1500.2± 0.3	7.8± 0.6	7.1± 0.5	8.0
	χ	1500.8± 0.4	17.1± 0.9	18.4± 0.5	17.6
	η	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*

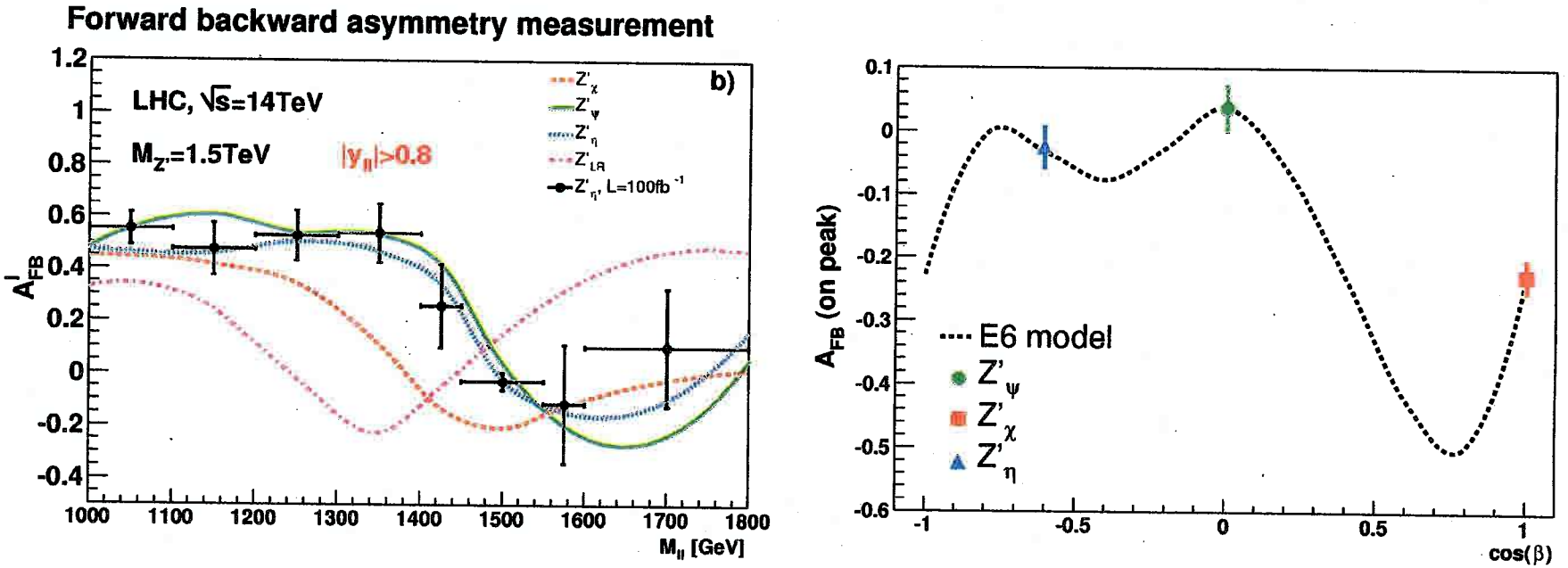
		σ_{ll}^{gen}(fb)	σ_{ll}^{rec}(fb)	$\sigma_{ll}^{rec} \times \Gamma_{rec}$(fb.GeV)
$M = 1.5$ TeV	SSM	78.4±0.8	78.8±1.8	3668±138
	ψ	22.6±0.3	22.7±0.6	178±13
	χ	47.6±0.6	48.4±1.3	828±48
	η	26.2±0.3	25.1±0.6	223±15
	LR	50.8±0.6	51.1±1.3	1515±75
$M = 4$ TeV	SSM	0.16±0.02	0.15±0.03	14±6
	KK	2.2±0.07	2.2±0.12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

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

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

(generator = PYTHIA)

A_{FB}



(a) (b)

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 $A_{FB} \simeq \frac{d\bar{\sigma}/dM}{d\sigma^t/dM}$, 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	$+0.088 \pm 0.013$	$+0.060 \pm 0.022$	$+0.108 \pm 0.027$
χ	100	-0.386 ± 0.013	-0.144 ± 0.025	-0.361 ± 0.030
η	100	-0.112 ± 0.019	-0.067 ± 0.032	-0.204 ± 0.039
η	300	-0.090 ± 0.011	-0.050 ± 0.018	-0.120 ± 0.022
ψ	100	$+0.008 \pm 0.020$	-0.056 ± 0.033	-0.079 ± 0.042
ψ	300	$+0.010 \pm 0.011$	-0.019 ± 0.019	-0.011 ± 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	$+0.077 \pm 0.025$	$+0.086 \pm 0.038$	$+0.171 \pm 0.045$
χ	100	$+0.440 \pm 0.019$	$+0.180 \pm 0.032$	$+0.354 \pm 0.039$
η	100	$+0.593 \pm 0.016$	$+0.257 \pm 0.033$	$+0.561 \pm 0.039$
ψ	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*

$0.8 \leq M_{ee} \leq 1.4$ 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..

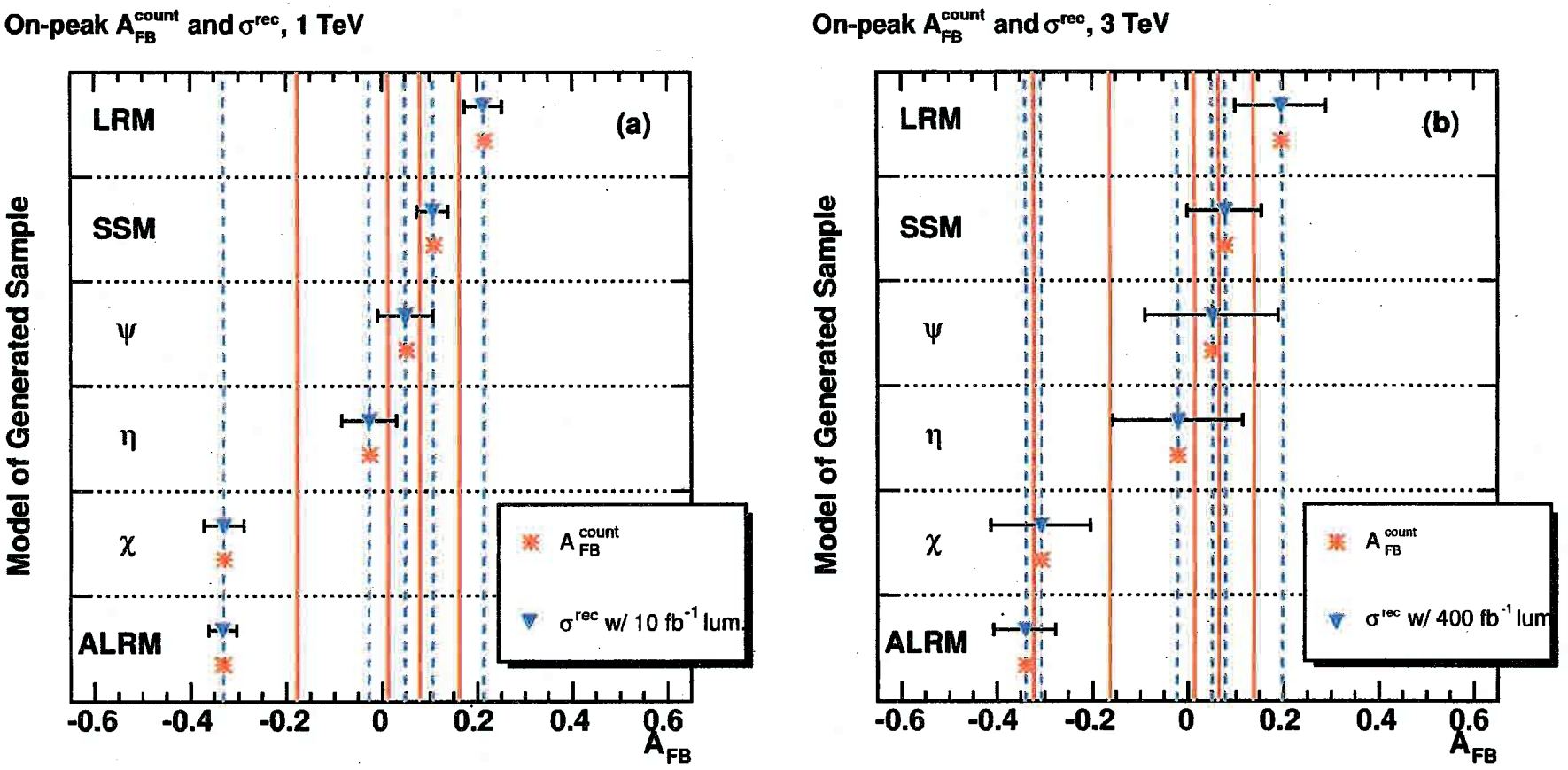


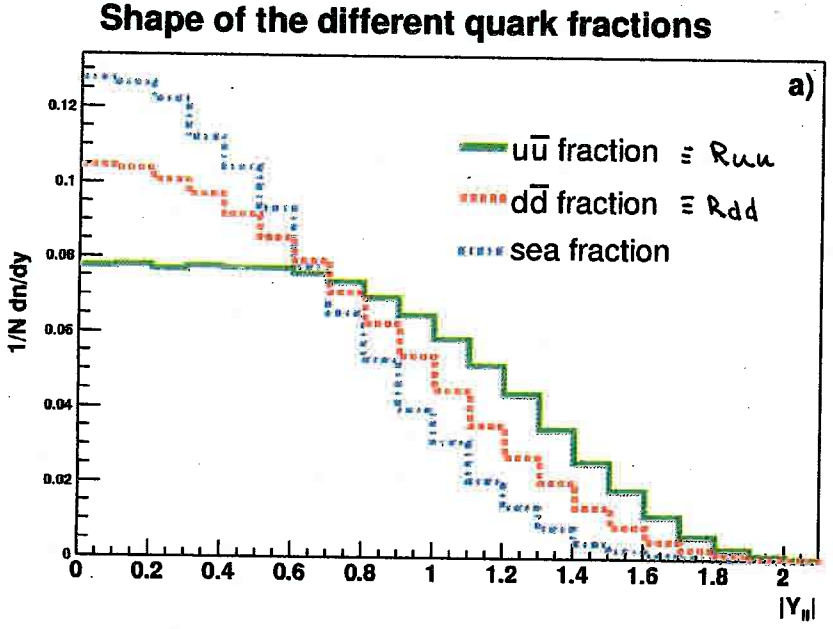
Fig. 1.11. CMS analysis of Z' model differentiation employing A_{FB} assuming $M_{Z'} = 1$ or 3 TeV.

Cousins, Mumford + Valuev CMS note 2005/022

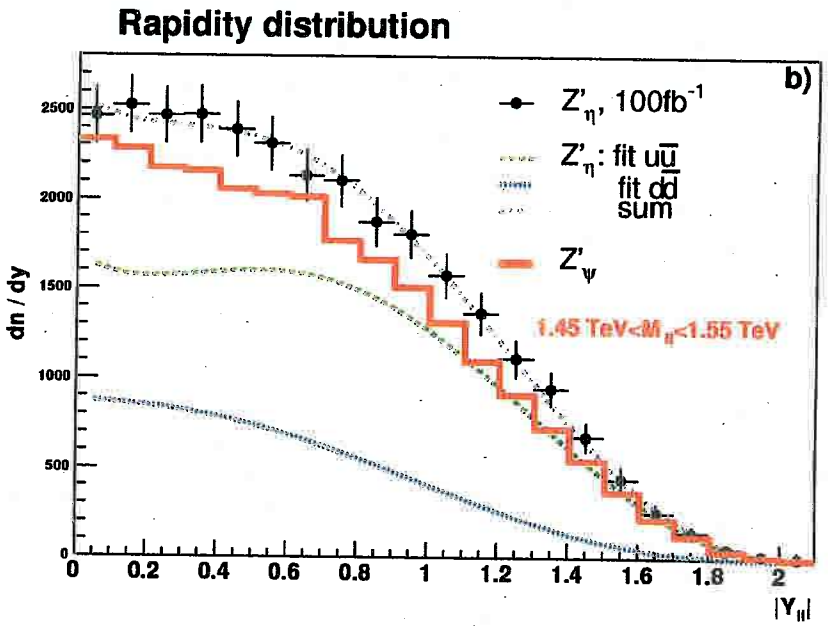
→ Relatively, easy to sep. models...

What about other leptonic observables ?

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. if PDF's are known, the Ruu, dd → $(v_u^2+a_u'^2)/(v_d'^2+a_d'^2)$...

DC1 Study by ATLAS

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.
χ	62.±12.	29.±14.	79.±17.	17.±19.
η	23.±13.	75.±14.	33.±6.	67.±8.
ψ	36.±12.	61.±13.	32.±15.	62.±17.
LR	57.±4.	43.±14.	53.±13.	46.±15.

$M_{Z'}$=1.5 TeV

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 Run,dd poorly determined unless high-lumi available.
- Anything else w/ leptons ?

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

Rapidity Ratio

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

$\approx$ central / forward leptons

· del Aguila etal ('93)

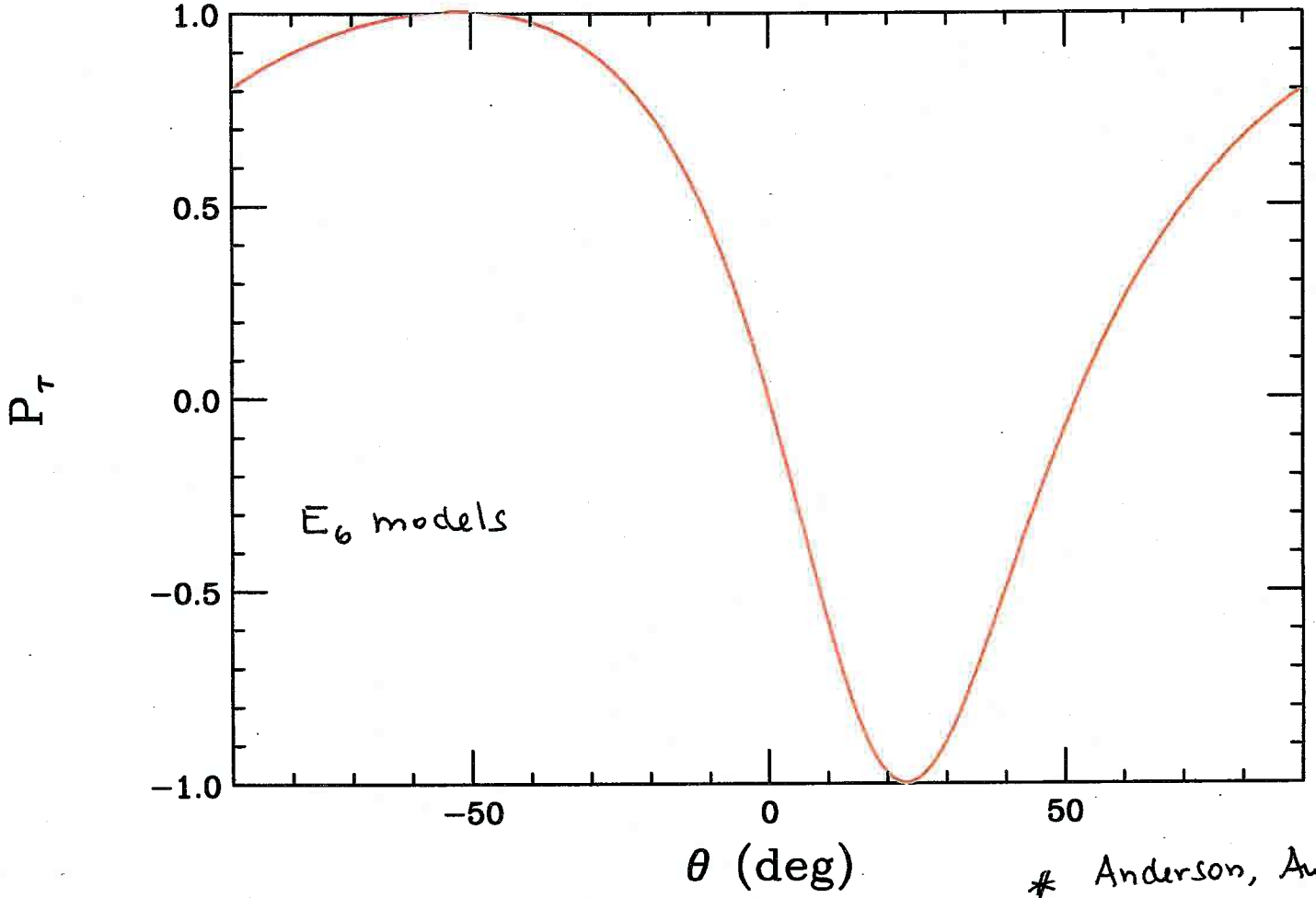
→ no detector studies (yet)

... 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



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

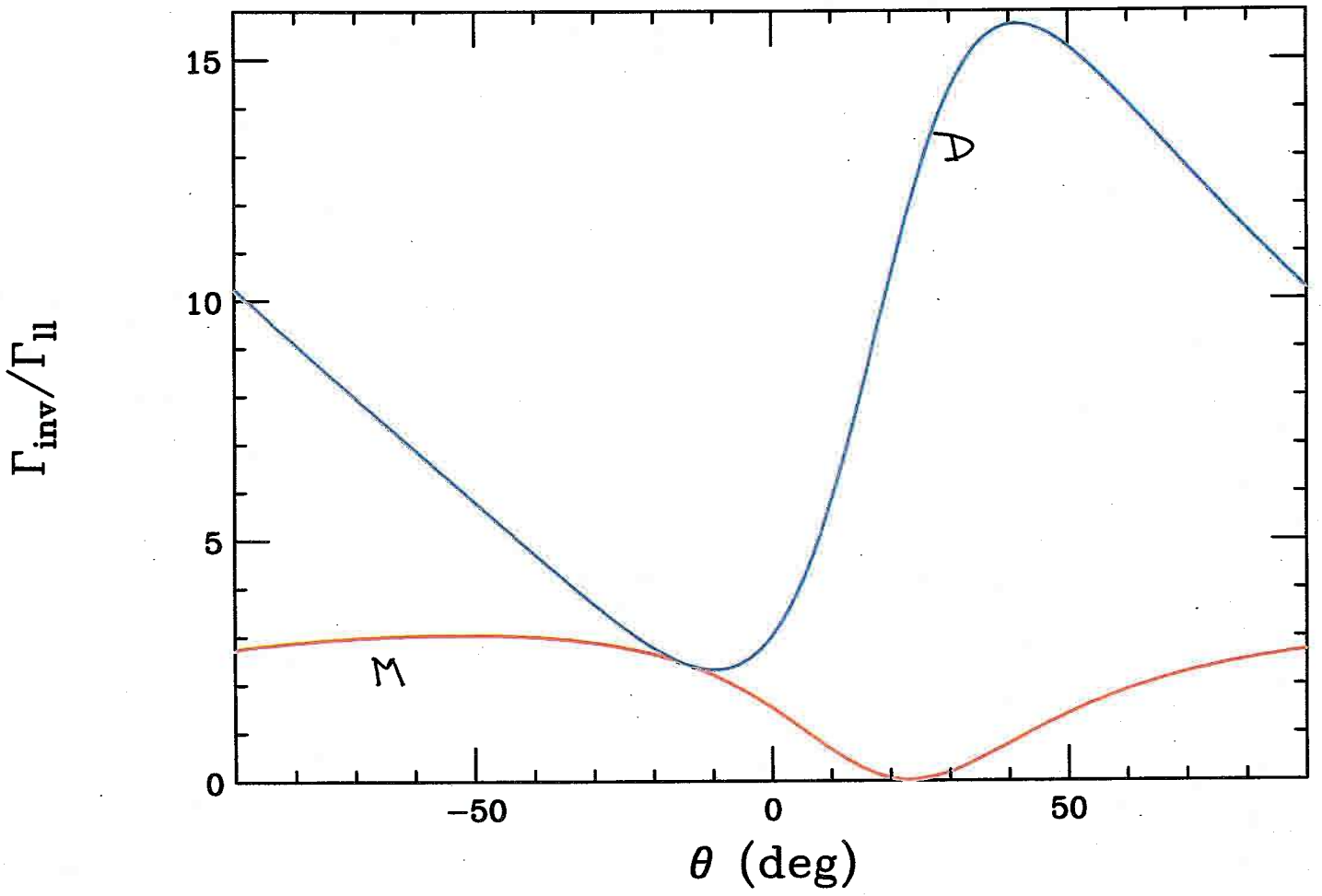
Clearly has coupling sensitivity...

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

(B insensitive)

* Anderson, Austern & Cahn,
PRD 46, 2980 '92
PRL 69, 25 '92

Dirac vs Majorana neutrinos ??



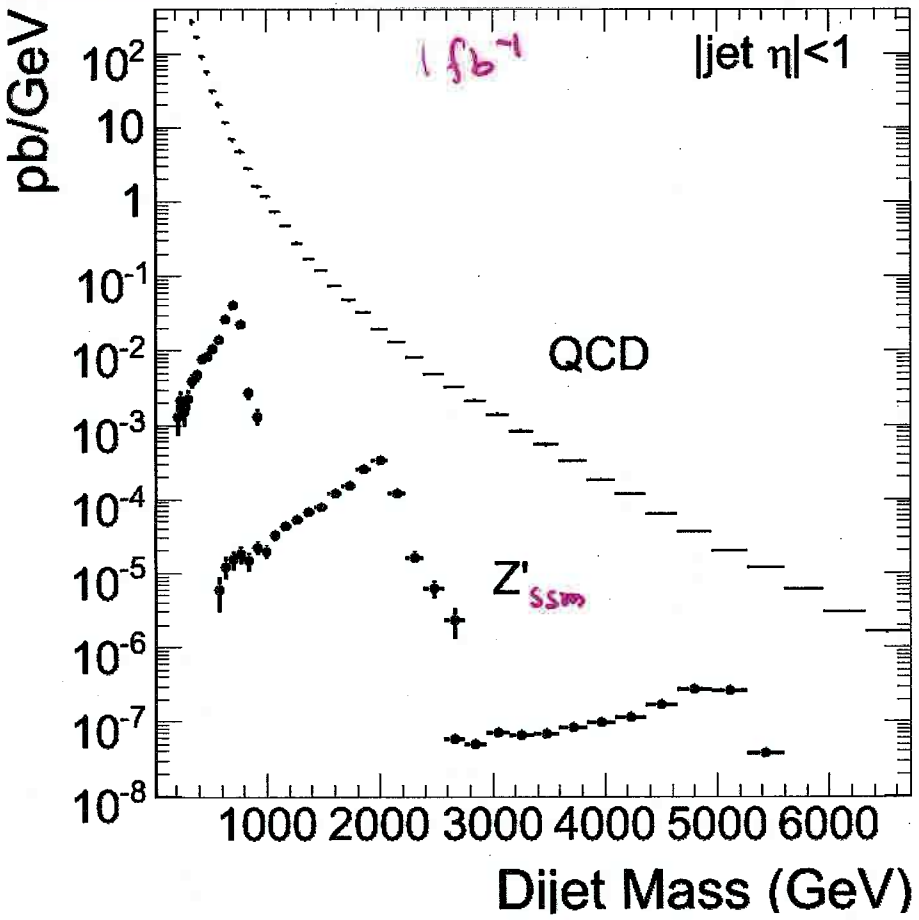
.. this may be the only clean way to ever know!

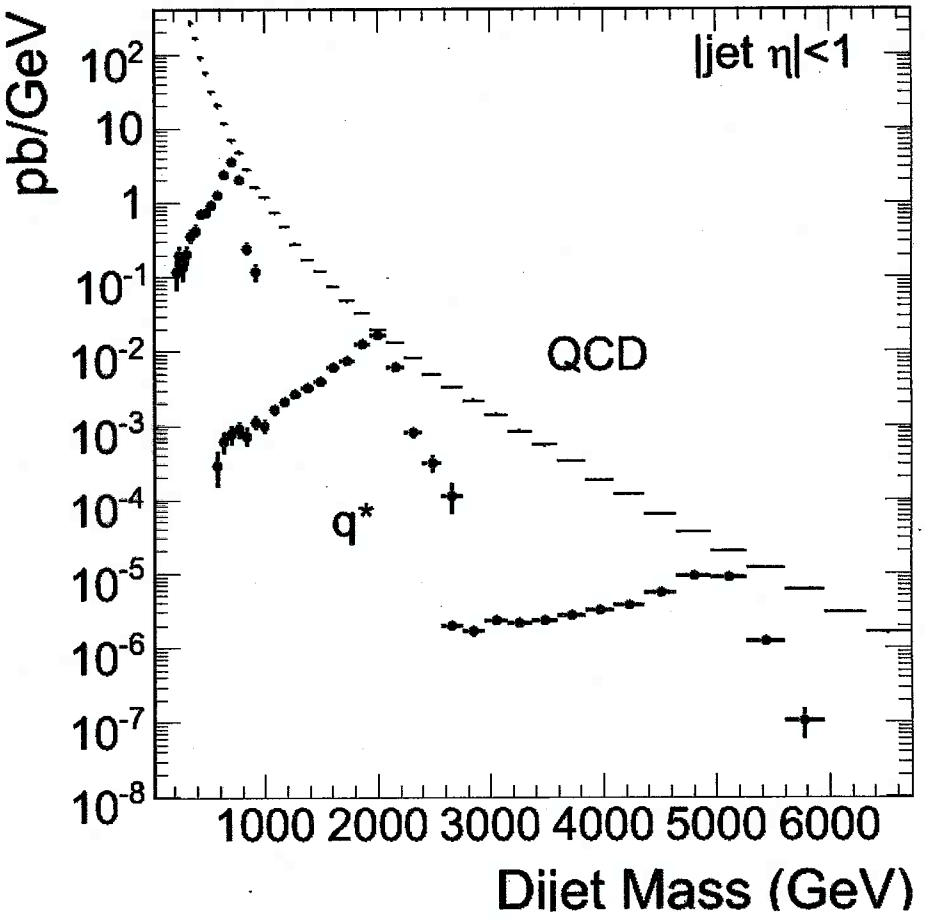
Too bad....

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

Very difficult to see $Z' \to jj$

Signal and Background





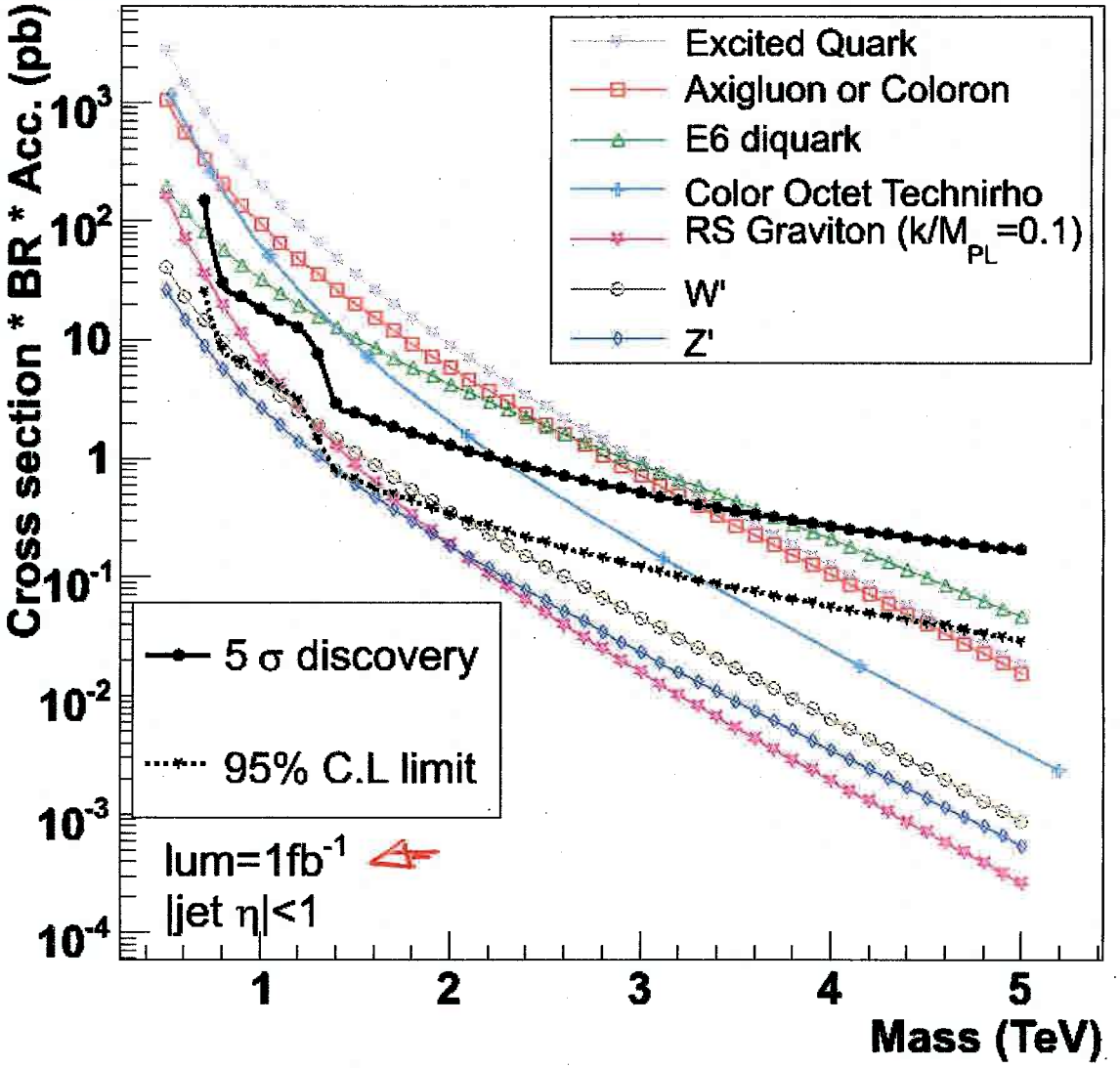
- QCD cross section falls smoothly as a function of dijet mass.
- Resonances produce mass bumps we can see if xsec is big enough.

Gumus et al
Cms note 2006/070

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

Sensitivity to Resonance Cross Section

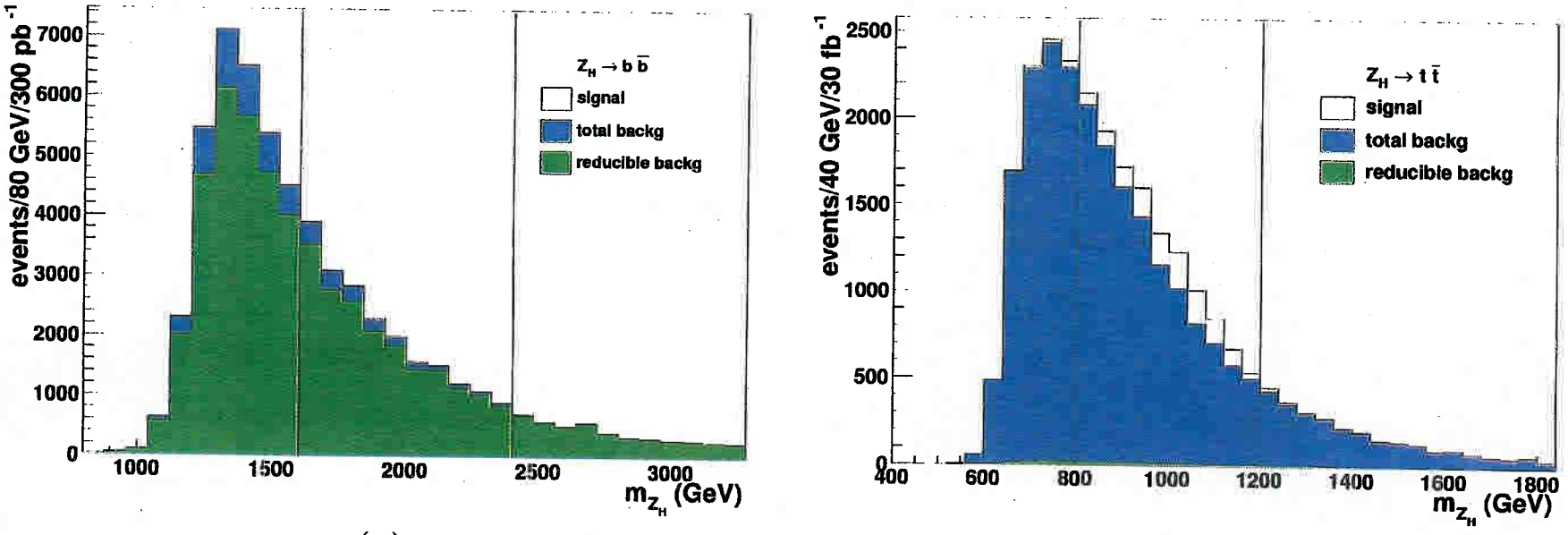
- Cross Section for Discovery or Exclusion
  - Shown here for 1 fb^{-1}
  - Also for 100 pb^{-1}, 10 fb^{-1}
- Compared to cross section for 8 models
- CMS expects to have sufficient sensitivity to
  - Discover with 5σ significance any model above solid black curve
  - Exclude with 95% CL any model above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



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

29

$Z' \rightarrow$ heavy flavors ??



(a) (b)

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. $Z' \rightarrow b\bar{b}$ 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

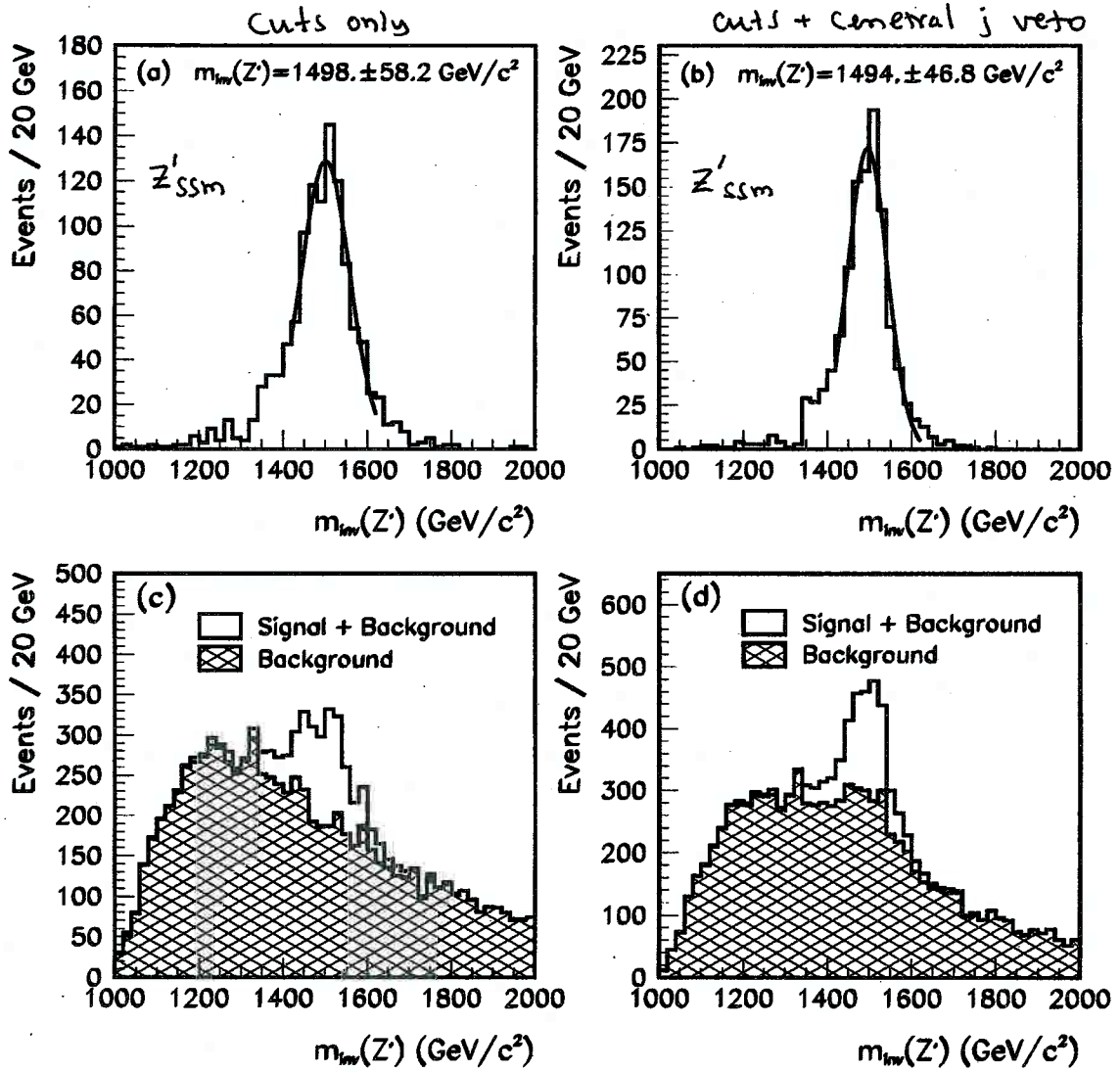
- Doesn't look too promising .. more work necessary for $t\bar{t}$ case .. but $Z' \rightarrow b\bar{b}$ (in this case) looks invisible

→ More general study needed !

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

(can be mixing induced)

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



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

Fig. 1.17. Results of two ATLAS 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 $\beta = 1$. ($\phi \simeq \beta (\Gamma_Z/\Gamma_{Z'})^2$)

Benchekroun, Driouichi + Hoummada - old analysis

SN-Atl-2001-001

Update? (DeRoeck) (cms)

$Z' \to Zh$ in Little Higgs models

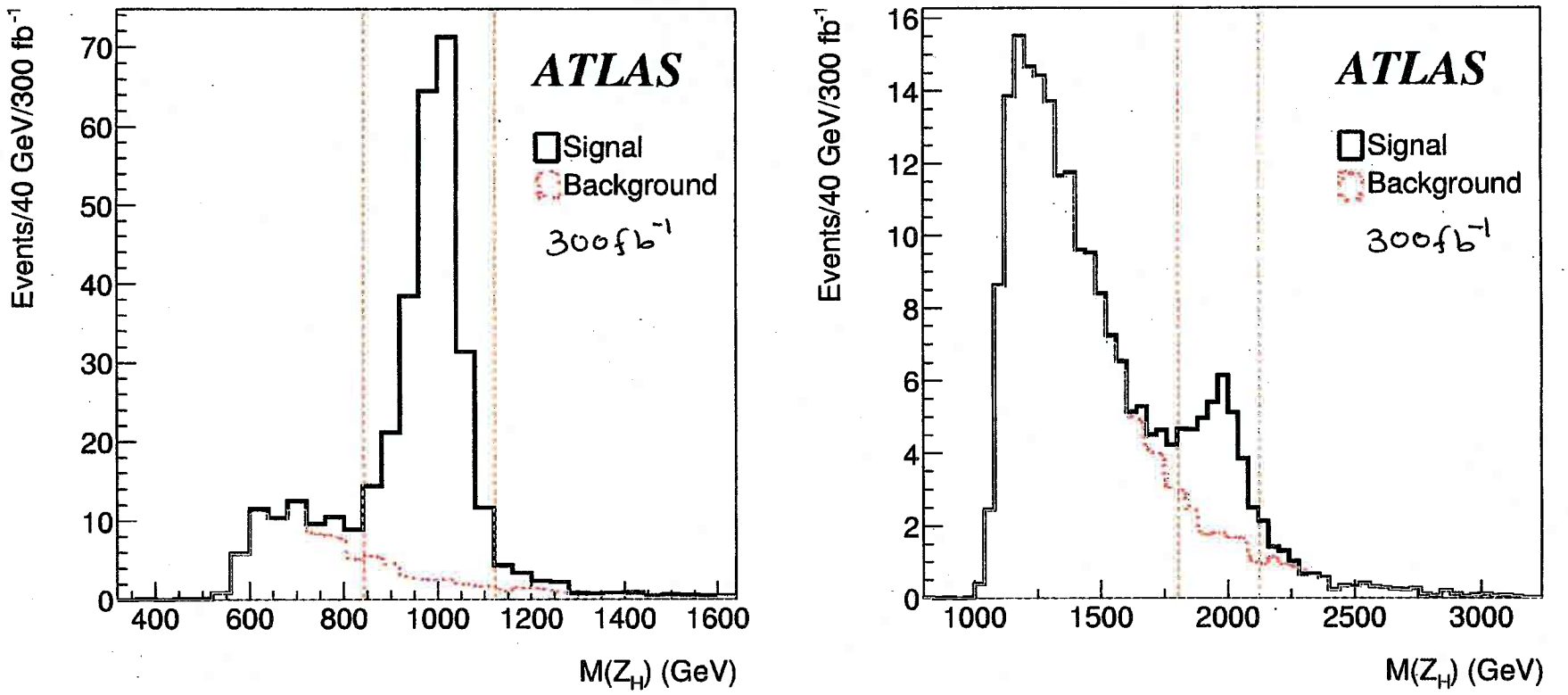


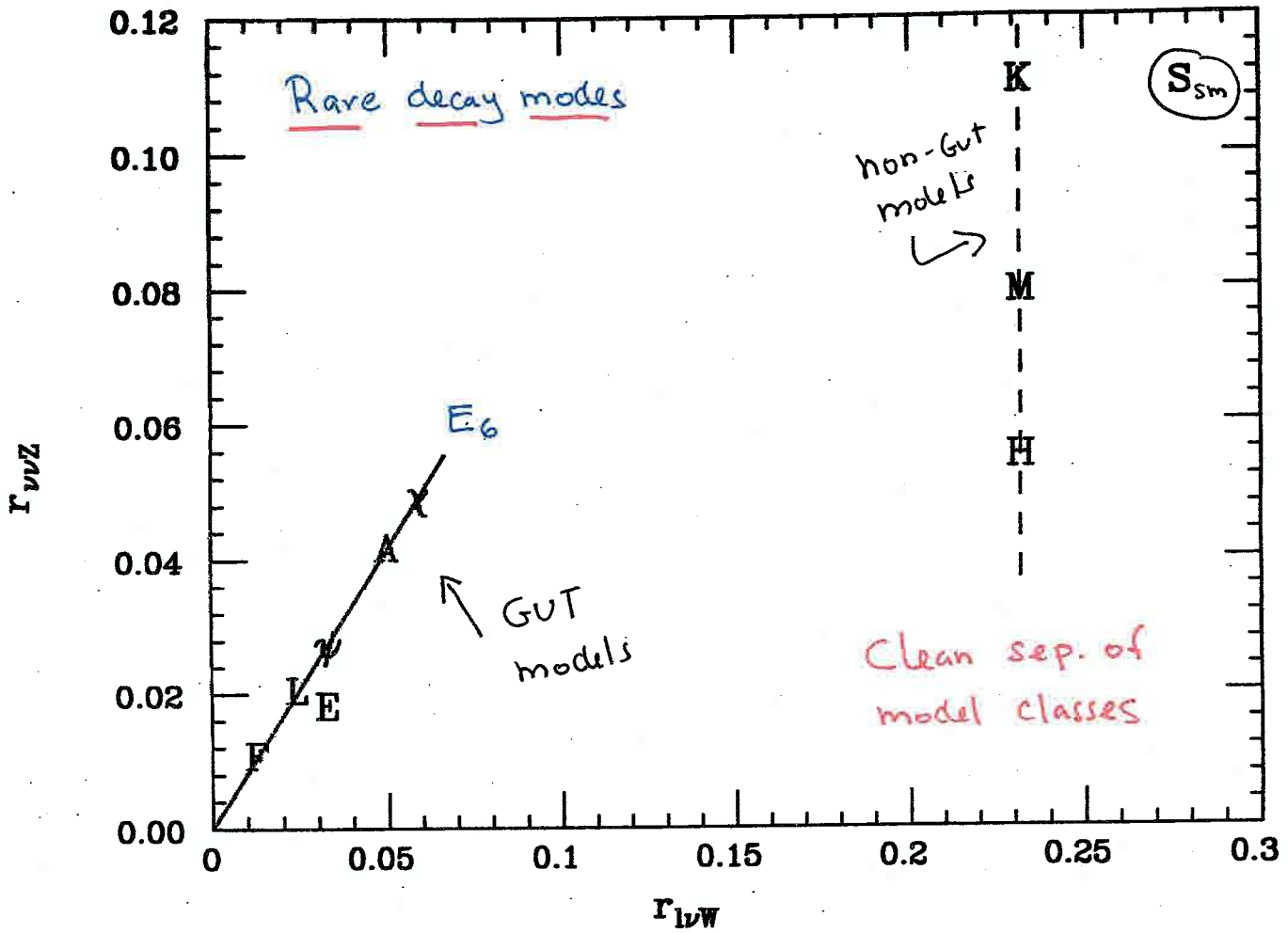
Fig. 1.18. Search study for the decay $Z' \to ZH$ by ATLAS in the Little Higgs model assuming $\cot\theta_H = 0.5$ for the $l^+l^-b\bar{b}$ mode assuming $M_{Z'}$=1 (a) or 2(b) TeV.

Azuelos et al, EPJ C39 S2 S13-S24 (2004)
Ros, Atl-phys-conf-2006-007

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

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

del Agnila, 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

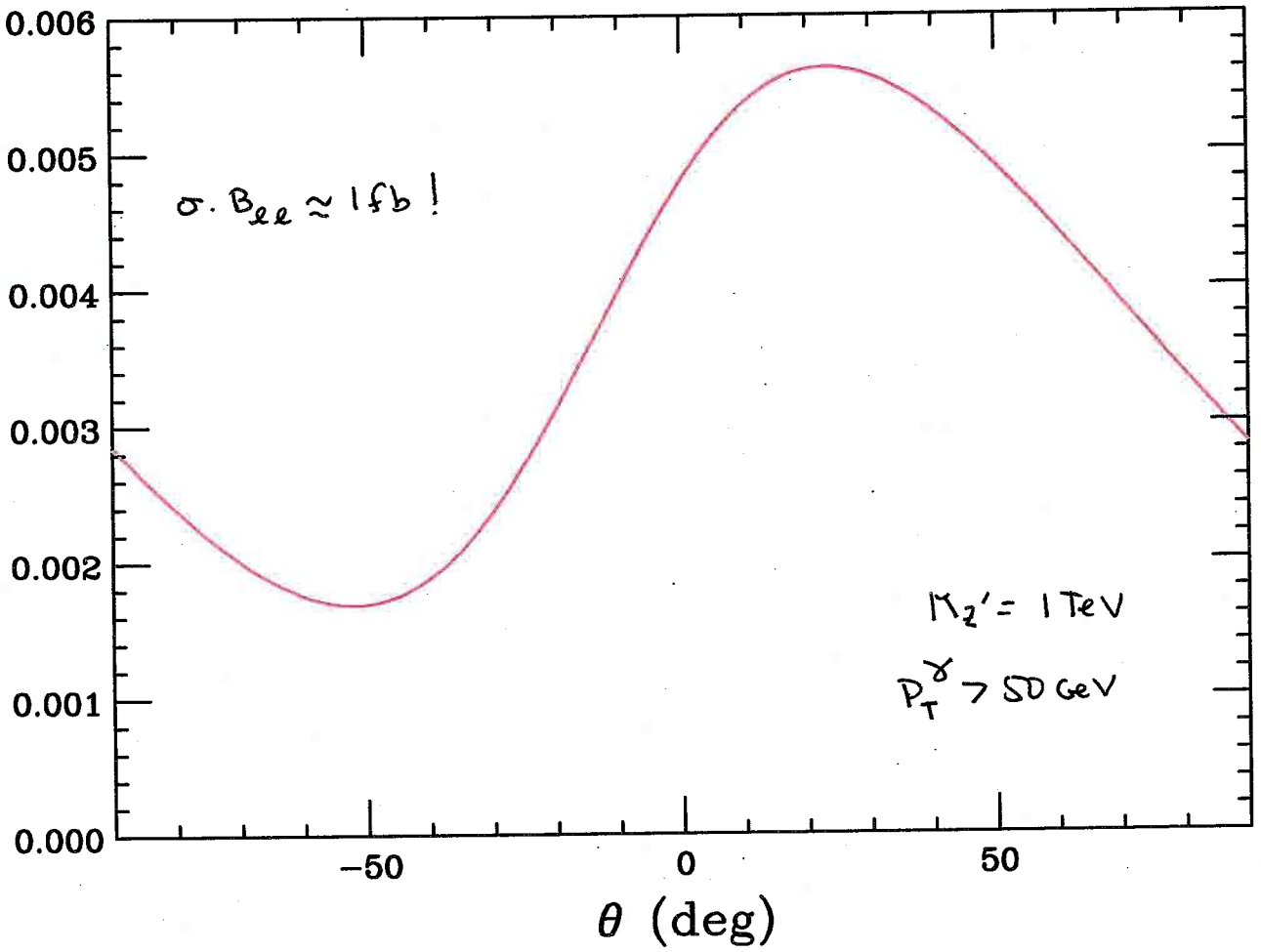
Associated Z' production

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

reweights Z' couplings

e.g, V=W $\quad \sigma \sim (v_q + a_q)^2$

→ strong model sensitivity



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

{ Rizzo ('93)
Langacker + Cvetic

- no experimental studies yet.*

low statistics

* See { Nepomuceno + Marroquim
D.lep/diphot subgroup of Exotics
9/28/06

Conclusions

- A light (~1 TeV) Z' can be rapidly discovered - measure spin!
- LHC data WILL 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 not 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 is discovered.. Experimenters are clever w/ data!!

LHC physics will be exciting!!